Higgs Review

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PDG Workshop on Searches

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Outline

- Introduction/state of the art
- Plan/topics for 2013 Higgs Review write up

  Theory Part (this presentation)

  Experimental part (Marumi)
- Comments/recommendations from the last PDG Advisory Committee

Introduction/State of the art

- Last Review submitted May 2012

  (pre-new Scalar boson discovery)

  Authors: Gregorio Bernardi, Thomas Junk, Marcela Carena

  * Includes a 6-page July 12th Addendum to discuss the July 4th discovery

  * Joint Theory-Experimental review

    We are discussing which format is better to pursue

    1 or 2 reviews (?)

Topics of the Previous review
HIGGS BOSONS: THEORY AND SEARCHES

Focus/emphasis driven by Searches, SM and BSM's

- I. Introduction
- II. The Standard Model (SM) Higgs Boson

  Indirect Constraints on the SM Higgs Boson

  Searches for the SM Higgs Boson at LEP

  Searches for the SM Higgs Boson at the Tevatron

  SM Higgs Boson Searches at the LHC

  Models with a Fourth Generation of SM-Like Fermions

Topics of the previous review
HIGGS BOSONS: THEORY AND SEARCHES

III. Higgs Model (MSSM)

- Radiatively-Corrected MSSM Higgs Masses and Couplings
- Decay Properties and Production Mechanisms of MSSM
- Higgs Bosons Searches for Neutral Higgs Bosons in the CP Conserving CPC Scenario
  - -- Searches for Neutral MSSM Higgs Bosons at LEP
  - -- Searches for Neutral MSSM Higgs Bosons at Hadron Colliders
- Searches for Charged MSSM Higgs Bosons
- Effects of CP Violation on the MSSM Higgs Spectrum
- Searches for Neutral Higgs Bosons in CPV Scenarios
- Indirect Constraints on Supersymmetric Higgs Bosons

IV. Other Model Extensions

V. Searches for Higgs Bosons Beyond the MSSM

VI. Outlook

VII. Addendum

After the Scalar boson Discovery

- compatible with a SM-like Higgs-

New approach needed:

- Focus on the new particle discovery and its properties
- Interpretation of data and precision physics in the light of the new particle
- Discussion in the framework of a SM-like Higgs
- Given that no other new physics has been discovered yet: focus on implications for possible new physics at a high energy scale (beyond LHC?)
- Discussion in the framework of specific New Physics models that are theoretically appealing
- Put in perspective other searches for Higgs particles

Outline for 2013 Higgs Review
Theory Part

Part I: SM

- Introduction to the SM and the SM Higgs Boson
  Include discussion of the hierarchy problem and
  of the stability of the Higgs potential
  [the above is already in the present version, needs to be updated]

-- Present results from next-to-next leading order analysis of the SM Higgs potential

-- Show the sensitivity to m_{top} and α_S

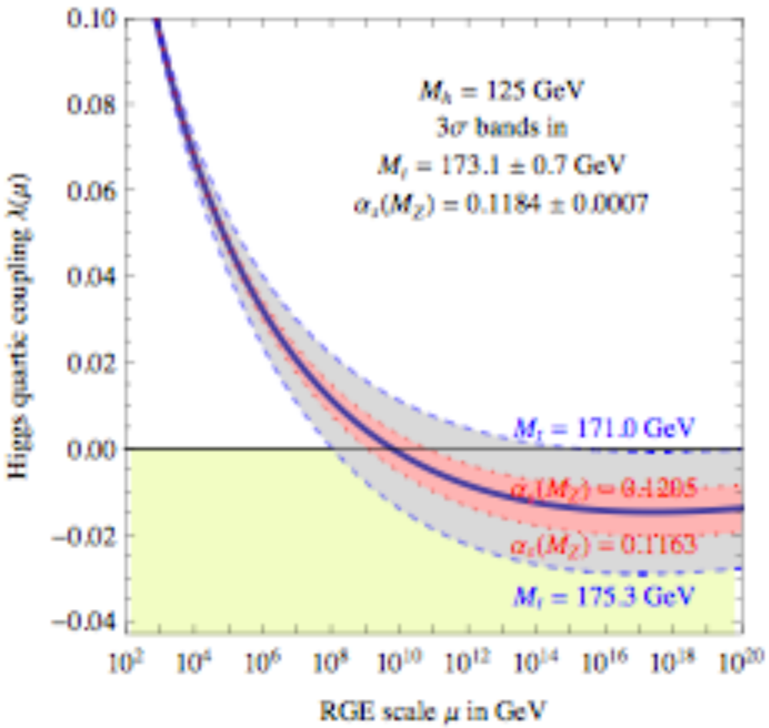
-- Address the issues of the uncertainties evaluated differently by various groups

