$\mathcal{M}$easurement of $\mathcal{H}$iggs $\mathcal{C}$ouplings and their $\mathcal{I}$mplications for $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales

$\mathcal{M}$ilada $\mathcal{M}$argarete $\mathcal{M}$ühlleitner (KIT)

Coll. with Englert, Freitas, Plehn, Rauch, Spira and Walz

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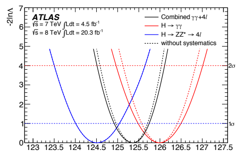
Outline

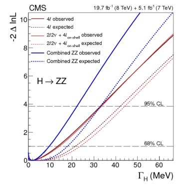
- ◇ Introduction
- ◇ Coupling Measurements at the LHC
  - ∗ What can we learn from coupling measurements?
- ◇ Effective Lagrangian Approach
- ◇ Specific Models
  - ∗ Composite Higgs
  - ∗ The 2HDM
  - ∗ The MSSM
  - ∗ The NMSSM
- ◇ Summary

$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson

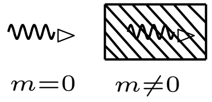
- **Investigation of properties of scalar particle:**

  $*$ Mass m, Total Width Γ

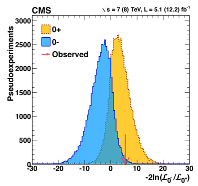


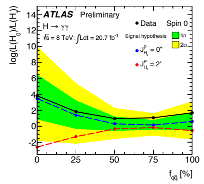


  $*$ Couplings to SM particles $g_{HXX} \sim m_X$

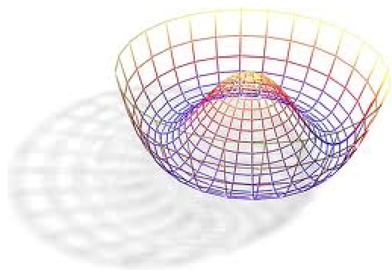


  $*$ Spin and Parity Quantum Numbers J^P (CP violation?)



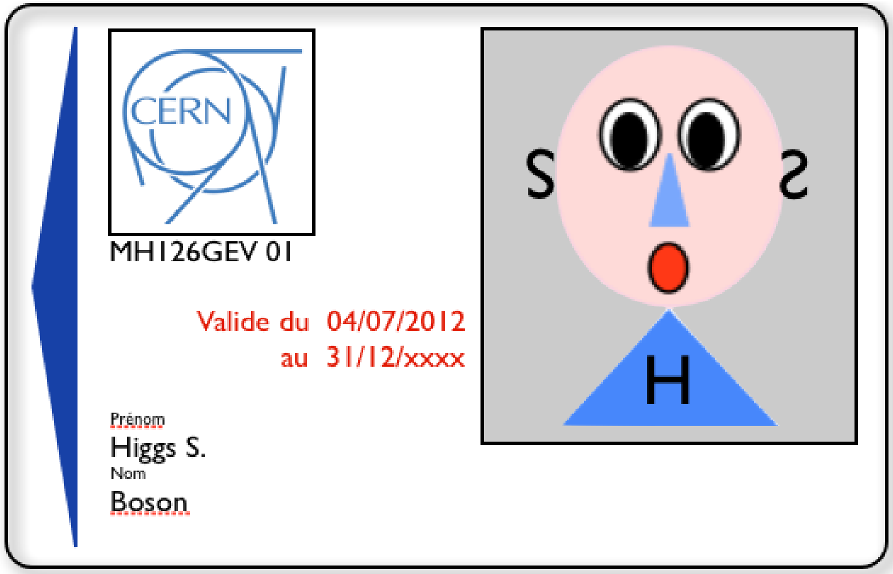


  $*$ Trilinear and Quartic Higgs Self-Coupling $\rightsquigarrow$ Higgs Potential



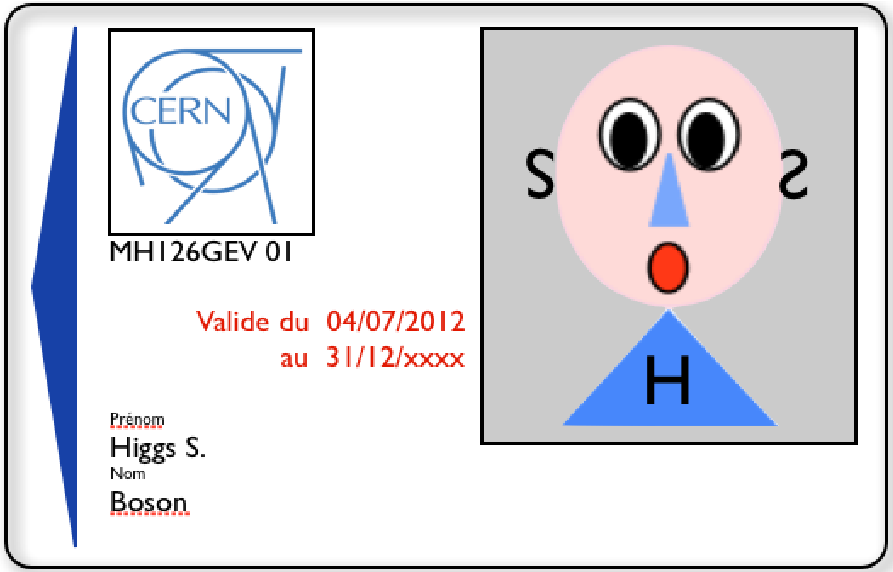
$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson

- **Investigation of properties of scalar particle:** $\rightsquigarrow$ Higgs Boson



$\mathcal{I}$t is the $\mathcal{H}$iggs $\mathcal{B}$oson

- **Investigation of properties of scalar particle:** $\rightsquigarrow$ Higgs Boson



- **Is it the SM Higgs Boson?**
- **Experimental reality:** No Beyond the Standard Model Physics discovered so far!

$\mathcal{W}$hat can we learn from $\mathcal{H}$iggs $\mathcal{P}$hysics in the $\mathcal{F}$uture?

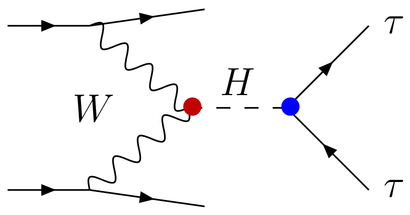
Coupling Measurements at the LHC

$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

Strategy

Combination of the production and decay channels $\Rightarrow$ decay rates, absolute couplings

E.g.:



$\sim \Gamma_{WW} \frac{\Gamma(H\to\tau\tau)}{\Gamma_{\text{tot}}}$ (narrow width approximation)

$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

Strategy

Combination of the production and decay channels $\Rightarrow$ decay rates, absolute couplings

$$\sigma_{\text{prod}}(H)\times \text{BR}(H \to XX) \sim \Gamma_{\text{prod}}\times\frac{\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}}$$

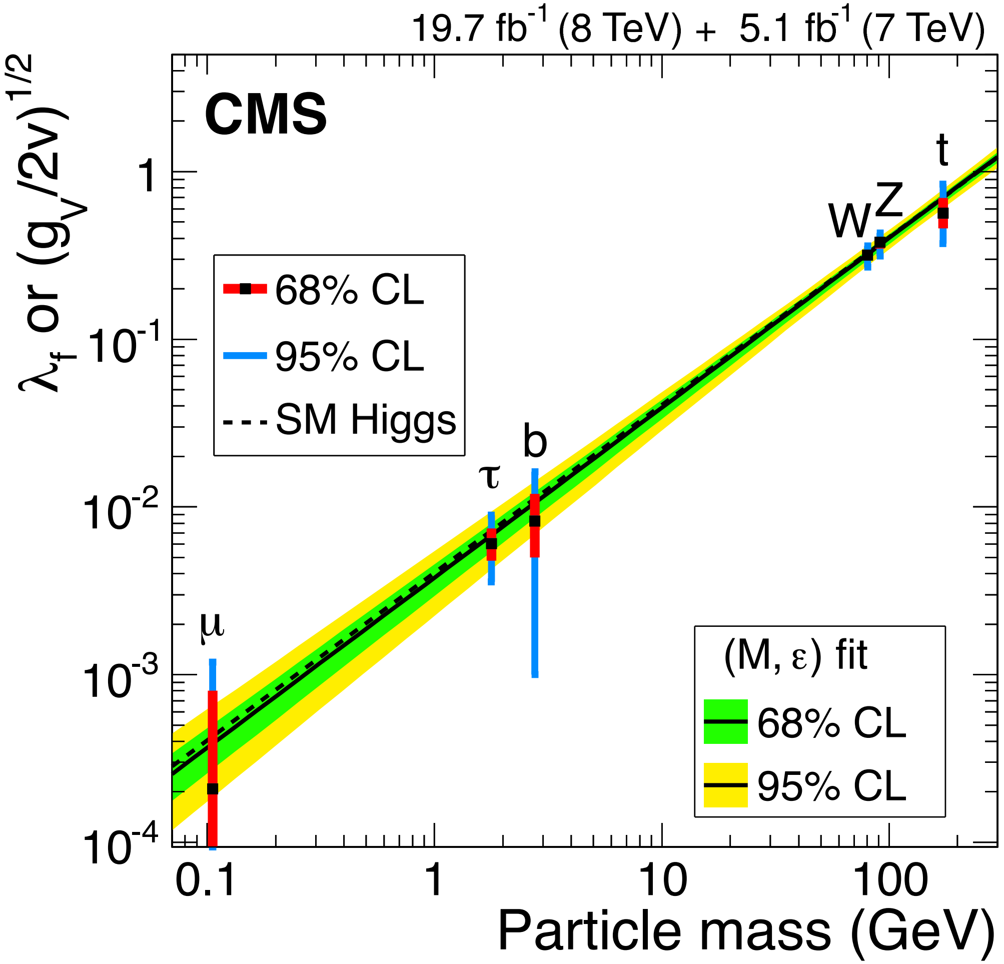
Coupling measurement at the LHC

* Determination of total width impossible w/o further assumptions
* Not all final states are accessible
* $\Rightarrow$ Only ratios of couplings can be measured
* $\Rightarrow$ Perform fits to reduced signal strengths μ

$$\mu = \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}}$$

$\mathcal{E}$xperimental $\mathcal{S}$tatus: $\mathcal{C}$ouplings

CMS arXiv:1412.8662



What Can We Learn From Coupling Measurements?

