Higgs & SUSY

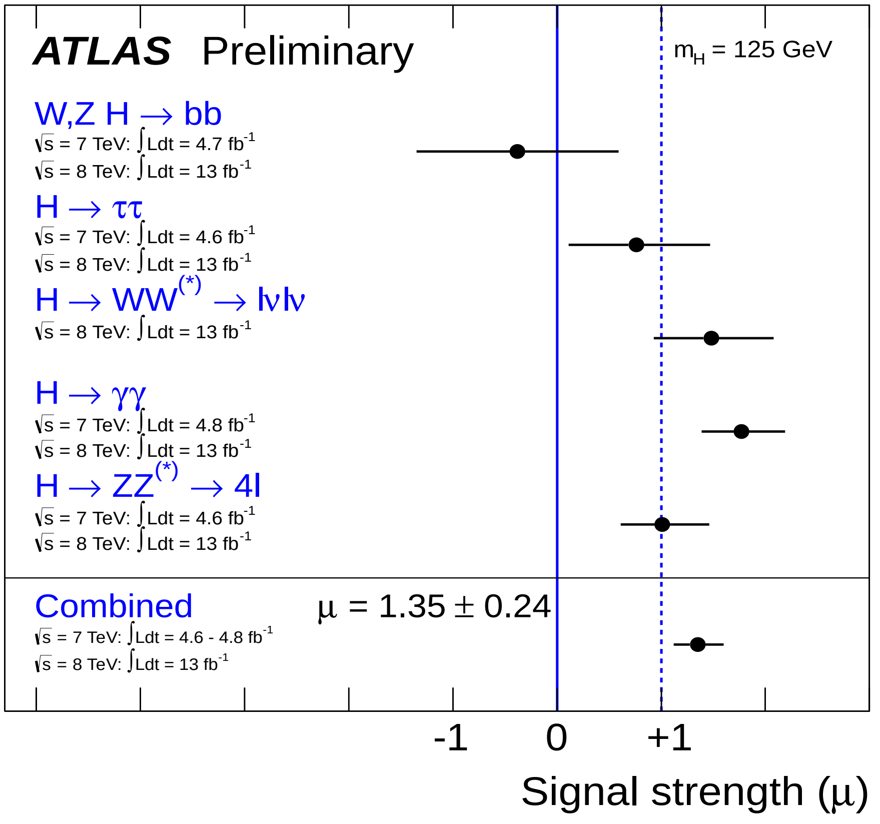
Georg Weiglein

DESY

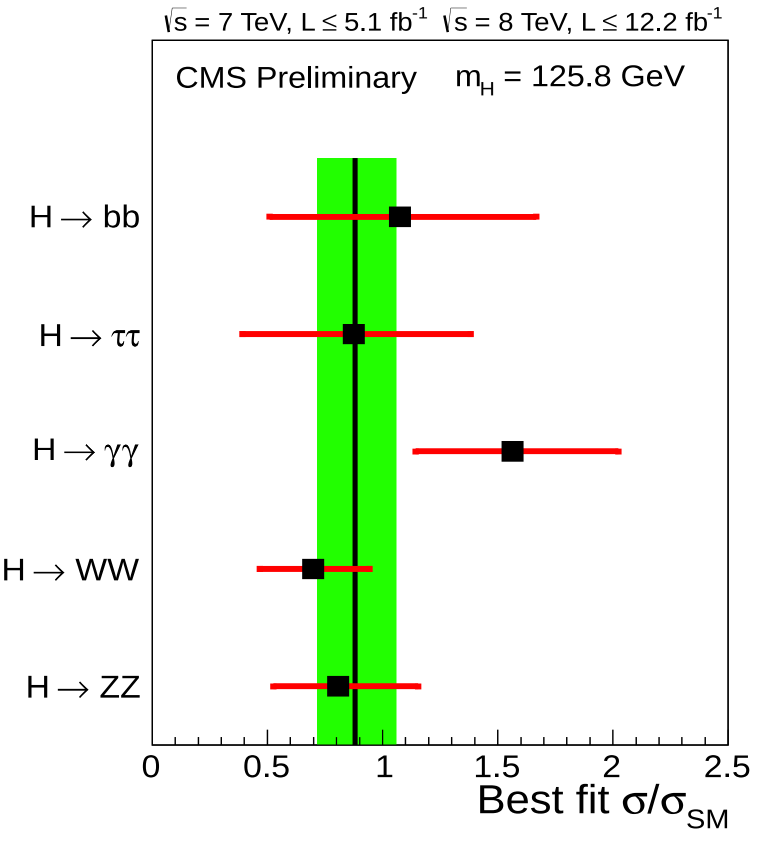
Santa Cruz, 01 / 2013

Introduction

[*ATLAS Collaboration '12*]



[*CMS Collaboration '12*]



⇒ Signal strengths compatible with a SM-like Higgs

$\gamma\gamma$ rate above the SM prediction both for ATLAS and CMS

CMS: no update on $\gamma\gamma$ channel since ICHEP12

A great time for Higgs hunters!

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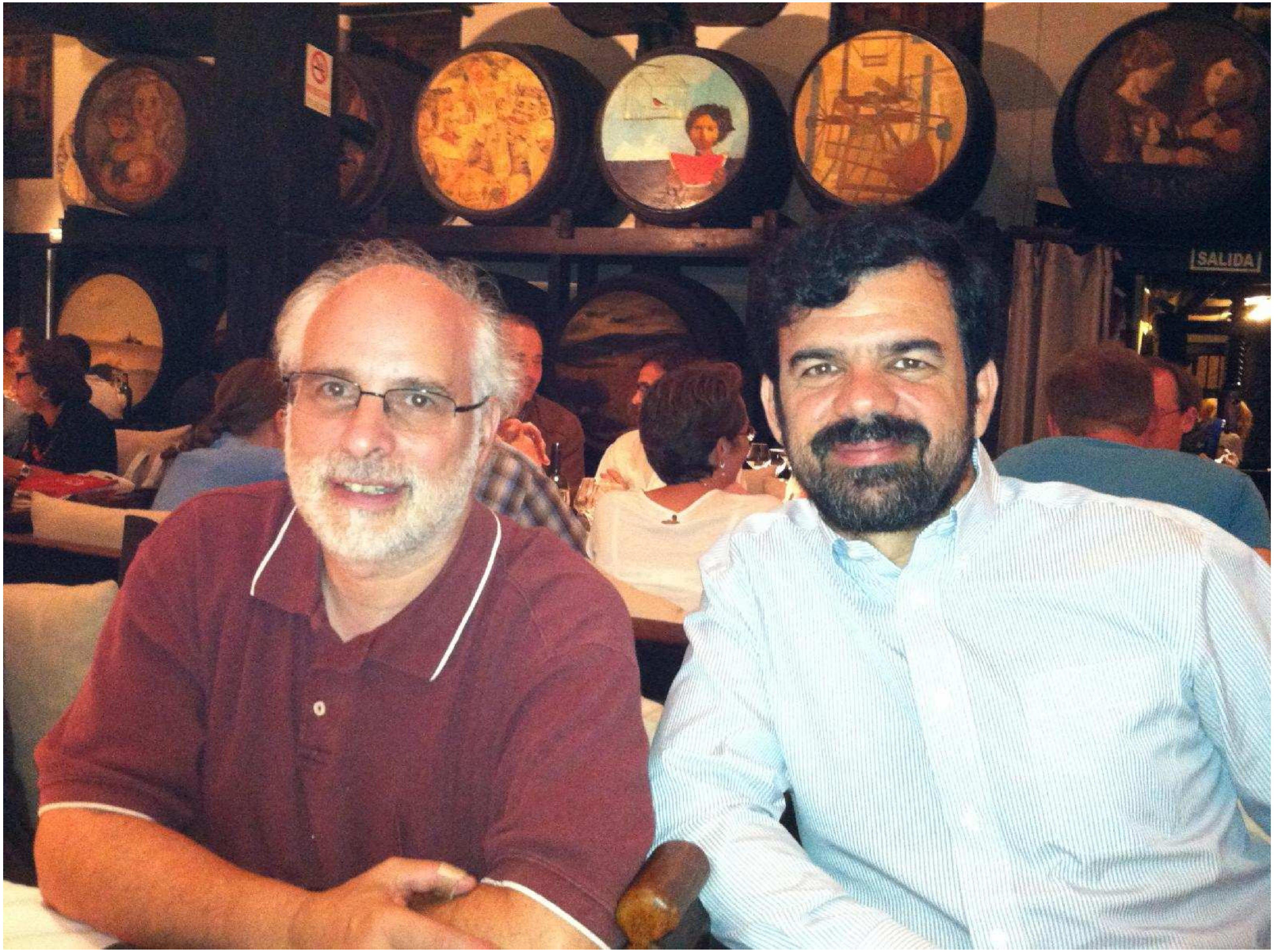

Significance of the discovery: a quote from Herbi . . .

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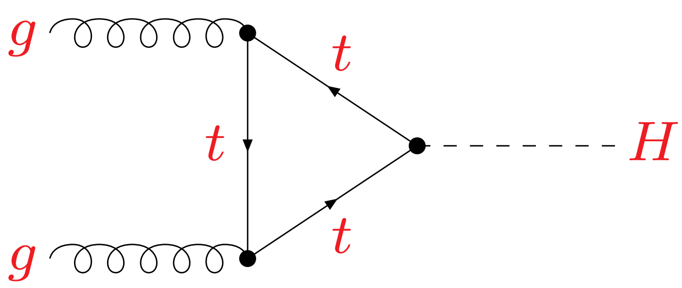
In July the Higgs boson was discovered and finally gave meaning to all of our lives.

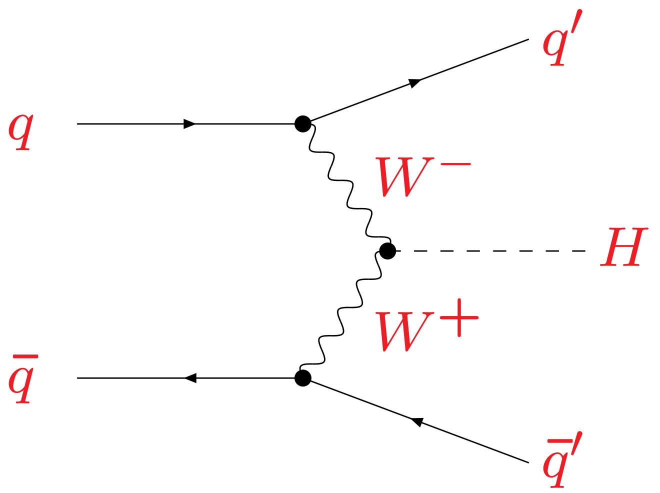
The question of mass has been settled and no more silly diets are required.

Search channels at the LHC

Dominant production processes for a SM-like Higgs at the LHC:

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$





Main decay channels

Good mass resolution:

- $H \to \gamma\gamma$ (loop induced)
- $H \to ZZ^* \to l^+l^-l^+l^-$, $l = e, \mu$

Poor mass resolution:

- $H \to WW^* \to \bar{\nu}l^-\nu l^+$, $l = e, \mu$
- $H \to \tau^+\tau^-$
- $H \to b\bar{b}$

Higgs phenomenology beyond the SM

Standard Model: a single parameter determines the whole Higgs phenomenology: M_{H}

In the SM the same Higgs doublet is used "twice" to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite "natural"

$\Rightarrow$ Would result in several Higgs states

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Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”

Higgs physics in Supersymmetry

"Simplest" extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

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Lowest order: $M_\mathrm{h} \leq M_\mathrm{Z}$

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Detection of a SM-like Higgs with $M_{\mathrm{H}} \gtrsim 135\ \mathrm{GeV}$ would have unambiguously ruled out the MSSM, signal at $\sim 126\ \mathrm{GeV}$ is well compatible with MSSM prediction

Higher-order corrections to the upper bound on $M_{\rm h}$ *in the MSSM*

VOLUME 66, NUMBER 14 PHYSICAL REVIEW LETTERS 8 APRIL 1991

Can the Mass of the Lightest Higgs Boson of the Minimal Supersymmetric Model be Larger than m_Z?

Howard E. Haber and Ralf Hempfling
Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, California 95064
(Received 3 January 1991)

In the minimal supersymmetric model (MSSM), the *tree-level* mass of the lightest Higgs scalar h^0 cannot be larger than the mass of the Z boson. We have computed the one-loop radiative correction to the upper bound on m_{h^0} as a function of the free parameters of the MSSM. We find that the dominant correction to $m_{h^0} - m_Z$ is large and positive and grows like m_t^4, where m_t is the top-quark mass. As a result, the MSSM cannot be ruled out if the CERN e^+e^- collider LEP-200 fails to discover the Higgs boson.

"One of the most expensive calculations in physics"

Higher-order corrections to the upper bound on $M_{\rm h}$ in the MSSM

ANL-HEP-PR-99-109
CERN-TH/2000-005
DESY 99-197
FERMILAB-Pub-00/028-T
KA-TP-10-1999
SCIPP-99/46
hep–ph/0001002

Reconciling the Two-Loop Diagrammatic and Effective Field Theory Computations of the Mass of the Lightest $\mathcal{CP}$-even Higgs Boson in the MSSM

M. Carena [§,†], H.E. Haber [♯], S. Heinemeyer [‡],

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Submission history

From: Howard E. Haber [view email]

[v1] Sat, 1 Jan 2000 09:57:43 GMT (44kb)

The first hep-ph number in the year 2000

SLAC–PUB–8324
UCLA/99/TEP/48
Saclay-SPhT-T99/147
hep-ph/0001001
January 1, 2000

A Two-Loop Four-Gluon Helicity Amplitude in QCD

Z. Bern⋆
Department of Physics and Astronomy
UCLA, Los Angeles, CA 90095-1547

L. Dixon†
Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94309

and

D.A. Kosower
Service de Physique Théorique♯
Centre d'Etudes de Saclay
F-91191 Gif-sur-Yvette cedex, France

Submission history

From: Lance Dixon [view email]

[v1] Sat, 1 Jan 2000 00:00:58 GMT (30kb)

Music, song and dance

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Do Phenomenologists Sing and Dance Better Than String Theorists?

By cjohnson | July 21, 2005 10:40 am

You may recall my recollection in an earlier post about the dancing of the string theorist participants of the Strings 1998 meeting in Santa Barbara, and you may have listened to the singing of the youth of the field at Strings 2005. A good time was had by all in each case, I understand.

Well, the good times continue. Last night, the participants of SUSY 2005, which is taking place in Durham (see some remarks in an earlier post) showed that they can holler and shake their collective booty too. At a barbecue in the sunny long evening, we saw a performance of the Institute for Particle Physics Phenomenology (IPPP)'s own *Ceilidh* band, (pronounced "Kaylee"), comprised of several physicists, their spouses and offspring, (see here for a list and more info) and joined by special guests and physicists Howie Haber on guitar, and David Lyth on fiddle, and led and *smoothly* MC'ed by the Institute's director James Stirling (also on guitar).

Howie's second life?

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Higgs & SUSY — SUSY & Higgs

Higgs & SUSY — SUSY & Higgs

Higgs and SUSY

Howard E. Haber
16 December, 2011

Annual Theory Meeting

IPPP
University of Durham
Durham, UK

Higgs & SUSY — SUSY & Higgs

Higgs and SUSY

SUSY and Higgs

King Henry and
Thomas Becket

Thomas Becket and
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Where is the new physics that stabilises the gauge hierarchy?

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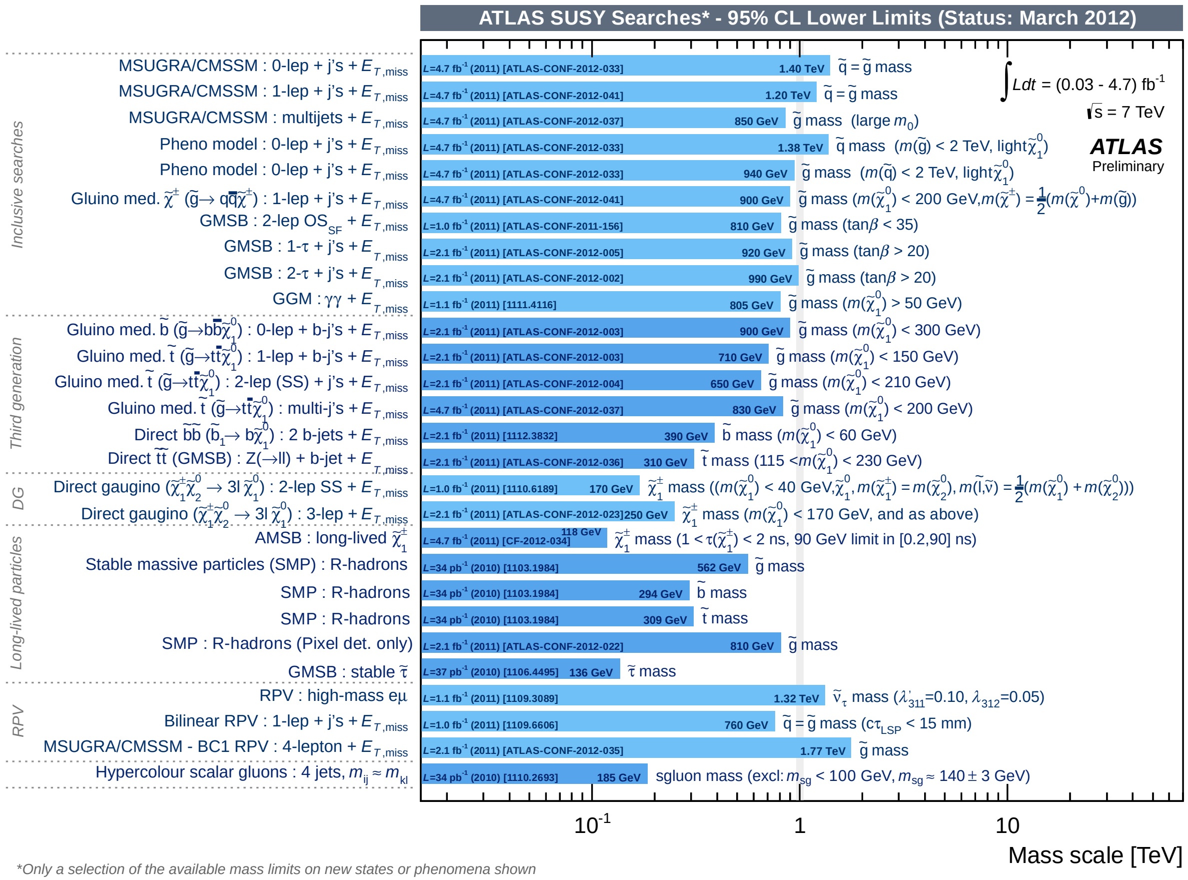
Large number of searches, many limits, . . . *[ATLAS Collaboration ’12]*



Interpretation in specific scenarios, e.g. CMSSM, and in “simplified models”

Tough times for SUSY hunters?

