Higgs Physics

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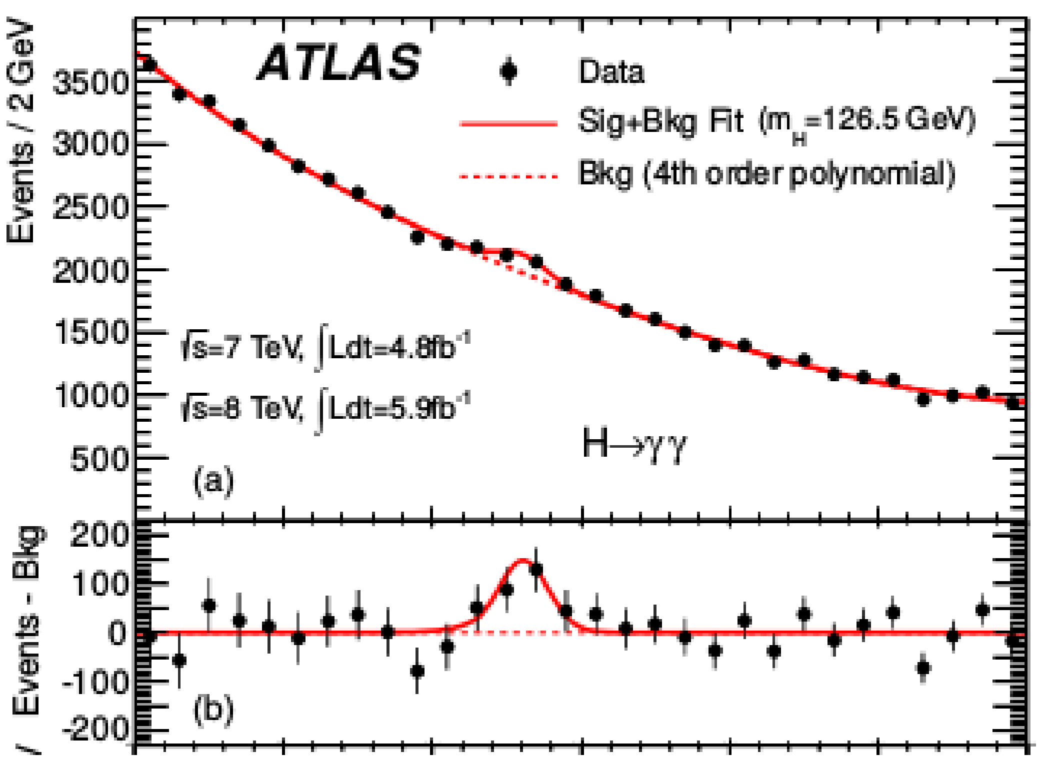
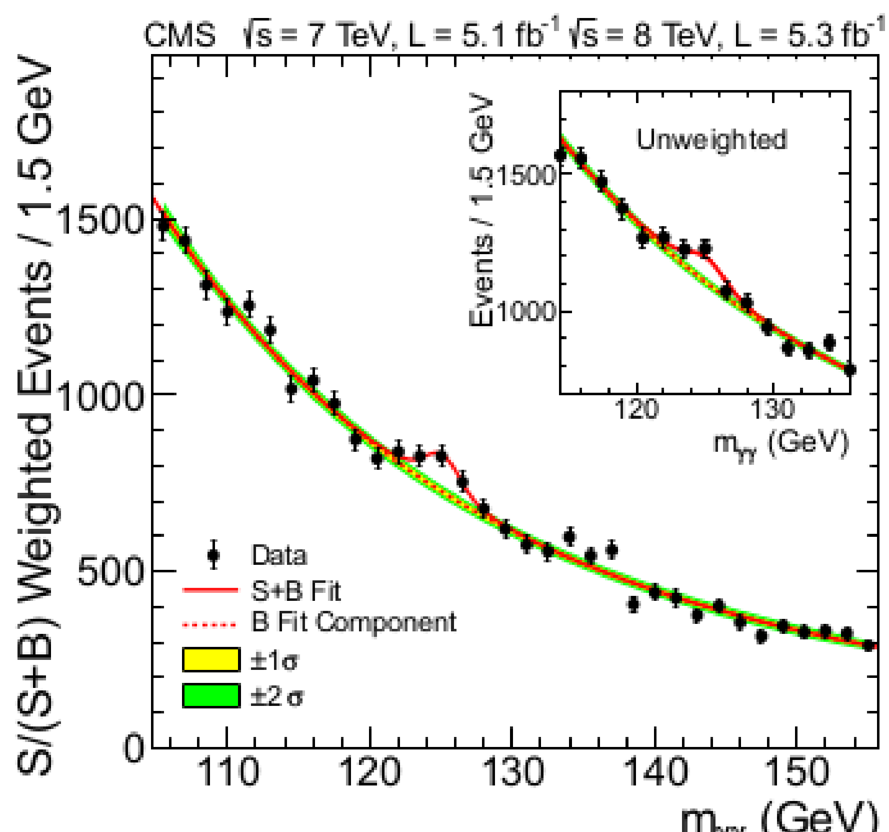
The Higgs is here

Since 2012 we know that there is Higgs like state

- Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, The ATLAS Collaboration, arXiv:1207.7214
- Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, The CMS Collaboration, arXiv:1207.7235





Outline

The Standard Model Higgs

The Higgs potential and EW symmetry breaking, custodial symmetry

The role of the Higgs of the SM

The flavor of the SM Higgs

Parametrizing deviations from the SM

Higgs phenomenology: single and double production, production of boosted and off-shell Higgs

Instabilities of the Higgs potential

Higgs and BSM: susy, composite Higgs and other theories

BSM searches at LHC: direct and indirect

The SM Higgs

The Standard Model

Building blocks

♦ QFT with Poincaré and gauge symmetry $SU(3)_c x SU(2)_L x U(1)_Y$

$$G^a_\mu \;, a = 1, \ldots 8; \quad W^a_\mu, \; a = 1, \ldots 3; \quad B_\mu$$

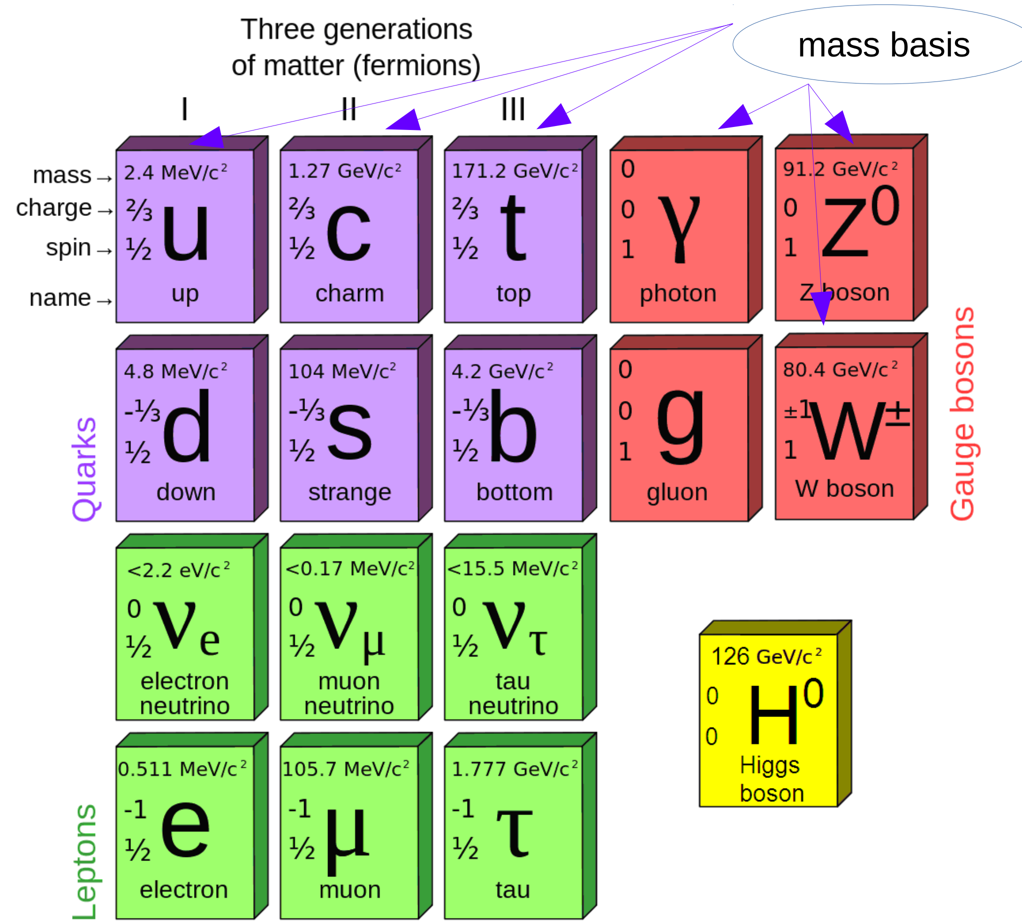
♦ Fermionic content

3 generations

quarks: Q=2/3,-1/3

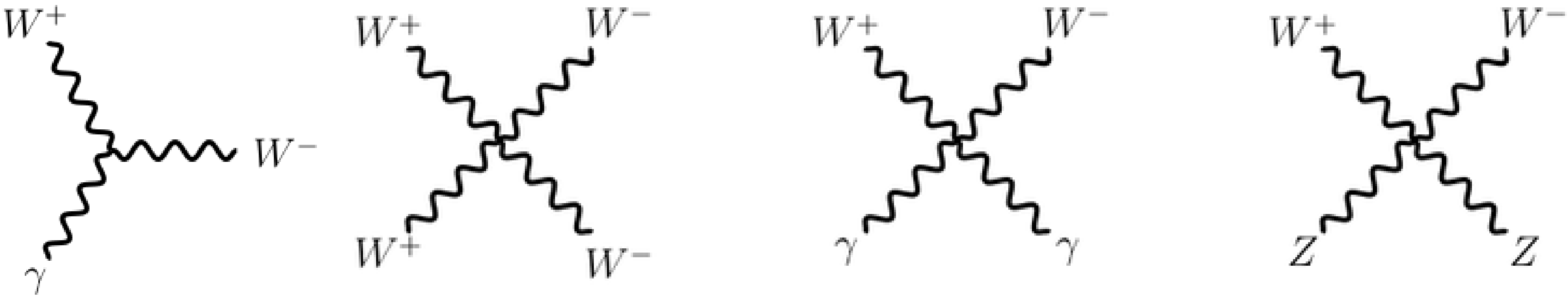
leptons: Q=0,-1

♦ Scalar content: 1 field **H**



Gauge structure of the SM

Lorentz and gauge symmetries precisely predicts the structure of triple and quartic gauge interactions

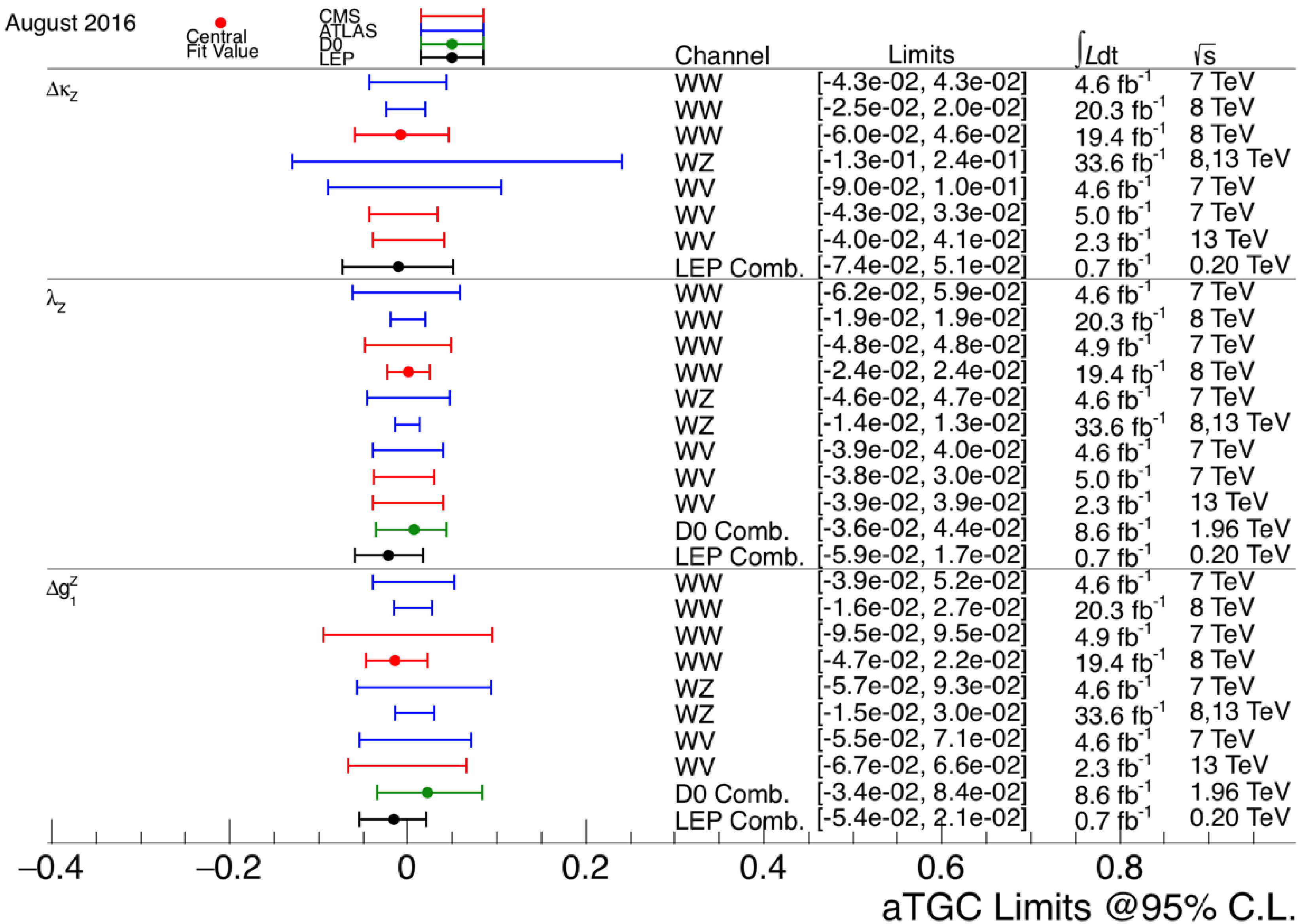


They also give relations between couplings

$$\mathcal{L} \supset -\frac{1}{4g^2} F^a_{\mu\nu} F^{\mu\nu a} \;, \quad F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i[A_\mu, A_\nu]^a$$

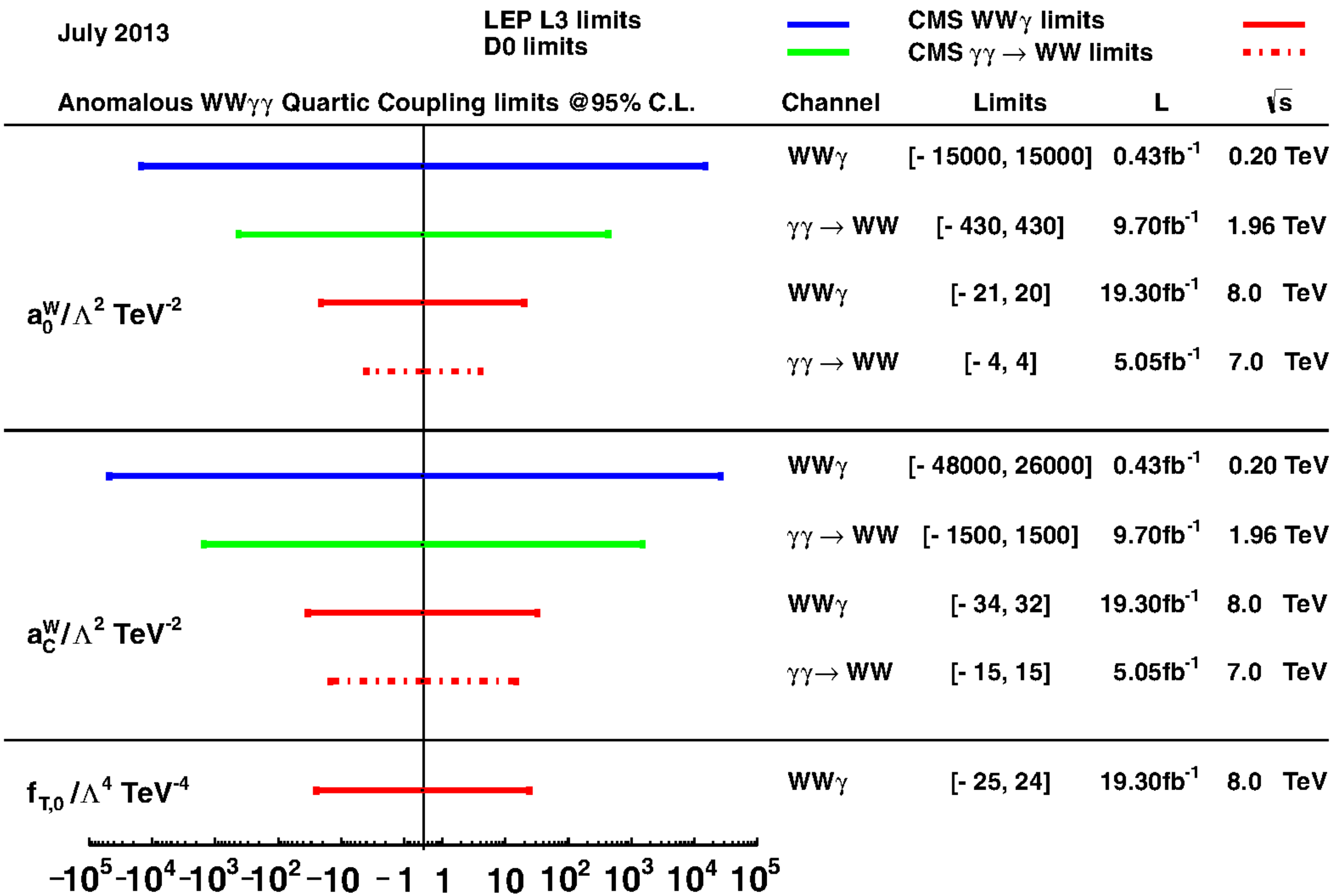
Gauge structure of the SM

Experimental tests of gauge symmetry:Limits on WWZ, aTGC coupling



Gauge structure of the SM

Experimental tests of gauge symmetry:Limits on γγWW QGC couplings



Masses of SM particles

W and Z masses are not compatible with gauge symmetries

$$\mathcal{L}_m \supset \frac{m^2}{2} A^a_\mu A^{\mu a} \text{ is not gauge invariant for } \delta A^a_\mu = \partial_\mu \theta^a + f^{abc} A^b_\mu \theta^c$$

Fermion masses are not compatible with gauge symmetries

$$\text{chiral fermions } \delta\psi^n_Q = i\theta^a T^a_{nm} \psi^m_Q \quad , \quad Q = L, R$$

$$\mathcal{L}_m \supset m\bar{\psi}_L \psi_R \text{ is not gauge invariant, also: } m_t \neq m_b, \; m_e \neq m_\nu$$

→ **Masses of SM particles do not seem compatible with Gauge Symmetry**

Masses of SM particles

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→ **Masses of SM particles do not seem compatible with Gauge Symmetry**

→ **Spontaneous gauge symmetry breaking**

The Higgs potential & EWSB

Global spontaneous sym. breaking

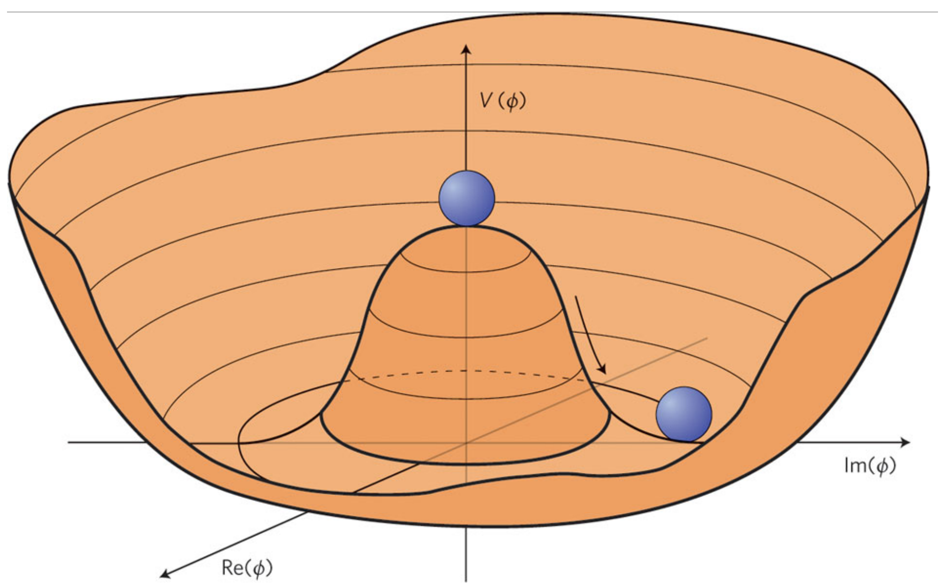
When a field or operator has a VEV, it can break symmetries: $T^a\langle 0|\mathcal{O}|0\rangle \neq 0$

Continuous global symmetry group: G, broken by the vacuum to a subgroup H

Nambu-Goldstone Theorem: one massless state for each broken generator of a continuous symmetry

ex: scalar th. with: $V(\phi) = -\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \;, \quad \phi = (\phi_1, \ldots \phi_N), \quad \phi^2 = \phi_j\phi_j$

if $m^2 > 0$: the scalar aquires a vev



SO(N)→SO(N-1):

(N-1) broken generators

→ (N-1) NG bosons

Local spontaneous sym. breaking or: **Higgs mechanism** (BEHG)

Local symmetry G, spontaneously broken to H

➡ gauge fields of broken generators become massive

- massless gauge fields: 2 polarizations (transverse)
- massive gauge fields: 3 polarizations (add longitudinal)

$$\text{NGB} = (A_\mu)_L \text{ longitudinal d.o.f.}$$ ← in unitary gauge

➡ **Having the NGB is enough to obtain massive Z and W**

The Higgs mechanism in the SM

- Given the gauge symmetry SU(2)xU(1) (neglect SU(3))

  the Higgs transforms in the fundamental irrep

$$H = \begin{pmatrix} h_1 + i h_2 \\ h_0 + i h_3 \end{pmatrix} \xrightarrow{\text{vev}} \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$v \simeq 246 \text{ GeV}$$

- Unbroken generator: $Q = T^3 + Y \to U(1)_Q$ with a massless field

  Broken generators: massive W and Z

- $$|D_\mu H|^2 \supset \frac{1}{4} g^2 v^2 W_\mu^+ W^{\mu -} + \frac{1}{8} v^2 (g W_\mu^3 - g' B_\mu)(g W^{\mu 3} - g' B^\mu)$$

- **Spectrum**

  # massive neutral state $\quad Z_\mu = c_W W_\mu^3 - s_W B_\mu \ , \quad c_W = \frac{g}{\sqrt{g^2 + g'^2}} \ , \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$

  # massless neutral state $\quad A_\mu = s_W W_\mu^3 + c_W B_\mu \ , \quad s_W = \frac{g'}{\sqrt{g^2 + g'^2}} \ , \quad m_A^2 = 0$

  # massive charged states $\quad W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp i W_\mu^2) \ , \quad m_W^2 = \frac{1}{4} g^2 v^2$

The Higgs mechanism in the SM: fermions

- Original motivation for the Higgs: massive spin-1 states, W and Z
- Fermion are also massive, but mass terms are not gauge invariant

$$q_L \sim (3,2)_{1/6},\ u_R \sim (3,1)_{2/3},\ d_R \sim (3,1)_{-1/3} \qquad \ell_L \sim (1,2)_{1/2},\ e_R \sim (1,1)_{-1}$$

$SU(2)_L$ doublet (q_L) — $SU(2)_L$ singlet (u_R, d_R)

Interactions distinguish chiralities

- Symmetries allow the following Yukawa int. with the Higgs

$$\mathcal{L}_y = y_u \bar{q}_L \tilde{H} u_R + y_d \bar{q}_L H d_R + y_e \bar{\ell}_L H e_R + \frac{y_\nu}{M} (\bar{\ell}_L H)^c (H^\dagger \ell_L)$$

neutrino sector still open

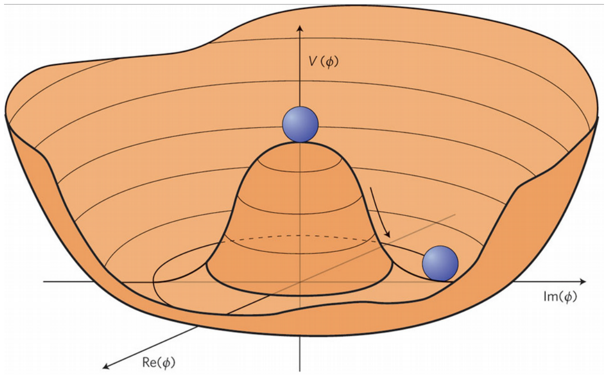
→ The Higgs vev generates masses for all the fermions

- From perspective of eff. field theory, add all the terms compatible with symmetries!

A single scalar is enough to generate masses for all SM massive particles!!!

The global symmetry of the Higgs sector

- $V(H) = -\frac{1}{2}m^2|H|^2 + \frac{1}{4}\lambda|H|^4$



a closer look

$$|H|^2 = \sum_j h_j^2 = (h_0, h_1, h_2, h_3).(h_0, h_1, h_2, h_3)$$

O(4)

rotate the components of the Higgs

$$h_j \to O_{jk} h_k \;\Rightarrow |H|^2 \to |H|^2 \;\; \text{if} \;\; O_{jk}O_{jl} = \delta_{kl}$$

V(H) is invariant under O(4)

the Higgs potential has a global symmetry O(4)

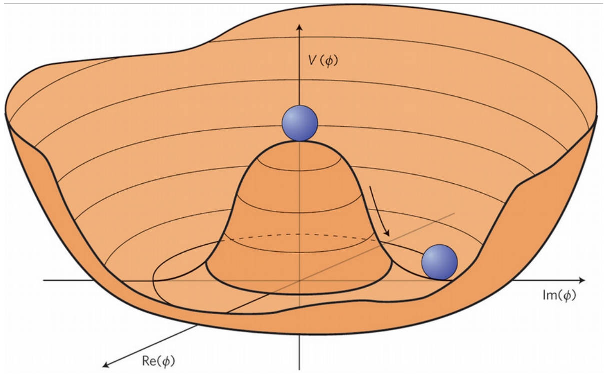
- the vacuum $(v/\sqrt{2}, 0, 0, 0)$ → Vacuum is invariant under O(3)

h_1, h_2 and h_3 are the NGB of O(4)/O(3) spontaneous breaking!

The custodial symmetry of the SM

- SO(4)~SU(2)xSU(2) and SO(3)~SU(2), also formulated in terms of SU(2)

The global symmetry of the Higgs sector phenomenological consequences



- One SU(2) can be identified with $SU(2)_L$

  ↳ the unbroken one is $SU(2)_{L+R}$

- W_1, W_2 and W_3 rotate as a triplet of the unbroken $SU(2)_{L+R}$

  ↳ The mass terms of all W_j have the same coef.: custodial symmetry

$$|D_\mu H|^2 \supset \frac{m_Z^2}{2}(c_w W_3 - s_W B)^2 = \frac{m_Z^2}{2} Z^2 \quad \Rightarrow \; m_W^2 = c_W^2 m_Z^2$$

custodial symmetry predicts → $\rho \equiv \frac{m_W^2}{c_W^2 m_Z^2} = 1$

- The hypercharge and Yukawa couplings explicitly break $SU(2)_{L+R}$ inducing corrections to rho=1 at loop level

The role of the neutral Higgs

If the NGB provide d.o.f. for W_L and Z_L, is h_0 needed at all?

- Parametrize the NGB “a la” pions of QCD: $U = e^{i\sigma^j \pi^j / v}$

change f_π by υ and work with chiral Lagrangian

NGB of $SU(2)_L x SU(2)_R / SU(2)_{L+R}$

$$\mathcal{L} = \frac{v^2}{4} \mathrm{tr}(D_\mu U^\dagger D^\mu U) \supset m_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu$$

The theory of the EW-NGB is similar to the theory of pions, we can learn about the EW sector by using the theory of pions

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- Besides the mass terms, the Lagrangian also includes NGB interactions

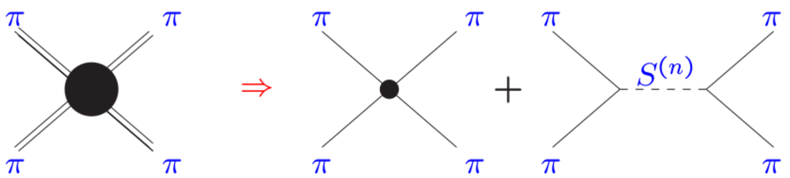
$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \pi^j)^2 + \frac{1}{6v^2}[(\pi^j)^2(\partial_\mu \pi^j)^2 - (\pi^j \partial_\mu \pi^j)^2]$$

pion scattering

- Consider the High energy behavior of the scattering
  Energy dependece of interactions: bad behavior for $E>4\pi f_\pi$

$\pi^j \pi^k \rightarrow \pi^m \pi^n \sim E^2/f_\pi^2$

- It only gives a valid description up to $E<4\pi f_\pi$ ~ GeV in QCD, meson exchange restores unitarity



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NGB of $SU(2)_L x SU(2)_R / SU(2)_{L+R}$

$$\mathcal{L} = \frac{v^2}{4} \mathrm{tr}(D_\mu U^\dagger D^\mu U) \supset m_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu$$

Change the QCD-NGB (pions) by the EW-NGB and proceed similarly

- Lagrangian includes EW-NGB interactions

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \pi^j_{EW})^2 + \frac{1}{6v^2}[(\pi^j_{EW})^2(\partial_\mu \pi^j_{EW})^2 - (\pi^j_{EW} \partial_\mu \pi^j_{EW})^2]$$

→ EW-NGB scattering

- Consider the High energy behavior of the scattering
  Energy dependece of interactions: bad behavior for $E > 4\pi\, υ$

→ $\pi^j_{EW}\, \pi^k_{EW} \rightarrow \pi^m_{EW}\, \pi^n_{EW} \sim E^2/υ^2$

- It only gives a valid description up to $E < 4\pi υ$ ~ TeV

in EW sector, who restores unitarity?