- ***The Standard Model Higgs Boson***
  - ◇ Test relation $g_{hXX} \sim m_X$ predicted by Higgs mechanism

- **Deviations from SM couplings ⟵ New Physics**
  - ◇ modified Higgs properties through mixing effects with other scalars; alternatively strongly interacting Higgs sector
  - ◇ modified Higgs properties through loop effects or effective low-energy operators; $e.g.$ SUSY, strong dynamics, extra dimensions, see-saw models, extended gauge groups

What is the Scale of New Physics that can be Probed?

$\mathcal{T}$heoretical $\mathcal{A}$pproach to $\mathcal{C}$oupling $\mathcal{E}$xtraction

Theoretical approach couplings extracted from experimental $\mu = (\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$ values

* $\Rightarrow$ Need Lagrangian to define the meaning of the couplings
* Effective Lagrangian w/ modified Higgs couplings $\rightarrow$ signal rates $\rightarrow$ fit to experimental μ values

General Coupling Modification

* absolute value and tensor structure
* $\Rightarrow$ determination of couplings and CP properties cannot be treated separately in general
* $\leadsto$ change of distributions $\leftrightarrow$ no simple rescaling of MC predictions
* $\Rightarrow$ LHC Higgs XS WG: interim framework:
  - ◇ signal from single narrow resonance of mass near 125 GeV
  - ◇ Higgs boson width neglected, zero-width approximation
  - ◇ only absolute value of couplings change, not tensor structure $\rightarrow$ CP-even scalar

The Effective Lagrangian Approach

(I) $\mathcal{N}$on-$\mathcal{L}$inear $\mathcal{E}$ffective $\mathcal{L}$agrangian

◇ **Field content:** SM with scalar field h; SM: $\kappa_i = 1, \overline{\kappa}_i = 0$

Contino eal '10,'12; Azatov eal; Alonso eal; Brivio eal; Elias-Miró eal; Isidori eal; Buchalla eal

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2}m_h^2 h^2 - \kappa_3 \left(\frac{m_h^2}{2v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + \kappa_\psi \frac{h}{v} + \ldots\right)$$

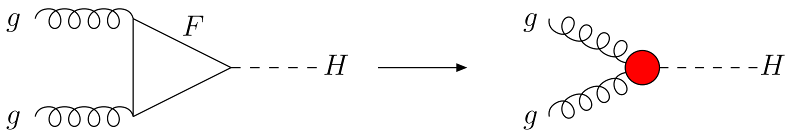
$$+ m_W^2\, W_\mu^+ W^{-\,\mu} \left(1 + 2\kappa_W \frac{h}{v} + \ldots\right) + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \left(1 + 2\kappa_Z \frac{h}{v} + \ldots\right) + \ldots$$

$$+ \left(\frac{\bar{\kappa}_{WW}\,\alpha}{\pi} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\bar{\kappa}_{ZZ}\,\alpha}{2\pi} Z_{\mu\nu}Z^{\mu\nu} + \frac{\bar{\kappa}_{Z\gamma}\,\alpha}{\pi} Z_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_{\gamma}\,\alpha}{2\pi} \gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_{g}\,\alpha_s}{12\pi} G^a_{\mu\nu}G^{a\mu\nu}\right)\frac{h}{v}$$

$$+ \left(\left(\bar{\kappa}_{W\partial W}\, W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + \bar{\kappa}_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \bar{\kappa}_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\frac{h}{v} + \ldots$$

◇ **Remarks:** $*$ Valid for h being singlet or doublet

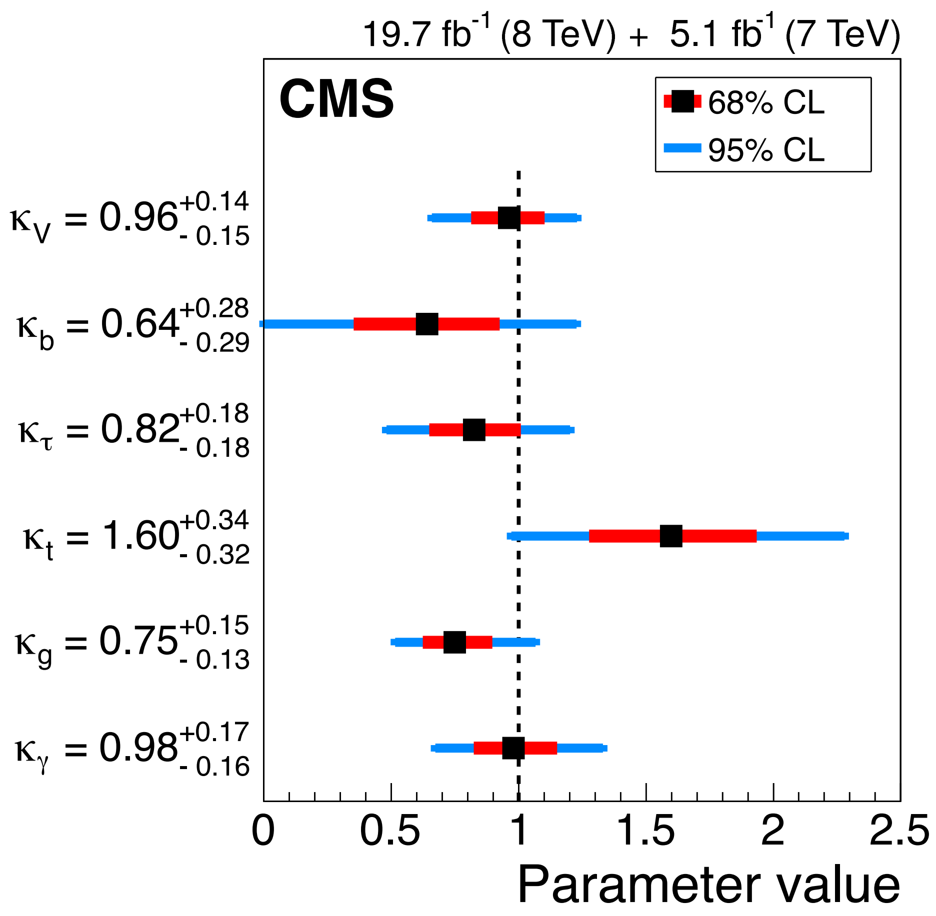
$*$ $\overline{\kappa}_{g,\gamma,Z\gamma}$ parametrize new physics in the hgg, $h\gamma\gamma$ and $hZ\gamma$ loop couplings

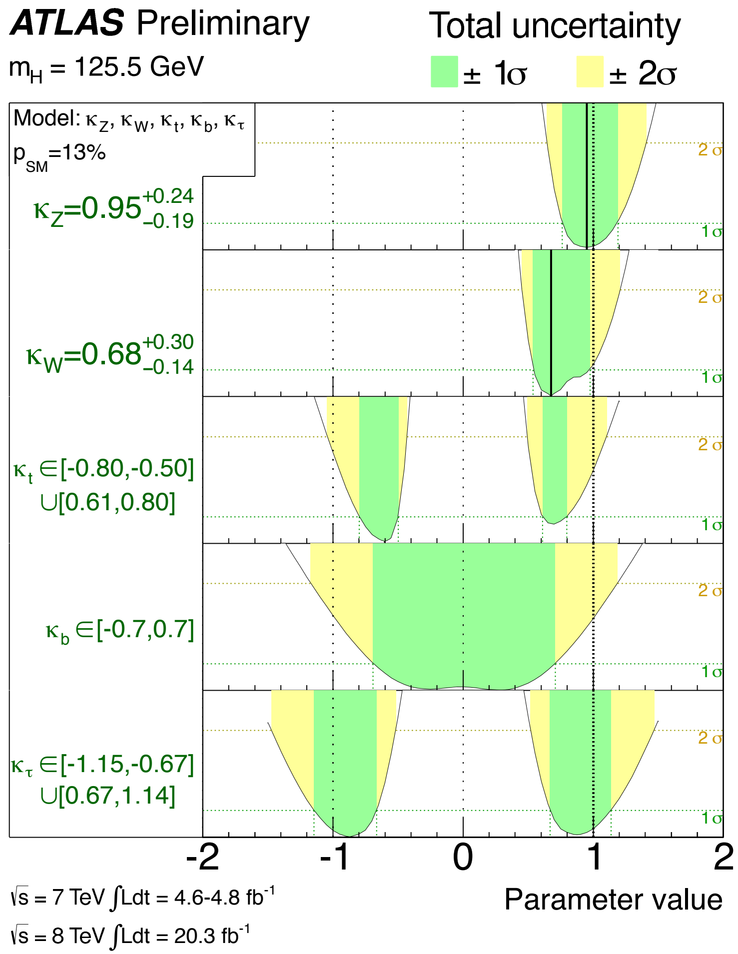


$\mathcal{S}$tatus: $\mathcal{C}$oupling $\mathcal{S}$cale $\mathcal{F}$actor $\mathcal{M}$easurements