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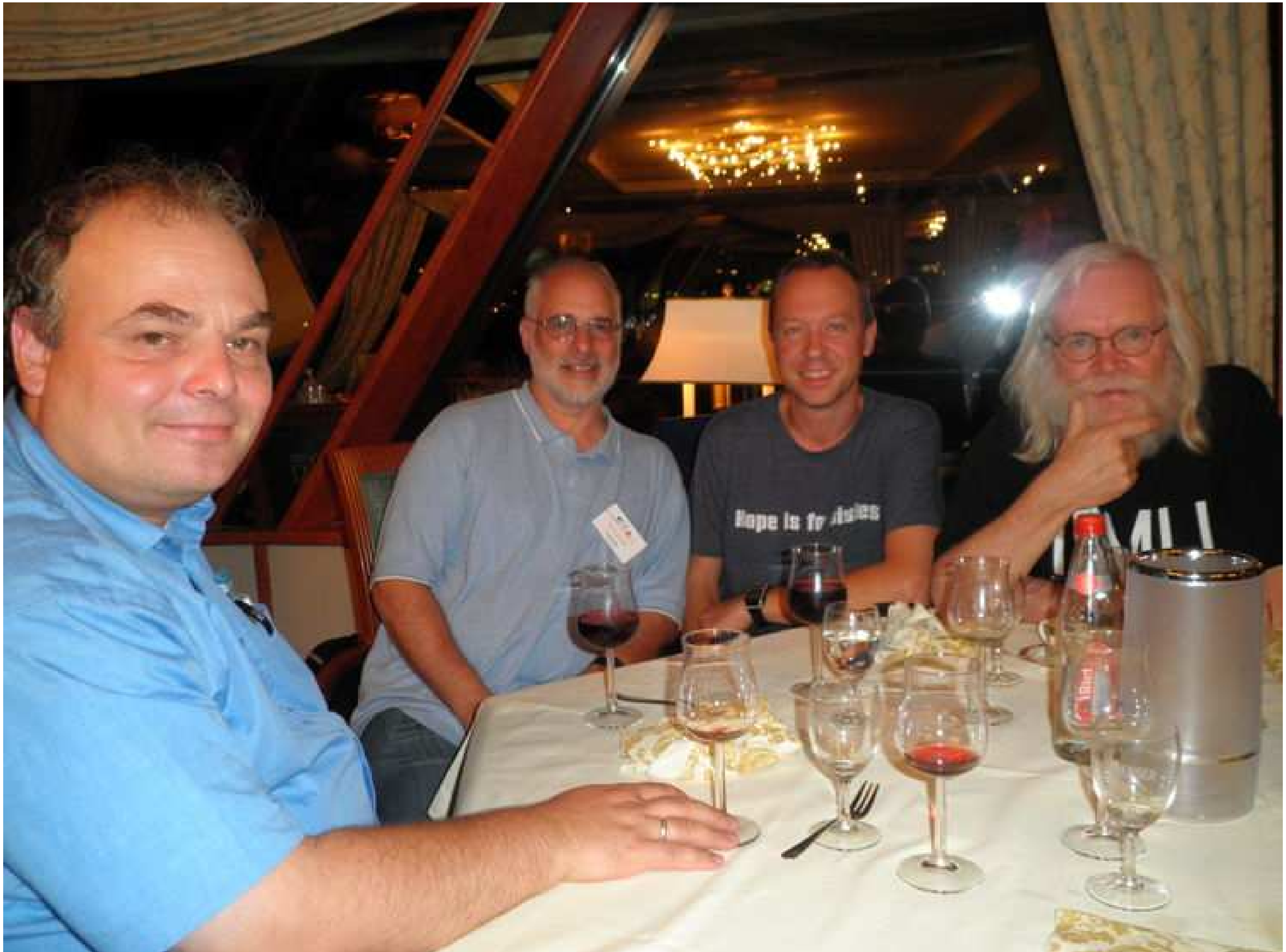

A look back to the pre–LHC days

Global fits in constrained SUSY models (CMSSM, . . .):

Best fit point was close to SPS 1a (LM1, . . .) benchmark point:

Low scale SUSY point

⇒ “plain vanilla” SUSY

⇒ “best case scenario” for LHC and LC

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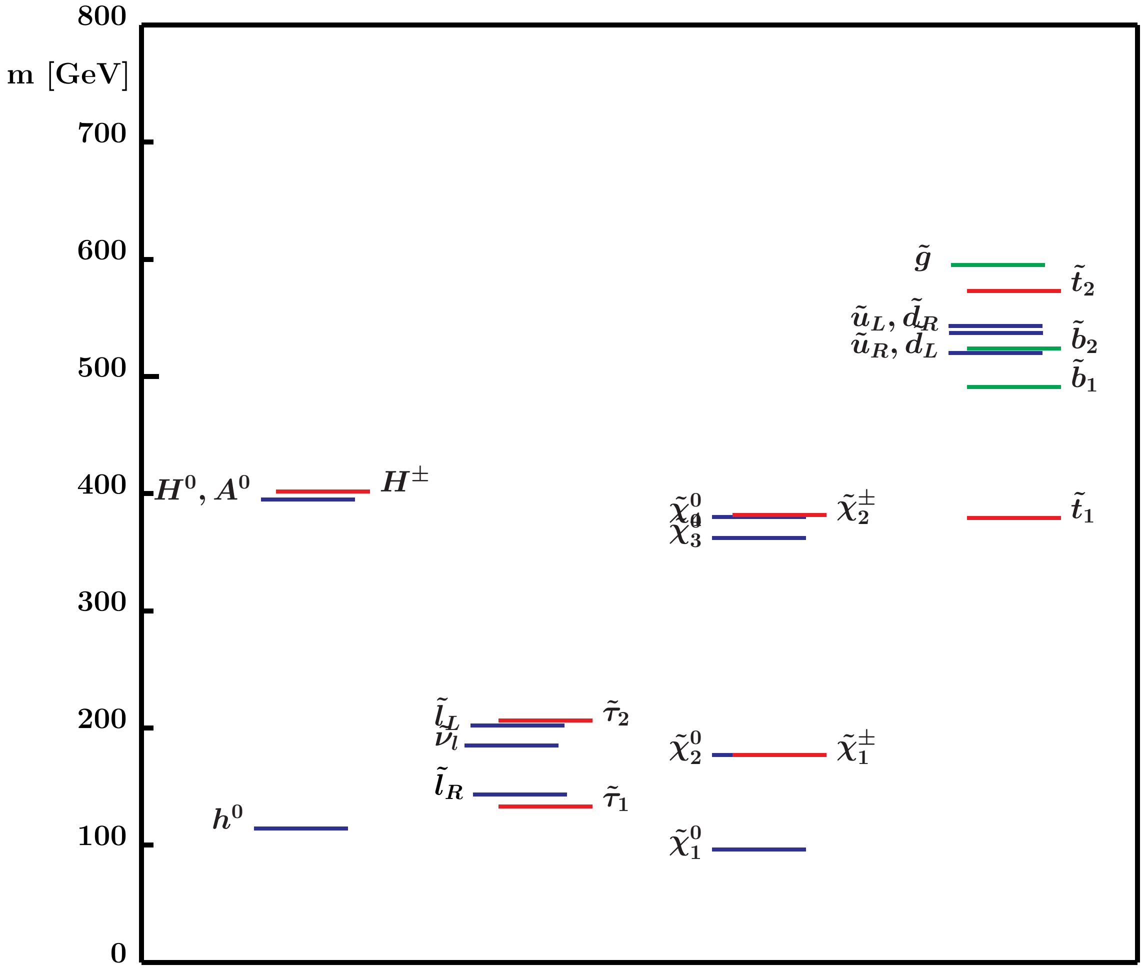
Preference for light SUSY scale was mainly driven by $(g-2)_\mu$

$\Rightarrow$ light $\tilde{e}$, $\tilde{\mu}$, $\tilde{\chi}$, . . . : light electroweak SUSY particles

Particle spectrum of the SPS 1a benchmark point



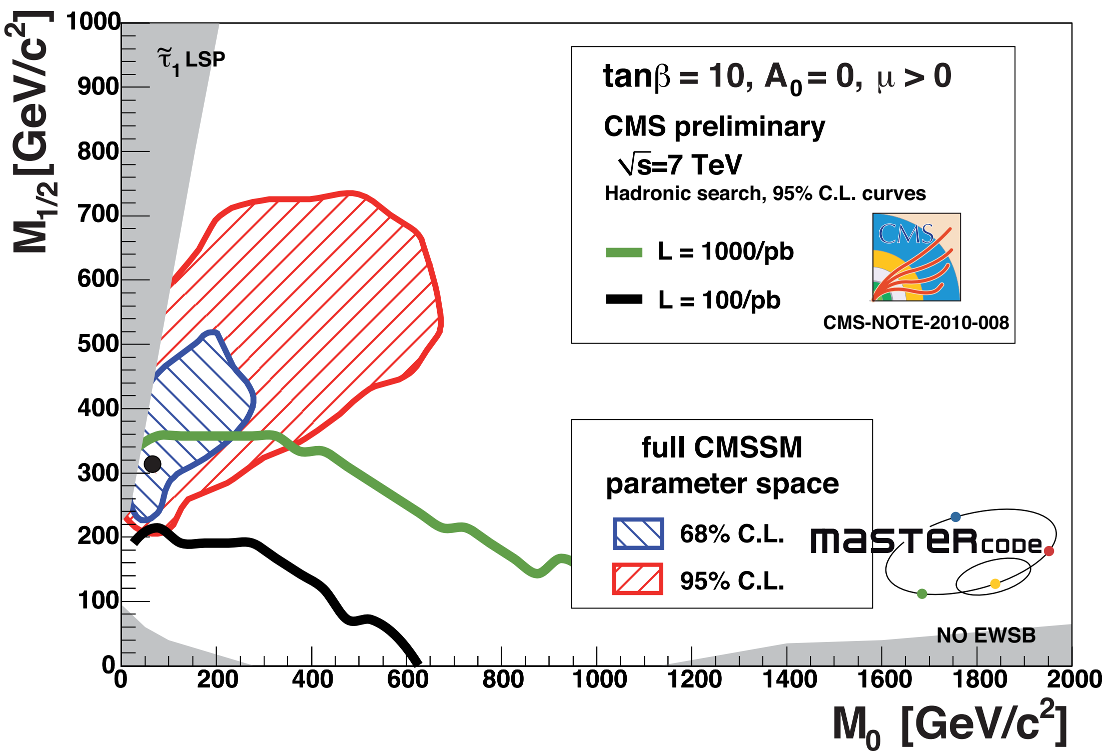
$\Rightarrow$ all SUSY masses below $600\ \mathrm{GeV}$

$\Rightarrow$ “plain vanilla” SUSY at its best

Pre–LHC: Fit results for the CMSSM from precision data

Comparison: preferred region in the m_0–$m_{1/2}$ plane vs. prospective CMS 95% C.L. reach for $0.1, 1 \text{ fb}^{-1}$ at 7 TeV

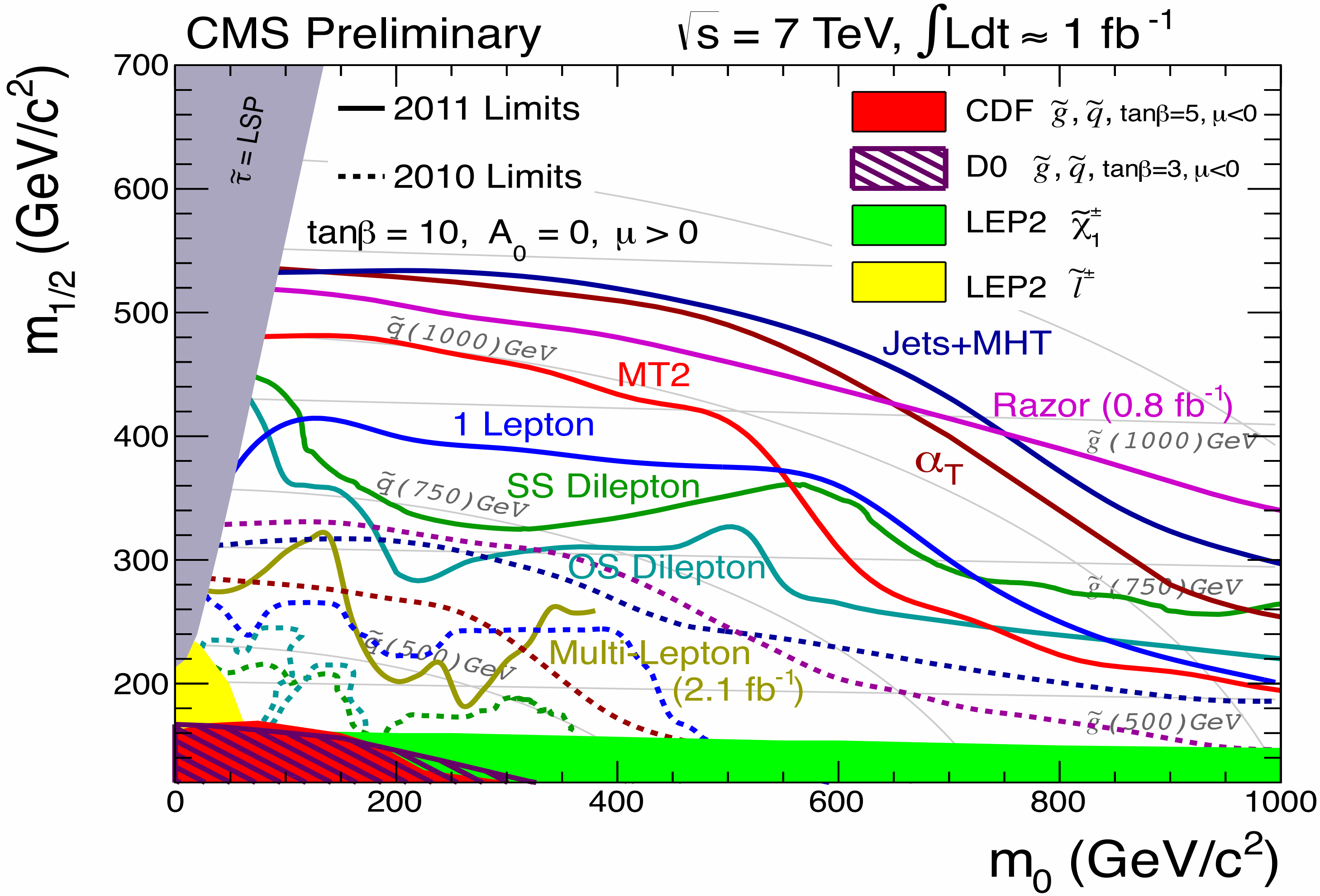
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



⇒ Best fit point was within the 95% C.L. reach with 1 fb^{-1}

Comparison: CMS results with $1\ \mathrm{fb}^{-1}$

[*CMS Collaboration '12*]



$\Rightarrow$ High sensitivity from search for jets + missing energy

Pre–LHC best-fit point excluded

What has actually been excluded?

A closer look on the SPS 1a spectrum

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The SPS 1a spectrum would still be perfectly allowed if just the gluino and the squarks of the first two generations were heavy (while all other SUSY particles are kept at their SPS 1a benchmark values)

$\Rightarrow$ The searches for direct production of third generation squarks and of electroweak SUSY particles do not yet have sufficient sensitivity to exclude even a “plain vanilla” SUSY spectrum like SPS 1a

How robust are the limits on squarks of the first two generations?

