The Higgs Portal: Constraints on New Physics

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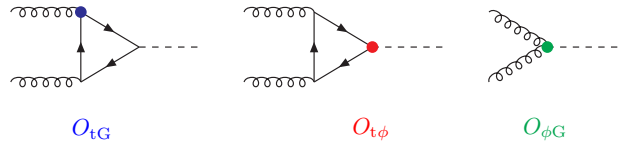
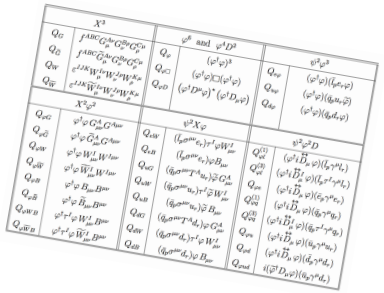
Outline

- Introduction SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

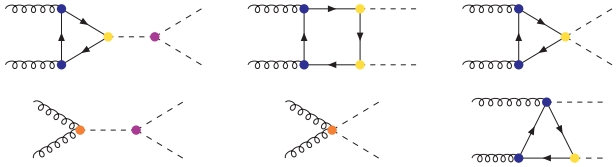
- The Top-Higgs Interface



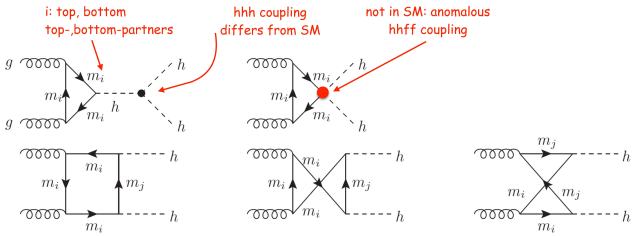


- Global Analysis

- Higgs Pair Production

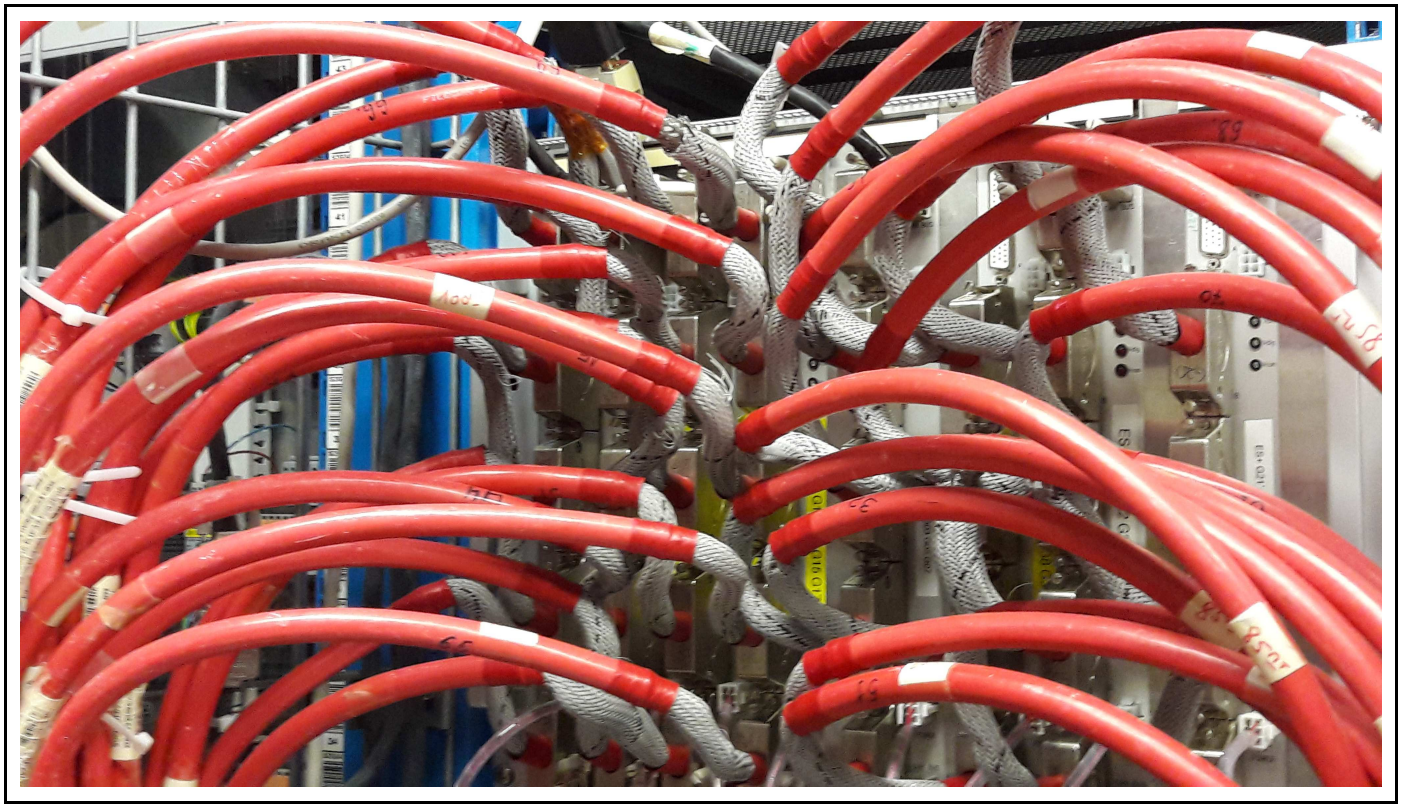


- UV Complete Models - Reality Check



- Conclusions

$\mathcal{S}$M $\mathcal{E}$ffective $\mathcal{T}$heory



Search for New Physics

Model-dependent

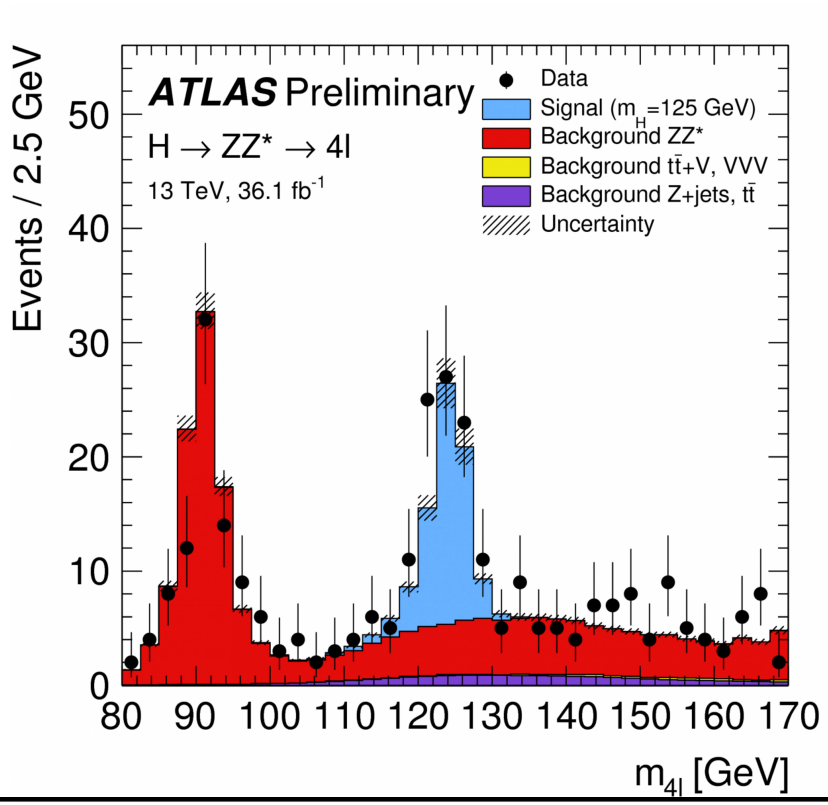
SUSY, 2HDM, composite Higgs, ...

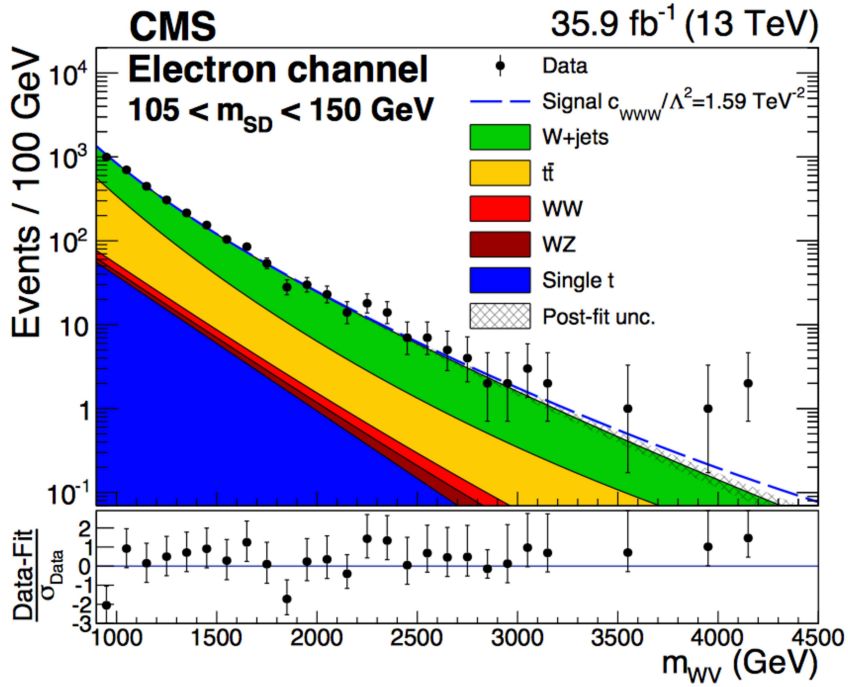
New particles

'Model-independent'

SMEFT, EWChL

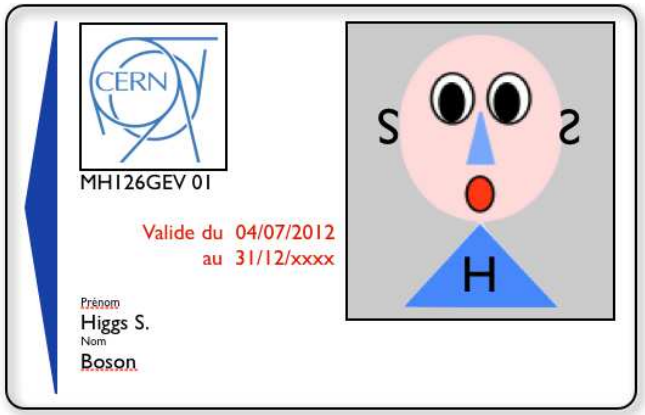
Anomalous couplings





The Higgs Portal to New Physics

Discovery of new scalar particle 4th July 2012



No Direct Discovery of New Physics so Far

How can we use Higgs Fits to access New Physics? What do we learn?

Higgs-Top Combination

Global Fits

EFT Limits on NP

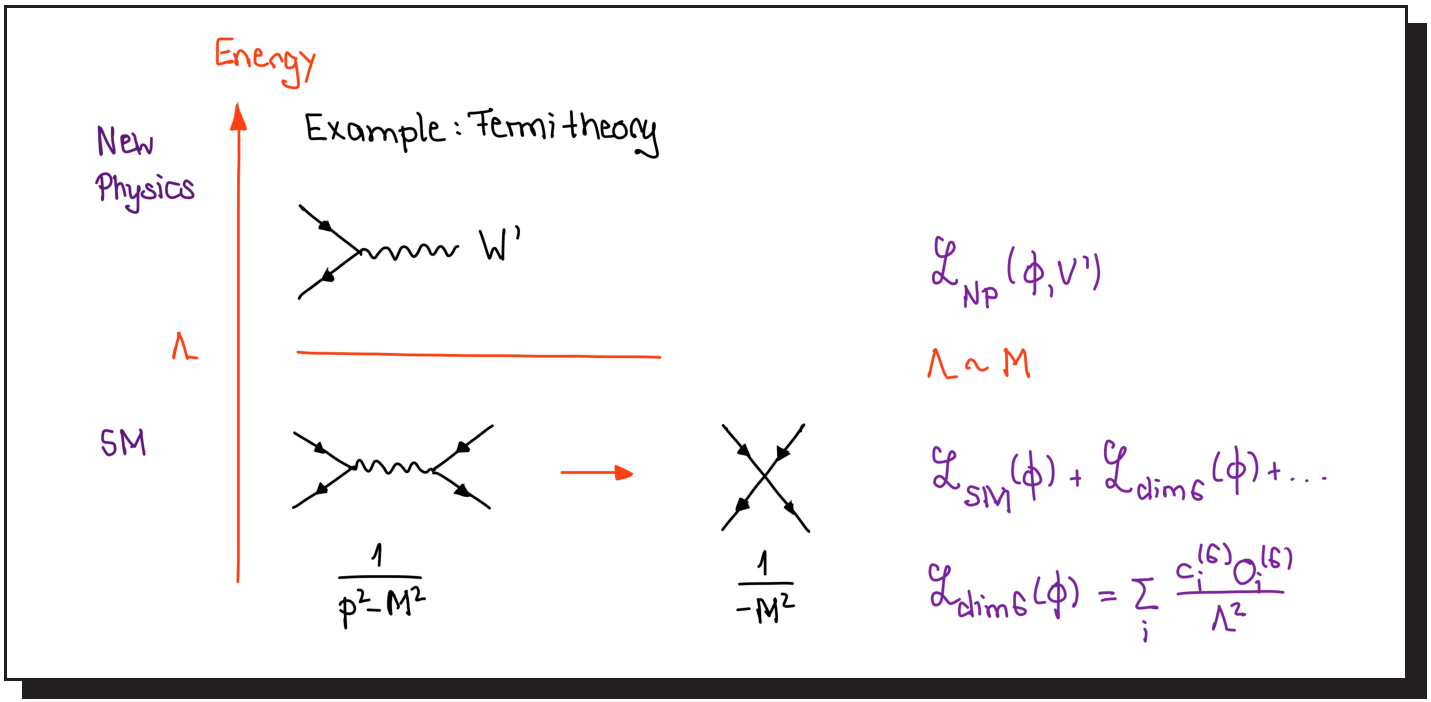
Use of HH information

$\mathcal{S}$M $\mathcal{E}$ffective $\mathcal{T}$heorie ($\mathcal{S}$MEFT)

- **SMEFT Approach:**

[Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal; Hagiwara,Ishihara,Szalapski,Zeppenfeld;Giudice eal]

  - SM field content and SM gauge symmetries, no New Physics at $E < \Lambda$
  - SM deviations: higher-dimensional operators built of SM fields
  - Operators = low-energy remnants of heavy NP integrated out at $\Lambda \Rightarrow$
  - Operators suppressed by scale Λ



$\mathcal{S}$M $\mathcal{E}$ffective $\mathcal{T}$heorie ($\mathcal{S}$MEFT)

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- **New interactions of SM particles:** Higgs part of a doublet field (EWSB linearly realized) $\rightsquigarrow$ leading NP effects described by $D = 6$ operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

$\mathcal{E}$lectroweak $\mathcal{C}$hiral $\mathcal{L}$agrangian (EWChL)

- **SMEFT Approach:** [Burgess,Schnitzer;Leung eal;Buchmüller,Wyler;Grzadkowski eal; Hagiwara,Ishihara,Szalapski,Zeppenfeld;Giudice eal]
  - EWSB linearly realized: Higgs boson part of a weak doublet
  - Additional expansion in $g_* v/\Lambda \ll 1$ (g_* typical coupling of the NP sector)

- **EW Chiral Lagrangian (EWChL):** [Contino eal; Azatov eal; Alonso eal; Brivio eal; Elias-Miró eal; Isidori eal; Buchalla eal]
  - EWSB non-linearly realized: Higgs treated as singlet
  - Chiral expansion

Comments on SMEFT

- **SMEFT approach well established**
  - ◇ numerous analyses on constraining Wilson coefficients of Higgs couplings, e.g.

    [Masso,Sanz '12; Pomarol,Riva '13; Dumon eal '13; Banerjee eal '13; Falkowski(,Riva) ('14)'15; Ellis,(Murphis),Sanz,You '14('18); Corbett eal '12,'15; Edezhath '15; Butter eal '16; Brivio,Trott '17; da Silva Almeida '18, Brivio eal '19 ...]

- **Many tools available**

  SFitter [Lafaye eal, '07,'09]

  FEYNRULES [Alloul,Fuks,Sanz, '13]

  eHDECAY [Contino,Ghezzi,Grojean,MM,Spira '13,'14]

  HPAIR for EFT [Gröber,MM,Spira,Streicher '15]

  Rosetta [Falkowski eal, '15]

  TopFitter [Buckley eal, '15]

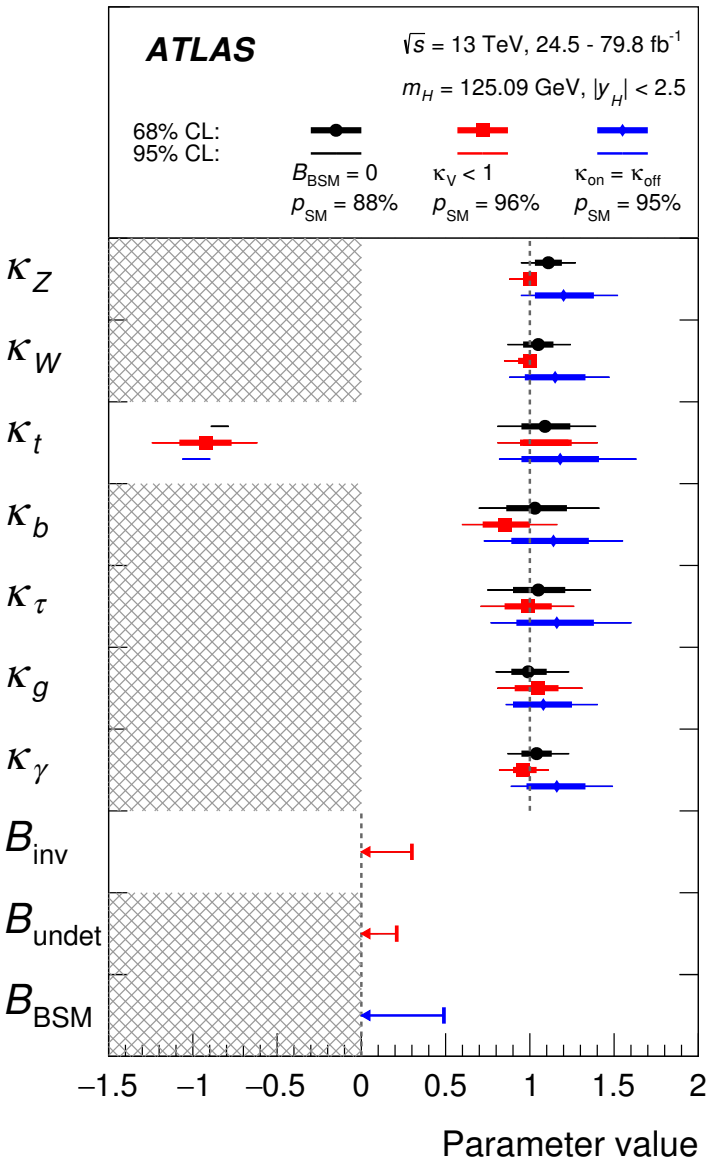
  MadGraph5_aMC@NLO [Alwall eal '14; Zhang '16]

  SMEFiT [Hartland eal '19]

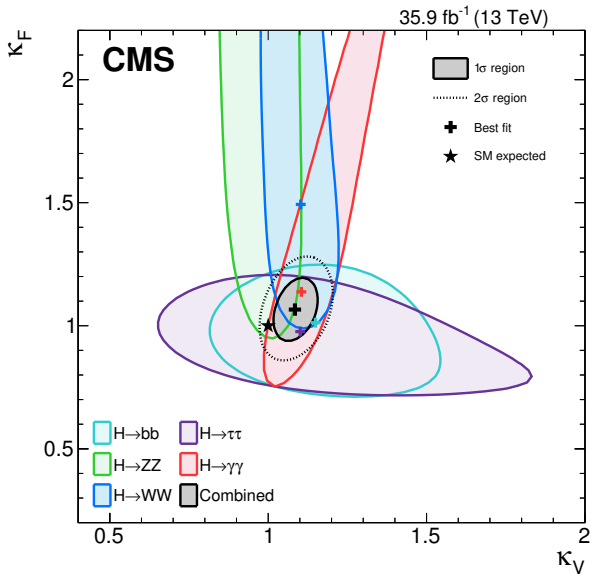
  Higgs characterisation [Artoisenet '13], [Aquino,Mawatari '13], Lilith [Kraml eal '19], ...