The role of the neutral Higgs

If the NGB provide d.o.f. for W_L and Z_L, is h_0 needed at all?

- Let's study the longitudinal component of a massive vector

$$A_\mu = e^{ip_\nu x^\nu}\epsilon_\mu, \qquad p_\nu = (E,0,0,p)$$
$$\epsilon_\mu p^\mu = 0, \qquad p^2 = m^2$$
$$polarization\ vectors$$
$$\epsilon_\mu^{\sigma=1} \propto (0,1,i,0), \qquad \epsilon_\mu^{\sigma=-1} \propto (0,1,-i,0), \qquad \epsilon_\mu^{\sigma=0} \propto (p,0,0,E)/M$$

longitudinal component grows with energy

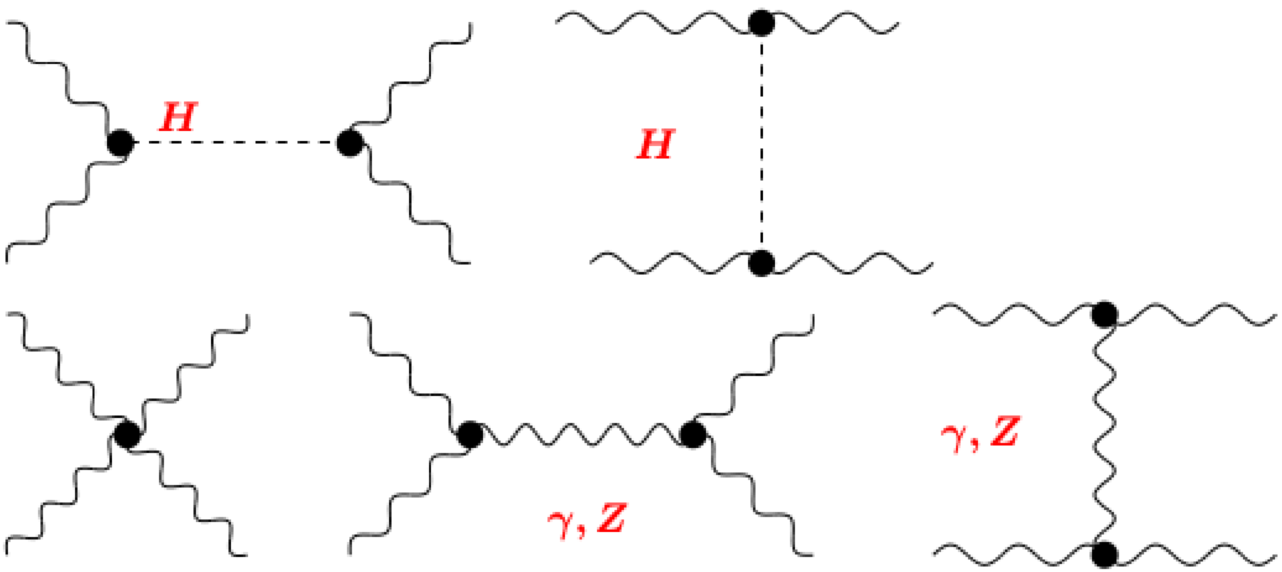
- W_L scattering at high energy: worst energy behavior

$W_L W_L \rightarrow W_L W_L \sim E^4/\upsilon^4$

- It only gives a valid description up to $E \sim \upsilon$

The role of the neutral Higgs

Restoration of perturbative unitarity in W_L scattering



$$\sim -g^2\left(\frac{E}{M_w}\right)^2$$

$$\sim +g^2\left(\frac{E}{M_w}\right)^2$$

$$\sim \left(\frac{m_h}{M_w}\right)^2$$

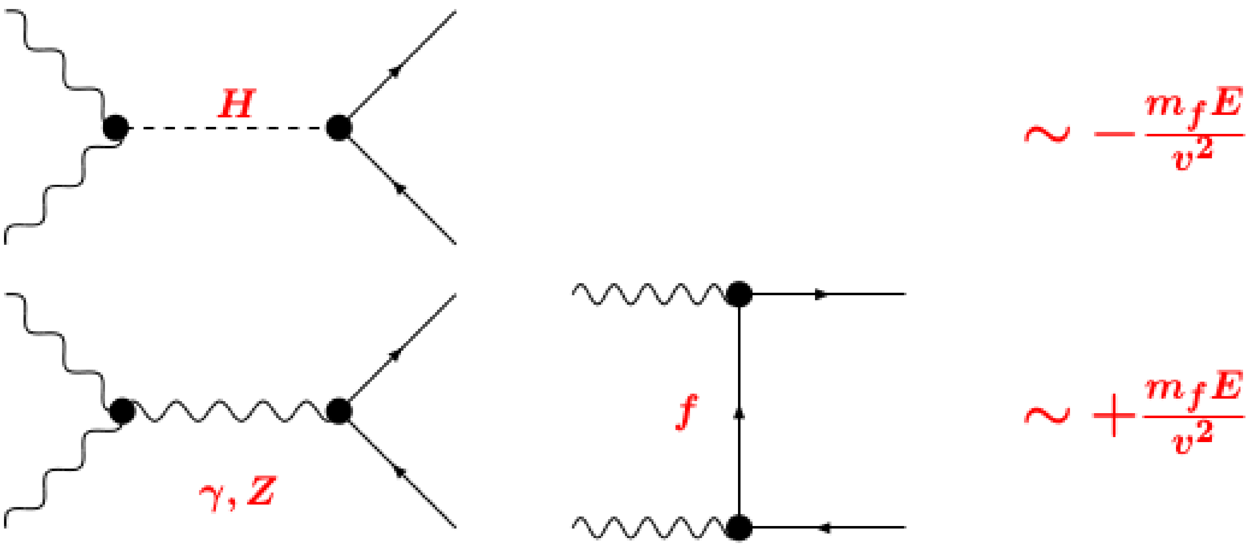
Cancellation of contributions with bad behavior at high energies!

(effective for m_h < TeV, a light Higgs m_h = 125 GeV is very efficient)

The role of the neutral Higgs

Restoration of perturbative unitarity in WW →ff

A similar analysis shows that the Higgs also unitarizes (at perturbative level) fermion pair creation in WW scattering



Cancellation of contributions with bad behavior at high energies!

The flavor of the Higgs

- In the SM only the Higgs contributes to fermion masses

  Yukawa interactions

$$\mathcal{L}_y = y_\psi^{jk} \bar{\psi}_L^j H \psi_R^k = y_\psi^{jk} \bar{\psi}_L^j (v + h_0) \psi_R^k = m_\psi^{jk} \bar{\psi}_L^j \psi_R^k (1 + h_0/v)$$

- Mass eigenstate basis: diagonalization of **m** by biunitary rotation

$$\mathcal{L}_y \to m_\psi^j \bar{\psi}_L^j \psi_R^j (1 + h_0/v) \supset \frac{m_\psi^j}{v} h_0 \bar{\psi}_L^j \psi_R^j$$

Higgs-fermion interactions are flavor diagonal in the SM

- No Flavor Changing Neutral Currents mediated by the Higgs at tree-level

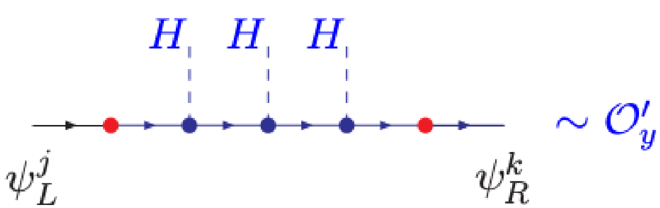
The flavor of the Higgs

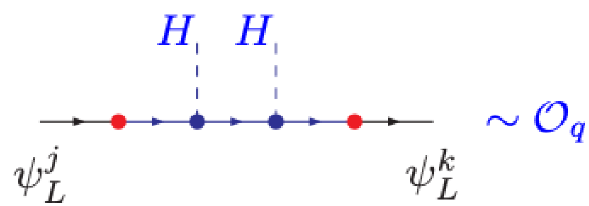
- Generic **BSM** induces

  higher dimensional operators

$$\mathcal{O}'_y = \bar{q}_L H d_R (H^\dagger H) \ ,$$
$$\mathcal{O}_q = \bar{q}_L i \not{D} q_L (H^\dagger H) \ ,$$
$$\mathcal{O}'_q = \bar{q}_L H H^\dagger i \not{D} q_L \ ,$$
$$\mathcal{O}_d = \bar{d}_R i \not{D} d_R (H^\dagger H)$$

- Ex: integrating out-heavy states





- For generic coefficients in flavor space: C_{jk} flavor violation is induced in Higgs int.

$$v \bar{\psi}^j_L \psi^k_R \left(y^{jk}_\psi - \frac{v^2}{\Lambda^2} \hat{C}^{jk}_\psi \right) + h \bar{\psi}^j_L \psi^k_R \left(y^{jk}_\psi - 3 \frac{v^2}{\Lambda^2} \hat{C}^{jk}_\psi \right)$$

With missalignment feeding from:

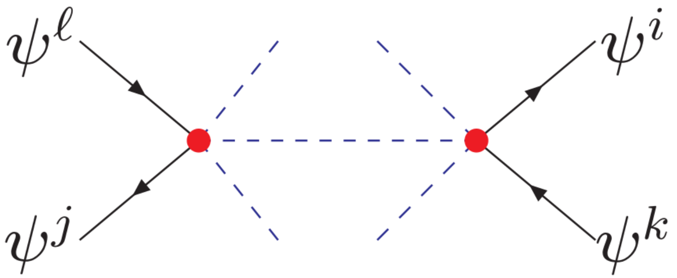
$$\hat{C} = \left[C'_y + (C_q + C'_q) C_y + C_y C^\dagger_d \right]$$

Higgs-fermion interactions become flavor violating

The flavor of the Higgs

Higgs mediated FCNC

In the presence of higher dimensional operators **$O_{y,q,d}$** integrating-out the Higgs



4-fermion operators are induced

$$\mathcal{O}_2^{jk} = (\bar\psi_R^{j\alpha}\psi_L^{k\alpha})(\bar\psi_R^{j\beta}\psi_L^{k\beta}) \ , \qquad \tilde{\mathcal{O}}_2^{jk} = \mathcal{O}_2^{jk}(L \leftrightarrow R)$$

$$\mathcal{O}_4^{jk} = (\bar\psi_R^{j\alpha}\psi_L^{k\alpha})(\bar\psi_L^{j\beta}\psi_R^{k\beta})$$

For generic Wilson coefficients, stringent bounds from meson systems

K**-system:** $\Lambda \gtrsim 10^2$ **TeV** , B_s**-system:** $\Lambda \gtrsim 15$ **TeV** , B_d**-system:** $\Lambda \gtrsim 5$ **TeV**

Comparable to bounds from exchange of BSM resonances

Parametrize deviations: non-linear

(Contino et al)

- General parameterization of Higgs couplings parameterizing NGB as: $\Sigma = e^{i\sigma_a \pi^a / v}$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \dots\right]$$

$$- m_i\, \bar{\psi}_{Li}\, \Sigma \left(1 + c\,\frac{h}{v} + \dots\right) \psi_{Ri} \, + \, \mathrm{h.c.}\,,$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 + \dots$$

- SM limit: $a=b=c=d_3=d_4=1$ as well as vanishing higher order interactions

  ↳ Recover the Higgs as a linear doublet

- **a=1** for perturbative unitarity in $V_LV_L \to V_LV_L$

  a²=b for perturbative unitarity in $V_LV_L \to hh$

  a.c=1 for perturbative unitarity in scattering: $V_LV_L \to f\bar{f}$

Parametrize deviations: κ-framework

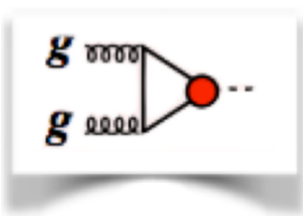
Experimentally, the fits to the Higgs are usually parametrized in terms of the signal strengths

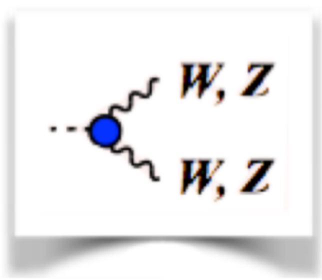
$$\mu_{if} = \frac{\sigma_i \times BR_f}{\sigma_i^{SM} \times BR_f^{SM}}$$

ex: single Higgs production from an initial state “i” to a final state “f”

The k-parametrization of the Higgs physics

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$$





In many situations the k-parameters are in one to one correspondence with couplings

Parametrize deviations: primaries

It is possible to parametrize deviations in different basis for operators

The primary operators (Grojean, Pomarol, Riva et al)

CP:
$$\mathcal{L}_h^{\text{primary}} = g_{VV}^h\, h \left[W^{+\,\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + \frac{1}{6}\, g_{3h}\, h^3 + g_{ff}^h\, \left(h \bar{f}_L f_R + h.c.\right)$$
$$+ \quad \kappa_{GG}\, \frac{h}{2v} G^{A\,\mu\nu} G_{\mu\nu}^A + \kappa_{\gamma\gamma}\, \frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}\,,$$

CPV:
$$\mathcal{L}_h^{\text{primary}} = \delta\tilde{g}_{hff}\, \left(ih \bar{f}_L f_R + h.c.\right) + \widetilde{\kappa}_{GG}\, \frac{h}{2v} G^{A\,\mu\nu} \widetilde{G}_{\mu\nu}^A + \widetilde{\kappa}_{\gamma\gamma}\, \frac{h}{2v} A^{\mu\nu} \widetilde{A}_{\mu\nu} + \widetilde{\kappa}_{Z\gamma} \frac{h}{v} A^{\mu\nu} \widetilde{Z}_{\mu\nu}$$

Primary Higgs couplings are those best measured at LHC
Non-primary operators can be constrained by non-Higgs physics

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CPV:in SM there are 2 CPV parameters: CKM angle and θ_{QCD} ($<10^{-10}$)
Electro- and chromo-magnetic dipole moments
strongly constrain the CPV couplings: Λ ~ 1-30 TeV

Higgs phenomenolgy
colliders

Higgs phenomenology

1 step: discover the Higgs

Measure the mass and width of the new state

Measure its spin and CP properties

Measure its couplings

Compare with the predictions of the SM

Rich phenomenology available at LHC

several production mechanisms (gg,VBF,tth,Vh,+jets,...)

many decay modes (bb,VV,Zγ,γγ,jets,...)

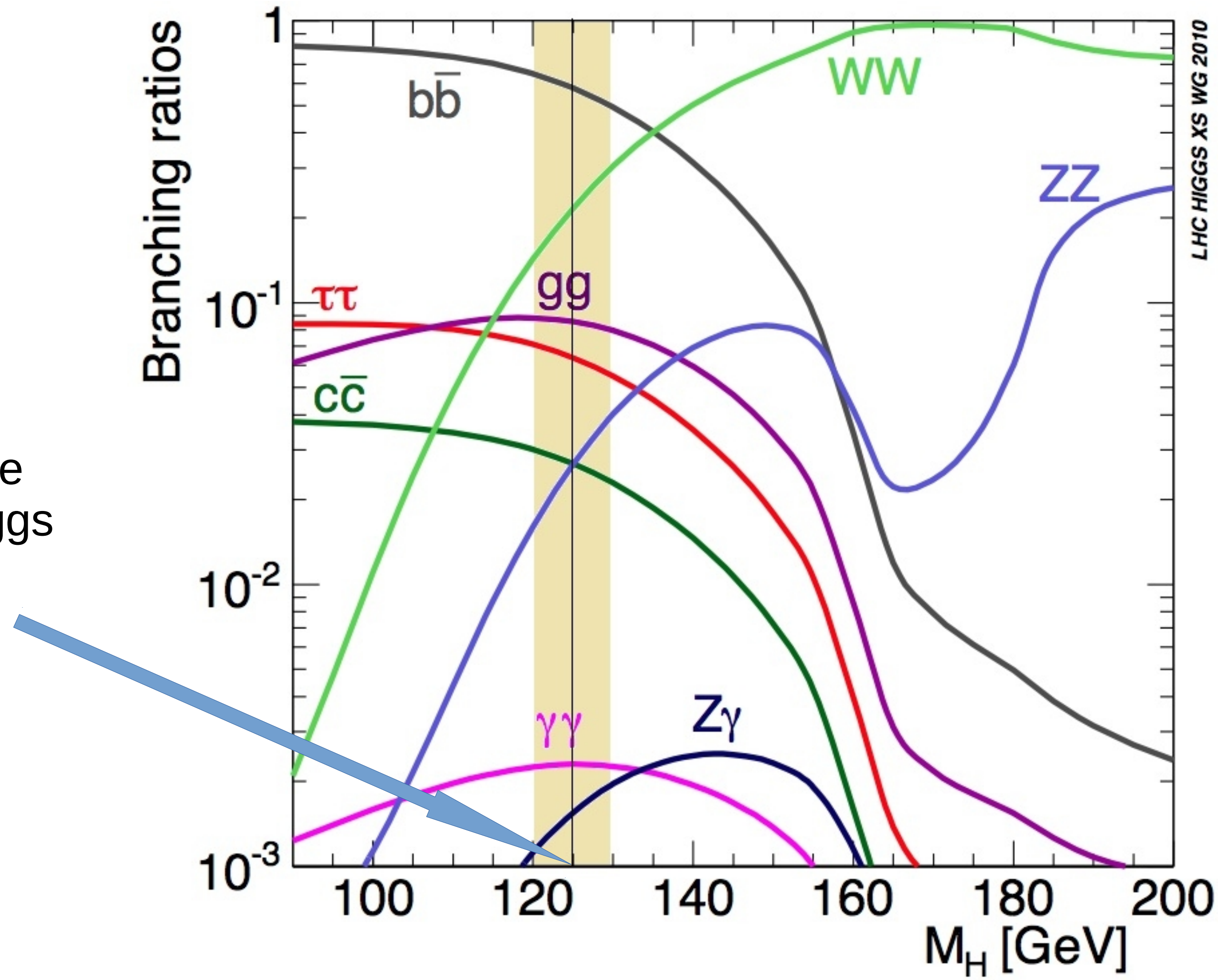
2nd step: if deviations with respect to the SM are found

Indirect evidence for BSM physics

Higgs phenomenology

Old days: before 2012 we used to study the SM Higgs x-sec and BR as function of m_h

After 2012 we know the Higgs mass



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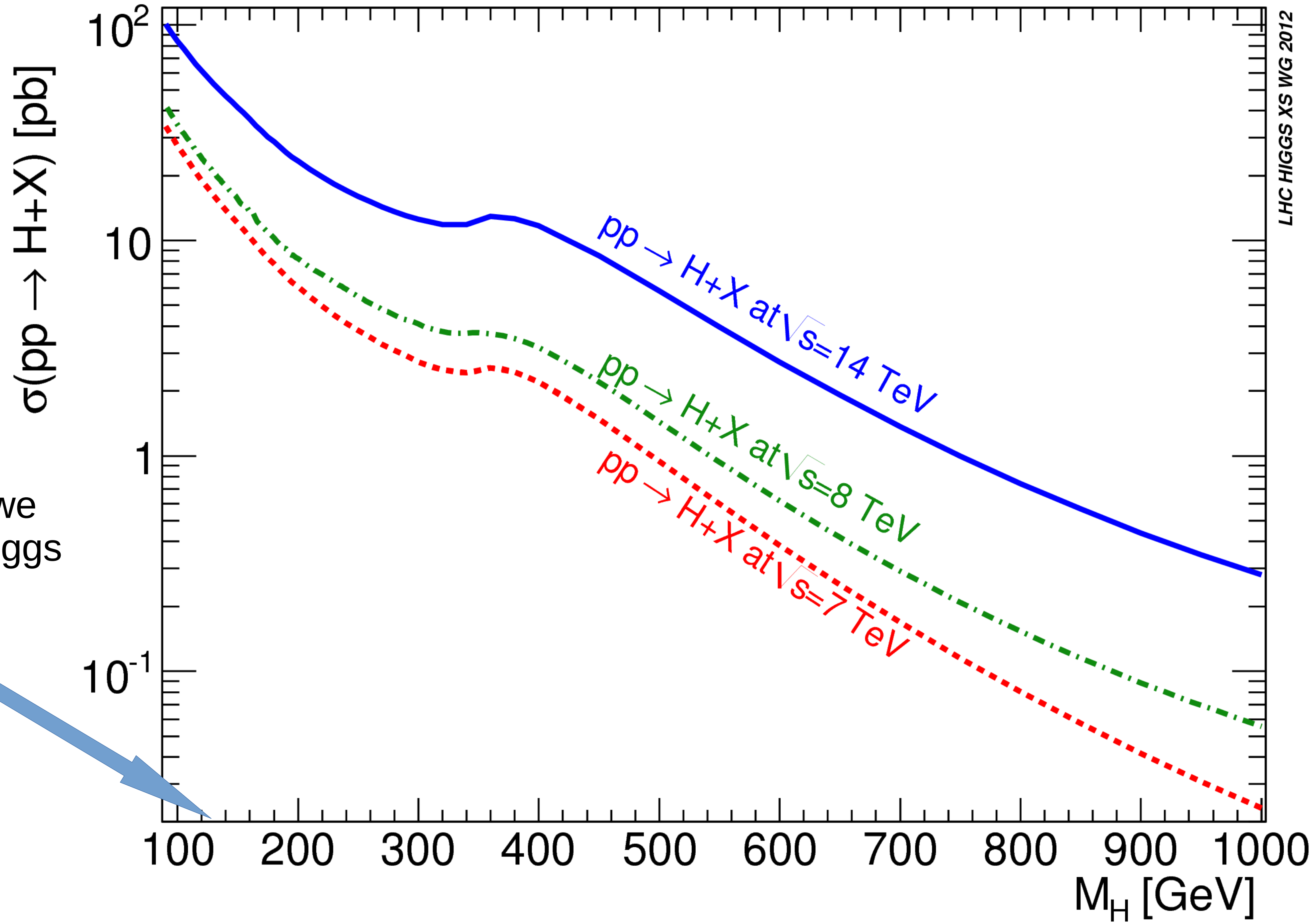
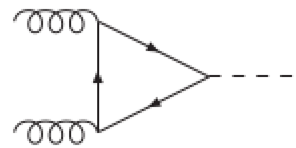


After 2012 we know the Higgs mass

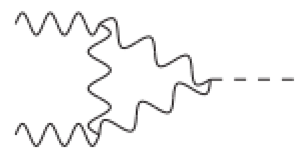
The Higgs at colliders

- **gluon fusion:** $\mathcal{O}_g = hG_{\mu\nu}G^{\mu\nu}$

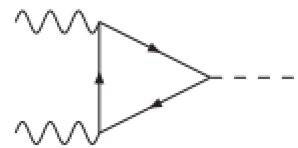


$\sim \frac{y_f}{m_f}$ **for** $m_f \gg m_h$

- **photon fusion:** $\mathcal{O}_\gamma = hF_{\mu\nu}F^{\mu\nu}$

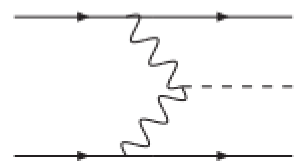


$\sim \frac{g}{m_W}$



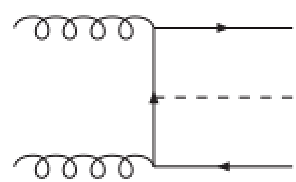
$\sim \frac{y_f}{m_f}$

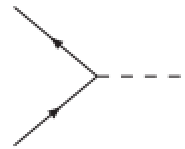
- **VBF + Vh:** $\mathcal{O}_V = hV_\mu V^\mu$



$\sim g\ m_V$

- **Yukawa:** $\mathcal{O}_f = h\bar{f}f$





$\sim y_f$

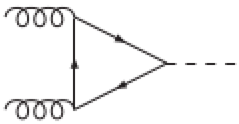
- $hZ\gamma$: $\mathcal{O}_{hZ\gamma} = hF_{\mu\nu}Z^{\mu\nu}$ **simil to** $h\gamma\gamma$ **but is possible to have 2 different particles in loop**

The Higgs at LHC: single production

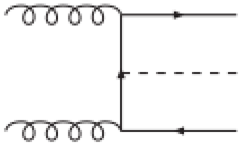
Main production channels:

LHC is an hadronic machine

- Gluon fusion: high E $\Rightarrow$ proton made of gluons

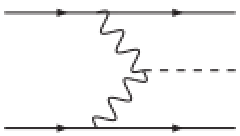


- $t\bar{t}h$: large top mass $\Rightarrow$ $y_t \simeq 1$



Subdominant production channel: EW

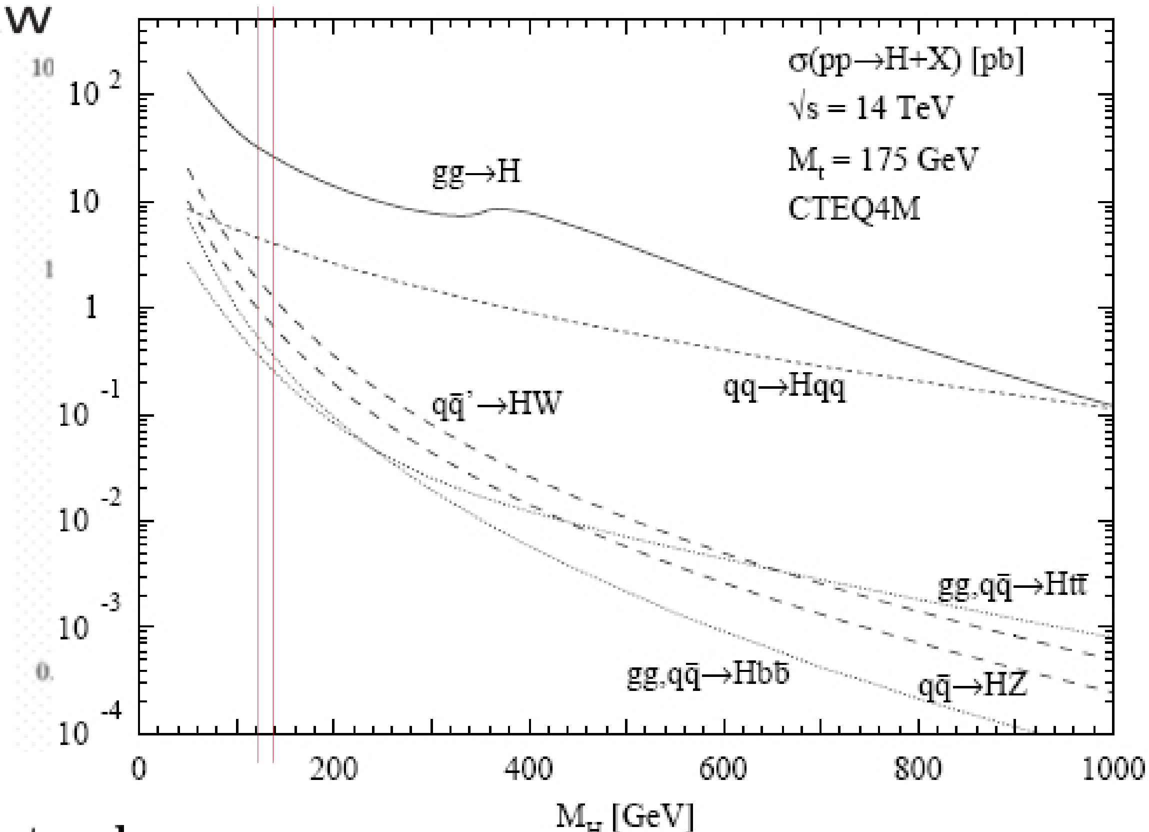
- VBF+Vh



these processes test unitarization of V_L scattering

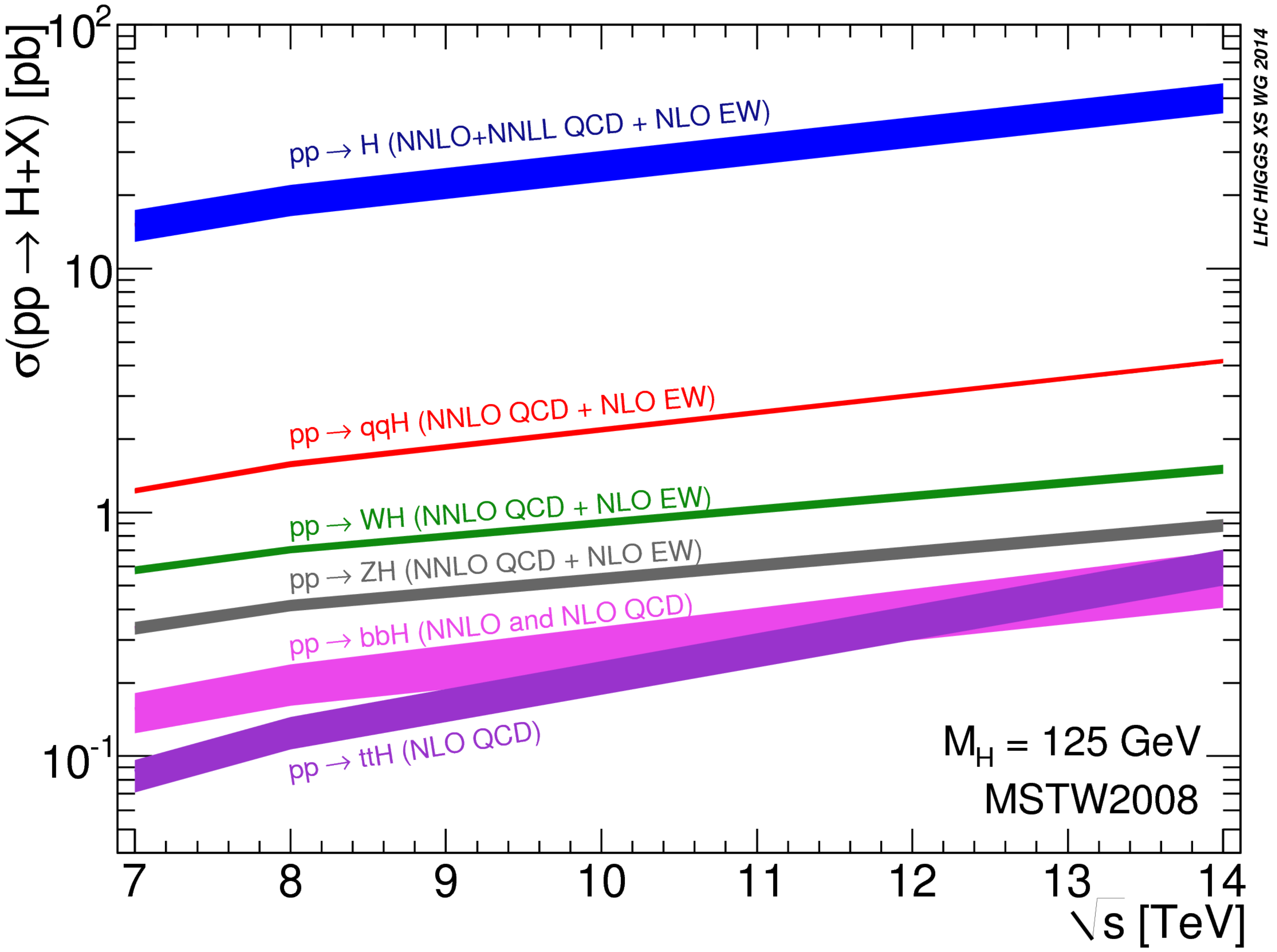
Other channels suppressed by small masses

ex : $q\bar{q} \to H$, suppressed by m_q/v



$\blacktriangleright$ since gluon fusion is dominted by $\mathrm{t-loop}$, κ_t and κ_g are not independent

