SILAFAE
XI SIMPOSIO LATINOAMERICANO DE FÍSICA DE ALTAS ENERGÍAS

Higgs Physics and Beyond

Eduardo Pontón

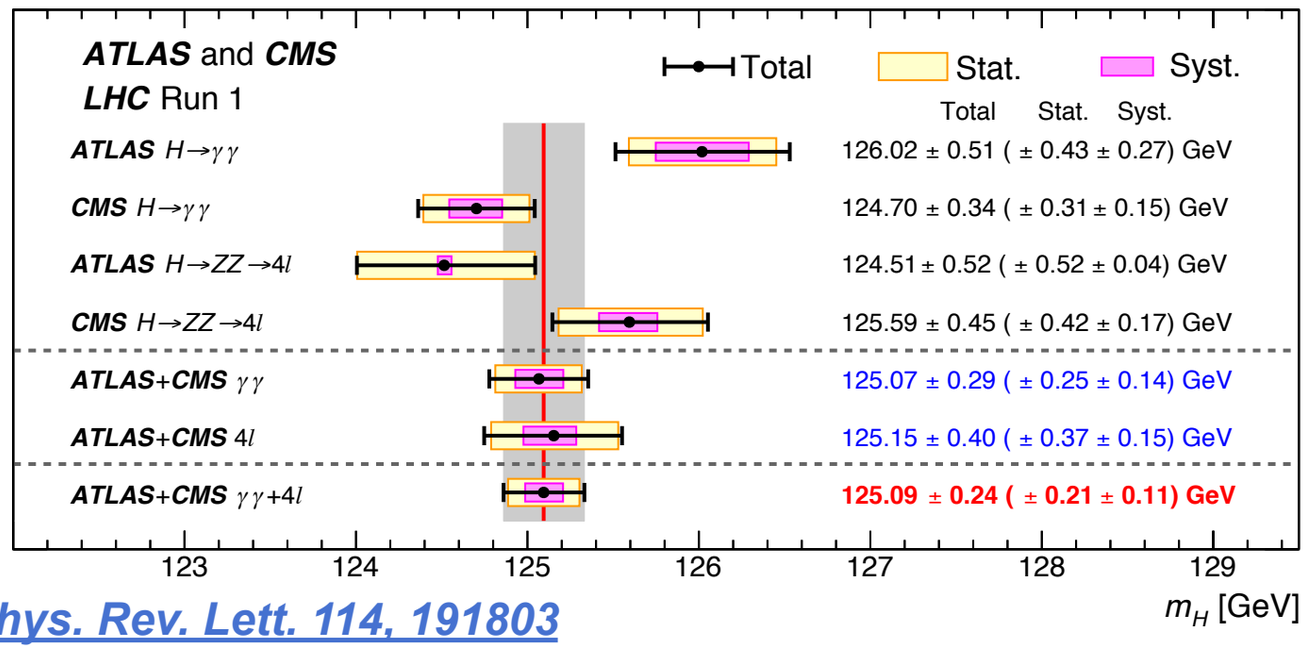
IFT-UNESP & ICTP-SAIFR

ICTP SAIFR International Centre for Theoretical Physics
South American Institute for Fundamental Research

unesp UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

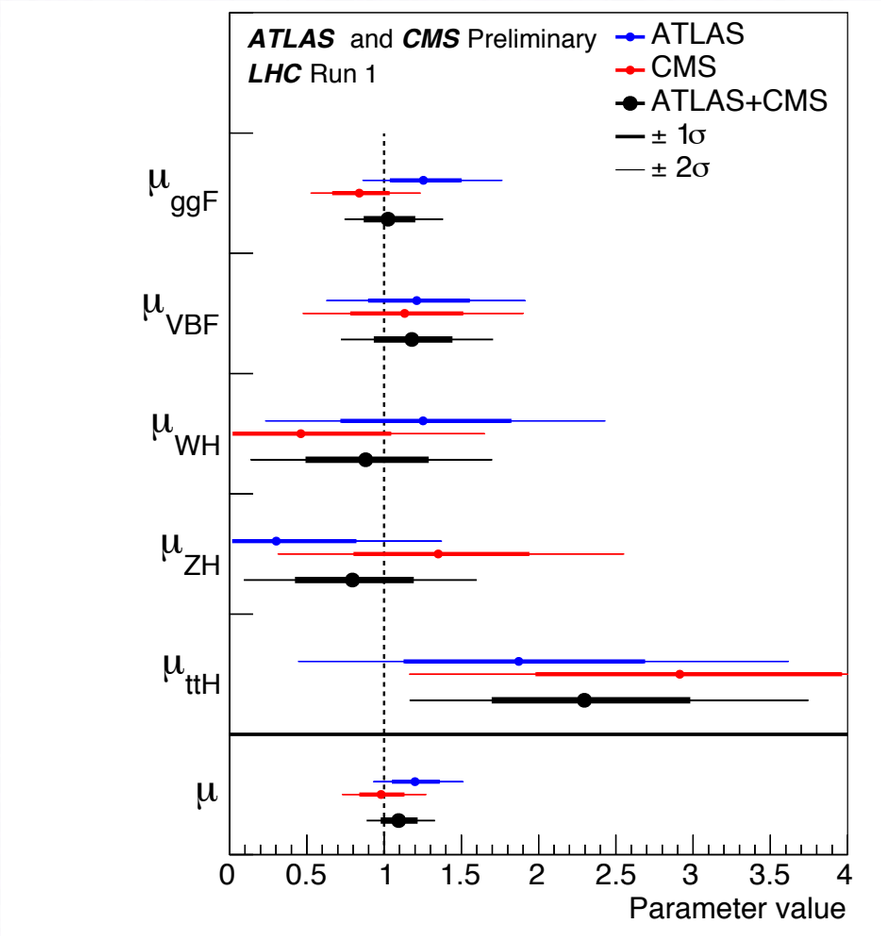
We are done celebrating…

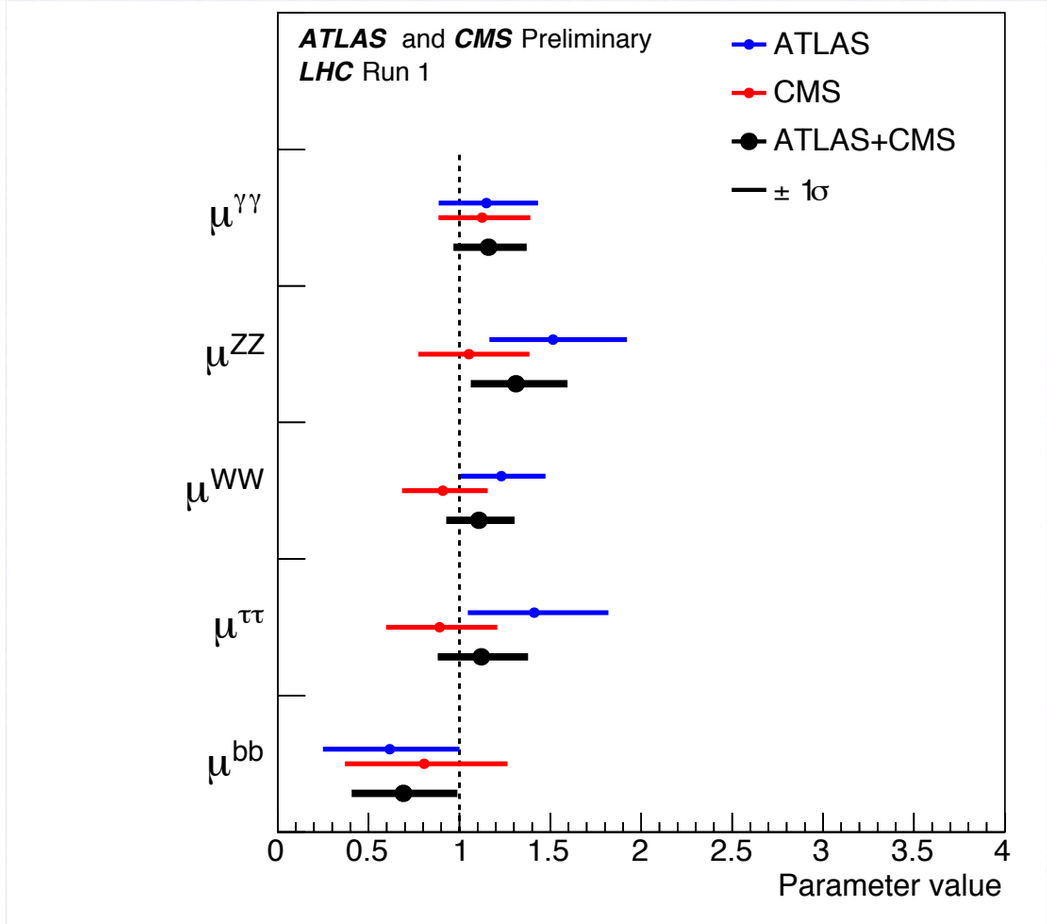
...and know a lot more!



Phys. Rev. Lett. 114, 191803

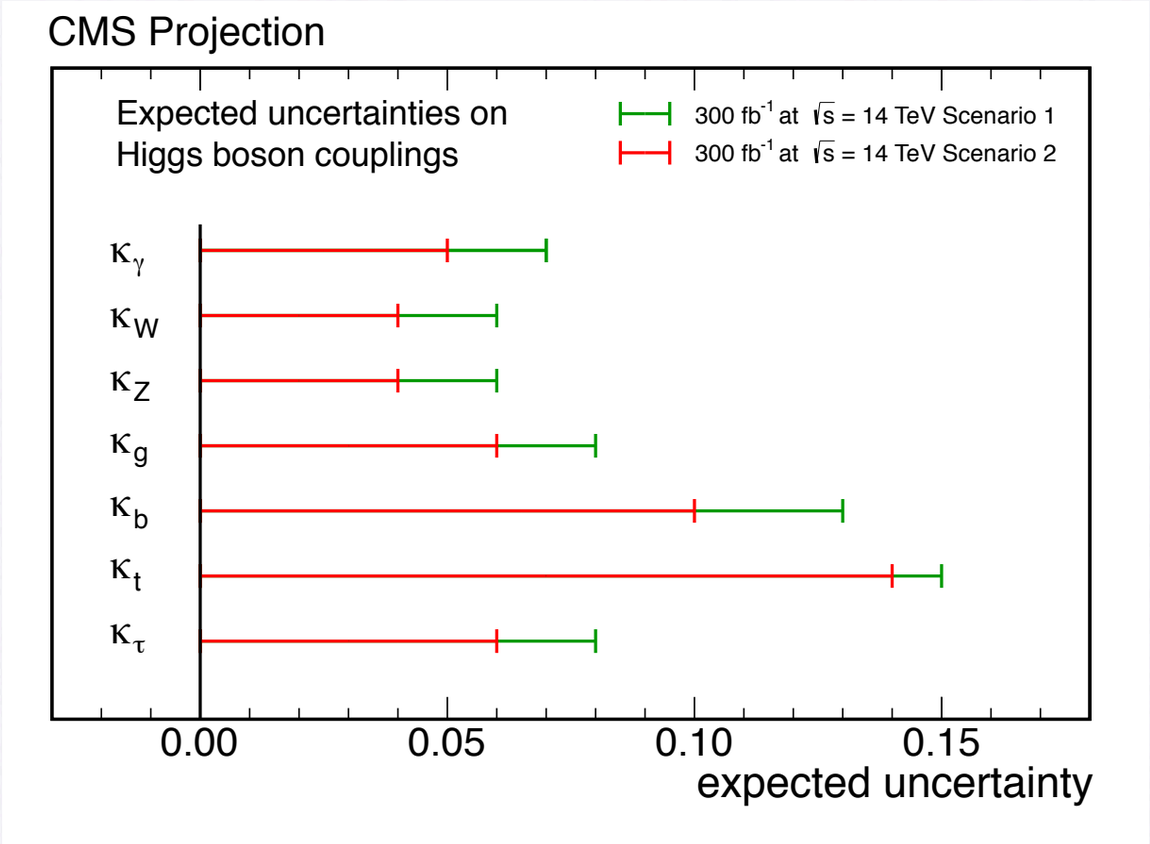
- Higgs mass measured to 0.2%
- Higgs couplings to heavier particles measured to 10-20% (with assumptions)
- A number of processes remain to be seen
- Some couplings will be hard or basically impossible to measure

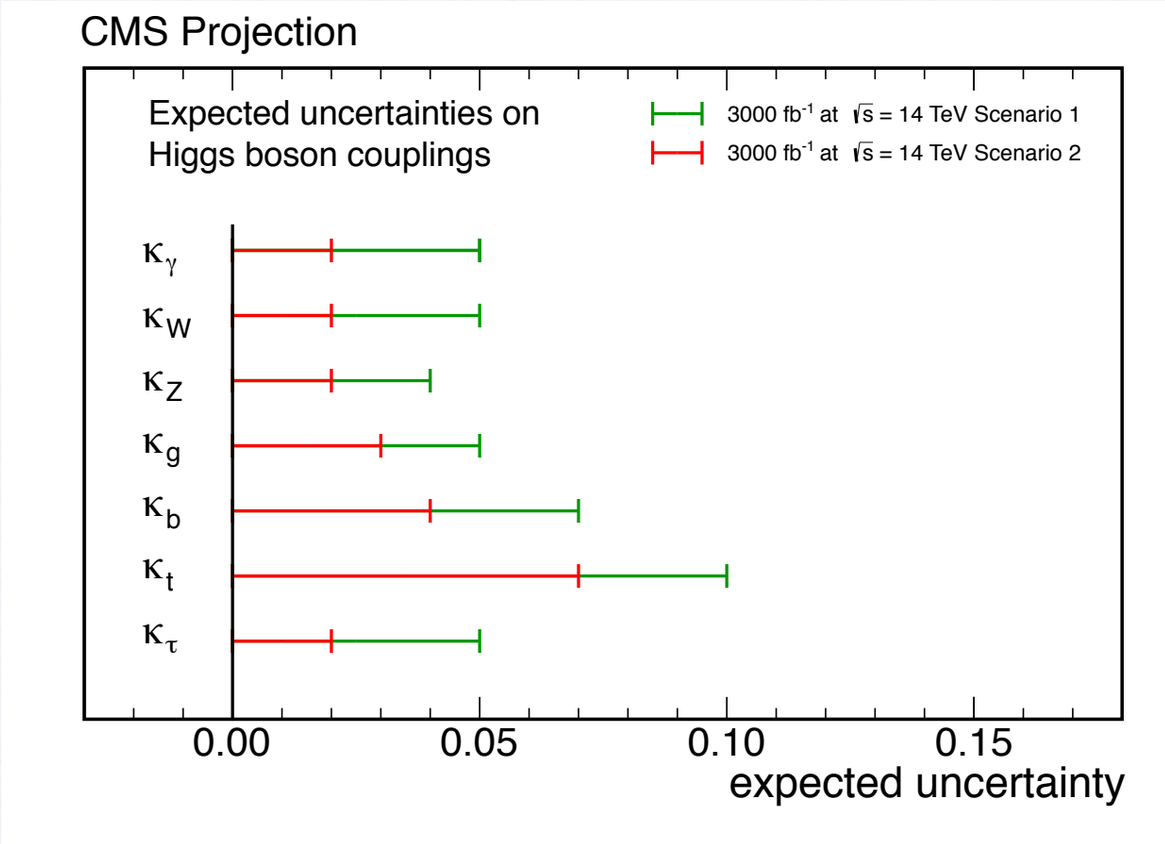




ATLAS-CONF-2015-044

Precision will improve





The "kappa" formalism: introduce "coupling strength" scaling factors κ_i

e.g. $$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \times \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

SM limit: $\kappa_i = 1$

The Higgs Boson

The 125 GeV resonance indeed looks very much like the *SM Higgs*

Yet, it is too soon to conclude it is the SM Higgs (as opposed to a SM-like Higgs)

Recall: *within the SM*, the Higgs mass measurement gives a measurement of the only parameter we were missing: the quartic coupling λ

This means the model predicts everything else about the properties of this particle and how it fits with the rest of the SM particles!

these are many predictions… that should be checked

Perspective:

- **After the discovery of neutral currents in 1973 and of the W & Z gauge bosons 10 years after, we could have been satisfied: after all, the interactions of spin-1 fields are "almost" fixed from theory (given minimal input)**
- **Yet, our confidence in the SM owes much to the precise measurements at LEP!**

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Perspective:

- **But scalar fields are much less constrained theoretically**
- **In addition, the Higgs sector holds the key to one of the crucial physics aspects: the spontaneous breaking of the electroweak symmetry**

We must check as much as we can experimentally!

Plenty of room for "surprises"

- **Rare Higgs decays:** $h \to \gamma Z, h \to \mu\mu$
- **Higgs flavor-violating couplings:** $h \to \mu\tau, t \to hc$
- **CP-violating couplings?**
- **Higgs self-couplings**
- **Higgs width**
- **Are there additional Higgs bosons?** **(Non-minimal Higgs sectors)**
- **Higgs *portal*: only renormalizable operator that can connect to a "dark sector"**

$$\frac{1}{2}\lambda_S H^\dagger H S^2$$

(S: SM singlet)

Invisible Higgs decay width?