CMS arXiv:1412.8662

ATLAS-CONF-2014-009





(II) $\mathcal{E}$ffective $\mathcal{L}$agrangian for a $\mathcal{L}$ight $\mathcal{H}$iggs-$\mathcal{L}$ike $\mathcal{S}$calar

- **Natural Mechanisms for EWSB suggest**
  - ◇ New physics at some scale $\Lambda \sim \mathcal{O}(\text{TeV})$
  - ◇ New physics generates deviations in SM Higgs physics

- **Convenient framework for model-independent analysis:** Effective Lagrangian Approach

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

  - ∗ assume few basic principles (e.g. field content, SM gauge symmetries)
  - ∗ parametrize SM deviations by higher-dimensional operators built of SM fields
  - ∗ Operators = low-energy remnants of heavy NP integrated out at $\Lambda \Rightarrow$
  - ∗ Operators suppressed by scale Λ

- **Example:** $SU(3) \times SU(2) \times U(1)$ invariance $\rightsquigarrow$ leading NP effects described by $D = 6$ operators

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

$\mathcal{S}$cales $\mathcal{P}$robed $\mathcal{I}$n $\mathcal{C}$oupling $\mathcal{M}$easurements

- **Use expansions in higher dimensional operators** to describe coupling deviation $\leadsto$

$$g_{hXX} = g^{\text{SM}}_{hXX}[1+\Delta] \; : \; \Delta = \mathcal{O}(v^2/\Lambda^2)$$

$\Lambda \gg v$ = characteristic scale of Beyond the SM Physics

[caveat: non-decouplings effects]

- **Scales to be probed in Mixing Effects**

LHC coupling precision:	$4-15\%$	$\leadsto$	$\Lambda = 640$ GeV...1.2 TeV
HL-LHC coupling precision:	$2-10\%$	$\leadsto$	$\Lambda = 780$ GeV...1.7 TeV

- **Scales to be probed in Loop Effects**

additional loop suppression factor $\leadsto$ $\Delta = \frac{v^2}{16\pi^2\Lambda^2}$

$\Rightarrow$ for $\Delta = 0.02$ scale probed: $\Lambda \approx 140$ GeV

$\mathcal{C}$oupling $\mathcal{A}$ccuracies

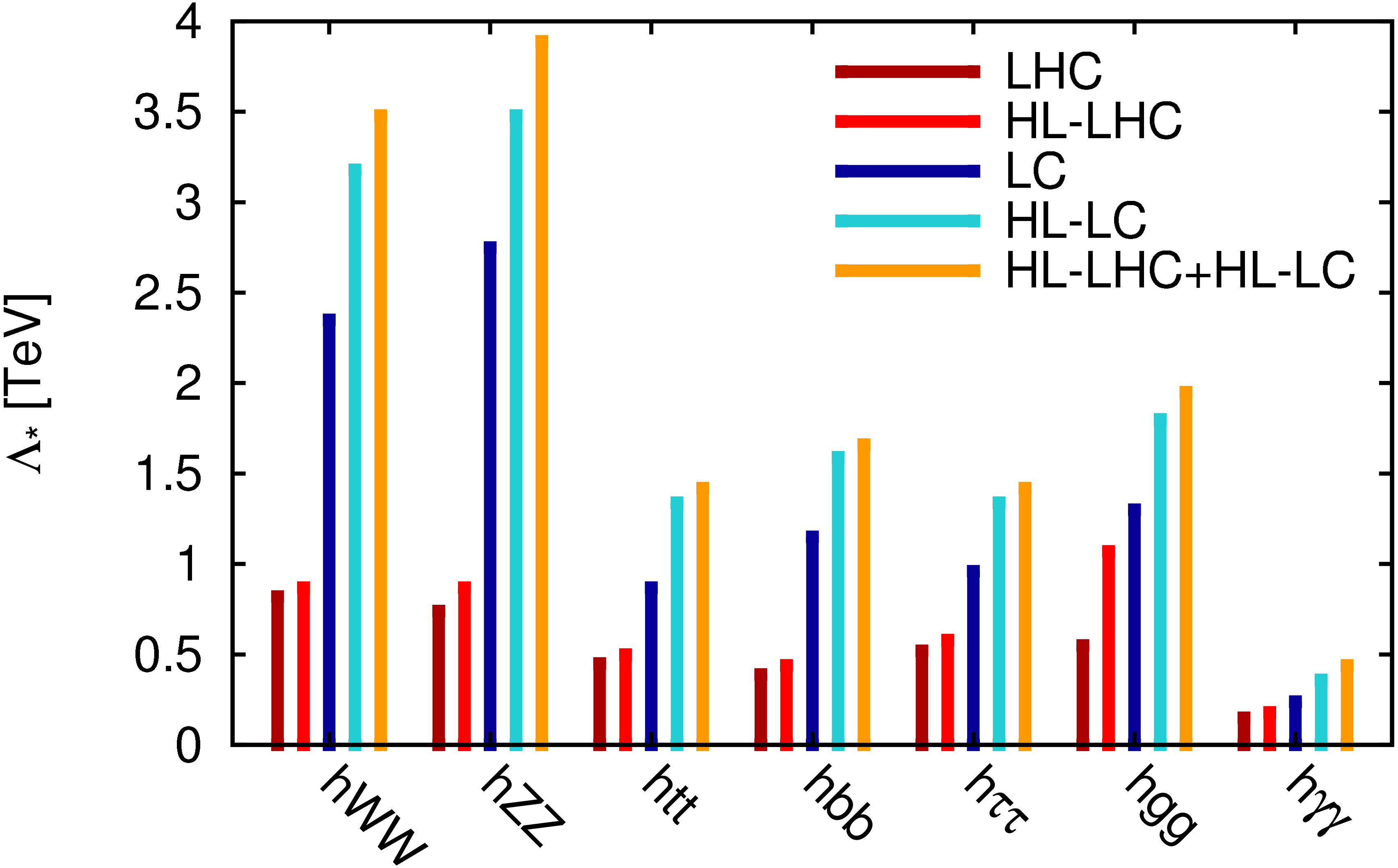
Englert eal

coupling	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.09	0.08	0.011	0.006	0.005
hZZ	0.11	0.08	0.008	0.005	0.004
htt	0.15	0.12	0.040	0.017	0.015
hbb	0.20	0.16	0.023	0.012	0.011
$h\tau\tau$	0.11	0.09	0.033	0.017	0.015
$h\gamma\gamma$	0.20	0.15	0.083	0.035	0.024
hgg	0.30	0.08	0.054	0.028	0.024
h_{invis}	—	—	0.008	0.004	0.004

- accuracy at 68% CL; deviations: $g = g_{\text{SM}}[1 \pm \Delta]$
- LHC/HL-LHC: $\int \mathcal{L} = 300$ fb^{-1} and 3000 fb^{-1}
- LC/HL-LC: 250+500 GeV/250+500 GeV+1 TeV, $\int\mathcal{L} = 250 + 500$ fb^{-1}/1150+1600+2500 fb^{-1}

$\mathcal{E}$ffective $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales

Rauch et al.