-- State-of-art description of the computations for the various kinematic distributions

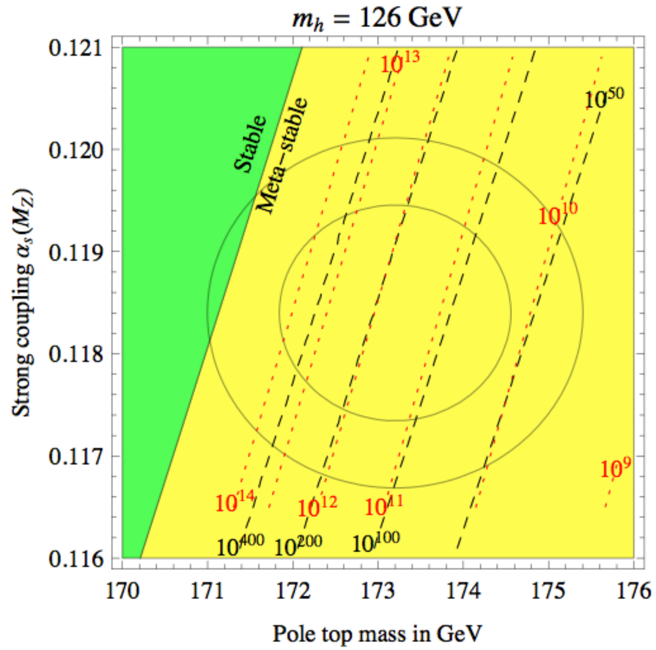
SM Stability Condition for fixed m_h

Degrassi et al;
Berzukov et al, etc

RG evolution of λ varying Mt and α_s by ±3σ.



The dotted red contour-lines show the instability scale Λ



Putting all the NNLO ingredients together, one can estimate an overall theory error on Mh of ±1.0 GeV. The condition of absolute stability up to the Planck scale is

$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

$M_h > 129.4 \pm 1.8\ \text{GeV}$ Hence SM vacuum stability excluded at 2σ for mh < 126 GeV

Part I: SM (cont'd)

- Discussion of production and decay mechanisms and state of the art precision calculations

  [this is already in the present version, needs to be updated]

- Add connection with the LHC-xsection working group
- Discuss increasing relevance of the computations of pdf's.
- Include a discussion of the relevance of boosted techniques in the Higgs searches [increasing importance for next run]

