Perspective of extended Higgs sectors in beyond Standard Model scenarios

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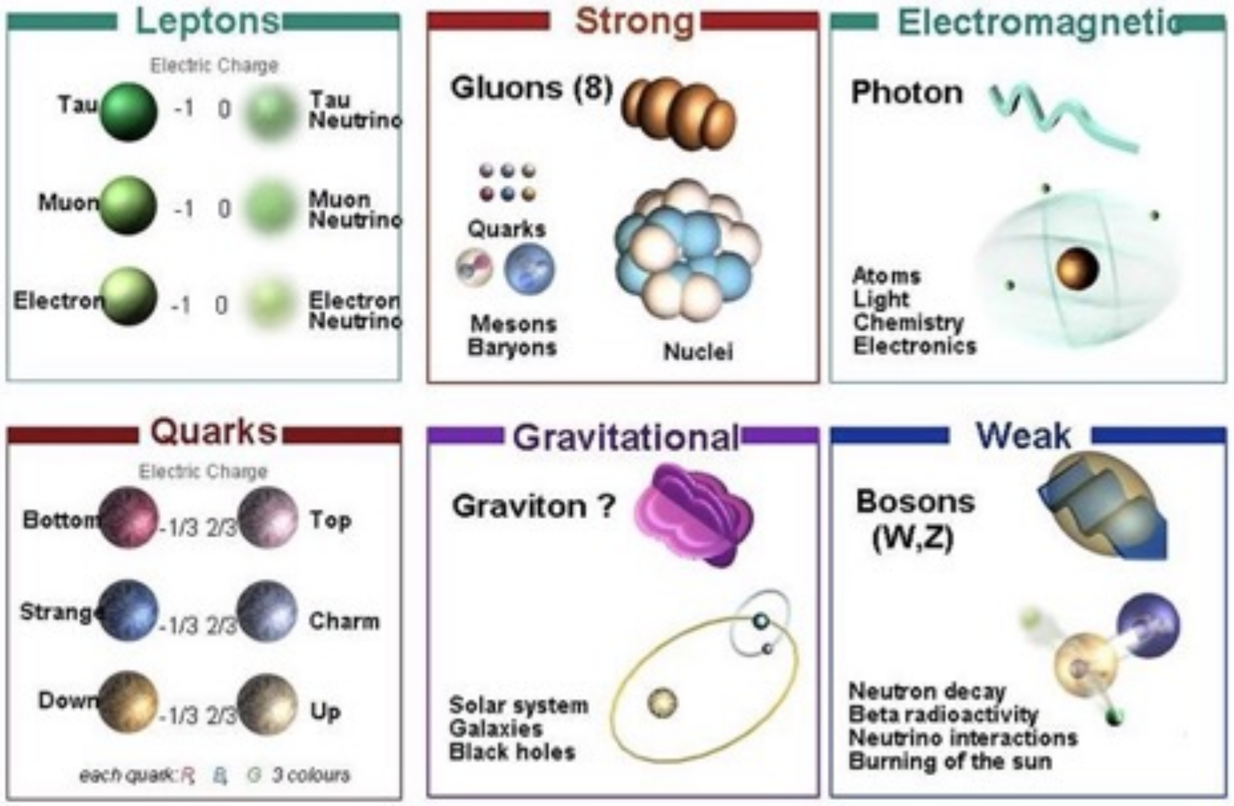
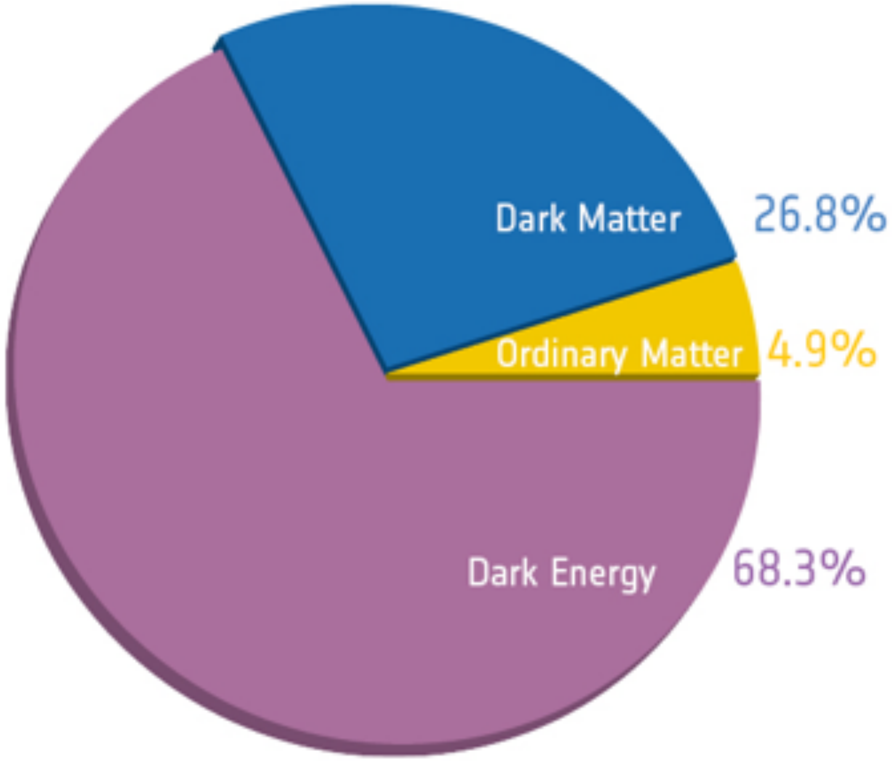
Plan

- Standard Model Higgs Boson
- Towards Higgs discovery and status
- Possible non-SUSY extensions in the Higgs sector
    - Singlet Higgs boson
    - Doublet Higgs boson
    - Triplet Higgs boson
    - Inert Higgs bosons
- Extended Higgs sectors with supersymmetry

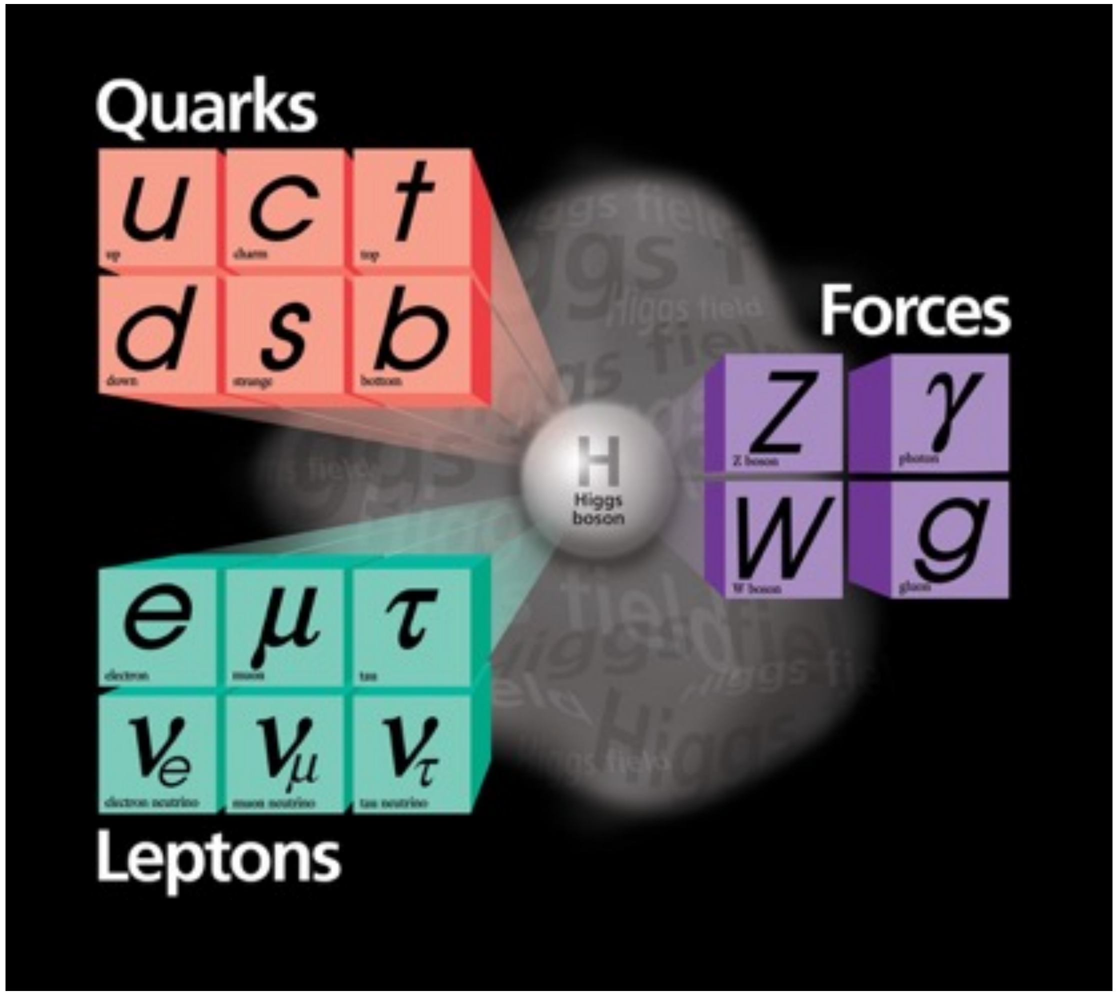
Forces of Nature





- 12 fermions constitute the matter.
- 12 gauge bosons are the force carriers
- They constitute the ~ 5% observed matter
- Unobserved matter, called as Dark Matter

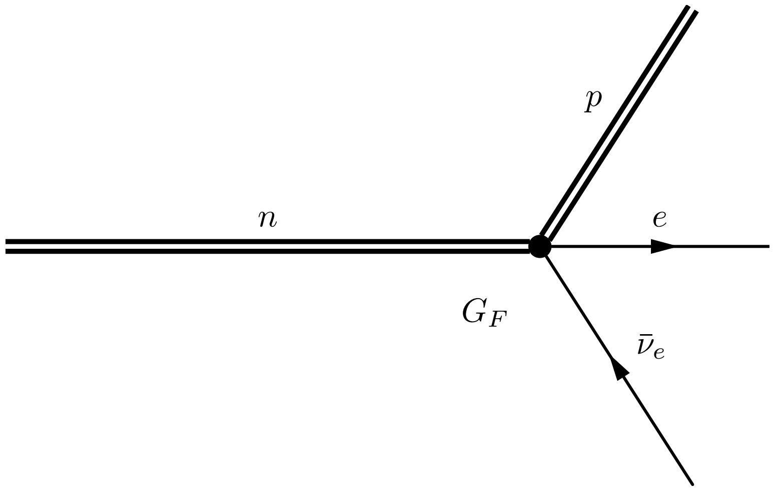
Particle physics is summarised as
‘Standard Model’

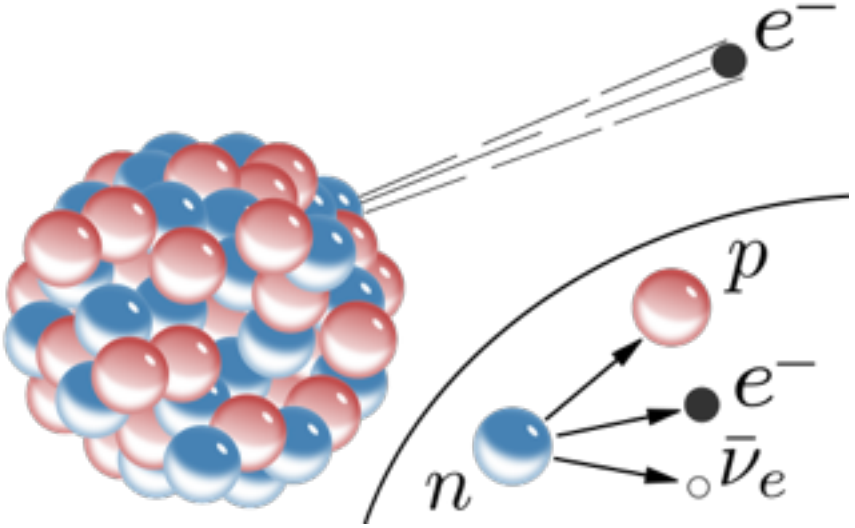


- Quarks come in pairs with charge 2/3 e and -1/3 e
- Each leptons has its own neutrinos
- Forces carriers communicate between the quarks and leptons

Fermi theory

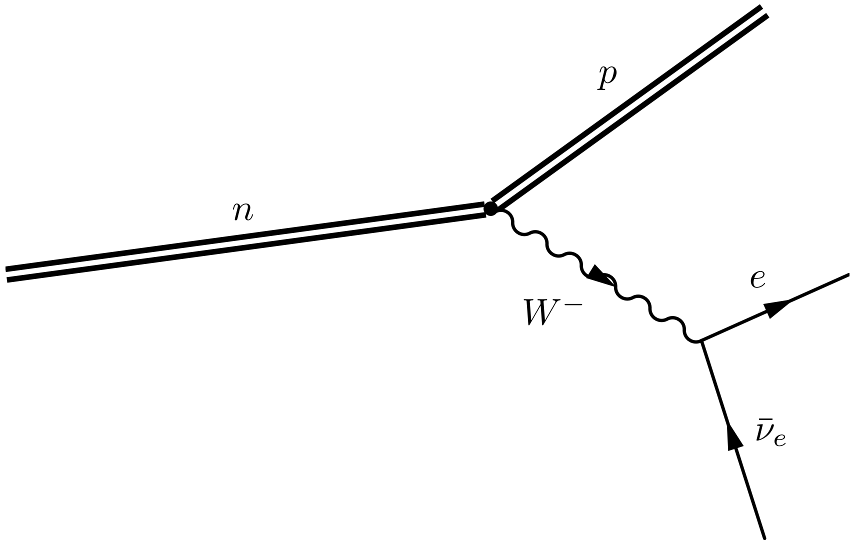
- Enrico Fermi in 1933 proposed theory for Nuclear beta decay with effective four fermion interaction





- That Fermi Theory can be seen as a result of exchange of force carrier

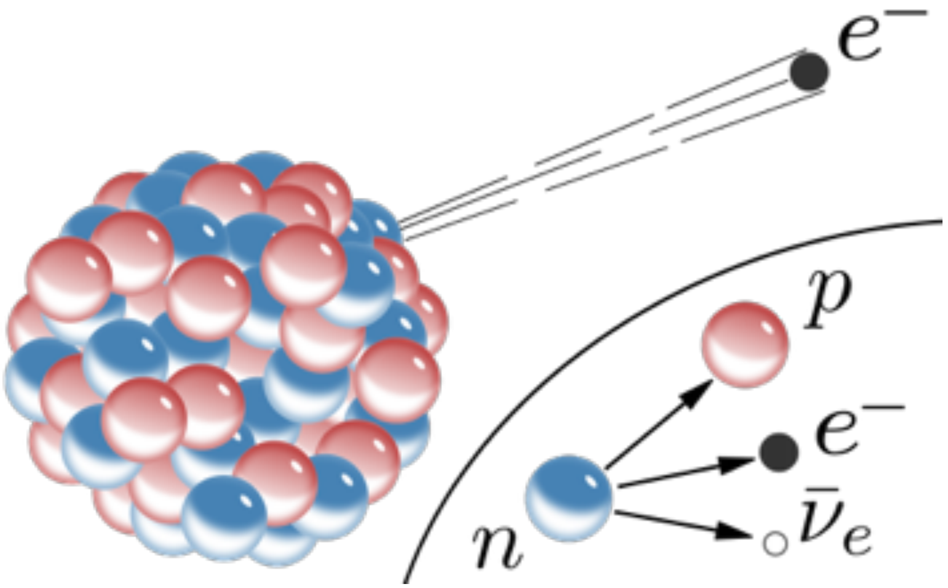
- A massive gauge boson W



With effective coupling

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2}$$

Fermi theory



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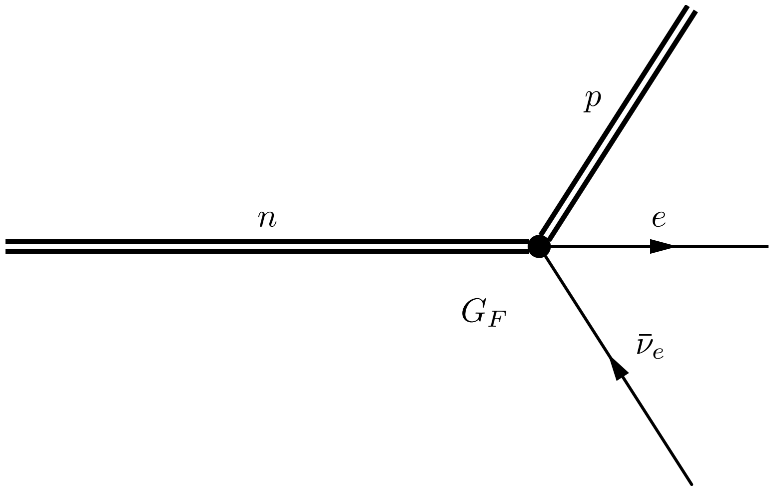
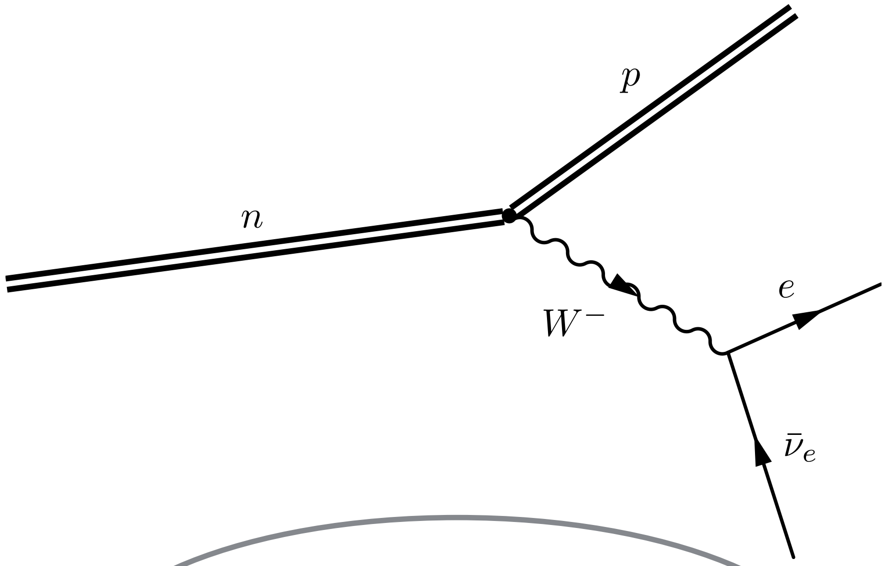




- That Fermi Theory can be seen as a result of exchange of force carrier

- A massive gauge boson W →

With effective coupling

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2} = \frac{1}{v^2}$$

It is related to Higgs mechanism

- Local gauge invariance of $SU(2)_L \times U(1)_Y$ gauge theory unifies electromagnetic and weak interactions
- Glashow, Weinberg, Salam were awarded the Nobel Prize in Physics in 1979
- In the same way local gauge invariance of SU(3) gauge group gives rise to Gluons

- Gauge theory describes the interaction between gauge bosons and fermions
- Leaves both the gauge bosons and fermions as massless

What we observed

- Gluon and photon are massless
- W/Z are required to be heavy

WHY ?

Why is Mass a Problem?

- Gauge invariance is guiding principle
- Mass term for gauge boson

$$\frac{1}{2}m^2 A_\mu A^\mu$$

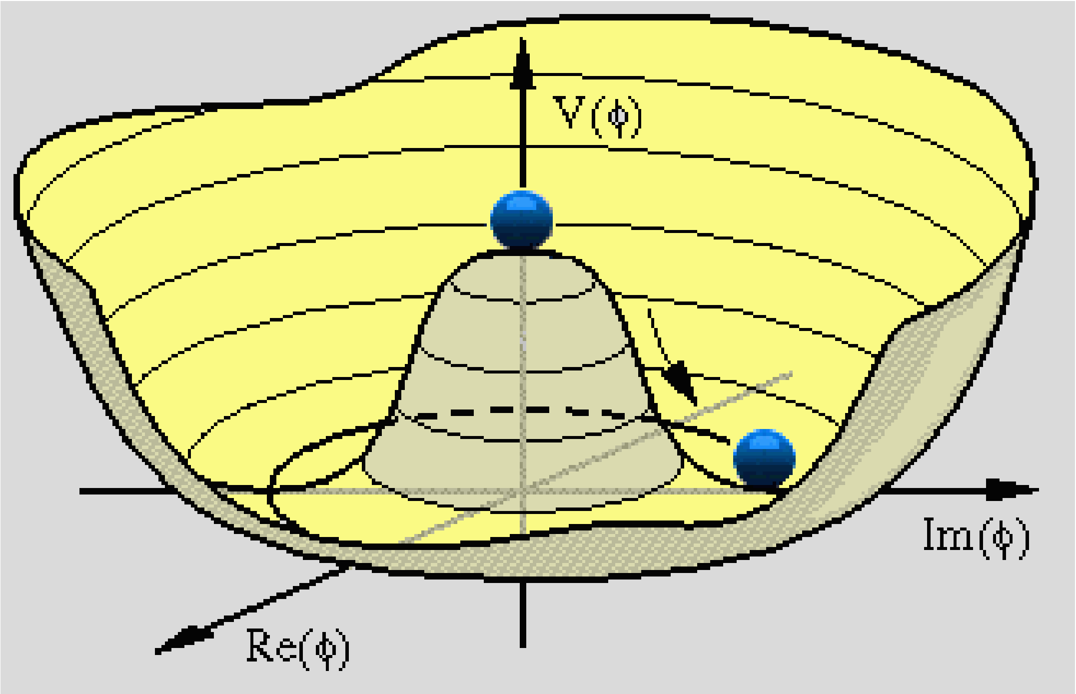
Violates gauge invariance

The explanation of this phenomenon leads to
Spontaneous Electro-Weak symmetry Breaking

Solution

- Lagrangian is gauge invariant at high scale

- Symmetry is broken only at the minima



$$SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$$

- Generates mass to the gauge bosons of the broken group

- Known as Higgs mechanism

- $U(1)_{\rm EM}$ is unbroken so photon remains massless

Standard Model Higgs boson

- Standard Model has a complex scalar SU(2) doublet

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

- The scalar Lagrangian density is given by

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \mid \Phi^\dagger \Phi \mid - \lambda \Big(\mid \Phi^\dagger \Phi \mid \Big)^2 ,$$

where,

$$D_\mu = \partial_\mu - i \frac{g_2}{2} \tau \cdot W_\mu - i \frac{g_1}{2} B_\mu Y \, .$$

- At the minimum, $<\Phi^+\Phi> = v^2 = \sqrt{-\frac{\mu^2}{2\lambda}}$, $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$

$$\mathcal{L}_s = \frac{1}{2} \partial^\mu h \partial_\mu h + \frac{(v+h)^2}{4} [g_2^2 W^{-\mu} W^+_\mu + \frac{1}{2}(g_2^2 + g_1^2) Z^\mu Z_\mu] + \lambda v^2 h^2 + \lambda v h^3$$

- The gauge bosons and fermions become massive

$$\mathcal{L}_{Yuk} = -\frac{y_f}{\sqrt{2}} (v+h) \bar{f} f$$

- The Higgs mass is given by $m_H = 2\,\lambda v^2$

Higgs mechanism: an analogy

- Any field that couples to the Higgs field gets mass!

