$\mathcal{BSM}$ $\mathcal{H}$iggs $\mathcal{P}$roperties

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

SFB TR-9, Final Meeting

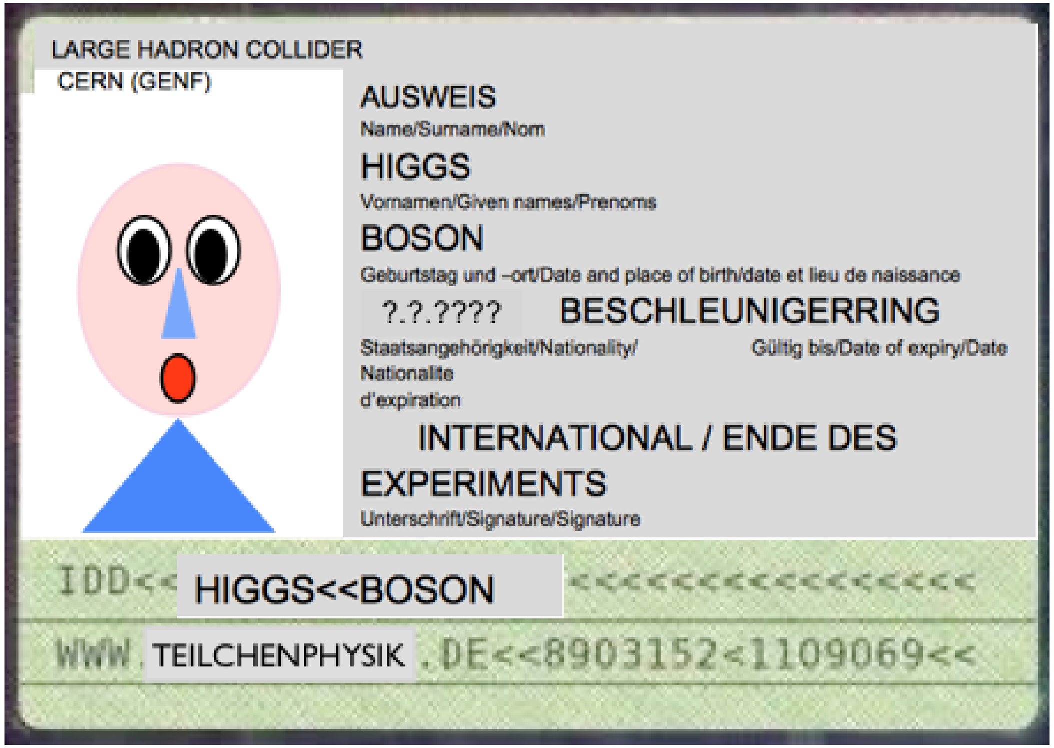
Durbach

15-19 Sept 2014

The Menu

$\mathcal{I}$ntroduction

- **Higgs Mechanism:** There is a Higgs Particle!
- **Verification:** First step: Production of the Higgs boson



𝒟iscovery of 𝒩ew 𝒫article - 4 𝒥uly 2012

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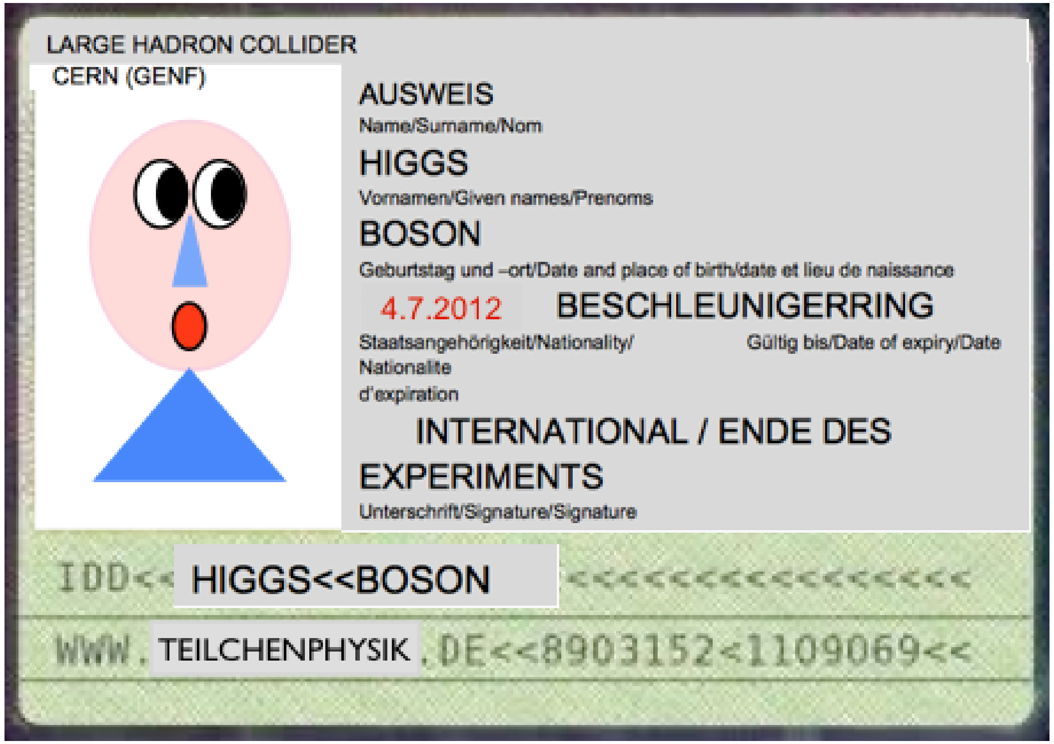

Discovered Particle is the Higgs Boson

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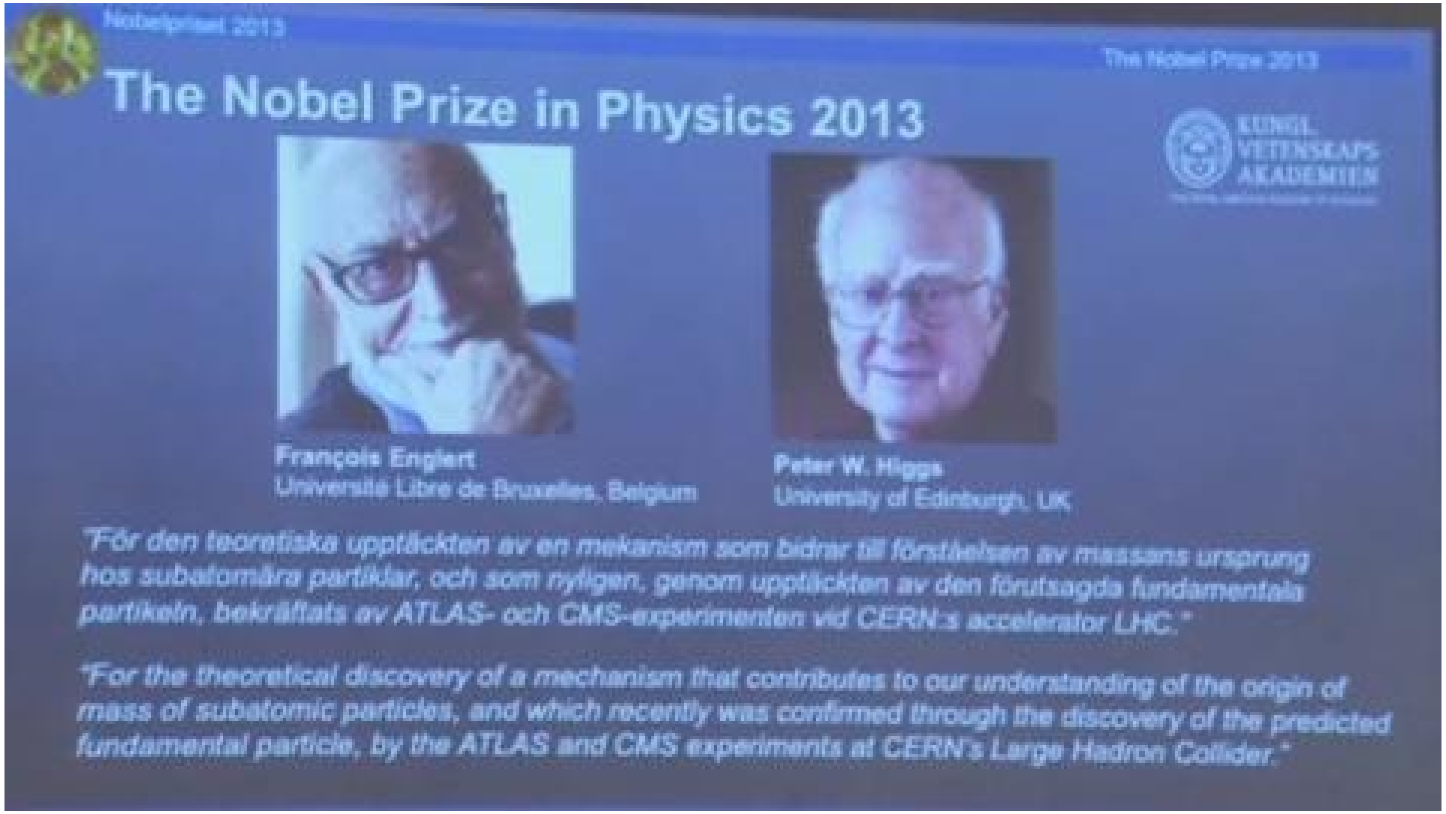
New results indicate that particle discovered at CERN is a Higgs boson

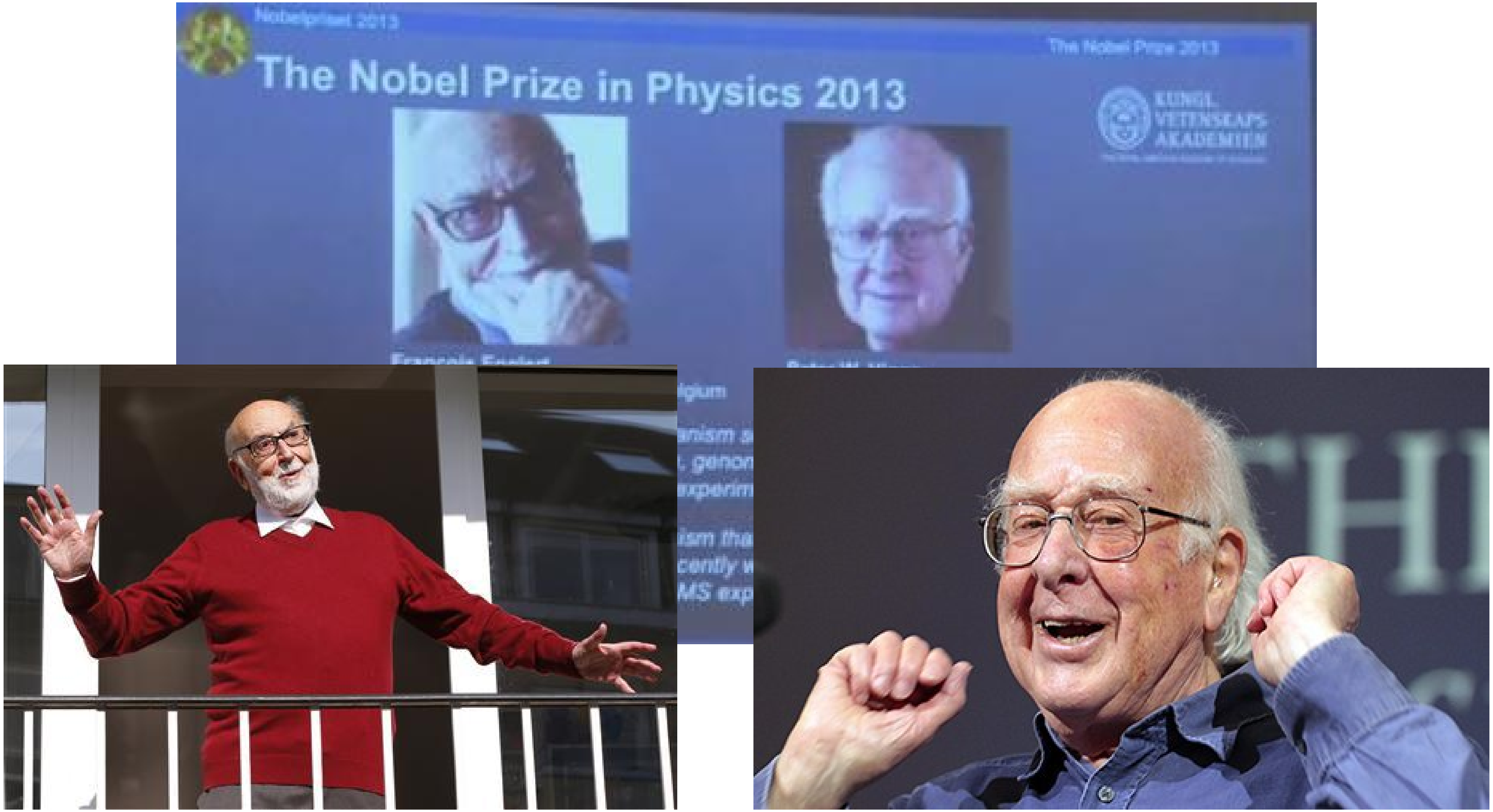
14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

$\mathcal{N}$obel $\mathcal{P}$rize in $\mathcal{P}$hysics 2013



$\mathcal{N}$obel $\mathcal{P}$rize in $\mathcal{P}$hysics 2013



$\mathcal{S}$tandard $\mathcal{M}$odel – $\mathcal{L}$imitations

- **Higgs Discovery $\rightsquigarrow$ New Era of Particle Physics:**
  consistent extrapolation to scales many orders of magnitude beyond directly accessible scales
- **Success of SM:**
  predictions at highest precision including quantum corrections $\longleftarrow$ tested experimentally
- **Open Questions:**
  $\rightsquigarrow$ Standard Model is low-energy effective theory of more fundamental theory at some high scale

*W*here is *N*ew *P*hysics?

- **Naturalness: Just around the corner!**
- **Experimental reality:** No Beyond the Standard Model Physics discovered so far!

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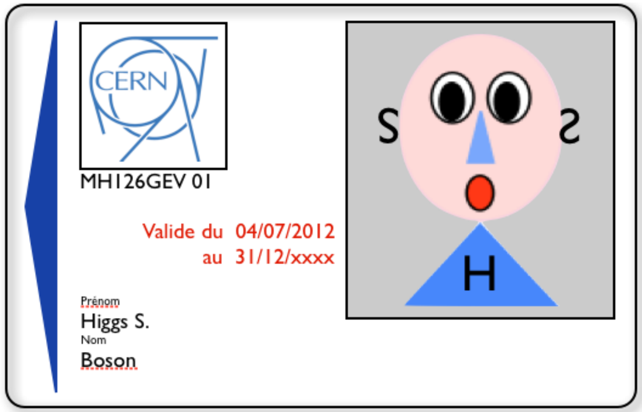
But: Discovery of new scalar particle 4th July 2012



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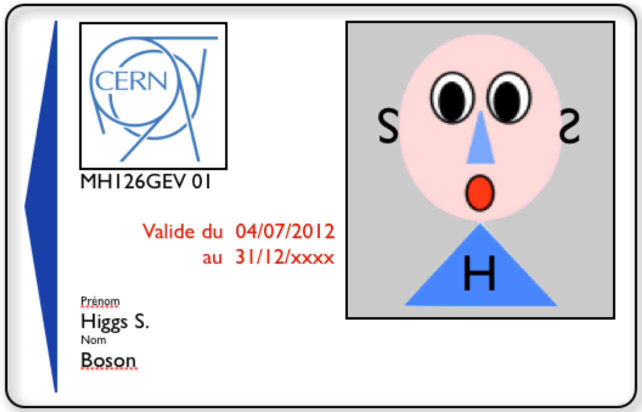
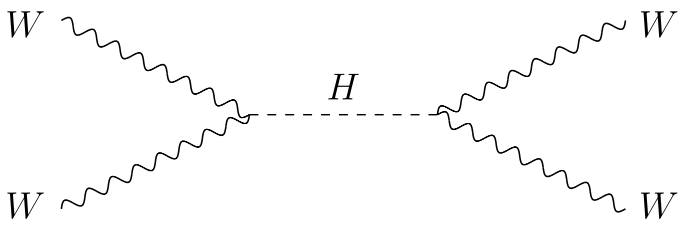


$\mathcal{W}$hat can we learn from $\mathcal{H}$iggs $\mathcal{P}$hysics in the $\mathcal{F}$uture?

$\mathcal{W}$hat is the $\mathcal{D}$ynamical $\mathcal{O}$rigin of $\mathcal{EWSB}$?

$\mathcal{I}$s the Higgs boson $\mathcal{E}$lementary or $\mathcal{C}$omposite?

Weakly coupled models

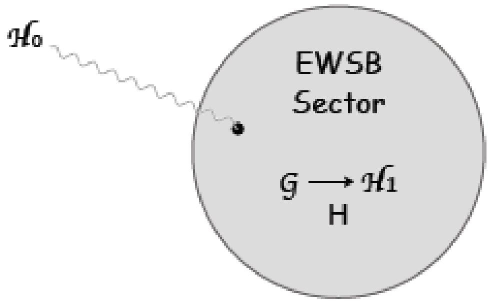


$\mathcal{S}$M, $\mathcal{S}$USY, ...

SUSY Partner ~ 1 TeV

New particles necessary to stabilise the Higgs boson mass

Strongly-interacting dynamics



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

top partners $\gtrsim 700$ GeV

Resonances for unitarity

Higgs boson composite object

Cartoon from R.Contino [1005.4269]

Higgs Boson Couplings

What Can We Learn From Coupling Measurements?

