Heavy quarks within the electroweak multiplet

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R. Romero and J. Besprosvany, "Quark horizontal flavor hierarchy and two-Higgs- doublet model in a (7+1)-dimensional extended spin space ", submitted to *Phys. Rev. D* arXiv:1611.07446[hep-ph].

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Plan

- Motivation: multiplet structure. Standard-model puzzle: independent scalar-vector, Yukawa sectors.
- 1) Beyond the standard model (SM)

Spin-extended model, (7+1)-dimensional chiral states and operators.

- 2) SM projection

Top-quark mass from SM. Scalar-field uniqueness: electroweak scalar-vector and Yukawa scalar-fermion term comparison.Quark-mass relation.

- 3) Collider physics

Chiral-scalar signature: type II two-Higgs models.

Motivation: multiplet structure

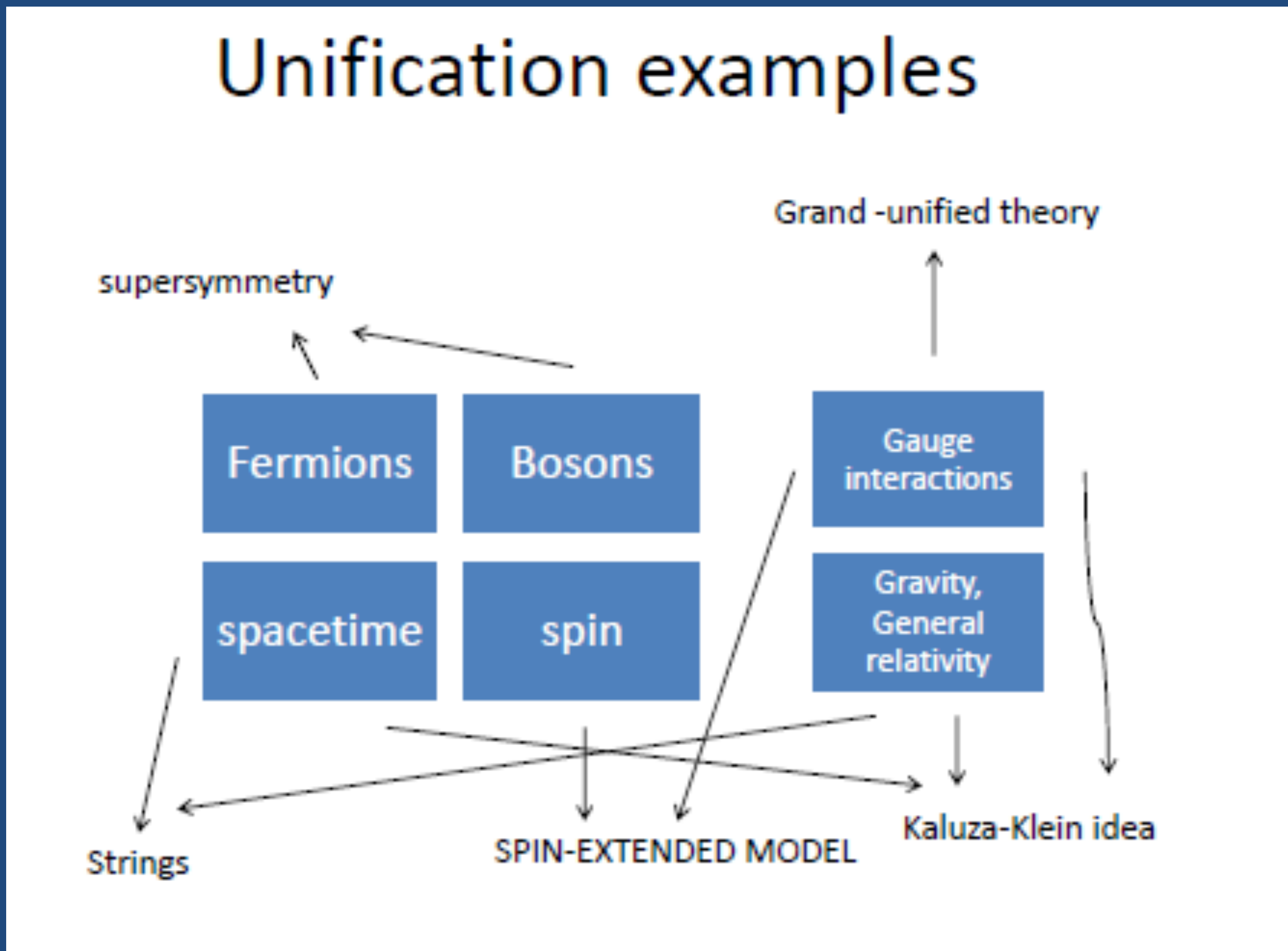
Electroweak-related puzzles in the standard model:

- Fermion-mass parameters; Yukawa sector independent of scalar-vector.
- Origin of electroweak symmetry breaking (Higgs mechanism).

	Masses (GeV)	Spin	Weak I^2	Hypercharge Y
• $W^{+/-}$	80.4	1	1	0
• Z	91.2	1	0	0
• H	126	0	½	1
• t	173	½	½ ,0	1/3, 4/3
• b	4	½	½ ,0	1/3, -2/3

Composite-multiplet structure suggested

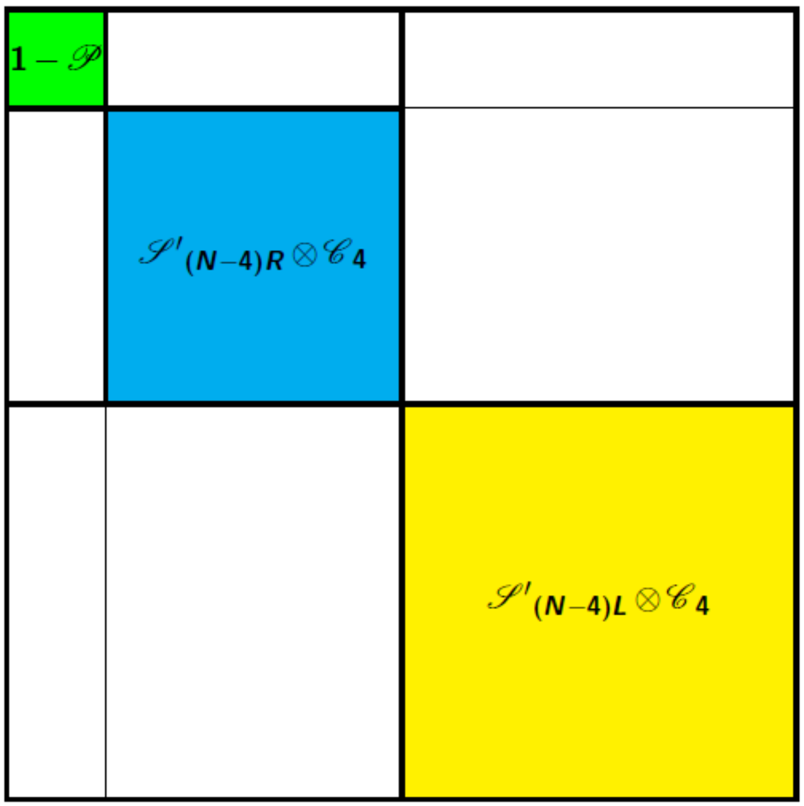
Spin-extended model within standard-model extensions