The Higgs at LHC: single production



The Higgs at LHC

Higgs decay

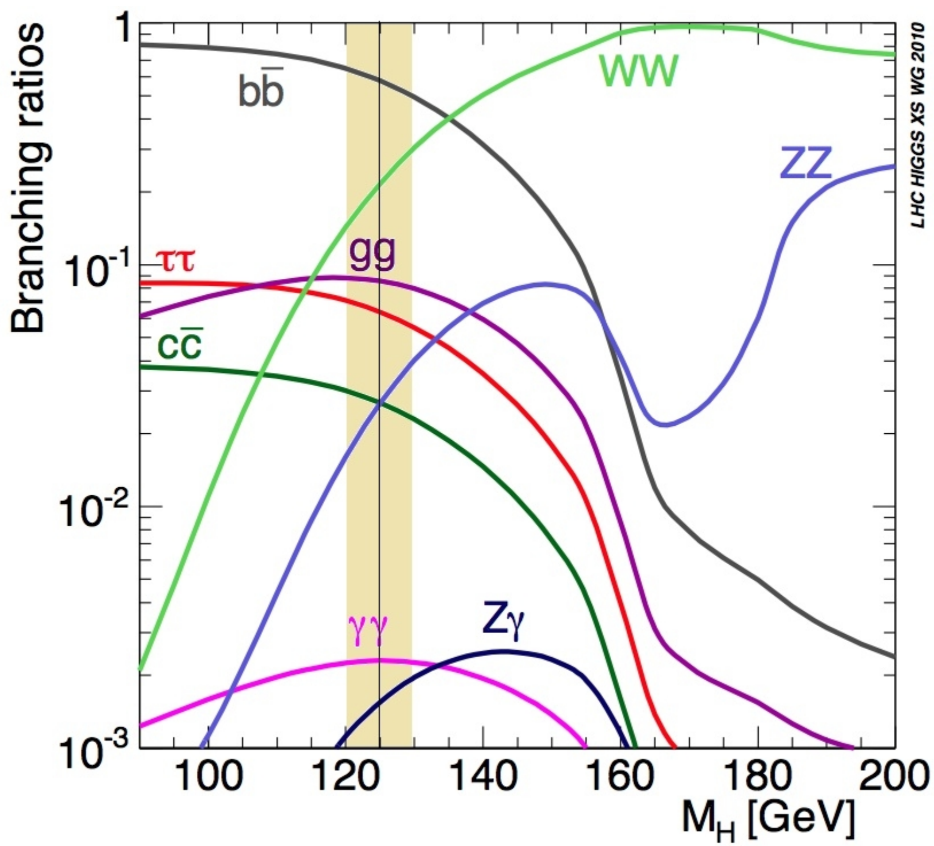
* Partial widths driven by couplings and phase space
* $\Gamma(m_h = 125\text{GeV}) \sim 5$MeV
* BR's arise from complicate interplay

Higgs coupling proportional to mass, thus largest decay fraction to heavy states

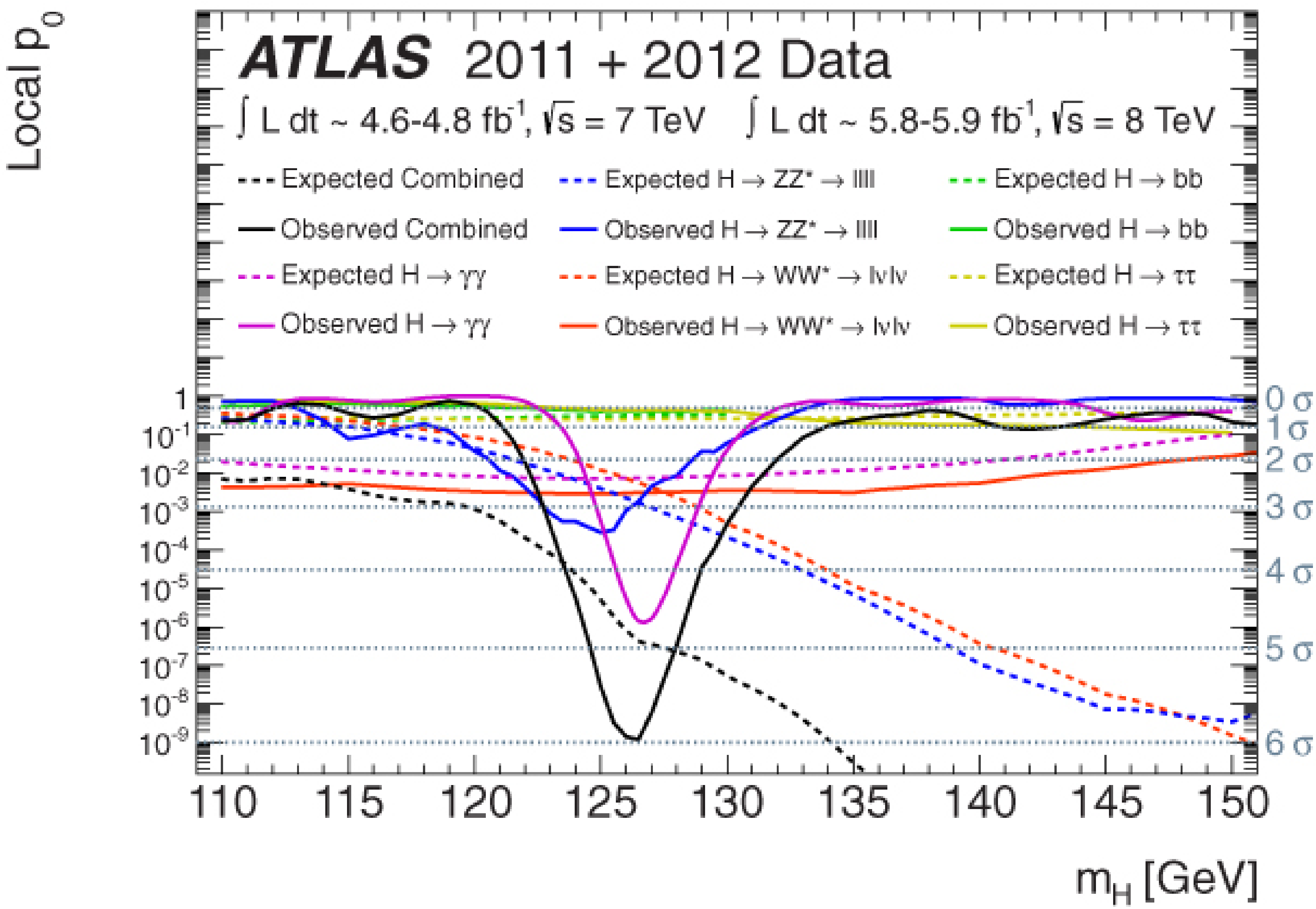
Main decay channels:

- $b\bar{b}$ dominates but ... QCD bckgd
- $\gamma\gamma$ tiny (1-loo EW) but no bckgd
- VV^* one V off-shell $\Rightarrow$ sizable
- $\tau\tau$ lepton channel $\Rightarrow$ "clean"

  y_τ largest lepton Yukawa

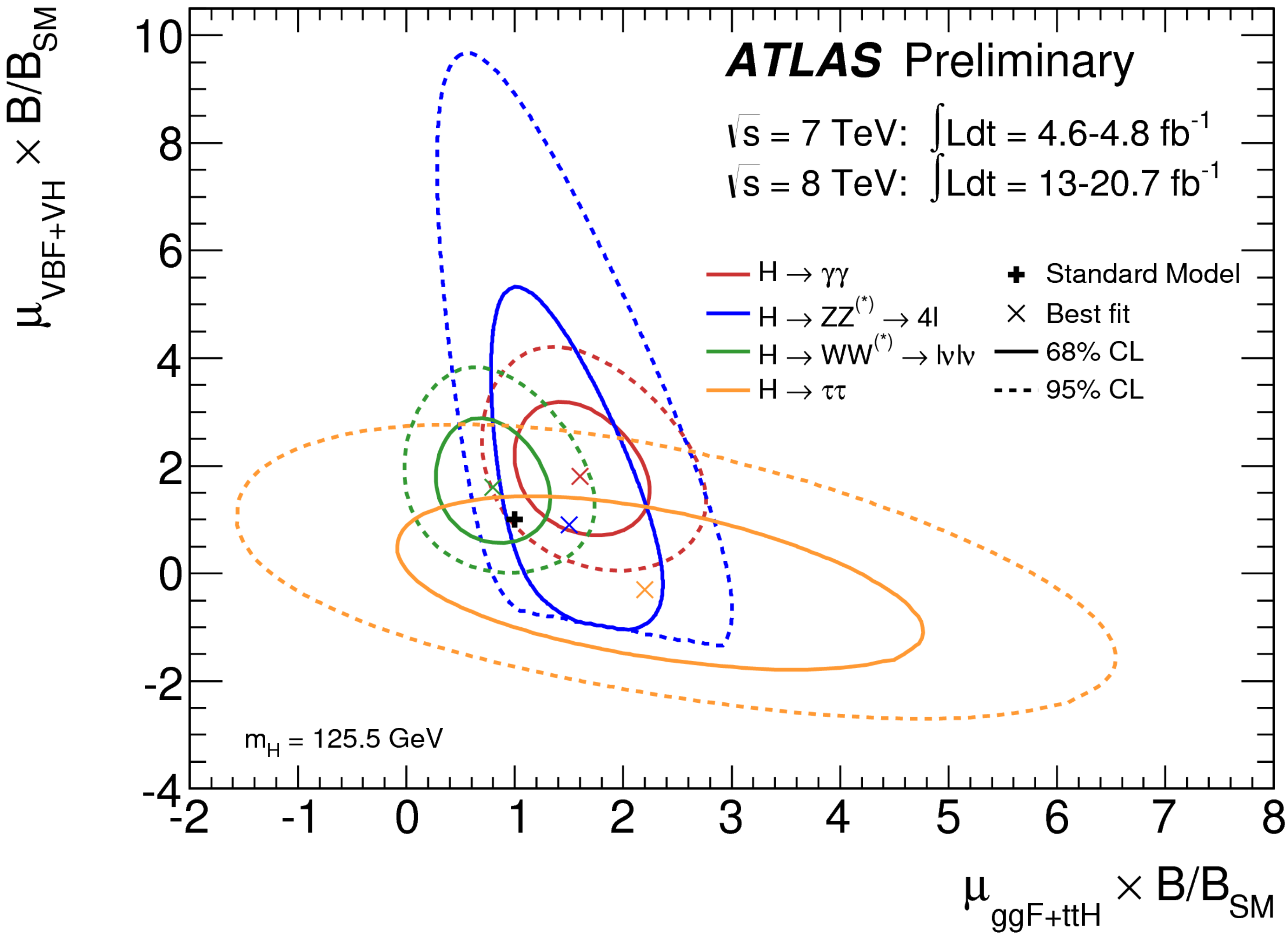


The Higgs at LHC: **Higgs discovery**



The Higgs at LHC

Measurement of the Higgs couplings: $\mu=\sigma/\sigma_{SM}$, B=branching fraction



The Higgs at LHC

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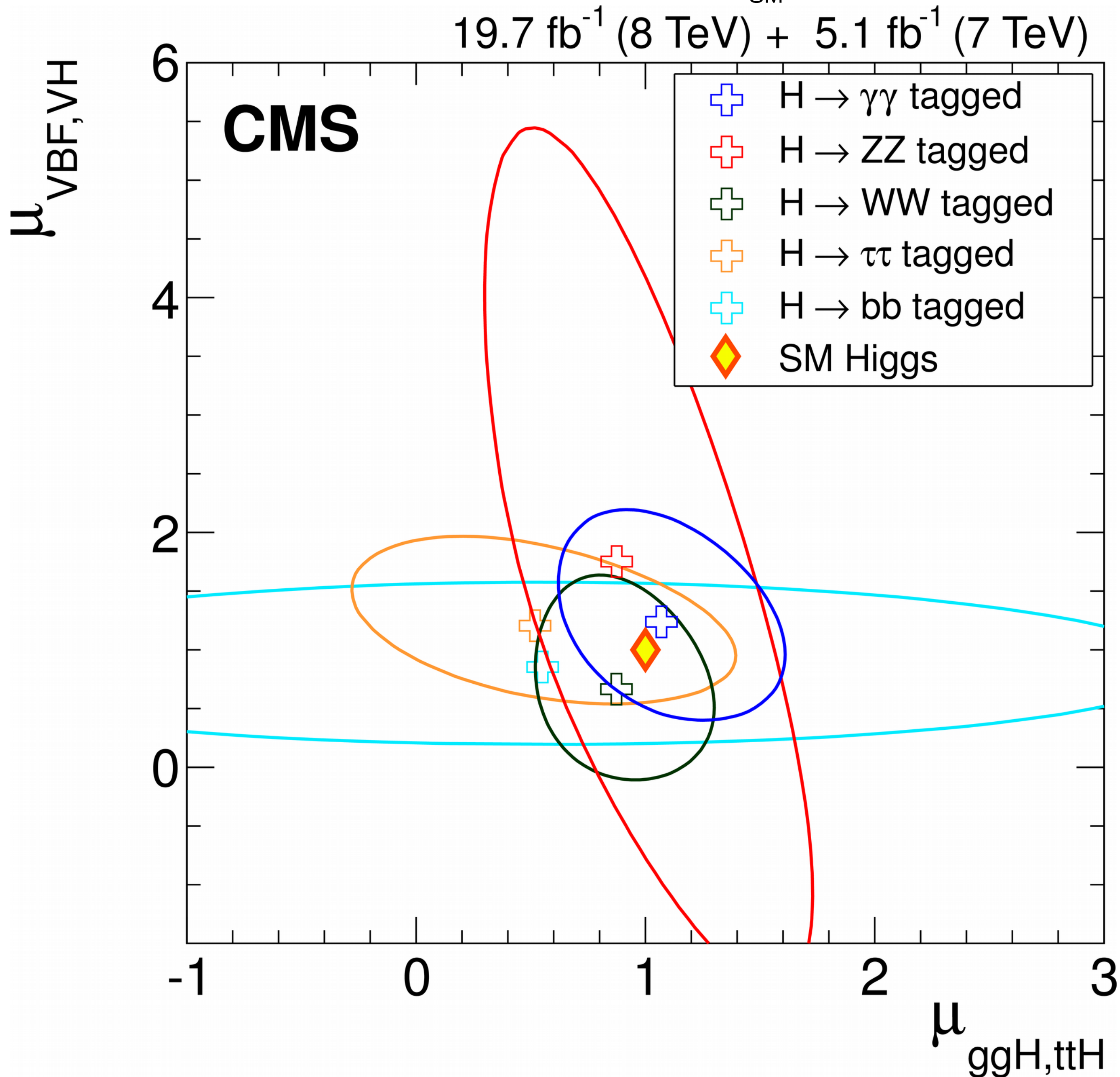
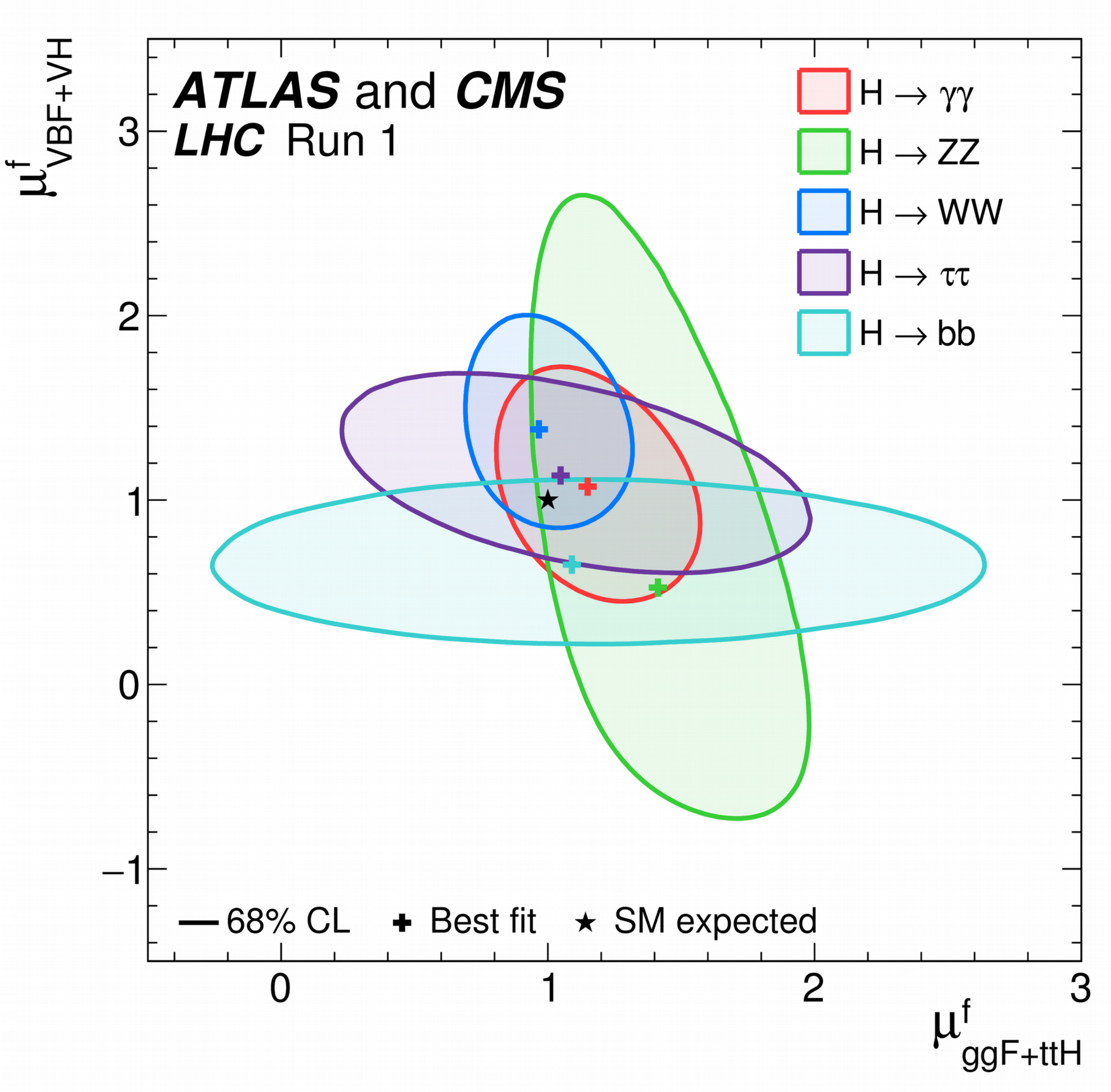


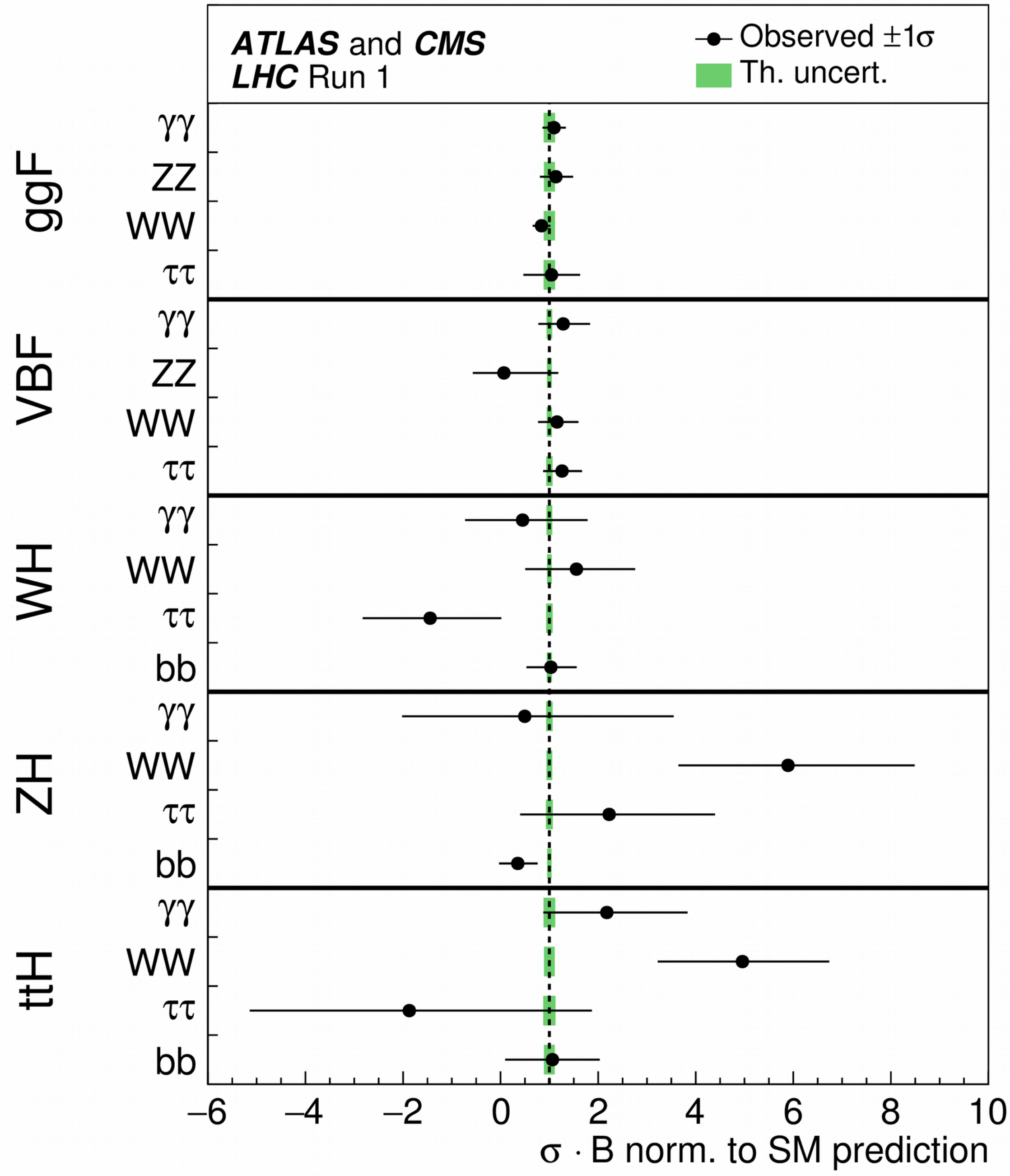
The Higgs at LHC

Measurement of the Higgs couplings: $\mu=\sigma/\sigma_{SM}$, B=branching fraction



The Higgs at LHC

Measurement of the Higgs couplings

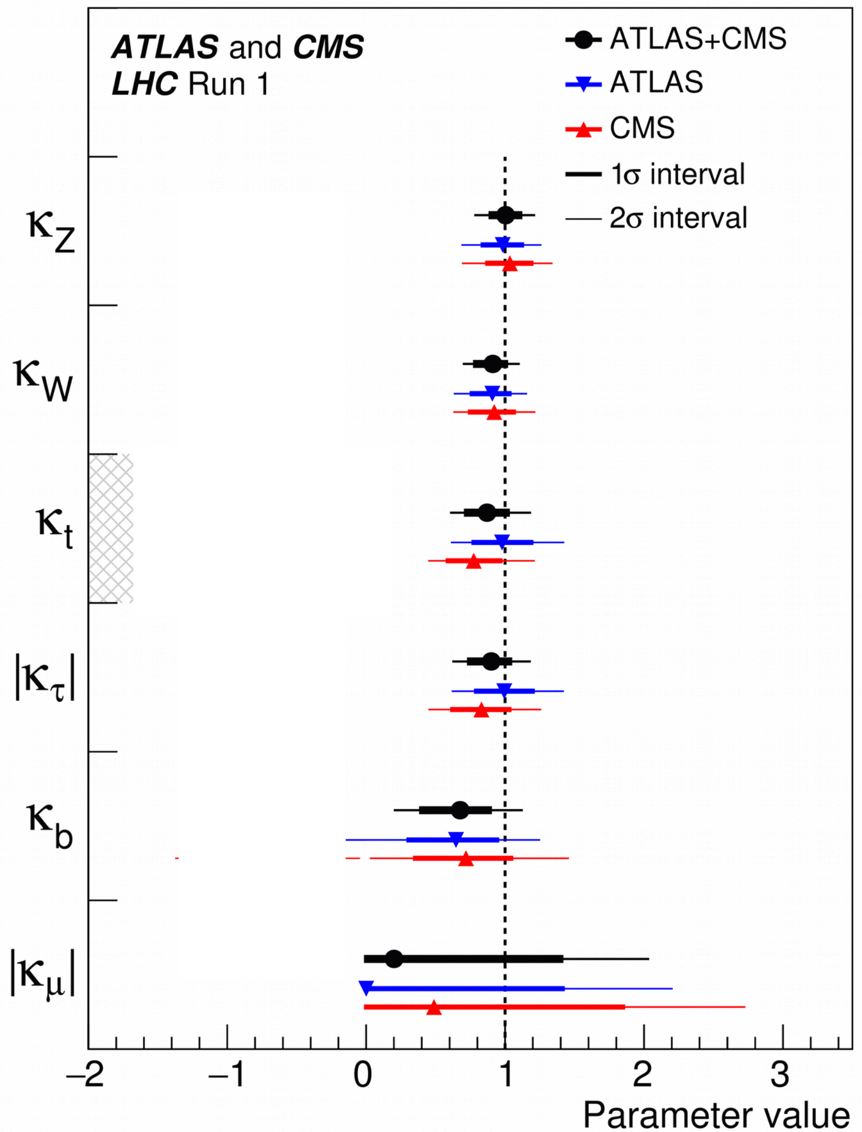


The Higgs at LHC: primaries

(Grojean, Pomarol, Riva et al)