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

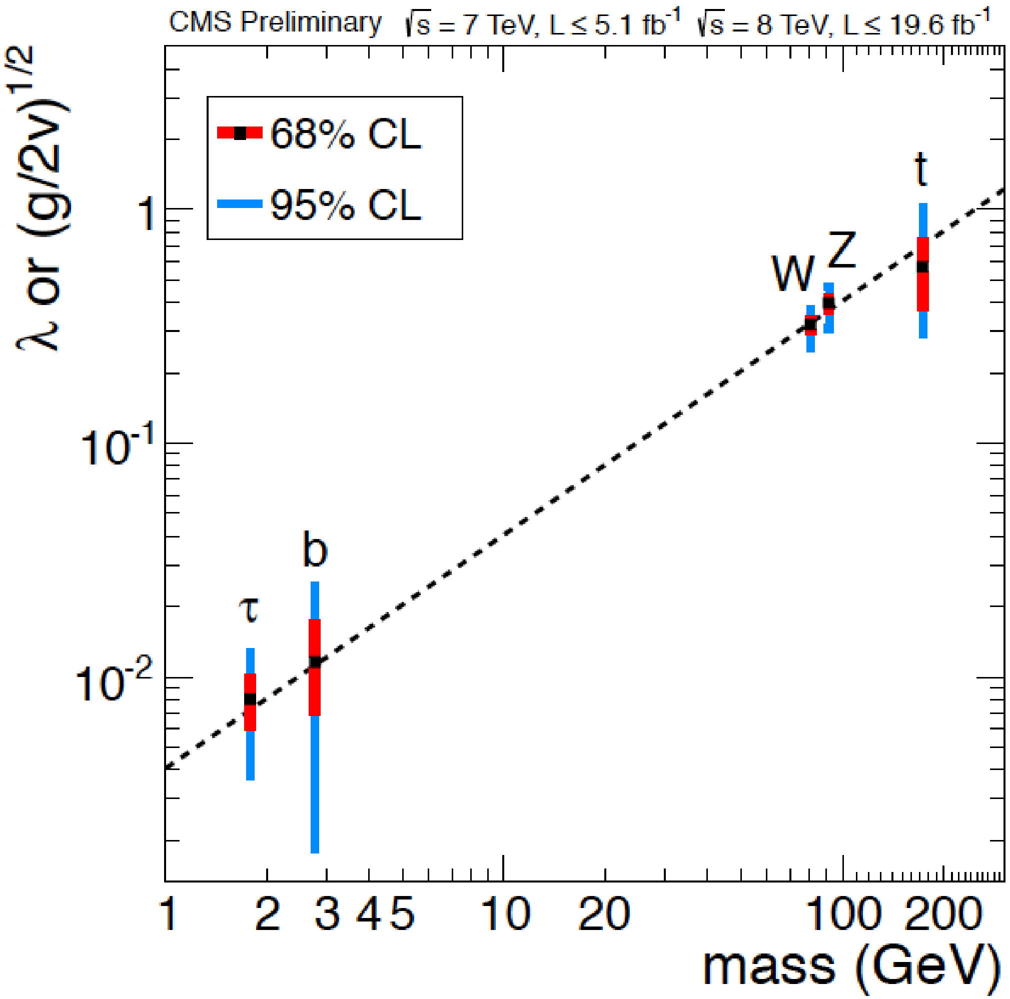
- **Deviations from SM couplings ⟵ New Physics**
  - ◇ modified Higgs properties through mixing effects with other scalars
  - ◇ modified Higgs properties through loop effects (⟵ virtual contributions of new gauge bosons, scalars or fermions)

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

[See talk by Michael Rauch]

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

CMS-PAS-HIG-13-005

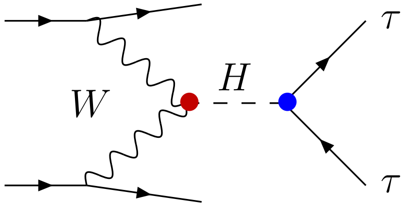


$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

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

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

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

- **Couplings extracted** from $\mu = (\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$ values provided by experiments

- **Theoretical approach**
  - ∗ Effective Lagrangian which defines the meaning of the couplings
  - ∗ Effective Lagrangian w/ modified Higgs couplings → signal rates → fit to experimental μ values

◇ **For further work, see:**

D.Carmi, A.Falkowski, E.Kuflik, T.Volansky; D.Carmi, A.Falkowski, E.Kuflik, T.Volansky, J.Zupan;
A.Azatov, R.Contino, J.Galloway; P.Giardino, K.Kannike, M.Raidal, A.Strumia;
J.Ellis, T.You; M.Klute, R.Lafaye, T.Plehn, M.Rauch, D.Zerwas; M.Montull, F.Riva;
I.Low, J.Lykken, G.Shaugnessy; T.Corbett, O.Eboli, J.González-Fraile, M.C. González-Garcia;
S. Banerjee, S. Mukhopadhyay, B. Mukhopadhyaya; Cao eal; T.Plehn, M. Rauch;
Baglio, Djouadi, Godbole; Bélanger, Dumon, Ellwanger, Gunion, Kraml; Buchalla, Cata, Krause; ...

(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

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

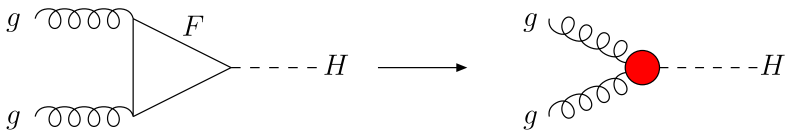
$$+ m_W^2\, W_\mu^+ W^{-\,\mu} \left(1 + 2\kappa_W \frac{h}{v} + \ldots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2\kappa_Z \frac{h}{v} + \ldots\right) + \ldots$$

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

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

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

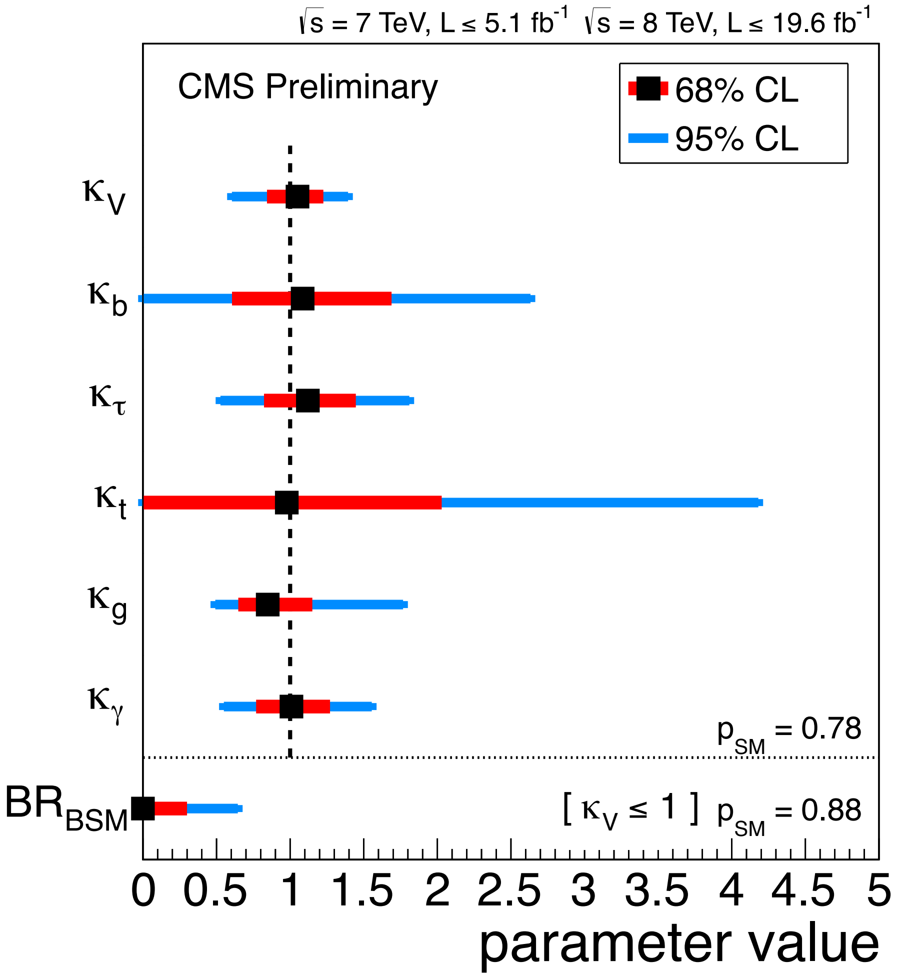
$*$ $\overline{\kappa}_{g,\gamma,Z\gamma}$ parametrize new physics in the hgg, $h\gamma\gamma$ and $hZ\gamma$ loop couplings

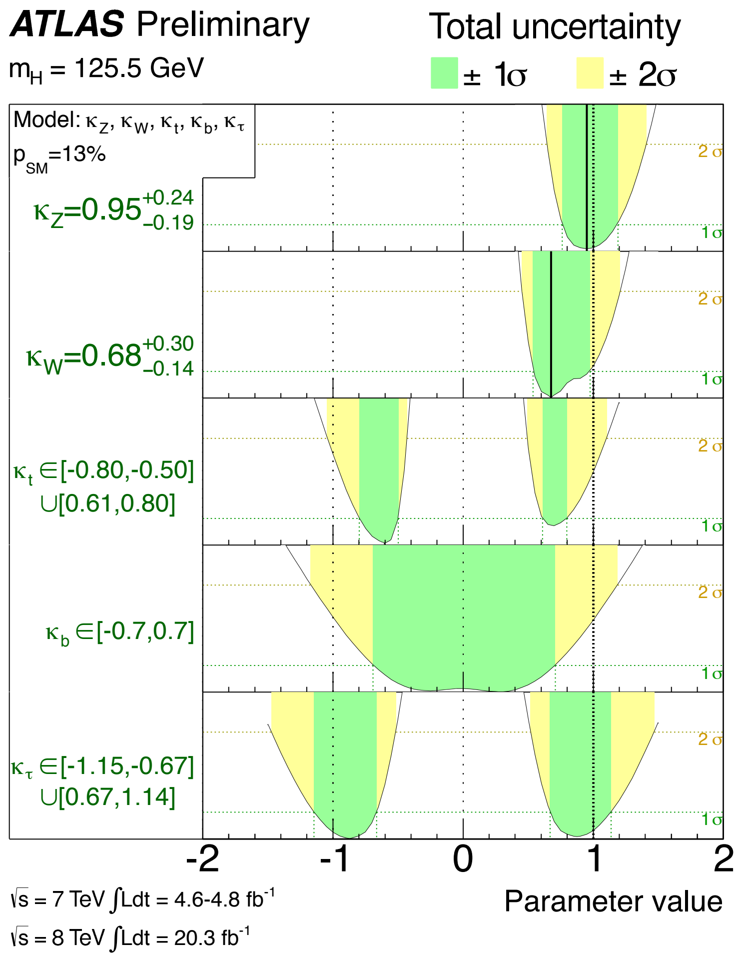


Status: Coupling Scale Factor Measurements

CMS Collaboration

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 $\rightsquigarrow$

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

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

[caveat: non-decouplings effects]

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

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

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

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

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

Effective Theory Approach Versus Specific Models

- **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

For example: 2HDM, Supersymmetry, Portal Higgs, ...


werbepause

$\mathcal{C}$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:

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:

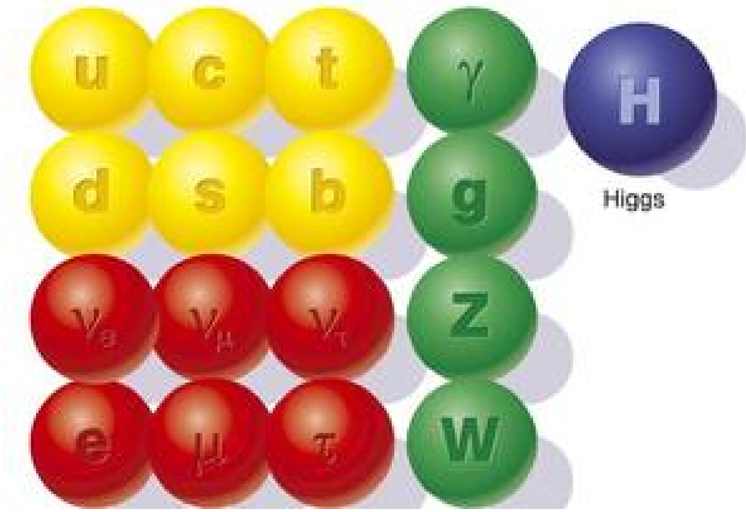
- Short explanations on the program are given here.
- To be advised about future updates or important modifications concerning the 2HDM version, send an E-mail to margarete.muehlleitner@kit.edu.
- Modifs/corrected bugs are indicated explicitly in this file.

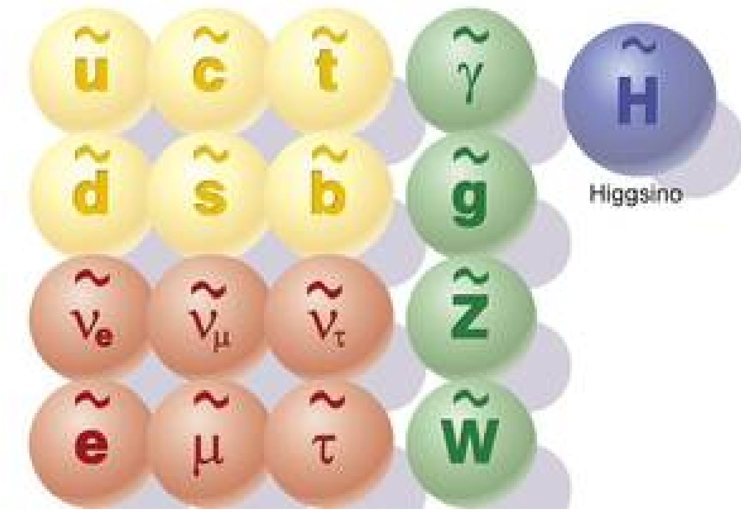
Downloading the files needed for HDECAY for 2HDM:

- 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.

Supersymmetry

SUSY *I*nterpretation of the *LHC* *H*iggs *R*esults





*M*any good reasons for *S*upersymmetry

- Solution of the hierarchy problem
- Gauge coupling unification
- Dark Matter candidate
- Dynamical generation of Higgs potential
- Maximal possible symmetry of the S-matrix
- Way to incorporate gravity?
- ...

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

$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$

$g_{\Phi dd} \uparrow$

$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

- **Vast literature on MSSM Higgs of ~ 125 GeV**

  Arbey eal; Li eal; Feng eal; Baer eal; Akula eal; Hall eal; Albornoz Vasquez eal; Heinemeyer eal; Desai et al.; Draper eal; Carena eal; Cao eal; Christensen eal; Kadastik eal; Buchmuller eal; Arvanitaki eal; Ellis eal; Curtin eal; Brummer eal; Barger eal; Hagiwara eal; Arbey eal; Blum eal; Beskidt eal; Baer eal; Giudice eal; Carena eal; Benbrik eal; Akula eal; Cahill-Rowley eal; Hirsch eal; ...

- **Compatibility of MSSM Higgs mass with LHC Search**

  ⋆ Upper mass bound on SM-like Higgs with higher-order correction Δm_h

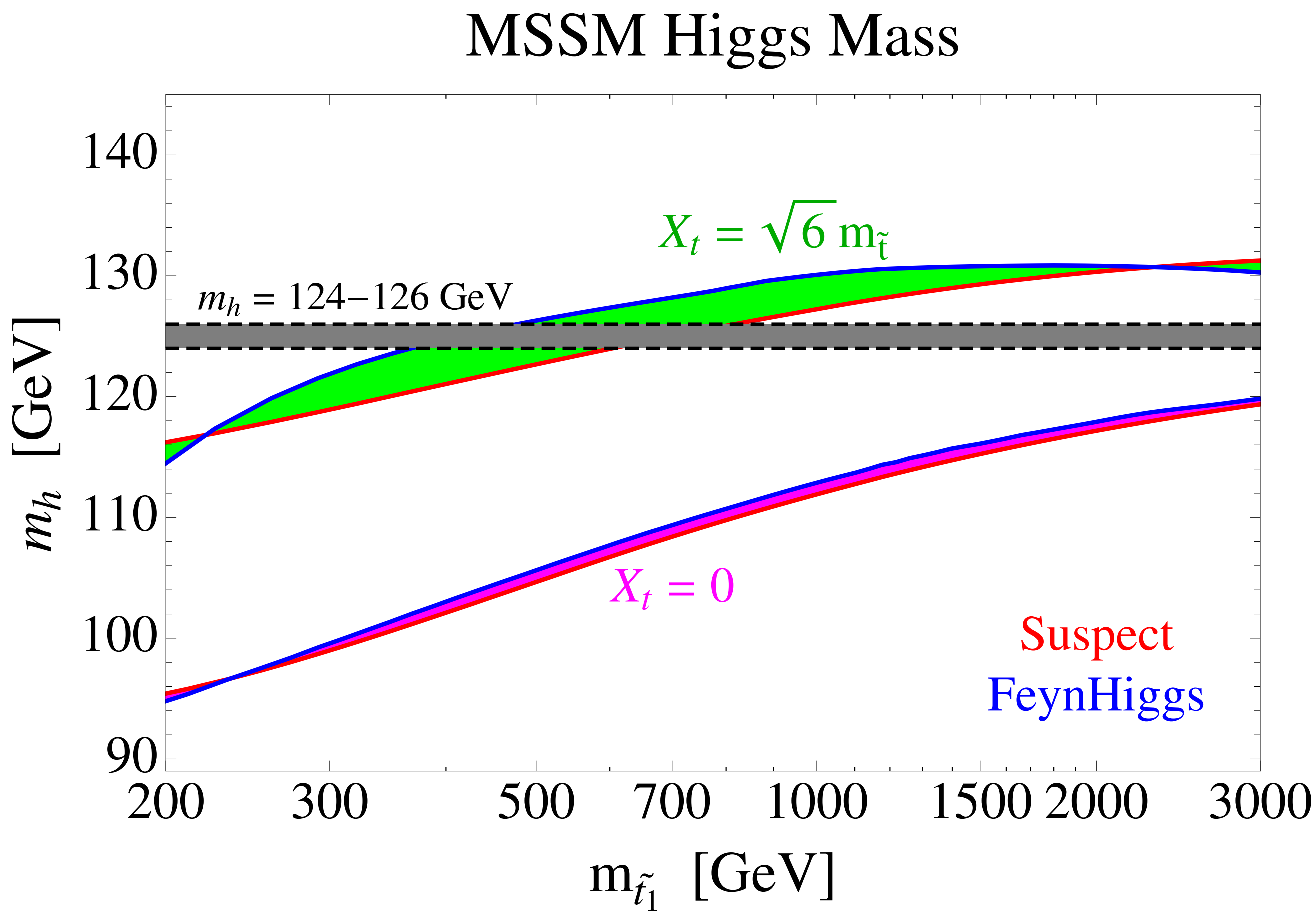
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

  ⋆ $\Rightarrow M_H \approx 125$ GeV requires

$$\Delta m_h \approx 85 \text{ GeV } (\tan\beta \text{ large}) \Rightarrow \text{large corrections} \rightsquigarrow \text{'fine'-tuning}$$

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

Hall,Pinner,Ruderman 1112.2703



- **Maximal stop mixing:** $m_{\tilde{t}_1} \overset{!}{\gtrsim} 500$ GeV

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

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

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

- **The μ-problem of the MSSM:**

  Higgsino mass parameter μ must be of order of EWSB scale Kim,Nilles

- **Solution in the NMSSM:**

  μ generated dynamically through the VEV of scalar component of an additional chiral superfield field $\hat{S}$: $\mu = \lambda \langle S \rangle$

- **Enlarged Higgs and neutralino sector:**

7 Higgs 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 Higgs boson phenomenology**

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

- **Vast literature on NMSSM Higgs of ~ 125 GeV**

  Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Albornoz Vasquez eal; Cao eal; Gabrielli eal; Ellwanger, Hugonie; Kang eal; Cheung eal; Jeong eal; Hardy eal; Kim eal; Arvanitaki eal; ...