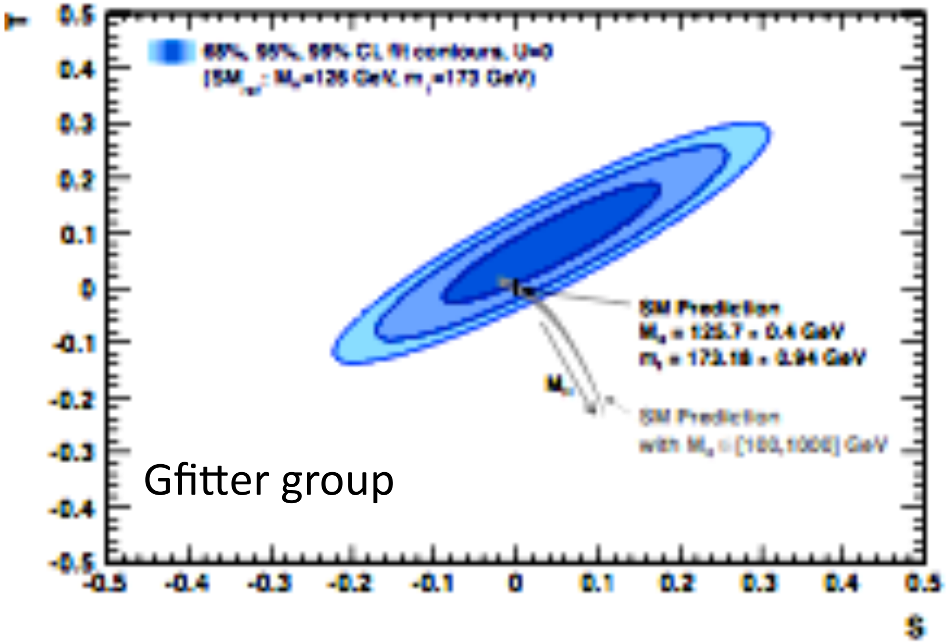
- Indirect constraints from EW data

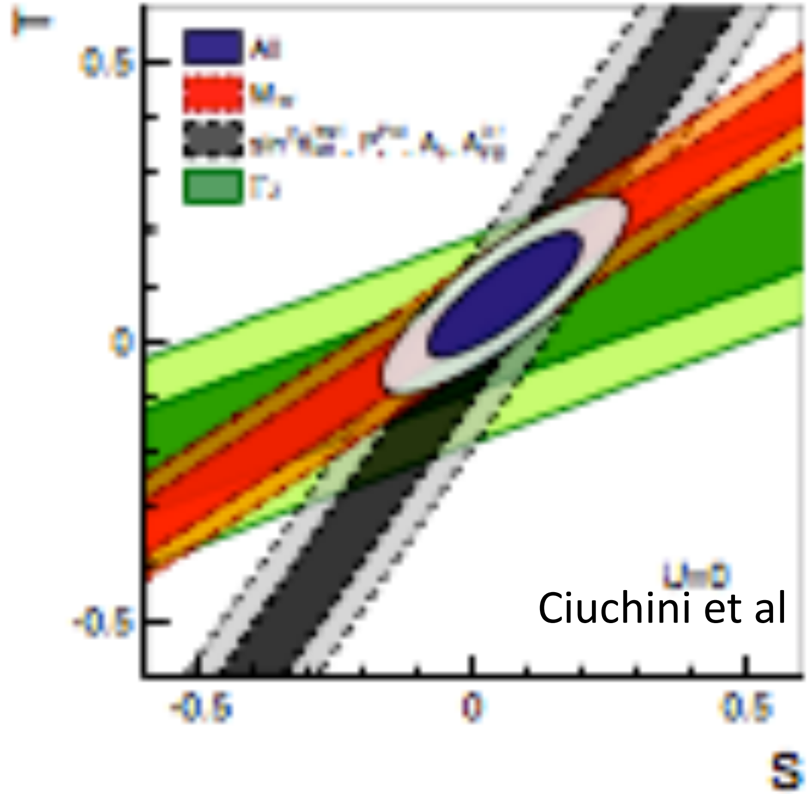
  Update results of the impact on the m_t and m_W measurements

  Include S and T fit as a function of the Higgs mass

  (EW fit within SM and also later in the case of NP)

EW global fit of the SM assuming the new particle is the SM Higgs





The knowledge of the Higgs mass dramatically improves the SM predictions of several key observables, including Mw and Mt

The improved accuracy sets a benchmark for direct measurements, which has been reached (and surpassed) only for Mt

Part I: SM (cont'd)

- Further discussion of SM properties of the Higgs boson: CP and spin

[This was only very shortly mentioned, we plan to discuss this in connection with the results of the experimental session]

Leave discussion of fit to couplings for the New physics part.

- ***Short discussion of the experimental results, referring to the experimental review, as conclusion for this part (?) or merge both reviews in one?***

- Introduction to the next sections:

What if the newly discovered particle is not the SM Higgs?

It can still be the Higgs boson of EWSB -

The SM Higgs Boson:

- Spin 0
- Neutral CP even component of a complex $SU(2)_L$ doublet with Y=1
- Singlet under the residual SU(2) custodial symmetry after EWSB

==> $g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$ at tree level

- Couplings to SM fermions proportional to fermion masses
- Self-coupling strength determined in terms of its mass and v = 174 GeV

A SM-like Higgs Boson:

Could be a mixture of CP even and CP odd states

Could have non-SM couplings to vector bosons and fermions

→ non-SM decay widths and production cross sections in many/all channels

Could have decays into new particles

Could be partly singlet or triplet instead of an $SU(2)_L$ doublet

Could be composite

Theory Part (cont'd)

Part II:

Properties and Nature of the newly discovered Particle beyond the SM framework - Effective Lagrangian Approach-

- Consider an effective Lagrangian approach with h.o. operators in the case of a light Higgs doublet (linear realization of the SU(2)L x U(1)Y electroweak symmetries at high energies) →L
- Give the constraints on the Wilson coefficients imposed by EW data and flavor physics
- Study the impact of the new operators on Higgs physical observables, in particular, identify which operators can probe the Higgs coupling strength to the new states

