Implication of Higgs Discovery

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Triggering Discoveries in High Energy Physics
9-14th September, 2013
University of Jammu, Jammu

Outline

- ❑ Higgs at the LHC
- ❑ Implication in SM
- ❑ Higgs and New Physics
- ❑ Conclusion

Higgs

The SM SU(2) X U(1) gauge theory unified electroweak interaction, but could not accommodate masses of particles,

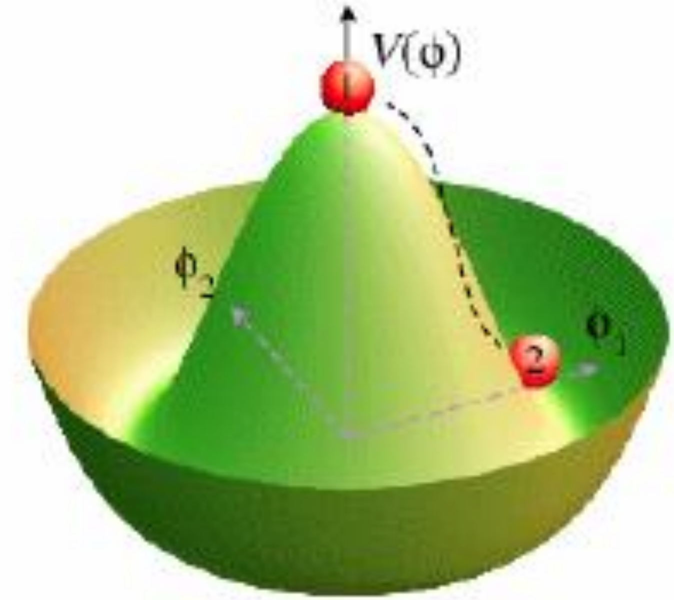
$$\Phi = \begin{pmatrix} \Phi^{+} \\ \Phi^{0} \end{pmatrix}$$

Brout, Englert, Higgs, ‘64
Guralnik, Hagen ,’64

$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2 \Phi^2 - \lambda \Phi^4,$$

$$< 0 | \phi | 0 > \neq 0$$

$$v = (-\mu^2 / \lambda)^{1/2}$$ **=246 GeV**



Vaccuum is not symmetric under SU(2)X U(1)

Yukawa coupling, fermion masses, same scalar field

$$\mathcal{L}_{\mathrm{Yuk}} = -\mathrm{f_e} (\bar{\mathrm{e}}, \bar{\nu})_{\mathrm{L}} \Phi \mathrm{e_R} + \ldots$$

SM predictions: Higgs Properties

Higgs Mechanism

↓

Three d.o.f for → $M_{W^{\pm}}, M_Z$

Residual degrees of freedom corresponds to spin-0 particle : Higgs

Higgs: A scalar particle with $J^{PC} = 0^{++}$

Higgs couplings: $g_{Hff} = \frac{m_f}{v}; \; g_{HVV} = 2\frac{M_V^2}{v}$

$M_H^2 = 2\lambda v^2$ **Not predictable!!**

Self Couplings: $g_{HHH} = 3\frac{M_H^2}{v}$ $\quad g_{HHHH} = 3\frac{M_H^2}{v^2}$

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

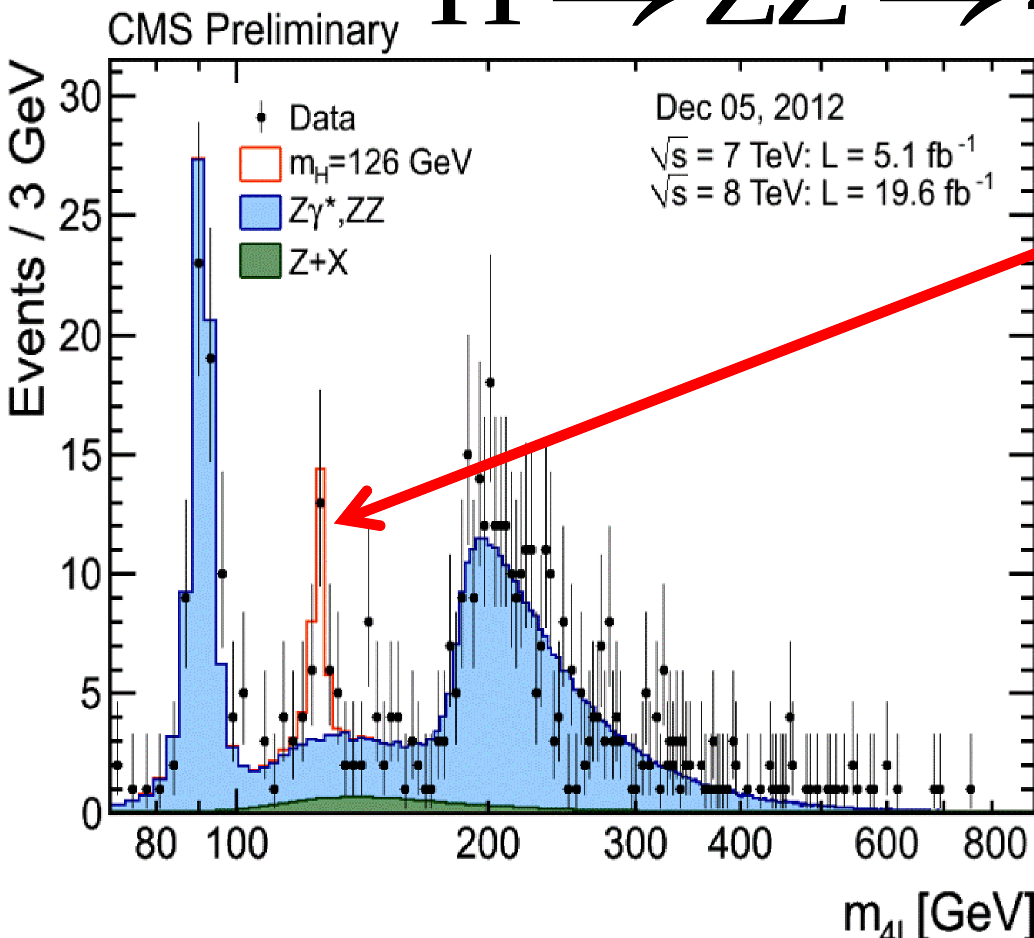
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

