Introduction to Higgs Physics (3rd Lesson)

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Escuela de FisicaFundamental, Xalapa, 2016

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•July 4th 2012
•The discovery of a new particle
International Herald Tribune
The New York Times
A giant leap for science
The Gazette
EL PAIS
Science : la matière dévoilée
Milhares de moradores de bairros sociais em risco de perderem RSI
ALGEMEEN DAGBLAD
Frankfurter Allgemeine
CHINA DAILY
THE TIMES OF INDIA
THE HINDU
Elusive particle found, looks like Higgs boson
CORRIERE DELLA SERA
La particella che può svelare i segreti dell'universo
gazeta
BOSKA MASA
বিজ্ঞানের 'ঈশ্বর' দর্শন

Then what?

What is the nature of EWSB?

Questions:

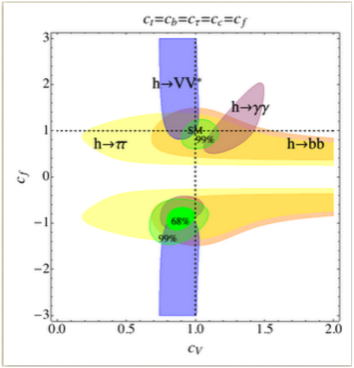
1. Is there only one Higgs doublet that generates the masses of all particles?
2. Will we be able to test Higgs couplings with light fermions?
3. Are the Higgs couplings diagonal in flavor space?
4. Why W-mass << Planck mass? ((Hierarchy problem))

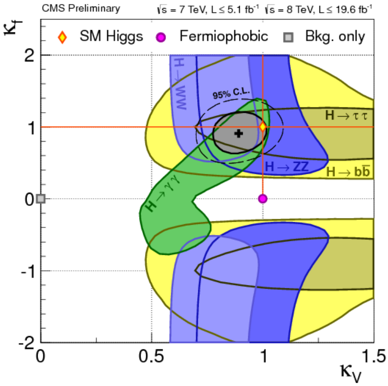
Possible Answers:

- Strongly Interacting -Higgsless world - DECEASED!
- Strongly Interacting - Composite Higgs - pNGB,
- Weakly interacting- SM valid up to Planck Scale,
- Weakly interacting- Multi-Higgs model (SUSY, THDM, etc),

Higgs identity: $g_{hXX} = c_X \, g^{sm}_{hXX}$

In the SM: $c_X = 1$,





The Universal Higgs fit - P. Giardino et al., arXiv:1303.3570 [hep-ph]

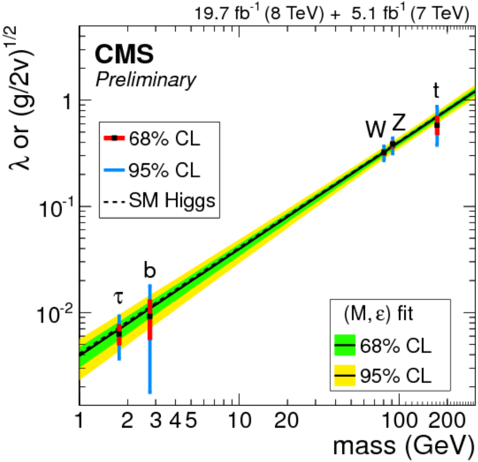
Under the small deviations approximation:

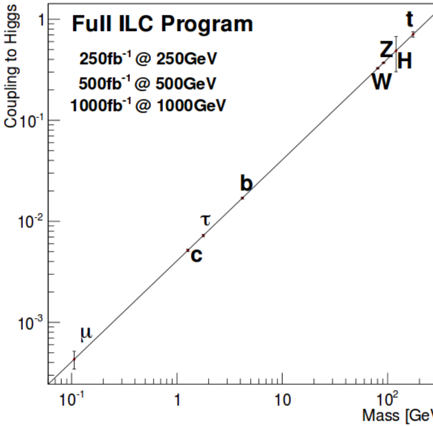
$$c_X = (1 + \epsilon_X) \tag{1}$$

From a fit to all observables (signal strengths), and assuming no new particles contribute to the loop decays hgg and $h\gamma\gamma$, they get:

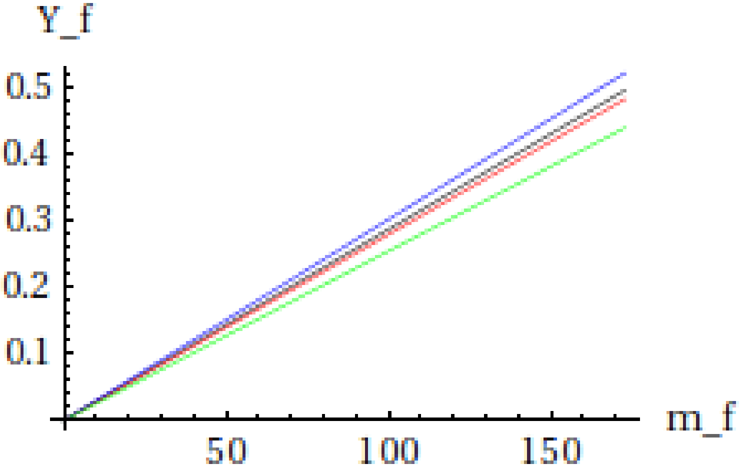
- hZZ (hWW): $\epsilon_Z = -0.01 \pm 0.13$ $(\epsilon_W = -0.15 \pm 0.14)$,
- hbb: $\epsilon_b = -0.19 \pm 0.3$,
- $h\tau\tau$: $\epsilon_\tau = 0 \pm 0.18$
- htt (from hgg): $\epsilon_t = -0.21 \pm 0.23$

SM Higgs identity: $g_{hXX}^{sm} = \frac{M_X}{v}$

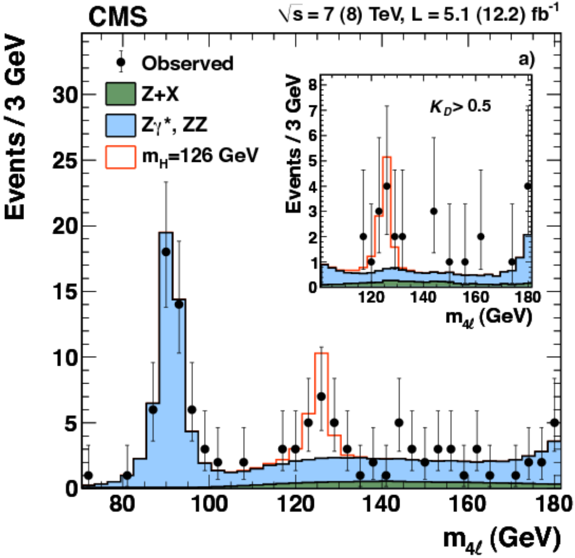




Higgs Couplings in 3+1 HDM



Higgs parity: $h\bar{f}f$ or $h\bar{f}\gamma_5 f$?



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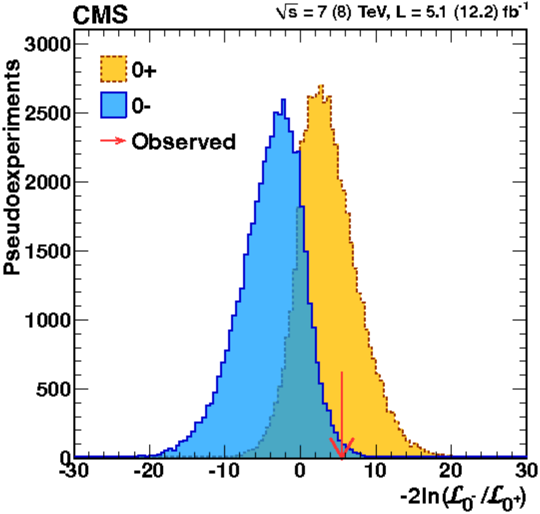


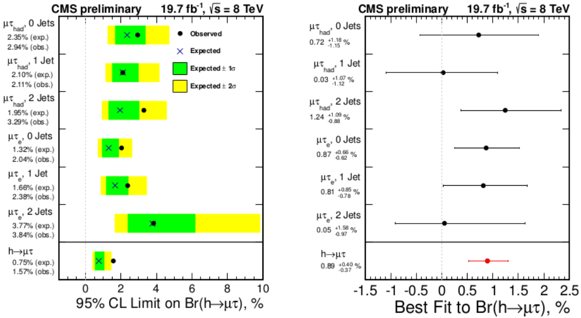
Higgs and Flavor Violation

Only FC Higgs couplings ($h\bar{f}f$) or also possible FV ($h\bar{f}_i f_j$)?, ex. $h \to \tau\mu$ (Diaz-Cruz and collab.),

Contact: cms-pag-conveners-higgs@cern.ch 2014/07/05

Search for lepton flavor violating decays of the Higgs boson

The CMS Collaboration



The Hierachy problem

When an scalar interacts with a heavy fermion M, with $L_Y = y\bar{\Psi}\Psi\phi$, and UV cutoff Λ, the scalar mass gest corrected, i.e.

$$m_h^2 = m_0^2 + \frac{y^2}{16\pi^2}[c_1\Lambda^2 + c_2 m_0^2 ln\frac{\Lambda}{m} + M^2] \quad (2)$$

The problem: $m_h = 125 - 126$ GeV but since $\Lambda >> O(1)$ TeV, need a large cancellation.