LHC analyses so far assume that all eight squarks of the first two generations are mass-degenerate

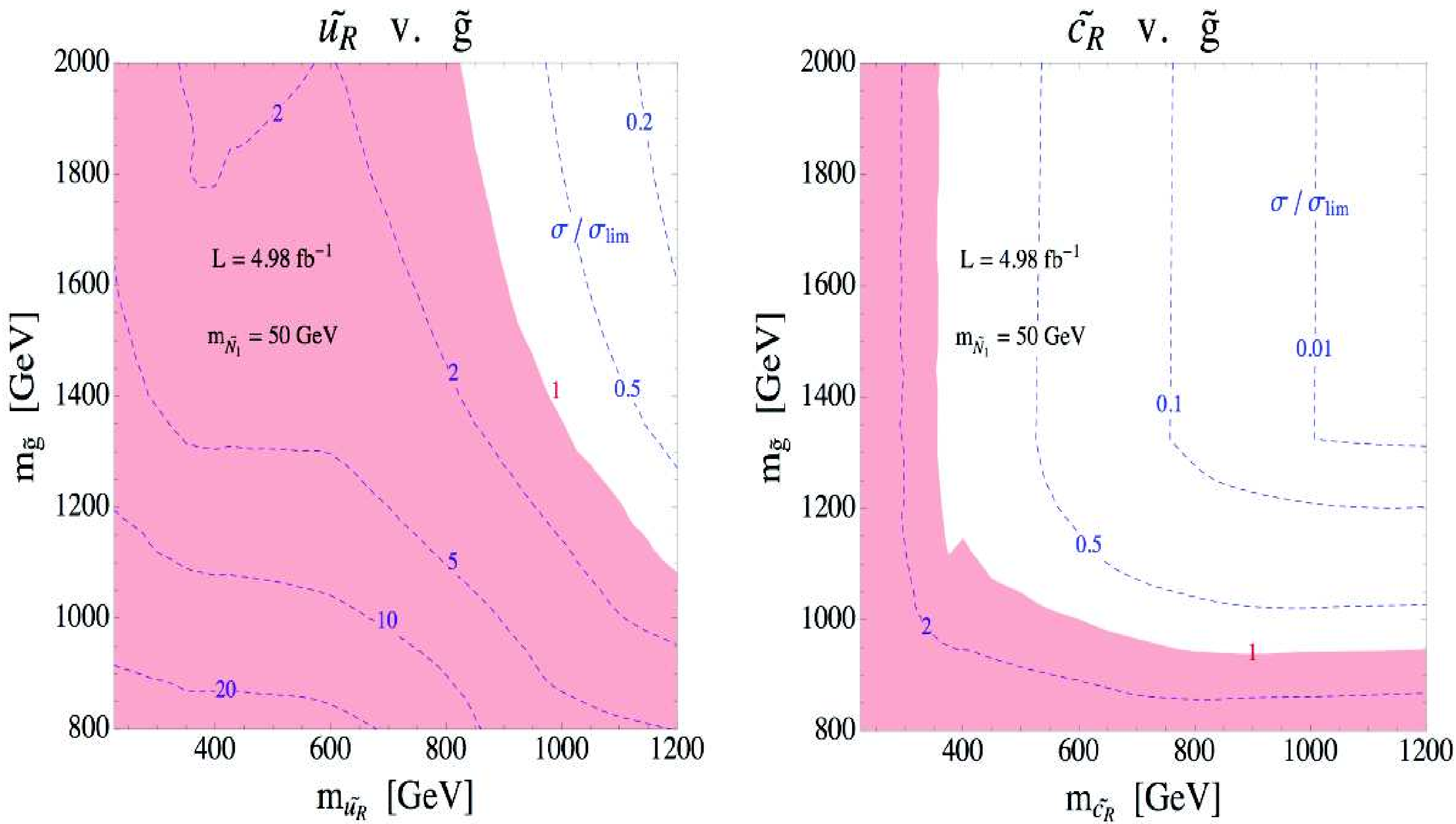
But: Squark spectra can be split within and across generations

$\Rightarrow$ could have important impact on LHC limits

Current limits are optimised for heavy degenerate squarks
Experimental efficiencies sharply deteriorate for lighter squarks

Reinterpretation of the ATLAS and CMS search results ($5\ \mathrm{fb}^{-1}$) for case of non-degenerate squarks (1st, 2nd gen)

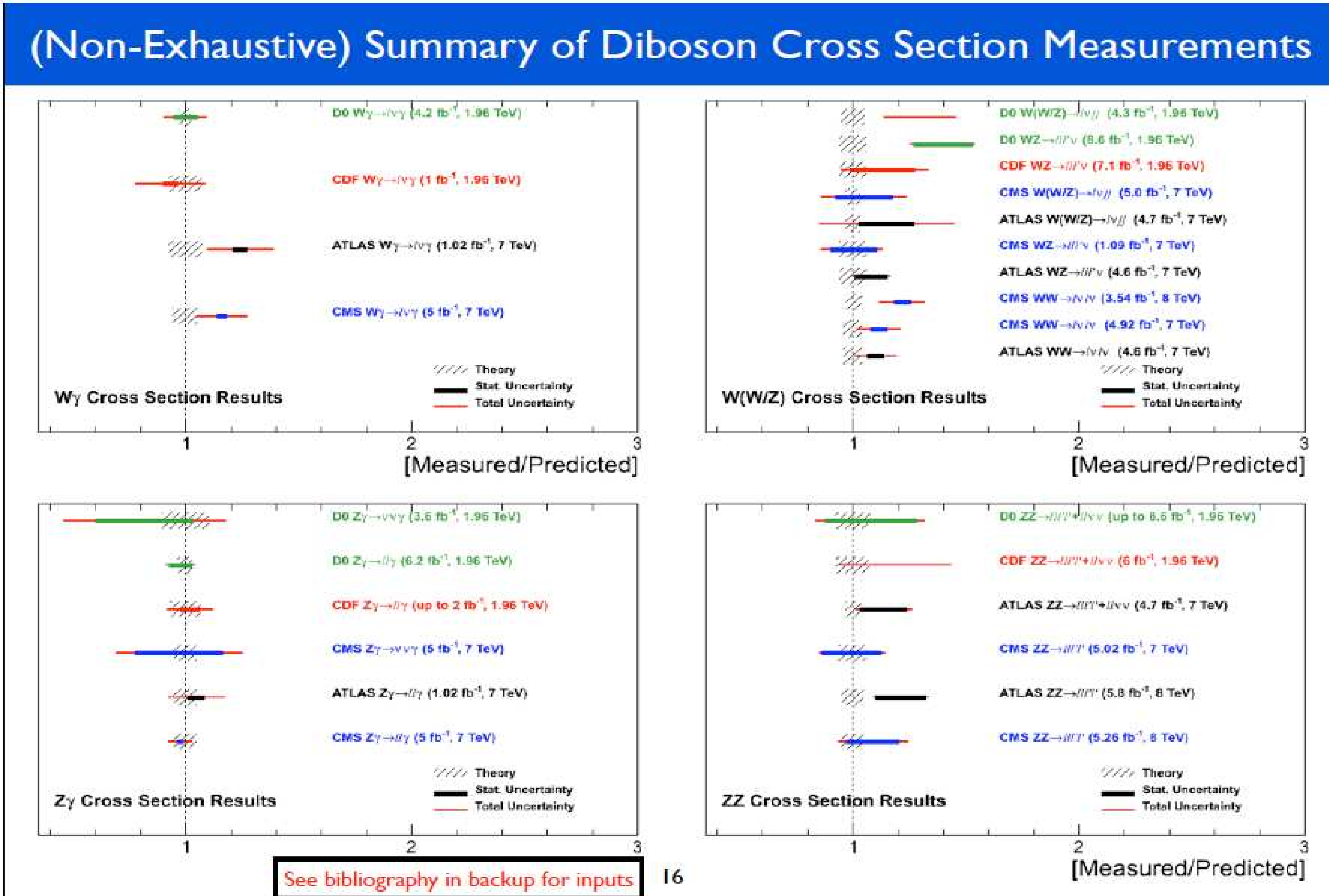
[*R. Mahbubani, M. Papucci, G. Perez, J. Ruderman, A. Weiler '12*]



$\Rightarrow$ Squark limits are drastically weakened compared to the degenerate case

Are there possible hints for effects of new physics elsewhere: how about the WW cross section?

[*D. Evans, HCP 2012*]

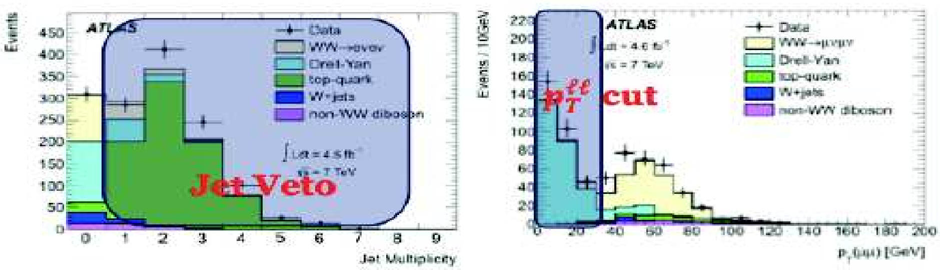


WW cross section: experimental results vs. SM prediction

[*M. Mangano, HCP 2012*]

WW Cross-sections WW cont.

❑ Backgrounds



Jet-veto and other systematics of kinematical origin are greatly reduced in the σ(8TeV)/σ(7TeV) ratio

Future greater statistics in pp→ZZ will allow to greatly reduce such systematics also for the predictions at fixed-energy

❑ Results (CERN-PH-EP-2012-242, CMS PAS SMP-12-005, CMS PAS SMP-12-013)

	$\int L$ (fb^{-1})	$\sigma(pp \to WW) \times B$ (pb)	SM NLO
ATLAS 7TeV	4.6	$51.9 \pm 2.0(stat.) \pm 3.9(syst.) \pm 2.0$(lumi.)	$44.7^{+2.1}_{-1.9}$
CMS 7TeV	4.9	$52.4 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2$(lumi.)	–
CMS 8TeV	3.5	$69.9 \pm 2.8(stat.) \pm 5.6(syst.) \pm 3.1$(lumi.)	$57.3^{+2.4}_{-1.6}$

1.5-2σ off

❑ Systematics (~8%)

– **Jet Veto efficiency (major), lepton, $E_{T,Rel}^{miss}$, lumi**

2012/11/14 Wednesday Y. WU @ HCP2012 10

A proposal for BSM interpretations of this discrepancy:

chargino production and leptonic decay

Feigl, Rzehak, Zeppenfeld, arXiv:1205.3468 29

⇒ Will be interesting to watch . . .

The MSSM is still doing well . . .

Determination of the properties of the state at $\sim 126\ \mathrm{GeV}$

Mass: statistical precision already remarkable with 2012 data

$\Rightarrow$ Need careful assessment of systematic effects for $\gamma\gamma$ and ZZ^* channels,

e.g. interference of signal and background, ...

Spin: Observation in $\gamma\gamma$ channel $\Rightarrow$ spin 0 or spin 2?

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But: How should one model a spin 2 particle?

Parametrisations for the spin 2 case

Spin 2: non-renormalisable theory

$\Rightarrow$ effective theory, in general has a bad high-energy behaviour

$\Rightarrow$ can have large impact on total cross section

$\Rightarrow$ focus on angular correlations, shape of distributions

Bad high-energy behaviour can be damped by introduction (ad hoc) of a “form factor”

$\Rightarrow$ preferable to focus on observables that are insensitive to form factors

Benchmark proposal under discussion in LM subgroup of the LHC Higgs XS WG

$\mathcal{CP}$ properties

$\mathcal{CP}$-properties: experimentally much more difficult than spin
Can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables investigated up to now ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu \right] + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

Pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However, in most BSM models a_3 would be loop-induced and heavily suppressed $\Rightarrow$ Realistic models usually predict $a_3 \ll a_1$

$\Rightarrow$ Observables involving HVV coupling provide little sensitivity to effects of a $\mathcal{CP}$-odd component

$\mathcal{CP}$ ***properties***

Observables involving the HVV coupling "project" to the $\mathcal{CP}$-even component of the observed state

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Which upper limit on a $\mathcal{CP}$-odd admixture can be set?

$\Rightarrow$ Channels involving only Higgs couplings to fermions provide much higher sensitivity

Coupling determination: theory issues

- What is meant by measuring a coupling?

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  A coupling is not directly a physical observable; what is measured is $\sigma \times \mathrm{BR}$ (within acceptances), etc.

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- Once (electroweak) higher-order corrections are taken into account, the Higgs couplings in the SM cannot be treated as free parameters
  $\Rightarrow$ Cannot "measure" the couplings directly from a comparison of SM predictions with the data

Coupling determination: experimental issues

- The experimental results that have been obtained for the various channels are not model-independent
  - Properties of the SM Higgs have been used for discriminating between signal and background
  - Need the SM to correct for acceptances and efficiencies

- The total Higgs width cannot be measured at the LHC without additional assumptions
  $\Rightarrow$ Can in general only determine ratios of couplings, not absolute coupling values

Experimental input: single channel results

Single channel results: signal strength parameters μ_i for separate search channels

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Correlations?

Very useful for confronting theory predictions with experimental results

Widely used in the literature

Single channel results vs. simultaneous information from several channels

Adding information from different channels increases sensitivity

But: interpretation of the results is in general more difficult

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But comparison of extracted couplings with “best” SM predictions (as defined by the LHCHXSWG, including higher-order corrections) is difficult

Is the chosen basis for the couplings sufficiently general to express the SM predictions including all available higher-order corrections?

Strategy for the coupling analysis

As long as the SM continues to be (roughly) compatible with the data:

$\Rightarrow$ Use full SM predictions including all available higher-order corrections (“best” SM predictions as defined by the LHCHXSWG)

$+$ parametrisation of deviations

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In case SM gets ruled out $\Rightarrow$ Move to other reference model

Parametrisation of deviations from the SM

Deviations from the SM: in general both the absolute value of the couplings and the tensor structure of the couplings (affects $\mathcal{CP}$ properties) will change

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Deviations from the SM would in general change kinematic distributions

$\Rightarrow$ No simple rescaling of MC predictions possible

$\Rightarrow$ Not feasible for analysis of 2012 data set

$\Rightarrow$ Proposal of “interim framework”

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Assumptions:

- Signal corresponds to only one state, no overlapping resonances, etc.
- Zero-width approximation
- Only modifications of coupling strenghts (absolute values of the couplings) are considered, no modification of the tensor structure as compared to the SM case

  $\Rightarrow$ Assume that the observed state is a $\mathcal{CP}$-even scalar

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i ($\kappa_i = 1$ corresponds to the SM case)

Note: scaling of couplings is in general not possible if higher-order electroweak corrections are included

In the SM: Higgs sector is determined by single parameter M_{H} ($+$ higher-order contributions)

$\Rightarrow$ Once M_{H} is fixed the Higgs couplings are determined and cannot be varied within the SM

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Scaling of couplings $\Leftrightarrow$ test of deviations from the SM

Note: acceptances and efficiencies are assumed to be as in the SM

$\Rightarrow$ This will have an impact on the interpretation in case a sizable deviation from the SM prediction gets established

$\Rightarrow$ Results obtained from the analysis with scaled couplings cannot be interpreted as “coupling measurements”

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Which kind of scaling factors should be considered?

In general, scale factors are needed for couplings of the new state to
t, b, τ, W, Z, $\ldots$

$+$ extra loop contribution to $\sigma(gg \to H)$, $\Gamma(H \to gg)$

$+$ extra loop contribution to $\Gamma(H \to \gamma\gamma)$

$+$ additional contributions to total width, Γ_H, from undetectable final states

Total width Γ_H cannot be measured without further assumptions (otherwise only coupling ratios can be determined, not absolute values of couplings)

Proposed “benchmarks” for scale factors κ_i

Different “benchmark” proposals, based on simplifying assumptions to reduce the number of free parameters

1 parameter: overall coupling strength μ

2 parameters: e.g. common scale factor κ_V for W, Z, and common scale factor for all fermions, κ_F

...

For each benchmark (except overall coupling strength) two versions are proposed:

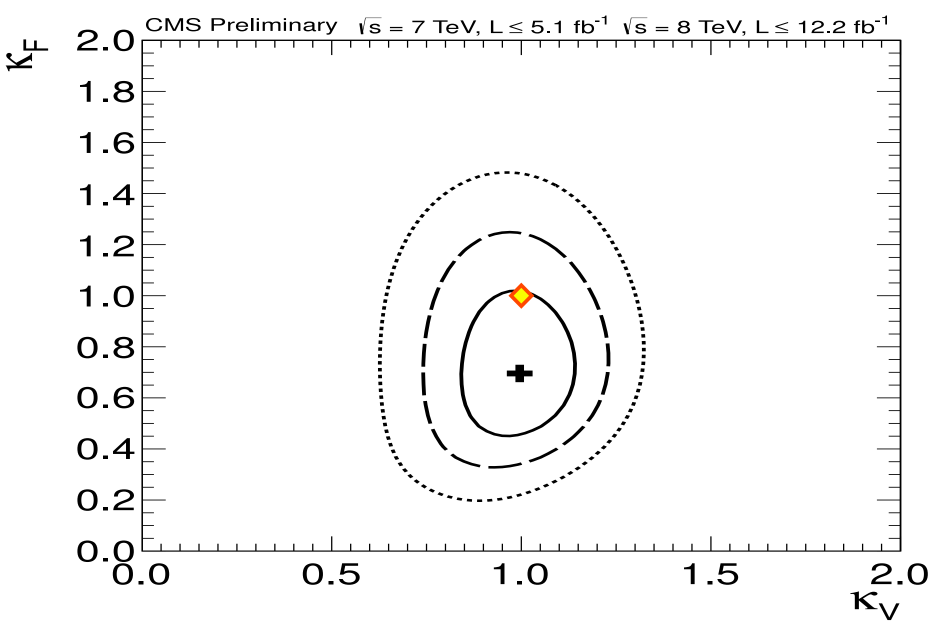
with and without taking into account the possibility of additional contributions to the total width

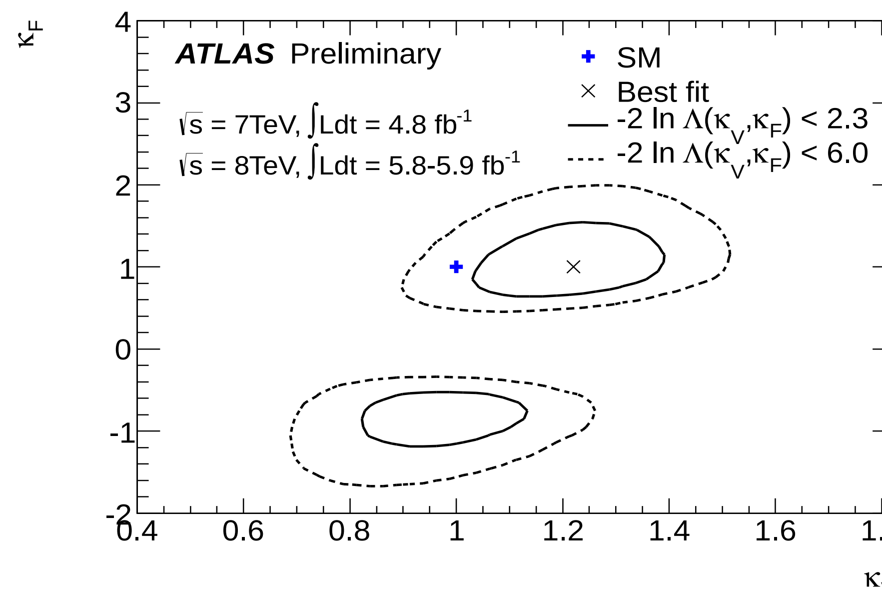
Proposed "benchmarks" for scale factors κ_i

If additional contributions to Γ_H are allowed
$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

If no additional contributions to $\Gamma(H \to \gamma\gamma)$, Γ_H, $\ldots$ are allowed
$\Rightarrow$ κ_γ can be determined in terms of κ_b, κ_t, κ_τ, κ_W
evaluated to NLO QCD accuracy