- **Compatibility of NMSSM Higgs mass with LHC Searches:**

  $\star$ Upper mass bounds + corrections to the MSSM, NMSSM Higgs boson mass:

  MSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$

  NMSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

  $\Rightarrow M_H \approx 125$ requires:

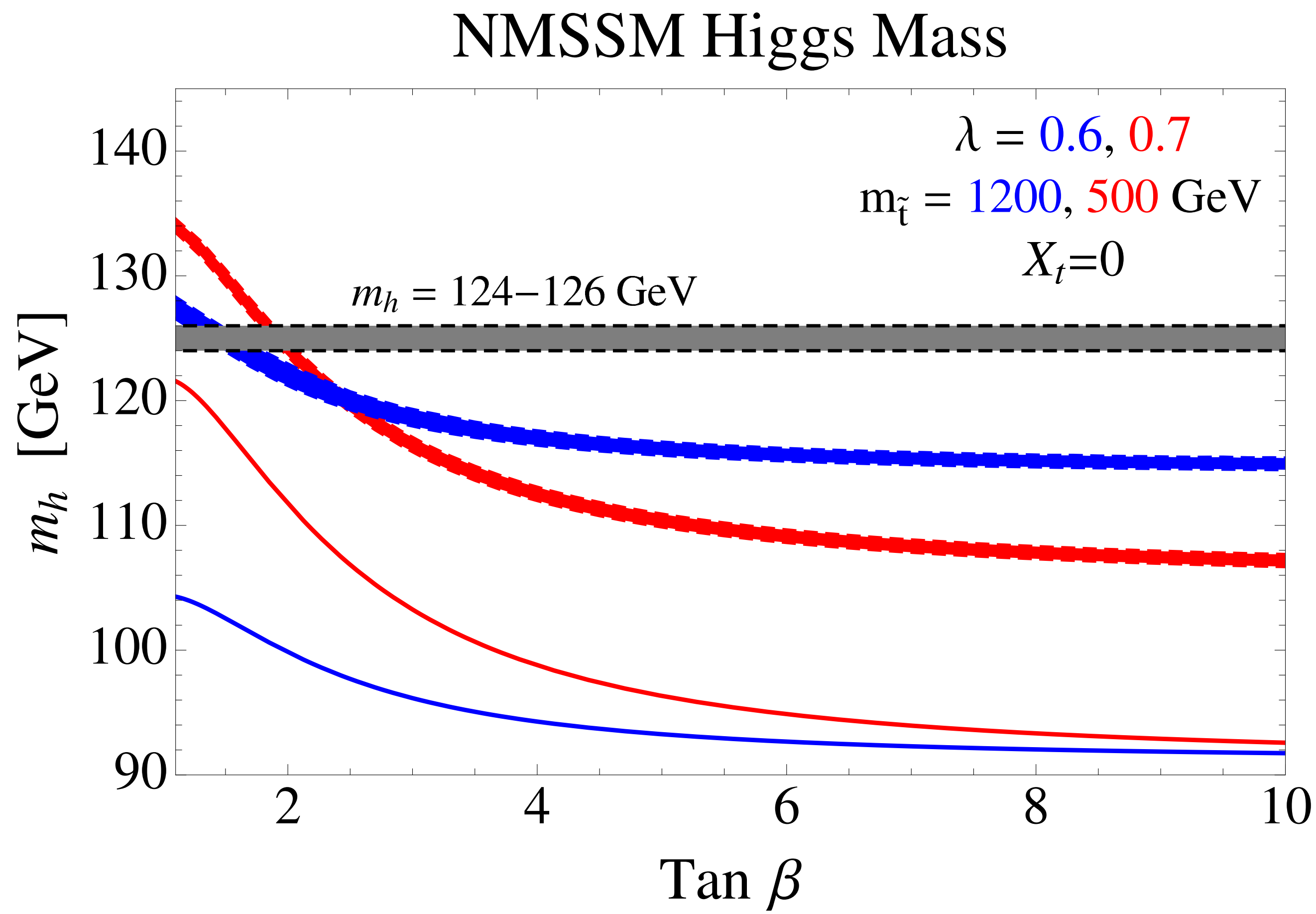
  MSSM: $\Delta m_h \approx 85$ GeV ($\tan\beta$ large) $\Rightarrow$ large corrections are needed $\rightsquigarrow$ conflict with fine-tuning

  NMSSM: $\Delta m_h \approx 55$ GeV ($\lambda = 0.7, \tan\beta = 2$)

  $\Rightarrow$ NMSSM requires less fine-tuning

  Hall,Pinner,Ruderman; Ellwanger; Arvanitaki,Villadoro; King,MMM,Nevzorov; Kang,Li,Li; Cao,Heng,Yang,Zhang,Zhu

Hall,Pinner,Ruderman 1112.2703



◇ m_h maximized for small values of $\tan\beta$

◇ $m_h \approx 125$ GeV can be achieved also for zero mixing $X_t = 0$ and $m_{\tilde{t}_1} \geq 500$ GeV

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{D}$iscovery at the $\mathcal{LHC}$

- **Present Status:**

  Higgs signal at 125 GeV

  No BSM Higgs discovered yet. True?

- **Could be that we already discovered NMSSM Higgs bosons!**

  Higgs signal at 125 GeV is built up by two degenerate Higgs bosons.

- **What about the MSSM?**

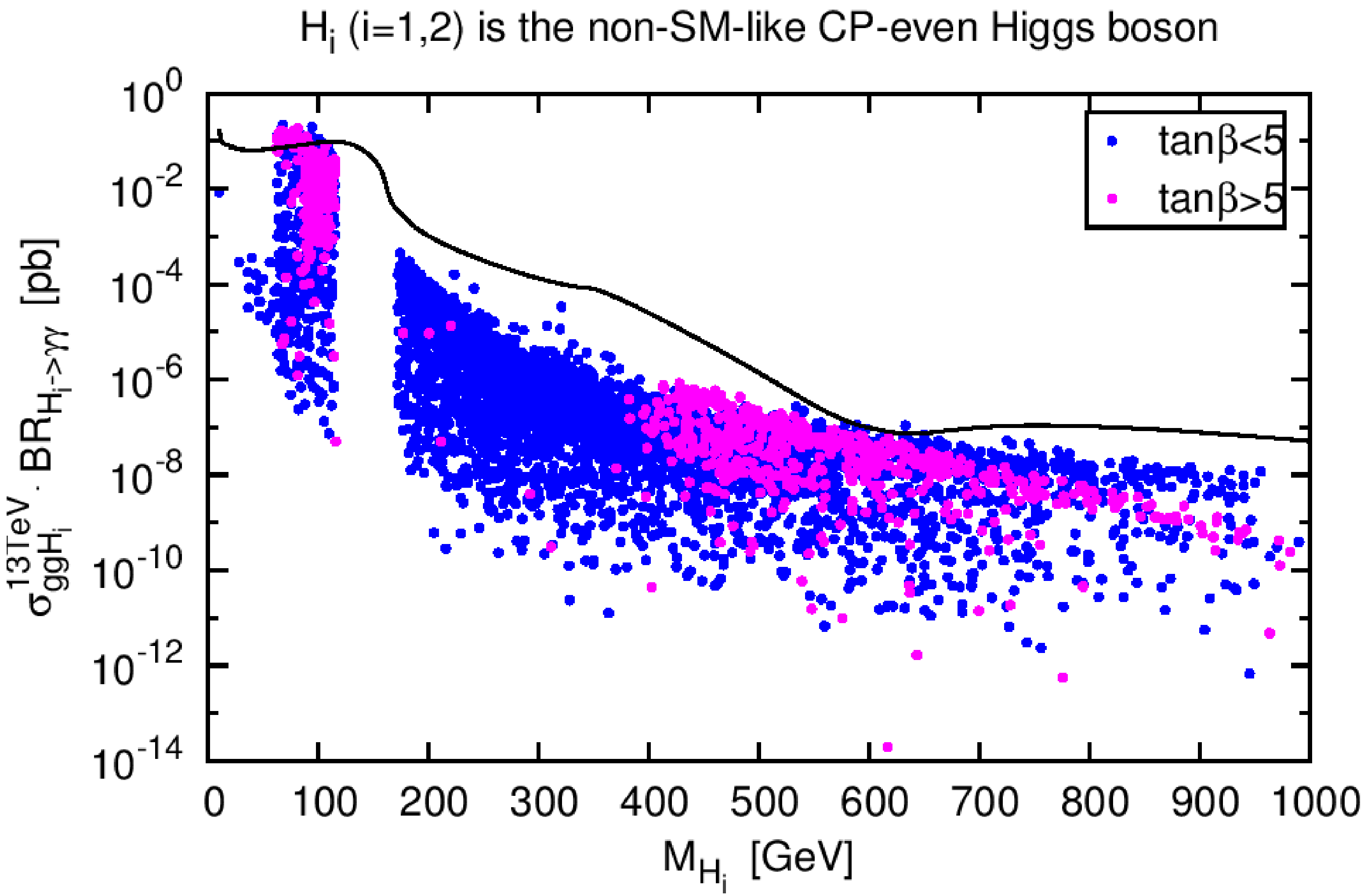
  Two light MSSM CP-even Higgs bosons $\Longleftrightarrow$ light CP-odd A, relatively light $H^\pm$

  light $M_{H^\pm}$ excluded ATLAS-CONF-2012-011 and 2013-090, CMS-HIG-12-052

- **SM-like Higgs boson:** can be lightest or next-to-lightest scalar Higgs boson

$\mathcal{S}$can $\mathcal{R}$esult for $\mathcal{N}$on-$\mathcal{SM}$-like $\mathcal{CP}$-even $\mathcal{H}$iggs $\mathcal{R}$ates

King,MMM,Nevzorov,Walz



$\mathcal{A}$lternative $\mathcal{P}$roduction $\mathcal{C}$hannels

- **Small direct production rates:** $\leadsto$ alternative production channels

- **Higgs-to-Higgs Decays:**

$$\sigma(gg \to \phi_i) \times BR(\phi_i \to \phi_j \phi_k) \times BR(\phi_j \to XX) \times BR(\phi_k \to YY)$$

- **Higgs-to-Higgs+Gauge-Boson Decays:**

$$\sigma(gg \to H) \times BR(H \to ZA_s) \; , \quad \sigma(gg \to A) \times BR(A \to ZH_s)$$

$\mathcal{B}$enchmarks for $\mathcal{H}$iggs-to-$\mathcal{H}$iggs $\mathcal{D}$ecays

• **Higgs-to-Higgs Decays**

$$\sigma(gg \to \phi_i) \times BR(\phi_i \to \phi_j\phi_k) \times BR(\phi_j \to XX) \times BR(\phi_k \to YY)$$

▷ Interesting for heavier ϕ_i discovery if σ_{prod} large enough and BR into lighter Higgs pairs dominates

▷ For lighter ϕ_j, ϕ_k interesting production if direct prod strongly suppressed due to singlet nature

• **Benchmarks for Higgs-to-Higgs Decays** King,Nevzorov,MMM,Walz

A) $H_2 = h, H_1 = H_s, \tan\beta$ small, light spectrum $\lesssim 350$ GeV

B) $H_1 = h, H_2 = H_s, \tan\beta$ small

C) $H_1 = h, H_3 = H_s, \tan\beta$ large

D) $H_2 = h$ decays into lighter Higgs pairs

$\mathcal{B}$enchmark $H_1 = h$ and $\tan\beta$ small

B.1 (Point ID Poi2a)	Scenario		
M_h, M_{H_s}, M_H	124.6 GeV	181.7 GeV	322.6 GeV
M_{A_s}, M_A	72.5 GeV	311.7 GeV	
$\|S_{H_2 h_s}\|^2, \|P_{A_1 a_s}\|^2$	0.90	1	
$\mu_{\tau\tau}$, μ_{bb}	1.54	1.01	
μ_{ZZ}, μ_{WW}, $\mu_{\gamma\gamma}$	0.93	0.93	1.54
$\tan\beta, \lambda, \kappa$	1.9	0.628	0.354
$A_\lambda, A_\kappa, \mu_{\text{eff}}$	251.2 GeV	53.8 GeV	158.9 GeV
M_1, M_2, M_3	890 GeV	576 GeV	1919 GeV
A_t, A_b, A_τ	1555 GeV	-1006 GeV	-840 GeV
$M_{Q_3} = M_{t_R}, M_{L_3} = M_{\tau_R}$, other SSB parameters	1075 GeV	540 GeV	3 TeV

BR$(A_s \to \gamma\gamma) = 0.84$, BR$(H_s \to A_s A_s) = 0.97$, BR$(H \to h H_s) = 0.51$, BR$(A \to H_s A_s) = 0.21$

$\mathcal{B}$enchmark $H_1 = h$ and $\tan\beta$ small

B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to 6\gamma)$	301.58 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to bb + 4\gamma)$	157.64 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to 4b + \gamma\gamma)$	27.47 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to \tau\tau + 4\gamma)$	14.99 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to \tau\tau + bb + \gamma\gamma)$	5.22 fb
$\sigma(ggA)$BR$(A \to H_s A_s \to A_s + A_s A_s \to 4\tau + \gamma\gamma)$	0.25 fb
$\sigma(ggA)$BR$(A \to h A_s)$	29.96 fb
$\sigma(ggA)$BR$(A \to h A_s \to \gamma\gamma + b\bar{b})$	16.25 fb
$\sigma(ggA)$BR$(A \to h A_s \to \gamma\gamma + \tau\tau)$	1.70 fb
$\sigma(ggA)$BR$(A \to h A_s \to b\bar{b} + b\bar{b})$	2.83 fb
$\sigma(ggA)$BR$(A \to Z H_s)$	554.38 fb
$\sigma(ggA)$BR$(A \to Z H_s \to bb + A_s A_s \to bb + 4\gamma)$	57.36 fb
$\sigma(ggA)$BR$(A \to Z H_s \to bb + A_s A_s \to 4b + \gamma\gamma)$	19.99 fb
$\sigma(ggA)$BR$(A \to Z H_s \to Z A_s A_s \to bb + \tau\tau + \gamma\gamma)$	6.35 fb
$\sigma(ggA)$BR$(A \to Z H_s \to ll/\tau\tau + A_s A_s \to ll/\tau\tau + 4\gamma)$	12.78 fb
$\sigma(ggA)$BR$(A \to Z H_s \to ll/\tau\tau + A_s A_s \to ll\tau\tau/4\tau + \gamma\gamma)$	0.42 fb

accessible:

$\lambda_{H_s A_s A_s}$
$\lambda_{H H_s h}$
$\lambda_{A A_s H_s}$
$\lambda_{A A_s h}$


Composite Higgs
Strong EWSB

$\mathcal{BSM}$ $\mathcal{E}$ffects - $\mathcal{E}$xample $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{B}$oson

- **Bound state from a strongly interacting sector** Kaplan,Georgi;Dimopoulos eal;Dugan eal

- **How can we obtain a light composite scalar boson?**

  Global symmetry of strong sector G spontaneously broken at scale f to subgroup H

  G/H: 4th Nambu-Goldstone Boson: Scalar boson

- **Possible symmetry patterns** $*$ H must contain SM gauge group

  $*$ G must contain an $SU(2) \times SU(2) \sim SO(4)$ symmetry $\rightsquigarrow$ PGB is a doublet field

  Example: - $SO(5)/SO(4) \rightsquigarrow$ PGB: one doublet

- **Higgs Boson Mass protected** $\leftarrow$ quantum corrections saturated at composite scale

- **Higgs Potential generated radiatively**

  ◇ By gauge boson and top quark loops

  ◇ EWSB triggered by top loops

$\mathcal{P}$artial $\mathcal{C}$ompositeness

- **Partial Compositeness**

Kaplan;
Contino,Kramer,Son,Sundrum

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

$$\mathcal{L}_{pc} = -\Delta_L \bar{q}_L Q_R - \Delta_R \bar{T}_L t_R + h.c.$$

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

◇ Linear couplings violate $\mathcal{G}$ explicitly $\rightsquigarrow$ Higgs potential induced

◇ Large top Yukawa couplings $\rightsquigarrow$ top largely composite

◇ Light Higgs boson requires light top partners

Matsedonskyi,Panico,Wulzer;
Redi,Tesi; Marzocca,Serone,Shu;
Pomarol,Riva

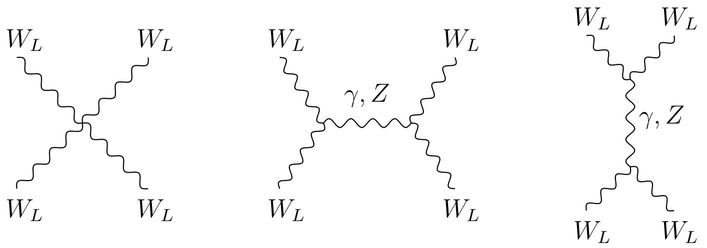
$\mathcal{P}$henomenological $\mathcal{I}$mplications?

▷ Modified Higgs couplings to SM gauge bosons and fermions

  * Unitarity not restored any more in $V_L V_L$ scattering

$\mathcal{I}$mplications of $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{D}$eviations

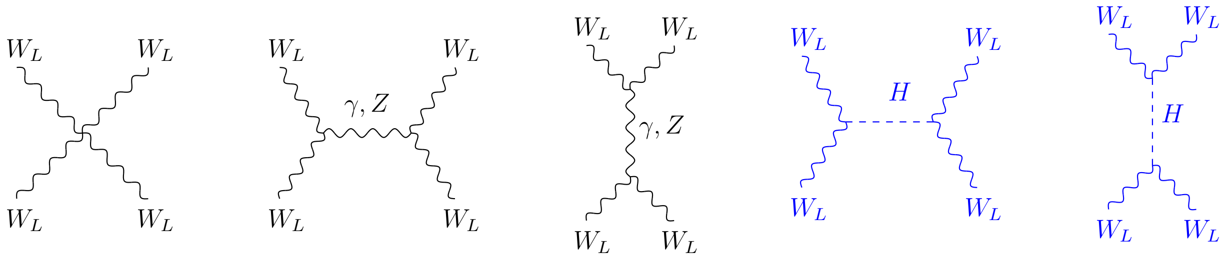
- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{s}{v^2}$$

$\mathcal{I}$mplications of $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{D}$eviations

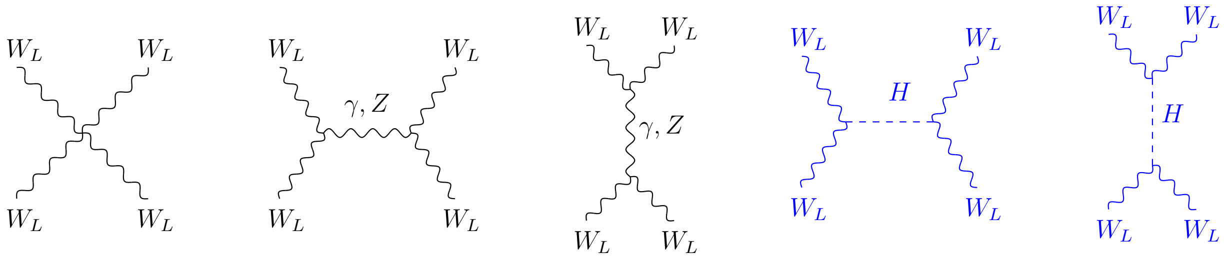
- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{\kappa_V^2 s^2}{s - m_h^2}\right)$$

$\mathcal{I}$mplications of $\mathcal{H}$iggs $\mathcal{C}$oupling $\mathcal{D}$eviations

- **Longitudinal W boson scattering**



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{\kappa_V^2 s^2}{s-m_h^2}\right)$$

$\kappa_V = 1$ perturbative unitarity in $WW \to WW$

- **Higgs couplings deviate from SM couplings** $\Rightarrow VV \to VV$ and $VV \to hh$ grow with E^2

Giudice,Grojean,Pomarol,Rattazzi; Contino eal '10,'13

$\mathcal{P}$henomenological $\mathcal{I}$mplications?