At last …

Prediction for 50 years, 25 years searching

A Higgs at the LHC

$$H \rightarrow ZZ \rightarrow 4\ell$$



Signal observed above the background about 4.7σ level

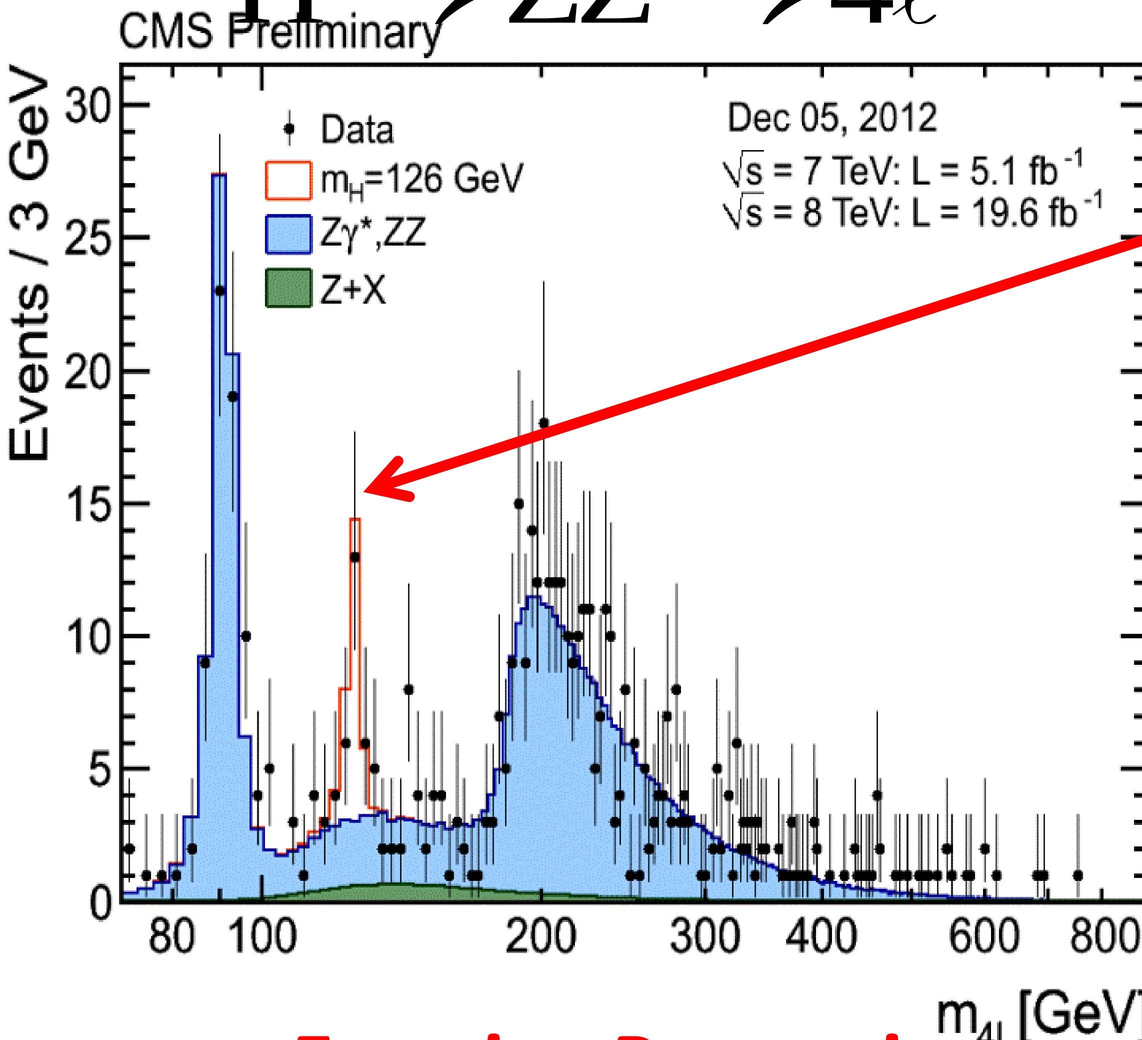
Talk by S. Banerjee, P. Thompson

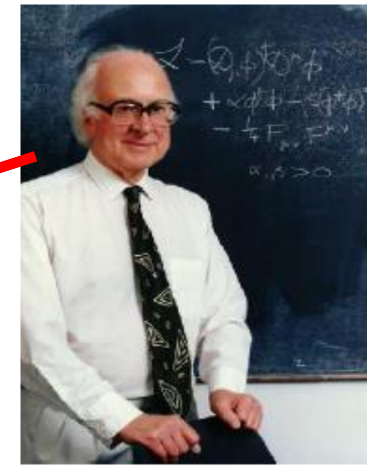
ATLAS: $m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)$

CMS : $m_H = 125.7 \pm 0.3(stat) \pm 0.3(syst)$

Is it..

