8 March 2013 @ NCTS

Implication of 126 GeV Higgs for Planck scale physics

Satoshi Iso (KEK, Sokendai)

with Yuta Orikasa (Osaka) PTEP *2013,023B08*

Higgs was discovered at
M_H =126 GeV

No evidence
of "new" physics
@ ATLAS,CMS & LHCb

What is the implication of these two?
together with some phenomena beyond SM
(ν oscillation, Baryon asymmetry, Dark matter)

3 major hints towards the physics beyond SM

(1) Higgs mass at 126 GeV (Moriond)

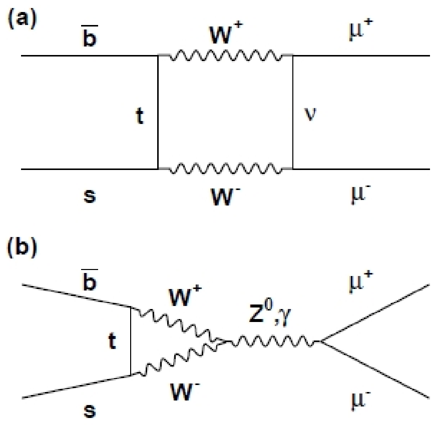
(2) No deviation from SM

Higgs decay

Flavor physics: LHCb, B-factory, MEG

e.g. $Br(B_s \rightarrow \mu\mu) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$

which is consistent with SM $(3.2 \pm 0.2) \times 10^{-9}$.



(3) But we also know that SM is not sufficient to explain

neutrino oscillation

Baryon asymmetry

dark matter

(also a big hint from Cosmology)

What can (or must) we do now
to go beyond the SM?

Is there a possibility to connect
with the string theory
or Planck scale physics?

Most investigations of physics beyond the SM
have been based on

"the central dogma" of particle physics

GUT → hierarchy problem → TeV SUSY etc.

i.e. Unification below the Planck scale requires
large symmetry enhancement at TeV scale.

It may be a good time to reconsider the basic strategy (central dogma) toward the physics BSM.

Hierarchy problem

Naturalness (Hierarchy problem)

$$\delta V(\phi) = \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\,\mathrm{Str}\log(k^2 + M^2(\phi))$$

Quadratic divergence

$$= \frac{\Lambda^2}{32\pi^2}\mathrm{STr}M^2(\phi) + \mathrm{STr}\frac{M^4(\phi)}{64\pi^2}(\ln(M^2/\Lambda^2) - 1/2)$$

$\mathrm{STr}M^2(\phi) \neq 0$ Quadratic divergence in Higgs mass term

$\mathrm{STr}M^2(\phi) = 0$ Cancellation of Quadratic divergence (supersymmetry etc.)

Bardeen (1995 @ Ontake summer school)

Standard model is classically scale invariant if Higgs mass term is absent.

$$T^\mu_\mu = 0$$

Quantum anomaly breaks the invariance (if not conformal)

$$T^\mu_\mu = \beta(\lambda_i)\mathcal{O}_i$$

But then, we cannot forbid the quadratically divergent mass term

$$T^\mu_\mu = \beta(\lambda_i)\mathcal{O}_i + const.\ \Lambda^2 \bar{h} h$$

Bardeen argued that it should be

$$T^\mu_\mu = \beta(\lambda_i) O_i + \delta m^2 \bar{h} h$$

$$\delta m^2 = const. \times m^2 \neq const. \times \Lambda^2$$

Hierarchy problem

Is quadratic divergence the issue of hierarchy problem?

NO

Bardeen(1995)

H Aoki, SI PRD(2012)

There are 3 different types of divergences

1. Quadratic divergences Λ^2
2. Logarithmic divergences $m^2 \log \Lambda$
3. Logarithmic but looks like quadratic $M^2 \log \Lambda$

(1) Quadratic divergence in mass can be simply subtracted, so it gives a boundary condition at UV cut off Λ.

→ If massless at Λ, it continues to be so in the IR theory.

(2) Logarithmic divergence gives a multiplicative renormalization. No Higgs mass term is generated if it is absent at UV scale.

$$\frac{dm^2}{dt} = \frac{m^2}{16\pi^2}\left(12\lambda + 6Y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right) + \boxed{\frac{M^2}{8\pi^2}\lambda_{mix}}$$

(3) If SM is coupled with a massive particle with mass M, logarithmic divergences give a correction to m as

$$\delta m^2 = \frac{\lambda_{mix} M^2}{16\pi^2}\log(\Lambda^2/m^2)$$

In order to solve the "hierarchy problem" without a special cancellation like supersymmetry, we need to control

(a) "quadratic divergence" → correct boundary condition at Planck

The most natural b.c. is NO MASS TERMS at Planck

(= classical conformal invariance)

(b) "large logarithmic divergence" by mixing with a large mass M

No intermediate scales between EW (or TeV) and Planck

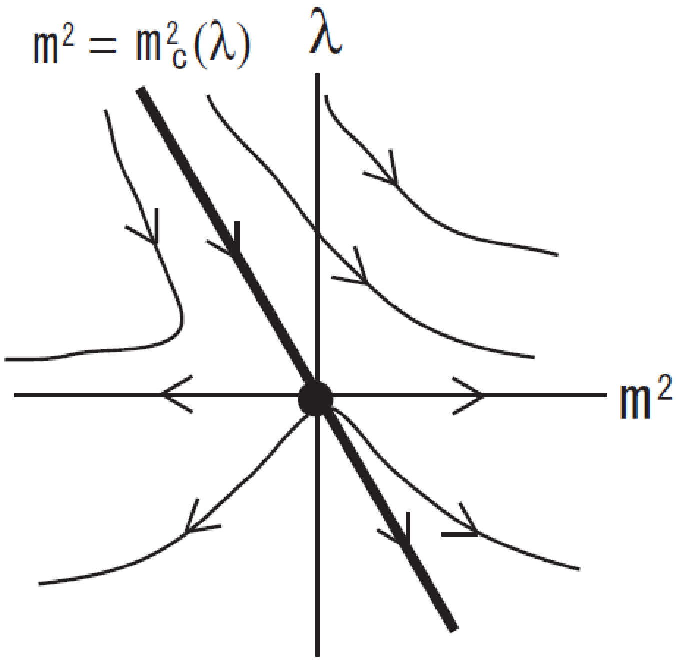
"Classical conformal theory with no intermediate scale" can be an alternative solution to hierarchy problem.

Bardeen (95)
Shaposhnikov (07)
Meissner Nicolai (07)
SI, Okada,Orikasa (09)

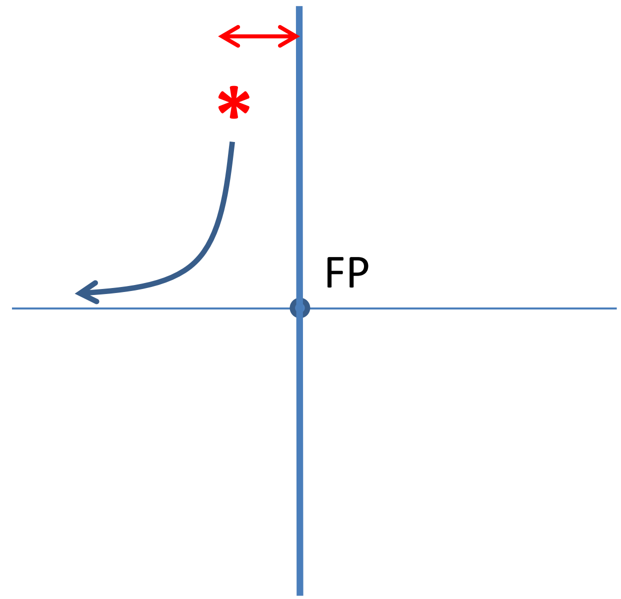
Hierarchy problem in Wilsonian RG

H Aoki, SI PRD(2012)]

Critical line



$\Lambda^2 \neq 0$



No quadratic div.