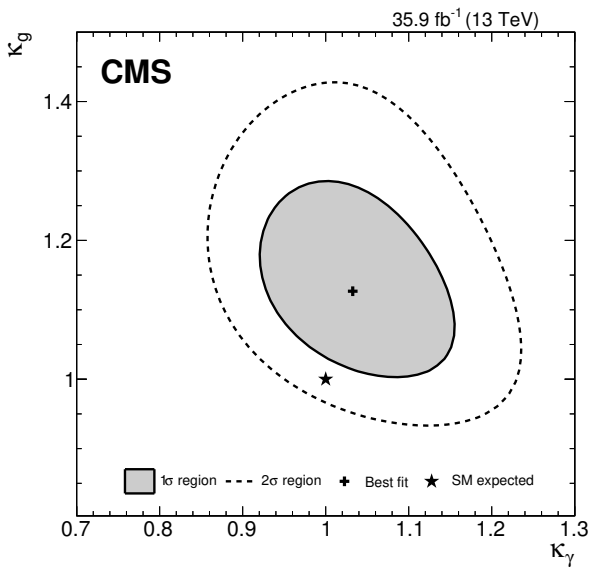
$\mathcal{E}$xperimental $\mathcal{F}$its

[ATLAS Coll., 1909.02845]



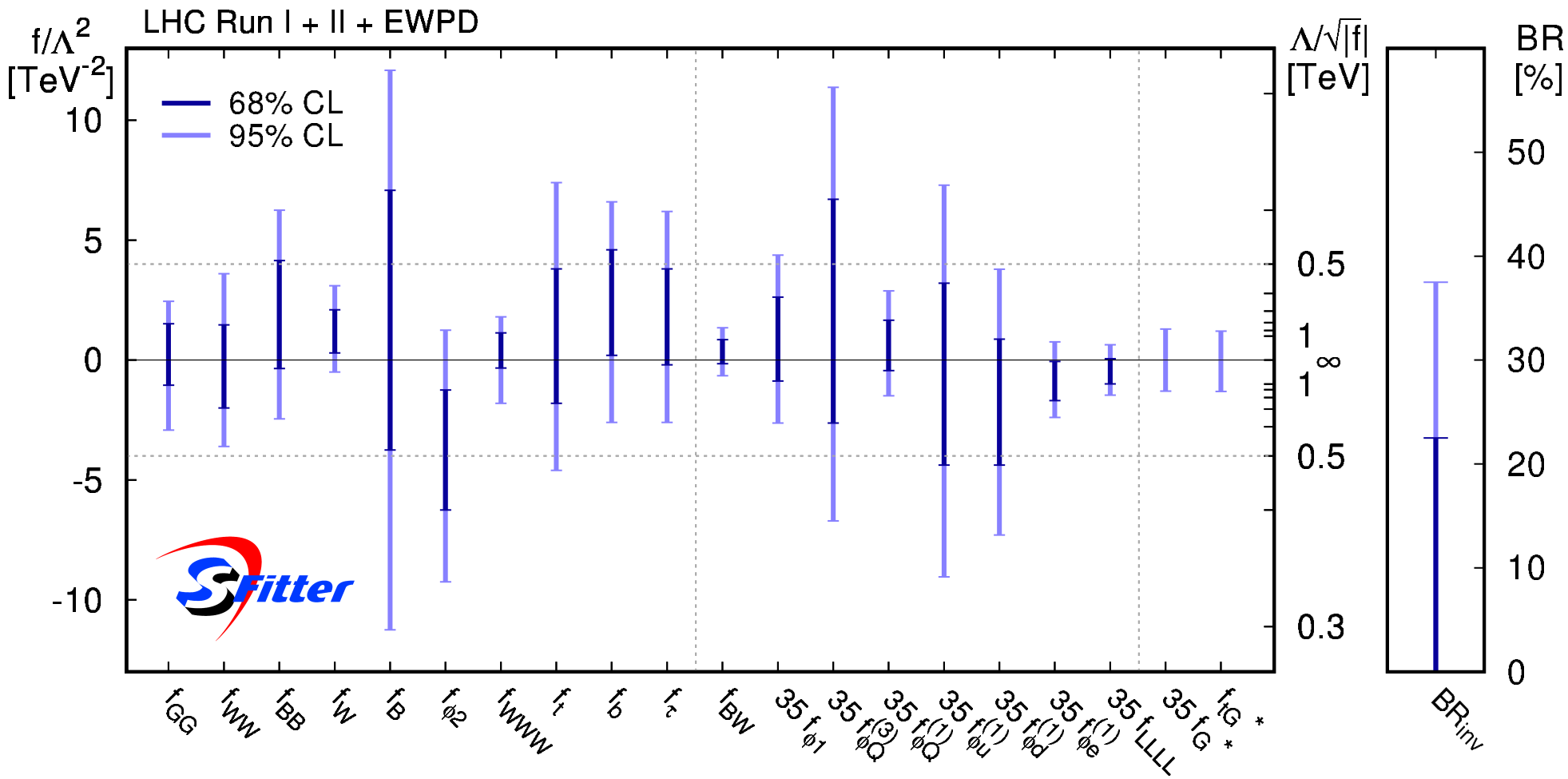
[CMS Coll., 1809.10733]





$\mathcal{S}$MEFT $\mathcal{F}$it

[Biekötter,Corbett,Plehn '19]



$\mathcal{W}$hat about $\mathcal{H}$igher-$\mathcal{O}$rder $\mathcal{C}$orrections in $\mathcal{S}$MEFT?

- **Higher-order corrections in EFT** [Passarino '12; Buchalla eal '18 (EWChL)]
  - ◇ consistent EFT NLO predictions required to match experimental sensitivity
  - ◇ improved predictions, reduced theoretical uncertainties $\rightsquigarrow$ improve limits on EFT operators

What about Higher-Order Corrections in SMEFT?

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	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

Inclusion of chromomagnetic dipole moment in $t\bar{t}$ at LO/NLO [Buarque,Zhang '15].
Limits on c_{tG}/Λ^2 at 95% CL.

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    distributions important in EFT global analyses: resolve degeneracies at inclusive level

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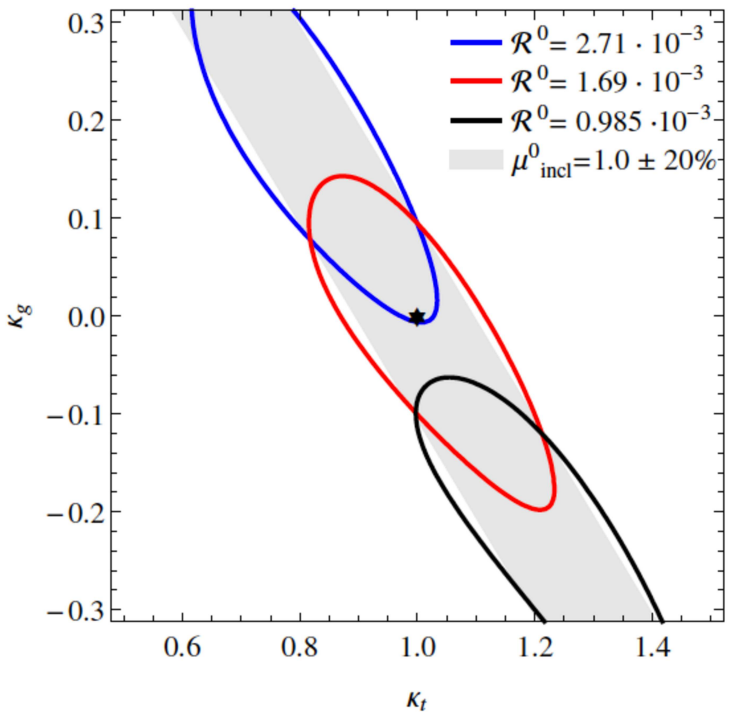
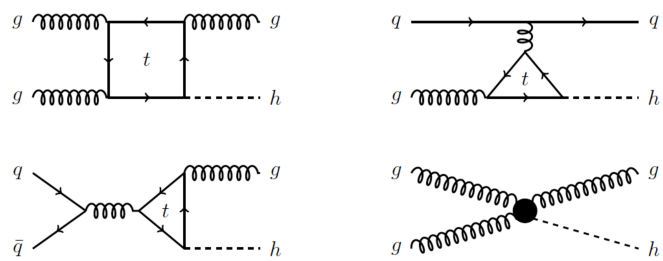


[Grojean,Salvioni,Schlaffer,Weiler '13]



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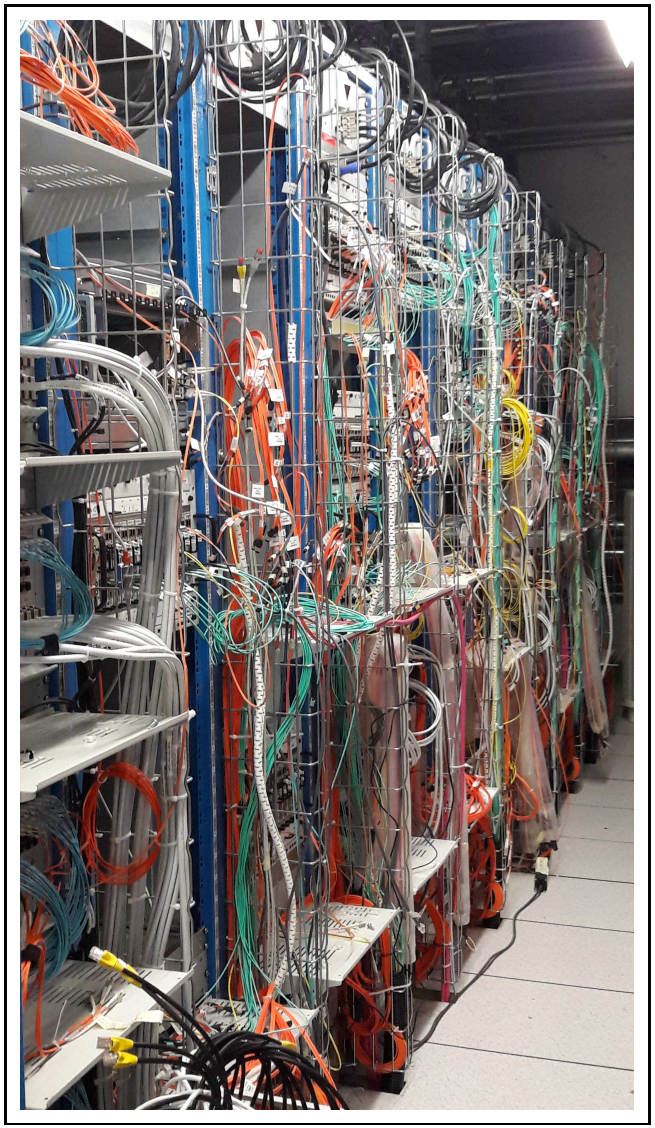
  - ◇ improved predictions, reduced theoretical uncertainties ⇝ improve limits on EFT operators
    [Buarque,Zhang'15;Gauld eal,'15;Hartmann,Trott,'15;Ghezzi eal,'15;Baglio eal,'17,'18,'20;Alioli eal,'18; Chiesa eal,'18;Campanario eal,'14;Granata eal,'17;Azatov eal,'19;Dawson,Giardino,'19,...]
  - ◇ HO corrections distort distributions in non-trivial way
    distributions important in EFT global analyses
    [Ellis eal '14; Edezhath '15; Corbett eal '15; Buckley eal '15; Butter eal '16; Zhang '16;...]
    - ∗ resolve degeneracies among operators at inclusive level
    - ∗ high-energy tail of distributions particularly sensitive to NP
      [Degrande eal'12;Banfi eal'13;Grojean eal'13;Harlander'13;Dawson eal'14;Langenegger al'15;Schlaffer eal,'14;Buschmann Goncalves eal,'14;Buschmann,Englert eal,'14,'18;Cao eal,'15;Azatov eal,'13,'16;Grazzini eal,'16,'17;Maltoni eal,'16,'19;...]
  - ◇ Renormalisation group, operator mixings effects and related uncertainties start to be controlled at NLO
    [Grojean eal '13; Elias-Miro eal '13; Jenkins eal '13; Alonso eal '13;'14; Buchalla eal '20 (EWChL);...]
  - ◇ Increased sensitivity to operators that are loosly constrained and enter at the loop level
    [Degrande eal, '12; Greiner eal '11; Zhang eal '12; Mebane eal '13; Blas eal '15; Elias-Miro eal '13;...]

The Top Higgs Interface



$\mathcal{T}$op $\mathcal{H}$iggs $\mathcal{I}$nterface

- **Importance of the Top-Quark for BSM**

$*$ Top is only fermion with $\mathcal{O}(1)$ Yukawa coupling $\rightsquigarrow$

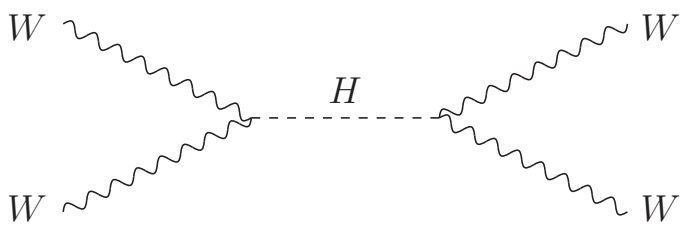
$\mathcal{T}$op $\mathcal{H}$iggs $\mathcal{I}$nterface

- **Importance of the Top-Quark for BSM**

∗ Top is only fermion with $\mathcal{O}(1)$ Yukawa coupling $\rightsquigarrow$

∗ Top plays a privileged role in most BSM scenarios $\rightsquigarrow$ explain EWSB, stabilise the weak scale

Weakly coupled models

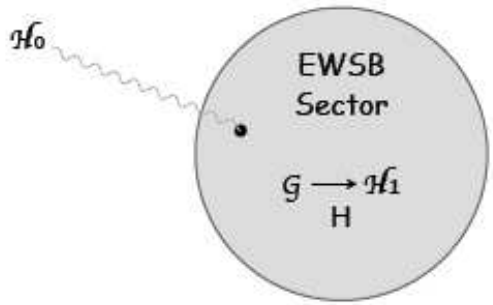


$\mathcal{S}$M, $\mathcal{S}$USY, ...

Stops

New particles necessary to stabilise the Higgs boson mass

Strongly-interacting dynamics



$\mathcal{C}$omposite $\mathcal{H}$iggs

Top partners

Resonances for unitarity

Higgs boson composite object

$\mathcal{T}$op $\mathcal{H}$iggs $\mathcal{I}$nterface

- **Importance of the Top-Quark for BSM**

∗ Top is only fermion with $\mathcal{O}(1)$ Yukawa coupling $\rightsquigarrow$

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∗ λ_{HHH} determination from HH relies on precise knowledge of top-Higgs interaction

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* Top is only fermion with $\mathcal{O}(1)$ Yukawa coupling $\rightsquigarrow$
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* λ_{HHH} determination from HH relies on precise knowledge of top-Higgs interaction

- **No global fit to all SMEFT operators**

- **Fits in the Top Sector**

* `TopFitter` Collaboration [Buckley eal, 1506.08845, 1512.03360]
* `SMEFiT` [Hartland eal, 1901.05965]
* `SFitter` [Lafaye eal; 0709.3985, 0904.3833]
* Further EFT analyses of the top quark sector at hadron colliders, e.g.:

  [Zhang eal, '12,'17; Durieux eal, '14;Aguilar-Saavedra, '10,'16; Englert, '16; Maltoni eal, '16; Alioli eal, '17; Degrande eal, '12,'18; D'Hondt eal, '18; Chala eal, '18; Brivio eal, '19]

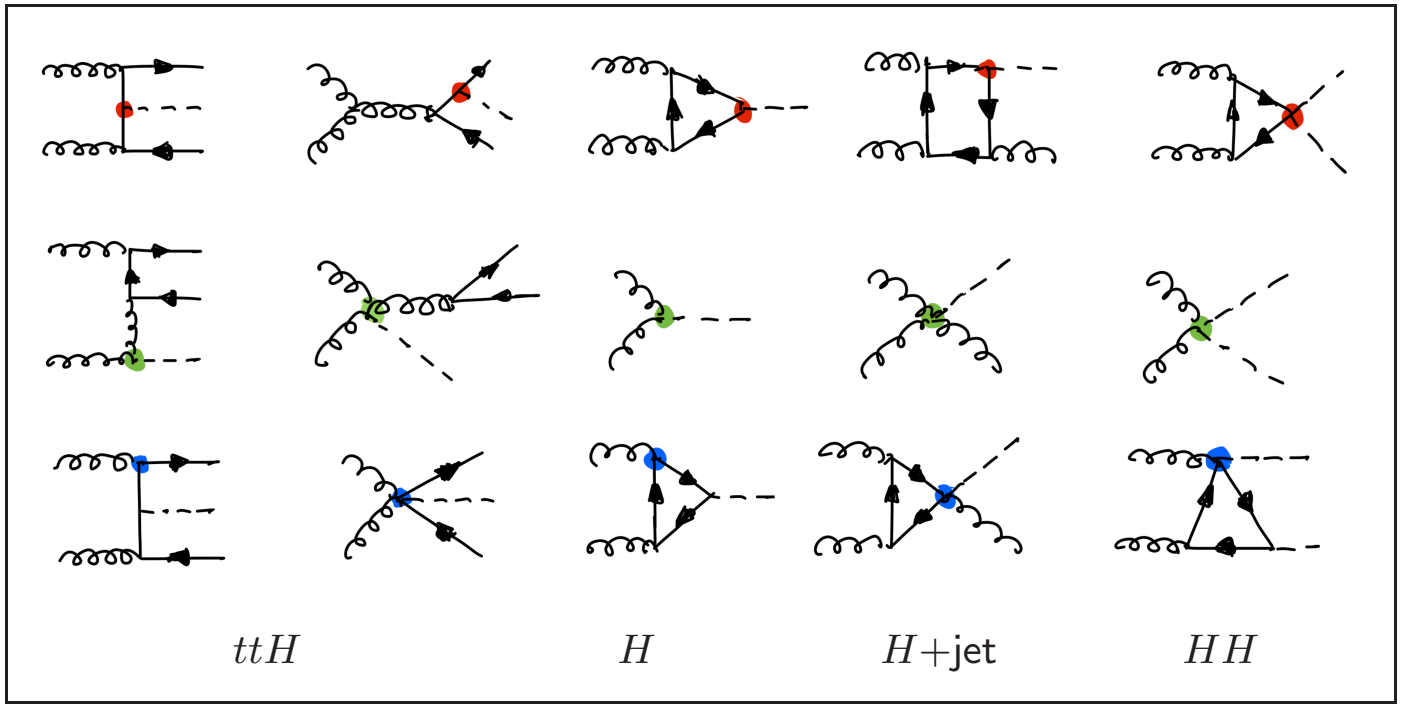
Top Higgs Interface - Relevant Operators

- **D6 operators at the top-Higgs interface** see e.g., [Degrande eal,'12;Grojean eal,'13;Dawson eal'14; Maltoni eal,'16,'17; Azatov eal,'16;Harlander eal'16;Anastasiou eal'16;Deutschmann eal,'17;Grazzini eal'16,'17;Hartland eal,'19]

$O_{t\phi} = (\phi^\dagger \phi)(\bar{Q}\tilde{\phi}t) + h.c.$

$O_{\phi G} = (\phi^\dagger \phi) G^a_{\mu\nu} G^{a\mu\nu}$

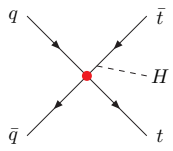
$O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^a t)\phi G^a_{\mu\nu} + h.c$



$\mathcal{R}$emarks

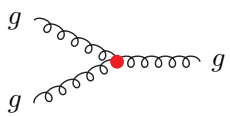
- **Further operators** to be considered in these processes:

- **Four-fermion operators:**
  affect $t\bar{t}H$ production



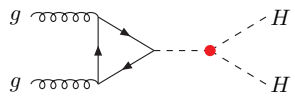
[Zhang, Willenbrock '10; Grzadkowski eal '10]

- **Gluon dim-6 operator:**
  $O_G = f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$ affects all SMEFT analyses
  constrained from multijet signatures; $\Lambda/\sqrt{c_G} > 4$-5 TeV



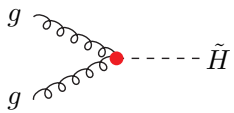
[Krauss eal, 1611.00767]

- **Higgs Self-interaction:**
  $O_6 = -(\phi^\dagger \phi)^3$, modifies Higgs self-interaction in Higgs pair production, see e.g.



