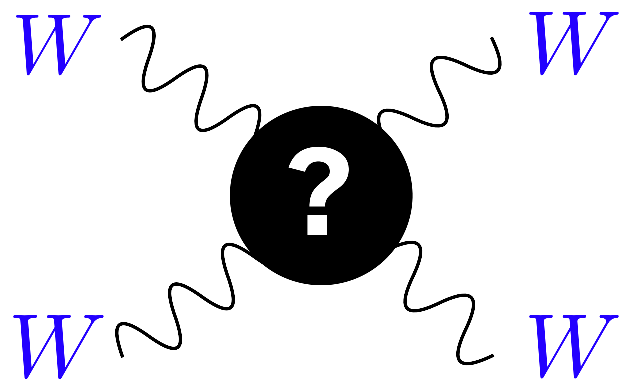
Higgs and co.

Alex Pomarol (Univ. Autonoma Barcelona)

based on work done with J.Mrazek, R.Rattazzi, M.Redi, J.Serra and A.Wulzer, in preparation...

(also Gripaios, AP, Riva, Serra arXiv:0902.1483)

First LHC Mission:



Who is the moderator
of $W_L W_L$-scattering amplitudes?

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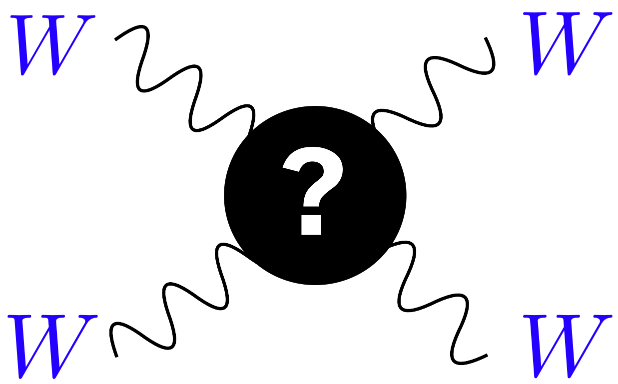

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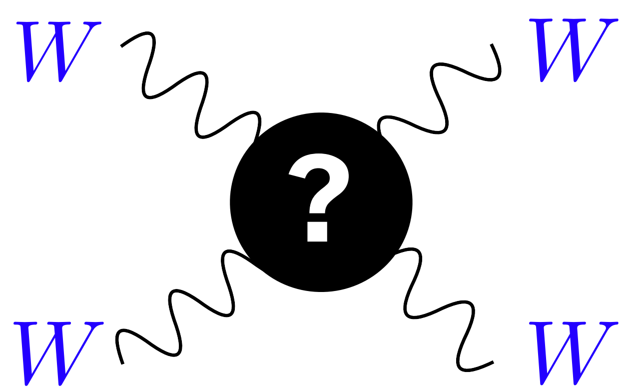

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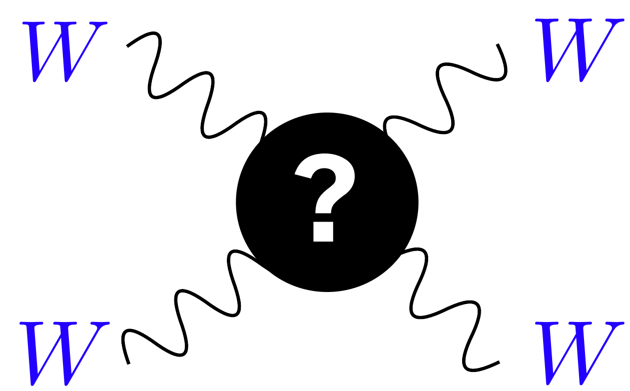

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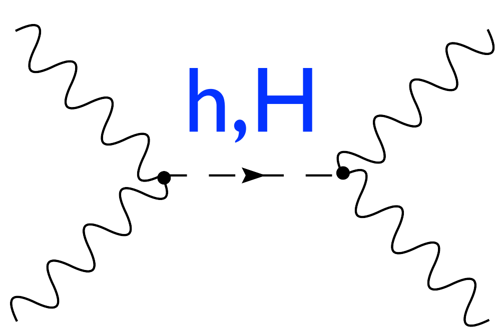
Susy option

MSSM: Extra weakly coupled scalars:
h, H, A, H^+



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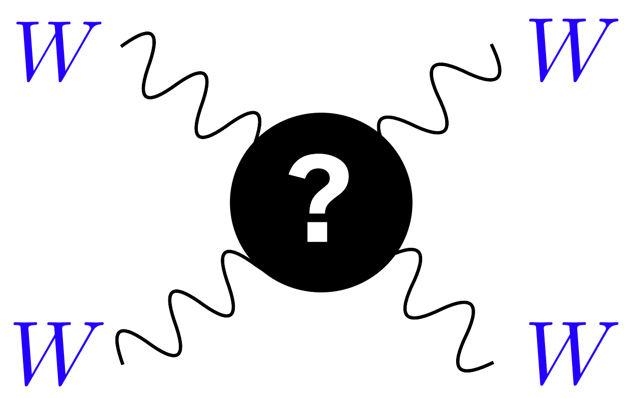

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Composite option (TC, Warped Extra Dim)

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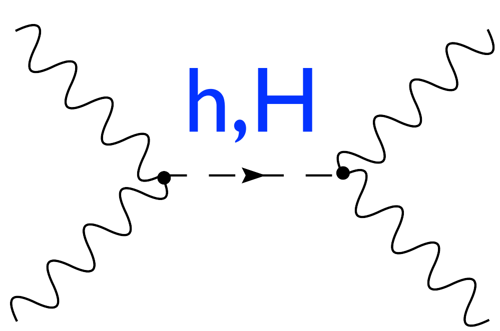
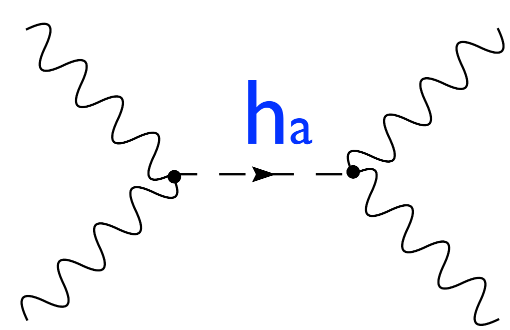


Composite Higgs: Strongly-Interacting Scalars



Not fully unitarizing

↓

Not true Higgses

Susy Option: Higgs sector of the MSSM and variations (NMSSM, CMSSM, nuMSSM, λ-MSSM, S-MSSM, ...)

➡ Fully explored

Composite Option: Higgs sector not yet fully explored:

In the "Higgs Hunter's Guide" only one page out of 400

➡ Purpose of this talk

Outline

1) Higgs content and properties in composite scenarios

2) Pheno constraints:
- EWPT
- FCNC

3) Collider implications

Composite Higgs idea

Higgs arising as Pseudo-Goldstone Bosons (PGB) from the breaking of global symmetry of a strong sector (or WED):

$$G \to H$$

Higgs (h) and company = PGB = coset G/H

From the strong sector (or WED): $V(h)=0$ $(h \to h+\alpha)$

Explicit breaking from SM fields: $V(h/f) \neq 0$ at the loop level

➥ $\langle h \rangle \sim f$ (PGB-decay constant)

As we will see, $f \sim 500$ GeV → Higgs masses 100-300 GeV

This is not the little-Higgs approach!