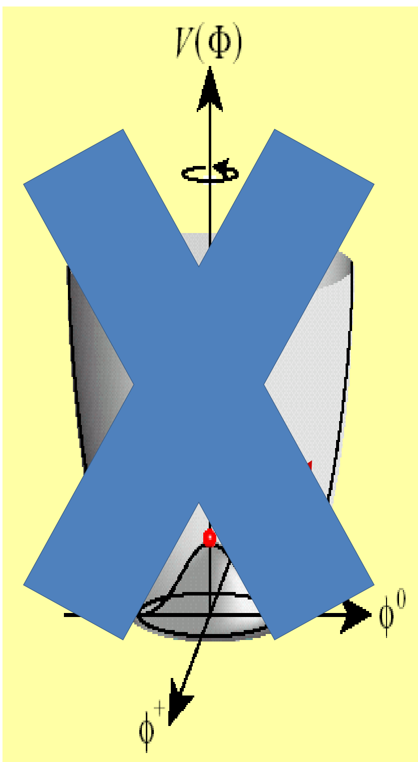
$\Lambda^2 = 0$

Fine - tuning of the **distance from the critical line** = **Low energy mass scale**

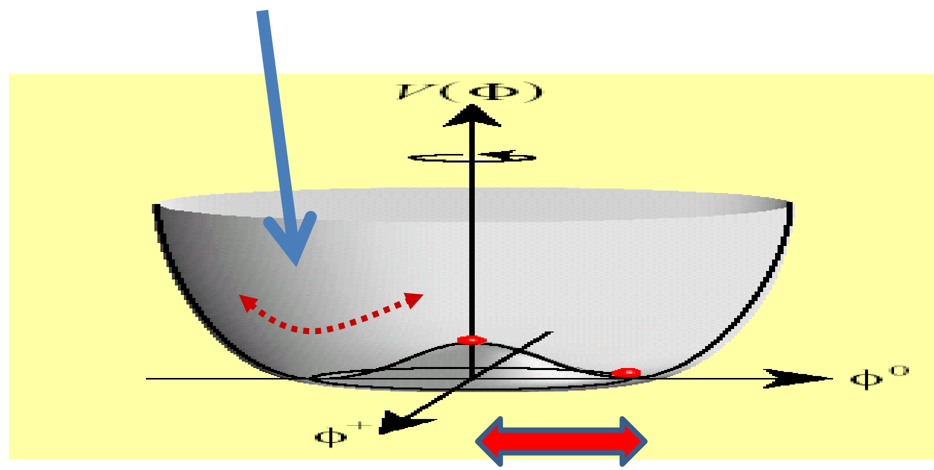
The difference is the **choice of the coordinates** of the parameter space.

Stability of Vacuum

Another Hint of 126 GeV Higgs mass is
Stability bound of the Higgs quartic coupling



$$m_H = 126\ \mathrm{GeV}$$



$$v = 246\mathrm{GeV}$$

RGE improved effective potential for large field (h >> v) $V_{\text{eff}}(h) = \frac{\lambda_{\text{eff}}(h)}{4} h^4$

RGE @1-loop $\frac{d\lambda_H}{dt} = \frac{1}{16\pi}\left(24\lambda^2 \underbrace{\boxed{-6Y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g_1^4 + \cdots}}_{\text{Already known}}\right)$

It is related to Higgs mass as $M_h^2 = 2\lambda v^2$

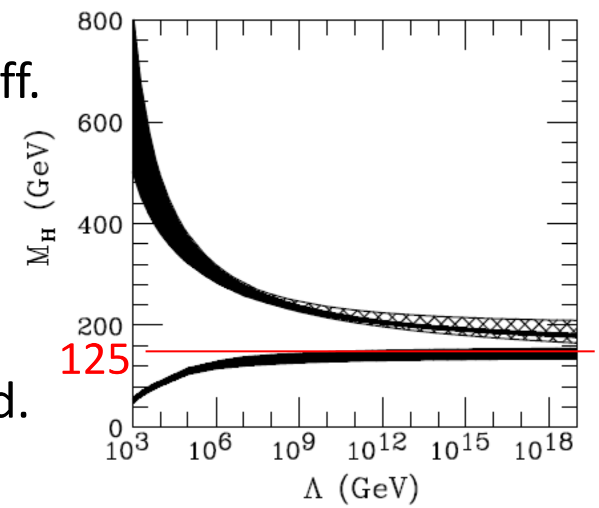
Higgs mass controls the behavior of Higgs potential at large values of h.

This gives two bounds for Higgs mass

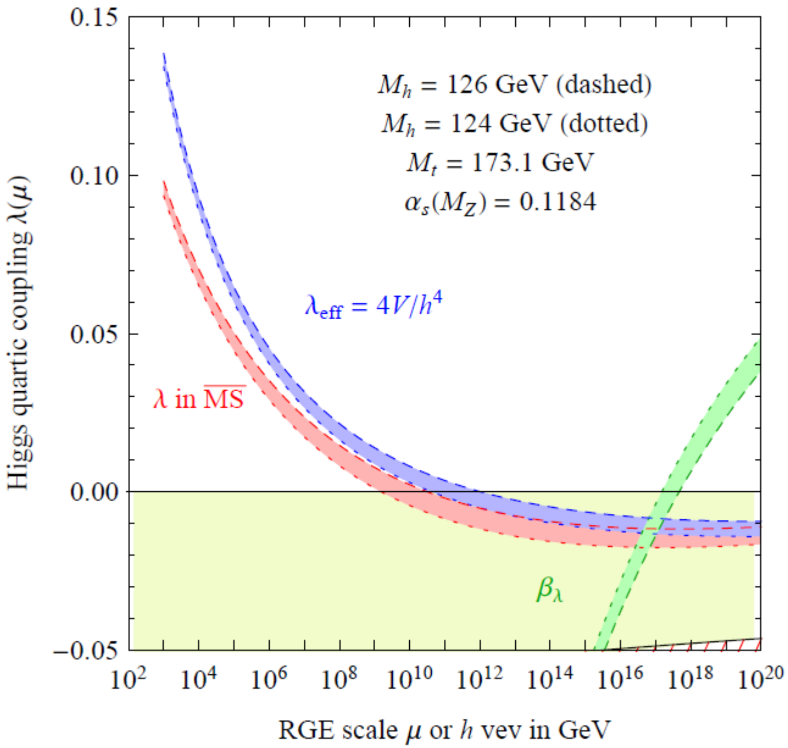
(1) The quartic coupling does not blow up until UV cut-off.
M < 180 GeV (triviality bound)

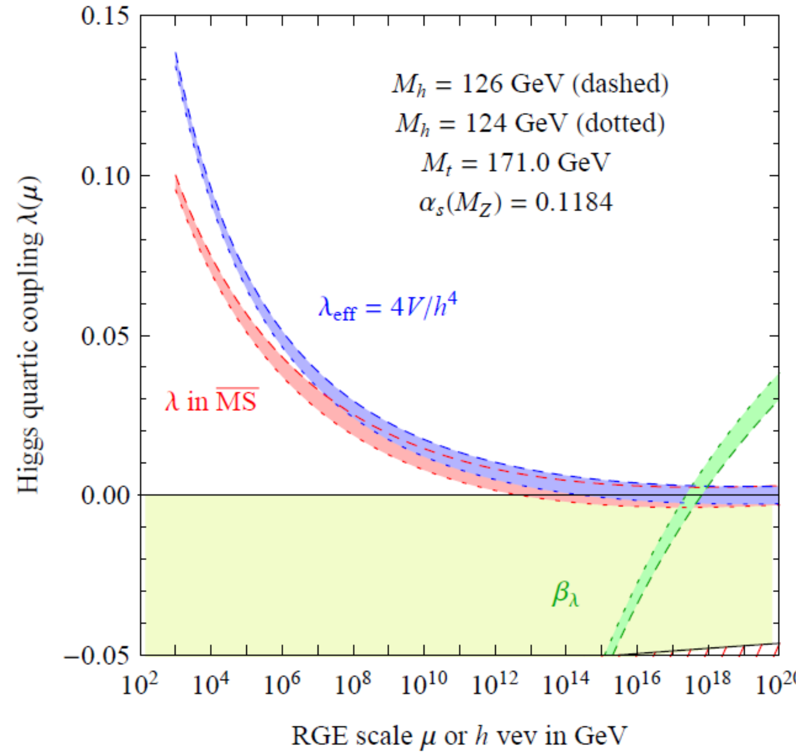
(2) The quartic coupling does not become negative
until UV cut-off. (Stability bound)

M = 125 GeV Higgs is very close to the stability bound.



