Perspective of extended Higgs sectors in Super-Symmetric beyond Standard Model scenarios

IOPB-2020

Bhubaneswar
16/01/2020

Priyotosh Bandyopadhyay
IIT, Hyderabad, India

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Plan

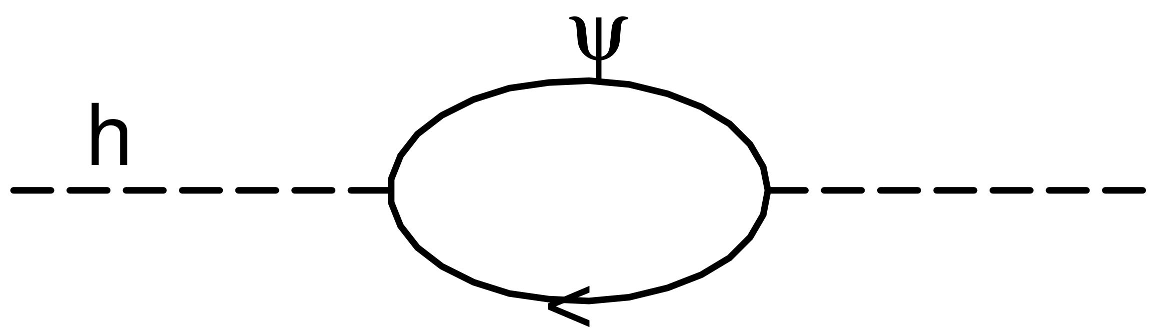
- Minimal Supersymmetric Standard Model
- Status of MSSM Higgs(es)
- Possible Higgs extensions

  - NMSSM: Singlet extension
  - TMSSM: Triplet extensions
  - TNMSSM: Singlet and Triplet extension
  - GMMSSM: Georgi-Machacek extension

- Extended Higgs sectors with supersymmetry

Higgs mass in Standard Model

- Higgs mass is a free parameter not predicted by SM

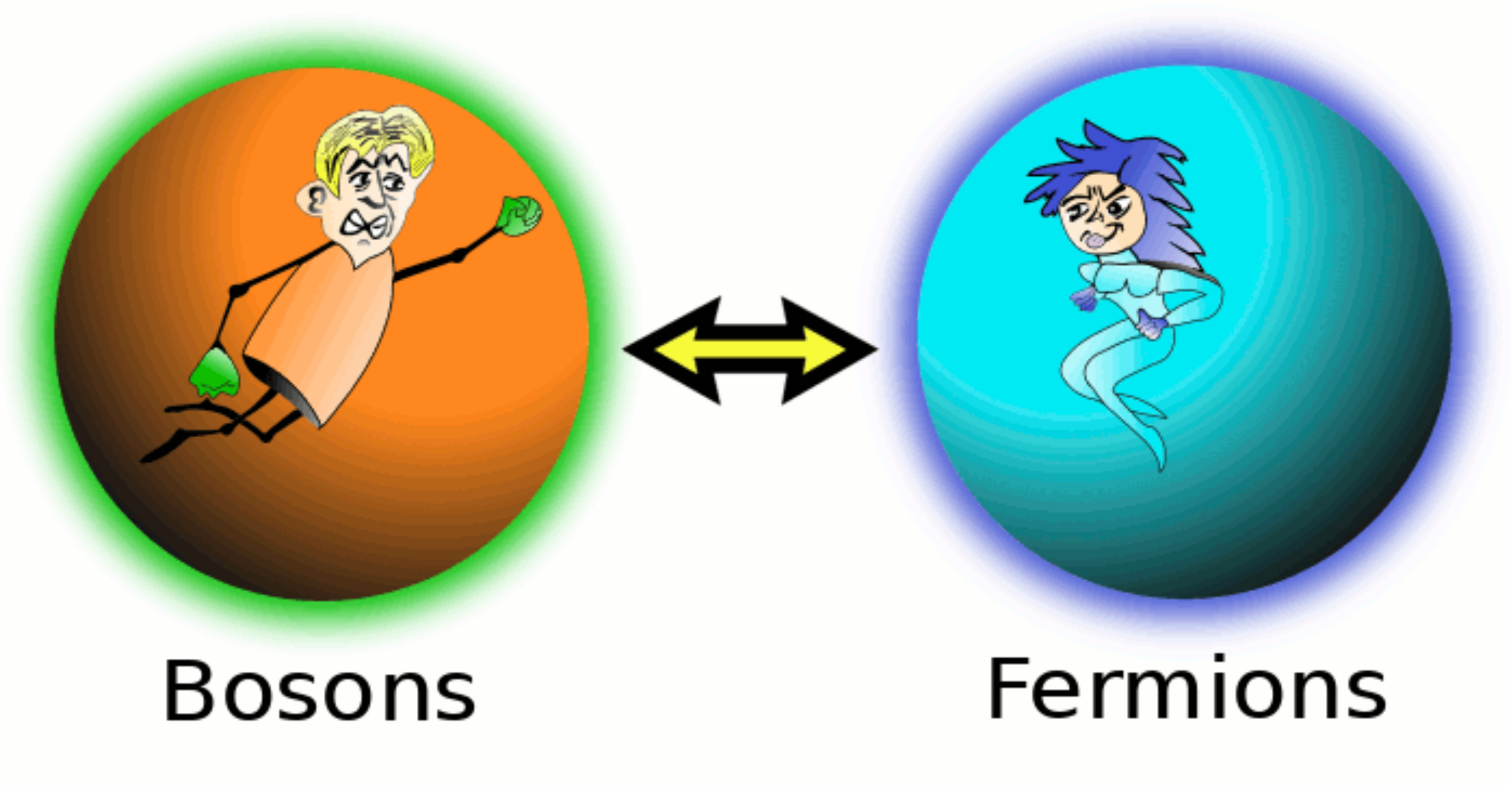


$\sim \Lambda^2$

Cut off scale of the theory

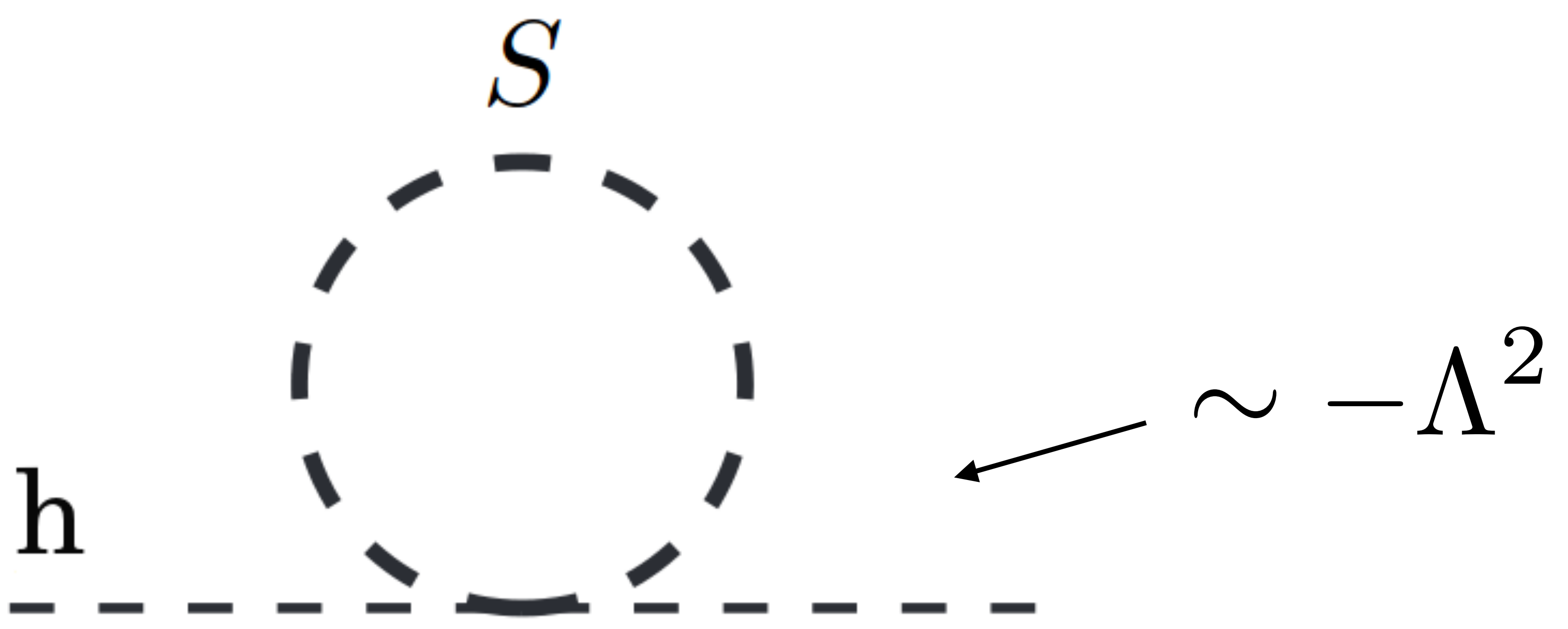
- Quantum correction to Higgs mass is divergent

We need additional symmetry to cancel the quadratic divergence



Supersymmetry !!

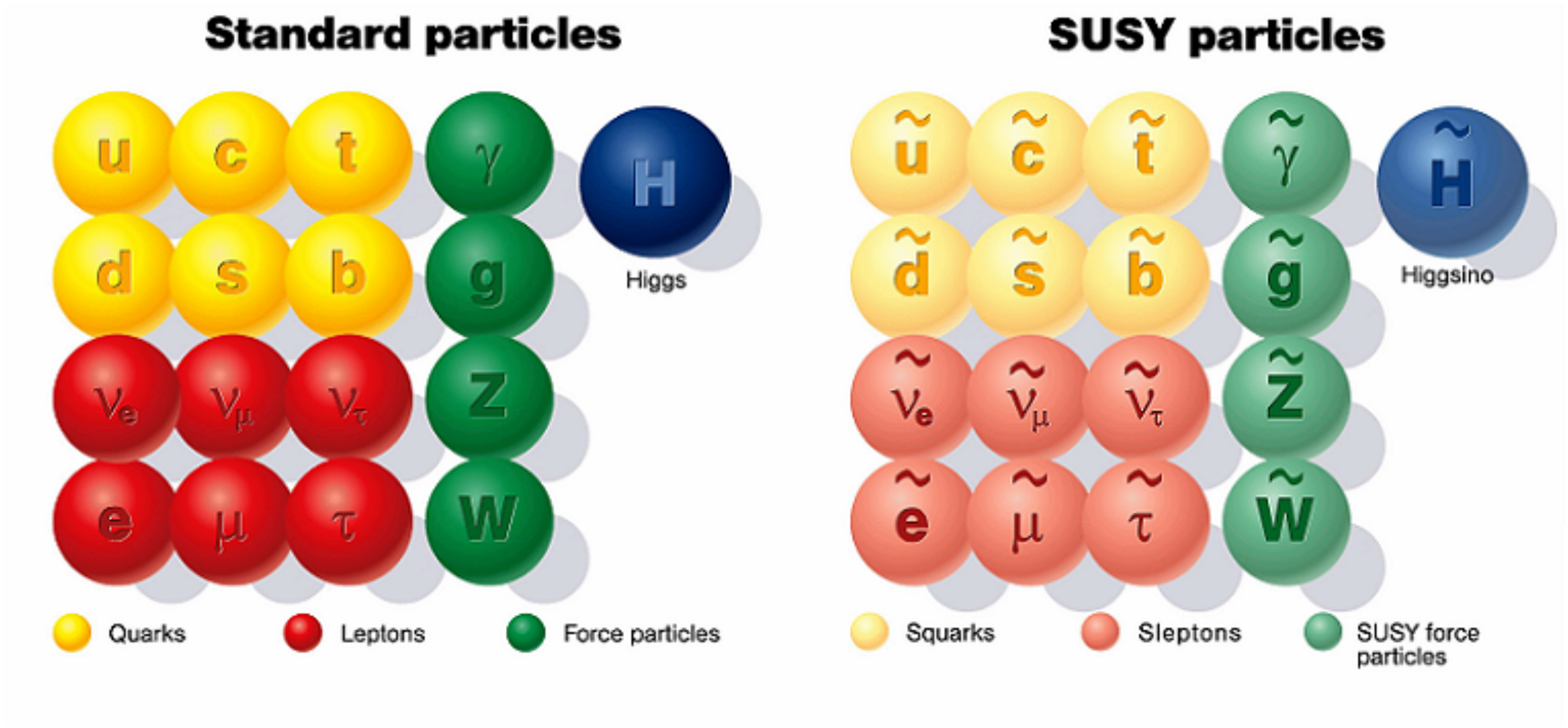
- Supersymmetry protects the Higgs mass with additional contributions



- Radiative correction to the Higgs mass is no longer divergent

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

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

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix},$$

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

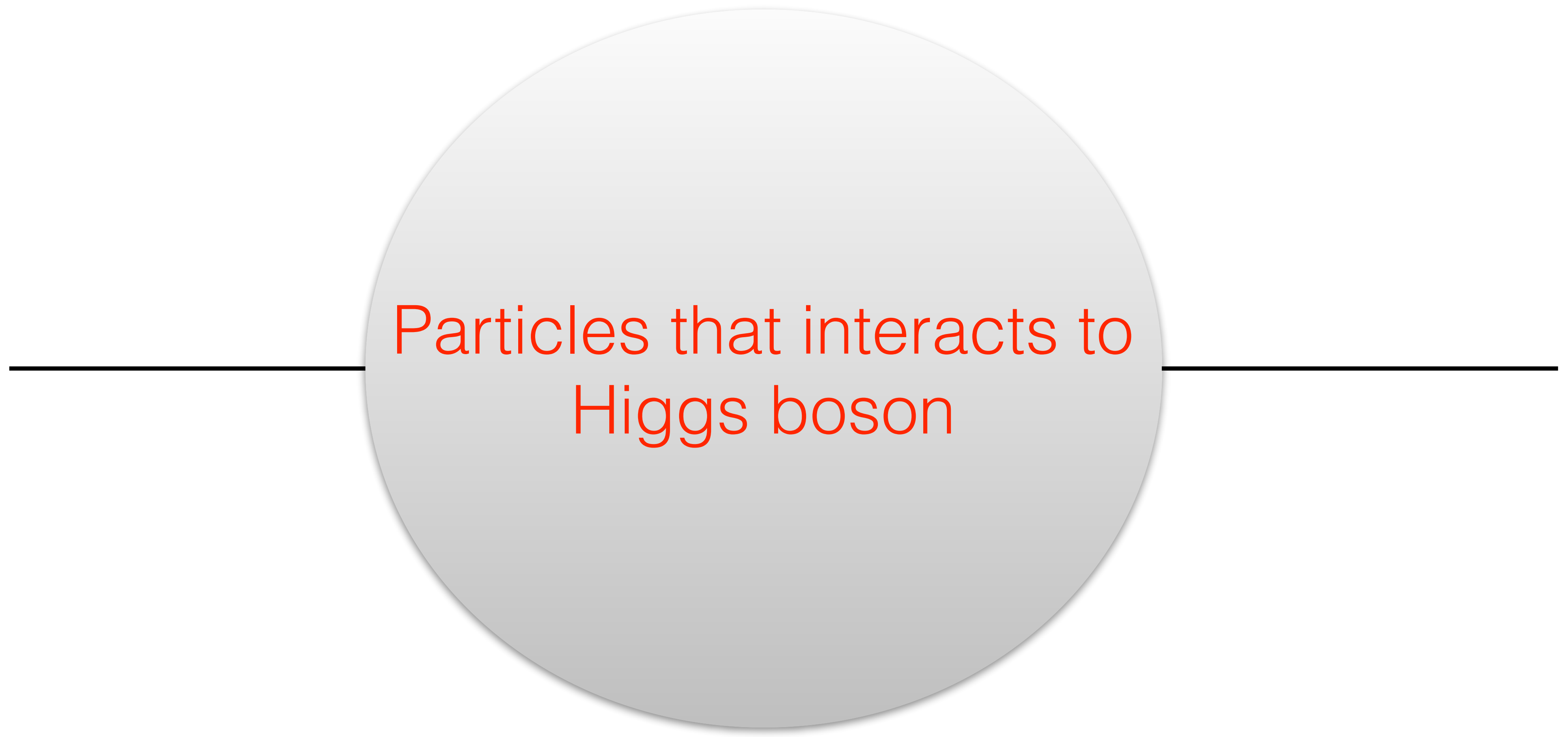
So far we have observed only one Higgs boson !