$\mathcal{E}$ffective $\mathcal{N}$ew $\mathcal{P}$hysics $\mathcal{S}$cales (loop, coupling factors factored out)

- **Effective New Physics scales Λ_*** extracted from coupling measurements

Λ_* [TeV]	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.82	0.87	2.35	3.18	3.48
hZZ	0.74	0.87	2.75	3.48	3.89
htt	0.45	0.50	0.87	1.34	1.42
hbb	0.39	0.44	1.15	1.59	1.66
$h\tau\tau$	0.52	0.58	0.96	1.34	1.42
hgg	0.55	1.07	1.30	1.80	1.95
$h\gamma\gamma$	0.15	0.18	0.24	0.36	0.44

Loop-induced couplings to gluons and photons contain only the contribution of the contact terms

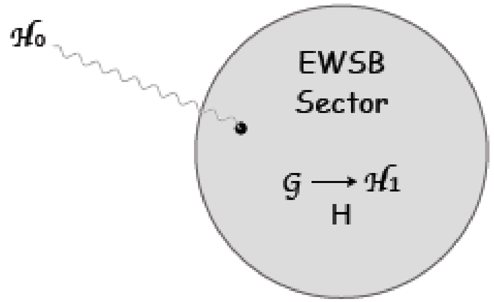
Composite Higgs

Composite Higgs Boson

Kaplan,Georgi; Dimopoulos eal; Dugan eal

- **Bound state from a Strongly Interacting Sector not much above weak scale**

- **How can we obtain a light composite Higgs?**



Higgs: Pseudo-Goldstone boson of strongly interacting sector

Global symmetry of strong sector $\mathcal{G}$ $\xrightarrow{\text{spontaneously broken at } f}$ subgroup $\mathcal{H}_1$

$\mathcal{G}/\mathcal{H}_1$: contains Higgs boson as Nambu-Goldstone Boson

- **Continuous interpolation between the SM and Technicolor:**

$\xi = 0$ SM limit $\longleftarrow$ $\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$ $\longrightarrow$ $\xi = 1$ "Technicolor" limit

strong sector resonances decouple, except boson

boson deccouples, vector resonances like in TC

- **No hierarchy problem** EWSB potential generated at one-loop through gauge and top loops

 Cartoon from R.Contino [1005.4269]

$\mathcal{S}$trongly $\mathcal{I}$nteracting $\mathcal{L}$ight $\mathcal{H}$iggs ($\mathcal{SILH}$)

- **SILH Lagrangian:** expansion for small $\xi = v^2/f^2$ [f: typical scale of strong sector]
  couplings modif. in terms of ξ; SM limit: $\xi \to 0$ Giudice,Grojean,Pomarol,Rattazzi

Englert,Freitas,MMM,Plehn,Rauch,Spira,Walz

ξ	LHC	HL-LHC	LC	HL-LC	HL-LHC+HL-LC
universal	0.076	0.051	0.008	0.0052	0.0052
non-universal	0.068	0.015	0.0023	0.0019	0.0019
f [TeV]					
universal	0.89	1.09	2.82	3.41	3.41
non-universal	0.94	1.98	5.13	5.65	5.65

universal: fermions in spinorial representation Agashe,Contino,Pomarol
non-universal: fermions in fundamental representation Contino,Da Rold,Pomarol

$\mathcal{C}$omputer $\mathcal{T}$ool for $\mathcal{H}$iggs $\mathcal{D}$ecay $\mathcal{W}$idths

- **Implementation for Higgs decay widths:** `eHDECAY`

  R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira

  URL: http://www.itp.kit.edu/∼maggie/eHDECAY/

- **Implemented Parametrisations**

SILH:	strongly interacting light Higgs boson, SU(2) doublet
MCHM4,5:	minimal composite Higgs models
non-linear:	expansion, allows large couplg deviations from SM

𝒫rogram eHDECAY

eHDECAY

The program eDHECAY is a modified version of the latest release of HDECAY 5.10.
It allows for the calculation of the partial decay widths and branching ratios of a Higgs-like boson within different parametrisations of the Lagrangian: the non-linear Lagrangian, the SILH Lagrangian and the composite Higgs parametrization according to MCHM4 or MCHM5.

Released by: Roberto Contino, Margherita Ghezzi, Christophe Grojean, Margarete Mühlleitner and Michael Spira

Program: eHDECAY obtained from extending HDECAY 5.10

When you use this program, please cite the following references:

eHDECAY:	R. Contino, M. Ghezzi, C. Grojean, M. Mühlleitner, M. Spira, in arXiv 1303.3876
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to margherita.ghezzi@roma1.infn.it or margarete.muehlleitner@kit.edu.

Downloading the files needed for eHDECAY:

The 2HDM

$\mathcal{M}$ixing $\mathcal{E}$ffects – 2HDM

- **ρ–parameter exp close to 1** $\rightsquigarrow$ extensions of Higgs sector by $SU(2)$ singlet or doublet

- **2HDM potential** assuming CP-conservation and global $\mathbb{Z}_2$ discrete symmetry $[\phi_{1,2} \to \mp\phi_{1,2}]$

Flores,Sher; Gunion et al; Lee; Branco et al; Gunion,Haber

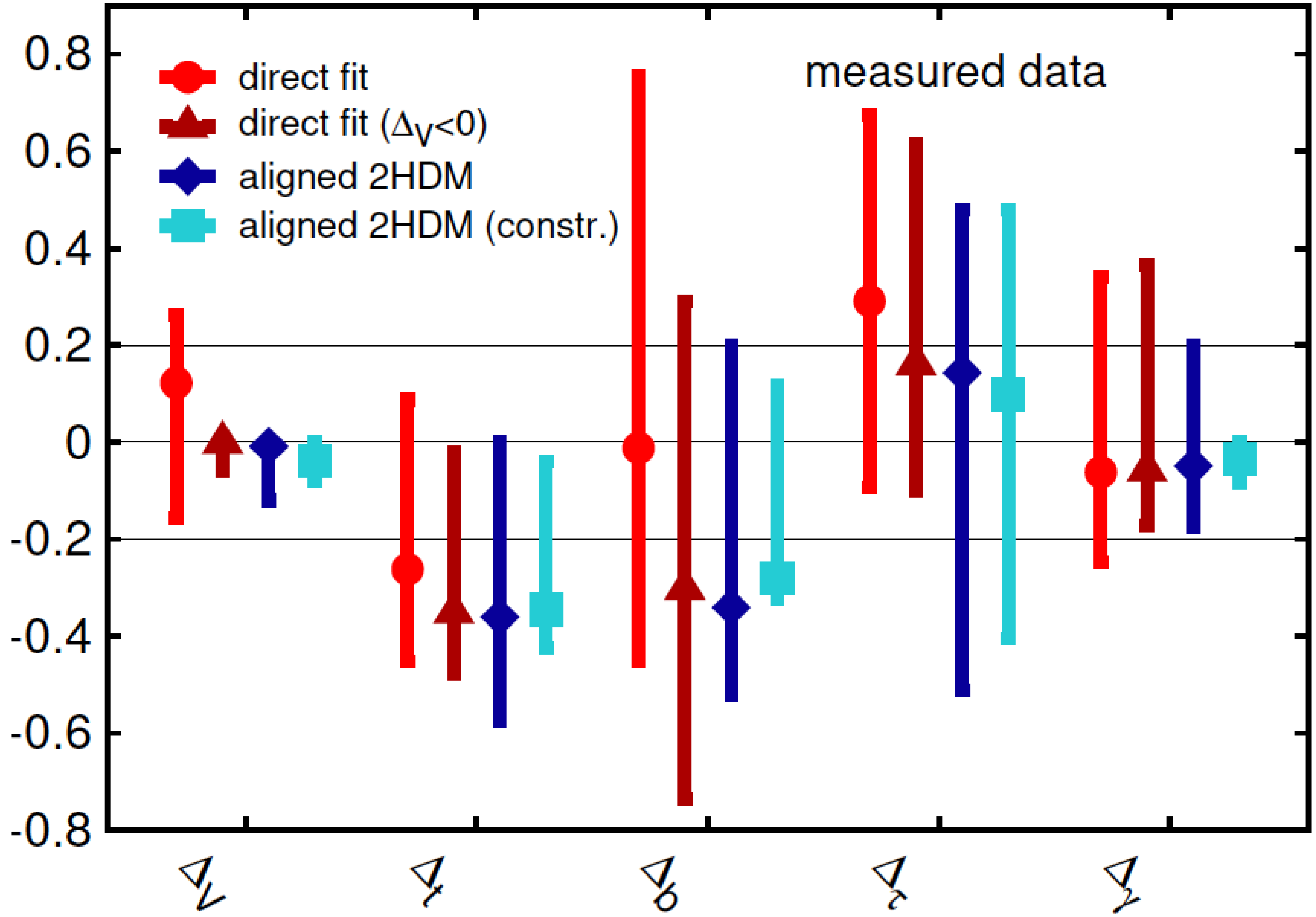
$$V = m_{11}|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + \text{h.c}) + \lambda_1|\phi_1|^4 + \lambda_2|\phi_2|^4 \\ + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \frac{1}{2}\lambda_5[(\phi_1^\dagger\phi_2)^2 + \text{h.c}]\,.$$

- **Couplings to fermions**
  - ◇ type I: all fermions couple only to ϕ_2;
  - ◇ type II: up-/down-type fermions couple to ϕ_2/ϕ_1, respectively; $\to$ MSSM
  - ◇ lepton-specific: quarks couple to ϕ_2 and charged leptons couple to ϕ_1;
  - ◇ flipped: up-type quarks and leptons couple to ϕ_2 and down-type quarks couple to ϕ_1.

- **Higgs sector after EWSB** CP-even neutral: h^0, H^0, CP-odd neutral; A^0, charged $H^\pm$

$\mathcal{F}$it to $\mathcal{C}$ouplings of $\mathcal{A}$ligned 2HDM

$g_X = g_X^{\mathrm{SM}}(1 + \Delta_X)$ L=4.6-5 (7 TeV)+12-21 (8TeV) fb^{-1}, 68% CL ATLAS+CMS Rauch et al.



