How Higgs physics can uncover the nature of flavour?

Family dependent Higgs Physics

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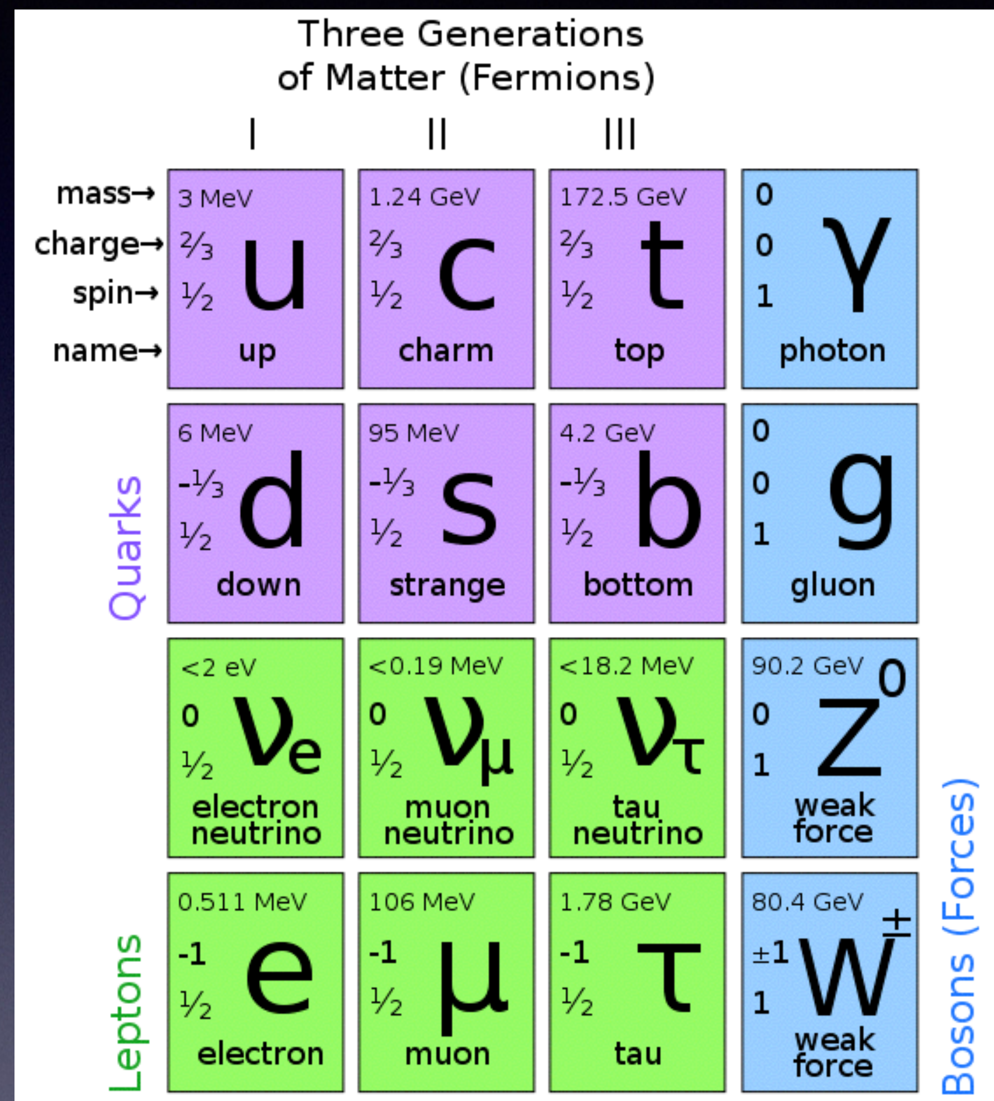