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

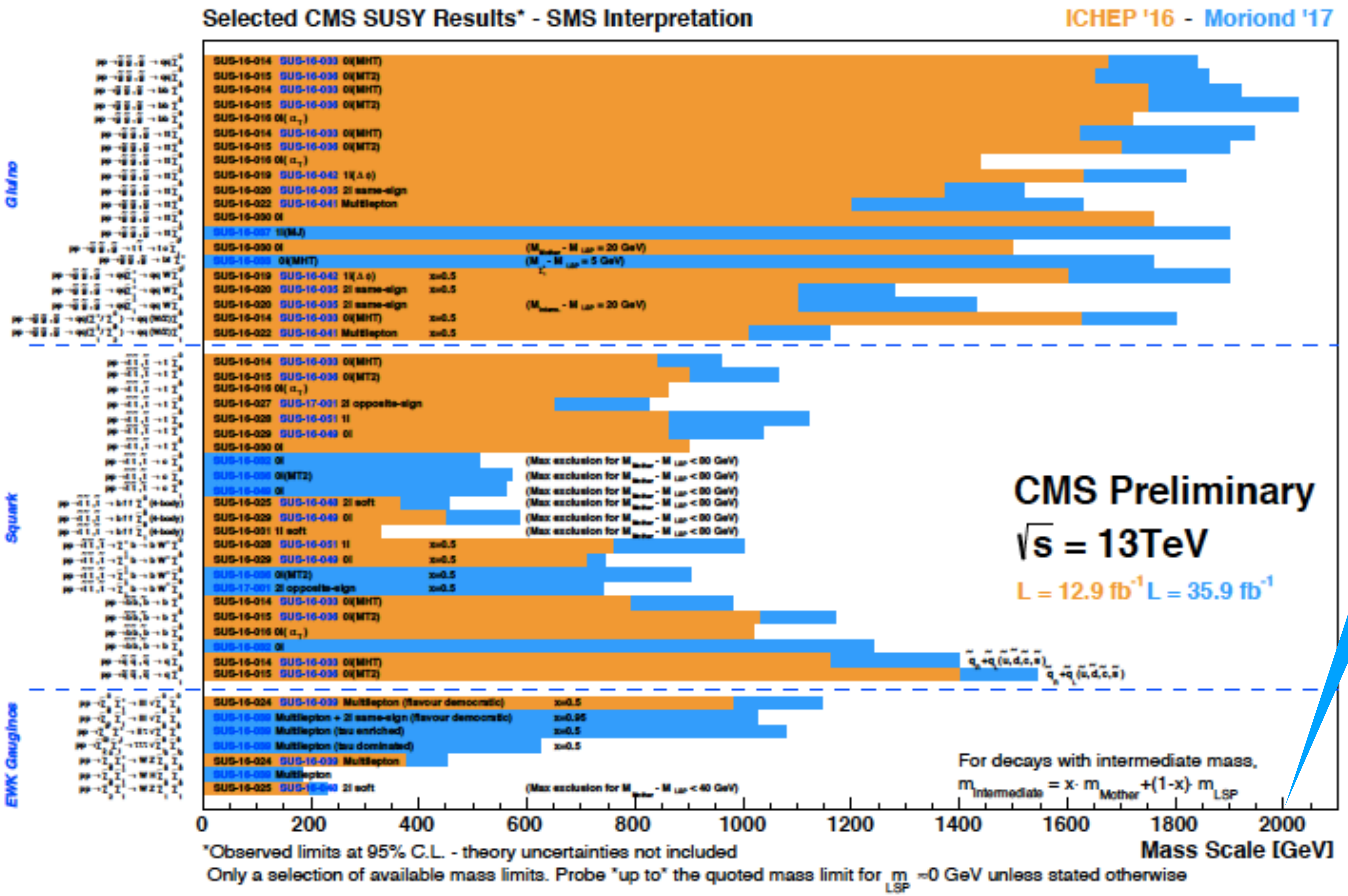
Quantum correction is important

$\Delta m_h \sim$



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

- Particles in the loop get indirect bounds



The direct limits are a big as 2 TeV

Status of Unified Scenarios

- mSUGRA: $m_0, m_{1/2}, A, \tan\beta, \text{sign of}\,\mu$
- AMSB: $m_{3/2},\ m_0^2,\ \tan\beta,\ sign(\mu)$
- GMSB: $m_{mess},\ N_{mess},\ \Lambda,\ \tan\beta,\ sign(\mu)$

All these models start from a unified scale

find it hard to generate ~125 GeV light Higgs

without fine-tuning

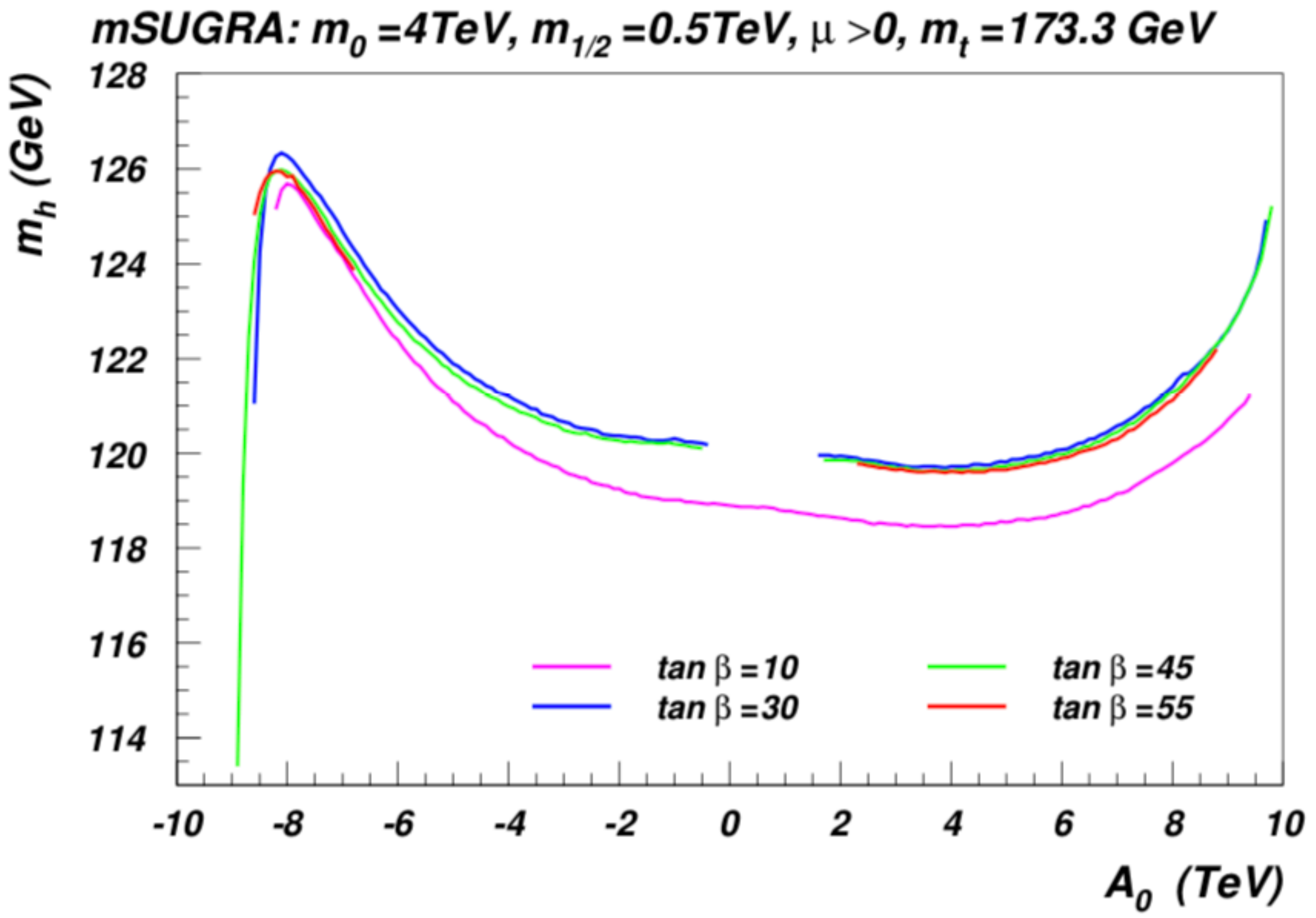
mSUGRA with ∼125 GeV Higgs Baer et al.

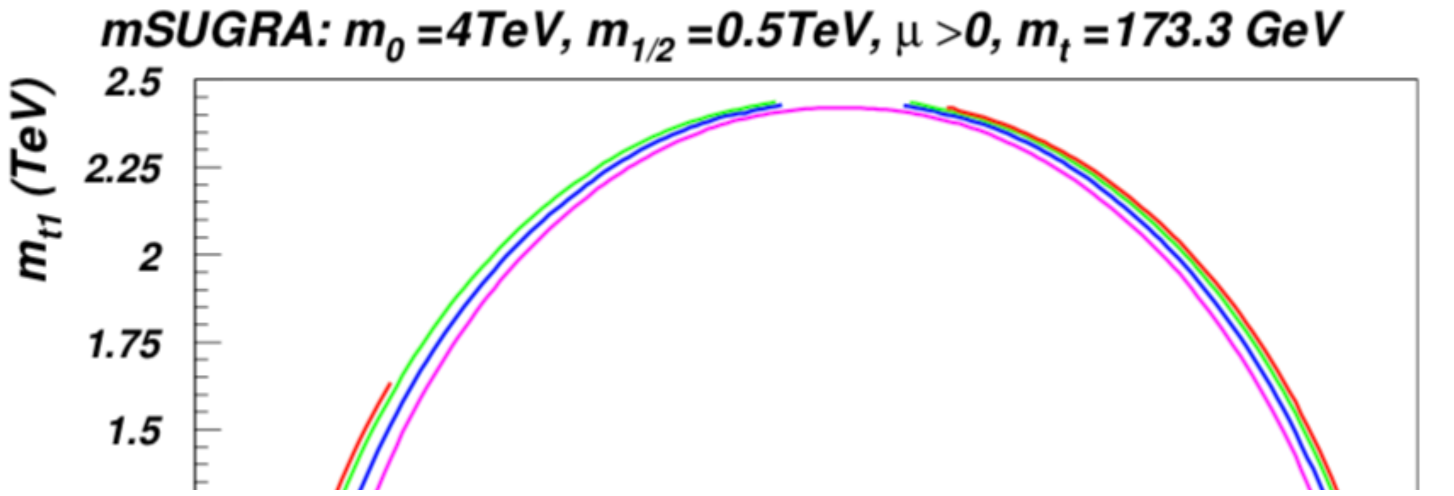
With ∼125 GeV Higgs

- For $A_0 = 0$, m_0 versus $m_{1/2}$ planes are excluded (only possible ∼ 125 GeV solutions with $m_{1/2} \sim m_0 \sim 10$ TeV; corresponding squark/gaugino masses ∼ 20 TeV).
- For $A_0 = \pm 2 m_0$ and $m_0 \sim 4 - 10$ TeV: Possible to get desired Higgs mass. Result: heavy scalars but light gauginos are still possible.
- $|A_0| < 1.8 m_0$ is excluded for $m_0 \lesssim 5$ TeV
- $|A_0| < 0.3 m_0$ is excluded for m_0 up to 20 TeV $\sim$

Conclusion: High m_0 and A_0 are required!.
PRD85(2012)075010

back





MSSM Higgs sector

- After ~ 125 GeV Higgs boson discovery, the parameter spaces of MSSM like theories are stringently constrained. Let's consider two well known theories: mSUGRA/cMSSM, pMSSM.
- mSUGRA/cMSSM Soft SUSY breaking parameters are unified at the high scale (GUT). Parameter space of the theory contains only sign(μ), $\tan\beta$, A_0, m_0, $m_{1/2}$.
- Phenomenological MSSM: CP conservation, flavor diagonal mass and coupling matrices, universality of the 1st and 2nd generations are imposed. Parameter space of the model (22 parameters) : $\tan\beta$, μ, M_A, gaugino Masses: M_1,M_2,M_3 A_f (3 for the 3rd generation+3 for 1st and 2nd generations) $m_{\tilde{f}_L}$ and $m_{\tilde{f}_R}$ $(5 \oplus 5)$