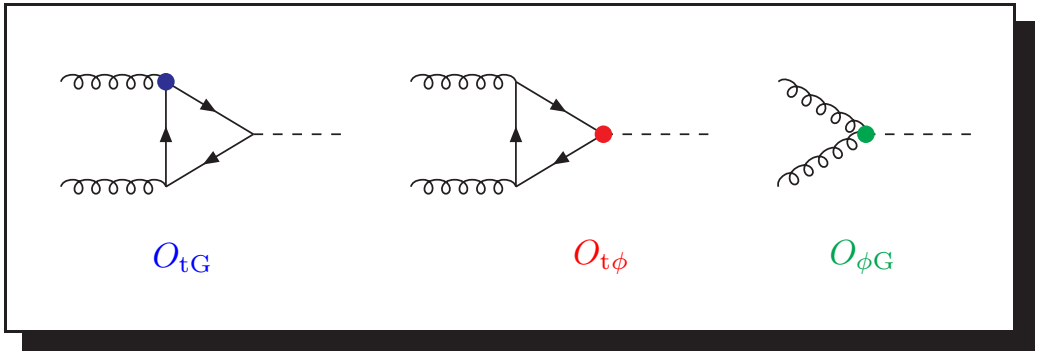
[Contino eal,'12; Goertz eal,'14; Azatov eal,'15; Gröber,MM,Spira,Streicher,'15;Buchalla eal,'18; Grazzini eal,'18; Heinrich eal,'19]

- **CP-violating operators:**
  can be left out under the assumption of CP conservation



For CP-violating effects, see $e.g.$ [Gröber,MM,Spira '17;Dorival eal '18;Englert eal '19]

$\mathcal{S}$MEFT in $\mathcal{H}$iggs $\mathcal{P}$roduction



$\frac{c_1}{\Lambda^2} O_{\phi G} \quad \rightarrow \quad \frac{\alpha_s}{\pi v} c_g h G^a_{\mu\nu} G^{a\mu\nu}$ controls Higgs gluon interaction

$\frac{c_{2/3}}{\Lambda^2} O_{q\Phi} \quad \rightarrow \quad \frac{m_q}{v} c_q h q\bar{q} \quad q = t, b$ modification of Higgs-t/b coupling

$\frac{c_4}{\Lambda^2} O_{tG} \quad \rightarrow \quad c_{tg} \frac{g_s m_t}{2v^3} (v+h) G^a_{\mu\nu} (\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c.)$ chromomagnetic dipole operator

modifies top-gluon interaction

ggH exhibits a two-fold degeneray in the $O_{t\phi} - O_{\phi G}$ and $O_{tG} - O_{\phi G}$ operators.

How can we resolve this degeneracy?

For EFT ggH, see e.g. [Choudhury '12;Degrande '12;Dawson eal'14;Chien eal '15;Schmidt, Spira '15;Harlander eal '13,'16; Anastasiou eal '16; Grazzini eal '16'17;Maltoni eal '16,'17;Deutschmann eal '17]

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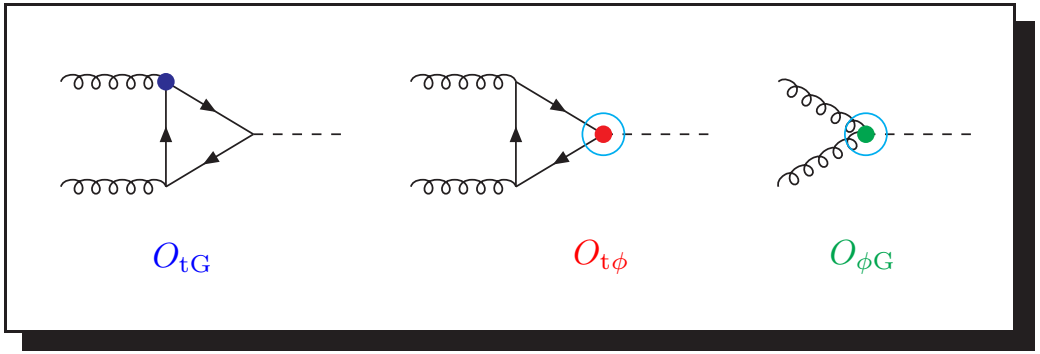

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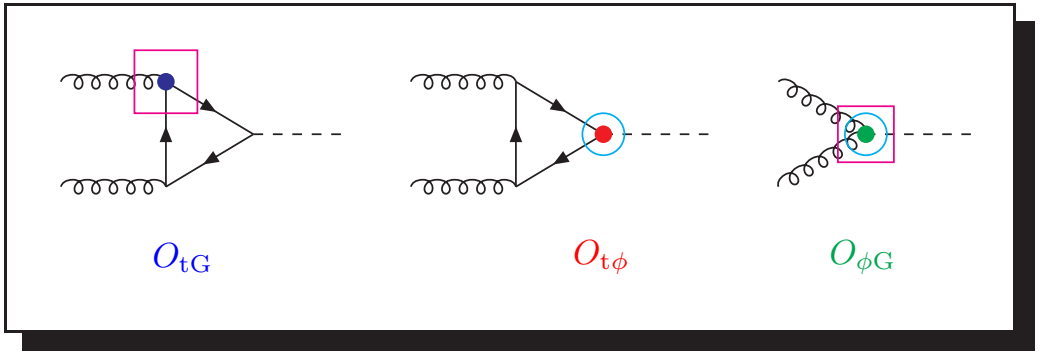

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$\frac{c_4}{\Lambda^2} O_{tG} \quad \rightarrow \quad c_{tg} \frac{g_s m_t}{2v^3} (v+h) G^a_{\mu\nu} (\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c.)$ chromomagnetic dipole operator

modifies top-gluon interaction

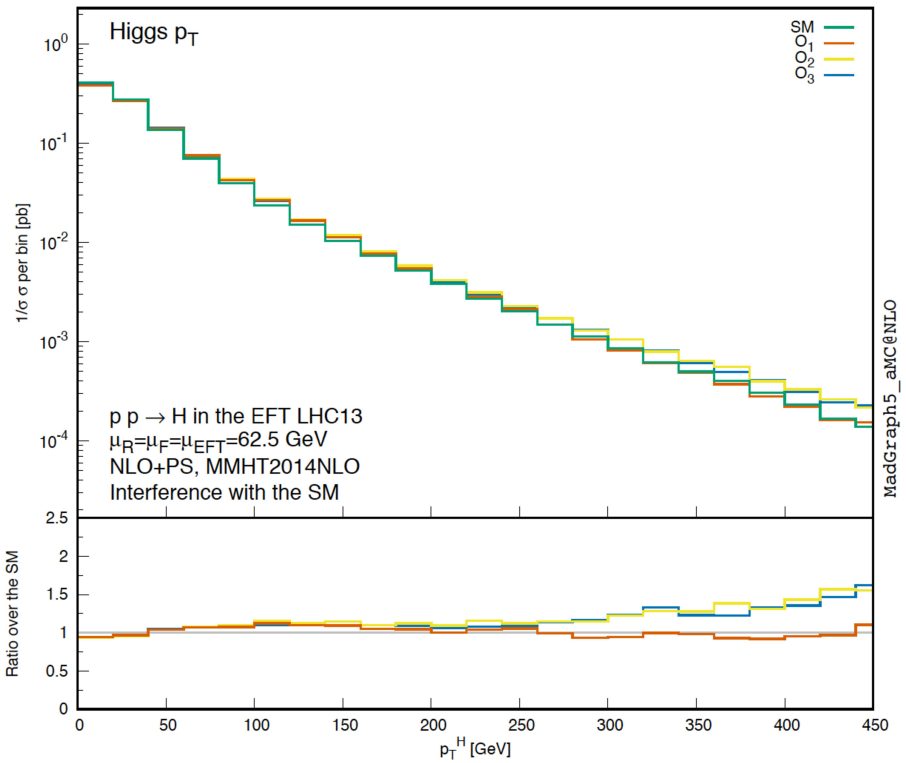
ggH exhibits a two-fold degeneray in the $O_{t\phi} - O_{\phi G}$ and $O_{tG} - O_{\phi G}$ operators.

How can we resolve this degeneracy?

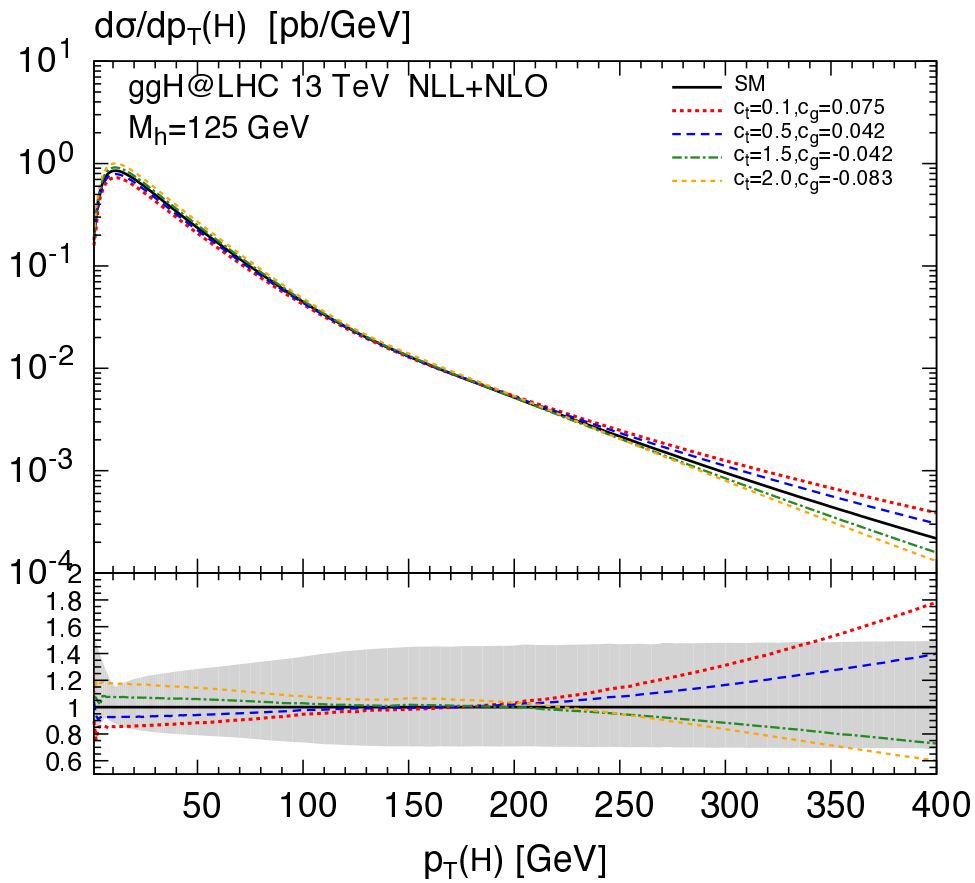
For further works on resolving the degeneracy, see e.g. [Azatov eal '13,'16;Banfi eal '13;Grojean eal '13;Buschmann,Goncalves eal '14; Buschmann,Englert eal '14,'18;Schlaffer eal '14;Cao eal '15;Langenegger eal '15]

The Role of Distributions

[Deutschmann, Duhr, Maltoni, Vryonidou, 1708.00460]



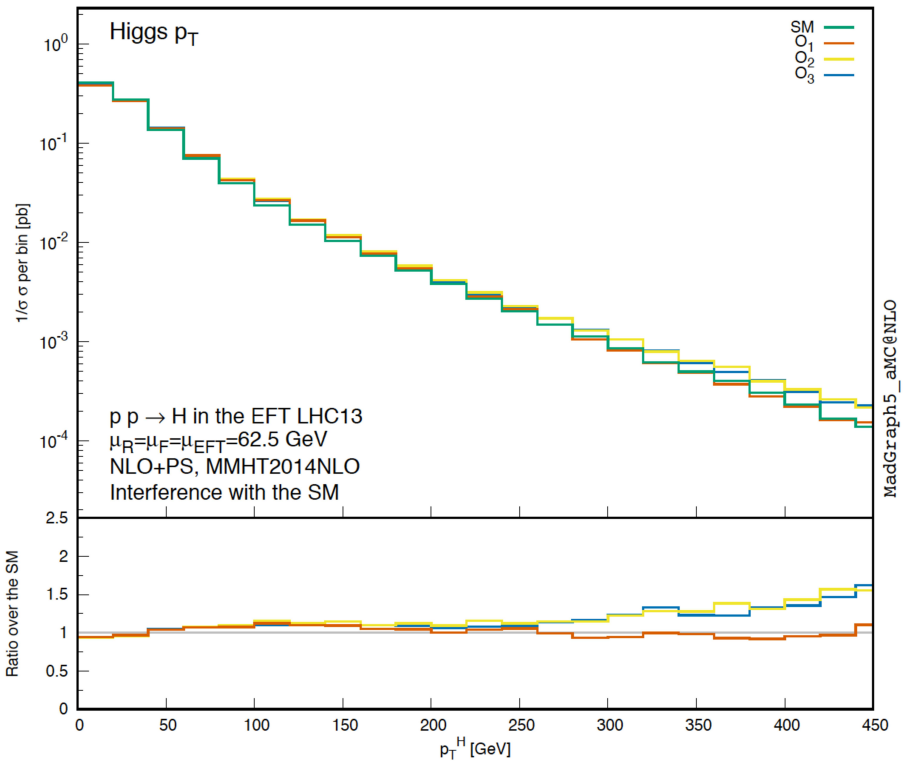
[Grazzini, Ilnicka, Spira, Wiesemann, 1612.00283]



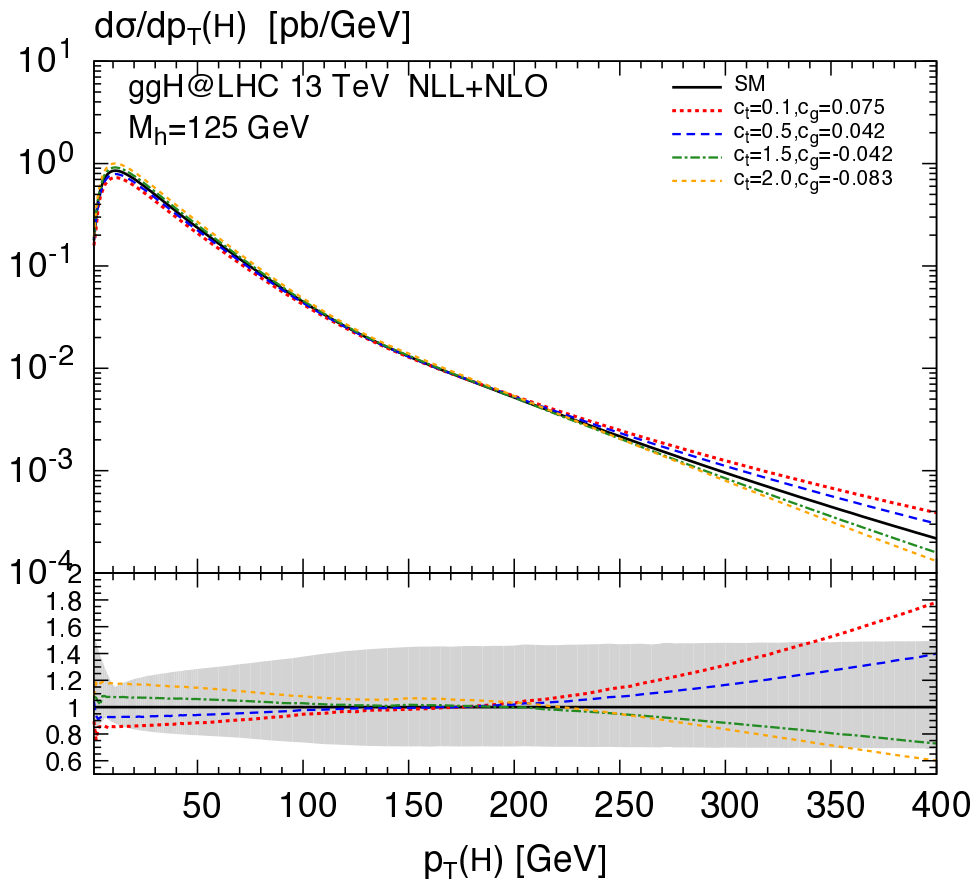
left: O_1: c_t, O_2: c_g, O_3: c_{tg}

The Role of Distributions

[Deutschmann, Duhr, Maltoni, Vryonidou, 1708.00460]



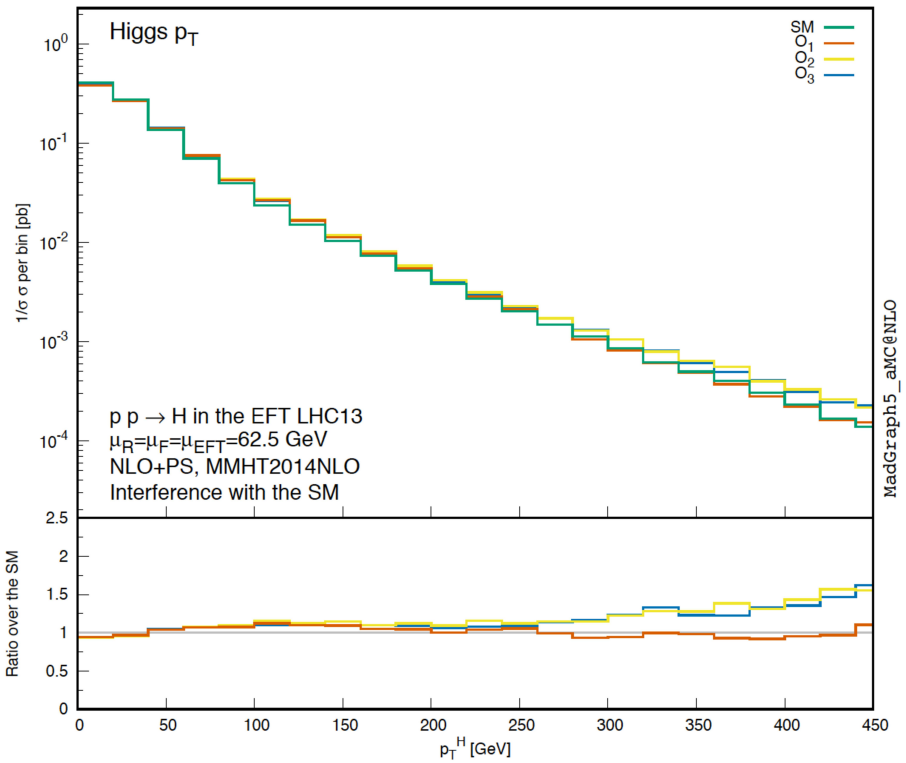
[Grazzini, Ilnicka, Spira, Wiesemann, 1612.00283]



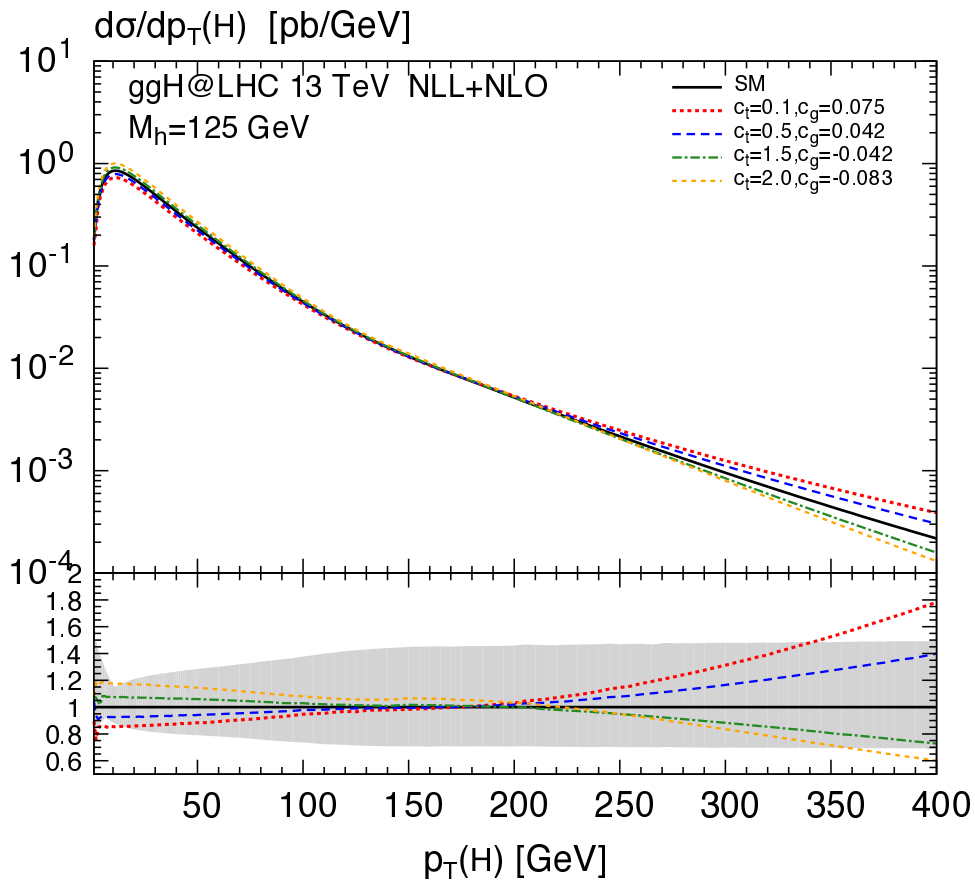
c_b sizeable effects at small p_T, c_g at high p_T, c_t rescaling of spectrum

The Role of Distributions

[Deutschmann, Duhr, Maltoni, Vryonidou, 1708.00460]



[Grazzini, Ilnicka, Spira, Wiesemann, 1612.00283]



c_g, c_{tg} similar shapes w/ harder tail than c_t, not distinguishable; $H, H+j, t\bar{t}H \rightsquigarrow$ constrain all 3