$$H \to ZZ \to 4\ell$$

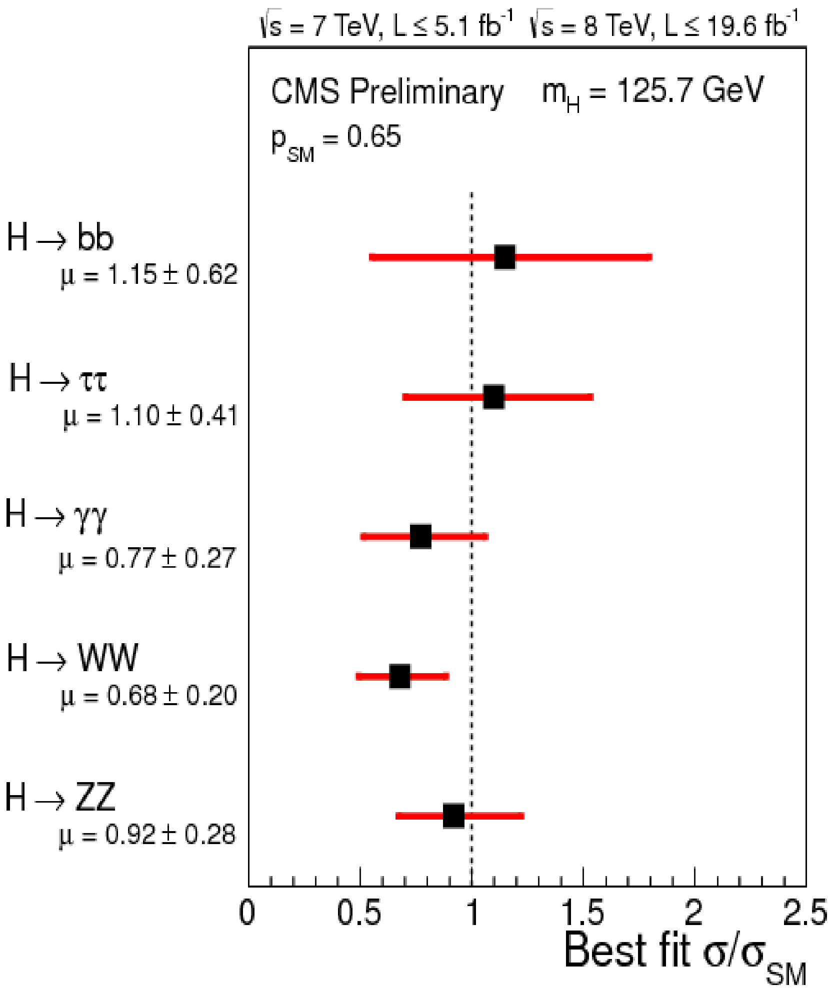


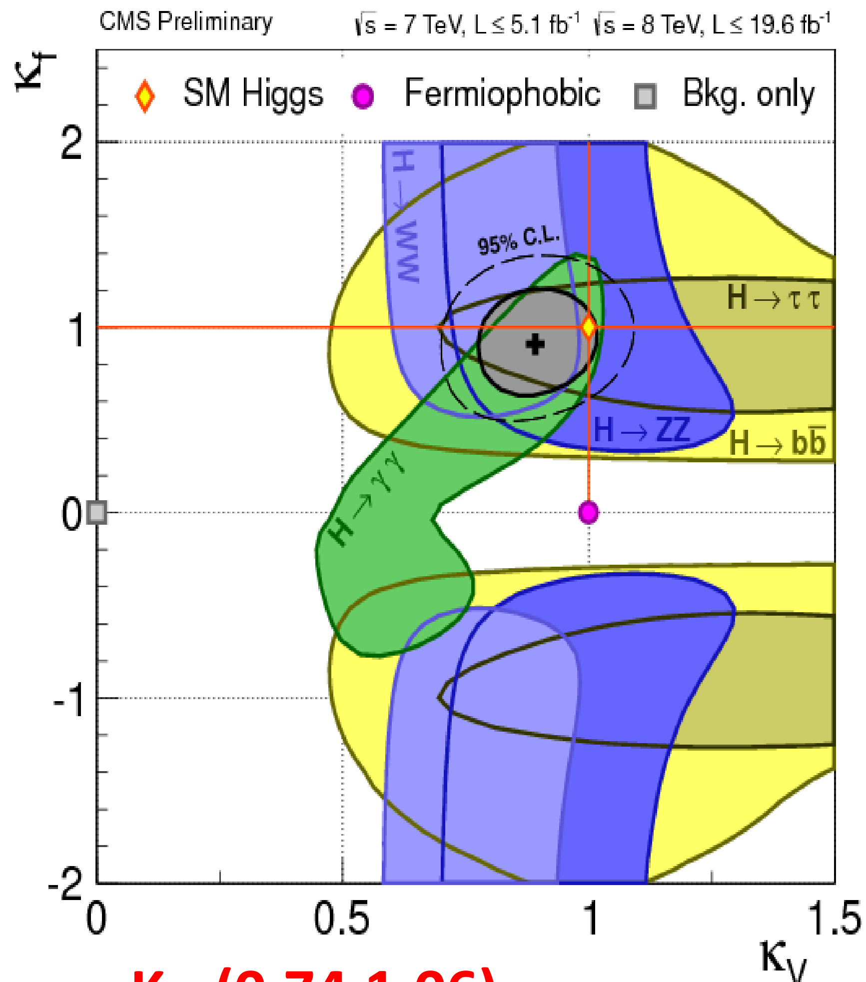


Examine Properties

Higgs Properties at the LHC

$$\mu_i = \frac{[\sigma_{j\to h} \times Br(h \to i)]_{observed}}{[\sigma_{j\to h} \times Br(h \to i)]}$$



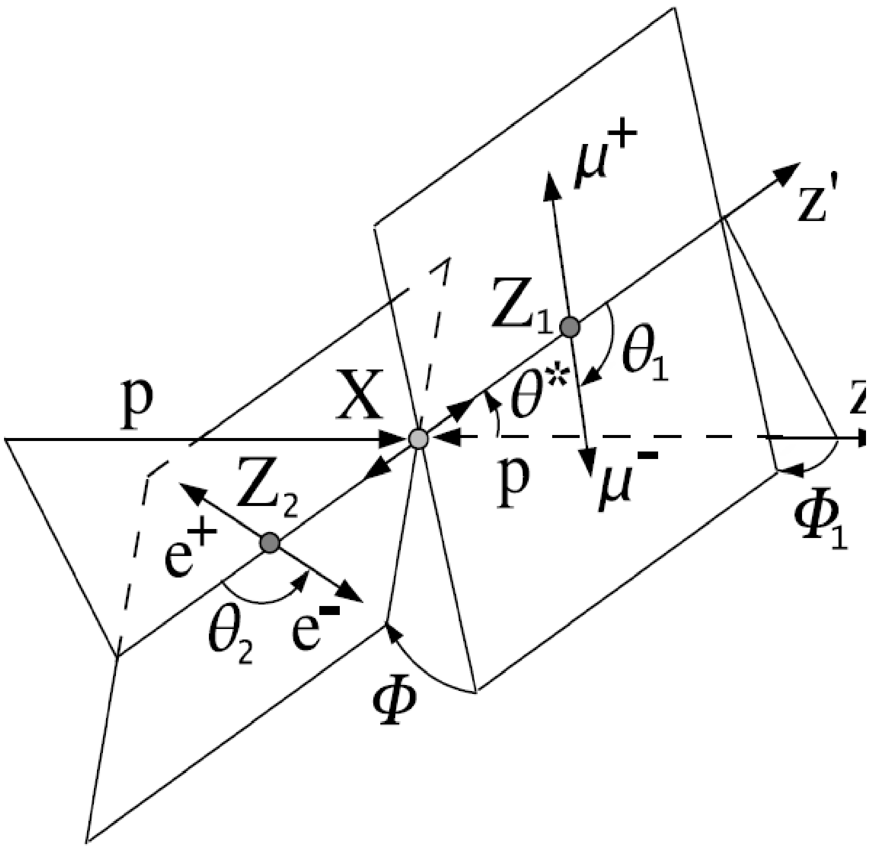


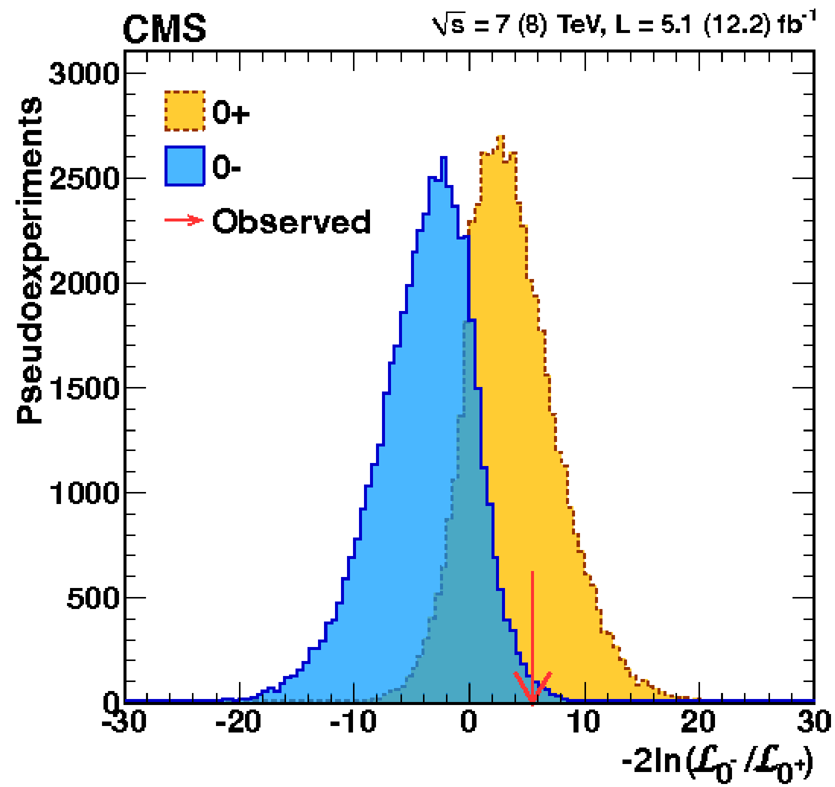
$\mu = 0.80 \pm 0.14$

$K_V = (0.74, 1.06)$

$K_f = (0.61, 1.36)$

Spin





0^+ hypotheses is favored very much over 0^-

What it is?

- ❑Couplings to WW, ZZ and γγ are as expected in SM.
- ❑ Couplings are proportional to Masses as predicted by Higgs mechanism.

Hence, it is

“ a new particle”, “a 126 GeV Boson”, ”new state”…

But it is a Higgs Boson

Is it “the SM Higgs Boson” or “a Higgs boson” from some other model..or something else..