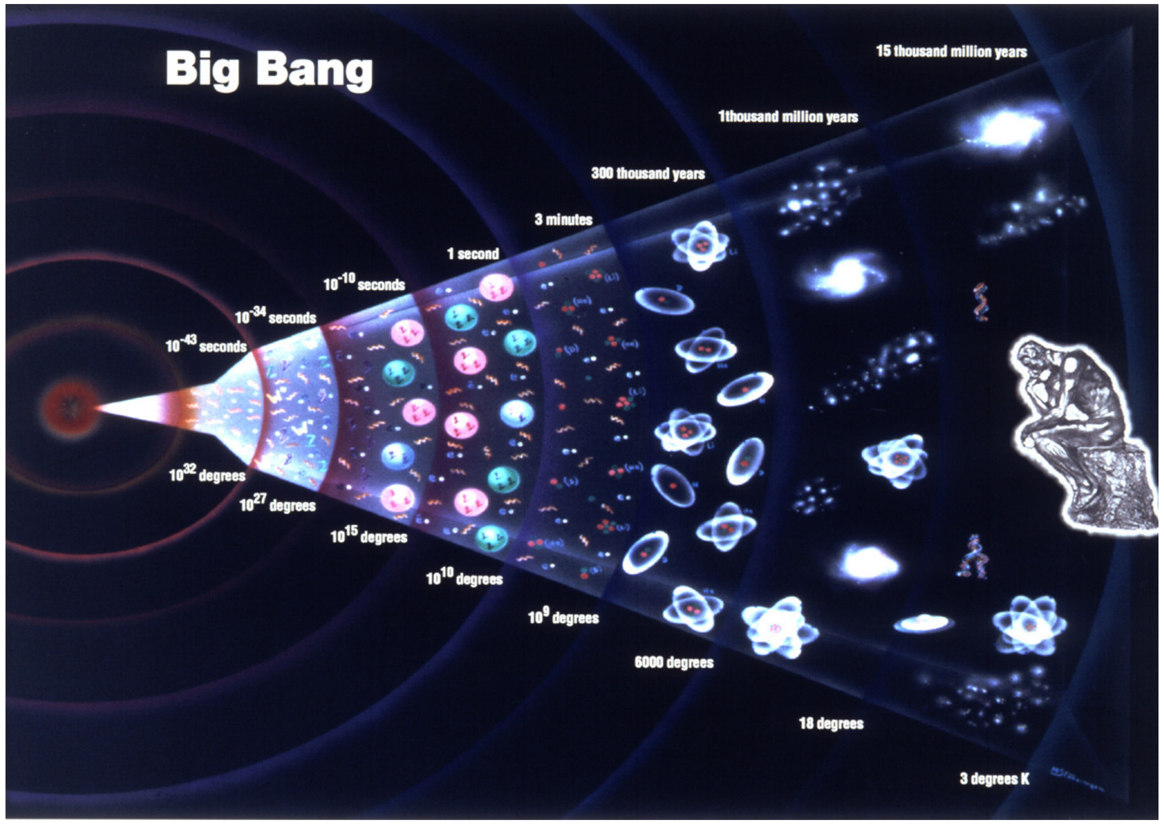
- Higgs field also gives mass to itself

Hunt for Higgs boson!

It took almost 50 years!

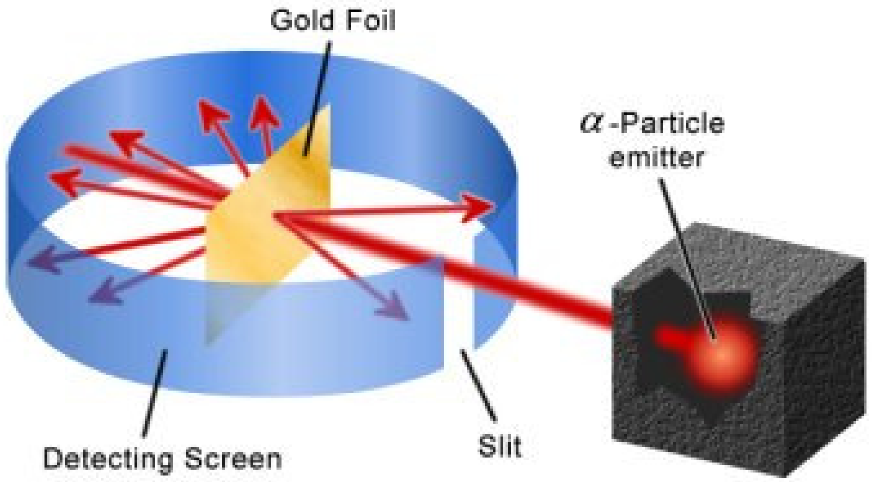
Looking back in our universe

- Popular Big bang theory predicts that universe was created by a big bang around 13.7 billion years ago



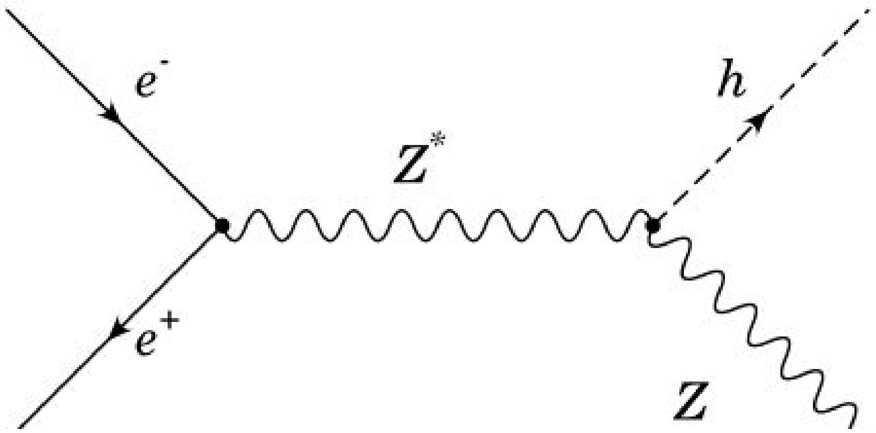
How to rediscover the theory?

- We have to look inside the matter
- Rutherford first collided alpha particles to the gold foil to see inside the atom
- Present day colliders are using the same technology



Large electron positron collider (LEP)

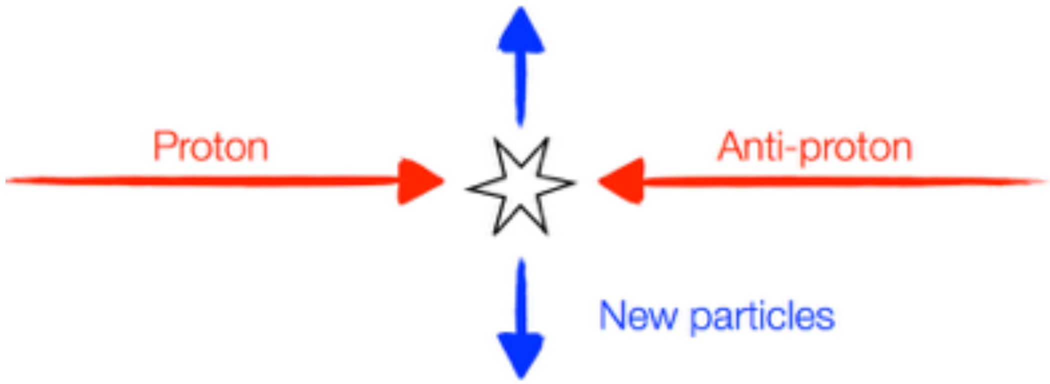
- It was a electron-positron collider at CERN
- It ran till 2000 with energy reached to 209 GeV
- LEP searched for Higgs boson



- Put a lower bound on the mass $m_H > 114.4$ GeV

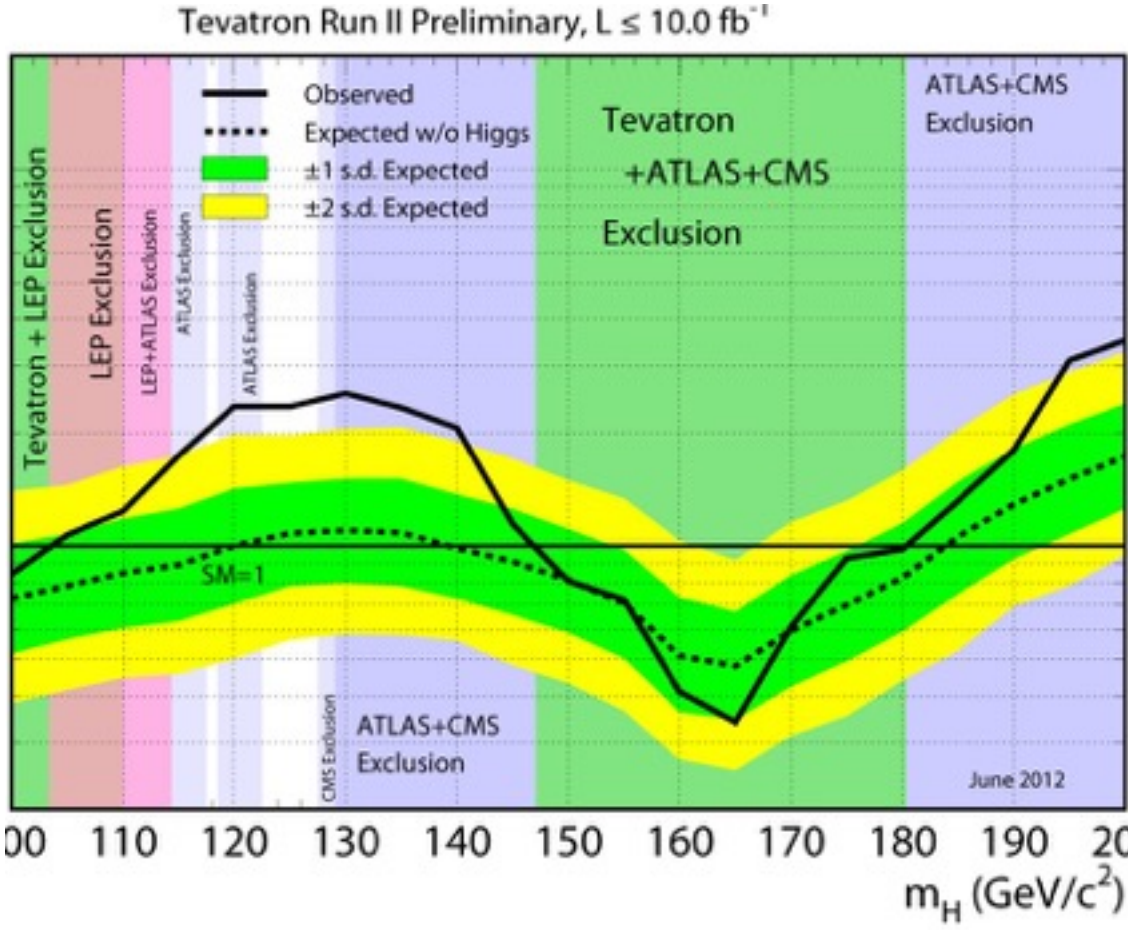
Tevatron

- It was a proton anti-proton collider at Fermilab with energy reached till ~ 2 TeV



- It discovered ‘top’ quark the missing Standard Model quark.

- It could not find the Higgs boson but put some exclusion limits.

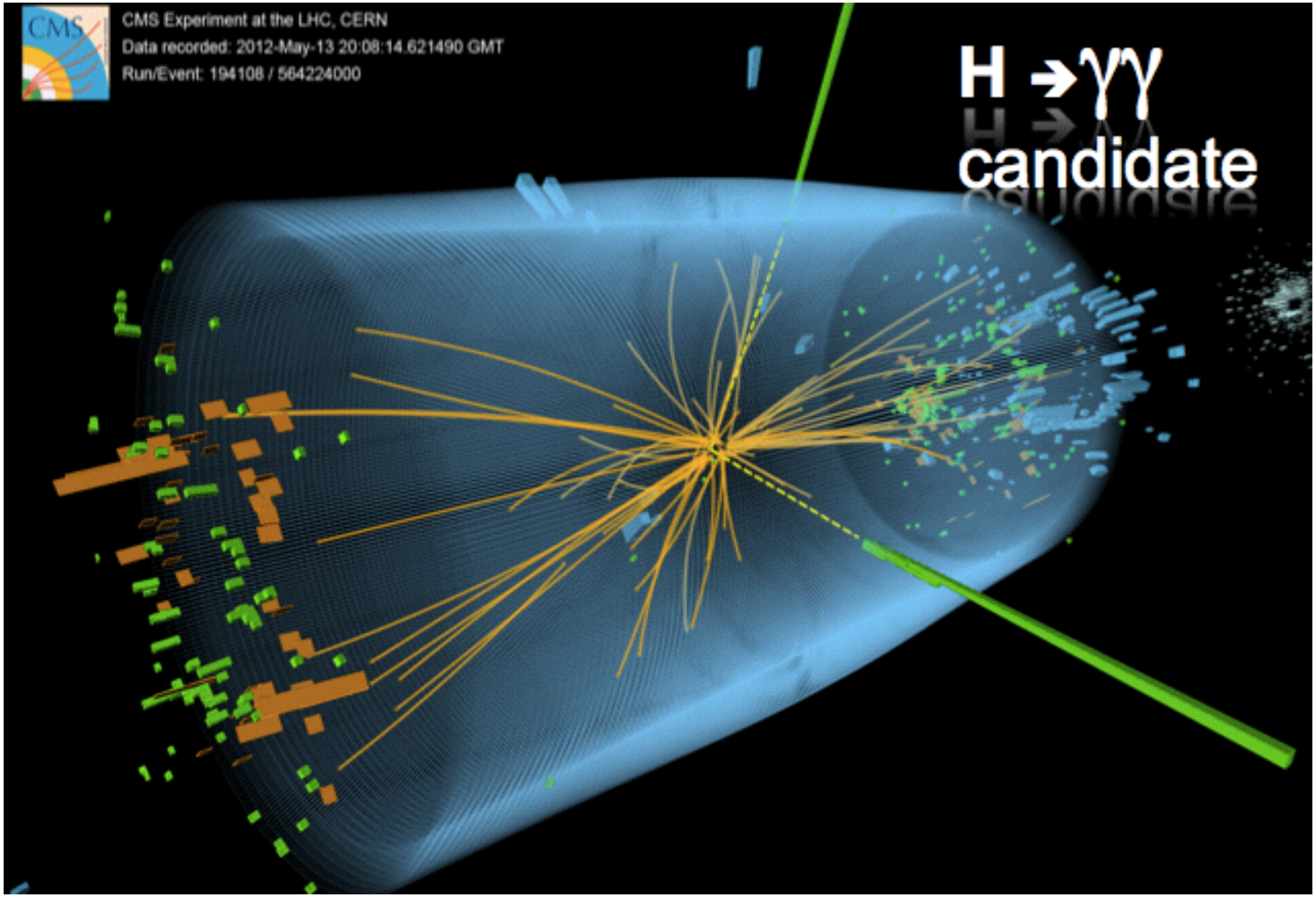


Large Hadron Collider (LHC)

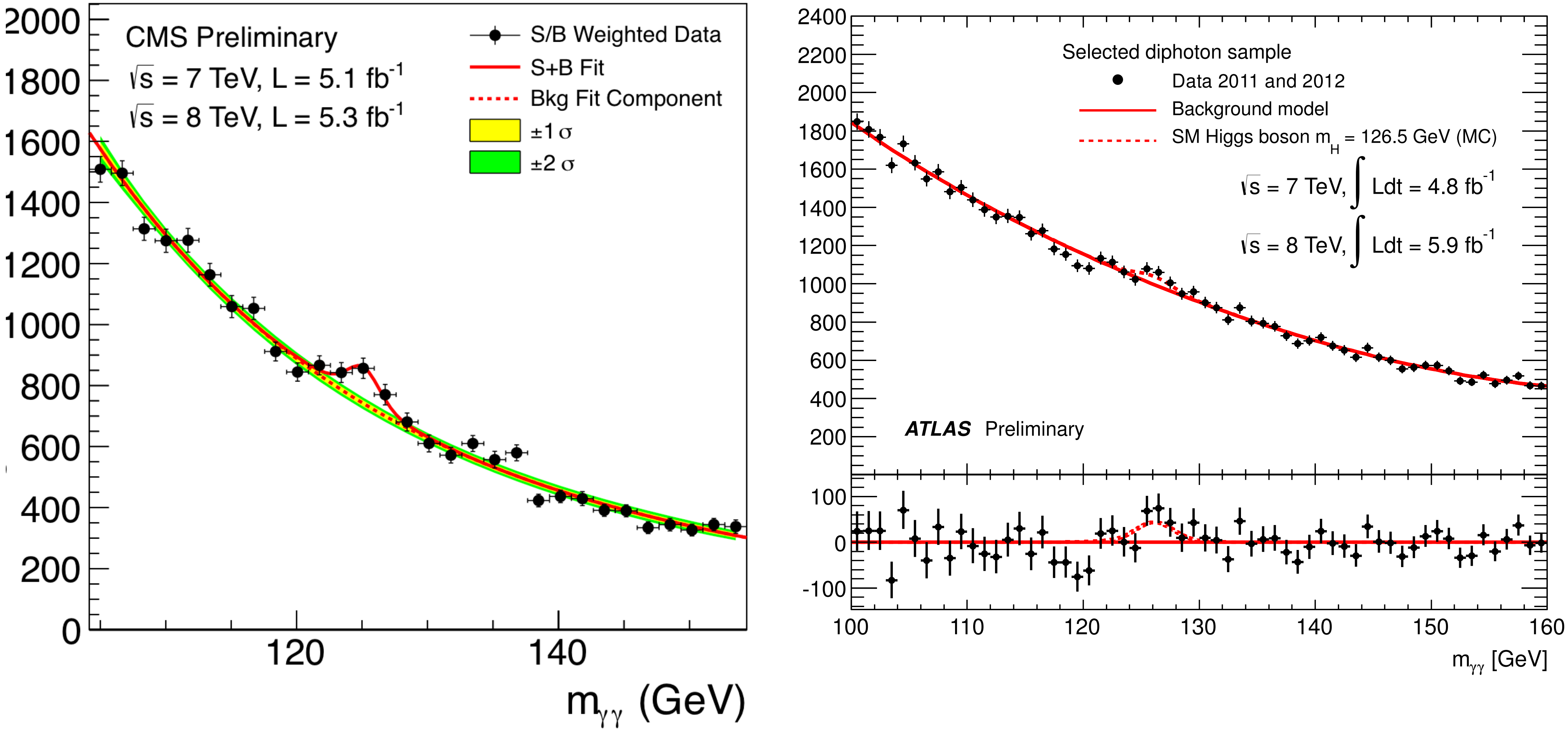
- It is a proton proton collider
- It lies in a tunnel of 27 km in circumference, around 100 m beneath the Franco-Swiss border near Geneva, Switzerland.
- It has four main detectors

  CMS, ATLAS, ALICE and LHCb
- It finished run of centre of mass energy of 7 and 8 TeV
- Currently running with 13 TeV of centre of mass energy.

We first observed Higgs boson in di-photon mode



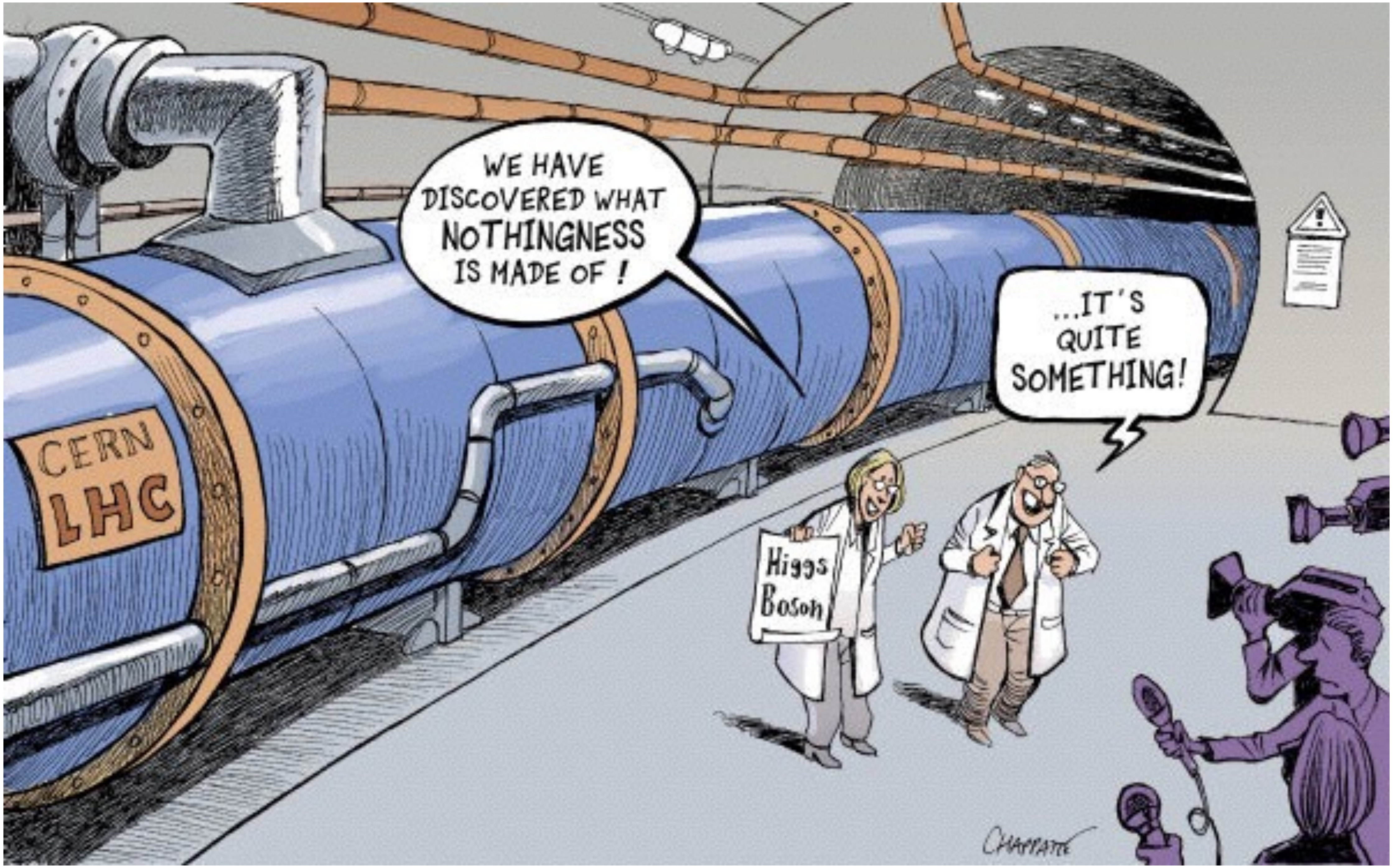
Discovery of Higgs boson



- ATLAS reported discovery of spin even-integer-spin particle with mass of 126.5 GeV at 5.0σ

- CMS finds a particle with a mass of 125.3 ± 0.6 GeV with 4.9σ significance.

