Testing Higgs sectors beyond the Standard Model with HiggsSignals

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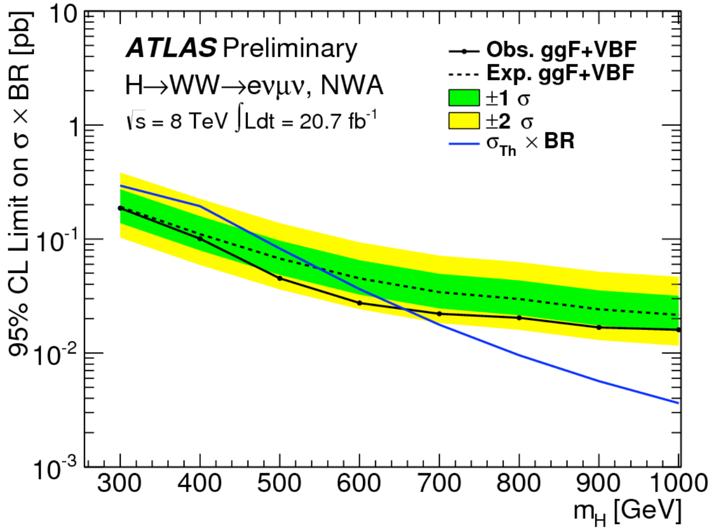
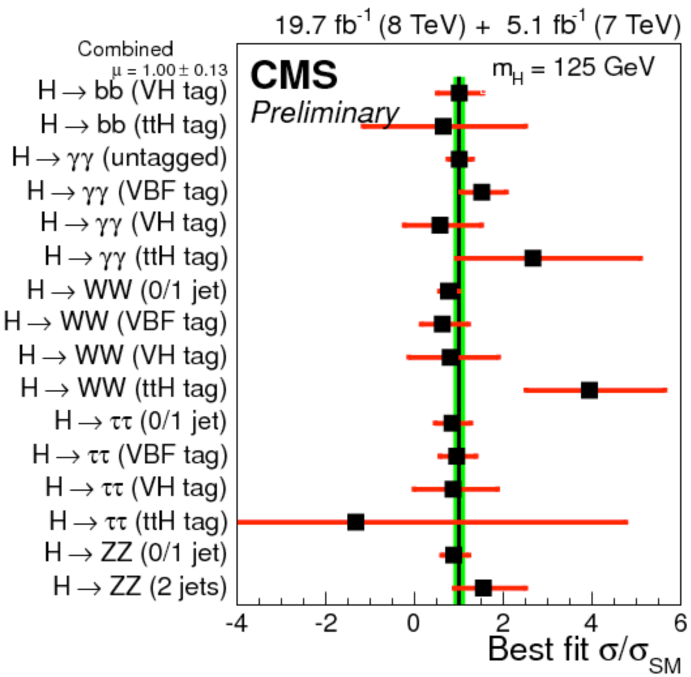
Constraining new physics with Higgs results





Exclusion Limits

Remains an important handle to constrain extended Higgs sectors

→ HiggsBounds

Bechtle, Brein, Heinemeyer, OS, Stefaniak, Weiglein, Williams [0811.4169], [1102.1898], [1311.0055]

Signal measurements

New physics models must also be compatible with the H(125) mass and rate measurements

→ HiggsSignals

Bechtle, Heinemeyer, OS, Stefaniak, Weiglein, [1305.1933]

HiggsSignals

- Like HiggsBounds, HiggsSignals is a public Fortran 90 code
  Its purpose is to test the compatibility of arbitrary models to current and future *measurements* of signals in Higgs searches

- HiggsSignals uses the same input structure as HiggsBounds (HB)
  -> Very easy to get started for users already familiar with HB

- Authors: P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein

  First release: 1.0.0 (May 2013) - Current version: 1.2.0 (March 2014)

- Detailed physics description and user manual published

  Bechtle, Heinemeyer, OS, Stefaniak, Weiglein, [1305.1933]

- HiggsSignals can be downloaded from:

http://higgsbounds.hepforge.org

Brief Description

- HiggsSignals tests Higgs sector predictions (user input) against measured Higgs mass(es) and rates from the LHC/Tevatron (experimental input) by evaluating a χ^2 value (output)

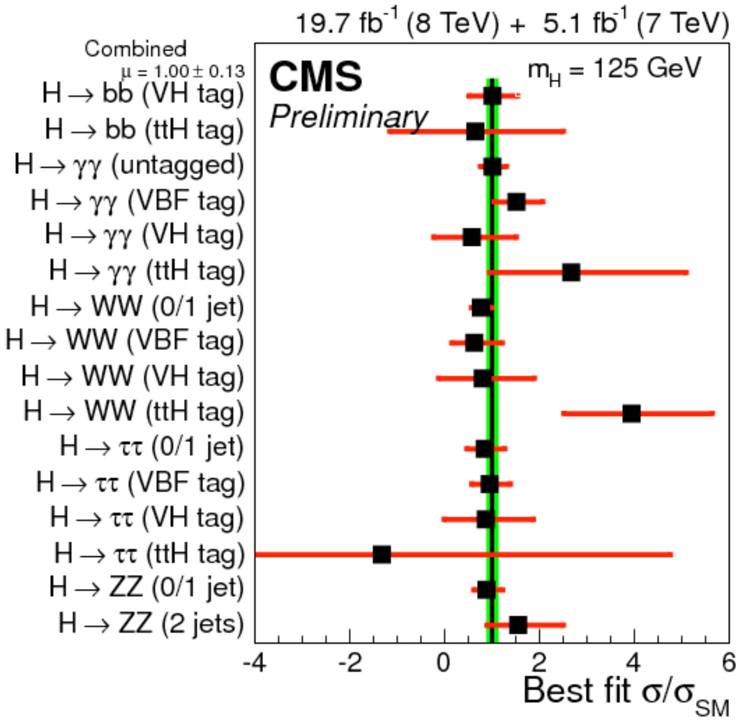
- The aim is to be
  - as model-independent as possible
    not by limiting studies to e.g. effective couplings, but by providing a generic tool that can be used to test (any) specific model