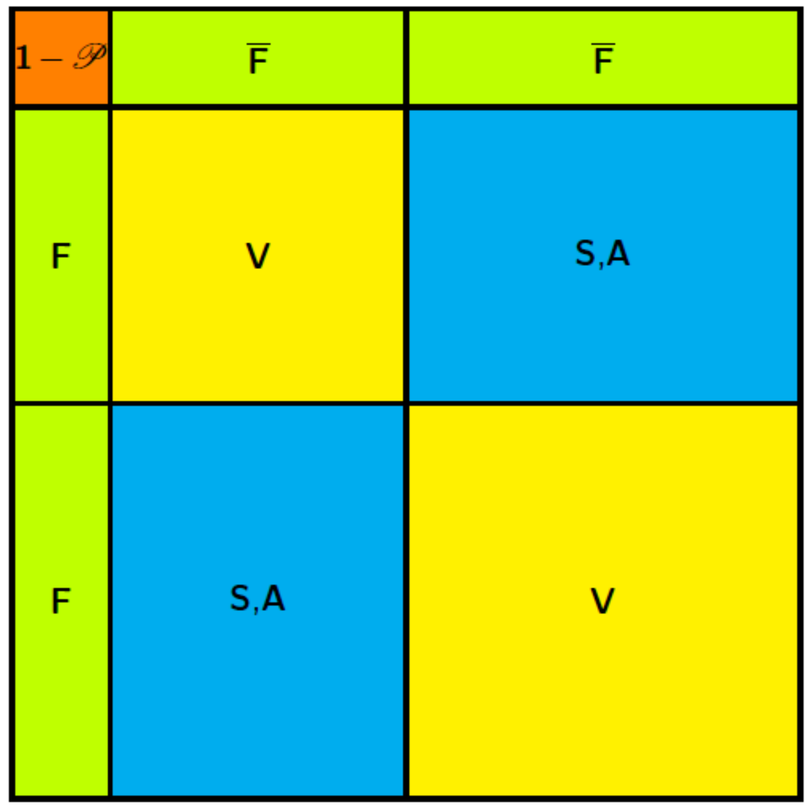
Spin-space structure, at each dimension

- Finite number of partitions at each *d*, consistent with Lorentz symmetry
- Operators: gauge and flavor (only act on fermions)
- States: fermions and bosons
- Chiral components

