Perspective of extended Higgs sectors in beyond Standard Model scenarios

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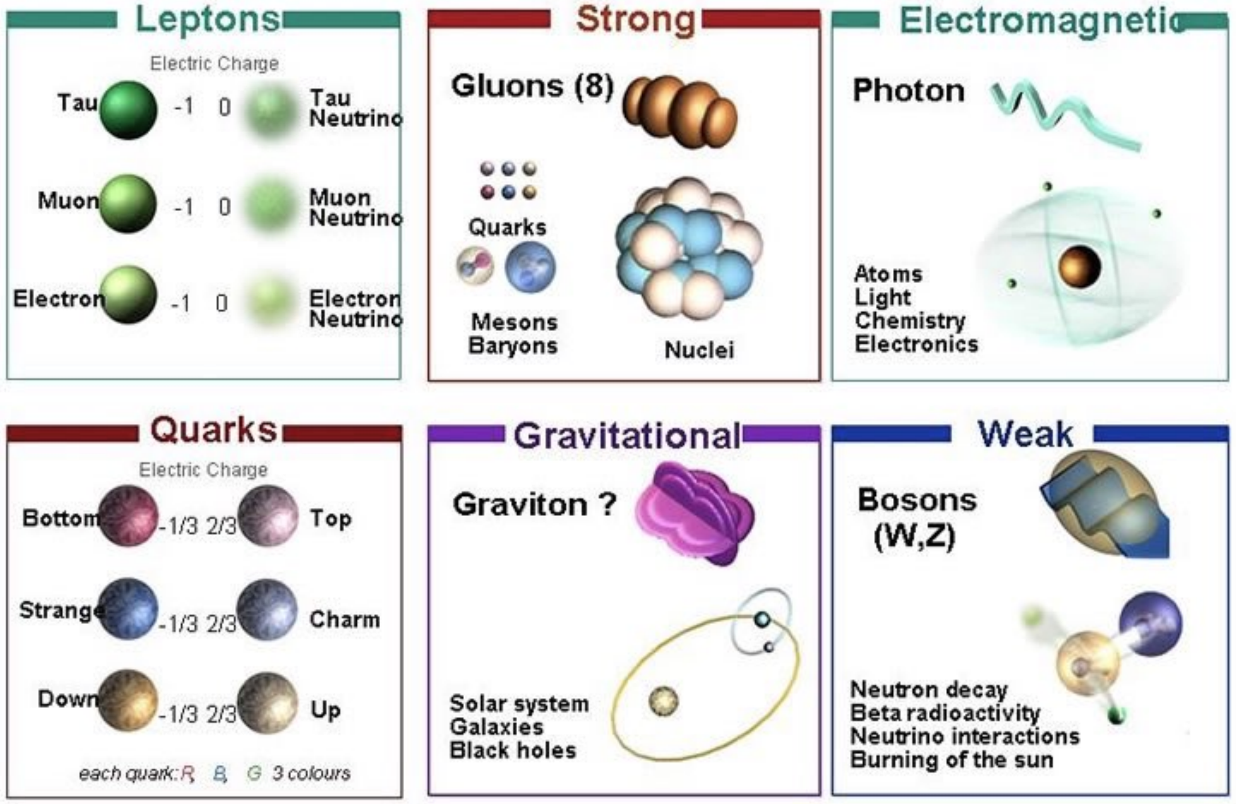
Plan

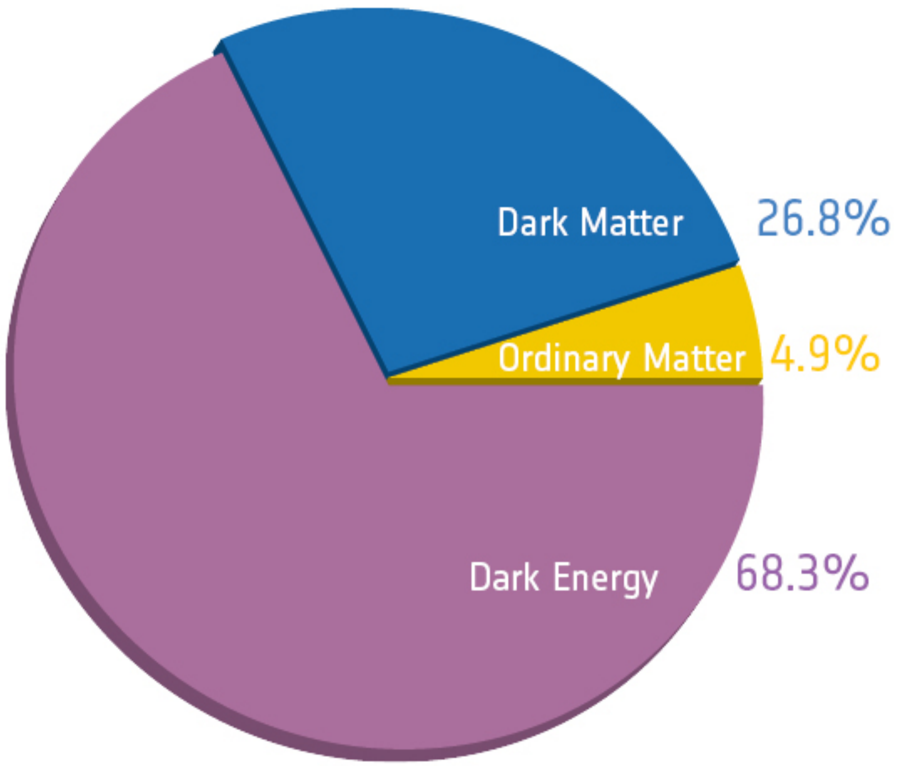
- Standard Model Higgs Boson
- Towards Higgs discovery and status
- Possible non-SUSY extensions in the Higgs sector

  - Singlet Higgs boson: Real and Complex
  - Doublet Higgs boson: Type-I, II, III, IV
  - Triplet Higgs boson: Real and complex
  - Inert Higgs bosons: Singlet, Doublet and Triplet

- Extended Higgs sectors with supersymmetry

Forces of Nature

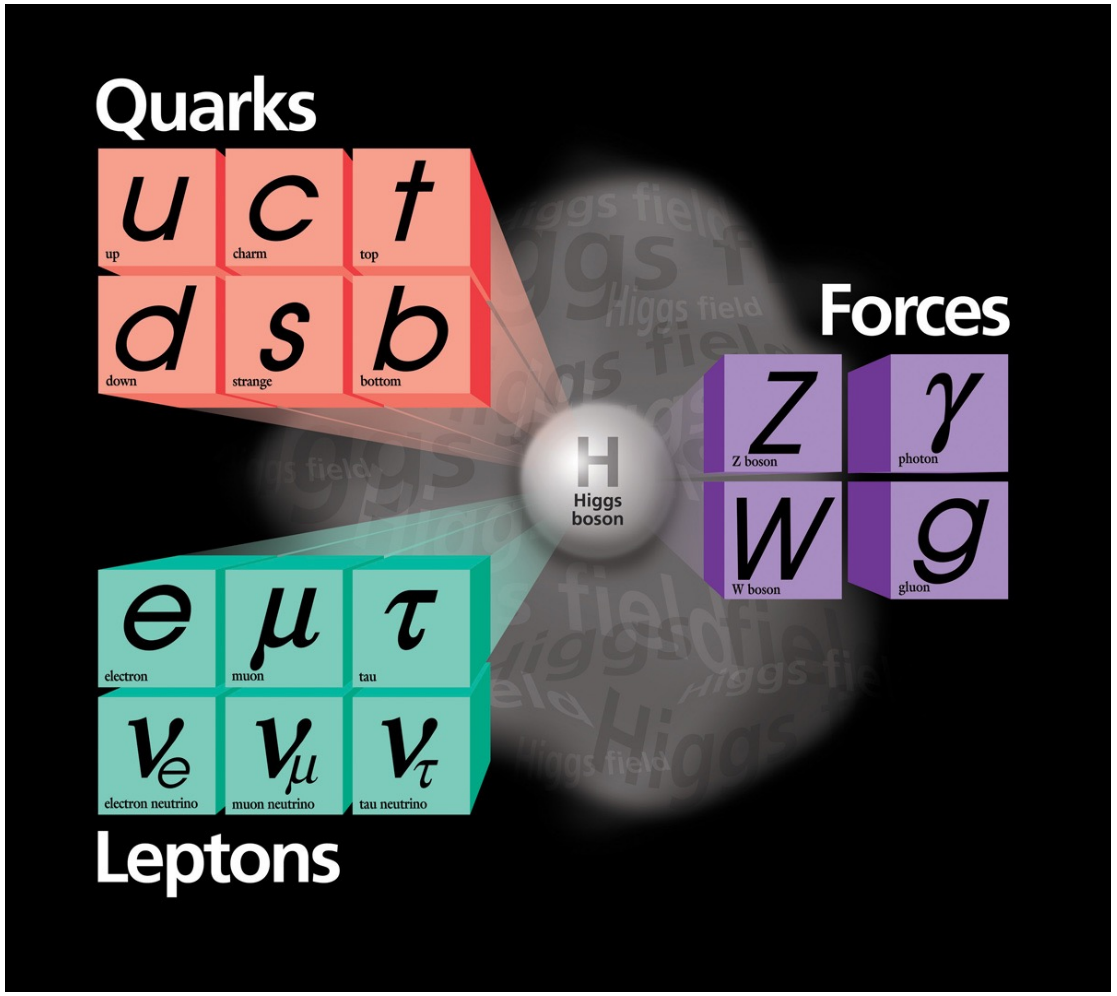




- 12 fermions constitute the matter.
- 12 gauge bosons are the force carriers
- They constitute the ~ 5% observed matter
- Unobserved matter, called as Dark Matter

Particle physics is summarised as

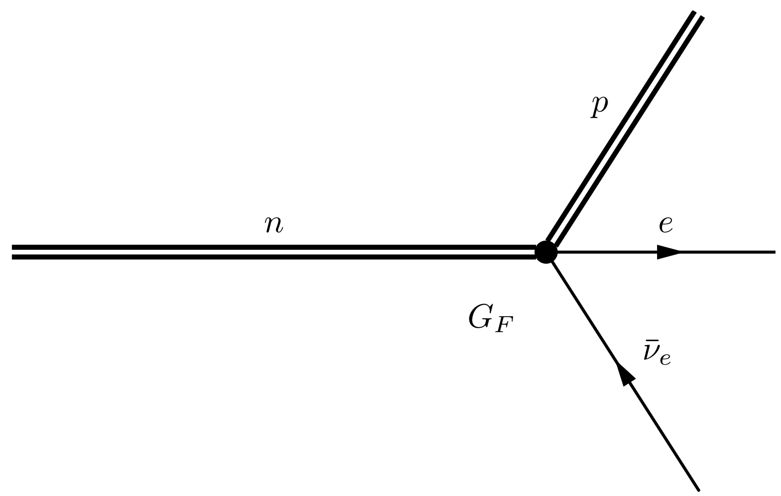
'Standard Model'

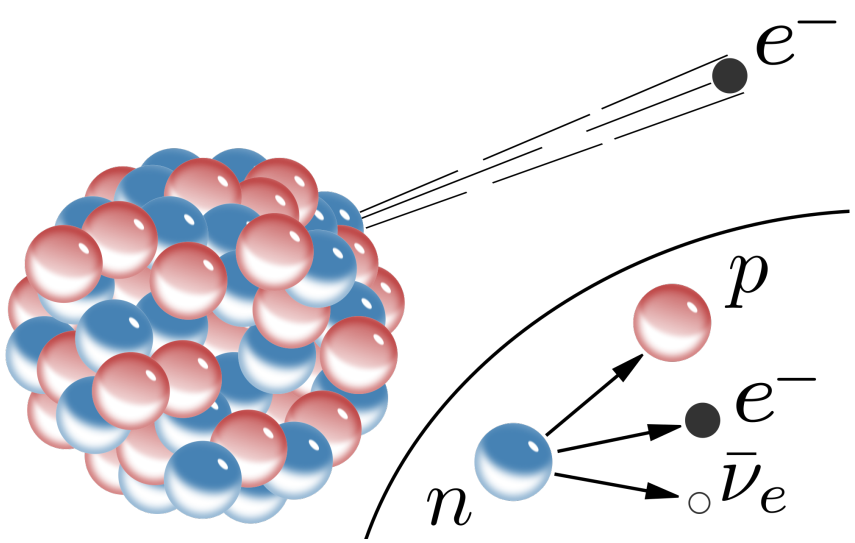


- Quarks come in pairs with charge 2/3 e and -1/3 e
- Each leptons has its own neutrinos
- Forces carriers communicate between the quarks and leptons

Fermi theory

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





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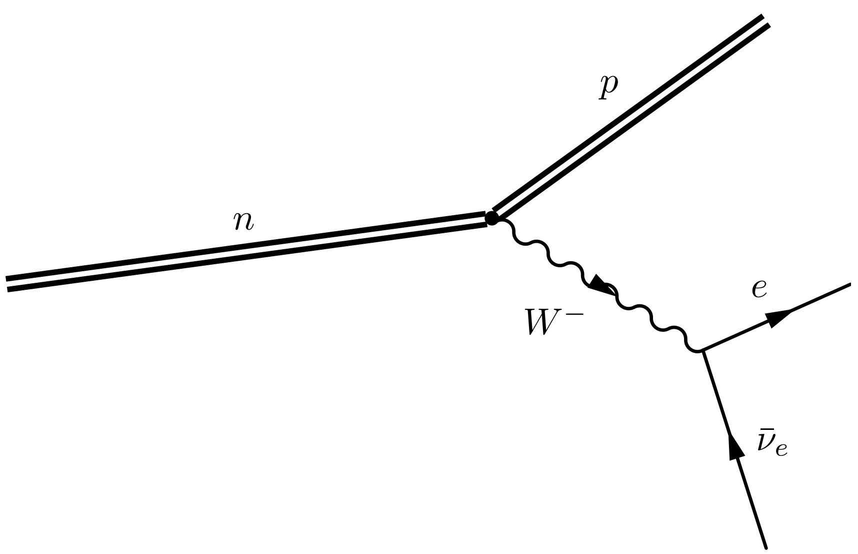
- That Fermi Theory can be seen as a result of exchange of force carrier