It is possible to parametrize deviations in different basis for operators

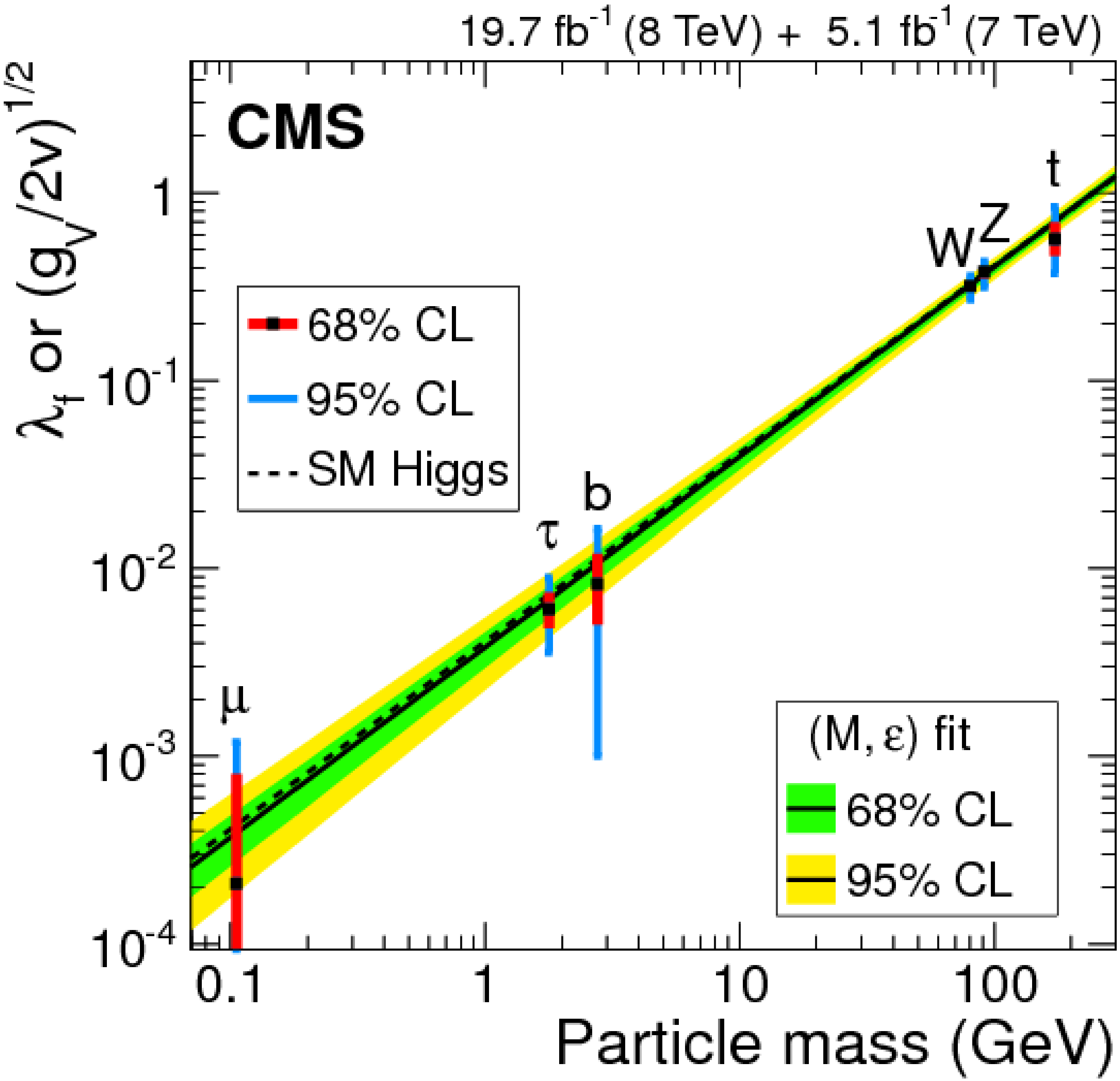
The primary operators are in correspondence with the κ's of the usual Higgs fit



The Higgs at LHC

The Higgs mechanism at work:

coupling vs mass

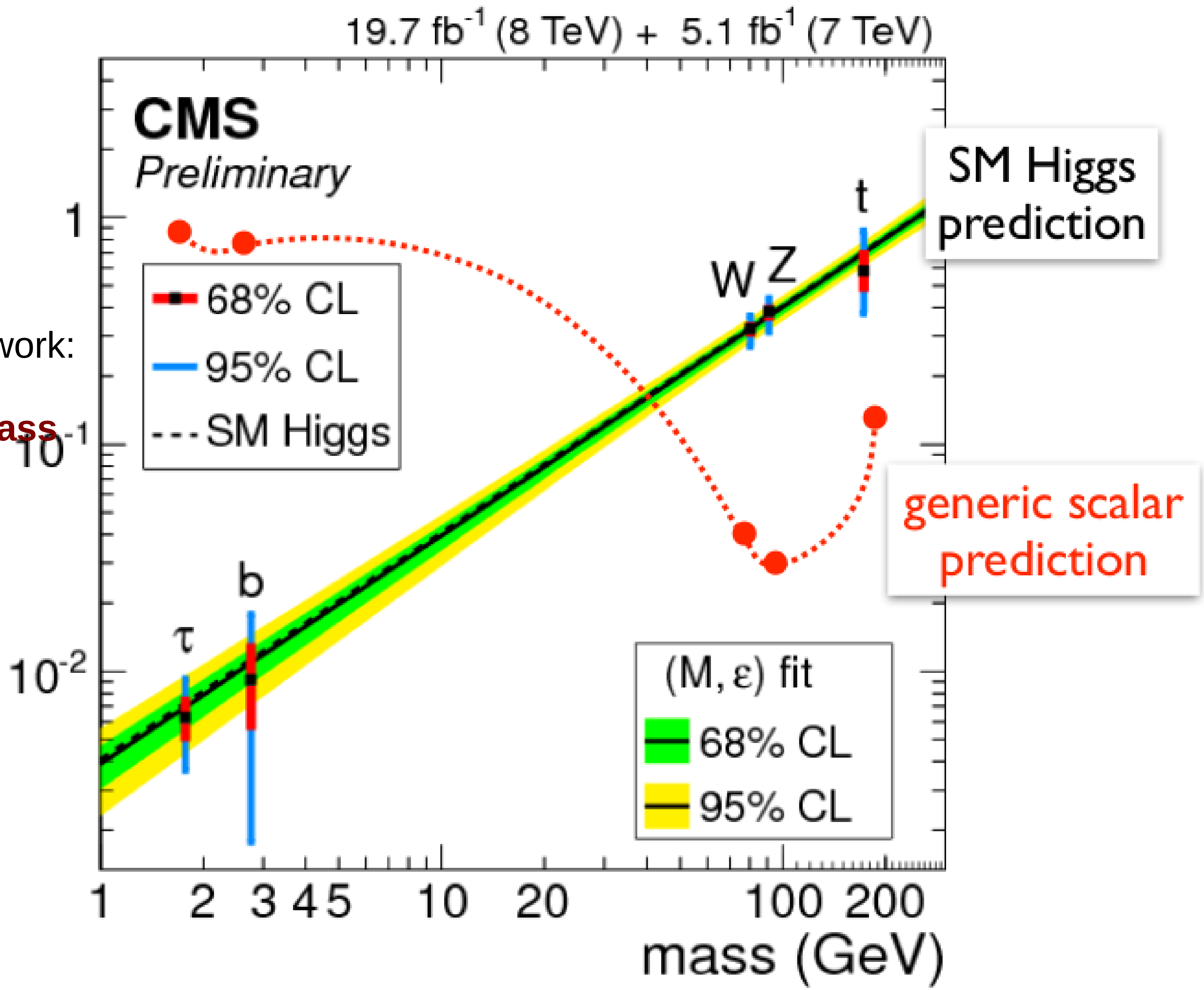


The Higgs at LHC

(Pomarol '14)

The Higgs mechanism at work:

coupling vs mass

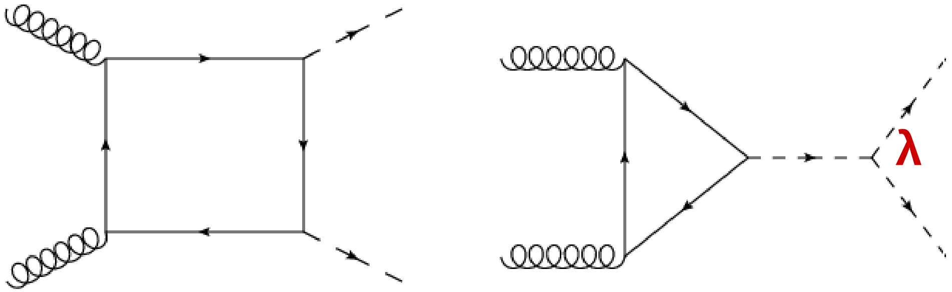


Challenging measurements: double Higgs

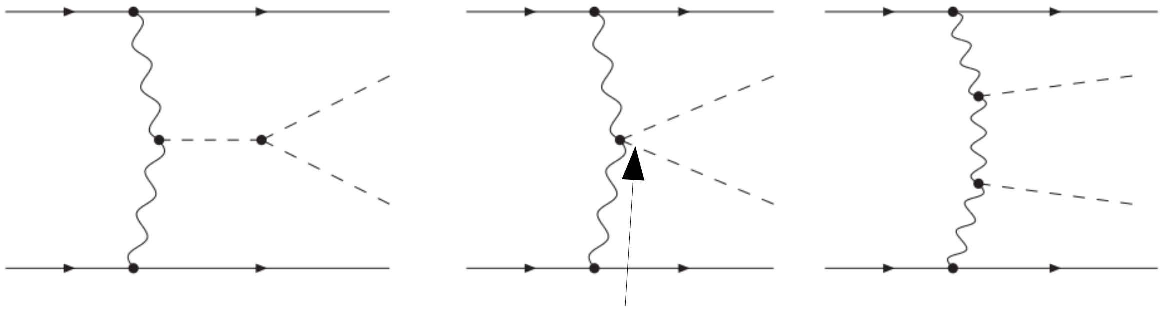
Double Higgs production gives acces to important aspects of the SM

- Test **λ** → triple (and quartic) coupling
- Test VVhh coupling

gluon fusion



vector boson fusion



probe the VVhh coupling

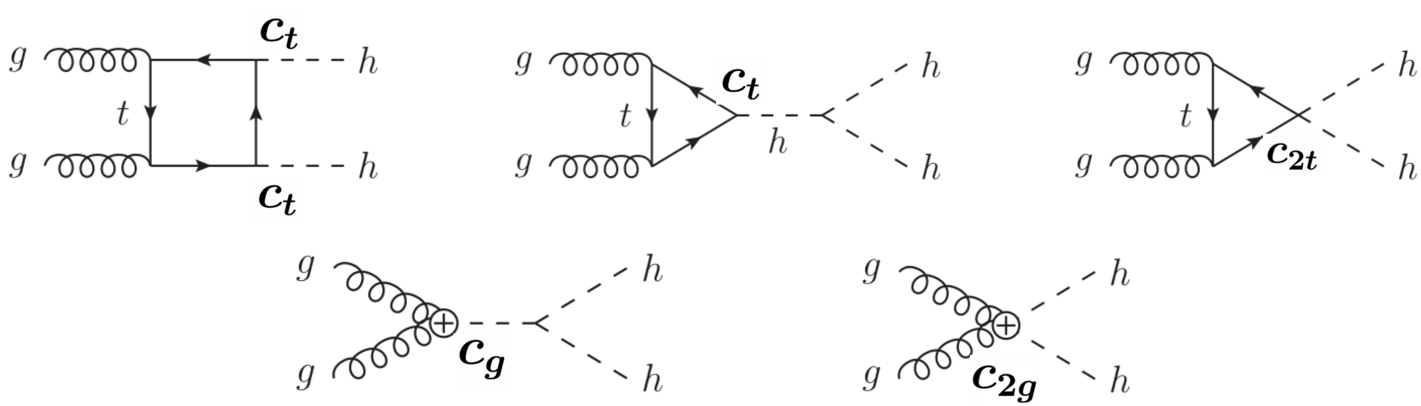
Single and double Higgs production are related in the SM
Independent measurements of the vertices involved allow to test the structure of the Higgs, and compare with the usual SM doublet.

Challenging measurements: double Higgs

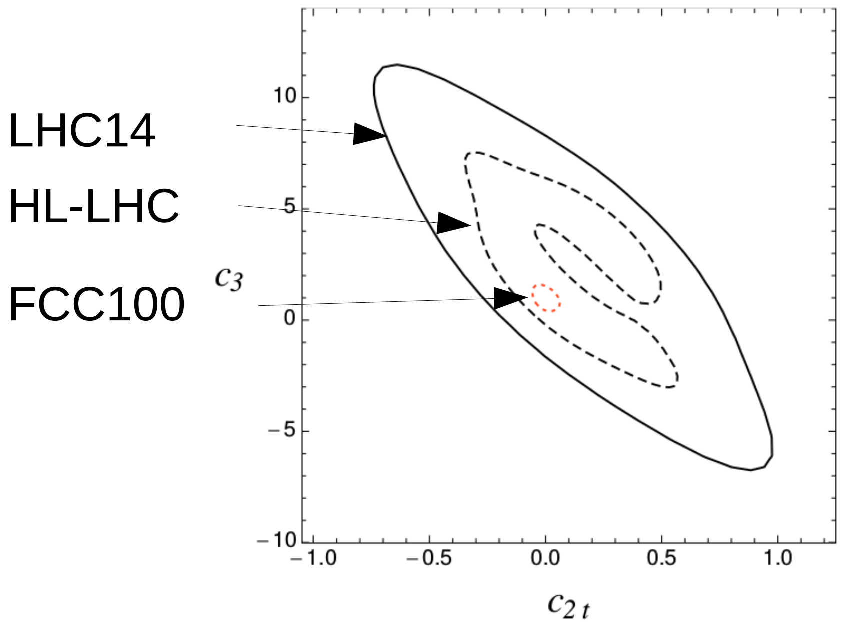
Double Higgs production gives acces to important aspects of the SM

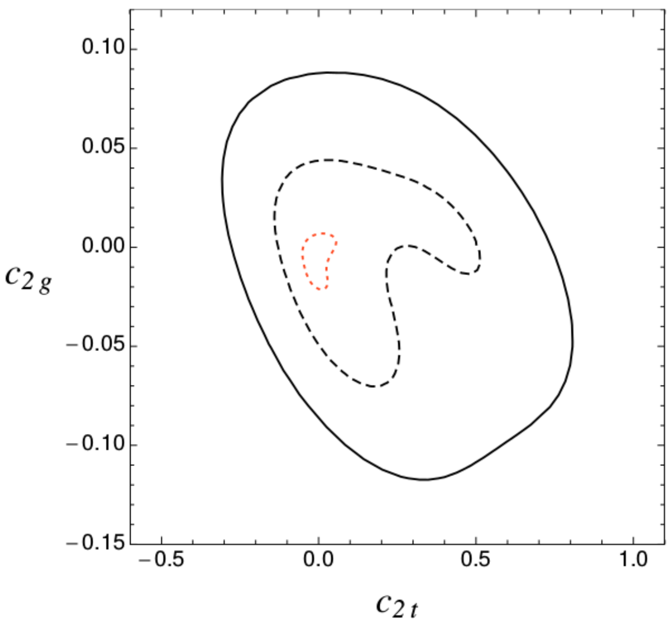
Including contact interactions in gluon fusion processes

(Azatov et al ‘15)



In the SM: $c_g = c_{2g}\ ,\quad c_{2t} = 3(c_t - 1)$





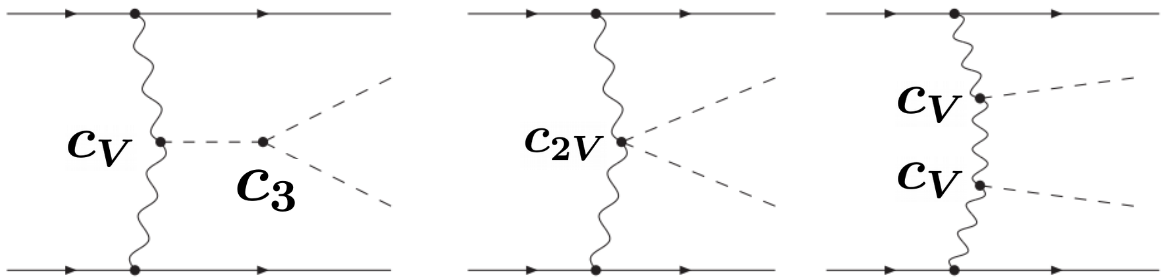
Possible to discriminate the coefficients, but higher luminosity and energy required

Challenging measurements: double Higgs

Double Higgs production gives acces to important aspects of the SM

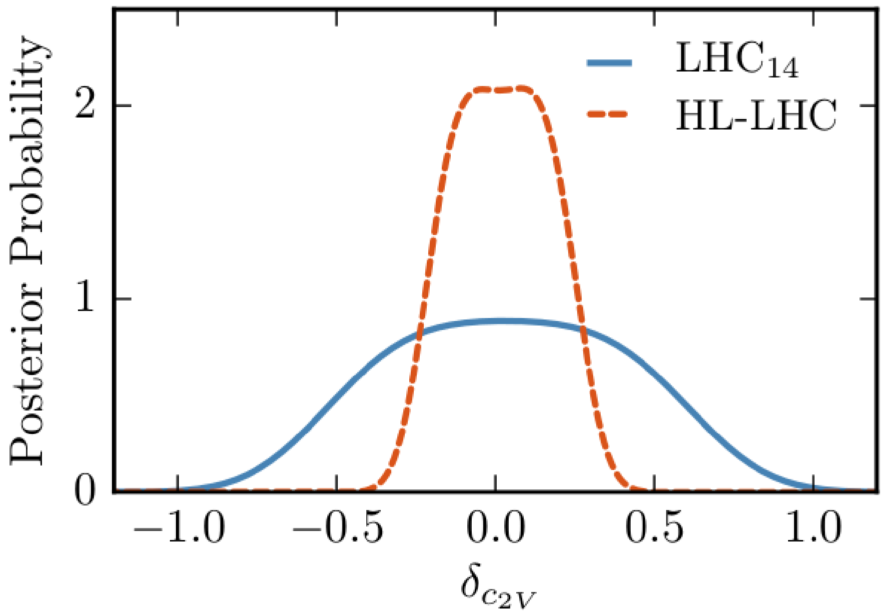
Analysing VBF

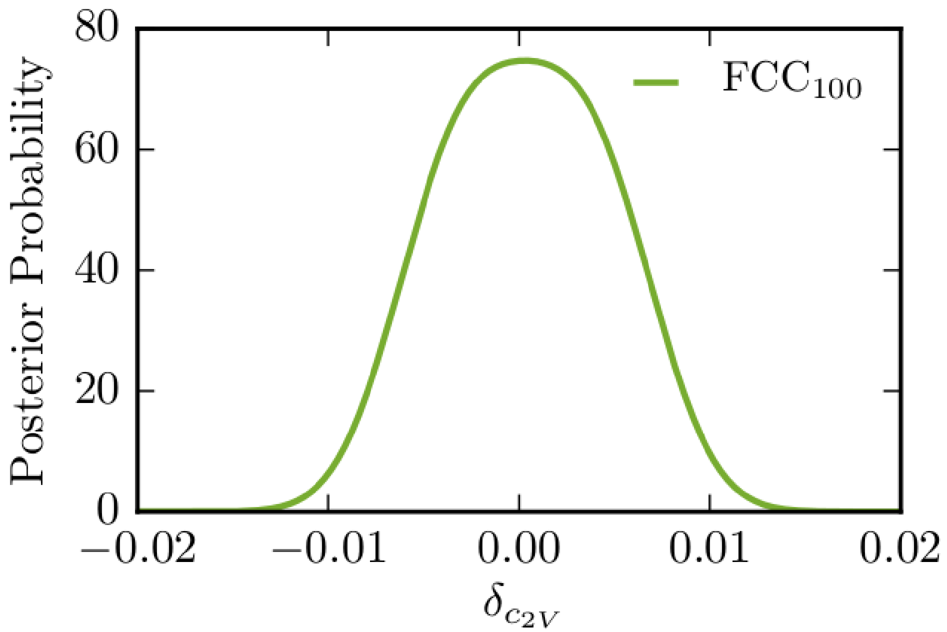
(Contino et al '16)



For large m_{hh} sensitivity to c_{2V} increases whereas to c_3 decreases, due to off-shell Higgs propagator

In the SM: $c_V = c_{2V} = c_3$

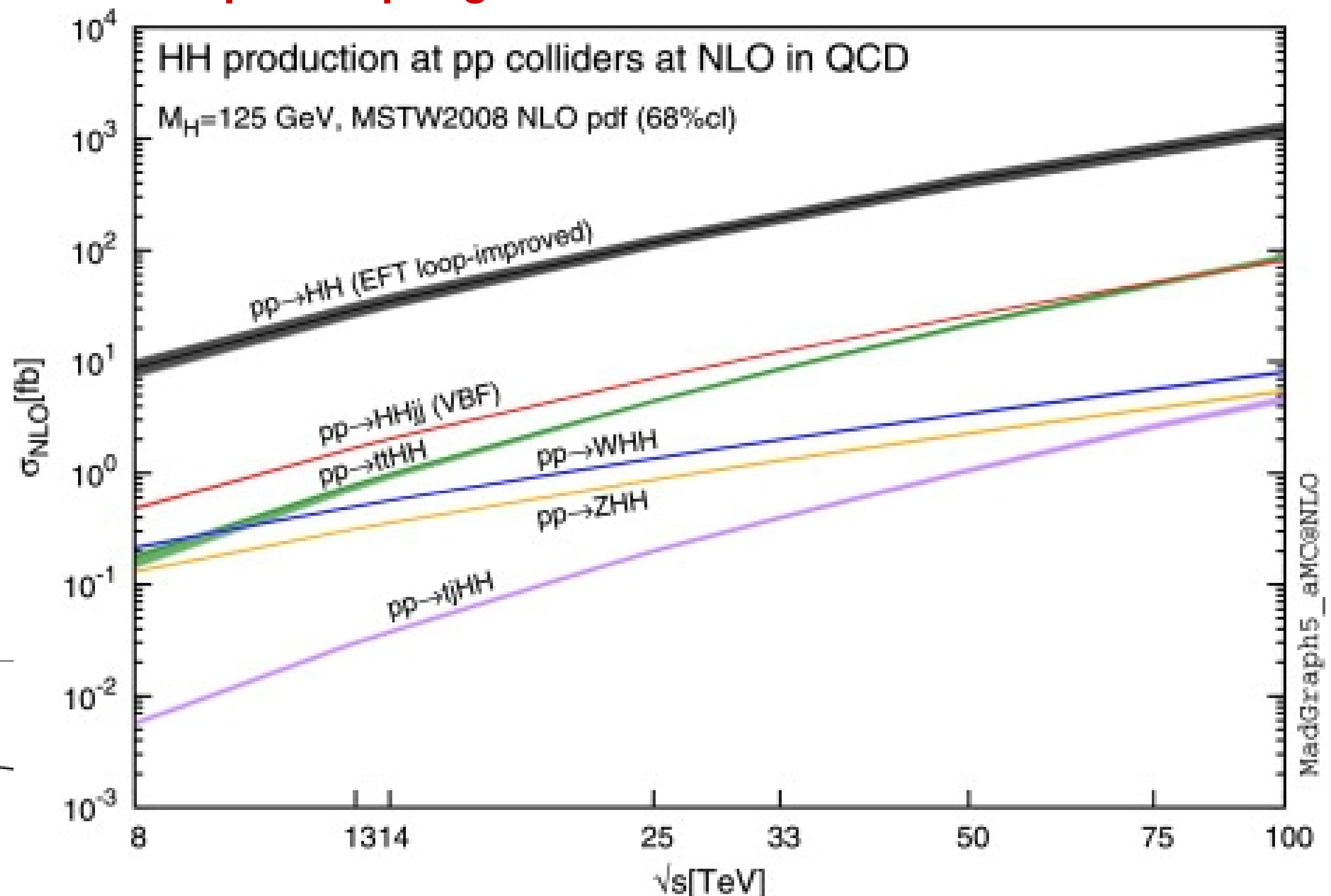




Challenging measurements: double Higgs

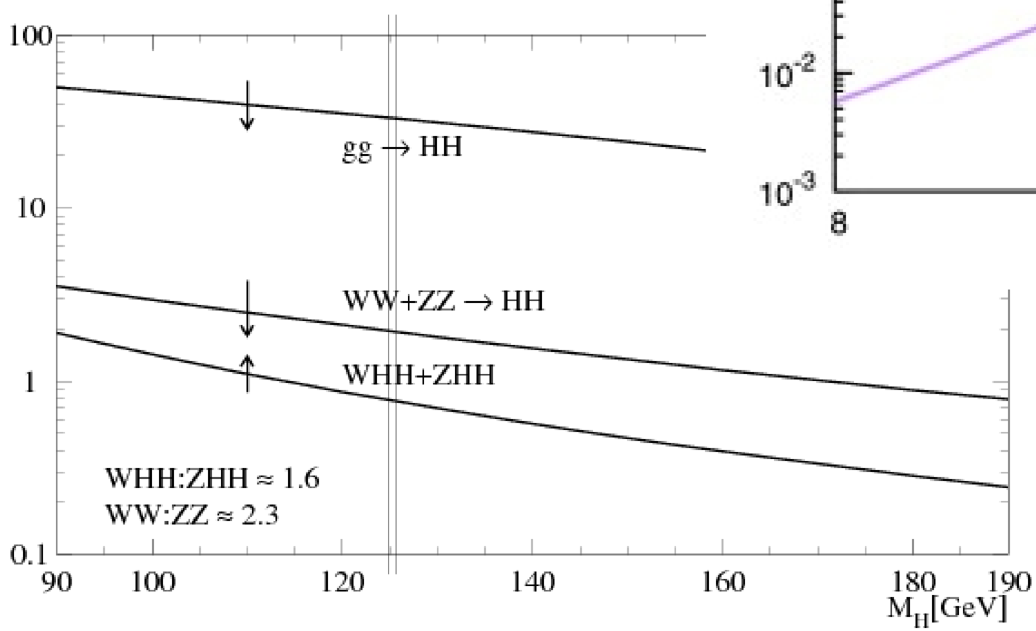
Double Higgs production: the triple coupling

(Frederix et al '14)



NLO cross section as function of the CM energy

(Djouadi et al '12)



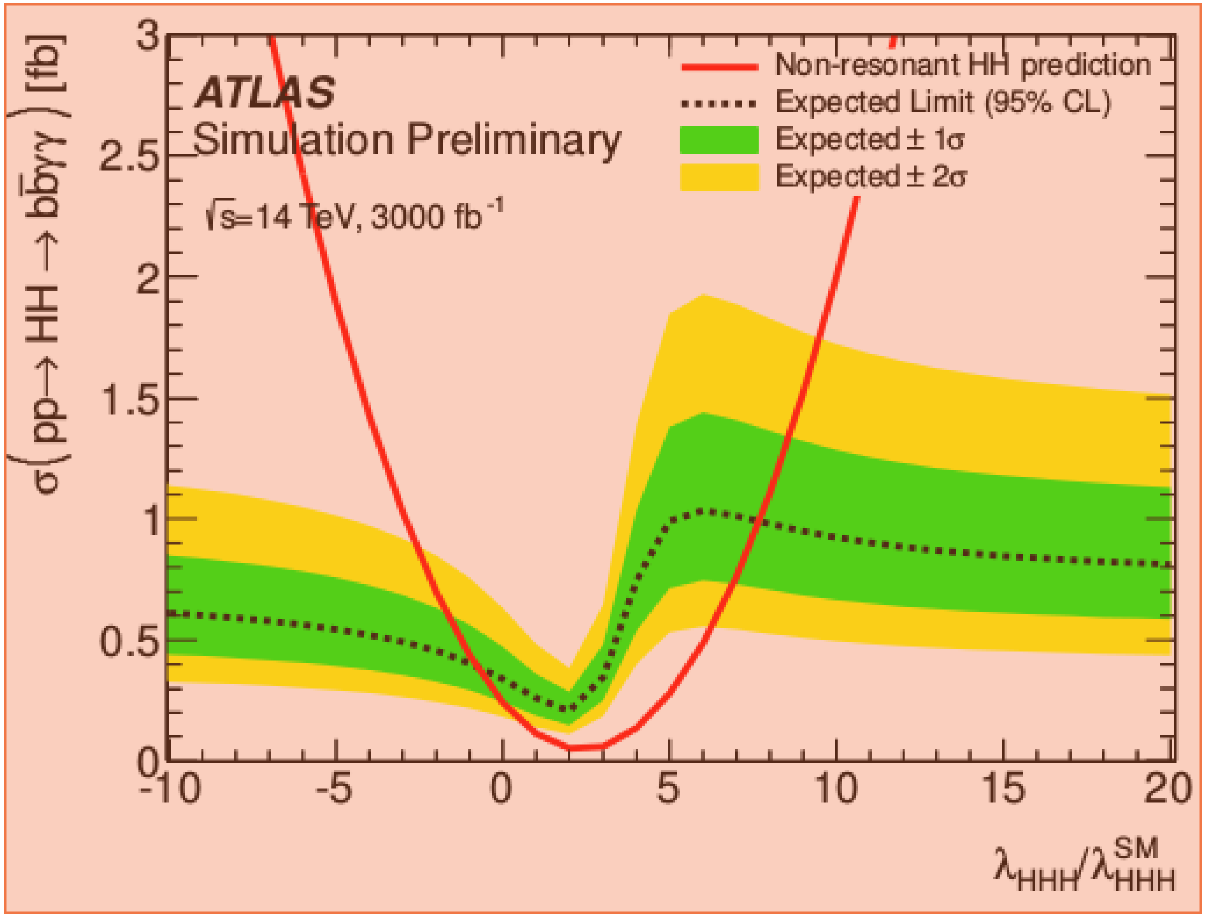
Different prod. channels at LHC 14 cross-section in fb
For m_h=125 GeV: gg→hh is 40fb

Challenging measurements: double Higgs

Double Higgs production: the triple coupling

HH production in the bbγγ channel

Prospects from ATLAS simulation ATLAS-PHYS-PUB-2017-001



The Higgs self-coupling is expected to be constrained to: $-0.8<\lambda/\lambda_{SM}<7.7$