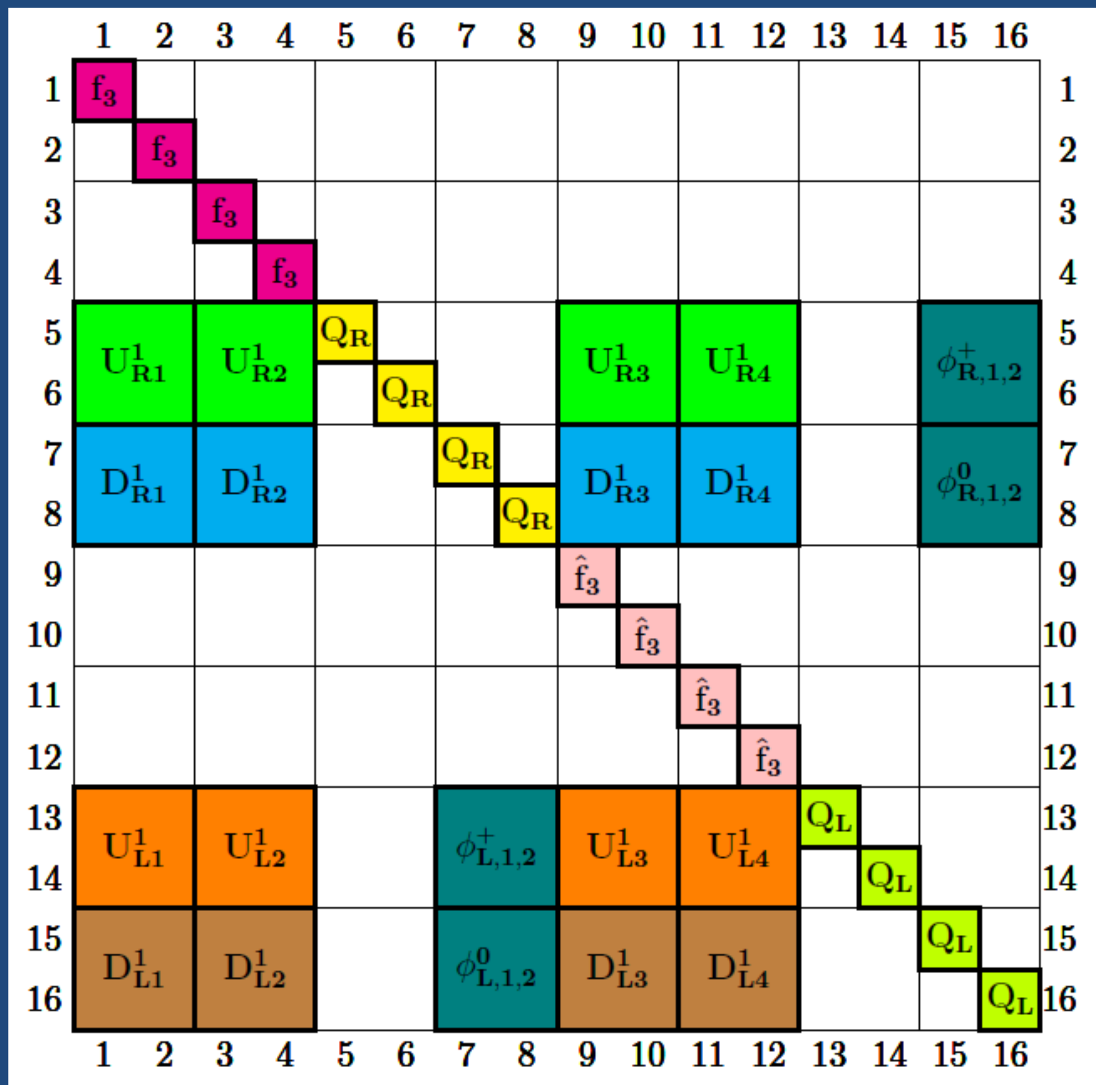
Operators



States



States in (7+1)-dimensional space



Use of conventional and spin bases

spin basis → conventional basis

- Finite number of possible partitions, consistent with 4-d Lorentz symmetry.
- Constrain representations and interactions at given dimension.

spin basis ← conventional basis

Reinterpretation of fields:

- Standard-model projection.
- SV: scalar operator acting over vectors
- SF: scalar operator acting over fermions

Conventional and spin-extended bases, Lagrangian equivalence: fermion-vector

conventional basis — spin-extended basis

Field formulation: $A_\mu(x) = g_\mu{}^\nu A_\nu(x)$ — $A_\mu(x)\gamma_0\gamma^\mu$

$$\mathcal{L}_{FV} = \bar{\mathrm{q}}_L(x)[i\partial_\mu + \frac{1}{2}g\tau^a W^a_\mu(x) + \frac{1}{6}g' B_\mu(x)]\gamma^\mu \mathrm{q}_L(x) +$$
$$\bar{t}_R(x)[i\partial_\mu + \frac{2}{3}g' B_\mu(x)]\gamma^\mu t_R(x) + \bar{b}_R(x)[i\partial_\mu - \frac{1}{3}g' B_\mu(x)]\gamma^\mu b_R(x)$$

$$\mathrm{q}_L(x) = \begin{pmatrix} t_L(x) \\ b_L(x) \end{pmatrix}$$

$$t_L(x) = \begin{pmatrix} \psi^1_{tL}(x) \\ \psi^2_{tL}(x) \end{pmatrix}$$

$$\mathcal{L}_{FV} = \mathrm{tr}\{\Psi^\dagger_{qL}(x)[i\partial_\mu + gI^a W^a_\mu(x) + \frac{1}{2}g' Y_o B_\mu(x)]\gamma^0\gamma^\mu \Psi_{qL}(x) +$$
$$\Psi^\dagger_{tR}(x)[i\partial_\mu + \frac{1}{2}g' Y_o B_\mu(x)]\gamma^0\gamma^\mu \Psi_{tR}(x) + \Psi^\dagger_{bR}(x)[i\partial_\mu + \frac{1}{2}g' Y_o B_\mu(x)]\gamma^0\gamma^\mu \Psi_{bR}(x)\}P_f$$

$$\Psi_{qL}(x) = \sum_\alpha \psi^\alpha_{tL}(x) T^\alpha_L + \psi^\alpha_{bL}(x) B^\alpha_L$$

