Extended Higgs sectors in supersymmetric context at the LHC

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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

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Supersymmetry addresses few of the problems

How many Higgs bosons are there ?

- Minimal model (MSSM) has:
- 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 !

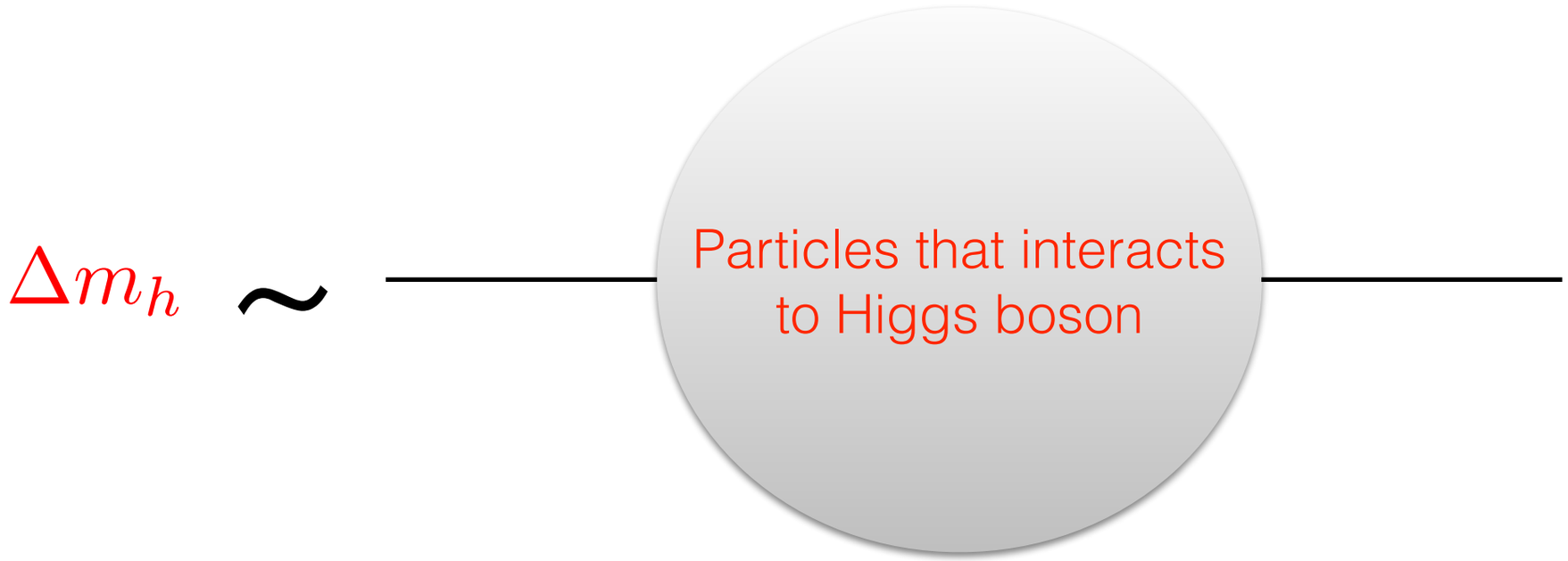
Lightest CP even Higgs boson

- 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



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

- Particles in the loop get indirect bounds

Status of minimal supersymmetric scenarios

- Trivial solution: Very large mass for super-partners

$\gtrsim$ few TeV

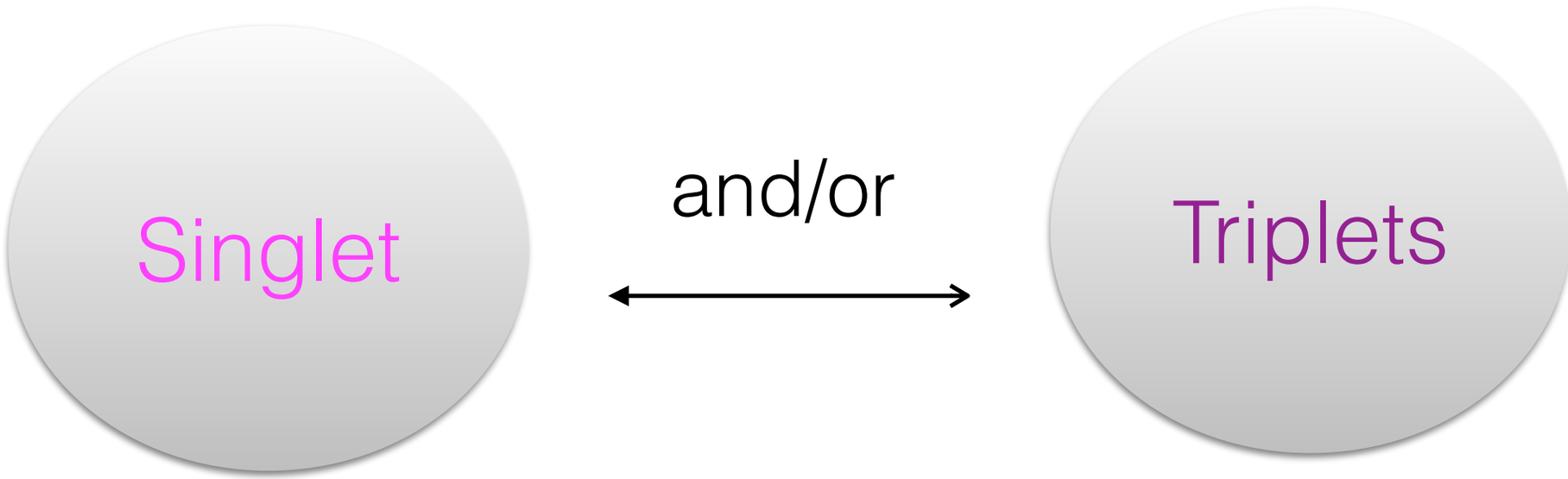
- Or large mass splitting between the super-partners

- Fine tuning is necessary

Solution ?

- Are there other Higgs bosons?
- Any theoretical possibility?

- There are possibility in different SU(2) representations