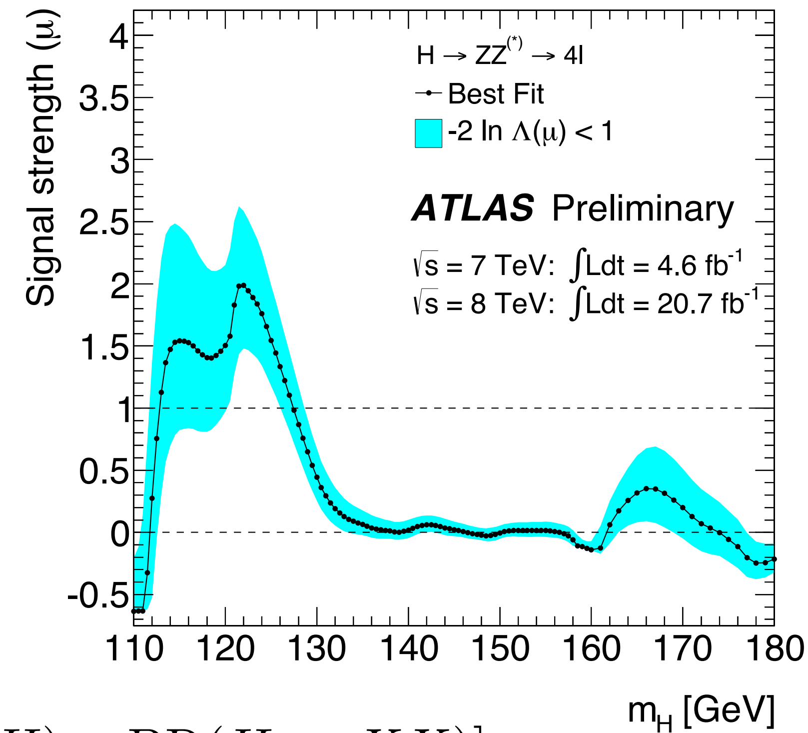
  - as precise as possible
    Primarily limited by the public information on experimental results

- HiggsSignals has been designed from the beginning to handle multiple Higgs bosons and multiple Higgs signals

Experimental data

- The basic quantity used in HiggsSignals is the *signal strength*





$$\mu_{H\to XX} = \frac{\sum_i \epsilon_i^{\text{mod}} \left[\sigma_i(pp \to H) \times \text{BR}(H \to XX)\right]_{\text{model}}}{\sum_i \epsilon_i^{\text{SM}} \left[\sigma_i(pp \to H) \times \text{BR}(H \to XX)\right]_{\text{SM}}}$$

$$i \in \{\text{ggF}, \text{VBF}, \text{WH}, \text{ZH}, \text{ttH}\}$$

- Experimental *efficiencies* (acceptance) ϵ_i from experimental publications. Default assumption: $\epsilon_i^{\text{model}} = \epsilon_i^{\text{SM}}$

Experimental data

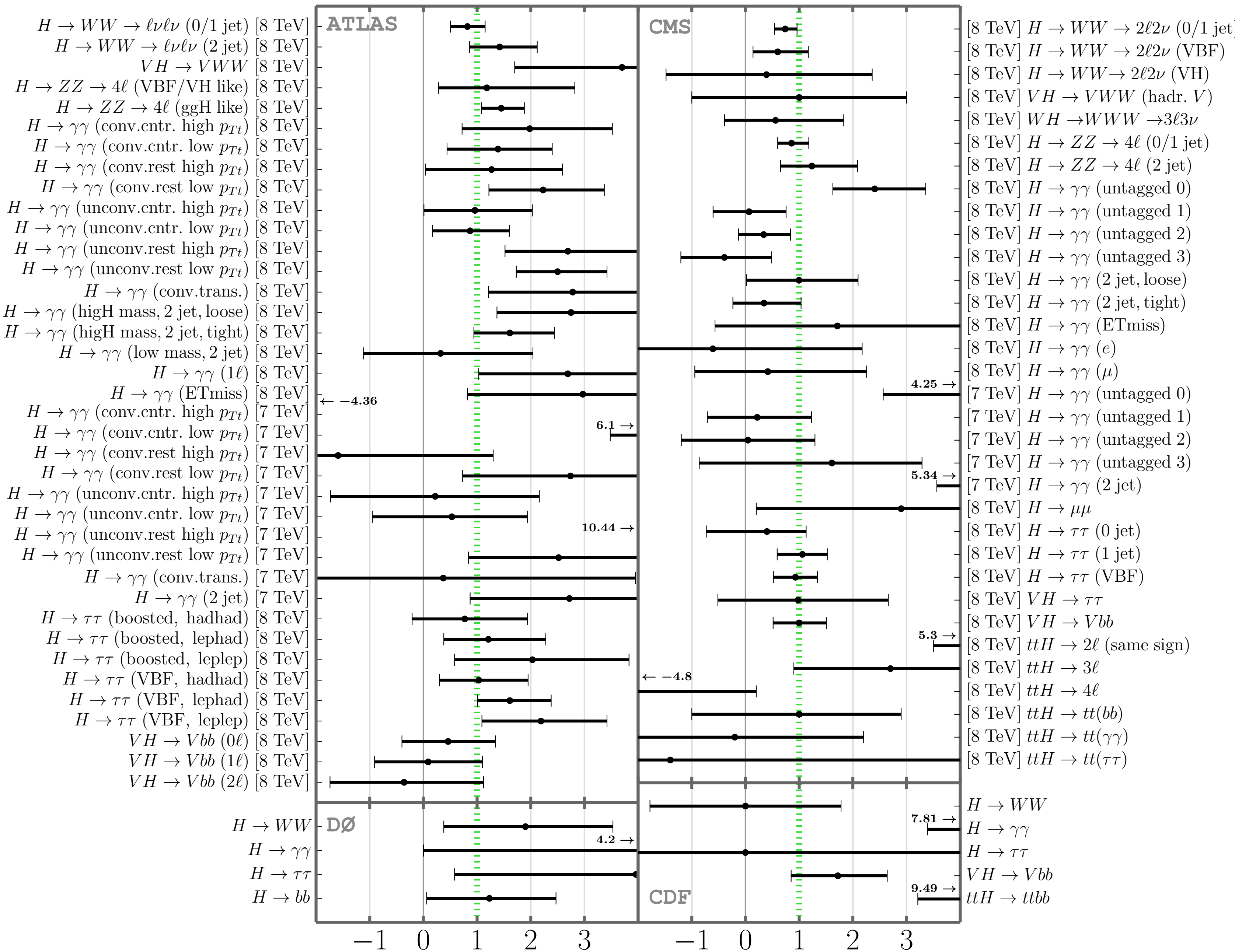
- The data format is easily accessible to the user (text files)
  Observables can be added/edited/removed and organized in directories

```
# Published at Moriond 2013.
# Data read in from Fig. 25a.
# No efficiencies are given (for this inclusive result)
# Mass uncertainty contains 0.6 GeV (stat) and 0.5 GeV (syst) error.
#(Gauss: 0.8, linear: 1.1)
2013013101 201301301 1
ATL-CONF-2013-013
LHC, ATL, ATL
(pp)->h->ZZ->4l
8 25.3 0.036
1 1
1.1
124.3 124.3 0.1
4 -1
13 23 33 43

       124.3           1.293           1.697           2.194
```

- For the 99% of users who are not interested in this, we (try to) maintain an up-to-date default set

- Public version (and this talk) contains results up to March 2014



User input

- To test a model, the user has to provide as input

  The number of (neutral) Higgs bosons: $N, \quad k = 1 \ldots N$

  Higgs masses: M_k

  Production cross sections: $\sigma_i(pp \to H_k)$

  Total decay widths: $\Gamma_k^{\rm tot}$

  Decay branching ratios: $\mathrm{BR}(H_k \to X)$

  Optional: Model-specific theoretical uncertainties: $\Delta M_k \quad \Delta\sigma_i \quad \Delta\mathrm{BR}$