4th July, 2012

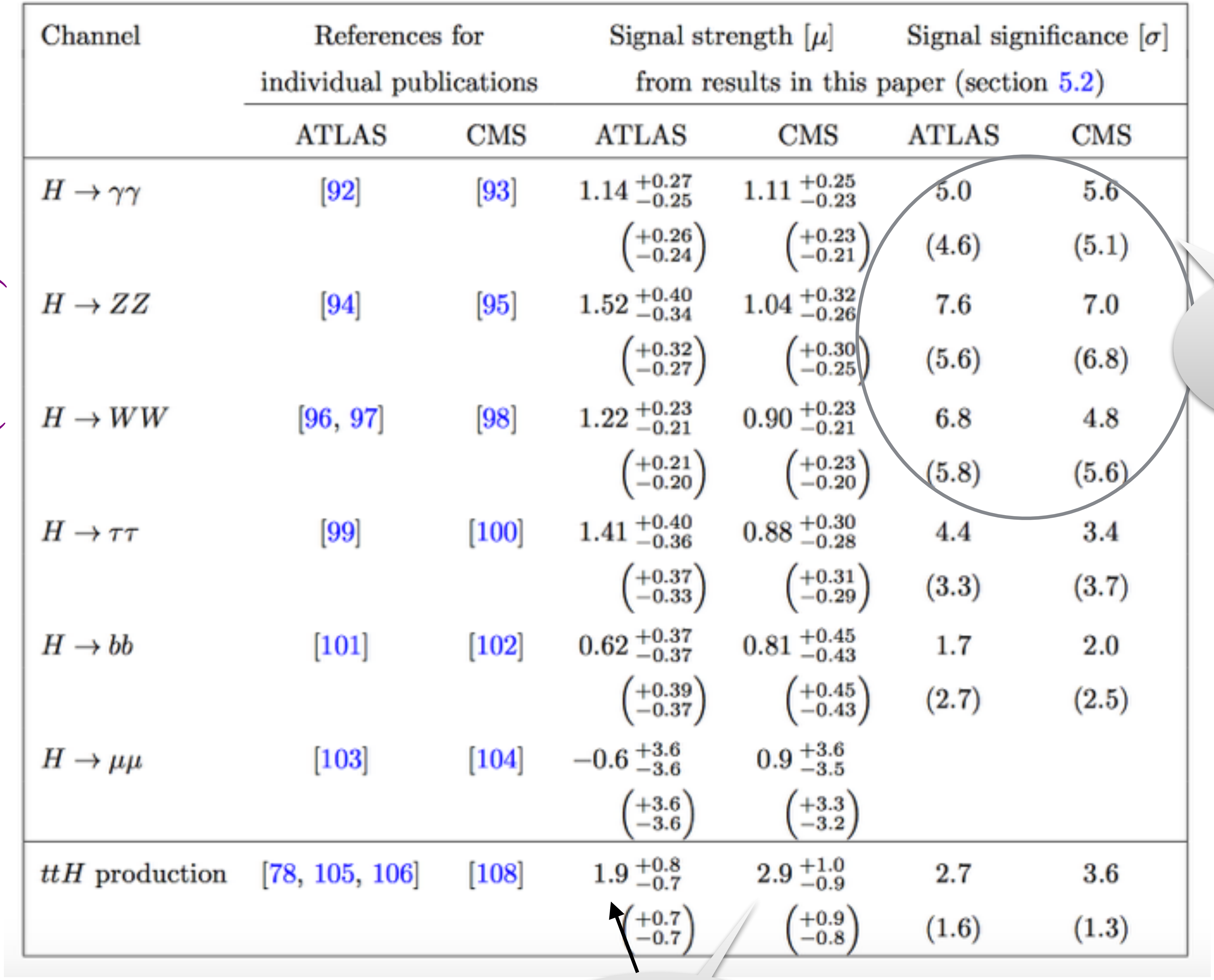


The real announcement

- Peter Higgs and François Englert were given Nobel Prize in 2013

Status of Standard Model Higgs

*JHEP*08(2016)045



Channel	References for		Signal strength [μ]		Signal significance [σ]	
	individual publications		from results in this paper (section 5.2)			
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[92]	[93]	$1.14^{+0.27}_{-0.25}$	$1.11^{+0.25}_{-0.23}$	5.0	5.6
			$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.23}_{-0.21}\right)$	(4.6)	(5.1)
$H \to ZZ$	[94]	[95]	$1.52^{+0.40}_{-0.34}$	$1.04^{+0.32}_{-0.26}$	7.6	7.0
			$\left(^{+0.32}_{-0.27}\right)$	$\left(^{+0.30}_{-0.25}\right)$	(5.6)	(6.8)
$H \to WW$	[96, 97]	[98]	$1.22^{+0.23}_{-0.21}$	$0.90^{+0.23}_{-0.21}$	6.8	4.8
			$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	[99]	[100]	$1.41^{+0.40}_{-0.36}$	$0.88^{+0.30}_{-0.28}$	4.4	3.4
			$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	[101]	[102]	$0.62^{+0.37}_{-0.37}$	$0.81^{+0.45}_{-0.43}$	1.7	2.0
			$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	[103]	[104]	$-0.6^{+3.6}_{-3.6}$	$0.9^{+3.6}_{-3.5}$		
			$\left(^{+3.6}_{-3.6}\right)$	$\left(^{+3.3}_{-3.2}\right)$		
ttH production	[78, 105, 106]	[108]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.9}_{-0.8}\right)$	(1.6)	(1.3)

5σ
discovery

Excess!

Does discovery of Higgs boson complete the Standard Model?

Well !

We have to look into other problems inside SM

A little list of problems

Dark Matter

Tiny neutrino masses

Higgs mass Hierarchy

Fermion mass hierarchy

.

Does Higgs potential say something?

Quantum corrections can limit the theory as well as the predictions

See Dr. Tirtha S. Ray's talk

Standard Model Higgs potential

$$V(\Phi)=\mu^2|\Phi^+\Phi| + \lambda\,(|\Phi^+\Phi|)^2$$

SM Higgs potential faces strong constraints

1. From triviality
2. Vacuum Stability
3. Unitarity (covered by Dr. Tirtha S. Ray)

This is due to the running of couplings.

At large field values $\mu\frac{d\lambda}{d\mu} \simeq \frac{3}{3\pi^2}\lambda^2$

$$\lambda(\mu) = \frac{\lambda(v)}{1 - \frac{3}{2\pi^2}\lambda(v)\ln\frac{\mu}{v}}$$

- At some scale $\mu = \Lambda,$ $\lambda(\mu)$ diverges, hitting the Landau pole.

Higgs mass bounds from Triviality

$$\Lambda \sim ve^{\frac{2\pi^2}{3\lambda}} = ve^{\frac{4\pi^2 v^2}{3m_h^2}}$$

Where we use $m_h^2 = 2\lambda v^2$

- This leads to upper bounds on the Higgs boson mass $m_h^2 < \frac{4\pi^2 v^2}{3\ln\frac{\Lambda}{v}}$

- The following bounds can be derived from the above expressions

$$\Lambda \sim 10^3 \mathrm{GeV} \Rightarrow \mathrm{m_h} < 700\mathrm{GeV}$$

$$\Lambda \sim 10^8 \mathrm{GeV} \Rightarrow \mathrm{m_h} < 246\mathrm{GeV}$$

$$\Lambda \sim 10^{24} \mathrm{GeV} \Rightarrow \mathrm{m_h} < 125\mathrm{GeV}$$

Stability bounds

- Higgs couples to fermions via Yukawa couplings

$$\mathcal{L}_Y = Y_t \bar{Q} \phi t_R$$

- At low values the top quark λ contribution is important

$$\mu \frac{d\lambda}{d\mu} \simeq -\frac{3}{8\pi^2} Y_t^4$$

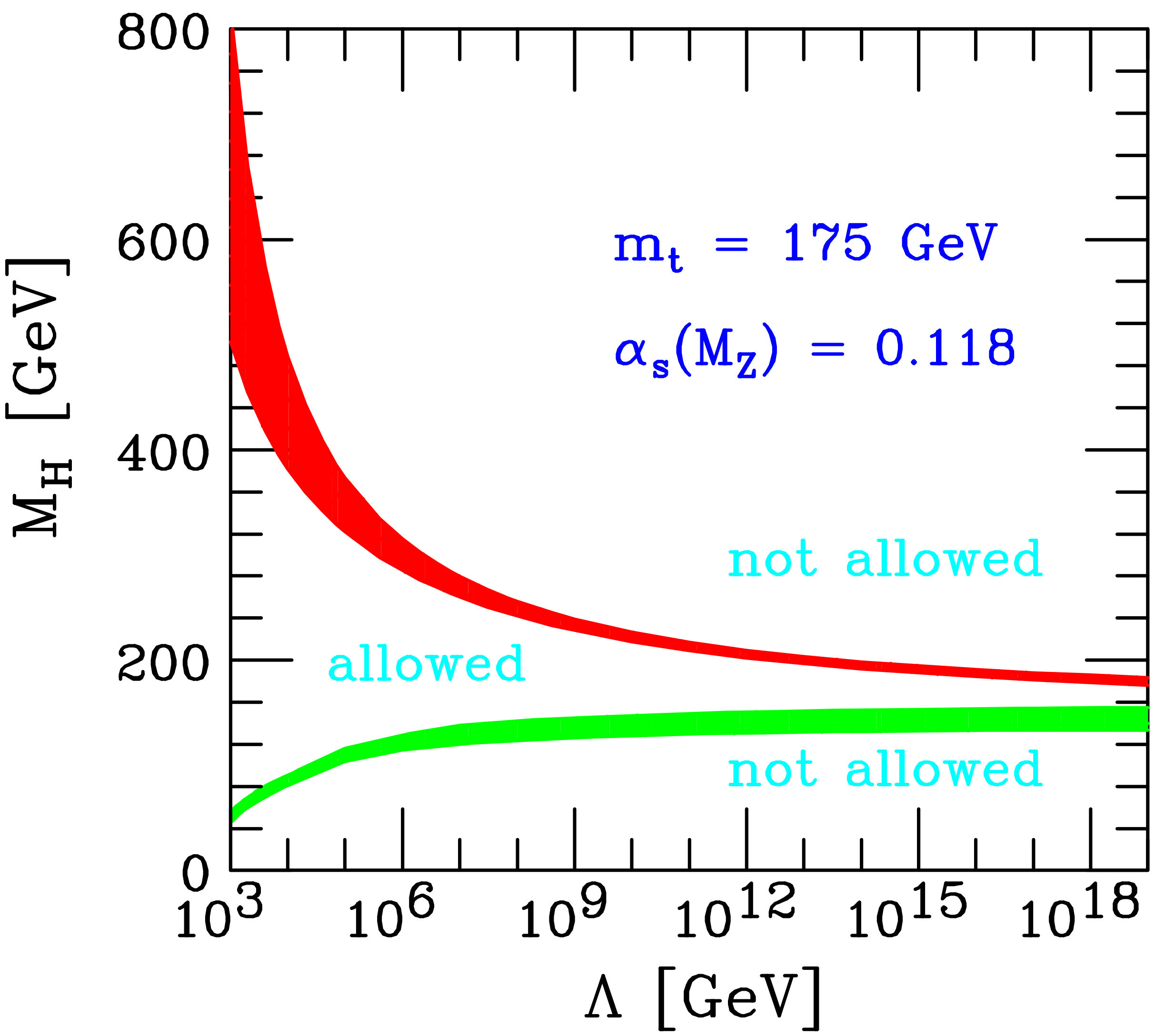
- The solution takes a form,

$$\lambda(\mu) = \lambda - \frac{3}{8\pi^2} \lambda_t^4 \ln \frac{\mu}{v}$$

where at some point we hit $\lambda(\mu) < 0$, leading instability to Higgs potential

$$m_h^2 > \frac{3m_t^2}{\pi^2 v^2} \ln \frac{\Lambda}{v}$$

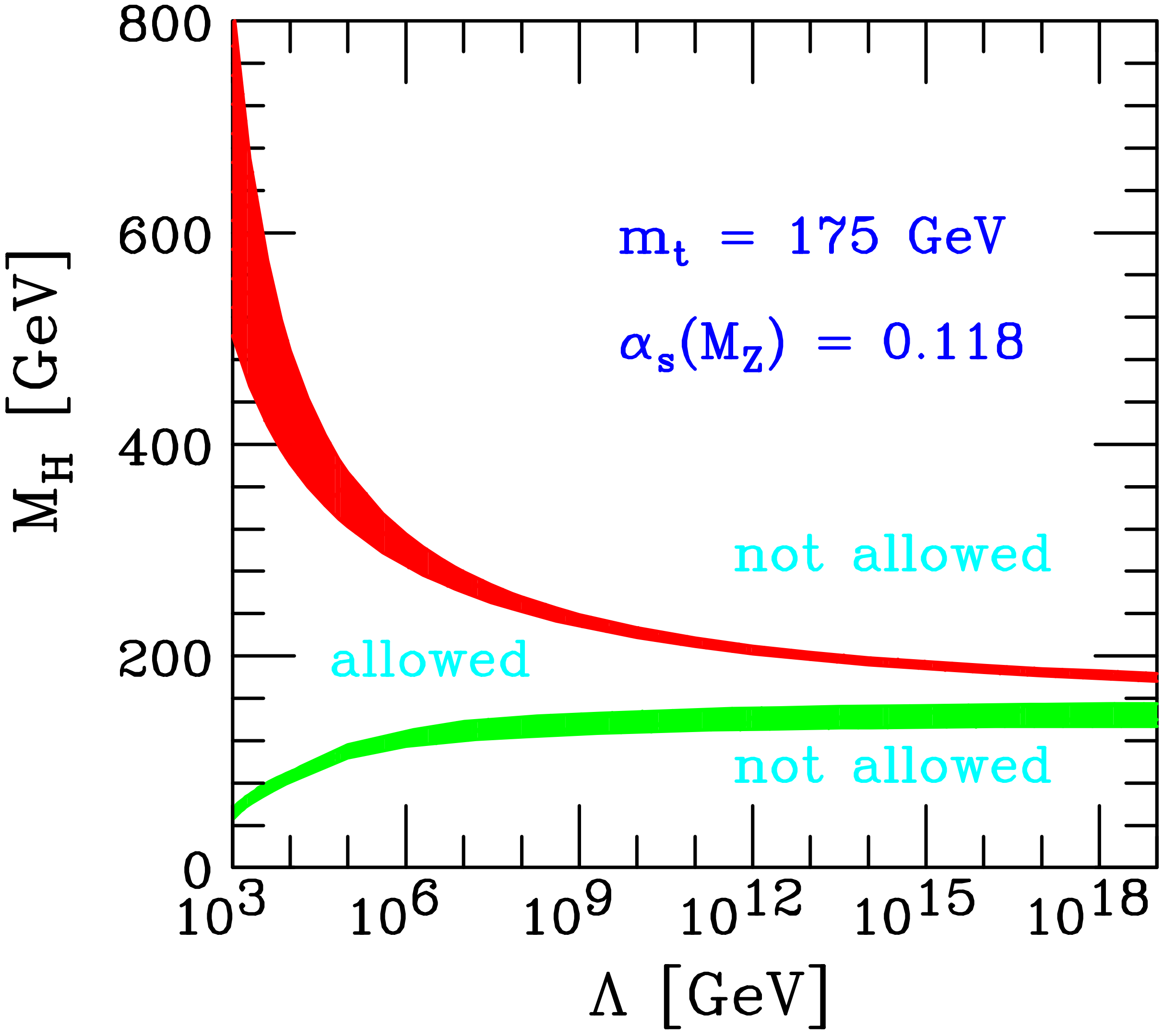
Theoretical Prediction of Higgs boson mass



- Perturbative unitarity ⇒ $m_H < 870$ GeV
- Triviality ⇒ $m_H < 160$ GeV
- Stability ⇒ $m_H > 126$ GeV.

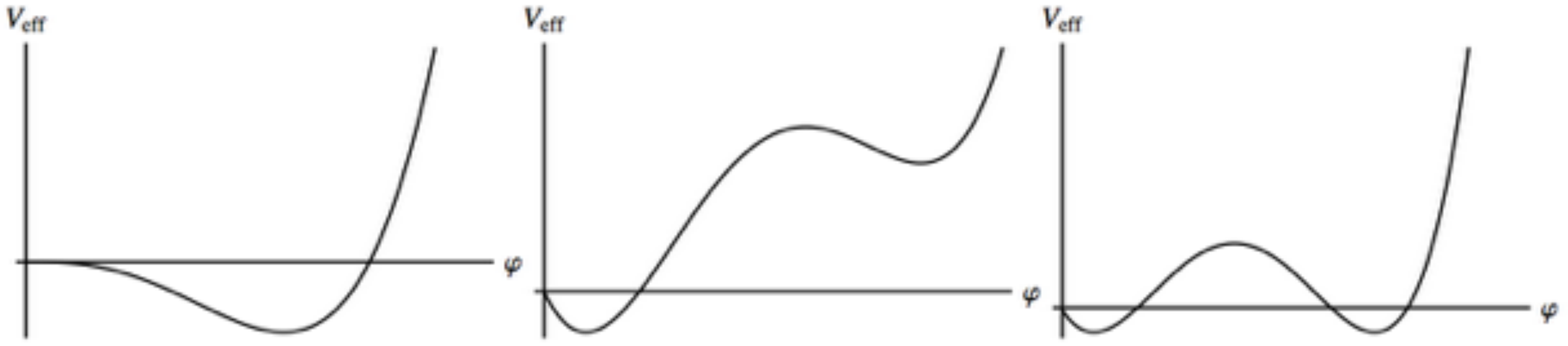
Generic guide lines of SM extensions

- Any addition of scalar will enhance the stability of the potential for larger scale.
- Any addition with fermions with large Yukawa can turn λ negative making the potential unstable.

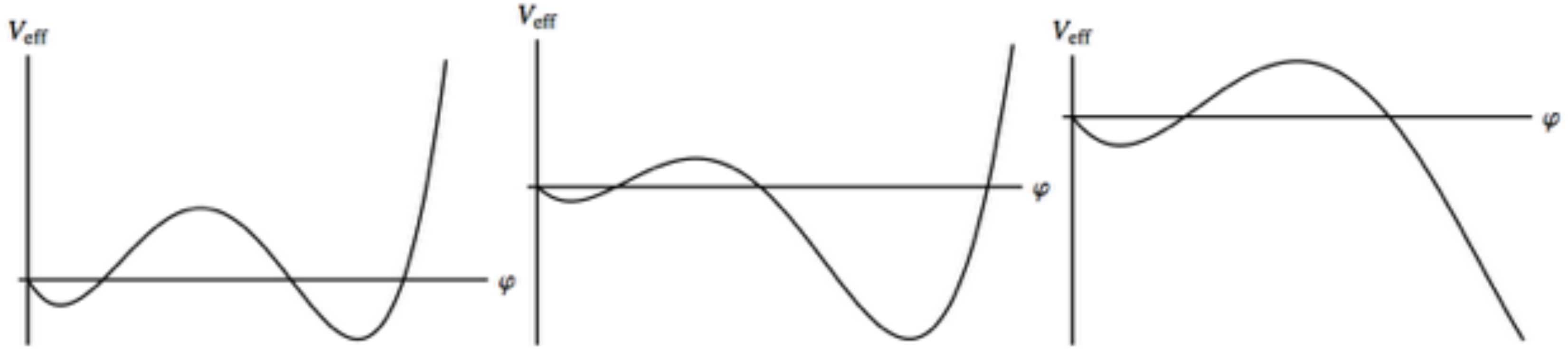


Extending Higgs sector will affect vacuum stability

Possible Potentials



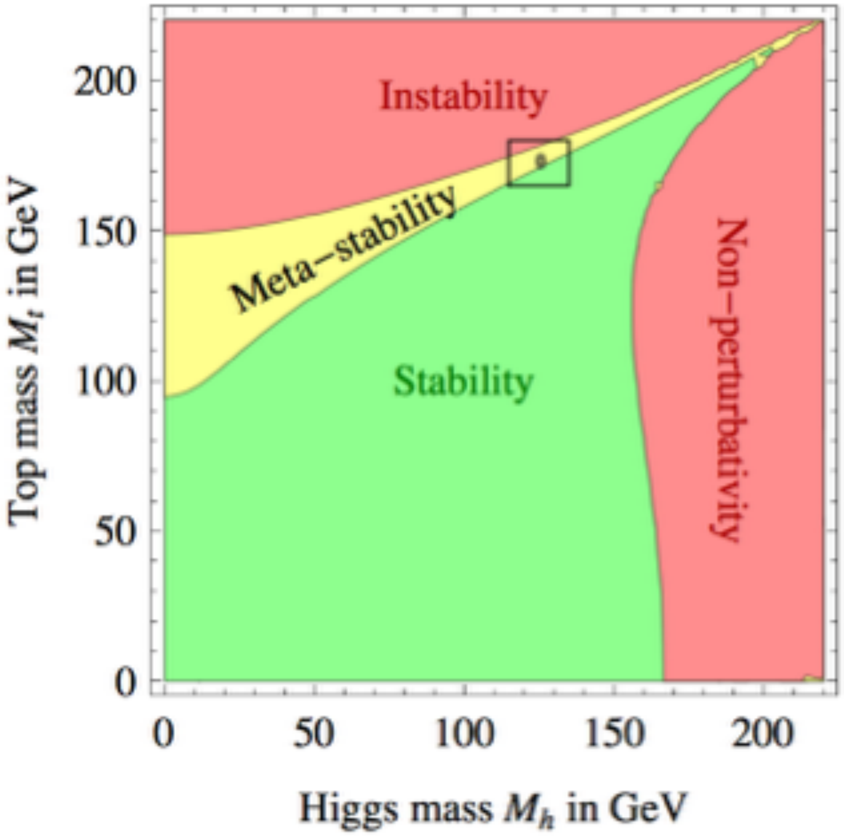
(a) stable (b) stable (c) metastable

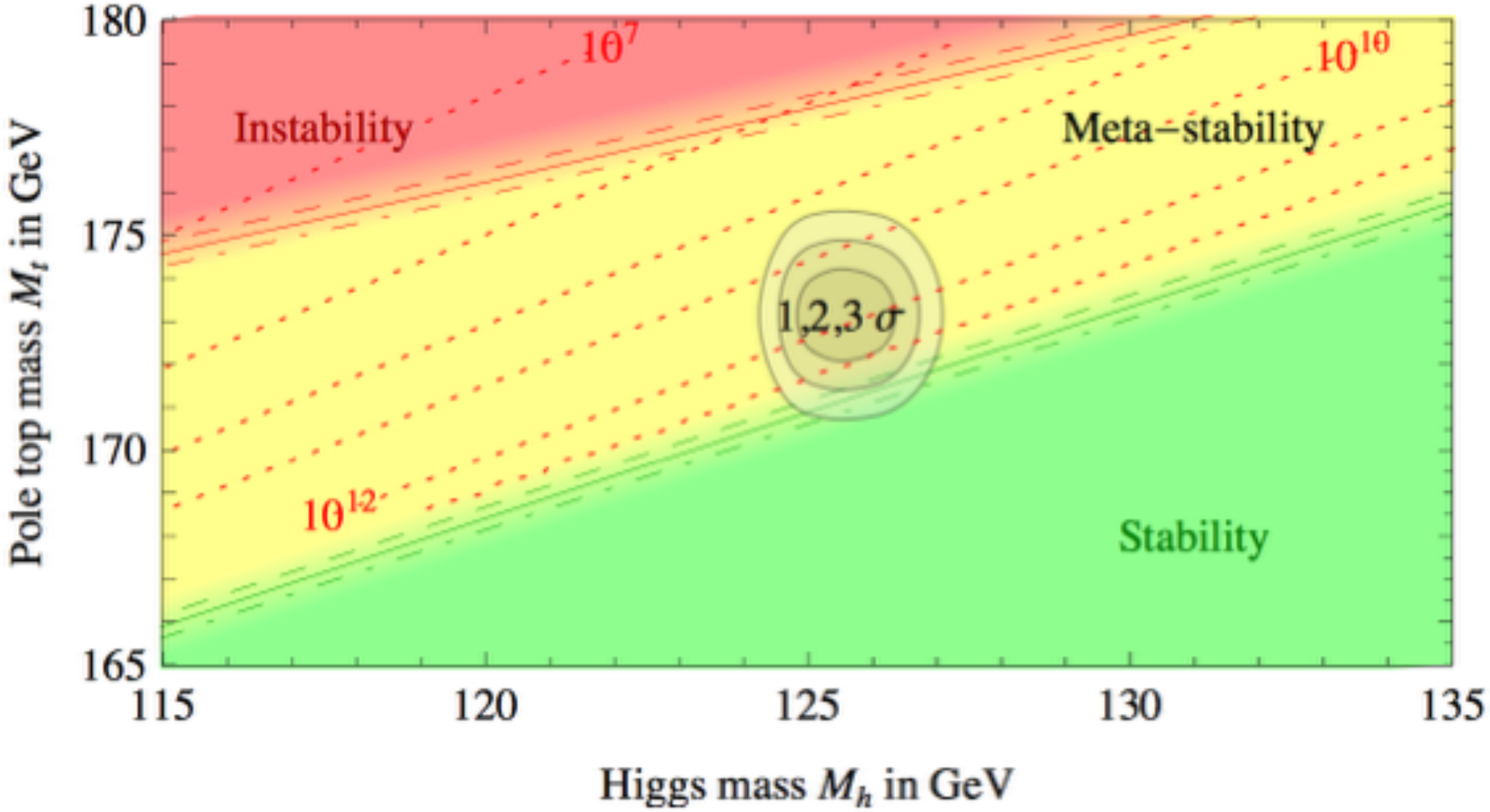


(d) metastable (e) unstable (f) unstable

- Various configurations of the effective potential.
- Local minimum near the original is the electroweak vacuum.