- 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

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

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

What happened to the Higgs sector ?

CP-even

h_1, h_2, h_3, h_4

CP-odd

a_1, a_2, a_3

Charged

$h_1^{\pm}, h_2^{\pm}, h_3^{\pm}$

Many Higgs bosons are possible

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’

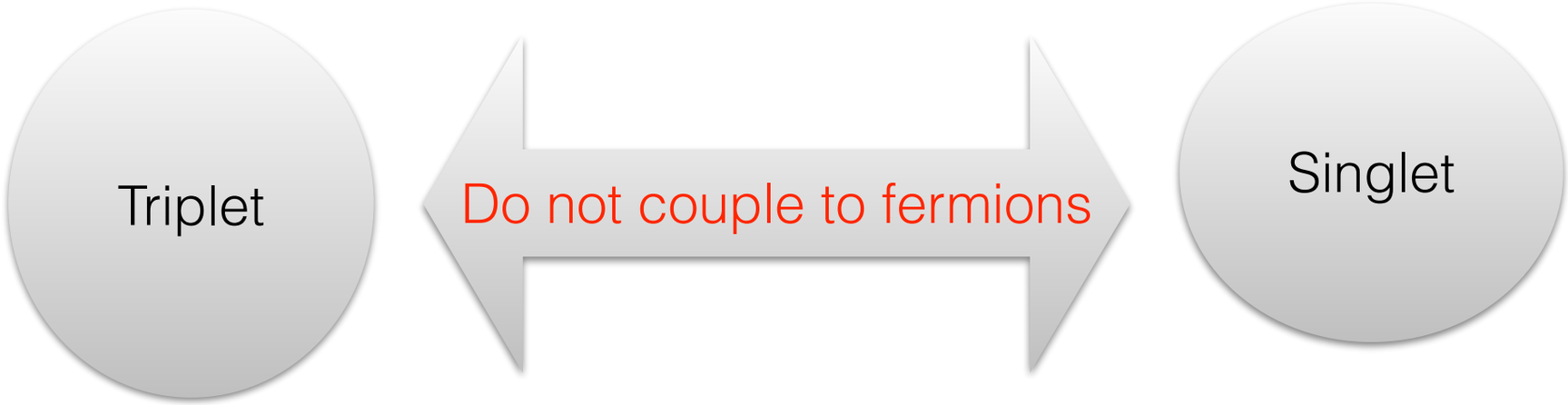
Supersymmetry can still exists below TeV !

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 ?



Singlet does not couple to gauge bosons

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

Is there a possibility of light Higgs bosons below 100 GeV and still not observed?

Yes!

$$V_{soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2$$
$$+ m_T^2 |T|^2 + m_Q^2 |Q|^2 + m_U^2 |U|^2 + m_D^2 |D|^2$$
$$+ (A_S S H_d . H_u + A_T H_d . T . H_u + A_{TS} S Tr(T^2)$$
$$+ A_\kappa S^3 + A_U U H_U . Q + A_D D H_D . Q + h.c),$$

- 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.