- A massive gauge boson W

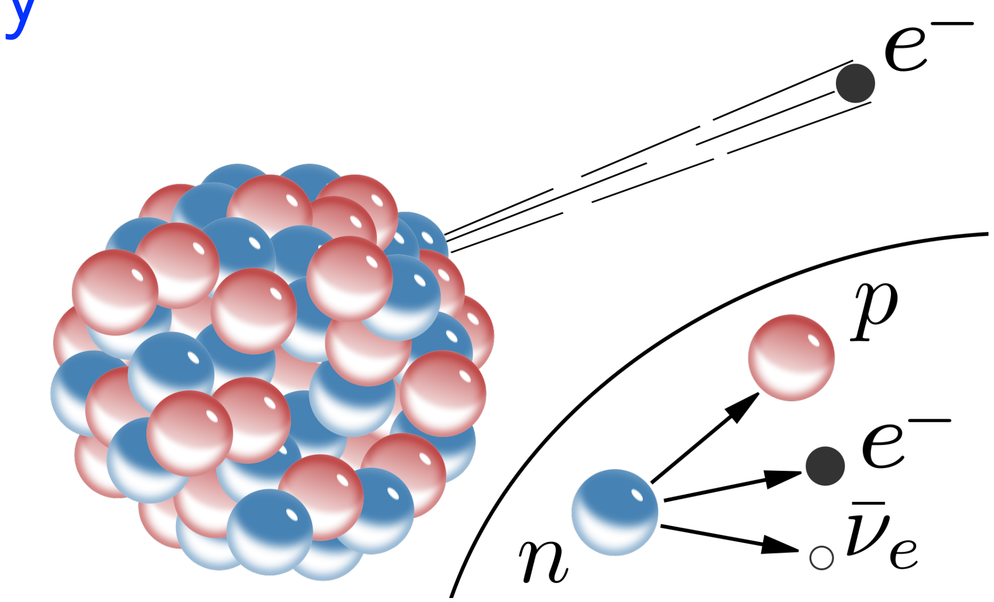


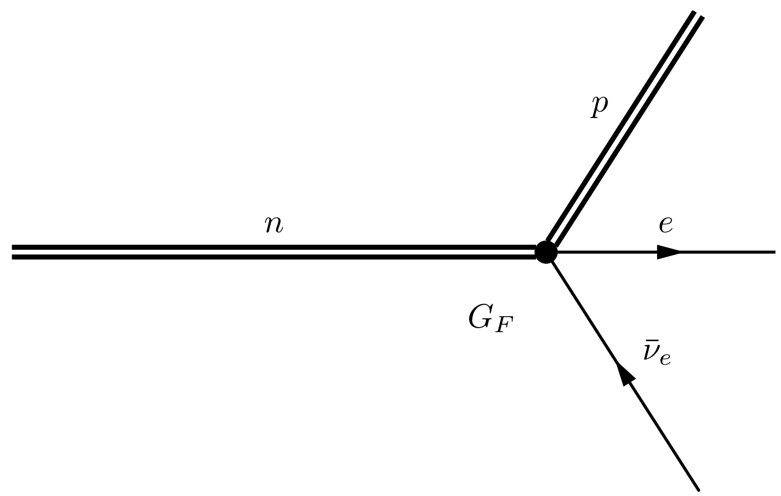
With effective coupling

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

Fermi theory

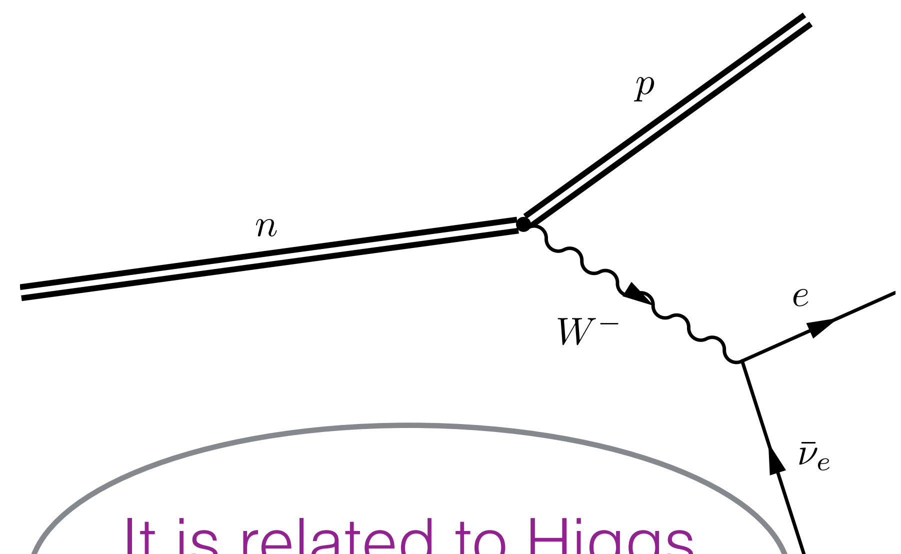
- Enrico Fermi in 1933 proposed theory for Nuclear beta decay with effective four fermion interaction





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

- A massive gauge boson W →



It is related to Higgs mechanism

With effective coupling

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

- 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

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

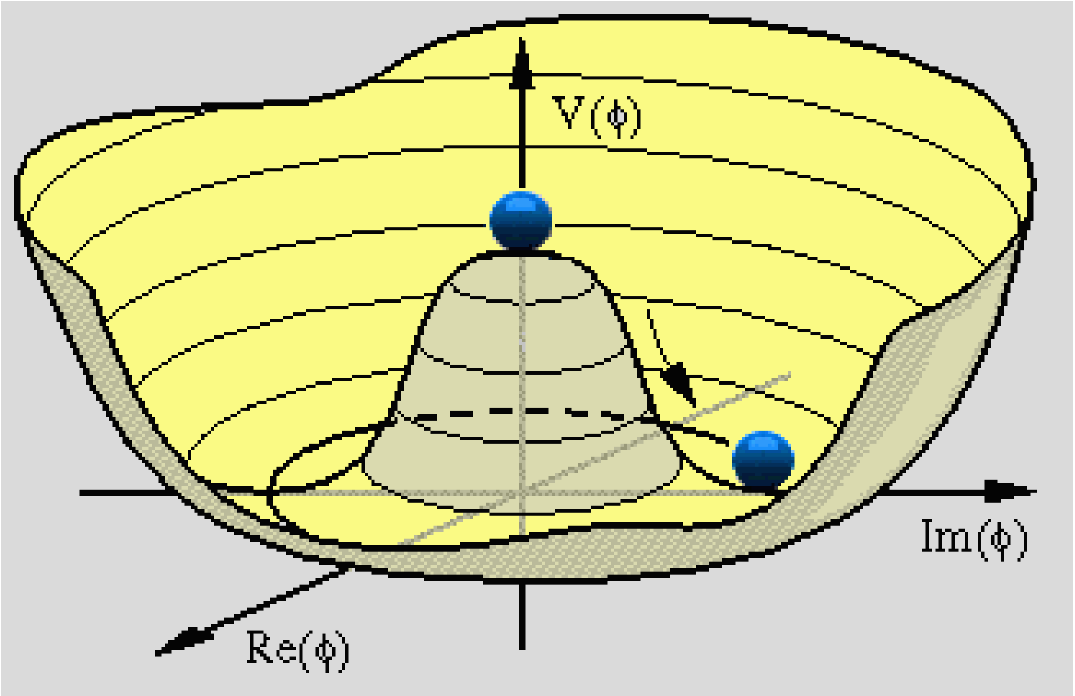
Violates gauge invariance

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

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

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, $\langle \Phi^+ \Phi \rangle = v^2 = \sqrt{-\frac{\mu^2}{2\lambda}}$, $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$

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

- 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!

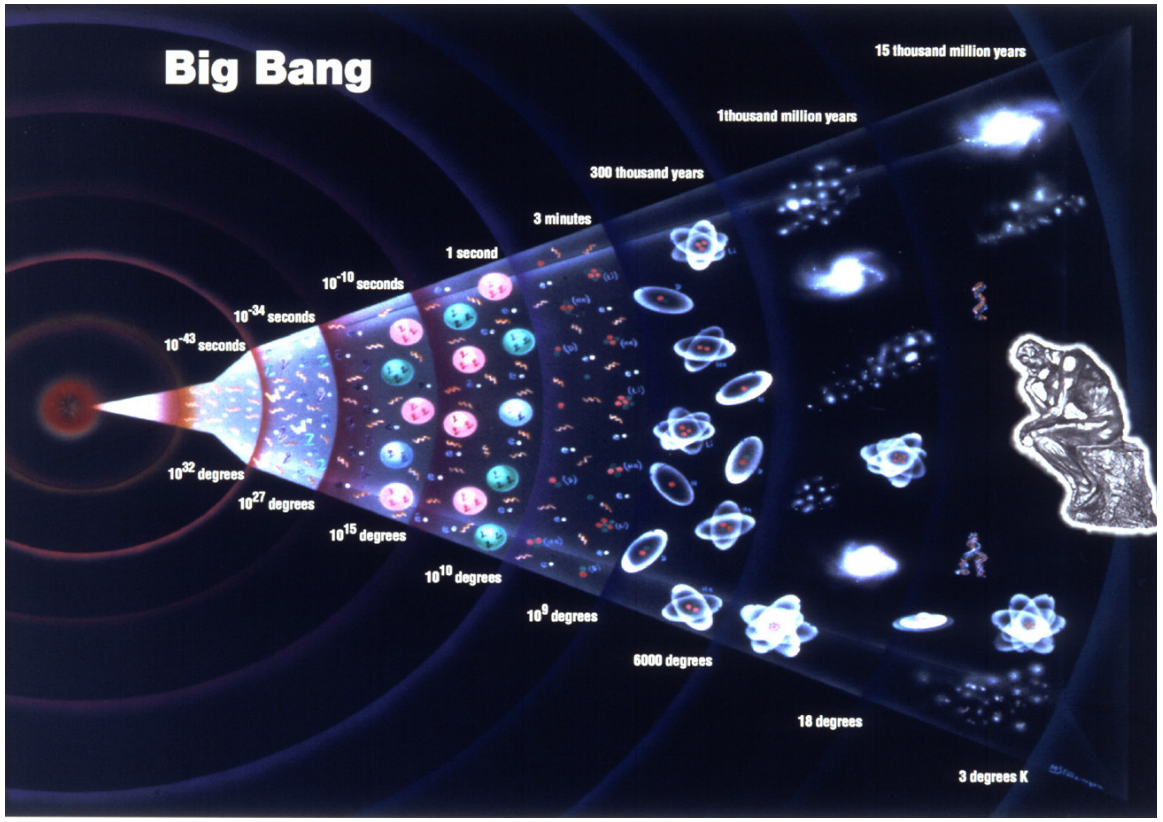
- Higgs field also gives mass to itself

Hunt for Higgs boson!

It took almost 50 years!

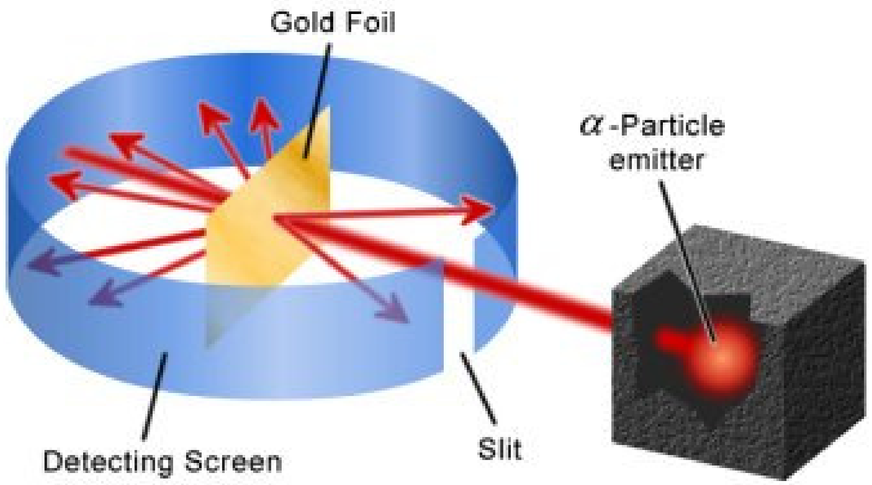
Looking back in our universe

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



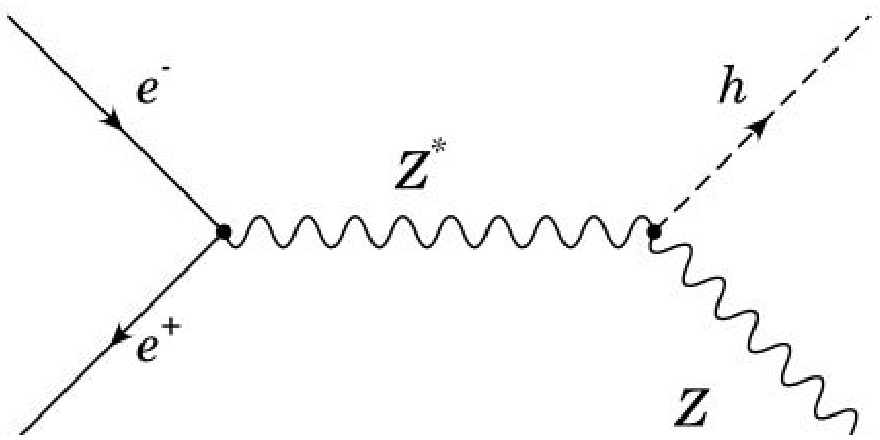
How to rediscover the theory?