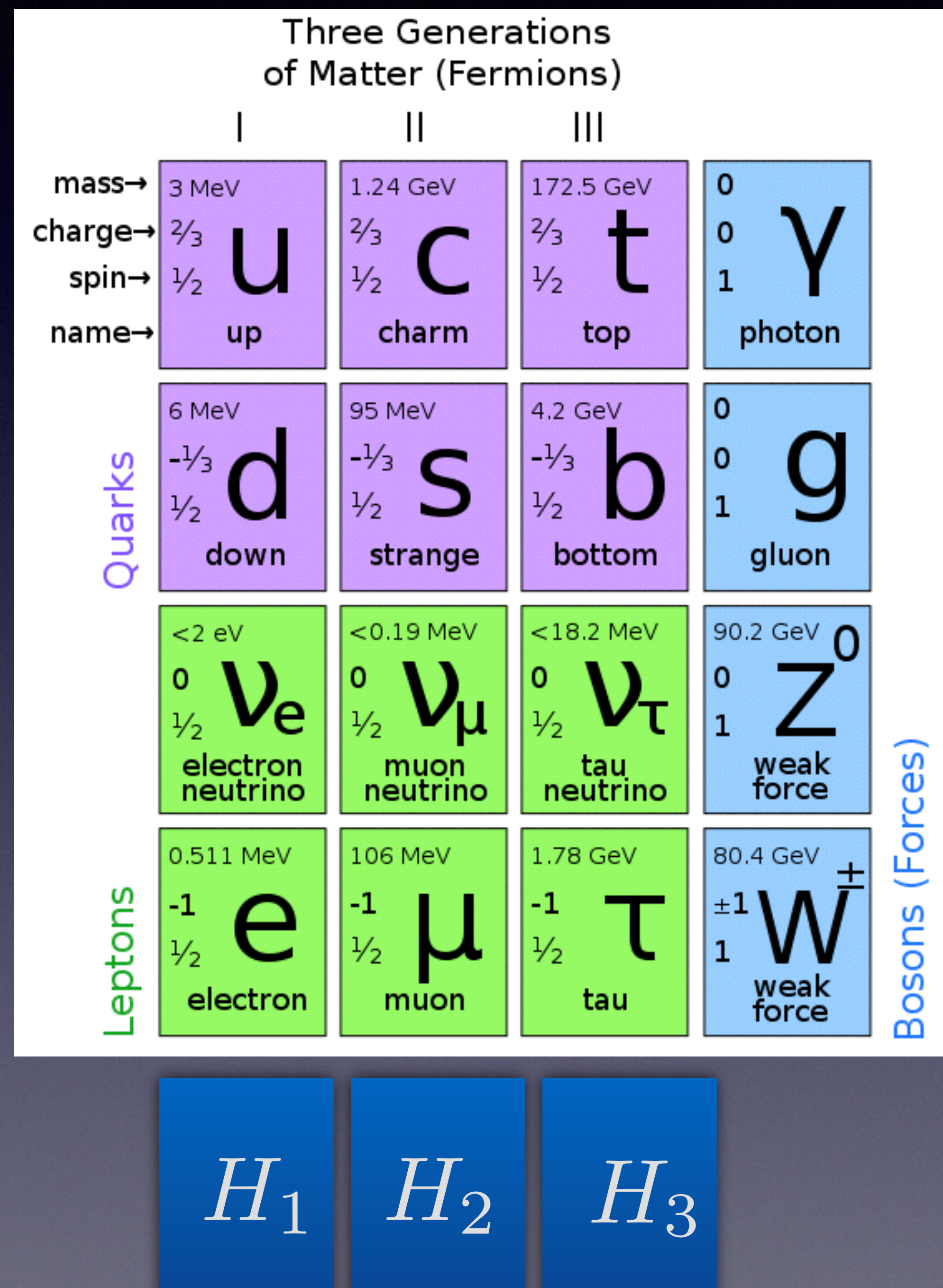
SM: 3 families of fermions, 1 of Higgs?



H

1 Higgs Boson

- Should not be considering this as well?