…it may be

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

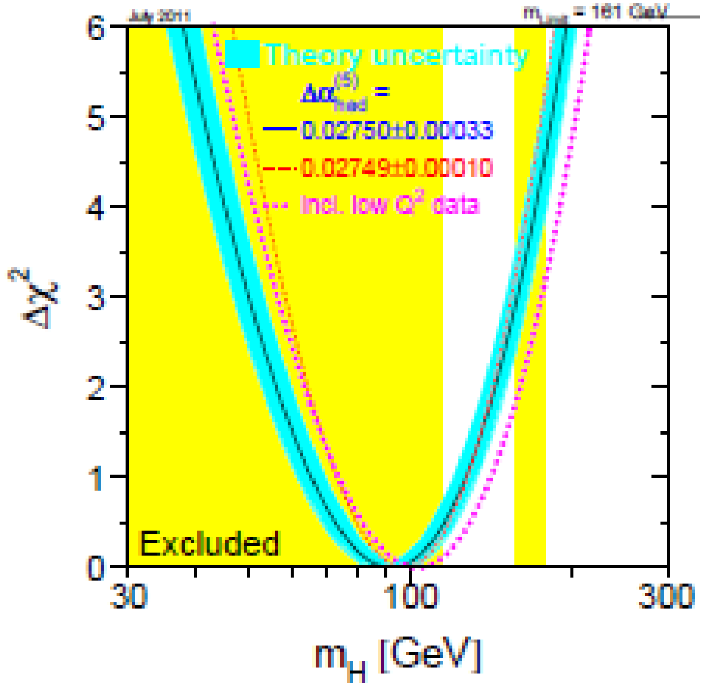
Cone Higgs

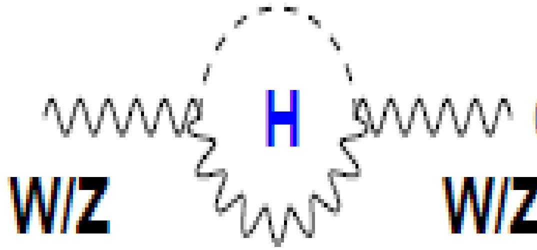
Simplest Higgs

Phantom Higgs

Implications in the SM

Implication: SM



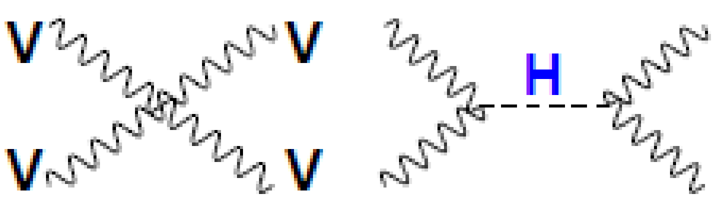


$$\propto \frac{\alpha}{\pi} \log \frac{M_H}{M_W} + \cdots$$

$$M_H = 92^{+34}_{-26}$$ **GeV @ 95% C.L**

$$M_H \leq 156$$ **GeV @ 95% C.L**

Very good consistency check



The theory holds Unitarity,

$$M_H \leq 870$$ **GeV**

Extrapolate SM to High scales

- **Is this the value of Higgs mass 125-126 GeV allows to extrapolate SM up to Planck scales keeping Higgs potential at an absolute electroweak minimum ?**

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda(\phi^+\phi)^2$$

- **Before Higgs discovery ground state was known: v=246 GeV**

- **After the Higgs discovery,**

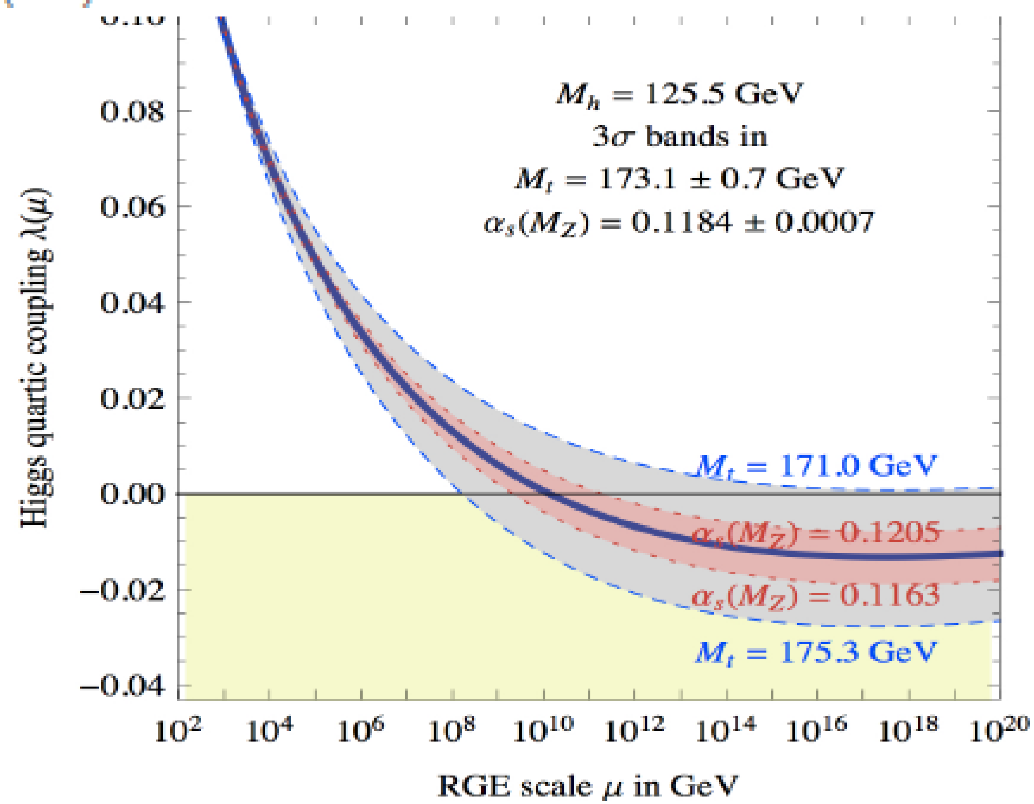
$$\lambda_{tree} = \frac{M_H^2}{2v^2} \approx 0.13 \qquad \mu^2 = \frac{M_H^2}{2}$$

Higgs Potential: Vacuum Stability

$$\lambda(\mu) = \frac{G_\mu M_H^2}{\sqrt{2}} + \Delta\lambda(\mu)$$

$$\frac{\lambda(Q^2)}{\lambda(v^2)} \approx 1 + 3\frac{2M_W^4 + M_Z^4 - 4m_t^4}{16\pi^2 v^4}\log\frac{Q^2}{v^2}$$

NLO level



$$\Delta M_H = \pm 2\,\text{GeV}$$

Vacuum stability requires,

$$\lambda_p \geq 0$$

Degrassi et .al '12

Vacuum Stability and Higgs Mass

$$\lambda_p \geq 0$$

Degrassi et .al '12

$$M_h\ [\mathrm{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

Combining in quadrature the theoretical uncertainty with the experimental errors in m_t and α_S