Some solutions:

- Composite Higgs (as in QCD!),
- Higgs is part of $D - dim$ vector field: $A_M = (A_\mu, A_i)$,
- Cancelation between boson-fermion loops ($\rightarrow$ SUSY),
- Accidental cancelacion (Veltman's condition):

$$\lambda = y_t^2 - \frac{1}{8}[3g^2 + g'^2] \quad (3)$$

NO LONGER WORKS!...at the EW scale ($\rightarrow m_h \simeq 200$ GeV,)

....BUT WHAT ABOUT AT M_{pl}?

Other problems in the SM

- Large/Little hierarchy problem,
- Neutrino masses and flavor problem,
- Strong CP problem,
- Dark Matter,
- Cosmological constant (Dark energy),
- Some deviations from the SM (a few std. dev.), e.g. Δa_μ, etc.
- Aesthetical questions,

They all suggest the need for New Physics.

Beyond the SM

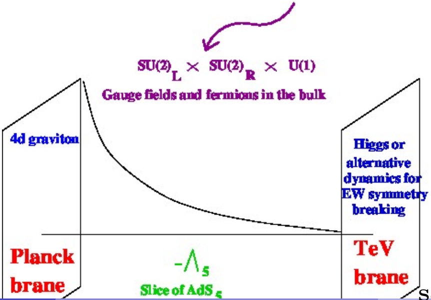
- Models with new fermions (4ta family, etc)
- Models with new gauge forces ($U(1)'$, Left-Right, ..)
- Models with extra Higgs multiplets (2HDM, triplets,..)
- Models with Grand Unification (ex. $SU(5), SO(10), E_6$,..)
- Models with new symmetries (SUSY),
- Models with extra dimensions extra.
- etc.

A modern view of Physics BSM

Physics BSM incorporates Extra Dimensions,

- Fermionic XD-
  $x^\mu \to Z^M = (x^\mu, Q, \bar{Q})$: Supersymmetry
- Bosonic XD-
  $x^\mu \to X^M = (X^\mu, X^i)$: Large Extra Dimensions,
- Curved XD -
  $x^\mu \to X^M = (X^\mu, X^i)$: Randall-Sundrum

AdS/CFT duality means XD $\to$ Strong Ints.

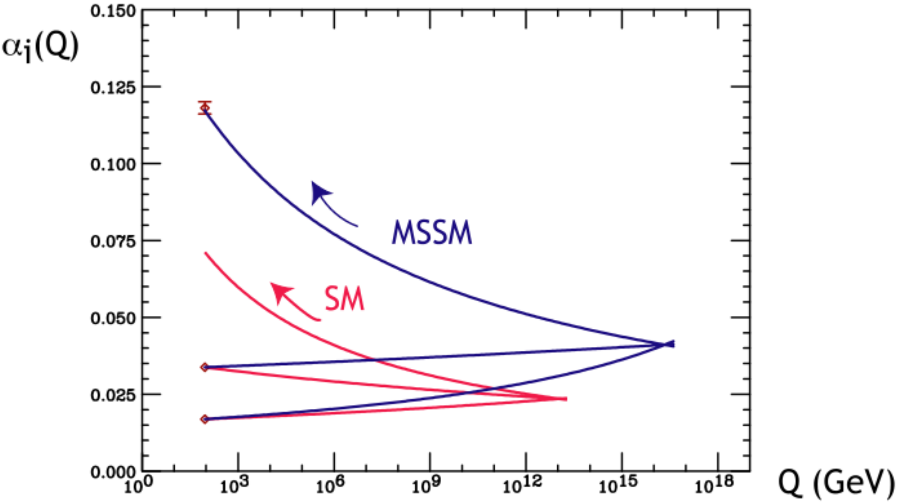


Supersymmetry (SUSY)

Why is SUSY attractive? It is a new symmetry that relates fermions and bosons,

- Offers the possibility to stabilize the Higgs mass and EWSB,
- Improves Unification and o.k. with proton decay,
- Favors a light Higgs boson, in agreement with EWPT (and LHC?), i.e. $m_h \leq 160$ GeV,
- New sources of flavor and CP violation may help to get the right BAU,
- LSP is stable and a possible Dark matter candidate.