Some of them can evade detection for earlier searches

Searches of the Higgs bosons

- Higgs bosons are searched via their decay modes

$h \to b\bar{b}$
$\to \tau\bar{\tau}$
} **Lepton and quark modes**

$\to ZZ^*$
$\to WW^*$
} **Gauge bosons**

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

- One Higgs boson around 125 GeV has been discovered in

$$\rightarrow \gamma\bar{\gamma}$$

$$\rightarrow ZZ^*$$

$$\rightarrow WW^*$$

- Other modes are yet to be discovered

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

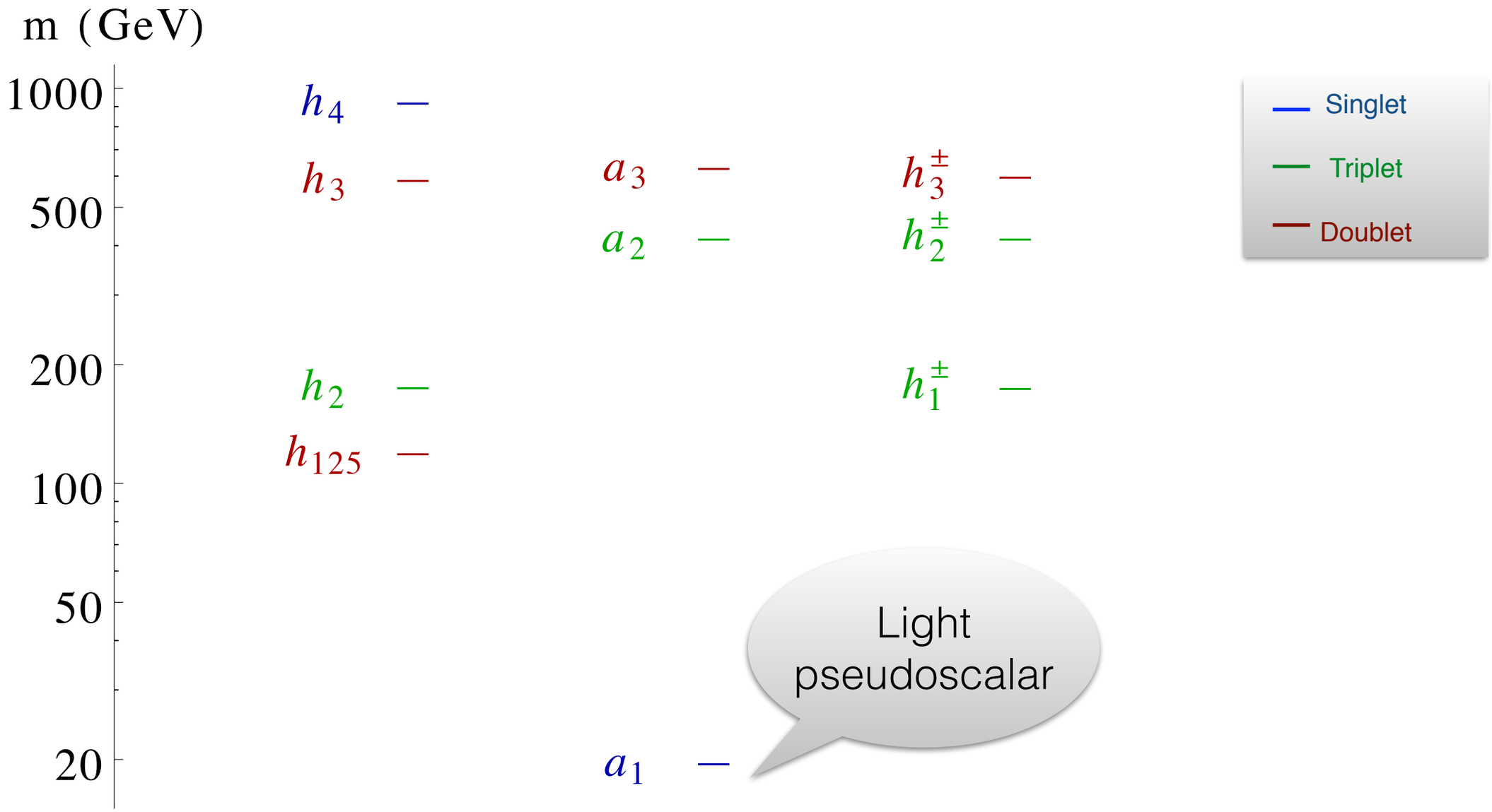
  - But other Higgs bosons may not be seen in normal decay modes!