▷ Modified Higgs couplings to SM gauge bosons and fermions

- ∗ Unitarity not restored any more in $V_L V_L$ — Giudice eal; Contino eal '10,'13
- ∗ Higgs production and decay rates changed — Espinosa,Grojean,MMM
- ∗ Influences compatibility with EWPT — Giudice eal; Barbieri eal; Contino; Agashe eal; Gillioz; Lavoura,Silva; Lodone; Anastasiou eal; Grojean eal; Gröber eal

▷ New couplings

- ∗ Compatibility with Flavour Constraints — Agashe,Perez,Soni; Csaki eal; Blanke eal; Bauer eal; Redi,Weiler; Keren-Zur eal; Barbieri eal; Redi; Vignaroli; Da Rold eal; Delaunay eal
- ∗ Influences Double Higgs Production — Gröber,MMM; Contino eal; Gillioz eal

▷ New Resonances

- ∗ Compatibility with LHC searches — Gillioz,Gröber,Kapuvari,MMM

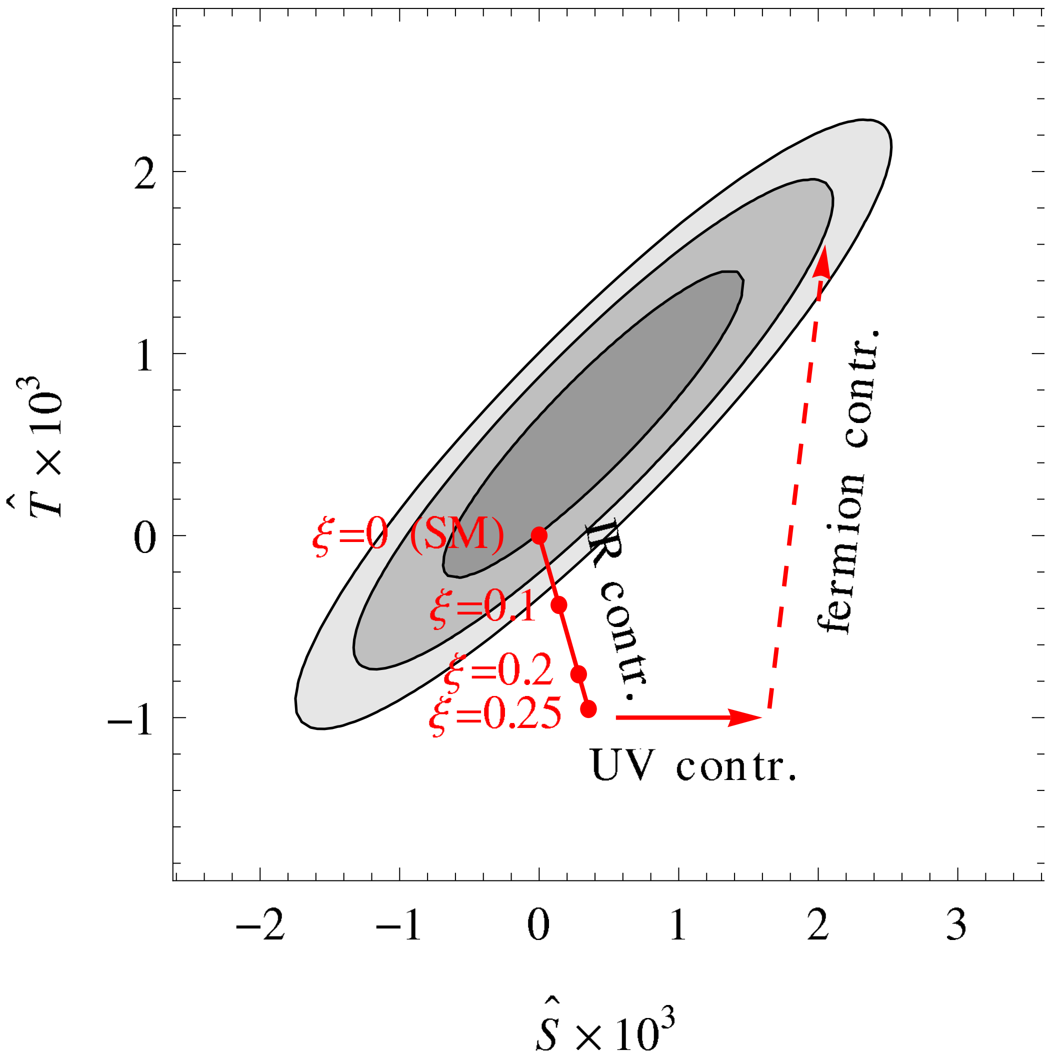
▷ Partial Compositeness — Kaplan;Contino,Kramer,Son,Sundrum

- ∗ Compatibility with Flavour Constraints
- ∗ Modified Higgs Yukawa couplings
- ∗ New particles in Loop induced processes
- ∗ Compatibibilty with direct LHC Searches for new fermions, with EWPT

$\mathcal{C}$onstraints on the $\mathcal{O}$blique $\mathcal{P}$arameters

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

Grojean,Matsedonskyi,Panico



$\mathcal{H}$eavy $\mathcal{Q}$uark $\mathcal{P}$artners and $\mathcal{LHC}$ $\mathcal{S}$earches

- **Decay Channels:**

Top Partners:	$\mathcal{T} \to Wb,\ Zt,\ ht$
Bottom Partners:	$\mathcal{B} \to Wt,\ Zb,\ hb$
Charge-5/3 Fermions:	$\mathcal{X} \to Wt$

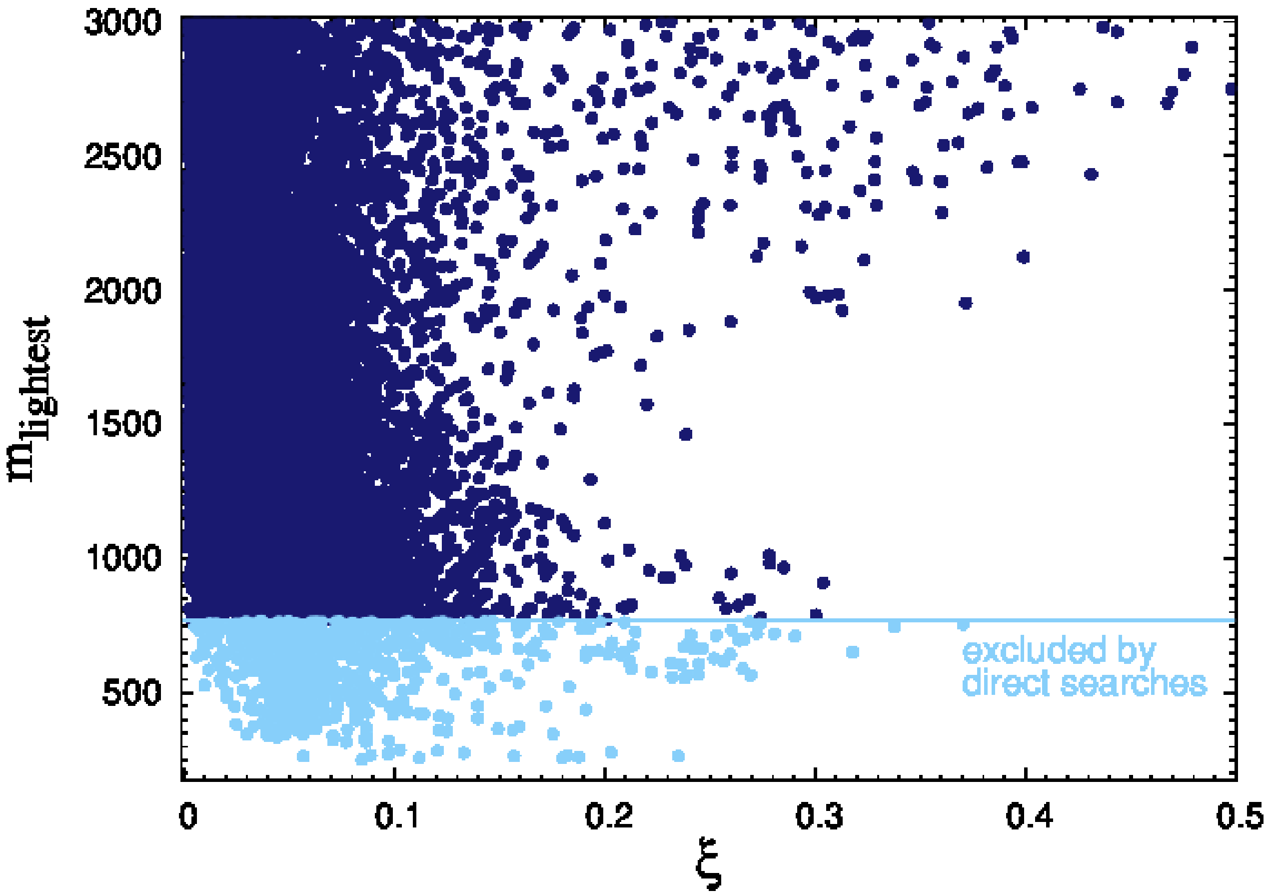
- **Limits from LHC Experiments:**

  The ATLAS Collaboration: ATLAS-CONF-2013-018, 051, 056, 060

  The CMS Collaboration: CMS PAS B2G-12-019, Phys. Lett. **B729** (2014) 149

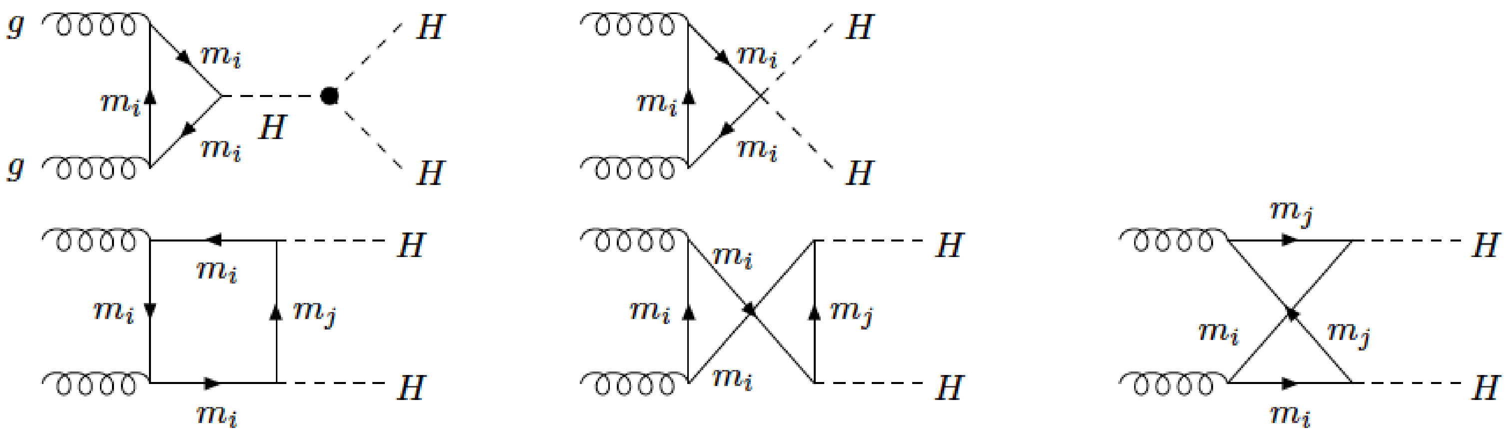
$\mathcal{H}$eavy $\mathcal{Q}$uark $\mathcal{P}$artners and $\mathcal{LHC}$ $\mathcal{S}$earches

Gillioz,Gröber,Kapuvari,MMM



$\mathcal{C}$omposite $\mathcal{D}$ouble $\mathcal{H}$iggs $\mathcal{P}$roduction

- **Double Higgs production through gluon fusion:**
  - ∗ sensitive to trilinear Higgs self-coupling — Baur,Glover; Spira eal; Djouadi,Kilian,MMM,Zerwas;Gröber,MMM
  - ∗ access to anomalous $HHf\bar{f}$ coupling — Contino eal '12



▷ Can be enhanced compared to the SM process

▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

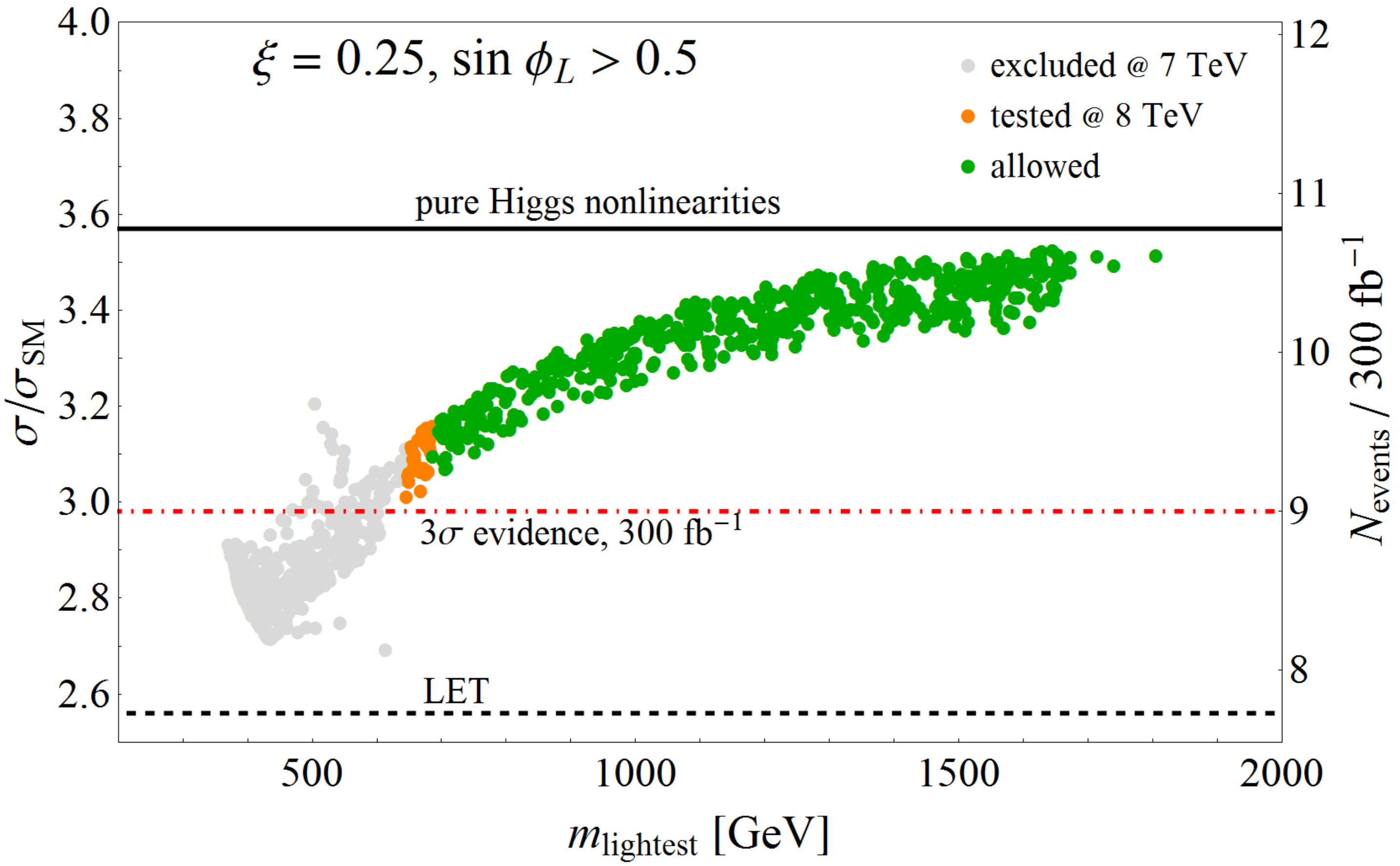
▷ Different fermions can contribute within one loop

▷ Sensitivity to details of heavy composite sector

Double Higgs Production in MCHM5 w/ Top Partners

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

Gillioz,Gröber,Grojean,MMM,Salvioni



only top; partners

⟵ integrated out

top and partners

⟵ integrated out

Summary

- **Higgs Discovery**
  - ∗ Higgs Signal compatible with SM-like Higgs Boson
  - ∗ Interpretation within numerous BSM physics models possible
- **Effective Lagrangian Approach**
  - ∗ Covers a large class of models
  - ∗ Complement by investigations in specific models
- **Supersymmetry**
  - ∗ MSSM/NMSSM: M_h compatible w/ LHC data
  - ∗ NMSSM: rich phenomenology
- **Composite Higgs Models**
  - ∗ Example for strong EWSB dynamics
  - ∗ Double Higgs Production sensitive to heavy fermion spectrum

Summary

Exciting times and discoveries are ahead of us.
With the LHC and HL-LHC we will have an excellent machine at hand
to investigate Higgs and New Physics and
gain insights in the true nature of the underlying theory

Work has only started!

Thank You For Your Attention!