Challenging measurements: tth

Coupling tth indirectly measured by gluon fusion

A direct determination of tth is crucial to test the SM

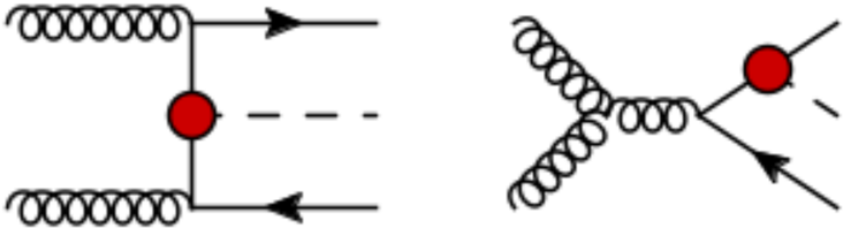
Eff. field theory operators

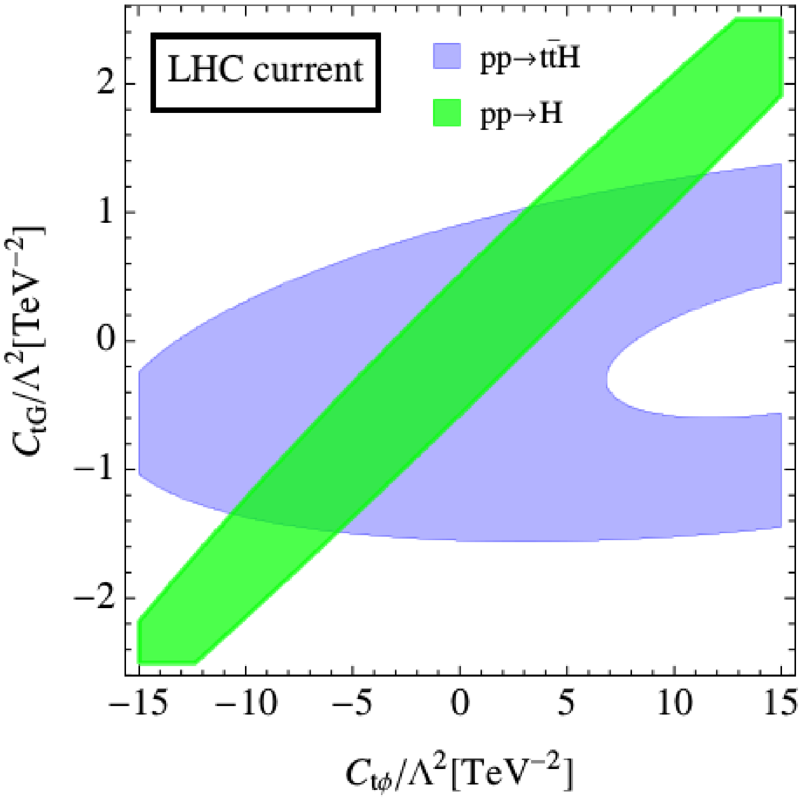
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi} \,,$$

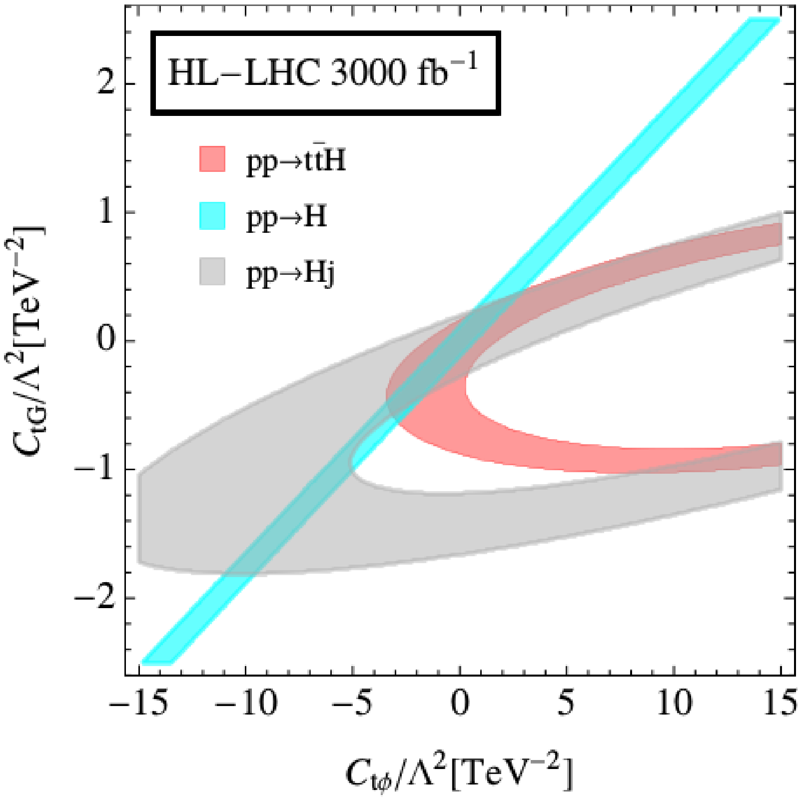
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu} \,,$$

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

(Maltoni et al ‘16)







High energy regime

- The LHC has mostly produced on-shell Higgses → E~m_h

  ↳ producing information on Higgs couplings at scale m_h

- Complementary studies: to probe Higgs production mechanisms and off-shell Higgs mediated processes that could be enhanced at high energies (E^2/Λ^2)

► Probe the Higgs couplings at higher energies

► Disentangle the degeneracy in tth and ggh couplings (due to lightness of Higgs), particularly critical for MCHM and some susy scenarios

$$-\kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu\,a} + i\tilde{\kappa}_t\frac{m_t}{v}\bar{t}\gamma_5 th + \tilde{\kappa}_g\frac{\alpha_s}{8\pi}\frac{h}{v}G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}$$

κ_t and κ_g control respectively the top loop and the direct ggh coupling

$$\frac{\sigma_{\rm incl}(\kappa_t,\kappa_g)}{\sigma_{\rm incl}^{\rm SM}} \simeq (\kappa_t+\kappa_g)^2\left(1-\frac{7}{15}\frac{\kappa_g}{\kappa_t+\kappa_g}\frac{m_h^2}{4m_t^2}\right) \simeq (\kappa_t+\kappa_g)^2$$

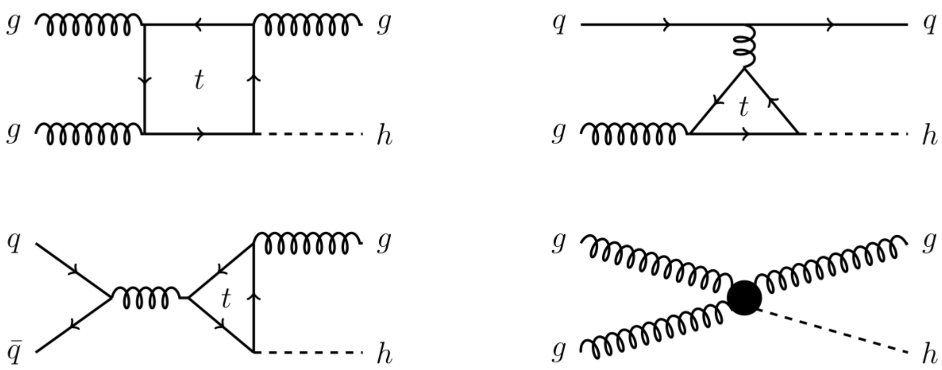
direct determination of κ_t in pp → tth is extremly difficult at LHC (small rate and complicated multiparticle final state)

- High E regime allows to “see” the fermions running in the loops: gg → h+j (Grojean et al ‘13) energetic j carry momentum and boost the top, enlightening the loop

High energy regime: boosted Higgs

Disentangling κ_t and κ_g with h+j boosted

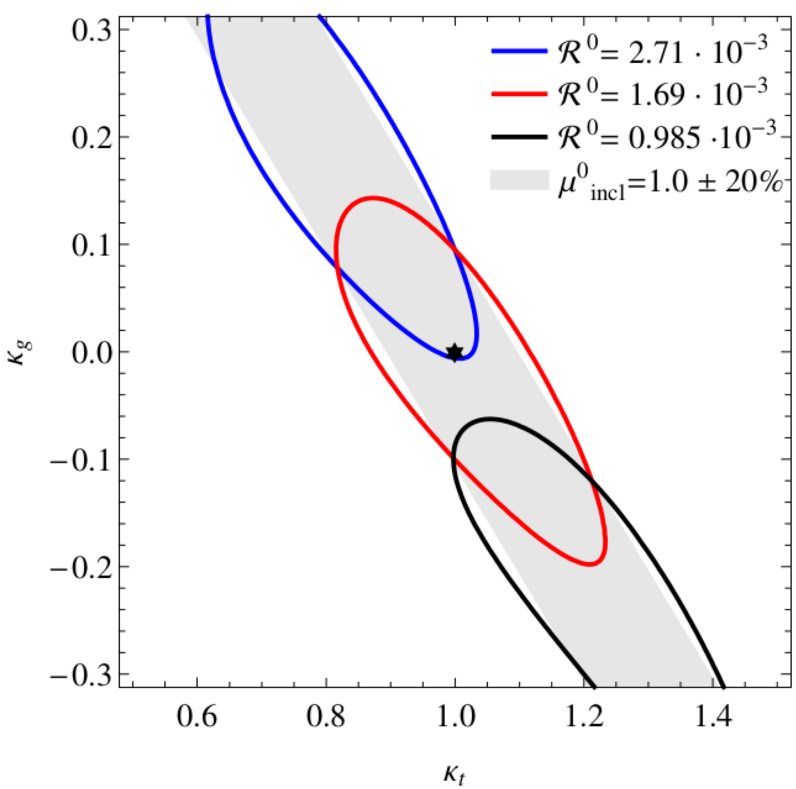
Putting a cut on p_T leads to



$$\frac{\sigma_{p_T^{\min}}(\kappa_t,\kappa_g)}{\sigma^{SM}_{p_T^{\min}}} = (\kappa_t+\kappa_g)^2 + \delta\,\kappa_t\,\kappa_g + \epsilon\,\kappa_g^2$$

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{SM}_{p_T^{\min}}$ [fb]	δ	ϵ
14	100	2180	0.0031	0.031
	150	837	0.070	0.13
	200	351	0.20	0.30
	250	157	0.39	0.56
	300	74.9	0.61	0.89
	350	37.7	0.85	1.3
	400	19.9	1.1	1.7
	450	10.9	1.4	2.3
	500	6.24	1.7	2.9
	550	3.68	2.0	3.6
	600	2.22	2.3	4.4
	650	1.38	2.6	5.2
	700	0.871	3.0	6.2
	750	0.562	3.3	7.2
	800	0.368	3.7	8.4
100	500	964	1.8	3.1
	2000	1.01	14	78

Defining the observable $\mathcal{R}(\kappa_t,\kappa_g) = \frac{\sigma_{650\,\mathrm{GeV}}(\kappa_t,\kappa_g)K_{650\,\mathrm{GeV}}}{\sigma_{150\,\mathrm{GeV}}(\kappa_t,\kappa_g)K_{150\,\mathrm{GeV}}}$



Predictions for:
k_t = **0.8**
1.0
1.2
k_g=0

HL-LHC14

(Grojean et al ‘13)

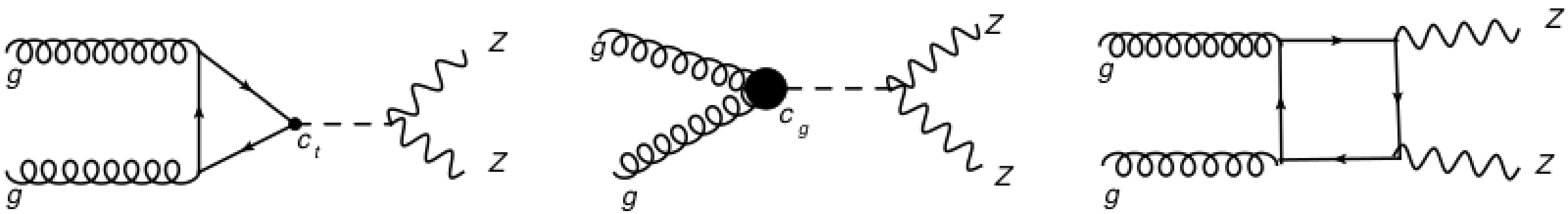
High energy regime: off-shell Higgs

For far off-shell single Higgs production, the partonic c.o.m. energy of the process is larger than m_t

the top can not be integrated-out and the degeneracy ($\kappa_t + \kappa_g$) is broken

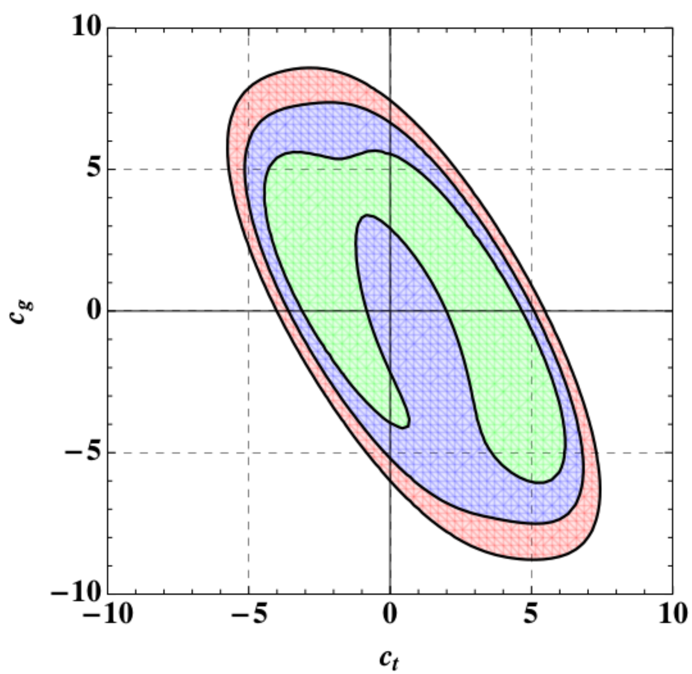
Adding contact interaction (eff. field theory approach) and considering ZZ-final state (with leptonic decay)

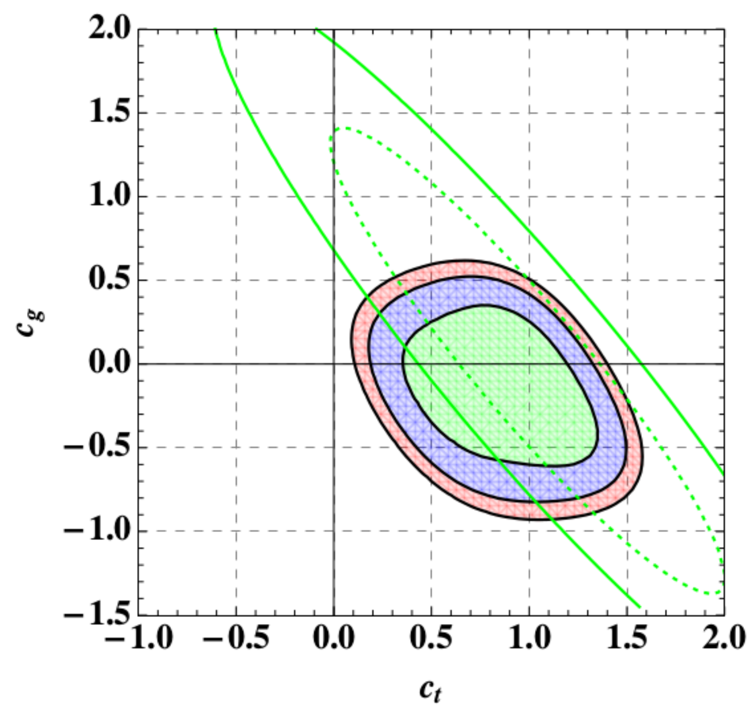
(Azatov et al '14)



Using the results for ZZ at high invariant mass by CMS8

68,95,99% probabilities





HL-LHC14

Is there something else?

What next? (1)

- Since the 70's, we had a very strong guiding principle: a SM particle (the Higgs) was missing, many ideas and experiments were developed to find it.

  A new state, compatible with the SM Higgs, has been discovered!

  All the SM particles have been found!!! (a few parameters to be measured yet: Higgs self-coupling, Yukawa of light fermions ...)

→ We have a "complete" theory of fundamental particles and interactions

the SM

- Now what? Is this the end of particle physics? A lot of questions in Higgs sector:
  - Is the SM valid up to arbitrarily high energies?
  - Is the Higgs potential stable?
  - What is the reason for EW symmetry breaking? (why $m^2 < 0$?)
  - What is the dynamics driving EW symmetry breaking?
  - Is there a rationale for the hierarchy of Higgs couplings?

(needless to say that most of the big questions are still there: quantization of gravity, dark matter, dark energy, bariogenesis, hierarchy of fermion masses, …)

What next? (2)

- The Higgs has been found, the SM is complete (not the same as saying “the SM is a complete theory”)

Higgs as a door to New Physics

- From the theoretical point of view:

  if there is NP solving the hierarchy problem, explaining the hierarchy of Yukawa couplings, stabilizing the Higgs potential → it must couple to the Higgs

- From the phenomenological point of view:

  if direct observation of NP is not possible at LHC, the Higgs discovery offers many possibilities:

→ deviations in single and double Higgs production cross-sections and distributions

→ deviations in Higgs branching ratios

→ flavor violating Higgs decays (eμ, μτ, bs, …)

→ flavor violating top decays (ch, uh)

Learn from this phenomenology to infer properties of BSM

deviations → NP is there

no-deviations → strong constraints to NP

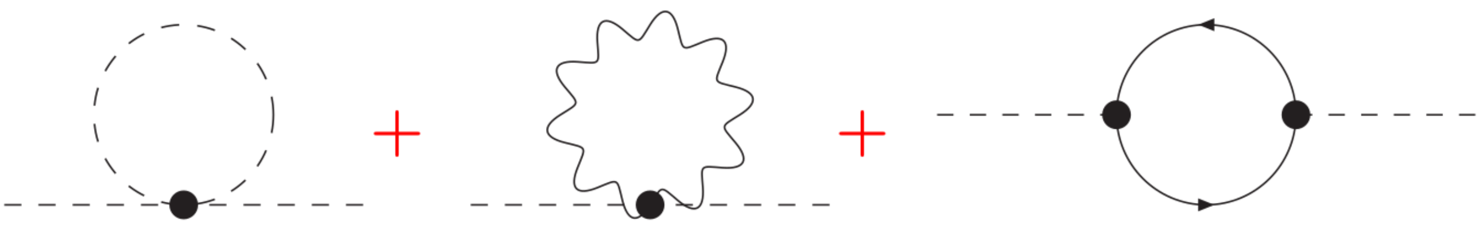
Instabilities of the Higgs potential

UV quadratic sensitivity of the mass term

The coefficient of the quadratic term in the Higgs potential is quadratically sensitive to the physics at high energies

$$V(H) = -\frac{1}{2}m^2|H|^2 + \frac{1}{4}\lambda|H|^4$$

1-loop radiative corrections regularized with UV cut-off



$$\delta m_h^2 = \frac{\Lambda^2}{16\pi^2}\left[6\lambda + \frac{1}{4}\left(9g^2 + 3g'^2\right) - 6y_t^2\right]$$

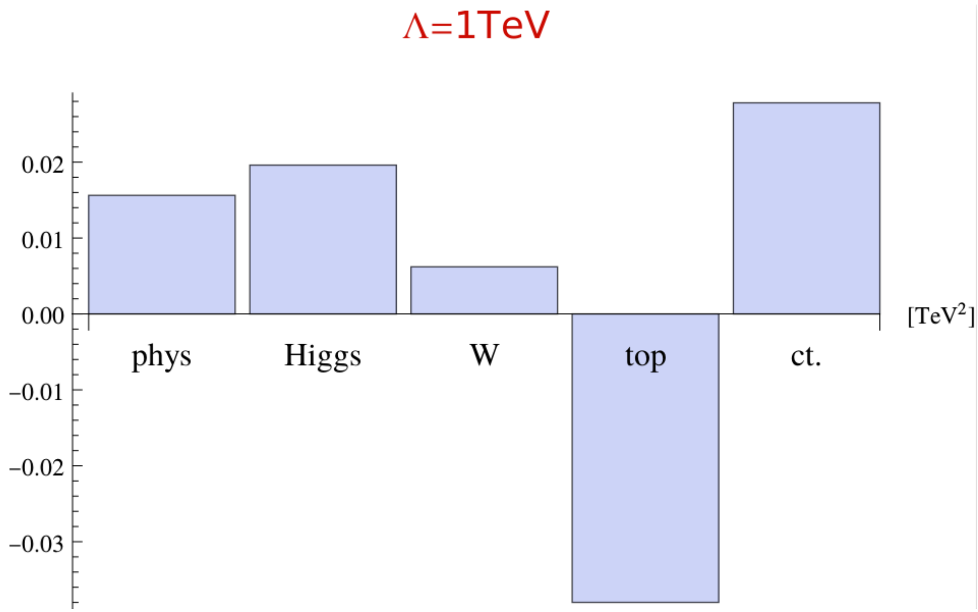
The top contribution dominates

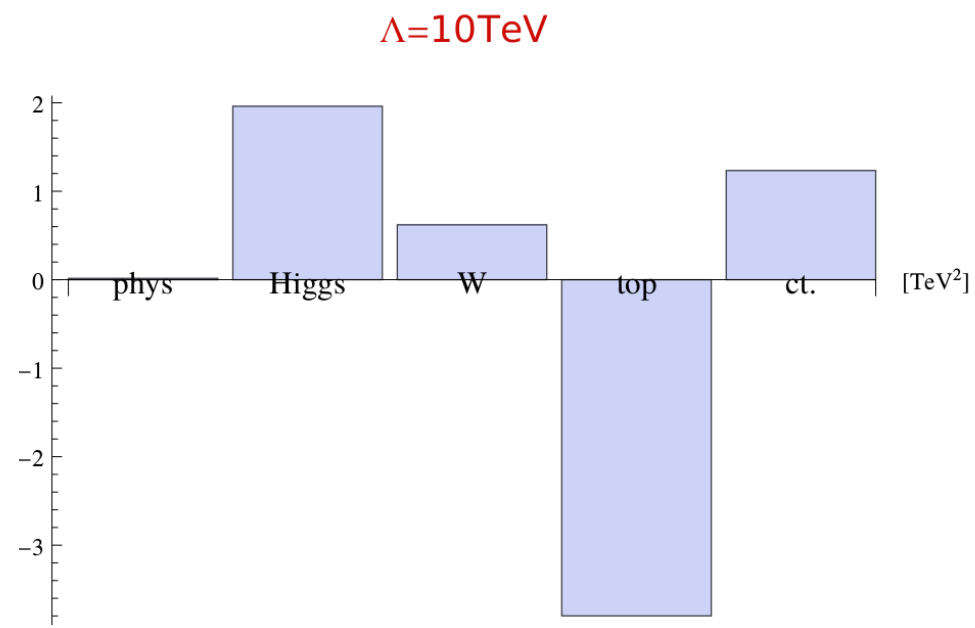
$$m_H^2 = (m_H^{tree})^2 - (125\mathrm{GeV})^2\left(\frac{\Lambda}{650\mathrm{GeV}}\right)^2$$

Instabilities of the Higgs potential

UV quadratic sensitivity

$$\delta m_h^2 = \frac{\Lambda^2}{16\pi^2}\left[6\lambda + \frac{1}{4}\left(9g^2 + 3g'^2\right) - 6y_t^2\right]$$





Obtaining the Higgs mass requires a tuning of order $(m_{phys} / \delta m_h)^2$

Instabilities of the Higgs potential

UV quadratic sensitivity → The meaning of the cut-off

Using dimensional regularization there is no quadratic divergence, only logs appear.
Can we avoid this problem just by using dim. reg.?

If there is no new physics beyond the SM, yes!, but …
If there are new particles, by using dim. reg. we obtain:

$$\delta m_H^2 \sim \frac{g^2}{(4\pi^2)} m_{NP}^2$$

g: coupling between the Higgs and the NP
m_{NP}: mass of the NP

Threshold effect: tuning of order $(m_{phys}/m_{NP})^2$

As in the previous calculation replacing the cut-off by the mass of NP

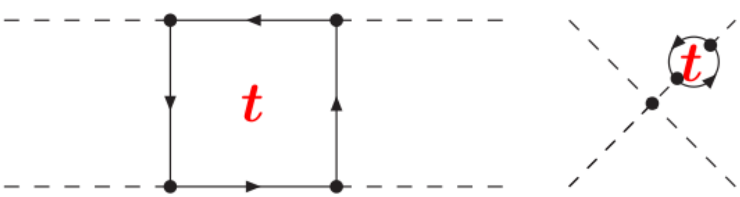
Instabilities of the Higgs potential

UV corrections to quartic coupling

- The coefficient of the quartic term in the Higgs potential is logarithmically sensitive to the physics at high energies

$$V(H) = -\frac{1}{2}m^2|H|^2 + \frac{1}{4}\lambda|H|^4$$

- 1-loop RGE



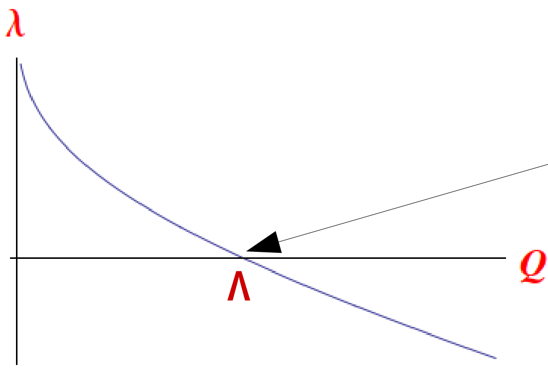
dominated by the **top** contribution

$$(4\pi)^2 \frac{d\lambda}{d\log Q} \simeq -6y_t^2$$

- Integrating the RGE:

$$\lambda(Q) = \lambda(Q_0) - \frac{\frac{3}{(4\pi)^2}[y_t(Q_0)]^4 \log\frac{Q^2}{Q_0^2}}{1 - \frac{9}{(4\pi)^2}[y_t(Q_0)]^2 \log\frac{Q^2}{Q_0^2}}$$

The quartic coupling decreases and can be negative → **stability bound**



$$\Lambda \lesssim v e^{4\pi^2 m_h^2/3y_t^4 v^2}$$

trading λ by m_h^2 and v^2

Instabilities of the Higgs potential

UV corrections to quartic coupling

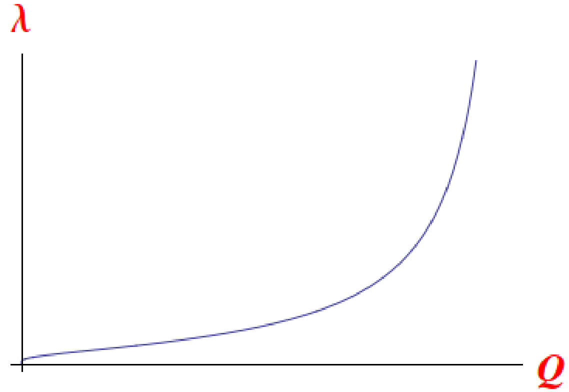
- The coefficient of the quartic term in the Higgs potential is logarithmically sensitive to the physics at high energies

$$V(H) = -\frac{1}{2}m^2|H|^2 + \frac{1}{4}\lambda|H|^4$$

- 1-loop RGE $(4\pi)^2\frac{d\lambda}{d\log Q} \simeq 24\lambda^2$ consider **Higgs** contribution only

- Integrating the RGE: $$\lambda(Q) = \frac{m_h^2}{2v^2 - \frac{3}{4\pi^2}m_h^2\log\frac{Q^2}{v}}\,,\quad Q_0 = v$$

The quartic coupling increases and diverges → **triviality bound**



$$\Lambda \lesssim v e^{4\pi^2 v^2/3m_h^2}$$

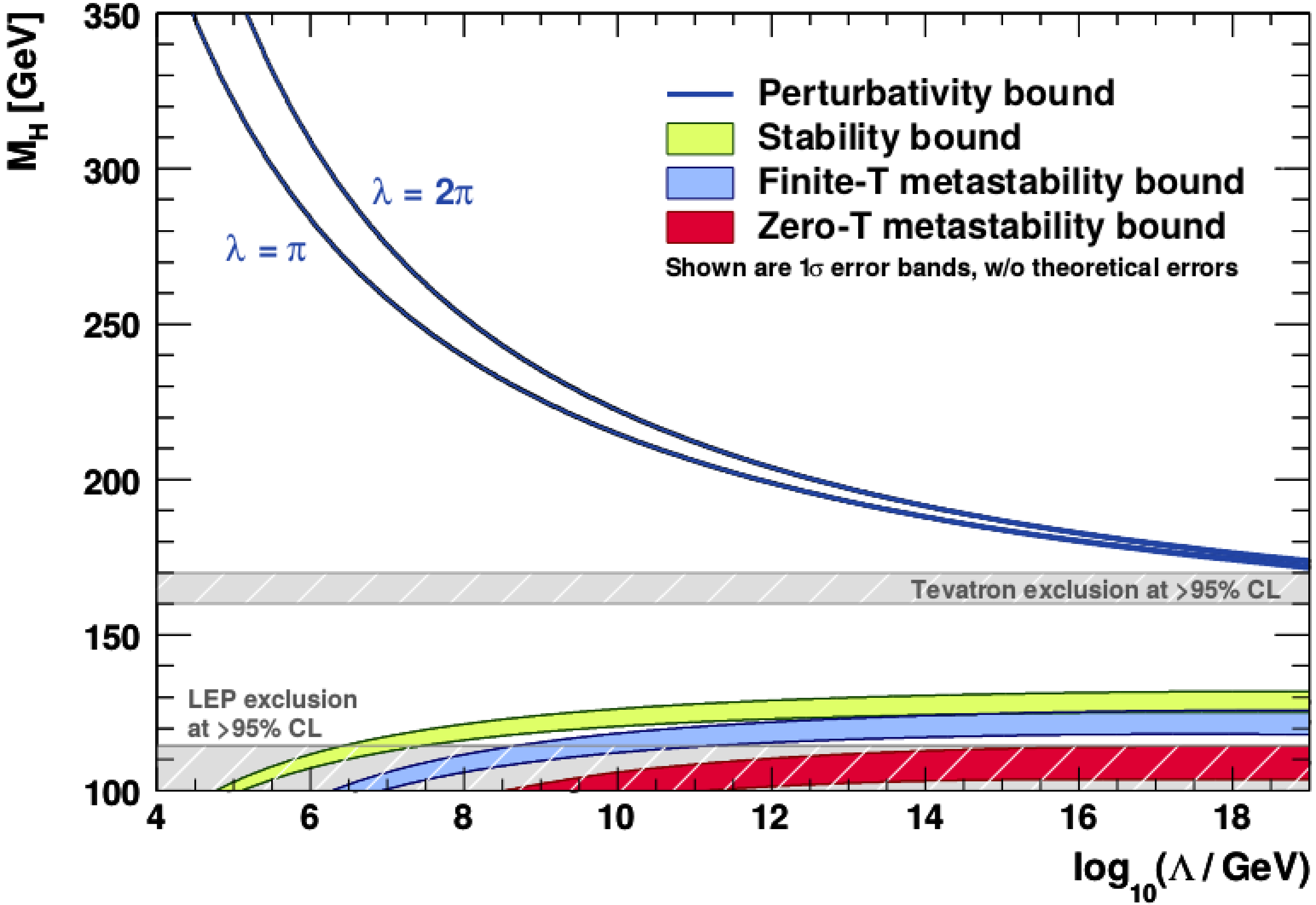
$$\Lambda \to \infty \text{ only for } \lambda = 0$$

Instabilities of the Higgs potential

Is it possible to extrapolate the SM up to high energy scales without reaching the instability, a singularity or the perturbativity bounds?