Requirements for the group G and H:

a) H must contain the SM gauge group

b) G must contain an SU(2)xSU(2) ~ SO(4) symmetry under which a PGB is a Higgs doublet is a (2,2) ~ 4

P.Sikivie, L.Susskind, M.B.Voloshin, V.I.Zakharov

$$H = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v \end{pmatrix}$$

} SO(3) unbroken subgroup: "Custodial" symmetry

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We could know more on G and H if we know the elementary states of the strong sector

e.g. For a strong SU(N) sector:

Minimal fund. fermion content: 4 (Ψ_L, Ψ_R) then G=SU(4)xSU(4) → H=SU(4)

But we are not yet able to know a strong sector that successfully explains all EWSB masses

→ We must a take a more modest approach and explore the different possibilities fulfilling (a) and (b)

Possible symmetry patterns:

G	H	PGB
SO(5)	SO(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
	SO(4)xSO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...

times $SU(3)_c \times U(1)$ of SM

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one doublet

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One doublet + Singlet

times $SU(3)_c$ x U(1) of SM

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→ Two doublets

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Two doublets

times $SU(3)_c \times U(1)$ of SM

Good: Scalar (PGB) spectrum fixed by symmetries

Bad: Not clear which G/H should be considered

➡ **Minimality is not a guide**

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Two doublets

Prototype to be studied here!

times $SU(3)_c \times U(1)$ of SM

Good: Scalar (PGB) spectrum fixed by symmetries

Bad: Not clear which G/H should be considered

➡ **Minimality is not a guide**

Bosonic Part:

Although the dynamics of the strong sector can be unknown, the low-energy effective lagrangian for PGB Higgses can be determined by symmetries (as chiral lagrangian for pions physics).

Lowest dim operator:

$$\frac{f^2}{8}\,\mathrm{Tr}\,|D_\mu \Sigma|^2$$

$$e^{iT_a h_a}$$ G/H coset

By expanding around the EWSB minimum, gives Higgs self-couplings and couplings to gauge bosons

SO(6)/SO(5) model: Doublet h + Singlet η

$$\frac{f^2}{8}\,\mathrm{Tr}|D_\mu\Sigma|^2 = \frac{f^2}{2}(\partial_\mu h)^2 + \frac{f^2}{2}(\partial_\mu \eta)^2 + \frac{f^2}{2}\frac{(h\partial_\mu h + \eta\partial_\mu \eta)^2}{1 - h^2 - \eta^2}$$

$$+\frac{g^2 f^2}{4}h^2\left[W^{\mu +}W^-_\mu + \frac{1}{2\cos^2\theta_W}Z^\mu Z_\mu\right]$$

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$h\eta\eta$ coupling:

$$-\frac{f^2\langle h\rangle}{2}\eta^2\partial^2_\mu h$$

can induce the decay $h \to \eta\eta$

Fixed by symmetries !!

SO(6)/[SO(4)xSO(2)] model: 2 Doublets: $H_{1,2}$
(spectrum: h, H, A, H^+)

$$\frac{f^2}{8}\mathrm{Tr}|D_\mu\Sigma|^2 = \ \cdots\ - \frac{g^2}{24}\left[|W_\mu|^2 + \frac{Z_\mu^2}{2\cos^2\theta_W}\right][(h^2+H^2)^2 + A^4] - \frac{g^2 Z_\mu^2}{8\cos^2\theta_W}h^2A^2$$

$$-\frac{gZ^\mu}{6\cos\theta_W}h^2 H\partial_\mu A + \ \cdots$$

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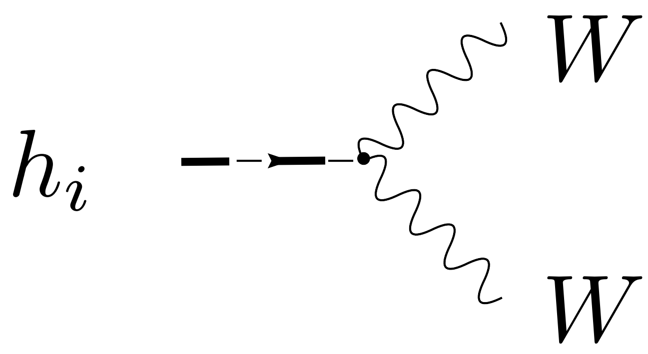
New couplings or deviations on renormalizable couplings of THDM of order $(v/f)^2 \sim 0.2$

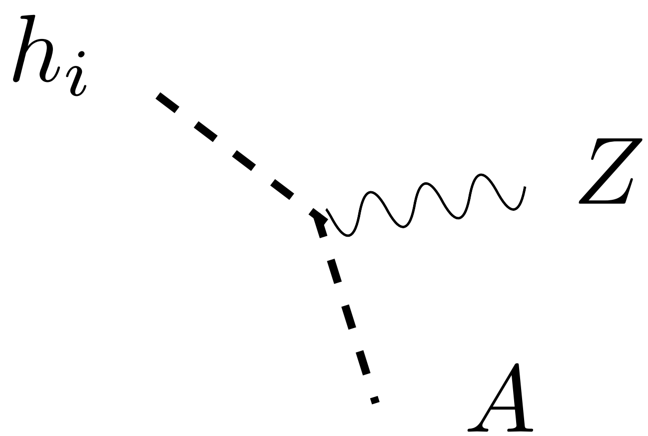
breaking of custodial symmetry if A gets VEV

Changes in the Higgs-coupling sum rules

In renormalizable THDM:



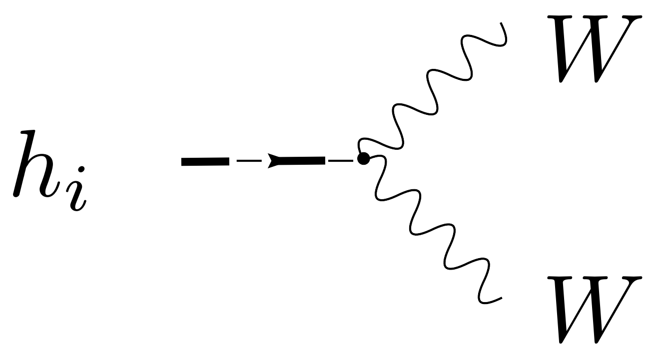
$$\sum_i g^2_{h_i WW} = g^2 m_W^2$$



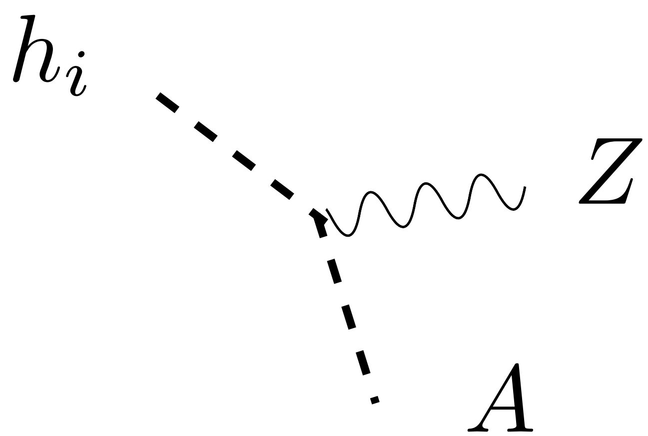
$$\sum_i g^2_{h_i AZ} = \frac{g}{\cos\theta_W}$$

