Heavy quarks within the electroweak multiplet

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J. Besprosvany and R. Romero, “Representation of quantum field theory in an extended spin space and fermion mass hierarchy " *Int. J. Mod. Phys. A* **29**, No. 29 1450144 (17 pp.) (2014), arXiv:1408.4066[hep-th].

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Contents

- Standard model puzzle: independent Yukawa, scalar-vector sectors. Motivation: multiplet structure
- Spin-extended model, context, and features
- Spin space: states and operators; (7+1)-dimensional case; conventional and spin-extended bases' use
- Lagrangian representation of vector-fermion electroweak and scalar-vector terms
- Scalar-field uniqueness: scalar-vector and scalar-fermion terms comparison
- Quark-mass relation, and hierarchy argument
- Summary

Motivation: multiplet structure

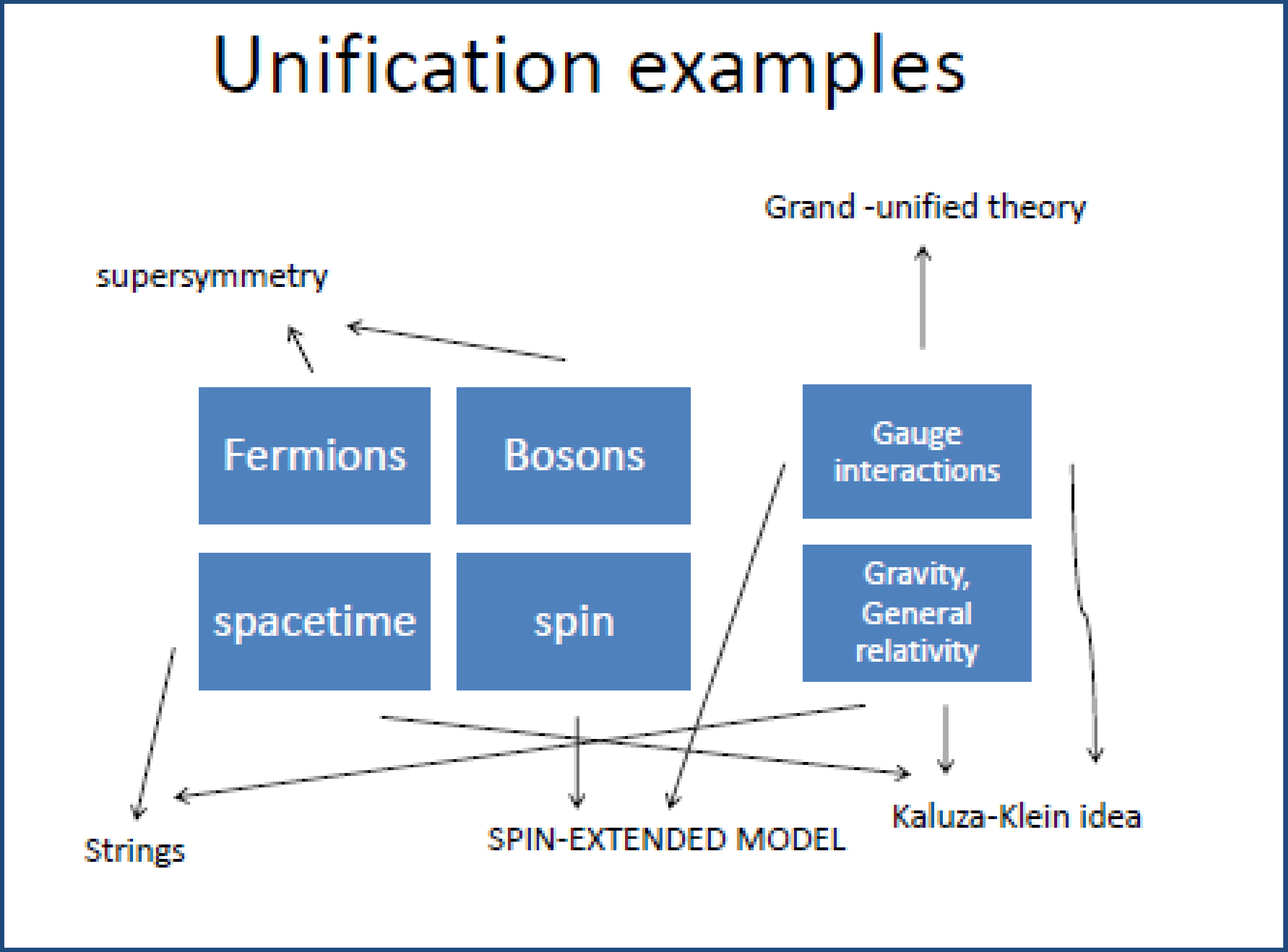
Electroweak-related puzzles in the standard model:

- 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

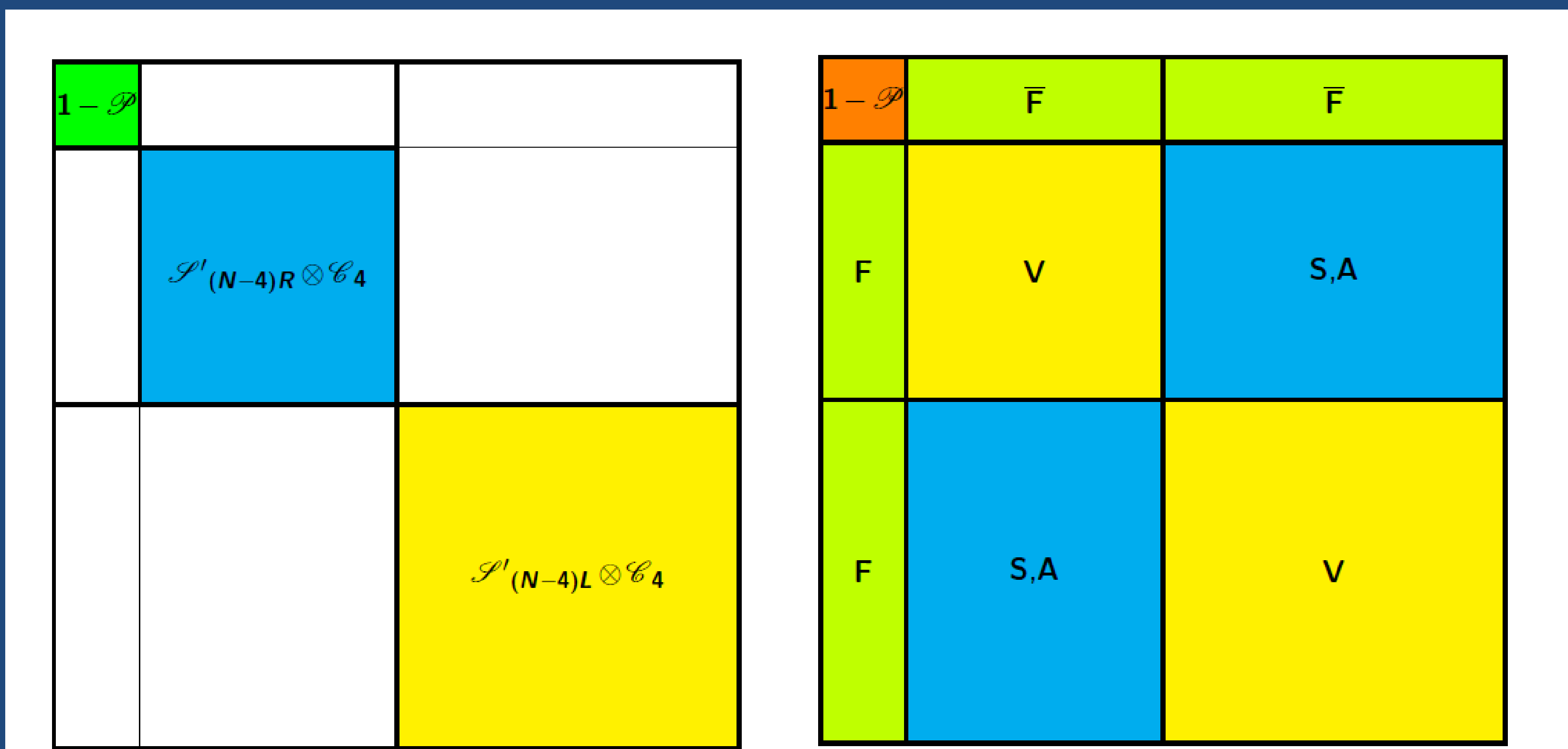
Spin-extended model within standard-model extensions