Traditionally

- The Higgs is special:

  Just one or family independent extensions

  GUT+ family symmetries can solve the problem of hierarchies

  and mixing for fermions

- Lots of complications if we add more Higgs bosons:

  Fine tuning to obtain EW breaking, non-perturbativiy, etc.

Kinds of models

- The Higgs is special:

  Flavour comes from other sector, e.g. **Flavons**

$$-\mathcal{L}_{\rm Flavon}(\varphi_n^\psi) = \sum_n \overline{\psi}_{Li}\psi_{Rj} H c^\psi_{\varphi_n^\psi\, ij} \left(\frac{\varphi_n^\psi}{\Lambda_{\varphi_n^\psi}}\right)^{p^\psi_{nij}} + {\rm H.c.},$$

$$\begin{aligned} H &\to \text{Higgs boson} \\ \psi &\to \text{SM fermions} \\ \varphi_n &\to \text{flavons} \end{aligned}$$

- There are really **family dependent Higgs bosons** : 3 for each kind of fermion

$$-\mathcal{L}_{\rm H} = \sum_{k=1,3,5} \overline{\psi}_{Li} D_{Rj} H_k + \sum_{k=2,4,6} \overline{\psi}_{Li} U_{Rj} H_k + {\rm H.c.},$$

Flavons at Colliders

- The flavon acquires vacuum expectation value

$$\varphi = \frac{(v_\varphi + H_f + iA_f)}{\sqrt{2}}$$

$$-\mathcal{L}_{\text{Flavon}}(\varphi_n^\psi) = c_{ij}^\ell \overline{L}_i e_{Rj} H \left(\frac{\varphi}{\Lambda}\right)^{-\mathcal{Q}_F\left(q_{Li}^{\overline{L}}+q_{Rj}^{e}\right)} + c_{ij}^d \overline{Q}_i d_{Rj} H \left(\frac{\varphi}{\Lambda}\right)^{-\mathcal{Q}_F\left(q_{Li}^{\overline{Q}}+q_{Rj}^{d}\right)}$$
$$+ c_{ij}^u \overline{Q}_i u_{Rj} \tilde{H} \left(\frac{\varphi}{\Lambda}\right)^{-\mathcal{Q}_F\left(q_{Li}^{\overline{Q}}+q_{Rj}^{u}\right)} + \text{H.c.},$$

0911.2149 K. Tsumura, L. V-S, 1603.06950 Bauer et al., L. V-S
1709.xxxx

- Full cancellation of anomalies possible with two flavons.

$U(1)_F$ charges						
Field	$\overline{Q}_{Li}$	d_{Ri}	u_{Ri}	$\overline{L}_{Li}$	e_{Ri}	ν_{Ri}
Charge	$q_{L\,i}^{\overline{Q}}$	q_{Ri}^{d}	q_{Ri}^{u}	$q_{Li}^{\overline{L}}$	q_{Ri}^{e}	q_{Ri}^{ν}

$$Y_{ij}^f = c_{ij}^f \left(\frac{v_\varphi}{\sqrt{2}\Lambda}\right)^{\left(q_{L\,i}^{\overline{f}}+q_{R\,j}^{f}\right)},$$

- Effective Lagrangian for phenomenology

$$-\mathcal{L}_{\varphi}^{\rm eff} = m_i^f\, \overline{f_{L}}_i f_{R i} \left(1 + \frac{h}{v}\right) + \kappa_{ij}^f\, \overline{f_{L}}_i f_{R j} \left(\frac{\varphi}{v_\varphi/\sqrt{2}}\right) + \text{H.c.},$$

- Collider phenomenology controlled by

$$\kappa_{ij}^f = \left[m_j^f \sum_k q_{L\,k}^f \left(U_L^f\right)_{ik} \left(U_L^f\right)_{jk}^* + m_i^f \sum_k q_{R\,k}^f \left(U_R^f\right)_{ik} \left(U_R^f\right)_{jk}^* \right].$$

