After the discovery of a Higgs boson(-like) particle – a theorist's perspective

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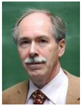
Discoveries at the LHC

Expectations (2008):



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"A Higgs, or more"

Gross:

"A super world"

Veltman:

"The unexpected"

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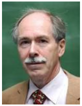

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“A Higgs, or more”

Gross:

“A super world”

Veltman:

“The unexpected”

. . .

Nov. 2011

HCP 2011:
Exclusion of a wide Higgs mass range, some theorists’ thought: “complete exclusion until the end of 2011”

13 Dec. 2011

ATLAS & CMS report an excess of events:
Too early to draw conclusions

4 July 2012

ATLAS & CMS announce the discovery of a Higgs-like particle

8 Oct. 2013

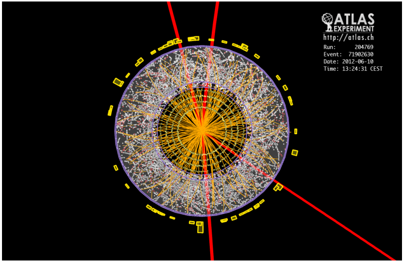
Nobel prize:
for the theoret. discovery of a mechanism that contributes to our understanding of the origin of mass . . .

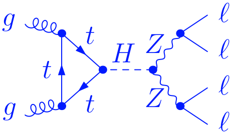
How was it discovered?

Discovery channels (LHC: $p\ p$ collider, p = proton):

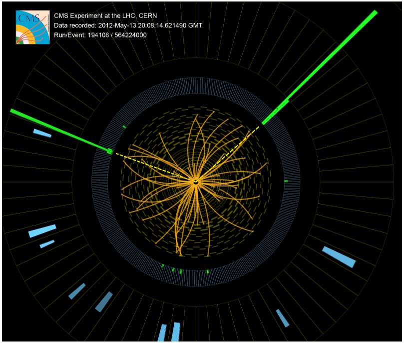
$pp \to H \to ZZ^* \to 4\ell$:

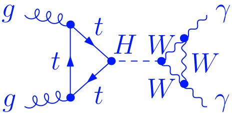
(here: $\ell = \mu$, μ = muon)





$pp \to H \to \gamma\gamma$:





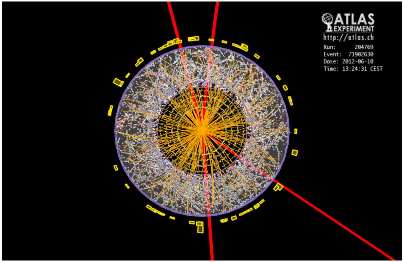
How was it discovered?

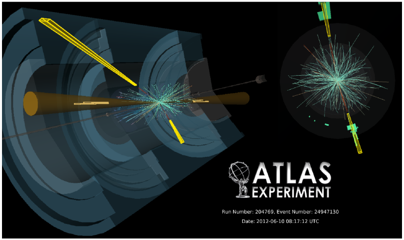
Discovery channels (LHC: $p\,p$ collider, p = proton):

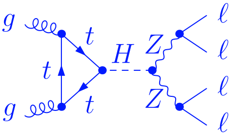
$pp \to H \to ZZ^* \to 4\ell$:

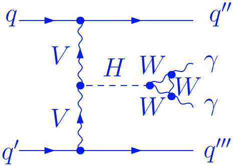
(here: $\ell = \mu$, μ = muon)

$pp \to H \to \gamma\gamma + 2$ jets:









Is it "the" Higgs boson?

- **Mass:** free parameter in the Standard Model

  expectation from precision measurements: $\mathcal{O}(100\text{ GeV})$

  (e.g. mass of the W boson)

  Moriond '13: CMS: $m_H = 125.7 \pm 0.3\text{ (stat)} \pm 0.3\text{ (syst) GeV}$

  ATLAS: $m_H = 125.5 \pm 0.2\text{ (stat)}\ ^{+0.5}_{-0.6}\text{ (syst) GeV}$

- **Spin?** Landau-Yang theorem:

  Massive spin-1 particle cannot decay into two photons:

  Decay into photons observed $\Rightarrow$ spin $\neq 1$

  Moriond '13: spin = 2: Excluded with $>$ 99% confidence level

  spin = 0: compatible

  model dependent

- **CP?** Moriond '13: CP-even: compatible

  spin = 0

  CP-odd: Exclusion with $\gtrsim$ 98% confidence level

Is it “the” Higgs boson?