SV Lagrangian and scalar t-b spin representation

Scalar correspondence

$$\mathbf{H}(\mathrm{x}) \to \phi_1(x) - \phi_2(x)$$

$$\tilde{\mathbf{H}}^\dagger(x) \to \phi_1(x) + \phi_2(x).$$

$$\mathbf{H}_t(x) = \phi_1(x) + \phi_2(x),\ \mathbf{H}_b(x) = \phi_1(x) - \phi_2(x)$$

$$R_5 = \tfrac{1}{2}(1+\tilde{\gamma}_5),\ \text{e. g.},\ R_5\mathbf{H}_t(x)L_5 = \mathbf{H}_t(x)$$

$$L_5\mathbf{H}_t(x)R_5 = 0,\ R_5\mathbf{H}_b(x)L_5 = 0$$

$$\mathbf{H}_{af}(x) = a\phi_1(x) + f\phi_2(x)$$

$$\mathbf{H}_{af}(x) = \frac{1}{\sqrt{2}}(\chi_t\mathbf{H}_t(x) + \chi_b\mathbf{H}_b(x))$$

$$\chi_t = \frac{1}{\sqrt{2}}(a+f),\ \chi_b = \frac{1}{\sqrt{2}}(a-f)$$

SV spin representation

$$\mathbf{F}''(x) = [i\partial_\mu + gW_\mu^i(x)I^i + \tfrac{1}{2}g'B_\mu(x)Y_o]\gamma_0\gamma^\mu$$

$$\mathcal{L}_{SV} = \mathrm{tr}\{[\mathbf{F}''(x), \mathbf{H}_{af}(x)]_\pm^\dagger[\mathbf{F}''(x), \mathbf{H}_{af}(x)]_\pm\}_{\mathrm{sym}}$$

Scalar-vector scalar-fermion comparison

$$\langle \eta_3(x)\rangle = v,\ \langle \mathbf{H}(x)\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

scalar-vector symmetry

Z-vector mass

Higgs mechanism

$$\langle \mathbf{H}_{af}(x)\rangle = H_n = \frac{v}{2}(\chi_t H_t^0 + \chi_b H_b^0),$$

$$\begin{aligned}\mathcal{L}_{SZm0} &= \mathrm{tr}[H_n, W_0^3(x) g I^3 + B_0(x)\frac{1}{2}g' Y_o]^\dagger [H_n, W_0^3(x) g I^3 + B_0(x)\frac{1}{2}g' Y_o] \qquad (11)\\ &= Z_0^2(x)\frac{1}{g^2+g'^2}\mathrm{tr}[H_n, g^2 I^3 - \frac{1}{2}g'^2 Y_o]^\dagger [H_n, g^2 I^3 - \frac{1}{2}g'^2 Y_o] = \frac{1}{2}Z_0^2(x) m_Z^2,\end{aligned}$$

Top-quark mass

Higgs mechanism

$$H_m = \langle \mathbf{H}_m(x)\rangle = m_t H_t^0 + m_b H_b^0$$

$$H_m^h T_M^1 = m_t T_M^1, \quad H_m^h T_M^{c1} = -m_t T_M^{c1},$$

$$H_m^h B_M^1 = m_b B_M^1, \quad H_m^h B_M^{c1} = -m_b B_M^{c1}, \qquad (13)$$

where $H_m^h = H_m + H_m^\dagger$, and T_M^{c1}, B_M^{c1} correspond to negative-energy solution states

Spin-space connection: vector and fermion masses

vector

$$m_Z = v\sqrt{g^2 + g'^2}/2$$

fermion

massive quarks	H_m^h	Q	$\frac{3i}{2}B\gamma^1\gamma^2$
$T_M^1 = \frac{1}{\sqrt{2}}(T_L^1 + T_R^1)$	m_t	$2/3$	$1/2$
$B_M^1 = \frac{1}{\sqrt{2}}(B_L^1 - B_R^1)$	m_b	$-1/3$	$1/2$
$T_M^{c1} = \frac{1}{\sqrt{2}}(T_L^1 - T_R^1)$	$-m_t$	$2/3$	$1/2$
$B_M^{c1} = \frac{1}{\sqrt{2}}(B_L^1 + B_R^1)$	$-m_b$	$-1/3$	$1/2$

Table 3: Massive quark eigenstates of H_m^h

$$\sqrt{2}H_n = H_m$$

Correspondence's physical interpretation

- Dynamical: action of scalar on fermion and vector share the same effect: common Hamiltonian H.

$$[H+H^\dagger, F] \quad \text{vs} \quad [H,V]^\dagger [H,V]$$

- Symmetry: e. g., $SU(2)_L xU(1)$ fundamental-adjoint representation connection.