- The interaction with extra Z is controlled by

$$\mathcal{L}(\varphi_i, Z_k) = (D^\mu H)^\dagger (D_\mu H) + \sum_i (D^\mu \varphi_i)^\dagger (D_\mu \varphi_i) - V(\varphi_i), \qquad k = 1, 2,\ i = 1, 2$$

$$D_\mu \varphi_i = \frac{1}{\sqrt{2}} \left(\partial_\mu - \frac{i}{2} g_{F_i} \mathcal{Q}_{F\,i} (Z_\mu)_k \right) \varphi_i$$

- The most stringent bounds may come from the FCNC decays

$$\Gamma_{\ell_i\to\ell_j\gamma} = \frac{m_i^3}{4\pi}\left(1-\frac{m_j^2}{m_i^2}\right)^3\left(\left|A^\gamma_{Lij}\right|^2+\left|A^\gamma_{Rij}\right|^2\right).$$

$$A^\gamma_{Lij} = \frac{1}{(4\pi)^2}\frac{Q_f\,\mathrm{e}}{2v_\varphi^2}\left[-\kappa^f_{jk}\kappa^f_{ki}m_k\;c_{11}+\kappa^f_{jk}\kappa^{*f}_{ik}[m_j(c_{11}-c_{12}+c_{21}-c_{23})+m_i(c_{12}+c_{23})]\right],$$

$$A^\gamma_{Rij} = \frac{1}{(4\pi)^2}\frac{Q_f\,\mathrm{e}}{2v_\varphi^2}\left[-\kappa^{*f}_{kj}\kappa^{*f}_{ik}m_k\;c_{11}+\kappa^{*f}_{kj}\kappa^f_{ki}[m_j(c_{11}-c_{12}+c_{21}-c_{23})+m_i(c_{12}+c_{23})]\right],$$

- The leading decay channels are given by

$$\Gamma_{A_f\to f_i\bar f_j} = N_C^f\frac{G_F m_\varphi}{8\sqrt{2}\pi}\left(\left|\kappa^f_{ij}\right|^2+\left|\kappa^f_{ji}\right|^2\right)\left(\frac{v}{v_\varphi}\right)^2\beta_{ij}\left[1-\frac{(m_i-m_j)^2}{m^2_{A_f}}\right],$$