- A number of different options exist for the physics input:
  hadronic cross sections, partonic cross sections, effective couplings

- … and also a number of technical interfaces to do it:
  tabulated data files, SLHA (for MSSM/NMSSM), library of subroutines

χ^2 Evaluation

- Summing over all observables α, a global χ^2 function is determined for the rates

$$\chi^2_\mu = \sum_{\alpha=1}^{N} \chi^2_{\mu,\alpha} = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})^T \mathbf{C}_\mu^{-\mathbf{1}} (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

- Correlations of major systematic uncertainties taken into account:
  - Luminosity uncertainties (fully correlated within experiments)
  - Theoretical rate uncertainties (fully correlated for same channels)

  Other (exp.) correlations could be included similarly ***if*** they were publicly available

- Total χ^2 with contribution from mass observables ($\gamma\gamma$/ZZ) added:

$$\chi^2_{\mathrm{tot}} = \chi^2_\mu + \chi^2_m$$

  Different Higgs mass pdfs (Gaussian, box, box+Gaussian) available

Multiple Higgs bosons

- In a multi-Higgs theory, e.g. the MSSM, any neutral Higgs boson could in principle be responsible for the observed signal(s)

- The theoretical prediction μ used for a particular observable α is determined by *assigning* one or more Higgs bosons to the signal, based on their masses:

$$|m_i - \hat{m}_\alpha| \leq \Lambda \sqrt{(\Delta m_i)^2 + (\Delta \hat{m}_\alpha)^2}.$$

Λ is a tuning parameter of O(1)

- When multiple Higgs bosons are assigned to the same signal, the rate is determined by an incoherent sum (interference neglected)

$$\mu_\alpha = \sum_i (\mu_\alpha)_i$$

- Observables with no assigned Higgs bosons contribute a χ^2 value corresponding to the prediction $\mu = 0$

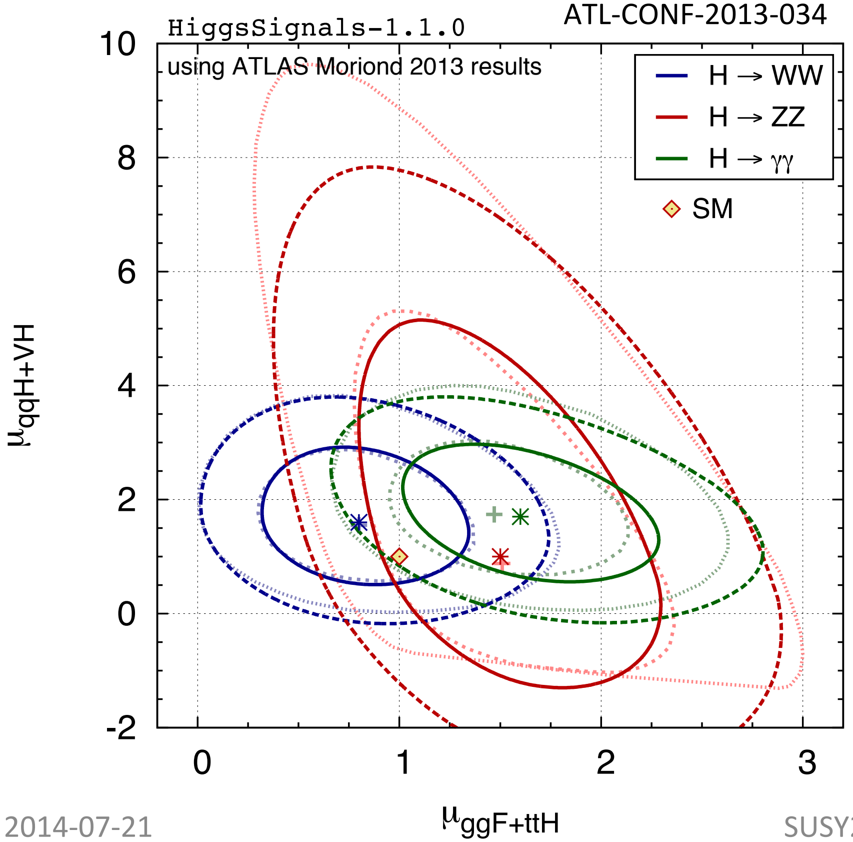
Applications

Coupling scale factors

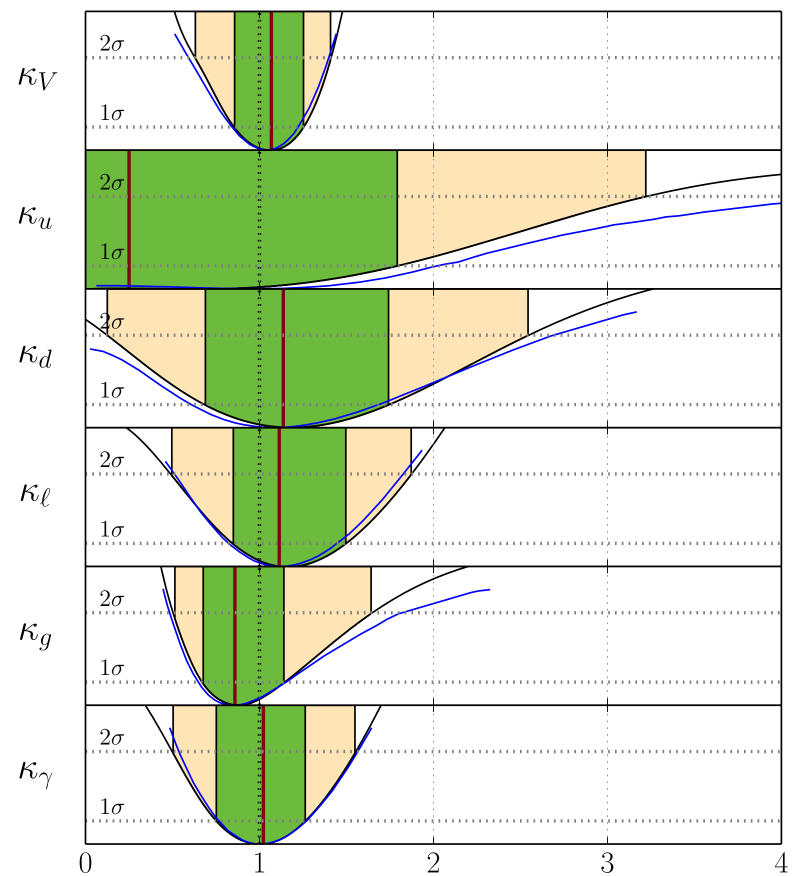
- Fit of universal coupling scale factors, κ_i (SM: $\kappa_i = 1$) Assumes single Higgs boson, SM coupling structure

LHC Higgs XS WG [1209.0040], [1307.1347]

- Official ATLAS/CMS coupling fits used to validate HiggsSignals procedure



CMS-PAS-HIG-13-005



Coupling scale factors

Bechtle, Heinemeyer, OS, Stefaniak, Weiglein, [1403.1582]