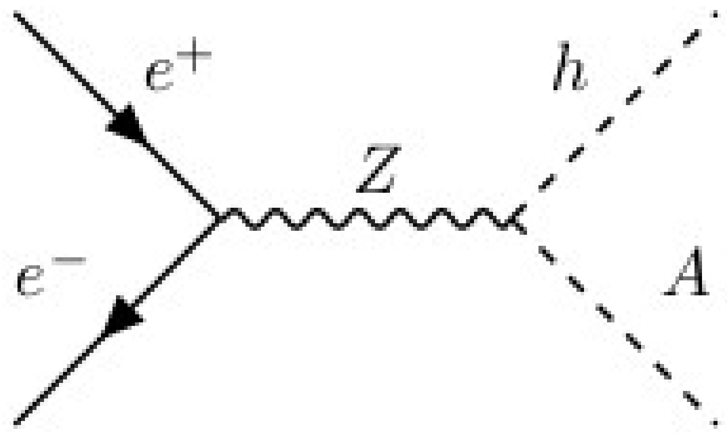
- We have to look inside the matter
- Rutherford first collided alpha particles to the gold foil to see inside the atom
- Present day colliders are using the same technology



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
- Associated production put bound $m_A \gtrsim 93\,\mathrm{GeV}$





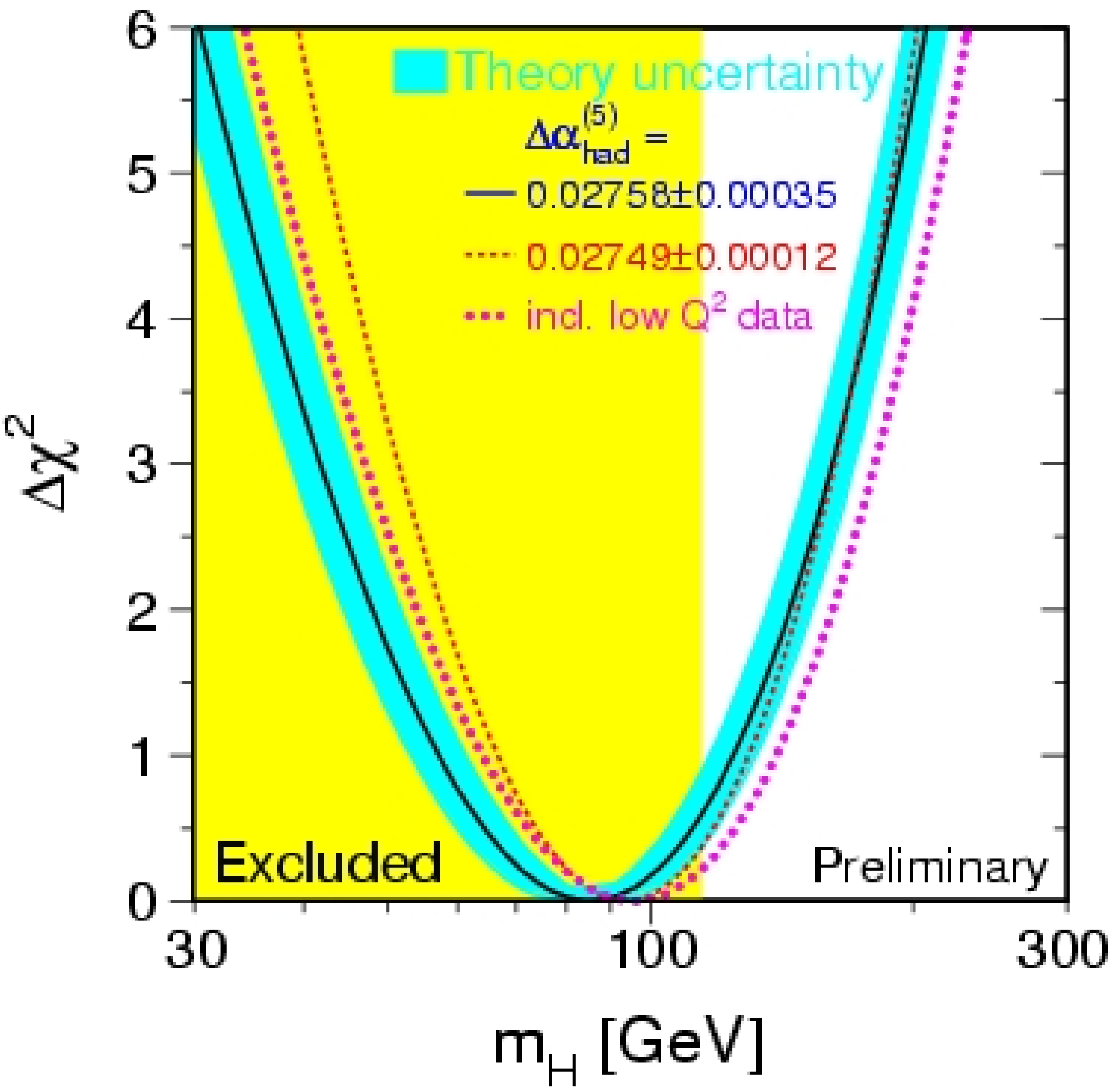
Electro-weak precision test

- The blue band implies that

$$m_H \simeq 85 \pm^{39}_{28} \ \text{GeV}$$

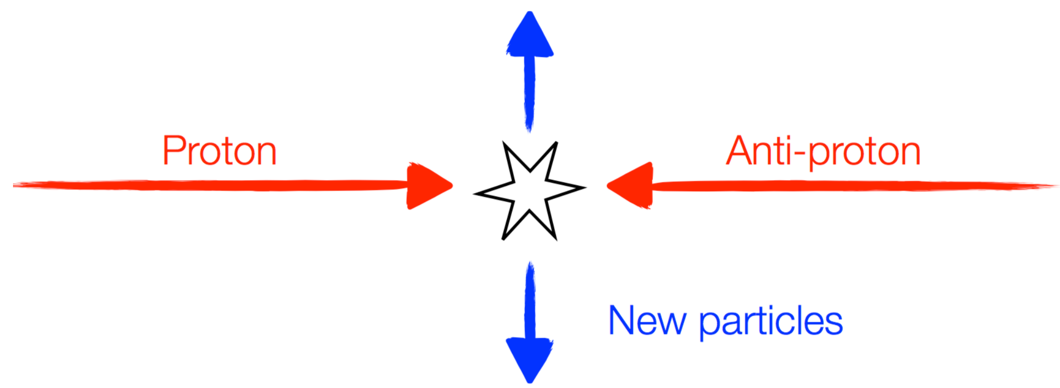
at 1σ level

$$\Rightarrow m_H \lesssim 124\,\text{GeV}$$



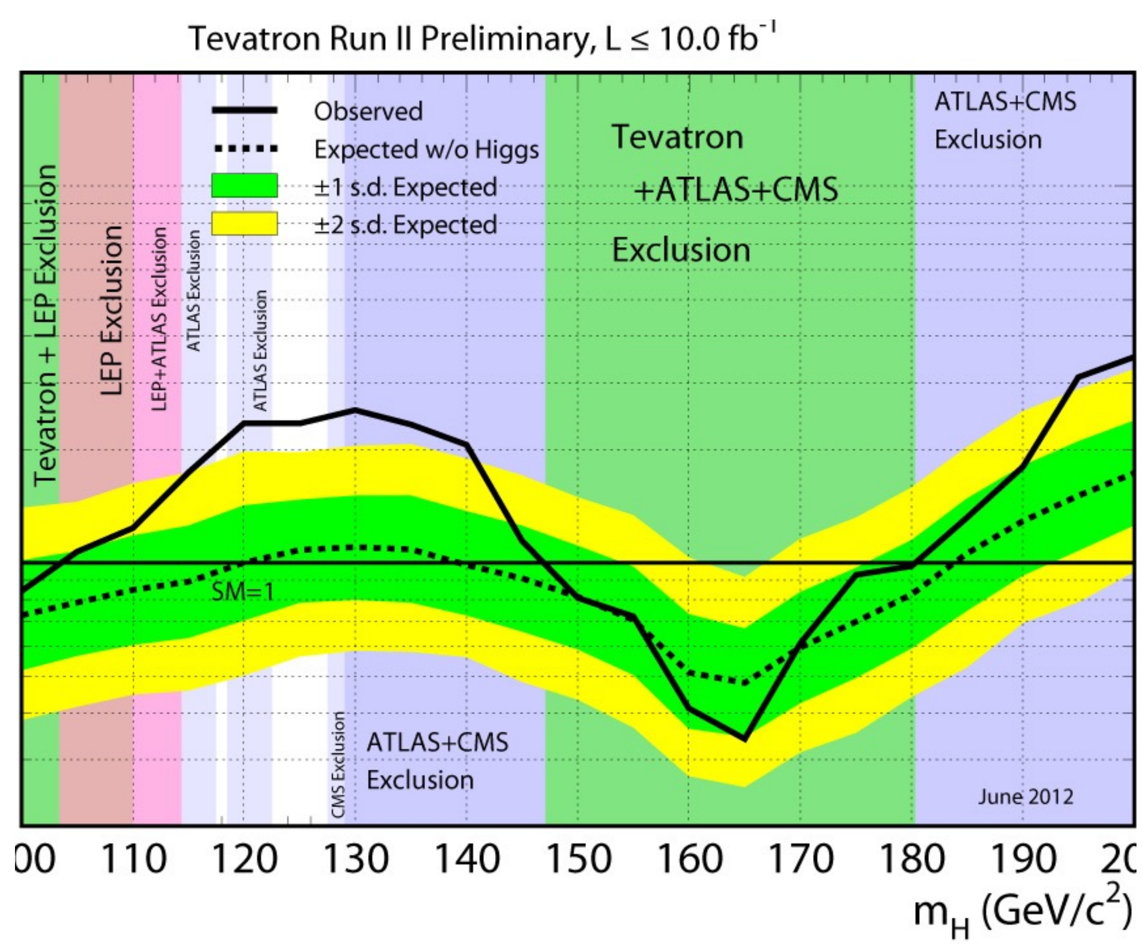
Tevatron

- 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.



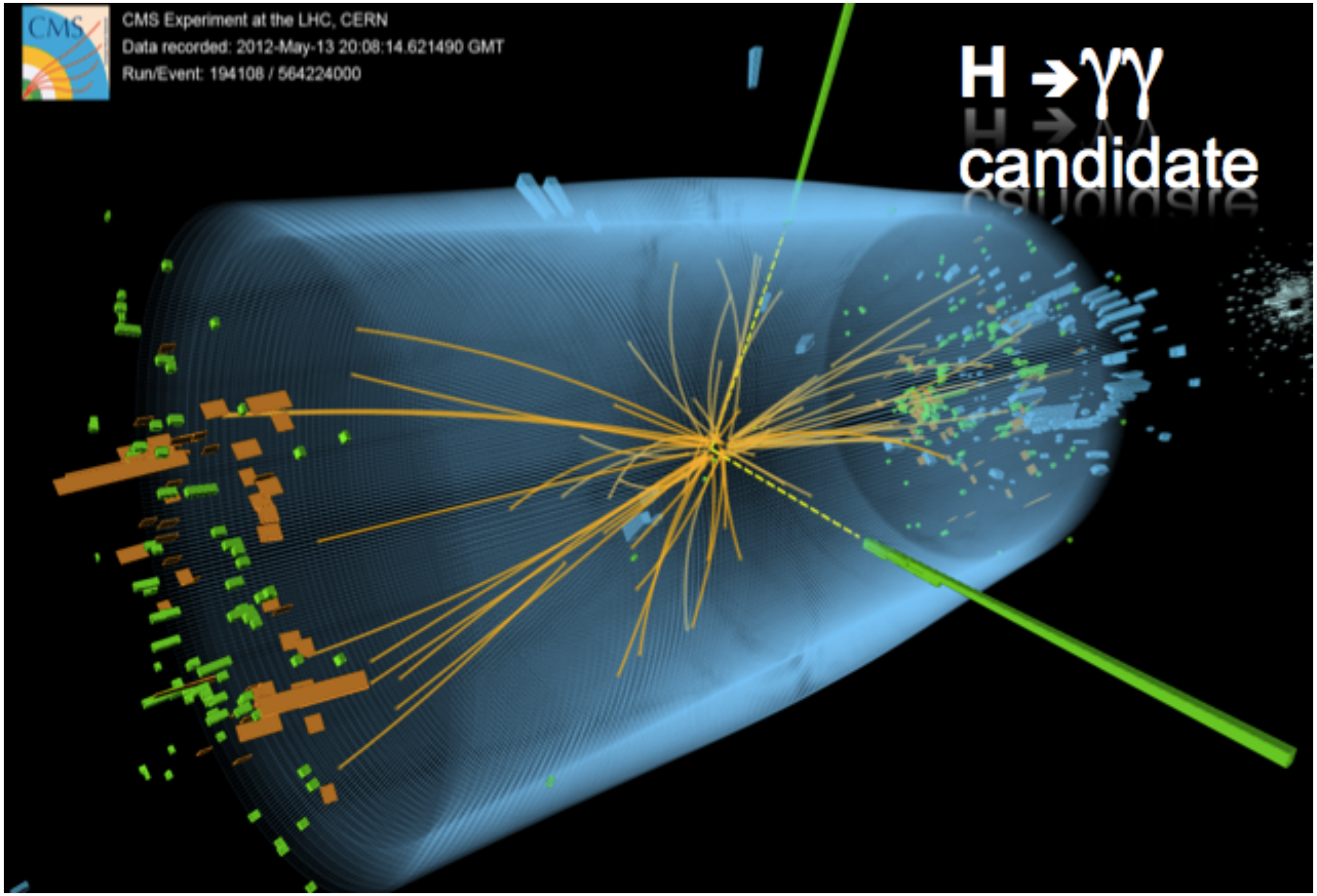
Large Hadron Collider (LHC)