Changes in the Higgs-coupling sum rules

In PGB Higgs:



$$\sum_i g^2_{h_i WW} = g^2 m^2_W \left(1 - \frac{2}{3}\frac{v^2}{f^2}\right)$$



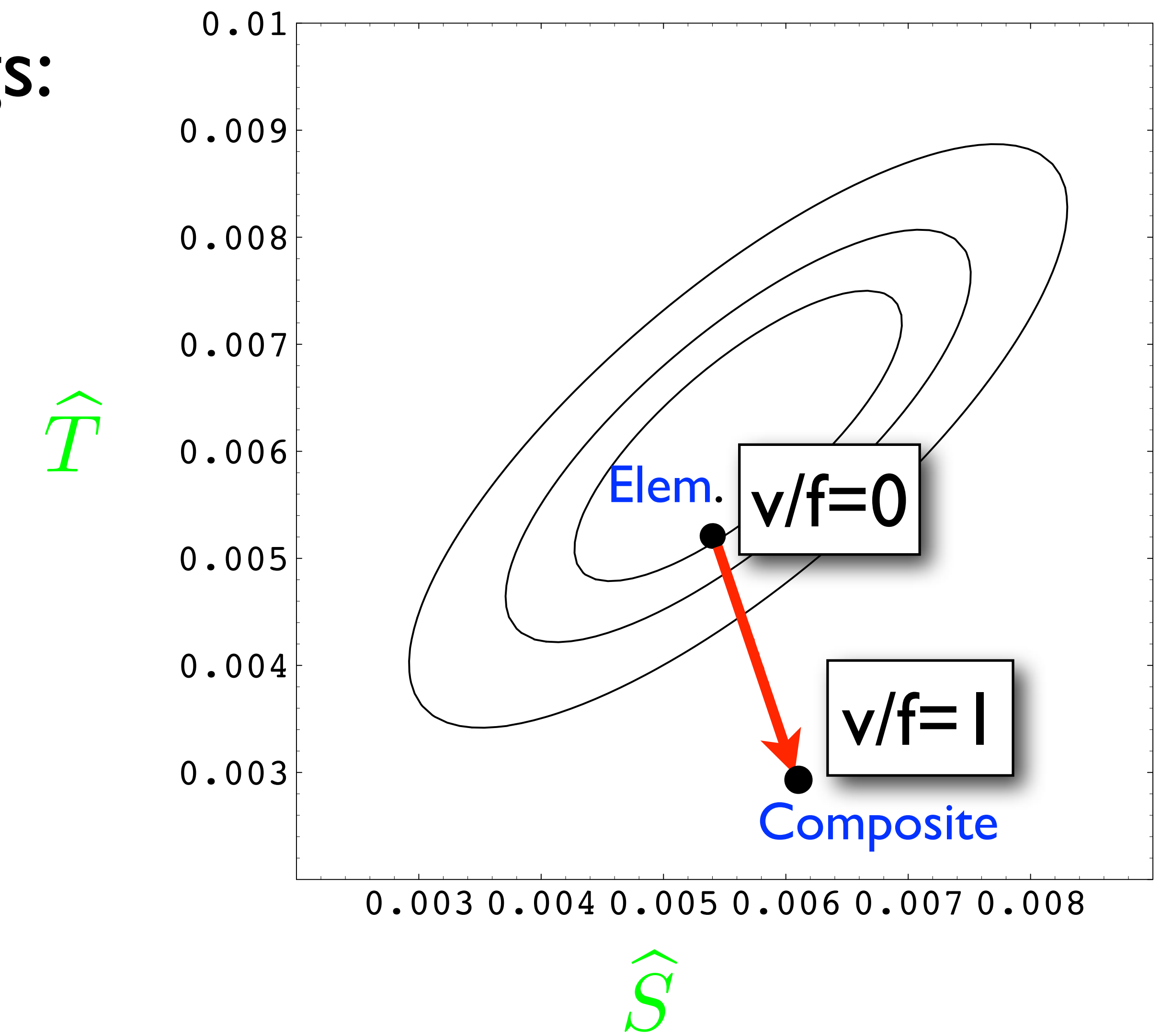
$$\sum_i g^2_{h_i AZ} = \frac{g}{\cos\theta_W}\left(1 - \frac{1}{6}\frac{v^2}{f^2}\right)$$

Possible 20% corrections!

Electroweak Precision Tests

Facing the S and T parameters bounds:

For a single composite Higgs:

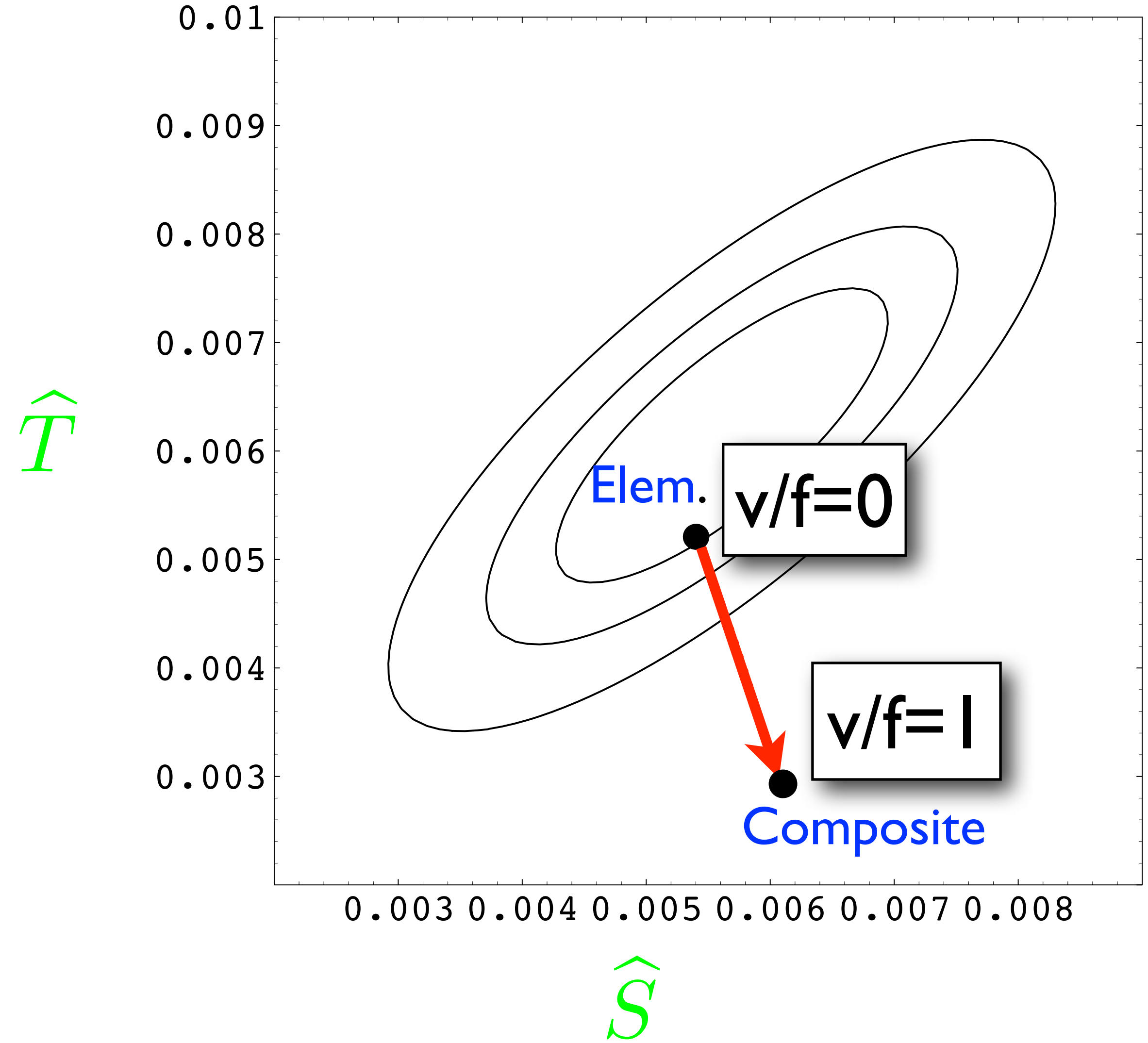


$\Rightarrow$ f>500 GeV

Facing the S and T parameters bounds:

If more than a doublet (or triplet), custodial symmetry must be kept after EWSB:

$$H_1 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix} \Bigg\} \text{ SO(3) unbroken subgroup } \Bigg\{ \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_2 \end{pmatrix} = H_2$$



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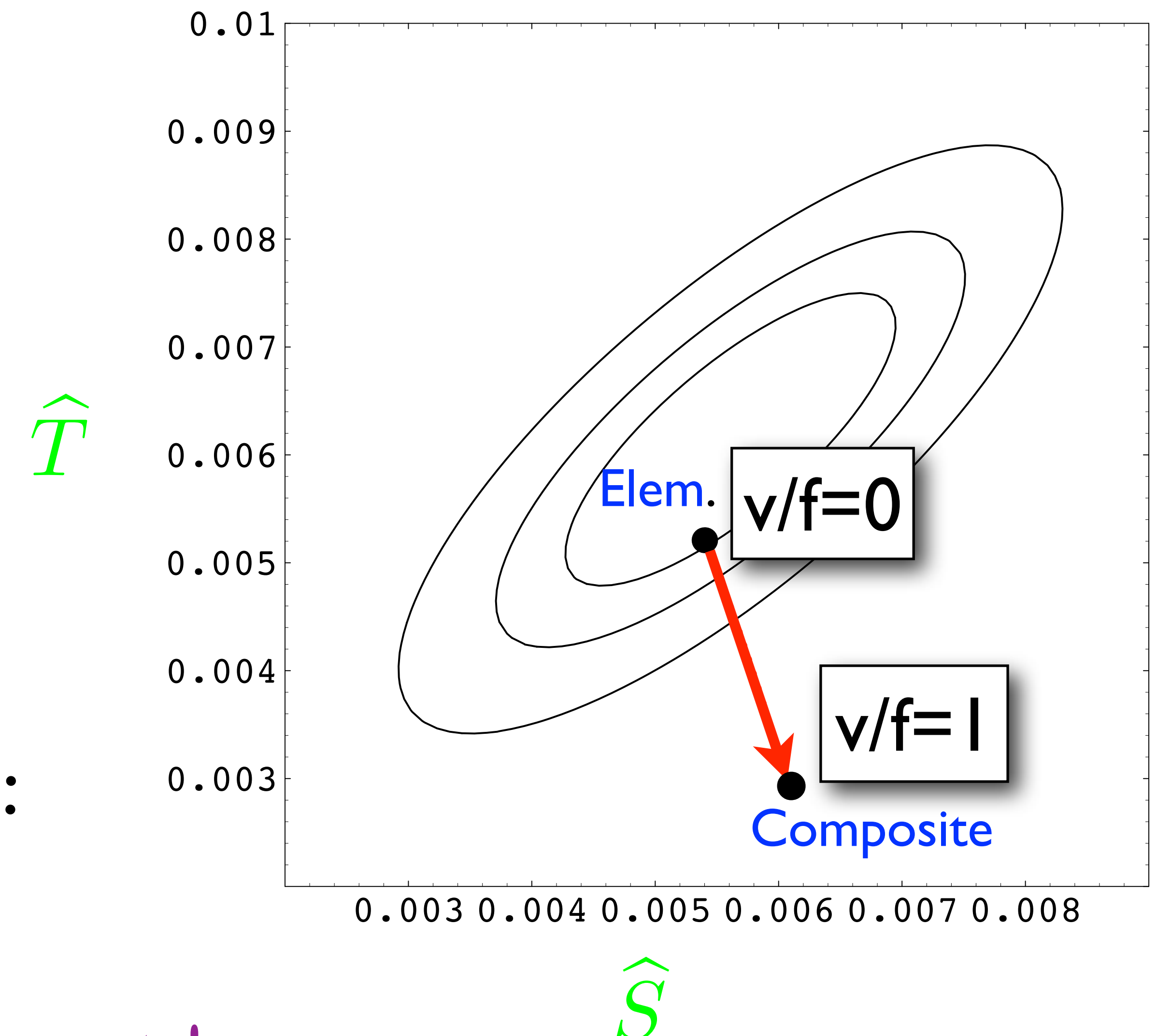

Can be guaranteed by discrete symmetries:

P_A : $H_1 \to H_1$, $H_2 \to -H_2$

CP: $H_i \to H_i^\dagger$

Symmetries of the cosets!

➟ see talk of J. Serra

FCNC

SM Fermion couplings to PGBs (Strong sector or WED):

Defined by choosing the SM fermion embedding in reps of G:

$$\left.\begin{array}{r} q_L \in Q \\ u_R \in U \end{array}\right\} \text{reps of G}$$

➠ spurions (or bulk fermions)

and write G-invariant mass terms:

$$\lambda_{ij}\ \bar{Q}_i \Sigma(h_a) U_j$$

→ see example...

EXAMPLE: G=SO(6) → H=SO(4)xSO(2)

Σ = coset SO(6)/SO(4)xSO(2) $\in$ 20

Fermions, for example, in the 6 of SO(6):

$$\mathbf{6} = \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \end{pmatrix} \begin{matrix} \left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} \text{SU(2)}_L \text{ doublet} \\ \left.\begin{matrix} \\ \\ \end{matrix}\right\} \text{two SU(2)}_L \text{ singlets} \end{matrix}$$

allows for the embedding:

$$q_L \in Q = \begin{pmatrix} q_L \\ \cdot \\ \cdot \end{pmatrix} \qquad u_R \in U = \cos\theta_u \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ \cdot \\ u_R \\ \cdot \end{pmatrix} + e^{i\alpha_u} \sin\theta_u \begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ u_R \end{pmatrix}$$

in WED this is determined by the bound. conditions

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two parameters (per fermion) [α_u, θ_u]