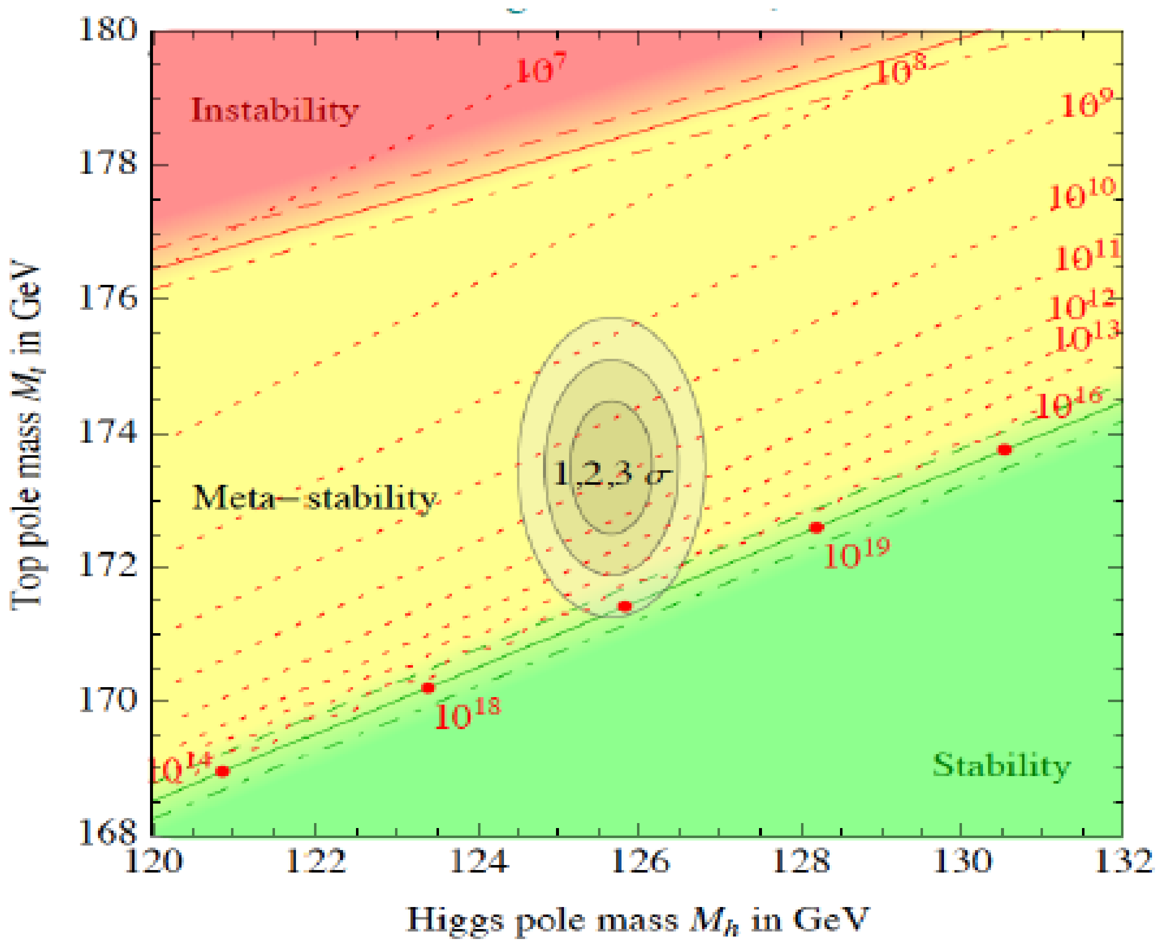
$M_H > 129.4 \pm 1.8$ GeV

The vacuum stability of the SM up to Planck scale is excluded at 2σ $M_H < 126$ GeV

Need to measure the top quark mass very precisely, may be final answer can be obtained from ILC.

Djouadi et .al '12

Stability and Higgs Mass



To understand stability, in absence of any new physics, requires very precise determination of top quark and Higgs mass.

Is SM can be regarded as Theory of everything?

Most probably answer is NO.

Many issues need to understand,

Hierarchy problem..

Higgs and New Physics

But….

Higgs is discovered

No evidence of any New Physics

But….

Higgs is discovered

No evidence of any New Physics

…..raising many uncomfortable questions

Higgs and New Physics

- But a very serious implications are there for BSM
  - Data is compatible with SM , but sensitivity is 15-20% can constrain BSM.
  - Some models are already “closed”: Higgsless model, fermiophobic, gauge phobic, fourth generation, extreme technicolour..
- Some models are under ‘nursing’: many other extension of Higgs model, private, portal light technicolor

Some models are very much constrained….

Higgs and Supersymmetry

Implication in SUSY

Stabilization of Higgs mass,
Hierarchy problem, m(Higgs)<<M(planck)

$$| f > \leftrightarrow | B >$$

The MSSM: particle content

Particle content:

quarks $\leftrightarrow$ squarks; gluons $\leftrightarrow$ gluinos

leptons $\leftrightarrow$ sleptons;

W,Z,$\gamma \leftrightarrow \tilde{W}, \tilde{Z}, \tilde{\gamma}$

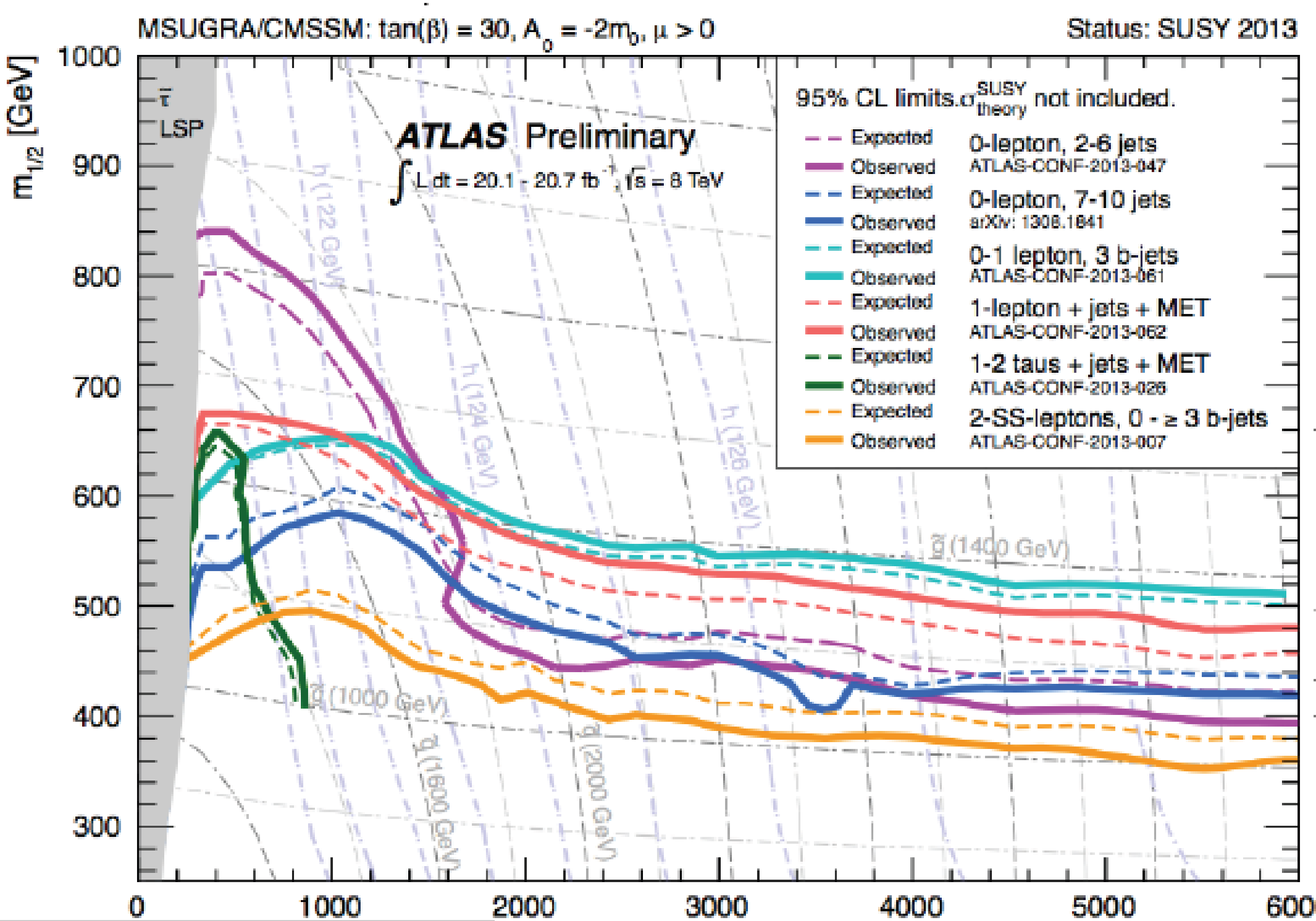
2 Higgs doublets

Supersymmetry is not an exact symmetry

100+ parameters

Supersymmetry and LHC

Inclusive searhces of squarks and Gluinos.