Status of SM

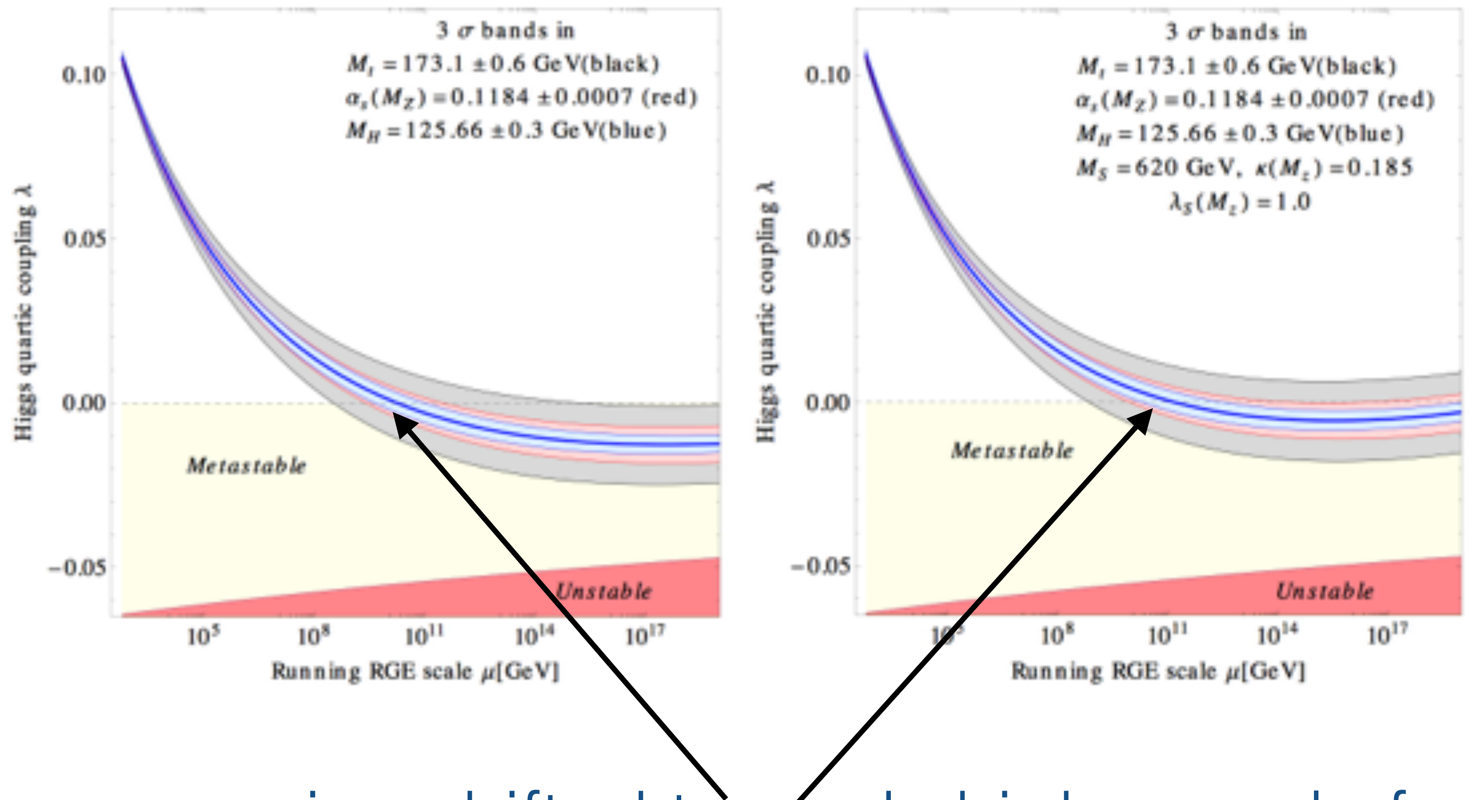




Within the uncertainty of top mass we are in a metastable vacuum

SM+ Singlet

$$V(\phi, S) = \mu^2|\phi|^2 + \lambda|\phi|^4 + m_S^2 S^2 + \lambda_{S\phi} S^2|\phi^2| + \lambda_S S^4$$



Khan et al, PRD 90, 113008 (2014)

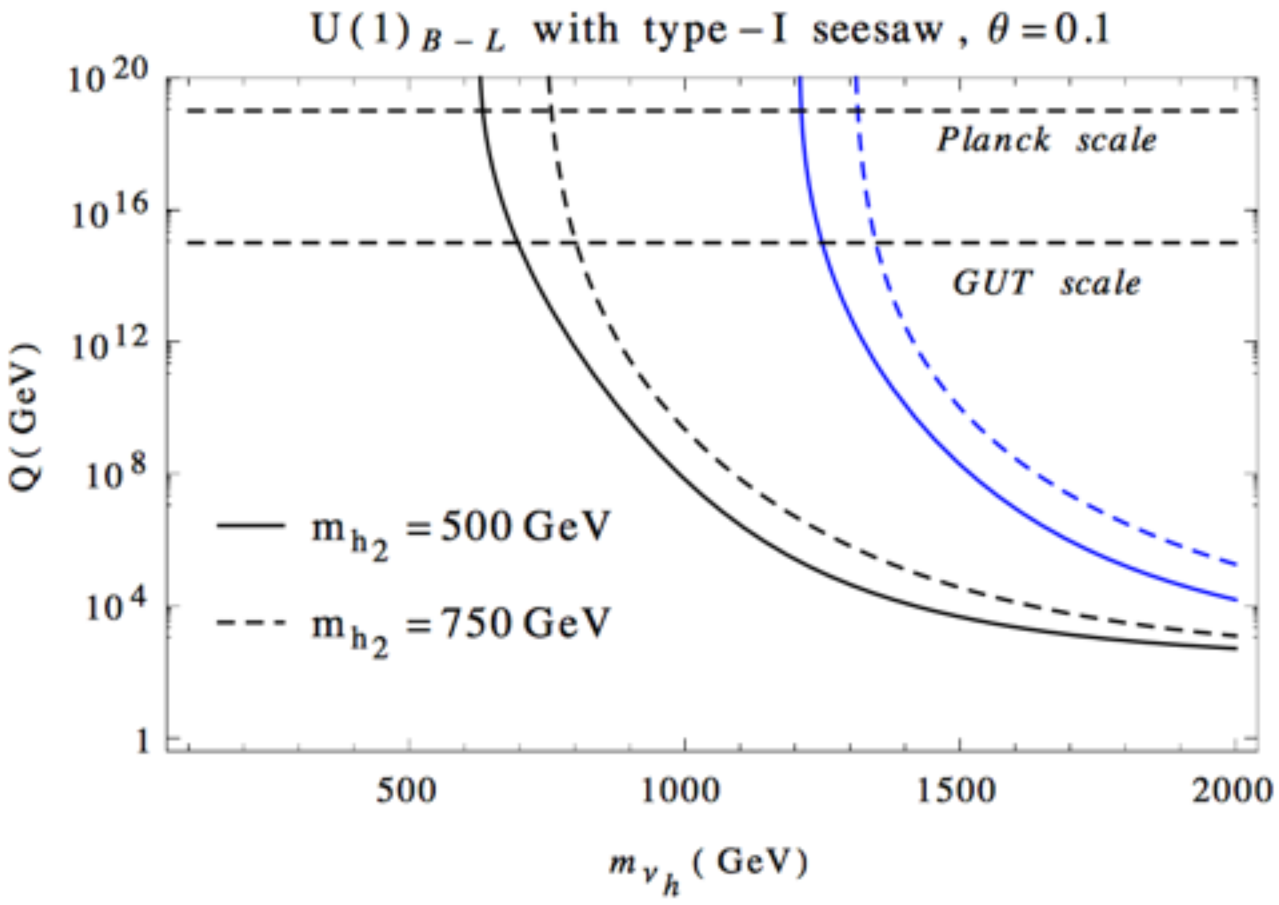
Cross over region shifted towards higher scale from SM

Scalar extension with right-handed neutrino

$$V(H,\chi) = m_1^2 H^\dagger H + m_2^2 \chi^\dagger \chi + \lambda_1 (H^\dagger H)^2 + \lambda_2 (\chi^\dagger \chi)^2 + \lambda_3 (H^\dagger H)(\chi^\dagger \chi)$$

$$-\mathcal{L}_Y = Y_d^{ij}\,\overline{Q_L^i} H d_R^j + Y_u^{ij}\,\overline{Q_L^i}\tilde{H} u_R^j + Y_e^{ij}\,\overline{L^i} H e_R^j + Y_\nu^{ij}\,\overline{L^i}\tilde{H}\nu_R^j + Y_N^{ij}\,\overline{(\nu_R^i)^c}\nu_R^j \chi + h.c.$$

$$\beta^{(1)}_{\lambda_1} \simeq \lambda_3^3 - 6Y_t^4 \qquad \beta^{(1)}_{\lambda_2} \simeq 2\lambda_3^3 - 48Y_N^4$$



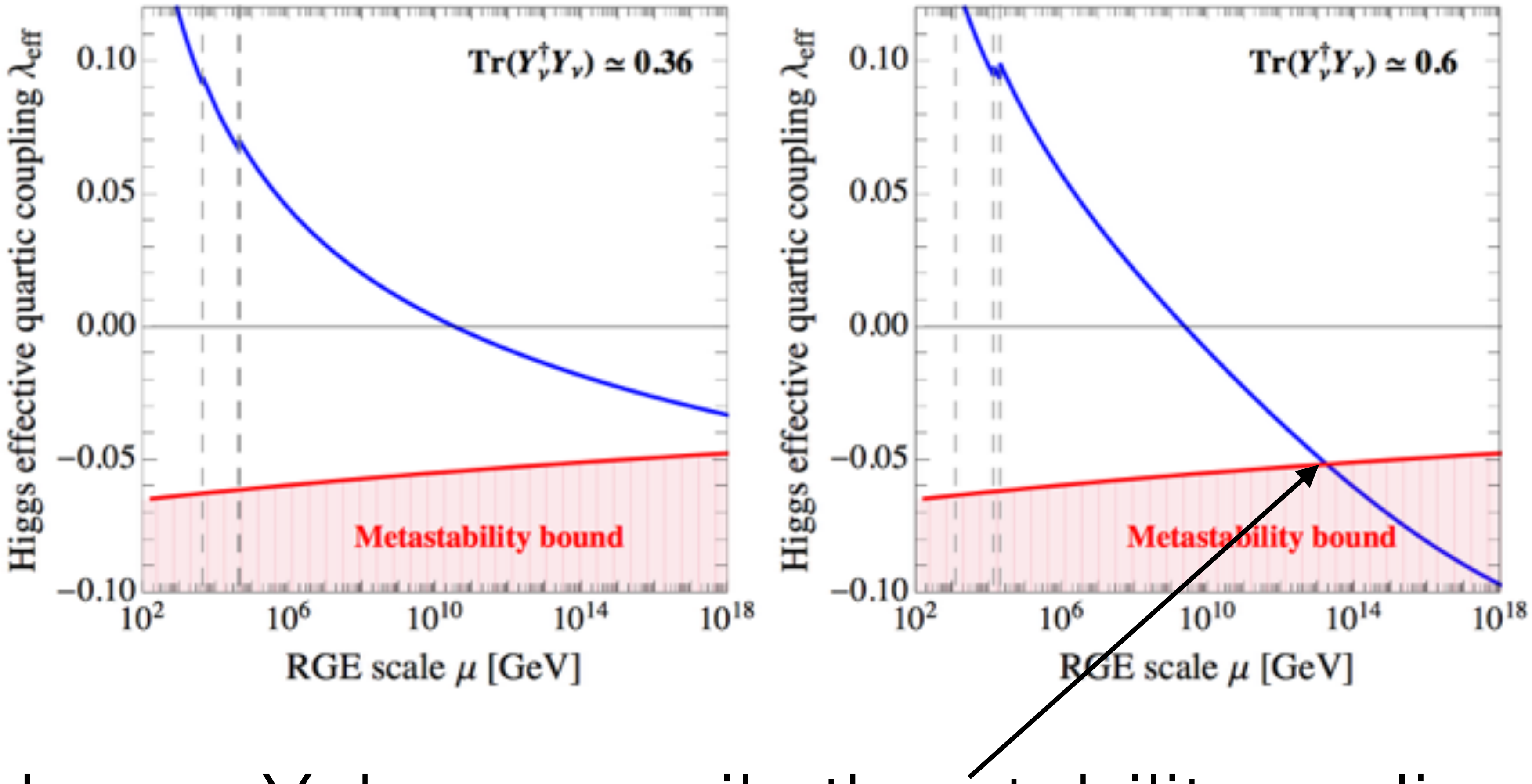
Stability conditions

$$\lambda_1 > 0\,, \quad \lambda_2 > 0\,, \quad 4\lambda_1\lambda_2 - \lambda_3^2 > 0$$

- — v′ = 3.5TeV
- — v′ = 7 TeV

Coriano et al. Phys.Lett. B738 (2014) 13-19, JHEP 1602 (2016) 135

Inverse seesaw



Large Yukawa spoils the stability earlier

Rose et al. JHEP 1605 (2016) 050

Are there other Higgs boson(s) ?

May be yes!

What are there gauge representations ?

We start with simple SM gauge singlet

Standard Model + SM gauge Singlet

- Why ?
- Other benefits ?
- Higgs mass gets any corrections?
- Dark singlet ?
- Vacuum stability ?

SM + Real Singlet

The Higgs potential look like

$$V(\phi, S) = \mu^2|\phi|^2 + \lambda|\phi|^4 + m_S^2 S^2 + \lambda_{S\phi} S^2|\phi^2| + \lambda_S S^4$$

This vev can generate both the mass terms for $\phi \, \mathrm{and} \, \mathrm{S}$

$$< S >= v_S \, \mathrm{and} \, \mathrm{S} = \mathrm{v_S} + \mathrm{S_r}$$

Similarly, $< \phi >= v + h$

$\lambda_{S\phi} < S >< \phi >= \lambda_{S\phi} v_S v$ generates the bi-linear mixing term

At the end we have two physical Higgs bosons

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \mathcal{R} \begin{pmatrix} h \\ S \end{pmatrix}$$

SM + Complex scalar

Now the singlet has two components

$$S = S_r + ia$$

The potential takes a form given below:

$$\begin{aligned} V(\phi, S) = &\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \\ &+ (\delta_1 \phi^\dagger \phi S + \delta_3 \phi^\dagger \phi S^2 + a_1 S + b_1 S^2 \\ &+ c_1 S^3 + c_2 S |S|^2 + d_1 S^4 + d_3 S^2 |S|^2 + c.c.) \\ &+ \delta_2 \phi^\dagger \phi |S|^2 + b_2 |S|^2 + d_2 |S|^4 \end{aligned}$$

However depending on the demand of additional symmetries we can remove some of the terms

Application of Z_2 symmetry : $S \rightarrow -S$

prohibits all the odd terms in *S*

S can be dark matter candidate

Barger et al. Phys.Rev.D79:015018,2009

SM+ complex scalar

Additional symmetries such as U(1) global will remove

$\delta_1, \delta_3, a_1, b_1, c_1, c_2, d_1$ and d_2

$$V(\phi, S) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + \delta_2\phi^\dagger\phi|S|^2 + b_2|S|^2 + d_2|S|^4$$

Giving vev to the singlet: $< S >= v_S + S_r + ia$

(h, S_r) will mix and a remains as Goldstone mode,

a massless degrees of freedom!

This cannot give a viable dark matter

SM+ complex scalar

- To have massive Goldstone We need to break the Global symmetry softly
- Non-zero b_1 naturally breaks U(1) and give mass to a
- Giving vev to the singlet, breaks both the U(1) and Z_2 symmetry!

  Leads to domain wall problem!

- Choosing non-zero a_1 breaks Z_2 explicitly

$$V(\phi, S) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^4 + \delta_2\phi^\dagger\phi|S|^2 + b_2|S|^2 + d_2|S|^4 + (b_1S^2 + a_1S + c.c)$$

- In stead of Z_2, if we apply $S \rightarrow S^* \Rightarrow a \rightarrow -a$

Barger et al. Phys.Rev.D79:015018,2009
Costa et al. JHEP06(2016)034

Gauge U(1) scalar extension

- In stead of z_2, if we apply $S \to S^* \Rightarrow a \to -a$
- For $v_a = 0$ and $\mathrm{v_S} \neq 0$, $(h, S_r) \to (h_1, h_2)$,

  and a becomes DM candidate

- For $v_a \neq 0$ and $\mathrm{v_S} \neq 0$, $(h, S_r, a) \to (h_1, h_2, h_3)$

$\Rightarrow$ Spontaneous CP-violation.

Costa et al. JHEP06(2016)034

Two Higgs doublet model

Here we have two SU(2) Higgs doublets with same hyper charges

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_{1r} + ia_1 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_{2r} + ia_2 \end{pmatrix}$$

The general Higgs potential takes the form

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + H.c) + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + [\frac{\lambda_5}{2}((\Phi_1^\dagger \Phi_2)^2) + \lambda_6(\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7(\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + H.c]$$

The Yukawa part of the Lagrangian is

$$-\mathcal{L}_Y = Y_{u\,1,2}^{ij} \tilde{\Phi}_{1,2} Q_i u_j^c \; + \; Y_{d\,1,2}^{ij} \Phi_{1,2} Q_i d_j^c \; + \; Y_{d\,1,2}^{ij} \Phi_{1,2} L_i e_j^c \; + h.c.$$

2HDM

After EWSB:

$$\Phi_{1,2} = \begin{pmatrix} \phi^+_{1,2} \\ \frac{1}{\sqrt{2}}[v_{1,2} + h_{1,2} + i a_{1,2}] \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}, \quad \begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} \phi^\pm_1 \\ \phi^\pm_2 \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}$$

We have four massive Higgs bosons: $h(\simeq h_{125}), H, A, H^\pm$

2HDM and Flavour problem

Generic Yukawa coupling leads to FCNC:

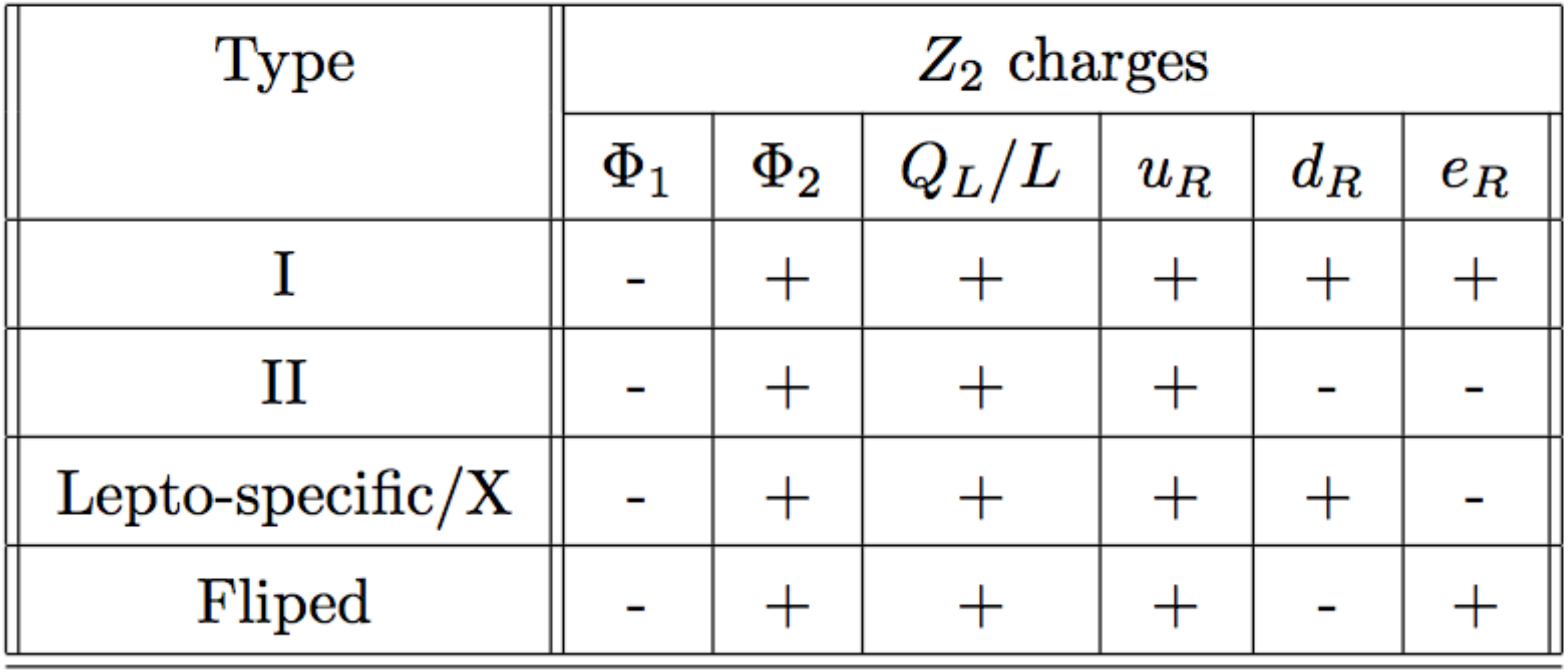
$$-\mathcal{L}_Y = Y^{ij}_{u\,1,2}\tilde{\Phi}_{1,2}Q_i u^c_j + Y^{ij}_{d\,1,2}\Phi_{1,2}Q_i d^c_j + Y^{ij}_{d\,1,2}\Phi_{1,2}L_i e^c_j + h.c.$$

$$\begin{tikzcd}
(Y^{ij}_{f_1}c_\beta + Y^{ij}_{f_2}s_\beta)\frac{v}{\sqrt{2}}f_i f^c_j \arrow[d] & \text{vs} & (\mathrm{Y^{ij}_{f_1}c_\alpha - Y^{ij}_{f_2}s_\alpha)hf_i f^c_j} \arrow[d] \\
m^{ij}_f & \text{Mass} \neq \text{Yukawa} & \mathrm{Y^{ij}_f}
\end{tikzcd}$$

- FCNC’s arise because of the impossibility to simultaneously diagonalise two arbitrary complex matrices.