- **Couplings?** so far compatible with the Standard Model:
  - Measurement of further production und decay channels:

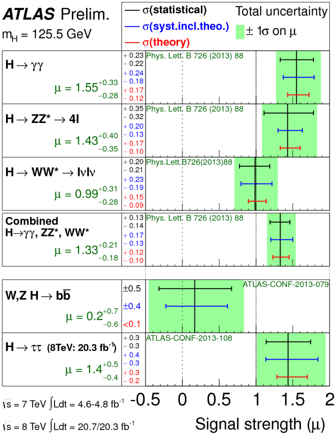
    $pp \to H \to WW$
    (compatible with SM)

    $pp \to H \to \tau\tau$ (Evidence!)

    $pp \to H \to bb$

    ...
  - still relatively large errors ($\sim$ 20 %)
  - not all couplings accessible

Signal strengths:



Is it "the" Higgs boson?

- **Mass:** free parameter in the Stand… Model

  expectation from pr… urements: $\mathcal{O}$(100 GeV)

  … W boson)

  Moriond '13: C… $\pm$ 0.3 (stat) $\pm$ 0.3 (syst) GeV

  ATLA… $= 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (syst) GeV

Other models: Higgs mass can be given by other parameters.

- **Spin?** Landau-Yang theorem:

  Massive spin-1 particle cannot decay into two photons:

  Decay into photons observed $\Rightarrow$ spin $\neq$ 1

  Moriond '13: spin = 2: Excluded with $>$ 99% confidence level

  spin = 0: … atible

  model dependent

- **CP?** Moriond '13: C… atible

  CP… xclusion with $\gtrsim$ 98% confidence level

  spin = 0

a mixture of CP-odd and -even?

Is it “the” Higgs boson?

• **Couplings?** so far compatibl… Standard Model:

– Measurement o… production…

$pp \to H \to$ …
(compatible …)

$pp \to H \to \tau\tau$ (Evidence!)

$pp \to H \to bb$

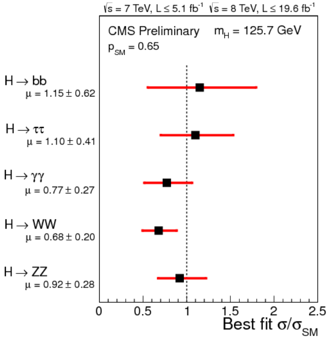
…

– still relatively large errors ($\sim$ 20 %)

– not all couplings accessible

Could be affected by an extended Higgs sector or other unknown particles: how much?

Signal strengths:



Further Results of the LHC

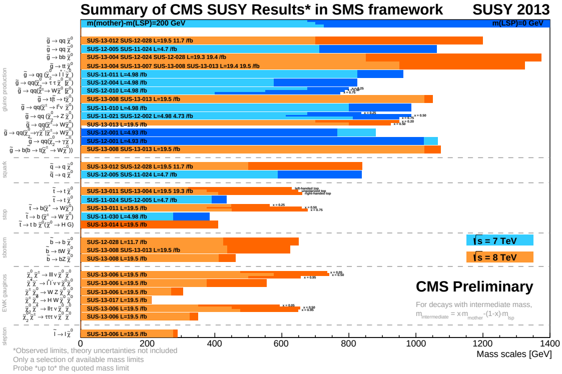
Supersymmetric partner particles:

- not found yet
- strongest constraints:

  colour charged particles:

  gluinos and
  first generation of squarks

  signature:
  jets and missing energy



- much less constrained:

  ⋆ top squarks

  ⋆ purely electroweak particles

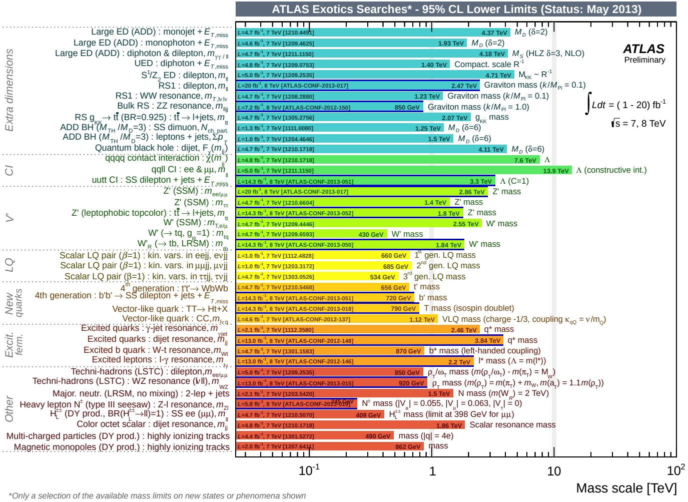
  signature:
  three charged leptons

Note specific assumptions:
simplified models, . . .