Chiral Lagrangian for a light Higgs-like scalar

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

$$- \left(m_W^2 W_\mu W_\mu + \frac{1}{2}m_Z^2 Z_\mu Z_\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi \frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right)$$

$$+ \frac{g^2}{16\pi^2}\left(c_{WW} W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ} Z^2_{\mu\nu} + c_{Z\gamma} Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$

$$+ \frac{g^2}{16\pi^2}\left[\gamma^2_{\mu\nu}\left(c_{\gamma\gamma}\frac{h}{v} + \ldots\right) + G^2_{\mu\nu}\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\right]$$

$$+ \ldots$$

In the SM

$a=b=c=d_3=d_4=1$

all the rest = 0

Contino et al '10

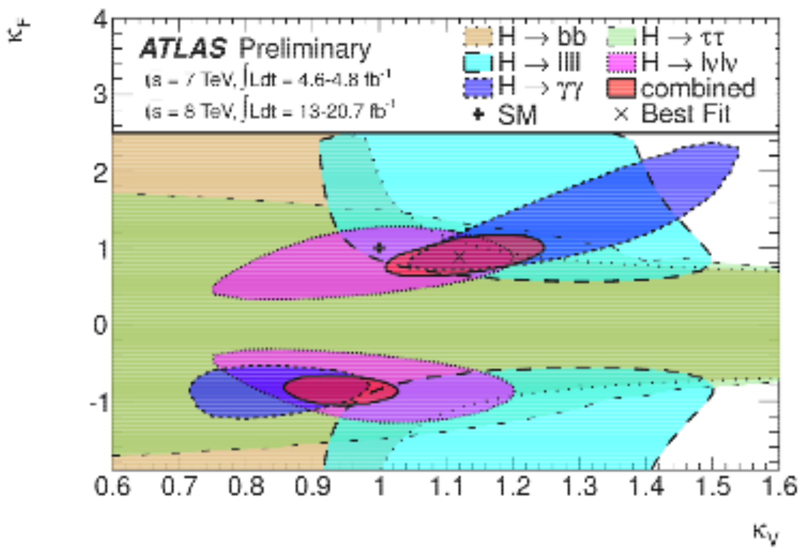
dimension 6 operators

linear realization of the $SU(2)_L \times U(1)_Y$ impose relations among coefficients

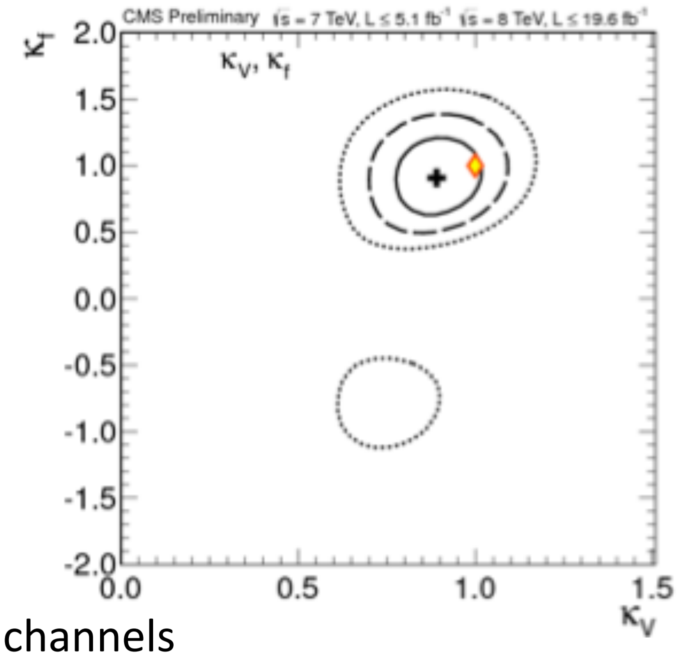
Many recent studies consider effective theory approaches and investigate the best fit to the data in a model independent way, but under certain assumptions

[Giardino, Kannike, Raidal, Strumia; Espinosa, Grojean, Muhlleitner, Trott; Carmi, Falkowski, Kuflik, Volansky, Zupan; Corbet, Eboli, Gonzalez-Fraile, Gonzalez Garcia; Montul, Riva; etc]

To Compare with Experimental fits to Fermion and Vector Couplings



non-zero and consistent with SM.