Why stability bound is important for Planck scale physics?





New physics at 10^{12} GeV
is necessary to stabilize the vacuum

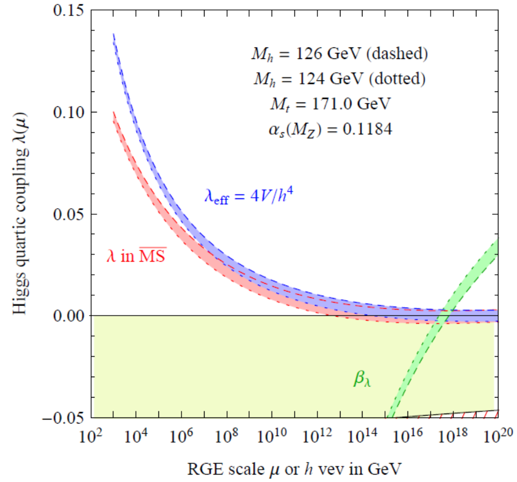
Flat Higgs potential
at Planck scale

$$M_H \geqslant 129.2 + 1.8 \times \left(\frac{m_t^{\rm pole} - 173.2\ {\rm GeV}}{0.9\ {\rm GeV}}\right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0\ {\rm GeV}.$$

very sensitive to top quark mass

Elias-Miro et.al.(12)
Alkhin, Djouadi, Moch (12)

If this



is the case ?

$$\lambda(\Lambda_0) = \beta_\lambda(\Lambda_0) = 0$$

Direct window to Planck scale

M.Shaposhnikov (07)

$$\boxed{\text{Emergence of Higgs potential}}$$

at the Planck scale

Indication on the Higgs potential

$$V = -\cancel{\mu^2 |H|^2} + \cancel{\lambda (|H|^2)^2}$$

Hierarchy
(classical conformality)

Stability
vanish at Planck

LHC data implies that
Higgs has a flat potential V(H)=0 at Planck.

How can we achieve EW symmetry breaking from $V(H)=0$ potential at Planck?

Everything should be radiatively generated.

Two mechanisms of symmetry breaking

（1）SSB by negative mass term

$$V = \frac{\lambda}{4}h^4 + \frac{\mu^2}{2}h^2 \quad (\mu^2 < 0) \longrightarrow \quad m_h^2 = 2|\mu^2| = \boxed{2\lambda\langle h\rangle^2}$$

（2）Coleman-Weinberg mechanism (radiative breaking)

$$V_{eff} = \underbrace{\frac{\lambda h^4}{4}}_{\text{tree}} + \underbrace{Bh^4\left(\ln\left(\frac{h^2}{\langle h\rangle^2}\right) - \frac{25}{6}\right)}_{\text{1-loop}} \qquad B = \frac{3}{64\pi^2}\left(3\lambda^2 + \frac{3g^4 + 2g^2g'^2 + g'^4}{16} - Y_t^4\right)$$

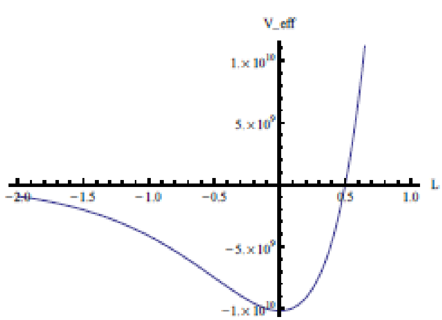


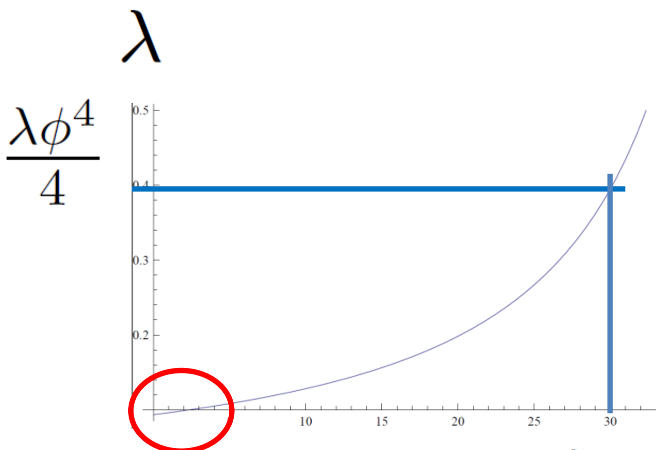
図 2.1 improve されていない有効ポテンシャル

Higgs mass is given by

$$V''|_{\langle h\rangle} = m_h^2 = 8\underline{B}\langle h\rangle^2 = \boxed{\frac{6}{11}\lambda\langle h\rangle^2}$$

（2’）RG improved CW mechanisms

Coleman-Weinberg radiative breaking



Symmetry is broken near the scale where the running coupling crosses zero.

$$M_{CW} = M_{UV} \exp(-\frac{\lambda_{UV}}{b} - \frac{1}{4})$$

Positive beta function

Dimensional transmutation

cf. Dimensional transmutation in QCD

$$\Lambda_{QCD} = M_{UV} \exp\left(-\frac{2\pi}{b_0 \alpha_s(M_{UV})}\right)$$

But CW does not work in SM.

the **large top Yukawa** coupling **invalidates the CW** mechanism

Extension of SM is necessary !

Meissner Nicolai (07)

(B-L) extension of SM with flat Higgs potential at Planck

SM + B-L sector
- U(1)B-L gauge
- SM singlet scalar ϕ
- Right-handed ν

N Okada, Y Orikasa, & SI
0902.4050 (PLB)
0909.0128 (PRD)
1011.4769 (PRD)
1210.2848(PTEP)

"Occam's razor" scenario

that can explain
- 126 GeV Higgs
- hierarchy problem
- ν oscillation, baryon asymmetry

Model: (B-L) extension of SM with Right Handed Neutrinos

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$+1/6$	$+1/3$
u_R^i	$\mathbf{3}$	$\mathbf{1}$	$+2/3$	$+1/3$
d_R^i	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$+1/3$
ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	-1
ν_R^i	$\mathbf{1}$	$\mathbf{1}$	0	-1
e_R^i	$\mathbf{1}$	$\mathbf{1}$	-1	-1
H	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$

N Okada, Y Orikasa, SI
PLB676(09)81,
PRD80(09)115007
PRD83(11)093011

H Higgs doublet

Φ B-L sector scalar field

- B-L is the only anomaly free global symmetry in SM.
- $[U(1)_{B-L}]^3$ is anomaly free if we have right handed fermion.
- B-L gauge symmetry is broken by vev of an additional scalar.

See-saw mechanism

$$\mathcal{L} \supset -Y_D^{ij}\overline{\nu_R^i}H^\dagger \ell_L^j - \frac{1}{2}Y_N^i \Phi \overline{\nu_R^{ic}}\nu_R^i + \text{h.c.},$$

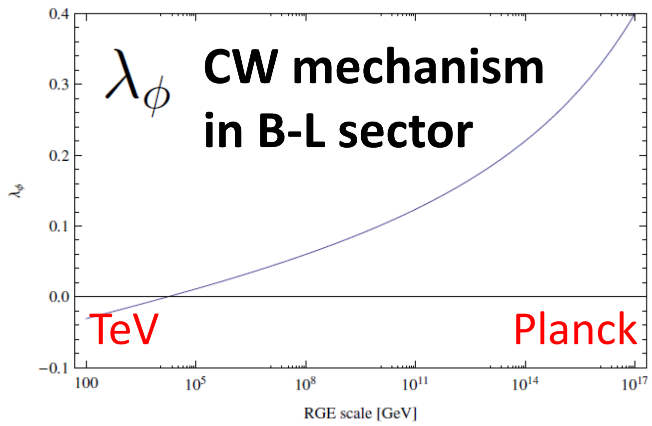
$$m = Y_D\langle H\rangle \qquad M_N = Y_N\langle \phi\rangle$$

$$\begin{pmatrix} 0 & m \\ m & M_N \end{pmatrix} \longrightarrow m_\nu = \frac{m^2}{M_N}$$

B-L can be broken by CW mechanism at TeV.

$$V(\Phi, H)|_{UV} = \lambda_\Phi (\Phi^\dagger \Phi)^2$$

$$M_{B-L} \sim M_{Planck} \exp(-\frac{\lambda_\phi}{b})$$



How about EWSB ?

$$\cancel{m_H^2 H^2} + \cancel{\lambda_H H^4} + \cancel{\lambda_{H\Phi} H^2}\Phi^2$$

classically conformal

126 GeV

key to relate EW and TeV

Can the small scalar mixing be naturally generated?