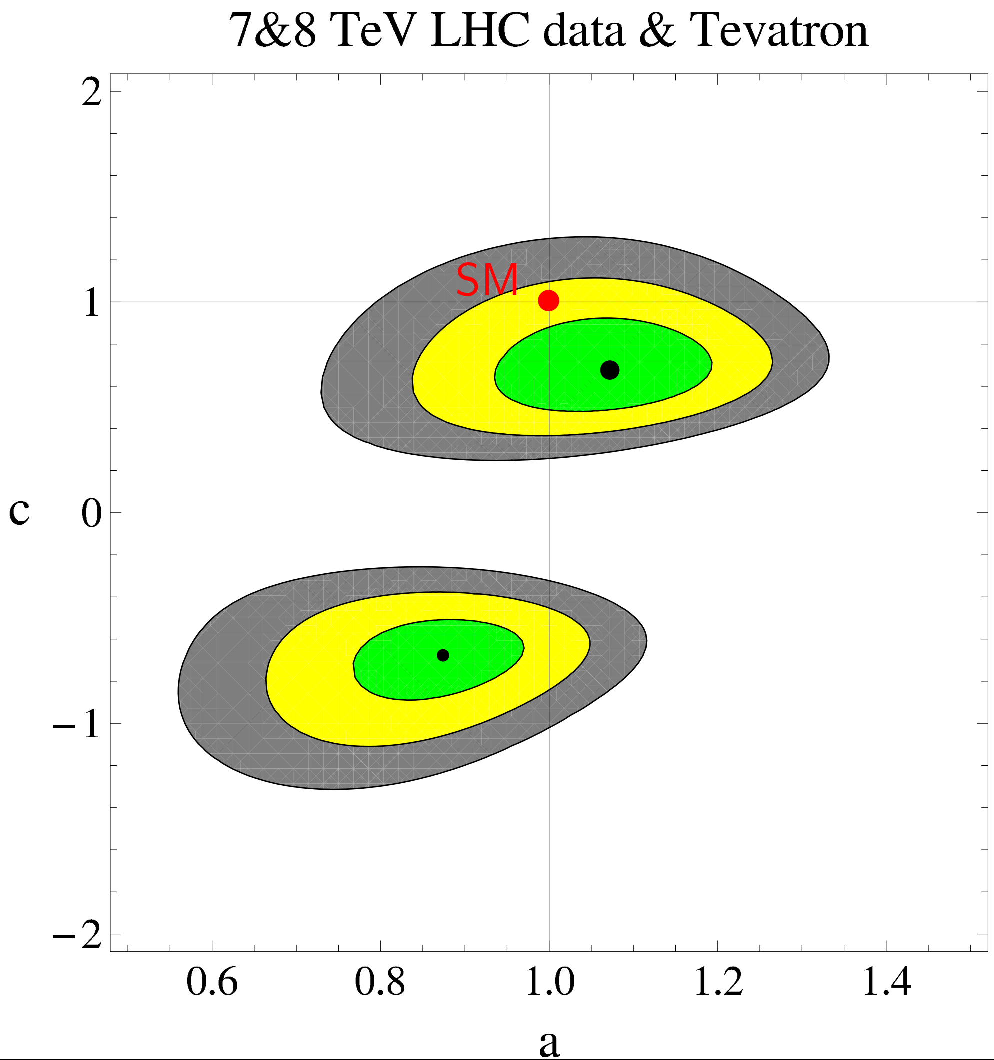
$\mathcal{F}$it to $\mathcal{LHC}$ $\mathcal{D}$ata within SM($a \equiv \kappa_V, c \equiv \kappa_F$) - $\mathcal{S}$ummer 2012

χ^2 fit to $\hat{\mu}_i \pm \sigma_i$ from 48 channels (ATLAS+CMS+Tevatron) Espinosa,Grojean,MMM,Trott '12

(green/yellow/grey)
(65/90/99% CL)

SM within $\sim 2\sigma$
from best fit point

Two minima:
approx. symmetry
$a \leftrightarrow -a \quad c \leftrightarrow -c$
broken by $H\gamma\gamma$ couplg
$\sim |1.26a - 0.26c|^2$



Note: a fermiophobic
Higgs is disfavoured
by data

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

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

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

$\Lambda \gg v =$ 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

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

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

- **2HDM potential:** CP-conservation and global $\mathbb{Z}_2$ discrete symmetry $[\phi_1 \to -\phi_1]$ (softly broken)

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

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

- **Expansion about the vacuum expectation values (VEVs)**

$$\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad \text{and} \quad \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

- **Higgs sector after EWSB** 2 CP-even neutral: h, H, CP-odd neutral: A, charged $H^\pm$

- **7 Free parameters + M_W:** $M_h, M_H, M_A, M_{H^\pm}, \tan\beta, \alpha, M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$

  $\tan\beta = \frac{v_2}{v_1}$: ratio of the VEVs and α : rotation angle of neutral CP-even sector

2HDM – $\mathcal{C}$ouplings

- **2HDM Couplings w.r.t. the SM:** $\kappa_i^\Phi = g^\Phi_{\text{2HDM}}/g_{\text{SM}}$

- **Higgs-Gauge Boson Couplings:**

$$\kappa_V^h = \sin(\beta-\alpha) \quad \text{for the light CP-even Higgs boson}$$
$$\kappa_V^H = \cos(\beta-\alpha) \quad \text{for the heavy CP-even Higgs boson}$$

- **Couplings to fermions** (no FCNC at tree-level)
  - ◇ Type I: all fermions couple only to ϕ_2;
  - ◇ Type II: up-/down-type fermions couple to ϕ_2/ϕ_1, respectively; $\rightarrow$ 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.

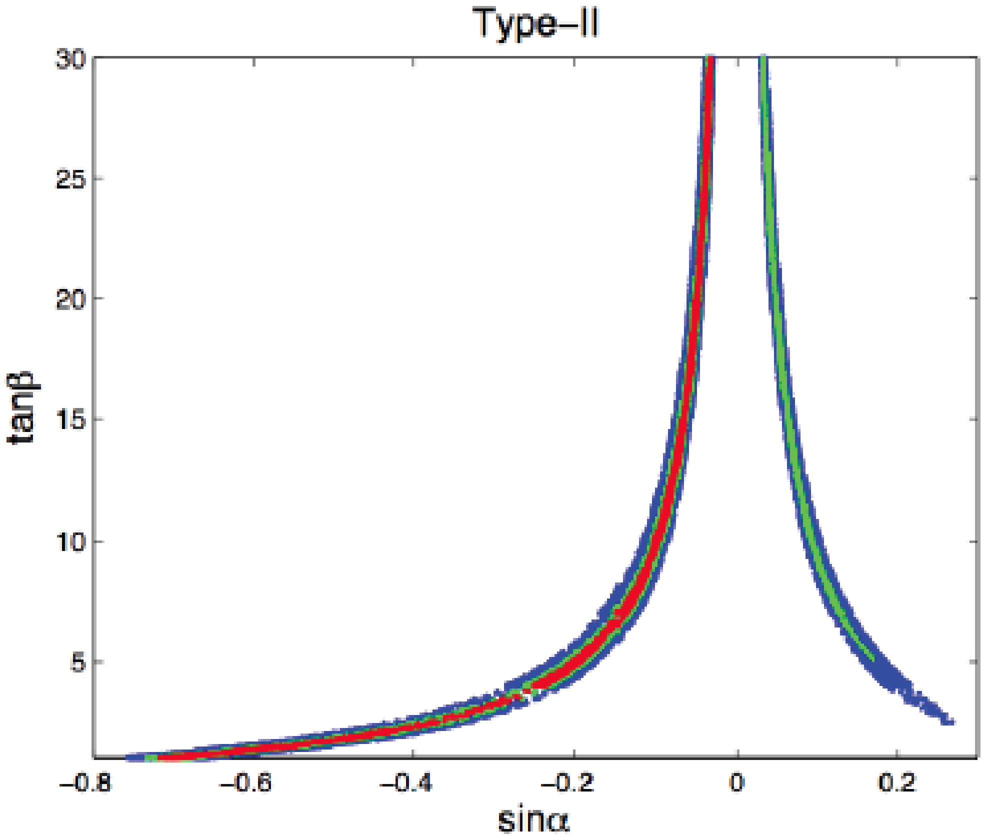
- **Example Type II:** ($U \equiv u, c, t$, $D \equiv d, s, b$, $L \equiv e, \mu, \tau$)

$$\kappa_U = \frac{\cos\alpha}{\sin\beta} \, , \quad \kappa_D = \kappa_L = -\frac{\sin\alpha}{\cos\beta}$$

$\mathcal{A}$llowed 2HDM $\mathcal{P}$arameter $\mathcal{S}$pace after $\mathcal{R}$un II

Ferreira,Gunion,Haber,Santos

Red: all μ's within 5%
Green: within 10%
Blue: within 20% of corresponding SM value



Left Branch: SM limit, *i.e.* $\sin(\beta-\alpha)=1, \kappa_D=\kappa_U=1$
Right Branch: Wrong Sign Yukawa Coupling, *i.e.* $\sin(\beta+\alpha)=1, \kappa_D=-1, \kappa_U=1$
(at least one Higgs Yukawa coupling has opposite sign to corresponding Higgs-VV coupling)

Wrong Sign Yukawa Couplings Scenario will be probed at High-Luminosity LHC and/or the ILC.

$\mathcal{A}$llowed 2HDM $\mathcal{P}$arameter $\mathcal{S}$pace after $\mathcal{R}$un II

Ferreira,Gunion,Haber,Santos

Red: all μ's within 5%
Green: within 10%
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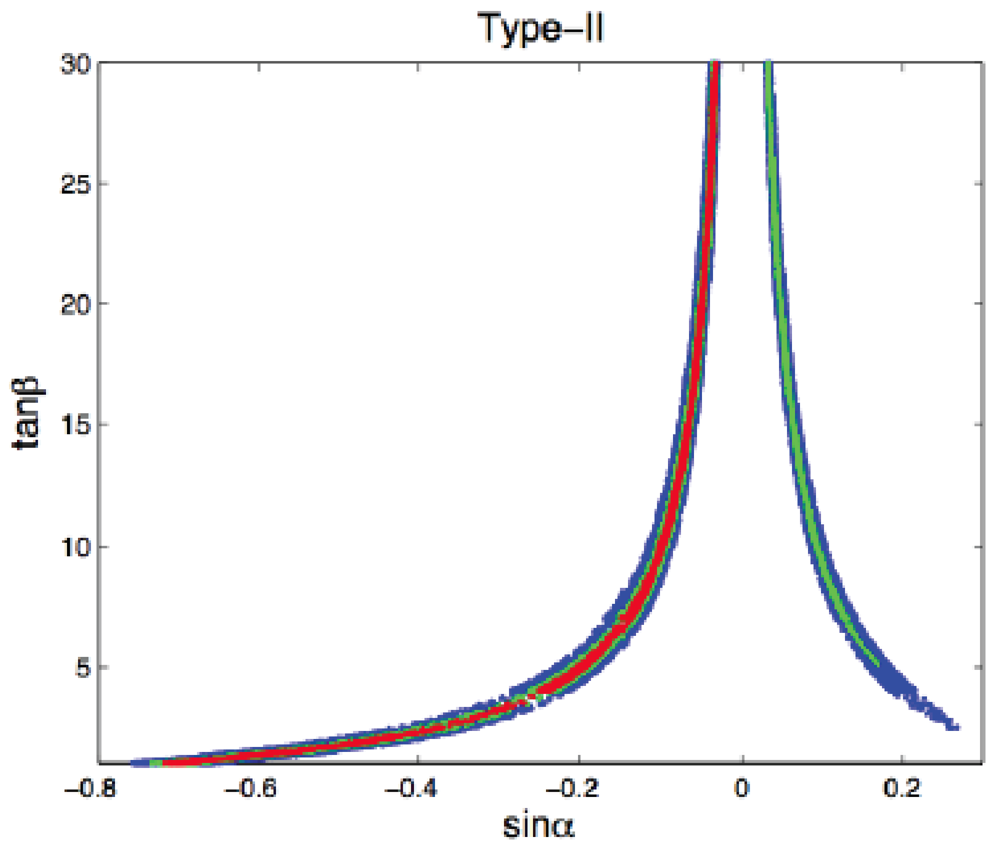


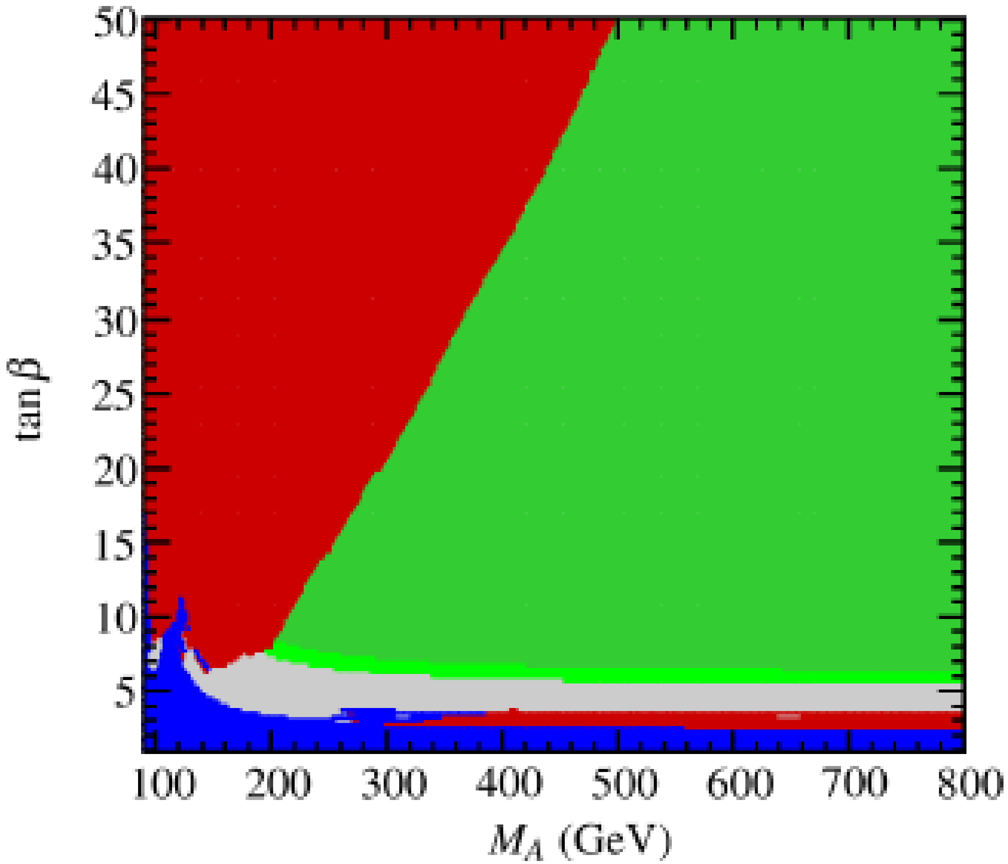
Left Branch: SM limit, $i.e.$ $\sin(\beta-\alpha)=1, \kappa_D=\kappa_U=1$

Right Branch: Wrong Sign Yukawa Coupling, $i.e.$ $\sin(\beta+\alpha)=1, \kappa_D=-1, \kappa_U=1$
(at least one Higgs Yukawa coupling has opposite sign to corresponding Higgs-VV coupling)

For further scans, see also [Baglio,Eberhardt,Nierste,Wiebusch;Dumont,Gunion,Jiang,Kraml;...]

$\mathcal{E}$xcluded $\mathcal{MSSM}$ $\mathcal{P}$arameter $\mathcal{S}$pace

Bechtle,Brein,Heinemeyer,Stal,Stefaniak,Weiglein,Williams



Red: exclusion by LHC

$M_h^{\text{mod+}}$ benchmark scenario

Blue: by LEP

Green: favored region w/ $M_h = 125.7 \pm 2$ GeV (dark green), w/ $M_h = 125.7 \pm 3$ GeV (light green)

$\mathcal{I}$nvestigation of $\mathcal{NMSSM}$ $\mathcal{D}$iscovery $\mathcal{P}$rospects - $\mathcal{S}$can

Mixing angle $\tan\beta$ and NMSSM couplings λ, κ: King,Nevzorov,MMM,Walz

$$1 \le \tan\beta \le 30\;, \qquad 0 \le \lambda \le 0.7\;, \qquad -0.7 \le \kappa \le 0.7$$

with perturbativity requirement

$$\sqrt{\lambda^2+\kappa^2} \le 0.7$$

Soft SUSY breaking trilinear NMSSM couplings and μ_{eff}:

$$-2 \text{ TeV} \le A_\lambda \le 2 \text{ TeV}\;,\; -2 \text{ TeV} \le A_\kappa \le 2 \text{ TeV}\;,\; -1 \text{ TeV} \le \mu_{\text{eff}} \le 1 \text{ TeV}$$

Remaining Parameters:

$$-2 \text{ TeV} \le A_U, A_D, A_L \le 2 \text{ TeV}$$

$$600 \text{ GeV} \le M_{\tilde{t}_R} = M_{\tilde{Q}_3} \le 3 \text{ TeV}\;,\; 600 \text{ GeV} \le M_{\tilde{\tau}_R} = M_{\tilde{L}_3} \le 3 \text{ TeV}\;,\; M_{\tilde{b}_R} = 3 \text{ TeV}$$

$$M_{\tilde{u}_R,\tilde{c}_R} = M_{\tilde{d}_R,\tilde{s}_R} = M_{\tilde{Q}_{1,2}} = M_{\tilde{e}_R,\tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 3 \text{ TeV}$$

$$100 \text{ GeV} \le M_1 \le 1 \text{ TeV}\;,\; 200 \text{ GeV} \le M_2 \le 1 \text{ TeV}\;,\; 1.3 \text{ TeV} \le M_3 \le 3 \text{ TeV}$$

$\mathcal{NMSSM}$ $\mathcal{S}$can

- **Conditions on the parameter scan:**

  * At least one CP-even Higgs boson $H_i \equiv h$ with: 124 GeV $\lesssim M_h \lesssim 127$ GeV
  * Compatibility with μ_{XX}^{exp} $(X = b, \tau, \gamma, W, Z)$: $|\mu_{XX}^{\text{scan}}(h) - \mu_{XX}^{\text{exp}}| \leq 2\sigma$
  * Relic density $\Omega_c h^2$ below PLANCK result $(\Omega_c h^2)^{\text{NMSSM}} \leq 0.1187 \pm 0.0017$ [PLANCK]

Constraints from low-energy observables, from LEP, Tevatron and LHC searches [NMSSMTools]

- **Signal can be superposition of two Higgs boson rates close in mass:** h **and** $\Phi = H_i, A_j$

$$\mu_{XX}(h) \equiv R_\sigma(h)\, R_{XX}^{BR}(h) \;+ \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_\sigma(\Phi)\, R_{XX}^{BR}(\Phi)\, F(M_h, M_\Phi, d_{XX})$$

δ : mass resolution in the respective XX final state

$F(M_h, M_\Phi, d_{XX})$: Gaussian weighting function

d_{XX}: experimental resolution of final state XX [NMSSMTools]

$\mathcal{E}$xperimental $\mathcal{S}$ignal $\mathcal{R}$ates

Based on: ATLAS-CONF-2013-034; CMS-PAS-HIG-13-005; combination à la Espinosa,MMM,Grojean,Trott

channel	best fit value	$2 \times 1\sigma$ error
$VH \to Vbb$	0.97	± 1.06
$H \to \tau\tau$	1.02	± 0.7
$H \to \gamma\gamma$	1.14	± 0.4
$H \to WW$	0.78	± 0.34
$H \to ZZ$	1.11	± 0.46

$\mathcal{B}$enchmark $H_1 = h$ and $\tan\beta$ small

B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggH_s)$	282.37 fb
$\sigma(ggH_s)\mathrm{BR}(H_s \to WW)$	5.09 fb
$\sigma(ggH_s)\mathrm{BR}(H_s \to A_s A_s)$	274.75 fb
$\sigma(ggH_s)\mathrm{BR}(H_s \to A_s A_s \to b\bar{b} + b\bar{b})$	5.87 fb
$\sigma(ggH_s)\mathrm{BR}(H_s \to A_s A_s \to \gamma\gamma + b\bar{b})$	67.33 fb
$\sigma(ggH_s)\mathrm{BR}(H_s \to A_s A_s \to \gamma\gamma + \gamma\gamma)$	193.22 fb
$\sigma(ggH)$	3.166 pb
$\sigma(ggH)\mathrm{BR}(H \to WW)$	264.73 fb
$\sigma(ggH)\mathrm{BR}(H \to ZZ)$	119.52 fb
$\sigma(ggH)\mathrm{BR}(H \to b\bar{b})$	297.37 fb
$\sigma(ggH)\mathrm{BR}(H \to \tau\tau)$	37.65 fb
$\sigma(ggH)\mathrm{BR}(H \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	383.33 fb
$\sigma(ggH)\mathrm{BR}(H \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	403.14 fb
$\sigma(ggH)\mathrm{BR}(H \to hH_s)$	1.609 pb
$\sigma(ggH)\mathrm{BR}(H \to hH_s \to bb + \tau\tau)$	1.44 fb