- One way to eliminate non-diagonal terms in the Lagrangian is by imposing flavour blind Z_2discrete symmetry

Types of 2HDM



Type	Z_2 charges					
	Φ_1	Φ_2	Q_L/L	u_R	d_R	e_R
I	-	+	+	+	+	+
II	-	+	+	+	-	-
Lepto-specific/X	-	+	+	+	+	-
Fliped	-	+	+	+	-	+

- Given a fermion couples only to one Higgs doublet

2HDM Type II Status

- Type II is excluded for low mass charged Higgs boson

$\bar{B} \to X_s \gamma$ puts a strong limit of $m_{H^\pm} > 480\ GeV$. Misiak, et.al., 1503.01789

$$Br(B_s \to \mu^+\mu^-) \propto t_\beta^4 / m_A^4$$

→ Excludes $m_A / t_\beta \lesssim 10\ GeV$.

- The main phenomenological searches at the LHC are

$$pp \to HA \quad hH \quad hA$$

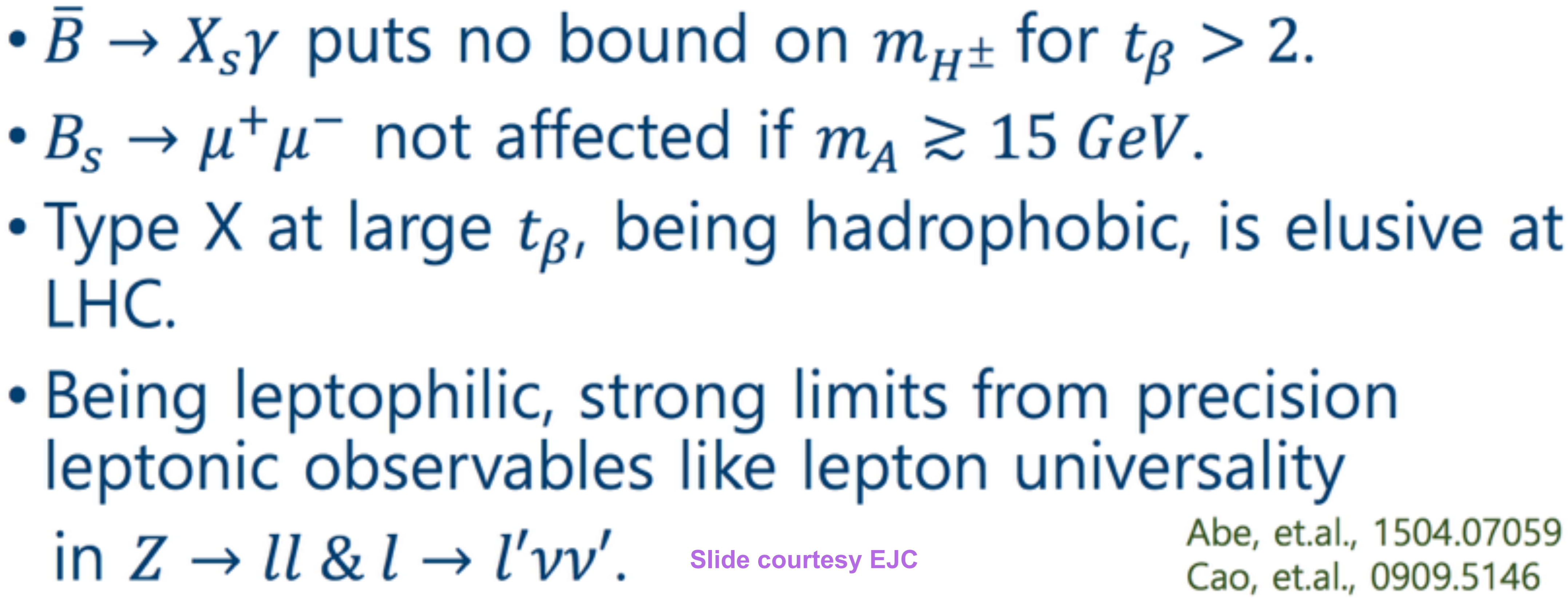
$$pp \to H^+H^-$$

$$pp \to tH^\pm$$

$$pp \to tbH^\pm$$

Branco et al. Phys.Rept. 516 (2012) 1-102

Status of 2HDM Type X



- $\bar{B} \to X_s\gamma$ puts no bound on $m_{H^\pm}$ for $t_\beta > 2$.
- $B_s \to \mu^+\mu^-$ not affected if $m_A \gtrsim 15\ GeV$.
- Type X at large t_β, being hadrophobic, is elusive at LHC.
- Being leptophilic, strong limits from precision leptonic observables like lepton universality in $Z \to ll\ \&\ l \to l'\nu\nu'$.

Slide courtesy EJC

Abe, et.al., 1504.07059
Cao, et.al., 0909.5146

- The light pseudoscalar and light charged Higgs boson is still allowed for Type X

Chun et al. PLB779 (2018) 201-205,PLB774 (2017) 20-25 ,
JHEP 1511 (2015) 099, JHEP 1411 (2014) 058

Inert Higgs doublet model (IHDM)

- What happens if one of the two Higgs doublets does not get vev ?
- You can say that it is inert or spectator Higgs doublet

- One of the Higgs doublet is odd under Z_2 symmetry
  and all the other SM particles are even under

$$\Phi_2 \to -\Phi_2, \quad \Psi_{SM} \to \Psi_{SM}$$

- It guarantees the absence of Yukawa couplings between fermions and the inert doublet

- This Higgs doublet does not get vev.

- Most generic Higgs potential can be written as:

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$

$$+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + [\frac{\lambda_5}{2}((\Phi_1^\dagger \Phi_2)^2) + +h.c.]$$

IHDM

- Higgs spectrum: $h(\simeq h_{125}), H, A, H^{\pm}$
- LEP-I exclude the possibility that massive SM gauge bosons decay into inert particles

$$m_{H^{\pm}} + m_{H,A} > m_{W^{\pm}}, \quad m_H + m_A, 2m_{W^{\pm}} > m_Z$$

- The lighter of H, A is the lightest inert particle (ILP) and can be a DM candidate.

Annihilation channel: $HH/AA \to W^{\pm}W^{\mp}, ZZ$

Co-annihilation: $HA \xrightarrow{Z} SMSM$ and $\mathrm{HH}^{\pm} \xrightarrow{\mathrm{W}^{\pm}} \mathrm{SMSM}$

LHC searches: $p, p \xrightarrow{Z/\gamma} HA,\ H^{+}H^{-}$

$$pp \xrightarrow{W^{\pm}} H/A\,H^{\pm}$$

PoS Charged 2010:030, 2010
Barbieri et al. PRD74,015007(2006),
Rajasekaran et al.PRD76:095011,2007
S. Chaubey JHEP 1711 (2017) 080

Decays: $H^{\pm} \to A/HW^{\pm}$

$$A \to HZ$$

Triplet extension

Possibilities ?

1. Inert
2. Real Triplet
3. Complex triplet with zero hypercharge
4. Triplets with non-zero hypercharge

Gain?

1. Dark matter
2. New Higgs bosons
3. Solving neutrino mass generation
4. Invisible Higgs boson!(?)

Constraints

- Due to SU(2) charged they couple to W boson and can contribute to W mass

SM+Real Triplet

- SM with a Y=0 real SU(2) triplet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad T = \begin{bmatrix} \frac{T^0}{\sqrt{2}} & T^+ \\ T^- & -\frac{T^0}{\sqrt{2}} \end{bmatrix}$$

$$V(\Phi, T) = m_\Phi^2 \Phi^\dagger \Phi + m_T^2 Tr(T^\dagger T) + \lambda_1 |\Phi^\dagger \Phi|^2 \\ + \lambda_2 (Tr|T^\dagger T|)^2 + \lambda_3 \Phi^\dagger \Phi Tr(T^\dagger T) + A(\Phi^\dagger T \Phi)$$

- EWSB condition: $\phi^0 = v_1 + \phi_r^0 + iG^0$ and $\mathrm{T}^0 = \mathrm{v_T} + \mathrm{T_r^0}$

- Particle spectrum: $h_1(h_{125}), h_2, H^\pm$

Triplets

Doublet

- Triplets do not couple to fermions: as no SU(2) gauge invariant vertex is possible.

Inert Triplet

- If the triplet field is odd under Z_2 then potential takes a form

$$V(\Phi, T) = m_\Phi^2 \Phi^\dagger \Phi + m_T^2 Tr(T^\dagger T) + \lambda_1 |\Phi^\dagger \Phi|^2 + \lambda_2 (Tr|T^\dagger T|)^2 + \lambda_3 \Phi^\dagger \Phi Tr(T^\dagger T)$$

- Triplet does not get vev and neutral component T^0 can become lightest inert particle (ITP) and a candidate dark matter.
- In this case triplet and doublet does not mix at all.

Y=0 complex triplet

- Here a complex triplet with Y=0 given as

$$T = T^a\sigma^a,\; T^a \in \mathbb{C} \qquad T = \begin{bmatrix} \frac{T^0}{\sqrt{2}} & T^+ \\ T^- & -\frac{T^0}{\sqrt{2}} \end{bmatrix}$$

Complex field

- The Higgs spectrum: $h_1(\simeq h_{125}), h_2, A, T^+, T^-$ ← Triplets

Not charged conjugate

- The Triplet does not couple to fermions

Triplet with Y=2

- A hypercharge non-zero triplet is manily motivated for Type-II Seesaw

$$\frac{M_\nu^{ij}}{v_\Delta} L_i^T C i\sigma_2 \Delta L_j + \text{h.c.}\,,$$

see EJC’s talk

$$T = \begin{bmatrix} \frac{T^+}{\sqrt{2}} & T^{++} \\ T_r^0 + iT_i^0 & -\frac{T^-}{\sqrt{2}} \end{bmatrix}$$

Melfo et al. PRD85 (2012) 055018,
EJC et al. PL B728 (2014) 256-261
, PLB722 (2013) 86-93
B.Mukhopadhyaya, D Chaudhury, T Han, S. Rai, M. Mitra
S.Niyogi,
JHEP 1402 (2014) 060
PLB434 (1998) 347-353, PLB633 (2006) 519-525
PRD76 (2007) 075013, PRD95(2017) no.3, 035042

- Mass spectrum: $h_1(\simeq h_{125}), h_2, A, T^{\pm}, T^{\pm\pm}$

Triplet like doubly
charge Higgs bosons

- Doubly charged Higgs boson is the main signature

- Z_2 odd triplet can give a inert triplet and a candidate DM.

Araki et al. PRD83, 075014 (2011)

Constrains

- N Higgs multiplets $\Phi_i (i = 1, ..N)$ with isospin charge T_i and hypercharge Y_i

$$\mathcal{L}_{Kin} = \sum C_i |D^i_\mu \Phi^i|^2$$

$$m_W^2 = \frac{g_2^2}{2} \sum v_i^2 [T_i(T_i + 1) - Y_i^2]$$

$$m_Z^2 = g_1^2 \sum v_i^2 Y_i^2, \quad v_i = \sqrt{2C_i} < \phi_i^0 >$$

- This leads to tree-level contribution to,

$$\rho_{tree} = \frac{m_W^2}{m_Z^2 cos^2\theta_W} = \frac{\sum v_i^2 [T_i(T_i + 1) - Y_i^2]}{2 \sum v_i^2 Y_i^2,}$$

- For Y=0 triplet $m_W^2 = g_2^2(v^2 + 4v_T^2)/2$, $\rho = 1 + 4v_T^2/v^2$

$$\rho = 1.0004^{+0.0003}_{-0.0004} \quad \Rightarrow \quad v_T \leq 5\,\mathrm{GeV}$$

Georgi-Machacek Model

- In SM $\rho = 1$ due to custodial symmetry
- One SU(2) doublet, one real and one complex triplet

Y=1 Y=0 Y=2

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad T = \begin{bmatrix} \frac{T^0}{\sqrt{2}} & T^+ \\ T^- & -\frac{T^0}{\sqrt{2}} \end{bmatrix} \quad \xi = \begin{bmatrix} \frac{\xi^+}{\sqrt{2}} & \xi^{++} \\ \xi_r^0 + i\xi_i^0 & -\frac{\xi^-}{\sqrt{2}} \end{bmatrix}$$

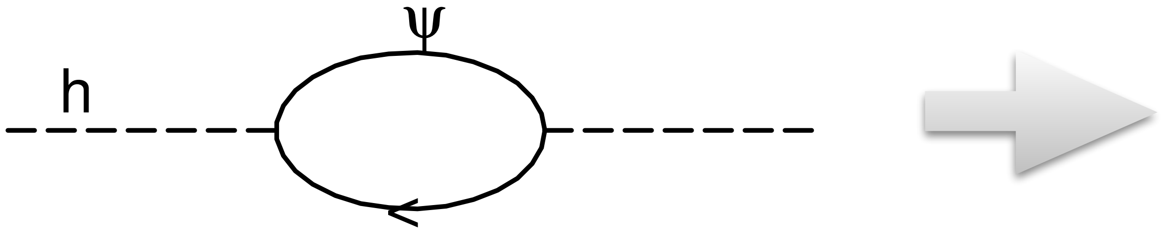
$$\rho_{tree} = \frac{m_W^2}{m_Z^2 cos^2\theta_W} = 1 + \frac{4v_T^2 - 2v_\xi^2}{v_\phi^2 + 4v_\xi^2}$$

- A choice of $v_T^2 = \frac{v_\xi^2}{2}$ leads to $\rho = 1$ at the tree level.

Supersymmetric extensions

Higgs mass in Standard Model

- Higgs mass is a free parameter not predicted by SM

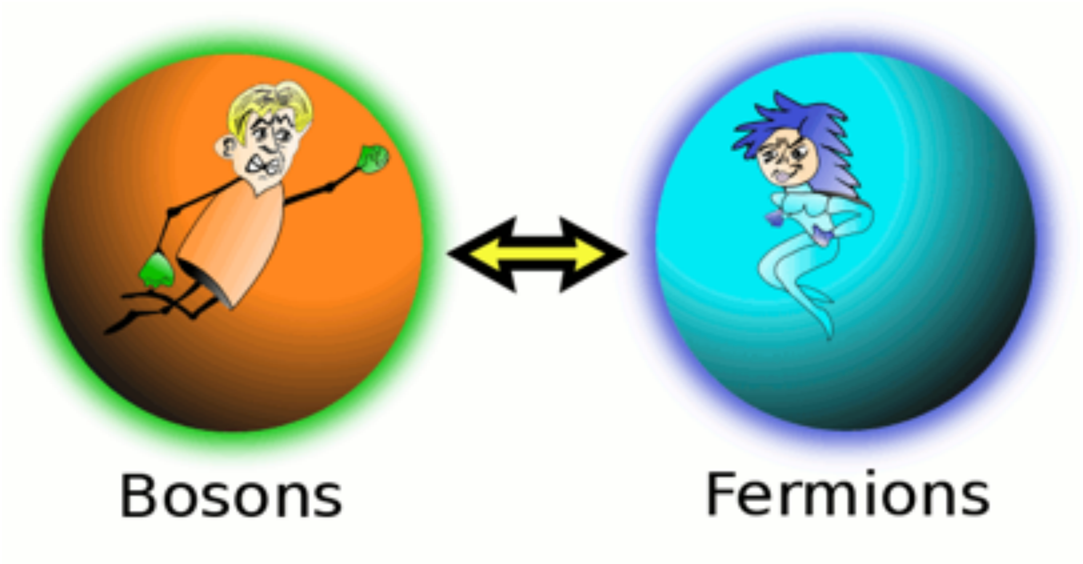


$\sim \Lambda^2$

Cut off scale of the theory

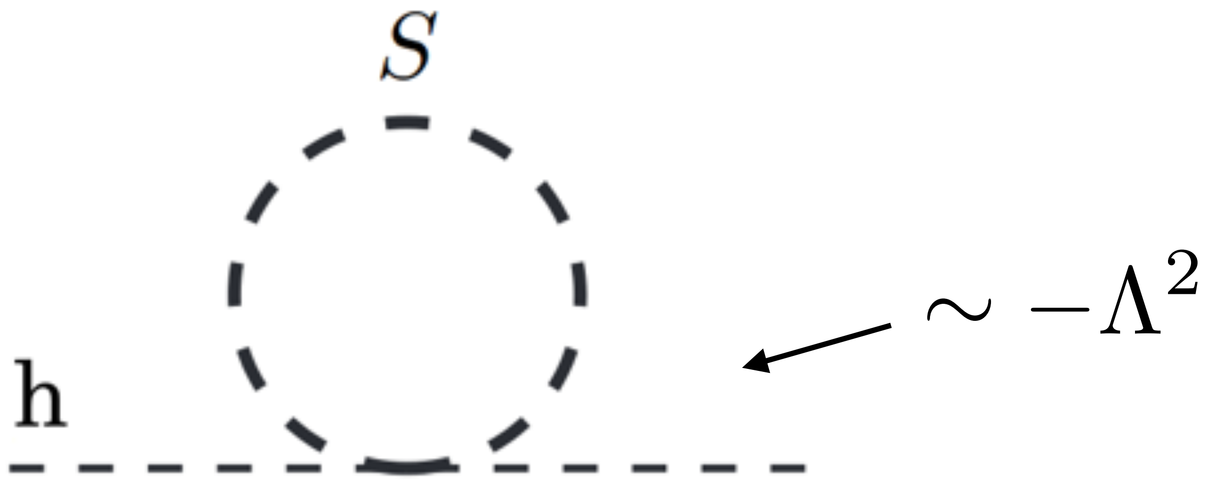
- Quantum correction to Higgs mass is divergent

We need additional symmetry to cancel the quadratic divergence



Supersymmetry !!

- Supersymmetry protects the Higgs mass with additional contributions

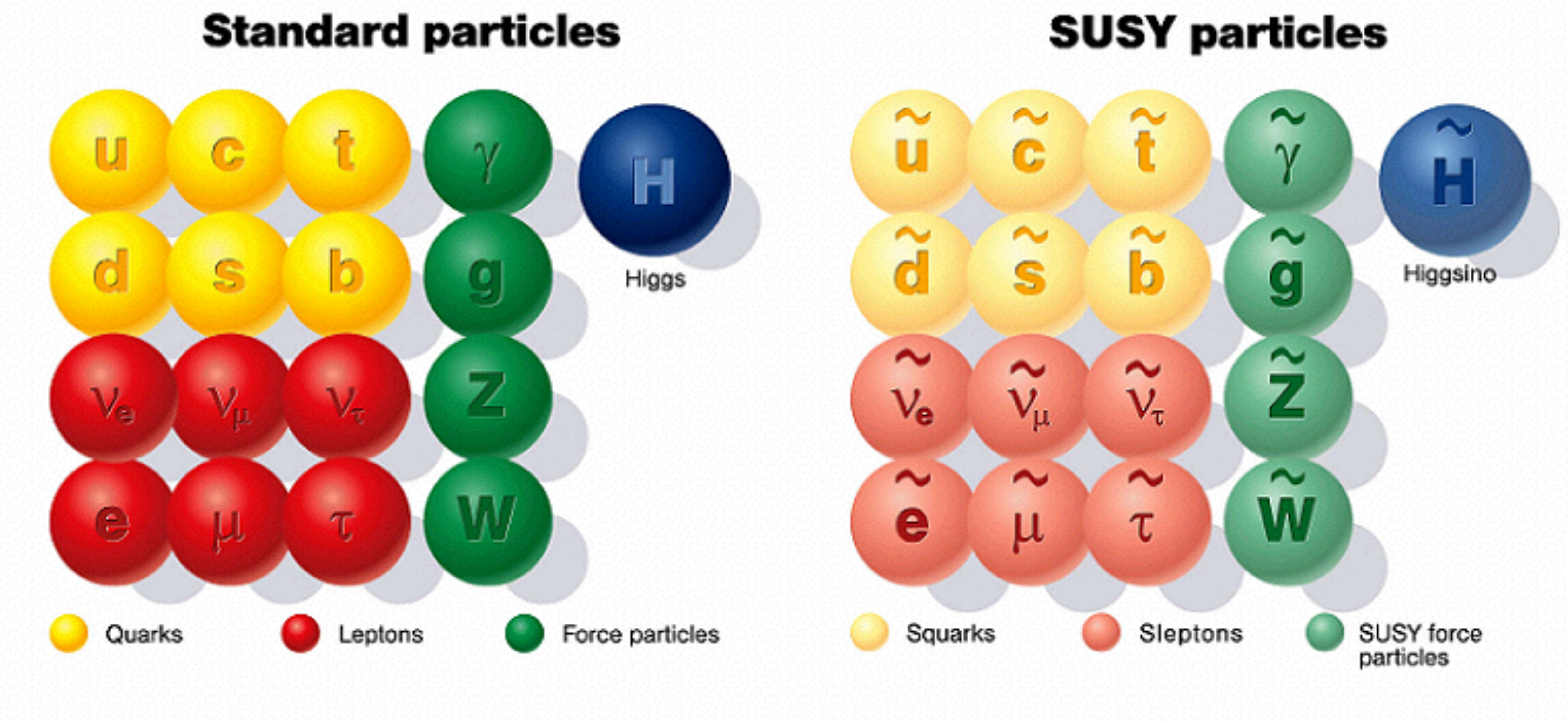


- Radiative correction to the Higgs mass is no longer divergent

- With and extra discrete symmetry R-parity, it can have dark matter candidate.

See Prof. EJC's talk

Even in the Minimal sector particle spectrum is enhanced



How many Higgs bosons ?

- Minimal sector has two Higgs doublets with hyper charges +1 and -1

$$H_u = \left(\begin{array}{c} H_u^+ \\ H_u^0 \end{array} \right), \quad H_d = \left(\begin{array}{c} H_d^0 \\ H_d^- \end{array} \right),$$

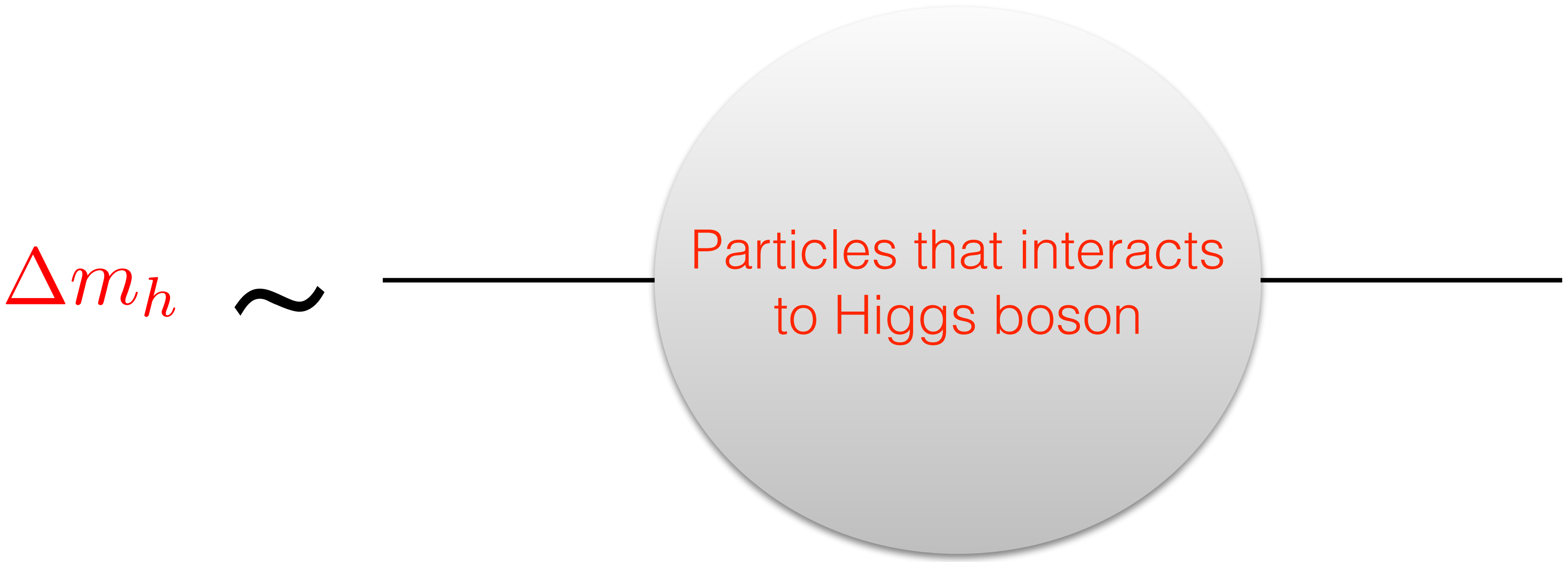
- Physical mass basis: two CP even Higgs boson: h, H
- One CP odd: A
- One charged Higgs boson: $H^{\pm}$

So far we have observed only one Higgs boson !