- Compositeness: Standard-model gauge structure. No information on whether this a formal or physical feature.

from gauge invariance. Formally, a boson field $B_o(x)$ expansion may be obtained using $B_o(x) = \sum_{lk} F_l(x)F_k(x) + [B_o(x) - \sum_{lk} F_l(x)F_k(x)]$, where $F_l(x)$, $F_k(x)$ are fermion fields reproducing $B_o(x)$'s quantum numbers, and the last two terms give corrections.

Quark-mass relation

The "punchline:" $|\langle Z|\sqrt{2}H_n|Z\rangle|^2 = m_Z^2$ and $\langle t|H_m + H_m^\dagger|t\rangle = m_t$

$$\sqrt{2}H_n = H_m$$

Higgs mechanism

$$\langle \mathbf{H}_{af}^\dagger(x)\mathbf{H}_{af}(x)\rangle = (|a|^2 + |f|^2)v^2/2 = (|\chi_t|^2 + |\chi_b|^2)v^2/2 = v^2/2$$

$$(|a|^2 + |f|^2)v^2/2 = |m_t|^2 + |m_b|^2 = v^2/2$$

$$m_t = \sqrt{v^2/2 - m_b^2} \simeq 173.90 \text{ GeV}$$

$v = 246$ GeV

$m_b = 4$ GeV

For colliders: 2 chiral Higgs doublet

General two-Higgs doublet produces Yukawa term with flavor changing neutral currents.

Chiral Higgs

$$
\begin{aligned}
\phi_1 &\rightarrow \frac{1}{2}(1+\tilde{\gamma}_5)\gamma^0\phi_1\frac{1}{2}(1-\tilde{\gamma}_5), \\
\phi_2 &\rightarrow \frac{1}{2}(1-\tilde{\gamma}_5)\gamma^0\phi_2\frac{1}{2}(1+\tilde{\gamma}_5), \\
\tilde{\phi}_1 &\rightarrow \frac{1}{2}(1+\tilde{\gamma}_5)\gamma^0\tilde{\phi}_1\frac{1}{2}(1-\tilde{\gamma}_5), \\
\tilde{\phi}_2 &\rightarrow \frac{1}{2}(1-\tilde{\gamma}_5)\gamma^0\tilde{\phi}_2\frac{1}{2}(1+\tilde{\gamma}_5),
\end{aligned}
$$

leads to feasible Type II Yukawa:

Type II 2HDM

$$
\begin{aligned}
\mathcal{L}^{\text{Chiral 2HDM}}_{Yukawa} \supset tr &\left[\sum_{iq} y^{U(2)}_{iq}\Psi^\dagger_{iR}(x)\tilde{\phi}_1\mathbf{\Psi}_{qL}(x)Y^{F(1)}_{iq} + \sum_{jq} y^{D(1)}_{qj}\mathbf{\Psi}^\dagger_{qL}(x)\phi_1\Psi_{jR}(x)Y^{F(1)}_{qj}\right] + hc \\
+tr &\left[\sum_{iq} y^{U(2)}_{iq}\Psi^\dagger_{iR}(x)\tilde{\phi}_2\mathbf{\Psi}_{qL}(x)Y^{F(2)}_{iq} + \sum_{jq} y^{D(1)}_{qj}\mathbf{\Psi}^\dagger_{qL}(x)\phi_2\Psi_{jR}(x)Y^{F(2)}_{qj}\right] + hc
\end{aligned}
$$

Relevant points

- A spin BSM extension constrains SM fields, reproduces the electroweak interaction and its chiral property, generating also chiral scalars.
- In a SM projection, the *same* scalar field within SV and SF terms connects such sectors, and determines the quark mass.
- Chiral 2 Higgs-doublet models lack FCNC, and are therefore still feasible candidates to be detected at colliders.