Gauge Coupling Unification



The MSSM

The minimal extension of the SM consistent with SUSY, is based on:

- SM Gauge Group ($\rightarrow$ gauge bosons and gauginos),
- 3 families of fermions and sfermions,
- Two Higgs doublets (H_u and H_d),
- Soft-breaking of SUSY (Hidden sector),
- R-parity distinguish SM and their superpartners
  $\rightarrow$ LSP is stable and DM candidate.

The MSSM particle content

	SM	Superpartners
SM Bosons	$W^{\pm}, Z, \gamma$ gluon Higgs bosons	Wino,Zino, Photino gluino Higgsinos
SM Fermions	quarks leptons neutrinos	squarks sleptons sneutrinos

Mixing of gauginos and Higgsinos $\rightarrow$
Charginos ($\chi_i^{\pm}$, $i = 1, 2$) and Neutralinos (χ_j^0, $j = 1, 4$),

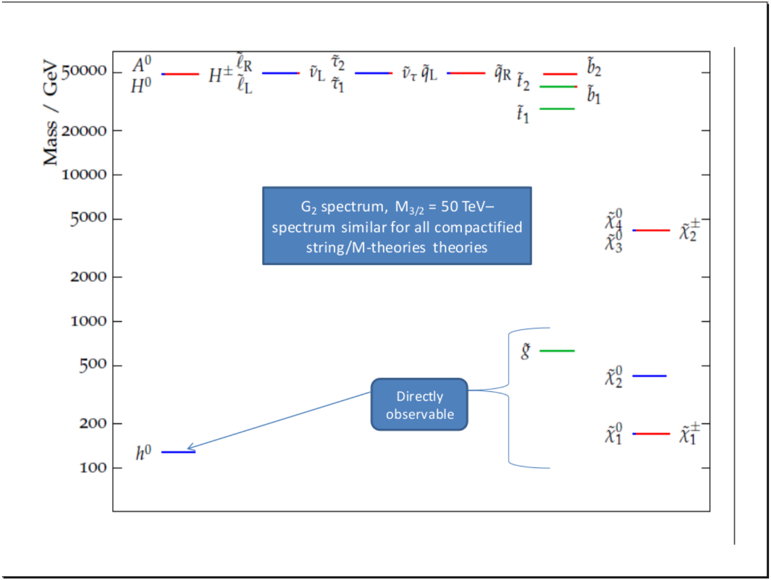
Gravitino is also part of the spectrum.

The parameters of the MSSM

In addition to SM parameters, the MSSM includes O(100) new ones:

- Scalar masses (Sleptons, squarks, Higgs),
- Gaugino masses $(\tilde{M}_G, \tilde{M}_W, \tilde{M}_B)$,
- Trilinear terms ($A_{\tilde{f}}$ for squarks and sleptons),
- From Higgs sector: $\tan\beta = v_2/v_1$ and μ,
- The masses of superpartners have important implications for EWSB,
- Spectrum of superpartners depends on mechanism of SUSY breaking,

Susy Spectrum



MSSM Higgs Potential

At tree-level MSSM Higgs sector is a 2HDM of type-II, i.e. it contains two Higgs doublets, with Potential:

Lagrangian. The F terms contriubute

$$V_F = \mu^2(H_u^{0*}H_u^0 + H_d^{0*}H_d^0)$$

The D terms contribute

$$V_D = \frac{g^2 + g'^2}{8}(H_u^{0*}H_u^0 - H_d^{0*}H_d^0)^2$$

The soft SUSY breaking terms contribute

$$V_{soft} = M_{Hu}^2 H_u^{0*}H_u^0 + M_{Hd}^2 H_d^{0*}H_d^0 - (B\mu H_u^0 H_d^0 + h.c.)$$

The MSSM Higgs spectrum

- CP-even neutral Higgs bosons h^0, H^0, at tree-level $m_h < m_Z$,
- CP-odd neutral Higgs A^0 with $m_H^2 = m_A^2 + m_Z^2 \sin^2 2\beta$,
- Charged Higgs $H^\pm$, with $m_{H^+}^2 = m_A^2 + m_W^2$,
- Masses and mixing angles fixed with: m_A and $tan\beta = v_2/v_1$,
- When $m_A \leq \tilde{m}$, Higgs search uses SM techniques.
- But $H^0, A^0, H^\pm$ may decay into SUSY modes; LHC search gets more complicated!,