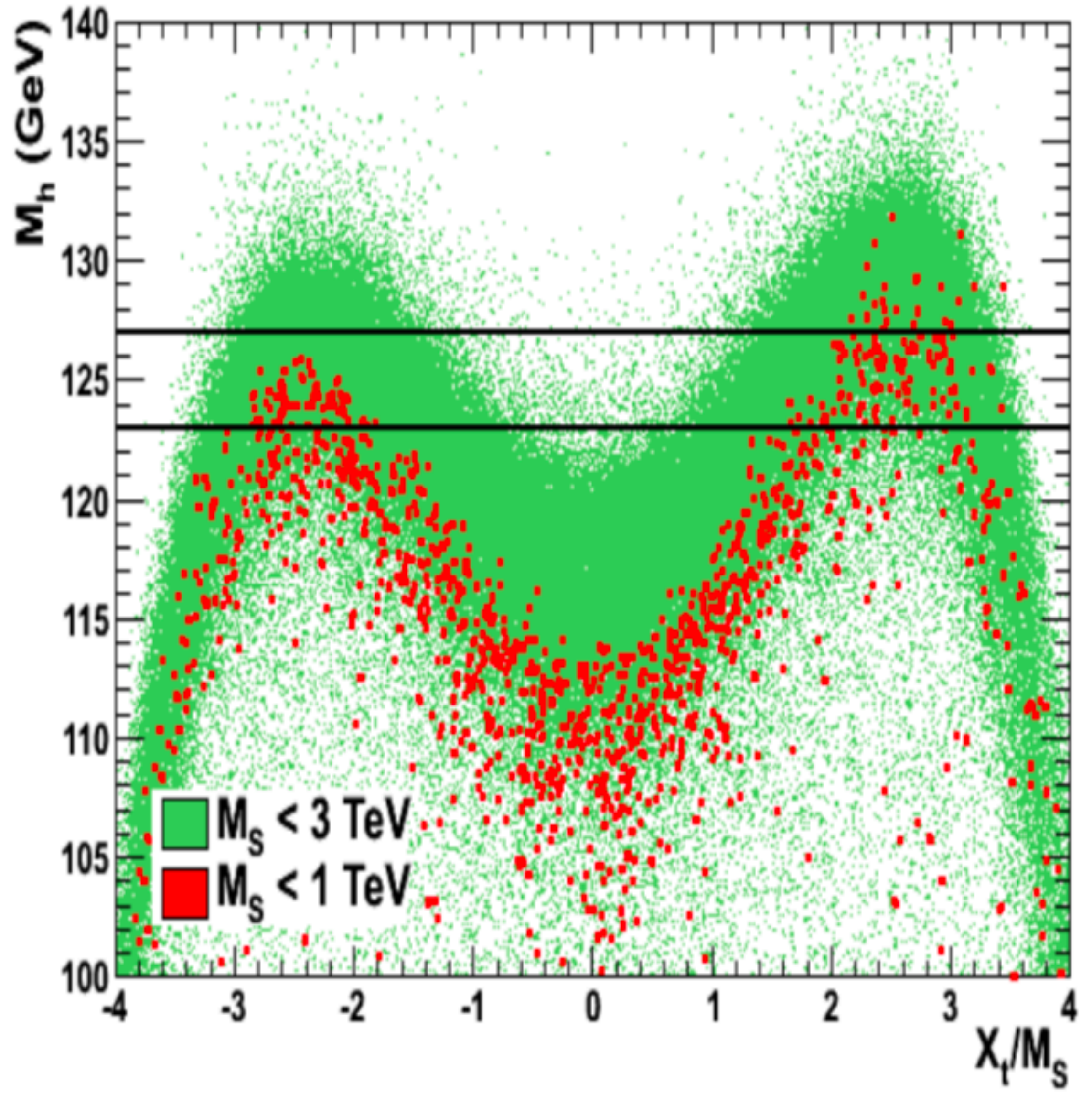
$\sim$ 125 GeV Higgs in MSSM

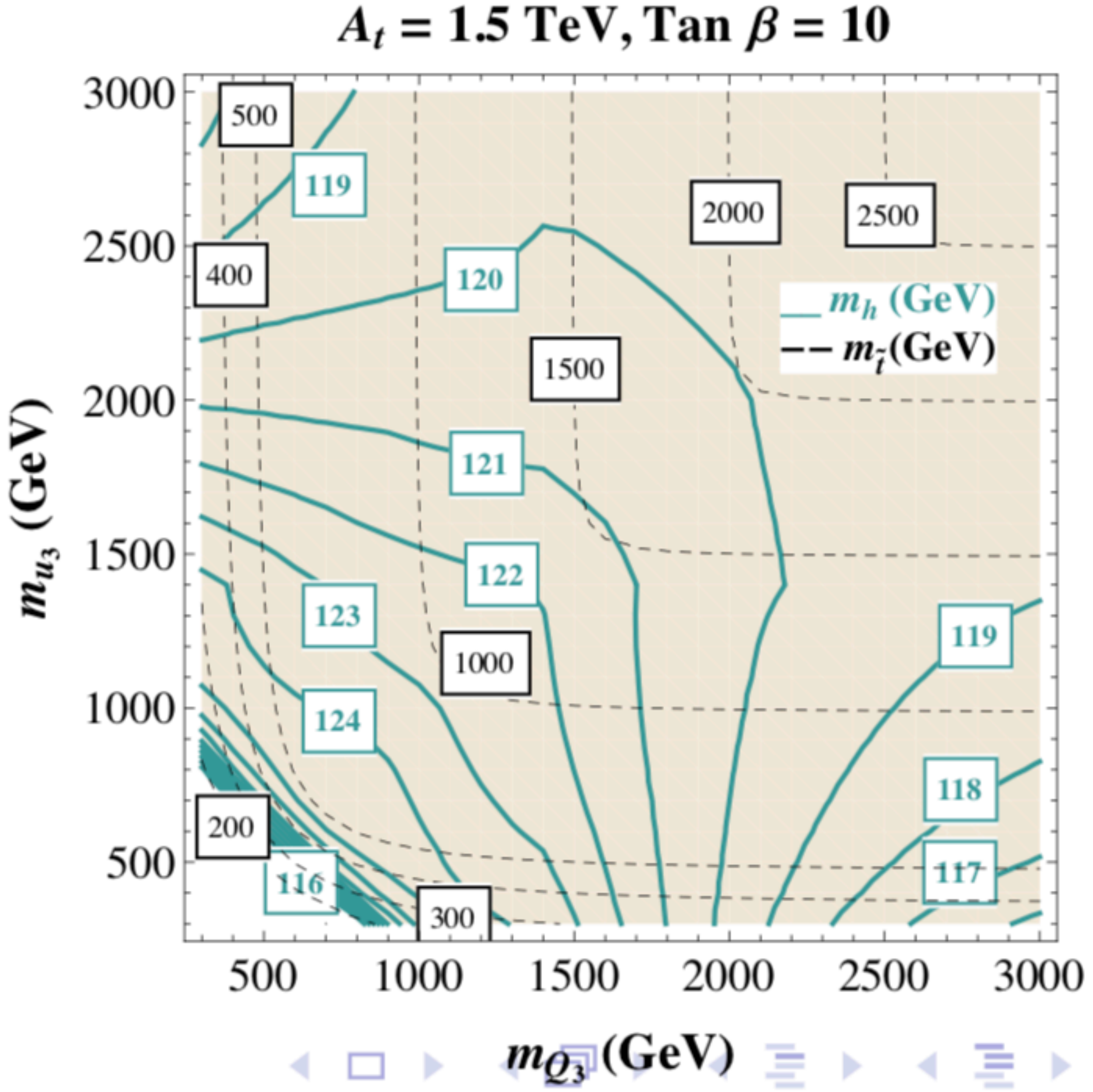
M_h^{max} in pMSSM, Djouadi et al. PLB708 (2012) 162-169

- Only the scenarios with large X_t/M_S values and, in particular, those close to the maximal mixing scenario $A_t/M_S \approx \sqrt{6}$ survive.
- The no–mixing scenario is ruled out for $M_S \lesssim 3$ TeV.
- The typical mixing scenario needs large M_S and moderate to large $\tan\beta$ values.
- $M_h^{\max}$=136, 123 and 126 GeV have been obtained in, the maximal, zero and typical mixing scenarios.

M_h^{max} in pMSSM, Carena et al. JHEP 1203 (2012) 014

- With the significant splitting of the stop soft masses, the mass of the heaviest stop is of the order of the largest soft stop mass, and the lightest stop mass can be as low as $\sim$ 100 GeV
- $\sim$ 125 GeV Higgs does not imply a hard lower bound on the squark masses.
- A_t larger than $\sim$ 2 TeV are required to achieve $\sim$ 125 GeV Higgs.
- In the case of no splitting between the two stop soft masses, values of A_t above $\sim$ 1.5 TeV are needed to achieve Higgs masses in the region of interest.
- In this case the mass of the lightest stop is naturally above a few hundred GeV.





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 !

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’

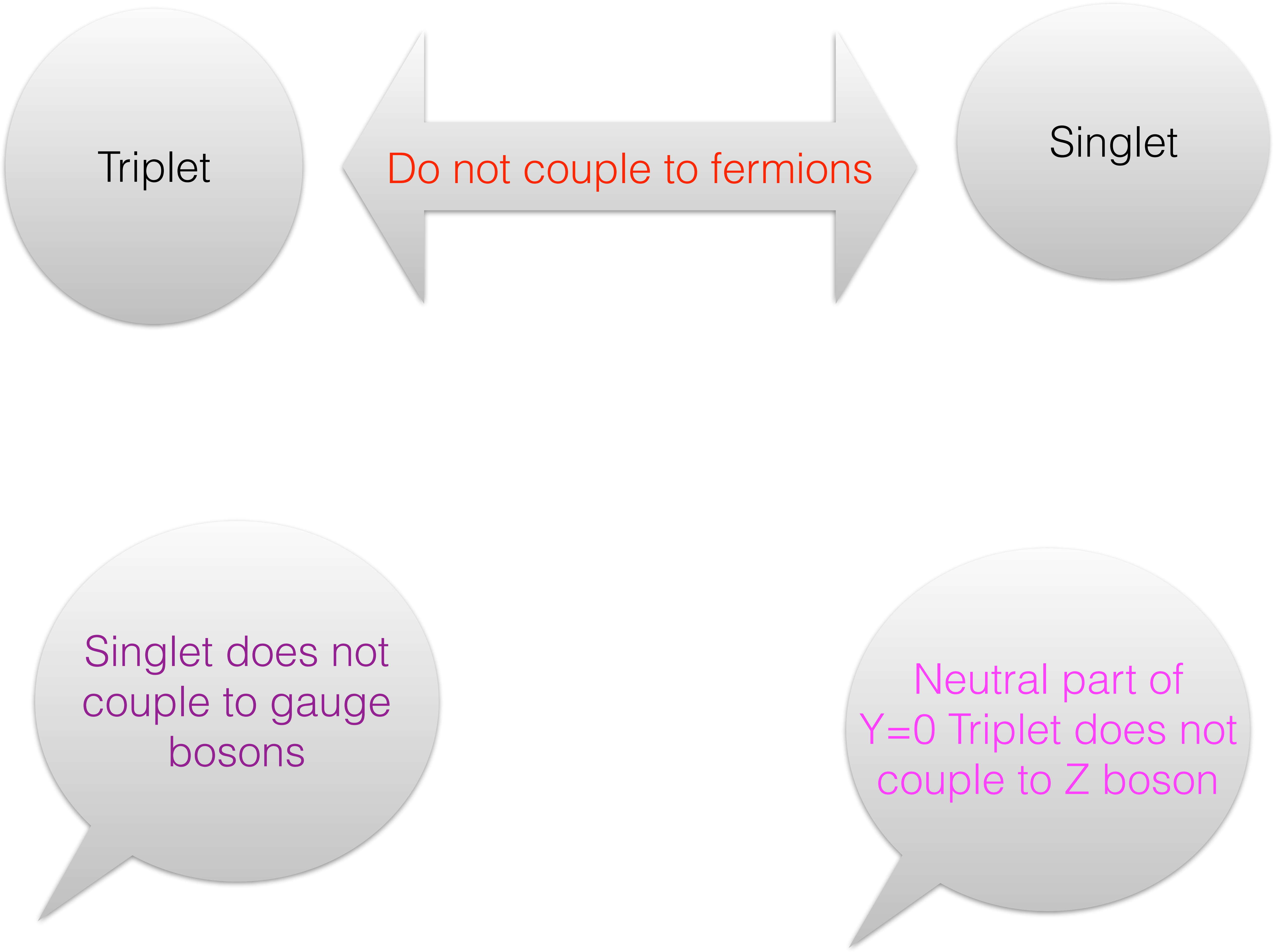
Supersymmetry can still exists below TeV !

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 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 !

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

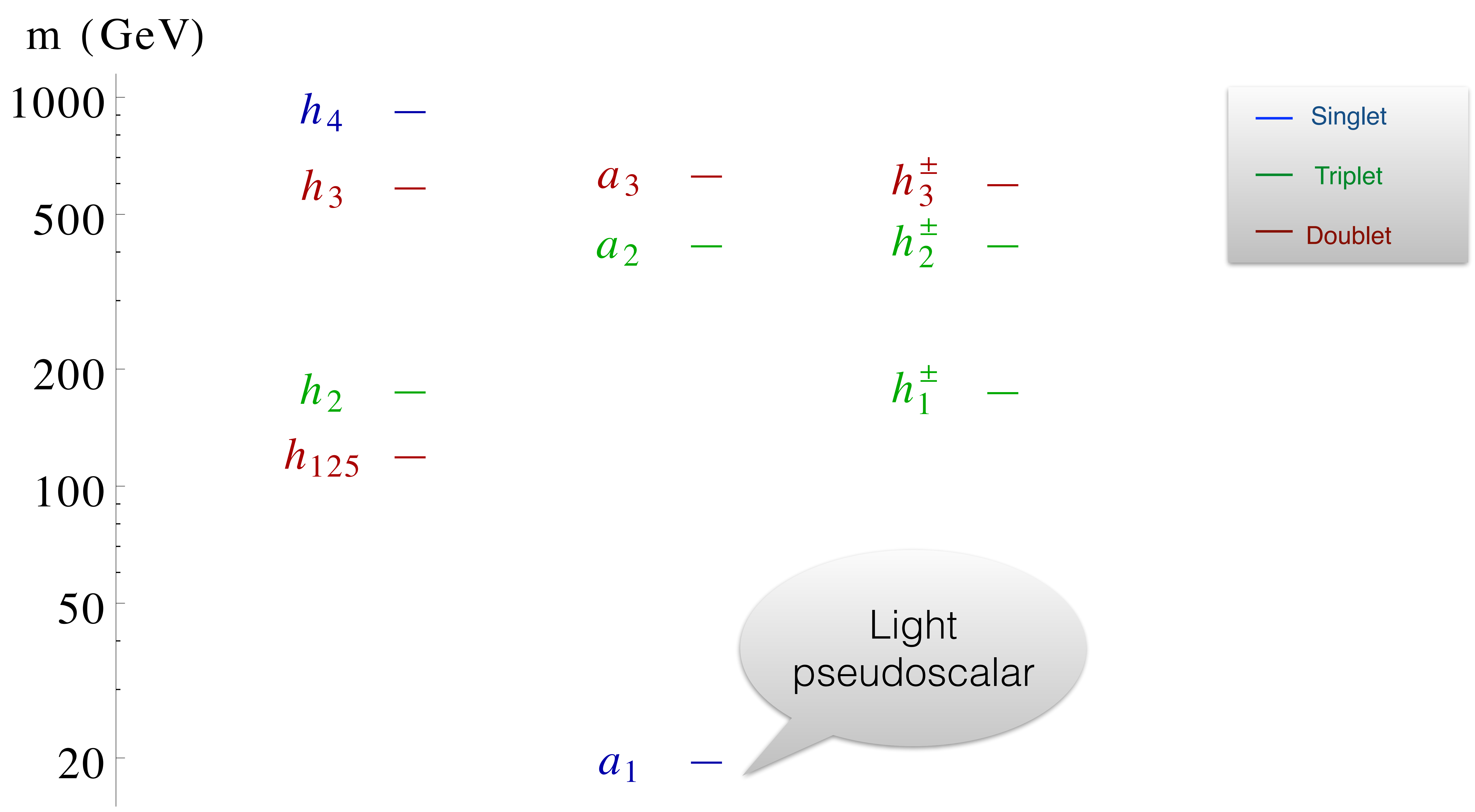
- In the limit where all the A parameters vanish the scalar potential accrues an enhanced U(1) symmetry