HDECAY for 2-$\mathcal{H}$iggs-$\mathcal{D}$oublet-$\mathcal{M}$odels

HDECAY for Two Higgs Doublet Models

This program is a modified version of HDECAY Version 5.11.
It allows for the calculation of the partial decay widths and branching ratios in the 2HDM.

Released by: Abdelhak Djouadi, Jan Kalinowski, Margarete Mühlleitner and Michael Spira
Program: HDECAY for 2HDM based on HDECAY 5.11

When you use this program, please cite the following references:

Manual:	R. Harlander, M. Muhlleitner, J. Rathsman, M. Spira, O. Stal, arXiv:1312.5571 [hep-ph]
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications concerning the 2HDM version, send an E-mail to margarete.muehlleitner@kit.edu.
- Modifs/corrected bugs are indicated explicitly in this file.

Downloading the files needed for HDECAY for 2HDM:

- hdecay2hdm.tar.gz contains the program package files: the input file hdecay.in; hdecay.f, dmb.f, elw.f, feynhiggs.f, haber.f, hgaga.f, hgg.f, hsqsq.f, susylha.f; a makefile for the compilation.

$\mathcal{F}$urther 2-$\mathcal{H}$iggs-$\mathcal{D}$oublet-$\mathcal{M}$odel $\mathcal{P}$rograms

- **Further Programs:**
  - ∗ Decay program `2HDMC` — Eriksson,Rathsman,Stål
  - ∗ Production program `SusHi` — Harlander,Liebler,Mantler
  - ∗ Production program `HIGLU` — Spira

- **Discussion and comparison, see:** Harlander,MMM,Rathsman,Spira,Stål, 1312.5571

The MSSM

The MSSM Higgs Sector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;Harlander et al
Degrassi et al;Kant et al;...

Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gtrsim v$

$M_h \to$ max. value, $\tan\beta$ fixed; h becomes SM-like

Modified couplings with respect to the SM: (decoupling limit Gunion,Haber)

Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \to 1$	$-s_\alpha/c_\beta \to 1$	$s_{\beta-\alpha} \to 1$
H	$s_\alpha/s_\beta \to 1/\text{tg}\beta$	$c_\alpha/c_\beta \to \text{tg}\beta$	$c_{\beta-\alpha} \to 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$
$g_{\Phi dd} \uparrow$
$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$

$\mathcal{D}$ecoupling $\mathcal{L}$imit

- **Partial widths of SM-like light state in the decoupling limit:**

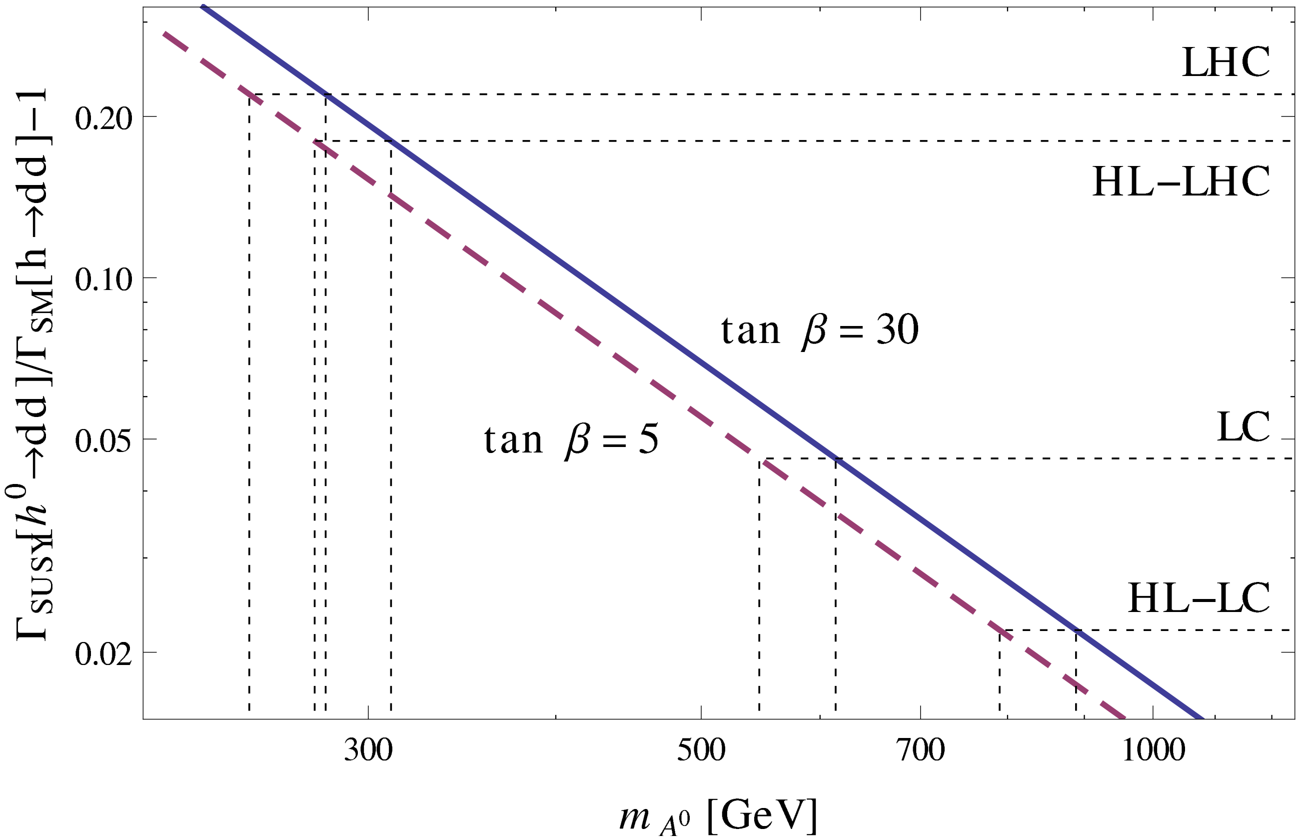
$$
\begin{aligned}
\frac{\Gamma_{\mathsf{SUSY}}[h^0 \to VV^*]}{\Gamma_{\mathsf{SM}}[h \to VV^*]} &\approx 1 - \frac{m_Z^4 \sin^2 2\beta}{m_{A^0}^4} (\cos 2\beta + R_t)^2 \,, \\
\frac{\Gamma_{\mathsf{SUSY}}[h^0 \to uu]}{\Gamma_{\mathsf{SM}}[h \to uu]} &\approx 1 + \frac{4 m_Z^2 \cos^2 \beta}{m_{A^0}^2} (\cos 2\beta + R_t) \,, \\
\frac{\Gamma_{\mathsf{SUSY}}[h^0 \to dd]}{\Gamma_{\mathsf{SM}}[h \to dd]} &\approx 1 - \frac{4 m_Z^2 \sin^2 \beta}{m_{A^0}^2} (\cos 2\beta + R_t)
\end{aligned}
$$

- **SUSY radiative corrections dominated by top/stop loop contributions**

$$
\begin{aligned}
R_t \approx \frac{3(g^2 + g'^2)}{16\pi^2 \sin^2 \beta} \frac{m_t^4}{m_Z^4} \Bigg[& \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + (A_t - \mu \cot 2\beta) \frac{A_t - \mu \cot \beta}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \log \frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2} \\
& + (A_t^2 - \mu^2 - 2 A_t \mu \cot 2\beta) \left(\frac{A_t - \mu \cot \beta}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \right)^2 \left(1 - \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} \log \frac{m_{\tilde{t}_1}}{m_{\tilde{t}_2}} \right) \Bigg]
\end{aligned}
$$

$\mathcal{L}$imits on $\mathcal{H}$eavy $\mathcal{MSSM}$ $\mathcal{M}$asses

Englert eal '14



$*$ $m_{\tilde{t}_1} m_{\tilde{t}_2} = 1$ TeV^2, $A_t - \mu \cot\beta \ll m_{\tilde{t}_i}$

$*$ derived limits $m_{A^0} \gtrsim 250$ GeV (LHC),
$m_{A^0} \gtrsim 280$ GeV/ $\gtrsim 380$ GeV (HL-LHC/CMS [1307.7135])

The NMSSM

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Supersymmetric Higgs Sector:** SUSY & anomaly-free theory $\Rightarrow$ 2 complex Higgs doublets

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Solution of μ problem (Higgsino parameter μ must be $\mathcal{O}(M_{\text{EWSB}})$)
  μ generated dynamically through the VEV of scalar component of an additional chiral superfield field $\hat{S}$: $\mu = \lambda\langle S\rangle$ from: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

- **Enlarged (pseudo-)scalar and neutralino sector:** 2 complex doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

7 bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Significant changes of the phenomenology**
  Higgs mass eigenstates: superpositions of doublet and singlet components $\leadsto$
  the more singlet-like the smaller the couplings to SM particles

$\mathcal{NMSSM}$ $\mathcal{C}$oupling $\mathcal{M}$easurement

- **What can we learn from coupling measurements?**

  Test coupling sum rules

$$\sum_{i=1}^{3} g^2_{H_i VV} = 1 \qquad \text{Higgs-gauge couplings}$$

$$\frac{1}{\sum_{i=1}^{3} g^2_{H_i tt}} + \frac{1}{\sum_{i=1}^{3} g^2_{H_i bb}} = 1 \qquad \text{Higgs-fermion couplings}$$