The MSSM Higgs mass

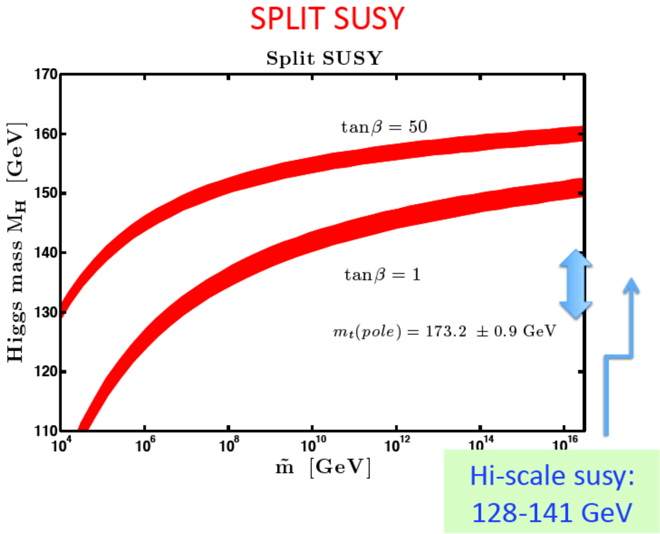
Radiative effects of Stop-top loops can make: $m_h > m_Z$

$$m_h^2 = m_Z^2[1 + \frac{3m_t^2}{2\pi^2 m_Z^2} log(\frac{m_{stop}}{m_t})] \quad (4)$$

But to get $m_h = 125$ GeV, with SM-like couplings, need:

- Large superpartner masses O(1) TeV,
- Only a few superpartners could be at the reach of LHC,
- Split SUSY? High Scale SUSY?
- O(1) or large $tan\beta$ allowed,
- Large $tan\beta \rightarrow$ enhanced production of $H + bb$ at LHC,

MSSM Higgs mass (Giudice and Strumia)

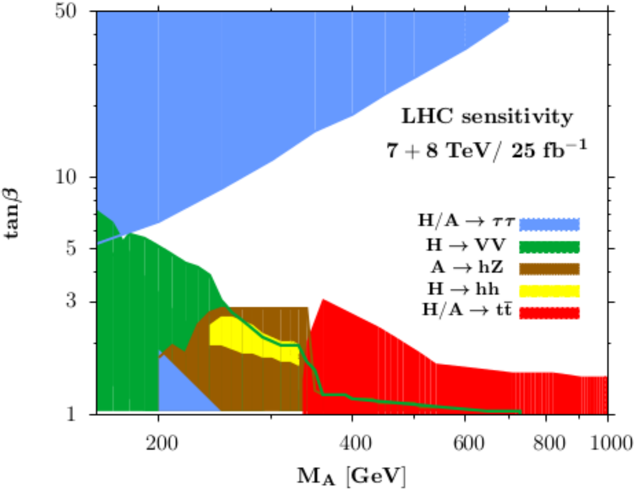


MSSM Higgs couplings:

- $(hVV):\quad \frac{2m_V^2}{v}\cos(\beta-\alpha),\quad v^2 = v_1^2 + v_2^2,$
- $(huu):\quad \frac{m_u}{v}(\frac{\cos\alpha}{\sin\beta}),$
- $(hdd):\quad \frac{m_d}{v}(\frac{\sin\alpha}{\cos\beta}),$
- $(hll):\quad \frac{m_l}{v}(\frac{\sin\alpha}{\cos\beta}),$
- $(hhh):\quad \simeq \lambda v,\quad \lambda = \frac{g^2+g'^2}{8},$
- $(hhhh):\quad \simeq \lambda.$

Similar expressions hold for H^0, A^0 and $H^{\pm}$.

Heavy Higgses at LHC

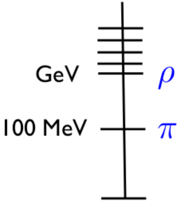


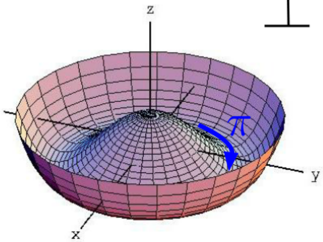
Composite Higgs (A. Pomarol, ICHEP12)

Composite PGB Higgs

Inspired by QCD where one observes
that the (pseudo) scalars are the lightest states

Spectrum:





Are Pseudo-Goldstone
bosons (PGB)

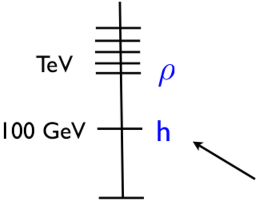
Mass protected by the
global QCD symmetry!

$$\pi \longrightarrow \pi + \alpha$$

Composite Higgs (A. Pomarol, ICHEP12)