Outline

- A couple of examples of “to do’s" in our list
- The Effective Field Theory Approach
- Composite Higgs models and Dynamical EWSB

The Symmetry Breaking Sector

The Standard Model posits the existence of a scalar (spin-0) field, transforming as a doublet of $SU(2)_L$ and with hypercharge $Y = 1/2$. In the vacuum, this ``Higgs doublet" has a vacuum expectation value (VEV):

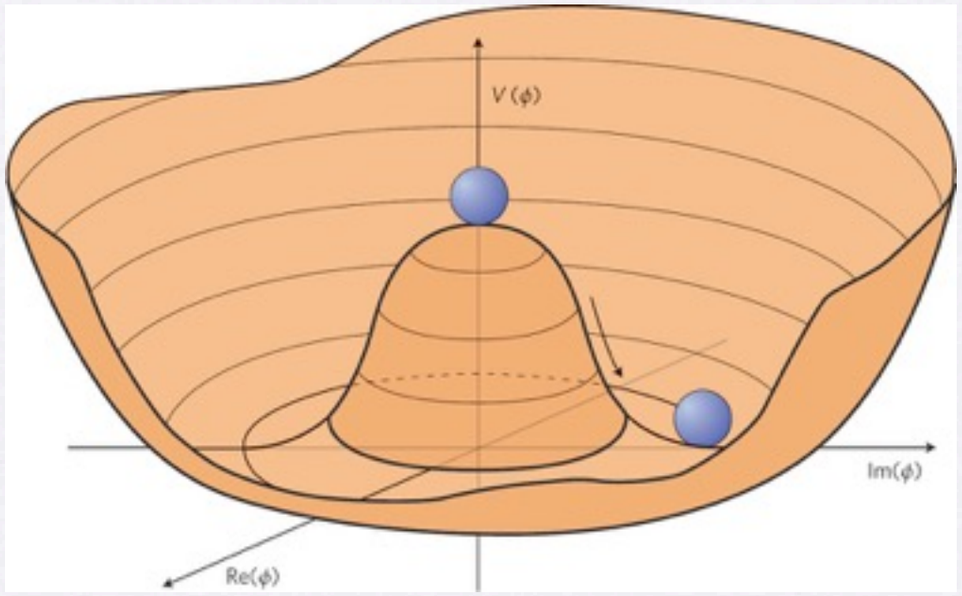
$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

The observed d.o.f. can be parametrized as follows:

$$H = e^{i\,\vec{\chi}\cdot\vec{\tau}} \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}\,h \end{pmatrix} \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

``eaten NGB's"

The 125 resonance (the ``Higgs boson")



``Higgs field" potential:

(Most general renormalizable one)

$$V(H) = \lambda\left(H^\dagger H - v^2\right)^2 \quad \longrightarrow \quad |\langle H \rangle| = v \approx 174 \text{ GeV}$$

Higgs Self-Interactions

Mapping the Higgs potential through Higgs self-interactions at the LHC

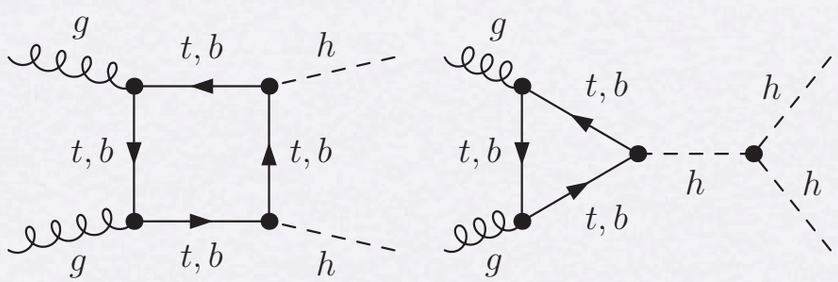
$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

SSB relations: $\lambda_3 = \lambda_4 = m_h^2/(4v^2)$

Measuring λ_3, λ_4: non-trivial check of spontaneous symmetry breaking $\longrightarrow$ Multi-Higgs boson (production)

- Small inclusive cross sections
- Difficult signal to background discrimination

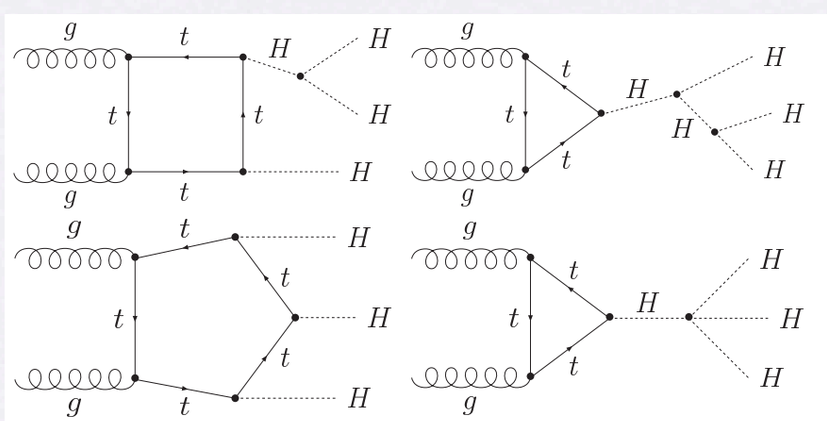
Double-Higgs production



$\sigma \sim 40\,(1750)$ fb at $\sqrt{s} = 14\,(100)$ TeV

at NLO QCD

Triple-Higgs production



$\sigma \sim 80\,(4500)$ ab at $\sqrt{s} = 14\,(100)$ TeV

Double Higgs Production

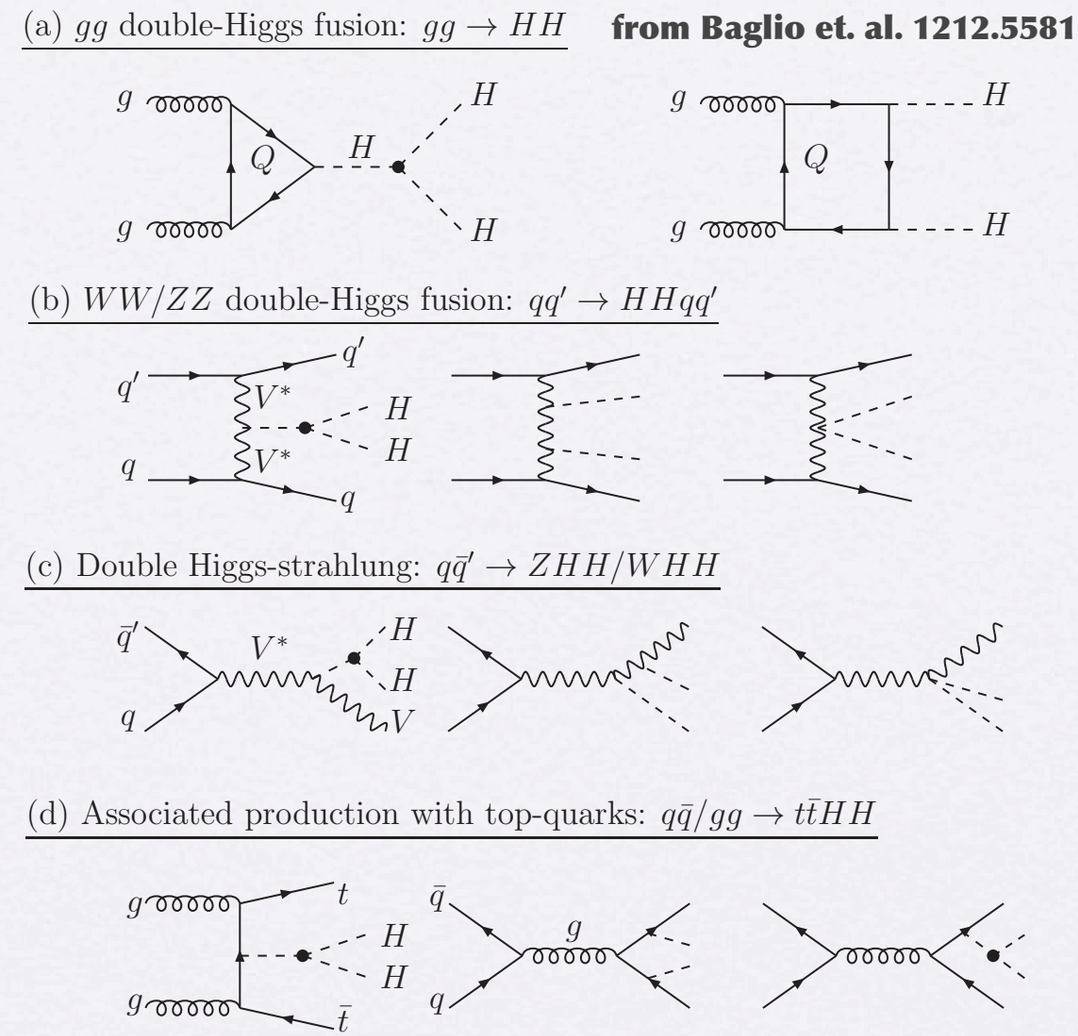
For $m_h = 125$ GeV

$$\sigma_{\rm NNLL} \approx 35\,(40)\ \text{fb} \quad \text{at} \quad \sqrt{s} = 13\,(14)\ \text{TeV}$$

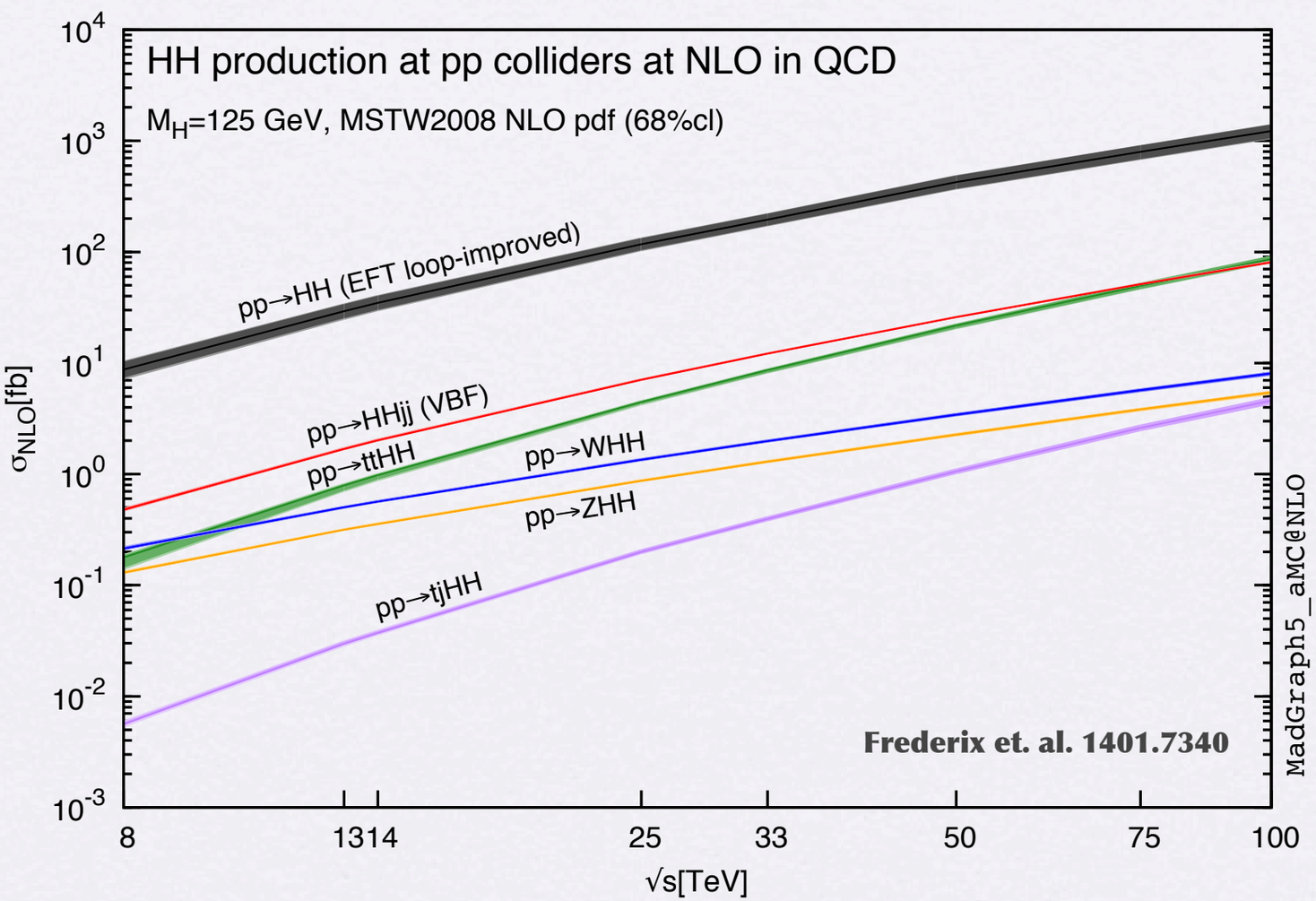
$$\sigma_{\rm NNLL} \approx 1750\ \text{fb} \quad \text{at} \quad \sqrt{s} = 100\ \text{TeV}$$

Uncertainty ~ 5-10%

LHC HXSWG 1610.07922



from Baglio et. al. 1212.5581



- **NLO fixed order, full top mass effects**

  Borowka et. al. 1608.04798

- **NNLO fixed order, large top mass limit**

  de Florián et. al. 1309.6594

Run I Resonant/Non-Resonant

Resonant production

Di-Higgs production through s-channel spin-0 resonance X

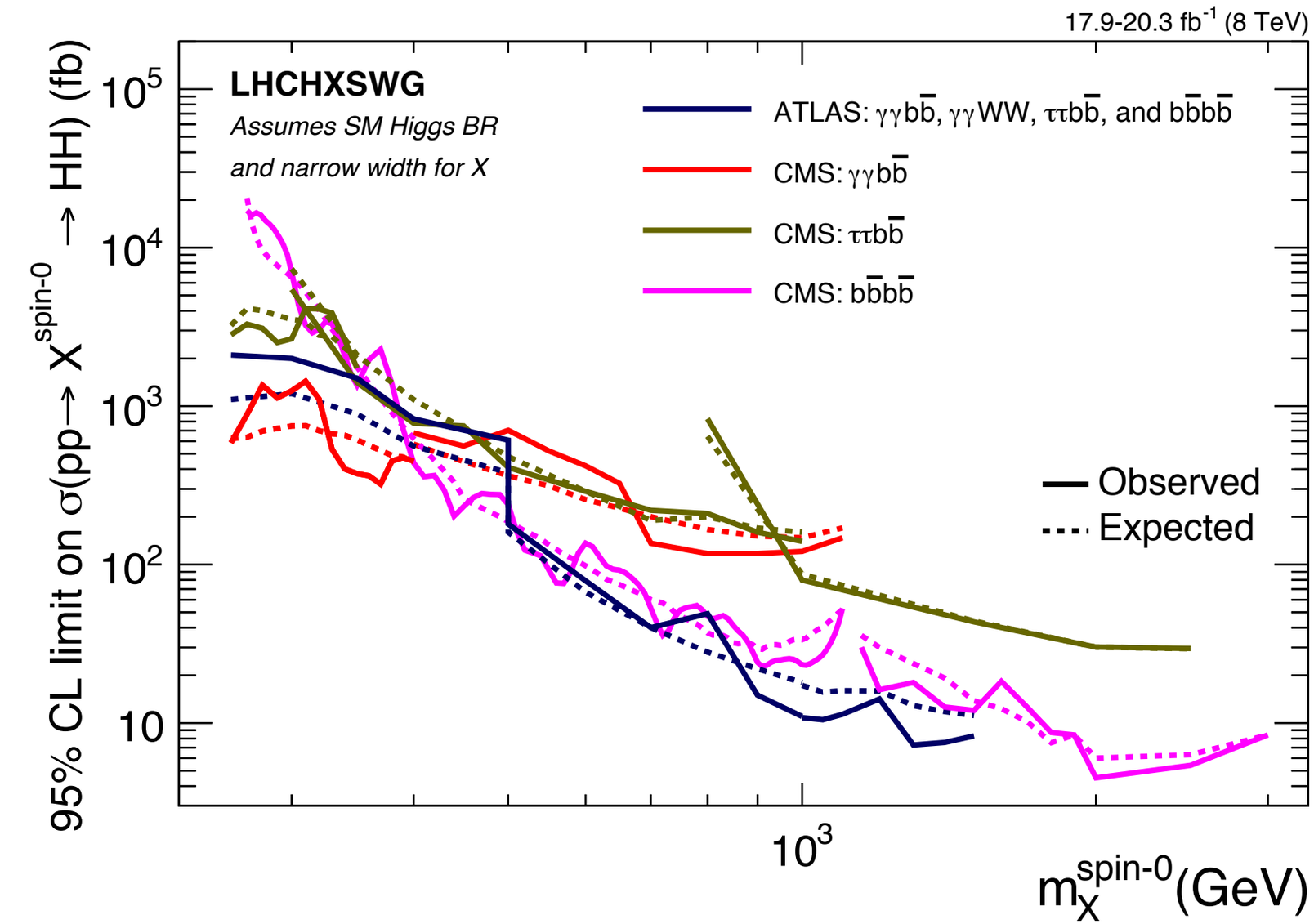
$\gamma\gamma b\bar{b}$ **best for lighter X**

$b\bar{b}b\bar{b}$ **best for heavier X**

Upper Limits:

$1 - 10$ pb **light X**

$1 - 10$ fb **heavy X**



Non-Resonant production

Upper Limits: 0.7 pb **compared to** $\sigma_{\rm NNLL}^{\rm SM} \sim 10$ fb at $\sqrt{s} = 8$ TeV

Off-Shell Higgs Bosons

- **So far we have been studying mostly the on-shell properties of the Higgs boson**

- **However, off-shell Higgs processes can provide additional information** (a different window)

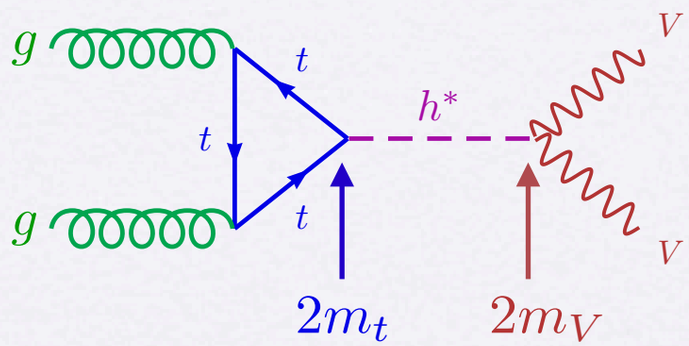
→ **More generally, we want to also study differential distributions**

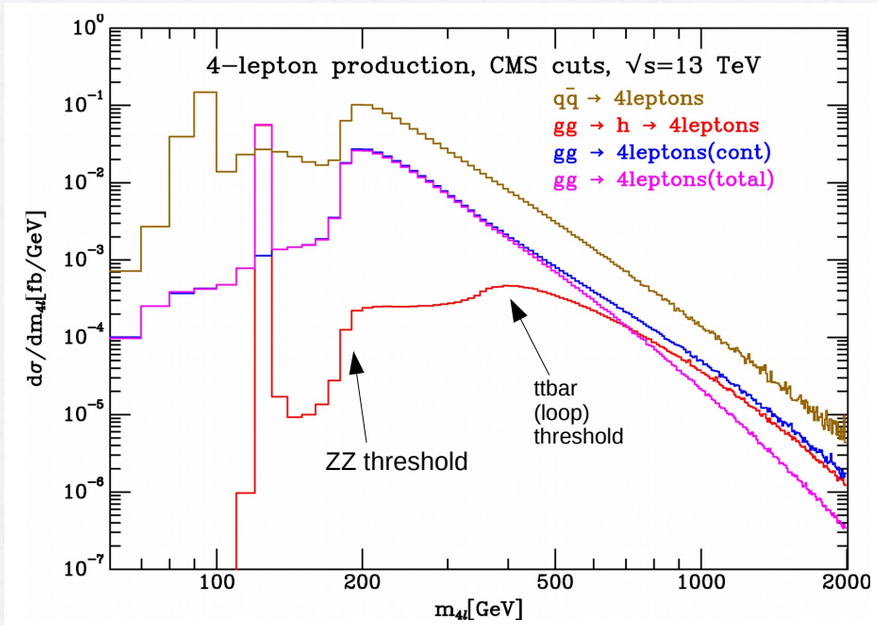
Off-Shell Higgs Bosons

Higgs width in the SM ~ 4 MeV, while the experimental resolution in $h \to \gamma\gamma, ZZ$ is about 1 GeV.

⟶ Direct measurement of the Higgs boson width not feasible at the LHC

Observation: off-shell $gg \to h^* \to VV$ contributes $\mathcal{O}(15\%)$ due to two threshold effects:

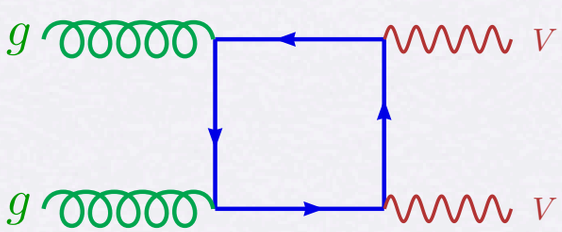




Campbell, Ellis, Williams '13

In this off-shell region, the width in the Higgs propagator is negligible, which gives direct access to the couplings themselves.

Backgrounds



interferes destructively with signal

(unitarization by the Higgs at high energies)

(Caola & Melnikov '13)

$$\sigma_{h,g} \times \mathrm{BR}(h \to ZZ \to 4\ell) \sim \frac{g_{ggh}^2\, g_{hZZ}^2}{\Gamma_h}$$

on-shell region

versus

$$\mathrm{d}\overline{\sigma}_h \sim \frac{g_{ggh}^2(\sqrt{s})\, g_{hZZ}^2(\sqrt{s})}{s}\ \mathrm{dLIPS}\times\mathrm{pdfs}$$

off-shell region

The Higgs Decay Width

If one assumes a connection between $g_i(m_h)$ and $g_i(\sqrt{s})$ one can constrain the Higgs width

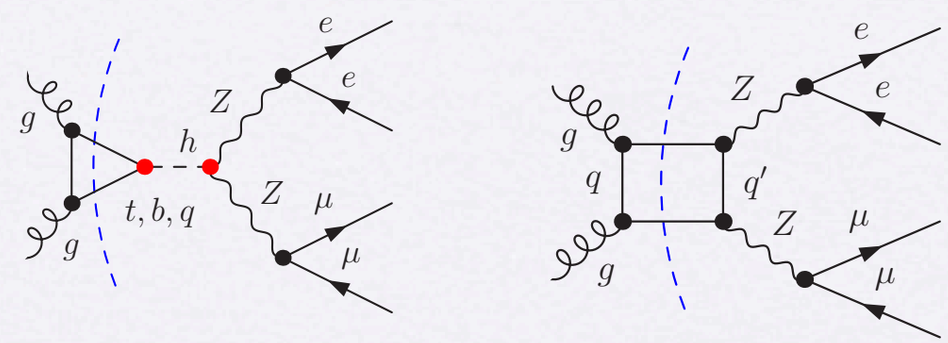
ATLAS: 95% CL upper limit on off-shell signal strength is 5.1-8.6 $\Gamma_h < 33$ MeV

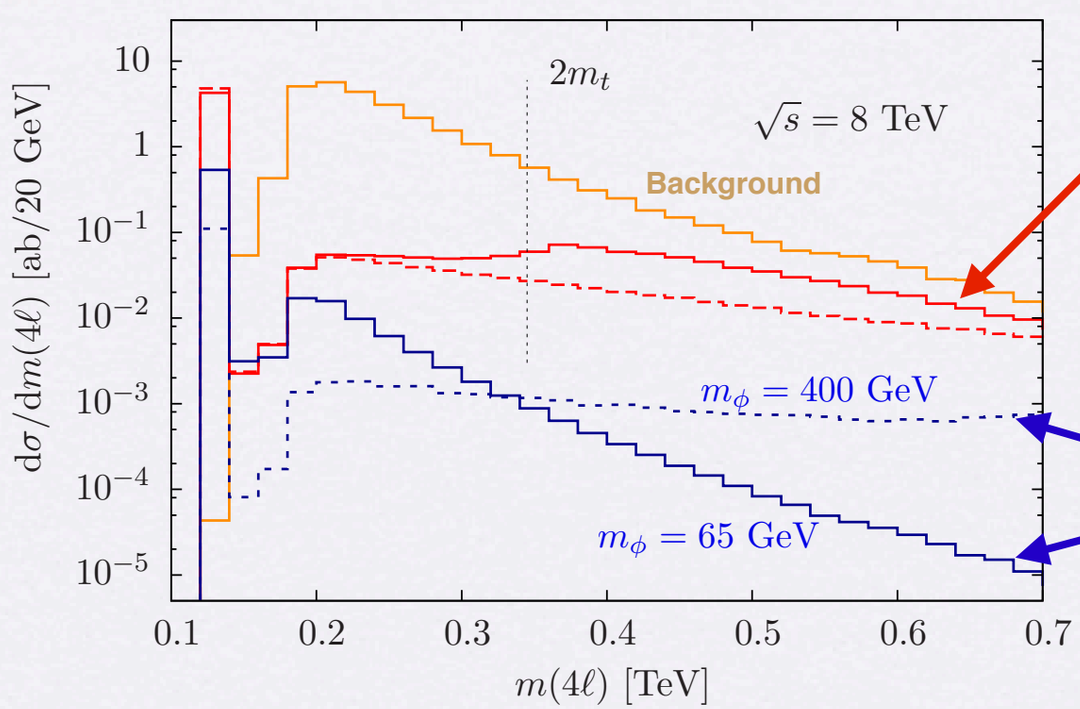
CMS: 95% CL upper limit on off-shell signal strength is 2.4-6.2 $\Gamma_h < 26$ MeV

(range due to variation in unknown background K-factor)

Interpretation is delicate: if width non-standard, but signal strengths are SM-like

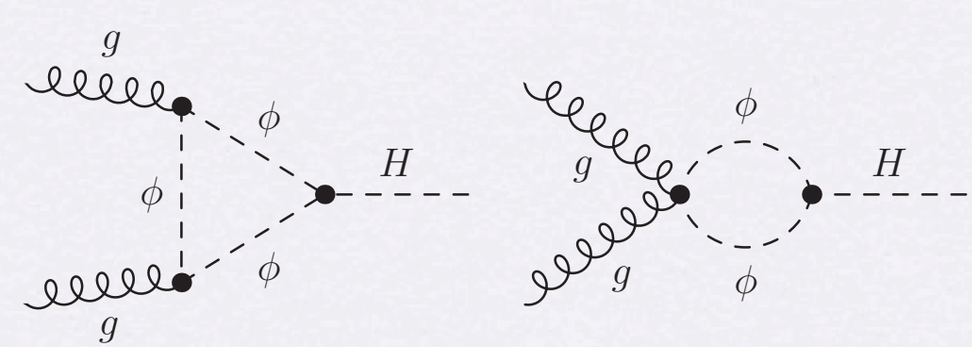
→ possible clash with unitarity





top and bottom only: non-negligible at large $m(4l)$

But, for example: scalar color octet, EW singlet:

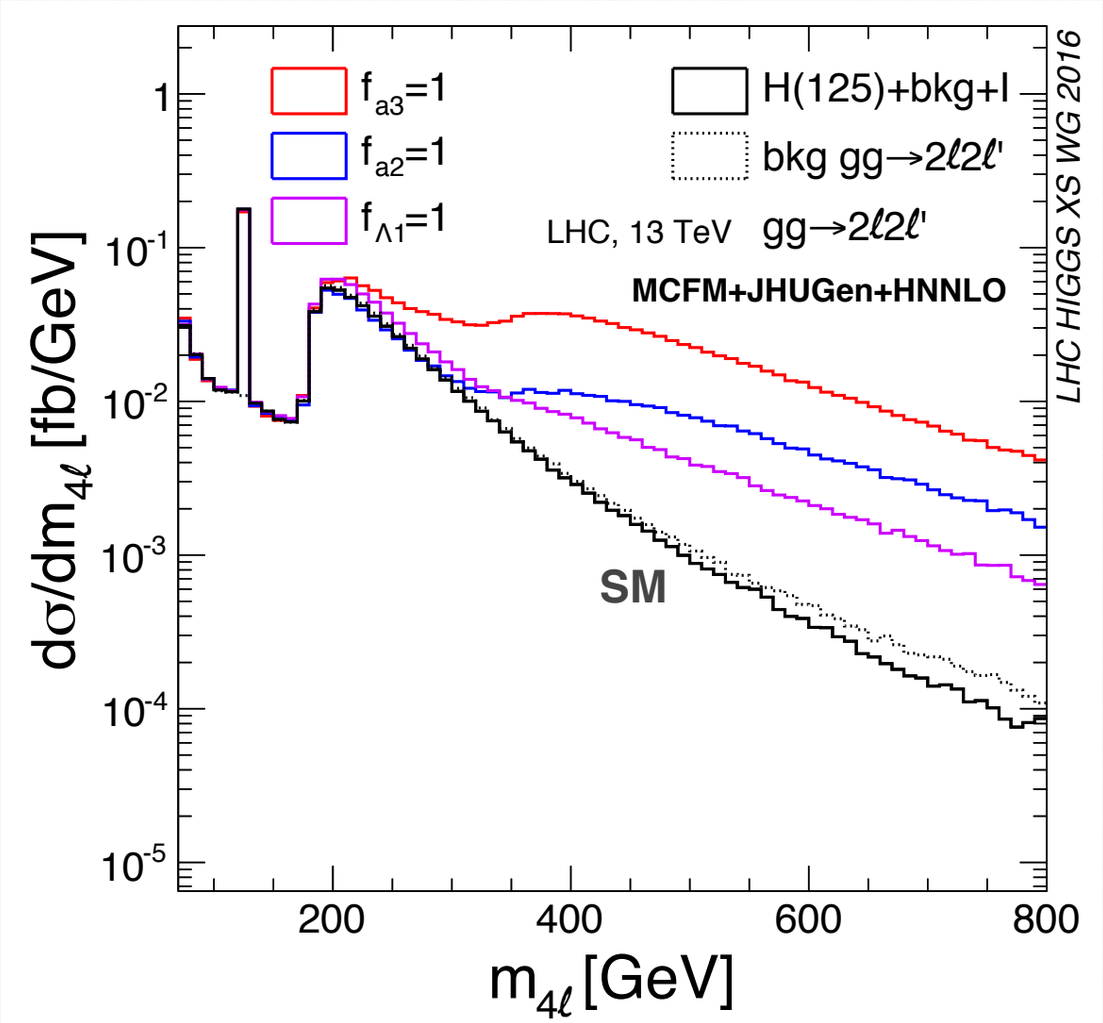


(Englert & Spannowsky, '14; see also Logan, '14)

Anomalous Couplings…

Anomalous couplings of the Higgs to di-bosons can introduce distinct kinematics for $m_{4\ell} > 2m_Z$

The LHC XS WG illustrates with the differential XS for $gg \to ZZ/Z\gamma^*/\gamma^*\gamma^* \to 2\ell 2\ell'$



SM: $a_1 \frac{m_Z^2}{2} \mathrm{H} Z^\mu Z_\mu$

Some anomalous couplings with the Z:

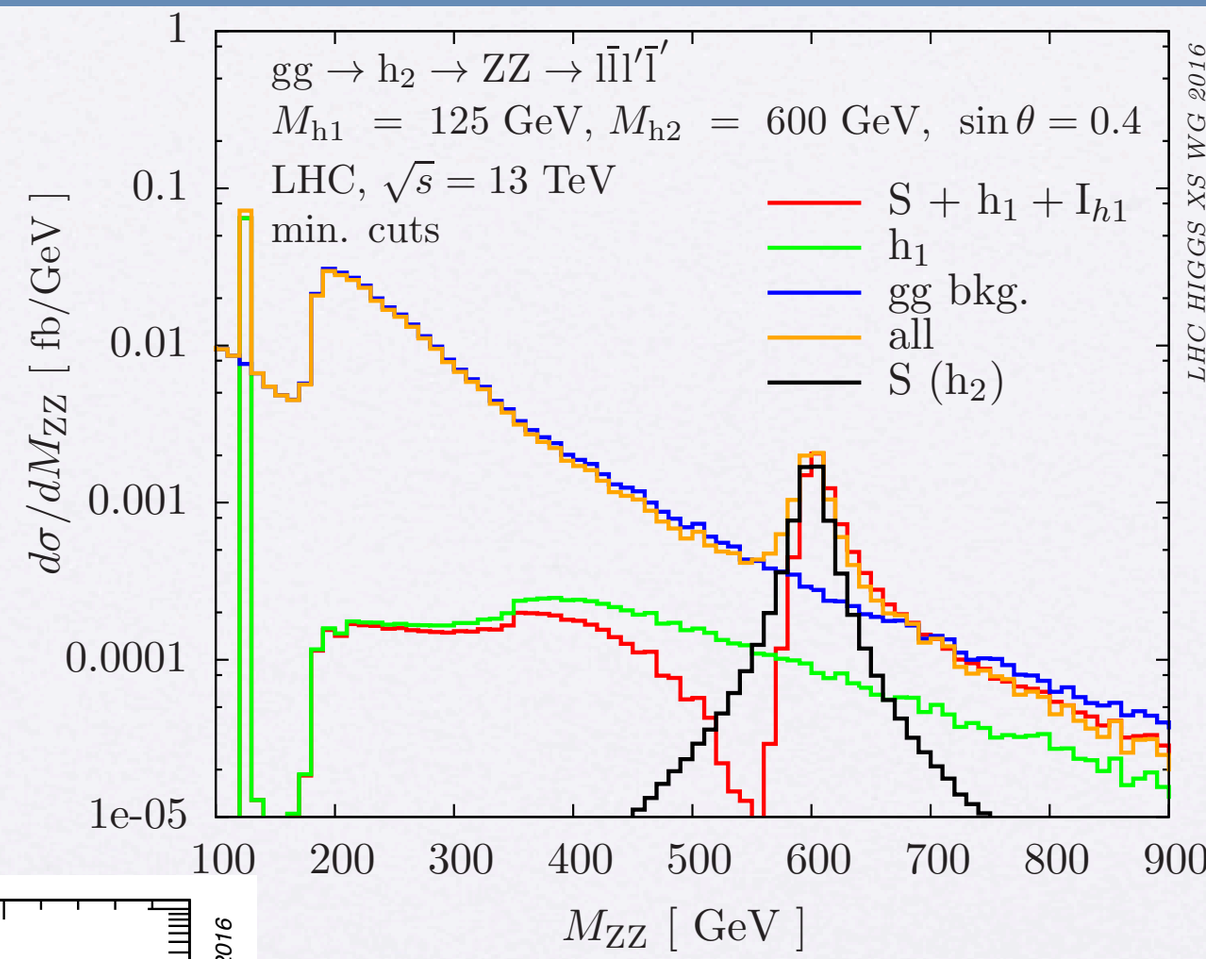
$$-\frac{1}{2} a_2 \mathrm{H} Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

$$-\frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{H} Z^\mu \Box Z_\mu$$