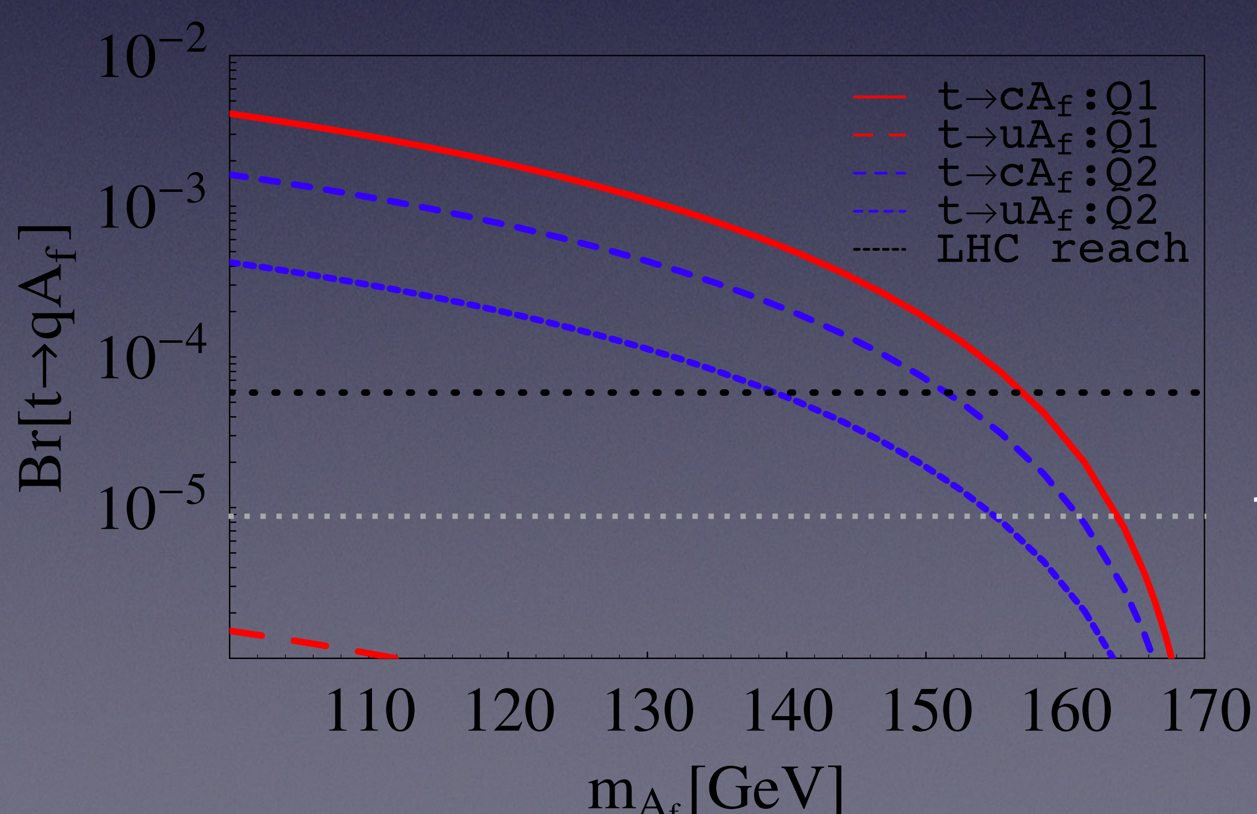
$$\Gamma_{A_f\to gg} = \frac{G_F\alpha_S^2 m_\varphi^3}{64\sqrt{2}\pi}\left(\frac{v}{v_\varphi}\right)^2\left|N_C\sum_q\kappa^q_{qq}\frac{I(m_q)}{m_q}\right|^2,$$

Most important constraints

- LEP bounds

$$e^-e^+ \to e^-e^+ \qquad \frac{M_{Z_1}}{g_{F_1}} \geq 26\ \mathrm{TeV}, \quad \frac{M_{Z_2}}{g_{F_2}} \geq 116\ \mathrm{TeV}$$