Further Results of the LHC

Further particles:

- not found yet



Reasons for further investigations

- Main question: What is the underlying theory?

- Reasons to search for beyond the Standard Model Physics

  From experiments:

  ⋆ dark matter

  ⋆ matter-antimatter asymmetry in the universe

  ⋆ neutrino oscillations

  From theory:

  ⋆ grand unification

  ⋆ embedding of gravity

  ⋆ Higgs mass M_H: sensitive to physics at high energy scales Λ
  quantum corrections: $\delta M_H^2 \sim \Lambda^2$ (hierarchy problem)

Minimal Supersymmetric Standard Model (MSSM)

MSSM: $\star$ Extension of the Standard Model (SM)

$\star$ Further symmetry:

Supersymmetry (SUSY):

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

$Q =$ supersymmetry generator

Recipe:

- Standard Model particles + 2^{nd} Higgs doublet (2HDM)
  (Generation of fermion masses, anomaly cancelations)
- Superpartners
- Explicit soft SUSY-breaking $\Rightarrow$ many new (complex) parameters
  (Else: $\text{mass}_{\text{superpartner}} = \text{mass}_{\text{2HDM-particle}} \leftarrow$ exp. excluded)
- R-Parity: discrete symmetry

Minimal Supersymmetric Standard Model (MSSM)

Particle content:

(2HDM)-Particle	Quarks	Leptons	Gauge bosons	Higgs bosons
Superpartner	Squarks	Sleptons		Gauginos Higgsinos

Particles with same quantum numbers can mix:

charged Higgsinos and Gauginos $\rightarrow$ Charginos

neutral Higgsinos and Gauginos $\rightarrow$ Neutralinos

Higgs Sector at Born Level

Higgs potential: gauge couplings

H_d, H_u: Higgs doublets

$$V_{\text{Higgs}} = \frac{g^2 + g'^2}{8}(H_d^+ H_d - H_u^+ H_u)^2 + \frac{g^2}{2}|H_d^+ H_u|^2$$

$$+ |\mu|^2 (H_d^+ H_d + H_u^+ H_u)$$

μ: coupl. betw. Higgs superfields

$$+ (m_1^2 H_d^+ H_d + m_2^2 H_u^+ H_u)$$

soft breaking terms

$$+ (\epsilon_{ij} |m_{12}^2| e^{i\varphi_{m_{12}^2}} H_d^i H_u^j + h.c.)$$

- one phase in the Higgs potential: $\varphi_{m_{12}^2}$
- phase difference of Higgs doublets ξ

non-vanishing phases:
$\Rightarrow$ maybe CP- or T-violation?

($T_{\text{ime reversal}}$-operator is antiunitary
$\Rightarrow$ complex conjugation

Higgs Sector at Born Level

Higgs potential: gauge couplings H_d, H_u: Higgs doublets

$$V_{\text{Higgs}} = \frac{g^2 + g'^2}{8}(H_d^+ H_d - H_u^+ H_u)^2 + \frac{g^2}{2}|H_d^+ H_u|^2$$

$$+ |\mu|^2 (H_d^+ H_d + H_u^+ H_u)$$ μ: coupl. betw. Higgs superfields

$$+ (m_1^2 H_d^+ H_d + m_2^2 H_u^+ H_u)$$ soft breaking terms

$$+ (\epsilon_{ij} |m_{12}^2| e^{i\varphi_{m_{12}^2}} H_d^i H_u^j + h.c.)$$

- one phase in the Higgs potential: $\varphi_{m_{12}^2}$
  can be rotated away
- phase difference of Higgs doublets ξ:
  vanishes because of minimum condition

} **no** CP violation at Born level in the Higgs sector

Higgs Sector at Born Level

Physical mass eigenstates (at Born level):

- 5 Higgs bosons: 3 neutral H, h, A; 2 charged $H^{\pm}$

Masses of the Higgs bosons:

- not all independent:

  often: Mass M_A or $M_{H^{\pm}}$ (and $\tan\beta$) as free parameter

  $\tan\beta = \frac{v_2}{v_1}$: ratio of the Higgs vac. expect. values

- lightest Higgs boson: h

  Upper theoretical Born mass bound:

  $M_h \leq M_Z = 91$ GeV

  with quantum corrections of higher orders: $M_h \lesssim 140$ GeV

  dependent on the MSSM parameters

Why a precise Higgs mass prediction?