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

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

- 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

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

Dublet

Triplet

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

- In particular the charged Goldstone has contribution from triplets

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

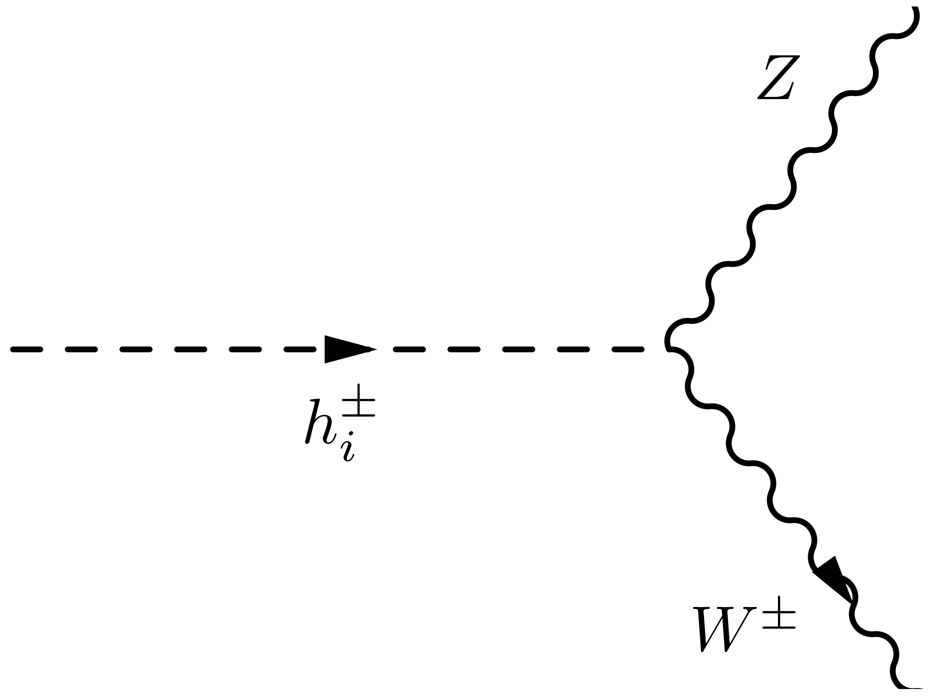
$$N_T = \frac{1}{\sqrt{1 + 4\frac{v_T^2}{v^2}}}$$

has a triplet contribution

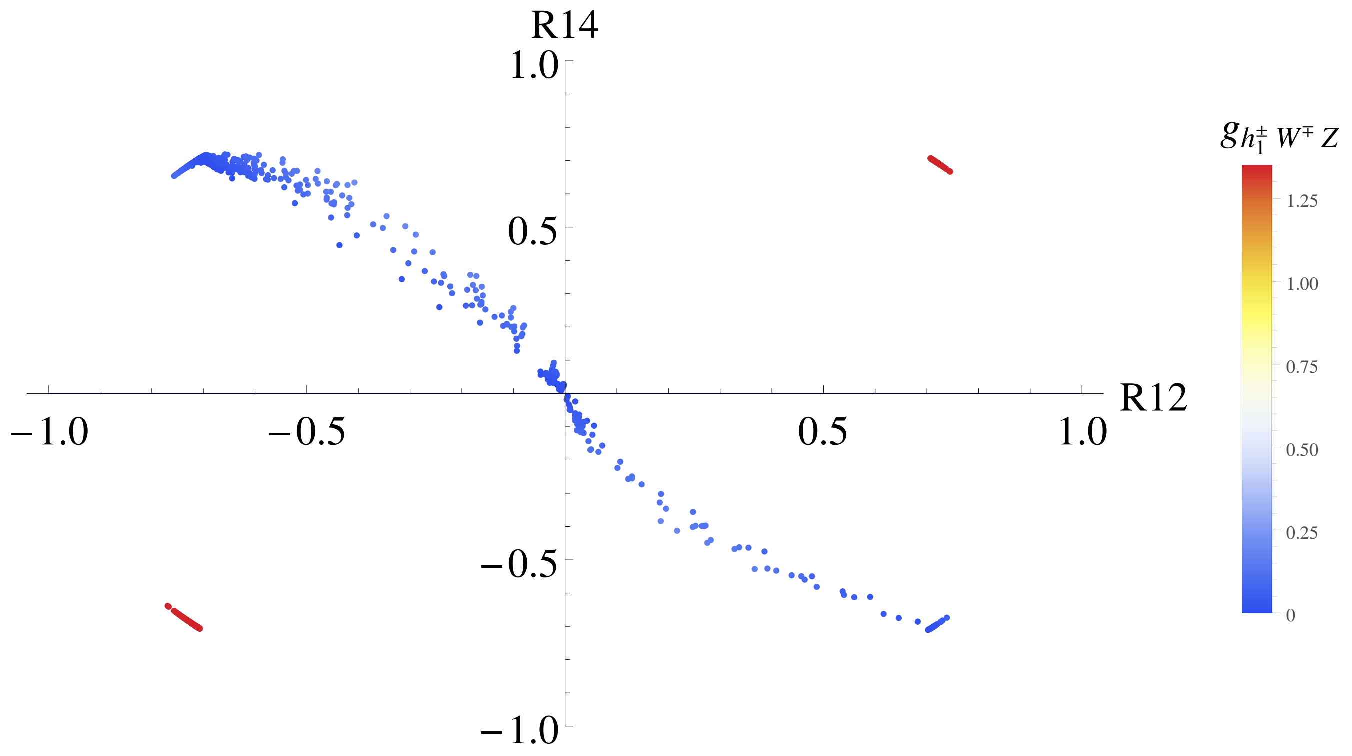
No λ_i

Non-standard decay modes

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



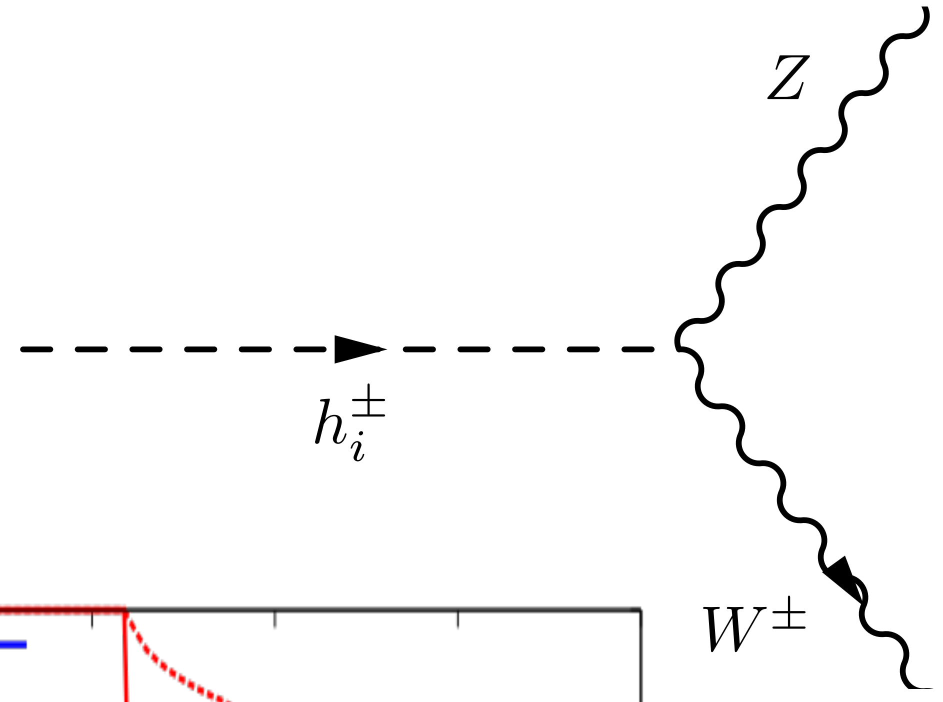
- For $\lambda_T \sim 0,\ \mathcal{R}^C_{12}$ and $\mathcal{R}^C_{14}$ take the same sign
- Hence $h_1^\pm - W^\mp - Z$ coupling is enhanced
- Non-zero triplet vev, initiates this vertex



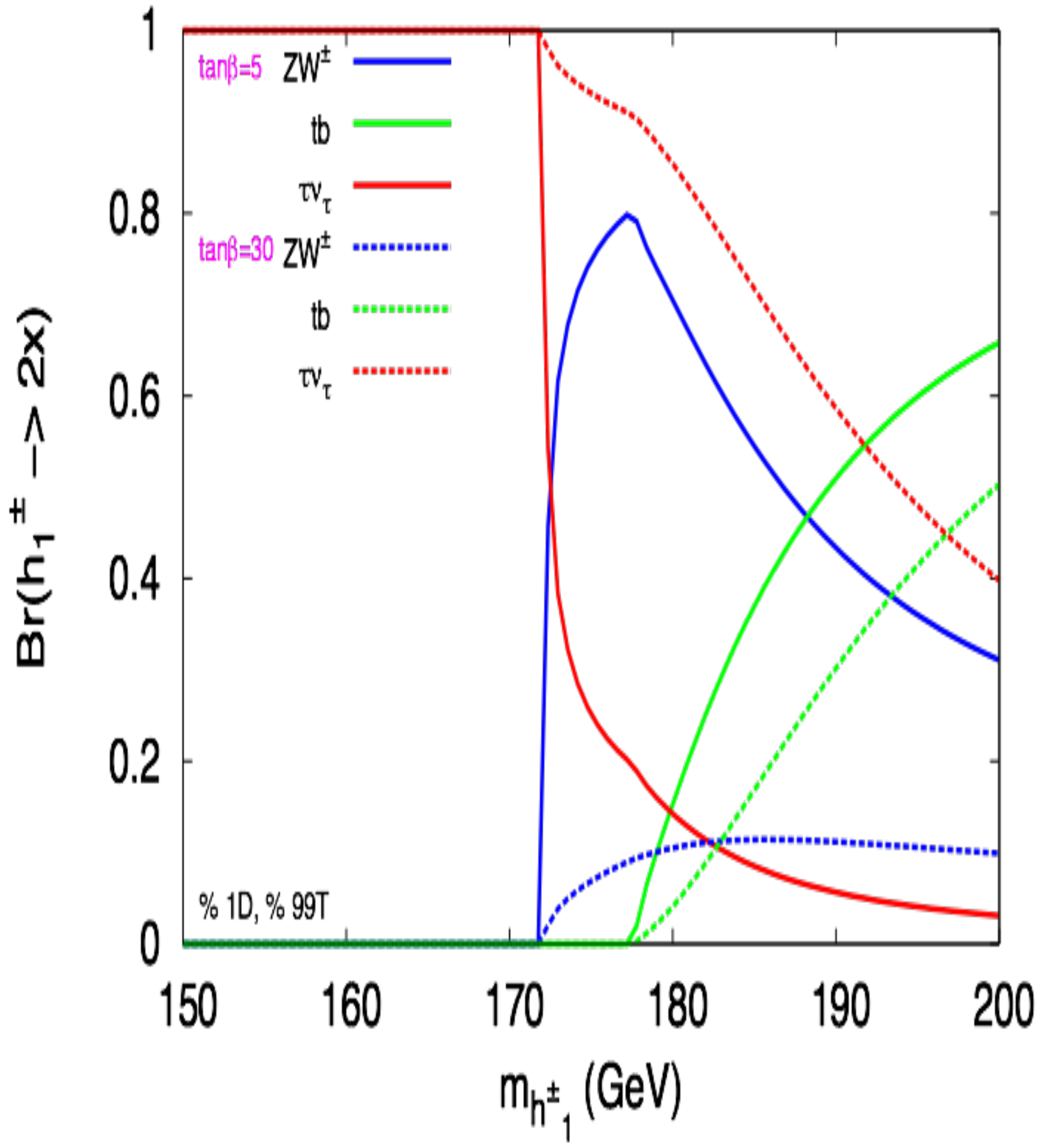
⇒ Triplet signature

Non-standard decay modes

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



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



- 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

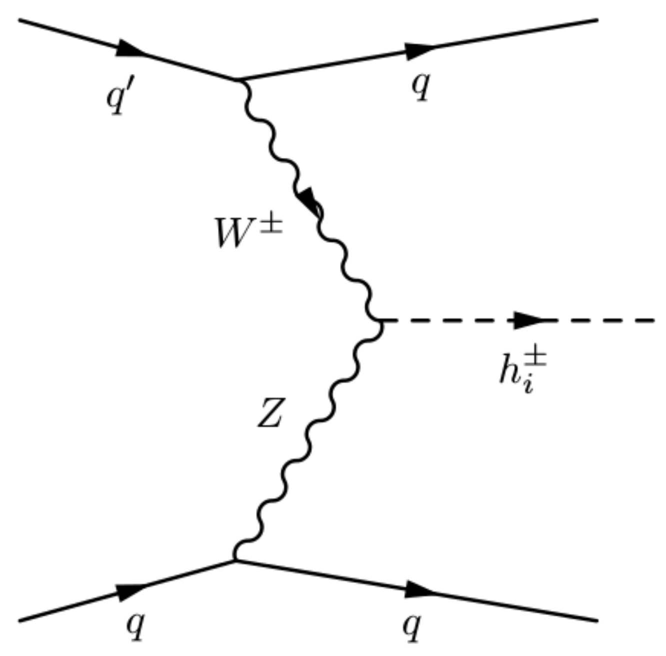
P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026