M(gluino)>1.5 TeV for degenrate gluino and squark masses, otherwise, >1 TeV In mSUGRA/CMSSM Model.

Exclusions are very model specific..

Talk by S. Vempati

Implication in SUSY

SM particles + SM sparticles + 2 Higgs doublets

5 Higgsses h, A, H, H^+, H-

At tree level, masses can be determined by two parameters:

$$m_A, \tan\beta \qquad \tan\beta = \frac{v_u}{v_d}$$

Large m_A, decoupling regime,

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\sin\alpha/\sin\beta \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$\cot\beta$	$\tan\beta$	0

$$h \to h_{SM}$$

Higgs Mass and SUSY

At the tree level, Higgs mass,

$$m_h = m_Z \cos\beta + \Delta m_h$$ **≤135 GeV** **Strong prediction**

CP odd Higgs mass M_A, tanβ, and the top quark mass.

Stop mixing matrix:

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

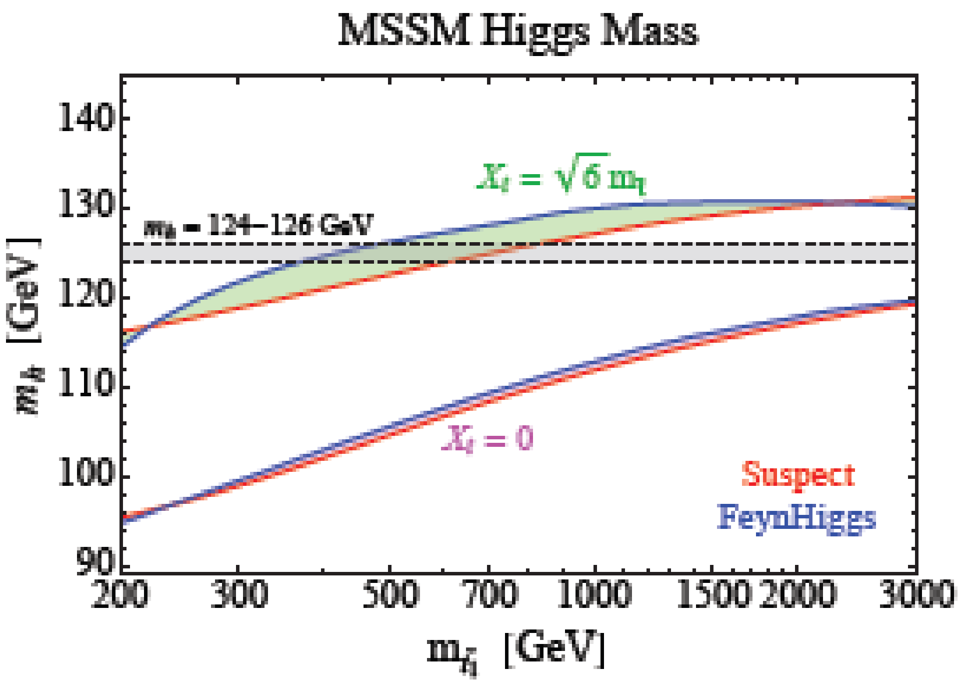
$$X_t = A_t - \mu \cot\beta$$

$$\tilde{t}_L, \tilde{t}_R \rightarrow \tilde{t}_1, \tilde{t}_2$$

M_H sensitive to X_t

Higgs and SUSY

$$\Delta m_h^2 \approx \frac{3m_t^4}{2\pi^2 v^2}\ln\frac{M_S^2}{m_t^2} + \frac{3m_t^4}{2\pi^2 v^2}\left(\frac{X_t^2}{M_S^2} - \frac{X_t^4}{12M_S^4}\right)$$

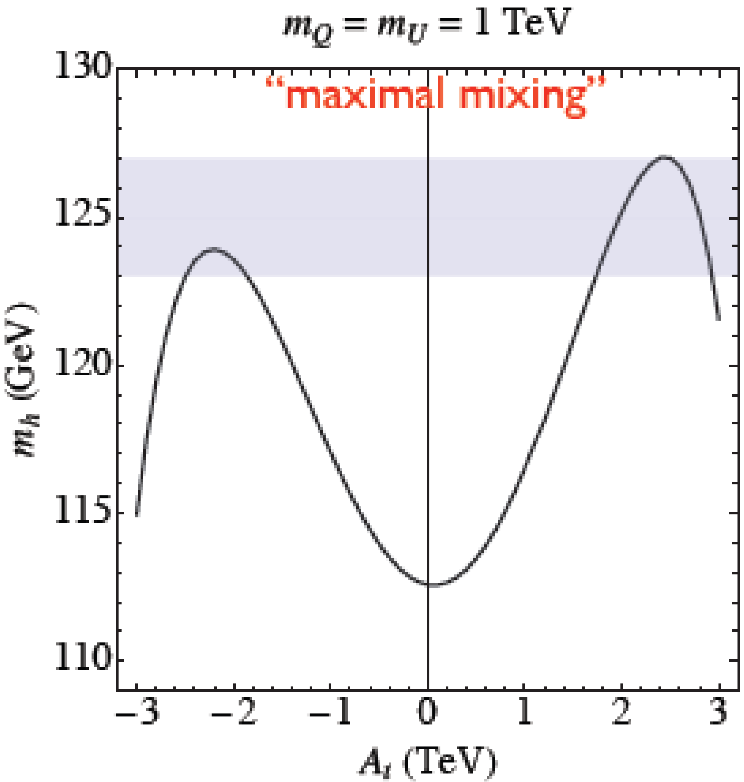


$$|X_t| = X_t^{max} = \sqrt{6} m_{\tilde{t}} \qquad m_{\tilde{t}} = \sqrt{m_{Q3} m_{u3}}$$

Higgs mass is sensitive to 3rd Generation squarks

Higgs in SUSY

$$-\mathcal{L}_{soft} \supset m^2_{Q_3}|\tilde{Q}_3|^2 + m^2_{U_3}|\tilde{U}_3|^2 + A_t H_u \tilde{Q}_3 \tilde{U}_3 + c.c.$$



