(Fundamental) Physics of Elementary Particles

Grand Unification: Pati-Salam, Georgi-Glashow, and other, more complex models

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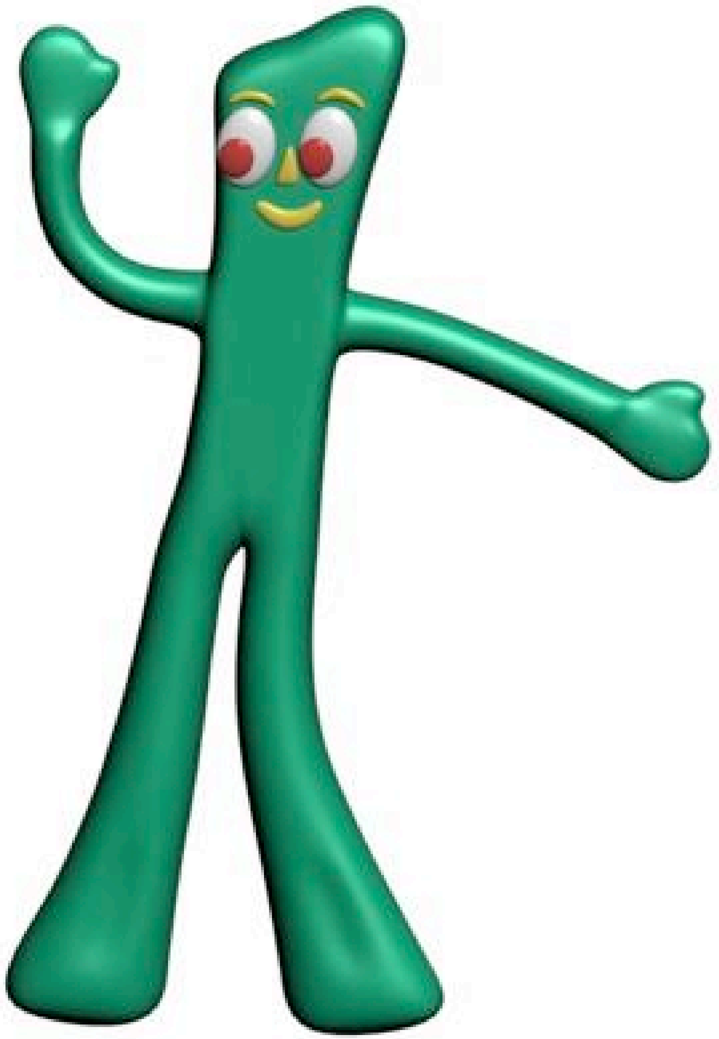
Fundamental Physics of Elementary Particles

Program

- The Grand Unification Model Building Yarn
- The Pati-Salam Model
  - Unification of quarks and leptons
  - Unification of left- and right-chirality
  - Addressing the mass hierarchy & structure
  - Consequences: proton decay, phases
- The Georgi-Glashow Model
  - Unification of gauge interactions
  - Consequences: proton decay, phases
- More Complex Models
  - Unification of fundamental fermion families
  - Other gauge symmetry groups
- Concerns



Grand Unification Model Building Yarn

General comments

- The fundamental fermion content of the Standard Model:

	fermion family 1	2	3	charges Q	I_w	Y_w
$\underbrace{\Psi_- = \gamma_- \Psi}_{\text{left-handed}}$	$\begin{bmatrix} u \\ d \end{bmatrix}_L$	$\begin{bmatrix} c \\ s \end{bmatrix}_L$	$\begin{bmatrix} t \\ b \end{bmatrix}_L$	$+2/3$ $-1/3$	$+1/2$ $-1/2$	$+1/3$ $+1/3$
	$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix}_L$	$\begin{bmatrix} \nu_\mu \\ \mu^- \end{bmatrix}_L$	$\begin{bmatrix} \nu_\tau \\ \tau^- \end{bmatrix}_L$	0 -1	$+1/2$ $-1/2$	-1 -1
$\underbrace{\Psi_+ = \gamma_+ \Psi}_{\text{right-handed}}$	u_R	c_R	t_R	$+2/3$	0	$+4/3$
	d_R	s_R	b_R	$-1/3$	0	$-2/3$
	e_R^-	μ_R^-	τ_R^-	-1	0	-2
	ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	0	0	0

- Notice the weak hypercharge values!