Vector coupling (κ_V) measured indirectly & directly in many channels

Fermion coupling (κ_F) measured:
-directly in H→bb and H→ττ – not well measured yet --
- indirectly via loop gg→H

EFA for a light Higgs doublet, **complete set up to Dim. 6 operators**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2}$$

It is possible to define 2 different bases of dim 6 operators

[Grzadkowski, Iskrzynski. Misiak and Rosiek or SILH; Giudice, Grojean,pomarol, Ratazzi]

Different groups have considered different bases, one can define relations among the bases

One base that includes the 59 independent operators:

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = & \frac{\bar{c}_H}{2v^2}\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}(H^\dagger H)^3 \\
& + \left(\left(\frac{\bar{c}_u}{v^2} y_u\, H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2} y_d\, H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2} y_l\, H^\dagger H\, \bar{L}_L H l_R\right) + h.c.\right) \\
& + \frac{i\bar{c}_W\, g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\, g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i\bar{c}_{HW}\, g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\, g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\, g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\, g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,
\end{aligned}$$

EFA for a light Higgs doublet, up to Dim. 6 operators (cont'd)

$$\Delta\mathcal{L}_{F_1} = \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$
$$+ \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}\left(\bar{d}_R\gamma^\mu d_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$+ \left(\frac{i\bar{c}_{Hud}}{v^2}\left(\bar{u}_R\gamma^\mu d_R\right)\left(H^{c\,\dagger} \overleftrightarrow{D}_\mu H\right) + h.c.\right)$$
$$+ \frac{i\bar{c}_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu L_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}\left(\bar{L}_L\gamma^\mu\sigma^i L_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)$$
$$+ \frac{i\bar{c}_{Hl}}{v^2}\left(\bar{l}_R\gamma^\mu l_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right),$$

$$\Delta\mathcal{L}_{F_2} = \frac{\bar{c}_{uB}\,g'}{m_W^2}\, y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\, y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\, y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{dB}\,g'}{m_W^2}\, y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\, y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\, y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu}$$
$$+ \frac{\bar{c}_{lB}\,g'}{m_W^2}\, y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\, y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.$$

Part II (cont'd)
Properties and Nature of the newly discovered Particle beyond the SM framework - Effective Lagrangian Approach-

- Consider the extended case with the general couplings of a spin-0 particle to the SM degrees of freedom (respecting Lorentz invariance and U(1) invariance) organized as an expansion in power of the momentum.
- Show formulae for signal strength normalized to the SM, in different production modes, $\mu_{ggH+ttH}$ & μ_{qqH+VH}, for a given Higgs decay, as a function of the couplings, to discuss the fits to the data (as performed by the experimentalists).
- Discuss CP determination and mention possible extensions of the chiral Lagrangian to other spin hypothesis
- Investigate precise bounds on invisible Higgs decays

Theory Part (cont'd)

Part III: Higgs Interpretation with specific BSM frameworks

- Example of specific models with a SM-like Higgs particle of mass 125 GeV
- Discussion of possible deviations from SM-couplings of the Higgs in various models
- Give brief description of the models under consideration to make the presentation of Higgs properties self contained
- **Coordinate** with BSM reviews to use same notation. Refer to them for definition of parameter space and relevant theoretical issues

This is challenging,

in the past the Higgs review was self-contained

but that will make it much longer

Part III: Higgs Interpretation within specific BSM frameworks

- 1) Supersymmetry

MSSM, NMSSM, extended Gauge sectors,…

** Requirements on parameter space to achieve mh= 125 GeV

**possible effects of light stops/sbottoms in gluon fusion Higgs production and Higgs to di-photon decays,

** effects of light staus/charginos in Higgs to di-photon decays

** effects of mixing in the Higgs sector affecting Hbb/ττ couplings and hence all BR's

** radiative effects on the 3rd generation Yukawa couplings

** invisible Higgs decays

Part III: cont'd

2) 2HDM's

** effects of mixing in the Higgs sector

3) Composite Higgs Models, models with vector-like fermions

** Effect in loop induced processes from the contribution of extra vector like fermions

** in composite H models, additional effect from mixing in the guage or scalar boson sectors

Discuss the interpretation of the signal to SM signal rate measurements in terms of models:

what do we learn about stop, staus, etc in susy?

what do we learn about top partners in Little Higgs models/ composite models…?