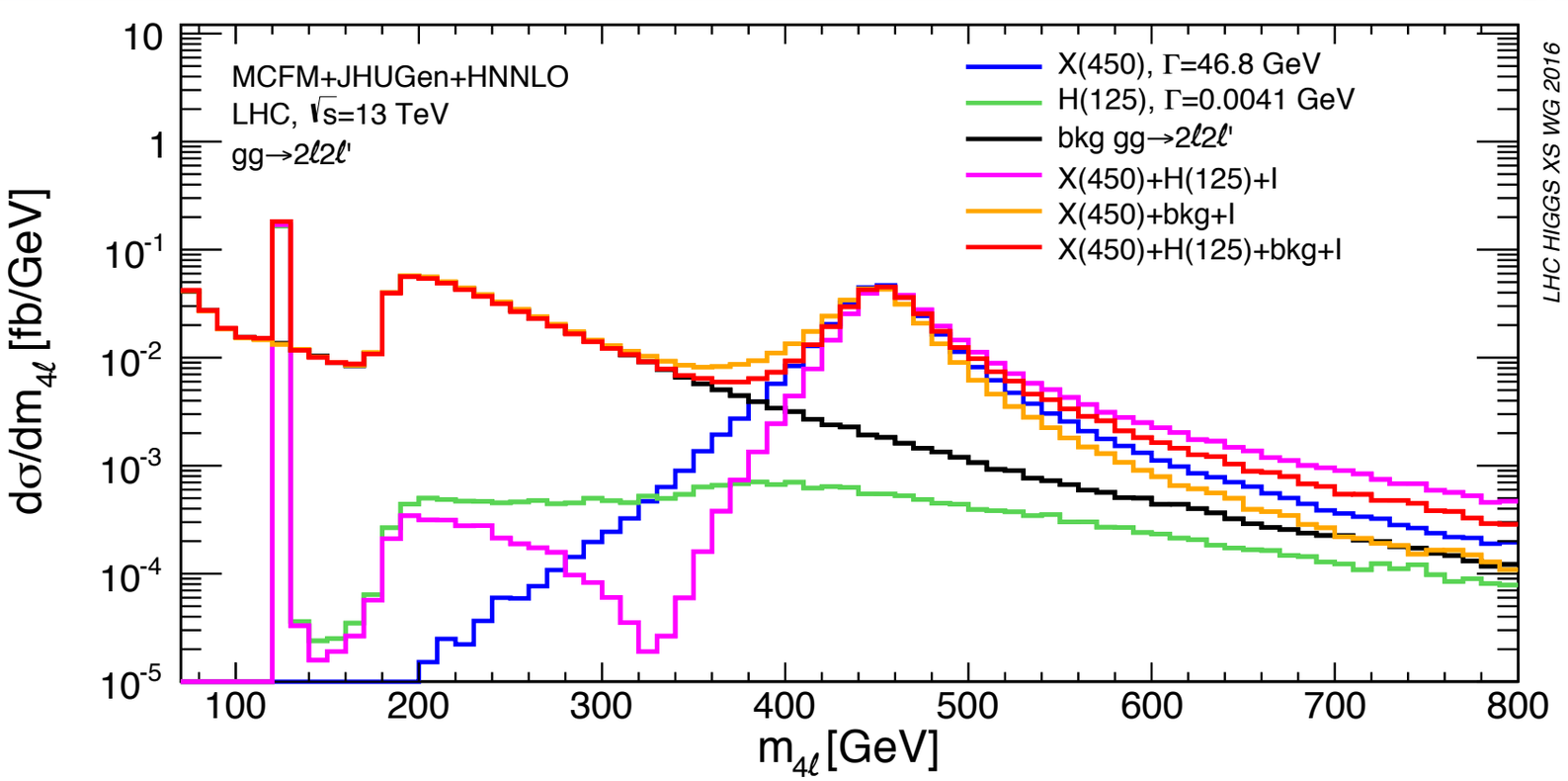
k-factor at NNLO ~ 2-2.5

… or additional Resonances

SM + singlet: parametrized by singlet mass and mixing angle with the Higgs boson



Non-trivial interference between SM Higgs (h1), the heavy Higgs (h2) and the gg background



Broad Higgs-like resonance

Heavy New Physics

We have not observed any degrees of freedom beyond those described by the SM

(except for DM, but only gravitational effects thus far, or indirect evidence for new d.o.f. from neutrino oscillations)

→ **For collider discussion, new physics heavier than energies probed so far**

Focus on indirect effects on SM properties after integrating out such heavy d.o.f., and describe by local higher-dimension operators, suppressed by a typical scale Λ

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

Provided the assumption is satisfied, such an expansion captures the low-energy effects of a *large class* of microscopic theories.

Motivation: cast the experimental information/bounds on the c-parameters, then interpret them as constraints on masses and couplings in a variety of BSM models.

→ **translation of experimental data into a theoretical framework done only once**

In principle: observed deviations could be used as a guide towards the UV theory.

Heavy New Physics

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Heavy New Physics

Assuming a linearly realized SU(3) x SU(2) x U(1)

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$\mathbf{N_g = 3}$

12 = 6 + h.c.

1542

(All violate B - L)

"Weinberg operator": $(\overline{L_i^c}\tilde{H}^*)(\tilde{H}^\dagger L_j)$

(lepton number violating)

Heavy New Physics

Assuming a linearly realized SU(3) x SU(2) x U(1)

General counting: Henning, Lu, Melia & Murayama, '15

Short multiplets of conformal group
Enumeration encoded in a Hilbert series

$\mathbf{N_g = 3}$ 2499 + 546 $\not{B}$ 36971 + 7836 $\not{B}$

$\mathbf{N_g = 1}$ 76 + 4 $\not{B}$ 895 + 98 $\not{B}$

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Dim-7: Lehman, '14
Dim-8: Lehman & Martin, '15

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$\mathbf{N_g = 3}$

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2499 + 546 $\not{B}$

B preserving & not counting h.c. $76 \to 59$

76 + 4 $\not{B}$

36971 + 7836 $\not{B}$

895 + 98 $\not{B}$

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Dimension-6

Focus on dimension-6 operators: leading order effects from heavy new physics

- **Baryon or lepton number violation** **(strong constraints: unimportant at colliders)**
- **Flavor structure**
- **CP violation**

<u>B-preserving operators:</u>

2499 $\xrightarrow[U(3)^5 \text{ flavor symm.}]{\text{Minimal Flavor violation}}$ **59** $\xrightarrow{\text{CP-preserving}}$ **53**

(broken only by Yukawa interactions)

Choice of Basis

A basis is a non-redundant and complete set of operators.

There are a number of widely used bases, for example:

- **The Warsaw basis:** First true basis (Grzadkowski et. al. ’10, following Buchmüller & Wyler, ‘86)

  Convenient for comparison with BSM theories that modify fermion couplings

  Drawback: blind direction w.r.t. EW precision tests

- **The SILH basis:** (Contino et. al. ‘13, following Giudice et. al. ’07; Elias-Miro et. al. '13)

  Designed to capture effects of “universal theories”

  (New physics mostly coupled to EW gauge bosons)

  Drawback: correlation between LEP2 and LHC constraints

- **The BSM primaries basis:** (Gupta et. al. ’14; Masso ’14; Pomarol, ‘14)

  More transparent connection to physical observables

  (formulated in terms of mass eigenstates)

  Drawback: more difficult comparison to BSM theories

The ROSETTA package allows to convert between bases (Falkowski et. al. ’15)

SILH Basis

(Contino et. al. '13, following Giudice et. al. '07; Elias-Miro et. al. '13)

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Barbieri, Bellazzini, Rychkov & Varagnolo, '07

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O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

$$\mathcal{O}_{WW} \equiv \mathcal{O}_W - \mathcal{O}_B + \mathcal{O}_{HB} - \mathcal{O}_{HW} + \frac{1}{4}\mathcal{O}_\gamma$$

Barbieri, Bellazzini, Rychkov & Varagnolo, '07

SILH Basis

(Contino et. al. '13, following Giudice et. al. '07; Elias-Miro et. al. '13)

Constrained by LEP

$\mathcal{O}_W + \mathcal{O}_B$

$\mathcal{O}_{WW} \equiv \mathcal{O}_W - \mathcal{O}_B + \mathcal{O}_{HB} - \mathcal{O}_{HW} + \frac{1}{4}\mathcal{O}_\gamma$

Two combinations constrained by TGC. Third related to $Z\gamma$

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Barbieri, Bellazzini, Rychkov & Varagnolo, '07

SILH Basis

(Contino et. al. '13, following Giudice et. al. '07; Elias-Miro et. al. '13)

Vertex

$[O_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i\gamma_\mu\ell_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i\sigma^k\gamma_\mu\ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{He}]_{ij}$	$\frac{i}{v^2}\bar{e}_i\gamma_\mu\bar{e}_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i\gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i\sigma^k\gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2}\bar{u}_i\gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2}\bar{d}_i\gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar{u}_i\gamma_\mu d_j \tilde{H}^\dagger D_\mu H$

Yukawa and Dipole

$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i}m_{e_j}}}{v^3}H^\dagger H\bar{\ell}_i H e_j$
$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i}m_{u_j}}}{v^3}H^\dagger H\bar{q}_i \widetilde{H} u_j$
$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i}m_{d_j}}}{v^3}H^\dagger H\bar{q}_i H d_j$
$[O_{eW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i\sigma^k H\sigma_{\mu\nu}e_j W^k_{\mu\nu}$
$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i H\sigma_{\mu\nu}e_j B_{\mu\nu}$
$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\tilde{H}\sigma_{\mu\nu}T^a u_j G^a_{\mu\nu}$
$[O_{uW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\sigma^k\tilde{H}\sigma_{\mu\nu}u_j W^k_{\mu\nu}$
$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\tilde{H}\sigma_{\mu\nu}u_j B_{\mu\nu}$
$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H\sigma_{\mu\nu}T^a d_j G^a_{\mu\nu}$
$[O_{dW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i\sigma^k H\sigma_{\mu\nu}d_j W^k_{\mu\nu}$
$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H\sigma_{\mu\nu}d_j B_{\mu\nu}$

The rest are four-fermion operators

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

The previous bases display explicitly the $\mathbf{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge invariance.

To make contact with experiment, replace Higgs vev: only the $\mathbf{SU(3)_C \times U(1)_Q}$ is explicit

→ underlying symmetry reflected in relations between coefficients

One can make further field redefinitions, integrate by parts, use EOM, to put the Lagrangian in a more transparent form, e.g.

- Require canonical normalization
- Preserve tree-level relations between EW parameters and input: transparent interpretation of g, g', v

  If $\mathbf{G_F}, \alpha, \mathbf{m_Z}$ taken as input: g, g' and v have the same numerical values as in the SM

- <u>Higgs basis:</u> separate parameters that impact the precision tests (already well determined) from parameters that impact only the Higgs observables

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

Canonical normalization and SM tree-level relation between EW parameters and input parameters preserved:

$$\mathcal{L}_{\text{kinetic}} = -\frac{1}{2}W^+_{\mu\nu}W^-_{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{4}A_{\mu\nu}A_{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu}$$
$$+ \frac{g^2v^2}{4}(1+\delta m)^2 W^+_\mu W^-_\mu + \frac{(g^2+g'^2)v^2}{8}Z_\mu Z_\mu$$
$$+ \frac{1}{2}\partial_\mu h \partial_\mu h - \lambda v^2 h^2 + \sum_{f\in q,\ell,u,d,e} \bar{f}\left(i\gamma_\mu\partial_\mu - m_f\right) f$$

No correction to Z mass

Definition of λ

$\equiv m_h^2/2$

Correction to W mass

$$\delta m = -\frac{g'^2}{g^2-g'^2}\left(\bar{c}_W + \bar{c}_B + \bar{c}_{2W} + \bar{c}_{2B} - \frac{g^2}{2g'^2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{Hl}]_{22}\right)$$

(vanishes if custodial symmetry)

Corrections to self-couplings of gauge bosons, plus four-fermion interactions: do not affect Higgs production and decay at leading order. Not displayed here.

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

Interactions between fermions and gluons/photons as in the SM. But W and Z receive vertex corrections:

$$\mathcal{L}_{\text{vertex}} = \sqrt{g^2 + g'^2}\, Z_\mu \sum_{f \in u,d,e,\nu} \bar{f}_{L,R} \gamma^\mu \left(T_f^3 - s_\theta^2 Q_f + \delta g_{L,R}^{Zf} \right) f_{L,R}$$

$$+ \frac{g}{\sqrt{2}} \left[W_\mu^+ \bar{\nu}_L \gamma^\mu \left(I_3 + \delta g_L^{W\ell} \right) e_L + W_\mu^+ \bar{u}_{L,R} \gamma^\mu \left(I_3 + \delta g_{L,R}^{Wq} \right) d_{L,R} + \text{h.c.} \right]$$

where, for example,

$$\delta g_L^{Ze} = -\frac{1}{2} \bar{c}'_{H\ell} - \frac{1}{2} \bar{c}_{H\ell} + \hat{f}(-1/2, -1)$$

$$\vdots$$

$$\delta g_L^{Wq} = \left[\bar{c}'_{Hq} + \hat{f}(1/2, 2/3) - \hat{f}(-1/2, -1/3) \right] V_{\text{CKM}}$$

$$\hat{f}(T_f^3, Q_f) \equiv \left[\bar{c}_{2W} + \frac{g'^2}{g^2} \bar{c}_{2B} + \frac{1}{2} \bar{c}_T - \frac{1}{2} [\bar{c}'_{H\ell}]_{22} \right] T_f^3$$

$$- \frac{g'^2}{(g^2 - g'^2)} \left[\frac{(2g^2 - g'^2)}{g^2} \bar{c}_{2B} + \bar{c}_{2W} + \bar{c}_W + \bar{c}_B - \frac{1}{2} \bar{c}_T + \frac{1}{2} [\bar{c}'_{H\ell}]_{22} \right] Q_f$$

Constrained by EW and other precision constraints

Also dipole operators, e.g.

$$e \sum_{f \in u,d,e} \frac{\sqrt{m_{f_i} m_{f_j}}}{v} \bar{f}_{L,i} \sigma^{\mu\nu} [d_{Af}]_{ij} f_{R,j} A_{\mu\nu}$$

$$d_{Ae} = -\frac{16}{g^2} \left(-\bar{c}_{eW} + \bar{c}_{eB} \right), \ldots$$

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

Single Higgs interactions with fermion pairs:

$$\mathcal{L}_{\rm hff} = -\frac{h}{v} \sum_{f\in u,d,e} \sum_{ij} \sqrt{m_{f_i} m_{f_j}} \left(\delta_{ij} + [\delta y_f]_{ij} e^{i[\phi_f]_{ij}}\right) \bar{f}_{R,i} f_{L,j} + \text{h.c.}$$

and to gauge bosons:

$$\begin{aligned}
\mathcal{L}_{\rm hvv} = \frac{h}{v} \Bigg[& (1+\delta c_w) \frac{g^2 v^2}{2} W^+_\mu W^-_\mu + (1+\delta c_z) \frac{(g^2+g'^2)v^2}{4} Z_\mu Z_\mu \\
& + c_{ww} \frac{g^2}{2} W^+_{\mu\nu} W^-_{\mu\nu} + \tilde{c}_{ww} \frac{g^2}{2} W^+_{\mu\nu} \tilde{W}^-_{\mu\nu} + c_{w\Box} g^2 \left(W^-_\mu \partial_\nu W^+_{\mu\nu} + \text{h.c.}\right) \\
& + c_{gg} \frac{g_s^2}{4} G^a_{\mu\nu} G^a_{\mu\nu} + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma} \frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} + c_{zz} \frac{g^2+g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} \\
& + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu} \\
& + \tilde{c}_{gg} \frac{g_s^2}{4} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma} \frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz} \frac{g^2+g'^2}{4} Z_{\mu\nu} \tilde{Z}_{\mu\nu} \Bigg]
\end{aligned}$$

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

Single Higgs interactions with fermion pairs:

$$\mathcal{L}_{\rm hff} = -\frac{h}{v}\sum_{f\in u,d,e}\sum_{ij}\sqrt{m_{f_i}m_{f_j}}\left(\delta_{ij}+[\delta y_f]_{ij}e^{i[\phi_f]_{ij}}\right)\bar{f}_{R,i}f_{L,j}+\text{h.c.}$$

and to gauge bosons:

Independent parameters

$$\begin{aligned}\mathcal{L}_{\rm hvv} = \frac{h}{v}\Bigg[&(1+\delta c_w)\frac{g^2v^2}{2}W^+_\mu W^-_\mu + (1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu\\
&+c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu}+\tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}+c_{w\Box}g^2\left(W^-_\mu\partial_\nu W^+_{\mu\nu}+\text{h.c.}\right)\\
&+c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu}+c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu}+c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu}+c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu}\\
&+c_{z\Box}g^2Z_\mu\partial_\nu Z_{\mu\nu}+c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu}\\
&+\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}+\tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu}+\tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu}+\tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}\Bigg]\end{aligned}$$