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

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

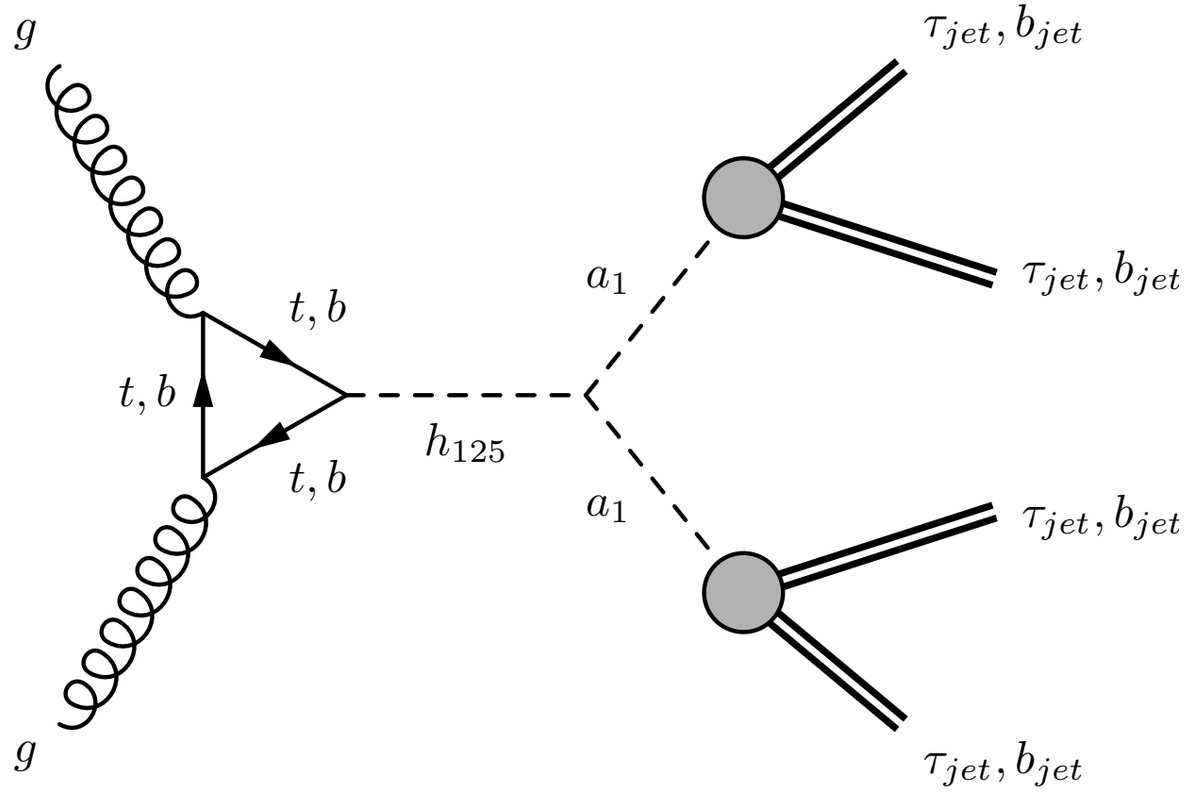
Still longer run at the LHC has a good chance

Possibility of hidden scalars



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

We can produce them via doublet Higgs boson



- Early data of LHC14 TeV can probe this!

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

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

Charged Higgs boson search

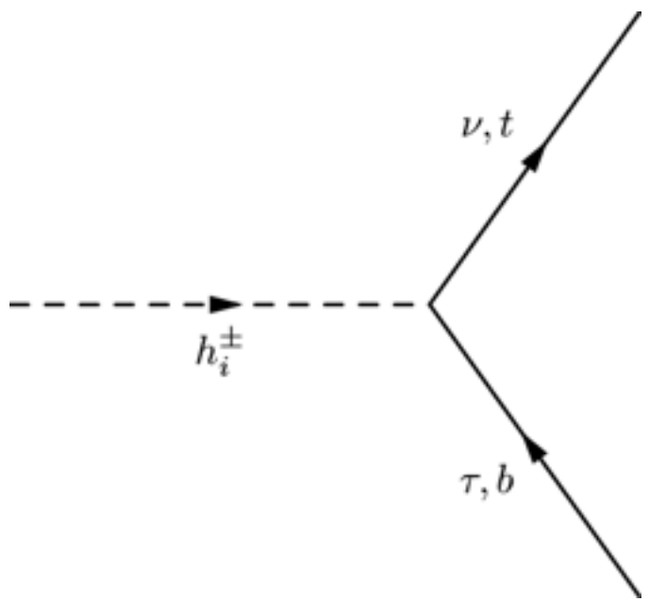
- Standard Model does not have any charged Higgs boson