SUSY Example:
Given the Discovery of a Higgs-like particle with mass ~ 125 GeV

- Do we still expect SUSY (some type of low energy SUSY) ?
  - If yes, what does it imply for SUSY models?

large mixing in the stop sector

or

new matter or gauge superfields

Both alternatives have important implications
for the Higgs production and decay rates

They also have implications for the flavor-Higgs connection
within assumption of MFV at the SUSY breaking scale

DM constraints less strongly correlated since predictions depend strongly
on gaugino soft masses, not very relevant for Higgs rad. corrections.

- MSSM ==> Large stop mixing necessary ($A_t/M_Q \sim 1$) (figs.)
  No lower bound on lighter stop

Implications of light 3rd generation scalars on loop induced processes:

** light stops with the required mixing tend to slightly suppress gluon fusion

** light staus with sizeable mixing (large tan beta) may enhanced $\gamma\gamma$ up to 50 % with SM-like ZZ/WW ;

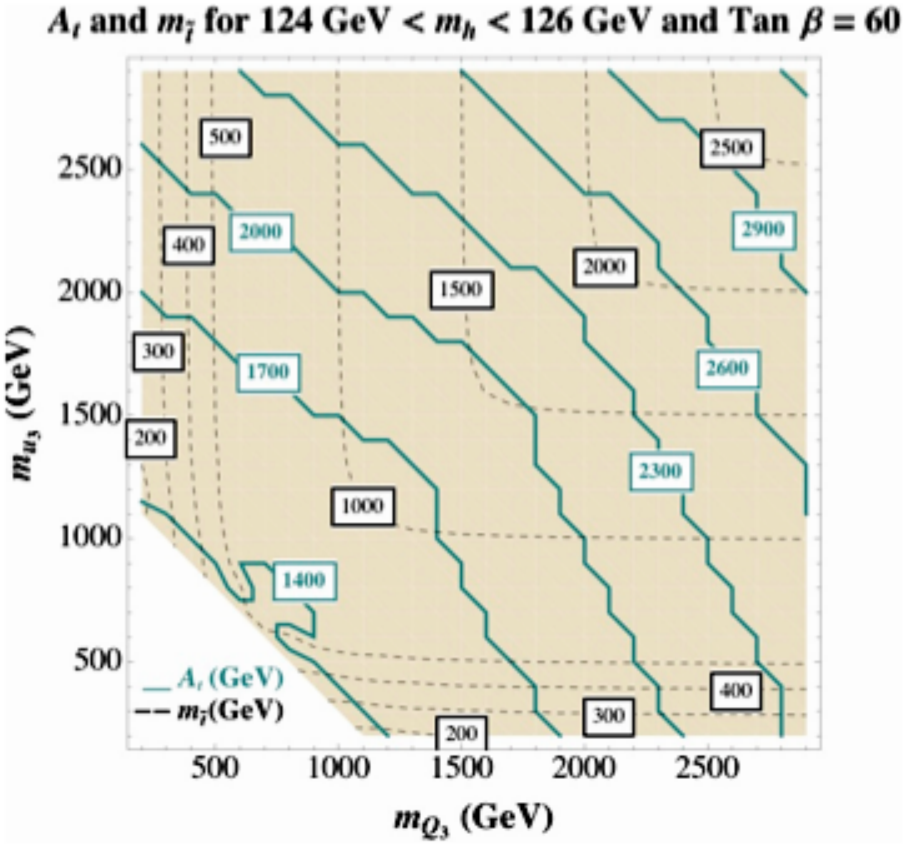
**possible variation on Higgs-bb/$\tau\tau$ couplings due to Higgs mixing (A_τ induced) can further enhance di-boson rates,

** additional radiative corrections to fermion-Higgs couplings can suppress $\tau\tau$/bb to Higgs couplings ratio (a few % in bb and 15-20 % in tau tau)