- Needed as consistent input for the calculation of cross sections and decay widths in the MSSM

- experimentally measured value $\Rightarrow$ constraint on viable MSSM parameter space

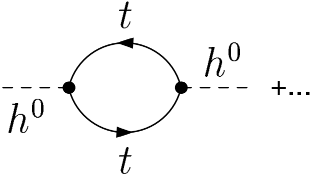
  A precise theoretical prediction is needed to fully exploit this constraint:

  $$\Delta M_H^{\text{exp.}} < 1 \text{ GeV} \qquad \text{vs} \qquad \Delta M_H^{\text{theory}} \approx 3 \text{ GeV}$$

- In the discussion of the amount of fine-tuning of the MSSM the precise theoretical prediction of the Higgs boson mass enters.

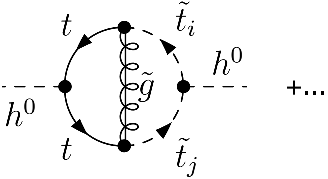
Contributions to the Higgs boson masses

Quantum corrections:



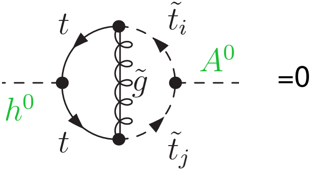
One-loop level $\mathcal{O}(\alpha_t)$:

$\alpha_t \sim$ (top Yukawa coupl.)^2



Two-loop level $\mathcal{O}(\alpha_t\alpha_s)$:

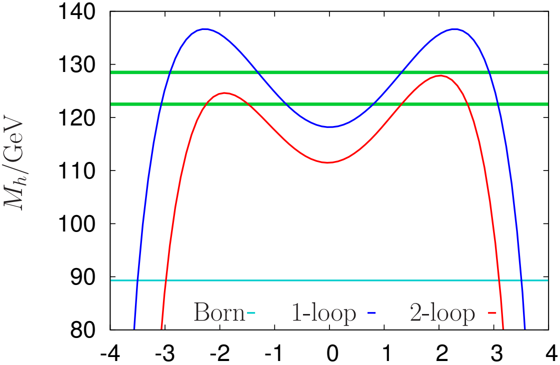
Real parameters:



no mixing between CP-even and CP-odd states

$\Rightarrow$ Lightest Higgs boson is CP-even.

Implications of a 125.5 GeV Higgs boson (MSSM)



X_t/TeV, X_t = squark mixing parameter

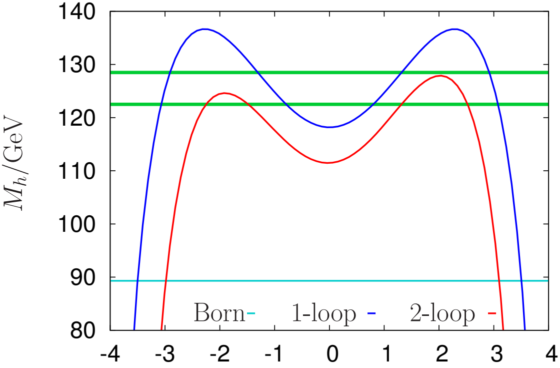
generated using FeynHiggs [Hahn, Heinemeyer, Hollik, H.R., Weiglein, Williams]

1-loop [Frank, Hahn, Heinemeyer, Hollik, H.R., Weiglein]

2-loop $\mathcal{O}(\alpha_{\{t,b\}}\alpha_s, \alpha^2_{\{t,b\}}, \alpha_t\alpha_b)$ [Degrassi, Slavich, Zwirner; Brignole, Degrassi, Slavich, Zwirner; Heinemeyer, Hollik, H.R., Weiglein; Dedes, Degrassi, Slavich]

- A 125.5 ± 3 GeV mass constrains the parameter space but does not exclude the MSSM. (theory uncertainty ≈ 3 GeV)
- here: no known 3-loop contributions included [Martin; Harlander, Kant, Mihaila, Steinhauser]

Implications of a 125.5 GeV Higgs boson (MSSM)



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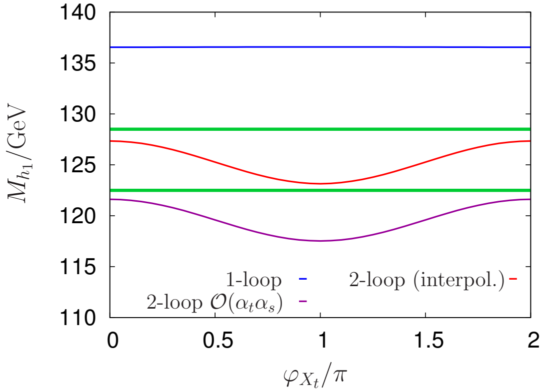
For parameter scans, see e.g.