in WED this is determined by the bound. conditions

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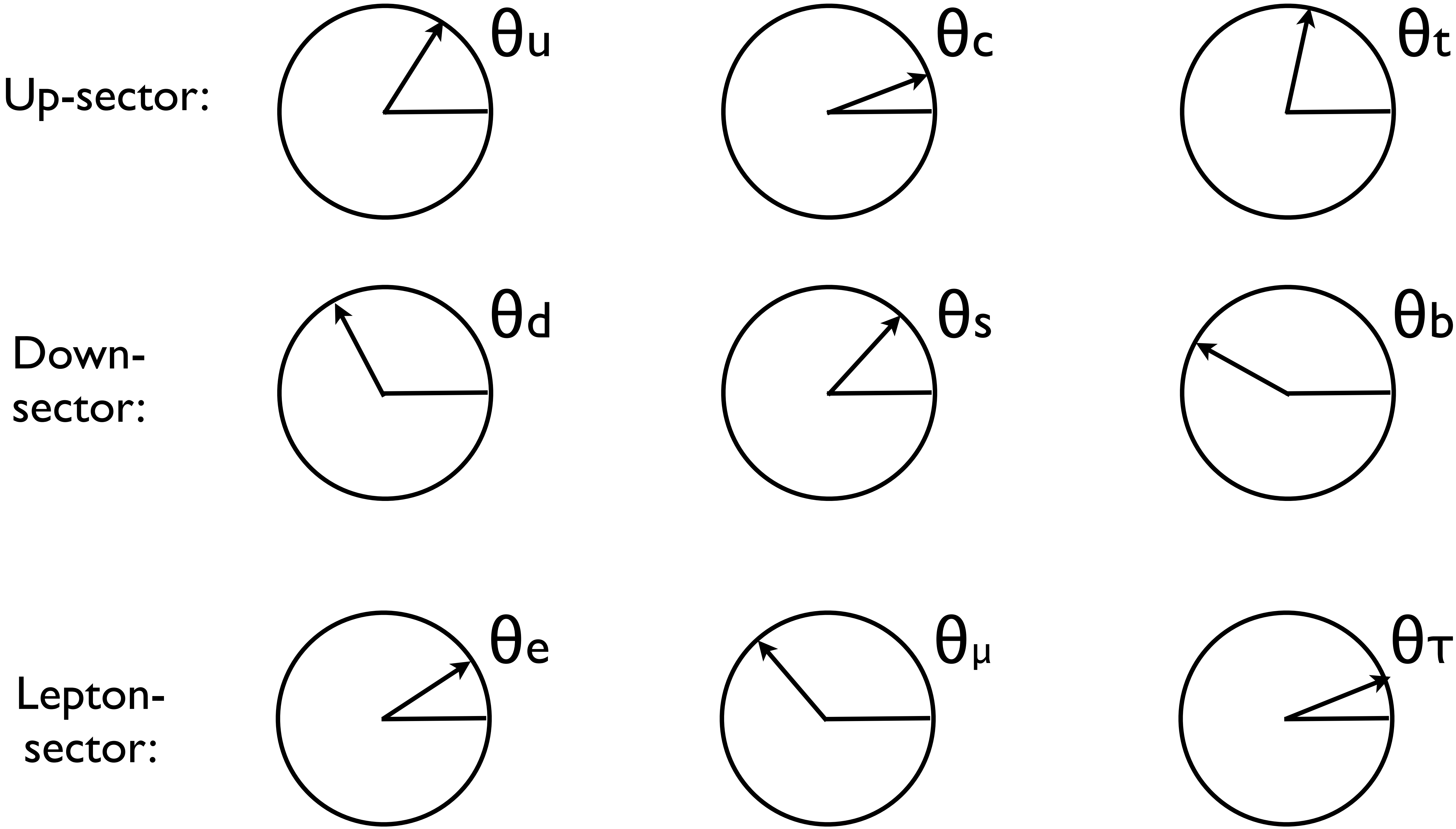
If only one operator QΣU possible, tree-level FCNC depends only on θ_u

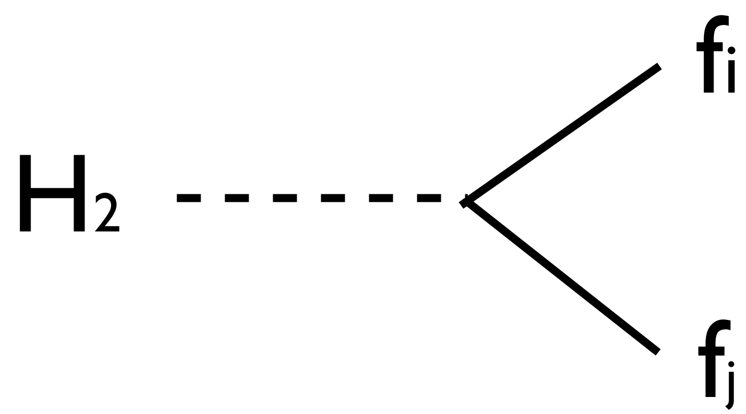
Flavor dependent case:



... and similarly for the CP-phases α_i

FCNC constraints:

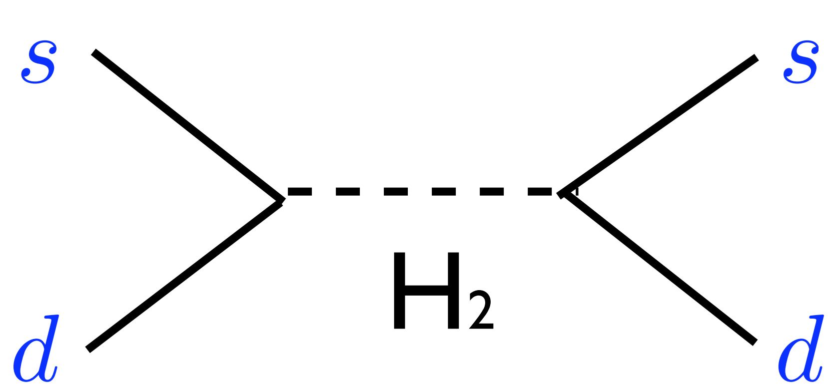
(for simplicity $\langle h_2 \rangle = 0$)



$$\propto m_{f_i} \sum_k U_{R\,ik}\, e^{i\alpha_k} \tan\theta_k\, U^\dagger_{R\,kj}$$

Main effect: ε_K

(for $U_R \sim V_{CKM}$)



$$\propto \frac{m_s^2 V_{us}^2}{m_{h_2}^2} [e^{i\alpha_s} \tan\theta_s - e^{i\alpha_d} \tan\theta_d]^2$$

$$\Rightarrow \; m_{h_2} \gtrsim 2\ TeV$$

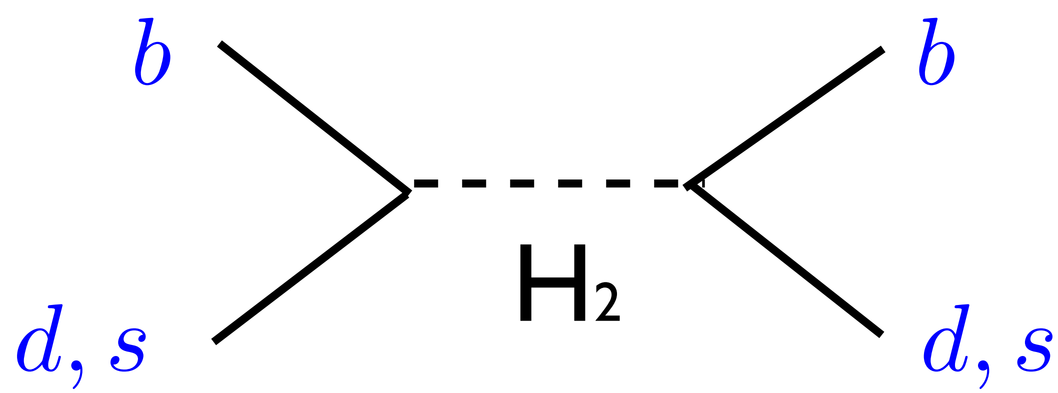
Too large!