Lightest CP even Higgs boson

- Unlike Standard Model, here light Higgs mass bounded from above
- At tree-level $m_h < m_Z$
- For desired Higgs mass around 125 GeV, one has to look for quantum correction

Quantum correction is important



$\Delta m_h \sim$

Particles that interacts to Higgs boson

$$h_{125} = m_h + \Delta m_h$$

- Particles in the loop get indirect bounds

Status of minimal supersymmetric scenarios

- Trivial solution: Very large mass for super-partners

$\gtrsim$ few TeV

- Or large mass splitting between the super-partners

- Fine tuning is necessary

- There are possibilities in different SU(2) representations

Singlet

and/or

Triplets

$$S = s_r + i s_i$$

Y=0 $$T = \begin{pmatrix} \frac{T^0}{\sqrt{2}} & T_2^+ \\ T_1^- & -\frac{T^0}{\sqrt{2}} \end{pmatrix}$$

Espinosa, Quiros, Agashe, ..

What is the gain?

$\Delta m_h \simeq$

Other
Higgs bosons
contribute
at tree-level

$+$

Contribute
at
quantum
level

Do not need much help from ‘super partners’

Supersymmetry can still exists below TeV !

Are there are other theoretical motivation ?

1. Spontaneous CP-violation
2. Solution of the μ_D in supersymmetry
3. Possibility of hidden Higgs bosons

…

How exotic are they ?

Triplet

Do not couple to fermions

Singlet

Singlet does not couple to gauge bosons

Neutral part of Y=0 Triplet does not couple to Z boson

Triplet extension

- Model I: Y=0 Triplet extension

$$W_T = \lambda H_d.T.H_u + \mu_D H_d.H_u + \mu_T Tr(T^2)$$

- It gives two additional triplet-like charged Higgs bosons
- Extra CP even and CP odd neutral Higgs bosons
- None of them couple to fermions

- Model II: A scale invariant superpotential with Y=0 SU(2) triplet and a singlet

Triplet

Singlet

$$W_S = \lambda_T H_d.T H_u + \lambda_S S H_d \cdot H_u + \lambda_{TS} S Tr[T^2] + \frac{\kappa}{3} S^3$$

- The complete Lagrangian with the soft SUSY breaking terms has an Z_3 symmetry

- During electro-weak symmetry breaking neutral parts get vev

$$< H^0_{u,d} >= \frac{v_{u,d}}{\sqrt{2}}, \quad < S >= \frac{v_S}{\sqrt{2}} \quad < T^0 >= \frac{v_T}{\sqrt{2}}$$

- Triplet vev contributes to the W mass but not the Z mass

$$m_W^2 = g_2^2(v^2 + 4v_T^2)/2 \qquad \rho = 1 + 4v_T^2/v^2$$

$$v_T \leq 5\,\mathrm{GeV}$$

Restricted from ρ parameter

What is the gain?

$$\Delta m_h \simeq$$

Other
Higgs bosons
contribute
at tree-level

+

Contribute
at
quantum
level

$$m_{h_1}^2 \leq m_Z^2(\cos^2 2\beta + \frac{\lambda_T^2}{g_L^2 + g_Y^2} + \frac{2\lambda_S^2}{g_L^2 + g_Y^2}\sin^2 2\beta)$$

Do not need much help from ‘super partners’

Supersymmetry can still exists below TeV !

$$V_{soft} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2$$
$$+ m^2_T|T|^2 + m^2_Q|Q|^2 + m^2_U|U|^2 + m^2_D|D|^2$$
$$+(A_S S H_d.H_u + A_T H_d.T.H_u + A_{TS} S Tr(T^2)$$
$$+ A_\kappa S^3 + A_U U H_U.Q + A_D D H_D.Q + h.c),$$

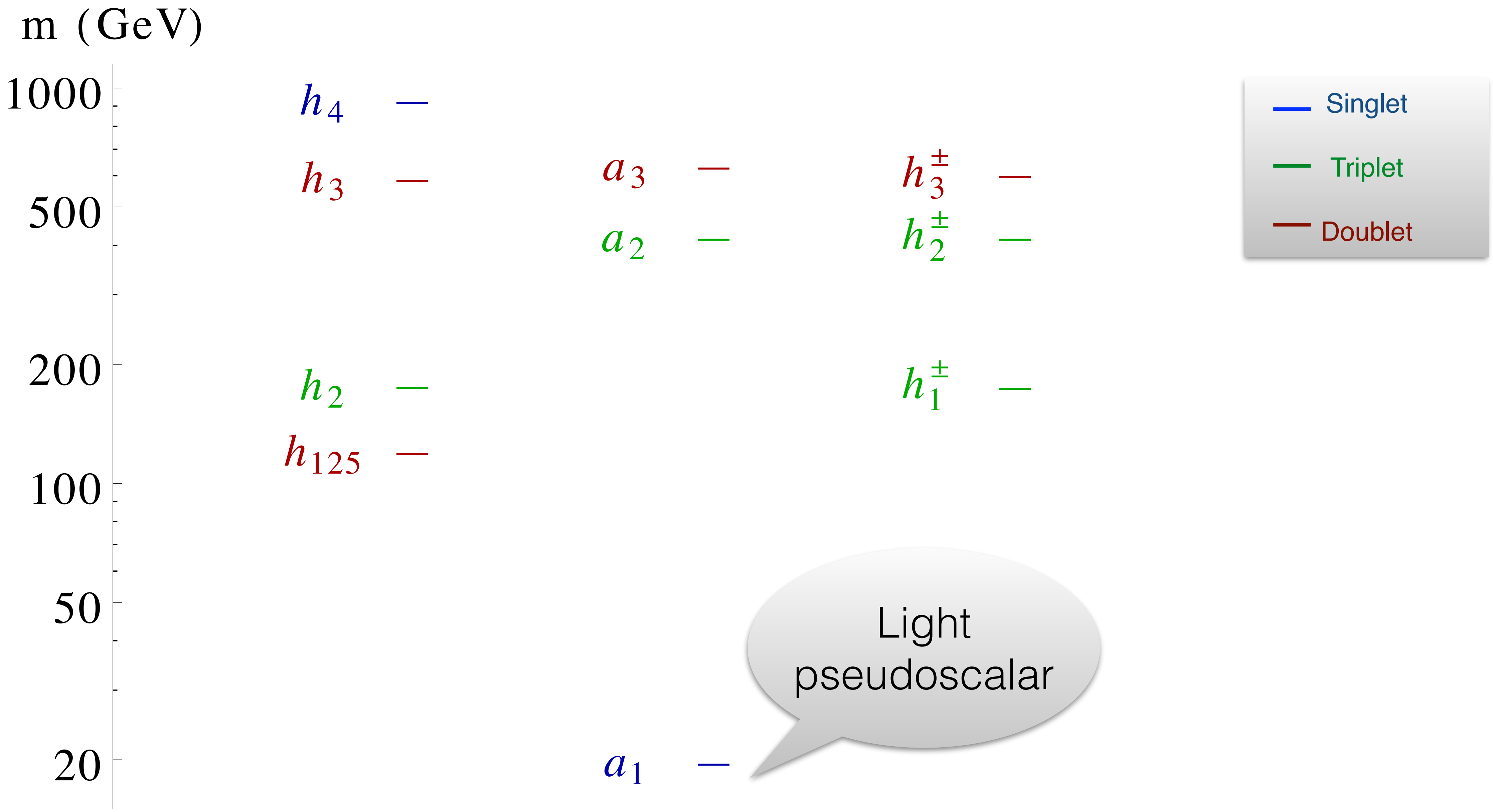
- In the limit where all the A parameters vanish the scalar potential accrues an enhanced U(1) symmetry

$$(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}) \to e^{i\phi}(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S})$$

- If this symmetry is softly broken by very small A parameters $\mathcal{O}(1)\mathrm{GeV}$,

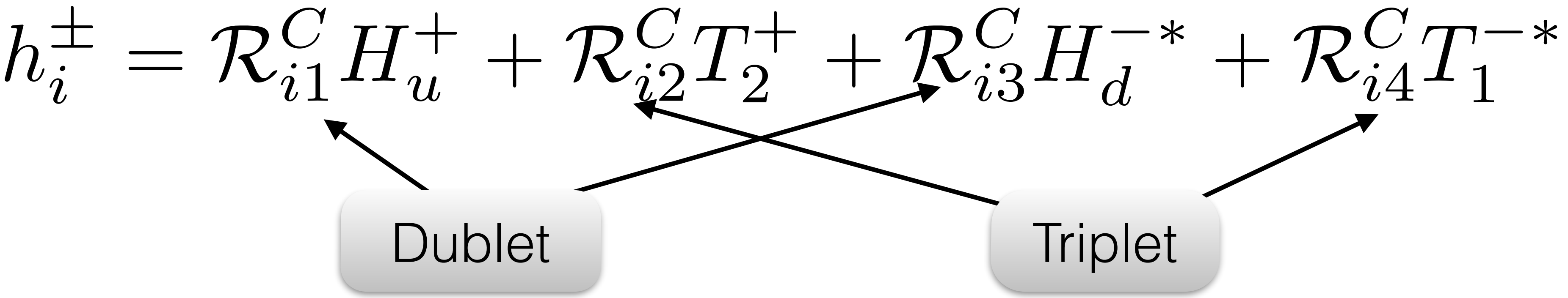
- We get a very light pseudoscalaras pseudo-Nambu-Goldstone boson of the symmetry.

Correlation of gauge-mass hierarchy and possibility of hidden scalars



PB, Claudio Coriano and Antonio Costantini, JHEP 1509 (2015) 045,
JHEP 1512 (2015) 127

Gauge structure



$$h_i^{\pm} = \mathcal{R}^C_{i1} H_u^+ + \mathcal{R}^C_{i2} T_2^+ + \mathcal{R}^C_{i3} H_d^{-*} + \mathcal{R}^C_{i4} T_1^{-*}$$

$$\mathcal{R}^C_{ij} = f^C_{ij}\left(v_u, v_d, v_T, v_S, \lambda_T, \lambda_{TS}, \lambda_S, A_i\right)$$

- In particular the charged Goldstone has contribution from triplets

$$h_0^{\pm} = \pm N_T \left(\sin\beta H_u^+ - \cos\beta H_d^{-*} \mp \sqrt{2}\, \frac{v_T}{v} (T_2^+ + T_1^{-*}) \right)$$

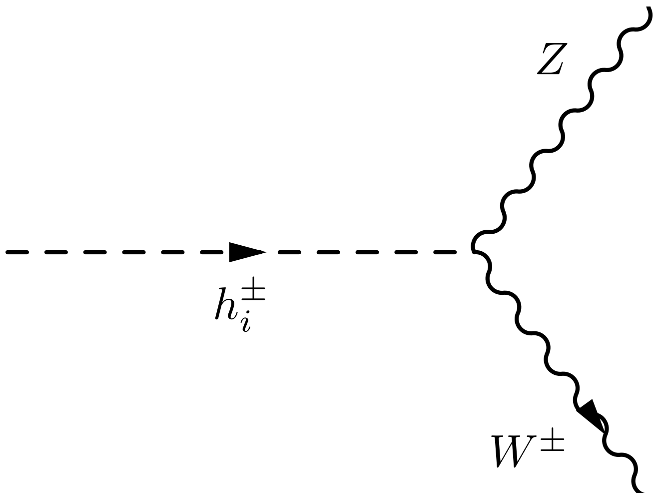
$$N_T = \frac{1}{\sqrt{1 + 4\frac{v_T^2}{v^2}}}$$

has
a triplet
contribution

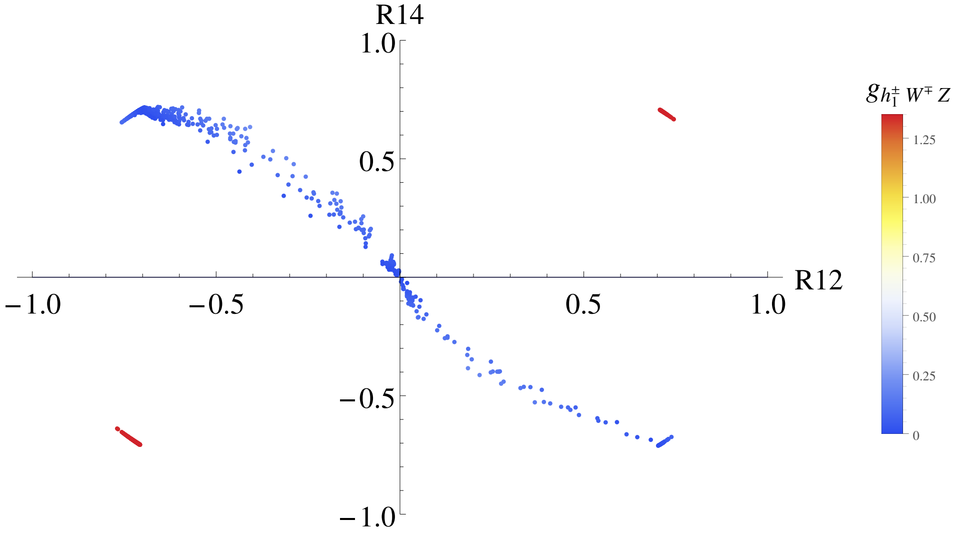
No λ_i

Non-standard decay modes

$$g_{h_i^\pm W^\mp Z} = -\frac{i}{2}\left(g_L\, g_Y\, (v_u \sin\beta\, \mathcal{R}^C_{i1} - v_d \cos\beta\, \mathcal{R}^C_{i3}) + \sqrt{2}\, g_L^2 v_T\, (\mathcal{R}^C_{i2} + \mathcal{R}^C_{i4})\right)$$



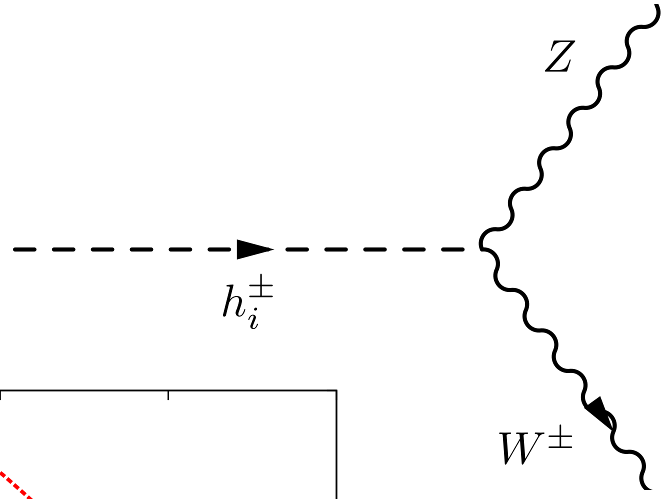
- For $\lambda_T \sim 0,\ \mathcal{R}^C_{12}$ and $\mathcal{R}^C_{14}$ take the same sign
- Hence, $h_1^\pm - W^\mp - Z$ coupling is enhanced
- Non-zero triplet vev, initiates this vertex



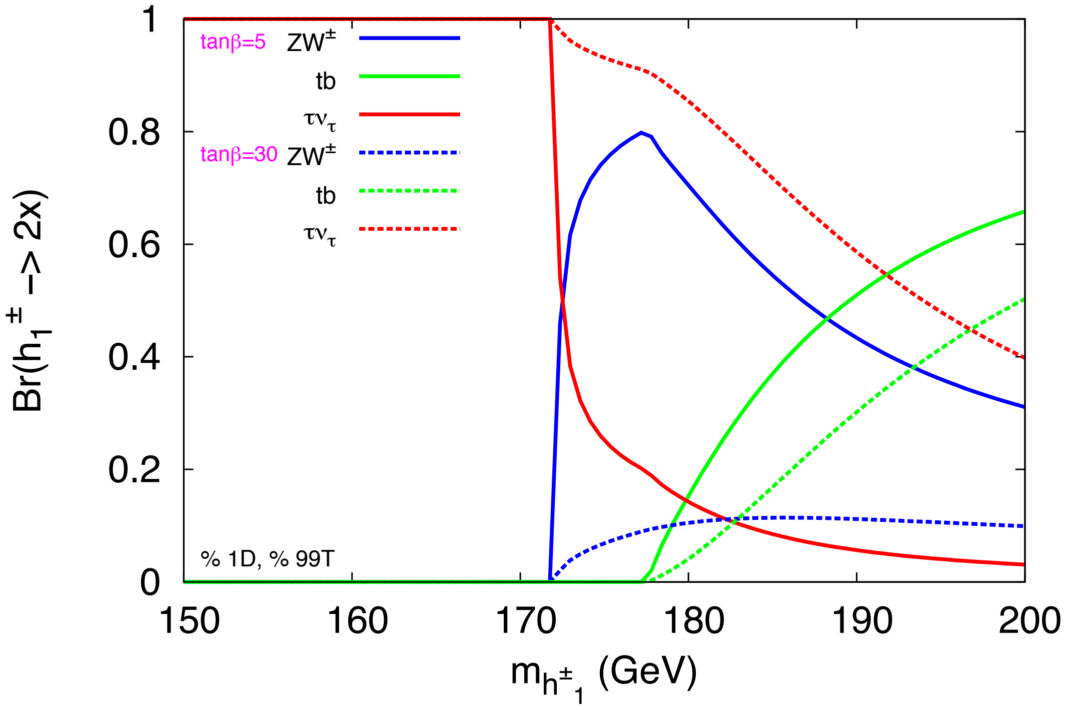
Triplet signature

Non-standard decay modes

$$g_{h_i^\pm W^\mp Z} = -\frac{i}{2}\left(g_L\, g_Y\,\left(v_u \sin\beta\,\mathcal{R}^C_{i1} - v_d \cos\beta\,\mathcal{R}^C_{i3}\right) + \sqrt{2}\, g_L^2 v_T\,\left(\mathcal{R}^C_{i2} + \mathcal{R}^C_{i4}\right)\right)$$



$$h_i^\pm \to tb$$
$$\to ZW^\pm$$
$$\to \tau\nu$$
$$\to h_j W^\pm$$
$$\to a_j\, W^\mp$$



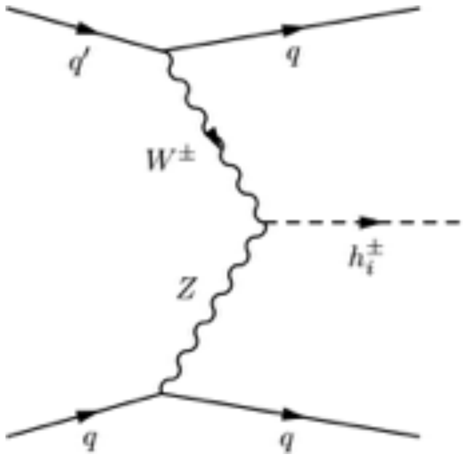
- Mixing with the doublets is crucial for the decays as well as production channels
- $h_1^\pm \to a_1 W^\pm$ opens up due to the presence of light pseudo scalar

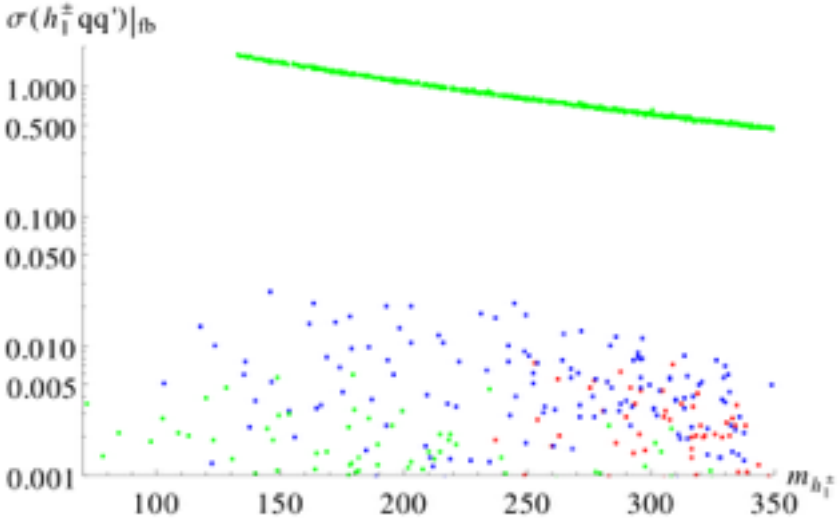
P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026

PB, Claudio Coriano, Antonio Costantini, PRD94 (2016) no.5, 055030

Vector boson fusion to charged Higgs boson

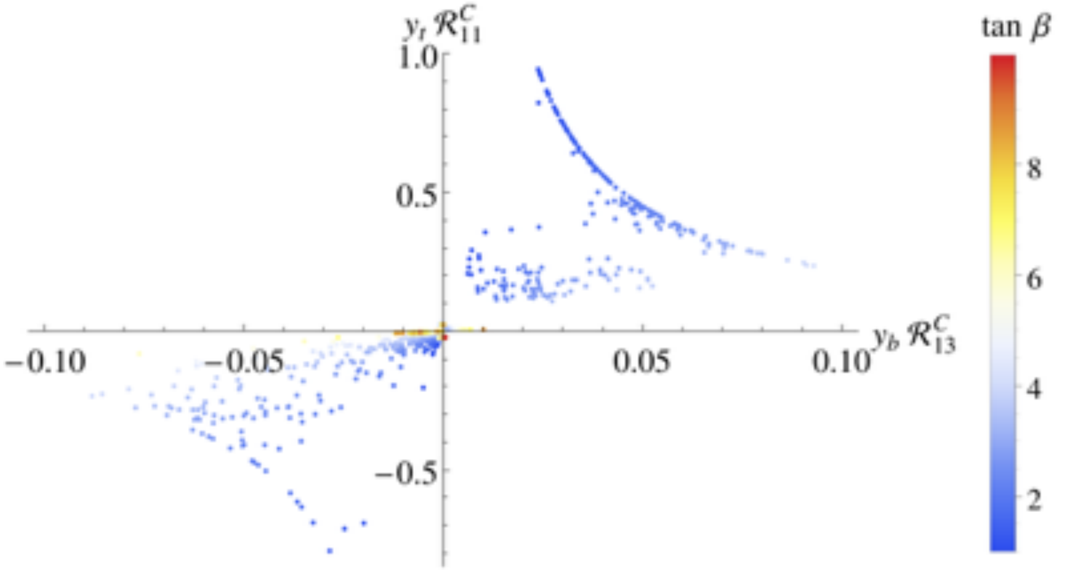
- $h_1^{\pm} - W^{\mp} - Z$ coupling creates additional tree-level production mode for the charged Higgs boson
- This process is absent for doublet-like charged Higgs boson