(Ellis et al ‘09)

Two loop calculation of the RGE of the Higgs quartic coupling

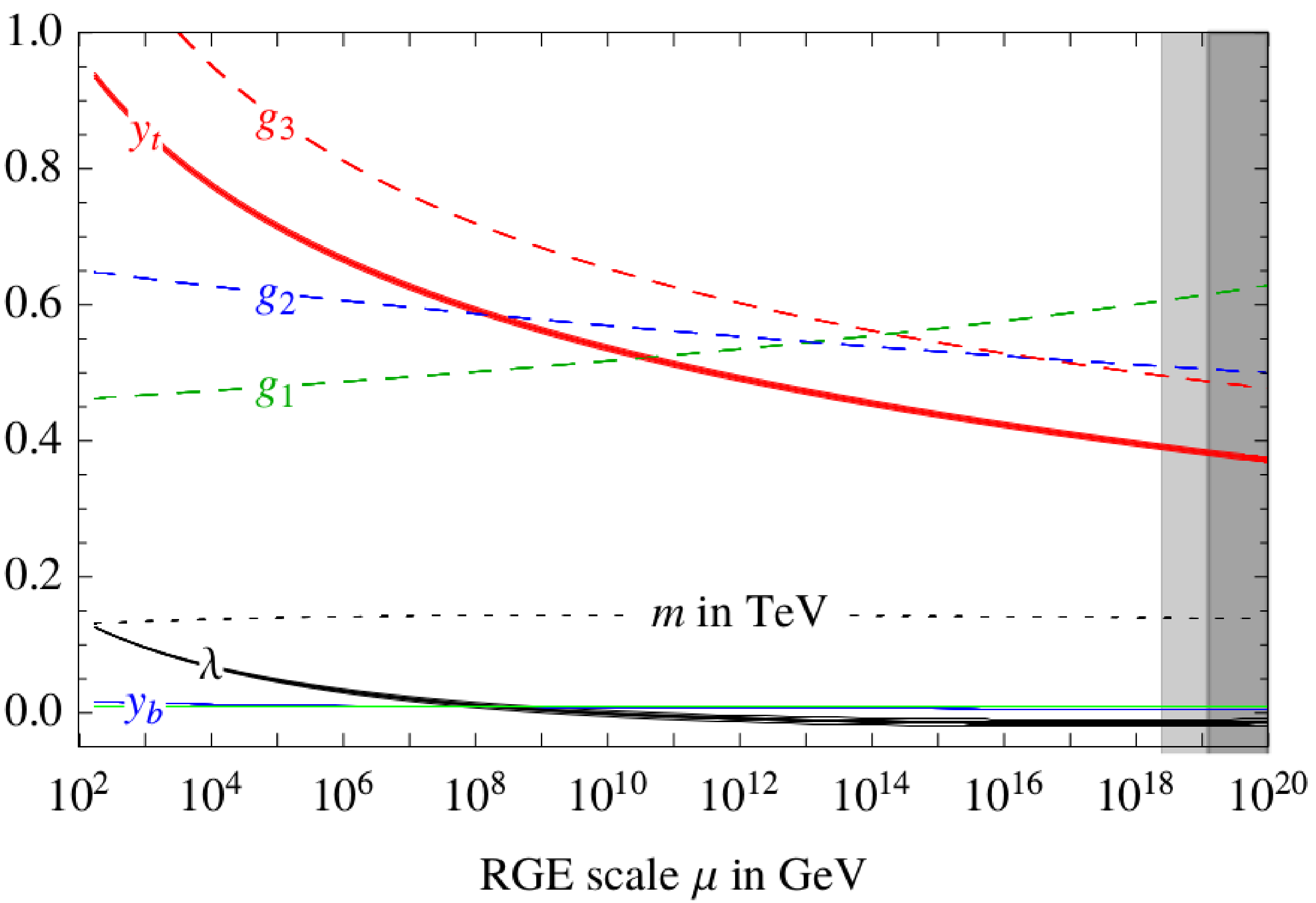


Instabilities of the Higgs potential

Is it possible to extrapolate the SM up to high energy scales without reaching the instability or the perturbativity bounds?

(Strumia et al '13)

Three loop calculation of the RGE of the SM couplings, for m_h=125GeV



Vanishing quartic coupling as boundary condition at M_{Pl} ?

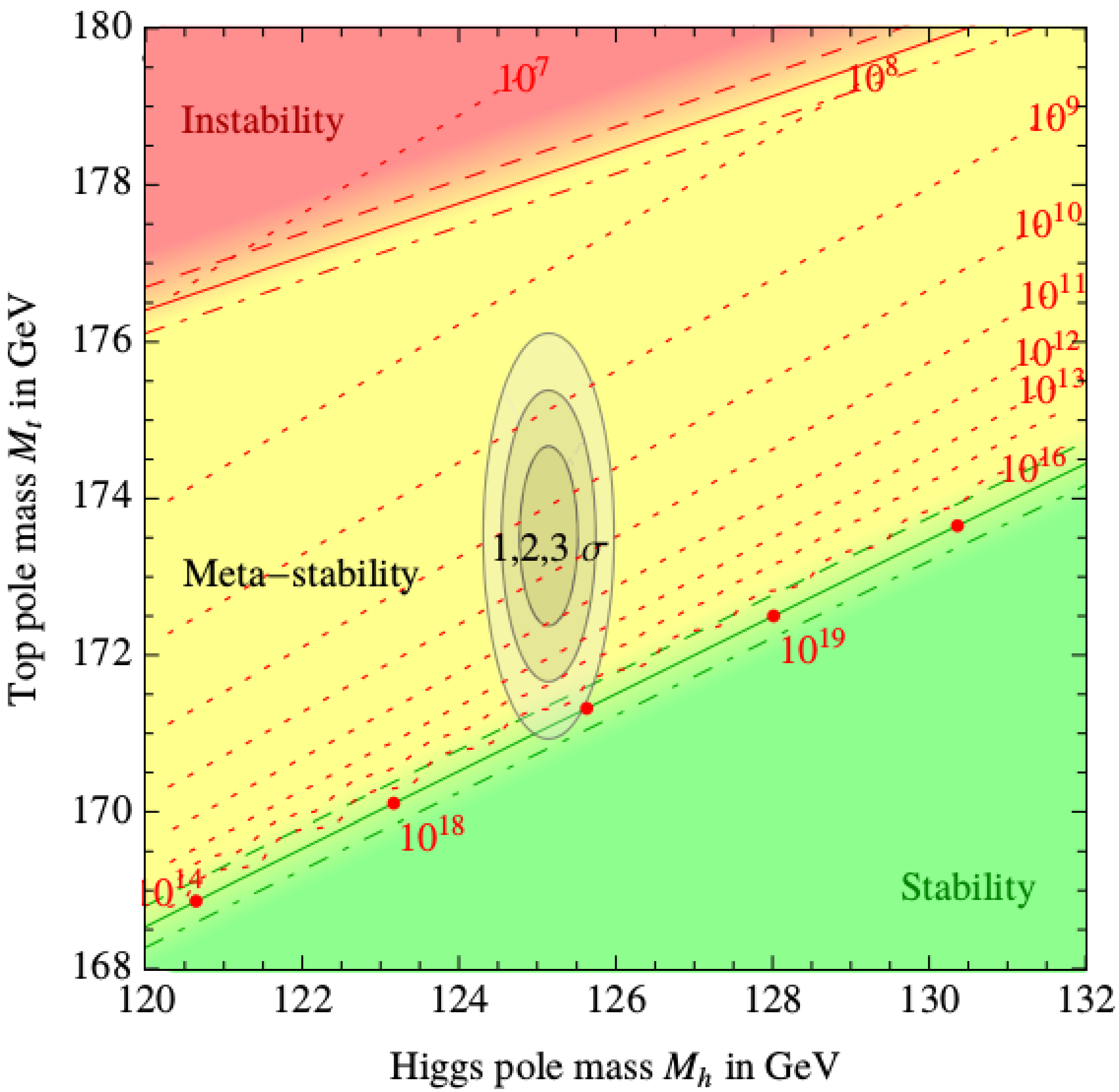
Not well motivated, it is not a fixed point, neither an enhanced symmetry point.

Instabilities of the Higgs potential

Is it possible to extrapolate the SM up to high energy scales without reaching the instability or the perturbativity bounds?

(Strumia et al '13)

Are we living in a Metastable universe?



The Higgs boson and BSM

BSM

The SM Higgs potential is just a “good” parameterization

- It does not explain the origin of EWSB
- It suffers the Planck-Weak hierarchy problem and instabilities

Other parameterizations are also possible

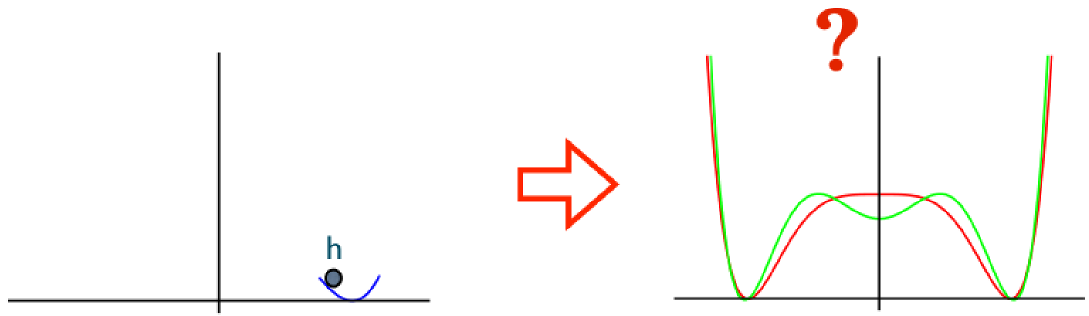
$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3$$

$$V(h) \to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

Different underlying dynamics.

Implications for naturalness and the structure of the QFT

(Arkani-Hamed et al ‘15)



BSM: naturalness and symmetries

- The SM Higgs is an elementary scalar field, it is the only scalar of the SM
- Scalars suffer UV quadratic sensitivity, why the Higgs mass is small (<< M_{Pl})?
- Naturalness (‘t Hooft): a physical parameter is allowed to be small only if its replacement by zero would increase the symmetry of the system
- Is there a symmetry in the limit of zero mass?

→ Vector fields: for zero mass → gauge symmetry

$$\delta A_\mu^a = \partial_\mu \theta^a + f^{abc} A_\mu^b \theta^c$$

thus no mass if the gauge symmetry is preserved.

→ Fermion fields: for zero mass → chiral symmetry

$$\delta \psi_Q^n = i \theta^a T_{nm}^a \psi_Q^m \quad , \quad Q = L, R$$

with different angles for different chiralities, thus no mass if the chiral symmetry is preserved.

→ Scalar fields: no new symmetry for vanishing mass ⇒ A light scalar is not natural

BSM: flavor and naturalness

- The hierarchy problem deals with the separation of scales: $\Lambda_{UV} >> \Lambda_{IR}$

  Implicit idea that: E-dependence of physical quantities is small for $\Lambda_{IR} < E < \Lambda_{UV}$

  ↳ approximate scale (and conformal) invariance

- Thus assume that the E-scaling is driven by the dimension of the operators Δ

$$\mathcal{L} = c\ \Lambda_{UV}^{4-\Delta}\ \mathcal{O} \Rightarrow \text{ an } IR \text{ scale is generated: } \Lambda_{IR} = c^{1/(4-\Delta)}\Lambda_{UV}$$

A hierarchy can be generated if:

(Rattazzi et al ‘08)

- c hierarchically small $\Rightarrow$ fine tuning (or symmetry)
- $(4-\Delta)$ algebraically small $\Rightarrow$ spans $(4-\Delta)$ orders of magn., ex : 0.1 spans 10 oom

- Ex: an elementary scalar field as the SM Higgs dimension Δ=1
- Ex: Higgs mass operator in the SM has dimension Δ=2, thus **no natural separation!**
- Ex: for a composite Higgs, if the mass op. has dimension Δ=4+ϵ, **natural separation!**

BSM: flavor and naturalness

Yukawa interactions

Call $\mathcal{O}_H$ the composite operator that excites a Higgs from the vacuum $\langle 0|\mathcal{O}_H|h\rangle \neq 0$

consider elementary fermions interacting with the composite Higgs:

$$\mathcal{L} = \frac{\omega_y}{\Lambda_{UV}^{\Delta-1}}\ \bar{q}_L\ \mathcal{O}_H\ q_R \Rightarrow \text{ at low energies: } y = \omega_y \left(\frac{\Lambda_{IR}}{\Lambda_{UV}}\right)^{\Delta-1}$$

- small masses for $\Delta > 1$
- top mass requires $y \sim \mathcal{O}(1)$: $\begin{cases} \bullet\ \Lambda_{UV} \sim \Lambda_{IR} = \text{TeV} \Rightarrow \text{ no separation of scales} \\ \bullet\ \Delta \simeq 1 \Rightarrow \text{ hierarchy problem recovered for Higgs mass} \end{cases}$

4-fermion interactions

We expect higher dimensional operators suppressed by the same scale

$$\mathcal{L} = \frac{c_{ijk\ell}}{\Lambda_{UV}^2}\ \overline{(}\bar{q}^i q^j)(\bar{q}^k q^\ell)$$

$$\begin{cases} \bullet\ \text{if}: \Lambda_{IR} \sim \Lambda_{UV} \Rightarrow \text{ incompatible with flavor bounds} \\ \bullet\ \Delta \simeq 1\ \&\ \Lambda_{UV} \gtrsim 10^{4\div5}\ \text{TeV} \Rightarrow \text{ back to SM}-\text{like}: \text{ flavor solved} \end{cases}$$

→ Unless the coefficients c_{ijkl} are not generic

BSM: symmetries

Stabilize the Higgs potential by making use of symmetries

- Supersymmetry: each bosonic d.o.f. is associated to a fermionic d.o.f.

  the chiral symmetry protecting fermion masses could also protect the Higgs mass
  embed the Higgs field in a chiral multiplet transforming under susy

- Gauge symmetry: if the Higgs is somehow associated to a gauge field

  the gauge sym. protecting the vector mass could also protect the Higgs mass
  embed the Higgs into a gauge multiplet …

  Ex: 1 extra-dimension $\rightarrow A_M=(A_\mu,A_5)$, M=0,1,2,3,5

  under 4-dimensional Lorentz transformations: $\begin{cases} A_\mu \text{ is a 4-vector} \\ A_5 \text{ is a scalar} \end{cases}$

- Global symmetry: if the Higgs is a NGB of a spontaneously broken symmetry

  vanishing potential, only derivative interactions

BSM: symmetries

Stabilize the Higgs potential by making use of symmetries

Conformal symmetry: includes scale invariance → no dimensional coefficients

↳ conformal symmetry forbids masses

but running of couplings break conformal symmetry

a possibility: conformal symmetry softly broken at low energies

Ghost symmetry: a “ghost” with oposite statistics (same spin) associated to each SM field

the wrong statistics allows to stabilize radiative corrections

however microscopic causality violation is present (Lee-Wick)

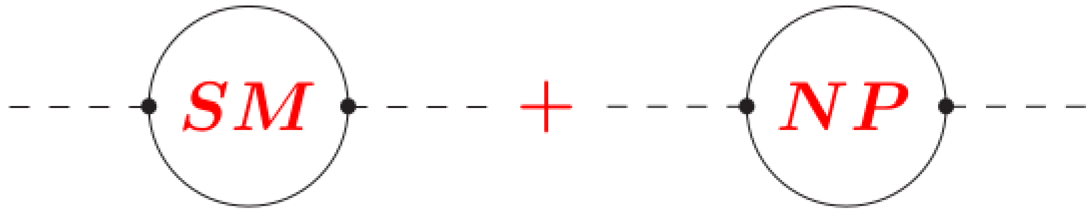
could be tested by wrong vertex displacements (Alvarez et al ‘10)

These symmetries must be broken to generate a Higgs mass

↳ but in a soft way to avoid desestabilizing the potential

BSM: solving quadratic divergence

Quadratic divergent contributions from loops cut-off by new states



$$a_{SM}\frac{g_{SM}^2}{(4\pi)^2}\Lambda^2 \qquad a_{NP}\frac{g_{NP}^2}{(4\pi)^2}\Lambda^2 \Rightarrow (a_{SM}g_{SM}^2 + a_{NP}g_{NP}^2)\frac{1}{(4\pi)^2}\Lambda^2$$

Cancellation of the divergencies require non-trivial relations ⇒ **Symmetries**

- Ex: supersymmetry → fermions & bosons are related, opposite signs in loop
- Ex: Little Higgs → cancellation by particles of same species
- Ex: higher dimensional gauge symmetry → cancellation by infinite towers of excitations (KK-states associated to each SM field)
- Ex: pions of QCD → cancellation by towers of resonances (simil KK-states), in effective theory with integrated resonances → form-factors
- Ex: Lee-Wick → cancellation by “physical Pauli-Vilars regulators”, with same spin but opposite statistics

BSM: quartic coupling

The quartic coupling can
- become negative and destabilize the potential
- reach a singular point

Symmetries can stabilize the quartic coupling

- Ex: supersymmetry → the quartic is related to EW gauge couplings and to Yukawa couplings, thus it can inherit good UV properties of these couplings.

- Ex: higher dimensional gauge symmetry → the quartic coupling is related with the gauge coupling arising from the higher dim. gauge symmetry

$$\lambda \sim g^2$$

It can inherit good UV behavior of gauge couplings

Susy

MSSM: the minimal supersymmetric SM

↳ one of the most natural extensions of the SM

(Hall et al '11)

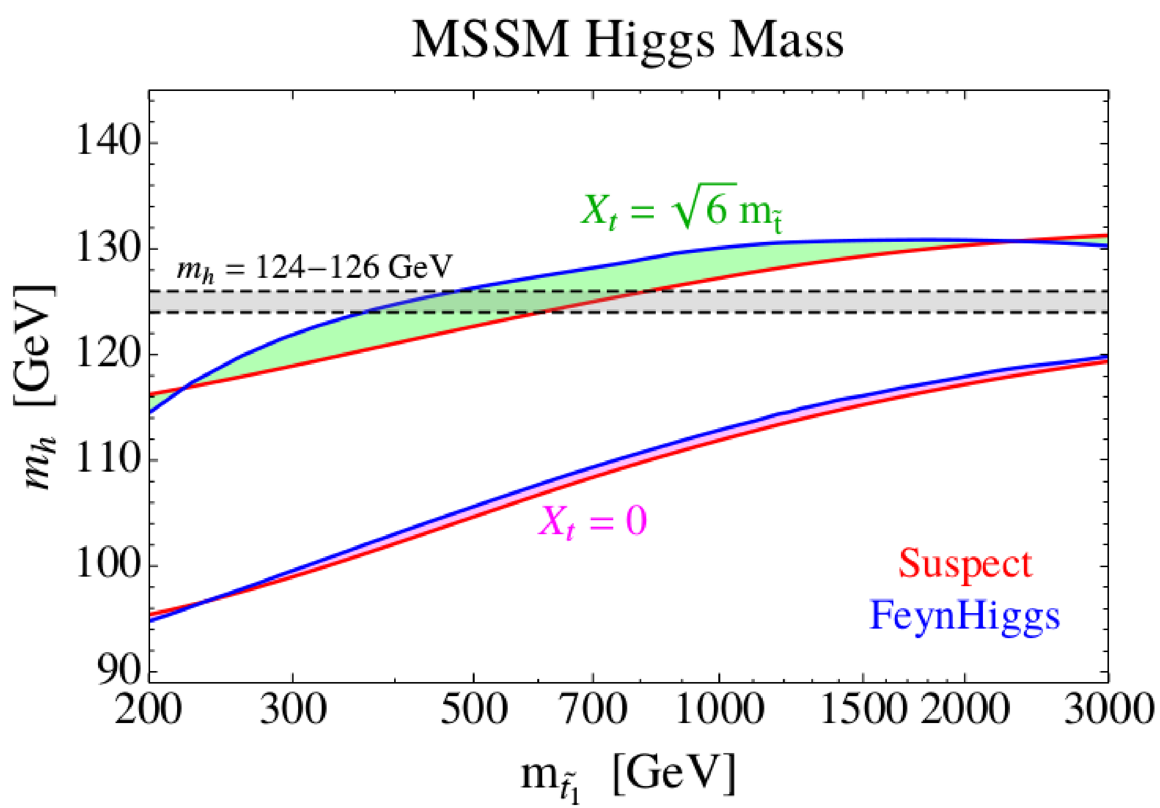
The Higgs mass is predicted as function of the stop masses and mixing, and tanβ

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde t}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde t}^2}\right)\right]$$

tree-level

1-loop level

For large tanβ: large loop contribution required = (87 GeV)^2

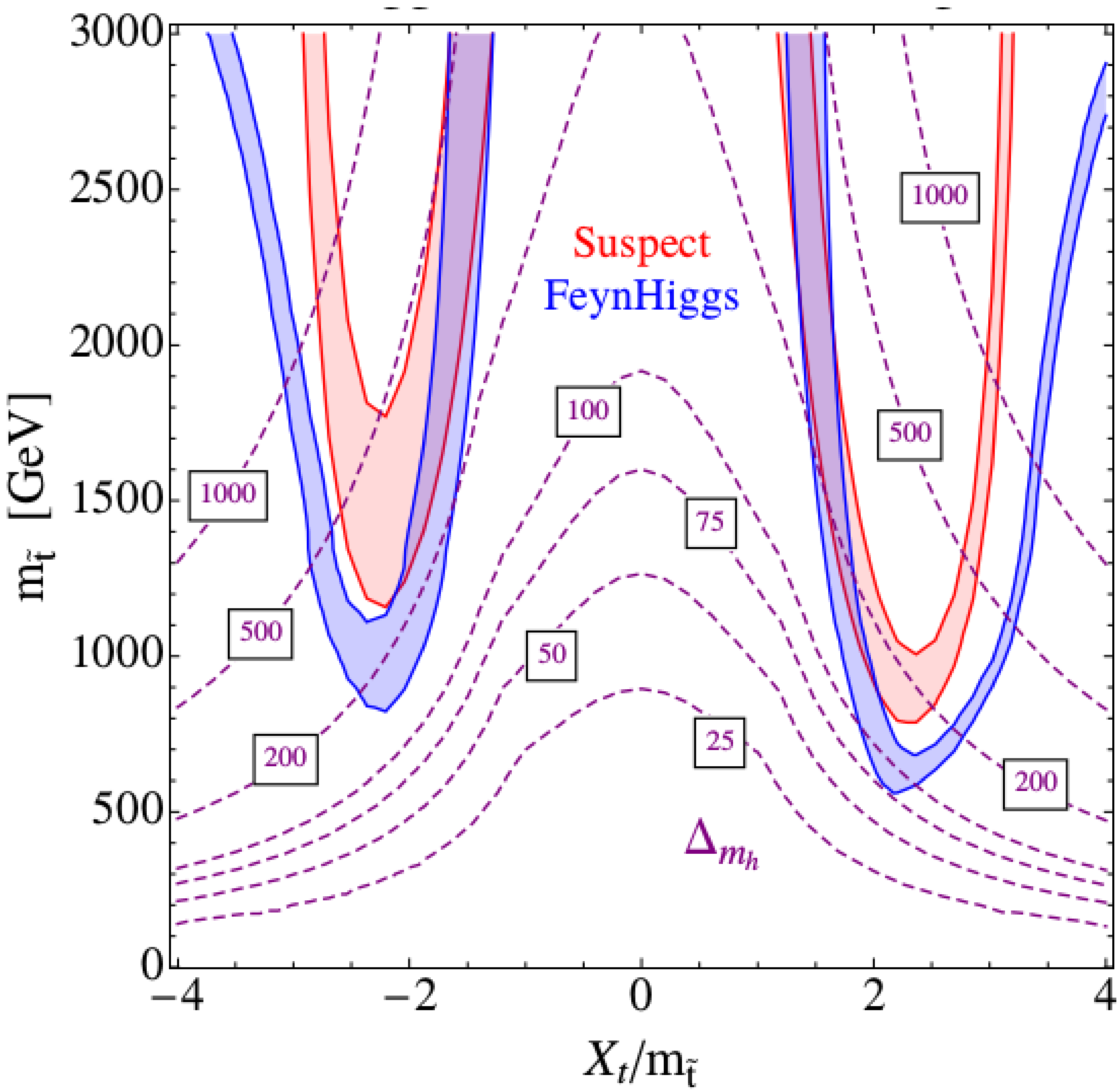


Even for large stop mixing m_h =125GeV, drives the MSSM to a corner of the parameter space

fine-tuning

Susy

MSSM
fine-tuning ~ 1%



(Hall et al '11)

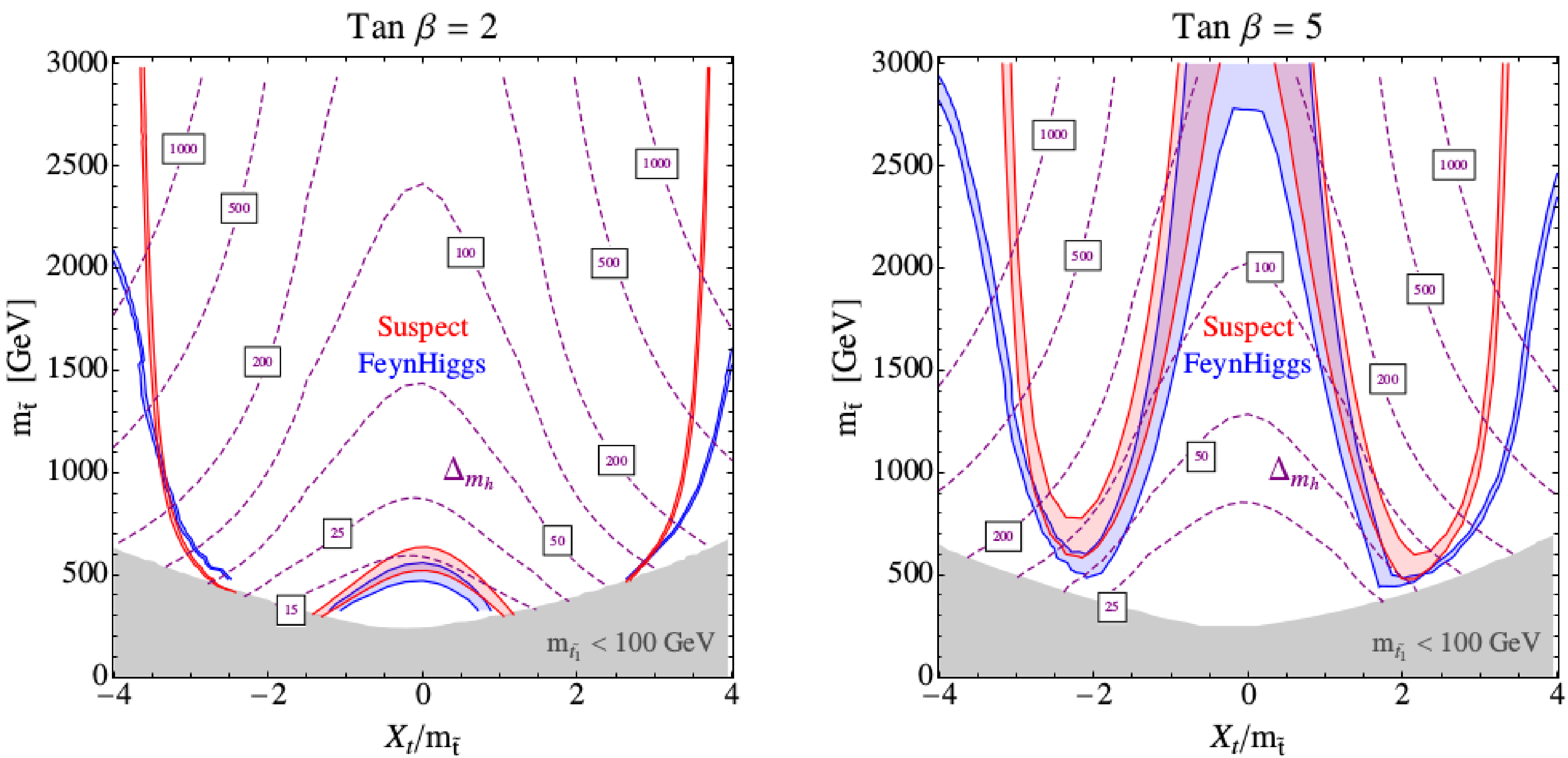
Susy

Simple extensions can relax the tuning significantly: **NMSSM**

New contribution

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

MSSM 1-loop contrib



(Hall et al '11)

tuning can be of order 7%

After 125GeV Higgs, susy still gives a natural extension of the SM

although not in its minimal version

Composite Higgs

BSM: composite Higgs

- Why should the Higgs be a composite state?
- Higgs compositeness would immediately mean **new particles and interactions**
  - ↳ the microscopic degrees of freedom and dynamics producing bound states
- We will show that Higgs compositeness can solve the EW-Planck hierarchy pbm
- There are other problems associated to the elementary nature of the Higgs:

  Instabilitiy of the Higgs potential

  Dynamical origin of EW symmetry breaking

  Origin of fermionic hierarchical spectrum and mixing

  Flavor problem of BSM: too much flavor violation in abscence of flavor sym

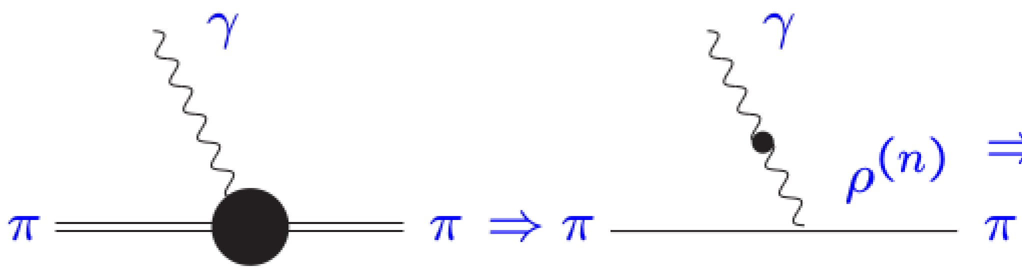
  ...