The Grand Unification Model Building Yarn

General comments

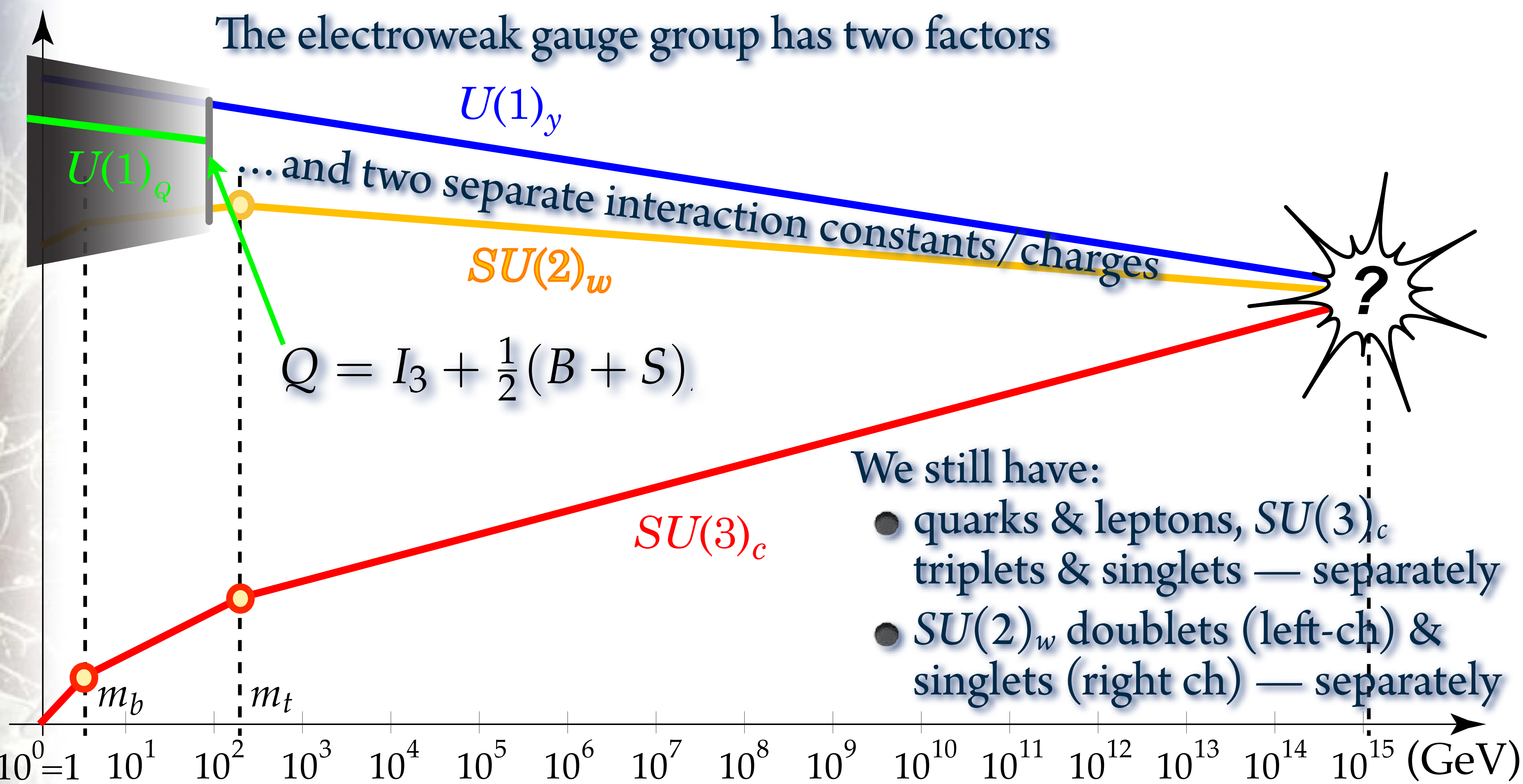
- With respect to the $SU(3)_c \times SU(2)_w \times U(1)_y$ gauge group
  - left-chirality quarks $(u, d)_L$ form a $(\mathbf{3}, \mathbf{2})_{1/3}$
  - left-chirality leptons $(e^-, \nu)_L$ form a $(\mathbf{1}, \mathbf{2})_{-1}$
  - right-chirality quarks form: $u_R = (\mathbf{3}, \mathbf{1})_{4/3} \oplus d_R = (\mathbf{3}, \mathbf{1})_{-2/3}$
  - right-chirality leptons form: $e^-{}_R = (\mathbf{1}, \mathbf{1})_{-2} \oplus \nu_R = (\mathbf{1}, \mathbf{1})_0$ *"sterile"*
- The gauge group representations determine the interactions
  - $SU(3)_c$ **3**'s interact w/gluons, **1**'s don't
  - $SU(2)_w$ **2**'s interact w/$W^\pm$ & W^3, **1**'s don't
  - $U(1)_y$ $q_y \neq 0$ interact w/gluons, $q_y = 0$ don't
  - Each gauge group factor has a separate gauge-coupling constant/parameter/charge and "fine structure parameter": α_c, α_w and α_y
- Besides the fundamental fermions, the Standard Model only has gauge interaction bosons and the Higgs boson, $(\mathbf{1}, \mathbf{2})_{+1}$.