Need large A term

Where can large A-terms come from? Need understanding

For example, large terns trough RG requires large Gluino mass>3 TeV

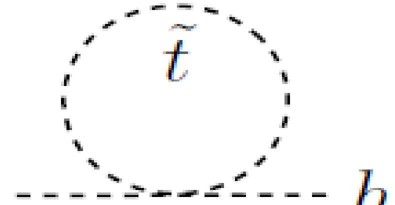
Higgs mass and FT

Heavy stop mass are required to boost Higgs mass to 125 GeV

In SUSY theories, $$\frac{m_h^2}{2} = m^2 = -|\mu|^2 + m_{H_u}^2$$

$$m_h = 125\text{GeV} \Rightarrow \left(m^2\right)^{1/2} < 88GeV.$$

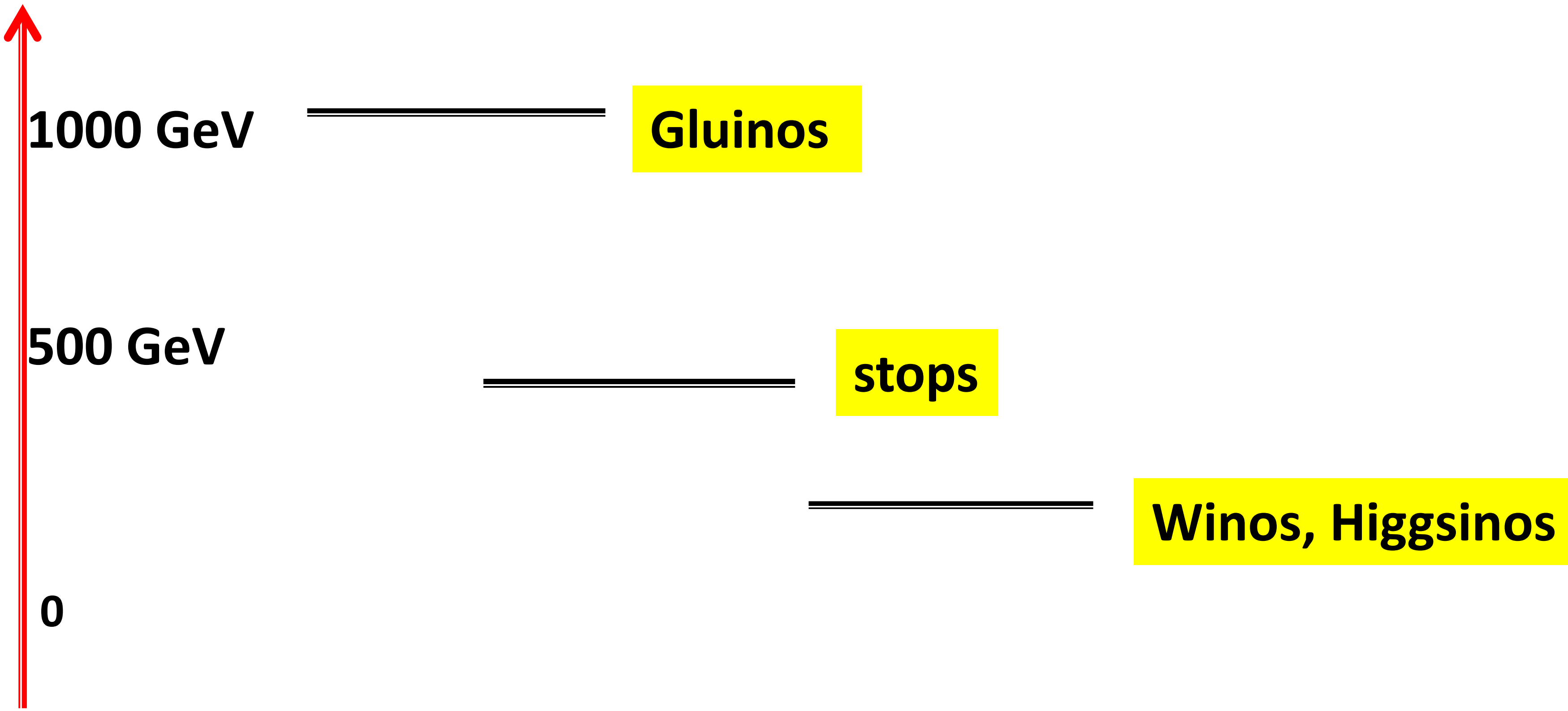
Top-stops-Higgs loop,



$$\delta m_{H_u}^2 \simeq -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right) \ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

Right hand side needs some tuning to achieve the correct scale of EWSB

FT: consequences



LHC should look for 3rd generation squarks and huge efforts are there to find these 3rd generation quarks

Beyond MSSM and NMSSM

The μ problem in the MSSM : The Higgsino mass parameter must be of the order of EWSB scale.

In NMSSM : μ is generated through VEV of scalar component of an extra single chiral superfield. S

$\mu = \lambda < \mathrm{S} >$ **from** $\lambda \hat{S} \hat{H}_u \hat{H}_d$

Extended Higgs and Neutralino sector

7 Higgs bosons:

$$\mathrm{H}_1, \mathrm{H}_2, \mathrm{H}_3, \mathrm{A}_1, \mathrm{A}_2 . \mathrm{H}^+, \mathrm{H}^-$$

NMSSM Higgs

Higgs mass from LHC and NMSSM compatibility

MSSM:

$$M_H^2 = M_Z^2 \cos^2 2\beta + \Delta M_H^2$$

NMSSM:

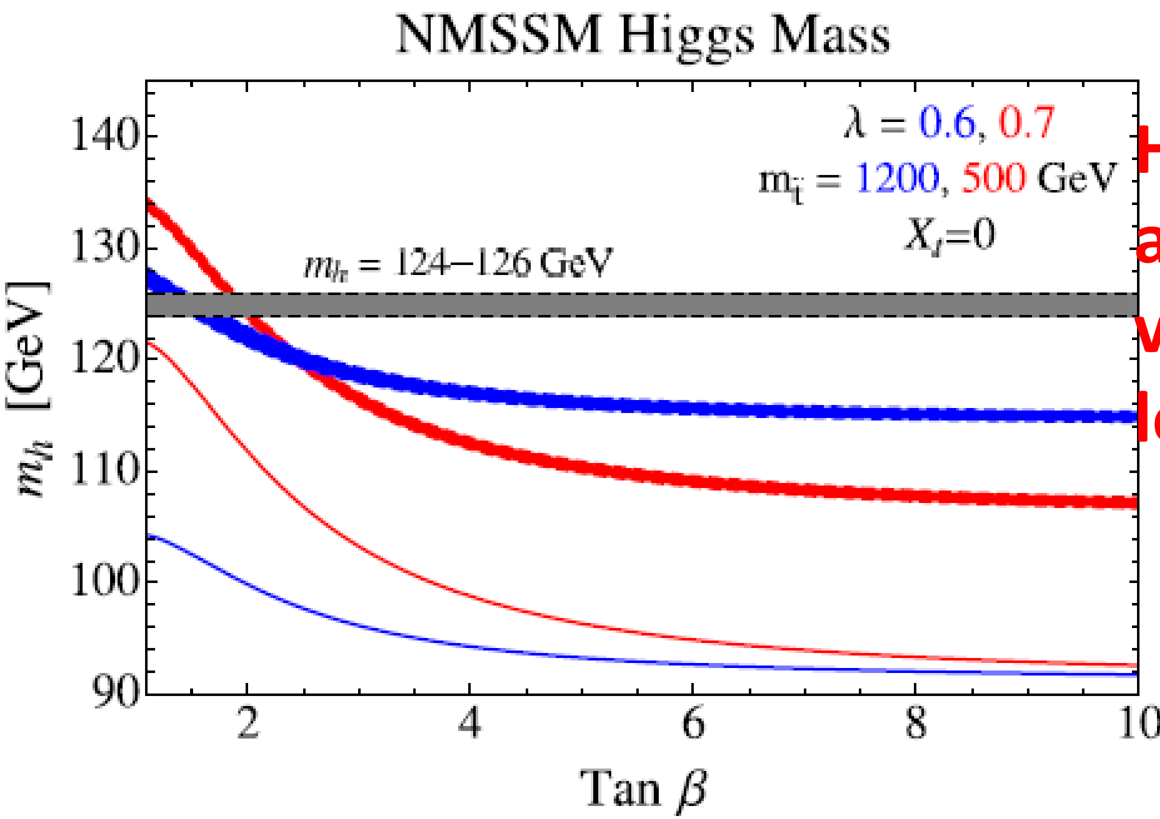
$$M_H^2 = M_Z^2 \cos^2 2\beta + \Delta M_H^2 + \lambda^2 v^2 \sin^2 2\beta$$

126 GeV Higgs mass

MSSM $\Delta M_H \approx$ **85 GeV** **Need huge fine tuning**

NMSSM $\Delta M_H \approx$ **55 GeV** **Need less fine tuning**

NMSSM Higgs Mass



Higgs mass can be achieved for small values of tanβ , also for low mixing scenario.