$\theta_d \sim \theta_s$ needed

Assuming equal embedding for 1st and 2nd family

→ 3rd family FCNC

Main contribution to ΔM_B



Saturates experimental bounds for B_d and B_s for:

$U_R \sim V_{CKM}$

$\tan \theta_b \sim 3$

Higgs masses ~ 200 GeV

→ expected impact in CP-violation: β_d , β_s and $B \to \mu\mu$

Flavor independent case

1) Only one operator QΣU possible
2) Equal embedding for all families

⇒ No tree-level FCNC

parameters: θ_u, θ_d, θ_e and α_u, α_d, α_e

➠ MFV with extra phases

Flavor transitions from loops of H^+:

$H^+ d_L u_R$:
$$M_u V_{\rm CKM} \times \frac{e^{i\alpha_u}\tan\theta_u \tan\beta - 1}{\tan\beta + e^{i\alpha_u}\tan\theta_u}$$

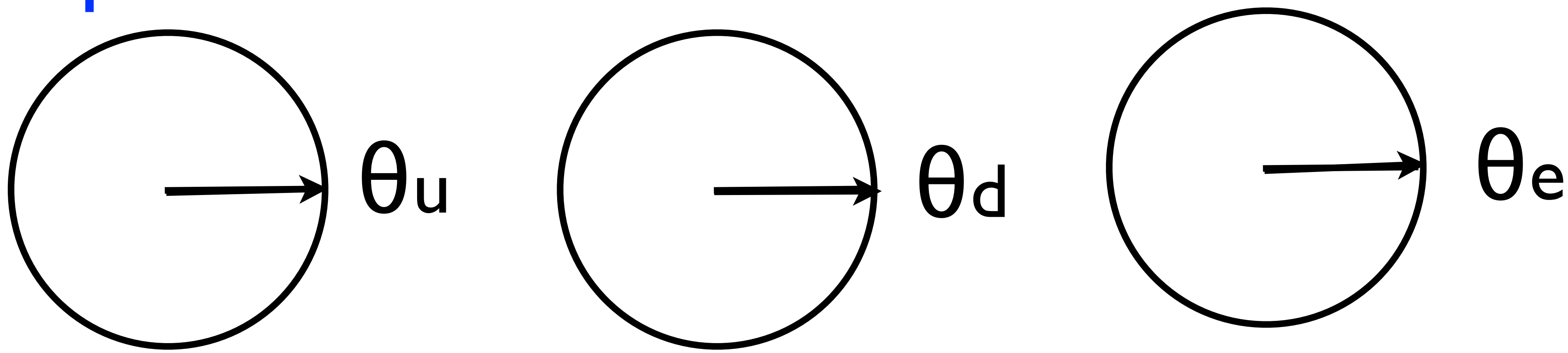
⇒ Expected deviations from SM

in EDMs, CP-violation in $b \to s\gamma$, $B \to \tau\upsilon$

Different from MSSM

Contact with previous THDMs:

Type I:



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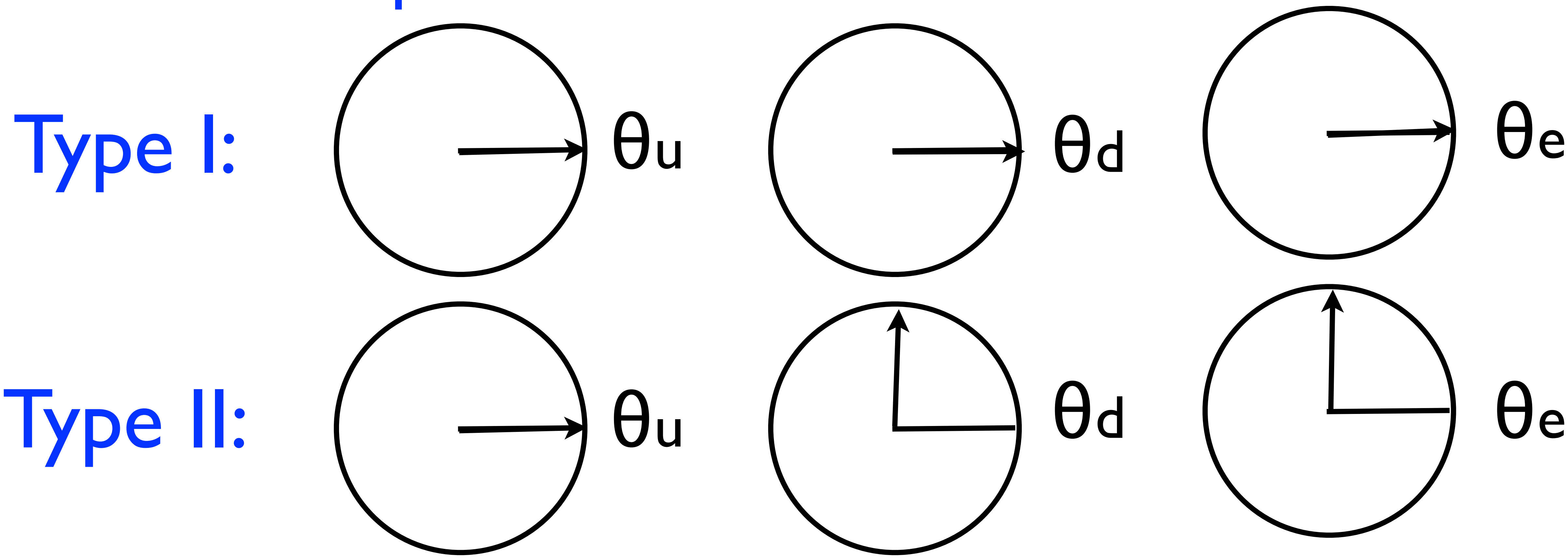