- Finding a charged Higgs boson is obvious proof of extended Higgs sectors, thus new physics

- Supersymmetry needs at least one charged Higgs boson

- Mostly searched Charged Higgs bosons are doublet type and couple to fermions

- Viz. 2HDM, MSSM



Experimental bounds on the charged Higgs mass

- LHC looked for this doublet type charged Higgs bosons
- 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 $\tau + \nu \,\text{and}\, t + b$ decay modes
- CMS puts 95\% CI upper limits as: 1.2-0.16 % on

$$\mathcal{B}(t \to bH^\pm) \times \mathcal{B}(H^+ \to \tau^+\nu_\tau) \quad \text{for} \quad \mathrm{m_{H^+}} \sim 80 - 160 \quad \mathrm{GeV}$$

- 0.38-0.026 pb on $\sigma(pp \to \bar{t}bH^+) \times \mathcal{B}(H^+ \to \tau^+\nu_\tau) \quad \text{for} \quad \mathrm{m_{H^+}} \sim 180 - 600 \ \mathrm{GeV}$

  CMS-PAS-HIG-14-020

- Similar bounds also found by ATLAS: for $m_{H^+} \sim 180 - 1000 \ \mathrm{GeV}$

  JHEP 1503 (2015) 088

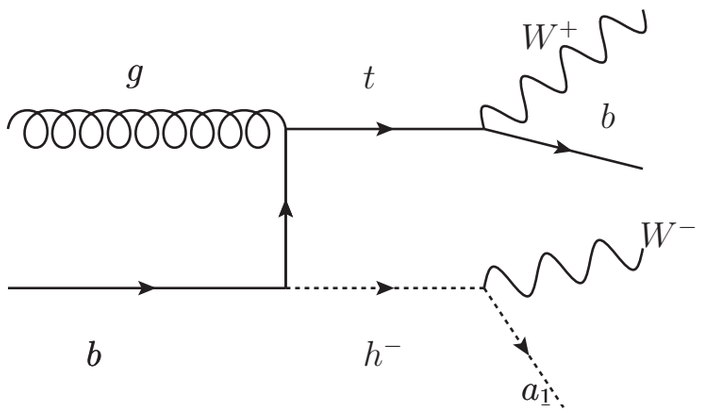
Charged Higgs in NMSSM

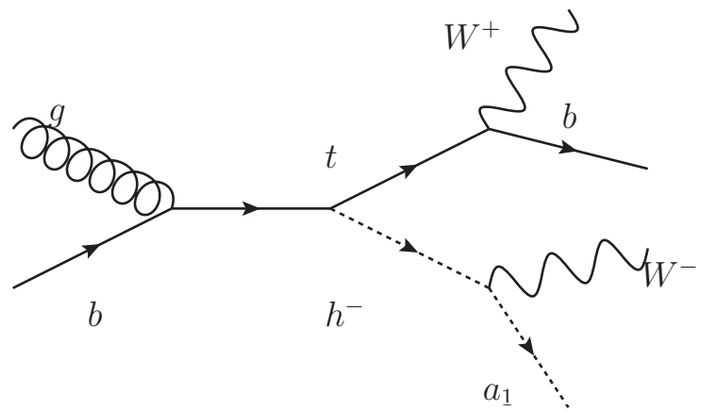
- NMSSM has one doublet like charged Higgs boson

- NMSSM, TNSSM with Z_3 symmetry has a light pseudosclar which opens a new mode

$$h^{\pm} \to a_1 W^{\pm}$$

- bg fusion processes are important





- $1b + 2\tau + 2\ell + \not{E}_T$, $1b + 2\tau + 2j + 1\ell + \not{E}_T$; $3b + 2\ell + \not{E}_T$ final states can probe the light charged Higgs bosons with the early data at the LHC @14 TeV