- Full data from ATLAS/CDF/CMS/D0 used simultaneously (80 observables)

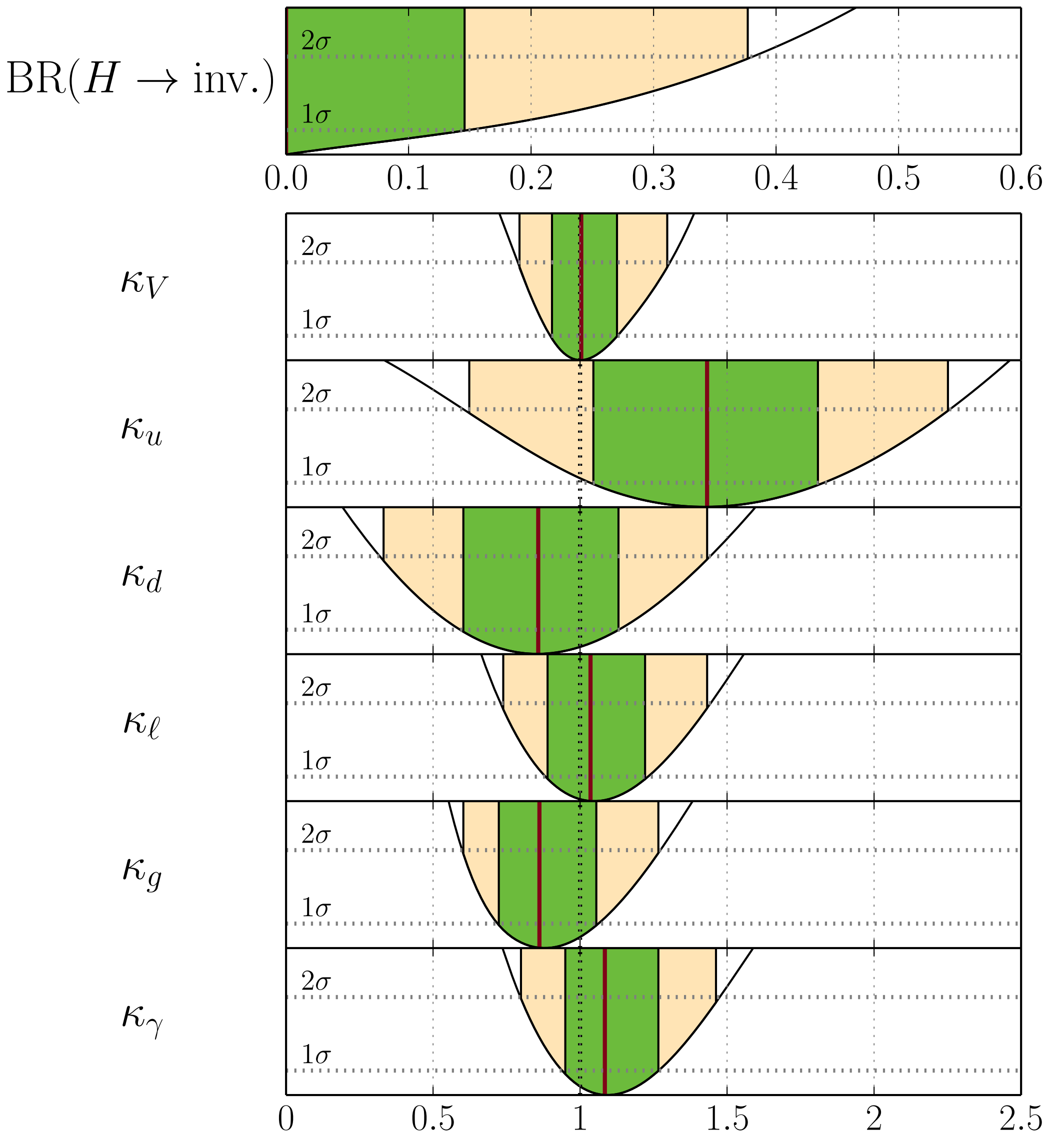
Fit I: universal κ Fit II: κ_V, κ_F Fit III: κ_W, κ_Z, κ_F
Fit IV: κ_V, κ_u, κ_d, κ_ℓ Fit V: κ_g, κ_γ Fit VI: κ_V, κ_u, κ_d, κ_ℓ, κ_g, κ_γ

Fit	κ_W		κ_Z		κ_u		κ_d		κ_ℓ	κ_g	κ_γ	$\mathrm{BR}^{95\%\mathrm{CL}}_{H\to\mathrm{inv}}$	χ^2/ndf	$\mathcal{P}$-value
I	1.01	=	1.01	=	1.01	=	1.01	=	1.01	1.01	1.01	< 37%	84.3/79	32.2%
II	1.02	=	1.02		0.95	=	0.95	=	0.95	0.95	1.04	< 37%	84.0/78	30.1%
III	1.00		1.06		0.93	=	0.93	=	0.93	0.93	1.02	< 36%	83.7/77	28.2%
IV	1.00	=	1.00		0.84		0.84		0.99	0.84	1.04	< 39%	82.8/76	27.8%
V	1.00	=	1.00	=	1.00	=	1.00	=	1.00	0.92	1.14	< 20%	82.6/78	33.9%
VI	1.00	=	1.00		1.42		0.86		1.05	0.88	1.09	< 39%	79.9/74	29.9%

SM: χ^2/ndf = 84.3/80, P = 35.0%

- Best fit values are very close to unity
- Invisible branching ratio < 40% (at 95% CL)
- None of the deformations yield a fit quantitatively better than the SM

Most general kappa fit



MSSM

- We now consider the MSSM with all soft parameters specified at low scale (pMSSM)

- Higgs spectrum, cross sections, and decay branching ratios are evaluated directly in the full model using FeynHiggs

  Hahn, Heinemeyer, Hollik, Rzehak, Weiglein [1312.4937]

  -> No simplifications, effective coupling frameworks or analytic approximations are necessary!

- **Higgs Constraints (parts I and II)**
  HiggsSignals χ^2 information on the H(125) signal +
  LEP χ^2 information (light Higgs) +
  HiggsBounds Direct search limits (95% C.L.)