I'll be back

The Grand Unification Model Building Yarn

General comments

- Recall the suggestive graph:



The Pati-Salam Model

Unification of quarks and leptons

- The fundamental fermion structure in each family and ignoring chirality is

$SU(3)_c$			ℓ		$SU(4)_c$			
					$SU(3)_c$			
q^r	q^y	q^b		$\rightarrow$	q^r	q^y	q^b	ℓ^ℓ
u^r	u^y	u^b	ν_e		u^r	u^y	u^b	$\nu_e{}^\ell$
d^r	d^y	d^b	e^-		d^r	d^y	d^b	$e^{-\ell}$

- The lepton-ness (non-quark-ness) of leptons is identified as the 4th color, "*lilac*," of a larger $SU(4)_c$ gauge group
- ... which then needs to be broken
  $SU(4)_c \rightarrow SU(3)_c \times U(1)_{y'}$ gauge group
- ... by means of some Higgs scalar.

The Pati-Salam Model

Unification of left- and right-chirality

- Remembering chirality, we have

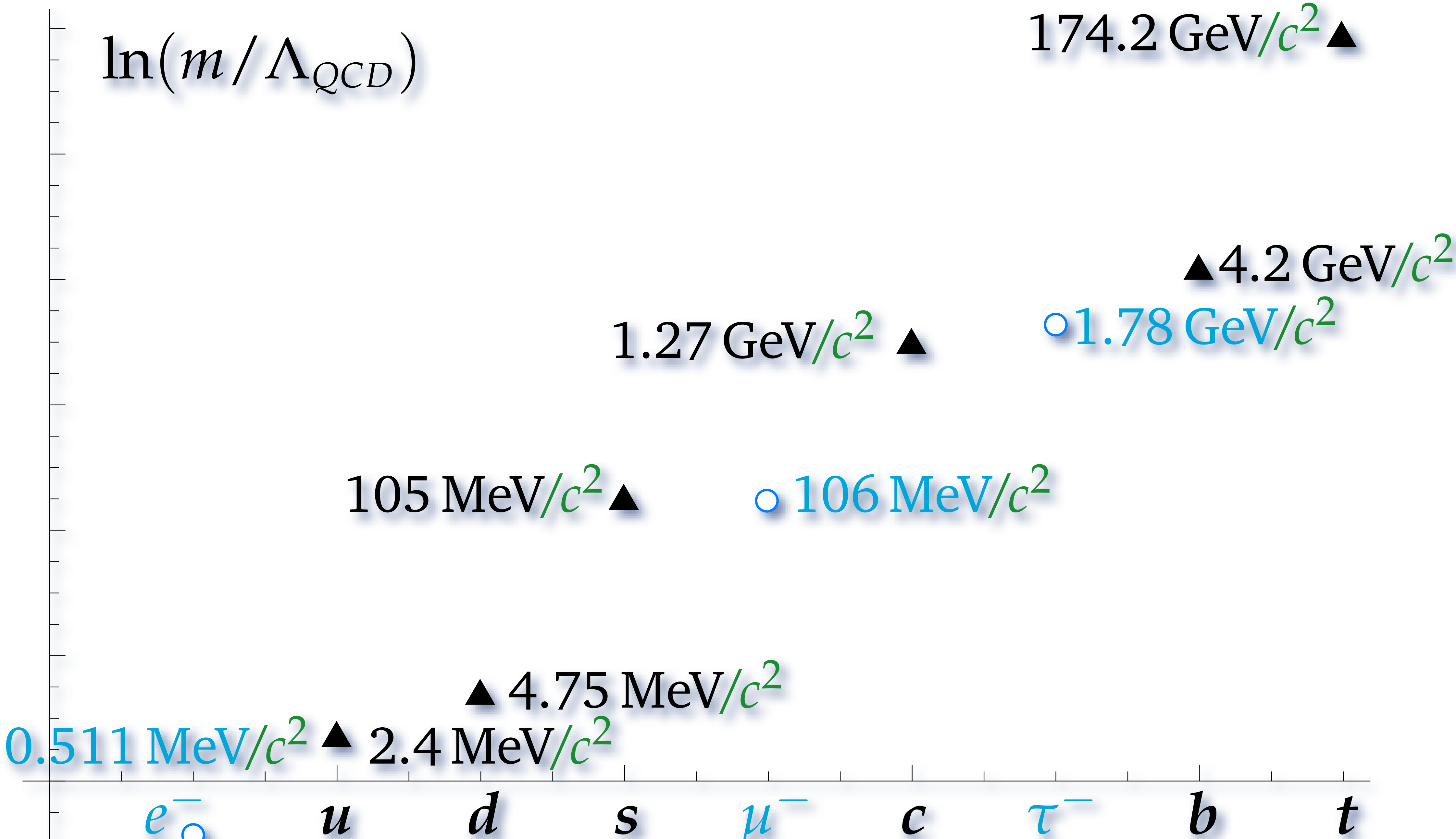
	electroweak interaction		chirality	$SU(4)_c$			
				$SU(3)_c$			
				r	y	b	ℓ
$\mathbb{Z}_2$	$SU(2)_L$	$+½$	L	u^r	u^y	u^b	ν_e^ℓ
		$-½$		d^r	d^y	d^b	$e^{-\ell}$
	$SU(2)_R$	$+½$	R	u^r	u^y	u^b	ν_e^ℓ
		$-½$		d^r	d^y	d^b	$e^{-\ell}$