P.B, Katri Huitu, Saurabh Niyogi, arXiv:1512.0924

Triplet charged Higgs bosons do not decay into fermions

- This makes it hard to produce them at colliders

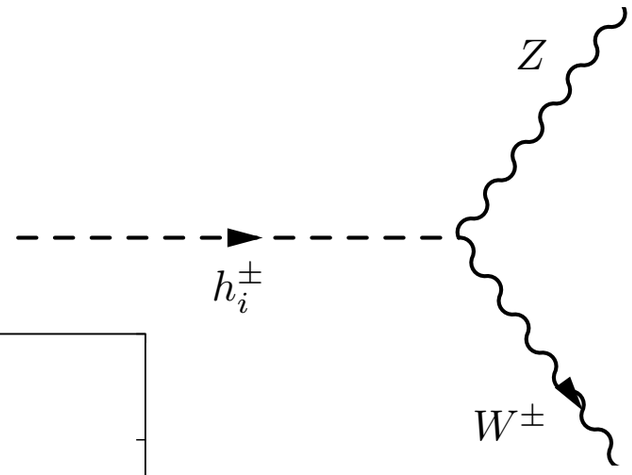
- Also to detect

- Is there a way to probe this exotic type of charged Higgs bosons ?

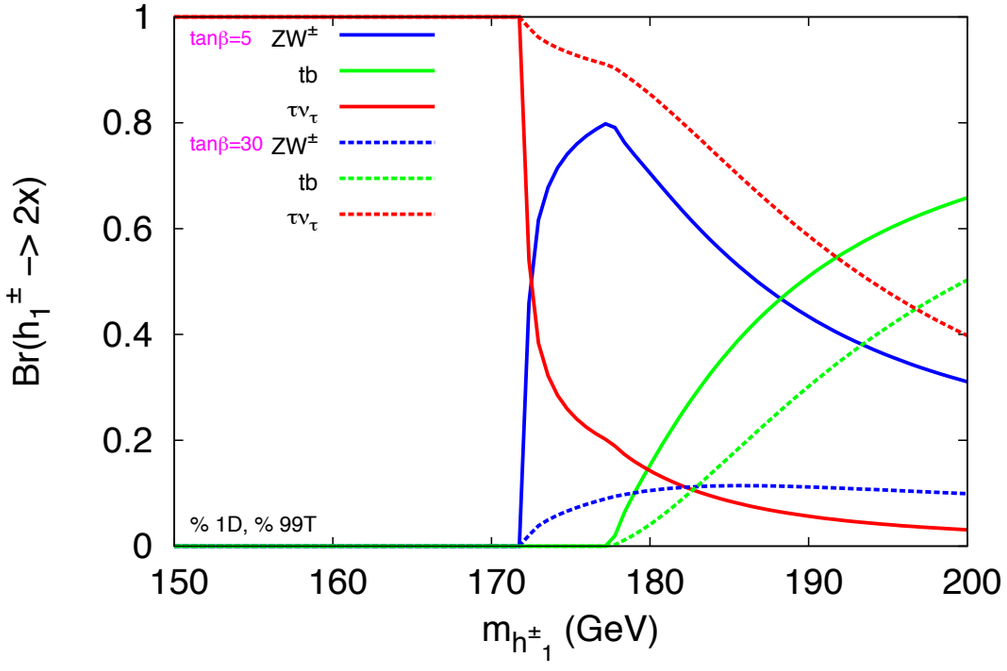
- Triplet type charged Higgs boson give rise to a non-standard vertex by breaking of custodial symmetry

$$g_{h_i^\pm W^\mp Z} = -\frac{1}{2} i g_2 \left(g_1 \sin\theta_w (v_u \mathcal{R}_{(i+1)1} - v_d \mathcal{R}_{(i+1)2}) \right) - \frac{1}{2} i g_2 \left(\sqrt{2} g_2 v_T \cos\theta_W (\mathcal{R}_{(i+1)3} + \mathcal{R}_{(i+1)4}) \right).$$

θ_W is the Weinberg angle and $h_i = R_{ij} H_j$



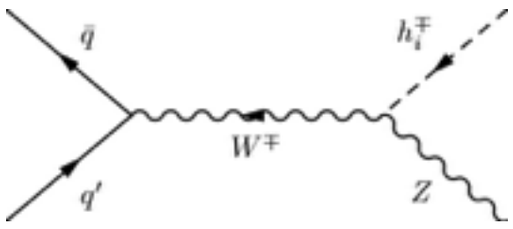
$$h_i^\pm \to tb$$
$$\to ZW^\pm$$
$$\to \tau\nu$$
$$\to h_j W^\pm$$