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

Single Higgs interactions with fermion pairs:

$$\mathcal{L}_{\rm hff} = -\frac{h}{v}\sum_{f\in u,d,e}\sum_{ij}\sqrt{m_{f_i}m_{f_j}}\left(\delta_{ij}+[\delta y_f]_{ij}e^{i[\phi_f]_{ij}}\right)\bar{f}_{R,i}f_{L,j}+\text{h.c.}$$

and to gauge bosons:

Dependent couplings

(underlying gauge invariance)

Independent parameters

$$\begin{aligned}\mathcal{L}_{\rm hvv} = \frac{h}{v}\Big[&(1+\delta c_w)\frac{g^2v^2}{2}W^+_\mu W^-_\mu + (1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu\\ &+c_{ww}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu}+\tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}+c_{w\Box}g^2\left(W^-_\mu\partial_\nu W^+_{\mu\nu}+\text{h.c.}\right)\\ &+c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^a_{\mu\nu}+c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu}+c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu}+c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu}\\ &+c_{z\Box}g^2Z_\mu\partial_\nu Z_{\mu\nu}+c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu}\\ &+\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}+\tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu}+\tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu}+\tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}\Big]\end{aligned}$$

Dipole-like Higgs couplings also fixed by corresponding dipole moment coefficients

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

Higgs boson self-couplings:

$$\mathcal{L}_{h,\text{self}} = -(\lambda + \delta\lambda_3) v h^3$$

plus terms h^4, h^5, h^6

$$\delta\lambda_3 = \lambda\left(\bar{c}_6 - \frac{3}{2}\bar{c}_H - \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right)$$

and double Higgs boson couplings:

$$\begin{aligned}
\mathcal{L}_{h^2} = {} & h^2\left(1 + 2\delta c_z^{(2)}\right)\frac{g^2 + g'^2}{4} Z_\mu Z_\mu + h^2\left(1 + 2\delta c_w^{(2)}\right)\frac{g^2}{2} W_\mu^+ W_\mu^- \\
& - \frac{h^2}{2v^2}\sum_{f;ij}\sqrt{m_{f_i} m_{f_j}}\left[\bar{f}_{i,R}[y_f^{(2)}]_{ij} f_{j,L} + \text{h.c.}\right] \\
& + \frac{h^2}{8v^2}\left(c_{gg}^{(2)} g_s^2 G_{\mu\nu}^a G_{\mu\nu}^a + \cdots\right) + \frac{h^2}{8v^2}\left(\tilde{c}_{gg}^{(2)} g_s^2 G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \cdots\right) \\
& - \frac{h^2}{2v^2}\left(g^2 c_{z\Box}^{(2)} Z_\mu \partial_\nu Z_{\nu\mu} + \cdots\right)
\end{aligned}$$

The Higgs Basis

Gupta et. al. '14; Falkowski, '15

Higgs boson self-couplings:

$$\mathcal{L}_{h,\text{self}} = -(\lambda + \delta\lambda_3) v h^3$$

plus terms h^4, h^5, h^6

$$\delta\lambda_3 = \lambda\left(\bar{c}_6 - \frac{3}{2}\bar{c}_H - \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right)$$

and double Higgs boson couplings:

$$\begin{aligned}
\mathcal{L}_{h^2} = {} & h^2\left(1 + 2\delta c_z^{(2)}\right)\frac{g^2 + g'^2}{4} Z_\mu Z_\mu + h^2\left(1 + 2\delta c_w^{(2)}\right)\frac{g^2}{2} W_\mu^+ W_\mu^- \\
& - \frac{h^2}{2v^2}\sum_{f;ij}\sqrt{m_{f_i} m_{f_j}}\left[\bar{f}_{i,R}[y_f^{(2)}]_{ij} f_{j,L} + \text{h.c.}\right] \\
& + \frac{h^2}{8v^2}\left(c_{gg}^{(2)} g_s^2 G_{\mu\nu}^a G_{\mu\nu}^a + \cdots\right) + \frac{h^2}{8v^2}\left(\tilde{c}_{gg}^{(2)} g_s^2 G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \cdots\right) \\
& - \frac{h^2}{2v^2}\left(g^2 c_{z\Box}^{(2)} Z_\mu \partial_\nu Z_{\nu\mu} + \cdots\right)
\end{aligned}$$

All double Higgs boson couplings fixed by single Higgs boson couplings

Simplified scenarios

A number of parameters are already well constrained by EW precision and dipole measurements:

$$\delta m,\ [\delta g_L^{Ze}]_{ij},\ [\delta g_R^{Ze}]_{ij},\ [\delta g_L^{W\ell}]_{ij},\ [\delta g_L^{Zu}]_{ij},\ [\delta g_R^{Zu}]_{ij},\ [\delta g_L^{Zd}]_{ij},\ [\delta g_R^{Zd}]_{ij},\ [\delta g_R^{Wq}]_{ij}$$

$$[d_{Gu}]_{ij},\ [d_{Gd}]_{ij},\ [d_{Ae}]_{ij},\ [d_{Au}]_{ij},\ [d_{Ad}]_{ij},\ [d_{Ze}]_{ij},\ [d_{Zu}]_{ij},\ [d_{Zd}]_{ij}$$

One may neglect these since LHC is not competitive. Focus instead on:

$$c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \tilde{c}_{gg},\ \tilde{c}_{\gamma\gamma},\ \tilde{c}_{z\gamma},\ \tilde{c}_{zz},\ \delta\lambda_3$$

$$[\delta y_u]_{ij},\ [\delta y_d]_{ij},\ [\delta y_e]_{ij},\ [\phi_u]_{ij},\ [\phi_d]_{ij},\ [\phi_\ell]_{ij}$$

These may be further reduced by imposing MFV: $[\delta y_f]_{ij} = \delta_{ij}\delta y_f$ **and** $[\phi_f]_{ij} = \delta_{ij}\phi_f$ **:**

$$\text{CP-even}: c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_u,\ \delta y_d,\ \delta y_e,\ \delta\lambda_3;$$ ← **10 pars**

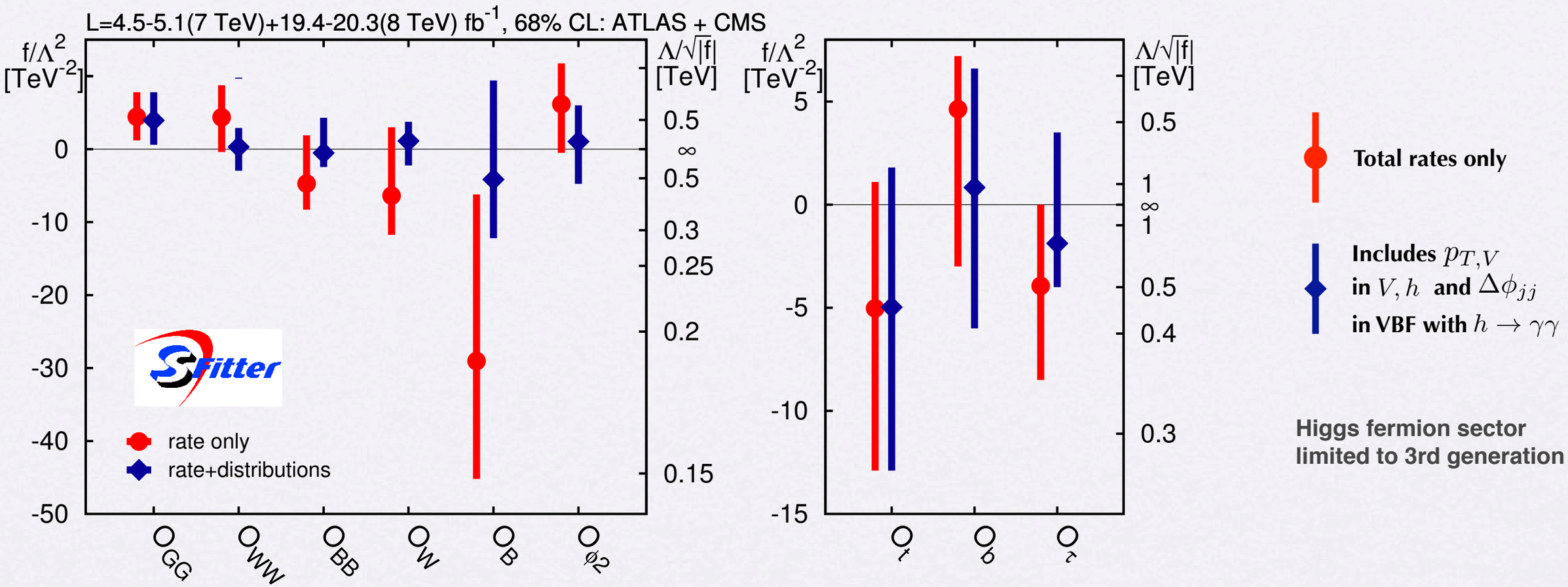
$$\text{CP-odd}: \tilde{c}_{gg},\ \tilde{c}_{\gamma\gamma},\ \tilde{c}_{z\gamma},\ \tilde{c}_{zz},\ \phi_u,\ \phi_d, \phi_e$$ ← **7 pars**

It may be feasible for LHC Run II to constrain these 17 pars. in a “model-independent” way.

Run I Fit: an Example

SFitter analysis of Run I, ATLAS + CMS data

Corbet, Éboli, Gonçalves, Gonzalez-Fraile, Plehn & Rauch, '15



These are translated into:

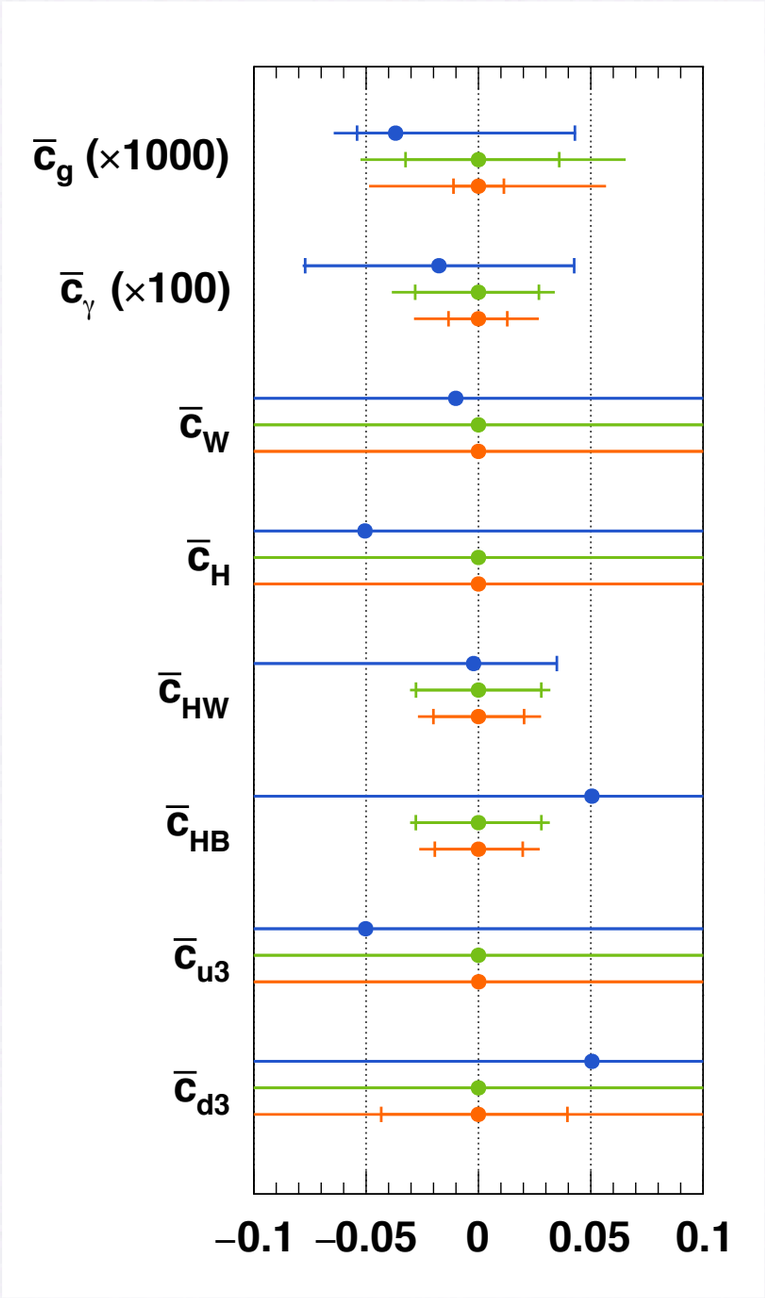
For $g = 1$ $\quad \Lambda \gtrsim 300 \text{ GeV}$ **(total rates only)**

$\Lambda \gtrsim 500 \text{ GeV}$ **(including distributions)**

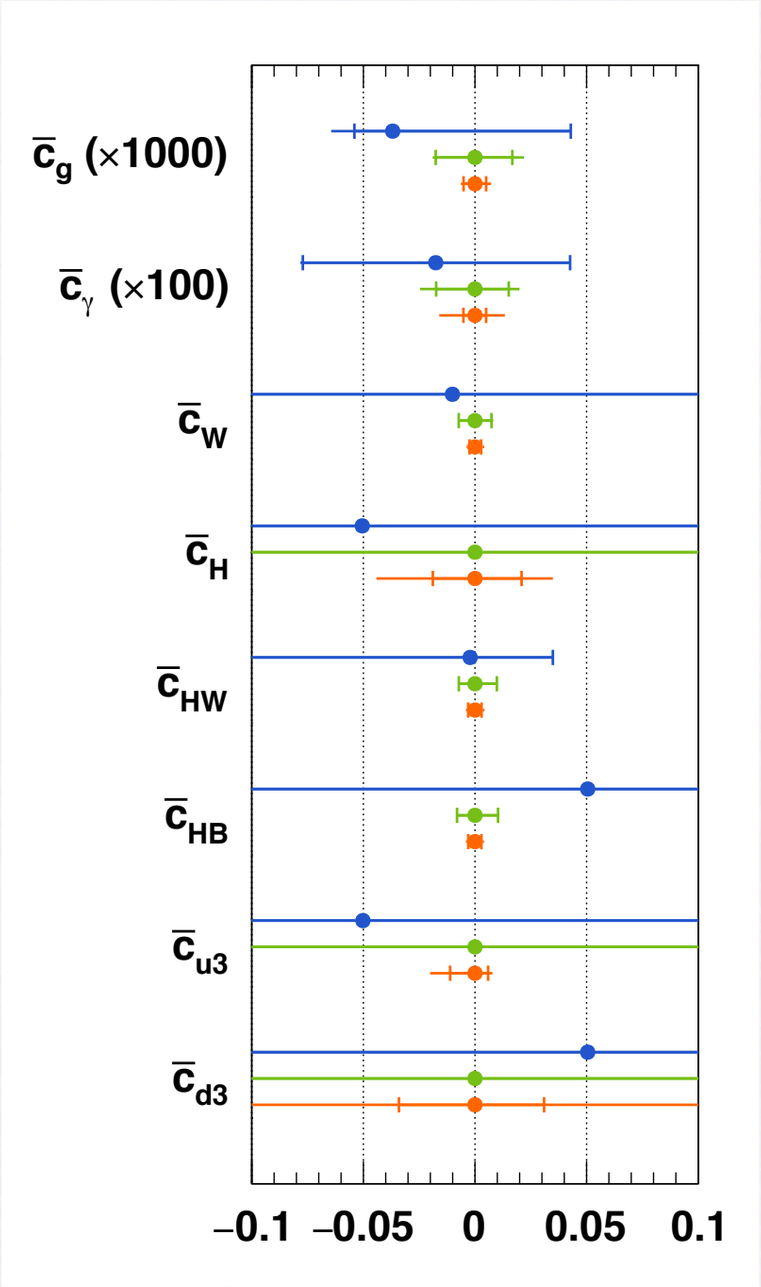
Run II Fit: a projection

Englert, Kogler, Schulz & Spannowsky, '15

Only signal strengths



With differential $p_{T,h}$ distr.



Marginalized 95% CL

- Current LHC
- LHC 14, $300\ \mathrm{fb}^{-1}$
- LHC 14, $3000\ \mathrm{fb}^{-1}$

Validity of the EFT

Contino et. al., '16

The crucial assumption of the EFT approach is that the new d.o.f. are much heavier than the energies probed (or the masses of the particles kept in the EFT description)

The consistency of the analysis is model dependent, and has to be checked on a case by case basis

If we identify Λ as the mass of new states, the EFT expansion requires

$$\kappa \equiv \frac{E}{\Lambda} < 1$$

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For $E \sim \Lambda$ a truncation of the tower is not justified. But higher-loop contributions are suppressed.

- If $E \ll \Lambda$ a truncation of the tower at dim-6, for example, leads to a theoretical uncertainty κ^2 from the neglected dim-8 operators, whether the UV theory is weakly or strongly coupled.