Example: κ_V, κ_F analyses from CMS and ATLAS





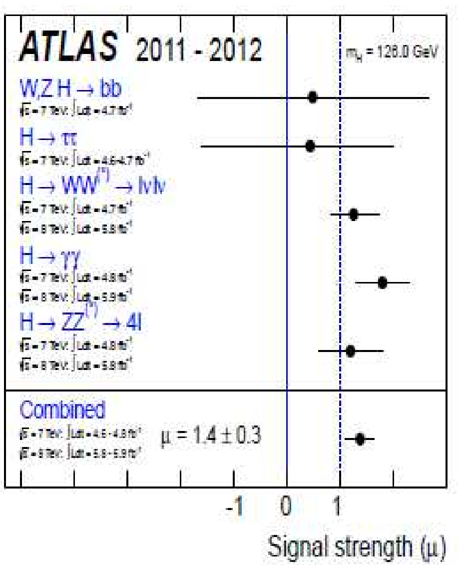
HiggsBounds and *HiggsSignals*

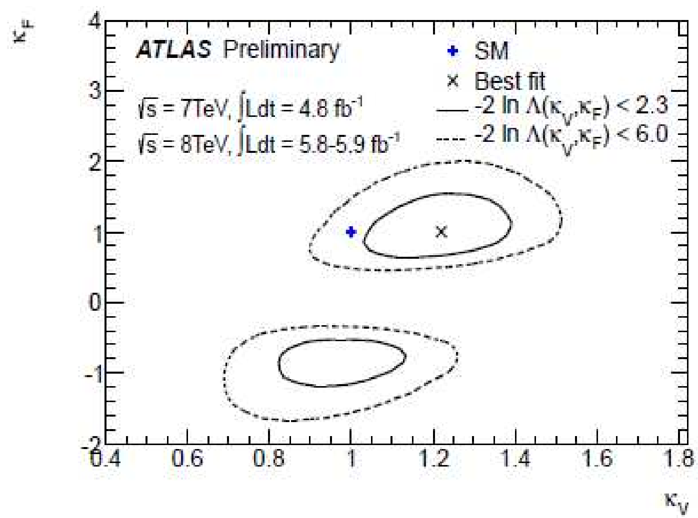
Programs that use the experimental information on cross section limits (*HiggsBounds*) and observed signal strengths (*HiggsSignals*) for testing predictions of BSM models

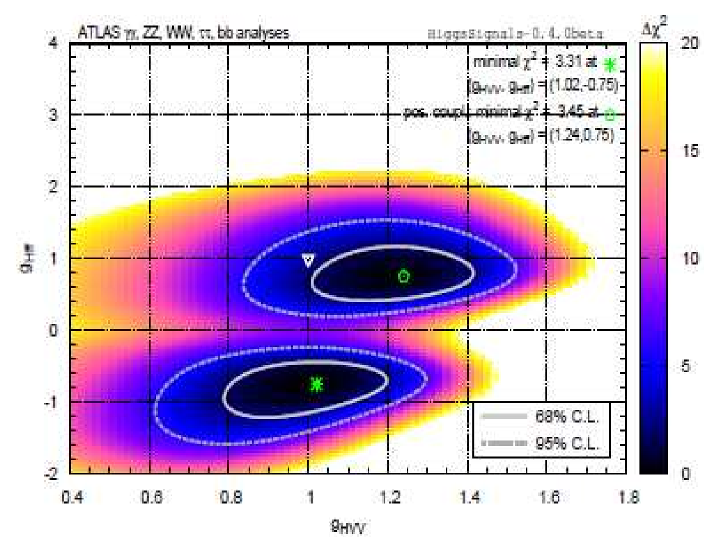
[*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., K. Williams '08, '12*]

HiggsSignals:

ATL-CONF-2012-127

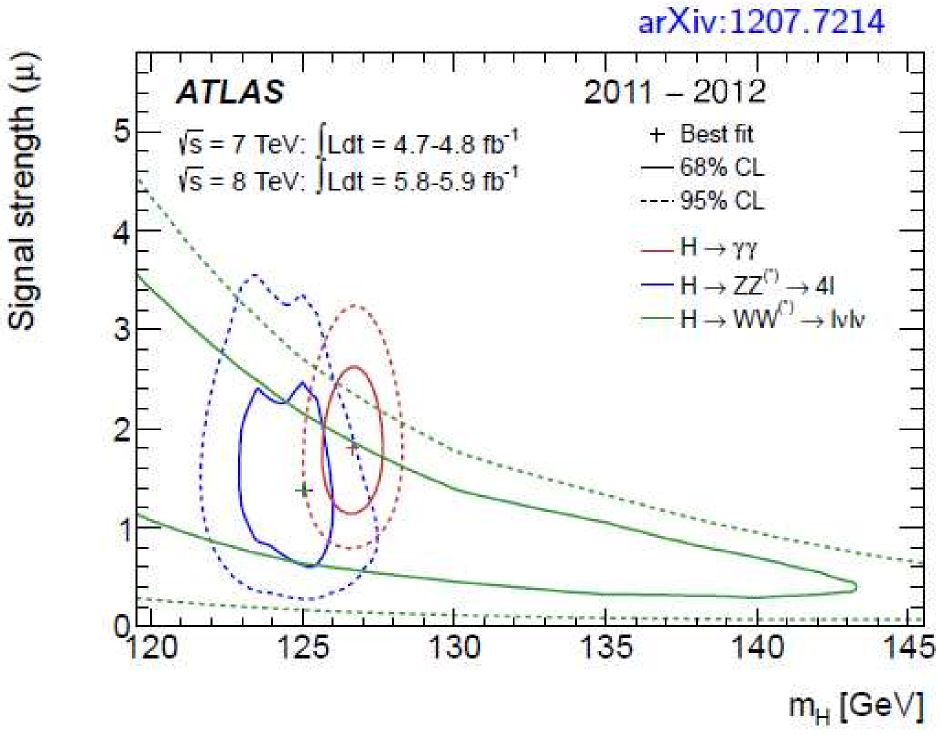


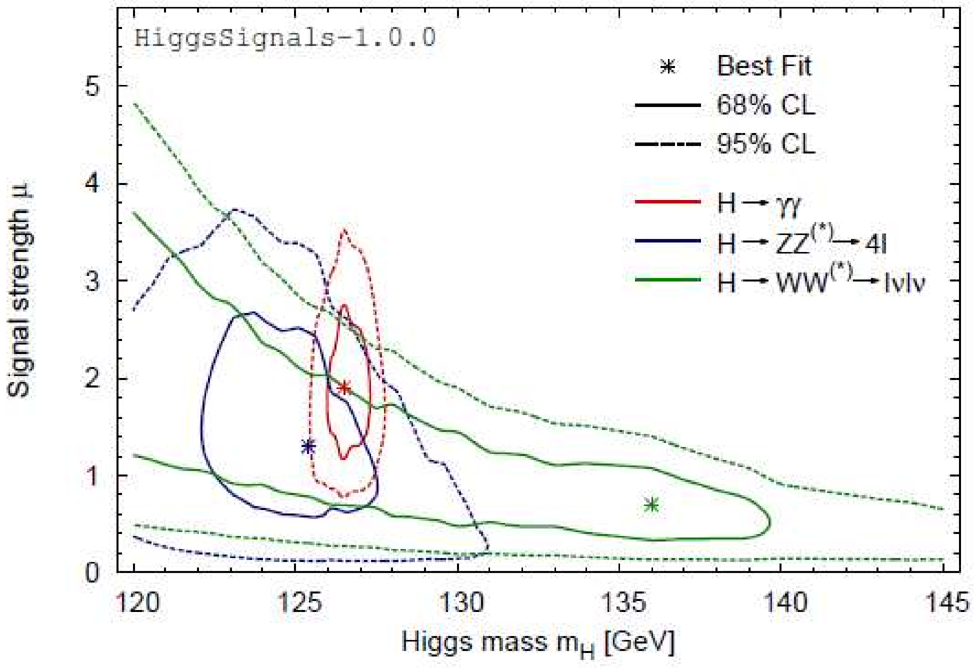




*Example of **HiggsSignals** application*

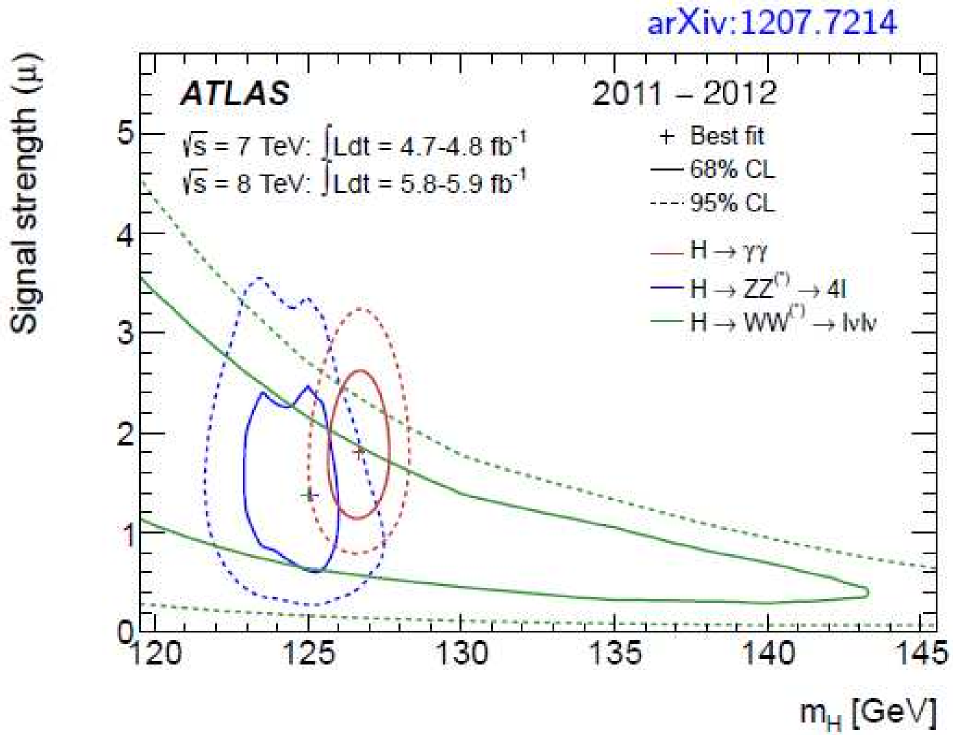
[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. '12*]

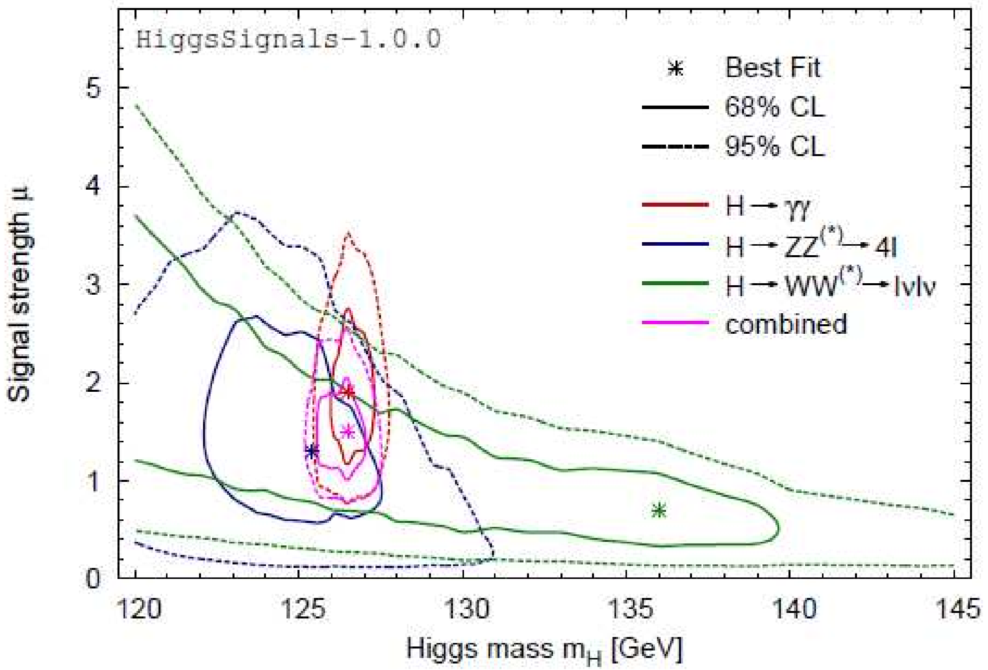




Example of HiggsSignals application

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W. ’12]





MSSM interpretation of scale factors κ_i?

- Higgs couplings to up-type and down-type fremions are different $\Rightarrow$ cannot be described in terms of common κ_F
- Large SUSY contributions can affect relation between coupling to $b\bar{b}$ and $\tau^+\tau^-$
- Extra contributions to $\sigma(gg \to H)$, $\Gamma(H \to gg)$, $\Gamma(H \to \gamma\gamma)$: $\tilde{\mathrm{t}}$, $\tilde{\tau}$, $\tilde{\chi}^{\pm}$, . . .
- Extra contribution to total width: $H \to$ invisible, . . .

Would need a larger number of free parameters than the ones allowed in the benchmark scenarios

$\Rightarrow$ Benchmark scenarios of this kind are usually too restrictive to allow an interpretation within a “realistic” model like the MSSM

Framework for future analyses of couplings: ongoing work

- Use “best” SM predictions (as defined by the LHCHXSWG) $+$ parametrisation of deviations

- Use effective Lagrangian for parametrisation of deviations

$\Rightarrow$ The tools that are used for obtaining the “best” SM predictions need to be extended to incorporate appropriate parametrisations of deviations from the SM

Which effective Lagrangian should be chosen?

- Should be sufficiently general so that the results can be interpreted in realistic models
  - One should not assume from the start that the new state is a $\mathcal{CP}$-even scalar
  - Consider both changes in the strength and the tensor structure of the couplings

  $\Rightarrow$ Analysis of couplings is directly linked with analyses of spin and $\mathcal{CP}$ properties

- Needs to be practicable so that it can be implemented into the tools that are used so far for the “best” SM predictions

Effective Lagrangian from integrating out heavy particles

Assumption: new physics appears only at a scale $\Lambda \gg M_\mathrm{h} \sim 126\ \mathrm{GeV}$

Systematic approach: expansion in inverse powers of Λ

$$\Delta\mathcal{L} = \sum_i \frac{a_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum_j \frac{a_j}{\Lambda^4} \mathcal{O}_j^{d=8} + \ldots$$

$\Rightarrow$ Higher-dimensional operators, parametrise effects of tree-level exchange and loop contributions of new heavy degrees of freedom

$\Rightarrow$ can parametrise deviations from the SM in terms of coefficients a_i (for on-shell matrix elemements some operators can be eliminated via eqns of motion)

Is this sufficient?

How about light BSM particles?

Difficult to incorporate in a generic way, need full structure of particular models

Need to be careful with interpretation of lower bounds on Λ (compare with flavour sector): assumption $\Lambda \gg M_\mathrm{h}$ was put in from the start in this approach

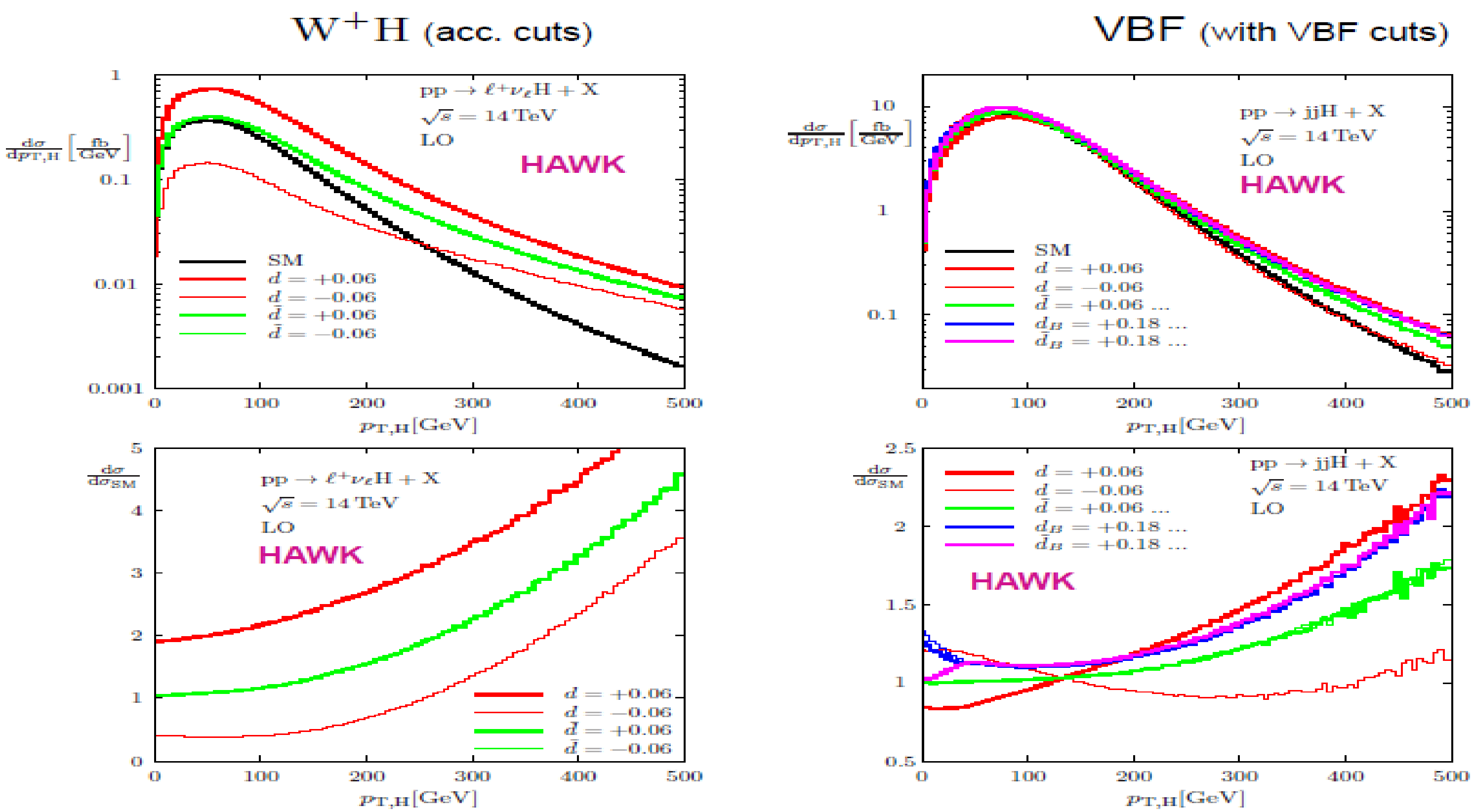
$\Rightarrow$ Analyses in terms of SM $+$ effective Lagrangian and in specific BSM models: MSSM, . . . are complementary

Implementation of parametrisations of deviations from the SM in tools for Higgs phenomenology

Ongoing efforts for *HAWK*, *VBFNLO*, *Prophecy4f*, *HDECAY*, . . .