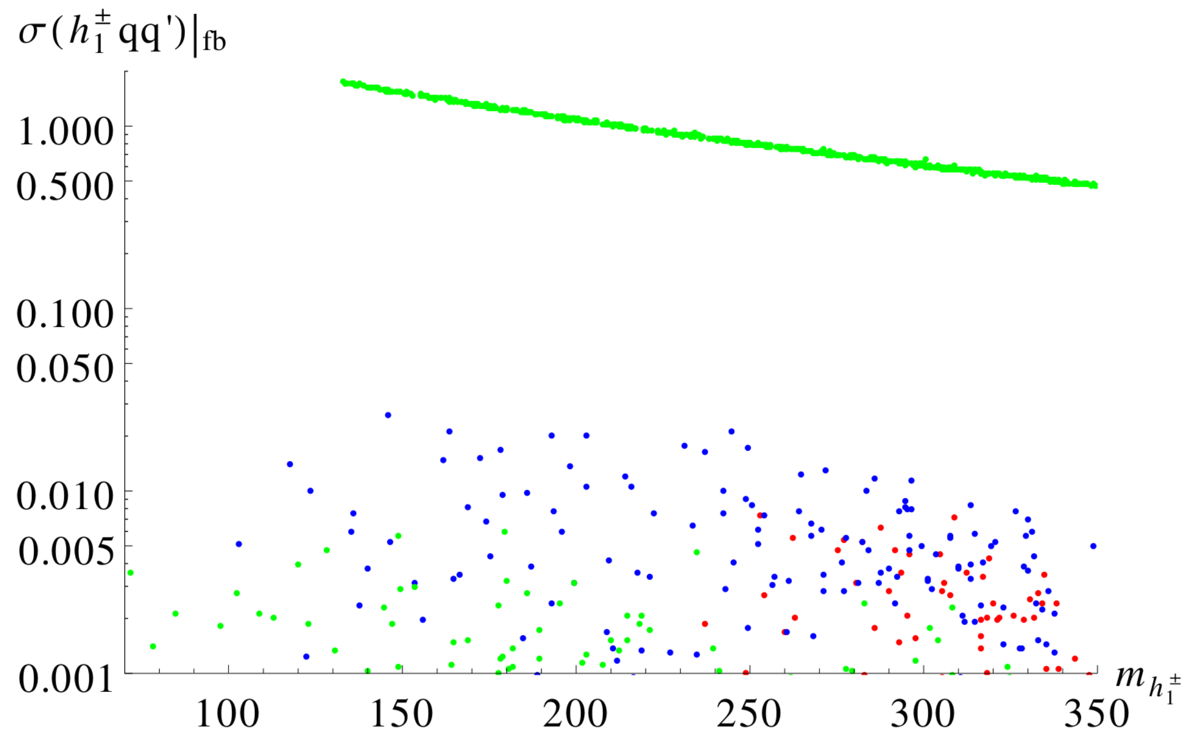
PB, Claudio Coriano, Antonio Costantini, PRD94 (2016) no.5, 055030

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

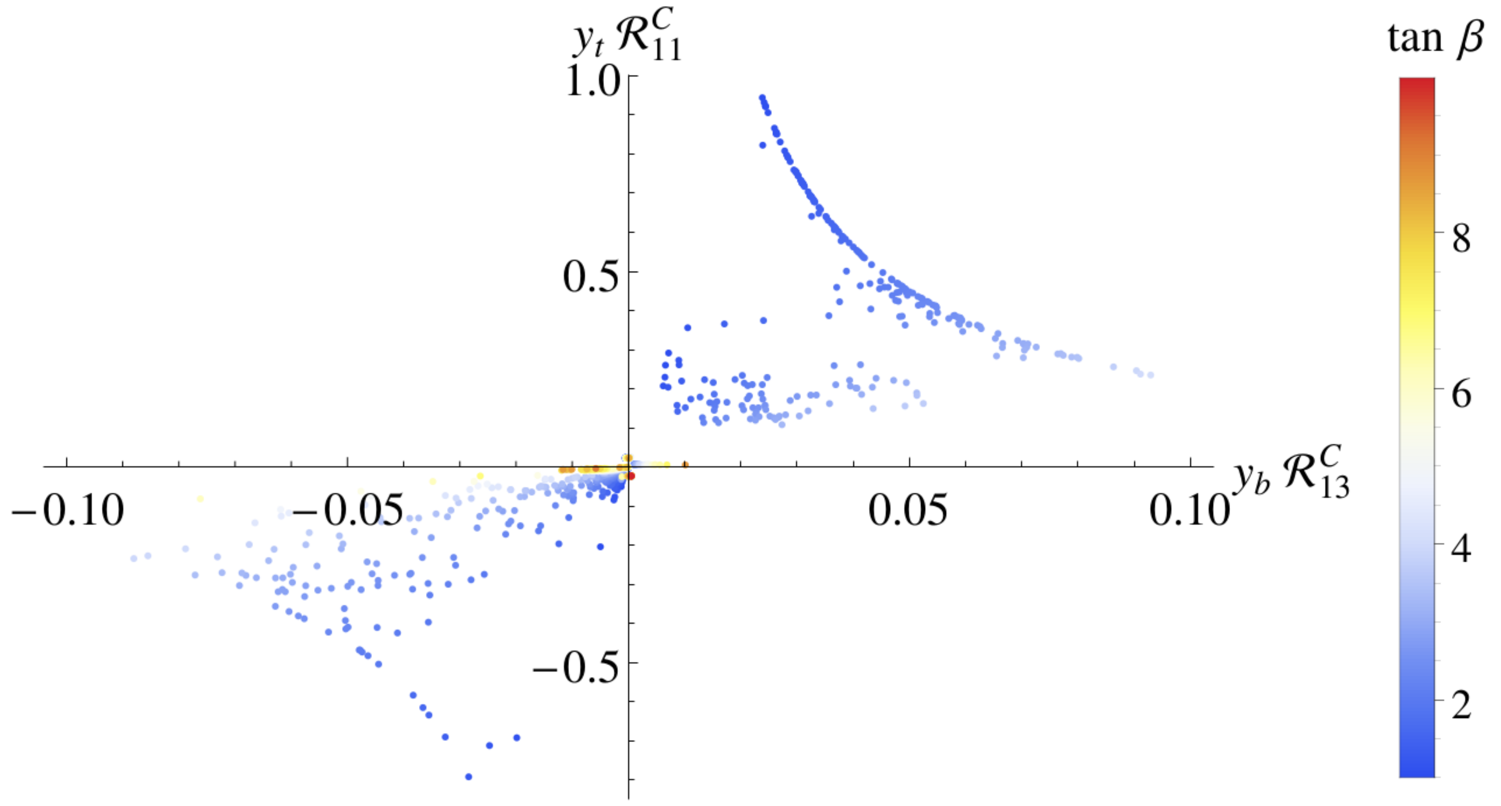
- This process is absent for doublet-like charged Higgs boson

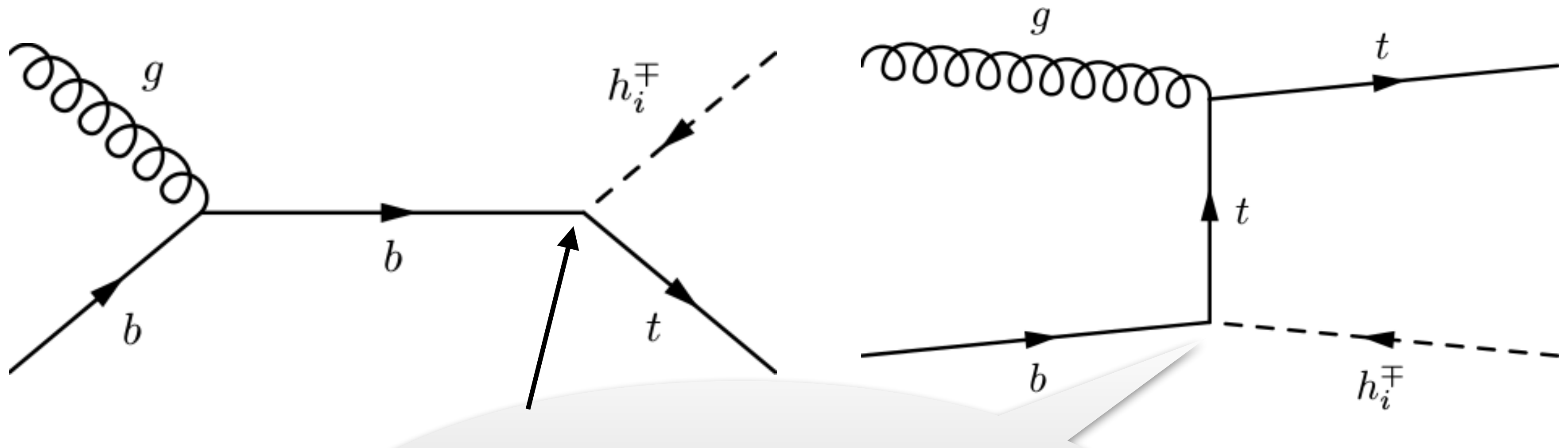




What happens to standard single charged Higgs production mechanism ?