YES

Radiatively generated scalar mixing λ_{mix} in V(H)

$$V(H) = \lambda_H H^4 + \lambda_{mix}\Phi^2 H^2$$ → EWSB

Why is small negative λ_{mix} generated?

U(1) gauge mixing

$$\frac{dg_{mix}}{dt} \sim \frac{2}{3\pi^2} g_{B-L} g_Y^2 \; + \; g_{mix} \left(******** \right)$$

$$\frac{d\lambda_{mix}}{dt} = \frac{1}{16\pi^2} \left[\lambda_{mix} \left(******** \right) \boxed{+12 g_{mix}^2 g_{B-L}^2} \right]$$

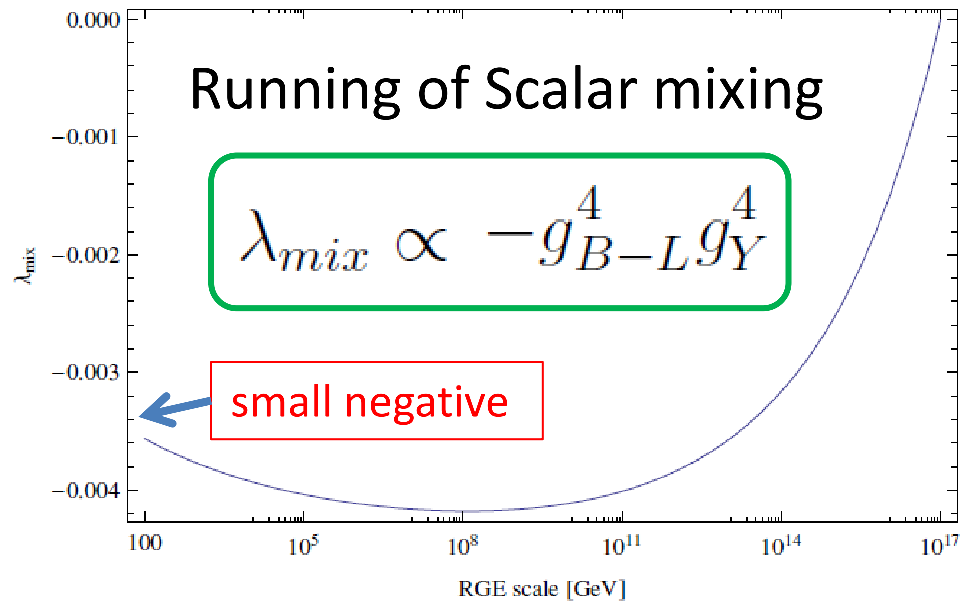
$$\lambda_{mix} \propto -g_{mix}^2 g_{B-L}^2 \propto -g_{B-L}^4 g_Y^4$$

Radiative generation of scalar mixing

$$V(H) = \lambda_H H^4 + \lambda_{mix} \Phi^2 H^2$$

$$\langle H \rangle = \sqrt{\frac{-\lambda_{mix}}{\lambda_H}} M_{B-L}$$

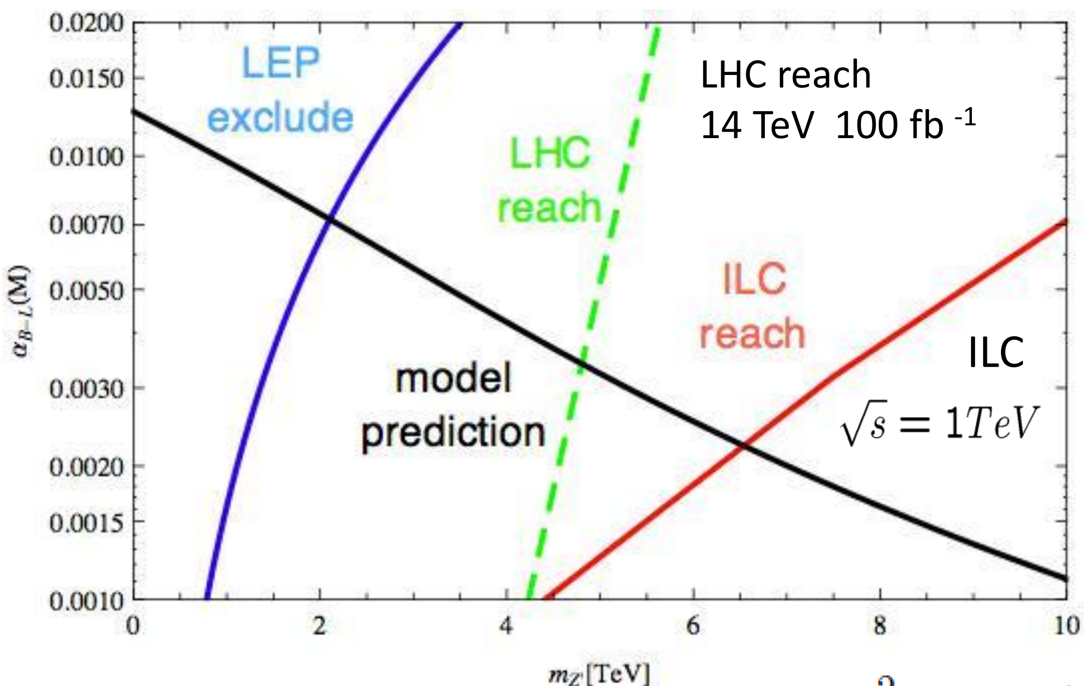
$$\sim c \frac{\alpha_{B-L} \alpha_Y}{\sqrt{\lambda_H}} M_{B-L}$$



Prediction of the model

In order to realize EWSB at 246 GeV,
B-L scale must be around TeV (for a typical value of α_{B-L}).