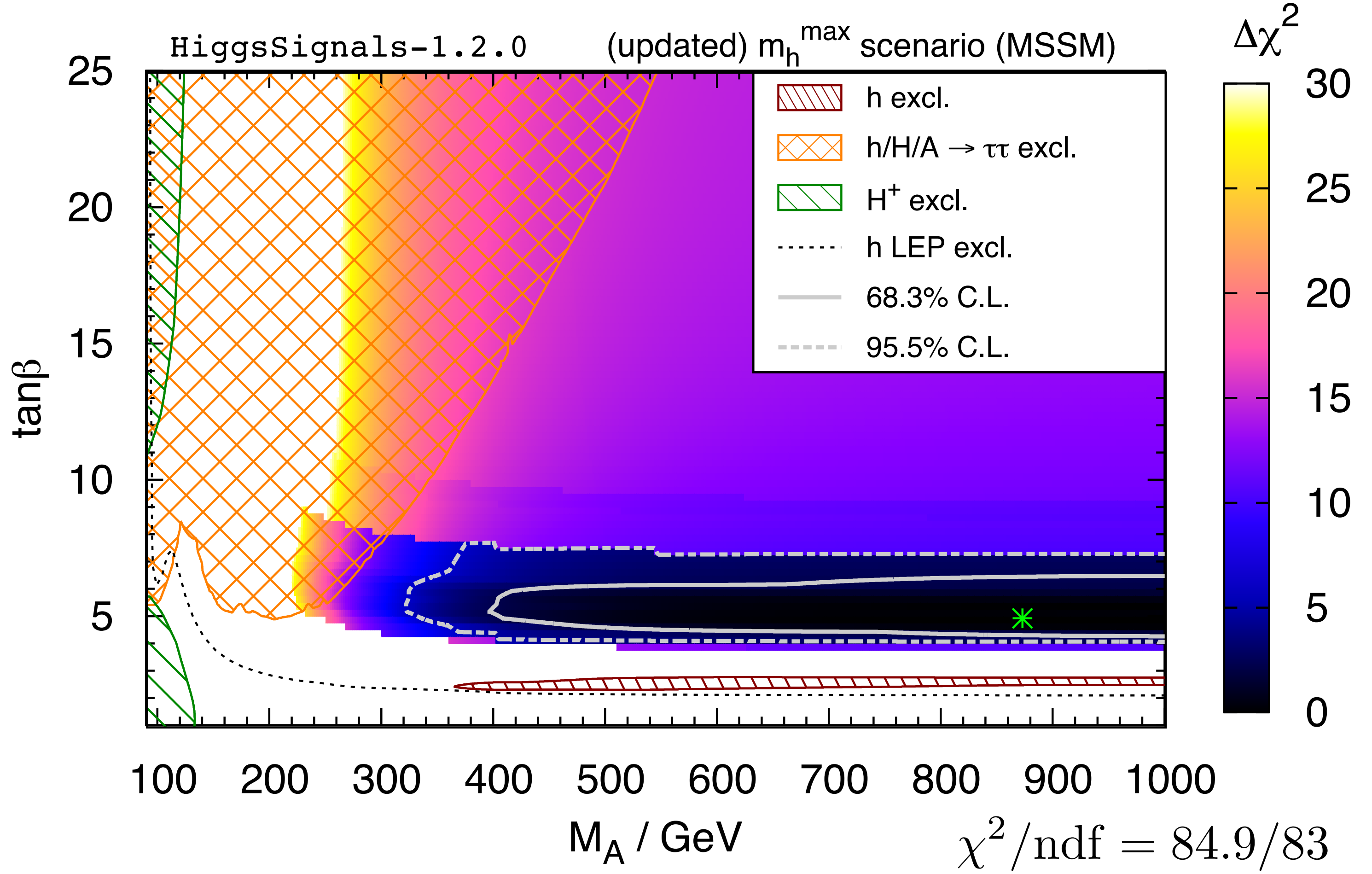
- **Low-energy observables (part II only)**
  Flavor constraints ($B \to X_s\gamma$, $B_s \to \mu^+\mu^-$, $B \to \tau\nu_\tau$) SuperIso
  Mahmoudi, [0710.2067]
  g-2 muon
  M_W
  Heinemeyer, Hollik, Weiglein, Zeune, [1311.1663]

M_h-max scenario

- One of several benchmark scenarios for MSSM Higgs searches at LHC
  Maximizes light Higgs mass through large stop mixing

$$X_t = A_t - \mu \cot\beta = 2\, M_S \qquad M_S = 1\,\text{TeV}$$

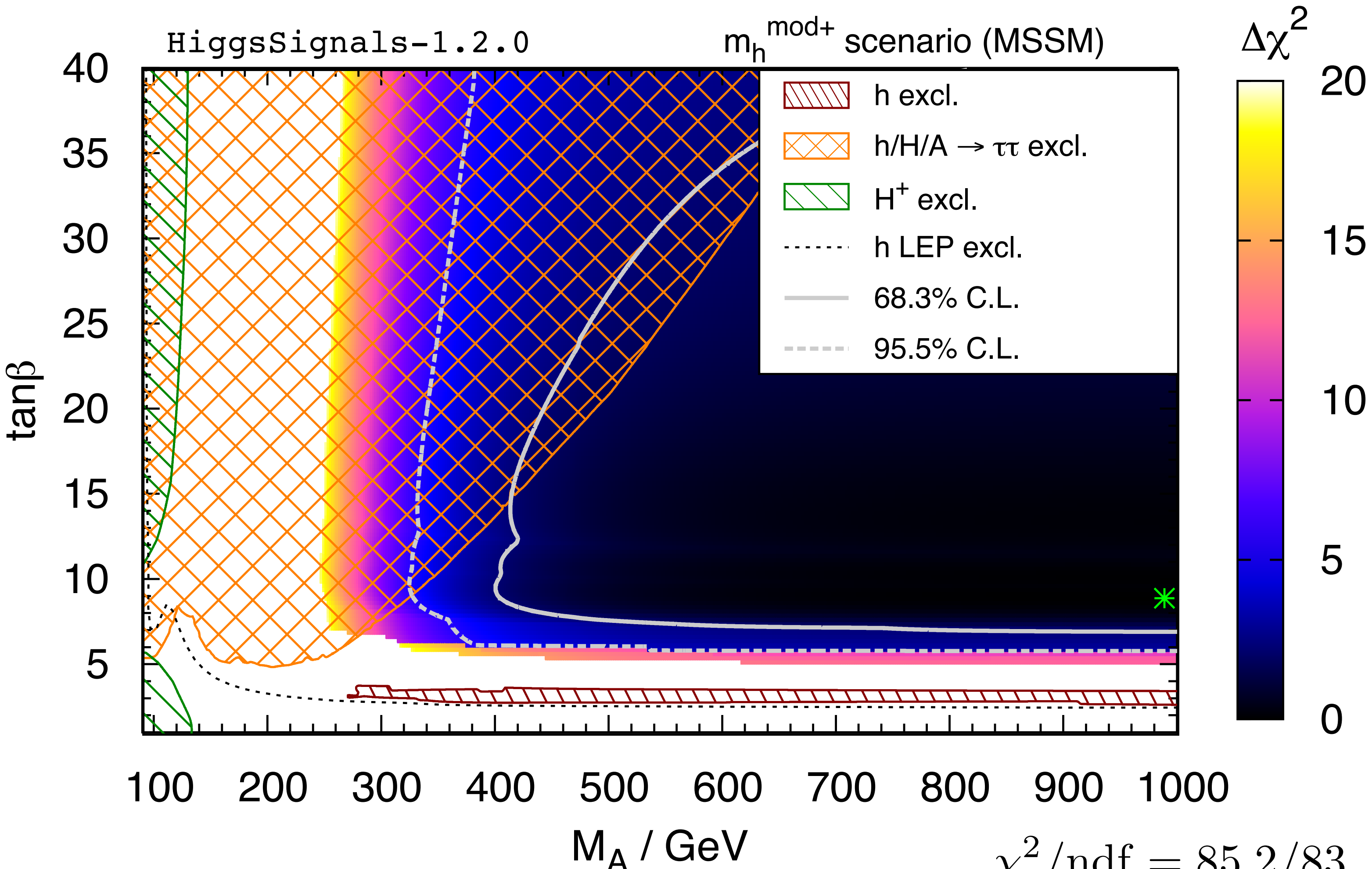
Carena, Heinemeyer, OS, Wagner, Weiglein, [1302.7033]