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$$c_i^{(6)} \equiv \frac{\hat{c}_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\mathrm{Exp}}(\kappa\Lambda)$$

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Fix κ according to the experimental sensitivity

(tolerated error due to truncation)

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Fix κ according to the experimental sensitivity

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Provide as a function of Λ

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g_* typical coupling of the heavy physics to the SM

(Need to determine the power counting, which depends on the UV theory)

Fix κ according to the experimental sensitivity

(tolerated error due to truncation)

Provide as a function of Λ

Finally, infer the bound on the new physics scale for the given model

Check for self-consistency (wants strongest bound)

Validity of the EFT

Contino et. al., '16

<u>Some warnings</u>

One should also note that special situations may arise, where one could naively think that the EFT expansion is breaking down, but it isn't. For example:

- If the BSM couplings are large compared to the SM ones, the largest contribution to some observables can arise from the higher-dimension operators

- Extreme case: when the SM does not contribute to a process (e.g. lepton-flavor violation), but the new physics does

  In both cases, the dim-6 effect is "large" without implying a breakdown of the EFT expansion

- One can also encounter UV examples where operators of dim-D give comparable or dominant effects than those induced by operators of lower dimension. Example: Higgs sector in SUSY theories

Carena, Kong, EP & Zurita, '09

Non-linear EFT

The SM EFT discussed thus far assumes that the observed Higgs boson fits, together with the NGB's, into a SU(2) doublet

$$H = U(x) \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}} h \end{pmatrix} \qquad U(x) = e^{i\,\vec{\chi}\cdot\vec{\tau}}$$

``eaten NGB's"

The resulting theory exhibits the SU(2) x U(1) symmetry linearly, and describes simultaneously a number of SM deviations:

- Gauge boson couplings to fermions
- Gauge boson self-interactions
- Higgs boson couplings

Given that the gauge boson properties are well constrained by precision measurements, it can be useful to have a consistent description where only the Higgs boson properties deviate from the SM expectation. This leads to a non-linear EFT:

EW Chiral Lagrangian plus a scalar gauge singlet h

Non-linear EFT

Buchalla, Catá & Krause, '14
Feruglio, '93; Bagger et. al., '93
and many others…

EW Chiral Lagrangian plus a scalar gauge singlet h

$$\mathcal{L}_2 = -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{\psi=q_L,l_L,u_R,d_R,e_R} \bar{\psi} i \not{D}\psi$$

$$+ \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle\,(1+F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

$$- v\left[\bar{q}_L\left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)}\left(\frac{h}{v}\right)^n\right) U P_+ q_R + \bar{q}_L\left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- q_R\right.$$

$$\left. + \bar{l}_L\left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- l_R + \text{h.c.}\right]$$

where

$$D_\mu U = \partial_\mu U + igW_\mu U - ig' B_\mu U T_3$$

$$F_U(h) = \sum_{n=1}^{\infty} f_{U,n}\left(\frac{h}{v}\right)^n, \qquad V(h) = v^4 \sum_{n=2}^{\infty} f_{V,n}\left(\frac{h}{v}\right)^n$$

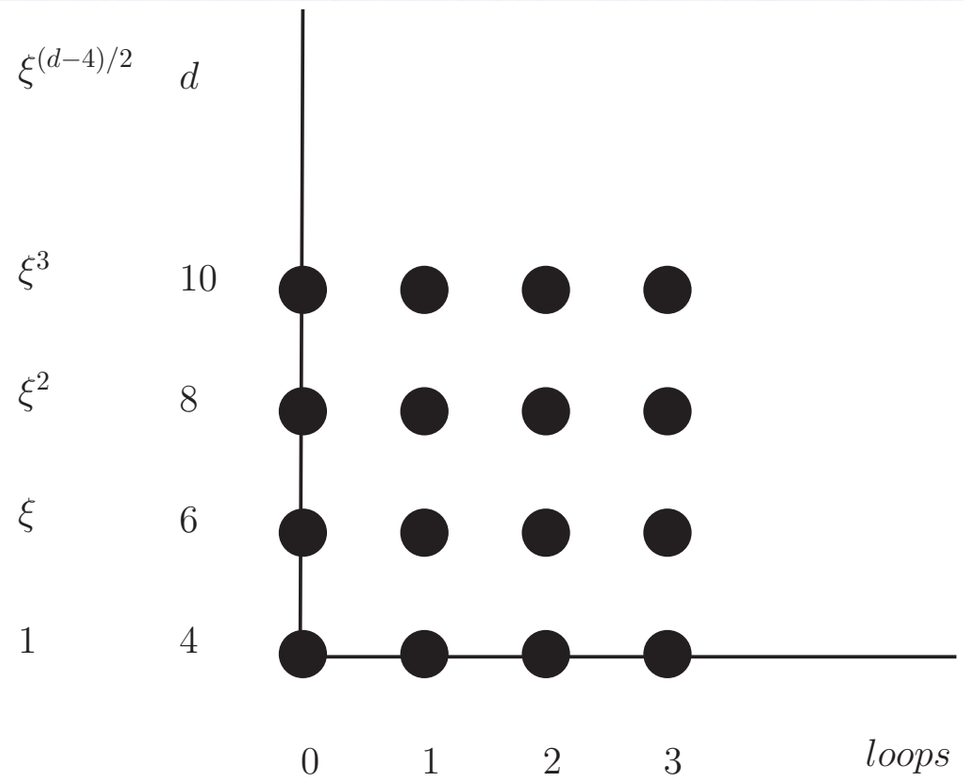
One also adds the "loop-induced" terms: $e^2 F_{\mu\nu}F^{\mu\nu}h, \qquad eg' F_{\mu\nu}Z^{\mu\nu}h, \qquad g_s^2\langle G_{\mu\nu}G^{\mu\nu}\rangle h$

Non-linear EFT

Focusing on single Higgs couplings and processes accesible at the LHC, leads to the "κ-formalism":

(with custodial symmetry)

$$\mathcal{L} = 2\kappa_V \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \frac{h}{v} - \kappa_t y_t \bar{t} t h - \kappa_b y_b \bar{b} b h - \kappa_\tau y_\tau \bar{\tau} \tau h$$
$$+ \frac{e^2}{16\pi^2} \kappa_\gamma F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} \kappa_g \langle G_{\mu\nu} G^{\mu\nu} \rangle \frac{h}{v}$$



Unlike the "linear SM EFT", the non-linear EFT can consistently accommodate order one deviations from the SM:

$$\xi \equiv v^2 / f^2$$

new scale in the "EWSB sector"

Breakdown at $\Lambda = 4\pi f$

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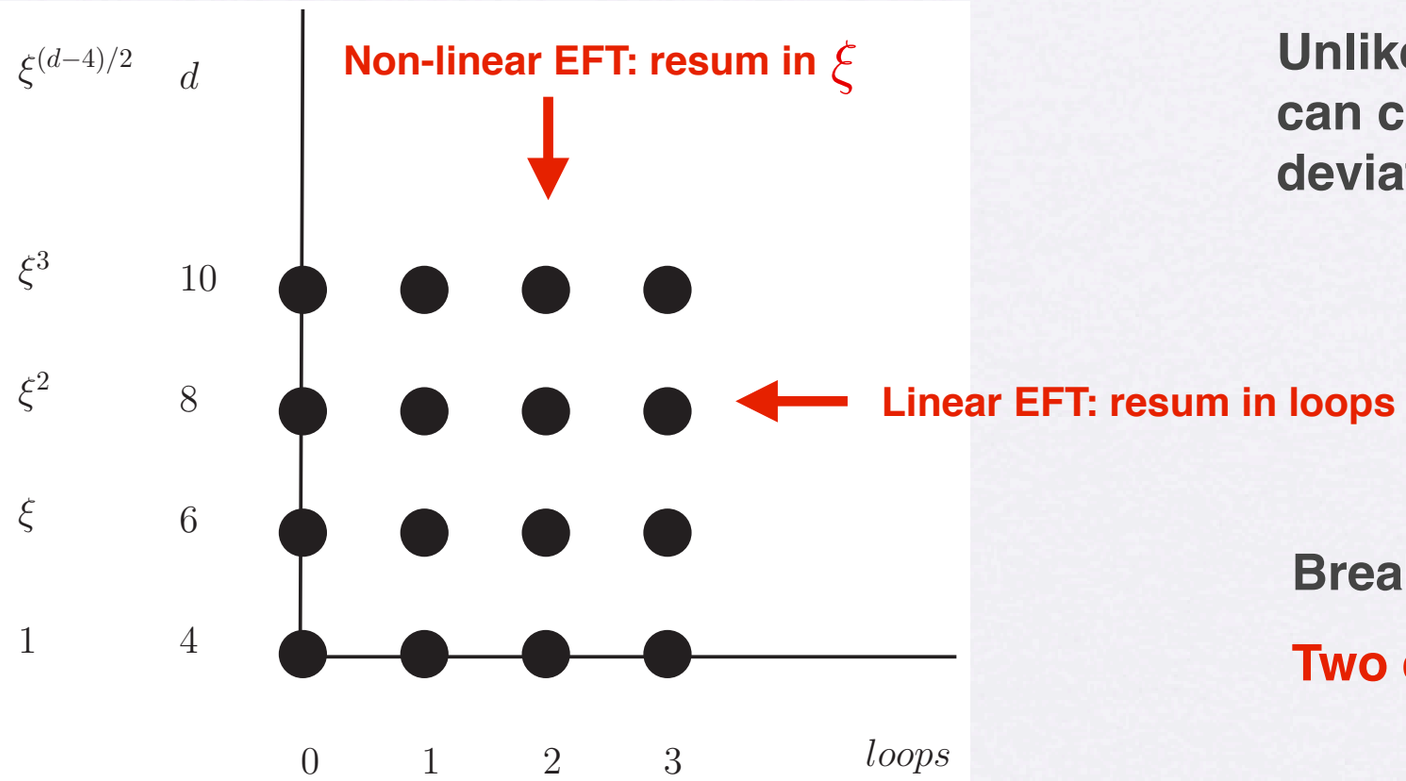

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Breakdown at $\Lambda = 4\pi f$

Two expansion parameters:

ξ **and** $\frac{1}{16\pi^2} = \frac{f^2}{\Lambda^2}$

Microscopic Models

Dynamics underlying EWSB?

Two broad possibilities:

a) Weakly coupled SUSY (See M. Carena's talk)

b) Strongly coupled Composite Higgs Models

The Higgs as a pNGB

BSM: Standard Model + Strongly coupled sector

Elementary sector:
SM gauge bosons, quarks & leptons

SM gauge interactions

$\longleftrightarrow$

Mixing

New strong sector:
resonances +
Higgs bound state

Sufficiently large global symmetry G

$(SU(3)_C \times SU(2)_L \times U(1)_Y \subset G)$

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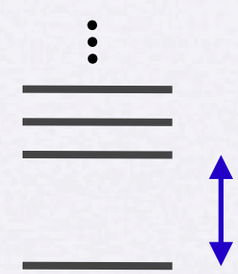
Dynamically generated scale Λ

$G \to \mathcal{H}$

Set of resonances



Mass gap: Higgs as a pNGB

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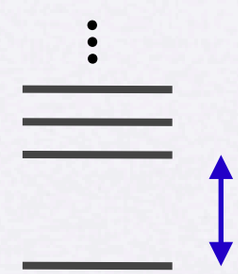


Mass gap: Higgs as a pNGB

- **Higgs lighter than other resonances if it is a pNGB of the G/H breaking** Georgi & Kaplan '84 Agashe et. al '03
- **Observed fermions (and gauge bosons) are admixtures of elementary and composite states. Observed flavor structure translates into a structure of mixing angles** Kaplan '91

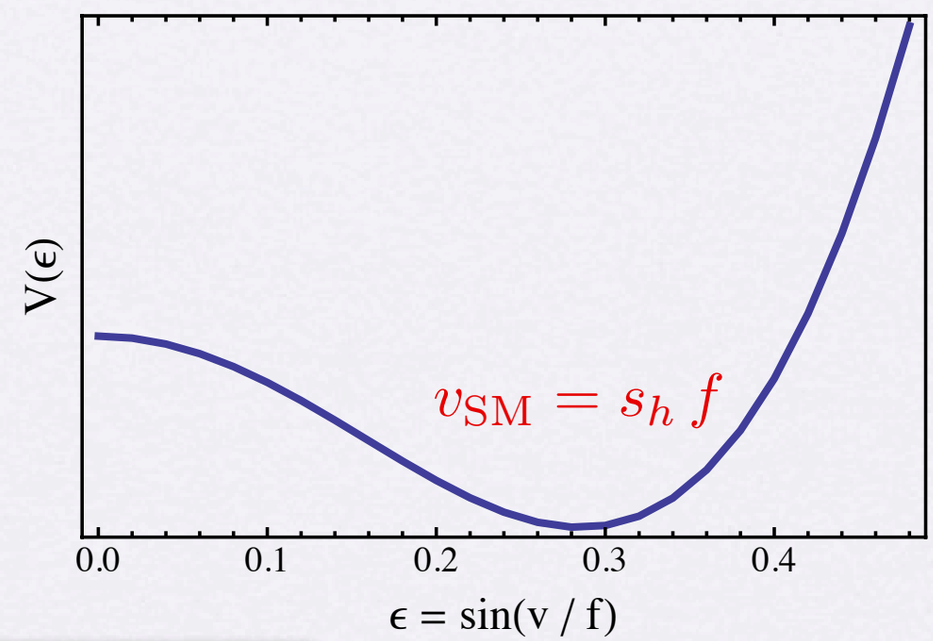
The Higgs as a pNGB

- In the absence of mixing with the elementary sector, the NGB Higgs has no potential
- The potential is generated at loop level as a result of the SM gauge and Yukawa int's.

(explicit breaking of G)

$$V = -\frac{\alpha}{2} s_h^2 + \frac{\beta}{4} s_h^4 + \mathcal{O}(s_h^6) \qquad s_h = \sin(h/f)$$

- Gauge interactions:
  prefer ``vacuum alignment'' (no EWSB)
- Yukawa interactions (dominated by top):
  can induce EWSB



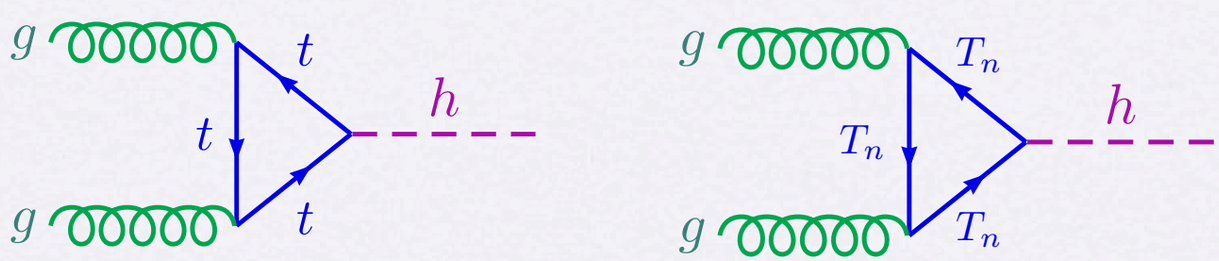
Expect deviations from SM ansatz

Effects of Strong Resonances

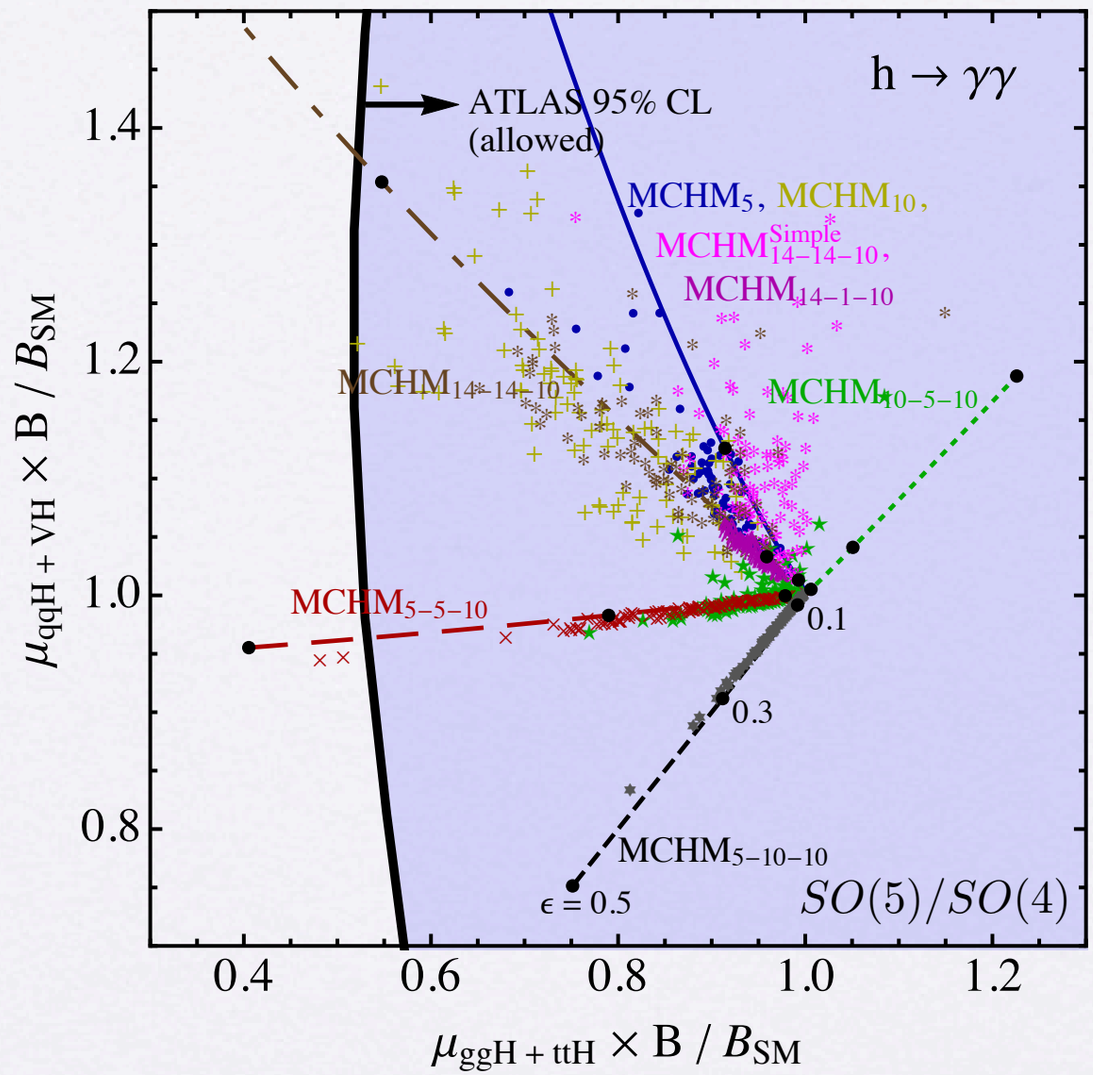
- Deviations from the SM depend on the G/H symmetry breaking pattern
- They also depend on the strong resonances

  → Model dependence

- Interesting (partial) cancellations



Falkowski '07, Low & Vicci '10, Azatov & Galloway '10



Carena, da Rold, EP '14
(updated to Run II)

- Typical bounds: f > 500-800 GeV

- Of course, the resonances can also be produced directly, with typical LHC bounds for top-like resonances around 700-800 GeV

Low-Energy Approach

- **The pattern of deviations from the SM in pNGB scenarios can be effectively studied in the context of a low-energy non-linear sigma-model**

G	$\mathcal{H}$	N_G	NGBs rep.$[\mathcal{H}]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}}+\bar{\mathbf{4}}_{-\mathbf{2}}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{+\mathbf{5}}=2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$
SO(9)	SO(8)	8	$\mathbf{8}=(\mathbf{2},\mathbf{2})_1+(\mathbf{2},\mathbf{2})_{-1}$

Modified from Mrazek et. al 2011

Approach: assume the symmetry breaking pattern, then write down non-linear sigma-model

$\longrightarrow$ **Doesn't care about the UV completion**

Origin of the Bound States?