α_{B-L}



$$M_{B-L} \sim \frac{1}{\alpha_{B-L}} \times 35 \text{ GeV}$$

$$m_{Z'} \sim \frac{1}{\sqrt{\alpha_{B-L}}} \times 250 \text{ GeV}$$

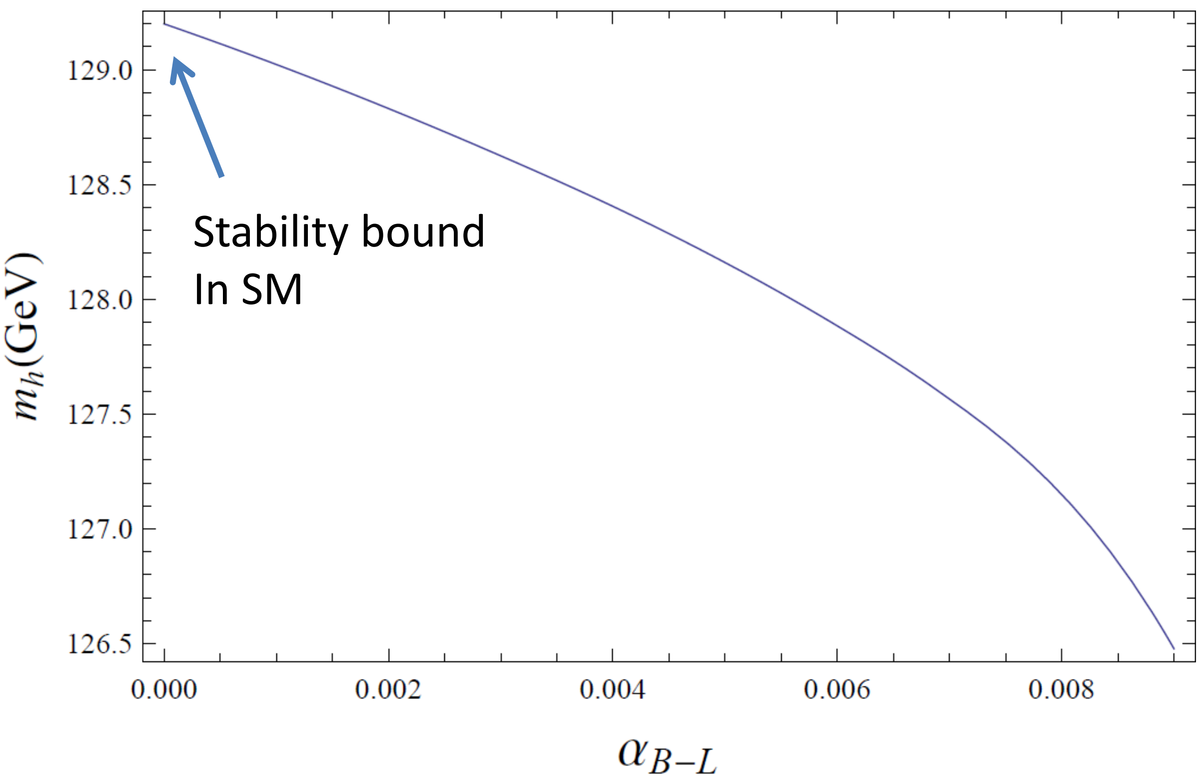
$$\boxed{m_\phi \sim 0.1\ m_{Z'}}$$

$$m_{Z'}^2 = 16\pi\alpha_{B-L}(0) M_{B-L}^2$$

Stability bound in TeV scale B-L model

$$\frac{d\lambda_H}{dt} = \frac{1}{16\pi}\left(24\lambda^2 - 6Y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g^2g_1^2 + \boxed{\frac{3}{4}(g^2+g_1^2)g_{mix}^2} + \cdots\right)$$

An extra positive term is added



Lower the stability bound

Summary

- 126 GeV Higgs = border of the stability bound of SM vacuum.
  → Direct window to Planck scale → Flat Higgs potential @Planck
  Hint for the origin of Higgs in string theory
- Occam's razor scenario beyond SM
  "Classically conformal B-L model" is proposed

(1) it can solve hierarchy problem
(2) it can explain why B-L breaking scale is around TeV.
(3) Stability bound can be lowered about 1 GeV
  $M_H \sim 128$ GeV
(4) phenomenologically viable
  Neutrino oscillation, resonant leptogenesis
(5) Highly predictive (or excludable)
  Prediction
  Z' around several TeV, $M_\phi < M_{Z'}$, Leptogenesis at TeV

Ongoing and Future projects

- Origin of flat Higgs potential at Planck

  Hierarchy problem & M_H =126 GeV

  → PNGB ? Moduli ? Gauge/Higgs ? …..

  Non-susy vacua of superstring with flat V(H)

- Resonant leptogenesis

  Garny, Kartavsev, Hohenegger (11)

  Kadanoff-Baym equation (quantum Boltzman)

- Non-susy GUT at Planck scale

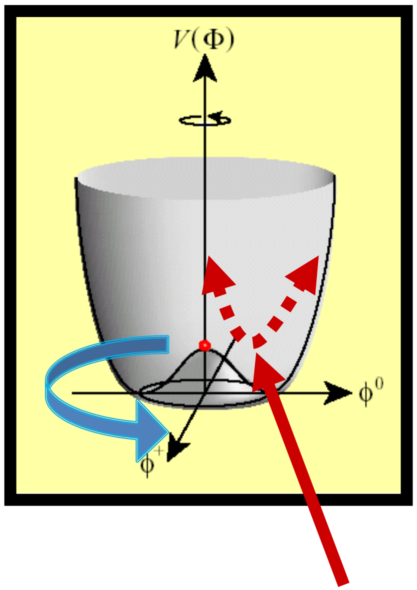
  SO(10) or E6 type or Pati-Salam

  Gravity or string threshold correction to RGE

Higgs potential

$$V = -\mu^2 |H|^2 + \lambda (|H|^2)^2 \Longrightarrow |H| = \sqrt{\frac{\lambda}{2\mu^2}} \equiv \frac{v}{\sqrt{2}}$$

Potential minimum



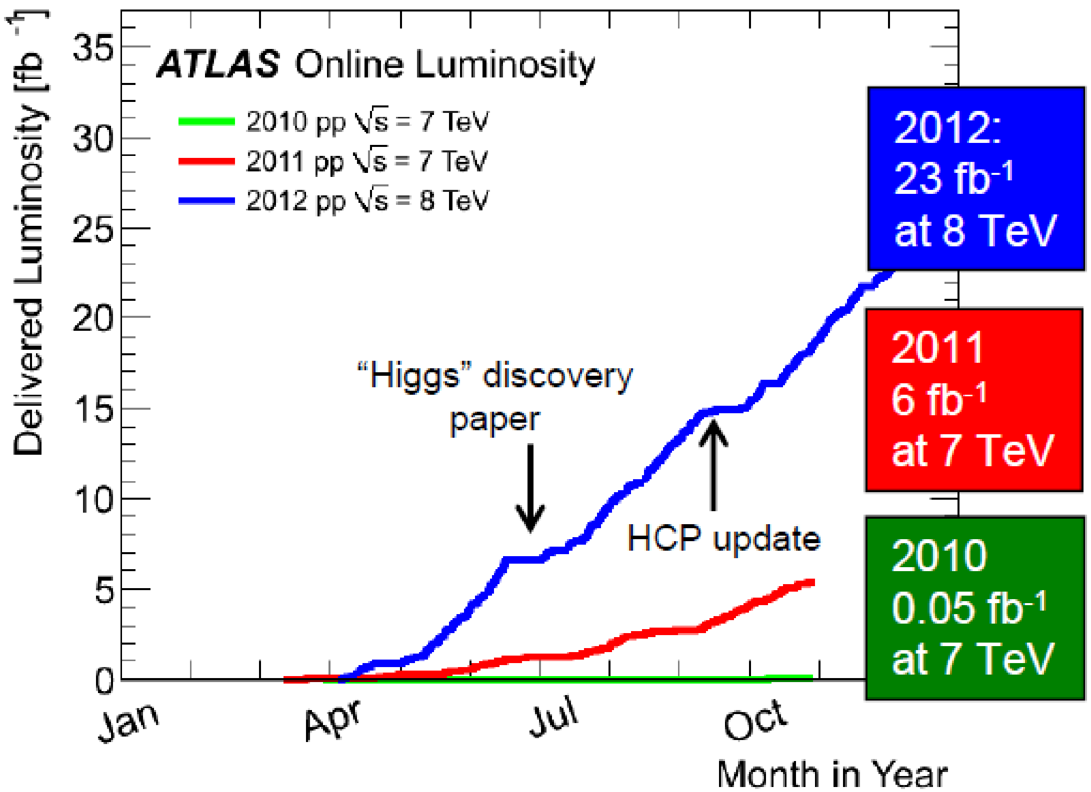
Spontaneous Symmetry Breaking

Higgs particle

Brief summary of recent results reported at Moriond

Discovery of Higgs(-like particle) was reported by CMS and ATLAS groups:

7 TeV L= 4.8 /fb (2011) + 8 TeV L= 20.7 /fb



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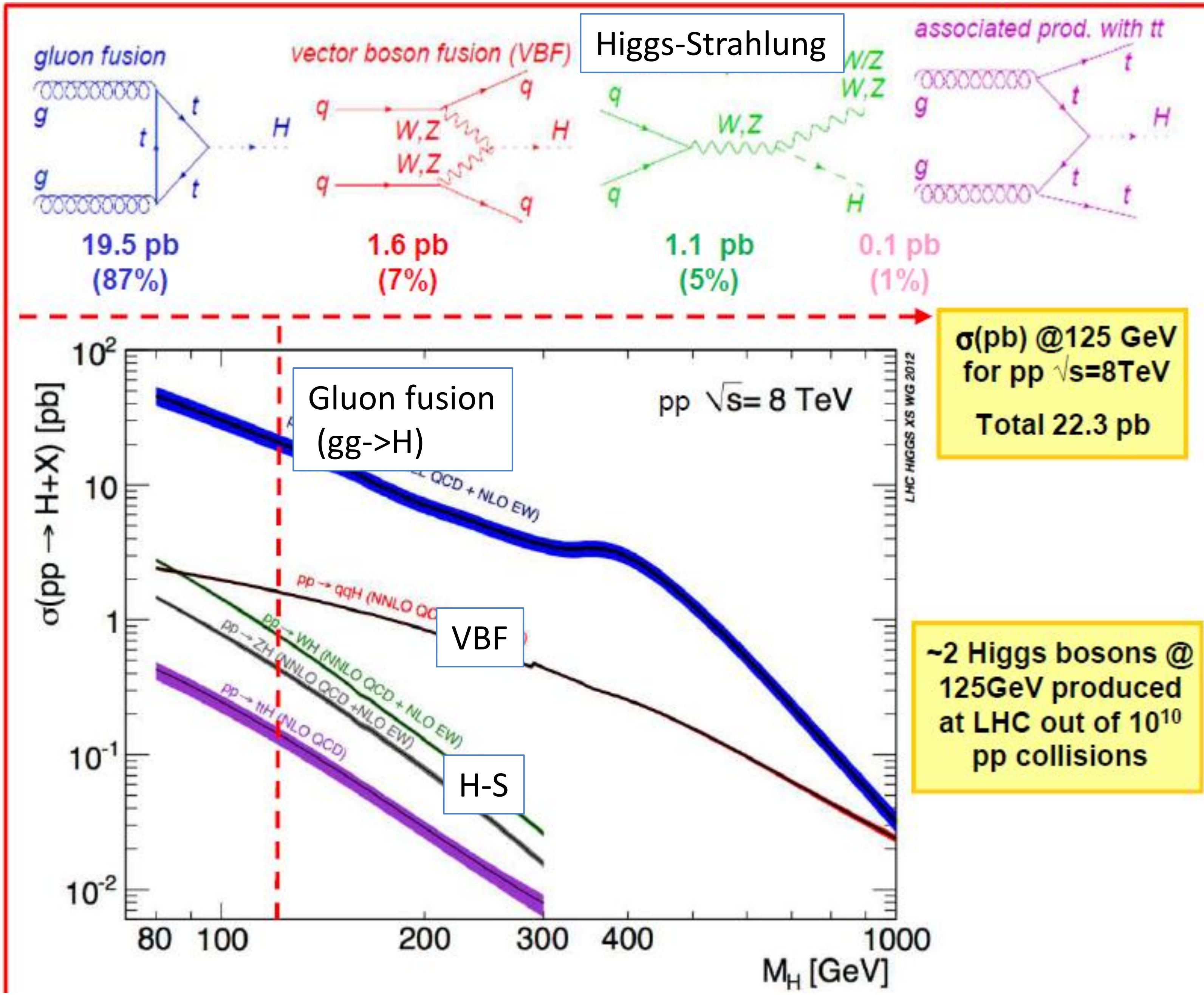
Production of SM Higgs



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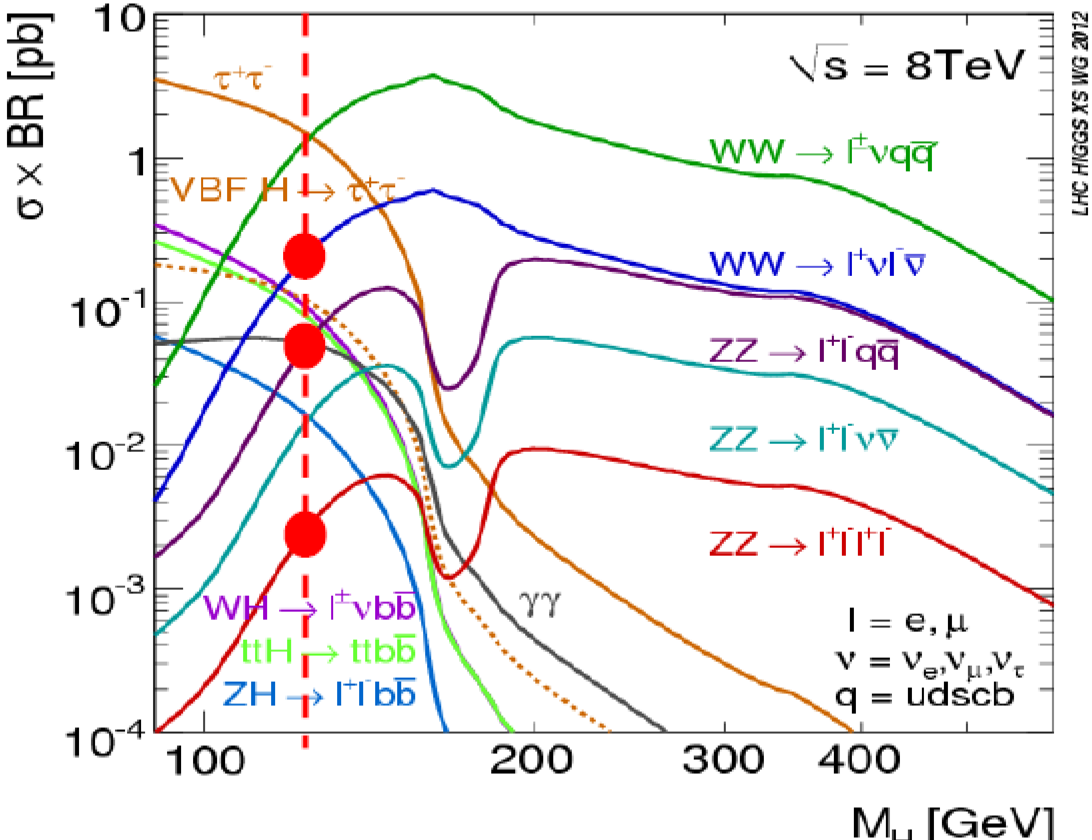
Decay modes of SM Higgs

Branching ratios at 125 GeV:

bb:	57.7%	ZZ:	2.6%
WW:	21.5%	$\gamma\gamma$:	0.23%
$\tau\tau$:	6.3%		

σ*BR for « useable » final states



3 major channels for low mass Higgs

- $\gamma\gamma$ final state
- ZZ*→4ℓ final state

1% mass resolution

- WW*→2ℓ+2ν final state

b$\bar{\text{b}}$, ττ,

Huge backgrounds:

- high-p_T b-jet production:
  - ➡ ~10^6 larger than $H \to b\bar{b}$ production
- **Drell-Yan/$Z \to \tau^+\tau^-$:**
  - ➡ 10^5 larger than $H \to \tau^+\tau^-$ production

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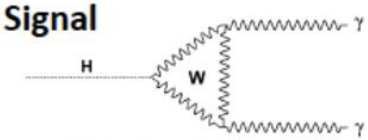
H→$\gamma\gamma$

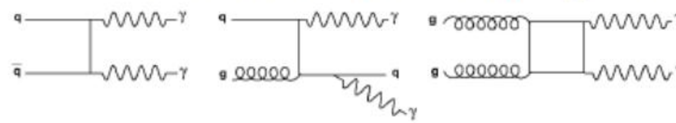
CS is low (50 fb), but relatively clean bkg

→ around 1250 events are expected @ 25 /fb identification efficiency 40 % (ATLAS)