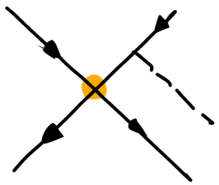
$\mathcal{R}$esolve the $\mathcal{D}$egeneracy

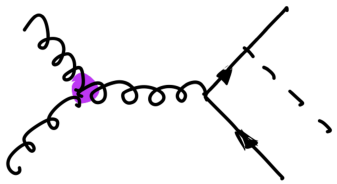
- **Two-fold degeneracy of $gg \to H$**
  - ◇ in $O_{t\phi}$-$O_{\phi G}$ and O_{tG}-$O_{\phi G}$
  - ◇ use $pp \to H$, $pp \to t\bar{t}H$, $pp \to Hj$ to resolve degeneracy

$\mathcal{R}$esolve the $\mathcal{D}$egeneracy

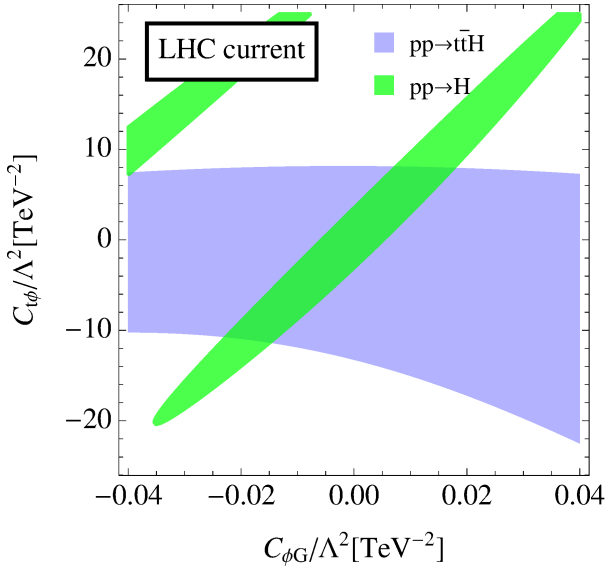
- **Not included in analysis:**
  - ◇ four-fermion operators: $t\bar{t}$ to constrain four-fermion operators
  - ◇ gluon dim-6 operators: constrainted from multi-jet production
    [Krauss,Kuttimalai,Plehn, 1611.00767]

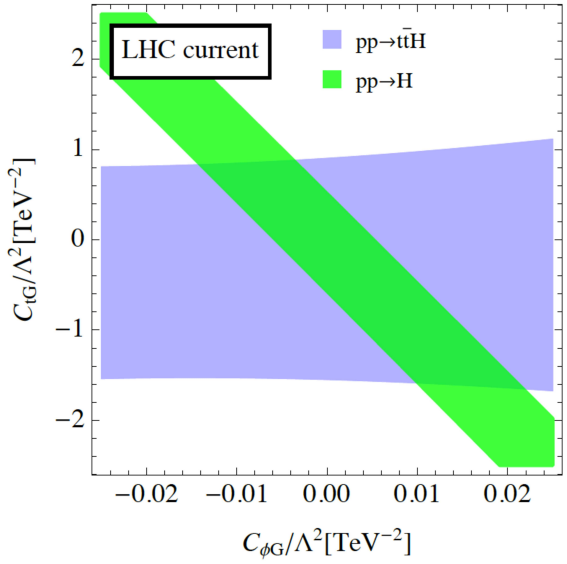
4-fermion and gluon operator in $t\bar{t}H$:





Resolve the Degeneracy

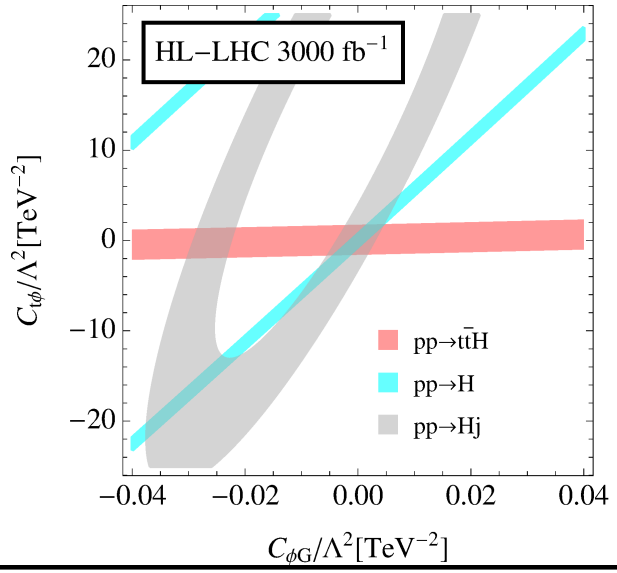


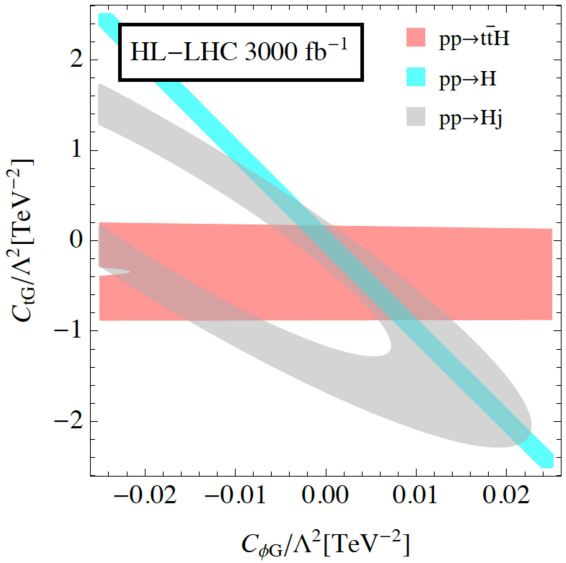


[Maltoni,Vryonidou,Zhang, 1607.05330]

current limits using LHC measurements

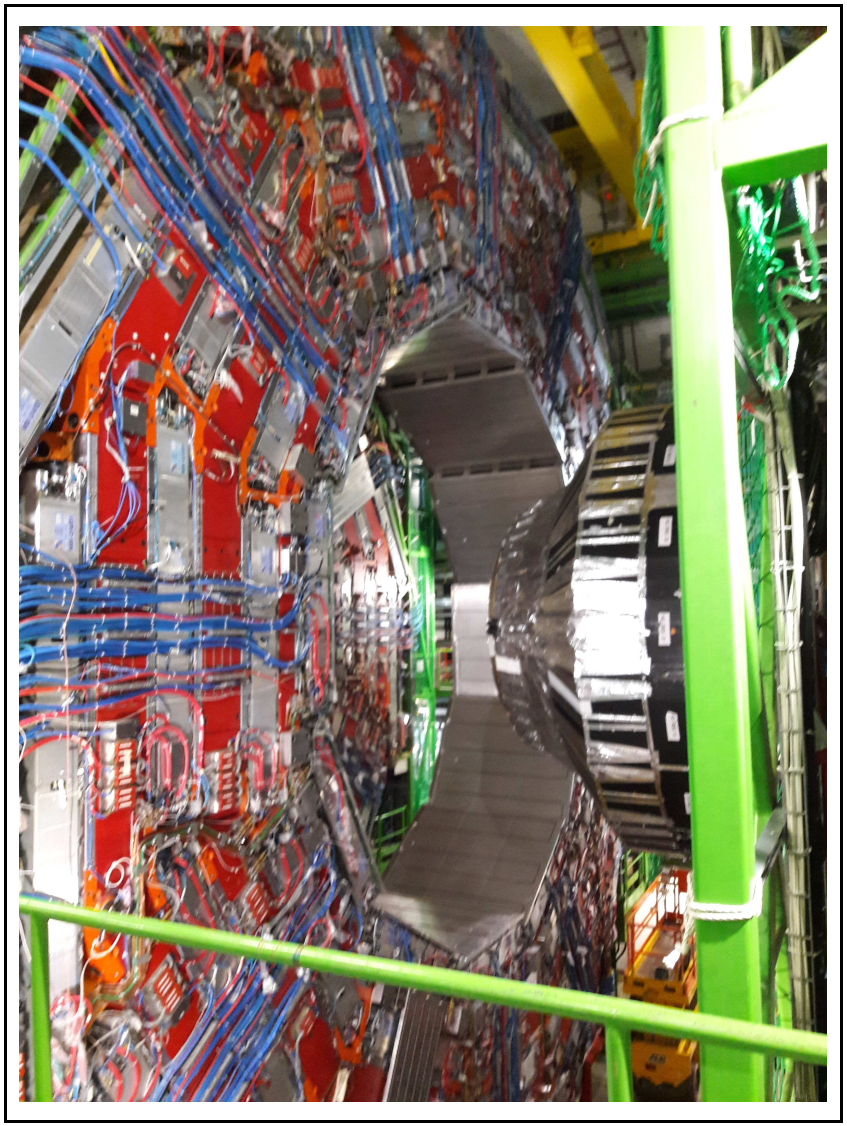
Higgs measurements start to become sensitive to O_{tG}





14 TeV projection 3000 fb^{-1}

Global Analysis



What About A Global Fit?

- **SMEFT analysis**

∗ Model and basis independence: *All* relevant operators need to be included

∗ Number of non-redundant dim-6 operators for 3 generations: 2499, 59 for 1 generation

[Grzadkowski eal; Alonso eal.]

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

$\mathcal{W}$hat $\mathcal{A}$bout $\mathcal{A}$ $\mathcal{G}$lobal $\mathcal{F}$it?

- **SMEFT analysis**

∗ Model and basis independence: *All* relevant operators need to be included

∗ Number of non-redundant dim-6 operators for 3 generations: 2499, 59 for 1 generation

[Grzadkowski eal; Alonso eal.]

∗ Global fit: complicated parameter space w/ many degenerate/flat directions and local minima $\rightsquigarrow$

∗ No global simultaneous fit to *all* operators available

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∗ Global fit: complicated parameter space w/ many degenerate/flat directions and local minima $\rightsquigarrow$

∗ No global simultaneous fit to *all* operators available

- **Practial approach - reduce number of operators by**

∗ symmetry assumptions, *e.g.* flavour, CP conservation

∗ focus on subsectors: Higgs, electroweak, top, Higgs-electroweak, top-Higgs, ...:

◇ include only operators relevant to the particle(s)/processes considered

◇ assume other operators well constrained from different processes

◇ note: not always justified!

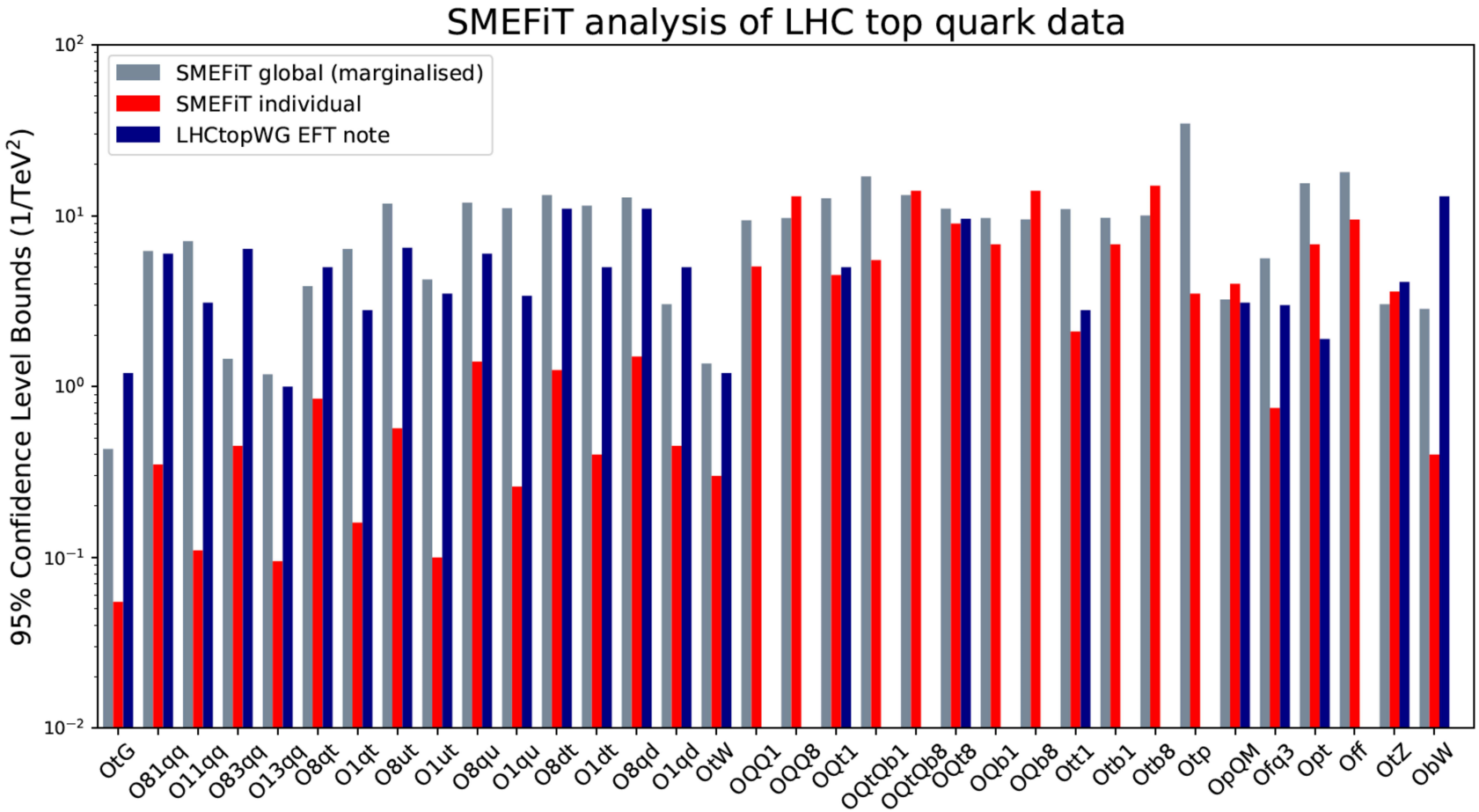
$\mathcal{M}$C $\mathcal{G}$lobal $\mathcal{A}$nalysis of $\mathcal{S}$MEFT in the $\mathcal{T}$op $\mathcal{S}$ector

[Hartland,Maltoni,Nocera,Rojo,Slade,Vryonidou,Zhang 1901.05965]

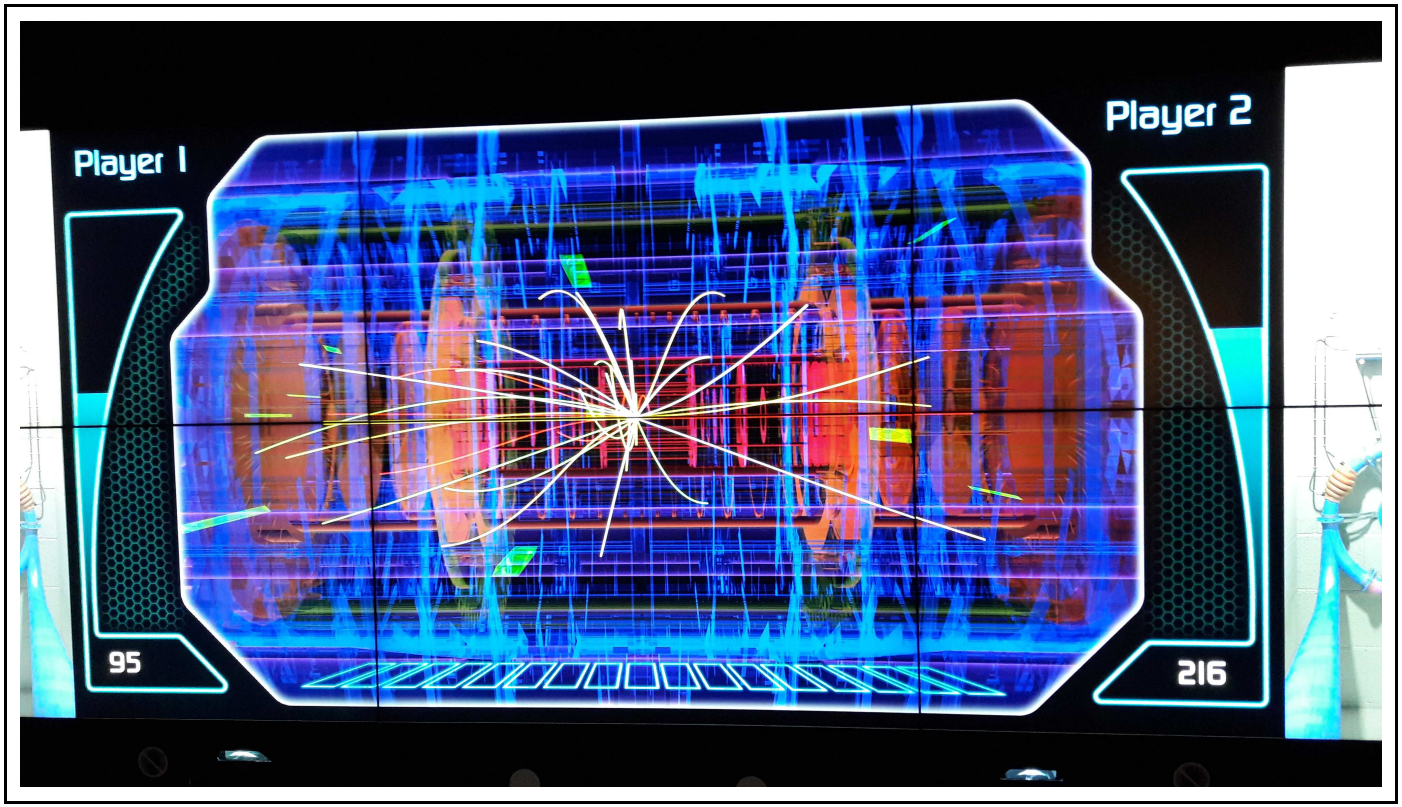
- **Towards a global analysis:** `SMEFiT`
  - presently included processes: $t\bar{t}$, single t, $t(\bar{t})V$, $t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$, $t\bar{t}H$
  - $N_{\text{op}} = 34$ dim-6 operators (Warsaw basis) relevant for top-sector (extension in progress)
  - inclusion of HO QCD corrections and $\mathcal{O}(\Lambda^{-4})$ effects

$\mathcal{T}$owards a $\mathcal{G}$lobal $\mathcal{A}$nalysis: $\mathcal{S}$MEFiT

$t\bar{t}$, single t, $t(\bar{t})V$, $t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$, $t\bar{t}H$ Hartland eal '19



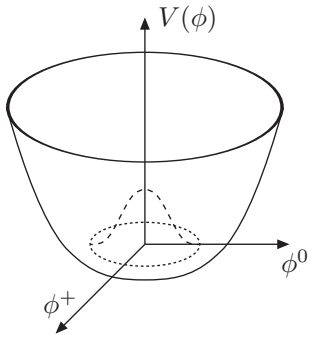
Higgs Pair Production

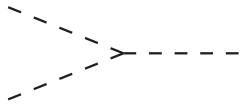


$\mathcal{U}$ltimate $\mathcal{T}$est of the $\mathcal{H}$iggs $\mathcal{M}$echanism

The EWSB potential:

$$V(H) = \frac{1}{2!}\lambda_{HH}H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^4$$



$\mathcal{T}$rilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
$\mathcal{Q}$uartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	

$\mathcal{M}$easurement of the scalar boson self-couplings
and
$\mathcal{R}$econstruction of the EWSB potential

$\mathcal{E}$xperimental verification
$\mathcal{O}$f the scalar sector of the
$\mathcal{E}$WSB mechanism

Determination of the scalar boson self-couplings at colliders:

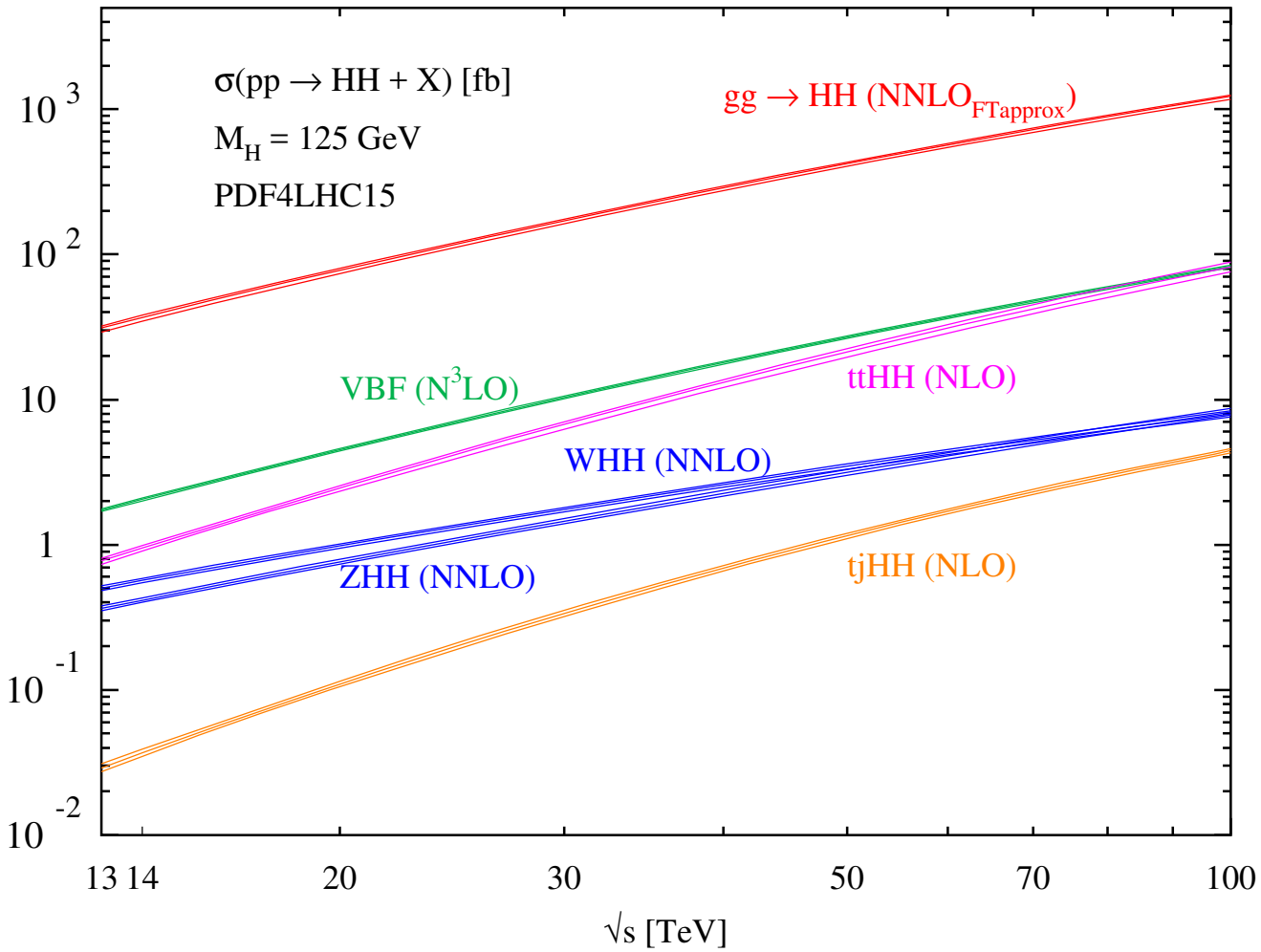
λ_{HHH} via pair production

λ_{HHHH} via triple production

radiation off W/Z, $t\bar{t}$, WW/ZZ fusion, gg fusion

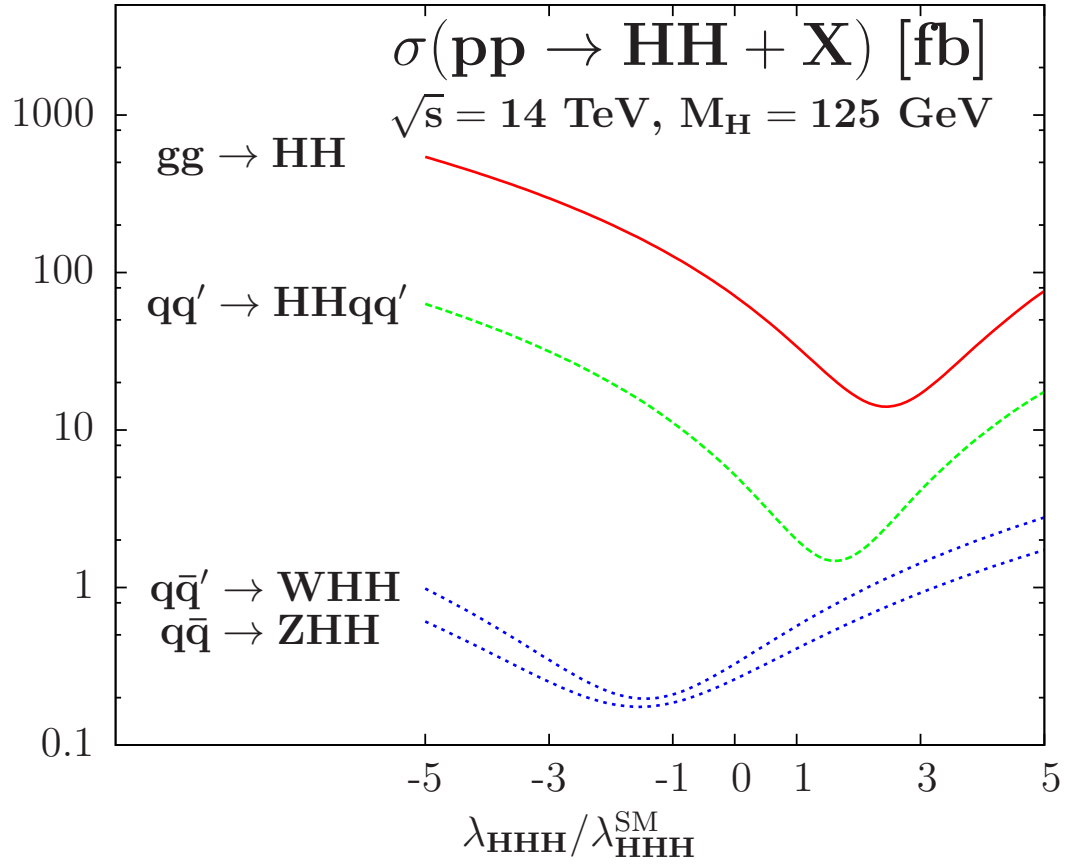
SM Higgs Pair Production

HH White Paper, '19



Dependence on Higgs Self-Coupling

[Baglio,Djouadi,Gröber,MM,Quevillon,Spira]



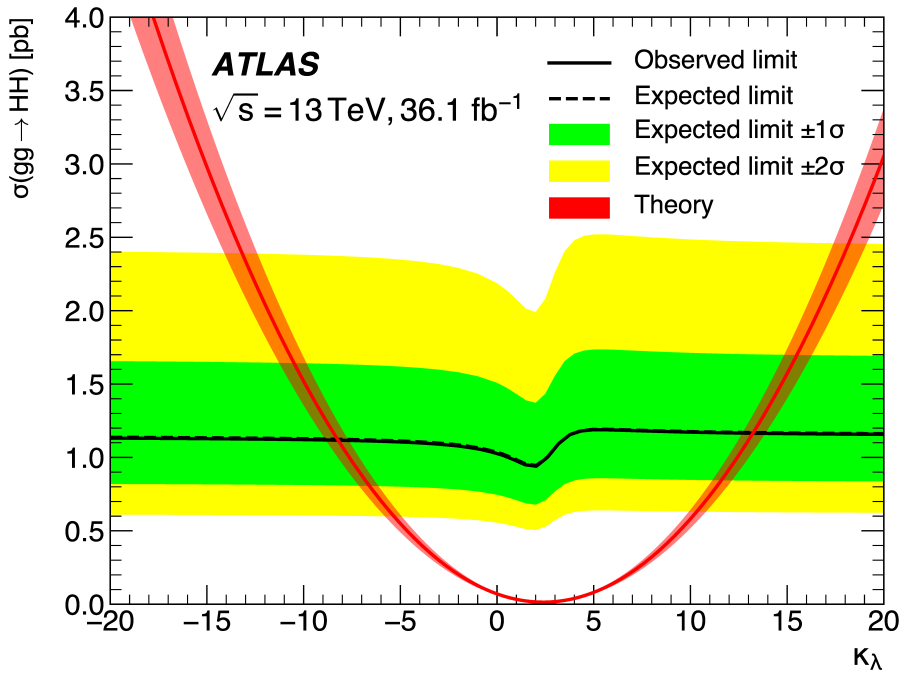
- threshold region sensitive to λ; large M_{HH} sensitive to New Physics
- $gg \to HH$: $\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$; decreasing with M_{HH}^2

Challenge Di-Higgs Production

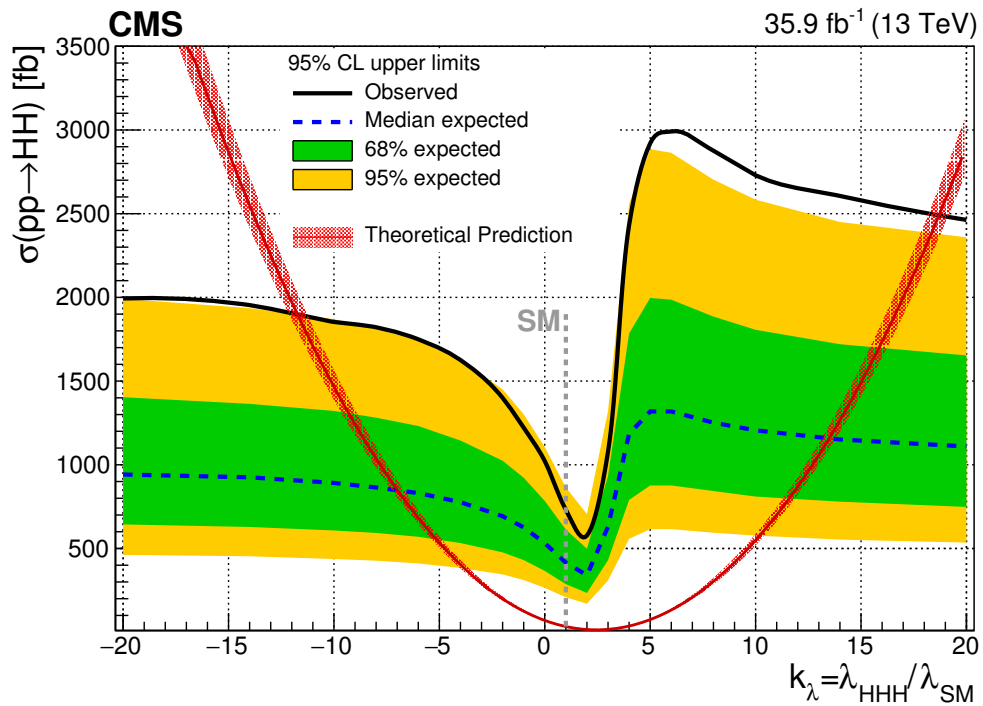
- **Small signal + large QCD background**

Combined $-5.0 < \kappa_\lambda < 12.0$ (observed) [1906.02025]

[ATLAS Collaboration, 1807.04873]

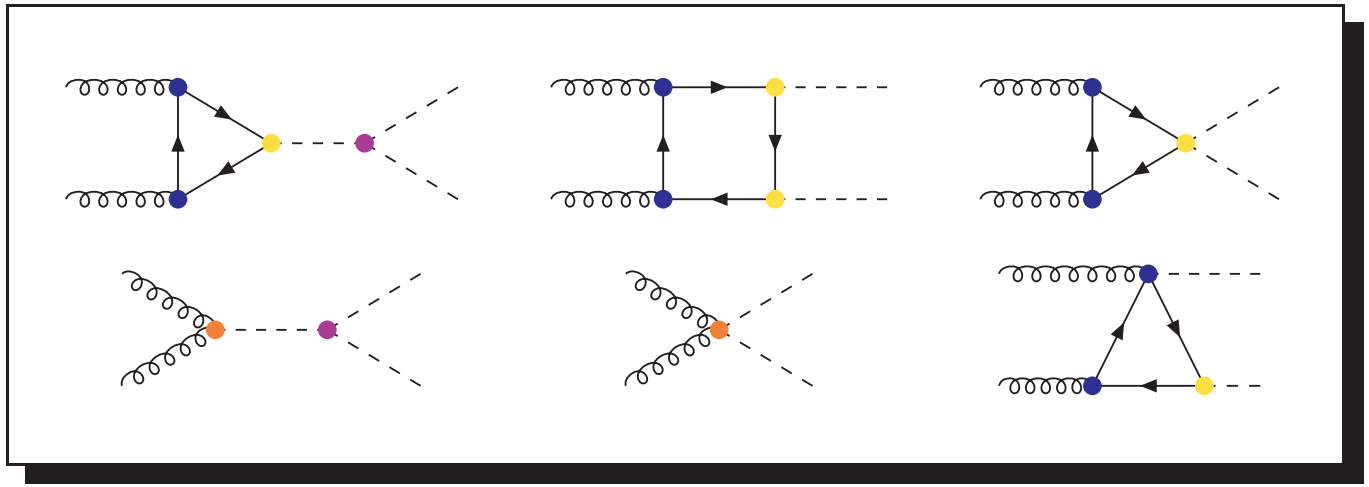


CMS Collaboration 1811.09689



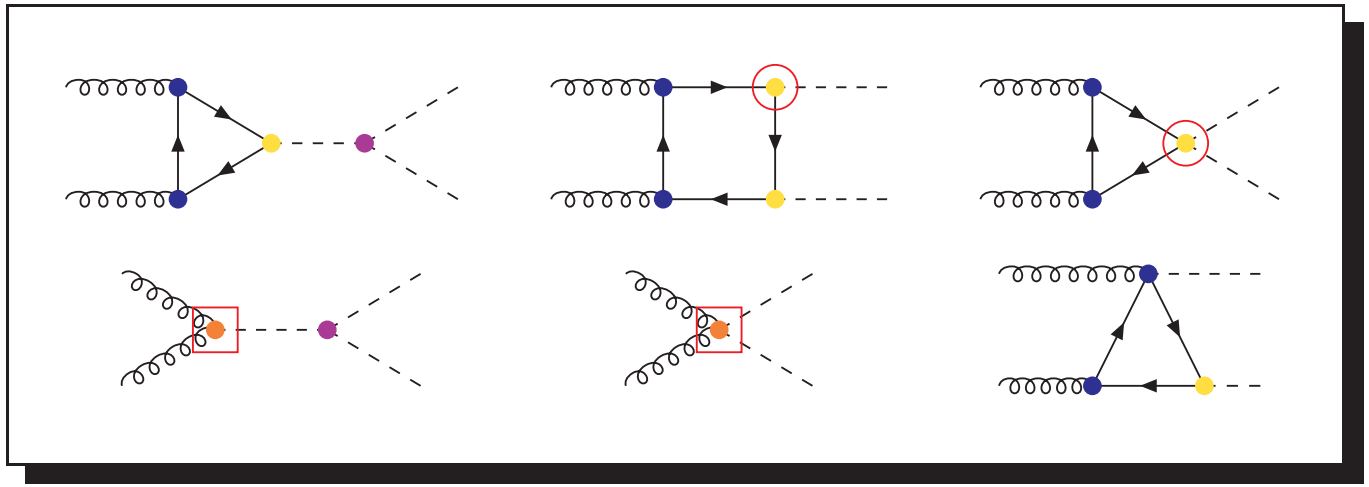
For SM Higgs pair production, see e.b. talk by Seraina Glaus at LHCP2020, "*HH and Decays*"

$\mathcal{E}$FT $\mathcal{O}$perators $\mathcal{C}$ontributing to $\mathcal{G}$luon $\mathcal{F}$usion into $\mathcal{H}$iggs $\mathcal{P}$airs



$\mathcal{O}_H$	$=$	$\frac{1}{2}(\partial_\mu(\phi^\dagger\phi))^2$	$\longrightarrow$	overall shift of couplings
$\mathcal{O}_6$	$=$	$-(\phi^\dagger\phi)^3$	$\longrightarrow$	shifts Higgs self-coupling
$\mathcal{O}_{t\phi}$	$=$	$(\phi^\dagger\phi)(\bar{Q}\tilde{\phi}t) + h.c.$	$\longrightarrow$	shifts top Yukawa coupling; $t\bar{t}HH$
$\mathcal{O}_{\phi G}$	$=$	$(\phi^\dagger\phi)G^a_{\mu\nu}G^{a\mu\nu}$	$\longrightarrow$	pointlike Higgs to gluon couplings
$\mathcal{O}_{tG}$	$=$	$(\bar{Q}\sigma^{\mu\nu}T^a t)\phi G^a_{\mu\nu} + h.c.$	$\longrightarrow$	chromomagnetic dipole operator

$\mathcal{E}$FT $\mathcal{O}$perators $\mathcal{C}$ontributing to $\mathcal{G}$luon $\mathcal{F}$usion into $\mathcal{H}$iggs $\mathcal{P}$airs



Non-linear EFT:

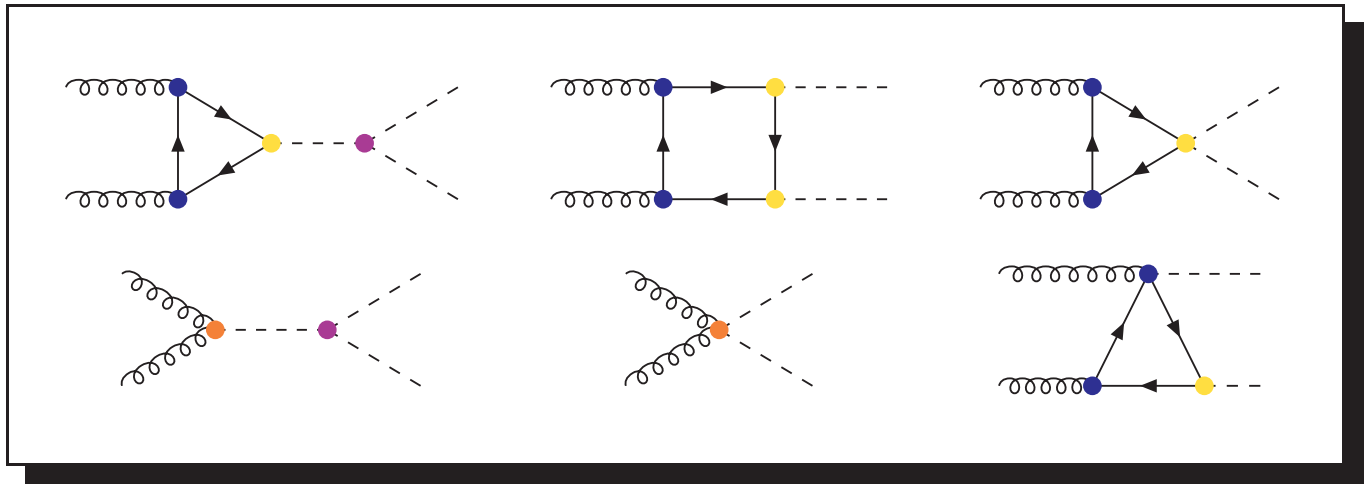
couplings of one/two Higgs bosons to gluons become linear independent

couplings of one/two Higgs bosons to fermions become linear independent

can be probed directly in di-Higgs productions

Processes w/ 0,1,2 Higgs boson need to be connected to disentangle linear/non-linear dynamics

$\mathcal{E}$FT $\mathcal{O}$perators $\mathcal{C}$ontributing to $\mathcal{G}$luon $\mathcal{F}$usion into $\mathcal{H}$iggs $\mathcal{P}$airs

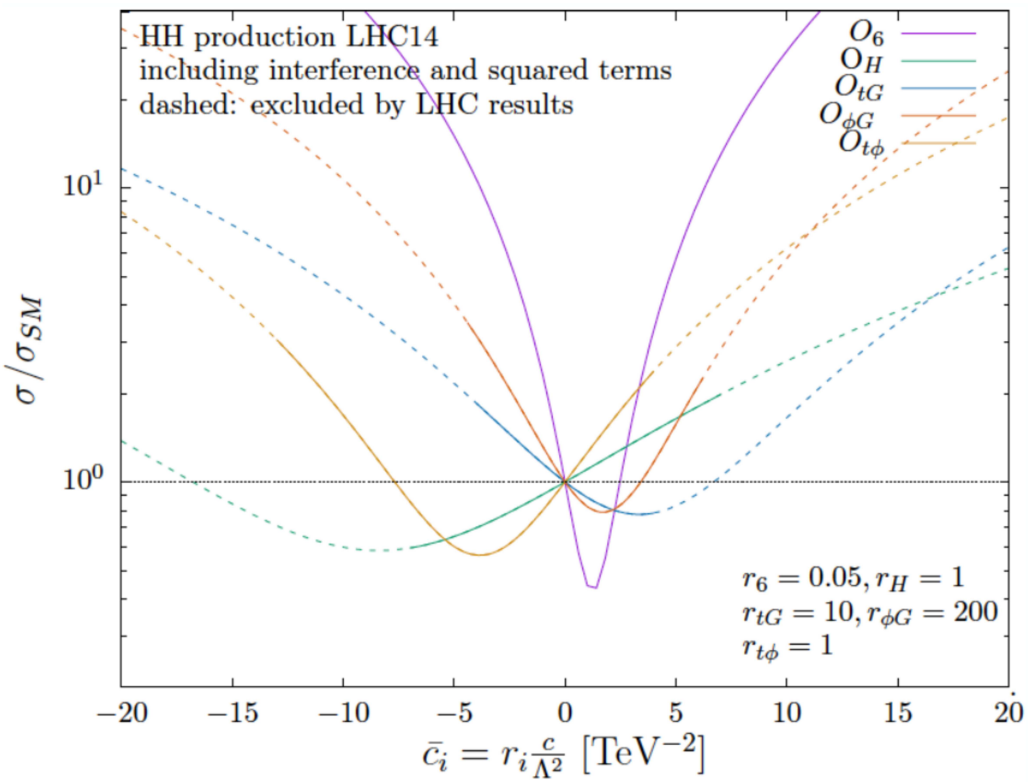


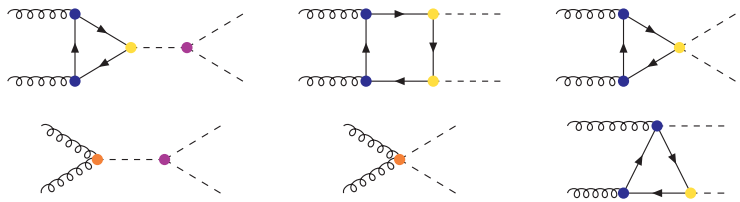
Note: EFT operators destroy SM cancellation between triangle and box diagrams