$\mathcal{B}$enchmark $H_1 = h$ and $\tan\beta$ small

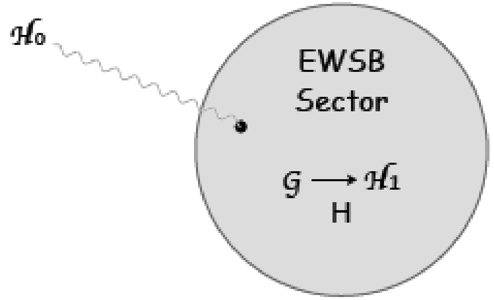
B.1 (Point ID Poi2a)	Decay Rates
$\sigma(ggH)$BR$(H \to hH_s \to h + A_sA_s \to bb + 4\gamma)$	712.47 fb
$\sigma(ggH)$BR$(H \to hH_s \to h + A_sA_s \to \gamma\gamma + 4b)$	248.02 fb
$\sigma(ggH)$BR$(H \to hH_s \to h + A_sA_s \to \tau\tau + 4\gamma)$	74.60 fb
$\sigma(ggH)$BR$(H \to hH_s \to h + A_sA_s \to \gamma\gamma + 4\tau)$	2.47 fb
$\sigma(ggH)$BR$(H \to hH_s \to h + A_sA_s \to 6\gamma)$	2.69 fb
$\sigma(ggH)$BR$(H \to hH_s \to h + A_sA_s \to \tau\tau + \gamma\gamma + b\bar{b})$	49.55 fb
$\sigma(ggH)$BR$(H \to A_sA_s)$	5.59 fb
$\sigma(ggH)$BR$(H \to A_sA_s \to 4\gamma)$	3.93 fb
$\sigma(ggA_s)$	0.08 fb
$\sigma(ggA)$	2.51 pb
$\sigma(ggA)$BR$(A \to \tau\tau)$	14.42 fb
$\sigma(ggA)$BR$(A \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$	963.87 fb
$\sigma(ggA)$BR$(A \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	273.57 fb
$\sigma(ggA)$BR$(A \to H_sA_s)$	525.56 fb

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

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

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

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

- **SM Gauge Group**
  - $*$ $\mathcal{H}_0 \subset \mathcal{G}$ gauged by external vector bosons
  - $*$ Identify $\mathcal{H}_0 = G_{\text{SM}} = SU(2)_L \times U(1)_Y$; $\mathcal{G} \to \mathcal{H}_1 \supset G_{\text{SM}}$
  - $*$ $\mathcal{H}_1$ contains 'custodial' $SO(4) \cong SU(2)_L \times SU(2)_R$ (protect T parameter)
  - $*$ SM fields are external to strong sector $\rightsquigarrow$ elementary

Composite Higgs Boson

- **Possible symmetry patterns**

  Examples:

  - $SO(5)/SO(4)$: 4 PGBs $= W_L^\pm, Z_L, h \rightarrow$ Minimal Comp. Higgs Model — Agashe,Contino,Pomarol
  - $SO(6)/SO(5)$: 5 PGBs $= W_L^\pm, Z_L, h, a \rightarrow$ Next MCHM — Gripaios,Pomarol,Riva,Serra
  - ... — For a list: Bellazzini,Csáki,Serra

- **Higgs Boson Mass protected** $\leftarrow$ quantum corrections saturated at composite scale

- **Higgs Potential generated radiatively**
  - ◇ By gauge boson and top quark loops
  - ◇ EWSB triggered by top loops

$\mathcal{P}$artial $\mathcal{C}$ompositeness

- **Partial Compositeness**

  Kaplan; Contino,Kramer,Son,Sundrum

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

$$\mathcal{L}_{pc} = -\Delta_L \bar{q}_L Q_R - \Delta_R \bar{T}_L t_R + h.c.$$

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

  ◇ Linear couplings violate $\mathcal{G}$ explicitly $\rightsquigarrow$ Higgs potential induced

  ◇ Large top Yukawa couplings $\rightsquigarrow$ top largely composite

  ◇ Light Higgs boson requires light top partners

  Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu; Pomarol,Riva

Higgs Anomalous Couplings

- **SILH effective Lagrangian** (SILH = strongly interacting light Higgs) expansion for small

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

Giudice,Grojean,Pomarol,Rattazzi

SM limit for $\xi \to 0$

Higgs Anomalous Couplings

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

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

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

spinorial representations of $SO(5)$

MCHM4

$$g_{Hff} = g^{SM}_{Hff}\sqrt{1-\xi} \equiv g^{SM}_{Hff}\; c$$

universal shift of couplings

no modifications of BRs

fundamental representations of $SO(5)$

MCHM5

$$g_{Hff} = g^{SM}_{Hff}\frac{1-2\xi}{\sqrt{1-\xi}} \equiv g^{SM}_{Hff}\; c$$

BRs depend on $\xi = v^2/f^2$

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

$\mathcal{H}$iggs $\mathcal{A}$nomalous $\mathcal{C}$ouplings

- **Implementation for Higgs BRs:** `eHDECAY` Contino,Ghezzi,Grojean,MMM,Spira

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

- **Gluon Fusion Production:**

  ▷ NNLO corrections '11 E.Furlan

  ▷ Two-loop Yukawa corrections in top partner singlet model '13 Dawson,Furlan

$\mathcal{C}$onstraints from $\mathcal{EWPD}$

- **Logarithmically divergent contributions to T (ϵ_1) and S (ϵ_3) parameters**
  $\leftarrow$ modified HZZ, HWW couplings

Barbieri eal

$$\Delta\epsilon_1^{\rm IR} = -\frac{3\,\alpha(M_Z)}{16\pi\cos^2\theta_W}\xi\log\left(\frac{m_\rho^2}{m_h^2}\right), \quad \Delta\epsilon_3^{\rm IR} = \frac{\alpha(M_Z)}{48\pi\sin^2\theta_W}\xi\log\left(\frac{m_\rho^2}{m_h^2}\right)$$

m_ρ lighest comp. res.

- **Vector- ρ and axial-vector a resonance contribution to S**

Contino; Agashe eal; Gillioz

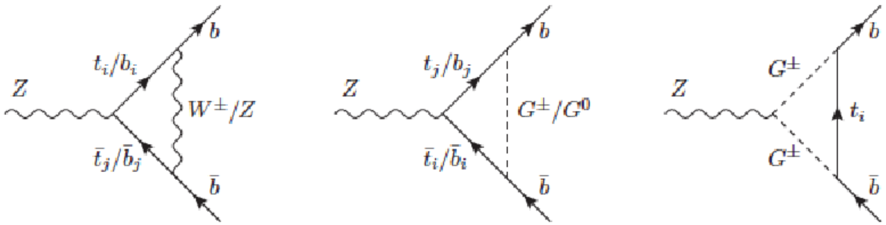
$$\Delta\epsilon_3^{\rm UV} = \frac{m_W^2}{m_\rho^2}\left(1+\frac{m_\rho^2}{m_a^2}\right) \cong 1.36\,\frac{m_W^2}{m_\rho^2}\,, \qquad \text{with } m_a/m_\rho \approx \frac{5}{3}$$

- **Fermion loop contributions to T**

Lavoura,Silva; Agashe,Contino; Gillioz;
Lodone;Anastasiou,Furlan,Santiago

- **Top and bottom partner contributions to $Zb\bar{b}$**

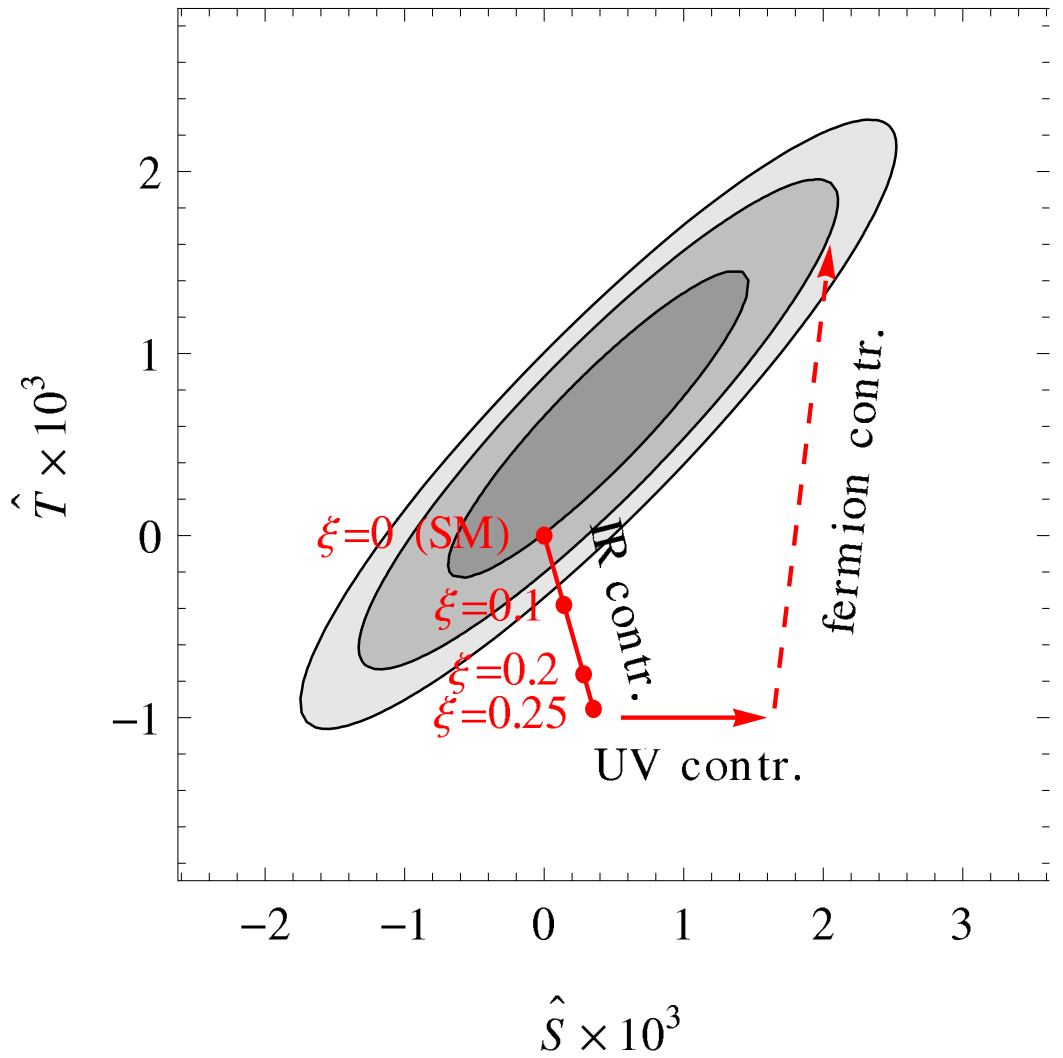
Anastasiou,Furlan,Santiago;
Gillioz,Gröber,Kapuvari,MMM



$\mathcal{C}$onstraints on the $\mathcal{O}$blique $\mathcal{P}$arameters

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

Grojean,Matsedonskyi,Panico



$\mathcal{C}$onstraints from $\mathcal{F}$lavour $\mathcal{P}$hysics

- **Constraints from flavour physics** due to four-fermion operators

$$\frac{g_\rho^2}{4m_\rho^2}(\sin\phi_L)^4(\bar{q}_L\gamma^\mu t^a q_L)(\bar{q}_L\gamma_\nu t^a q_L)$$

$\rightsquigarrow$ contributions to FCNC processes, electric dipole moments $\longleftarrow$ stringent constraints

Agashe,Perez,Soni; Csaki eal; Blanke eal; Bauer eal; Redi,Weiler; Keren-Zur eal; Barbieri eal; Redi; Vignaroli; Da Rold eal; Delaunay eal

Low f values allowed if flavour-symmetric strong sector — Redi,Weiler; Barbieri eal

LHC results on dijet angular distributions $\rightsquigarrow$ constraints on mixing $\sin\phi_L$

Relaxed constraints if deviating from MFV (top-quark treated differently) — Barbieri eal; Redi

$\mathcal{H}$eavy $\mathcal{Q}$uark $\mathcal{P}$artners and $\mathcal{LHC}$ $\mathcal{S}$earches

- **Decay Channels:**

Top Partners:	$\mathcal{T} \to Wb,\ Zt,\ ht$
Bottom Partners:	$\mathcal{B} \to Wt,\ Zb,\ hb$
Charge-5/3 Fermions:	$\mathcal{X} \to Wt$

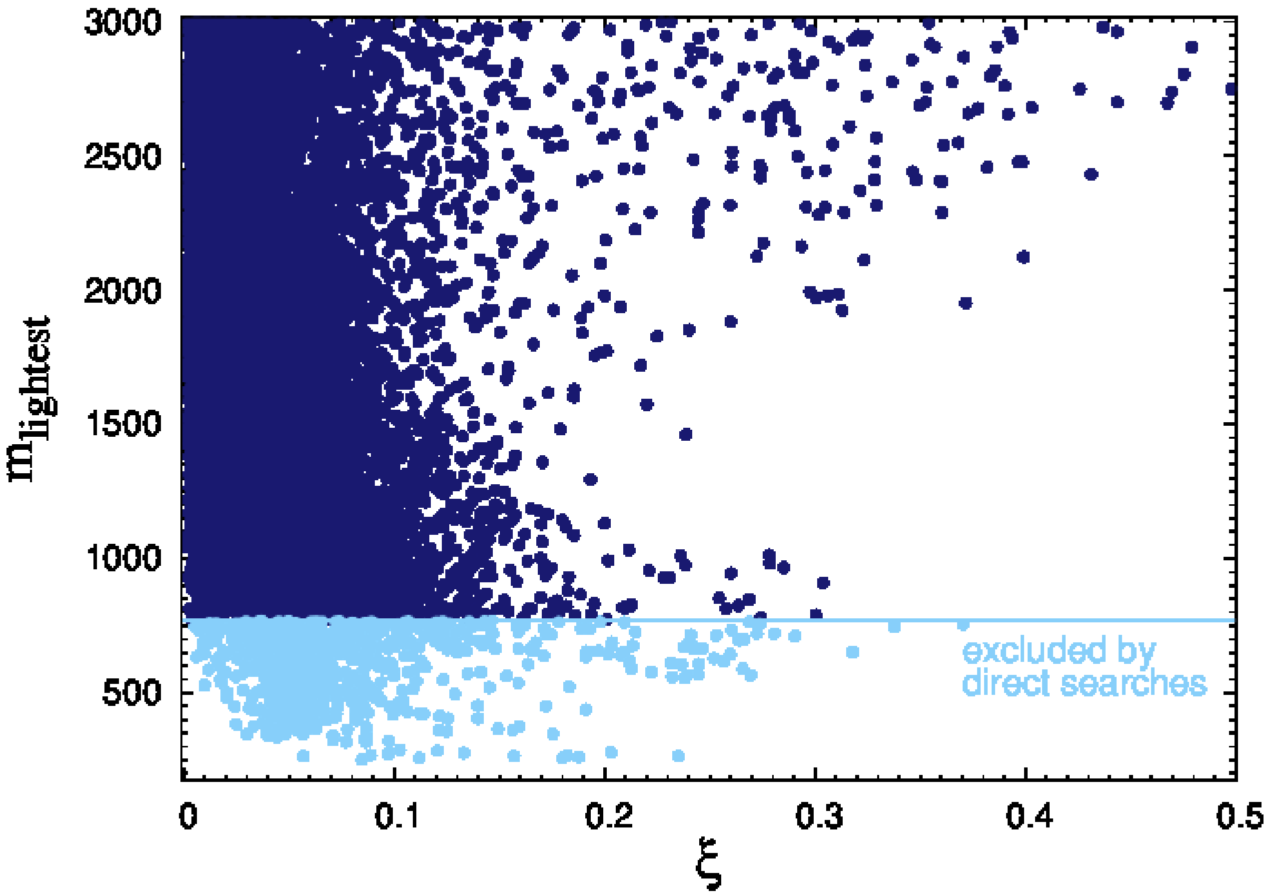
- **Limits from LHC Experiments:**

  The ATLAS Collaboration: ATLAS-CONF-2013-018, 051, 056, 060

  The CMS Collaboration: CMS PAS B2G-12-019, Phys. Lett. **B729** (2014) 149

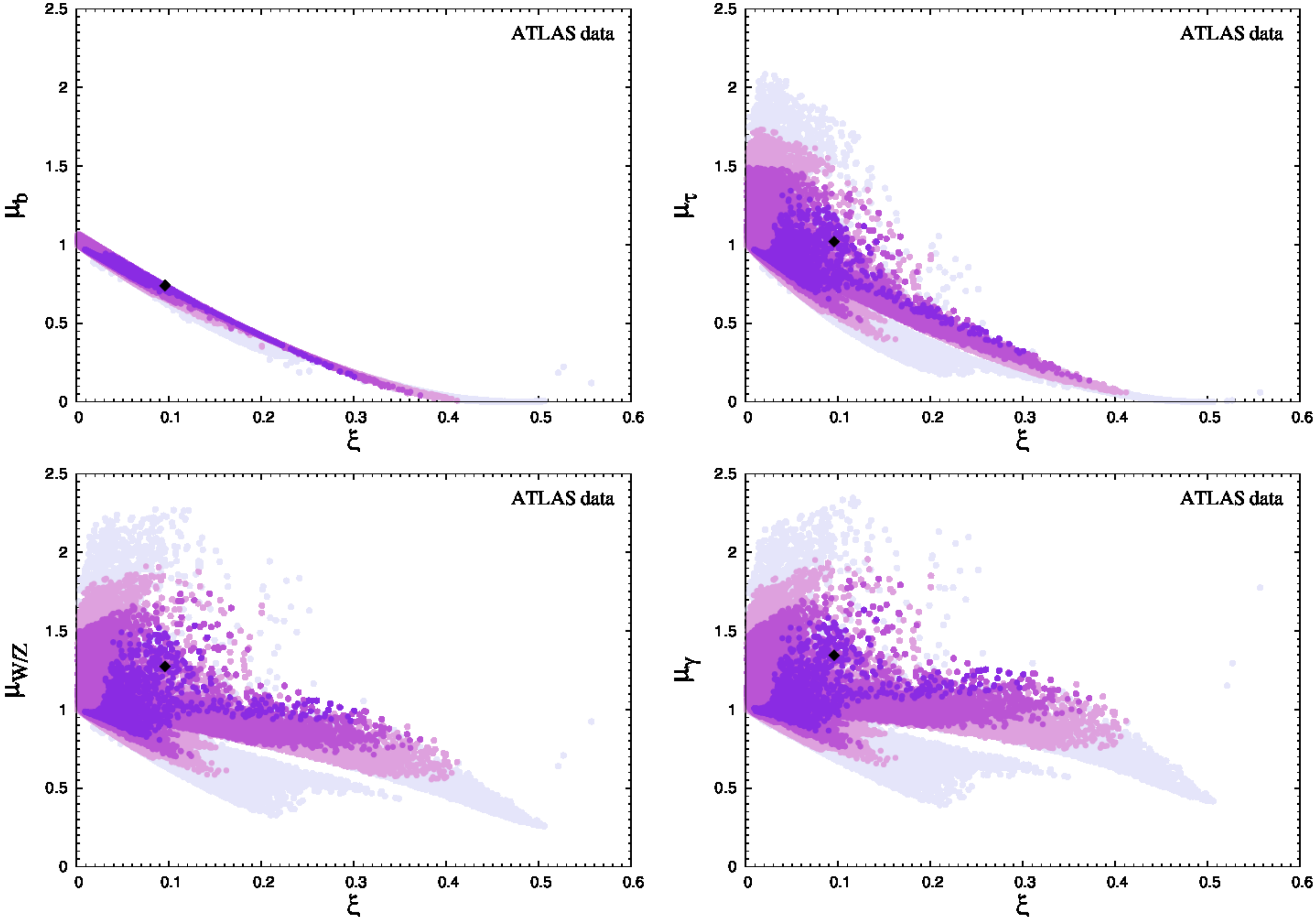
$\mathcal{H}$eavy $\mathcal{Q}$uark $\mathcal{P}$artners and $\mathcal{LHC}$ $\mathcal{S}$earches