- The "mirror" weak isospin $SU(2)_R$ gauge group
- and also the discrete parity symmetry, $\mathbb{Z}_2$.
- Pati-Salam group: $SU(4)_c \times SU(2)_L \times SU(2)_R \times \mathbb{Z}_2$.

The Pati-Salam Model

Fermion mass hierarchy & structure

- Recall:



The Pati-Salam Model

Fermion mass hierarchy & structure

- Fundamental fermions: $(\mathbf{4},\mathbf{2},\mathbf{1})_L \oplus (\mathbf{4},\mathbf{1},\mathbf{2})_R$ irreducible under $\mathbb{Z}_2$
- Under $SU(4)_c \to SU(3)_c \times U(1)_{y'}$: $\mathbf{4} \to \mathbf{3}_{1/3} \oplus \mathbf{1}_{-1}$ ("q" ⊕ "ℓ")
- Under $SU(2)_R \to U(1)_R$: $\mathbf{2} \to (+1/2) \oplus (-1/2)$ ("spin-↑", "spin-↓")
- So, $(\mathbf{4},\mathbf{2},\mathbf{1})_L \to [(\mathbf{3}_{1/3},\mathbf{2})_0 \oplus (\mathbf{1}_{-1},\mathbf{2})_0]_L$ and
  $(\mathbf{4},\mathbf{1},\mathbf{2})_R \to [(\mathbf{3}_{1/3},\mathbf{1})_{+1/2} \oplus (\mathbf{3}_{1/3},\mathbf{1})_{-1/2} \oplus (\mathbf{1}_{-1},\mathbf{1})_{+1/2} \oplus (\mathbf{1}_{-1},\mathbf{1})_{-1/2}]_R$
- Now, $U(1)_{y'} \times U(1)_R \to U(1)_y$, according to $q_y = q_{y'} + 2I_{3R}$, so
- $(\mathbf{4},\mathbf{2},\mathbf{1})_L \oplus (\mathbf{4},\mathbf{1},\mathbf{2})_R \to [(\mathbf{3},\mathbf{2})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1}]_L \oplus$
  $[(\mathbf{3},\mathbf{1})_{4/3} \oplus (\mathbf{3},\mathbf{1})_{-2/3} \oplus (\mathbf{1},\mathbf{1})_0 \oplus (\mathbf{1},\mathbf{1})_{-2}]_R$
- …the $U(1)_y$ charges reproduce those in the Standard Model
- The Higgs field then itself needs to be a $(\mathbf{4},\mathbf{1},\mathbf{2})$, so that
- … $\langle(\mathbf{4},\mathbf{1},\mathbf{2})\rangle = \ldots + \langle(\mathbf{1},\mathbf{1})_0\rangle \neq 0$. This simultaneously breaks $SU(4)_c \times SU(2)_R \times \mathbb{Z}_2 \to SU(3)_c \times U(1)_y$ & leaves $SU(2)_w$ intact.