[Heinemeyer, Stål, Weiglein, arXiv:1112.3026;
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon, arXiv:1112.3028]

Higgs boson mass and CP-violating phases



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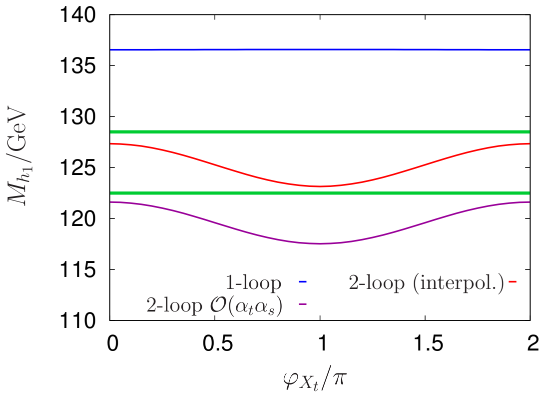
2-loop (interpol.): corrections for real parameters are interpolated [Degrassi, Slavich, Zwirner; Brignole, Degrassi, Slavich, Zwirner; Dedes, Degrassi, Slavich]

(no resummation)

- The Higgs mass does depend on the squark mixing phase φ_{X_t}.
- For $\varphi_{X_t} \neq n\pi, n \in \mathbb{N}_0$, h_1 is not a CP-eigenstate.

Higgs boson mass and CP-violating phases



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To do: Implementation of $\mathcal{O}(\alpha_t^2)$ contr. [Hollik, Passehr, arXiv:1401.8275]

Higgs boson mass for large stop masses

Prediction obtained via Feynman diagrammatic approach:

+ all log and non-log terms are taken into account
  at a certain order of perturbation theory

- possible appearance of large logs:

$$\Delta M_H \sim \log \frac{M_S}{m_t}$$

M_S: SUSY particle mass scale
m_t: top quark mass

⇒ • good prediction for lower SUSY mass scales

• no reliable prediction for large SUSY mass scales

Higgs boson mass for large stop masses

Other approach: Renormalization Group Equation (RGE) approach:

⋆ assume: all SUSY particles are heavy of order $\sim M_S$:

above M_S: MSSM

below M_S: Standard Model
(as effective theory)

match at scale M_S:

$\lambda^{\text{MSSM}}(M_S) = \lambda^{\text{Standard Model}}(M_S)$

quartic Higgs coupling

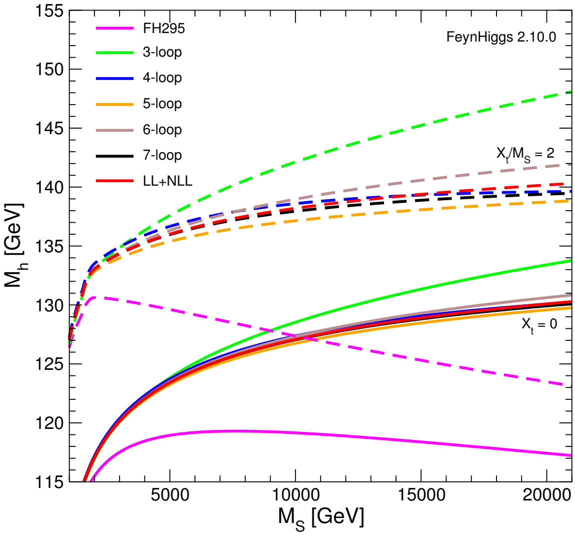
⋆ evolve λ to lower scale using Standard Model running (RGE)

⋆ the Higgs mass² is then $M_h^2(m_t) = 2\lambda(m_t)v^2$ $\quad v \approx 174$ GeV

$\Rightarrow$ logs resummed to all orders: good prediction for large SUSY masses

$\rightarrow$ Combine both approaches (now:only for real parameters)

Higgs boson mass for large stop masses



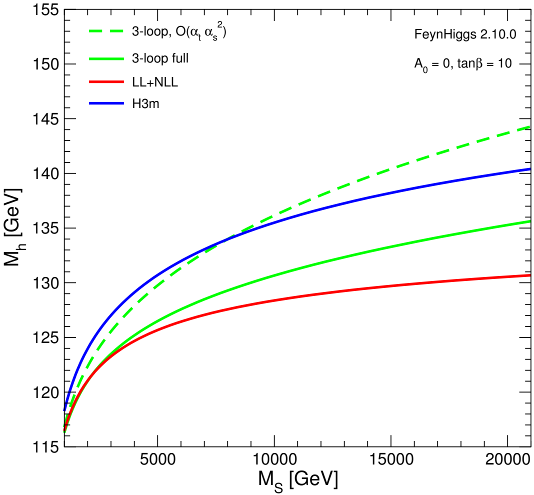
Comparison of:

- ⋆ old FeynHiggs reliable up to $M_s = \mathcal{O}(1\text{TeV})$
- ⋆ analyt. solution of RGE: 3-loop ... 7-loop level: Logs of order $\mathcal{O}(\alpha_t \alpha_s^2, \alpha_t^2 \alpha_s, \alpha_t^3)$ ...
- ⋆ numerical solution: LL+NLL: logs resummed to all orders

$M_A = M_2 = \mu = 1$ TeV, $m_{\tilde{g}} = 1.6$ TeV, $\tan\beta = 10$

[T. Hahn, S. Heinemeyer, W. Hollik, H.R., G. Weiglein, arXiv:1312.4937]

Higgs boson mass for large stop masses



Comparison with `H3m`:

[Kant, Harlander, Mihaila, Steinhauser, arXiv:1005.5709]

3-loop: $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t^3)$

- ⋆ only leading and next-to leading logs
- ⋆ single scale M_S

H3m:
- ⋆ complete $\mathcal{O}(\alpha_t\alpha_s^2)$ result
- ⋆ different scales

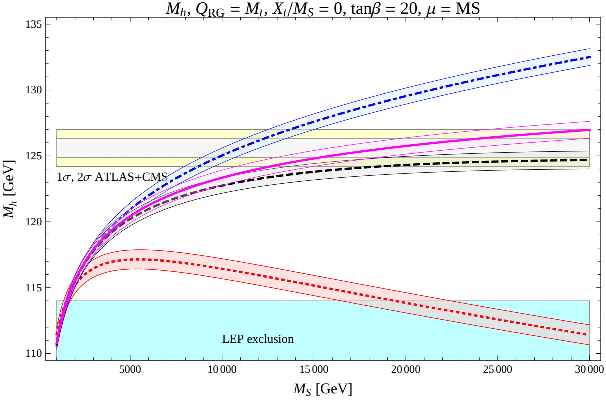
At 2-loop: different ren. schemes

CMSSM: $m_0 = m_{1/2} = 200 \ldots 15000$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, spectra generation with `SoftSUSY` [Allanach, hep-ph/0104145]

Higgs boson mass for large stop masses

Similar findings for large SUSY masses (pure RGE approach):

[Draper, Lee, Wagner, arXiv:1312.5743]



2-loop NNLL result

3-loop NNLL result

4-loop NNLL result

resummed result

Differences:

- 3-loop running for λ
- 2-loop matching
- not yet implemented into a computer code

Deviations from the Standard Model?

[Frank Vincentz, http://de.wikipedia.org/wiki/Kleeblatt; Uwe Vogel, http://www.oldskoolman.de/]

Deviations from the Standard Model (SM)?

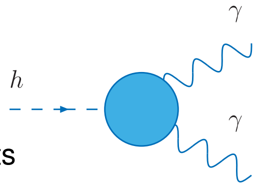
Needed:

- precise predictions of the signal cross sections in the SM
  Calculation of higher-order corrections necessary
- precise determination of the background
- good error estimate
  (e.g. including possible errors originating from a contamination of control regions by events of unknown particles [Feigl, H.R., Zeppenfeld, arXiv:1205.3468])

Deviations from the Standard Model (SM)?

Where can they originate from?

- changes in loop-induced couplings due to unknown particles



- changes of couplings due to mixing effects in an enlarged Higgs sector
- changes due to additional decay into invisible particles
- changes due to two degenerate Higgs bosons

Next-to Minimal Supersymmetric Standard Model (NMSSM)

In the MSSM: Parameter μ in the superpotential W, $W = \mu H_1 H_2 + \dots$

A priori: arbitrary value

But: Order of the electroweak/SUSY-breaking scale

In the NMSSM: Additional Higgs superfield singlet S:

μ is generated via a vacuum expectation value of the scalar Higgs singlet, $W = \lambda S H_1 H_2 + \dots$, $\lambda =$ new coupling

- 7 Higgs bosons: h_1, h_2, h_3, A_1, A_2, $H^\pm$
- CP-violation in the Higgs sector possible already at Born level (complex parameters)
- Mass of the light CP-even MSSM-like Higgs boson can be larger than in the MSSM
- 5 neutralinos (4 neutralinos in the MSSM)