- Production through top decays

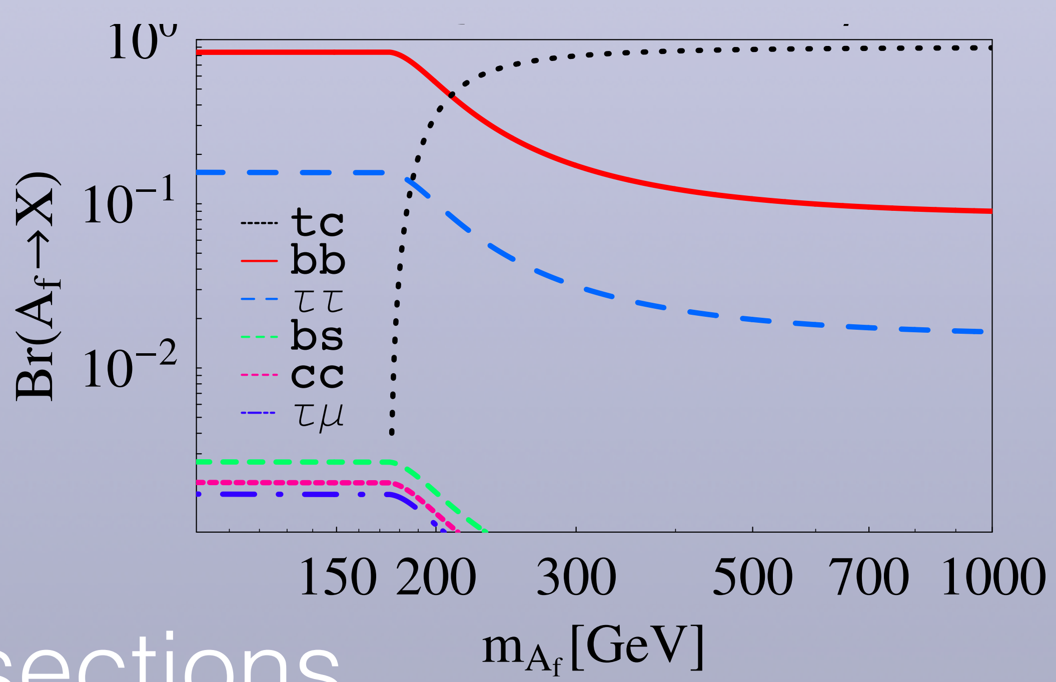


14 Tev

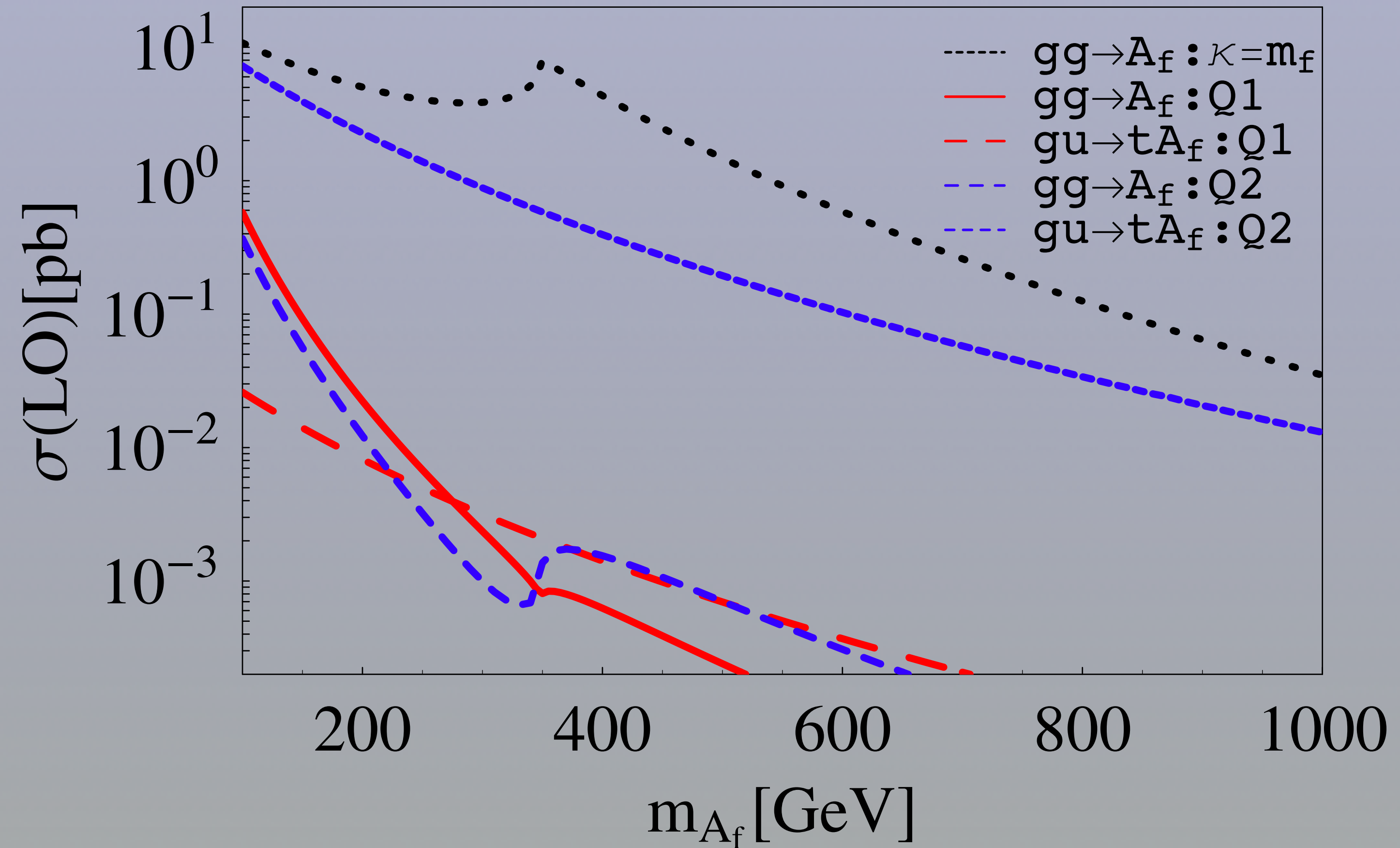
100 Tev

Signatures

- Flavon decays



- Typical production cross sections



Family Dependent Higgs bosons at Colliders

$$-\mathcal{L}_{\mathrm{H}} = \sum_{k=1,3,5} \overline{\psi}_{Li} D_{Rj} H_k + \sum_{k=2,4,6} \overline{\psi}_{Li} U_{Rj} H_k + \mathrm{H.c.},$$

- Non-supersymmetric: Need Z_2 symmetries to forbid arbitrary couplings to D and U quarks

- Supersymmetric: Holomorphicity in the superpotential determines the way they couple: only 3 Higgs doublets couple to D, and 3 different ones to U

$$W(H_k) = \sum_{k=1,3,5} \overline{\psi}_{Li} D_{Rj} H_k + \sum_{k=2,4,6} \overline{\psi}_{Li} U_{Rj} H_k \mathrm{H.c.},$$

0512046, Munoz et.al, 1709. xxx L. V-S.

- The soft potential is given by

$$V_{\rm soft} = \sum_{i,j=1,3,5} (m_d^2)_{ij}\, H_i^\dagger\, H_j + \sum_{k,l=2,4,6} (m_u^2)_{kl}\, H_k^\dagger\, H_l - \sum_{\substack{i=1,3,5\\ l=2,4,6}} \left[(B\mu)_{il}\, H_i\, H_l + {\rm H.c.}\right] .$$