Example: Impact of anomalous VHH couplings on Higgs $p_{\rm T}$ spectra in WH and WBF [*S. Dittmaier '12*]

Anomalous VHH couplings in $p_{\rm T,H}$ spectra



similar VBF results by Hankele, Klämke, Zeppenfeld, Figy '06

$\mathcal{L} \propto HW_{\mu\nu}W^{\mu\nu}$

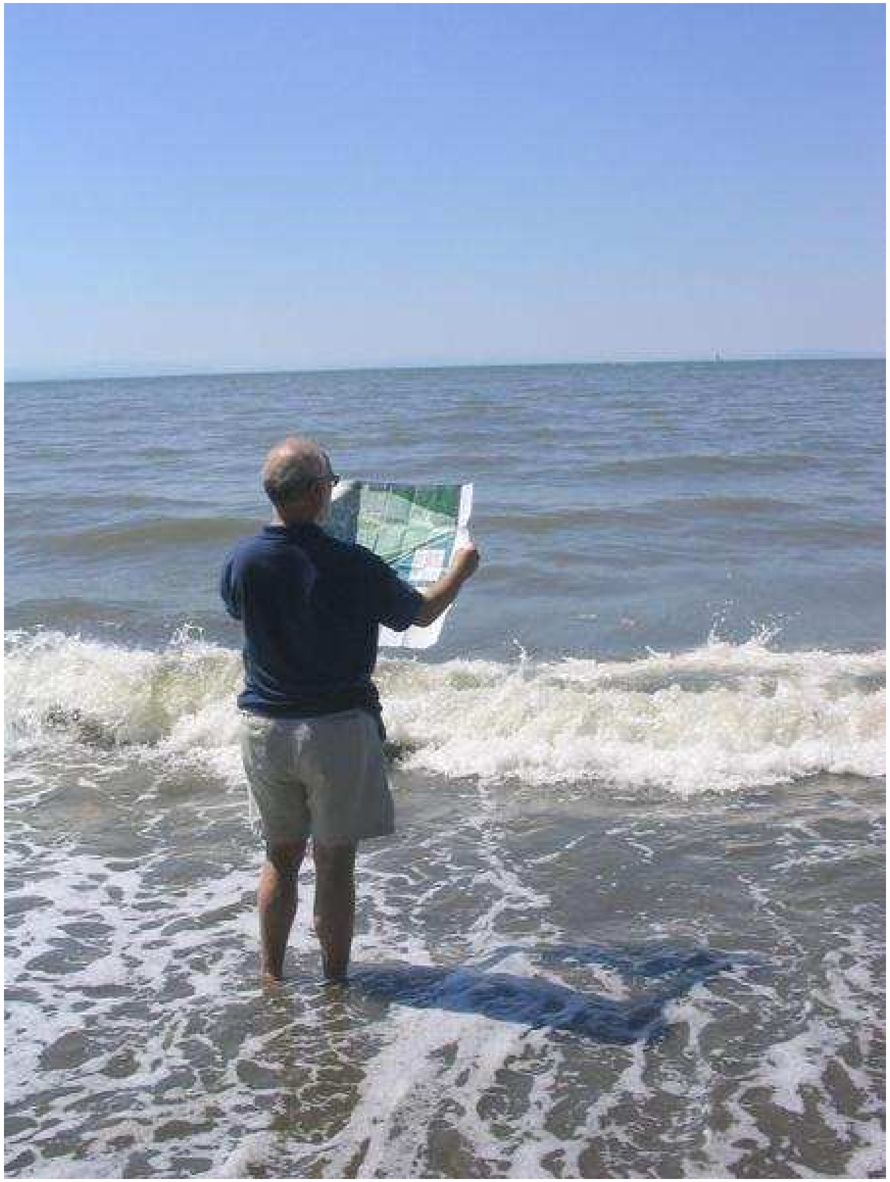
$\mathcal{L} \propto H\tilde{W}_{\mu\nu}W^{\mu\nu}$

$\mathcal{L} \propto HB_{\mu\nu}B^{\mu\nu}$

$\mathcal{L} \propto H\tilde{B}_{\mu\nu}B^{\mu\nu}$

Impact of ACs larger in WH production than in VBF !

How to interpret the observed signal and what next?



SM vs. Supersymmetry

Detection of a SM-like Higgs with $M_{\mathrm{H}} \gtrsim 135~\mathrm{GeV}$ would have unambiguously ruled out the MSSM

$\Rightarrow$ Signal at $\sim 126~\mathrm{GeV}$ is well compatible with MSSM prediction

- MSSM can accomodate enhancement of $\mathrm{BR}(H \to \gamma\gamma)$ (e.g.: additional particles in the loop, light stau, . . .), suppression of $\mathrm{BR}(H \to \tau^+\tau^-)$, . . .

- Interpretation of the observed signal at $\sim 126~\mathrm{GeV}$ is in principle possible both in terms of the lightest (h) and in terms of the next-to-lightest (H) neutral Higgs of the MSSM!

SUSY interpretation of the observed signal?

Interpretation of the observed signal at $\sim 126\ \mathrm{GeV}$ in terms of the light MSSM CP-even Higgs h

Observed signal at $\sim 126\ \mathrm{GeV}$ implies lower bound on M_{h}

$\Rightarrow$ Set parameters entering via higher-order corrections such that M_{h} is maximised ($m_{\mathrm{h}}^{\mathrm{max}}$ benchmark scenario)

$\Rightarrow$ Lower bounds on M_{A}, $\tan\beta$

Search limits from LEP and from LHC ($H, A \to \tau^+\tau^-$ search) taken into account:

HiggsBounds

[*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., K. Williams '08, '12*]

HiggsBounds: determination of 95% C.L. exclusion region from given cross section limits

[*P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., K. Williams '08, '12*]

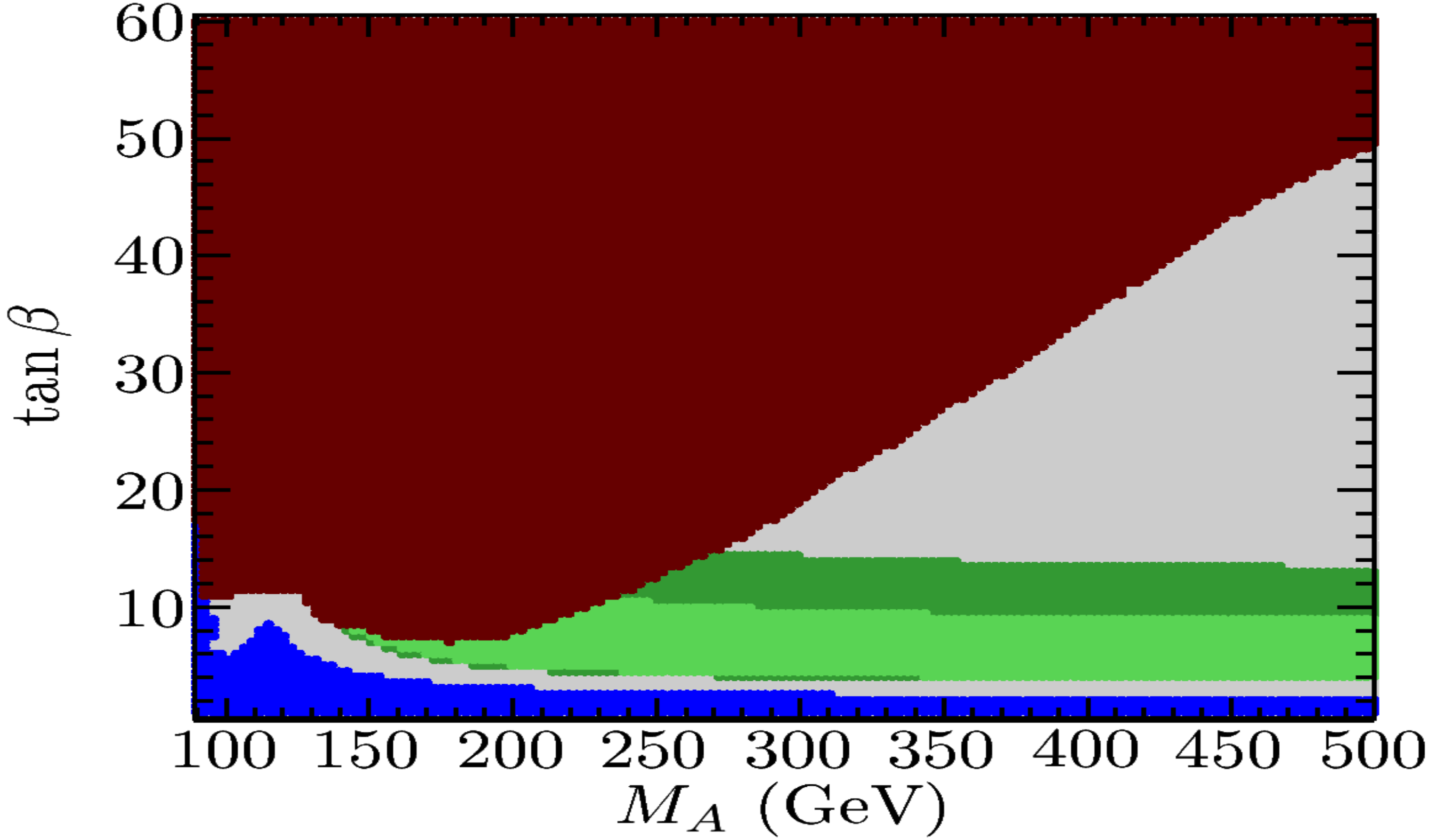
In order to obtain an exclusion limit having the correct statistical interpretation as a 95% C.L.:

- On the basis of the expected search limits for different channels in a given model one needs to determine for every parameter point the search channel having the highest statistical sensitivity for setting an exclusion limit

- For this single channel only one needs to compare the observed limit with the theory prediction for the Higgs production cross section times decay branching ratio to determine whether or not the considered parameter point of the model is excluded at 95% C.L.

Lower bounds on M_A *and* $\tan\beta$ *from interpreting signal at* $\sim 126\ \mathrm{GeV}$ *as light MSSM Higgs boson* h

Red: LHC limits from $H, A \to \tau^+\tau^-$ search; Blue: LEP limits
Green: compatible with interpreting signal at $126\ \mathrm{GeV}$ as light MSSM Higgs h (+ m_t variation) [*S. Heinemeyer, O. Stål, G. W. '11, '12*]



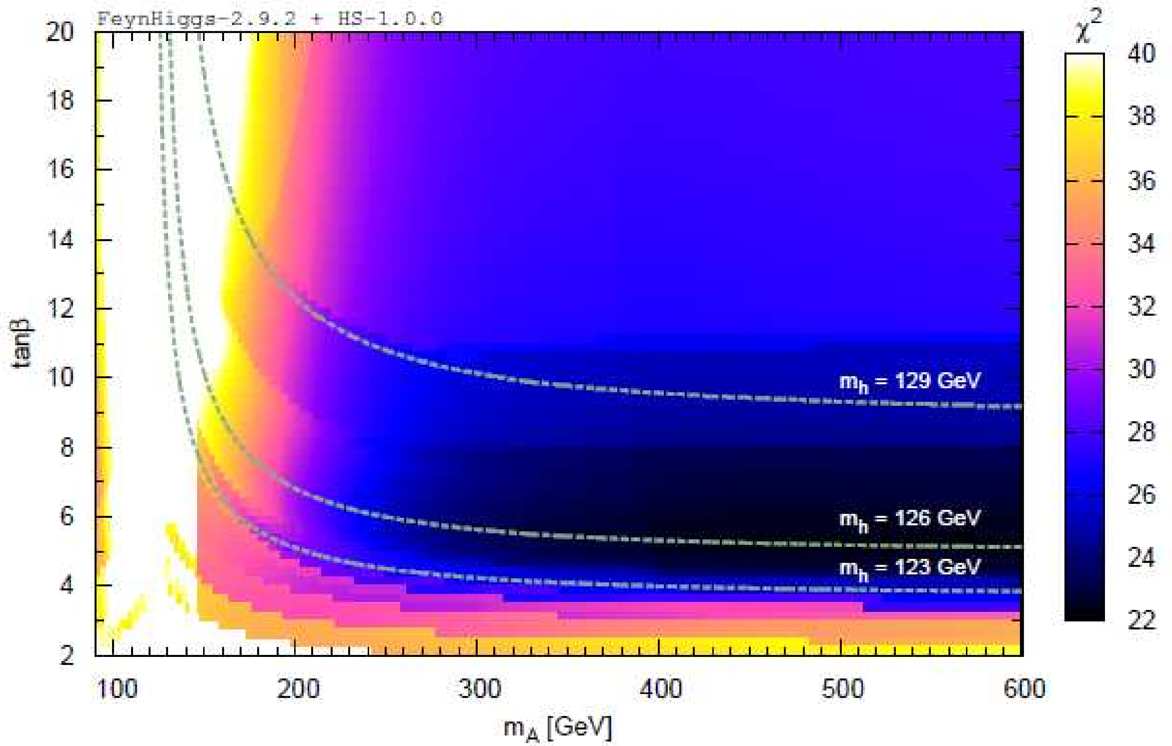
$\Rightarrow \tan\beta \gtrsim 4$, $M_\mathrm{A} \gtrsim 140\ \mathrm{GeV}$, $M_{\mathrm{H}^\pm} \gtrsim 160\ \mathrm{GeV}$

Analysis in $m_\mathrm{h}^\mathrm{max}$ benchmark scenario

The m_h^max scenario

$(M_\mathrm{SUSY} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV$)$

1. Run `HiggsSignals` with peak-centered χ^2 method, $\Delta m_h^\mathrm{th} = \Delta m_H^\mathrm{th} = 2$ GeV.



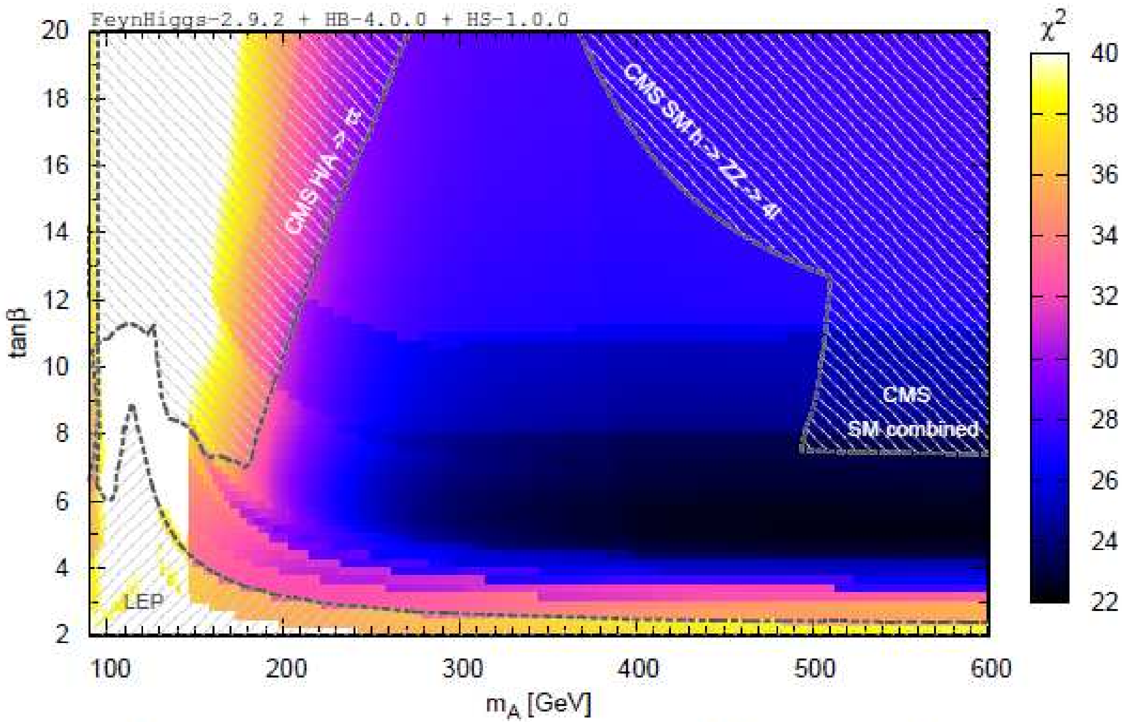
- Large m_A and $\tan\beta \gtrsim 4$ favored (decoupling limit).

Analysis in $m_h^{\max}$ benchmark scenario

The $m_h^{\max}$ scenario

($M_{SUSY} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV)

2. Run HiggsBounds to obtain 95% C.L. exclusion limits from LEP and LHC (*no* theory mass uncertainty yet).



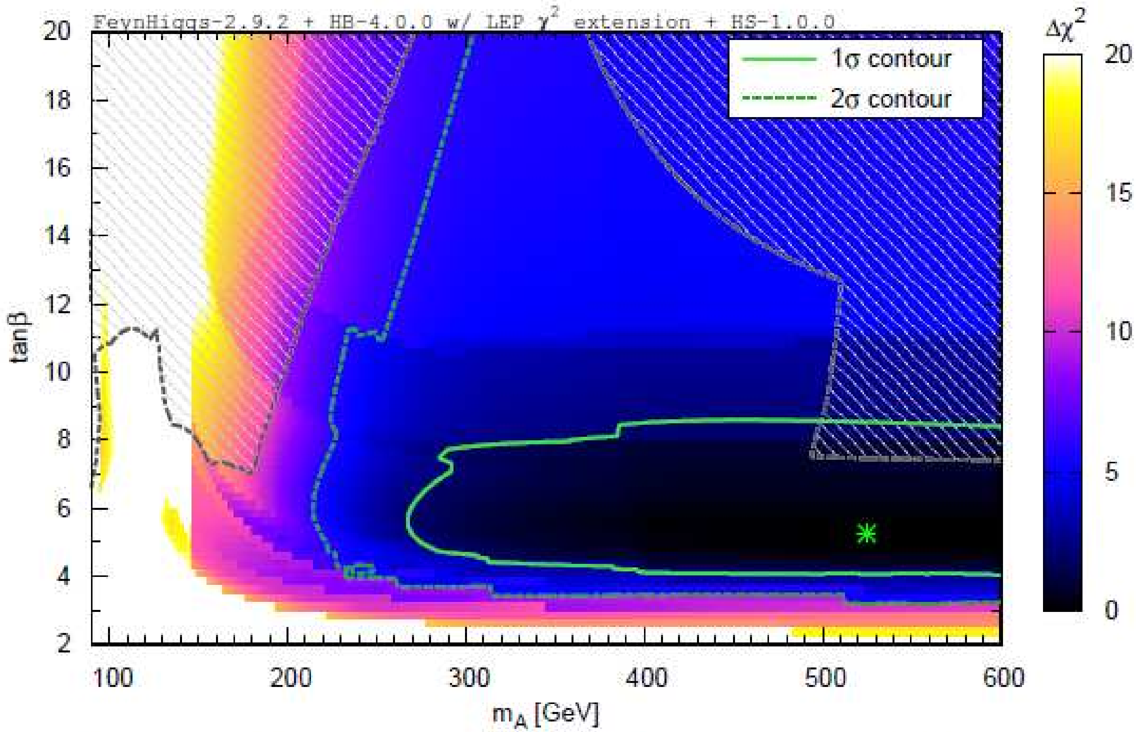
- CMS limits: $H/A \to \tau\tau$ (pre-ICHEP2012), SM $H \to ZZ^{(*)} \to 4\ell$ and SM combined (HCP2012).