Question: can such symmetry breaking patterns arise from microscopic theories?
If so, what form might such UV theories take?

Many of the proposed groups are of the SO(N) type. But gauge theories involving fermions lead naturally to global SU(N) symmetries (Of course, the space of strongly coupled-theories remains largely unexplored)

Simple observation: unlike fermion bilinears, 4-fermion interactions can respect only an SO(N) symmetry, e.g.

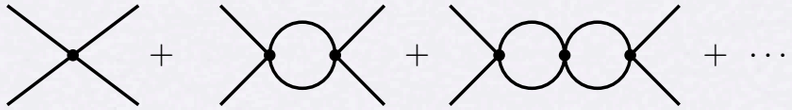
$$\mathcal{L}_F = i\bar{F}_L \partial\!\!\!/ F_L + i\bar{S}_R \partial\!\!\!/ S_R + \frac{G_S}{2}\left(\bar{S}_R F_L + \bar{F}_L S_R\right)^2 - \frac{G'_S}{2}\left(\bar{S}_R F_L - \bar{F}_L S_R\right)^2$$

Gersdorff, EP, Rosenfeld '15

Two SO(5) structures: if $G_S = G'_S$ **then** $2G_S|\bar{S}_R F_L^i|^2$ **is** $SU(5)$ **invariant**

In addition: **in a large N limit, one can show that the global symmetry is spontaneously broken, and that there is a massive scalar mode** (provided Gs above a critical value)

à la Nambu-Jona Lasinio



Allows the building of models where

- **Higgs constituents are explicitly identified**
- **One identifies the interactions that hold the Higgs bound state together**

Some signatures

- Deviations in the Higgs sector reflecting pNGB Higgs
- Fermionic (and other) resonances at the TeV scale
- A second "light" scalar: the *global* Higgs

The Global Higgs

Fichet, Gersdorff, EP, Rosenfeld '16

In analogy to SM h + NGB decomposition: $H = e^{i\,\vec{x}\cdot\vec{\tau}} \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}}\,h \end{pmatrix}$ **...**

... consider a radial mode, ϕ, of the global symmetry breaking vacuum

$$\Phi = e^{iH^{\hat{a}}\cdot T^{\hat{a}}/\hat{f}}(\hat{f} + \phi)\hat{e}_5$$

(Excitation of the global-symmetry breaking vacuum)

Essentially model-independent couplings to SM gauge bosons and fermions

$$\mathcal{L} \supset f_H^{-1}\phi\,|D_\mu H|^2 - \frac{m_t}{\hat{f}}\phi\,\bar{t}\,t$$

<u>Tree-level</u>: Higgs boson, longitudinal gauge bosons, SM fermions and fermion resonances

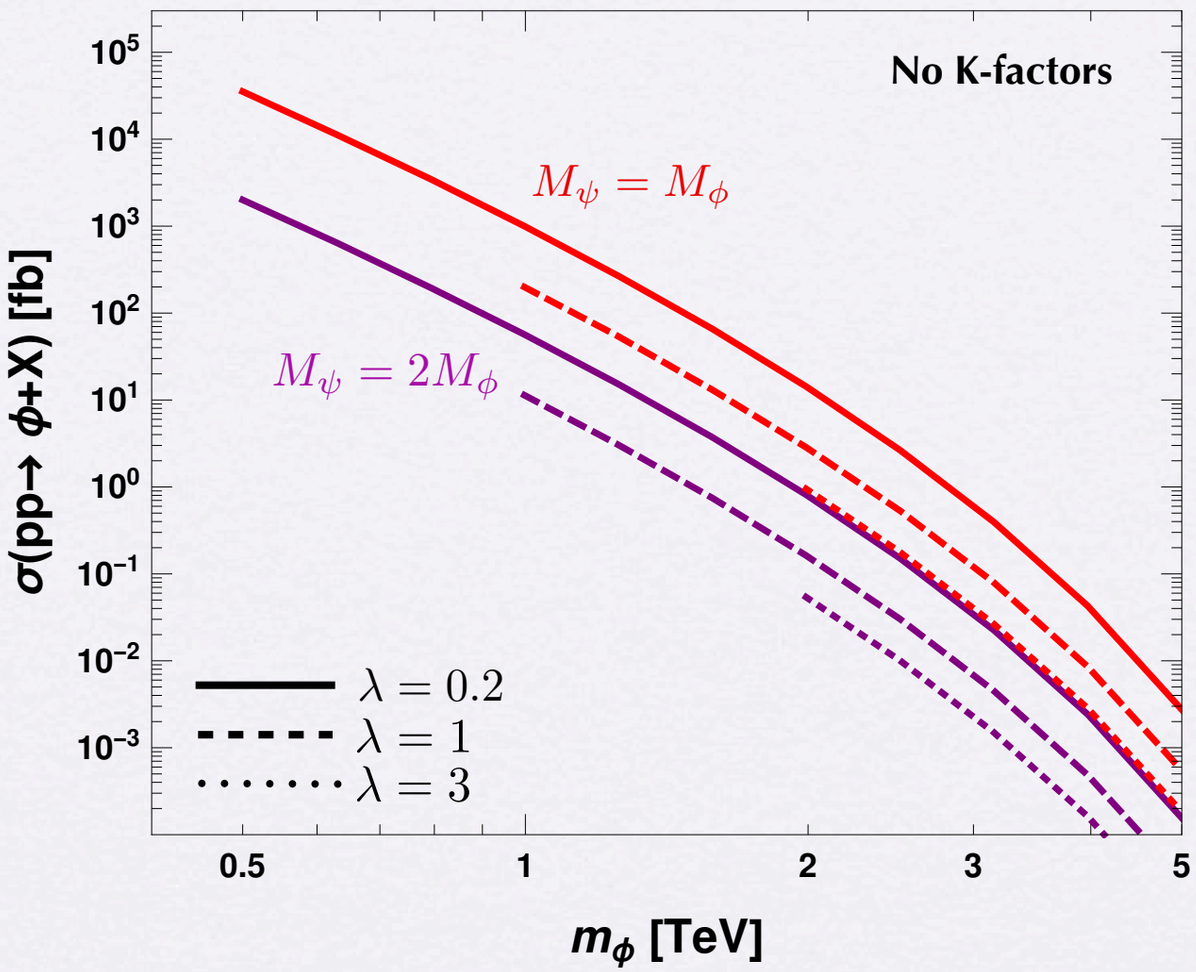
<u>Loop level</u>: transverse gauge bosons (e.g. gluons/photons)

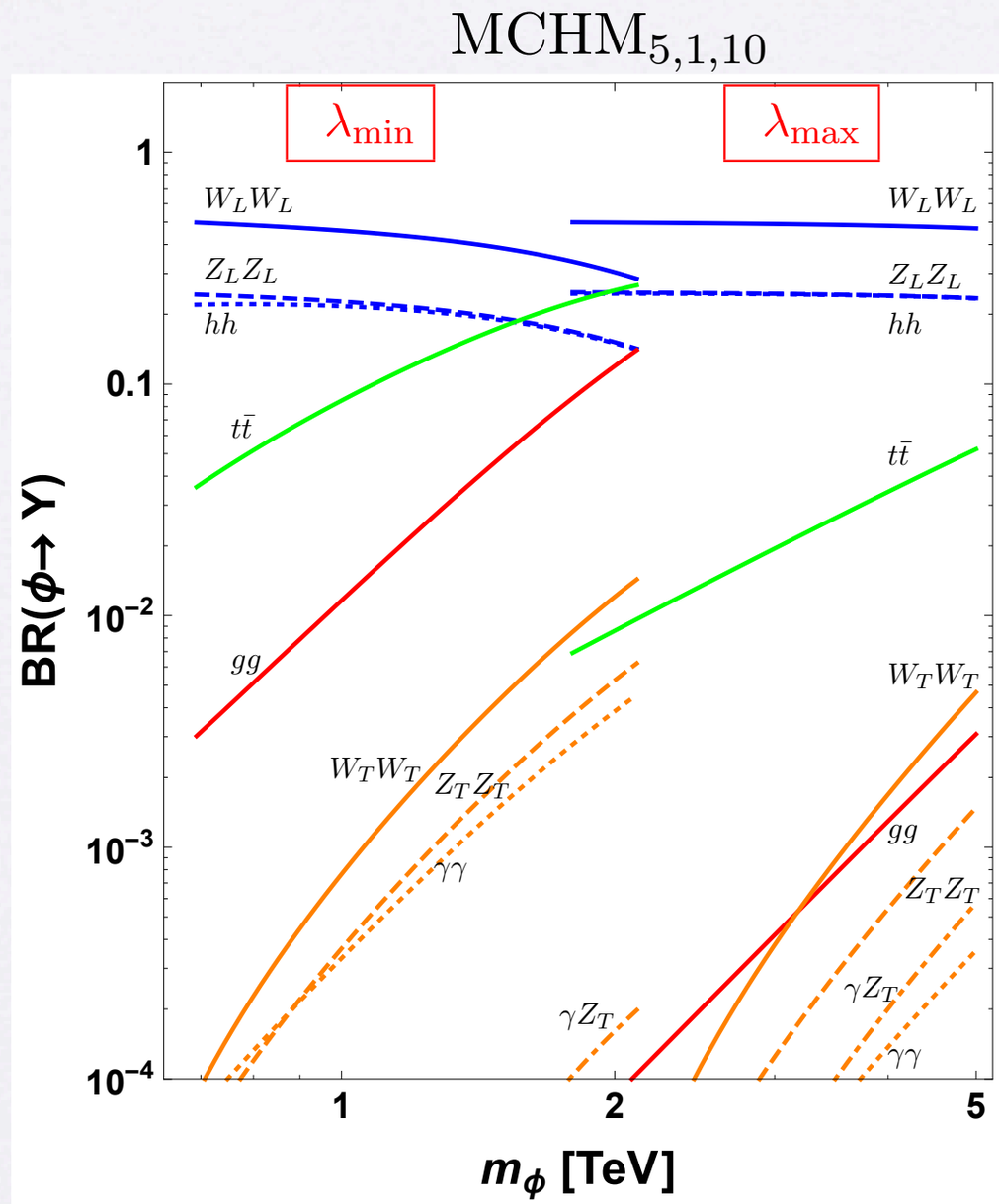
Our UV model: predicted to have a mass around the fermionic resonances