- 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

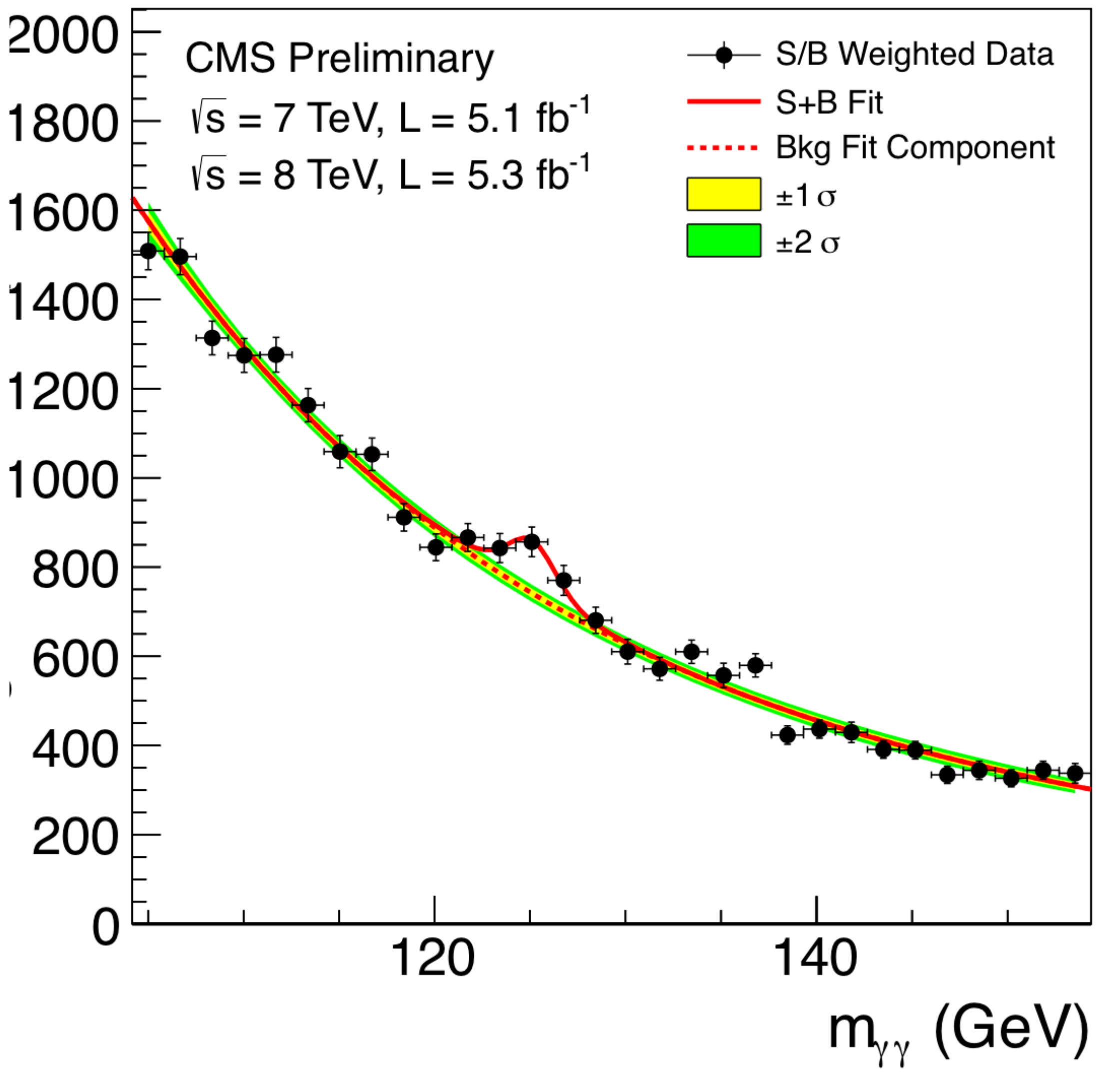
  CMS, ATLAS, ALICE and LHCb

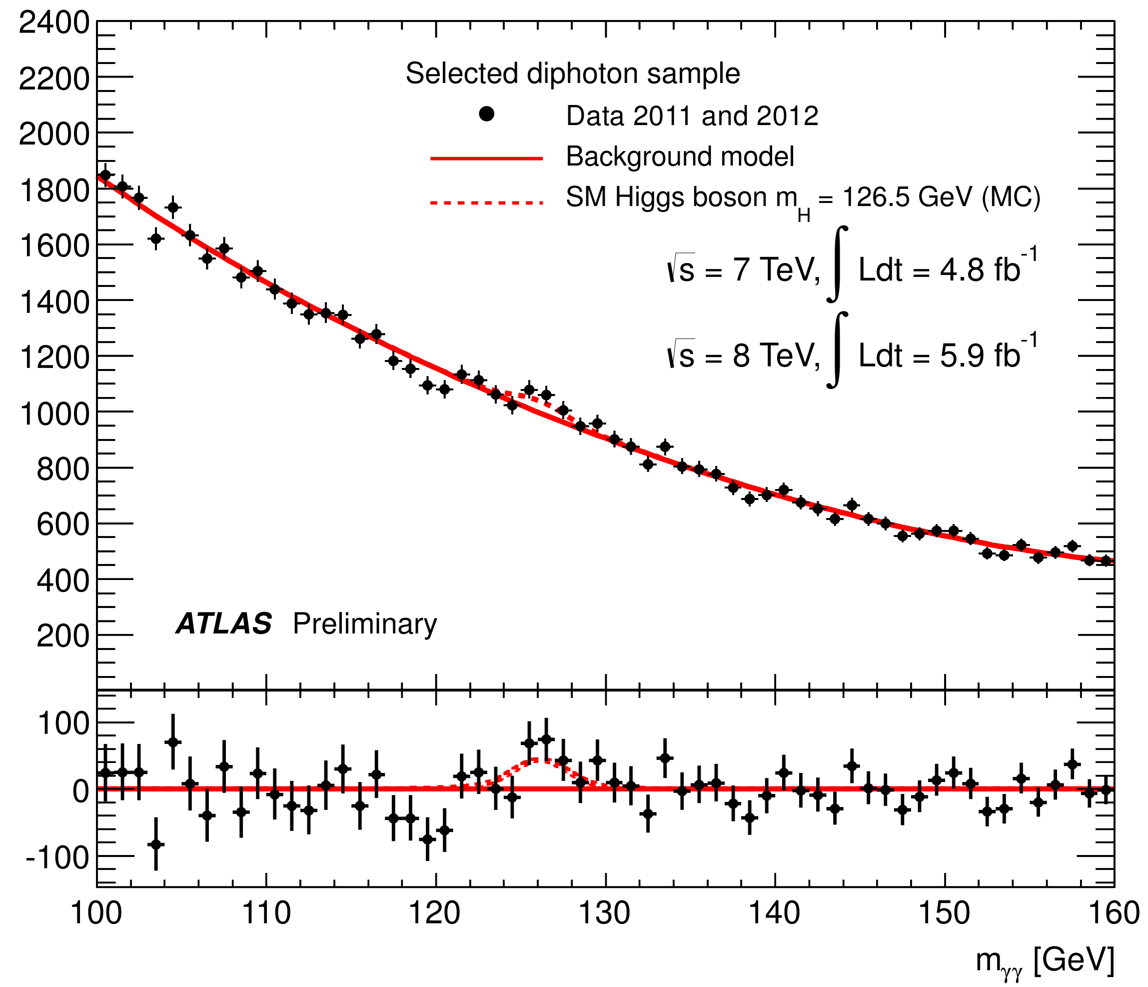
- It finished run of centre of mass energy of 7 and 8 TeV, 13 TeV
- Next run is expected in Spring 2021

We first observed Higgs boson in di-photon mode



Discovery of Higgs boson

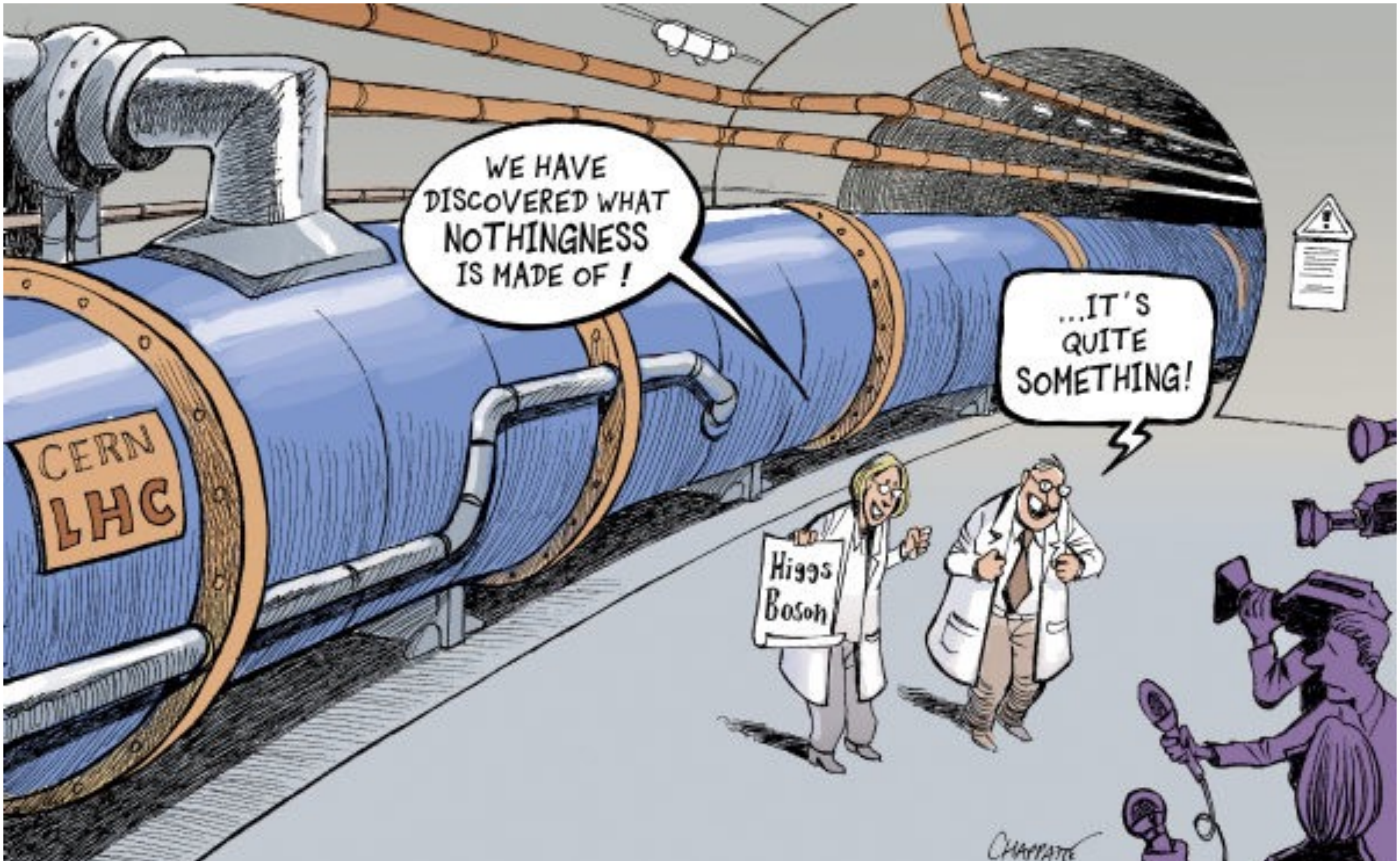




- ATLAS reported discovery of spin even-integer-spin particle with mass of 126.5 GeV at 5.0σ

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

4^{th} July, 2012



The real announcement

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

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

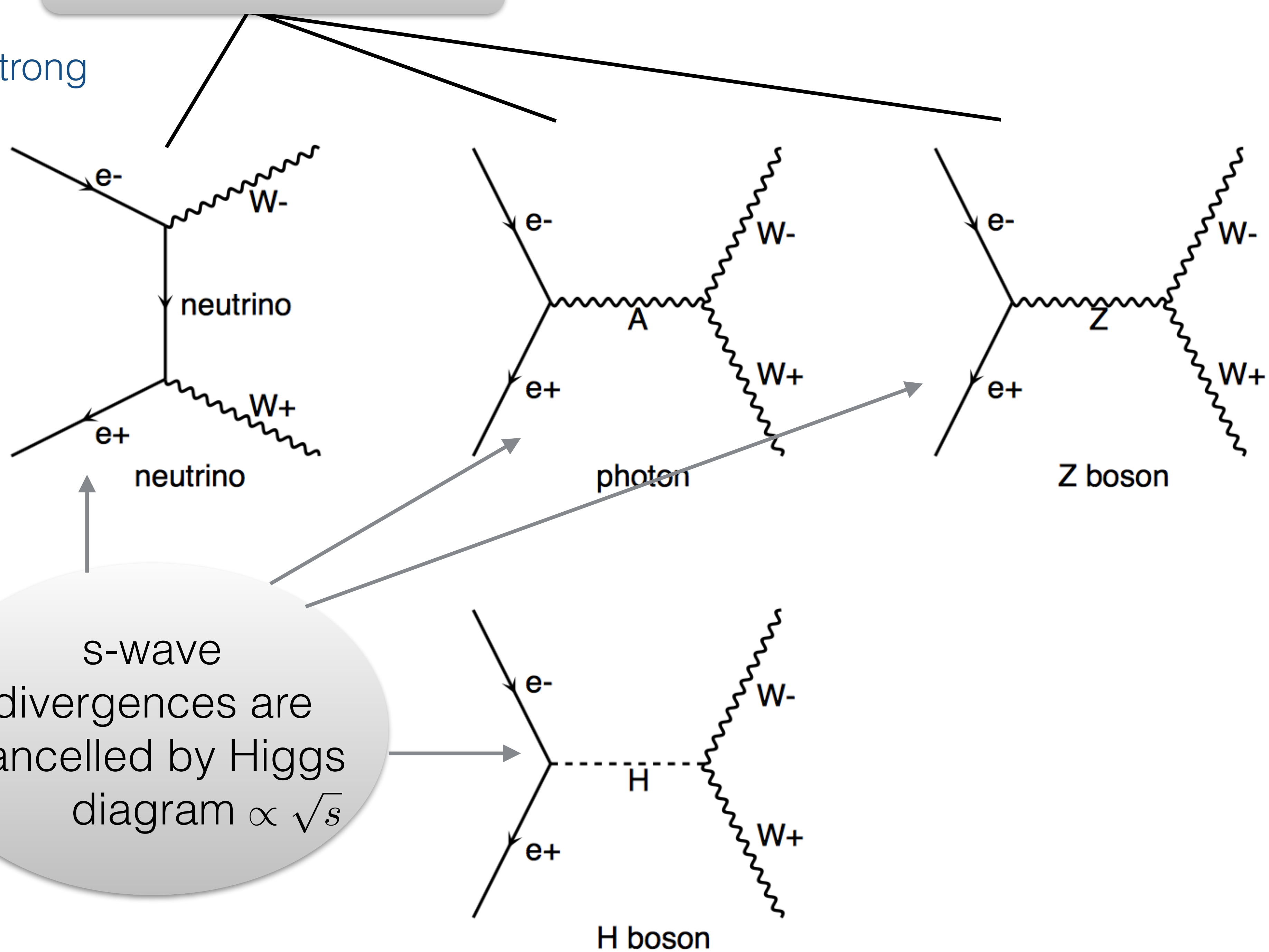
Standard Model Higgs mass bound

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

p-wave divergences cancel $\propto s$

SM Higgs potential faces strong constraints

1. Unitarity
2. From triviality
3. Vacuum Stability



s-wave divergences are cancelled by Higgs diagram $\propto \sqrt{s}$

- If the Higgs boson did not exist, we should have to invent something very much like it.