The light Higgs can be a kind of pion from a new strong sector

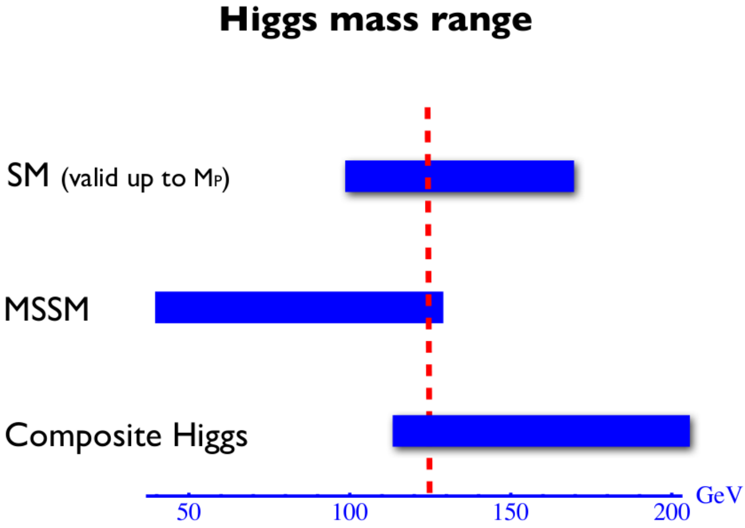
The spectrum of the new strong sector could be:



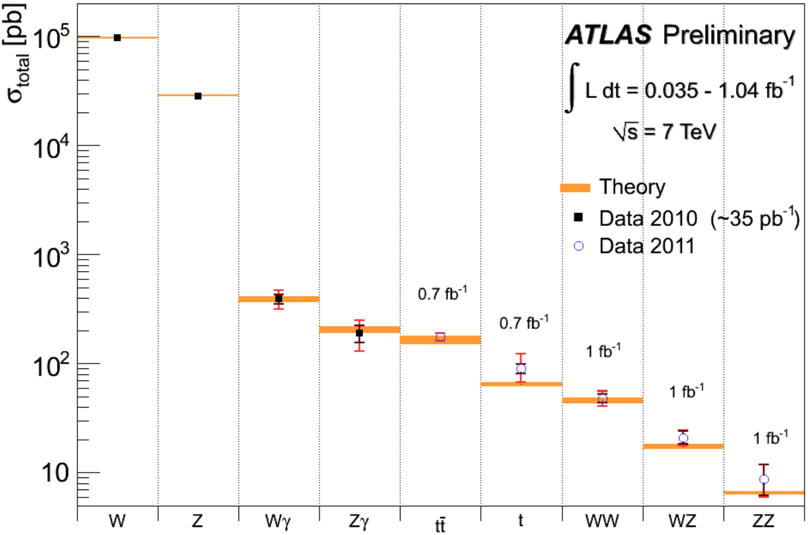
Pseudo-Goldstone bosons (PGB)

Mass protected by the global symmetries!

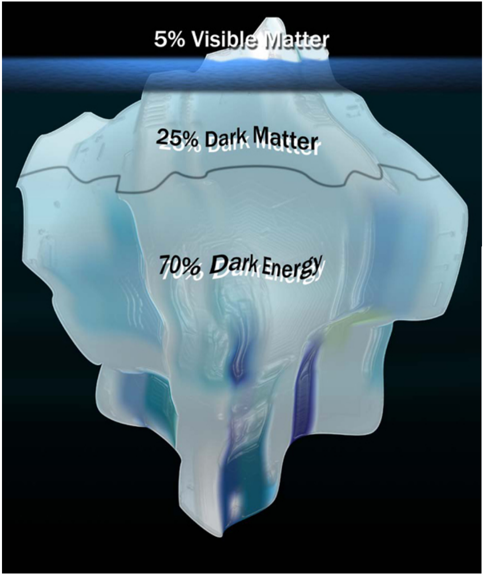
Higgs mass and new physics (A. Pomarol, ICHEP12)

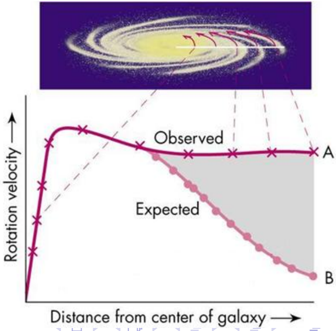


LHC tests of the SM:



Implications for Dark Matter





MSSM Higgs and Dark matter

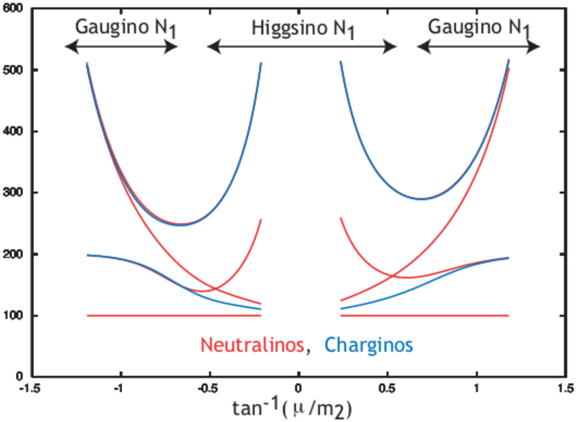
For heavy sfermions the DM relic density is:

$$\Omega_X h^2 = C_X (\frac{m_X}{TeV})^2 \tag{5}$$

- For DM $X =$ pure Bino, no aceptable solution,
- For DM $X = \tilde{H}$ pure Higgsino, $C_{\tilde{H}} = 0.09$ and an aceptable solution is obtained for $1 < M_{\tilde{H}} < 1.2$ TeV,
- For DM $X = \tilde{W}$ pure Wino, $C_{\tilde{H}} = 0.02$ and an aceptable solution is otained for $2 < M_{\tilde{W}} < 2.5$ TeV,

In such case detection at LHC may be harder,

LSP Composition



Holographic Dark matter

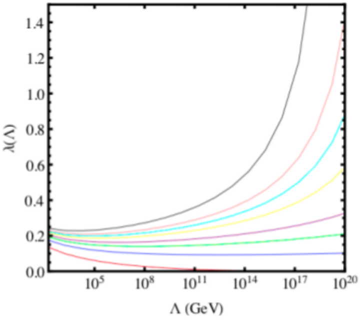
- Composite Higgs can have a ”baryon” partner,
- This composite state can be (Holographic) Dark matter (J.L. Diaz-Cruz, PRL81, 2008),
- Deviations from SM Higgs properties can show evidence of dark matter,

The Higgs and the roots of Physics

Was it premature to rule our Veltman condition?

A special Value of λ at M_{planck} ?

ML '86



downward flow of RG trajectories

➔ IR QFP ➔ random λ flows to $m_H > 150$ GeV

➔ $m_H \simeq 126$ GeV flows to tiny values at M_{Planck}…

Holthausen, ML Lim (2011)

Different conceivable special conditions:

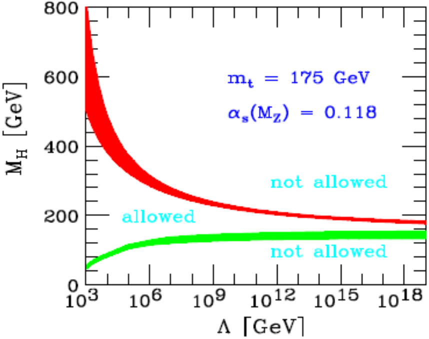
- Vacuum stability
  $\lambda(M_{pl}) = 0$ [7–12]
- vanishing of the beta function of λ
  $\beta_\lambda(M_{pl}) = 0$ [9, 10]
- the Veltman condition [13–15] $\mathrm{Str}\mathcal{M}^2 = 0$,

$$\delta m^2 = \frac{\Lambda^2}{32\pi^2 v^2}\mathrm{Str}\mathcal{M}^2$$
$$= \frac{1}{32\pi^2}\left(\frac{9}{4}g_2^2 + \frac{3}{4}g_1^2 + 6\lambda - 6\lambda_t^2\right)\Lambda^2$$

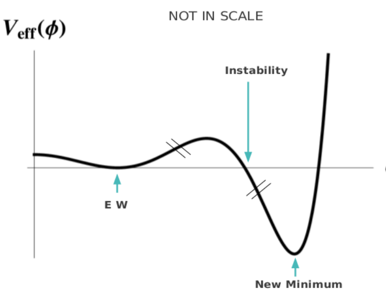
- vanishing anomalous dimension of the Higgs mass parameter
  $\gamma_m(M_{pl}) = 0,\ m(M_{pl}) \neq 0$

M. Lindner, MPIK | SCALARS 2013, Warsaw | 8

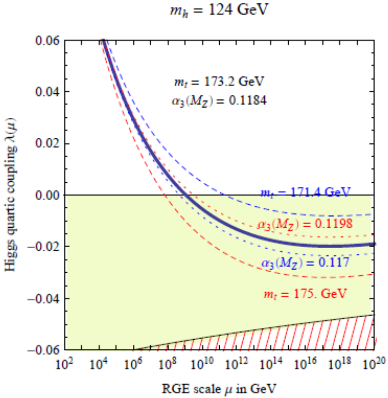
Hows does the Higgs potentail looks at higher energies?