$\chi^2/\text{ndf} = 84.9/83$

M_h-mod+ scenario

- Modified stop mixing to yield M_h compatible with signal over large parts of the parameter space



$\chi^2/\text{ndf} = 85.2/83$

Global pMSSM analysis

- Analysis of individual benchmark scenarios indicate:
  - decoupling limit strongly favored -> SM-like rates
  - M_A > 400 GeV (68% C.L.), > 320 GeV (95% C.L.)

  Does this picture persist in a global scan of the (TeV-scale) pMSSM?

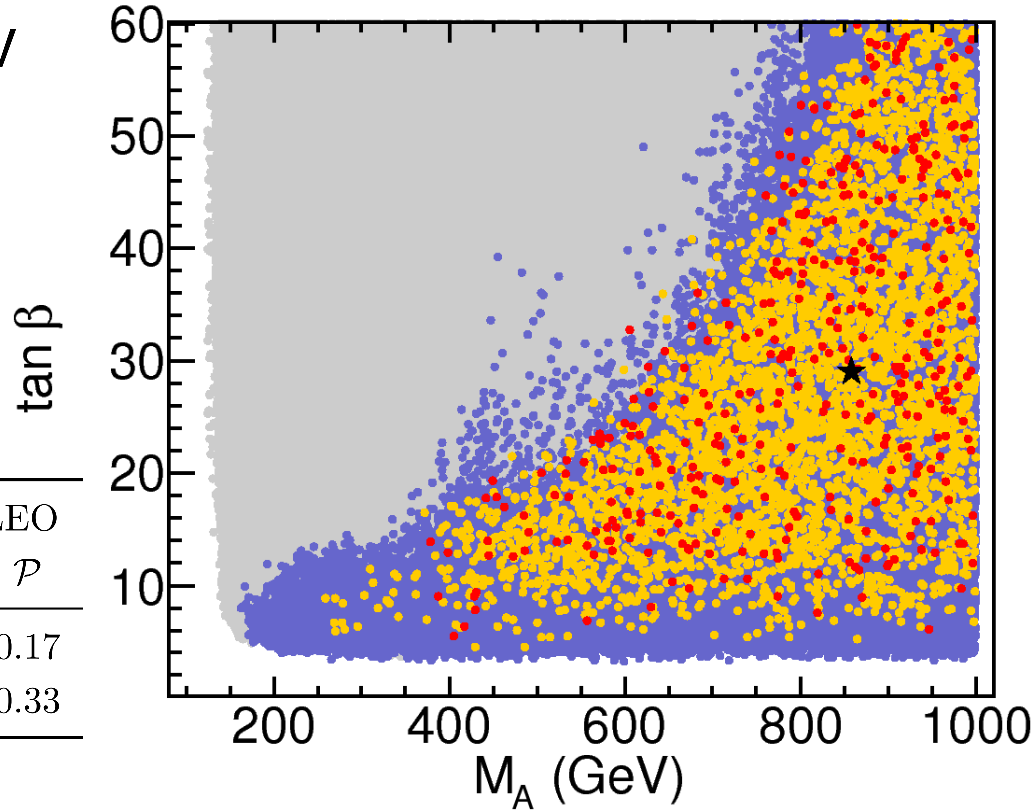
Parameter	Minimum	Maximum
M_A [GeV]	90	1000
$\tan\beta$	1	60
μ [GeV]	200	4000
$M_{\tilde{Q}_3}$ [GeV]	200	1500
$M_{\tilde{\ell}}$ [GeV]	200	1500
A_f [GeV]	-3 $M_{\tilde{Q}_3}$	3 $M_{\tilde{Q}_3}$
M_1 [GeV]	100	M_2
M_2 [GeV]	200	500

$$M_{\tilde{Q}_{1,2}} = m_{\tilde{g}} = 1500 \text{ GeV}$$

- Higgs constraints as before (HB+HS), low-energy observables (LEO) included into total χ^2

pMSSM Global Analysis: Results

- All points: $120 < M_h < 130$ GeV
- Allowed by direct limits (HB)
- ★ Best fit point
- $\Delta\chi^2 < 2.30$
- $\Delta\chi^2 < 5.99$



	LHC+Tevatron			LHC+Tevatron+LEO		
	χ^2/ν	χ^2_ν	$\mathcal{P}$	χ^2/ν	χ^2_ν	$\mathcal{P}$
SM	87.5/83	1.05	0.35	102.8/88	1.17	0.17
h	84.3/77	1.09	0.27	87.2/82	1.06	0.33