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

This is due to the running of couplings.

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

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

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

Higgs mass bounds from Triviality

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

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

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

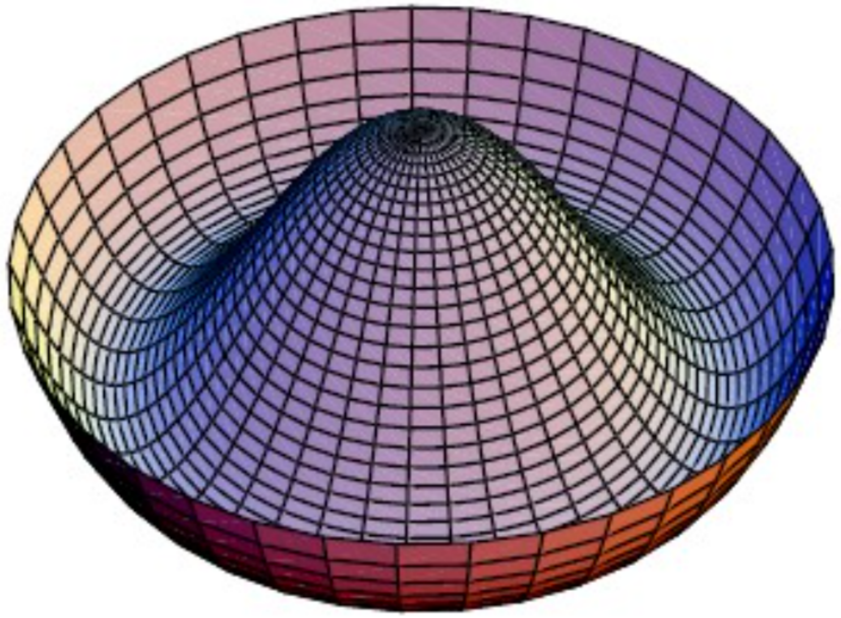
- The solution takes a form,

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

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

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

Stability of the potential



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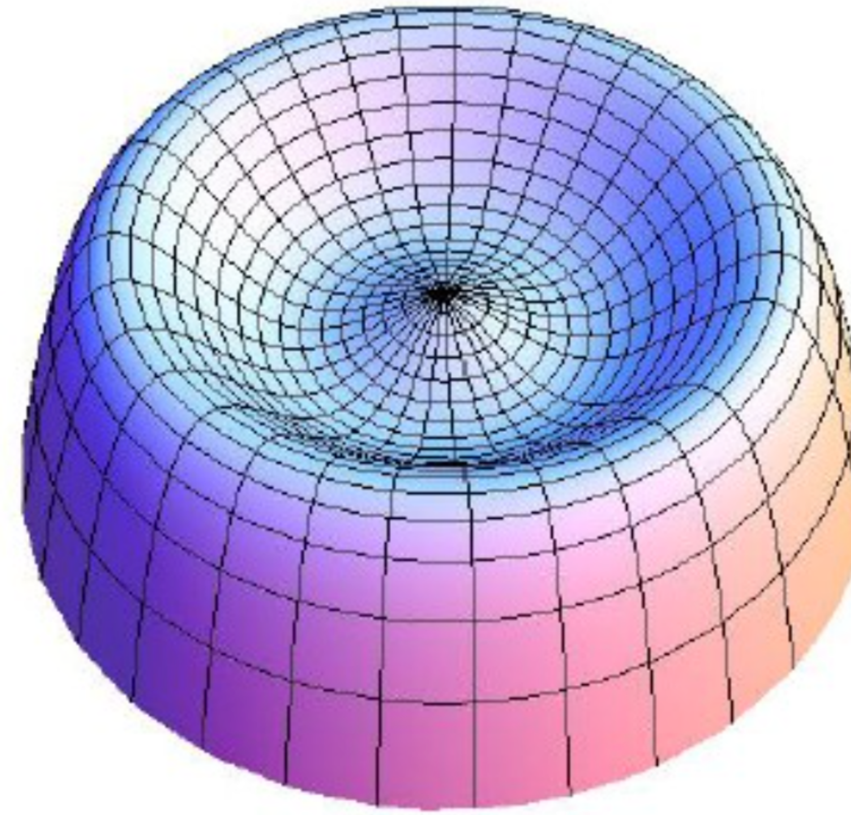
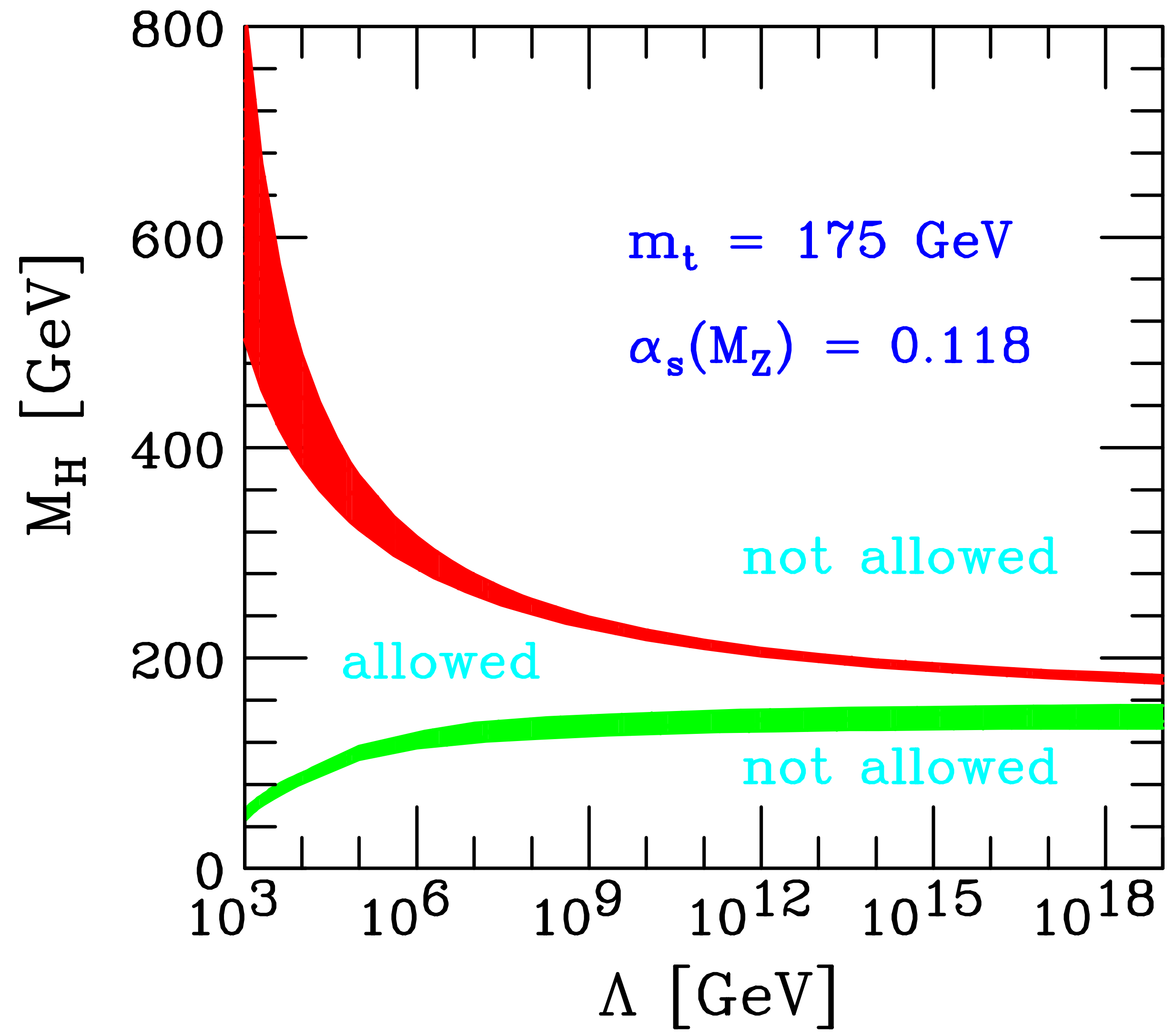


If your mexican hat turns out to be a dog bowl you have a problem...

from A. Strumia

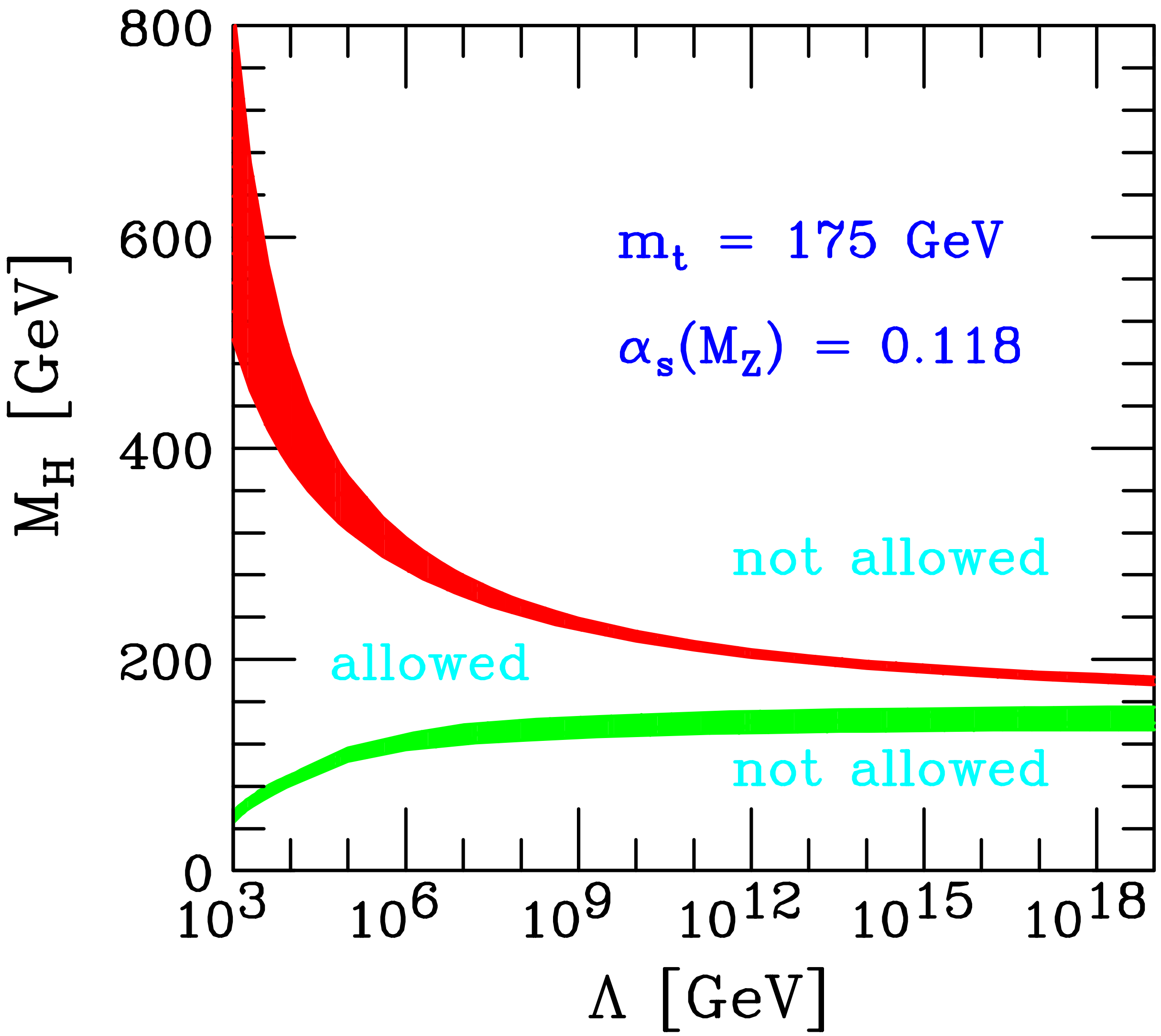
Theoretical Prediction of Higgs boson mass



- Perturbative unitarity $\Rightarrow \quad m_H < 870$ GeV
- Triviality $\Rightarrow \quad m_H < 160$ GeV
- Stability $\Rightarrow \quad m_H > 126$ GeV.