Analysis in $m_h^{\max}$ *benchmark scenario*

The $m_h^{\max}$ scenario

$(M_{\rm SUSY} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV$)$

4. Find best-fit point and CL contour regions.



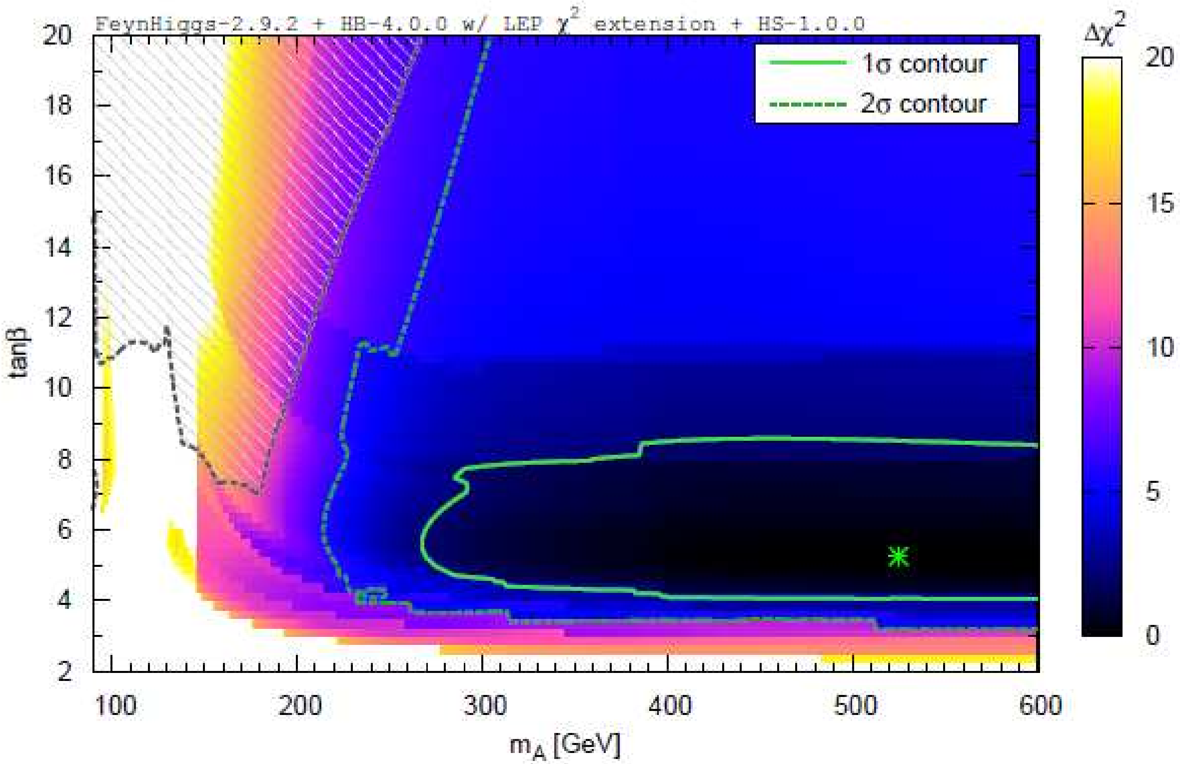
- minimal $\chi^2/\mathrm{ndf} = 22.4/35$ at $(m_A, \tan\beta) = (525.0\ \mathrm{GeV}, 5.3)$.
- HiggsBounds excludes part of the 68% C.L. region with $m_h \gtrsim 128$ GeV!?

Analysis in $m_{\rm h}^{\rm max}$ benchmark scenario

The $m_h^{\rm max}$ scenario

($M_{\rm SUSY} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV)

5. Take into account $\Delta m_h^{\rm th} = \Delta m_H^{\rm th} = 2$ GeV in HiggsBounds.

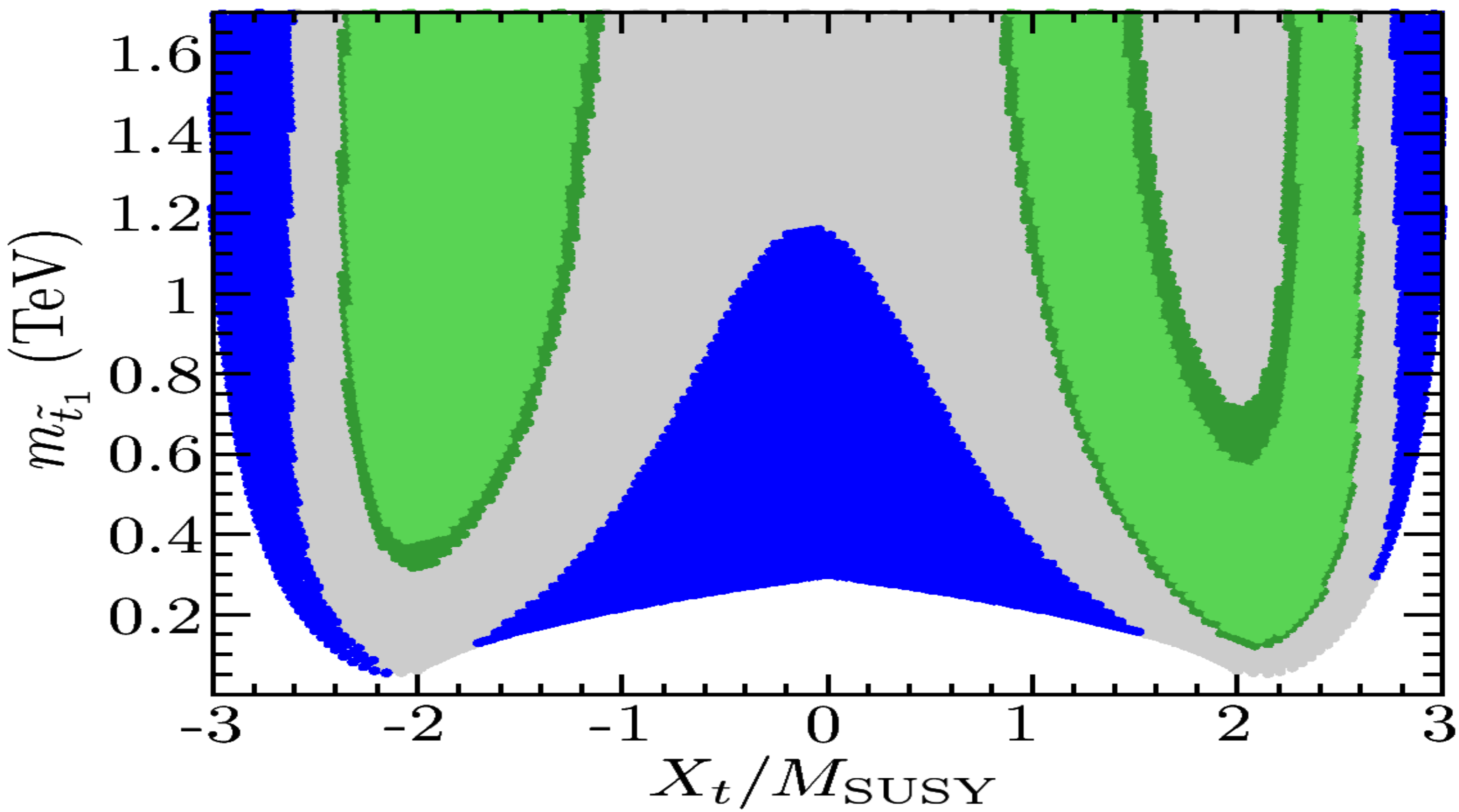


- Exclusion in large m_A region vanishes (now, $m_h \lesssim 130$ GeV is allowed).

Lower bound on the lightest stop mass from assumed Higgs signal at ~ 126 GeV

M_A, $\tan\beta$ chosen in decoupling region: $M_A = 1$ TeV, $\tan\beta = 20$

[*S. Heinemeyer, O. Stål, G. W. '11, '12*]



$\Rightarrow$ $m_{\tilde{t}_1} > 150\ (300)$ GeV for positive (negative) X_t

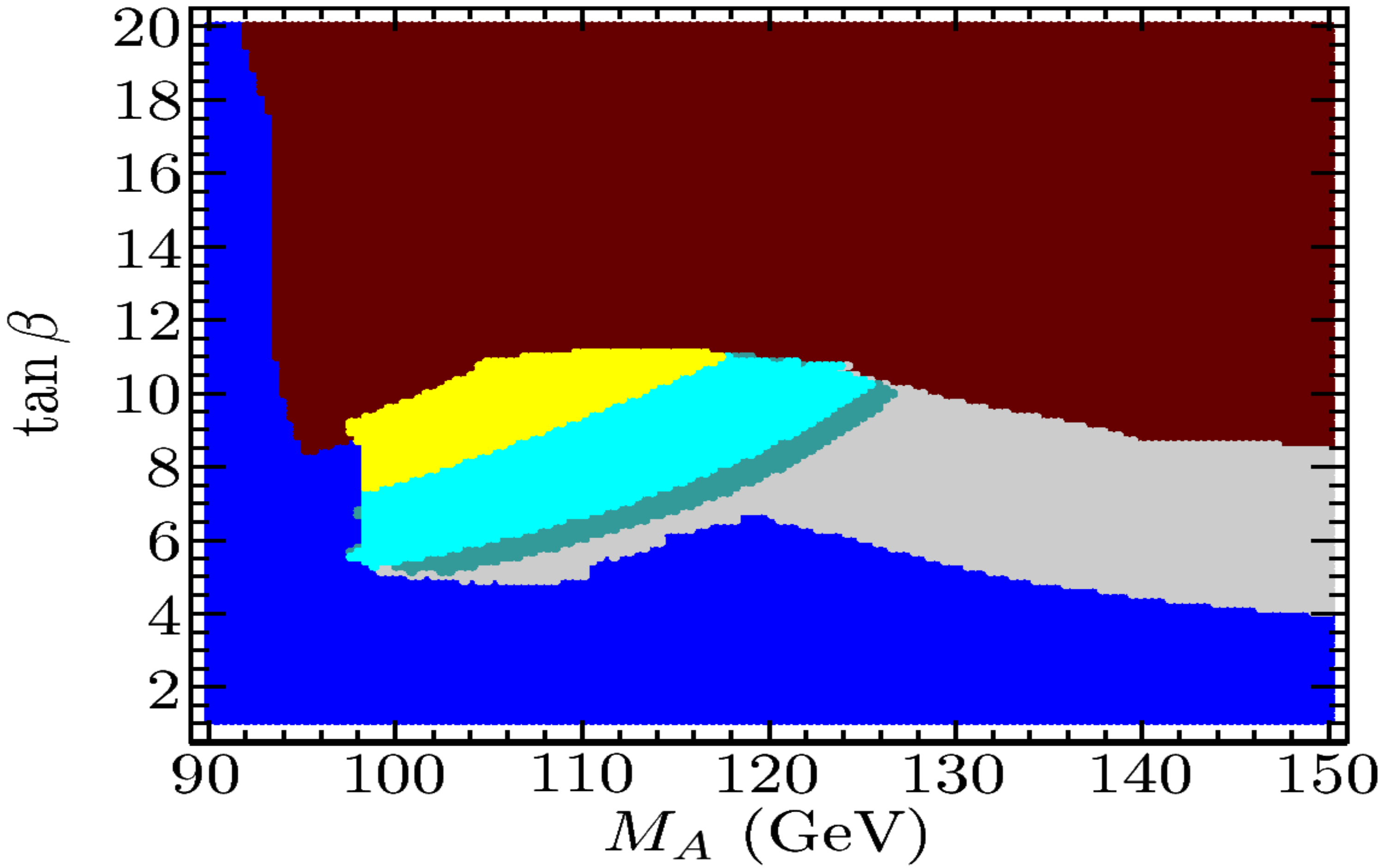
$\Rightarrow$ $M_h \sim 126$ GeV is compatible with a light Stop!

Interpretation of the observed signal at ~ 126 GeV

in terms of the heavy MSSM CP-even Higgs H

Scan over M_A, $\tan\beta$, M_{SUSY}, X_t

[*S. Heinemeyer, O. Stål, G. W. '11*]

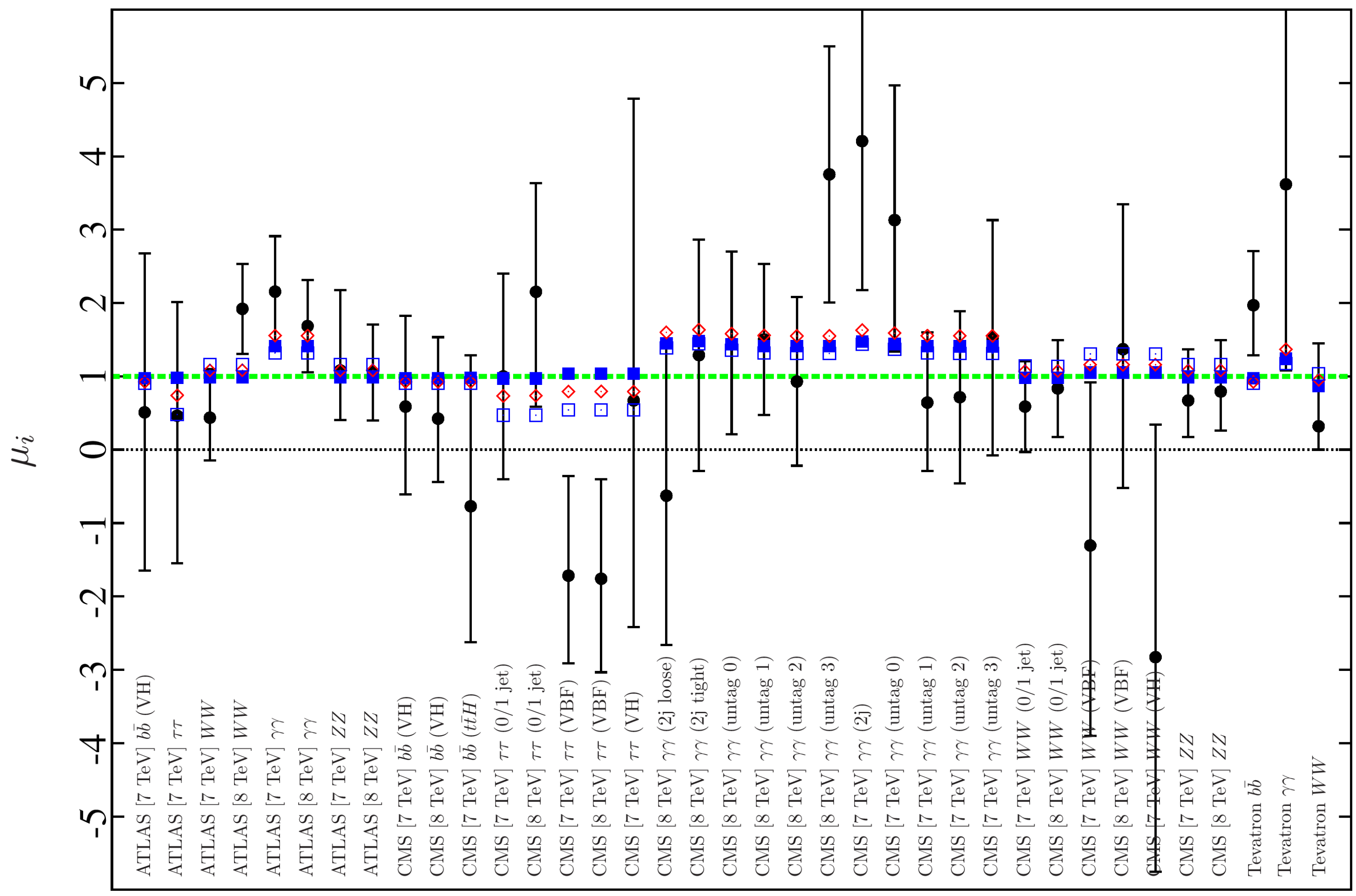


$\Rightarrow$ possible for low M_A, moderate $\tan\beta$
(in yellow region: $\gamma\gamma$ rate compatible with LHC results)

MSSM fit (pre HCP): comparison of SM with MSSM interpretation in terms of light Higgs h

[P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12]

- LHC / TeV. data, ■ full fit, ⊡ without TeV., ◇ without low. en. obs.