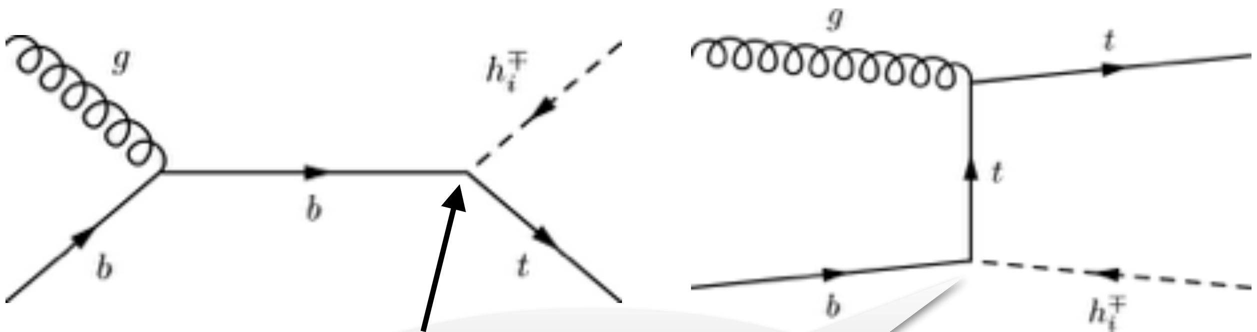




What happens to standard single charged Higgs production mechanism ?

$$g_{h_i^+\bar{u}d} = i\left(y_u\,\mathcal{R}^C_{i1}\,\mathrm{P_L} + y_d\,\mathcal{R}^C_{i3}\,\mathrm{P_R}\right)$$



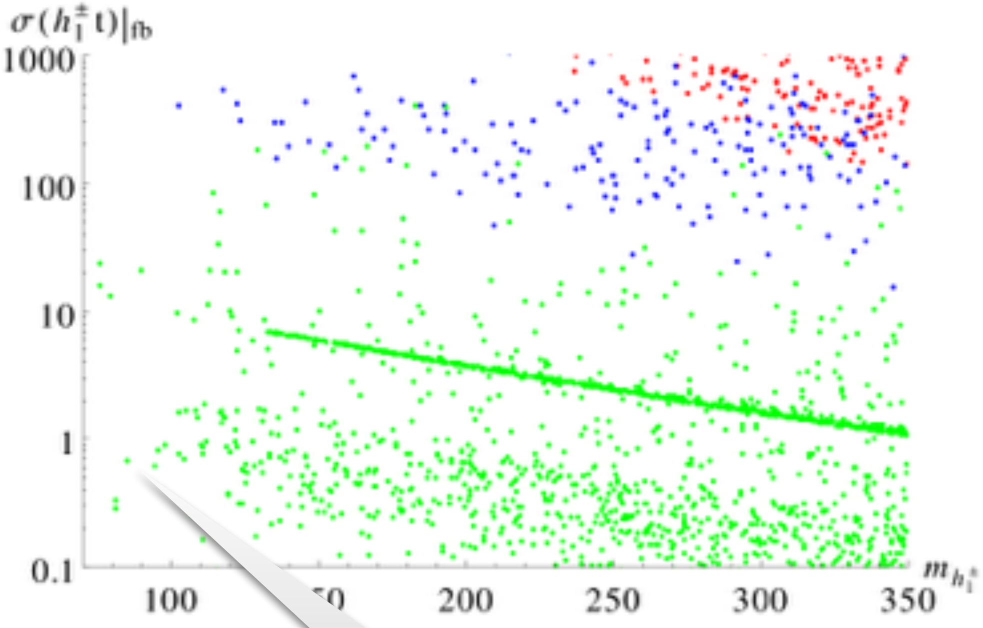


Suppressed for triplet-like Higgs

- Triplets do not couple to fermions

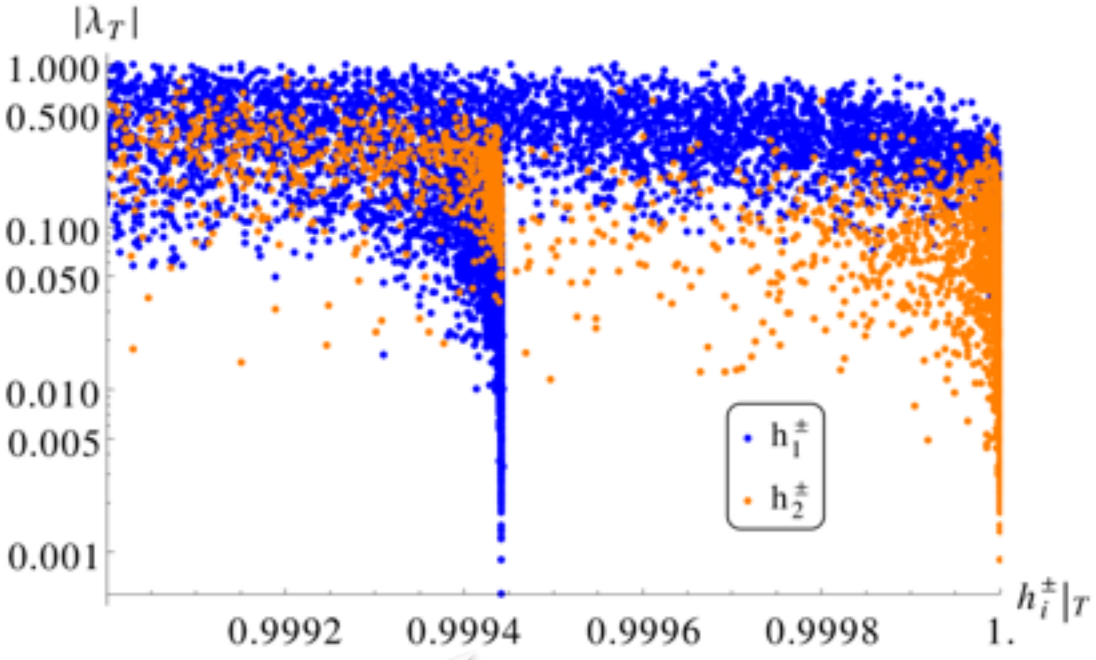
→ bg fusion is really suppressed

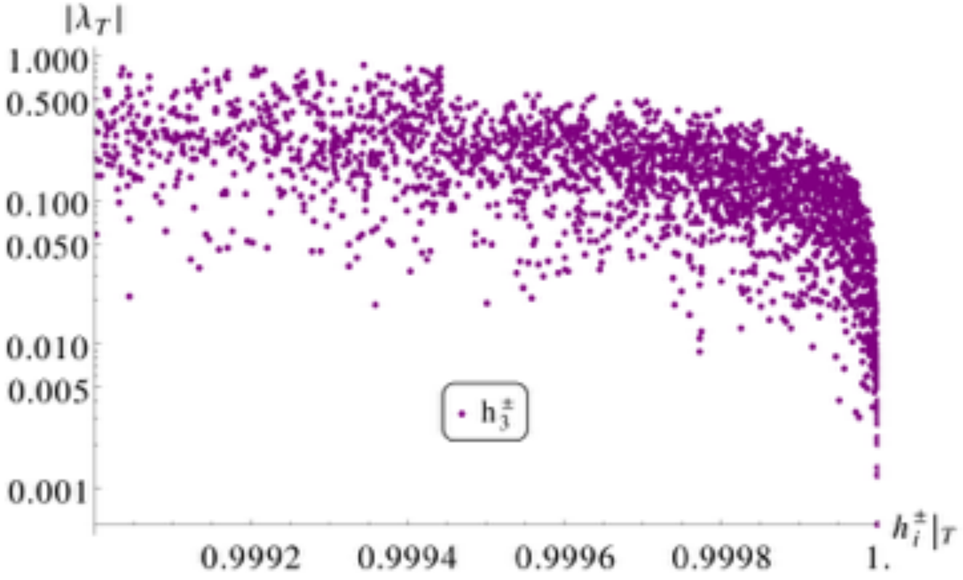
- Even if $\lambda_T = 0$, lightest charged Higgs boson still has some doublet component!



For pure triplet the coss-section goes to zero.

$\boxed{\lambda_T \simeq 0}$ limit



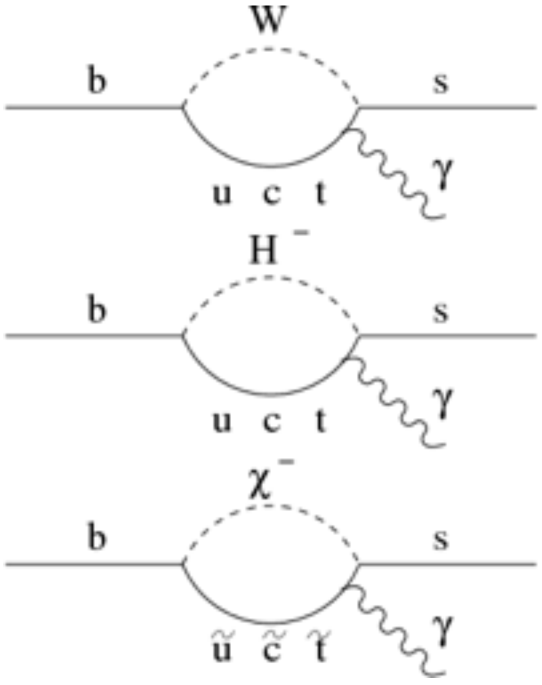


Not 100%

$$\lambda_T = 0$$

- $h^{\pm}_{2,3}$ only can be pure triplets
- $h_1^{\pm}$ has some doublet parts as perpendicular mode of the charged Goldstone

Rare decay



- The triplet type charged Higgs bosons, charginos and neutralinos do not couple to fermions

- This affect the indirect bounds coming from rare fermionic decays

- We calculated $\mathcal{B}(B \to X_s\gamma)$at NLO and showed that

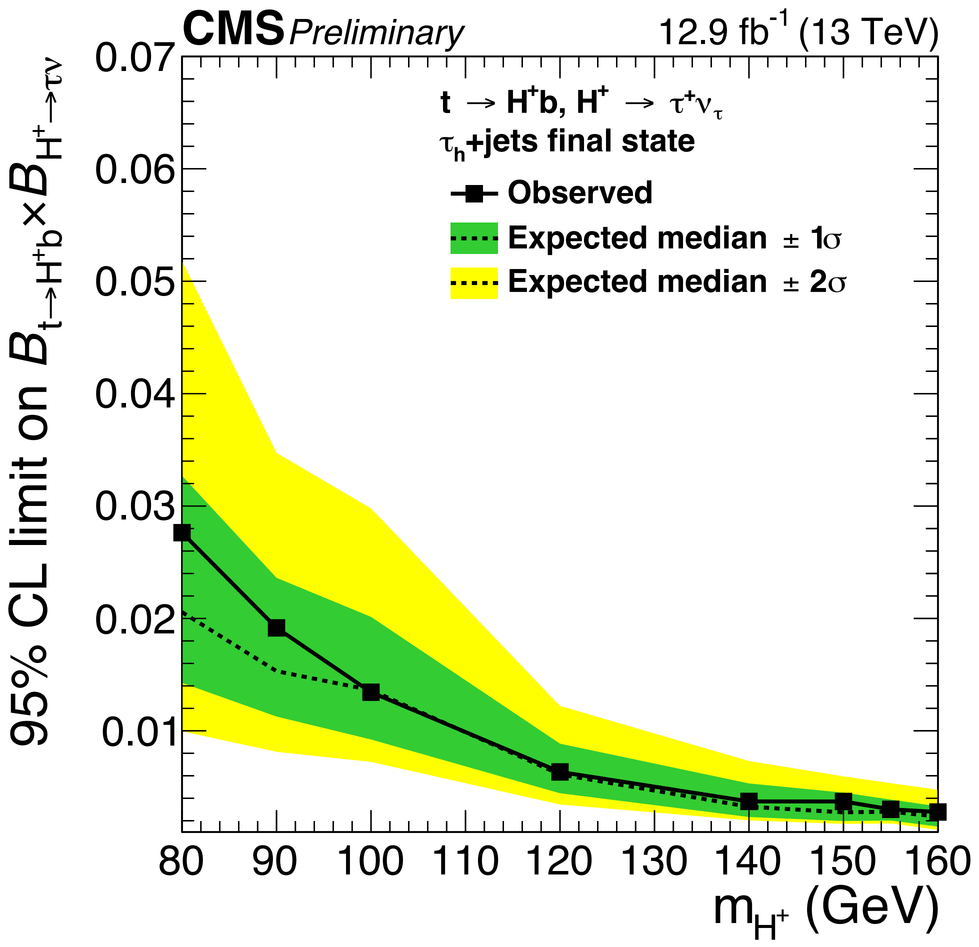
- Allowed 2σ region constrains the high λ_T region of parameter space preferred by naturalness.

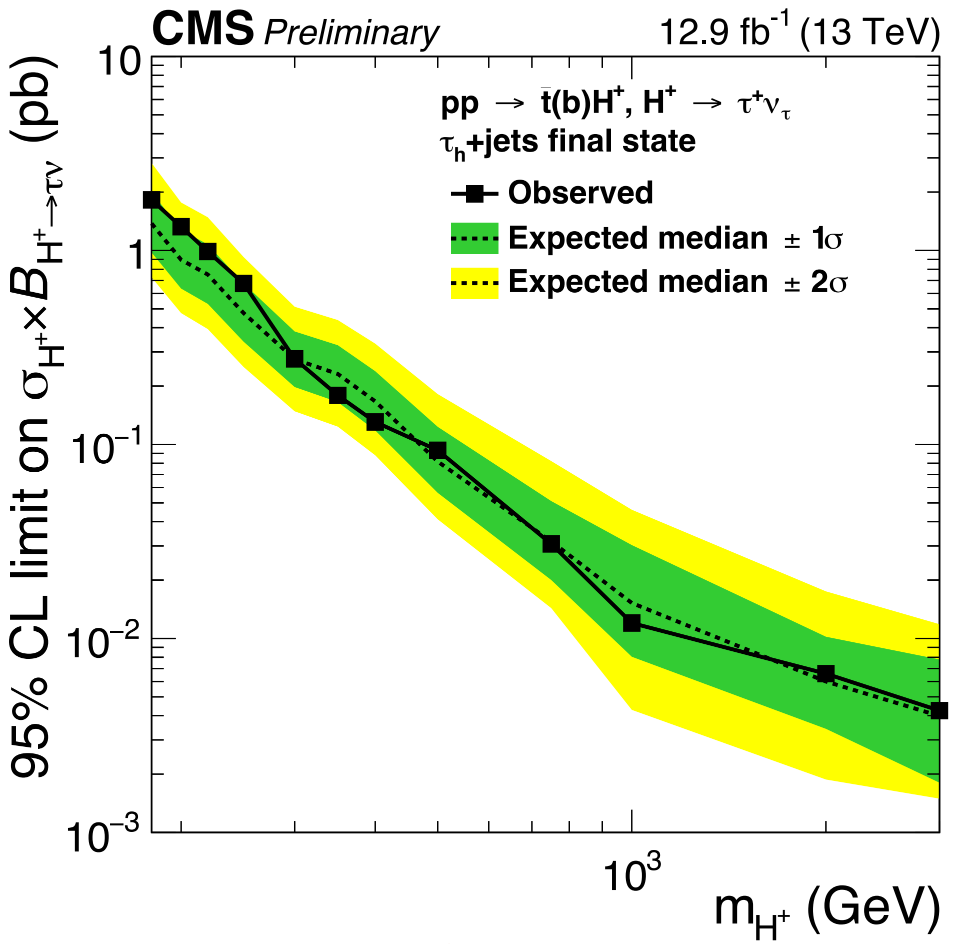
PB, Katri Huitu, Asli Sabanci, JHEP 1310 (2013) 091
PB, Stefano Di Chiara, Katri Huitu, Asli Sabanci, JHEP 1411 (2014) 062

Experimental searches of the charged Higgs boson

- LHC looked for this doublet type charged Higgs bosons via mainly its couplings to fermions
- Light charged Higgs boson: $pp \to t\bar{t} \to bW^+\bar{b}H^-$
- Heavy charged Higgs boson: $pp \to tbH^\pm$
- Where charged Higgs boson is search in decay modes $\tau + \nu$ and $t + b$

Experimental bounds on the charged Higgs





- CMS puts 95% Cl upper limits as: $E_{cm} = 13\,\mathrm{TeV\ and\ 12.9\,fb}^{-1}$

$$\mathcal{B}(t \to bH^{\pm}) \times \mathcal{B}(H^{\pm} \to \tau\nu) = 0.004 - 0.05\,\mathrm{for\ m_{H^{\pm}}} \sim 80 - 160\,\mathrm{GeV}$$

$$\sigma(pp \to H^{\pm}W^{\pm}b\bar{b}) \times \mathcal{B}(H^{\pm} \to \tau\nu) = 2 - 0.01\,\mathrm{pb\ for\ m_{H^{\pm}}} \sim 180\,\mathrm{GeV} - 3\,\mathrm{TeV}$$

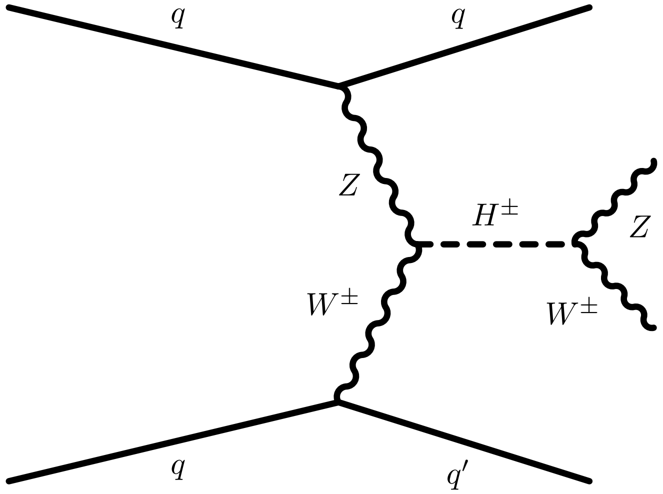
CMS-PAS-HIG-16-031

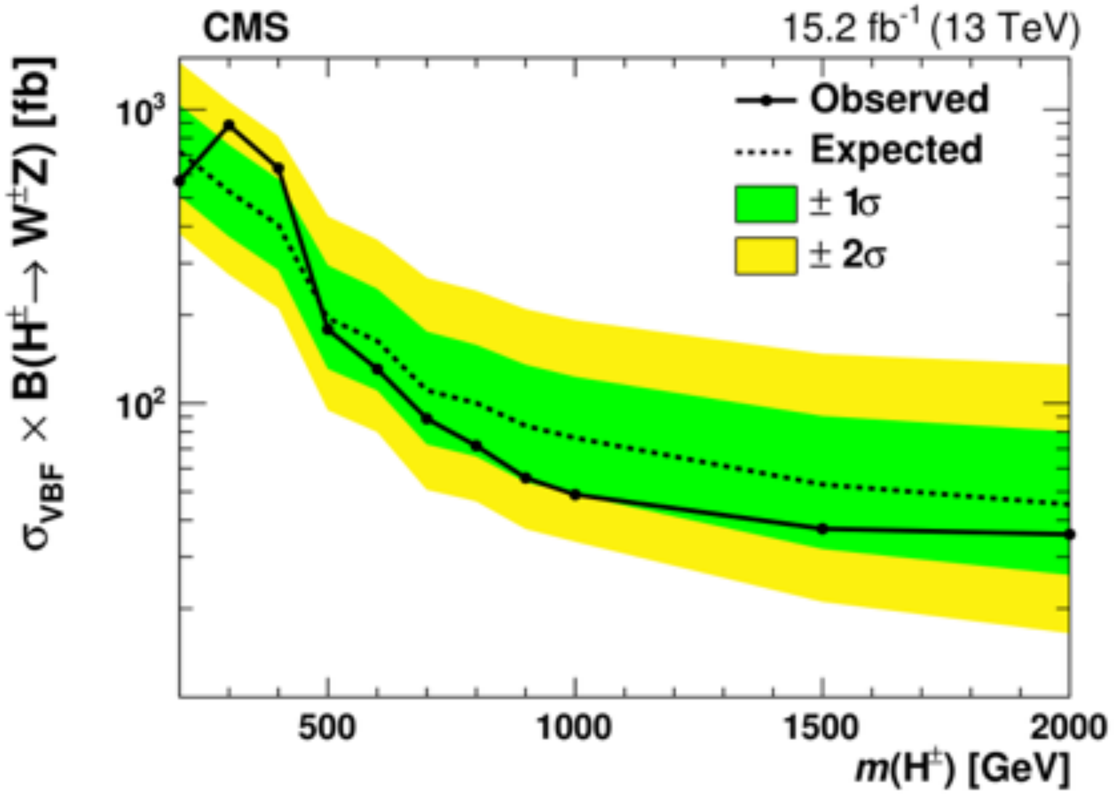
- ATLAS puts 95% Cl upper limits as: $E_{cm} = 13\,\mathrm{TeV\ and\ 3.2\,fb}^{-1}$

$$\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(H^{\pm} \to \tau\nu) = 1.9\,\mathrm{pb} - 15\,\mathrm{fb\ for\ m_{H^{\pm}}} \sim 200 - 2000\,\mathrm{GeV}$$

PLB 759(2016)555-574

Experimental bounds on the Triplet charged Higgs





- CMS puts 95% Cl upper limits on $\sigma_{VBF} \times (H^{\pm} \to W^{\pm} Z)$ for $200 \leq m_{H^{\pm}} \leq 2000\,\mathrm{GeV}$

  CMS-PAS-HIG-16-027/PRL119(2017)14180

- ATLAS puts 95% Cl upper limits at $E_{cm} = 8\,\mathrm{TeV\ with}\,20.3\,\mathrm{fb}^{-1}$

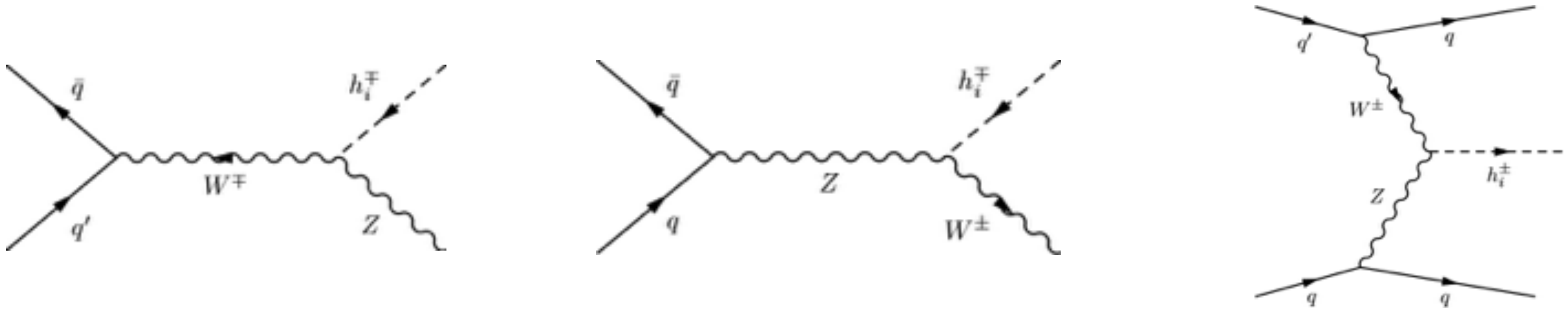
$$\sigma_{VBF} \times \mathcal{B}(H^{\pm} \to ZW^{\pm}) \sim 31 - 1020\,\mathrm{fb\ for}\,200 \leq \mathrm{m_{H^{\pm}}} \leq 2000\,\mathrm{GeV}$$