Degenerate Higgs bosons

In the NMSSM:

2 Higgs bosons could be nearly degenerate with masses of $\sim$ 125 GeV

[Gunion, Jiang, Kraml, arXiv:1207.1545]

For illustration (one possibility):

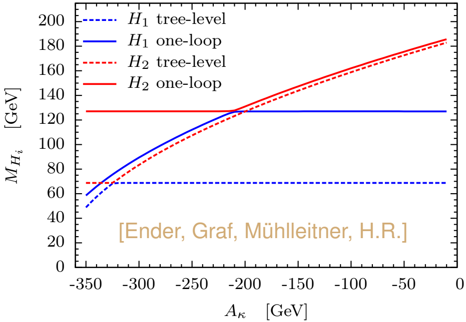


Illustration: Cross-over region of H_1 and H_2 at $A_\kappa \approx -210$ GeV:

- Masses $M_{H_i} \sim 125$ GeV
- H_1 and H_2 interchange their role

trilinear, SUSY-breaking singlet coupling

Degenerate Higgs bosons

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2 Higgs bosons could be nearly degenerate with masses of $\sim$ 125 GeV

$\Rightarrow$ Change of the effective couplings

[Gunion, Jiang, Kraml, arXiv:1207.1545]

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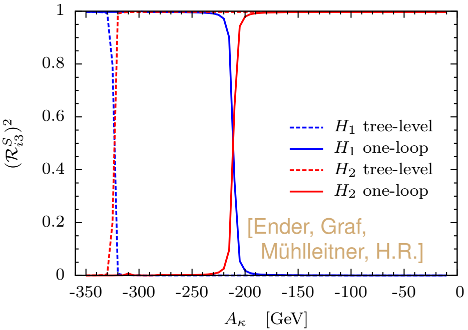

Illustration: Cross-over region of H_1 and H_2: Masses $\sim$ 125 GeV

$A_\kappa < -210$ GeV: H_1 singlet-like, H_2 non-singlet like

$A_\kappa > -210$ GeV: H_1 non-singlet like, H_2 singlet-like

Degenerate Higgs bosons

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[Gunion, Jiang, Kraml, arXiv:1207.1545]

For illustration (one possibility):

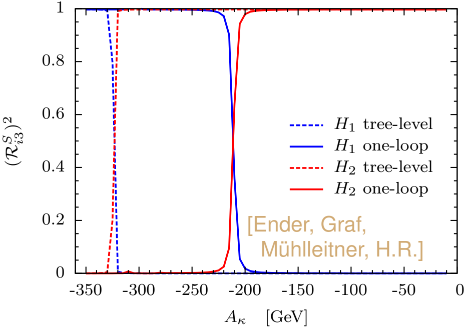


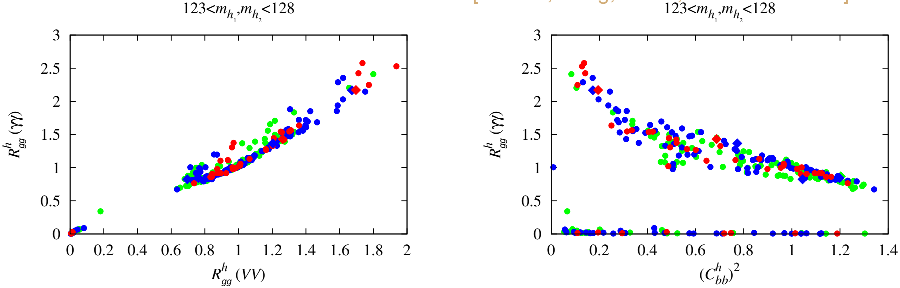
Illustration: • Higher-order corrections are necessary

• Implemented in `NMSSMCalc`: program for evaluation of mass spectra and decay widths (allows also for complex parameters)

[Baglio, Gröber, Mühlleitner, Nhung, H.R., Spira, Streicher, Walz]

Degenerate Higgs bosons

[Gunion, Jiang, Kraml, arXiv:1207.1545]



Legend: $m_{h_2} - m_{h_1} \leq 1$ GeV, 1 GeV $< m_{h_2} - m_{h_1} \leq 2$ GeV,
2 GeV $< m_{h_2} - m_{h_1} \leq 3$ GeV