$\rightsquigarrow$ limits derived on λ_{HHH} depend on EFT description

Impact of Different Operators

[taken from talk by E. Vryonidou]





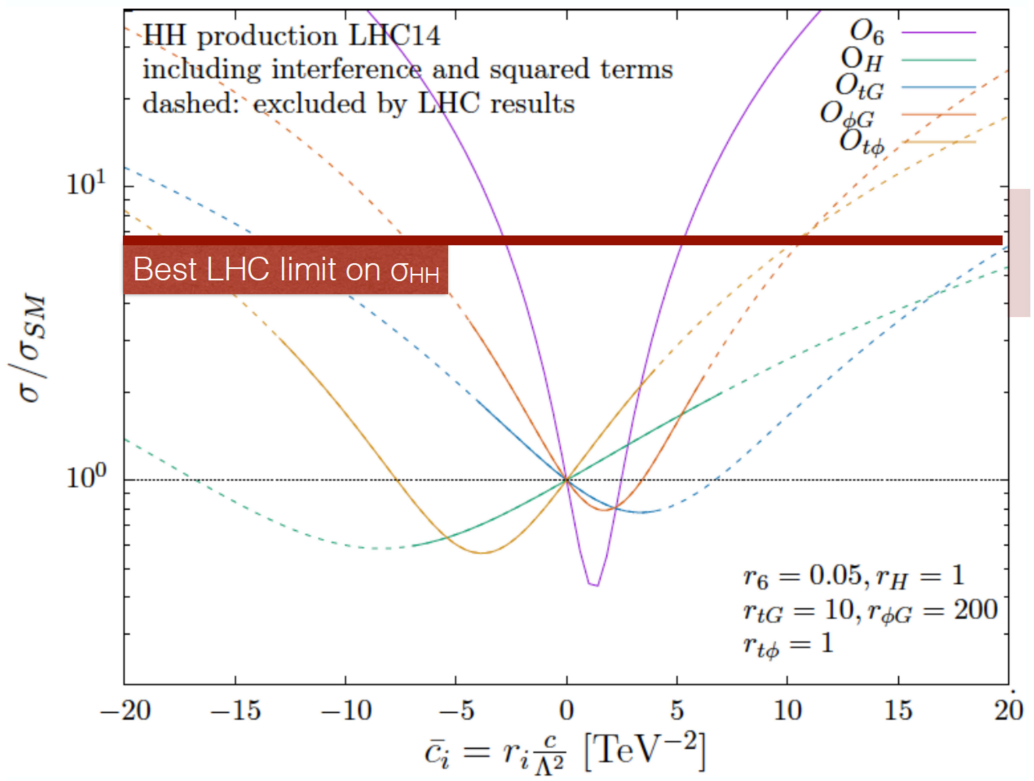
$t\bar{t}h(h)$, $ggh(h)$, top-gluon interactions, Higgs self-coupling plus overall normalization

Is it sufficient to vary λ_{hhh} only?

dashed lines: excluded by single Higgs

Impact of Different Operators

[taken from talk by E. Vryonidou]



Present situation

w/ current constraints on $\sigma(HH)$, $\sigma(H)$ and $t\bar{t}H$, the Higgs self-coupling can be constrained ignoring other couplings

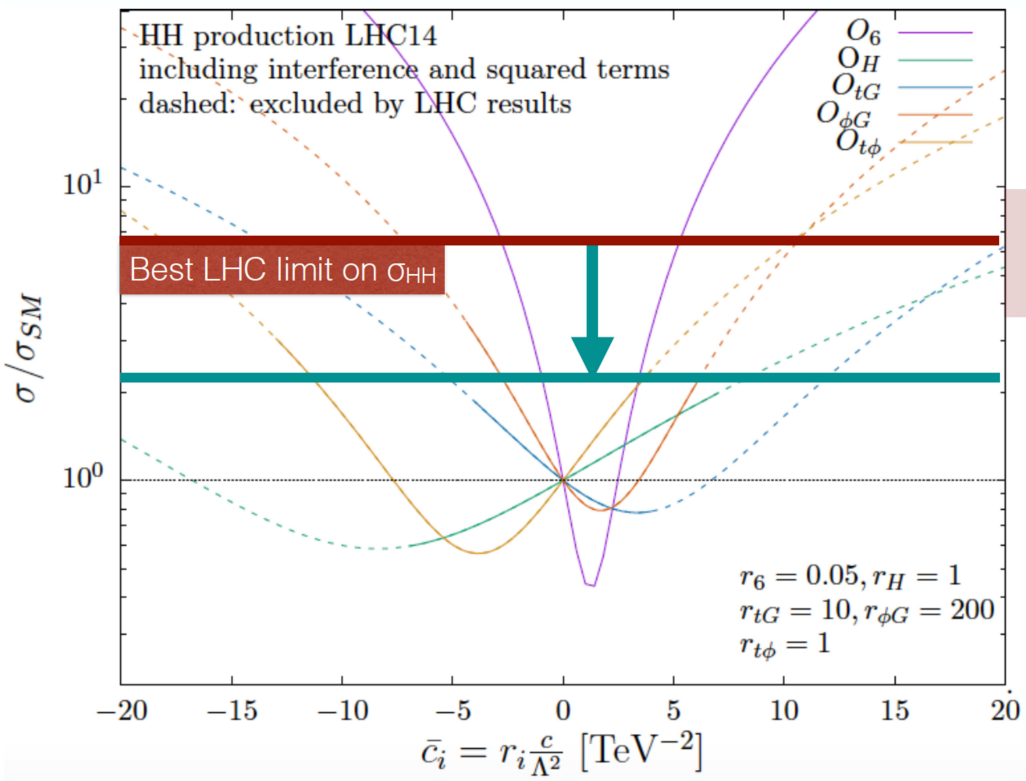
σ_{HH}-limit [ATLAS, 1906.02025]

Is it sufficient to vary λ_{hhh} only?

experimental results so far mostly for varying only λ_{hhh}

Impact of Different Operators

[taken from talk by E. Vryonidou]



Future situation

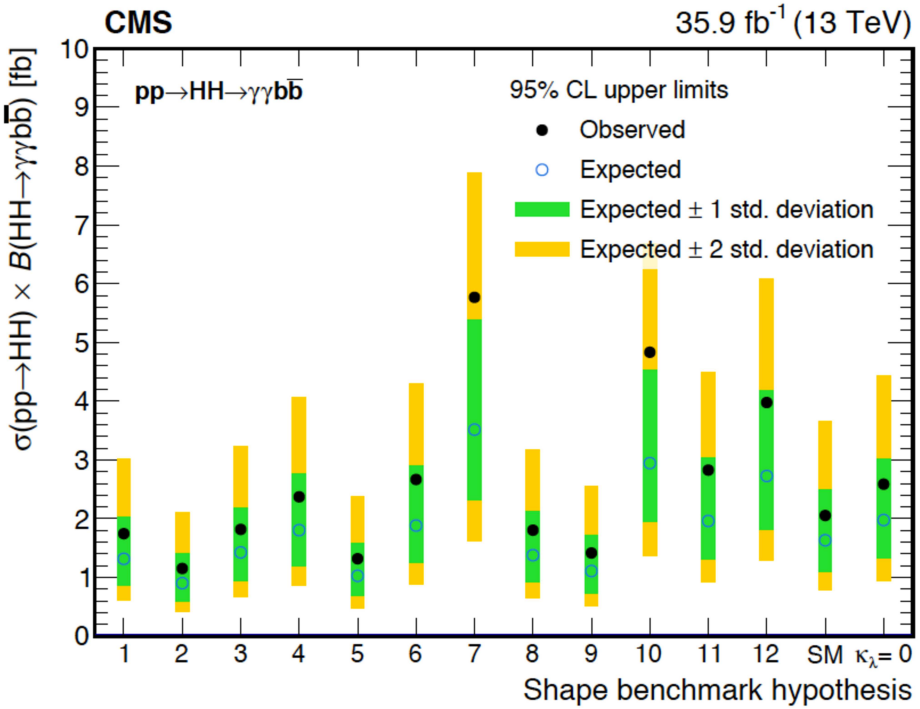
precise knowledge of other Wilson coefficients will be required to put bound on λ_{HHH} as we move closer to SM

differential distributions also required due to different kinematic shapes of the operators

results for varying $\kappa_\lambda, \kappa_t, c_2 (= c_{hhtt})$ [CMS: 1603.06896, 1806.00408, 1811.09689]

$\mathcal{L}$imits on σ_{HH} for $\mathcal{D}$ifferent $\mathcal{B}$enchmarks

CMS, 1806.00408, $\sqrt{s} = 13$ TeV, $\int \mathcal{L} = 35.9$ fb^{-1}

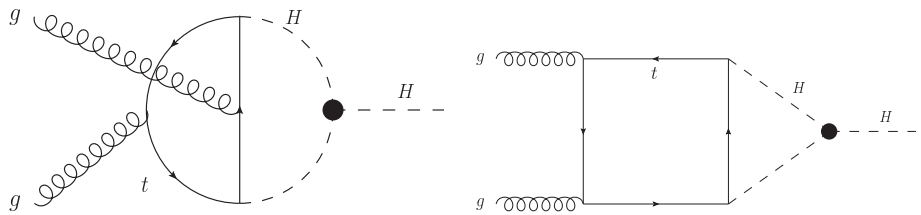


	SM	$\kappa_\lambda = 0$	1	2	3	4	5	6	7	8	9	10	11	12
κ_λ	1.0	0.0	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0
κ_t	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0
c_2	0.0	0.0	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0
c_g	0.0	0.0	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0
c_{2g}	0.0	0.0	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0

$\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling from $\mathcal{S}$ingle $\mathcal{H}$iggs $\mathcal{P}$roduction

- **Alternative strategy for extraction of κ_λ**
  - $*$ $\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\text{SM}}$ from EW corrections to single Higgs
  - $*$ competitive and complementary bound to HH

[McCullough'13; Degrassi,Giardino, Maltoni,Pagani'16; Bizon,Gorbahn, Haisch,Zanderighi'16; Maltoni,Pagani, Shivaji,Zhao'17;Gorbahn,Haisch'16,'19]



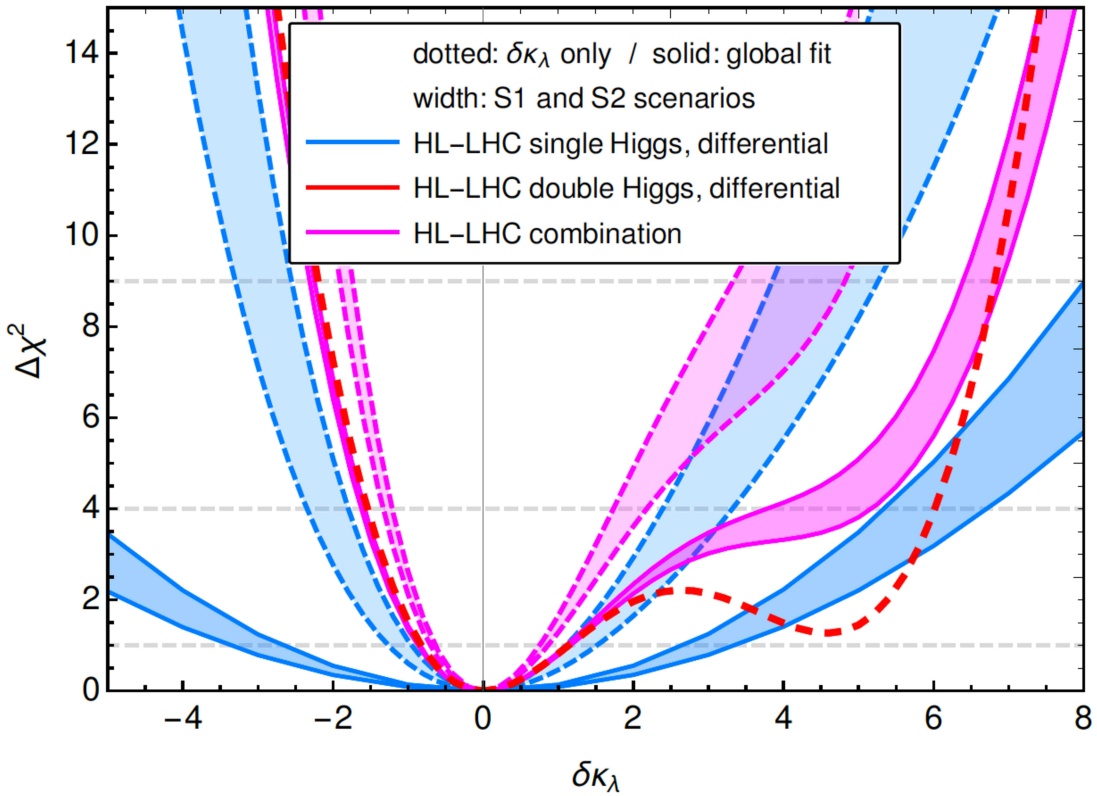
- **Challenging:** $*$ several processes w/ different functional dependence on κ_λ to be considered
  $\rightsquigarrow$ global fit necessary [Di Vita,Grojean,Panico,Riembau,Vantalon'17]
  - $*$ nine additional EFT coefficients to be varied
  - $*$ dominant effect on single Higgs from other LO operators

- **Remark:**

$*$ For λ_{HHH} limits from 2-loop effects in EW observables, see [Degrassi eal, '17; Kribs eal, '17]

Higgs Self-Coupling from Single Higgs Production

[HH White Paper '19]



HH production: stronger constraints

[Azatov eal, 1502.00539]

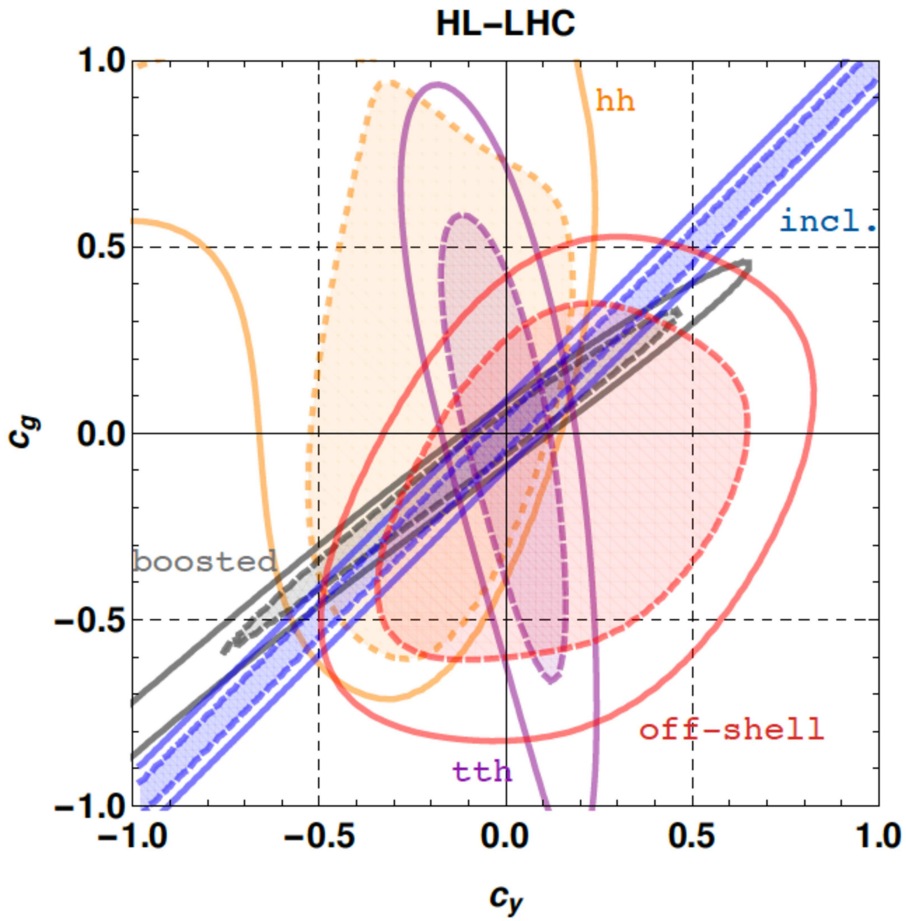
Single Higgs production helps to lift degenerate minima at $\delta\kappa_\lambda \approx 5$

ATLAS: ggH, VBF, VH, 5 decay modes + partially differential information from STXS categories

[ATLAS-PHYS-PUB-2019-009]

$\mathcal{R}$esolve $\mathcal{D}$egeneracies with $\mathcal{HH}$

[Azatov, Grojean, Paul, Salvioni, 1608.00977]



Higgs pair production can help to resolve degenery between $O_{\phi G}$ and $O_{t\phi}$

$\mathcal{E}$ffective $\mathcal{O}$perators at $\mathcal{H}$igher $\mathcal{O}$rders

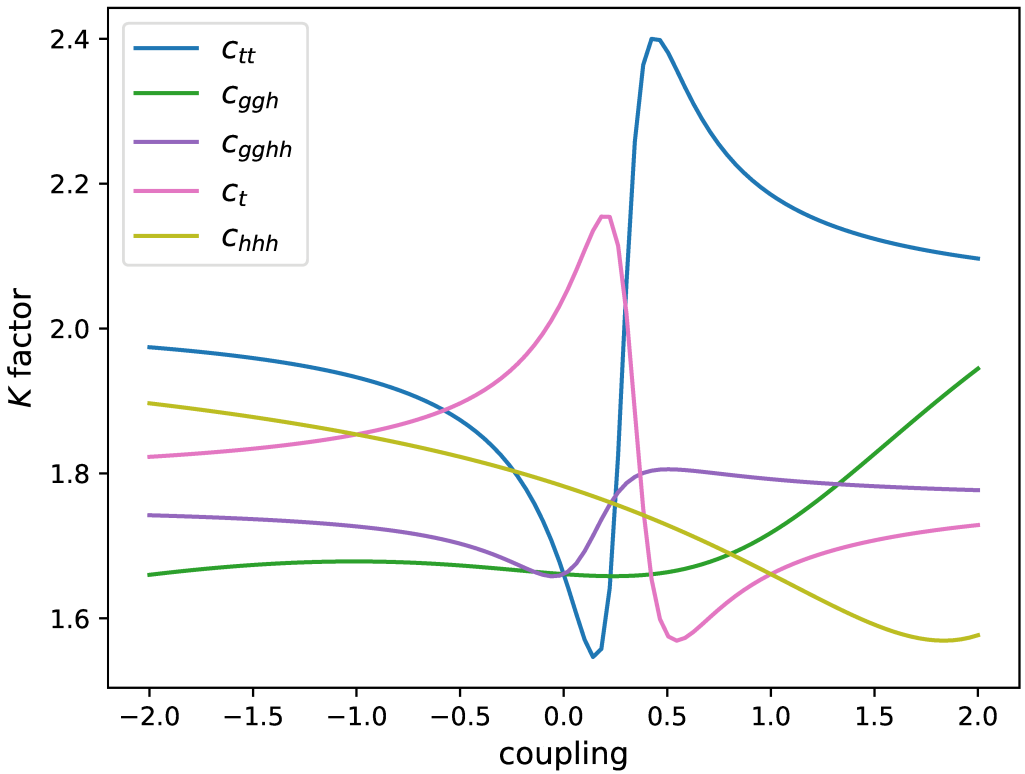
Red terms appear at NLO for the first time [Buchalla,Capozi,Celis,Heinrich,Scyboz '18]

$$\begin{aligned}\sigma^{\rm NLO}/\sigma^{\rm NLO}_{SM} &= A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh} \\ &+ A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh} \\ &+ A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh} \\ &+ A_{16}\, c_t^3 c_{ggh} + A_{17}\, c_t c_{tt} c_{ggh} + A_{18}\, c_t c_{ggh}^2 c_{hhh} + A_{19}\, c_t c_{ggh} c_{gghh} \\ &+ A_{20}\, c_t^2 c_{ggh}^2 + A_{21}\, c_{tt} c_{ggh}^2 + A_{22}\, c_{ggh}^3 c_{hhh} + A_{23}\, c_{ggh}^2 c_{gghh}\,.\end{aligned}$$