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



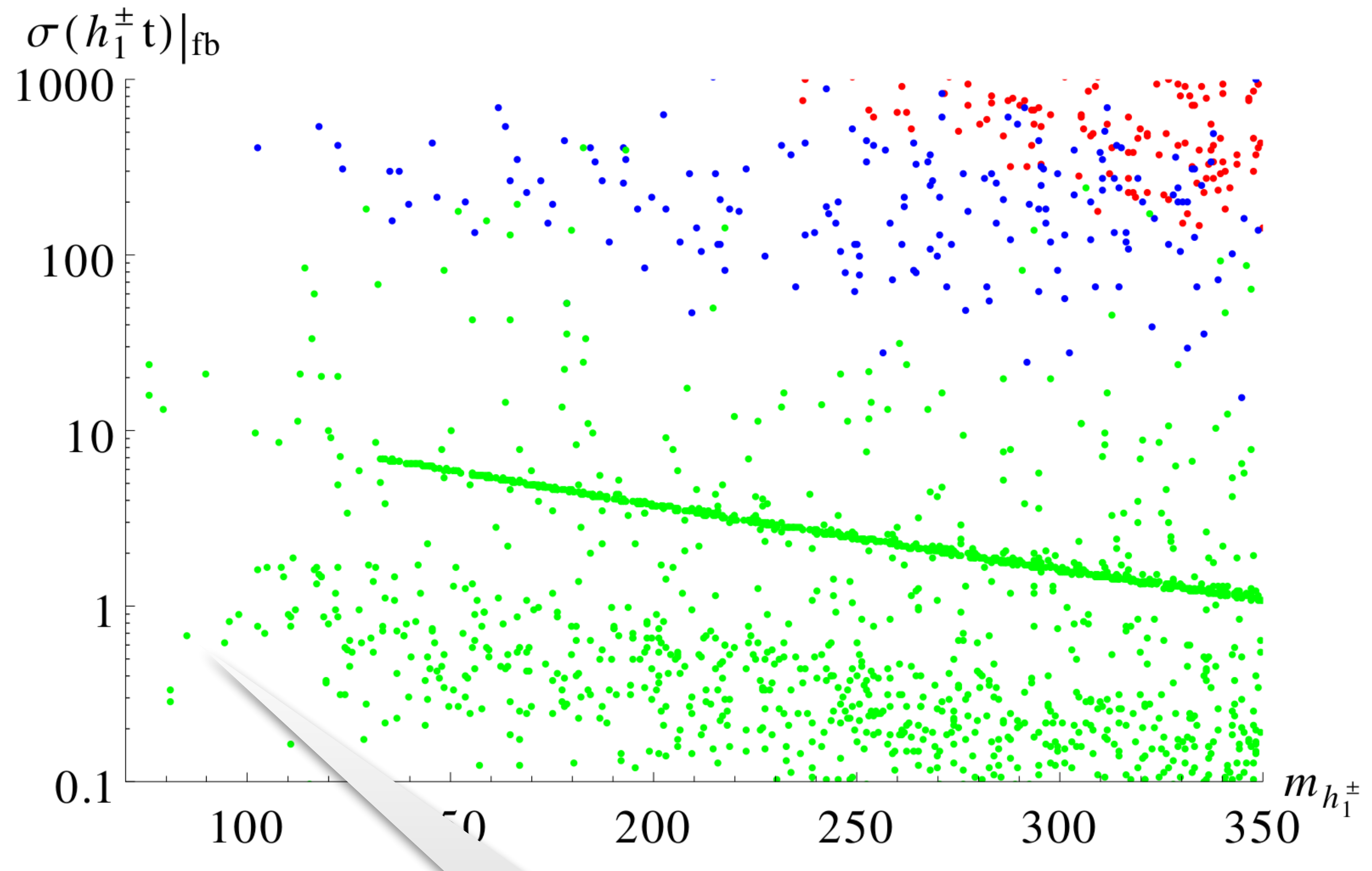


Suppressed for triplet-like Higgs

- Triplets do not couple to fermions

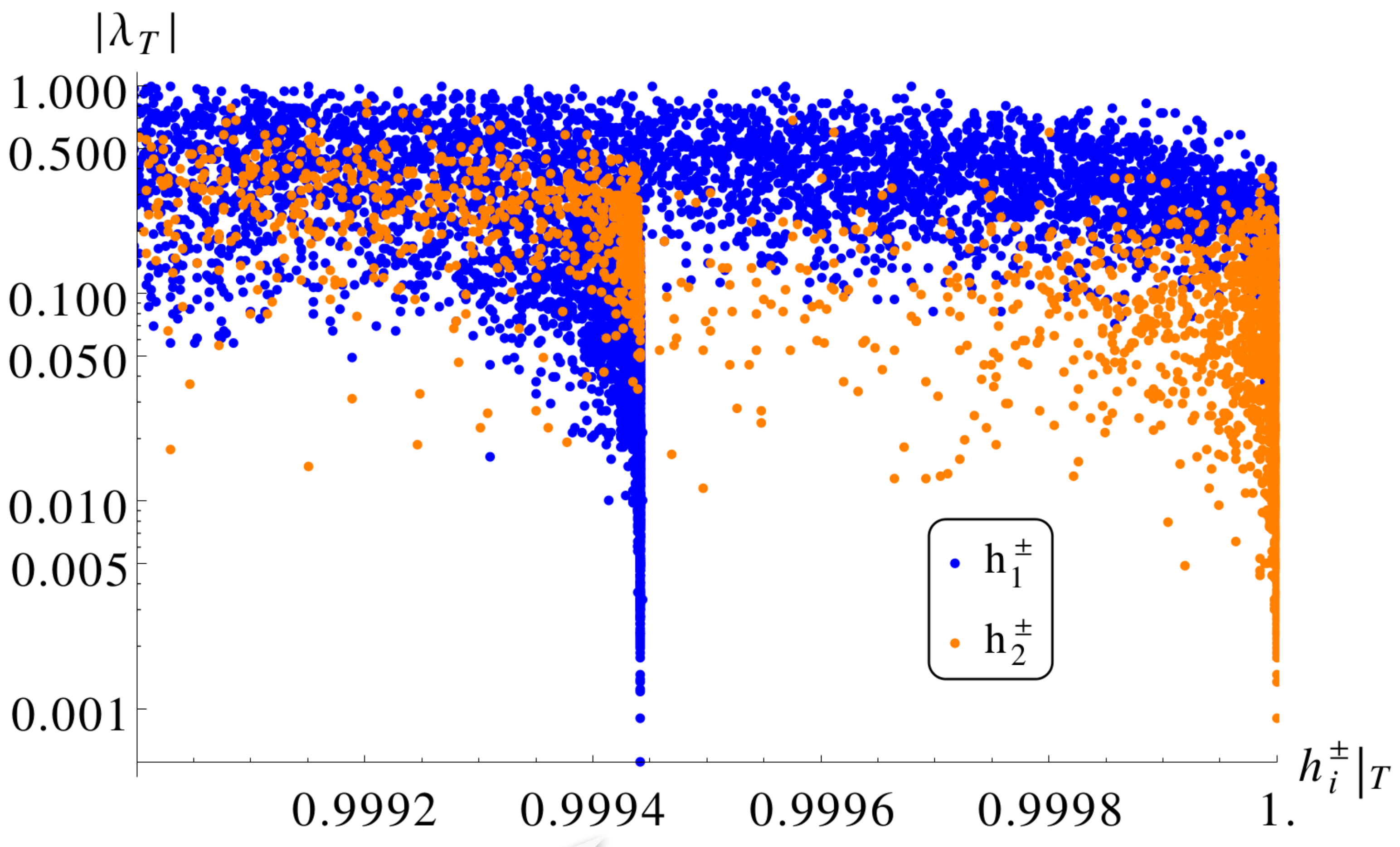
➡ bg fusion is really suppressed

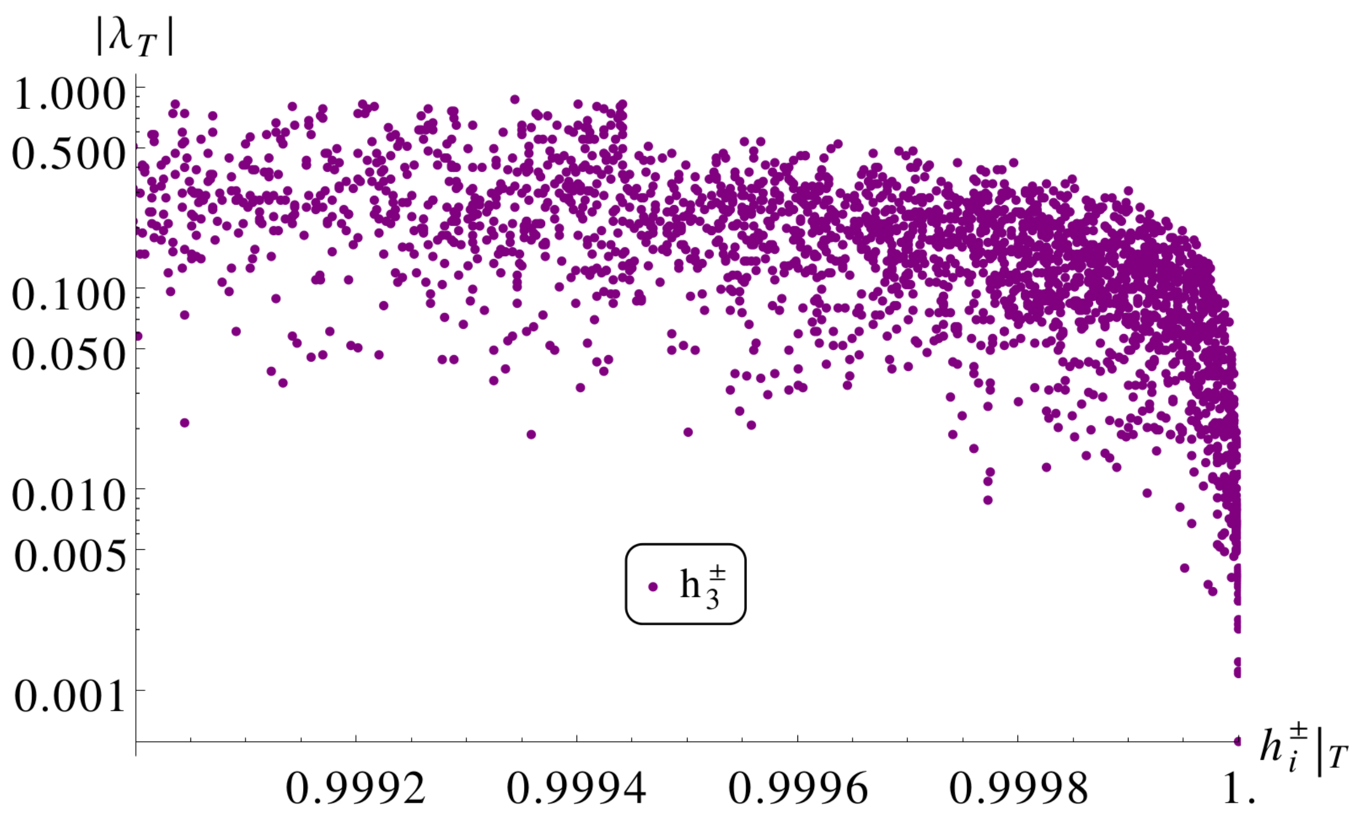
- Even if $\lambda_T = 0$, lightest charged Higgs boson still has some doublet component!



For pure triplet the coss-section goes to zero.

$\lambda_T \simeq 0$ limit





Not 100%

$$\lambda_T = 0$$

- $h^{\pm}_{2,3}$ only can be pure triplets
- $h^{\pm}_1$ has some doublet parts as perpendicular mode of the charged Goldstone

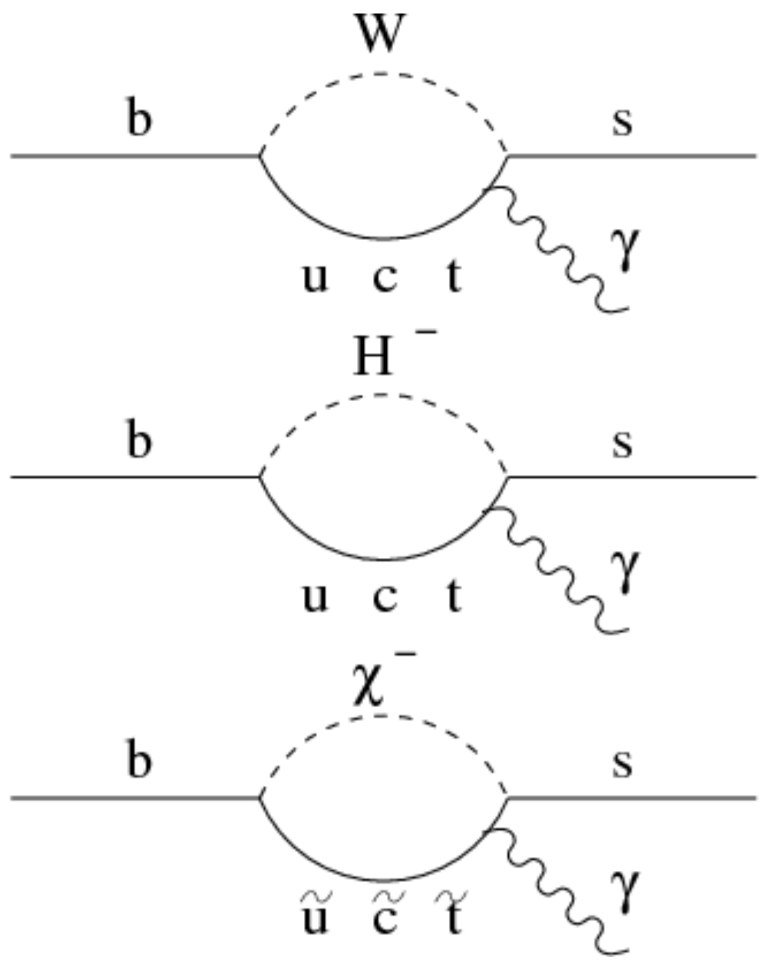
Rare decay

- 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

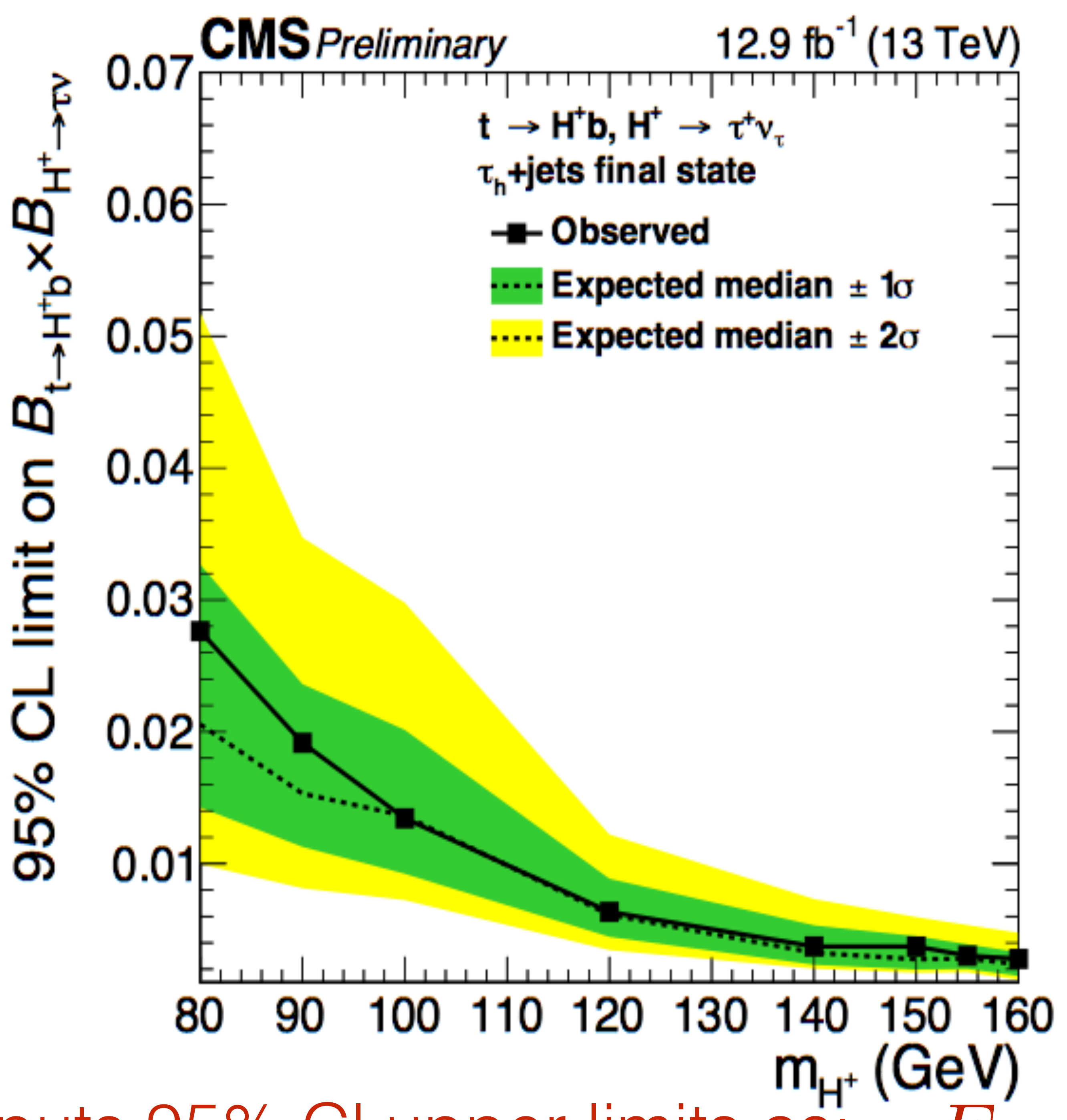
- LHC looked for this doublet type charged Higgs bosons via mainly its couplings to fermions

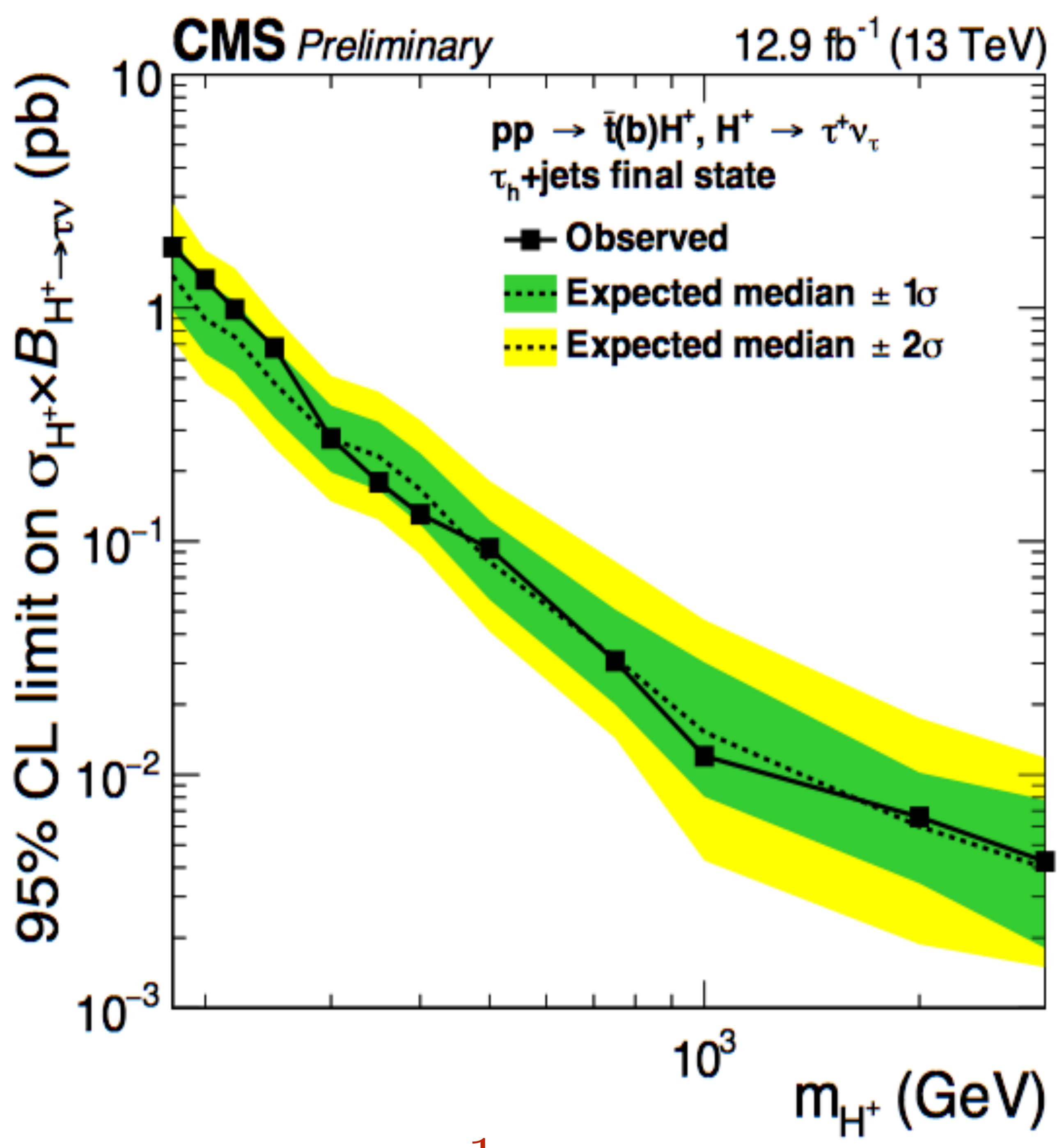
- Light charged Higgs boson: $pp \to t\bar{t} \to bW^+\bar{b}H^-$

- 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: $E_{cm} = 13\,\mathrm{TeV\ and\ } 12.9\,\mathrm{fb}^{-1}$