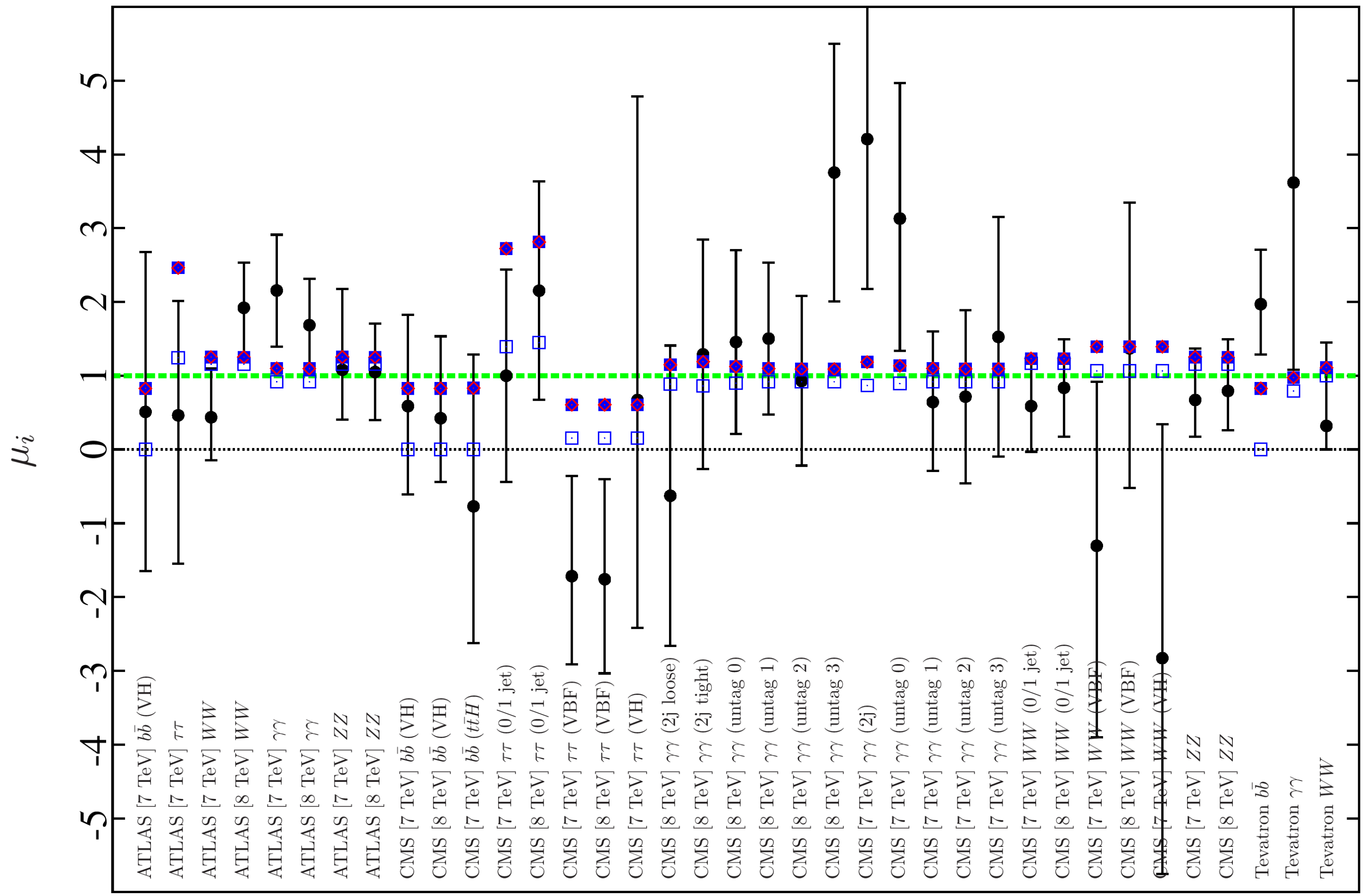


$\Rightarrow \chi^2$ reduced compared to SM case, better fit probability

MSSM fit (pre HCP): comparison of SM with MSSM interpretation in terms of heavy Higgs H

[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]

- LHC / TeV. data, ■ full fit, ⊡ without TeV., ◇ without low. en. obs.



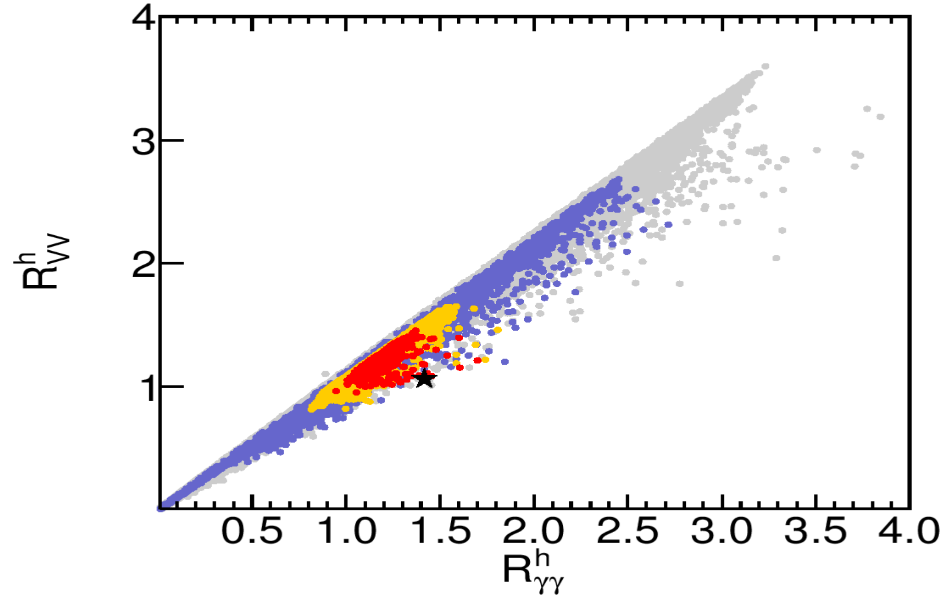
⇒ viable description of data (lower fit quality than MSSM–h)

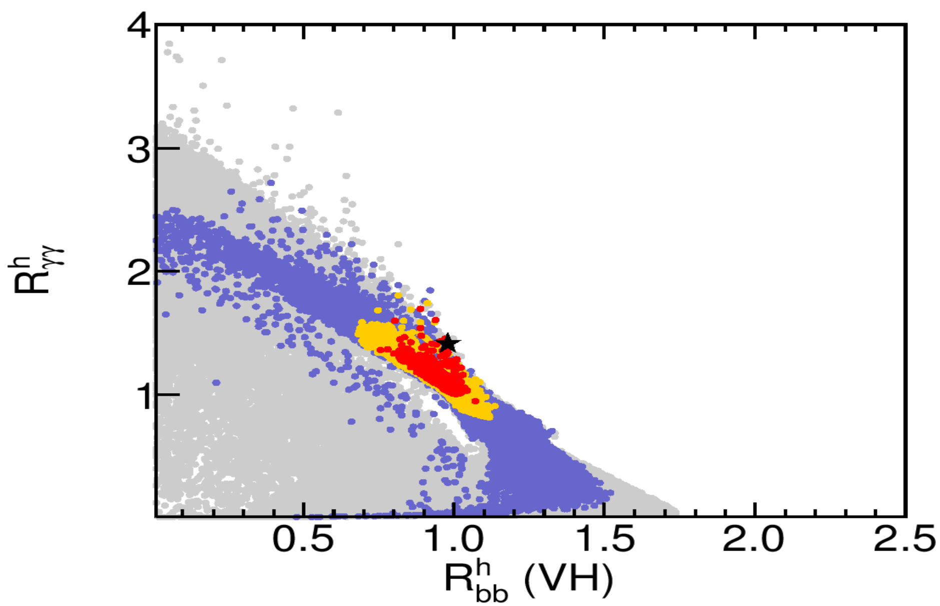
MSSM interpretation in terms of *light Higgs* h: Rates in different channels normalised to the SM

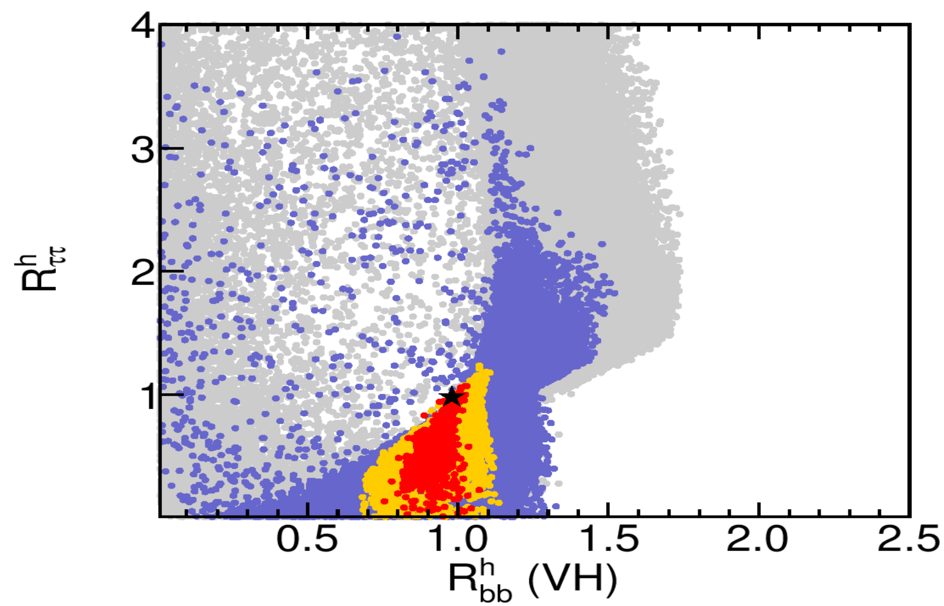
Rate modifiers

- All points: $121 < M_h < 129$ GeV
- Allowed by HiggsBounds
- $\Delta\chi^2 < 2.30$
- $\Delta\chi^2 < 5.99$

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

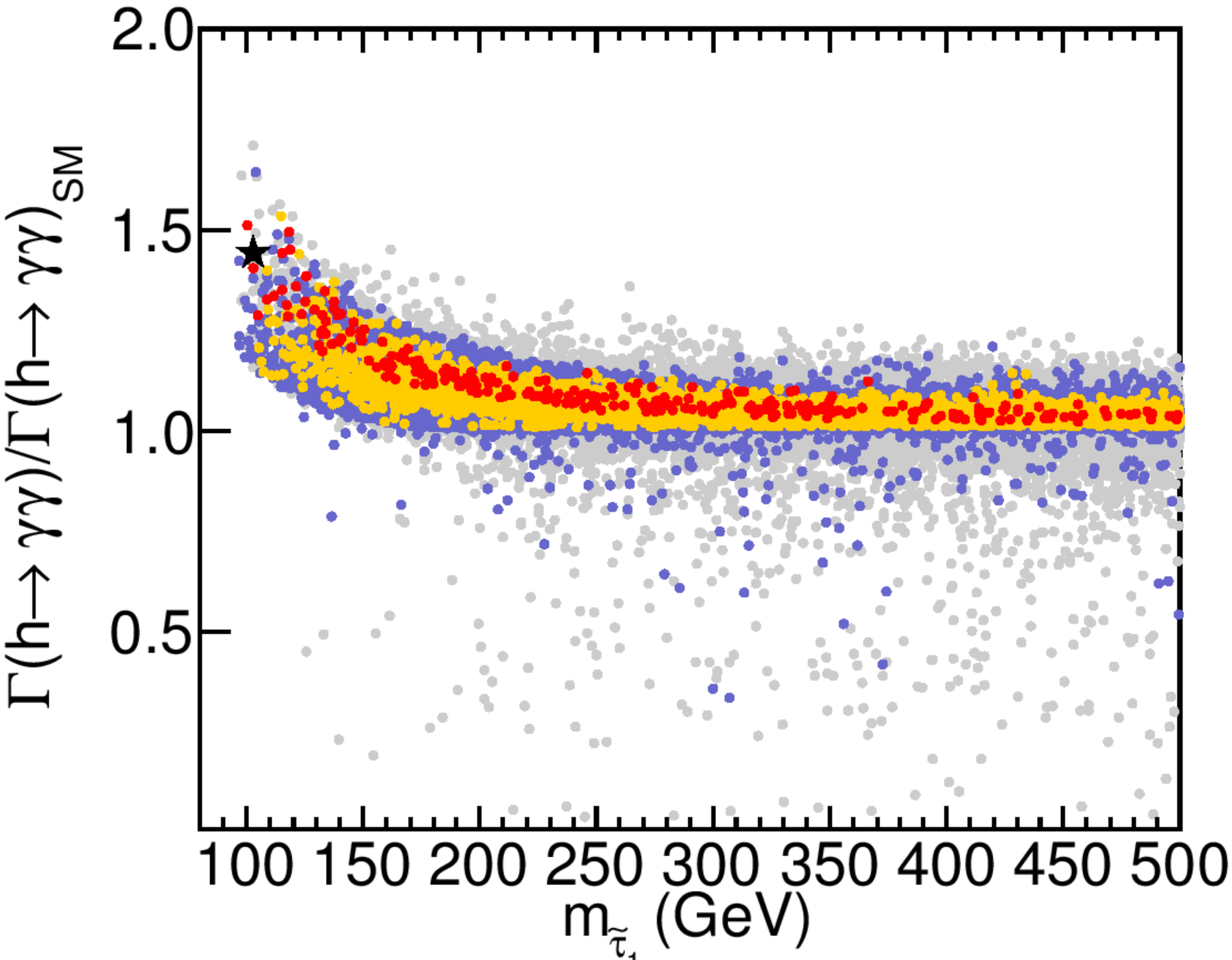






MSSM interpretation in terms of light Higgs h: enhancement of $\gamma\gamma$ partial width from light staus

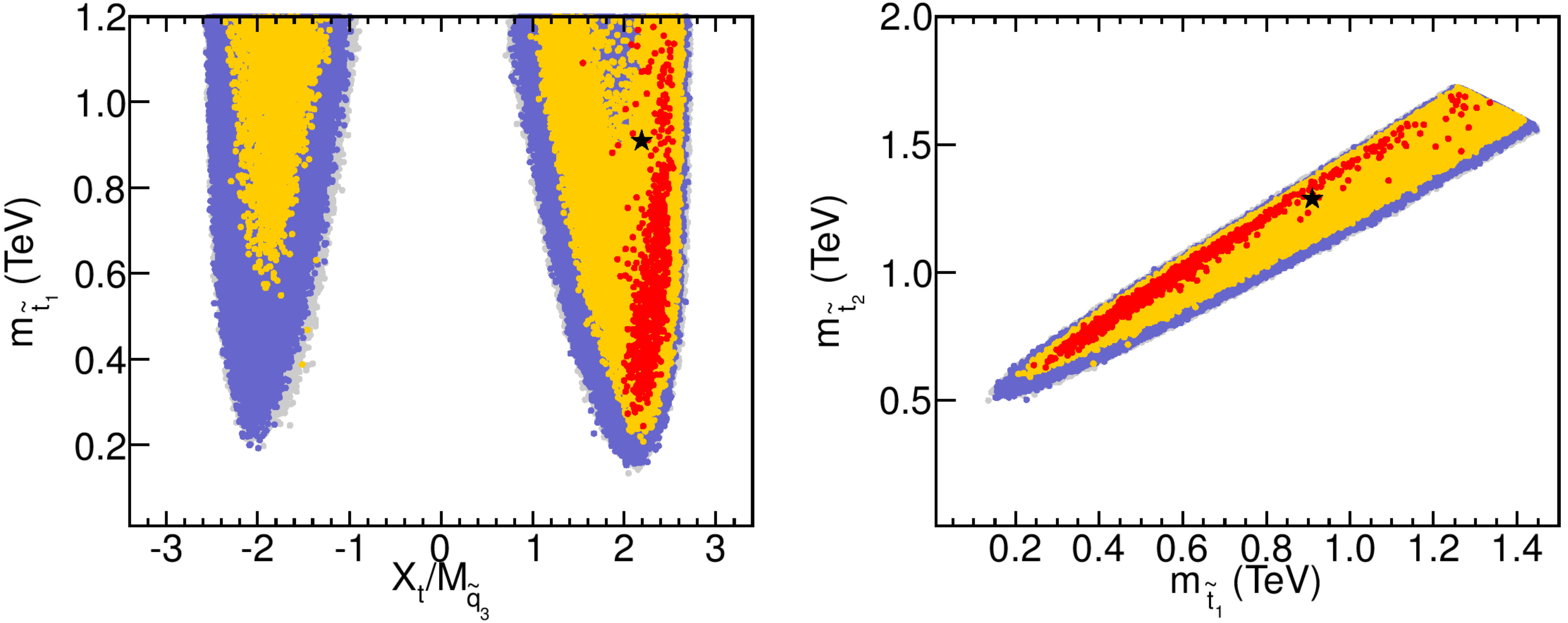
[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]



$\Rightarrow$ Light staus can lead to significant enhancement

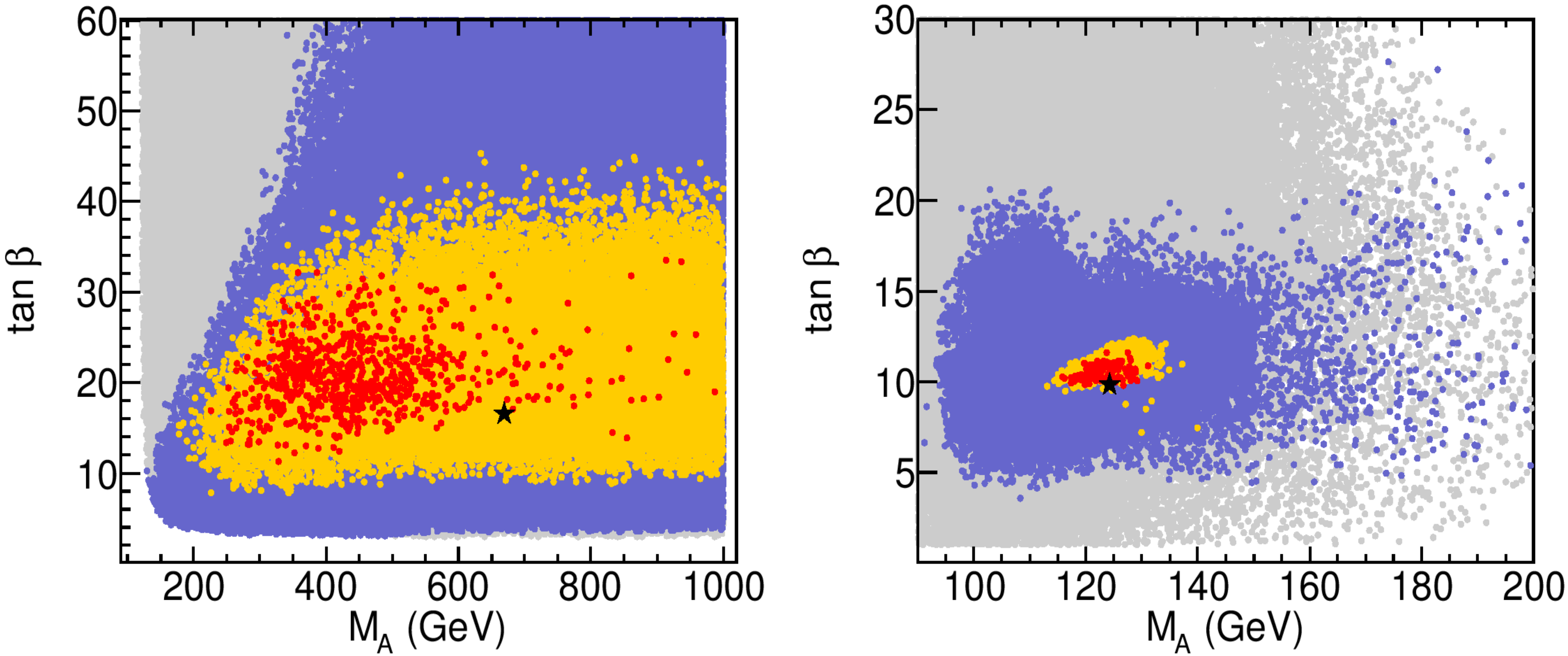
MSSM interpretation in terms of light Higgs h: preferred values for stop masses