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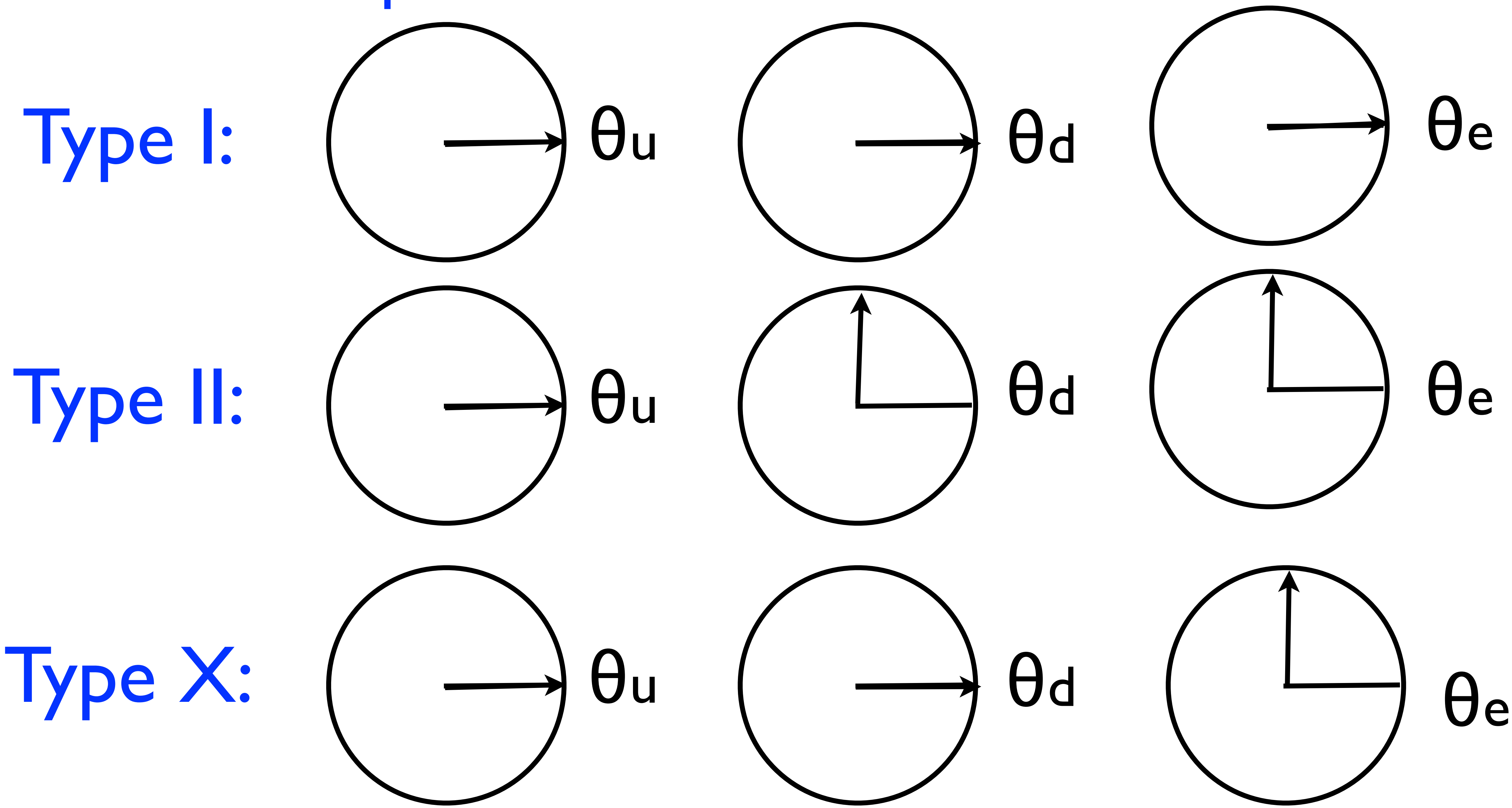

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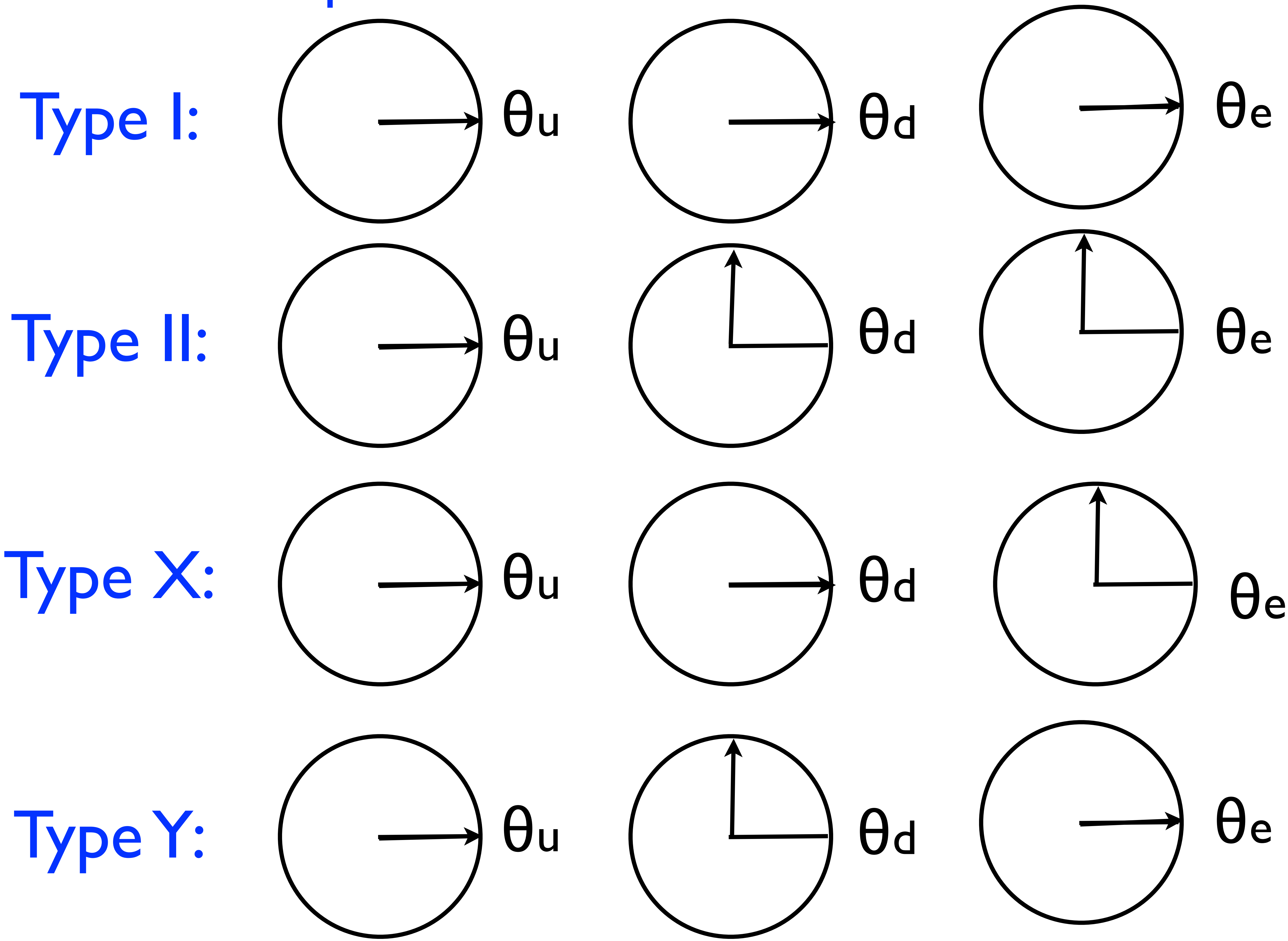