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

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

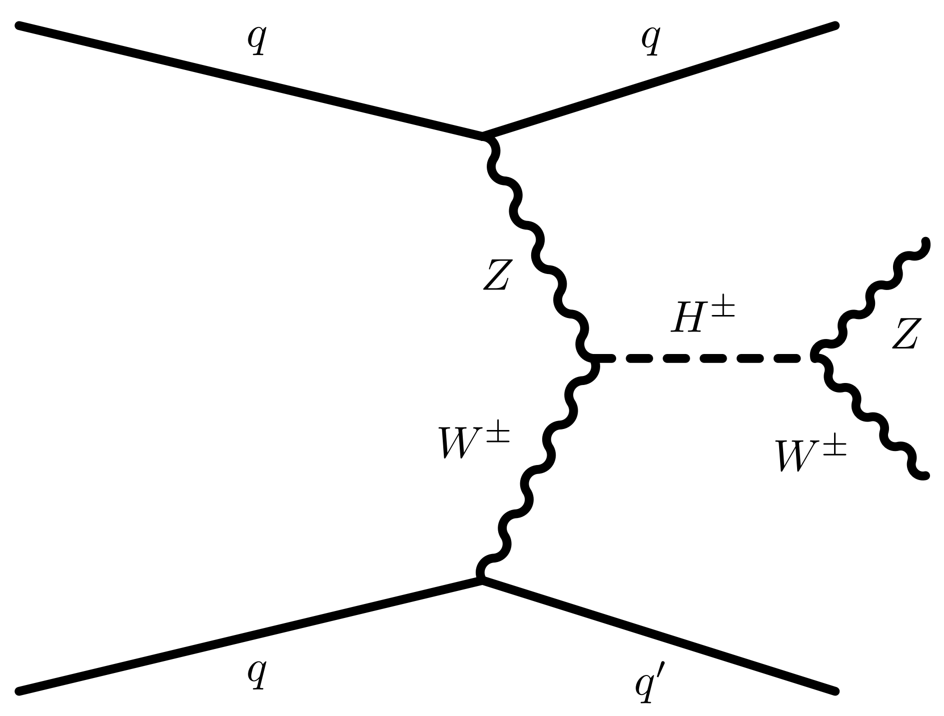
CMS-PAS-HIG-16-031

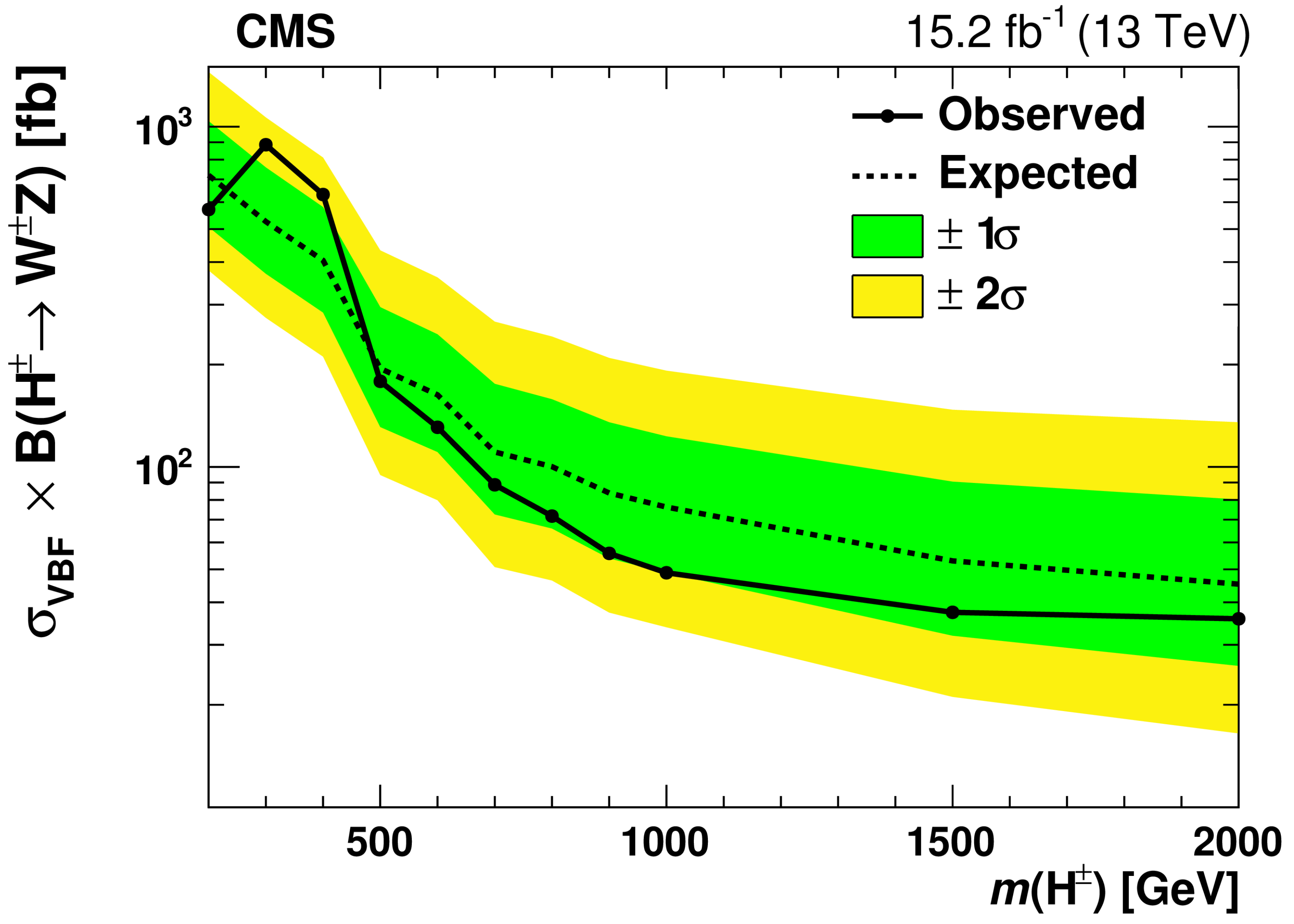
- ATLAS puts 95% Cl upper limits as: $E_{cm} = 13\,\mathrm{TeV\ and\ } 3.2\,\mathrm{fb}^{-1}$

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

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 $200 \le m_{H^\pm} \le 2000\,\mathrm{GeV}$

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

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

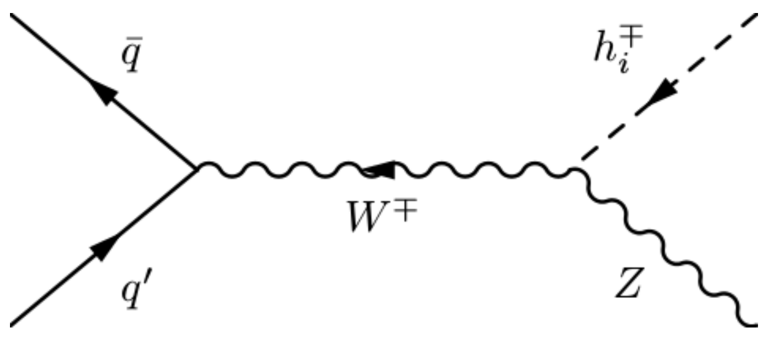
$$\sigma_{VBF} \times \mathcal{B}(H^\pm \to ZW^\pm) \sim 31 - 1020\,\mathrm{fb} \text{ for } 200 \le \mathrm{m_{H^\pm}} \le 2000\,\mathrm{GeV}$$

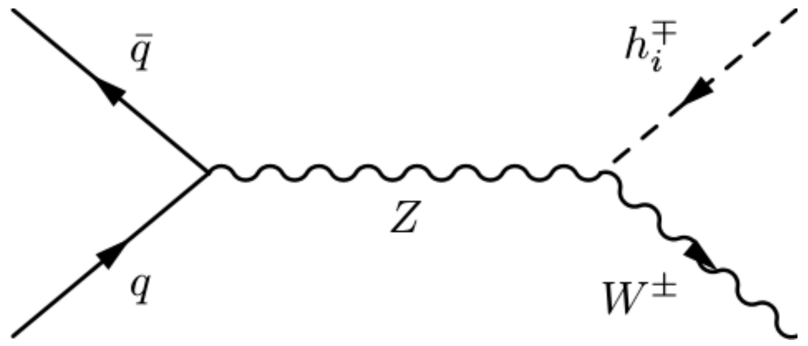
PRL 114,23801(2015)

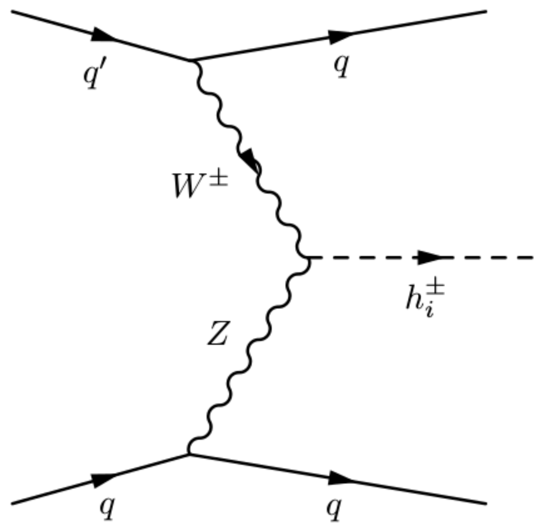
- Doubly charged Higgs boson: $E_{cm} = 13\,\mathrm{TeV}$ with $36.1\,\mathrm{fb}^{-1}$

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

Look for new production modes





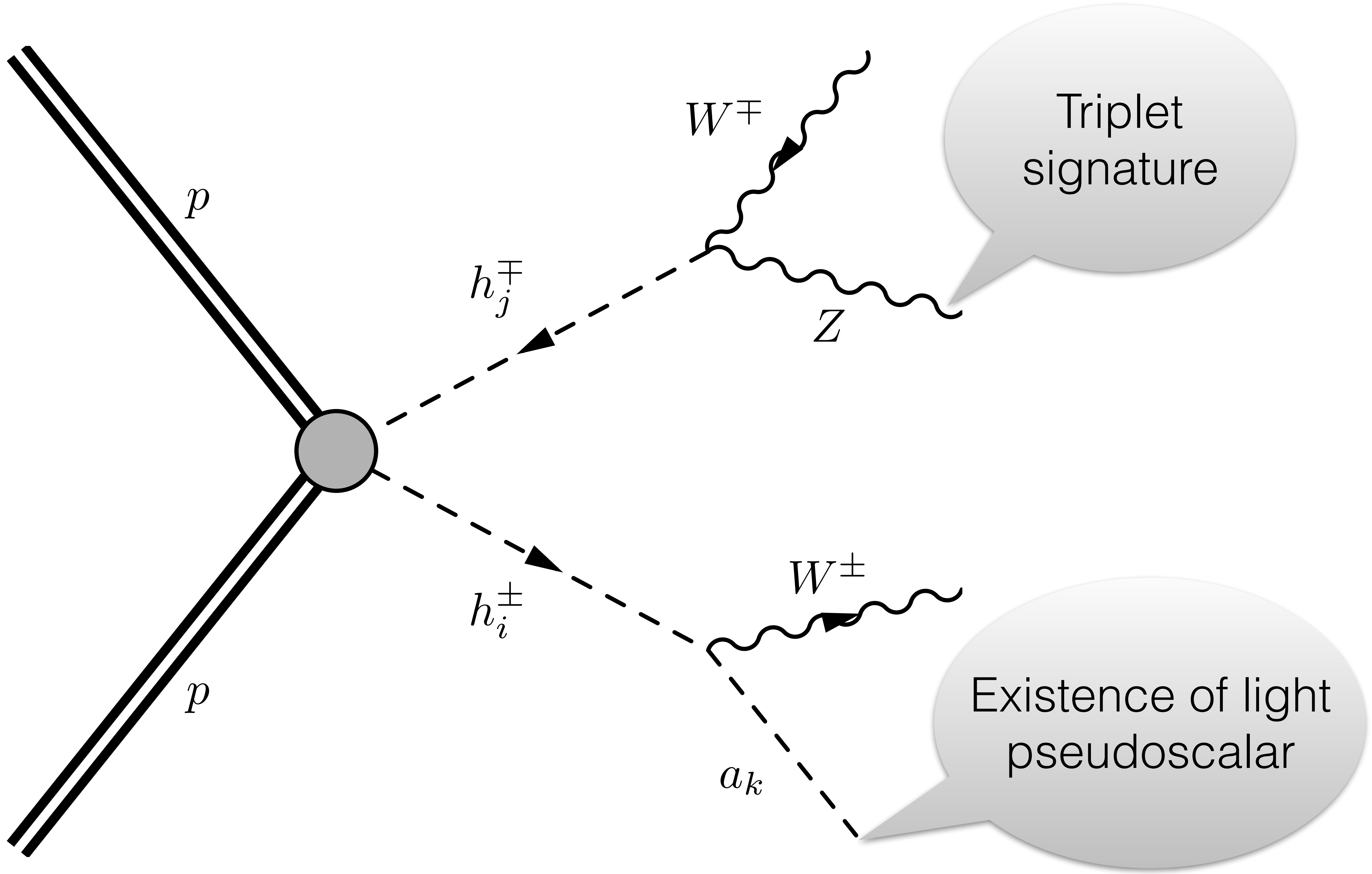


- Multi-leptonic final states can probe the triplet mode
- $3\ell + 2j,\, 3\ell + 2b$ final states can probe such triplet signature by $\sim 100\,\mathrm{fb}^{-1}$ of integrated luminosity at the LHC@14 TeV
- Higher lepton multiplicities can be probed at further higher luminosities.

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

- Is it possible to distinguish different possible extensions ?