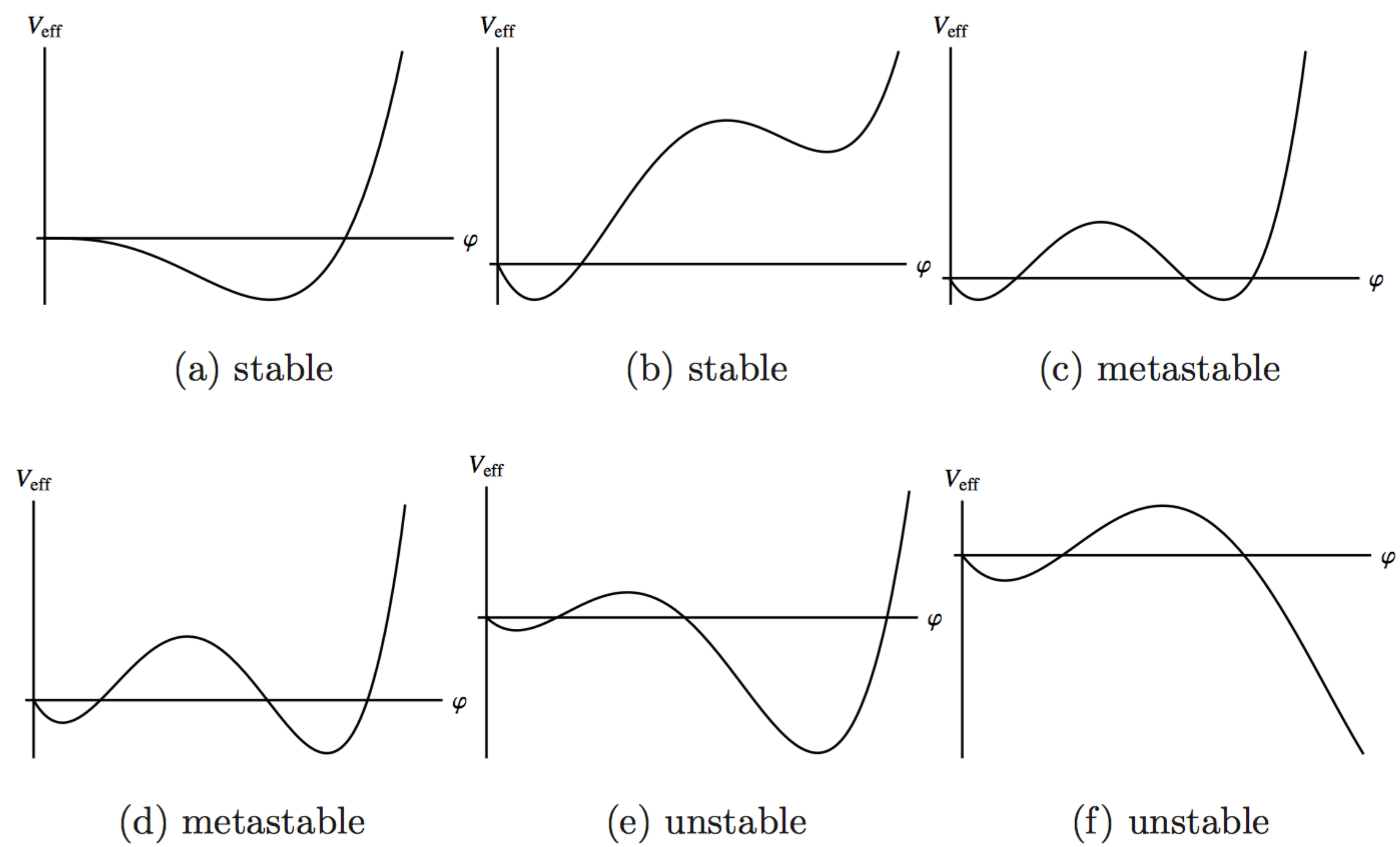
Generic guide lines of SM extensions

- 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.



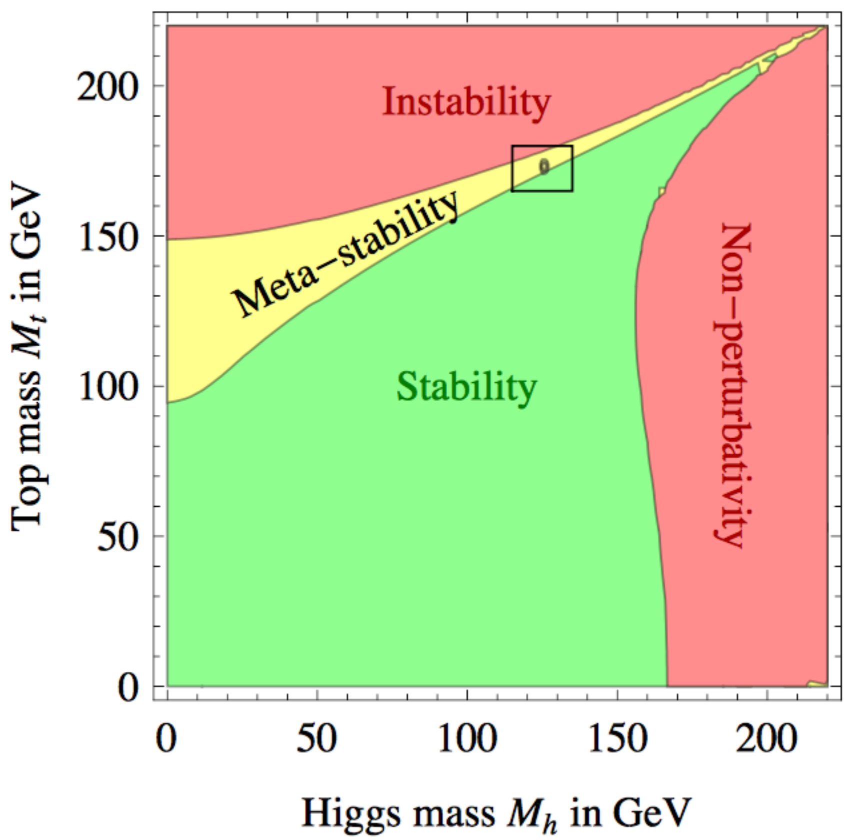
Extending Higgs sector will enhance vacuum stability