- **Large mixing also constrains SUSY breaking model building**

SUSY parameter Space

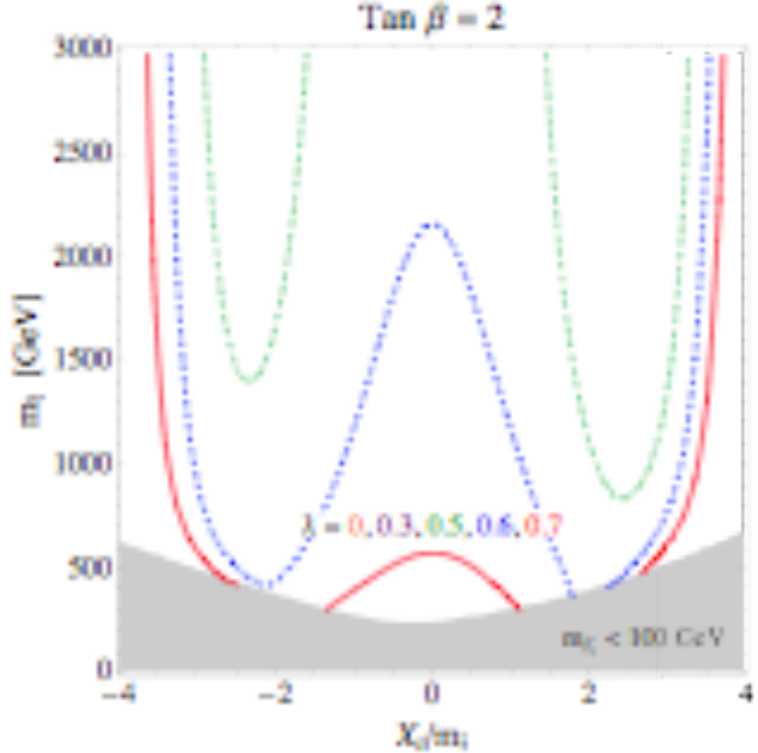
MSSM



M. C., S. Gori, N. Shah, C. Wagner ’11 +L.T.Wang ‘12

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon ’11Draper Meade, Reece, Shih’11

NMSSM



Hall, Pinner, Ruderman’11

Ellwanger. 12
Benbrik, Bock, Heinemeyer, Stal, Weiglein, Zeune’12
Gunion, Jiang, Kraml ’12

NMSSM :At low tan beta, trade requirement on large stop mixing by sizeable trilinear Higgs-Higgs singlet coupling $\lambda \longrightarrow$ more freedom on gluon fusion production

- **Higgs mixing effects can be also triggered by extra new parameter λ**
- Higgs-Singlet mixing ==> wide range of ZZ/WW and Diphoton rates
- Light staus cannot enhance the di-photon rate (at low tanβ stau mixing is negligible)
- Light chargino at low tanβ can contribute to enhance the di-photon rate

Extensions with extra gauge groups: 125 GeV Higgs mass from D terms plus chargino contribution to the quartic (plus usual top-stop)

Enhancement of γγ rate from new (strong) charginos (~60% max. to avoid too large Higgs mass)

Models with mixtures of singlets, W' Z', triplets:

Higgs mass = 125 GeV easy to achieve for light stops, **small mixing**
Enhancement of h to di-photons due to bb suppression or light staus
Higgs cascade decays from large splitting in masses : h/H to AA

Split SUSY: (no extra light scalars below 100-1000 TeV)
$\longrightarrow$ diphoton rate constrained to be about the SM value

Part IV: Searches for Additional Higgs Bosons

- Rare decays of the Higgs: h → μμ, cc, lepton flavor violating decays
- Second neutral CP even Higgs
- An additional CP odd Higgs
- Charged Higgs
- Defined some benchmark scenarios that may give us information about the SUSY spectrum through searches from additional Higgs bosons
- CP violation in the Higgs sector
- Additional singlets

The above addresses most of the suggestions/recommendations from the PDG Advisory Committee

- Rewrite the review in a substantial way with the "final" results from ATLAS and CMS from the 7 and 8 TeV runs, with focus on SM Higgs
- Take the Higgs Review out from the category Hypothetical Particles and Concepts.
- Experiment: Re-organize the review to include:

  A summary of the status before July 4 (a condensation of the present section)

  Detail of the data that has subsequently been collected
- Theory

  Change focus to reflect the transition to a precision measurement era.

  Consider a model-independent interpretation of data to parameterize both the tree-level structure of the theory and the loop-induced effects, to provide a guide for future measurements

Suggestions/recommendatios of the PDG AC to be discussed

- *The discussion of possible alternative interpretations and searches for beyond SM Higgs particles could appear in the reviews covering beyond the standard model processes.*

  We consider that the review will not be self contained and useful for the community without including a discussion of Higgs Physics in alternative interpretations, as well as Higgs searches BSM

- The committee recommends that the PDG *formalize* its collaboration with the developing LHC averaging working groups.

We intend to strengthen the contact with the LHC averaging working groups