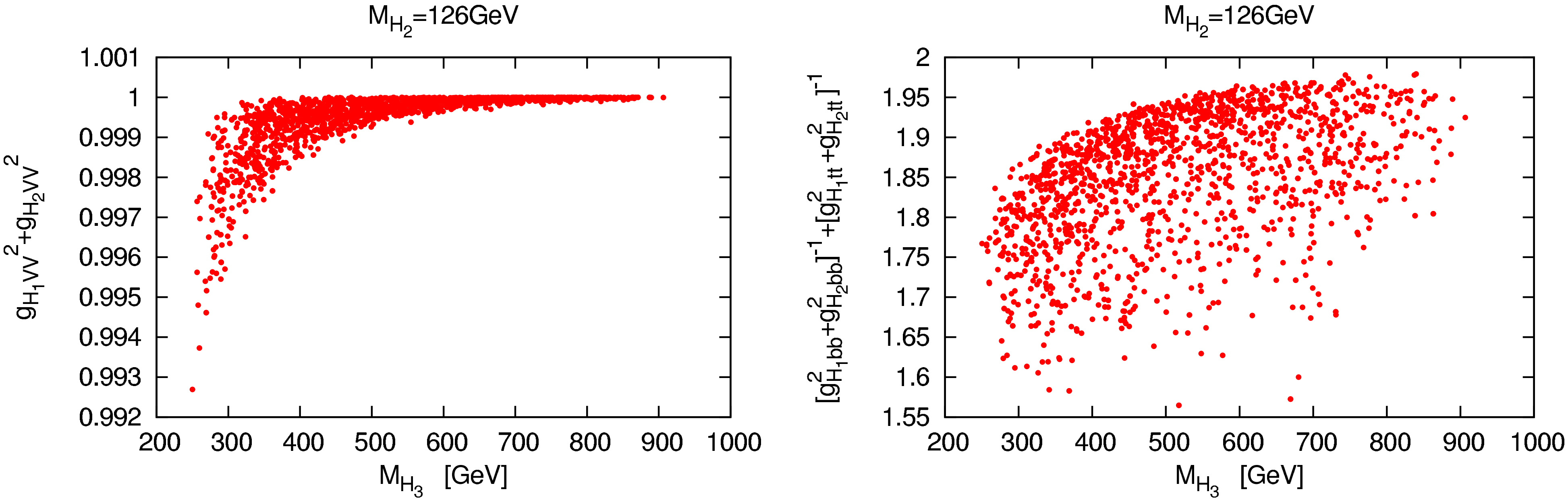
[in units of SM couplings].

- **Scenario:** H_2 SM-like, only two lightest CP-even bosons discovered

  Deviation of sum rules: distinguish NMSSM from MSSM

$\mathcal{V}$iolation of $\mathcal{S}$um $\mathcal{R}$ules

Walz,MMM



H_2 is SM-like and only H_1, H_2 have been discovered

H_1 singlet-like, H_2 doublet H_u-like $\rightsquigarrow$ H_3 doublet H_d-like $\Rightarrow$
Missing H_2 implies large violation of fermion couplings sum rule

$\mathcal{NMSSM}$ $\mathcal{C}$oupling $\mathcal{M}$easurement

- **What can we learn from coupling measurements?**

  Test coupling sum rules

$$\sum_{i=1}^{3} g_{H_i VV}^2 = 1 \qquad \underline{\text{Higgs-gauge couplings}}$$

$$\frac{1}{\sum_{i=1}^{3} g_{H_i tt}^2} + \frac{1}{\sum_{i=1}^{3} g_{H_i bb}^2} = 1 \qquad \underline{\text{Higgs-fermion couplings}}$$

[in units of SM couplings].

- **Scenario:** H_2 SM-like and only two lightest CP-even bosons discovered

  Deviation of sum rules: distinguish NMSSM from MSSM

- **What can we learn about high mass scale?**

  some dependence of sum rule on heavy mass can be seen, however large spreading of points

  large number of parameters at tree-level influence mixing $\rightsquigarrow$ couplings of the Higgs bosons

Summary

Englert,Freitas
MMM,Plehn
Rauch,Spira,Walz

	Scenario/framework	LHC	HL-LHC	LC	HL-LC
Mixing effects	Higgs portal	0.23	0.28	0.44	0.56
	2HDM type-II ($\tan\beta \approx 1$)	0.52	0.58	1.15	1.6
	2HDM type-II ($\tan\beta \approx 10$)	0.33	0.36	0.7	1.0
Effective interactions	$D = 6$ effective operators:				
	hVV	0.78	0.87	2.6	3.3
	hff	0.45	0.50	1.0	1.4
	hgg contact	0.55	1.1	1.3	1.8
	$h\gamma\gamma$ contact	0.15	0.18	0.24	0.36
	Strong interactions	0.9	1.1–2.0	2.8–5.1	3.4–5.6
Loop effects	hgg loop effects:				
	scalar triplet	0.16	0.31	0.37	0.52
	scalar octet	0.39	0.75	0.92	1.3
	vector octet	1.8	3.5	4.2	5.8
	$h\gamma\gamma$ loop effects:				
	scalar triplet	0.15	0.18	0.24	0.36
	scalar octet	0.25	0.29	0.39	0.60
	vector octet	1.1	1.3	1.8	2.7
	Vector-like leptons	—	—	1.2	1.5

Summary

Higgs precision data can be sensitive to multi-TeV scales,
beyond the reach of direct LHC searches, unless minimally
weakly coupled scenario ($\leftarrow$ complement LHC searches).
Pattern of deviation carries additional information on BSM physics.
LHC+LC coupling measurement $\rightsquigarrow$ unique window into BSM.

Work has only started!

Thank You For Your Attention!

$\mathcal{N}$on-$\mathcal{L}$inear $\mathcal{E}$ffective $\mathcal{L}$agrangian

Contino eal;Alonso eal;Brivio eal;Elias-Miró eal;Isidori eal;Buchalla eal

- **Expansion at $\mathcal{O}(p^4)$** and conservation of fermionic currents, CP-invariance:

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi \frac{h}{v} + \dots\right)$$

$$+ m_W^2\, W_\mu^+ W^{-\,\mu}\left(1 + 2c_W\,\frac{h}{v} + \dots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z\,\frac{h}{v} + \dots\right) + \dots$$

$$+ \left(c_{WW}\, W_{\mu\nu}^+ W^{-\mu\nu} + \frac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}\, G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v}$$

$$+ \left(\left(c_{W\partial W}\, W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu\partial_\mu\gamma^{\mu\nu}\right)\frac{h}{v} + \dots$$

$*$ contains 10 hVV couplings

$*$ custodial symmetry $\Rightarrow$ 3 relations among the $c_i \rightsquigarrow$ 7 couplings

$*$ EW doublet Higgs: 1 coupling $\leftrightarrow$ S oblique parameter, 2 couplings $\leftrightarrow$ anomalous gauge couplings

$\Rightarrow$ 4 coupling parameters $c_{\gamma\gamma}, c_V, c_{\gamma Z}, c_{gg}$

$\Rightarrow$ from hVV couplings alone cannot tell an EW doublet Higgs from a singlet Higgs

$\mathcal{P}$rojected $\mathcal{P}$recisions on $\mathcal{C}$oupling $\mathcal{M}$easurements

ATLAS Collaboration,
arXiv:1307.7292

Coupling	With theory systematics	Without theory systematics
300 fb^{-1}		
κ_V	$+5.9\%$ -5.4%	$+3.0\%$ -3.0%
κ_F	$+10.6\%$ -9.9%	$+9.1\%$ -8.6%
3000 fb^{-1}		
κ_V	$+4.6\%$ -4.3%	$+1.9\%$ -1.9%
κ_F	$+6.1\%$ -5.7%	$+3.6\%$ -3.6%

Projected Precisions on Coupling Measurements

CMS Collaboration, arXiv:1307.7135

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	5–7%	2–5%
κ_g	6–8%	3–5%
κ_W	4–6%	2–5%
κ_Z	4–6%	2–4%
κ_u	14–15%	7–10%
κ_d	10–13%	4–7%
κ_l	6–8%	2–5%
Γ_H	12–15%	5–8%

- ▷ scenario 1: theoretical uncertainties scale by 1/2; other systematics scaled by $1/\sqrt{\mathcal{L}}$
- ▷ scenario 2: systematics unchanged (statistics uncertainty reduction taken into account)
- ▷ κ_u from $t\bar{t}h$ production and $h \to \gamma\gamma$, $h \to b\bar{b}$

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Γ_H	12–15%	5–8%

- ▷ 95% CL: BR$_{\text{BSM}} < 14 - 18\%$ at 300 fb^{-1}; BR$_{\text{inv}} < 7 - 11\%$ at 3000 fb^{-1} $[\kappa_W, \kappa_Z \leq 1]$
- ▷ $\kappa_{Z\gamma} < 41 - 41\%$ at 300 fb^{-1}; $\kappa_{Z\gamma} < 10 - 12\%$ at 3000 fb^{-1}
- ▷ $\kappa_\mu < 23 - 23\%$ at 300 fb^{-1}; $\kappa_\mu < 8 - 8\%$ at 3000 fb^{-1}

$\mathcal{S}$trongly $\mathcal{I}$nteracting $\mathcal{L}$ight $\mathcal{H}$iggs ($\mathcal{SILH}$)

- **SILH Lagrangian:** expansion for small $\xi = v^2/f^2$ [f: typical scale of strong sector]
  couplings modif. in terms of ξ; SM limit: $\xi \to 0$ Giudice,Grojean,Pomarol,Rattazzi

$\mathcal{M}$inimal $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{M}$odels

- **Large ξ?** The 5D MCHM ($SO(5)/SO(4)$) provides completion for large ξ Contino eal; Agashe eal
- **Gauge couplings**

$$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}$$

- **Fermion couplings** depend on embedding into representations of the bulk symmetry

spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5
$g_{Hff} = g_{Hff}^{SM}\sqrt{1-\xi}$	$g_{Hff} = g_{Hff}^{SM}\frac{1-2\xi}{\sqrt{1-\xi}}$
universal shift of couplings no modifications of BRs	BRs depend on $\xi = v^2/f^2$

- **Higgs self-couplings** also model-dependent Contino eal; Gröber,MMM; Bock eal; Barger eal

$\mathcal{V}$iability of $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{M}$odels?