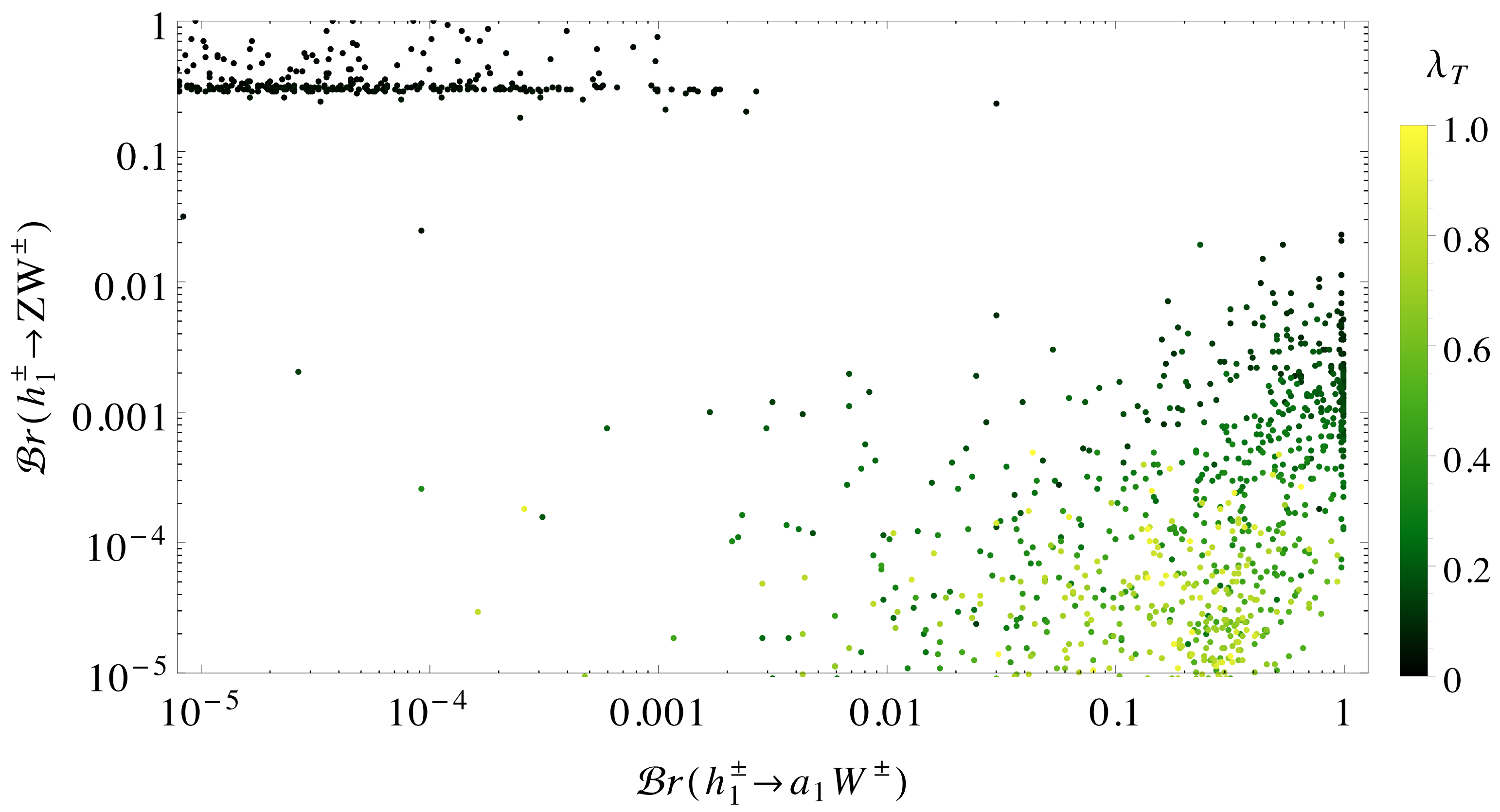
$$W_S = \lambda_T H_d.T H_u + \lambda_S S H_d \cdot H_u + \lambda_{TS} S Tr[T^2] + \frac{\kappa}{3} S^3$$



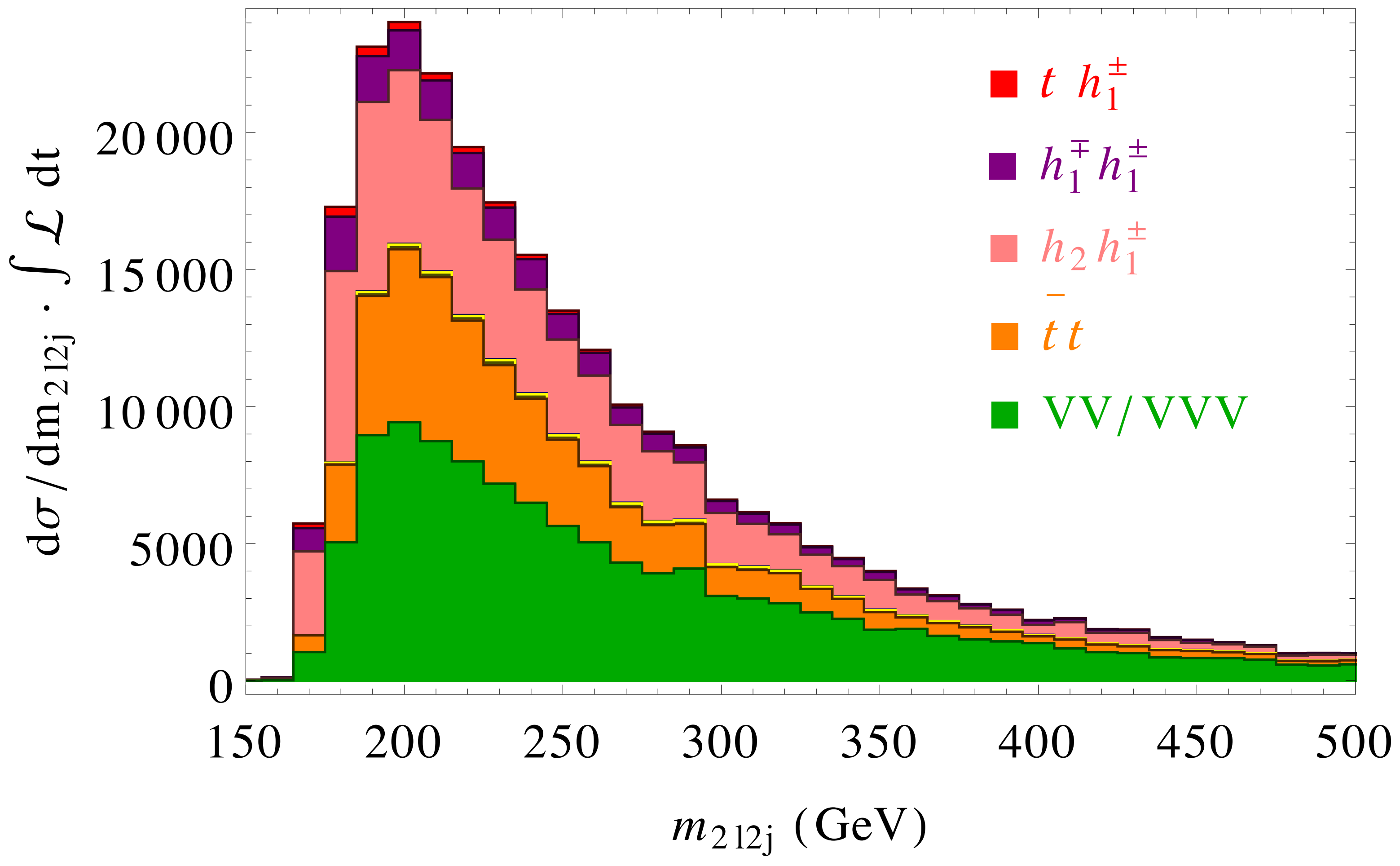
-

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

Status of triplet Y=0 charged Higgs boson



- Probing $a_1 W^\pm$ and $ZW^\pm$ together is challenging
- $a_1 W^\pm$ can be probed via $2b + 2\tau + 1\ell + m_{jj} \sim m_W$ at the LHC with $43\,\text{fb}^{-1}$
- ZW mode can be probed via $3\ell + 1\tau$ with $54\,\text{fb}^{-1}$



- Light pseudo scalar mass can probed with early data of $55\,\text{fb}^{-1}$
- Probing charged Higgs mass via reconstruction of Z and W will take around $712\,\text{fb}^{-1}$ of integrated luminosity
- It is possible to distinguish charged Higgs bosons from different representations of SU(2)

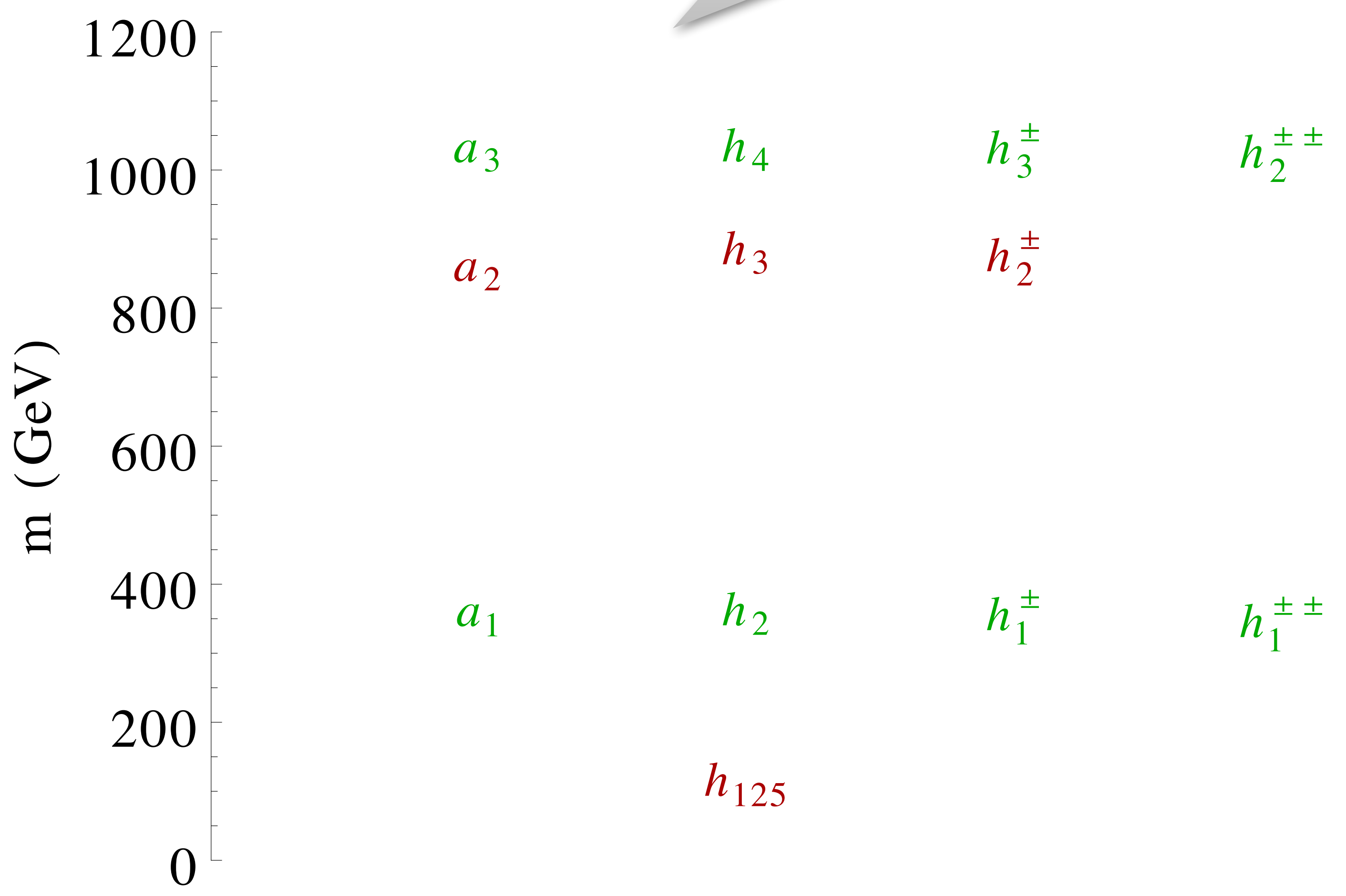
PB, Antonio Costantini, JHEP 1801 (2018) 067

Georgi-Machacek Model

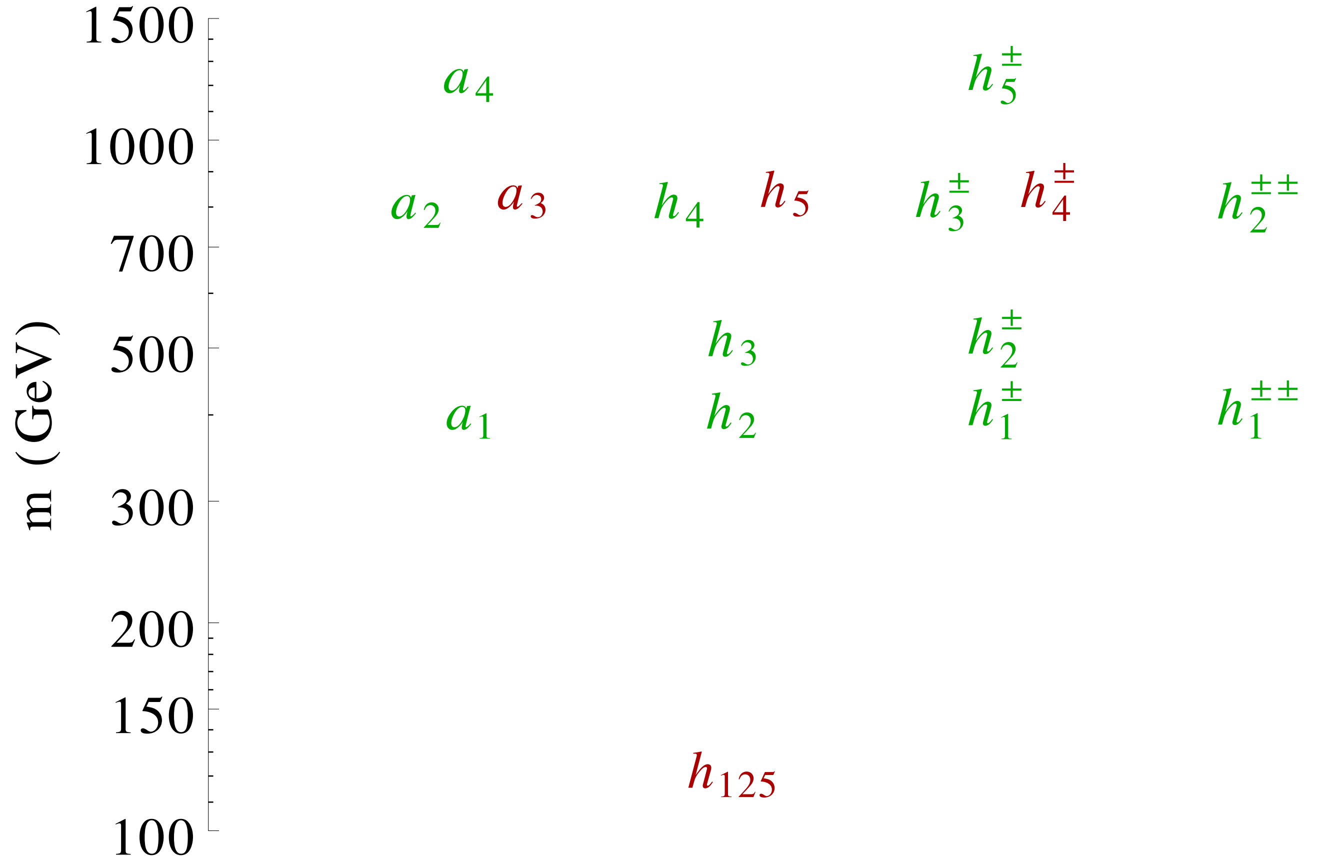
Status of non-zero Hyper-charged triplets charged Higgs bosons

- $Y=\pm1$ invokes $\mathrm{H}^{\pm\pm}$ in the spectrum but constrained from ρ parameter
- $Y=\pm1,0$ can form custodial triplets known as Georgi-Machacek triplets which can evade the constraints from ρ parameter

$Y=\pm1$



$Y=\pm1,0$ GM



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

CP-violating Higgs sectors

- MSSM: Not-Spontaneous
- NMSSM: King et. All.
- TSSM:

Baoyogenesis and Leptogenesis

- How extended Higgs sector helps?
- May be first order phase transition is required?
- CP-violation in Higgs sectors