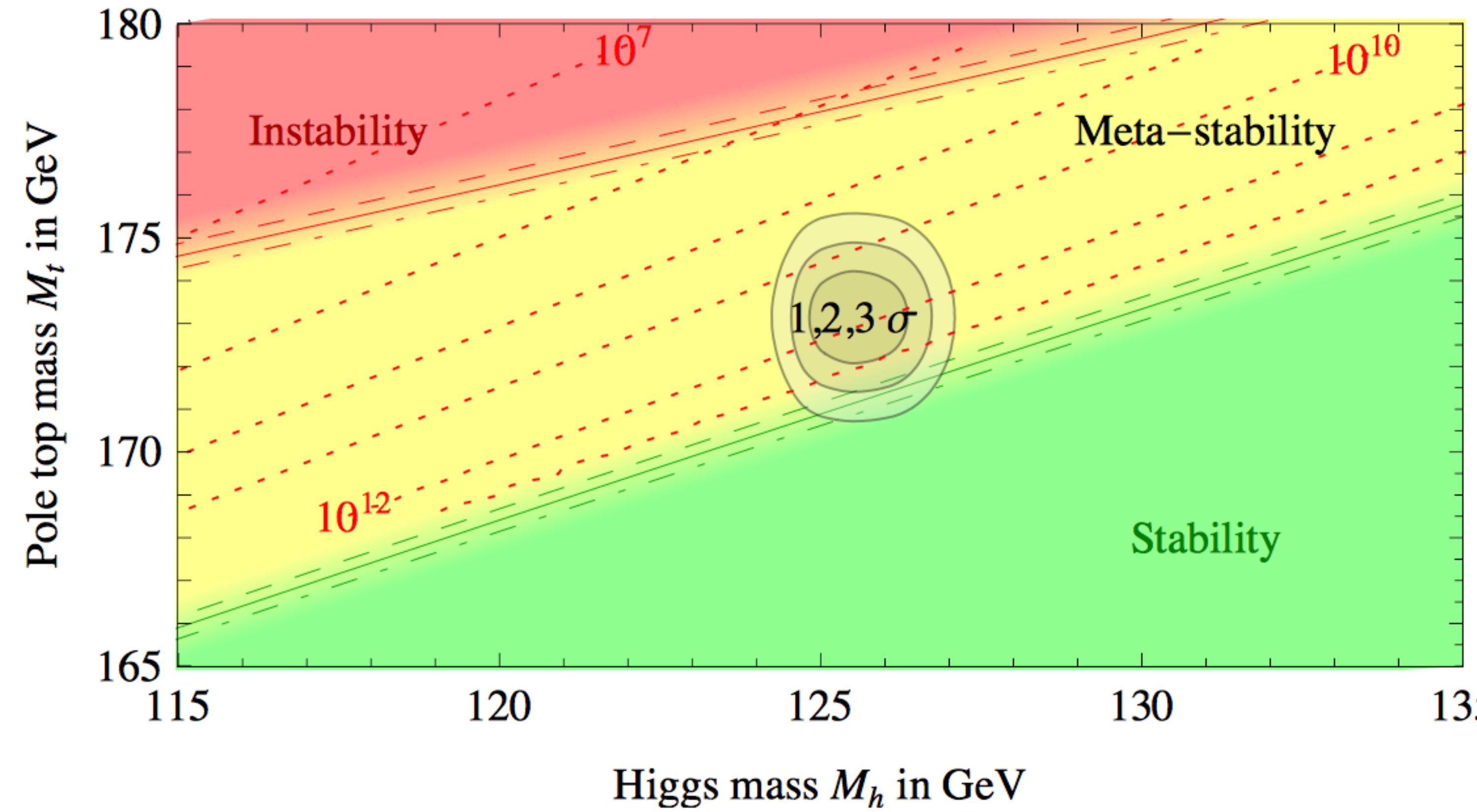
Possible Potentials



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

Status of SM

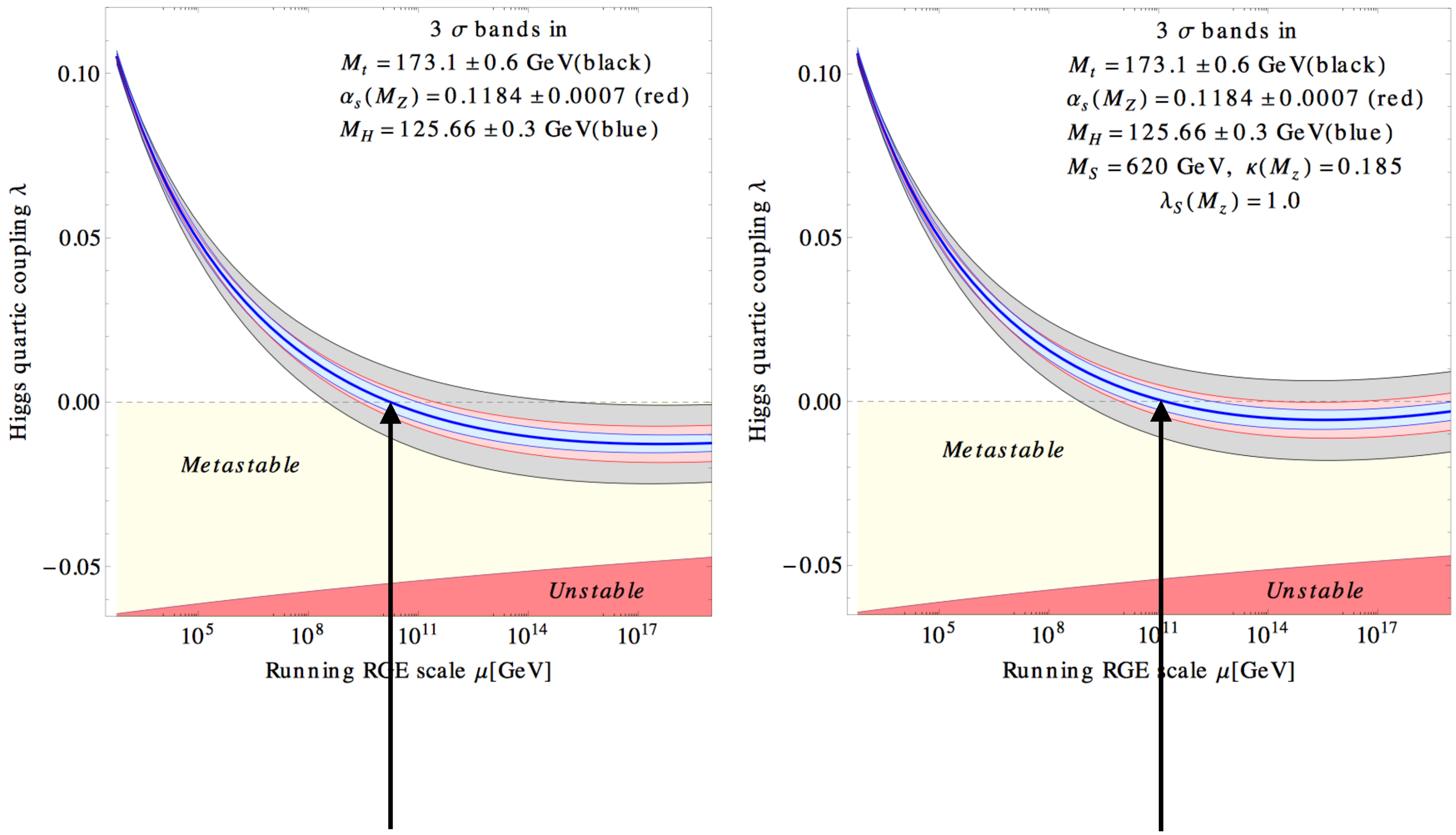




Within the uncertainty of top mass we are in a metastable vacuum

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

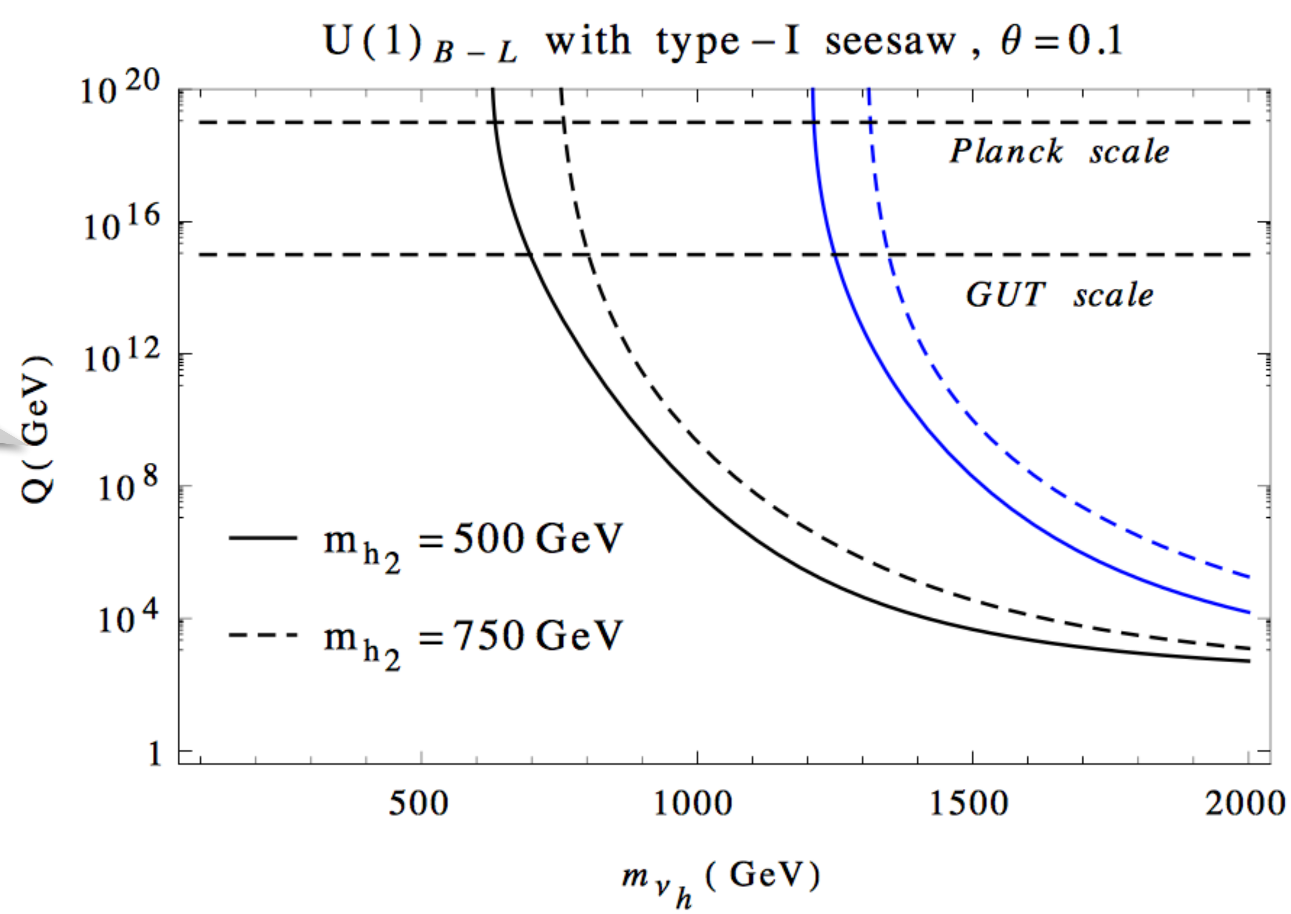
Scalar extension with right-handed neutrino

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

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

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

Stability Scale



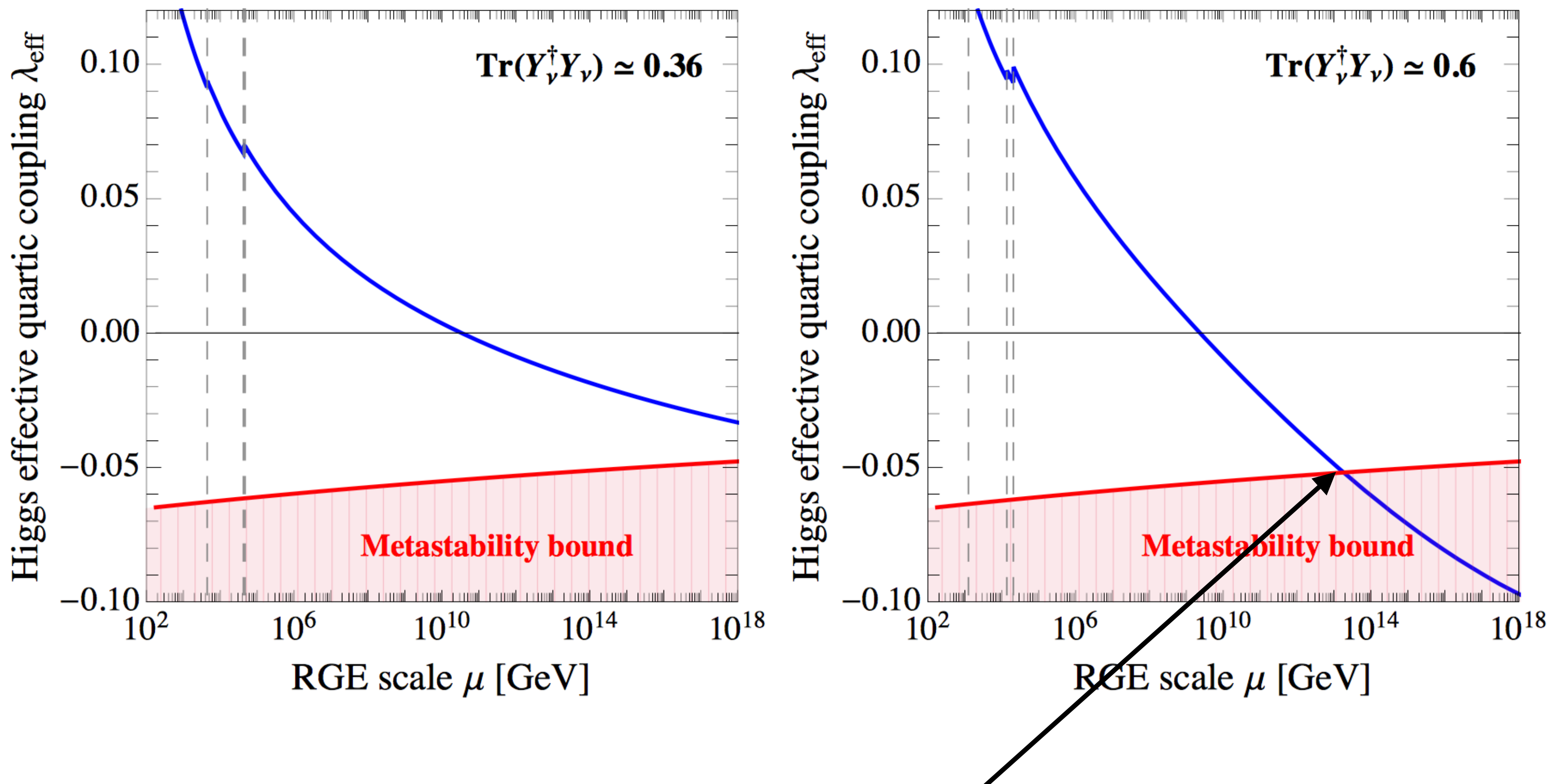
Stability conditions

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

- — $v' = 3.5$TeV
- — $v' = 7$ 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 1512 (2015) 050

Discovered Higgs bosons decay modes

- Higgs boson is discovered above 5σ

$$h \to b\bar{b}$$
$$\to \tau\bar{\tau}$$

} **Lepton and quark modes**

Phys. Rev. Lett. 121 (2018) 121801, Phys. Lett. B 779 (2018) 283

$$\to ZZ^*$$
$$\to WW^*$$

} **Gauge bosons**

$\to \gamma\gamma$(di-photon) } **Loop decay**

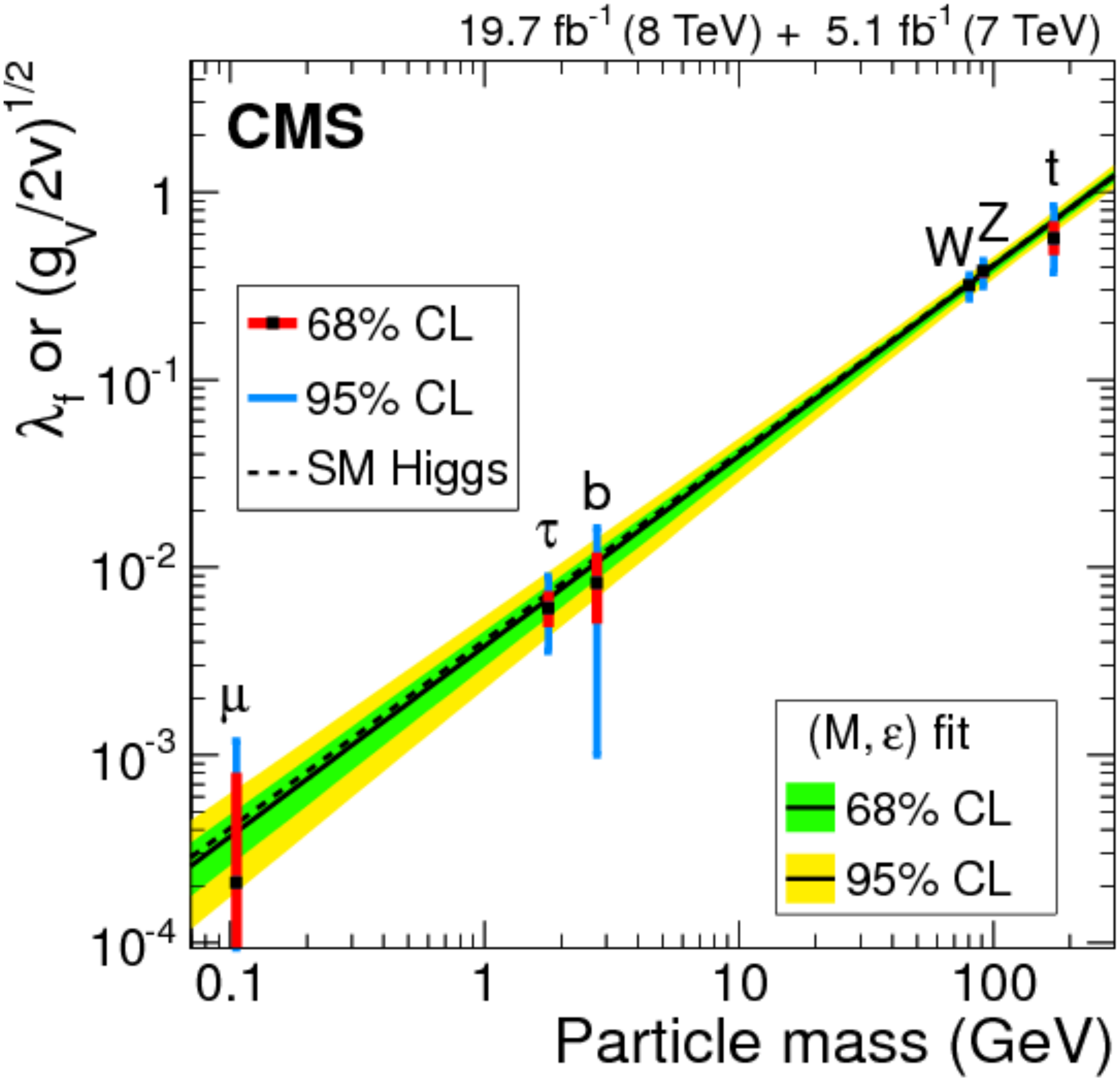
Higgs to invisible

- CMS at 13 TeV put $\mathcal{B}(H \to inv) \lesssim 0.33$ at 95% CL
- A combined analysis of 7,8 and 13 TeV shows $\mathcal{B}(H \to inv) \lesssim 0.19$

CMS: Phys. Lett. B 793 (2019) 520

- Higgs boson decaying to anything undetected

Higgs measured couplings



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 : $S \to -S$

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

$\delta_1,\ \delta_3,\ a_1,\ b_1,\ c_1,\ c_2,\ d_1\ \mathrm{and}\ \mathrm{d}_3$

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

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

Breaks U(1) Symmetry

$$V(\phi, S) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^4 + \delta_2 \phi^\dagger \phi |S|^2 + b_2 |S|^2 + d_2 |S|^4 + (\underbrace{b_1 S^2}_{} + a_1 S + c.c)$$