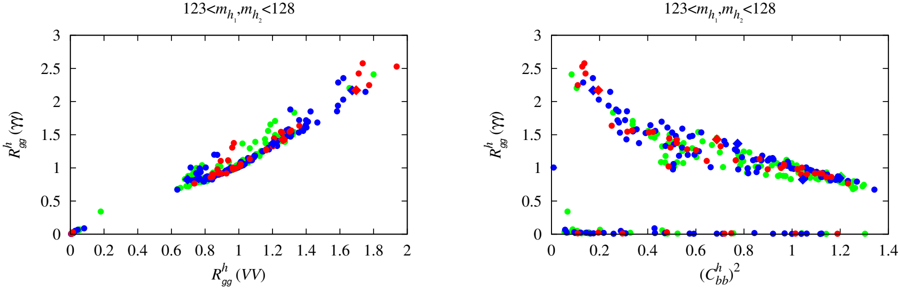
Signal ratio: $$R^h_{gg}(XX) = \sum_{i=1}^{2} \frac{\sigma(gg \to h_i)\mathrm{BR}(h_i \to XX)}{\sigma^{\mathrm{SM}}(gg \to h)\mathrm{BR}^{\mathrm{SM}}(h \to XX)}$$

with an effective SM Higgs mass

(Parameter scans with `NMSSMTools` [Ellwanger, Gunion, Hugonie])

Degenerate Higgs bosons

[Gunion, Jiang, Kraml, arXiv:1207.1545]



- Enhancement of the $h \to \gamma\gamma$ channel by a factor of 1.5 possible without enhancing $h \to VV$
- Enhancement of the $h \to \gamma\gamma$ channel is generally achieved by reducing the average $b\bar{b}$ coupling strength C^h_{bb}

Only a single Higgs boson discovery at the LHC?

[Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

If no beyond Standard Model (SM) physics is seen at the LHC:
(related to electroweak symmetry breaking)

How large can deviations from the SM Higgs couplings be?

How precisely do we need to measure the Higgs couplings at least?

Which future collider and detectors?

Only a single Higgs boson discovery at the LHC?

[Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

No completely model independent answer possible:

- MSSM

- Mixed-in singlet model = Standard Model + exotic Higgs boson singlet S:

  Scalar fields mix via $|H_{SM}|^2 |S|^2$ [Schabinger, Wells, hep-ph/0509209; Bowen, Cui, Wells, hep-ph/0701035]

  $\Rightarrow$ 2 CP-even mass eigenstates: SM-like h, heavier H

  with couplings[2] $g_h^2 = c_h^2\, g_{SM}^2$ and $g_H^2 = s_h^2\, g_{SM}^2$

  $c_h = \cos\theta_h$
  $s_h = \sin\theta_h$
  θ_h = mix. angle

- Composite Higgs models: SM-like Higgs boson = pseudo-Goldstone:

  SM vector bosons and fermions + strong sector with Higgs multiplet

  in terms of an effective field theory
  for a strong interacting light Higgs (SILH) boson [Guidice, Grojean, Pomarol, Rattazzi, hep-ph/0703164]

Only a single Higgs boson discovery at the LHC?

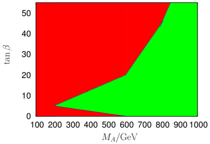
Take into account: [Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

⋆ discovery potential of the LHC
for further particles related to electroweak symmetry breaking

⋆ constraints from electroweak precision tests

- MSSM:

  Deviations constrained mainly by discovery potential ←



- Mixed-in singlet model:

  Deviations constrained by discovery potential, electroweak precision tests

- Composite Higgs models:

  Deviations constrained by electroweak precision tests

Only a single Higgs boson discovery at the LHC?

[Gupta, H.R., Wells, arXiv:1206.3560, arXiv:1305.6397]

Maximal deviations from the SM Higgs couplings? (no new physics at the LHC)

	$\lvert\Delta hVV\rvert$ c. to gauge bosons V	$\lvert\Delta h\bar{t}t\rvert$ c. to top quarks t	$\lvert\Delta h\bar{b}b\rvert$ c. to bottom quarks b	$\lvert\Delta hhh\rvert$ triple Higgs coupl.
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %

(MSSM: first values — $\tan\beta > 20$, no superpartners; second values — all other cases)

$\Rightarrow$ a challenge for the future!

Summary

- Exciting times: Discovery of a Higgs boson
- Still exciting: What is its true nature?
- At the moment: compatible with the Standard Model
- Constraints on the parameter space of extension of the Standard Model (e.g. coming from the Higgs mass)
- Precise measurement of its couplings can help with the complete identification of the particle
- Program development:

  ⋆ `FeynHiggs`: Higgs mass prediction for large stop masses improved

  ⋆ `NMSSMCALC`: New program for the NMSSM Higgs masses/decay widths