  PRL 114,23801(2015)

- Doubly charged Higgs boson: $E_{cm} = 13\,\mathrm{TeV\ with}\,36.1\,\mathrm{fb}^{-1}$

$$m_{H^{++}} > 770 - 870\,\mathrm{GeV}$$

Look for new production modes

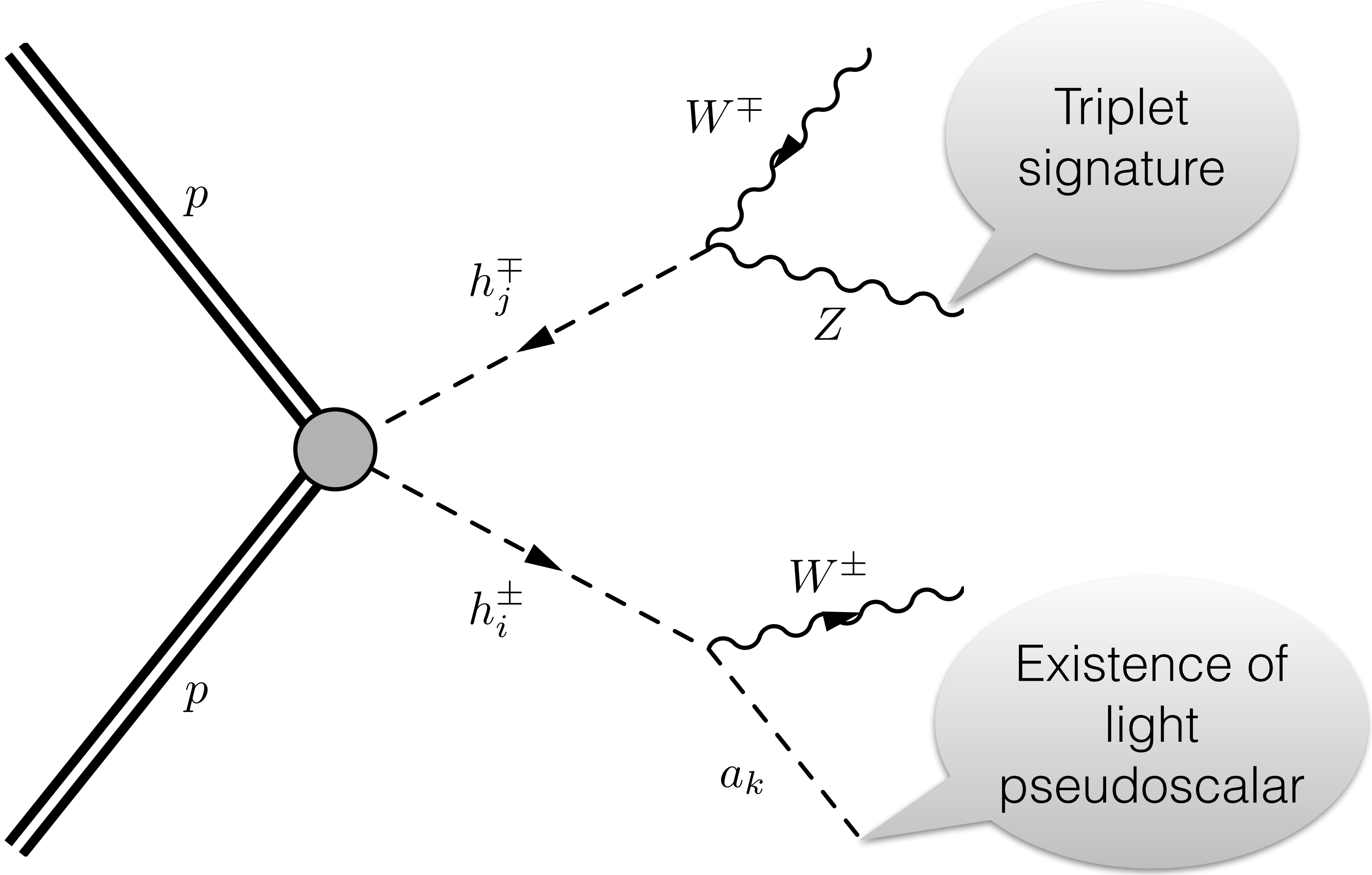


- Multi-leptonic final states can probe the triplet mode
- $3\ell + 2j,\ 3\ell + 2b$ final states can probe such triplet signature by $\sim 100\,\mathrm{fb}^{-1}$ of integrated luminosity at the LHC@14 TeV
- Higher lepton multiplicities can be probed at further higher luminosities.

P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026

- Is it possible to distinguish different possible extensions ?

$$W_S = \lambda_T H_d.TH_u + \lambda_S S H_d \cdot H_u + \lambda_{TS} S Tr[T^2] + \frac{\kappa}{3} S^3$$

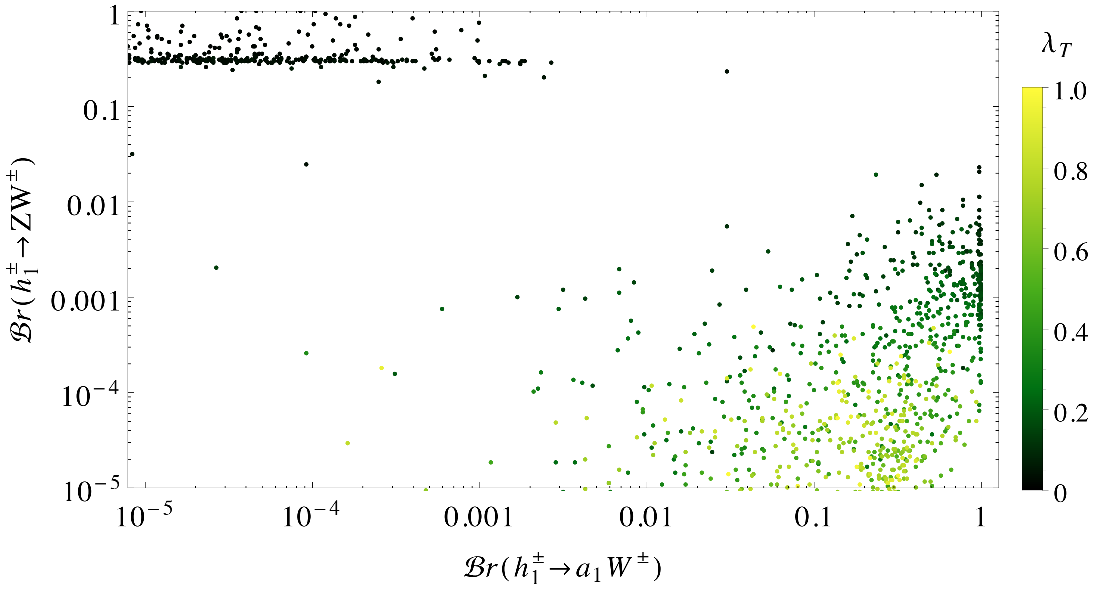


Triplet signature

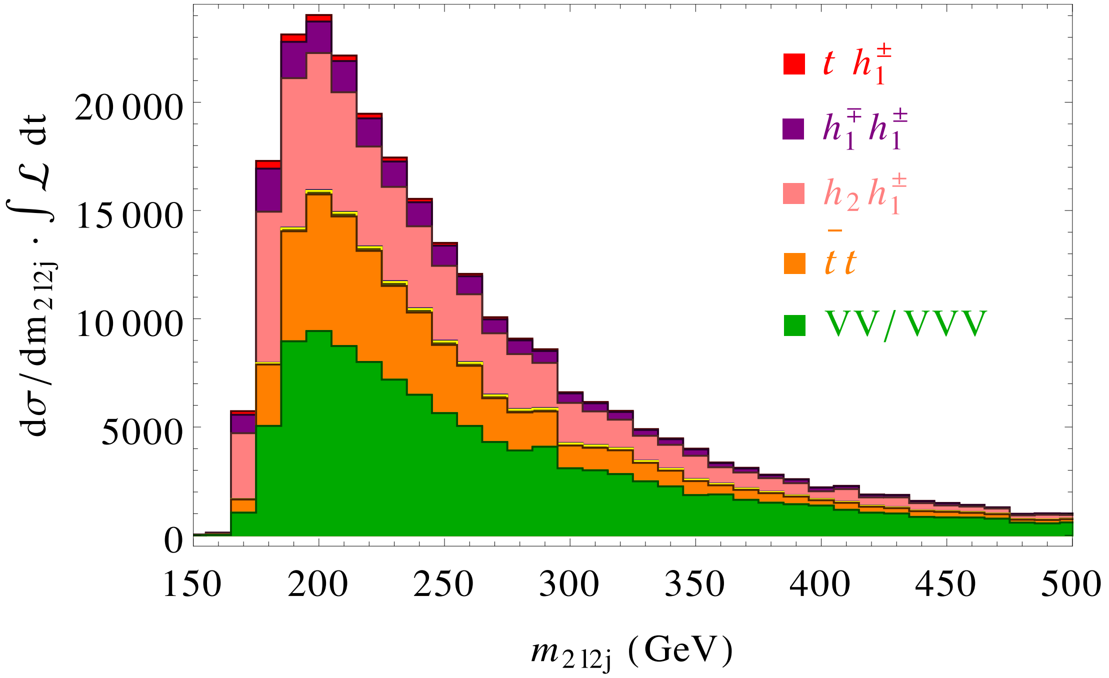
Existence of light pseudoscalar

PB, Claudio Coriano, Antonio Costantini, Phys.Rev. D94 (2016) no.5, 055030

Status of triplet Y=0 charged Higgs boson



- Probing $a_1W^\pm$ and $\mathrm{ZW}^\pm$ together is challenging
- $a_1W^\pm$ can be probed via $2b + 2\tau + 1\ell + m_{jj} \sim m_W$ at the LHC with $43\,\mathrm{fb}^{-1}$
- ZW mode can be probed via $3\ell + 1\tau$ with $54\,\mathrm{fb}^{-1}$



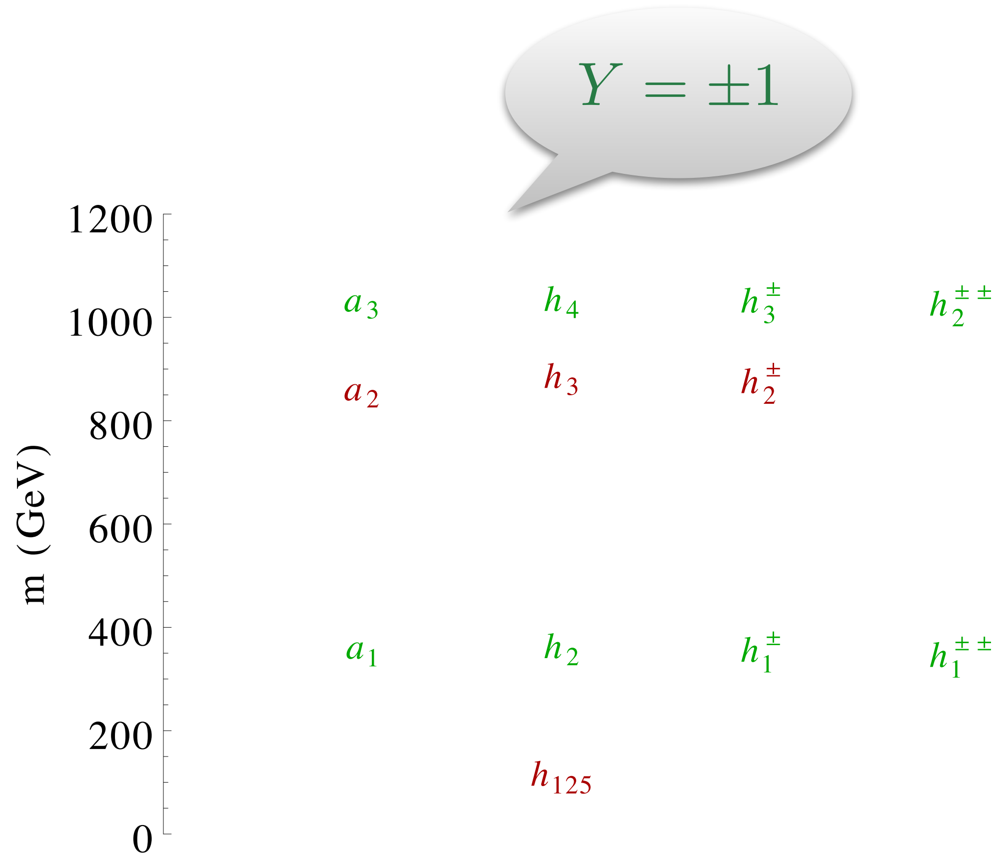
- Light pseudo scalar mass can probed with early data of $55\,\mathrm{fb}^{-1}$
- Probing charged Higgs mass via reconstruction of Z and W will take around $712\,\mathrm{fb}^{-1}$ of integrated luminosity

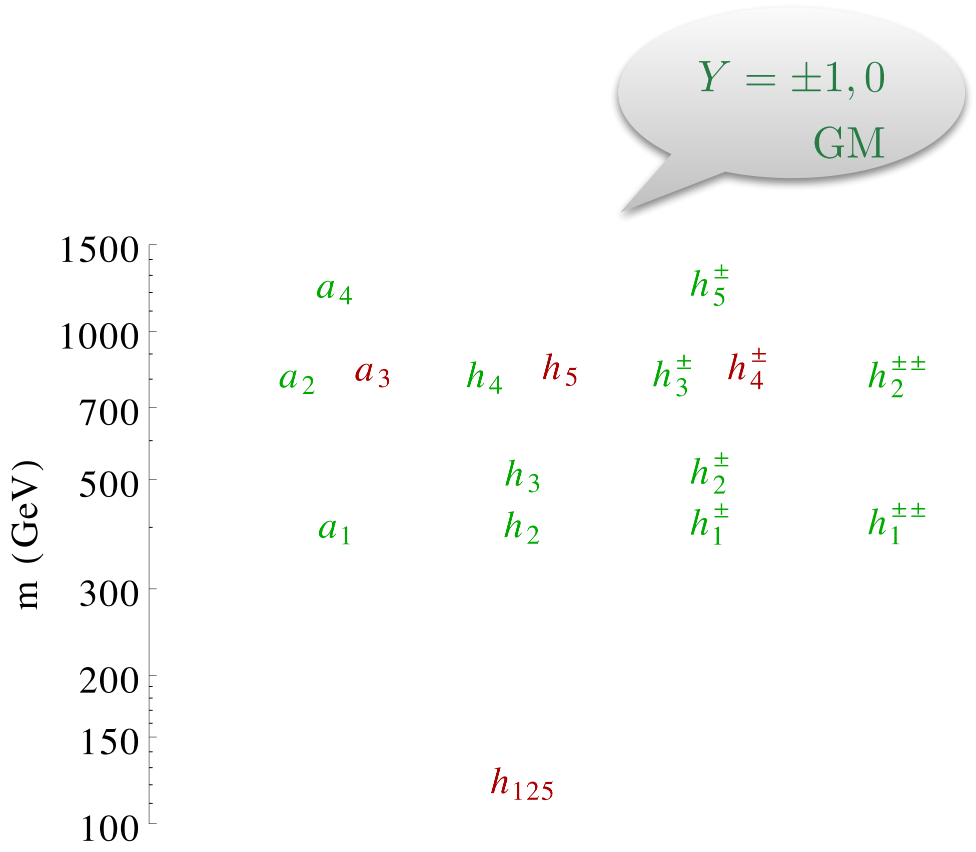
- It is possible to distinguish charged Higgs bosons from different representations of SU(2)

PB, Antonio Costantini, JHEP 1801 (2018) 067

Status of non-zero Hyper-charged triplets charged Higgs bosons

- $Y = \pm 1 \,\mathrm{invokes}\, \mathrm{H}^{\pm\pm}$ in the spectrum but constrained from ρ parameter
- $Y = \pm 1, 0$ can form custodial triplets known as Georgi-Machacek triplets which can evade the constraints from ρ parameter





- For these cases one needs to find out the doubly charged states with the given hierarchy

Conclusions

- So far we have observed one Higgs boson at 125 GeV
- All standard and non-standard modes are yet to be explored
- Observation of Charged Higgs would be a direct proof of extended Higgs sector.
- Non-standard decay modes $h^\pm \to a_1 W^\pm$ and $h^\pm \to ZW^\pm$ are direct proofs of higher representations of Higgs sectors.
- $t - b - h_1^\pm$ coupling will also be good measure
- Indirect searches can also give us some hints
- We hope LHC bring some more discoveries

THANK
YOU!

Some of them can evade detection for earlier searches

Searches of the Higgs bosons

- Higgs bosons are searched via their decay modes

$$\left.\begin{array}{r} h \to b\bar{b} \\ \to \tau\bar{\tau} \end{array}\right\} \textbf{Lepton and quark modes}$$

$$\left.\begin{array}{r} \to ZZ^{*} \\ \to WW^{*} \end{array}\right\} \textbf{Gauge bosons}$$

$$\to \gamma\bar{\gamma} \text{ (di-photon)} \Big\} \textbf{ Loop decay}$$

- Add-mixture or possibility of other Higgs bosons are not ruled out

  - But other Higgs bosons may not be seen in normal decay modes!

  - Triplets or Singlet type Higgs bosons are hard to produce and find

  - There is possibility of lighter Higgs bosons but not observed yet

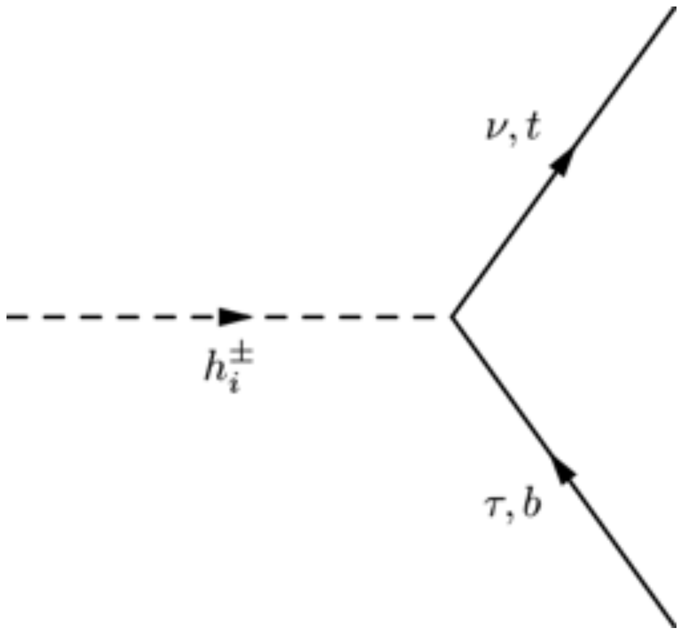
Still longer run at the LHC has a good chance

- How about charged Higgs boson ?
- Is there a charged Higgs boson in nature ?
- Do we really need them?

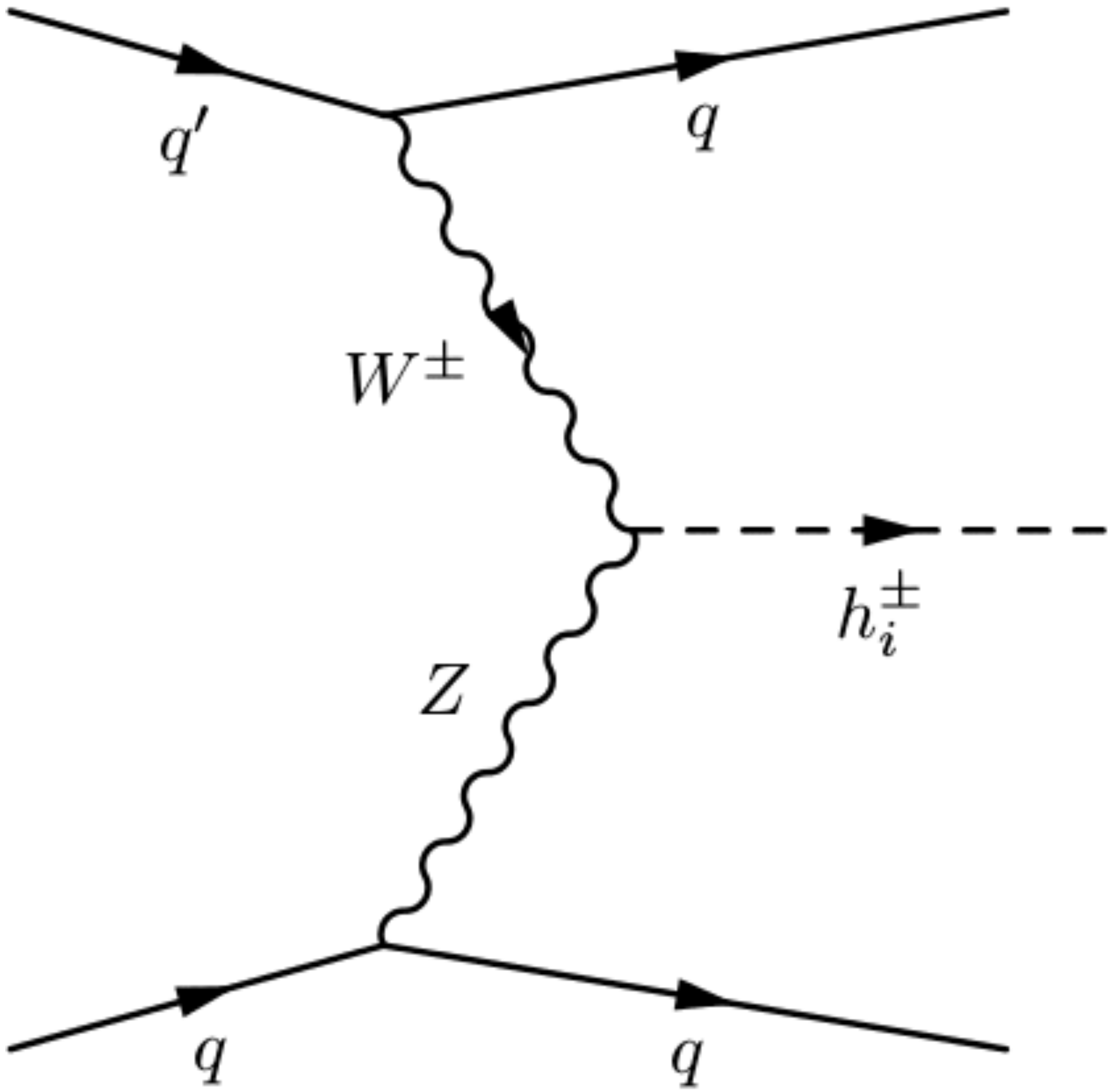
- In the current form of Standard Model we do not have any charged Higgs boson

- It is certainly a beyond Standard Model physics
- Necessary for Supersymmetric theories

  - If they are there, how do we see them?
  - They will leave charged track as their signature



Look for new production modes



Prospects at the LHC

- More data
- New resonance !
- New Discoveries !