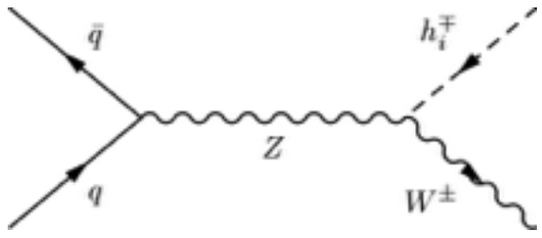


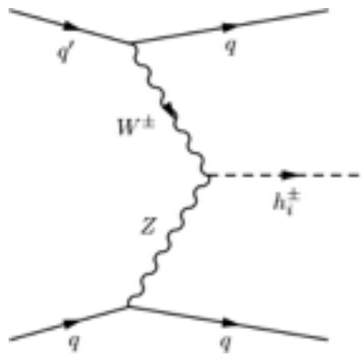
- Mixing with the doublets is crucial for the decays as well as production channels

P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026
PB, Claudio Coriano, Antonio Costantini, arXiv:1512.08651

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

Indirect effects!

- It also affects the B-observables as triplet type charged Higgs and chagrinos do not couple to the fermions.

- We have calculated $Br(B \to X_s\gamma)$ for the triplet extended scenario and also fit the model with other experimental data

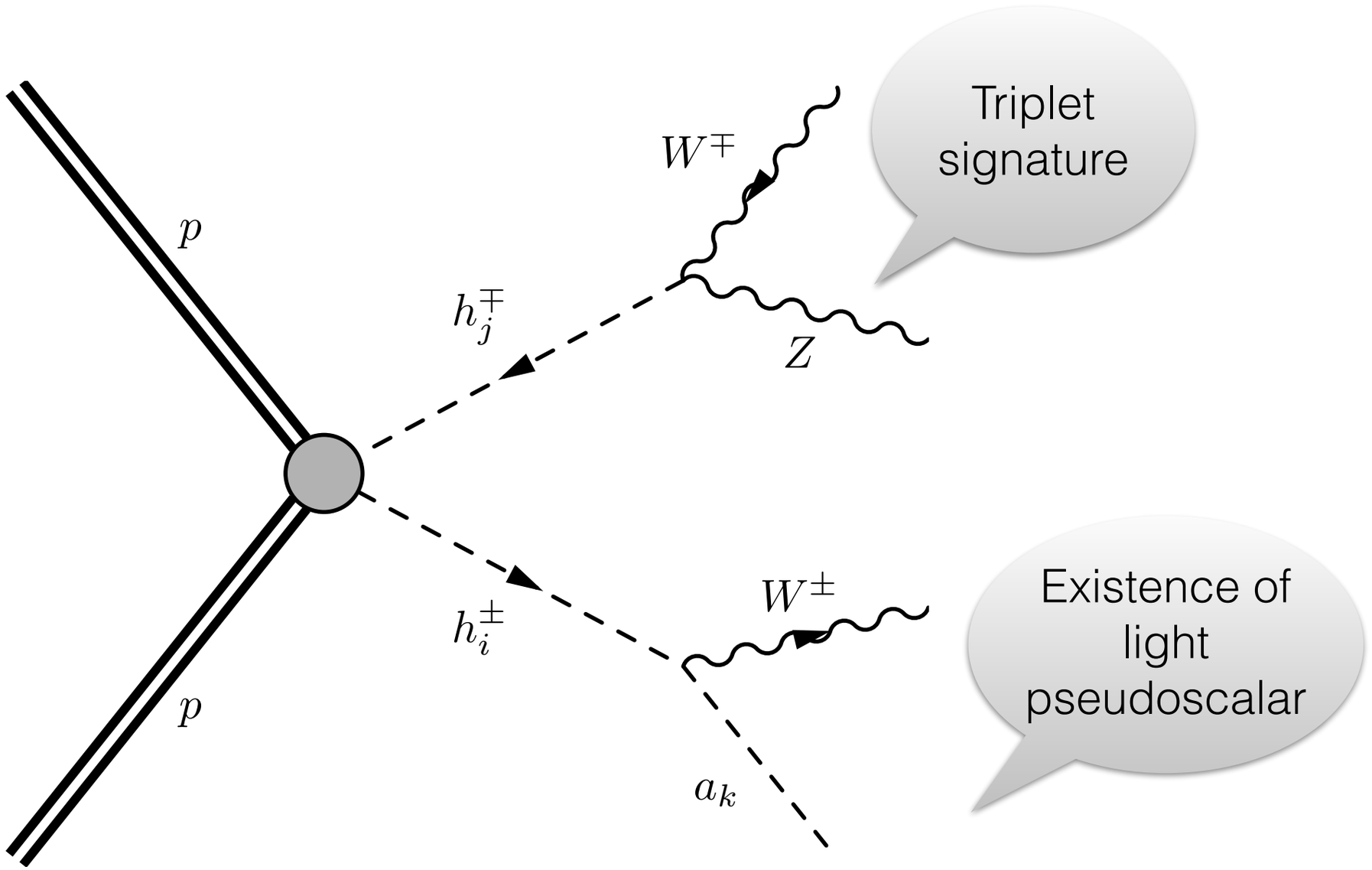
- Light triplet charged charged Higgs still a possibility