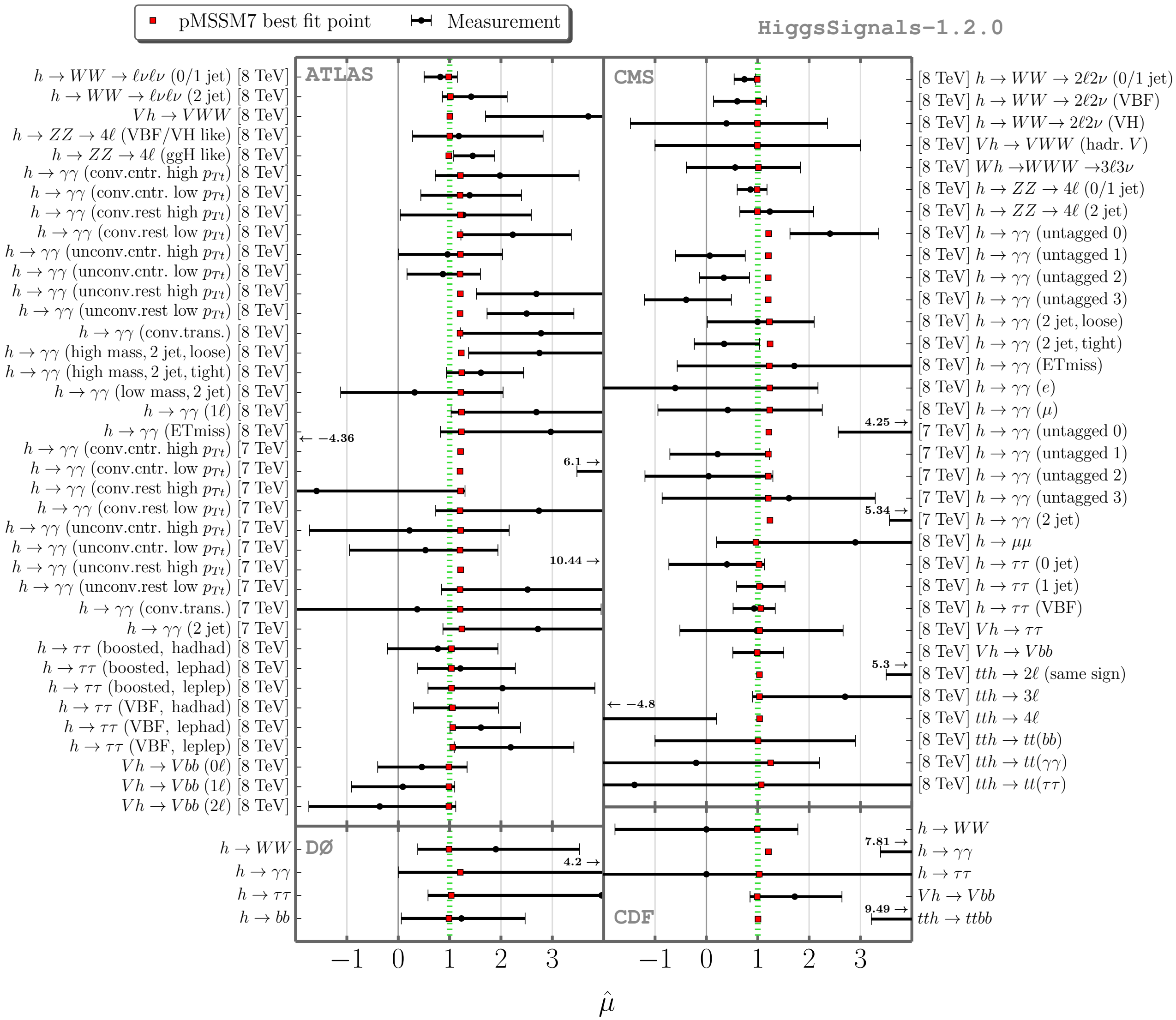
- SM and MSSM provide similar quality of fit for the Higgs observables, MSSM does better with low-energy data included

- Decoupling scenario of benchmarks reproduced:
  $M_A > 250$ GeV (95% C.L.), $M_A > 400$ GeV (68% C.L.)
  Wide range of tan β allowed

Preliminary

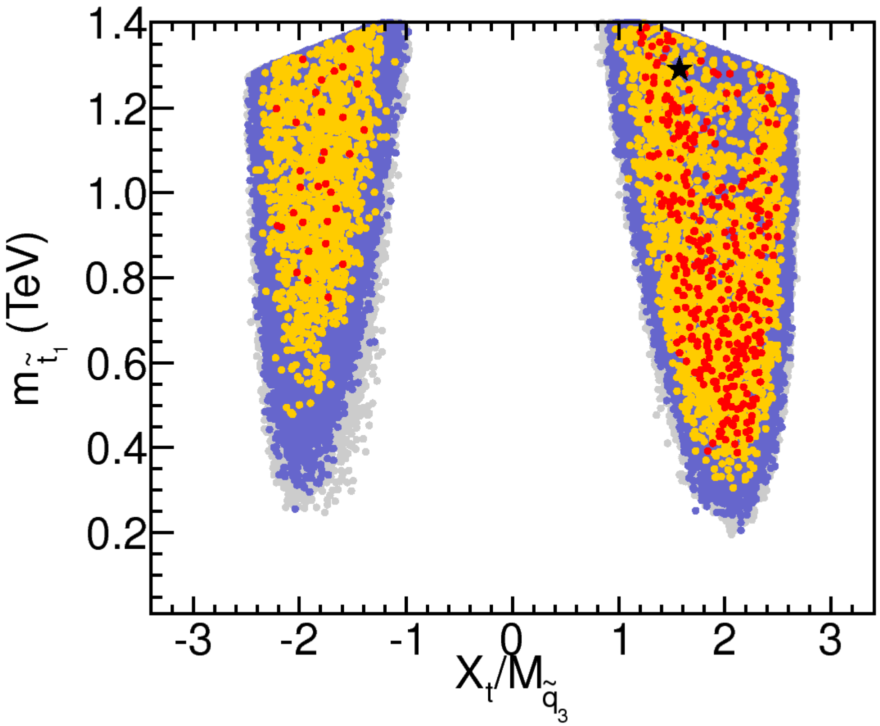
Best fit point

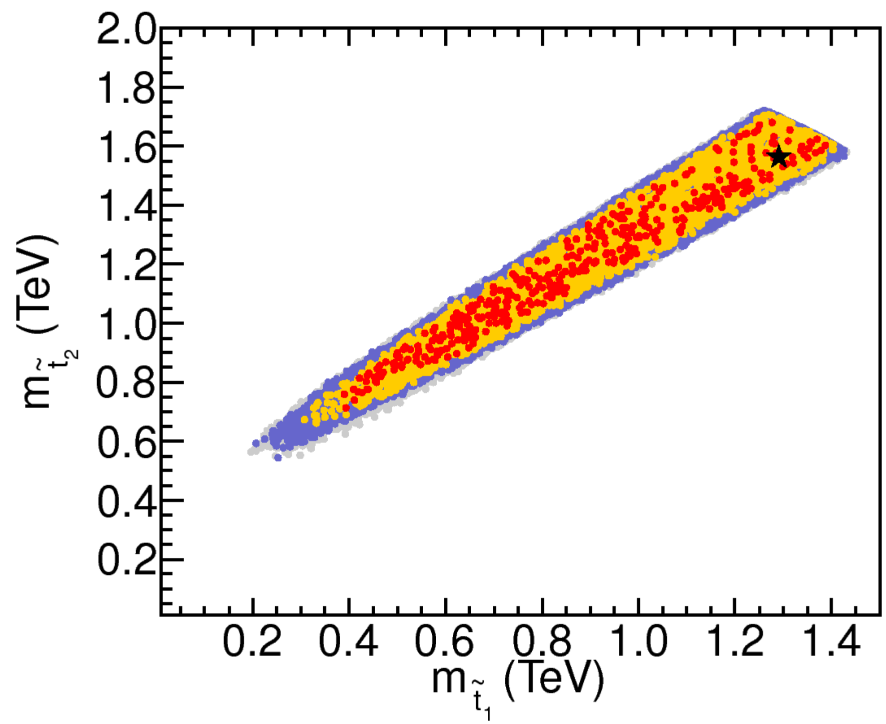
Preliminary



- Overall results is very SM-like, the ~10% enhancement of $\gamma\gamma$ from light staus also gives better fit to $(g\text{-}2)_\mu$ due to assumed slepton universality

Implications for the stop sector





Preliminary

- $X_t = 0$ strongly disfavored (unless stops multi-TeV)
- Both signs of X_t allowed in the most favored region
- Lower limit on lightest stop mass from Higgs physics ($m_{\tilde{t}_1} \gtrsim 300\,\mathrm{GeV}$) complementary to limits from direct searches