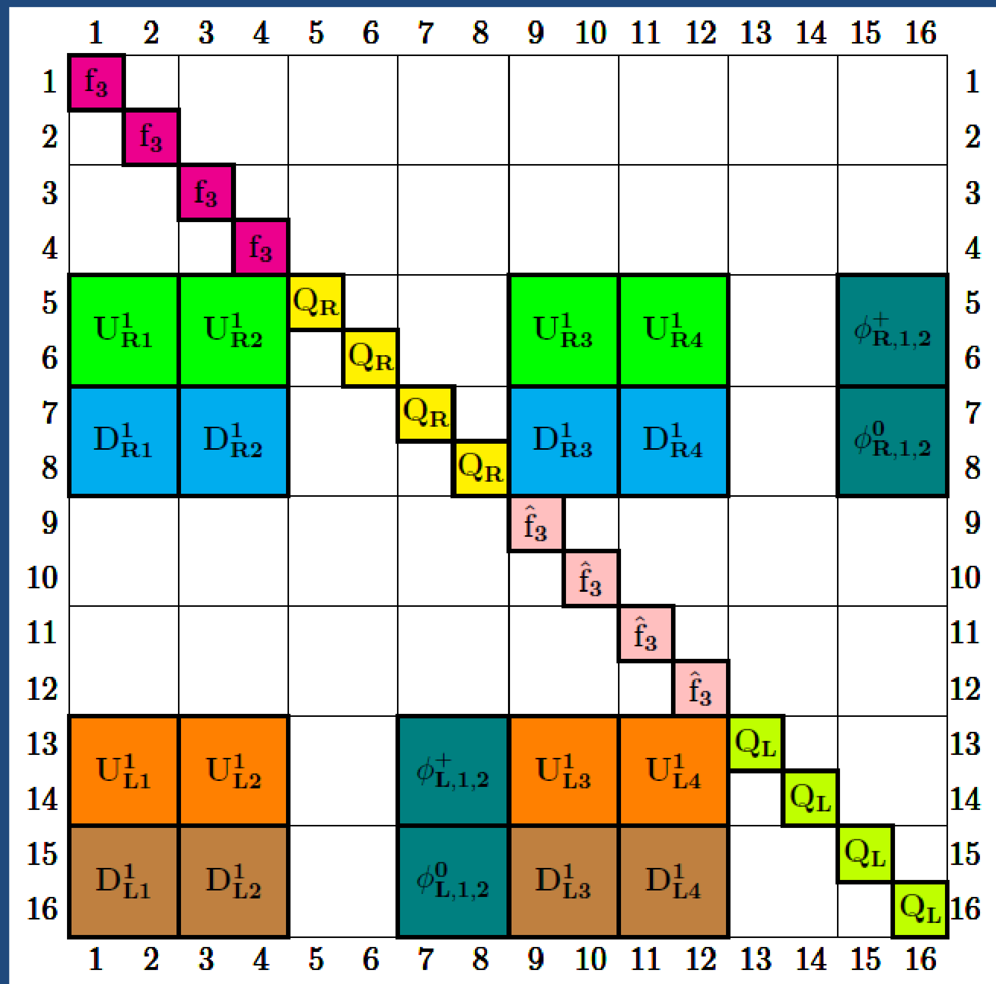
Spin-space structure, at each dimension

- 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: $A_\mu(x) = g_\mu{}^\nu A_\nu(x)$

$A_\mu(x)\gamma_0\gamma^\mu$

$$\mathcal{L}_{FV} = \bar{\mathrm{q}}_L(x)[i\partial_\mu + \frac{1}{2}g\tau^a W^a_\mu(x) + \frac{1}{6}g' B_\mu(x)]\gamma^\mu \mathrm{q}_L(x) +$$

$$\bar{t}_R(x)[i\partial_\mu + \frac{2}{3}g' B_\mu(x)]\gamma^\mu t_R(x) + \bar{b}_R(x)[i\partial_\mu - \frac{1}{3}g' B_\mu(x)]\gamma^\mu b_R(x)$$

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

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

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

$$\Psi^\dagger_{tR}(x)[i\partial_\mu + \frac{1}{2}g' Y_o B_\mu(x)]\gamma^0\gamma^\mu \Psi_{tR}(x) + \Psi^\dagger_{bR}(x)[i\partial_\mu + \frac{1}{2}g' Y_o B_\mu(x)]\gamma^0\gamma^\mu \Psi_{bR}(x)\} P_f$$

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

SV Lagrangian and scalar t-b spin representation

Scalar correspondence

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

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

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

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

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

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

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

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

SV spin representation

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

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

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

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

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

Top-quark mass

Higgs mechanism

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

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

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

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

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

Quark-mass relation

Higgs mechanism

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

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

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

$$v = 246 \text{ GeV}$$

$$m_b = 4 \text{ GeV}$$

Top-quark mass from hierarchy argument

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

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

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

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

$$\mathrm{O}(a) \simeq \mathrm{O}(f),\ (m_b \ll m_t,)\ \text{we get } \frac{1}{\sqrt{2}}v \simeq 173.95,\ \text{for } v = 246\ \text{GeV}$$

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

Higgs mechanism

Argument summary

- Electroweak conventional fields and their Lagrangian can be written in a spin-extended space.
- Scalar-vector term, invariant under scalar and conjugate parametrization.
- *Same* scalar field within SV and SF terms connects V and F; after the Higgs mechanism, it constrains quark masses.
- Multiplet structure suggested for heavy standard-model particles.