Gillioz,Gröber,Kapuvari,MMM



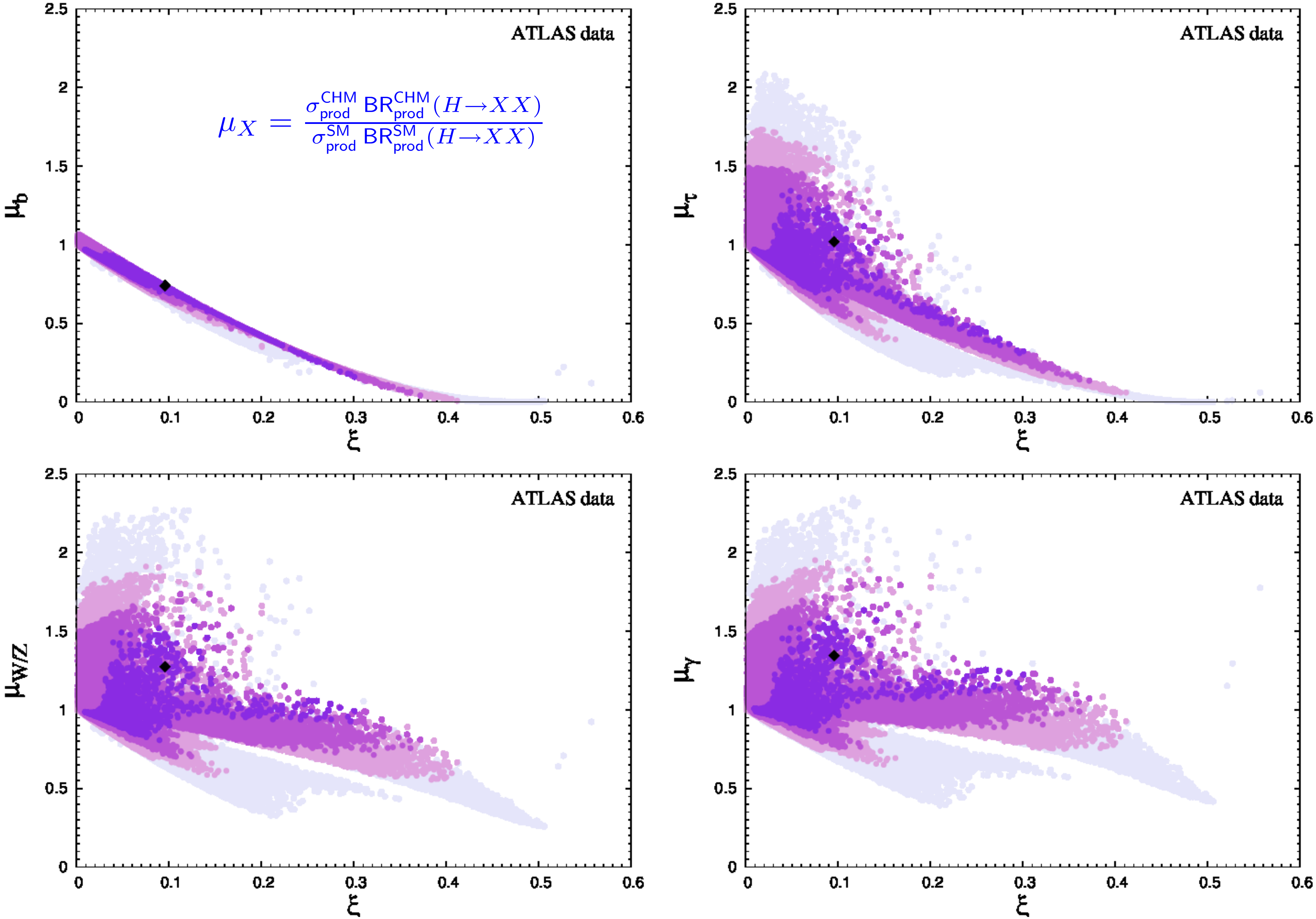
- **Compatibility with ATLAS Moriond'13 data, EWPD, $|V_{tb}|$, direct searches, w/ top&bottom partners** ($\xi^{\text{best fit}} = v^2/f^2 = 0.096$)

Gillioz,Gröber,Kapuvari,MM



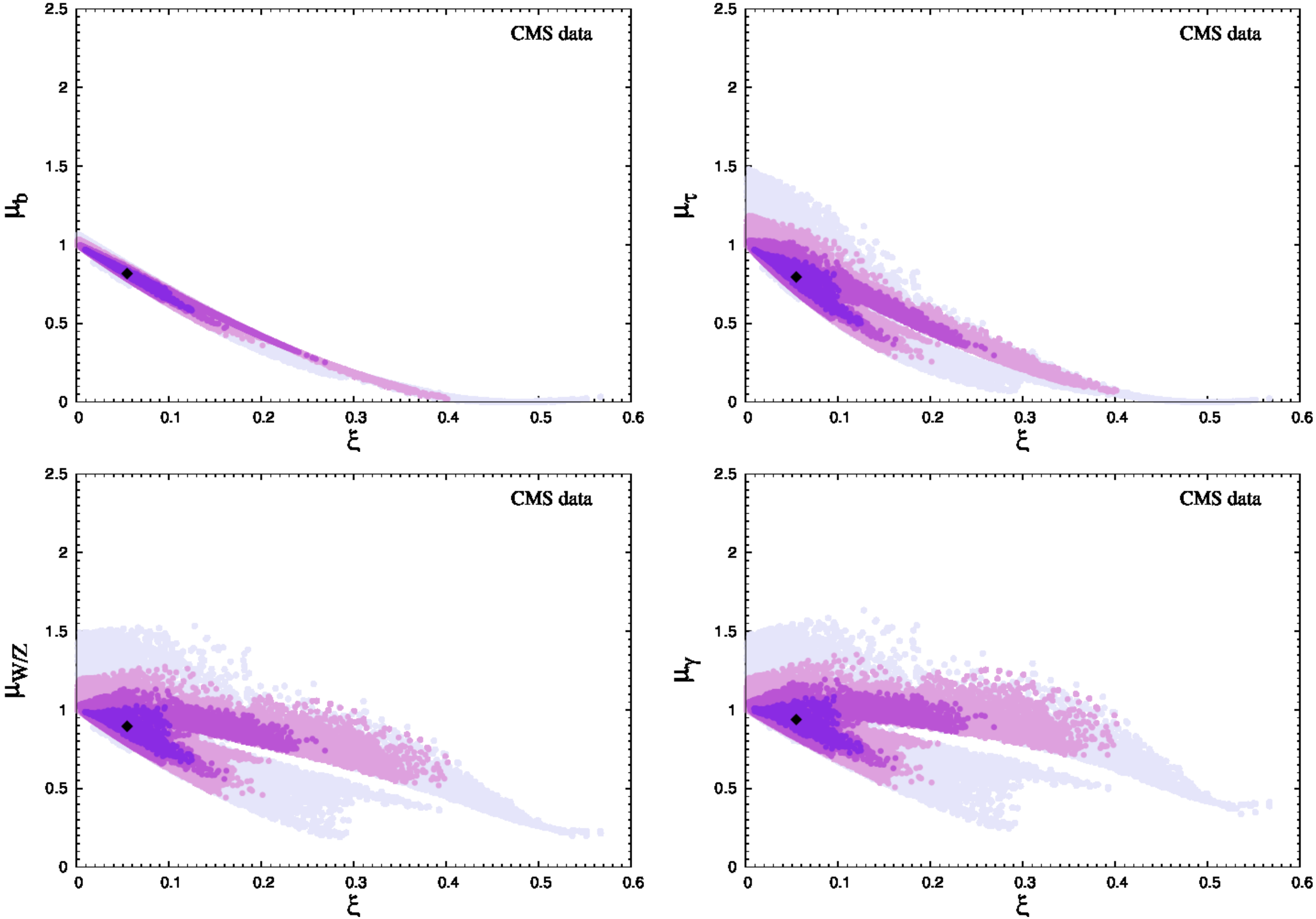
- **Compatibility with ATLAS Moriond'13 data, EWPD, $|V_{tb}|$, direct searches, w/ top&bottom partners** $(\xi^{\text{best fit}} = v^2/f^2 = 0.096)$

Gillioz,Gröber,Kapuvari,MM



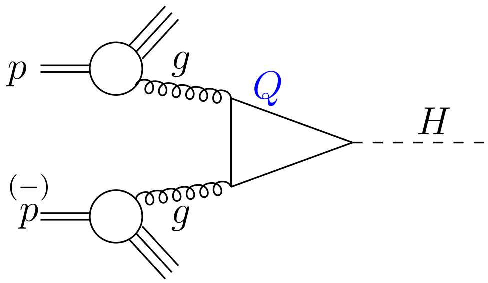
- **Compatibility with CMS Moriond'13 data, EWPD, $|V_{tb}|$, direct searches, w/ top&bottom partners** ($\xi^{\text{best fit}} = v^2/f^2 = 0.055$)

Gillioz,Gröber,Kapuvari,MM



$\mathcal{L}$oop $\mathcal{P}$rocesses: $\mathcal{S}$ensitivity to the $\mathcal{T}$op $\mathcal{P}$artners?

- **Single Higgs production through gluon fusion:** dominant production process at LHC

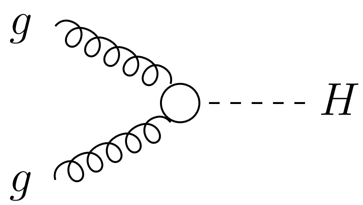


▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

▷ Sensitivity to details of heavy composite sector?

$\mathcal{L}$oop $\mathcal{P}$rocesses: $\mathcal{S}$ensitivity to the $\mathcal{T}$op $\mathcal{P}$artners?

- **Single Higgs production through gluon fusion:** via Low-Energy Theorem (LET)



▷ Gluon fusion computed within LET is insensitive to details of the couplings and masses of strong sector   Falkowski;Low,Vichi;Azatov,Galloway;Furlan;Gillioz eal;Delaunay eal;Montull eal

▷ Reason: Cancellation between

∗ Correction of top Yukawa coupling due to mixing with heavy resonances and

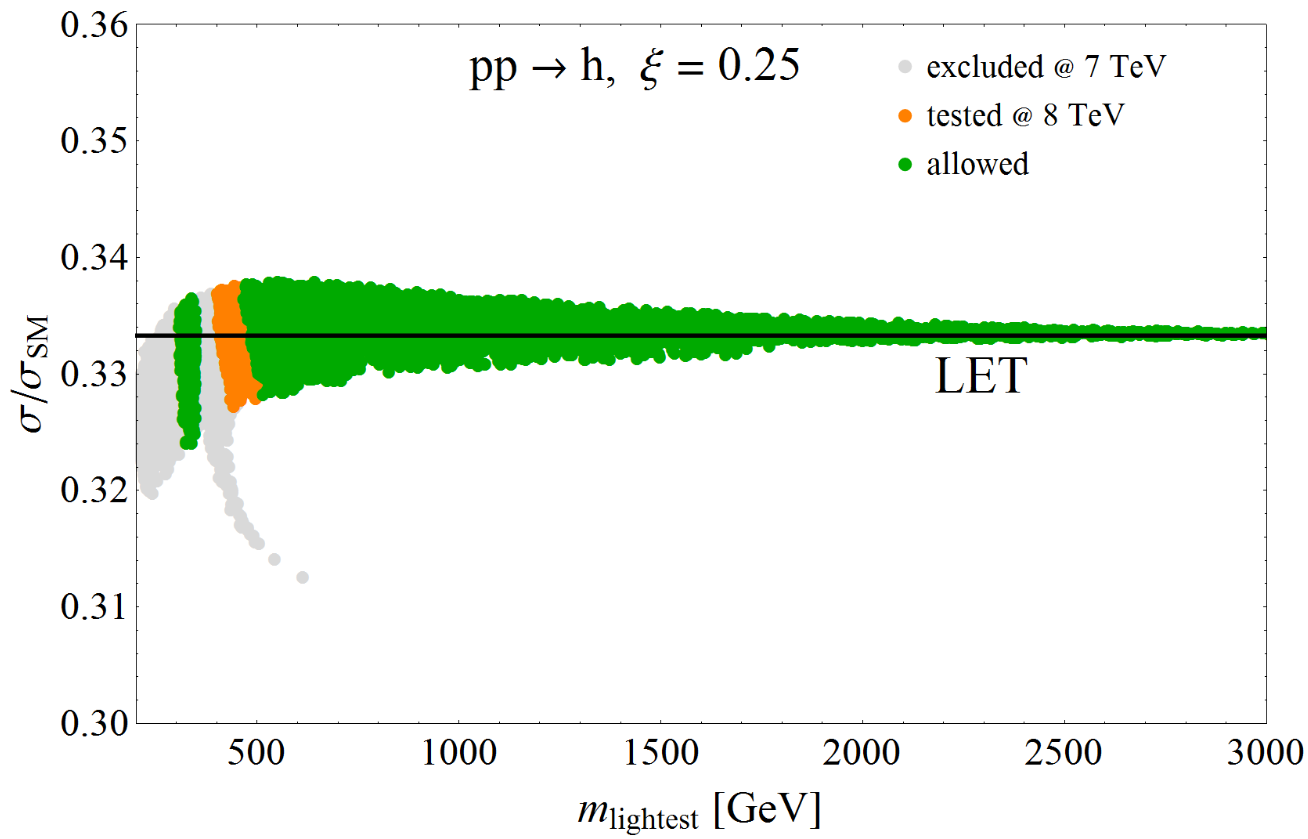
∗ Loops of extra fermions

▷ ⇒ Cross section depends only on Higgs non-linearities $\sim \xi = v^2/f^2$, mixing effects drop out

▷ LET approximates full cross section within a few percent

$\mathcal{S}$ingle $\mathcal{H}$iggs $\mathcal{P}$roduction in $\mathcal{MCHM}$5 w/ $\mathcal{T}$op $\mathcal{P}$artners

Gillioz,Gröber,Grojean,MMM,Salvioni



⋆ LET very accurate cross section for any heavy fermion spectrum: $\frac{\sigma}{\sigma_{\rm SM}} = \frac{(1-2\xi)^2}{1-\xi}$

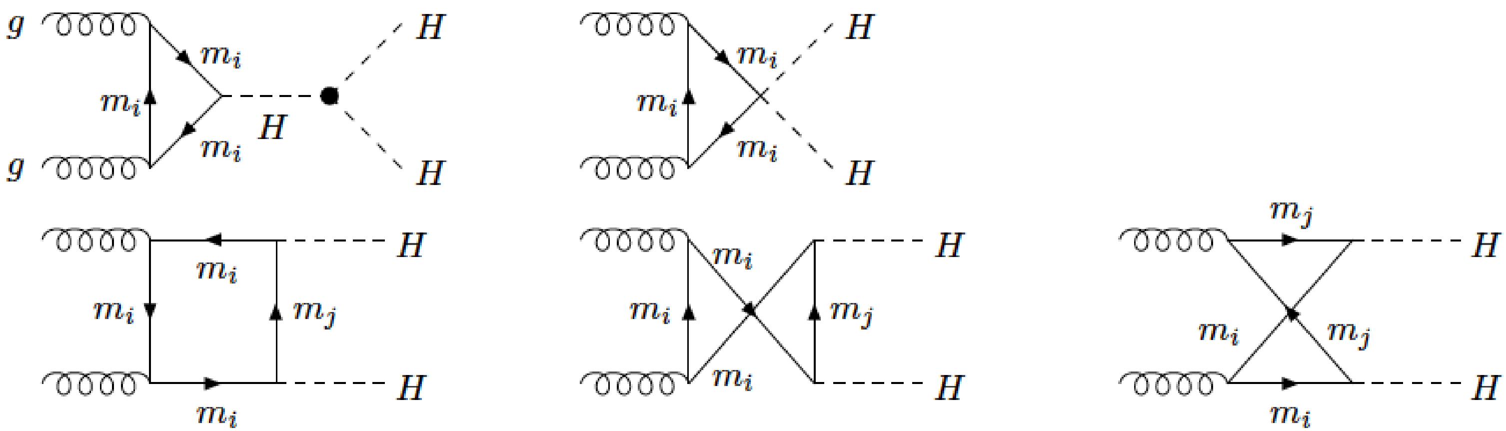
- Green points: allowed by EWPD and collider constraints
- Grey points: excluded by current collider constraints
- Orange: Projected exclusion by LHC8

$\mathcal{W}$hat about $\mathcal{C}$omposite $\mathcal{D}$ouble $\mathcal{H}$iggs $\mathcal{P}$roduction?