* coefficients A_i (EWChL) $\rightsquigarrow$ cross sections can be given for arbitrary Wilson coefficients
* also available for m_{hh} differential distributions
* based on [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,(Schubert),Zirke '16 ('16)]
* parametrisation introduced at LO in [Carvalho eal, '15'16]
* available in POWHEG [Heinrich,Jones,Kerner,Luisoni,Seyboz '19]
  variation of Higgs self-coupling (+ description on how to vary top Yukawa coupling)

$\mathcal{E}$ffective $\mathcal{O}$perators at $\mathcal{H}$igher $\mathcal{O}$rders

[Buchalla,Capozi,Celis,Heinrich,Scyboz '18]

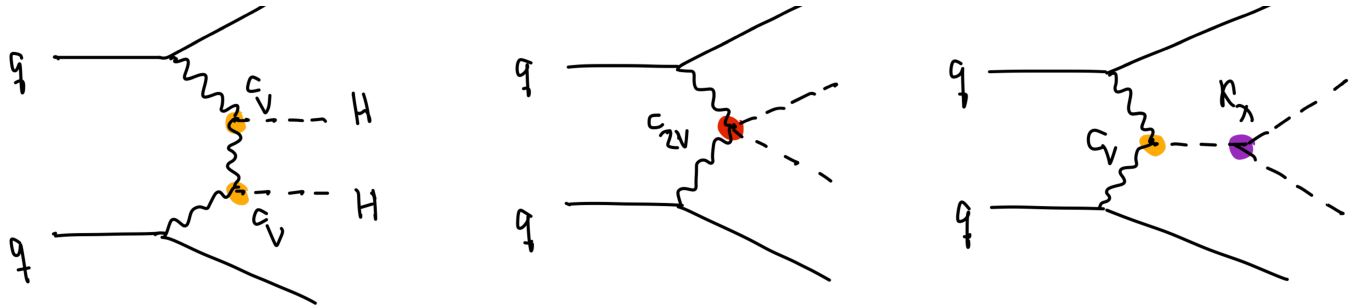


∗ HEFT K-factors: small dependence on coupling modifications

[Gröber,MM,Spira,Streicher '15; de Florian,Fabre,Mazzitelli '17]

∗ Inclusion of full top mass dependence: non-uniform K-factors; EWChL

$\mathcal{E}$FT $\mathcal{O}$perators $\mathcal{C}$ontributing to $\mathcal{V}$ector $\mathcal{B}$oson $\mathcal{F}$usion into $\mathcal{H}$iggs $\mathcal{P}$airs



* VBF and GF are sensitive to different sources of physics beyond the SM
* ATLAS study on VBF-HH: quartic Higgs-gauge boson coupling c_{2V} can be constrained (non-linear EFT) [ATLAS-PHYS-CONF-2019-030]

observed limit: $-1.02 < c_{2V} < 2.71$

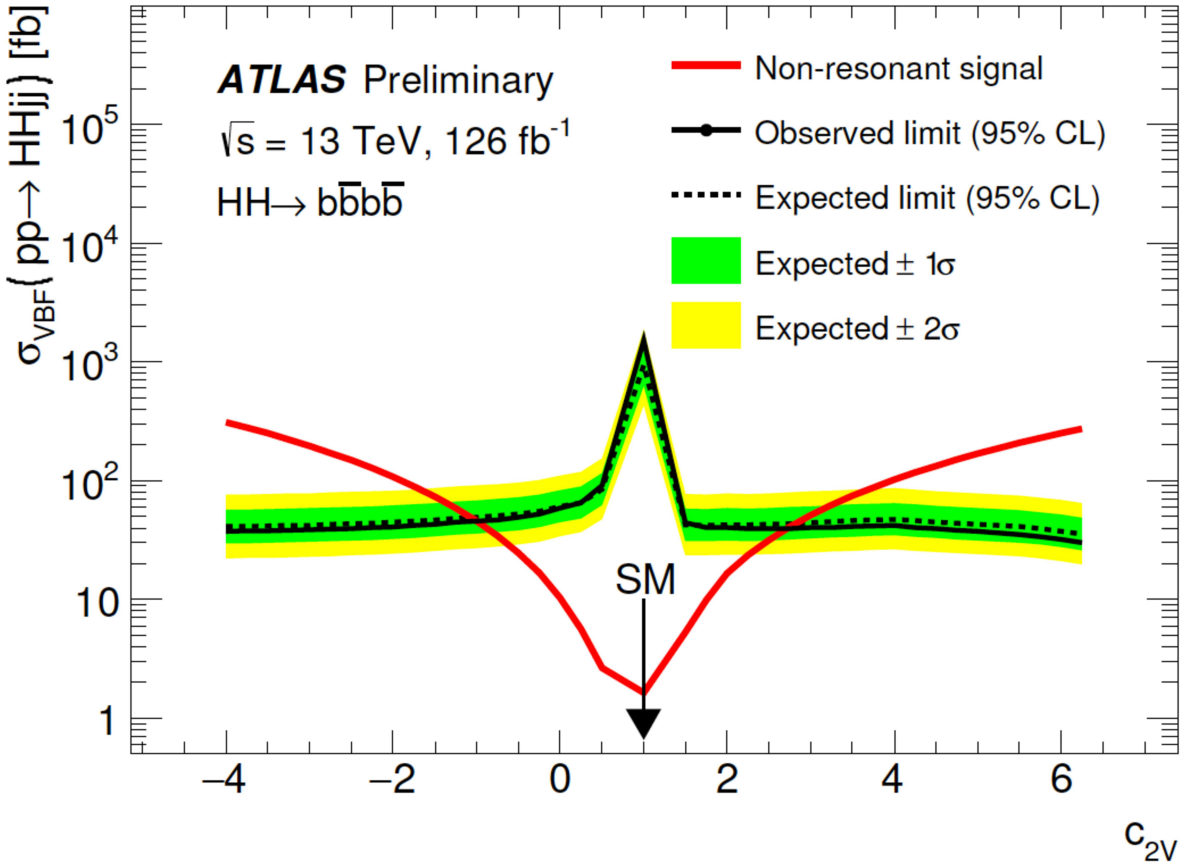
* investigation of $hhjj$ production at the LHC: constraints on c_{2V}

[Dolan,Englert,Greiner,Nordstrom,Spannowsky '15]

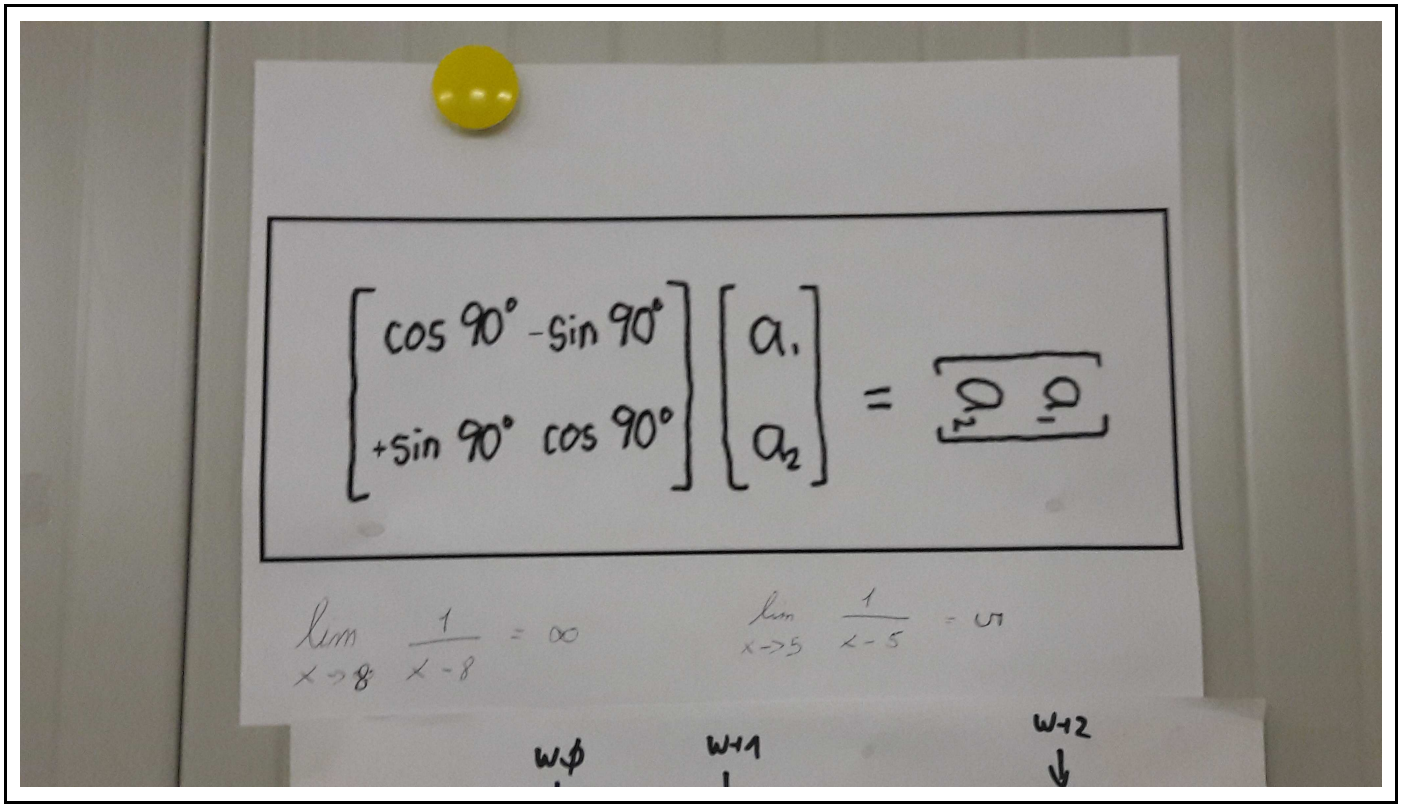
* constraints on c_{2V} from VBF into HH [Bishara,Contino,Rojo '16]

$\mathcal{L}$imits from $HH \to b\bar{b}b\bar{b}$ in $\mathcal{V}$BF

ATLAS-CONF-2019-030, $\sqrt{s} = 13$ TeV, $\int \mathcal{L} = 126$ fb^{-1}



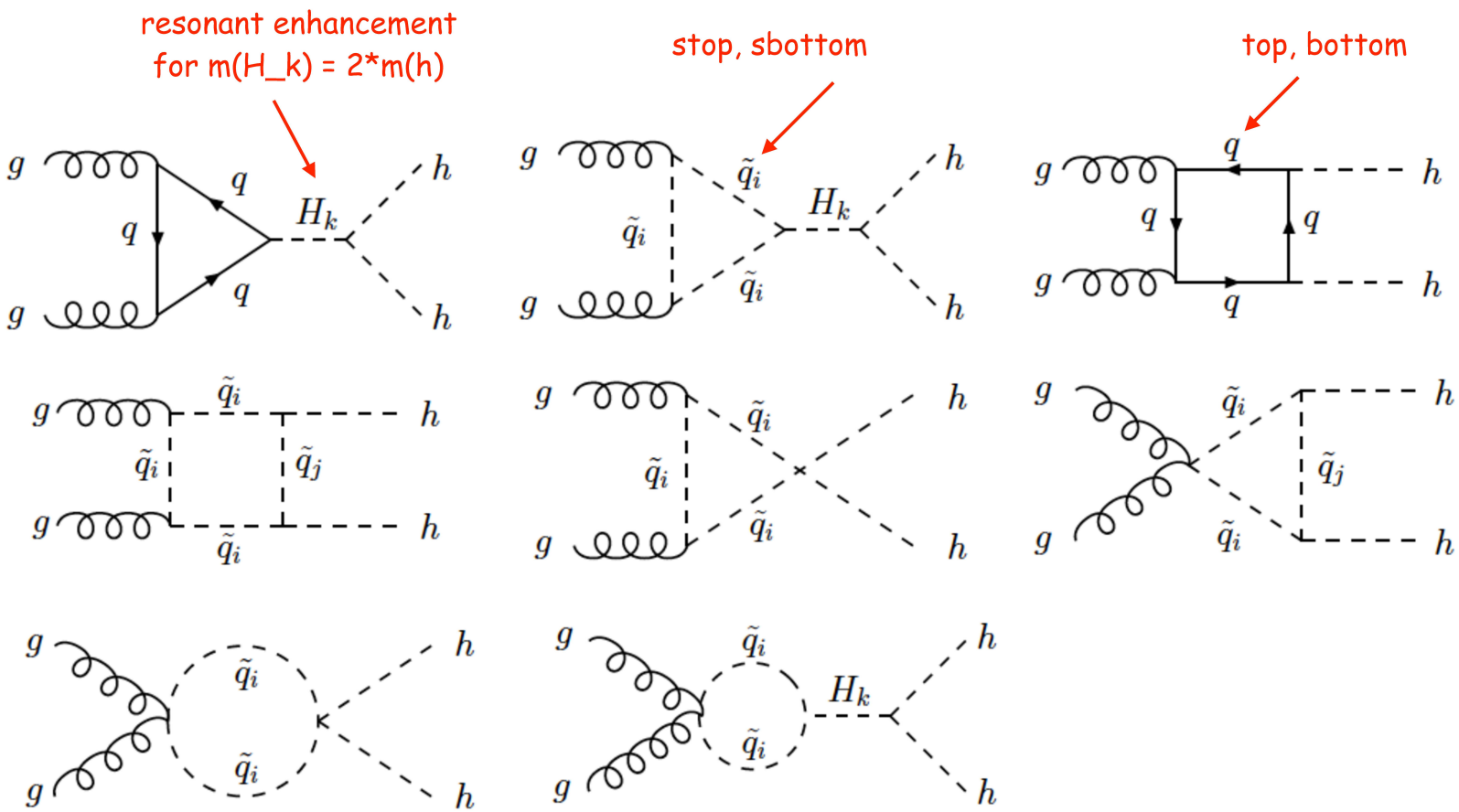
$\mathcal{U}$V $\mathcal{C}$omplete $\mathcal{M}$odels - $\mathcal{R}$eality $\mathcal{C}$heck



$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: NMSSM

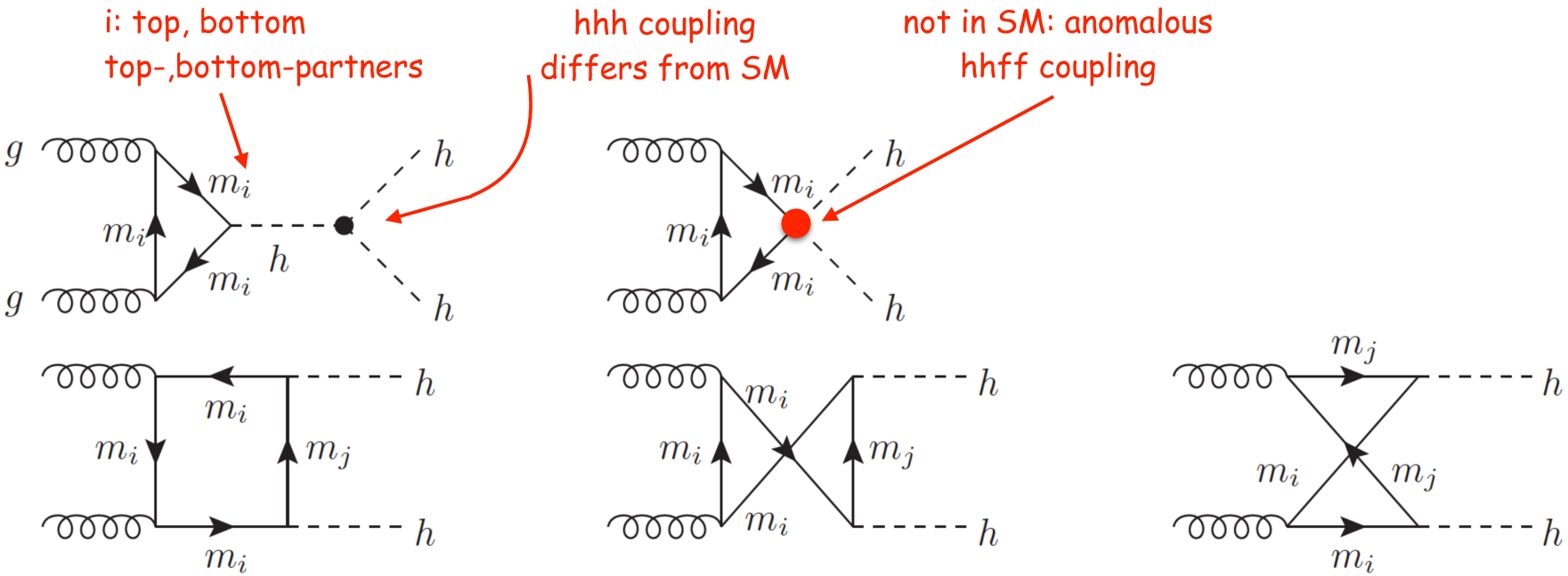
  $*$ different λ_{3H}; $*$ novel couplings; $*$ novel particles in the loop; $*$ resonant enhancement



$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: composite Higgs

  $*$ different λ_{3H}; $*$ novel couplings; $*$ novel particles in the loop; $*$ resonant enhancement



$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **How large can λ_{3H} be?** $\lambda_{3H} = \kappa_\lambda \lambda_{3H}^{\text{SM}}$
  - Limits based on vacuum stability and perturbative unitarity and $\Lambda_{\text{NP}} = \mathcal{O}(\text{TeV})$: $|\kappa_\lambda| \leq 6$

    [Di Vita, Grojean, Panico, Riembau, Vantalon, 1704.01953; Di Luzio, Grober, Spannowsky, 1704.02311; Falkowski,Rattazzi, 1902.05936; Chang,Luty, 1902.05556]
  - Model-specific bounds can be more stringent, see *e.g.*

    [Basler,MM,Müller, 1912.10477; Baum,Shah, 1904.10810; Braathen,Kanemura, 1903.05417; Arco eal, 2005.10576; Basler,Dawson,Englert,MM, 1812.03542; Babu,Jana, 1812.11943; Basler,MM,Wittbrodt, 1711.04097; Ellwanger,Rodriguez-Vazquez, 1707.08522; Lewis,Sullivan, 1704.08774; Gupta,Rzehak,Wells, 1305.6397; ...]

- **Expect the unexpected:**

∗ Higgs-to-Higgs cascade decays in non-minimal Higgs sectors $\rightsquigarrow$
Exotic multi-fermion and/or multi-photon final states

∗ Example NMSSM benchmark point BP7_P2 [King,MM,Nevzorov,Walz]

$gg \to A_2 \to H_s A_1 \to A_1 A_1 A_1 \to bb + 4\gamma$ 13.12fb

$gg \to A_2 \to H_s A_1 \to A_1 A_1 A_1 \to 4b + 2\gamma$ 84.78fb

$\mathcal{H}$igher-$\mathcal{O}$rder $\mathcal{C}$orrections in $\mathcal{S}$pecific $\mathcal{B}$SM $\mathcal{M}$odels

- **Higher-order corrections to σ_{hh}:**
  - for higher-order corrections in specific models (MSSM, NMSSM, (C)2HDM, singlet model, composite Higgs), see [Dawson,Dittmaier,Spira '98; Hespel,Lopez-Val,Vryonidou '14; Dawson,Lewis '15; Agostini,Degrassi,Gröber,Slavich '16; Gröber,MM,Spira '16,'17; ...]
  - available in large loop particle mass limit
  - K-factor typically of $\mathcal{O}(1.5-2)$
  - new physics effects on K-factors in general small
  - new physics effects on absolute cross section large

- **Higher-order corrections to triple Higgs couplings and Higgs-to-Higgs decays**

  [Hollik,Penaranda; Dobado eal; Arhrib eal; Aoki eal; Kanemura eal; Senaha; Spira,Brucherseifer; Nhung,MM,Streicher,Walz; MM,Nhung,Ziesche; Krause,Santos,MM,Ziesche; Braathen eal; Bojarksi eal; Liebler,MM,Spira,Stadelmaier; ...]