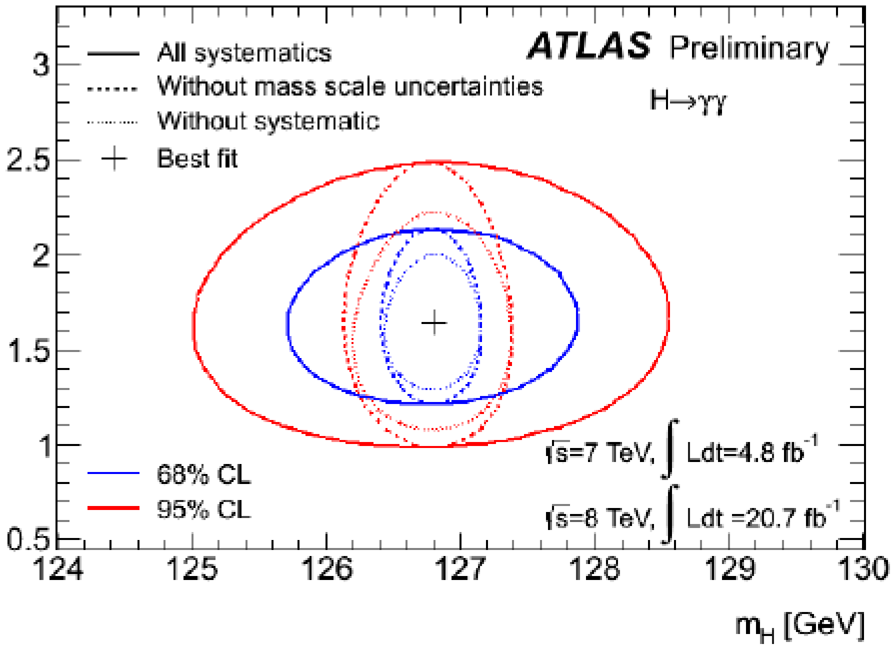
Signal



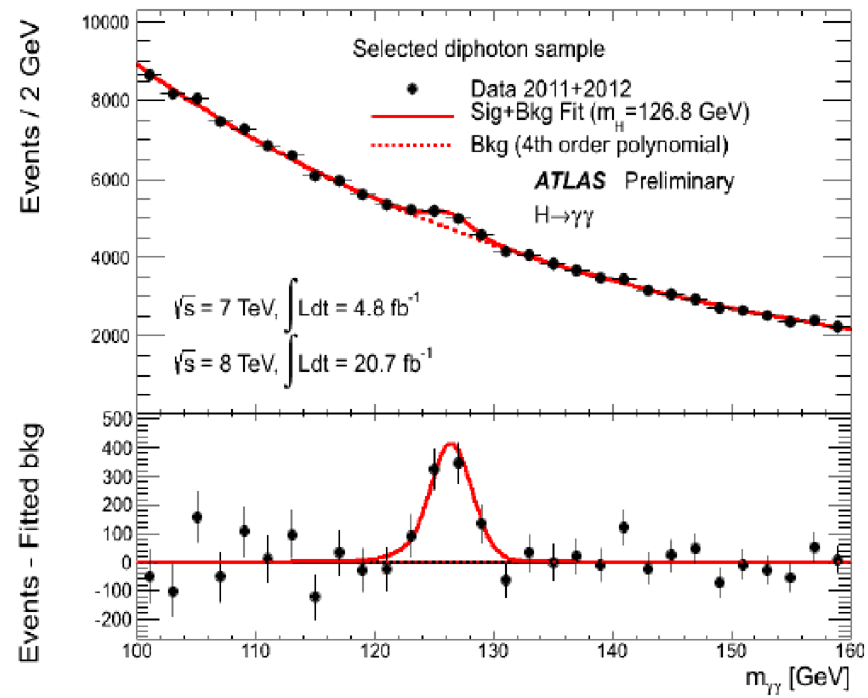
Irreducible background: pp→γγ + X



126.8 ± 0.2 (stat) ± 0.7 (syst) GeV



ATLAS



$\mu = 1.65^{+0.34}_{-0.30} = 1.65 \pm 0.24\ (\text{stat})\ ^{+0.25}_{-0.18}\ (\text{syst})$

The data went closer to SM. Consistency with SM at 2.3 σ

CMS did not report on H → 2γ

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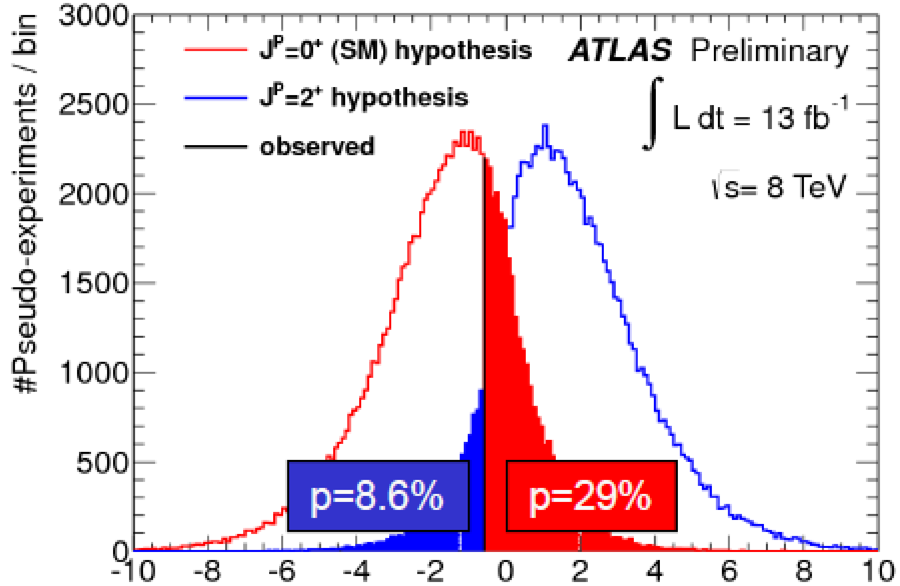
Spin-Parity



From angular distribution of photons, we can identify whether it is spin 0 or 2

- Spin-2^+ hypothesis expected exclusion CL_s at 93% [for 100% gg spin-2 production]
- Observation compatible with spin-0^+, slightly favored over spin-2^+ hypothesis

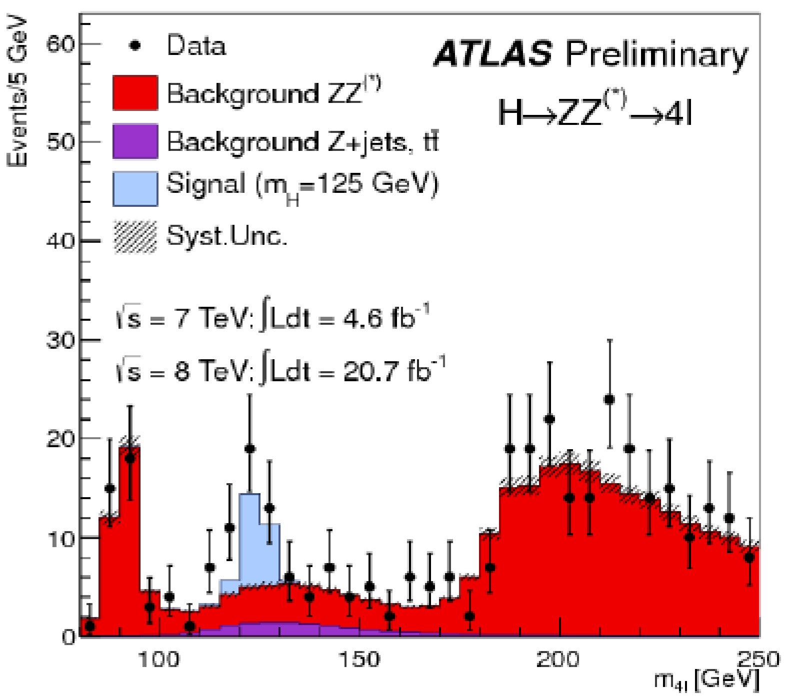
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

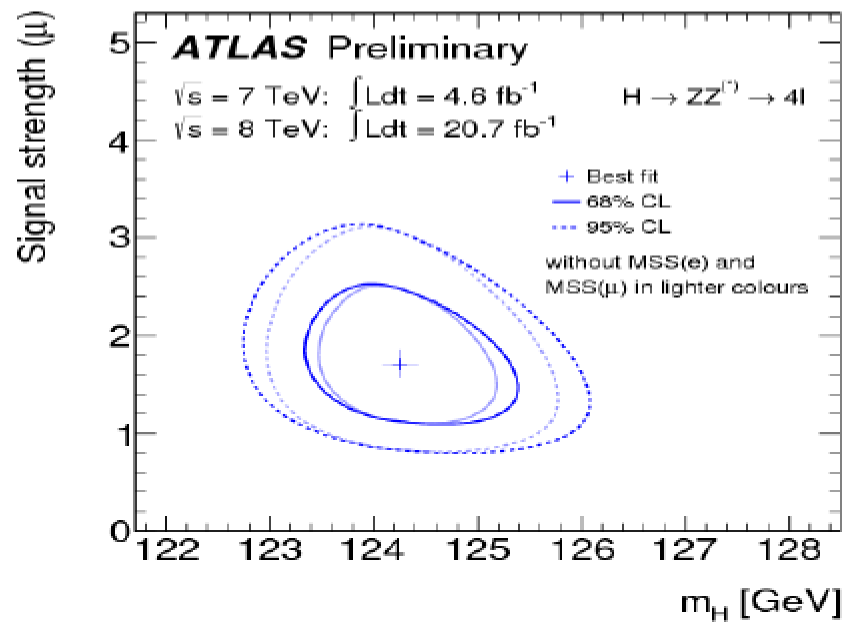
$\sigma \times BR \sim 2.5$ fb $m_H \sim 126$ GeV