- Light Triplet like charginos have interesting phenomenologies

PB, K. Huitu, A. S. Keçeli, JHEP 1310 (2013) 091;

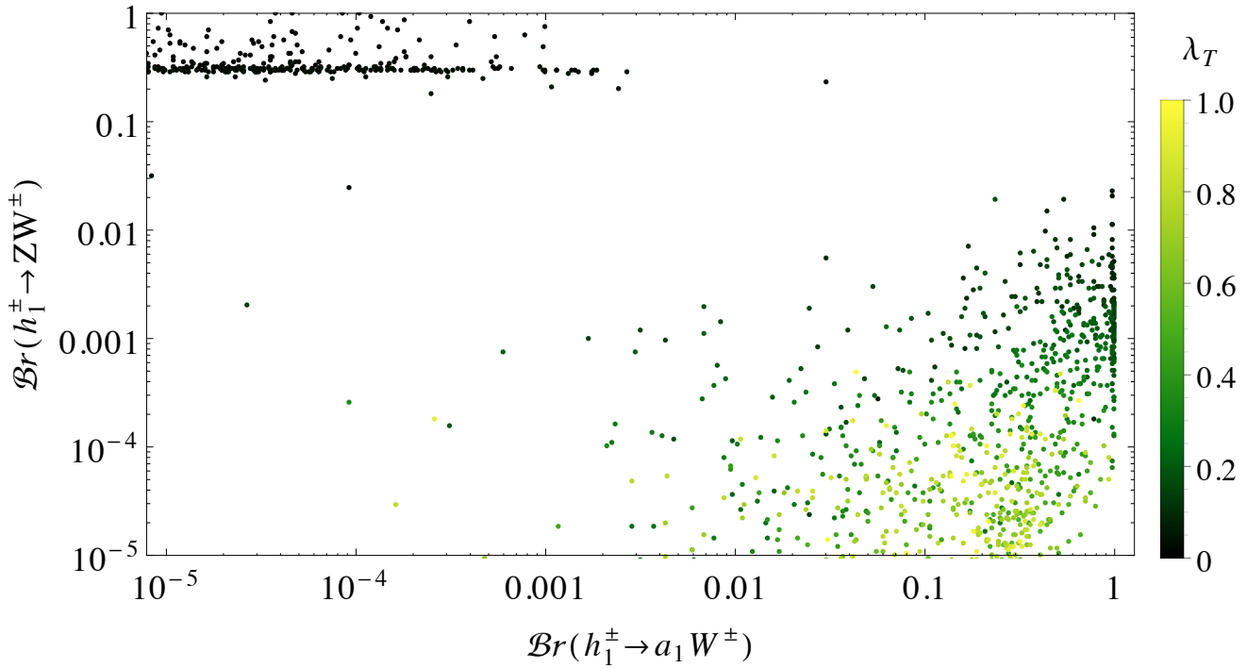
PB, KH, SC, AS, JHEP 1411 (2014) 062

- Is it possible to distinguish different possible extensions ?



- It can be a proof of both the existence of a triplet and singlet

- Charged Higgs Branching to singlet and triplet modes often belong to different regions of parameter space



- For this reason probing the existence of singlet and triplet together needs much higher luminosity at the LHC@14 TeV

Conclusions

- So far we have observed one Higgs boson at 125 GeV
- All possible Standard Model modes are yet to be discovered.
- Hidden Higgs is still a possibility.
- 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 $h^{\pm} \to Z W^{\pm}$ are direct proofs of higher representations of Higgs sectors.
- Indirect searches can also give us some hints
- We hope LHC bring some more discoveries

THANK
You!