$\mathcal{H}$H in the $\mathcal{C}$2HDM and $\mathcal{N}$MSSM: $\mathcal{S}$cans and $\mathcal{N}$otation

- **Scan in C2HDM & NMSSM spaces:**
  keep only points compatible with theoretical and experimental constraints

- **Notation C2HDM & NMSSM:**

  h - SM-like Higgs boson

  $H_\downarrow$ - lighter non-SM-like Higgs boson

  $H_\uparrow$ - heavier non-SM-like Higgs boson

- **Additionally in NMSSM:**

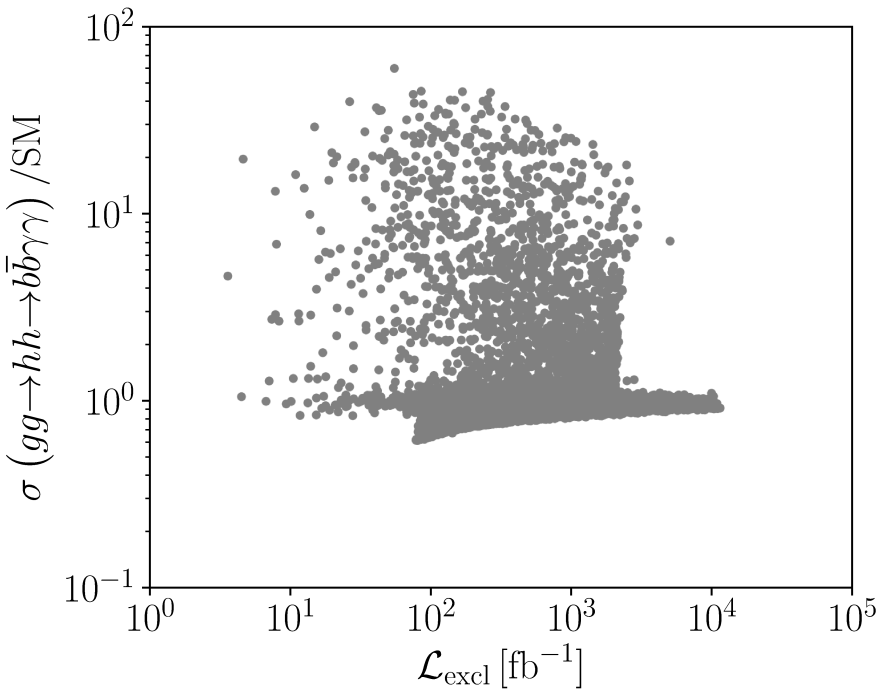
  $A_\downarrow$ - lighter non-SM-like pseudoscalar Higgs boson

  $A_\uparrow$ - heavier non-SM-like pseudoscalar Higgs boson

$h, H_\downarrow, H_\uparrow$ CP-mixing states in C2HDM, pure scalars in CP-conserving NMSSM

$\mathcal{H}$H $\mathcal{P}$roduction in the $\mathcal{C}$2HDM and $\mathcal{N}$MSSM

[Basler,Dawson,Englert,MM '18] CP-violating 2HDM (C2HDM), Type 1



Singe-Double Higgs-Top interplay:

Heavy Higgs bosons ϕ w/ dominant decay into $t\bar{t}$

$\rightsquigarrow$ large $gg \to \phi\phi \to (t\bar{t})(t\bar{t})$ rates

in conflict with $gg \to \phi \to t\bar{t}$ exclusion bounds

$\mathcal{H}$H $\mathcal{P}$roduction in the $\mathcal{C}$2HDM and $\mathcal{N}$MSSM

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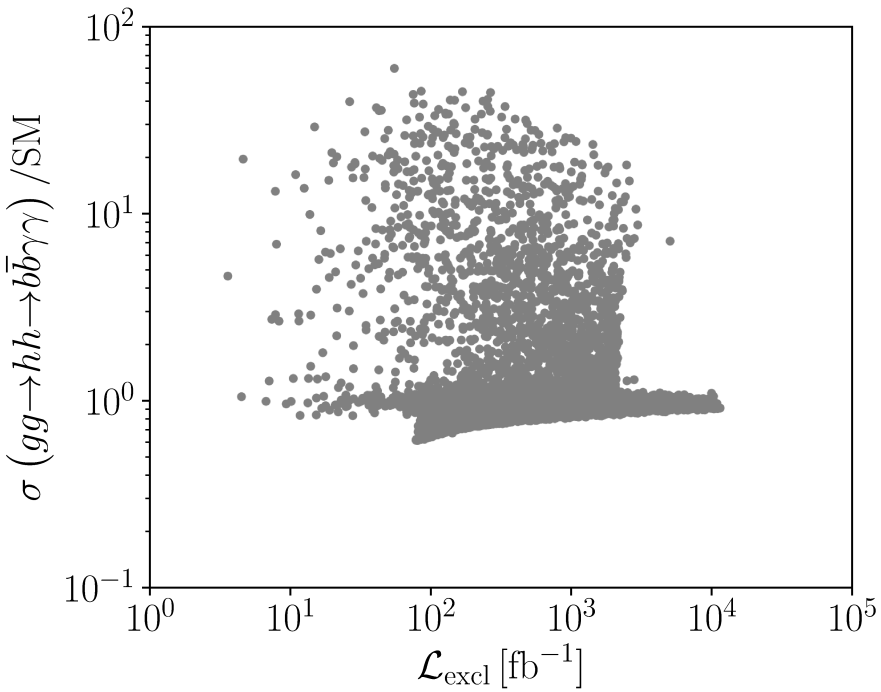

- **Maximum C2HDM $\sigma_{\phi_1\phi_2}$ [fb]:**

H_iH_j/model	T1	T2
hh	794	34.2
$hH_\downarrow$	49.17	11.38
$hH_\uparrow$	17.65	10.84
$H_\downarrow H_\downarrow$	3196	0.18
$H_\downarrow H_\uparrow$	12.58	0.11
$H_\uparrow H_\uparrow$	7.10	0.18

Singe-Double Higgs-Top interplay:

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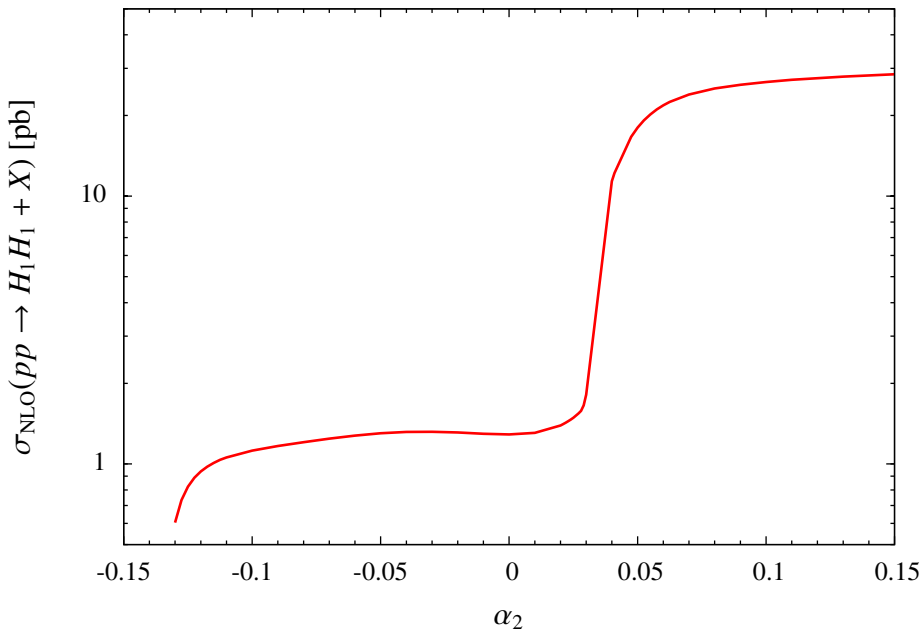
$\mathcal{C}$2HDM $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction

- **3 CP-mixed neutral scalars in C2HDM:**
  Resonant heavy Higgs producion possible $\rightsquigarrow$ strong increase of cxn

α_2 CP mixing angle; cxn at NLO QCD

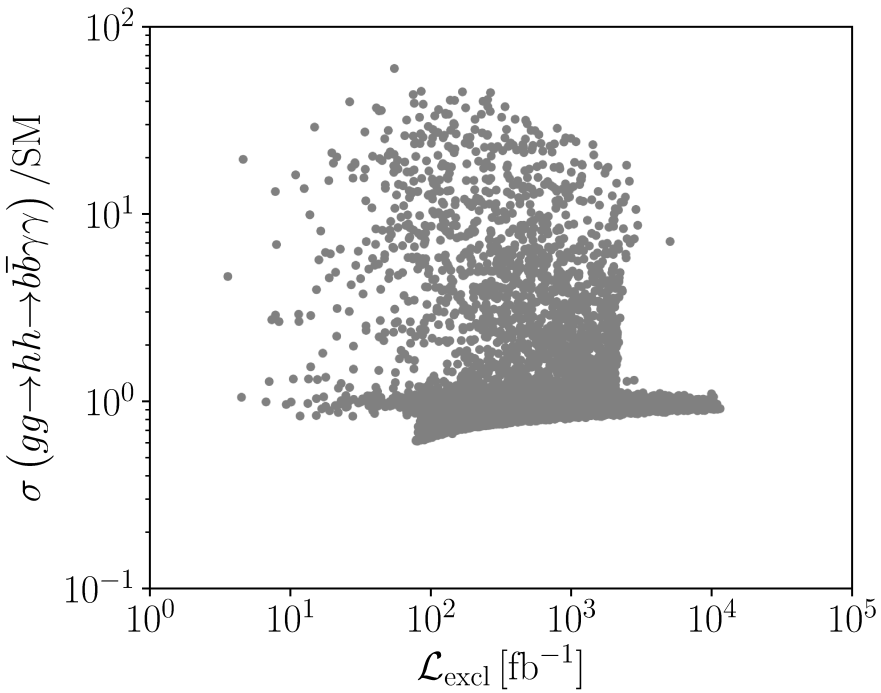
Gröber, MMM, Spira '17



For recent works on di-Higgs production in 2HDMs, see also e.g.
[Kon,Nagura,Ueda,Yagyu; Babu,Jana]

$\mathcal{H}$H $\mathcal{P}$roduction in the $\mathcal{C}$2HDM and $\mathcal{N}$MSSM

[Basler,Dawson,Englert,MM '18] CP-violating 2HDM (C2HDM), Type 1



- **Maximum NMSSM $\sigma_{\phi_1\phi_2}$ [fb]:**

H_iH_j	NMSSM
hh	34
$hH_\downarrow$	125
$hA_\downarrow$	70
$hH_\uparrow$	1.1
$H_\downarrow H_\downarrow$	3.7
$H_\downarrow H_\uparrow$	0.2
$H_\uparrow H_\uparrow$	0.004
$A_\downarrow A_\downarrow$	70

Singe-Double Higgs-Top interplay:

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$\rightsquigarrow$ large $gg \to \phi\phi \to (t\bar{t})(t\bar{t})$ rates

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$\mathcal{H}$H $\mathcal{P}$roduction in the $\mathcal{C}$2HDM and $\mathcal{N}$MSSM

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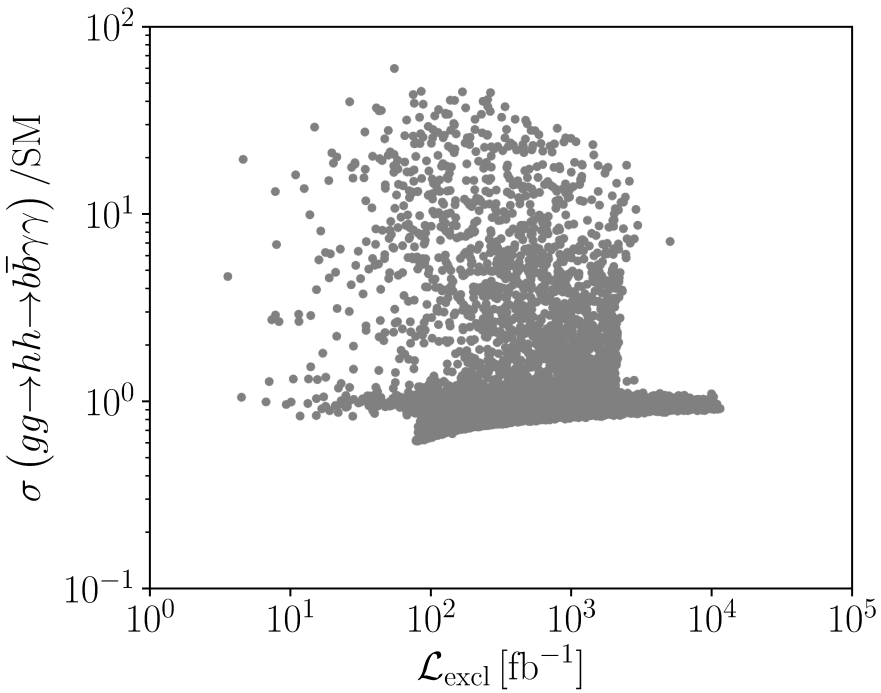

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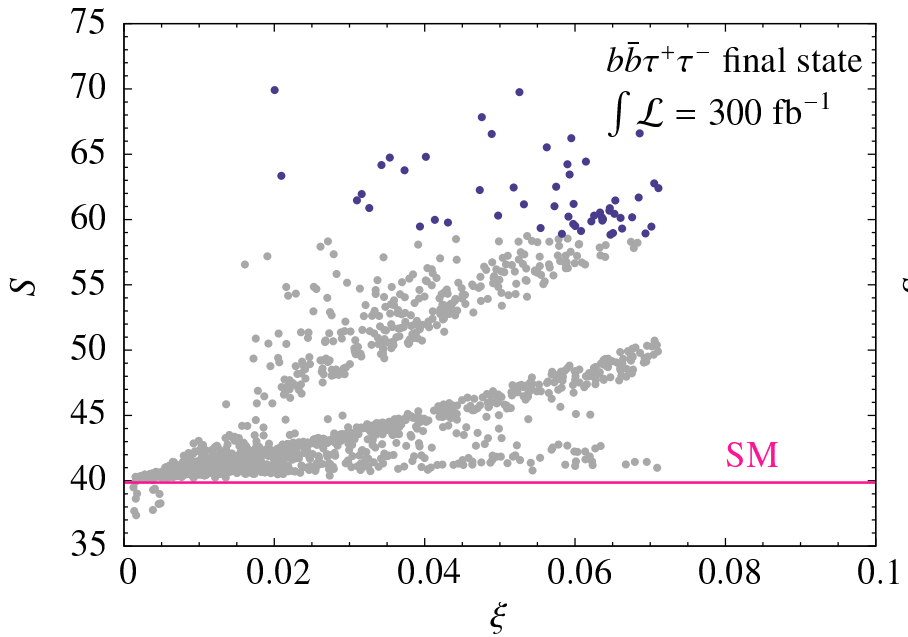
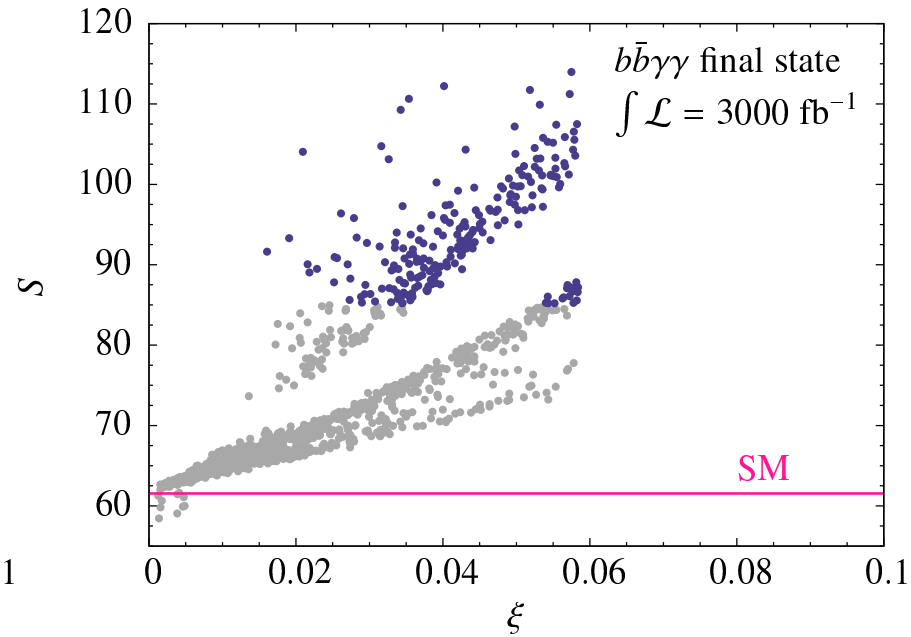
See NP first in HH?

[Gröber,MM,Spira '16;Basler,Dawson,Englert,MM '19]

$\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{F}$irst in $\mathcal{H}$iggs $\mathcal{P}$air $\mathcal{P}$roduction? [Gröber,MM,Spira '16]





- **MCHM10:** minimal composite Higgs model with heavy top and bottom partners; cxn at NLO QCD

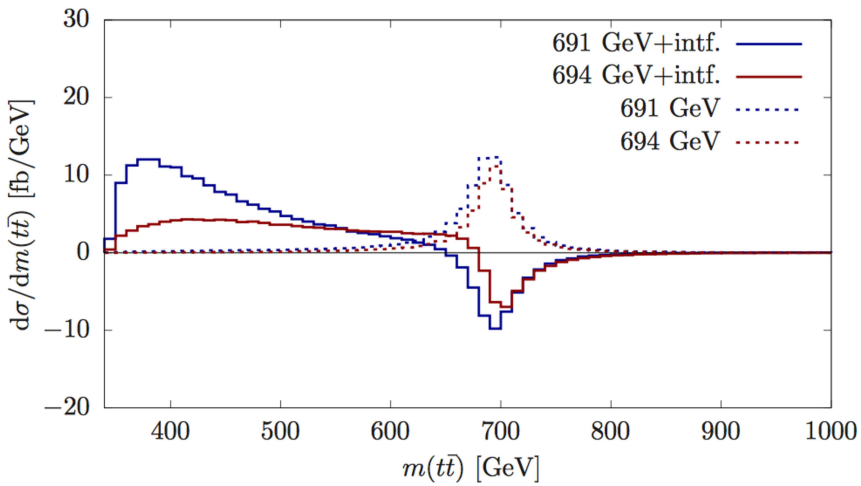
Blue points - Signal events S: $S_{\text{SM}} + 3\sqrt{S_{\text{SM}}} \leq S$ or $S_{\text{SM}} - 3\sqrt{S_{\text{SM}}} \geq S$

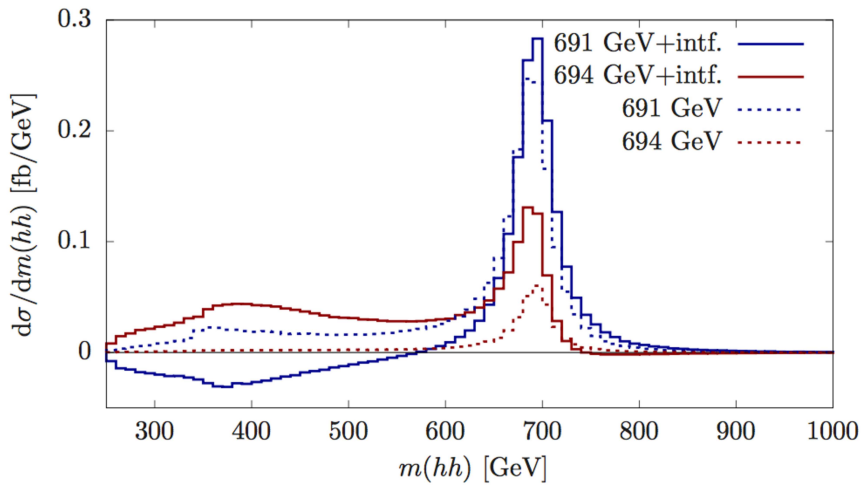
Assumption: Deviations of Higgs couplings to SM particles $<$ projected experimental sensitivity

$\mathcal{S}$ingle-$\mathcal{D}$ouble-$\mathcal{T}$op-$\mathcal{H}$iggs $\mathcal{I}$nterplay

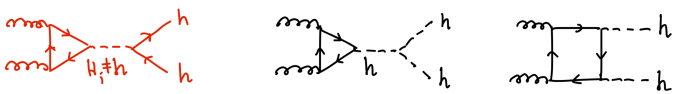
- **Di-Higgs Peaks and Top Valleys** (C2HDM) [Basler,Dawson,Englert,MM, 1909.09987]

  $gg \to H_i \to t\bar{t}$ and $gg \to H_i \to hh$ (h SM-like Higgs boson, $H_i \neq h$)





$*$ Destructive signal-background interference may be correlated with constructive signal-signal interference



For interference effects, see also [Dawson,Lewis '15; Djouadi eal '19; Lewis/Carena eal/Bagnaschi eal in 1910.00012]

$\mathcal{C}$onclusions

- ◇ EFT approach well established
- ◇ Increasing experimental and theoretical precision
  - ∗ requires inclusions of higher-order corrections in EFT
  - ∗ requires inclusion of more operators in the fits
- ◇ EFT distributions
  - ∗ particularly sensitive to new physics
  - ∗ allow for resolution of flat directions ($\leftarrow$ also combination of observables)
  - ∗ can probe several operators at once
- ◇ SMEFT and EWChL:
  - ∗ κ_λ limits sensitive to EFT description
- ◇ Confrontation with UV complete models:
  - ∗ EFT not sensitive to light resonances
  - ∗ large BSM deviations, in particular in HH, still possible

Thank You For Your Attention!