Gold plated mode

Clean signature: narrow peak, low background

- Tiny rate, BUT:
  -- mass can be fully reconstructed
  -- pure: S/B ~ 1





Best mass fit **124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV**

In region 125±5 GeV: 32 events observed [11.1±1.3 expected from bknd & 15.9±2.1 from SM Higgs]

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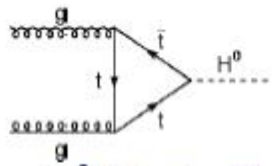
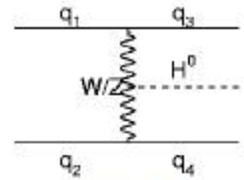
Higgs coupling : information from production and decay rates

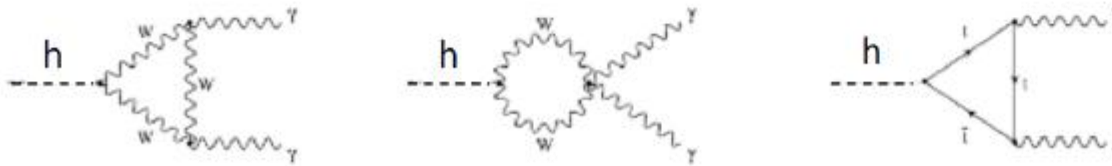
- **For each observed final state, production and decay involve several couplings**
- **Best example: $\gamma\gamma$**
  - **Production**



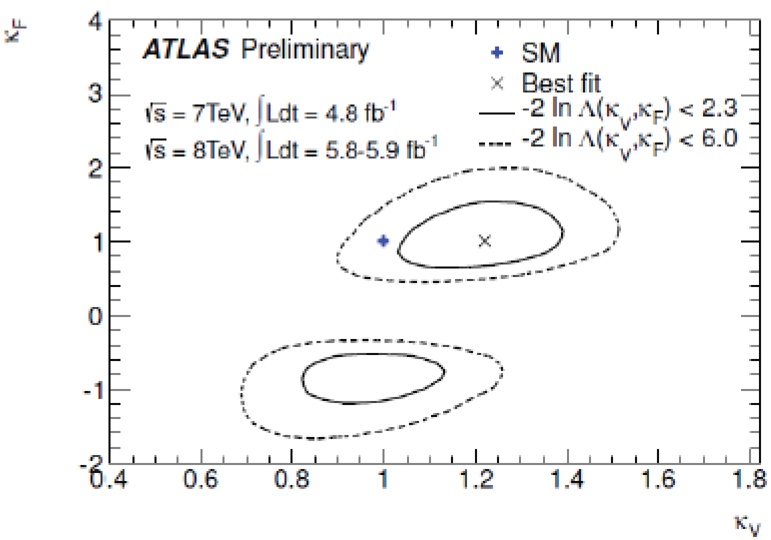


$\sim \kappa_g^2\ (\kappa_t, \kappa_b, m_H\ ) \quad + \quad \sim \kappa_W^2$

  - **Decay**



Decay width : $\sim (\kappa_W - 0.2\ \kappa_t)^2$ ***[note: interference]***



$\kappa_V = \kappa_W = \kappa_Z\ ; \qquad \kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

- **Higgs couplings (partial dataset)**
  Compatible with SM hypothesis.
- **BR(H→inv.) < 65% (95% C.L.)**

Consistent with SM
No sign of BSM

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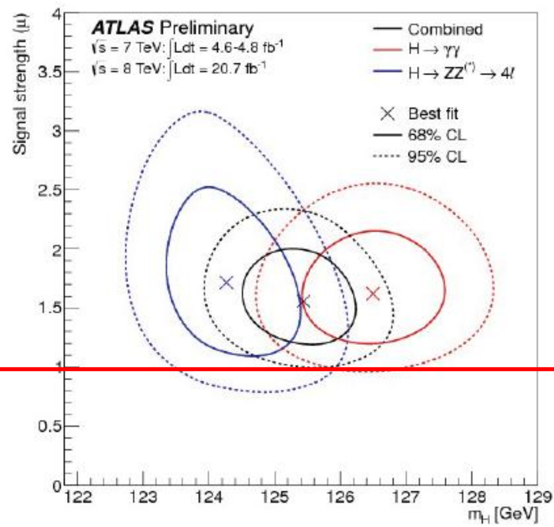
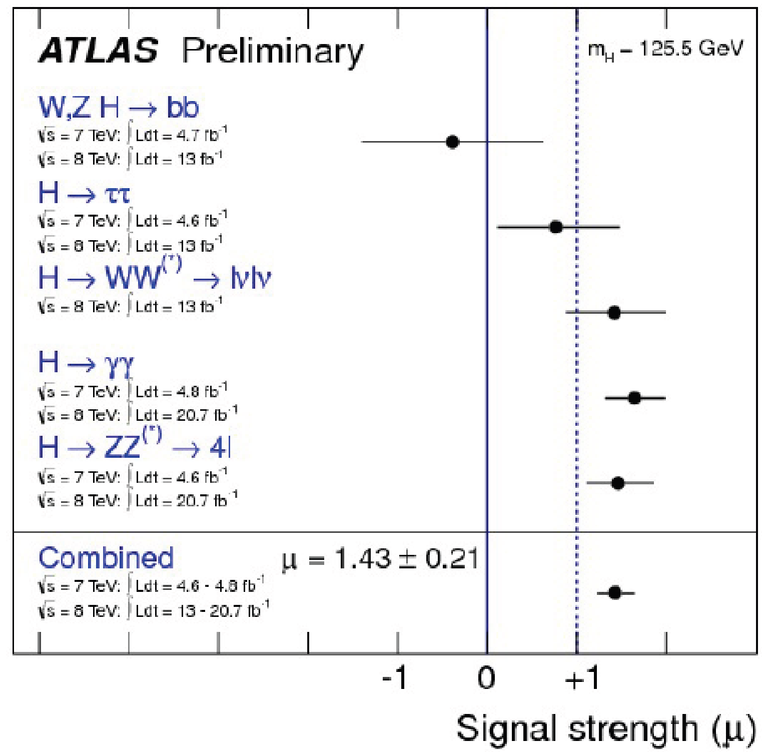
ATLAS

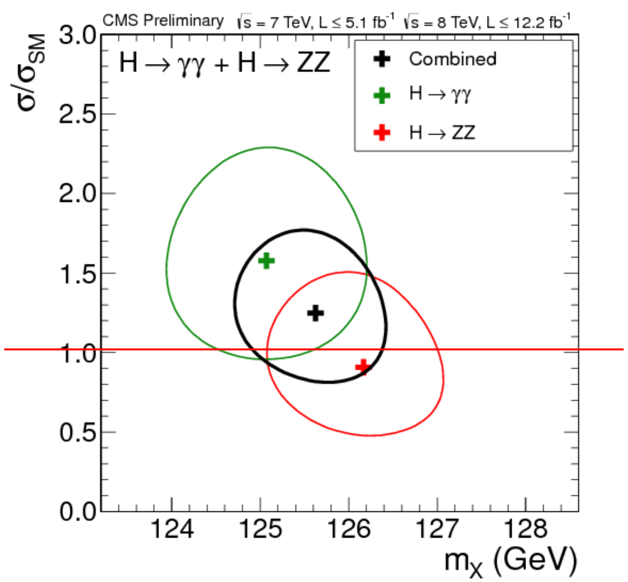


SM



CMS
(Dec 12)

SM



$M_h = 125.8 \pm 0.4 \pm 0.4$ GeV (CMS)
$\quad\;\; 125.5 \pm 0.2\ ^{+0.5}_{-0.6}$ GeV (ATLAS)

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