Breaks Z_2 symmetry

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

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

CP-even Higgs bosons mix

- 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

Higgs portal dark matter in $U(1)_{\mathrm{B-L}}$ with RHN

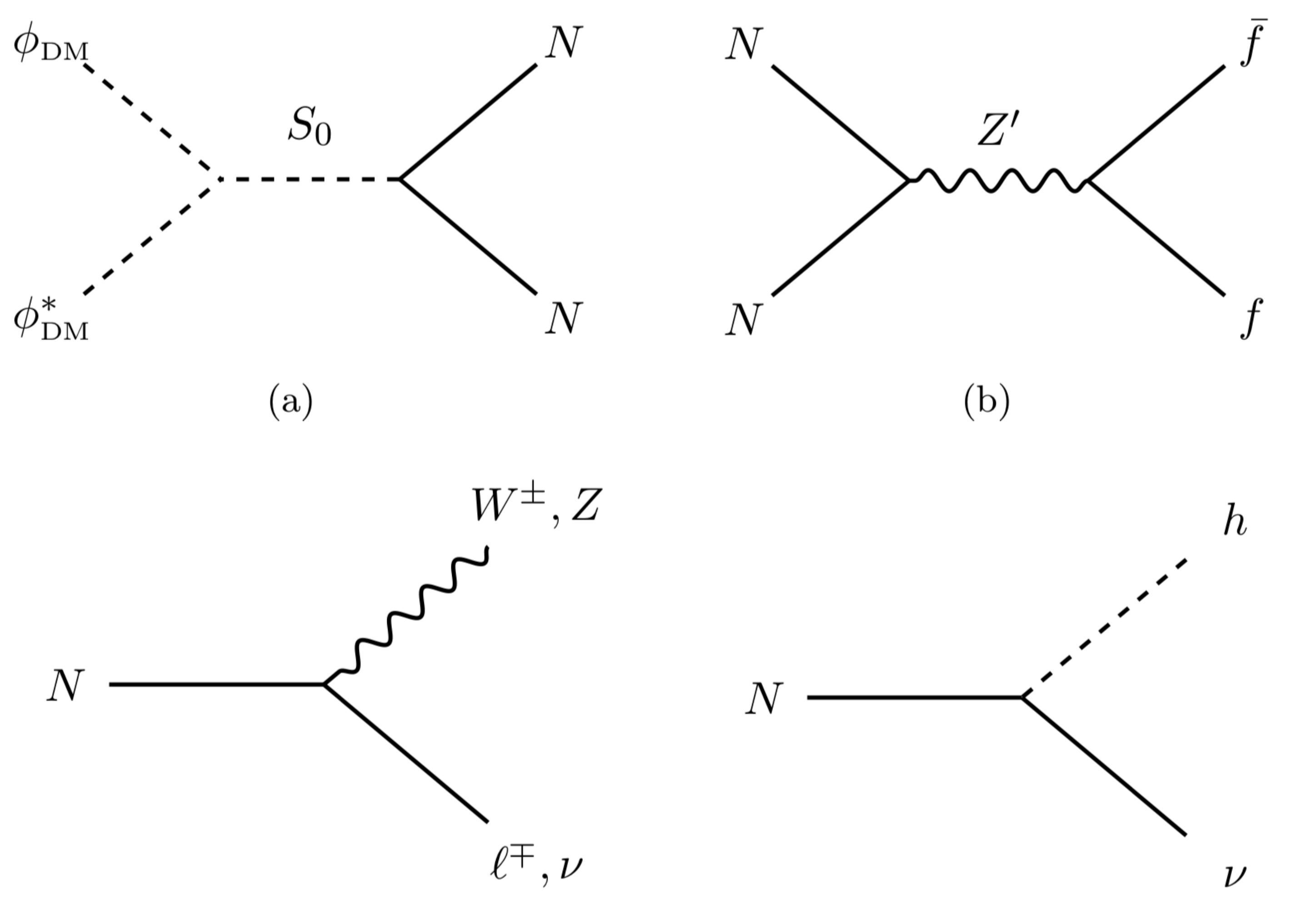
B-L scalar

RHN

$$\mathcal{L}_{\mathrm{NP}} = -m_S^2|S|^2 - \frac{1}{2}\lambda_{SH}|S|^2|\Phi|^2 - \lambda_S(S^\dagger S)^2 - \lambda_{N_i} S\bar{N}_i^c N_i - y_{ij}\bar{L}_i\Phi^\dagger N_j$$
$$- m_D^2|\phi_{\mathrm{DM}}|^2 - \frac{1}{2}\lambda_{DH}|\phi_{\mathrm{DM}}|^2|\Phi|^2 - \frac{1}{2}\lambda_{DS}|\phi_{\mathrm{DM}}|^2|S|^2 - \lambda_D({\phi_{\mathrm{DM}}}^\dagger\phi_{\mathrm{DM}})^2.$$

Scalar DM

- Dark matter annihilation modes



(a) (b) (c) (d)

- Type-I Seesaw also generates small neutrino mass

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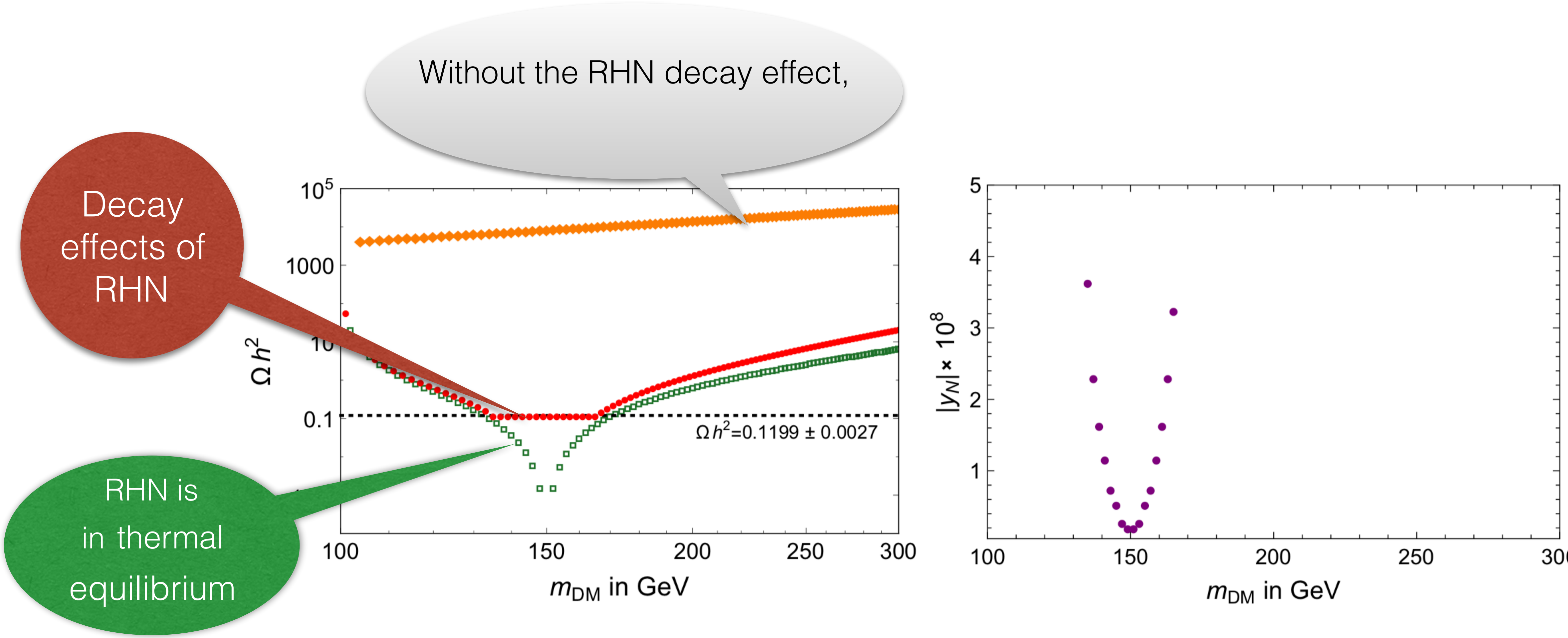
Phys.Rev. D97 (2018) no.1, 015001

Higgs portal dark matter in $U(1)_{\mathrm{B-L}}$ with RHN



- We get $y_N \sim 10^{-8}\, \mathrm{for}\, \mathrm{m_N} \sim 100\, \mathrm{GeV}$

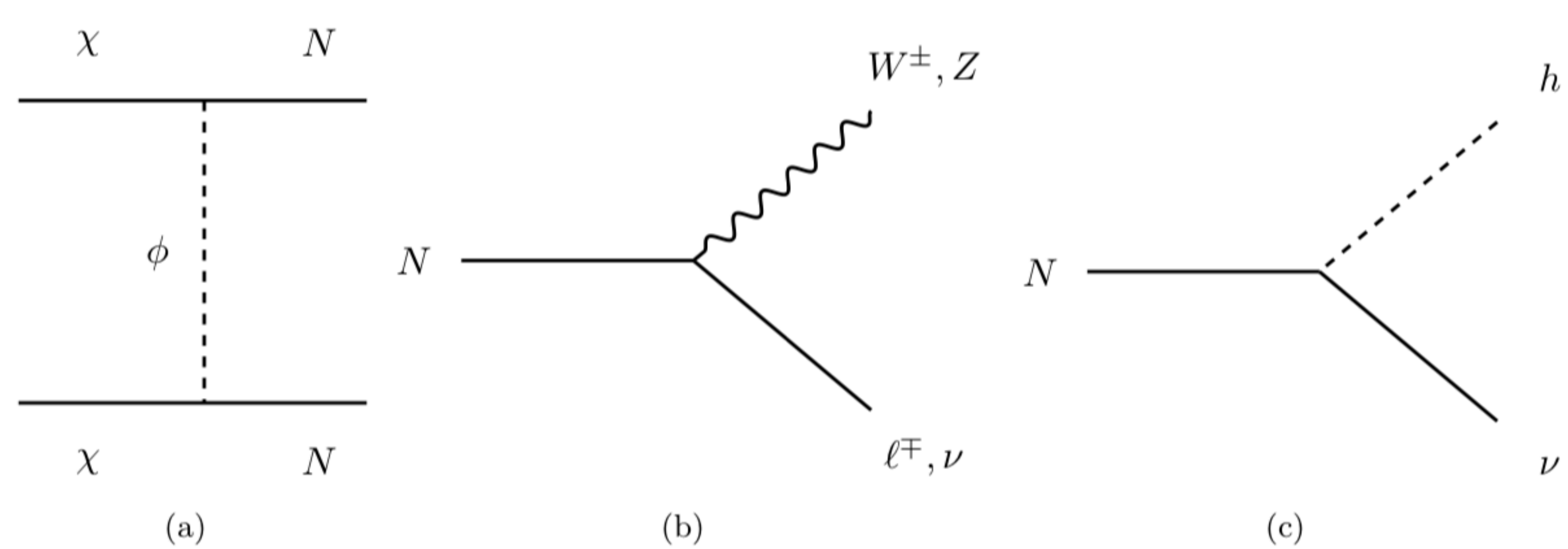
PB, Rusa Mandal, Eung Jin Chun
Phys.Rev. D97 (2018) no.1, 015001

Right-Handed Neutrino portal Dark Matter

- The RHN as a portal to DM was suggested in a simple setup assuming the coupling among RHN, fermion χ and scalar ϕ

$$-\mathcal{L} \subset \frac{1}{2}m_0^2\phi^2 + \kappa\phi^2|H|^2 + \left\{\frac{1}{2}m_\chi\chi\chi + \frac{1}{2}m_N NN + y_N LHN + \lambda N\chi\phi + \text{h.c.}\right\}. \quad (1)$$

- Here both χ or ϕ can be dark matter candidate
- DM can annihilates via RHN portal



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Phys.Lett. B788 (2019) 530-534

Loop induced Higgs-DM coupling

- No tree-level coupling of the fermionic DM to the Higgs boson
- An effective h-χ-χ coupling arises from the one-loop diagram

$$-\mathcal{L}_{h\chi\chi} = \kappa' h \bar{\chi}\chi \quad \text{where}$$
$$\kappa' \equiv \frac{\lambda^2 \kappa v}{16\pi^2} \frac{m_\chi c_1(x) - m_N c_0(x)}{m_\phi^2},$$

and $c_{1,0}(x)$ are loop-functions of $x \equiv m_N^2/m_\phi^2$

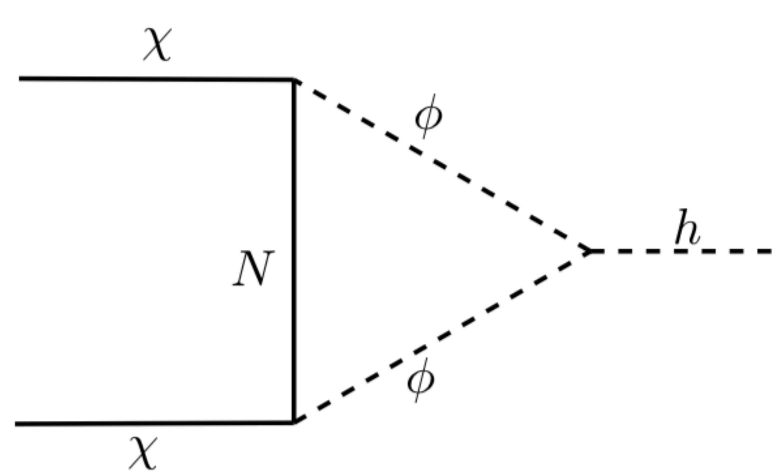

Figure 4: The interaction of the DM χ with the Higgs h induced at one-loop level.

- Latest data from XENON1T experiment excludes $|\lambda^2\kappa| \geq O(1)$ for $m_\chi \leq 150$ GeV
- Future sensitivity of XENONnT can rule out such value of $|\lambda^2\kappa|$ up to 600GeV DM mass

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Two Higgs doublet model

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

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_{1r} + i a_1 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_{2r} + i a_2 \end{pmatrix}$$

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

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

2HDM

After EWSB:

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

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

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}$$

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

2HDM and Flavour problem

Generic Yukawa coupling leads to FCNC:

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

$$(Y^{ij}_{f_1}c_\beta + Y^{ij}_{f_2}s_\beta)\frac{v}{\sqrt{2}}f_i f^c_j \quad \text{vs} \quad (\mathrm{Y}^{\mathrm{ij}}_{\mathrm{f}_1}\mathrm{c}_\alpha - \mathrm{Y}^{\mathrm{ij}}_{\mathrm{f}_2}\mathrm{s}_\alpha)\mathrm{h}\mathrm{f}_\mathrm{i}\mathrm{f}^\mathrm{c}_\mathrm{j}$$

↓ ↓

$$m^{ij}_f \quad \text{Mass} \neq \text{Yukawa} \quad \mathrm{Y}^{\mathrm{ij}}_{\mathrm{f}}$$

- 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_2 discrete 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 in SUSY and Non-SUSY: K.Ghosh et al., M. Mitra et al. B. Mukhopadhyay, S. Goswami , E. Chun et al, Rose et al., D. Das et al, D. Chaudhoury et al. and many

Heavy Higgs bounds

- H->WW: Combined upper limits at 95% confidence level on the product of the cross section and branching fraction exclude a heavy Higgs boson with SM-like couplings and decays up to 1870 GeV

CMS: arXiv:1912.01594 [hep-ex]

- H->ZZ: Bounds cross-section in ZZ decay modes are given till 3 TeV.

CMS:JHEP 06 (2018) 127

- $A \to b\bar{b}/\tau\bar{\tau}$: Bounds on cross-section give till 900 GeV in $2b + 2\tau$ mode

CMS:Phys. Lett. B 778 (2018) 101