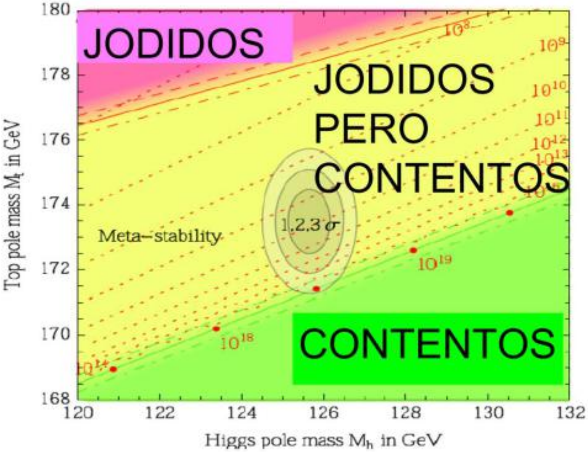
RG Improved Effective Potential $V_{eff}(\phi$



From JR Espinosa et al.



Higgs mood


JODIDOS
JODIDOS
PERO
CONTENTOS
CONTENTOS
Meta–stability
1,2,3 σ
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{18}
10^{19}
180
178
176
174
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170
168
120
122
124
126
128
130
132
Top pole mass M_t in GeV
Higgs pole mass M_h in GeV

Why I believed in the Higgs and BSM

Is the Higgs something natural? I would say, yes.

Spin and Isospin:

T / S	0	1/2	1	3/2	2
0	?	Neutrinos-R	gluon	?	?
1/2	Higgs	electron quarks	?	?	?
1	?	?	W, Z	?	?

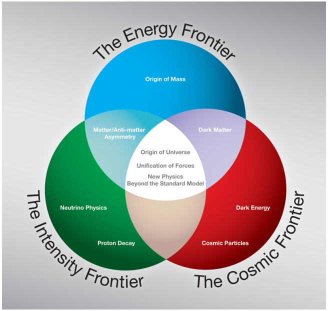
$$Q_{em} = T_3 + Y \tag{6}$$

(Where have all the large representations gone?)

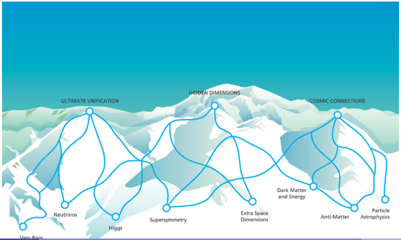
Conclusions.

- LHC is already giving great results,
- Evidence for a SM-like Higgs with $m_h = 125$ GeV,
- No evidence at LHC, so far, of new phyics,
- Still possible to find evidence of Dark matter,
- Tests of Higgs couplings at LHC could show deviations from SM (3+1 HDM),
- FCNC decays of Higgs/top could also provide another window into PBSM,
- If no signal of BSM physics shows up at LHC, then what? Super-split SUSY

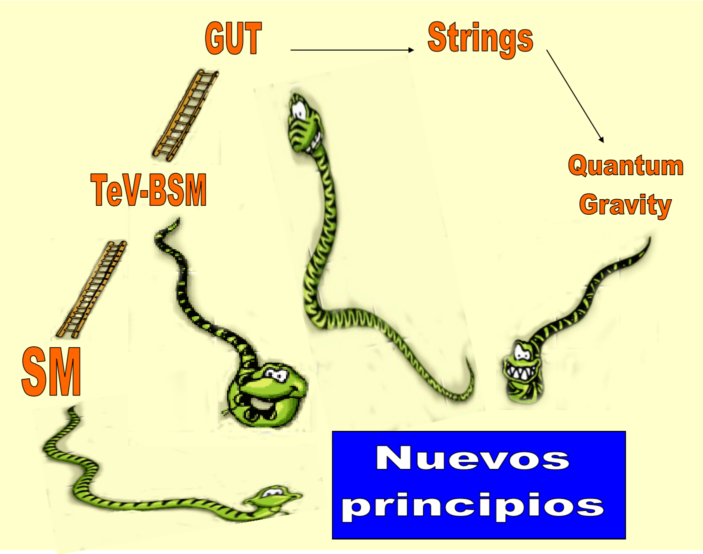
Fronteras del micro y macro cosmos



Ademas, podemos agregar una ”Frontera Conceptual” (JLDC),



"This could be heave or this could be hell .."



Interesting times!