↳ Some of them can be easily solved if the Higgs is a composite state of new dynamics

BSM: composite Higgs

- Microscopic constituents of the Higgs could be out of reach ever
  - however it could be possible to measure its properties
  - probe the new dynamics with external sources: the SM states

- Form factors expected (simil to DIS)



$$\Rightarrow \mathcal{F}_\pi(\mathrm{p}) = \sum_\mathrm{n} \mathrm{g}_{\mathrm{V_n}\pi\pi} \frac{\mathrm{M_{V_n} F_{V_n}}}{\mathrm{p}^2 + \mathrm{M}^2_{\mathrm{V_n}}}$$

(with the equivalence obtained in a large N limit)

Anomalous couplings expected (LHC accuracy of order 10%)

BSM: composite Higgs

Soft breaking of the symmetries is required to keep the good properties protecting the Higgs potential

Ex: pions of QCD ⟶ pseudo-NGB

QCD: global symmetry $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\pi^{\pm}, \pi^0$ are Goldstones associated to spontantenous breaking

- $g, g' \to 0 \qquad m_q \to 0 \Rightarrow m_\pi = 0$
- $m_q \neq 0 \Rightarrow m_\pi^2 \simeq m_q B_0$

$e \neq 0 \Rightarrow m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda_{QCD}^2$

Idea: H= a pseudo GB (composite of a new strong sector)

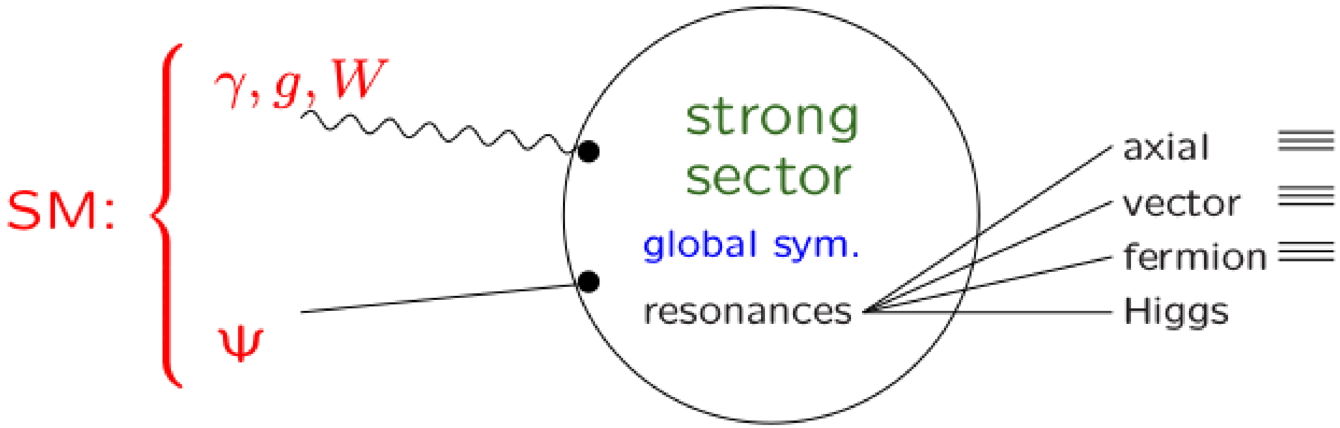
(Georgi,Kaplan'84)

Problem: how to compute in a strongly int. theory + EWPT

BSM: composite Higgs

Soft breaking of the symmetries is required to keep the good properties protecting the Higgs potential

Ex: EW sector



$$\mathcal{L} = \mathcal{L}_{SM} + W_\mu J^W_\mu + B_\mu J^B_\mu + \lambda_\psi \bar{\psi} \mathcal{O}_\psi + \mathcal{L}_{CFT}$$

pattern of symmetry breaking: $G \underset{f_\pi}{\longrightarrow} F$ by the strong sector

pseudo Goldstone Higgs: $H \in \frac{G}{F}$

Higgs potential: SM gauging and fermions explicitly break the sym → V(H)

BSM: Minimal Composite Higgs Model (MCHM)

Soft breaking of the symmetries is required to keep the good properties protecting the Higgs potential

Ex: choosing the symmetries

* ex 1: $H = \frac{SU(3)}{SU(2)_L \times U(1)_Y}$, Higgs = complex doublet

* ex 2: $H = \frac{SO(5)}{SO(4)}$, Higgs = (2,2) of $SU(2)_L \times SU(2)_R$

$\Rightarrow$ contains custodial symmetry of SM ($SU(2)_L \times SU(2)_R \sim SO(4)$)

Pattern of Symmetry breaking

(Agashe et al '04)

gauge: $SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$

$\uparrow$ $\uparrow$

global: $SO(5) \rightarrow SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ custodial

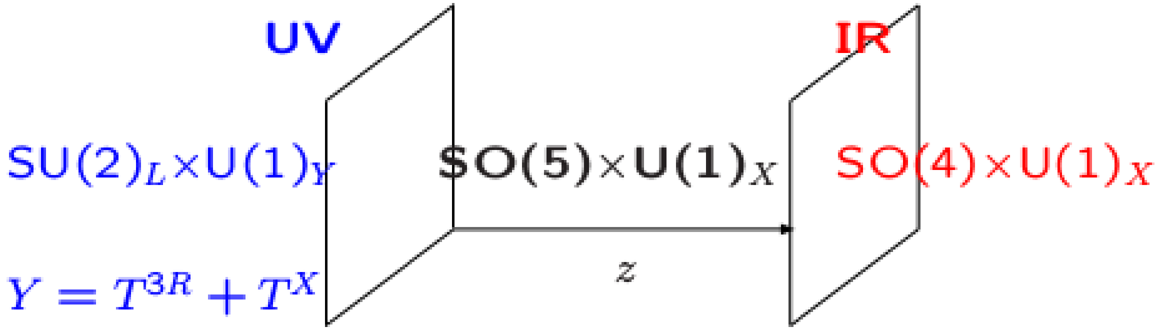
$E \sim f_\pi$ $E \sim v$

BSM: MCHM

Soft breaking of the symmetries is required to keep the good properties protecting the Higgs potential

(Agashe et al ‘04)

Ex: a realization in 5D, warping in AdS allows to solve EW-Planck hierarchy problem



Symmetries:

- breaking by IR bound. cond $\Rightarrow$ $A_5 = GB$ Higgs quantum numbers
- breaking by UV bound. cond. $\Rightarrow$ potential for A_5
- non-local breaking in 5D $\Rightarrow$ finite calculable potential

Fermions:

- for every SM fermion $\Rightarrow$ a full 5D fermion
- choose representations for fermions: ex: $\psi_{5D} = 10_{2/3}$
- V(H) and 4D fermion masses depending on M_ψ^{5D}

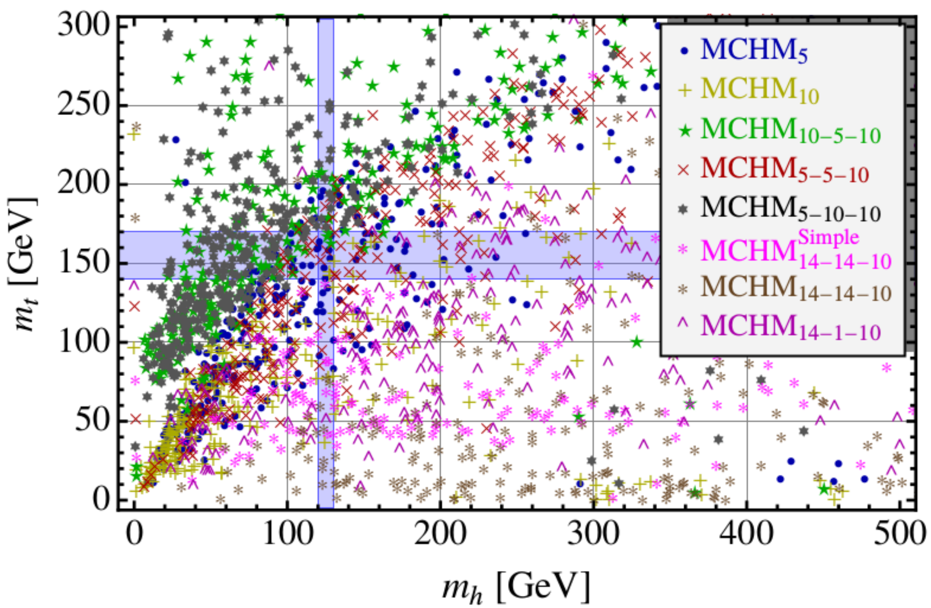
The Higgs mass in the MCHM

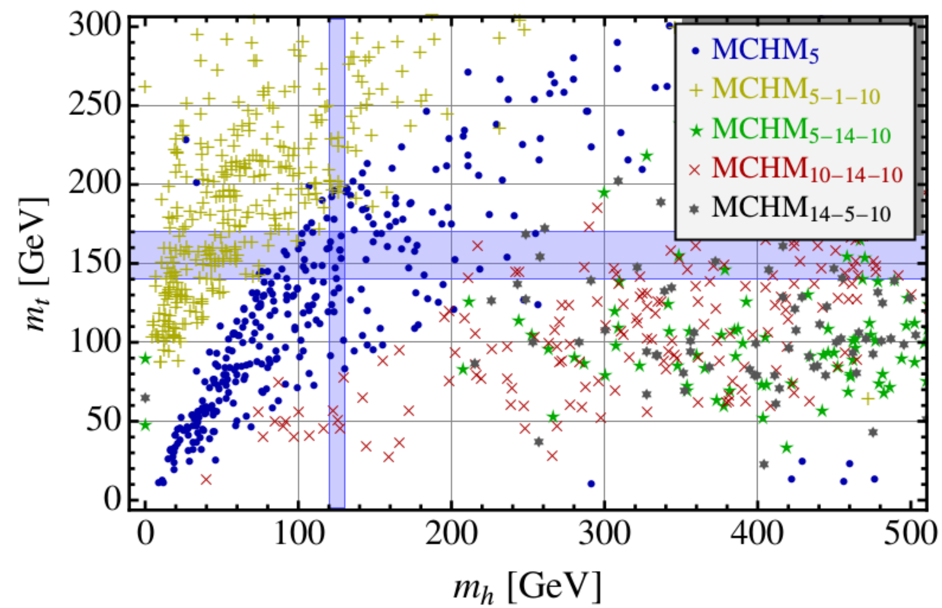
At 1-loop the Higgs potential is finite and calculable

Using the holographic technique (int-out heavy NP states) the Coleman-Weinberg potential is

$$V(h) = \int \frac{d^4p}{(2\pi)^4} \left[\frac{6}{2} \sum_{i=1}^{2} \log \Pi_{w_L^i} + \frac{3}{2} \log \left[\Pi_{w_L^3} \Pi_b - (\Pi_{w_L^3 b})^2 \right] - 2N_c \sum_{\psi} \log[p^2 \Pi_{\psi_L} \Pi_{\psi_R} - |M_\psi|^2] \right] ,$$

EWSB is triggered dynamically, dominated by the top contributions





Deviations in MCHM

Composite sector scale: f of order TeV

Corrections of order $\xi = \epsilon^2 \equiv \frac{v^2}{f^2}$

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 , \qquad \mathcal{O}_{y_f} = |H|^2 \bar{q}_L H f_R ,$$

$$\mathcal{O}_{GG} = |H|^2 G_{\mu\nu} G^{\mu\nu} , \qquad \mathcal{O}_{BB} = |H|^2 B_{\mu\nu} B^{\mu\nu} ,$$

$$\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) D^\nu W^a_{\mu\nu} , \qquad \mathcal{O}_B = \frac{i}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial^\nu B_{\mu\nu} ,$$

$$\mathcal{O}_{HW} = i\left(D^\mu H\right)^\dagger \sigma^a \left(D^\nu H\right) W^a_{\mu\nu} , \qquad \mathcal{O}_{HB} = i\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu} .$$

$$c_H = 1 ; \qquad c_W = c_B = \frac{27\pi^2}{256} \simeq 1.0$$

$$\begin{cases} c_{y_t} = 1 , & \text{for the MCHM}_{5,\ 10,\ 14-14-10,\ 14-1-10,\ 5-5-10} , \\ c_{y_t} = 0 , & \text{for the MCHM}_{10-5-10,\ 5-10-10} , \end{cases}$$

$$\begin{cases} c_{y_b} = 1 , & \text{for the MCHM}_{5,\ 10,\ 14-14-10,\ 14-1-10,\ 10-5-10} , \\ c_{y_b} = 0 , & \text{for the MCHM}_{5-5-10,\ 5-10-10} . \end{cases}$$

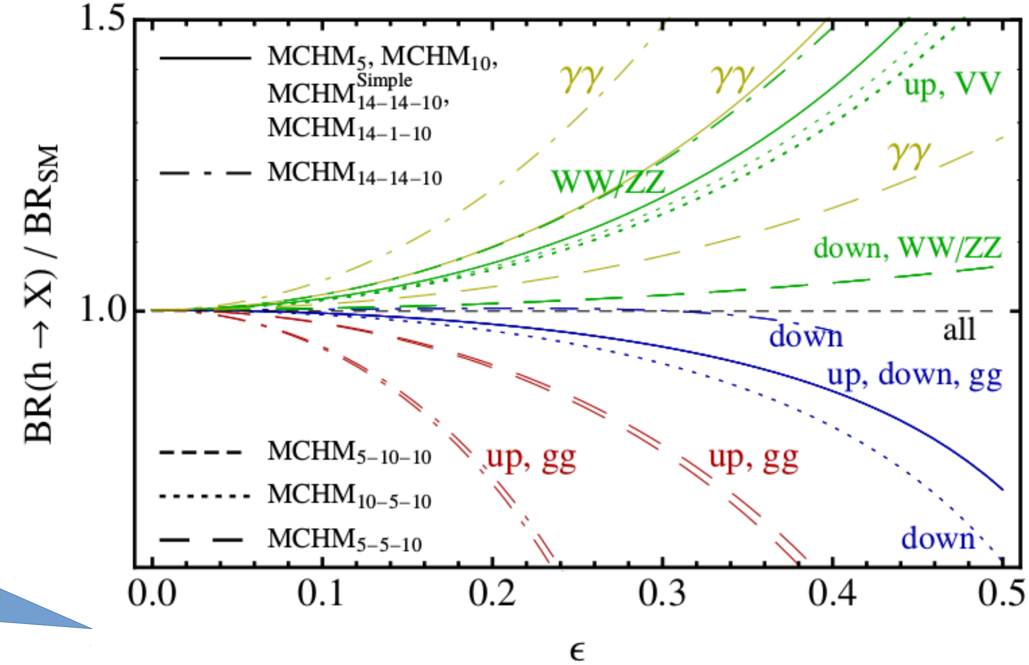
(Carena et al '14)

Deviations in MCHM

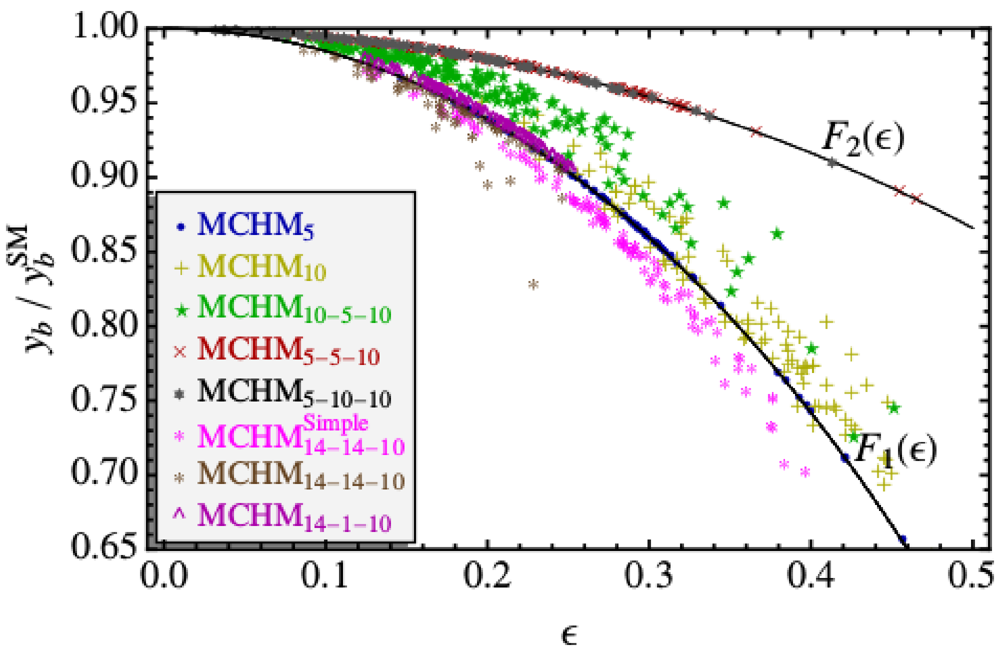
Composite sector scale f of order TeV

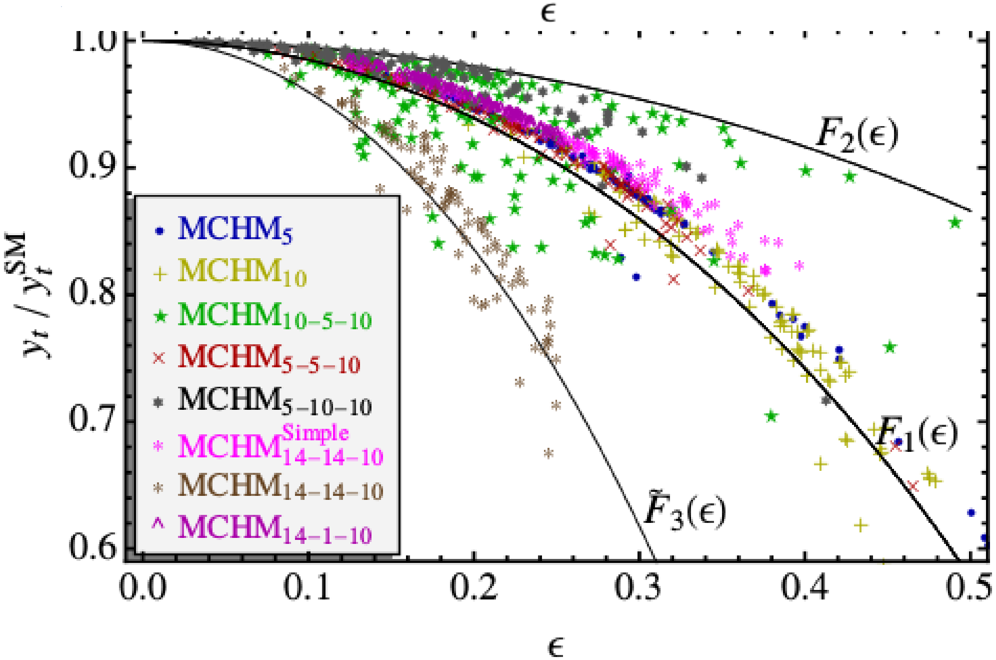
Corrections of order $\xi = \epsilon^2 \equiv \frac{v^2}{f^2}$

Corrections to BR's



Corrections to Yukawa couplings





(Carena et al '14)

Deviations in MCHM: EWPT

Composite sector scale f of order TeV

Corrections of order $\xi = \epsilon^2 \equiv \frac{v^2}{f^2}$

Oblique parameters: S, T, W, Y, … and **Zbb** (Grojean et al '13)

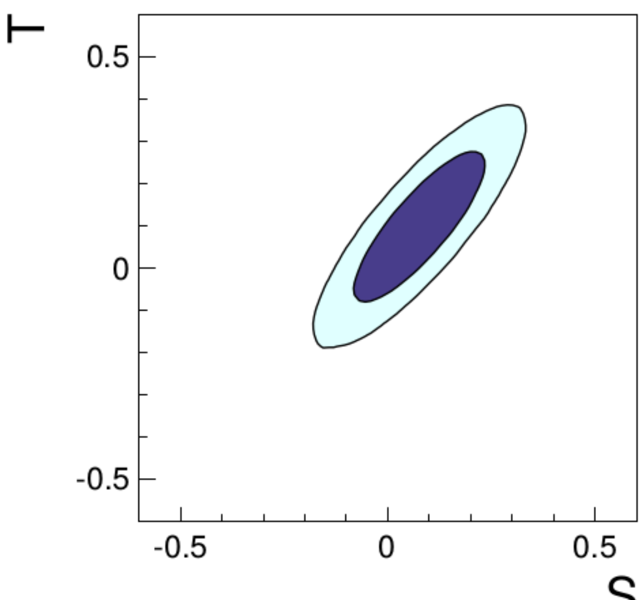
Tree level $\Delta\widehat{S} \simeq \frac{g^2}{g_*^2}\xi \simeq \frac{m_w^2}{m_*^2}$

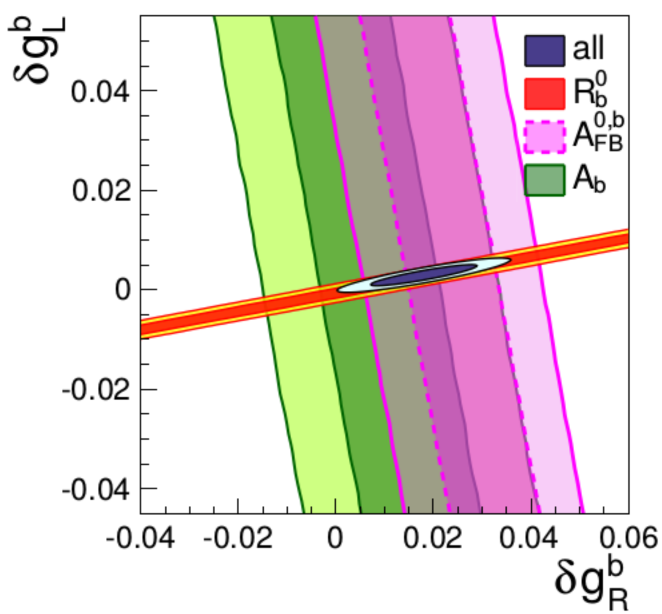
1-loop level $\Delta\widehat{S}^{div}_{ferm} = \frac{g^2}{8\pi^2}(1-2c^2)\,\xi\log\left(\frac{m_*^2}{m_h^2}\right)$

$$\Delta\widehat{T} = -\frac{3g'^2}{64\pi^2}\xi\log\left(\frac{m_*^2}{m_h^2}\right) \simeq -3.8\cdot 10^{-3}\,\xi$$

$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \sim \frac{y_L^2 f^2}{m^2}\frac{m_z^2}{m_*^2} \simeq 8\cdot 10^{-4}\,\frac{f}{m}\left(\frac{4\pi}{g_*}\right)^2\xi$$

$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \simeq \frac{y_L^2}{16\pi^2}\frac{y_L^2 f^2}{m^2}\xi \simeq \frac{y_t^2}{16\pi^2}\xi \simeq 6\cdot 10^{-3}\,\xi$$





$\xi \lesssim 0.1$

Small deviations expected, difficult scenario for BSM

(Silvestrini et al '14)

Light top partners in MCHM

Quadratic divergence cut-off by light resonances

(Contino et al '06, Carena et al '06,Wulzer etal '12)

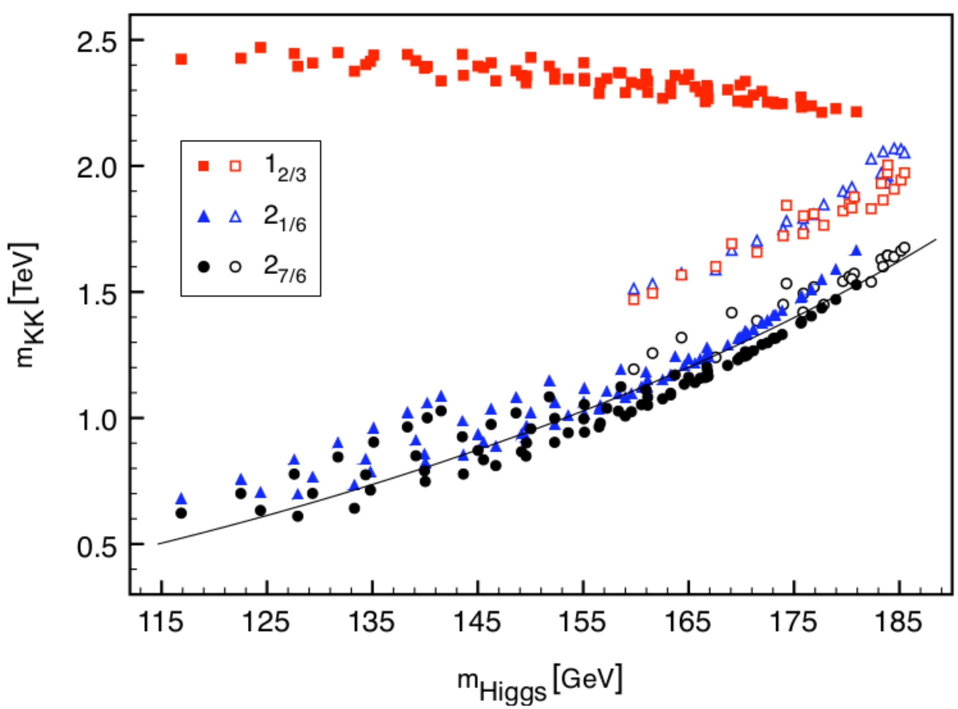
→ light top partners cut-off the top contribution

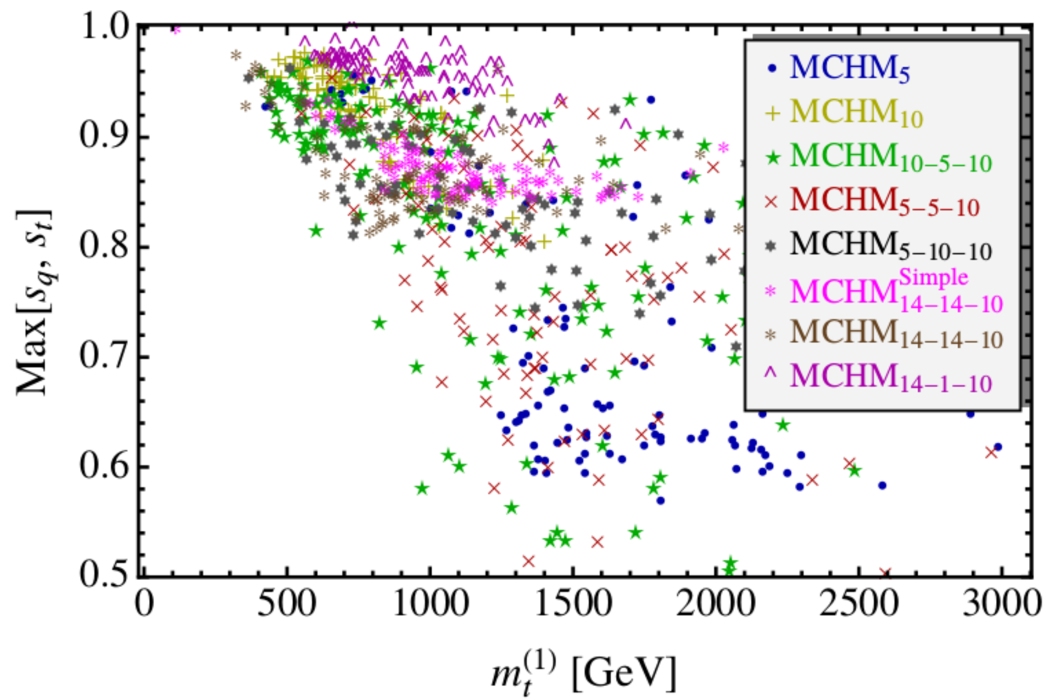
$$m_{q^*} \simeq \Lambda \simeq 900\ \mathrm{GeV} \left(\frac{m_h}{150\ \mathrm{GeV}}\right)\left(\frac{0.5}{\epsilon}\right)$$

$$\frac{m_H}{m_t} \simeq \frac{\sqrt{2N_c}}{\pi}\frac{m_{T_-} m_{\tilde{T}_-}}{f_\pi}\sqrt{\frac{\log\left(m_{T_-}/m_{\tilde{T}_-}\right)}{m_{T_-}^2 - m_{\tilde{T}_-}^2}}$$

Model building: free to choose the representation of the composite fermions under SO(5)

Custodial symmetry for Zbb coupling gives restrictions.