Collider signatures

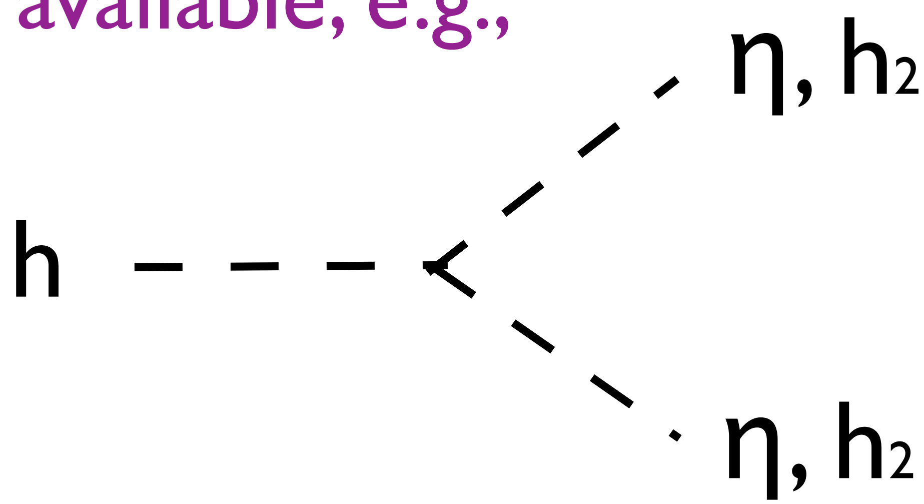
... mostly in progress

• Unraveling composite Higgs nature:
precise measurements needed of Higgs Production Cross Sections x BR

Giudice, Grojean, AP, Rattazzi

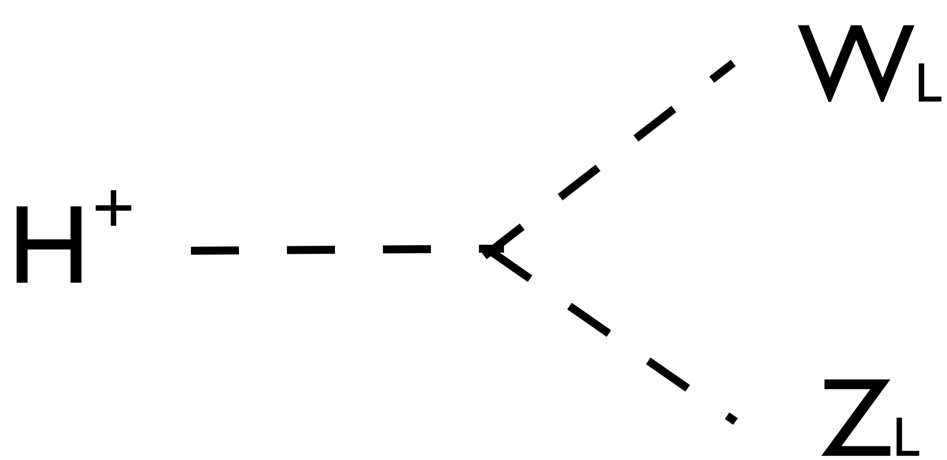
• Extra scalars can make life easier or more difficult:

New decays available, e.g.,



$\sim (p/f)^2$

Fixed by symmetry:
the G/H coset

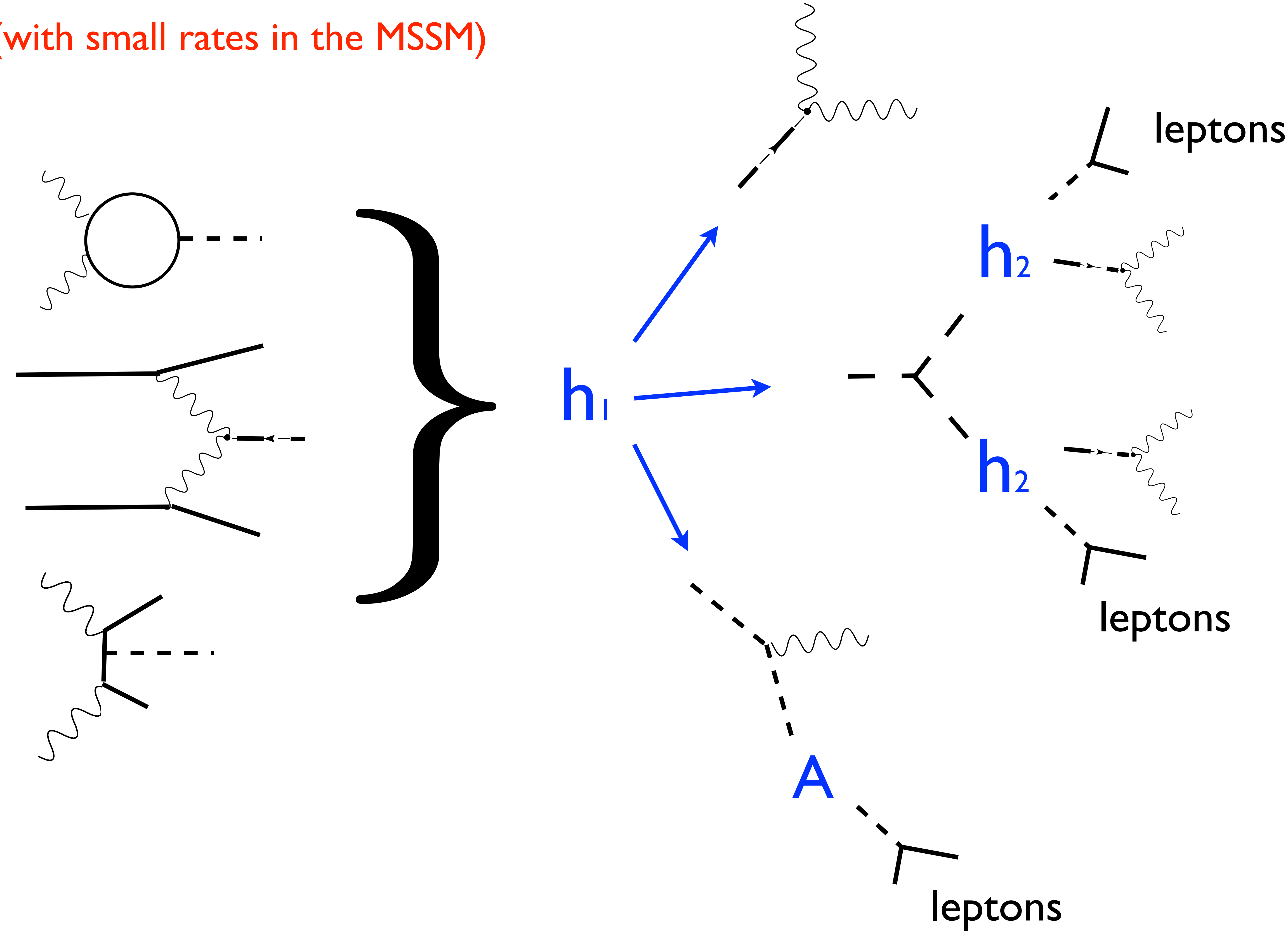


Unfortunately, protected
by the custodial symmetry

Induced at the one loop-level
but with a bigger size than in the MSSM

Easiest signatures:

(with small rates in the MSSM)



Charged Higgs:

a) Light H^+: $pp \to t\bar{t}$

$t \to H^+ b$

$H^+ \to \tau\upsilon$

b) Heavy H^+: $gb \to tH^-$

1) $H^- \to Zh$

$h \to ZZ$

2) $H^- \to WZ$ if sizable

Conclusions

- If the hierarchy problem is solved by a strong dynamics (or WED), rich phenomenology of Pseudo-Goldstone Bosons expected
- Higgs spectrum and gauge-boson couplings fixed by G/H
- Rich FCNC phenomenology: Important B-physics impact
- It provides a (motivated) framework for multi-Higgs physics