[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]



$\Rightarrow M_\mathrm{h} \sim 126\ \mathrm{GeV}$ requires large stop mixing,
but stop masses can still be light

Preferred region in $(M_\mathrm{A}, \tan\beta)$ plane for interpretation of observed signal in terms of h (left), H (right), pre HCP

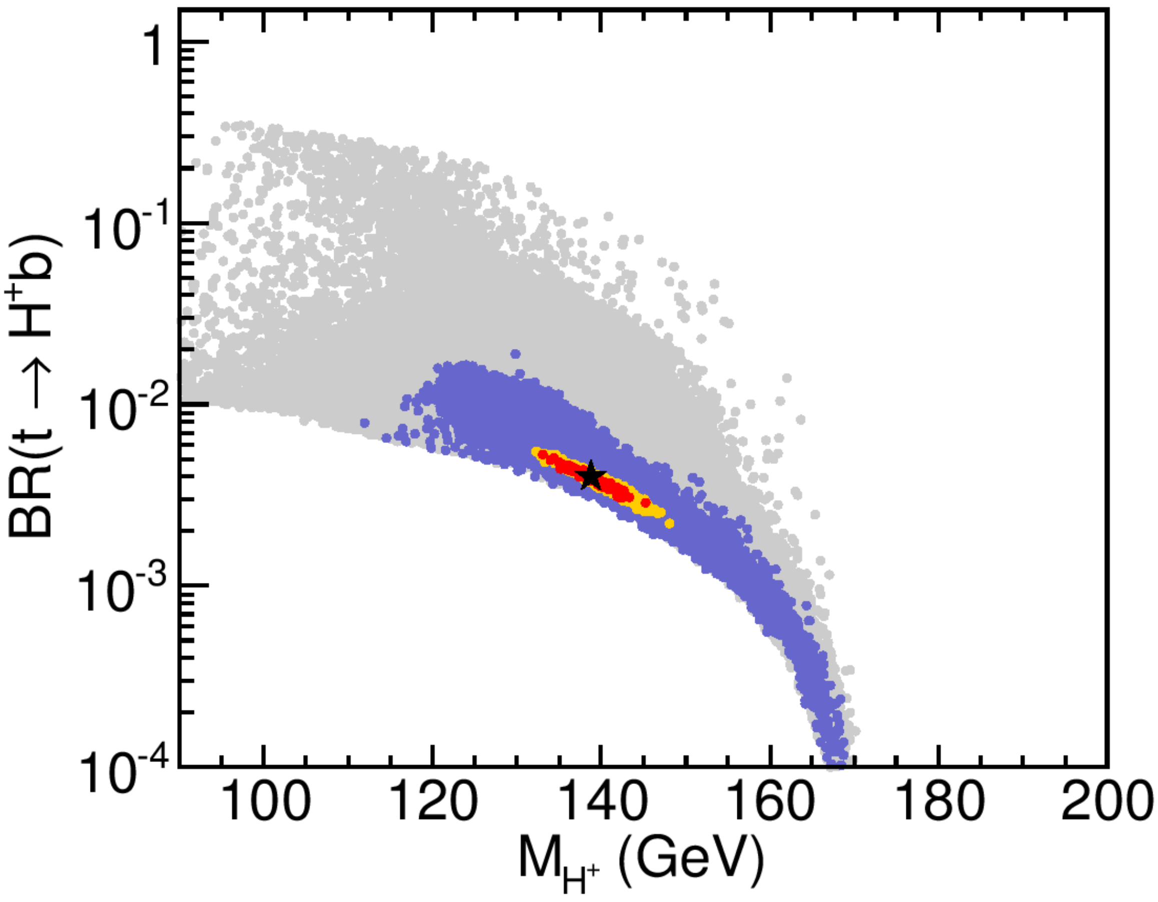


⇒ Effect of limit from $H, A \to \tau^+\tau^-$ searches weaker than in the $m_\mathrm{h}^\mathrm{max}$ scenario

⇒ Need cross section limits from CMS to assess impact of latest HCP results

MSSM interpretation in terms of ***heavy Higgs*** H*:* *preferred values for* $M_{\mathrm{H}^\pm}$ *and* $\mathrm{BR}(t \to H^+ b)$

[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]



$\Rightarrow$ MSSM interpretation in terms of heavy Higgs H can be probed by charged Higgs searches

Where do we stand and what next?

What we know so far about the new state at $\sim 126\ \mathrm{GeV}$ still leaves open many possible interpretations

- Many models of physics beyond the SM have a SM-like Higgs over large parts of their parameter space
- Does the new state have the right properties to unitarize $W_L W_L$ scattering?
- Fundamental or composite?

$\Rightarrow$ Need high-precision measurements of the couplings and the total width

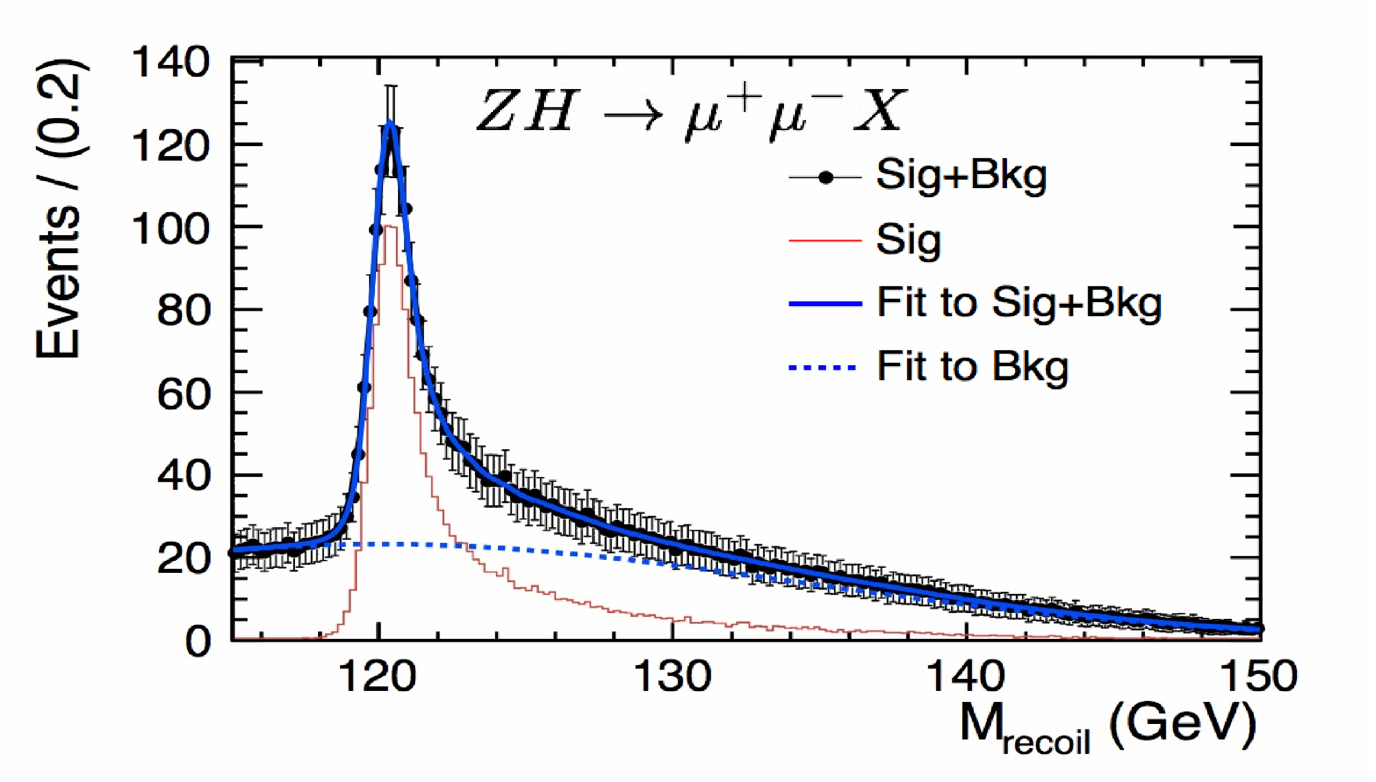
Higgs self-coupling $\Leftrightarrow$ experimental access to Higgs potential

$\Rightarrow$ Strong case for an e^+e^- Linear Collider: “Higgs factory”

Decay-mode independent measurement: “recoil” against Z

LC: high-precision measurements of Higgs properties

"Recoil" method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$ [*R. Poeschl et al. '12*]



Measurement of mass, couplings, $\mathcal{CP}$ properties, self-coupling, ... + high sensitivity to additional Higgses

$\Rightarrow$ Identification of the underlying nature of electroweak symmetry breaking

The mechanism of electroweak symmetry breaking

It seems very likely that the state observed at $\sim 126\ \mathrm{GeV}$ is directly related to the physics of electroweak symmetry breaking

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Other possibilities? Dilaton? ...

The mechanism of electroweak symmetry breaking

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Other possibilities? Dilaton? . . .

One would expect to see other signatures of the EWSB dynamics in such a case soon . . .

What else? Fundamental or composite?

- Radion
- Composite "pseudo-Goldstone boson", like the pion in QCD $\Rightarrow$ Would imply new kind of strong interaction

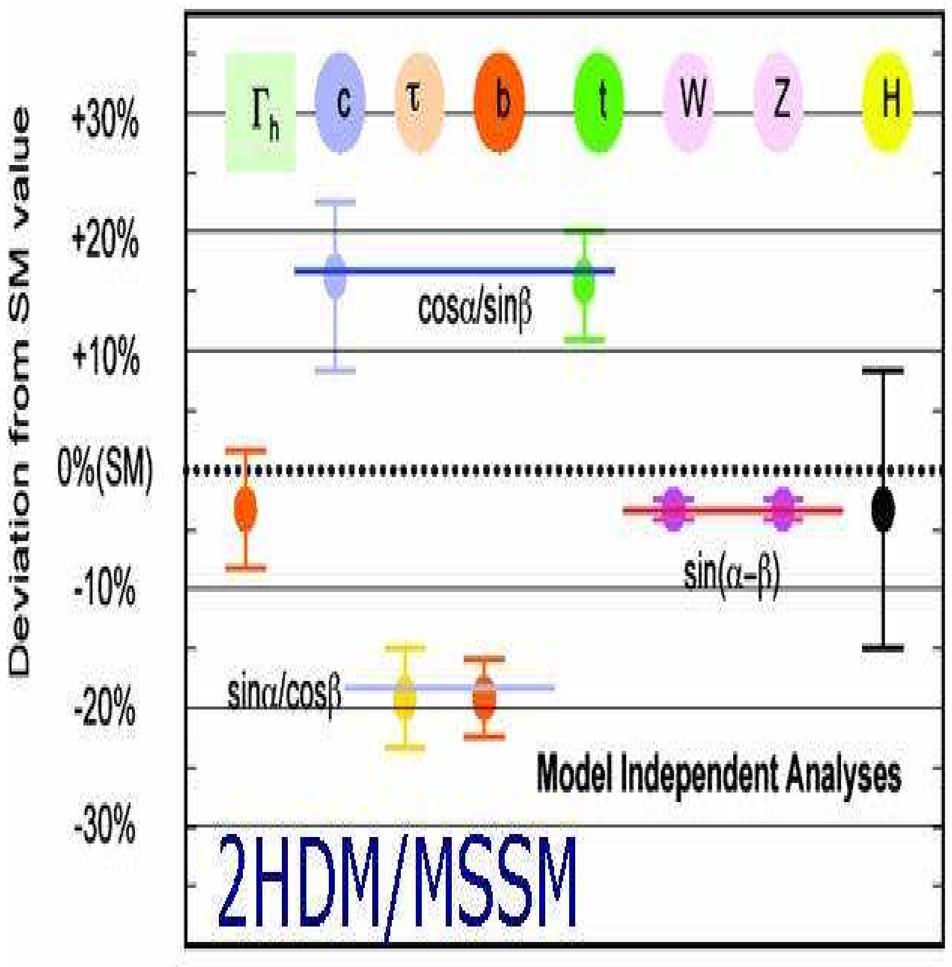
  Relation to weakly-coupled 5-dimensional model (AdS/CFT correspondence)

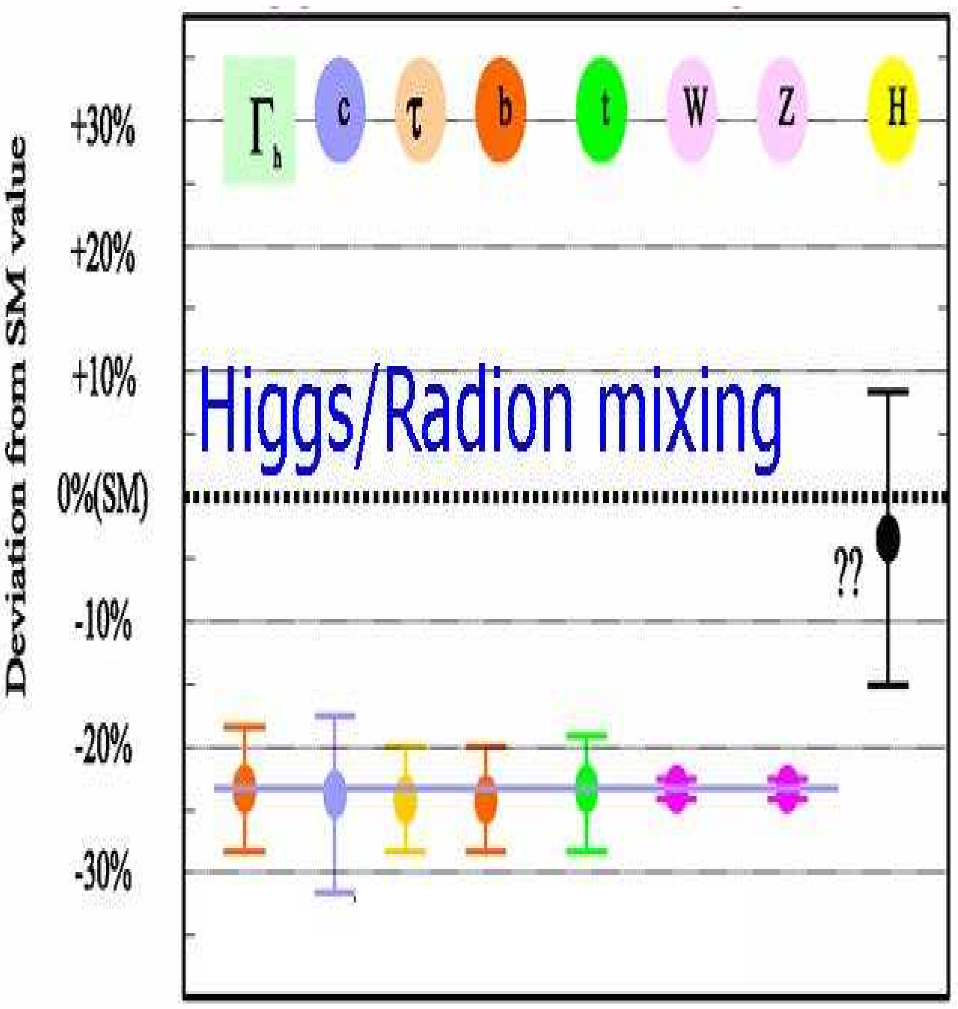
  Discrimination from fundamental scalar

  - Precision measurements of couplings ($\Rightarrow$ high sensitivity to compositeness scale), $\mathcal{CP}$ properties, . . .
  - Search for resonances
    (light Higgs $\Leftrightarrow$ light resonances?)
- . . .

The quest for identifying the underlying physics

Discrimination between different kinds of underlying physics via precision measurements of Higgs couplings





Higgs searches after the discovery

Extended Higgs sectors with a (more or less) SM-like Higgs at $\sim 126\ \mathrm{GeV}$ predict further Higgs states that may be heavier but also lighter than the state at $\sim 126\ \mathrm{GeV}$

Example: interpretation of the signal in terms of the second-lightest neutral SUSY Higgs would imply at least one additional non-SM like light Higgs, may have mass below the LEP limit of $M_{\mathrm{H}_{\mathrm{SM}}} > 114.4\ \mathrm{GeV}$ (with reduced couplings to gauge bosons, in agreement with LEP bounds)

$\Rightarrow$ Observation of a SM-like signal at $\sim 126\ \mathrm{GeV}$ provides a strong motivation to look for non SM-like Higgses elsewhere

$\Rightarrow$ The best way of experimentally proving that the observed state is not the SM Higgs is to find in addition (at least one) non-SM like Higgs!

Search for a light non-standard Higgs

- Extend searches (e.g. $H \to \gamma\gamma$, $b\bar{b}H, H \to b\bar{b}$, ...) to the region below $100\ \mathrm{GeV}$

- In case of SUSY, such a light Higgs could be produced in a SUSY cascade, e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$

  $\Rightarrow$ Could get a signal for SUSY $+$ non-standard Higgs at once

Conclusions

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Happy Birthday,

Michael and Howie!