▷ Example: Composite Higgs Model with composite top and bottom quarks

- Partial compositeness: Giudice eal; Contino eal '10,'13

  Elementary fermions couple linearly to heavy states of strong sector w/ same quantum numbers

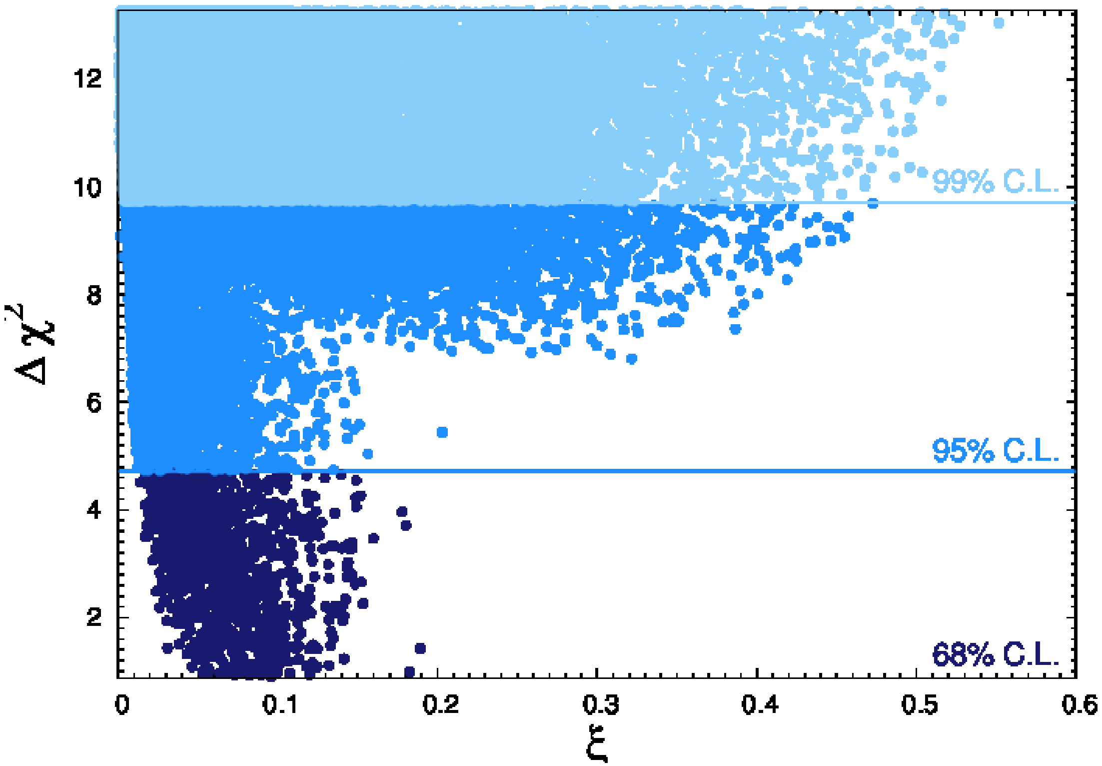
- Fermions acquire mass through mixing with new vector-like strong sector fermions

▷ Constraints

- electroweak precision data
- flavour constraints
- direct searches for heavy fermion partners
- Higgs data
- measurement of $|V_{tb}|$

$\mathcal{C}$onstraints from $\mathcal{EWPT}$ - $\mathcal{M}$CHM5 w/ $\mathcal{C}$omposite $\mathcal{T}$op and $\mathcal{B}$ottom

Gillioz,Gröber,Kapuvari,MMM



$\Delta\chi^2 \equiv \chi^2 - \chi^2_{min}$

Fair blue to dark blue: Points fulfill EWPT at 99%, 95%, 68% CL and $|V_{tb}| > 0.92$

$\mathcal{B}$est $\mathcal{F}$it $\mathcal{P}$oint

⋆ Best Fit Point including: EWPT, ATLAS and CMS Higgs data, $|V_{tb}|$ Gillioz,Gröber,Kapuvari,MMM

Experiment	ξ	χ^2
ATLAS	0.096	12.34
CMS	0.055	6.36

⋆ Light Higgs boson requires light top partners

⋆ Approximate formula Pomarol,Riva

$$m_Q \leq \frac{m_h \pi v}{m_t \sqrt{N_c}\sqrt{\xi}}$$

⋆ Best fit points using approximate formula: Gillioz,Gröber,Kapuvari,MMM

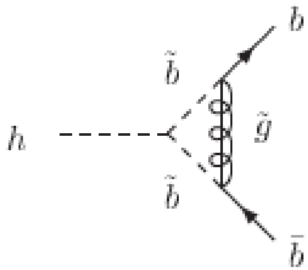
Experiment	ξ	χ^2
ATLAS	0.067	10.07
CMS	0.055	5.30

$\mathcal{N}$on $\mathcal{D}$ecoupling $\mathcal{E}$ffects

- $\tan\beta$**-enhanced non-decoupling effects:** $\mu \sim M_{\text{SUSY}} \ll v$

Δ_b corrections to Higgs-$b\bar{b}$ coupling in the MSSM:

Hall eal; Carena eal; Guasch eal; Noth eal; Mihaila eal



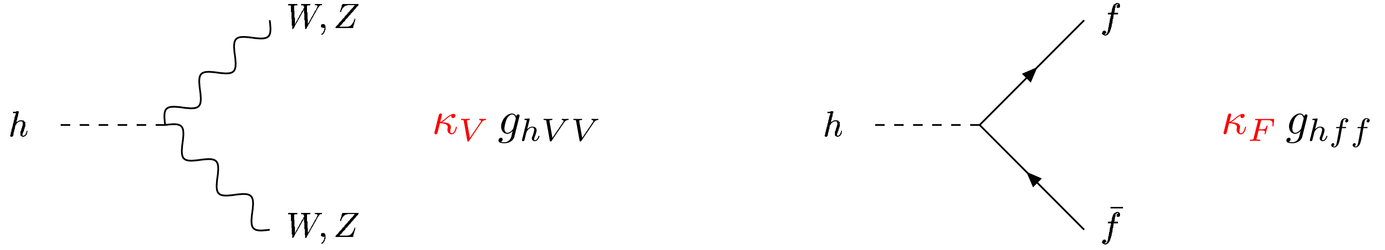
$$+\cdots \qquad \propto \frac{\alpha_s}{\pi} \frac{m_{\tilde{g}} \mu \, \text{tg}\beta}{M^2_{SUSY}}$$

$\mathcal{I}$s it the $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{B}$oson? - $\mathcal{E}$ffective $\mathcal{L}$agrangian $\mathcal{A}$pproach

$$\mathcal{L} = \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)]$$
$$-m_{\psi_i} \bar{\psi}_i \psi_i [1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)] + \ldots$$

- **Extension of the SM Lagrangian by two parameters κ_V, κ_F**; SM: $(\kappa_V, \kappa_F) = (1,1)$

- **Modified decays rates:** HDECAY: Djouadi, Spira, Kalinowski, MMM



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$$
\begin{aligned}
\mathcal{L} \;\; = \;\; & \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)] \\
& - m_{\psi_i} \bar{\psi}_i \psi_i [1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)] + ...
\end{aligned}
$$

- **Extension of the SM Lagrangian by two parameters** κ_V, κ_F; SM: $(\kappa_V, \kappa_F) = (1,1)$

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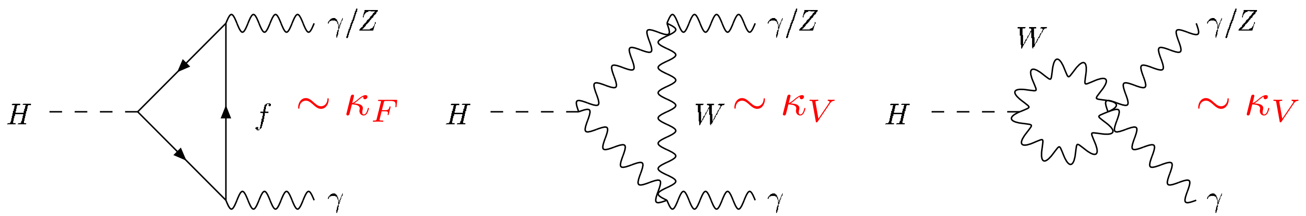
$h \to \gamma\gamma$:



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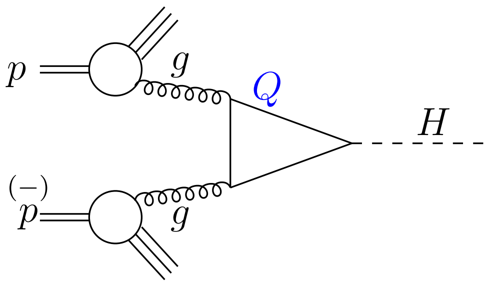
Modified Higgs-gluon-gluon coupling:



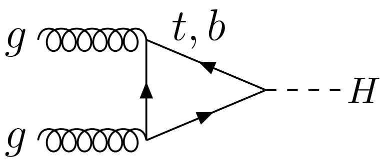
$\sim \kappa_F^2$

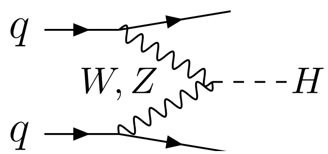
Signal Rates

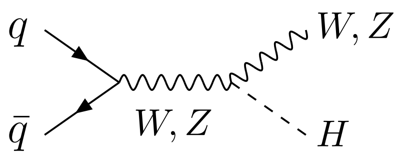
▷ **Coupling modifications affect** Higgs signal but not background
signal rates changed, but kinematics unaffected ⇒ Rescale SM searches

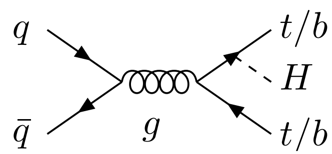
▷ **NNLO QCD corrections:** not affected by modified Higgs couplings (not true for NLO EW)

▷ **Rescaling - Production (NNLO QCD)**









$\frac{\sigma_{QCD}}{\sigma_{QCD}^{SM}}$ κ_F^2 κ_V^2 κ_V^2 κ_F^2

▷ **Rescaling - Decay**

$$\frac{\Gamma(H \to f\bar{f})}{\Gamma(H \to f\bar{f})^{SM}} = \frac{\Gamma(H \to gg)}{\Gamma(H \to gg)^{SM}} = \kappa_F^2 \quad \frac{\Gamma(H \to VV)}{\Gamma(H \to VV)^{SM}} = \kappa_V^2 \quad \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to \gamma\gamma)^{SM}} = \frac{(\kappa_V J_\gamma - \kappa_F I_\gamma)^2}{(J_\gamma - I_\gamma)^2}$$

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[in units of SM couplings].

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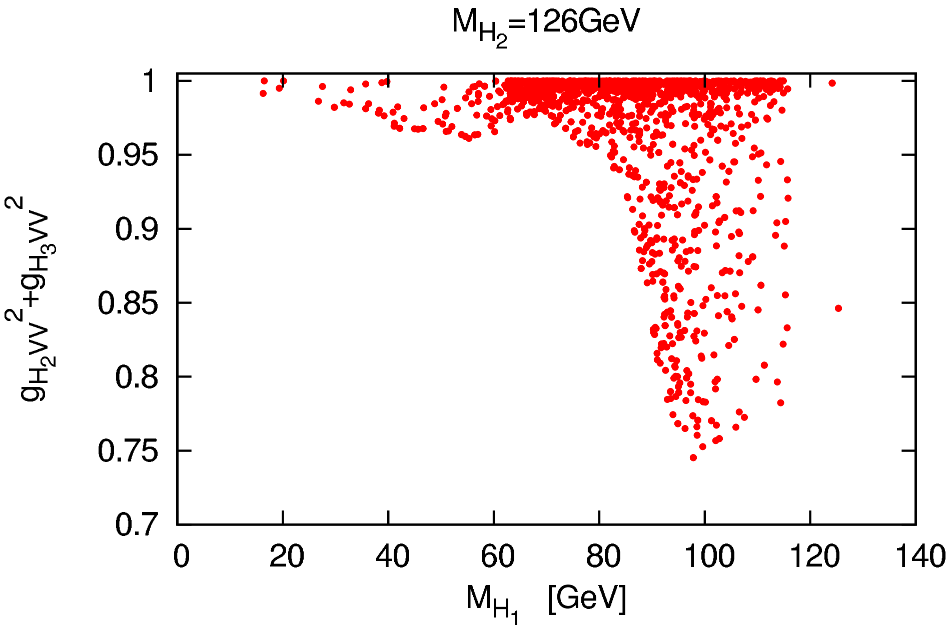
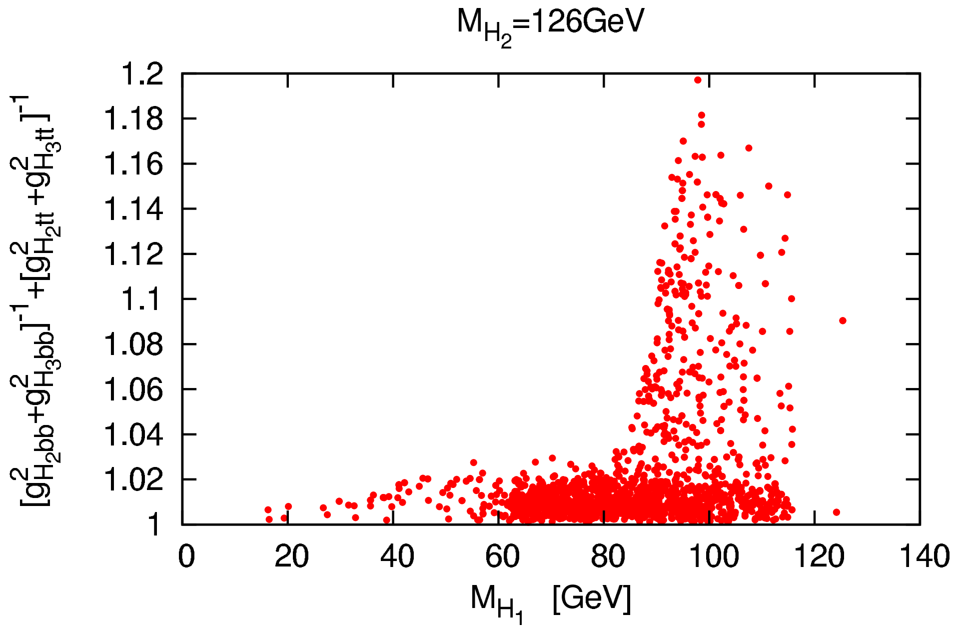
- **Scenario 2** H_2 SM-like and only H_2 and H_3 have been discovered

  Deviation of sum rules: distinguish NMSSM from MSSM

$\mathcal{V}$iolation of $\mathcal{S}$um $\mathcal{R}$ules

Walz,MMM





H_2 is SM-like and only H_2, H_3 have been discovered

around 100 GeV H_1 and H_2 close in mass $\rightsquigarrow$ large mixing

$\mathcal{D}$ecoupling $\mathcal{L}$imit

- **Heavy Higgs masses $\gg v$**

$$m_A^2,\, m_{H^0}^2,\, m_{H^\pm}^2 = \frac{2m_{12}^2}{\sin(2\beta)} + \mathcal{O}(v^2)$$

- **h^0 behaves SM-like**
  Leading coupling modifications with respect to SM parametrized by

$$\xi = \frac{v^2}{2m_A^2}\, \sin^2(2\beta)\, \left[\lambda_1 - \lambda_2 + (\lambda_1 + \lambda_2 - \lambda_3 - \lambda_4 - \lambda_5) \cos 2\beta\right]$$

- **Modifications of couplings resp partial widths w/ resp to SM** expressed in terms of

$$\sin^2(\beta - \alpha) \approx 1 - \xi^2, \qquad \frac{\cos^2\alpha}{\sin^2\beta} \approx 1 + 2\xi \cot\beta, \qquad \frac{\sin^2\alpha}{\cos^2\beta} \approx 1 - 2\xi \tan\beta.$$

- **Numerically** for $\lambda_i \sim \mathcal{O}(1)$ and $\tan\beta \approx 1$:
  $\xi \approx 0.03/(m_A/\text{TeV})^2 \Rightarrow$ corrections of tens of percent for moderate m_A and $\tan\beta$ values

$\mathcal{E}$ffective $\mathcal{T}$heory $\mathcal{A}$pproach $\mathcal{V}$ersus $\mathcal{S}$pecific $\mathcal{M}$odels

- **Effective Field Theory Approach**
  - $*$ assume few basic principles (e.g. field content, SM gauge symmetries)
  - $*$ parametrize SM deviations by higher-dimensional operators

Advantage: study large class of models

Disadvantage: cannot account for effects from light particles in the loops, Higgs decays into non-SM particles

Solution: study specific BSM models capturing these features