May be, there is a light Higgs of the order 60-110 GeV

L. Hall et al 1112.2703

What next in SUSY?

- Higgs mass 126 GeV is not a very comfortable value with MSSM, but manageable.

- SUSY spectrum is very heavy, EW sector, may be light stop need to give more emphasis in SUSY searches.

More work for MSSM Higgs searches,

$gg, bb \rightarrow H/A \rightarrow \tau\tau, \mu\mu$

Charged Higgs: $t \rightarrow H^{+}b$, $gg \rightarrow t H^{-}$,

$H \rightarrow WW, ZZ$, like SM,

$H \rightarrow hh$, $A \rightarrow Zh$

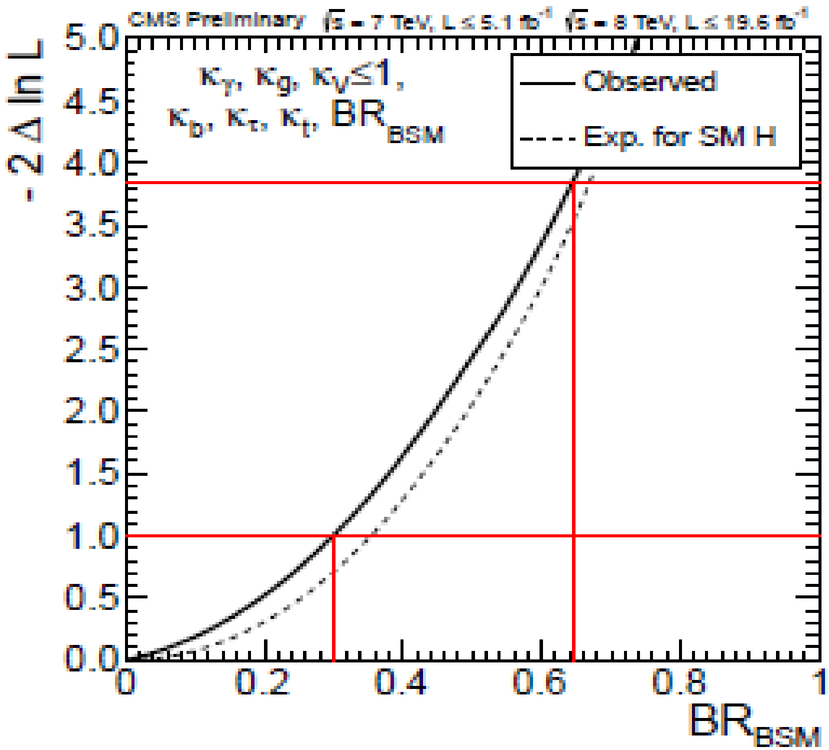
Certainly sparticle searches…

Invisible Higgs: Window for NP

$$H \rightarrow \chi\chi$$

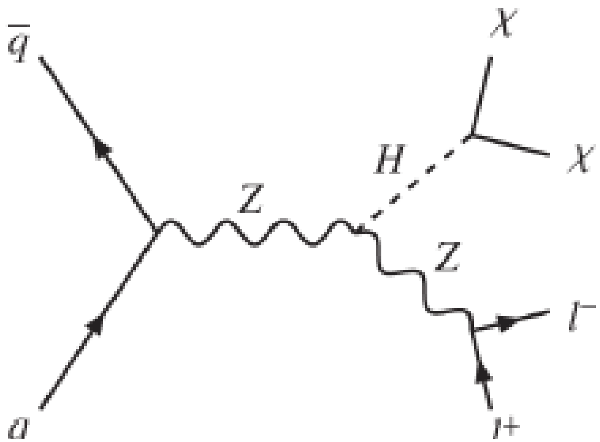
$$Br_{inv} = \frac{\Gamma_{inv}}{\Gamma_{inv} + \Gamma_{SM}}$$

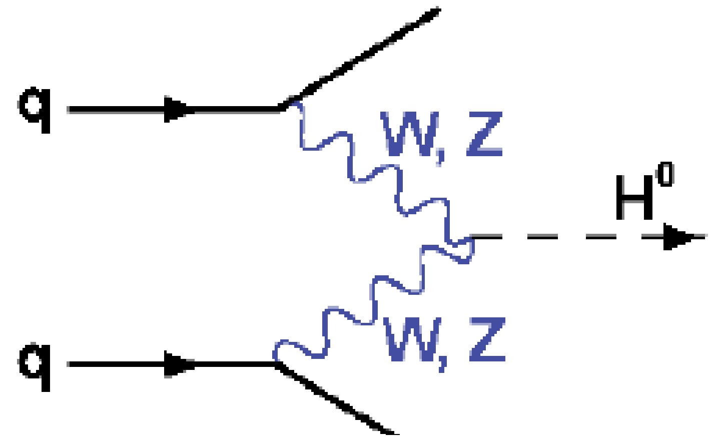
$$\Gamma_H = \Gamma_{SM} + \Gamma_{BSM} \Rightarrow BR_{BSM} = 1 - BR_{SM}$$



CMS: $(BR)_{BSM} < 0.64$ @ 95% C.L.

Invisible Higgs@LHC





$\mathrm{BR_{inv}}$ sensitivity at 5σ

Process	8 TeV ($20\ \mathrm{fb}^{-1}$)	14 TeV ($30\ \mathrm{fb}^{-1}$)	14 TeV ($100\ \mathrm{fb}^{-1}$)
VBF	0.34	0.33	0.17
$Z(\to l^+l^-)H$	0.58	0.32	0.18
$Z(\to b\bar{b})H$ (substructure)	–	–	0.50
$Z(\to b\bar{b})H$ (b-jet cluster)	–	–	0.55

D. Ghosh, R. Godbole, MG, K. Mohan, D.Sengupta, PLB 13, 1211.7015

CMS: BR(H→ inv) <0.75% @ 95% C.L, CMS - PAS-HIG 13-018

ATLAS: BR(H→ inv) <0.65% @ 95% C.L, ATLAS CONF 2013-011

Conclusion

- A Higgs boson is observed, properties are very close to SM hypothesis
- Need for precise measurements, need to also measure self coupling
- No signal of any New physics, but Higgs signal can constrain new physics.
- If this Higgs is from some BSM Higgs , then need to find signal, SUSY, need to find more Higgs, and of course, Sparticles, NMSSM Higgs, there might be a lighter Higgs
- Although there is no signal of any NP, but no reason to be panicked.

Have patience

and

Stay tuned

Have patience

and

Stay tuned

Thank you