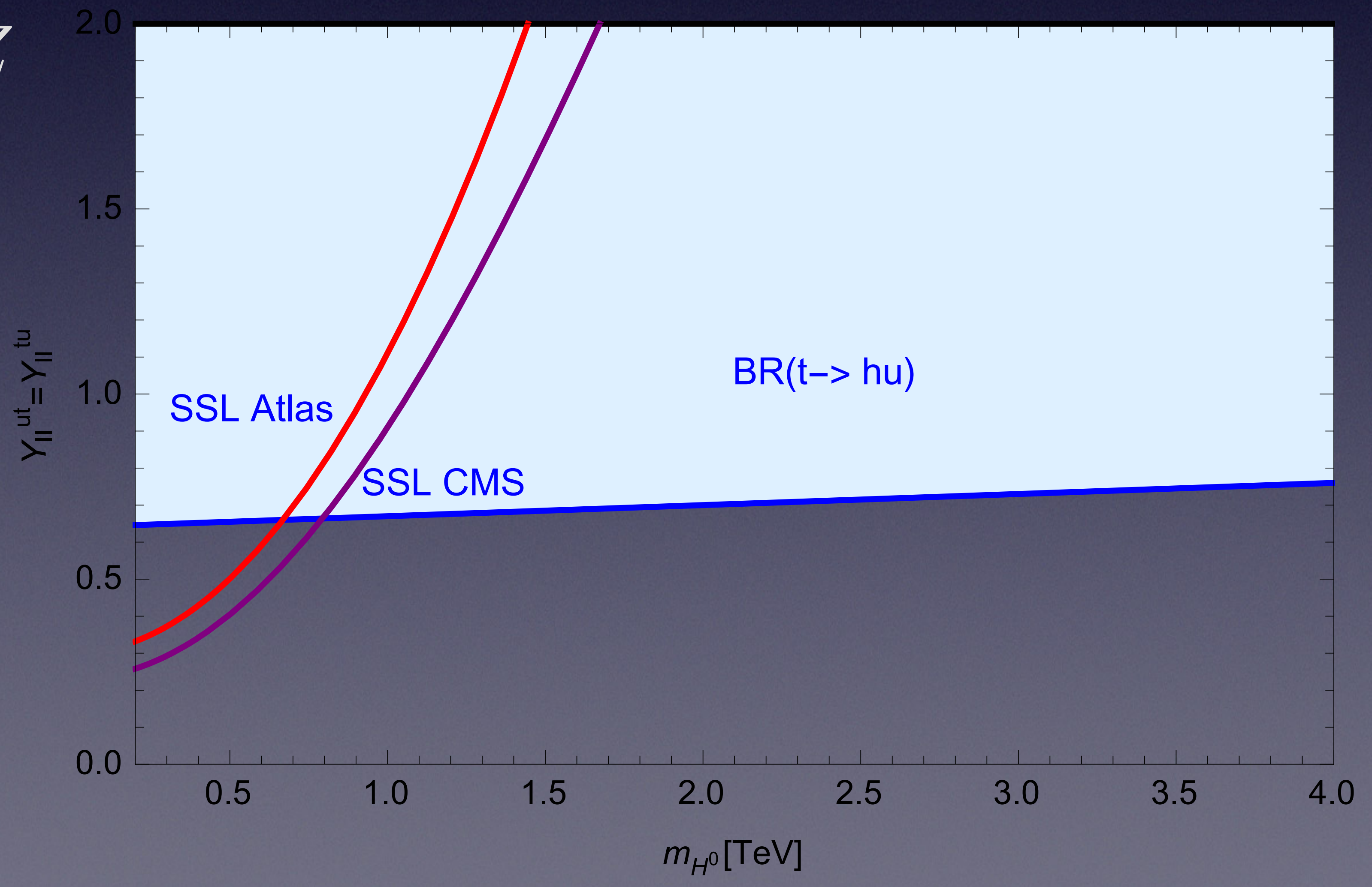
- Symmetries force the following alignment

$$Y_I = \begin{pmatrix} 0 & 0 & 0 \\ 0 & O(1) & O(1) \\ 0 & O(1) & O(1) \end{pmatrix},\ Y_{II} = \begin{pmatrix} O(1) & O(1) & O(1) \\ O(1) & O(1) & O(1) \\ O(1) & O(1) & O(1) \end{pmatrix},\ Y_{III} = \begin{pmatrix} O(1) & O(1) & O(1) \\ O(1) & 0 & 0 \\ O(1) & 0 & 0 \end{pmatrix}$$

Most important constraints

- Top decay $\mathrm{BR}\,(\mathrm{t} \to \mathrm{hu})$
- Same-sign di-lepton (SSL) + b jet searches

$H^0 \to WW, ZZ$



Summary

- Family dependent Higgs Bosons and/or flavons can give an explanation to CKM matrix and values of fermions masses

- Interesting phenomenology

- Good prospects of test/exclusion at Colliders

Field	Decay	Production	FCNC: Most constraining?	Precision to be discriminated
φ_k Flavon	✓	✓	✓ (From top decays)	O(1%)
H_K Heavy extra Higgs	✓	×	✓ (From top decays)	O(1%)

TABLE I: Processes which can be tested at Colliders.