The global Higgs can be a narrow or broad resonance

The Global Higgs

Fichet, Gersdorff, EP, Rosenfeld '16

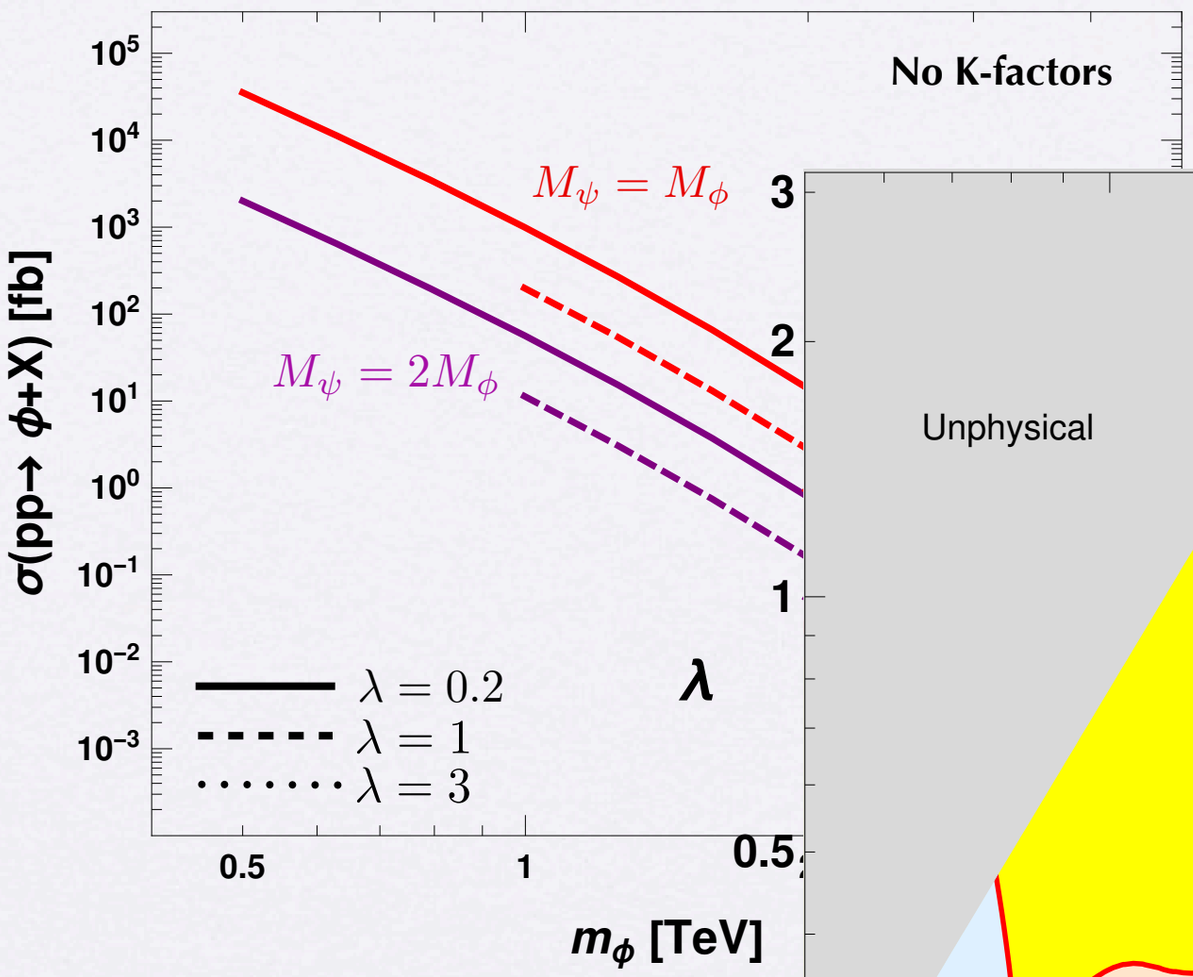


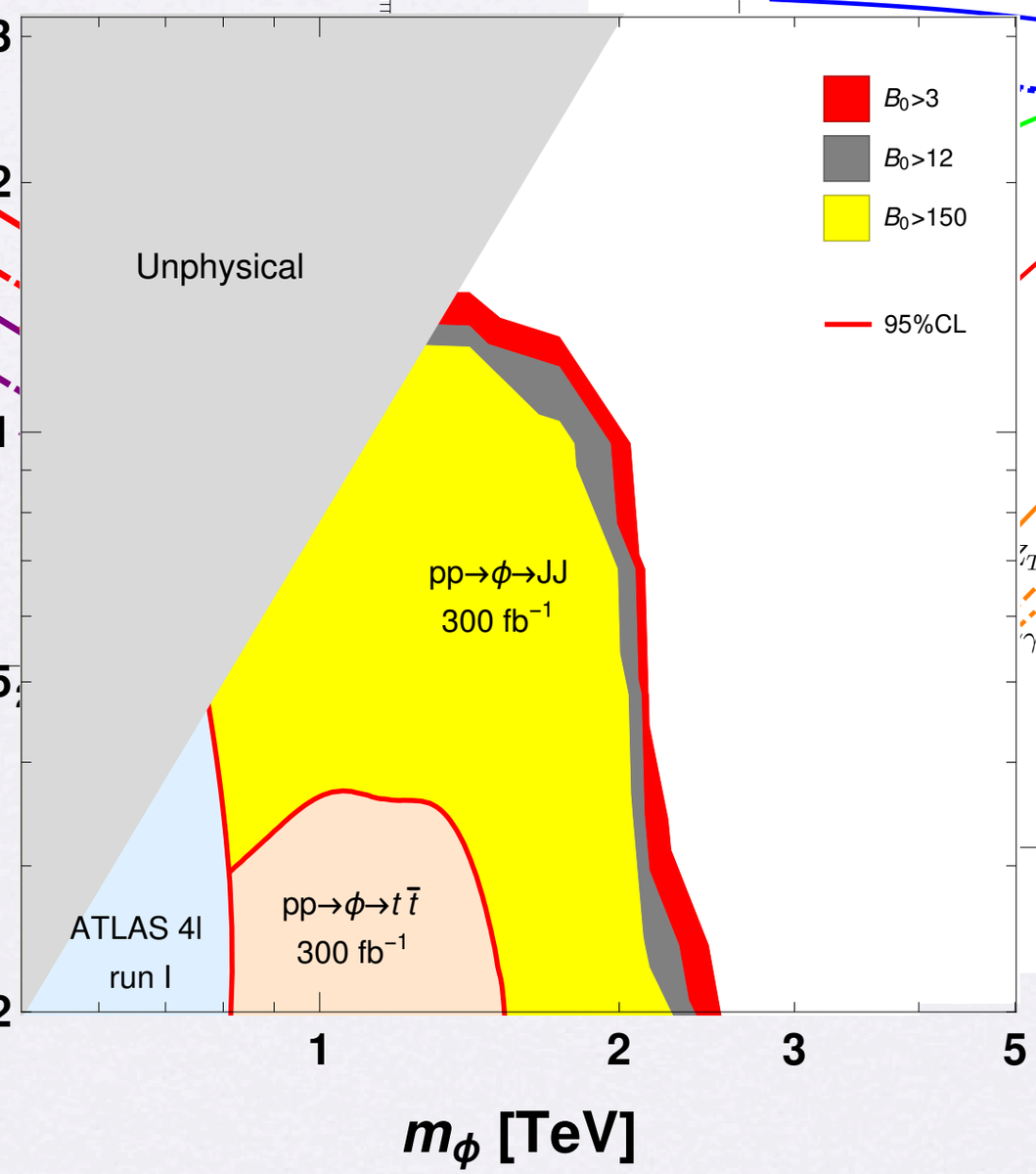


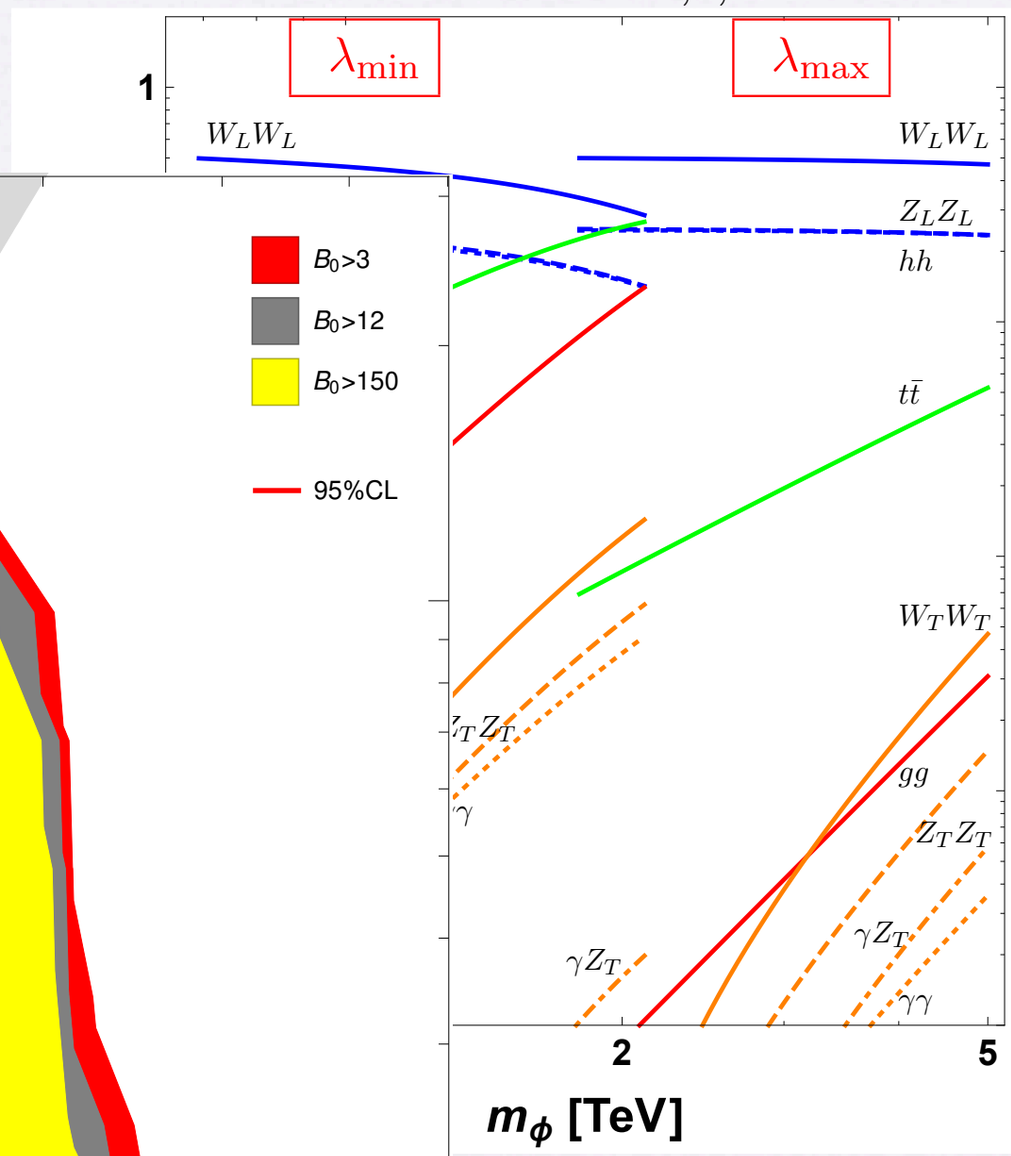
Fermion resonance channels closed

The Global Higgs

Fichet, Gersdorff, EP, Rosenfeld '16





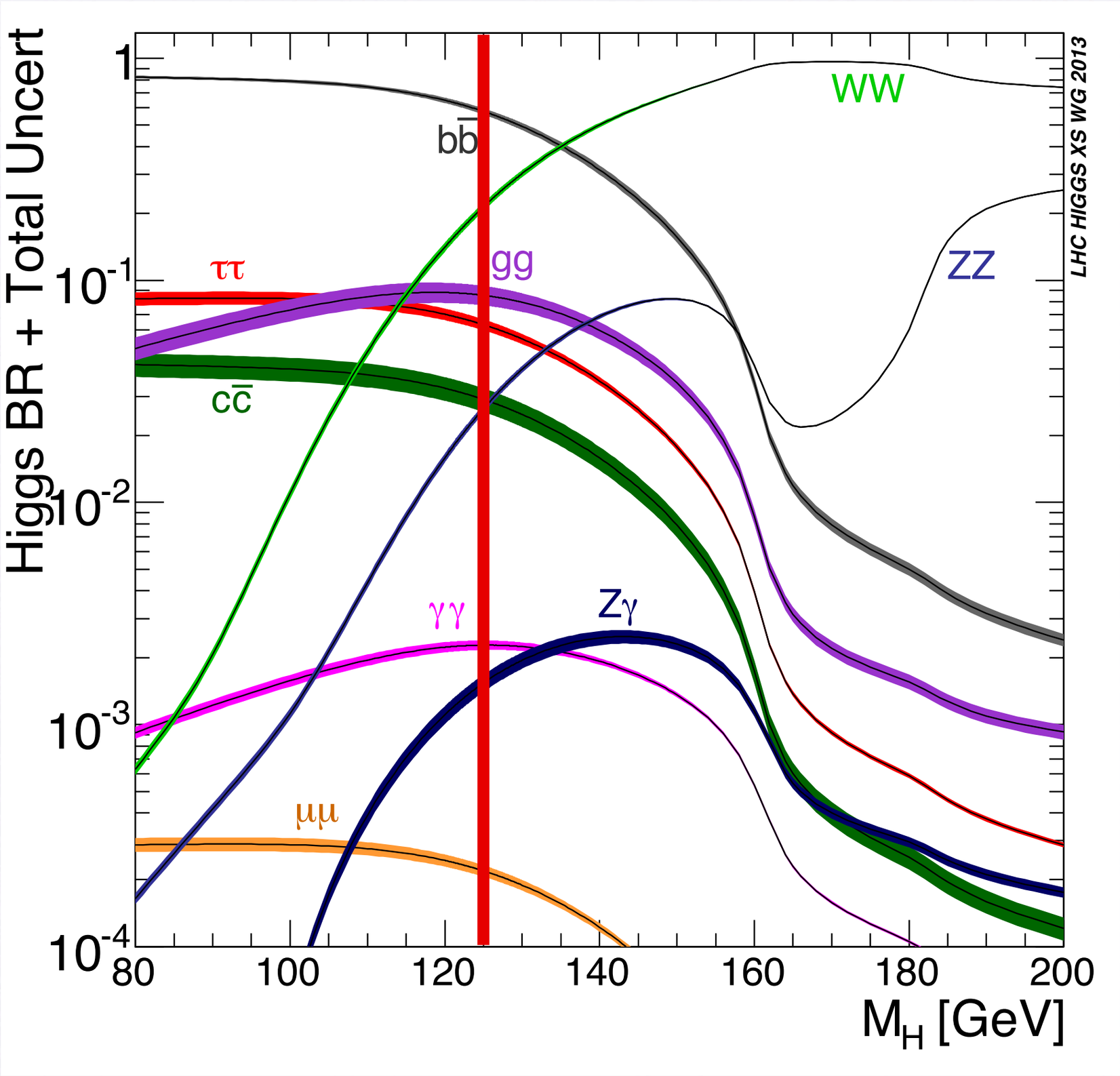


Fermion resonance channels closed

Summary

- Checking the Higgs properties fully is a high-priority program (e.g. distributions)
- Important to use theoretically consistent frameworks to encode the Higgs LHC results: strong interplay between theorists and experimentalists
- "Model-independent" studies are important, but must remember that their interpretation is model-dependent
- The study of specific models, while making specific assumptions, will be complementary to the EFT approach… even in the case of null results
- There is room for non-SM properties. In particular, the Higgs could be a composite state, which could provide a deeper understanding of EWSB.

SM Higgs Branching Fractions



$m_h \approx 125$ GeV

$\mathrm{BR}(b\bar{b}) \approx 0.6$

$\mathrm{BR}(WW) \approx 0.20$

$\mathrm{BR}(gg) \approx 0.077$

$\mathrm{BR}(\tau\bar{\tau}) \approx 0.06$

$\mathrm{BR}(c\bar{c}) \approx 0.026$

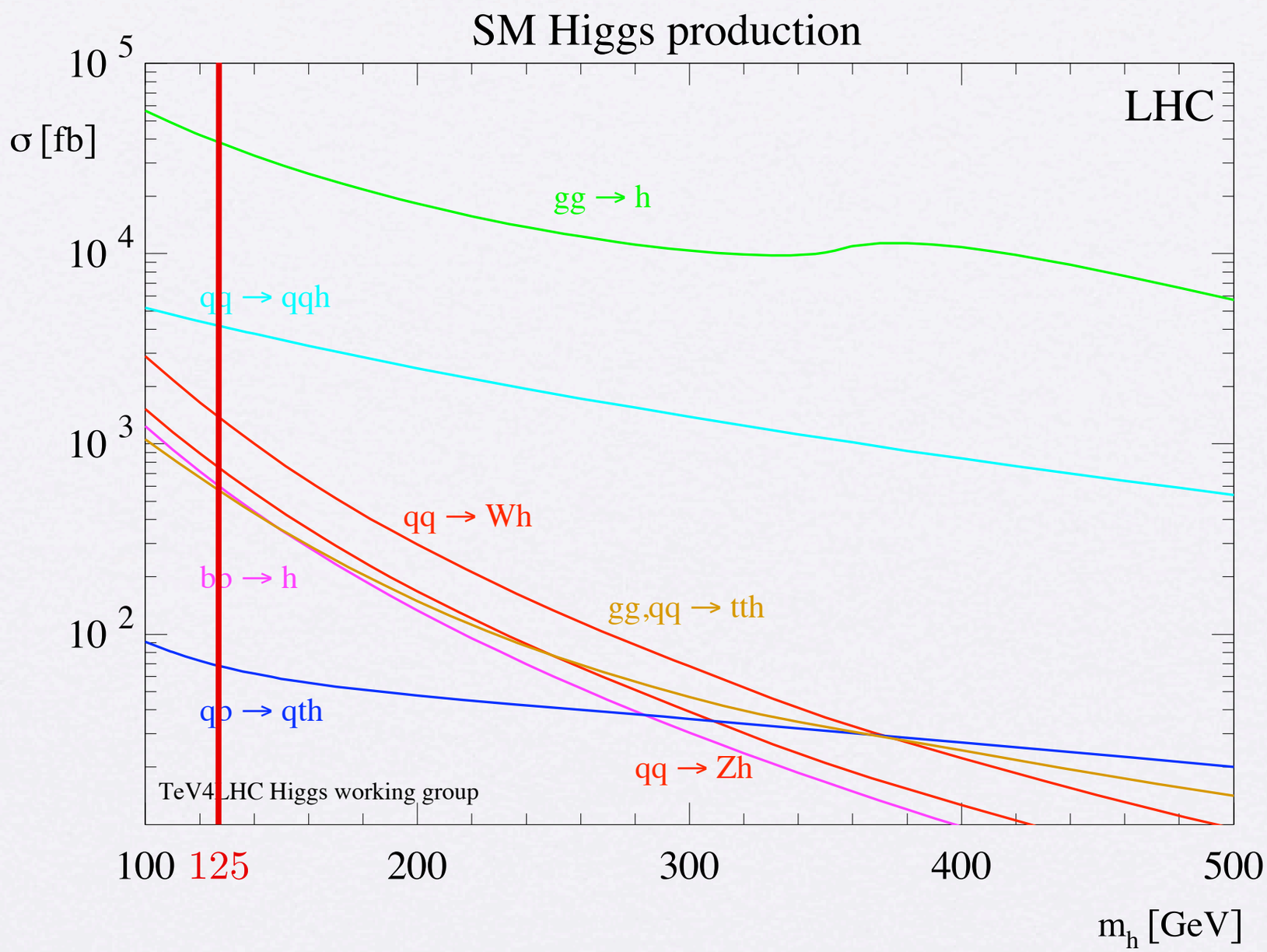
$\mathrm{BR}(ZZ) \approx 0.025$

$\mathrm{BR}(\gamma\gamma) \approx 0.002$

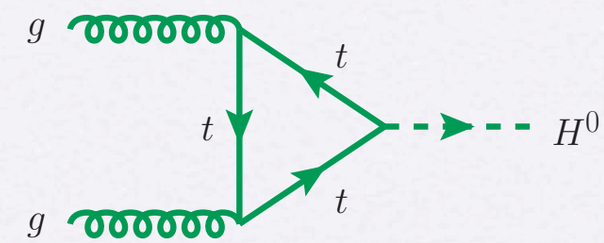
$\mathrm{BR}(Z\gamma) \approx 0.001$

$\Gamma_{\mathrm{Tot}} \approx 4.4$ MeV

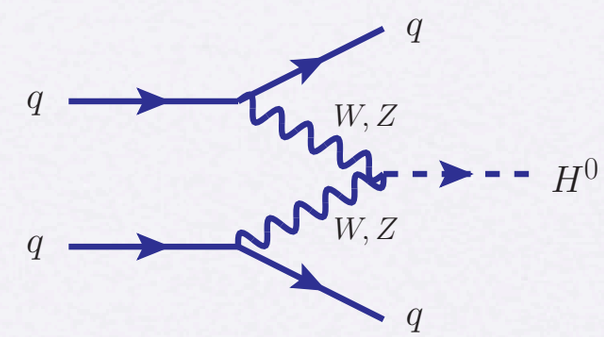
Higgs Production XS at the LHC



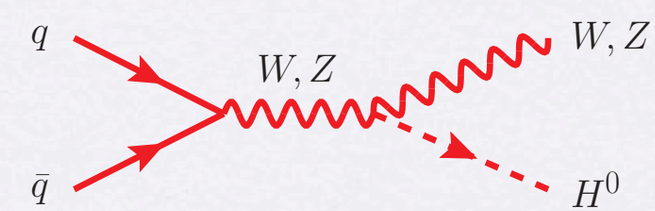
"Gluon fusion"



"Vector boson fusion" or $qq \to qqh$



"Associated production with W or Z"



tth