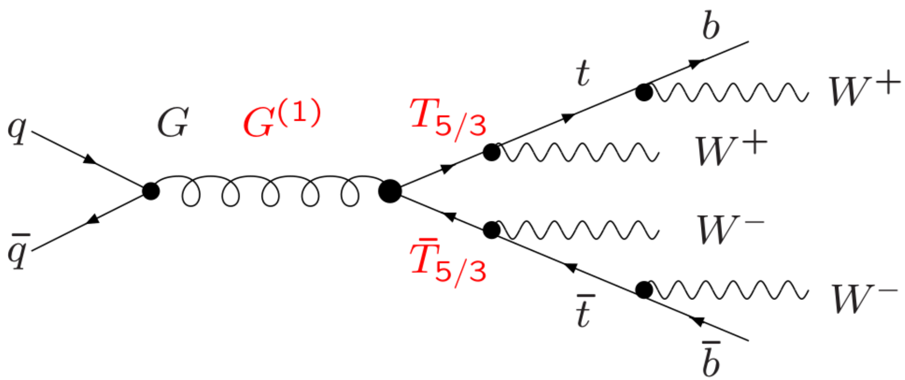


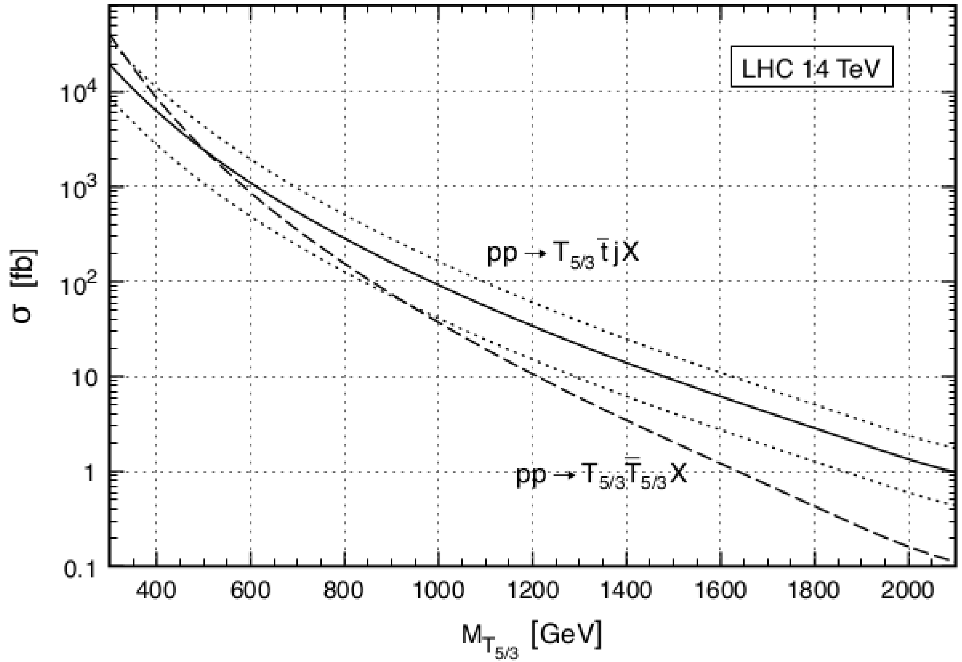


LHC signals of MCHM

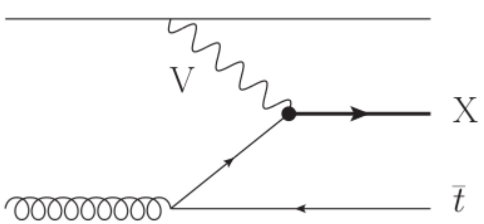
Production of light partners (lightness required for a light Higgs)

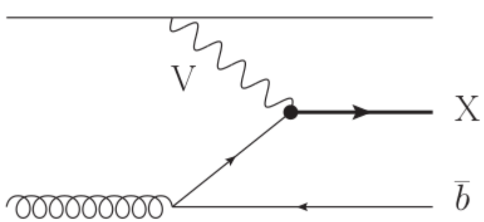
- QCD double production of top-partners (Contino et al '08)
  Best signal: detect the exotic states with charge Q=5/3 (custodians)





- EW single production of top-partners

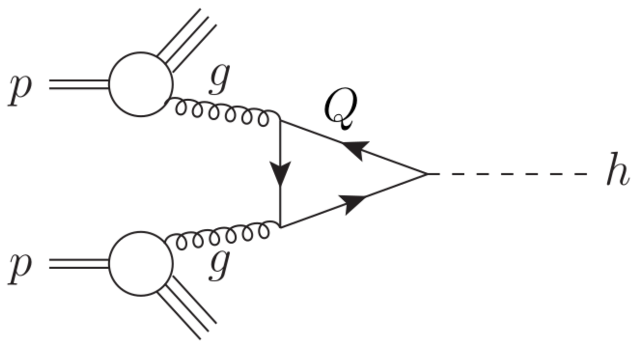




(De Simone et al '08)

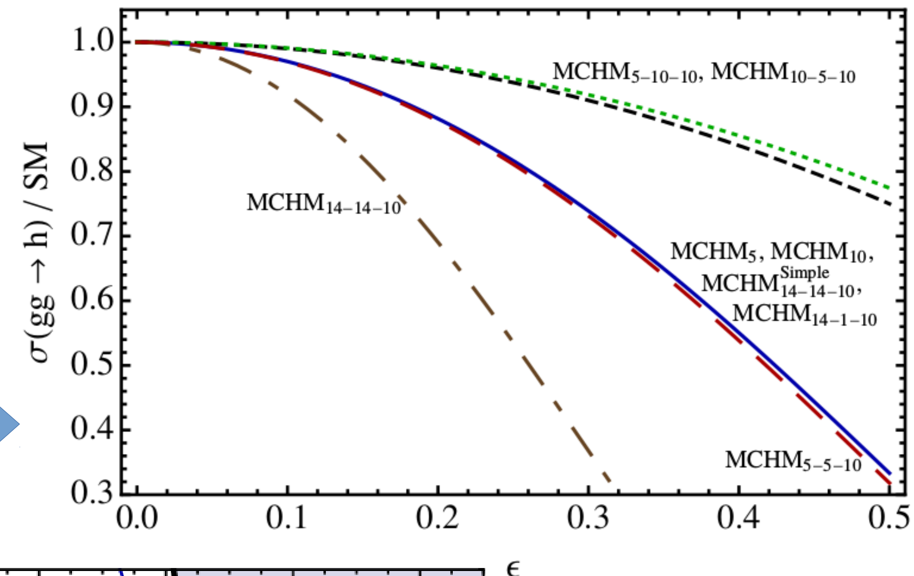
Single Higgs production in MCHM

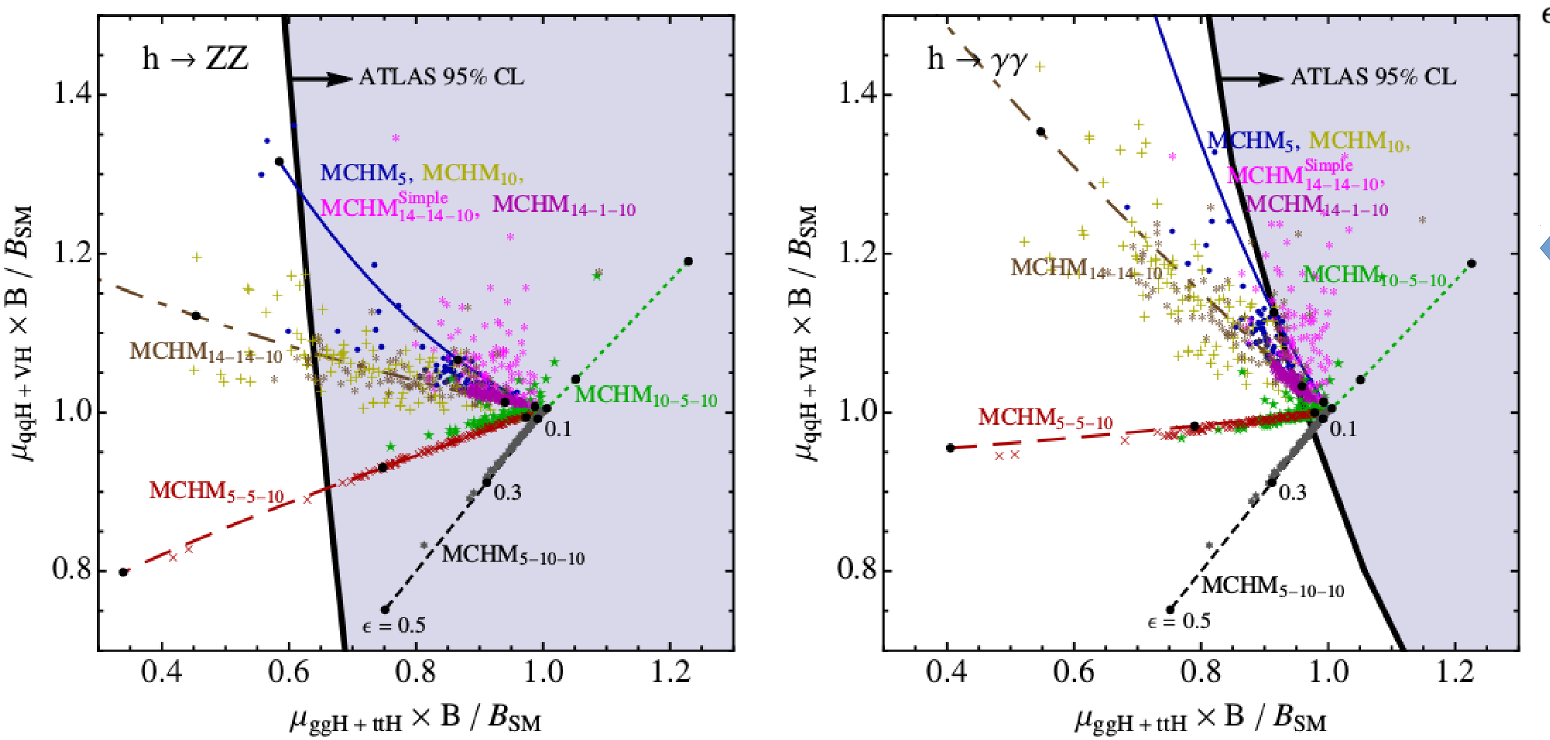
Top partners running in the loops



Correction to gluon fusion production

(Falkowsky '07, Azatov et al '11, Delaunay et al '13, Gillioz et al '14, Carena et al '14)





Corrections to Higgs production in ZZ and γγ

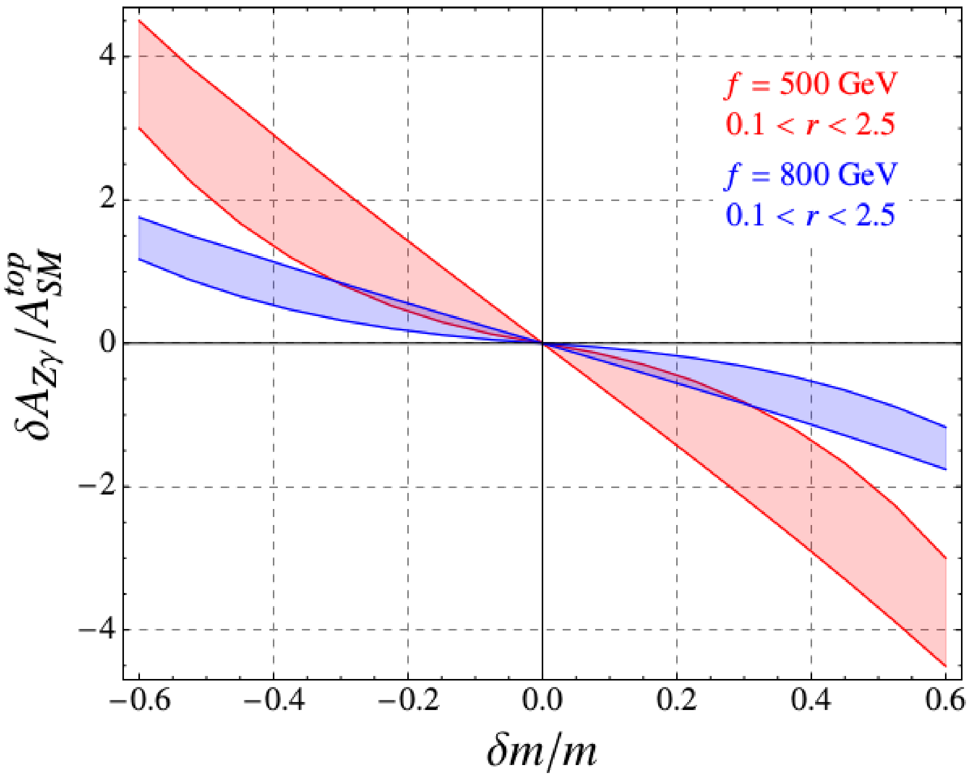
(Carena et al '14)

Single Higgs production in MCHM

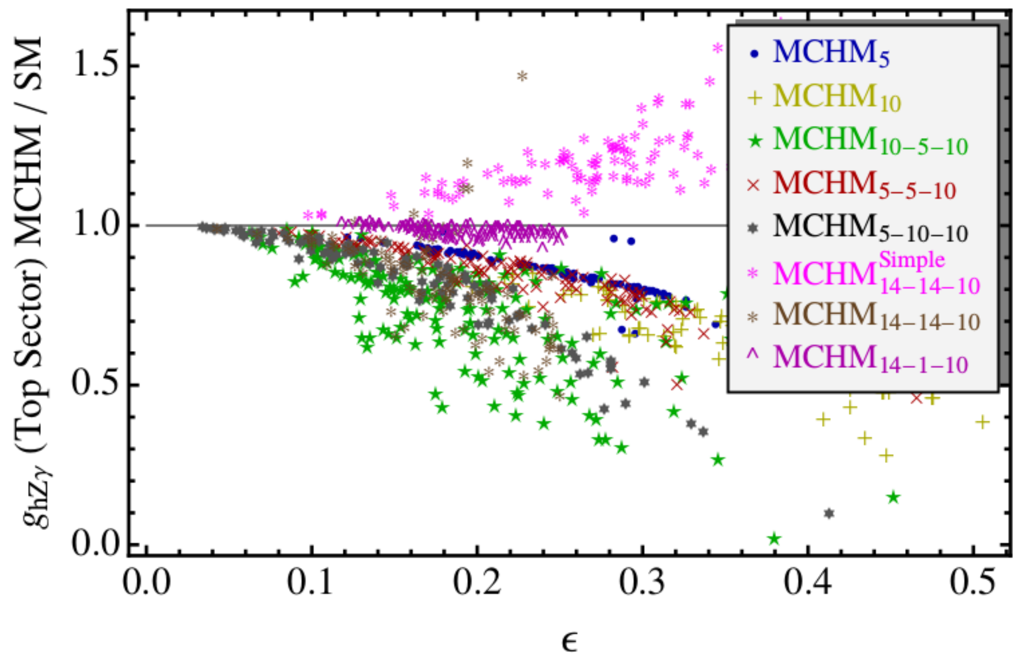
Higgs to Zγ allows different fermions running in the loop

Small deviations if P_{LR} symmetry (protecting Zbb) is present (Azatov et al '13)

Large deviations if P_{LR} symmetry is violated



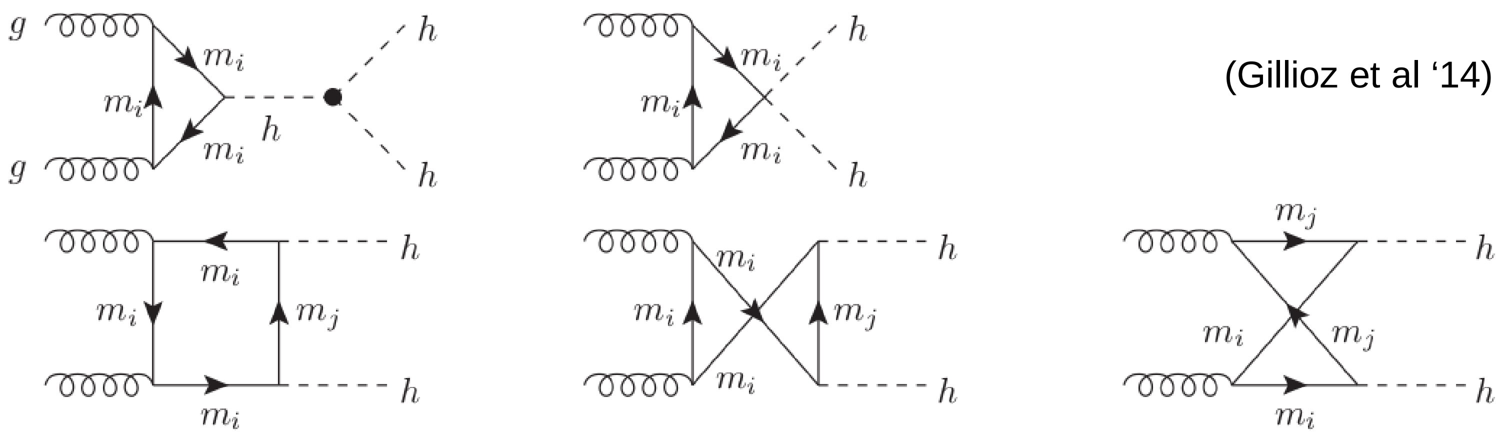
(Azatov et al '13)



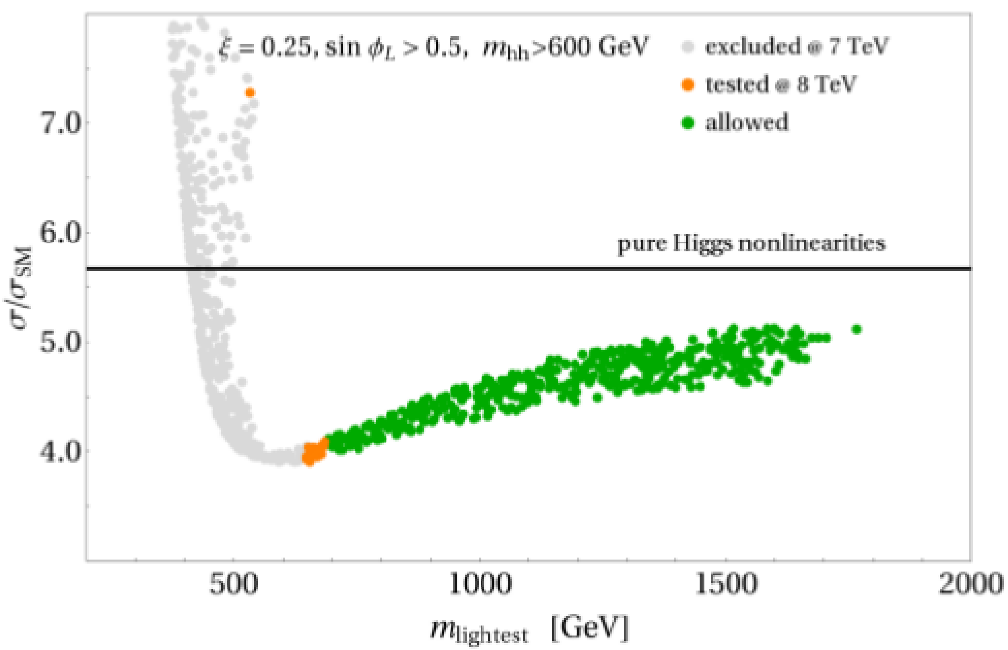
(Carena et al '14)

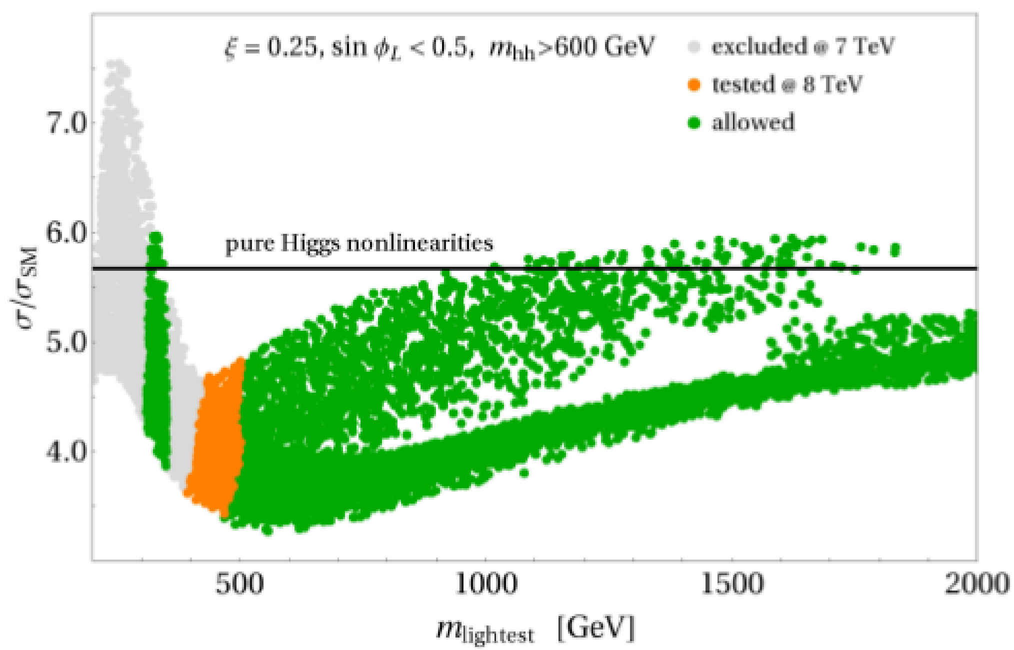
Double Higgs production in MCHM

Top partners running in the loops



(Gillioz et al '14)

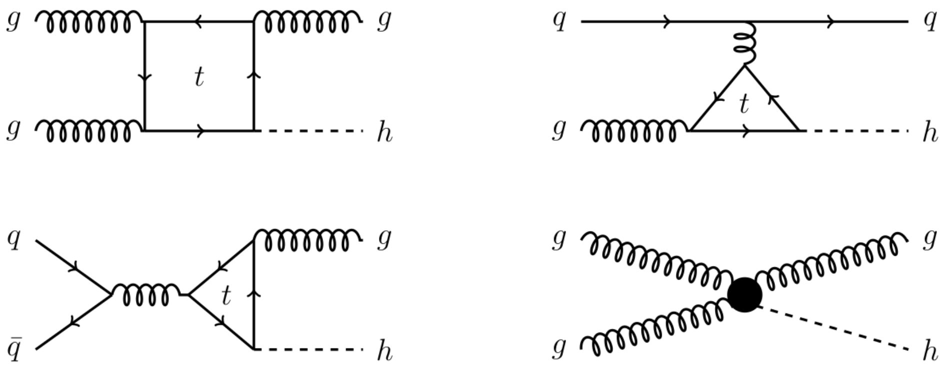


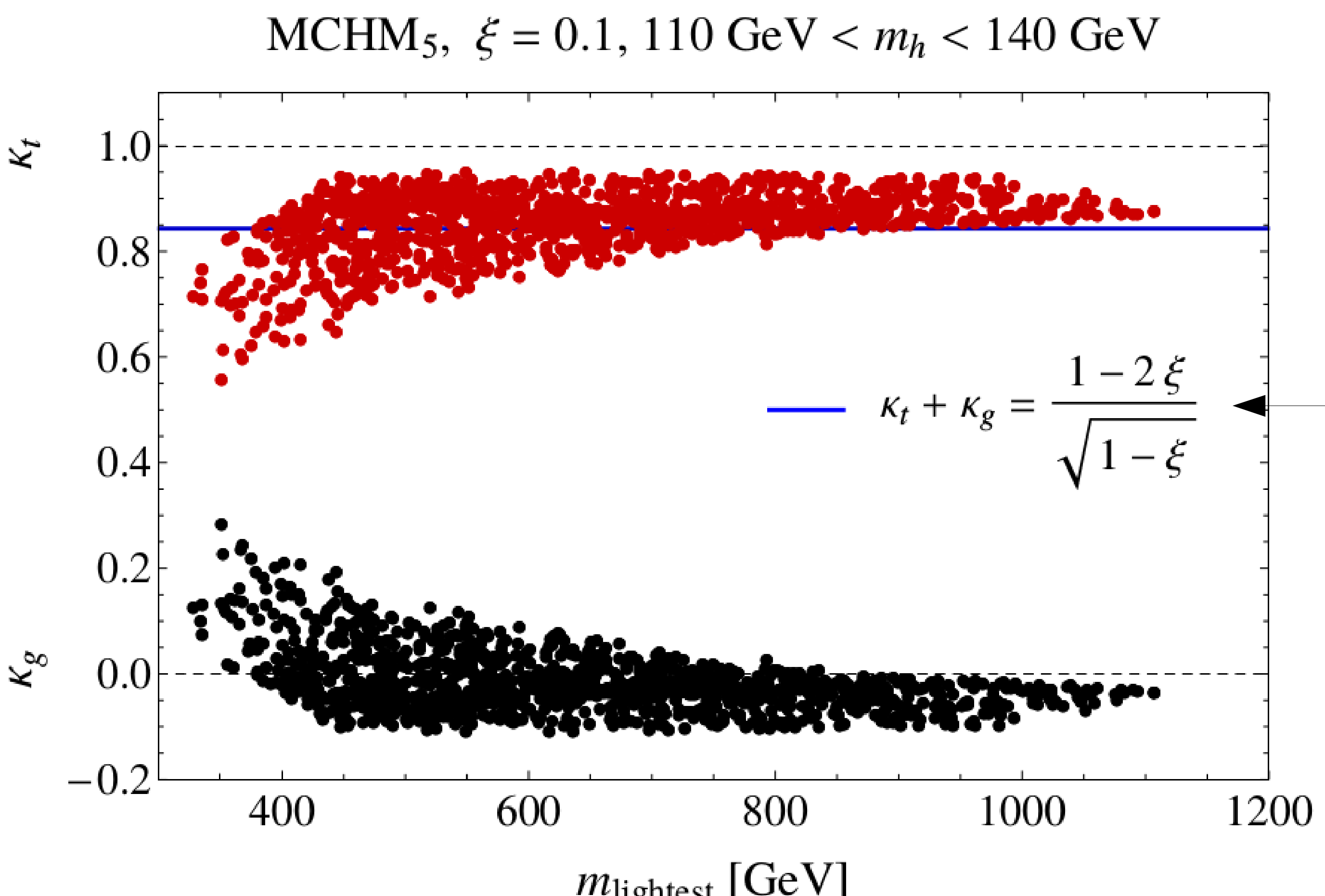


High energy regime: boosted Higgs in MCHM

Disentangling κ_t and κ_g with h+j boosted

Putting a cut p_{Tmin} leads to





In the $MCHM_5$ there is a precise relation between **κ_t and κ_g**

(Grojean et al '13)

BSM: summary of corrections

Expected largest contributions to Higgs couplings

(Pomarol ‘14)

	g^h_{ff}	g^h_{VV}	κ_{GG}	$\kappa_{\gamma\gamma}$	$\kappa_{Z\gamma}$	g_{3h}
MSSM	✓					✓
NMSSM	✓	✓	✓	✓	✓	✓
MCHM	✓	✓			✓	✓
SUSY Composite Higgs	✓	✓				✓
Higgs as a Dilaton			✓	✓	✓	✓
Partly-Composite Higgs			✓	✓	✓	✓
Bosonic TC						✓

Final comments

- 40 years after its theoretical proposal a Higgs has been disovered.
- Is it “the SM Higgs”?, it looks very similar but ...

  precise measurements and calcuations are needed to fully characterize the new scalar.
- On the other hand, the mechanism triggering EWSB is not known yet.

  The dynamics separating the EW and Planck scale is still veiled.

  NP discovered at LHC would certainly shed light on these questions.
- After the Higgs discovery, there is no guaranteed guiding principle to look for new particles and phenomena.

  Naturalness has been “the guide” for NP at TeV … LHC is putting it under preassure.

  Experimental results are needed.
- Keep your minds open, question all the proposals, come with new ideas, designs for experiments and new theories!

  Most of the big questions are still open.

➡ Let’s wait for more LHC results on Moriond this week,

good news could be around the corner!