- **Double Higgs production through gluon fusion:**

  ∗ sensitive to trilinear Higgs self-coupling — Baur,Glover; Spira eal; Djouadi,Kilian,MMM,Zerwas;Gröber,MMM

  ∗ access to anomalous $HHf\bar{f}$ coupling — Contino eal '12



▷ Can be enhanced compared to the SM process

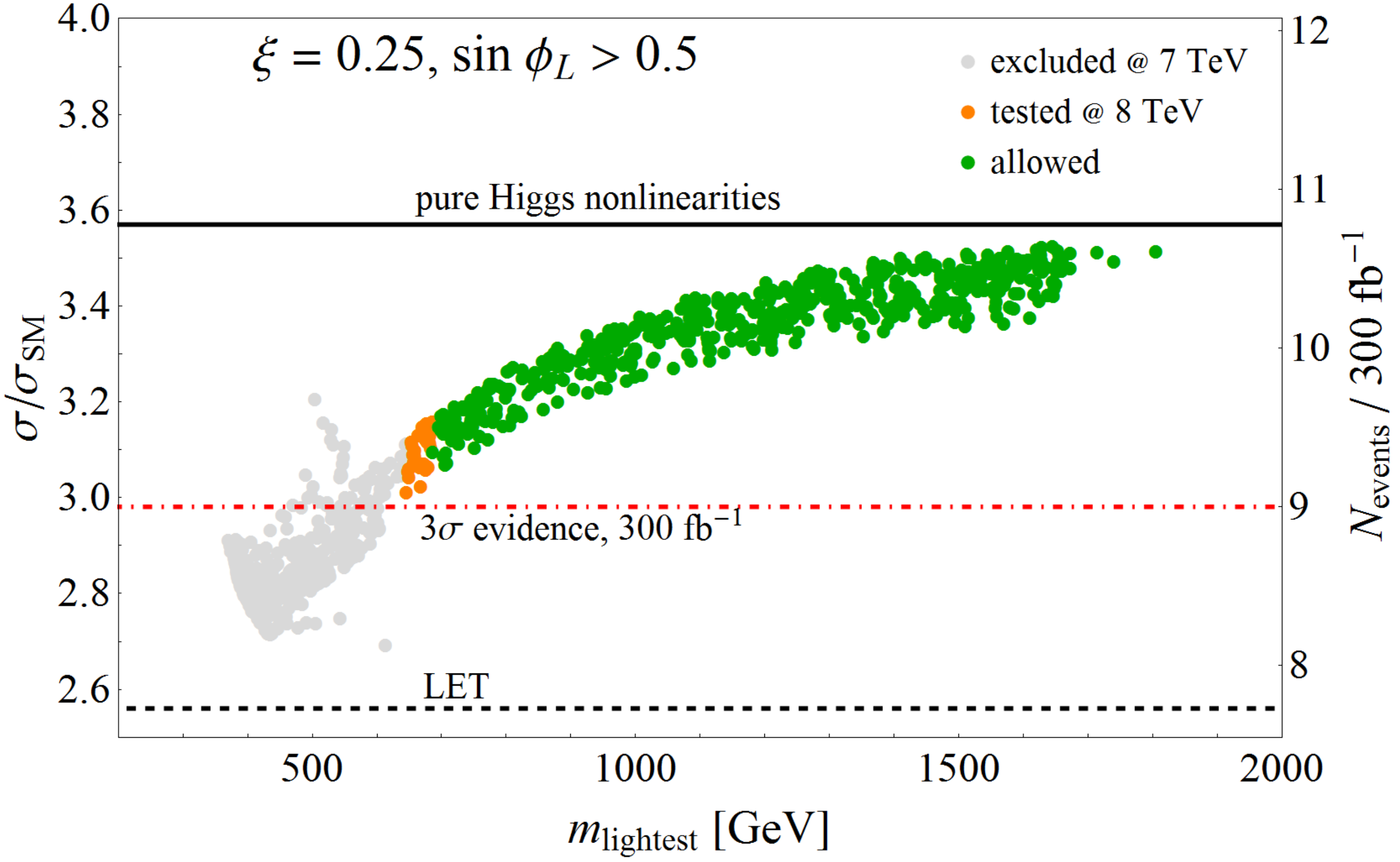
▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

▷ Different fermions can contribute within one loop

▷ Sensitivity to details of heavy composite sector?

Double Higgs Production in MCHM5 w/ Top Partners

Gillioz,Gröber,Grojean,MMM,Salvioni



only top; partners

⟵ integrated out

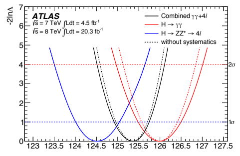
top and partners

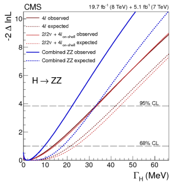
⟵ integrated out

$\mathcal{I}$s it the $\mathcal{H}$iggs $\mathcal{B}$oson?

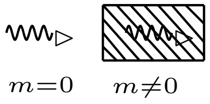
- **Investigation of properties of scalar particle:**

  $*$ Mass m, Total Width Γ

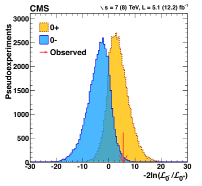


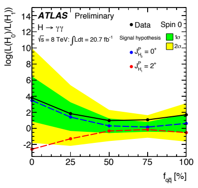


  $*$ Couplings to SM particles $g_{HXX} \sim m_X$

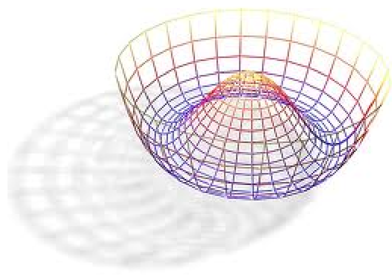


  $*$ Spin and Parity Quantum Numbers J^P $(CP$ violation?)



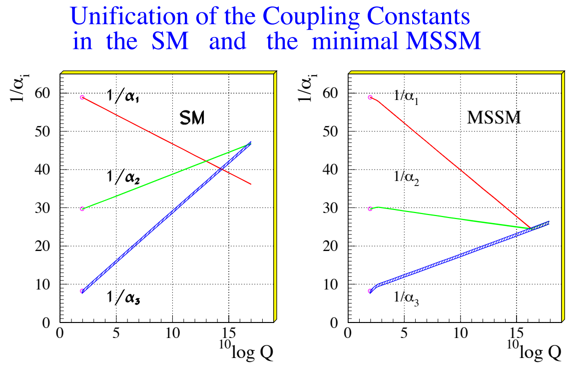


  $*$ Trilinear and Quartic Higgs Self-Coupling $\rightsquigarrow$ Higgs Potential

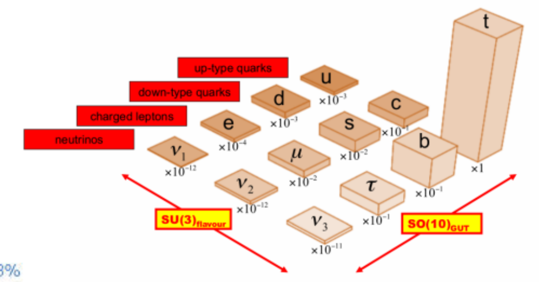


Open Problems

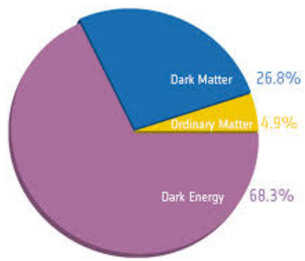
- ◇ What is the mechanism beyond EWSB? Weak or strong dynamics?



- ◇ Huge Higgs mass corrections - finetuning?
- ◇ Do the gauge couplings unify?
- ◇ Incorporation of gravity?

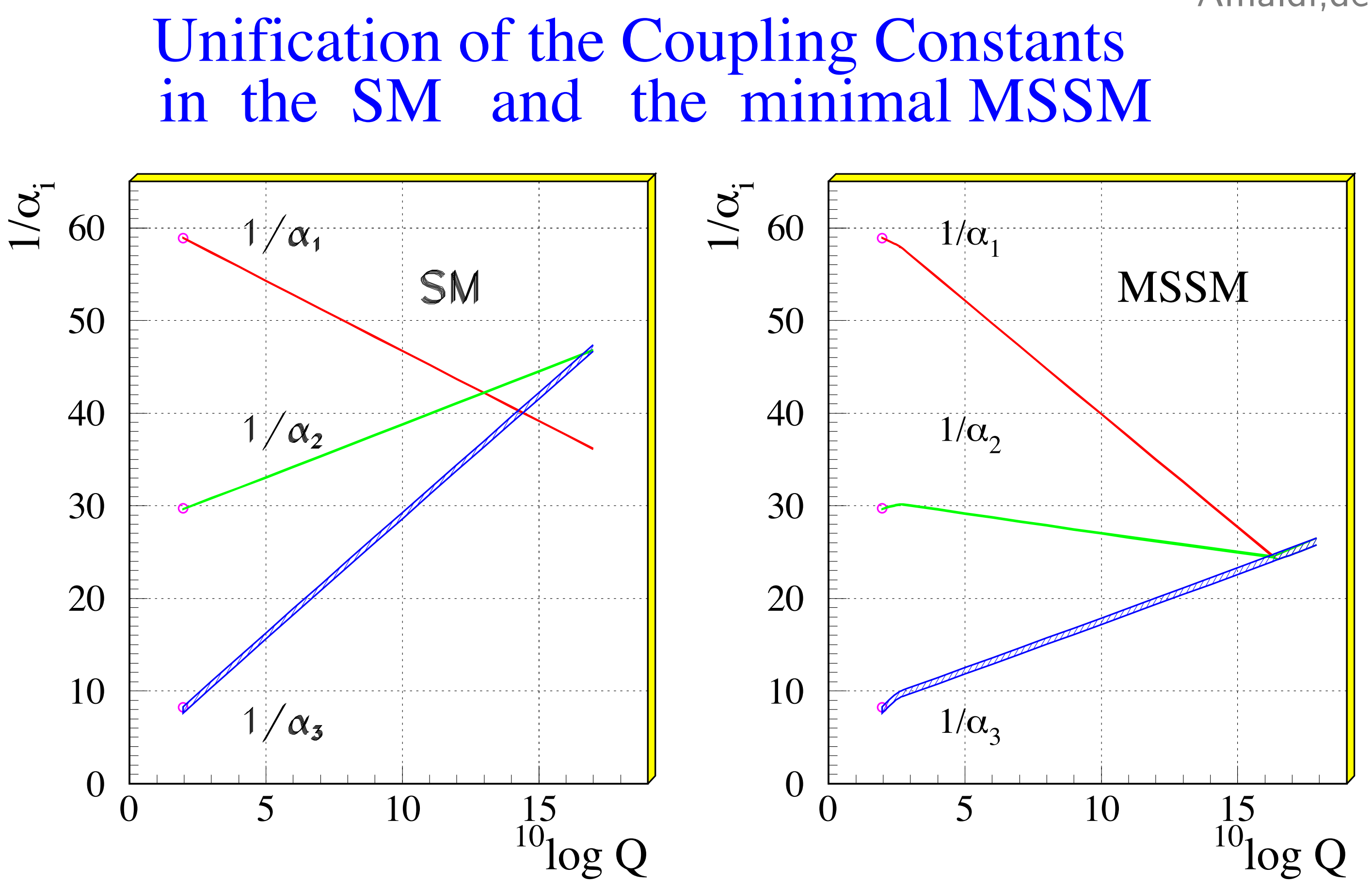


- ◇ Puzzling spectrum of fermion masses and mixings
- ◇ What is the nature of Dark Matter?

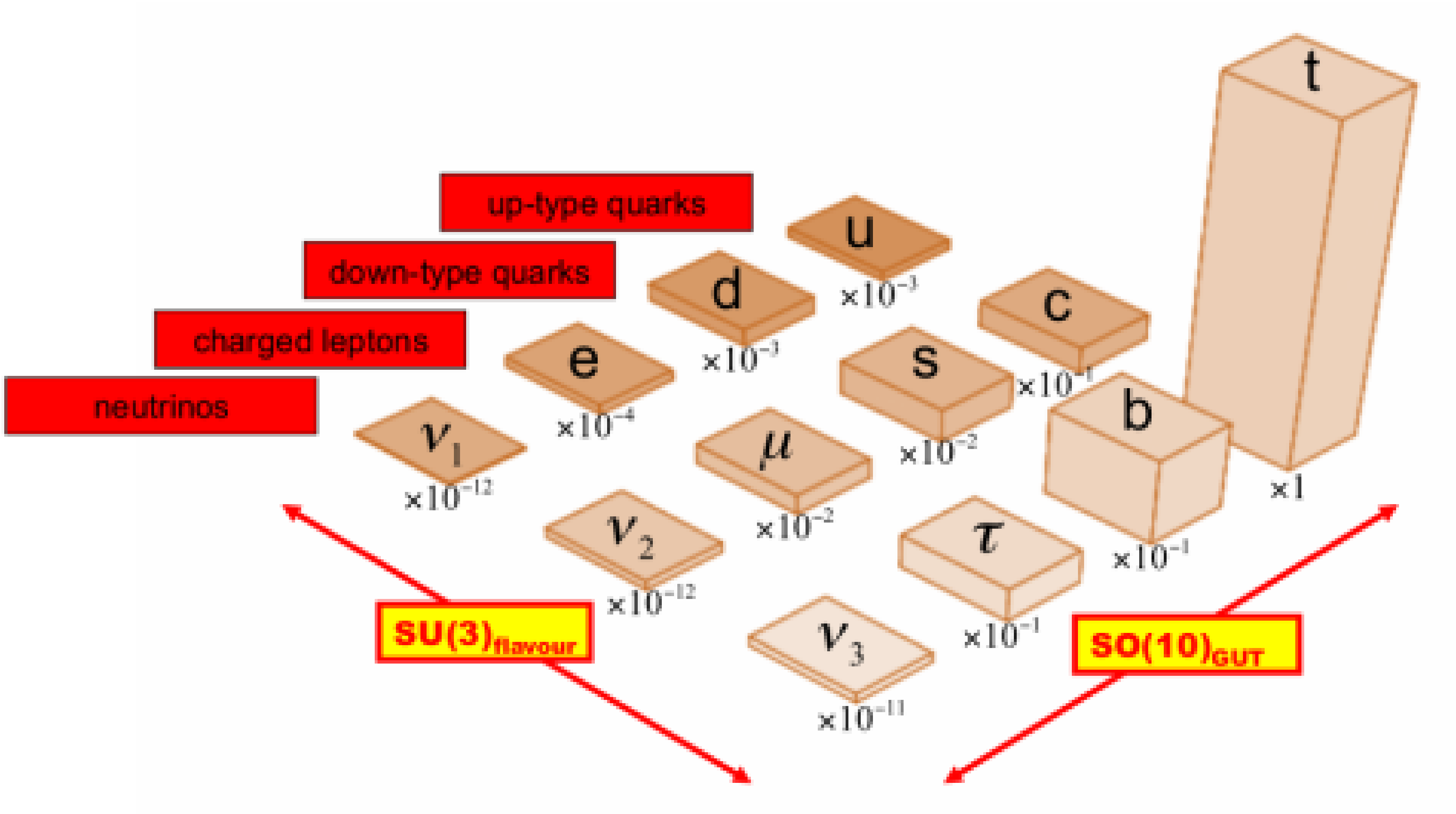


- ◇ Origin of matter-antimatter asymmetry?
- ◇ New sources of CP violation?
- ◇ ...

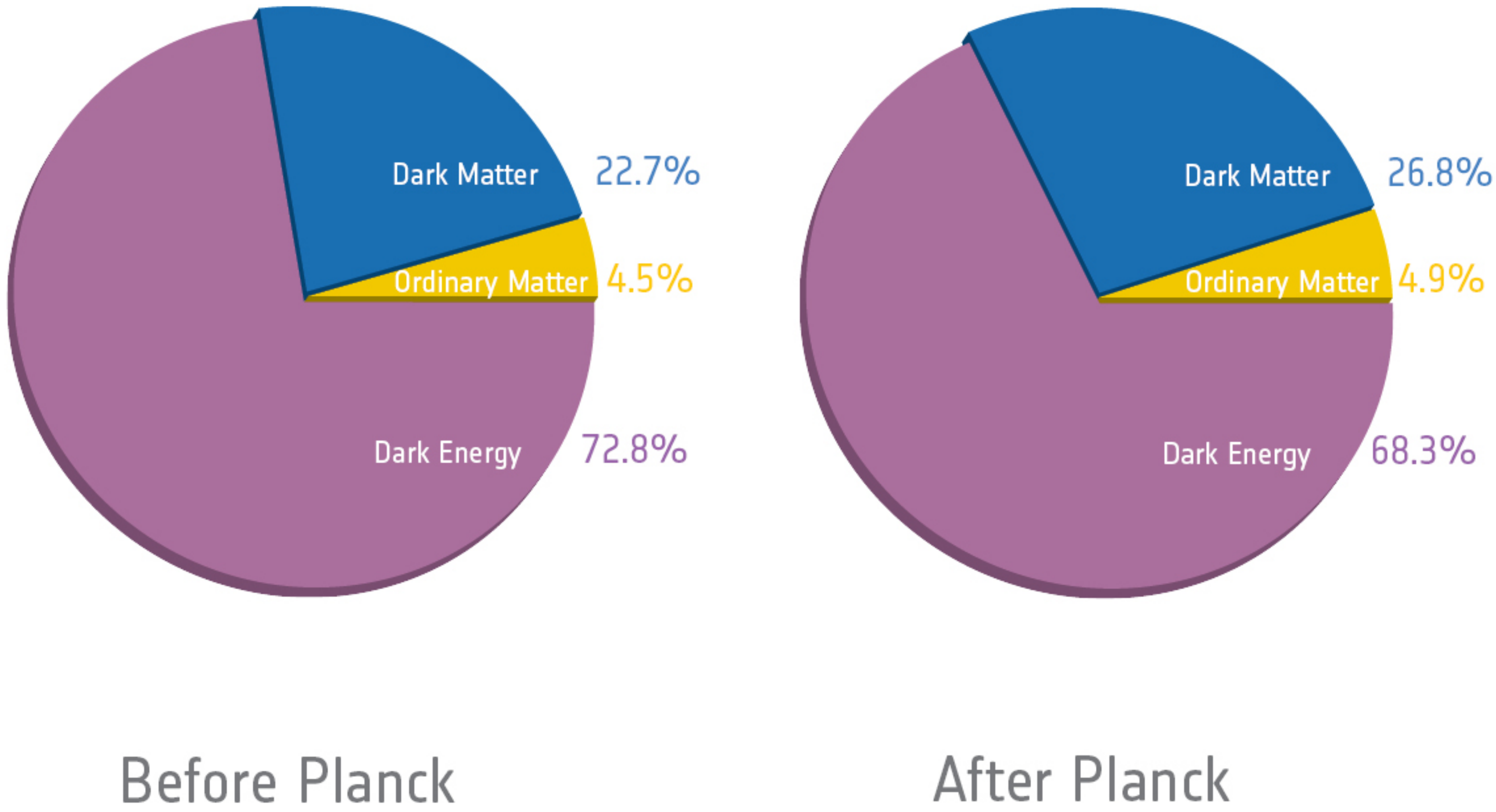
Amaldi,de Boer,Fürstenau



$\mathcal{F}$ermion $\mathcal{M}$ass $\mathcal{H}$ierarchy



Dark Matter



Dark Matter
22.7%
Ordinary Matter
4.5%
Dark Energy
72.8%
Before Planck
Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%
After Planck

$\mathcal{B}$ig $\mathcal{Q}$uestions - $\mathcal{B}$ig $\mathcal{I}$deas

- ◇ What is the mechanism beyond EWSB? Weak or strong dynamics?
- ◇ Huge Higgs mass corrections - finetuning?
- ◇ Do the gauge couplings unify?
- ◇ Incorporation of gravity?
- ◇ Puzzling spectrum of fermion masses and mixings
- ◇ What is the nature of Dark Matter?
- ◇ Origin of matter-antimatter asymmetry?
- ◇ New sources of CP violation?
- ◇ ...

Supersymmetry

Compositeness

Extra Dimensions

Extended Higgs Sectors

Top Partner W'/Z'

Minimal Dark Matter

Hidden Sector ...

Big Questions - Big Ideas

- ◇ What is the mechanism beyond EWSB? Weak or strong dynamics?
- ◇ Huge Higgs mass corrections - finetuning?
- ◇ Do the gauge couplings unify?
- ◇ Incorporation of gravity?
- ◇ Puzzling spectrum of fermion masses and mixings
- ◇ What is the nature of Dark Matter?
- ◇ Origin of matter-antimatter asymmetry?
- ◇ New sources of CP violation?
- ◇ ...

No Observation of Physics Beyond the SM so Far!

Supersymmetry

Compositeness

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Hidden Sector ...