Conclusions

- The public code HiggsSignals makes use of LHC/Tevatron measurements to evaluate a χ^2 function comparing Higgs data <-> theory for BSM models

- Our general strategy for this code is to
  - be model-independent (allow testing different explicit BSM models)
  - be as precise as possible (using public information)
  - keep it up-to-date with latest results

- The procedure and code is validated against official CMS/ATLAS fits

- Rescaling of SM Higgs couplings was analyzed (six scenarios) – no indication in the combined result of deviations from $\kappa_i = 1$

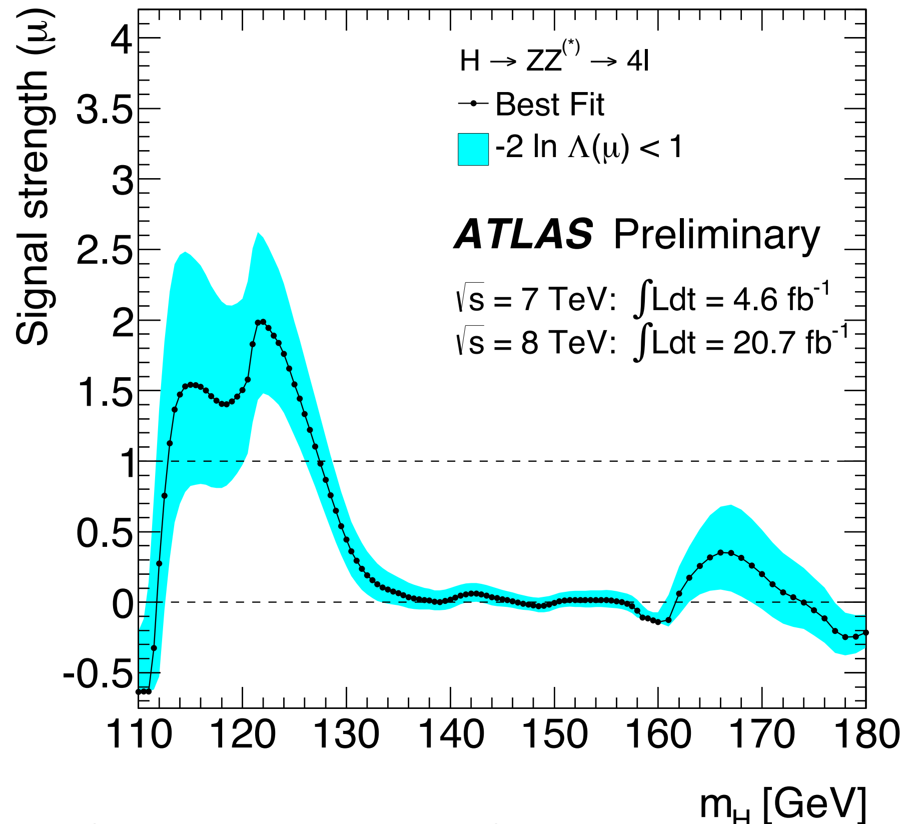
- MSSM benchmark scenarios show best fit in decoupling region, rates for lightest Higgs very close to SM -> Lower limit on M_A
  More detailed results will follow from the global pMSSM fit – stay tuned!

http://higgsbounds.hepforge.org

Backup

Mass-Centered χ^2 method

- Compares model prediction to measured data directly at the *predicted* Higgs mass values
- Combines rate predictions for Higgs bosons that are "nearby" in mass (within exp. resolution)
- Applicability of this method is currently limited by available exp. results, e.g. $M_H < 200$ GeV



- Can be used simultaneously with peak-centered method for Higgs bosons that have not been assigned to any signal

Derived scale factors

- Interim framework proposed by LHCXSWG for fitting (small) deviations from the SM Higgs couplings
- Assumes structure of couplings unchanged from SM, only coupling *strengths* modified
- Large deviations from the SM should be interpreted with care

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

Higgs coupling scale factors

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma_{\mathrm{Z}\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

Parameter values for MSSM benchmark scenarios

Parameter	$m_h^{\max}$	$m_h^{\text{mod}+}$	$m_h^{\text{mod}-}$	*light stop*	*light stau*	τ*-phobic*	*low-*M_H
m_t	173.2	173.2	173.2	173.2	173.2	173.2	173.2
M_A	varied	varied	varied	varied	varied	varied	110
$\tan\beta$	varied	varied	varied	varied	varied	varied	varied
M_{SUSY}	1000	1000	1000	500	1000	1500	1500
$M_{\tilde{l}_3}$	1000	1000	1000	1000	245 (250)	500	1000
$X_t^{\text{OS}}/M_{\text{SUSY}}$	2.0	1.5	-1.9	2.0	1.6	2.45	2.45
$X_t^{\overline{\text{MS}}}/M_{\text{SUSY}}$	$\sqrt{6}$	1.6	-2.2	2.2	1.7	2.9	2.9
A_t	Given by $A_t = X_t + \mu\cot\beta$						
A_b	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$
A_τ	$= A_t$	$= A_t$	$= A_t$	$= A_t$	0	0	$= A_t$
μ	200	200	200	350	500 (450)	2000	varied
M_1	Fixed by GUT relation to M_2						
M_2	200	200	200	350	200 (400)	200	200
$m_{\tilde{g}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{q}_{1,2}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{l}_{1,2}}$	500	500	500	500	500	500	500
$A_{f\neq t,b,\tau}$	0	0	0	0	0	0	0

pMSSM fit

LEO	O_i	χ^2_h	Pull
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	3.55	0.03	0.18
$\mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^9$	3.66	0.77	0.88
$\mathrm{BR}(B_u \to \tau\nu_\tau) \times 10^4$	0.78	2.00	−1.41
$\delta a_\mu \times 10^9$	2.76	0.09	−0.29
M_W [GeV]	80.382	0.01	−0.10

Parameter	Light Higgs case Original 2012 analysis Best fit			Light Higgs case Updated analysis Best fit			Heavy Higgs case Original 2012 analysis Best fit		
M_A [GeV]	300	669	860	398	858	(1000)	120.5	124.2	128.0
$\tan\beta$	15	16.5	26	9.8	29	(60)	9.7	9.8	10.8
μ [GeV]	1900	2640	(3000)	845	2128	3824	1899	2120	2350
$M_{\tilde{q}_3}$ [GeV]	450	1100	(1500)	637	1424	1481	580	670	740
$M_{\tilde{l}_3}$ [GeV]	250	285	(1500)	230	356	463	(200)	323	(1500)
A_f [GeV]	1100	2569	3600	1249	2315	3524	1450	1668	1840
M_2 [GeV]	(200)	201	450	(200)	229	(500)	(200)	304	370
M_h [GeV]	122.2	126.1	127.1	124.6	125.5	126.4	63.0	65.3	72.0
M_H [GeV]	280	665	860	386	858	(1000)	123.9	125.8	126.4
$M_{H^\pm}$ [GeV]	310	673	860	405	858	(1000)	136.5	138.8	141.5