The Pati-Salam Model

Fermion mass hierarchy & structure

- What? You did *not* memorize that?!
- OK:

"P-S 4-2-2"	"$3_{y'}$-2-$1^{(R)}$"	"S.M. 3-2-1"
$(\mathbf{4},\mathbf{2},\mathbf{1})$	$(\mathbf{3}_{\frac{1}{3}},\mathbf{2})_0 \oplus (\mathbf{1}_{-1},\mathbf{2})_0$	$(\mathbf{3},\mathbf{2})_{\frac{1}{3}} \oplus (\mathbf{1},\mathbf{2})_{-1}$
$(\mathbf{4},\mathbf{1},\mathbf{2})$	$(\mathbf{3}_{\frac{1}{3}},\mathbf{1})_{\frac{1}{2}} \oplus (\mathbf{1}_{-1},\mathbf{1})_{\frac{1}{2}} \oplus$ $(\mathbf{3}_{\frac{1}{3}},\mathbf{1})_{-\frac{1}{2}} \oplus (\mathbf{1}_{-1},\mathbf{1})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{1})_{\frac{4}{3}} \oplus (\mathbf{1},\mathbf{1})_0 \oplus$ $(\mathbf{3},\mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1},\mathbf{1})_{-2}$

$$U(1)_{y'} \times U(1)_R \to U(1)_y : \quad q_y = q_{y'} + 2I_{3,R}$$

- Recall: $\overline{\Psi}\big[i\hbar c\boldsymbol{\gamma}^\mu D_\mu - \frac{mc}{\hbar}\mathbb{1}\big]\Psi = \cdots - \frac{mc}{\hbar}\big[\overline{\Psi_-}\Psi_+ + \overline{\Psi_+}\Psi_-\big]$
- So an $SU(4)_c \times SU(2)_L \times SU(2)_R \times \mathbb{Z}_2$-invariant mass-term is

$$\overline{(\mathbf{4},\mathbf{1},\mathbf{2})}\langle\mathbb{H}\rangle(\mathbf{4},\mathbf{2},\mathbf{1}) \;\Rightarrow\; \mathbb{H} \sim (\mathbf{1},\mathbf{2},\mathbf{2}) \;\to (\mathbf{1}_0,\mathbf{2})_{\pm\frac{1}{2}} \;\to (\mathbf{1},\mathbf{2})_{\pm 1}$$

one of the four gets a vev

The Pati-Salam Model

Fermion mass hierarchy & structure

- So:
- Then, e.g., $-h_u\,\overline{u_R}\,(\mathbb{H}^c)^\dagger \begin{bmatrix} u \\ d \end{bmatrix}_L$
- stems from the Pati-Salam mass term of the form

$$\begin{array}{ccccc}
(\mathbf{3}^*,\mathbf{1})_{-\frac{4}{3}} & \cdot & (\mathbf{1},\mathbf{2})_{\pm 1} & \cdot & (\mathbf{3},\mathbf{2})_{+\frac{1}{3}} \\
\uparrow & & \uparrow & & \uparrow \\
(\mathbf{3}^*{}_{-\frac{1}{3}},\mathbf{1})_{-\frac{1}{2}} & \cdot & (\mathbf{1}_0,\mathbf{2})_{\pm\frac{1}{2}} & \cdot & (\mathbf{3}_{\frac{1}{3}},\mathbf{2})_0 \\
\uparrow & & \uparrow & & \uparrow \\
(\overline{\mathbf{4}},\mathbf{2},\mathbf{1}) & \cdot & (\mathbf{1},\mathbf{2},\mathbf{2}) & \cdot & (\mathbf{4},\mathbf{1},\mathbf{2})
\end{array}$$

	fermion family 1	2	3	charges Q	I_w	Y_w
$\Psi_- = \gamma_-\Psi$ left-handed	$\begin{bmatrix} u \\ d \end{bmatrix}_L$	$\begin{bmatrix} c \\ s \end{bmatrix}_L$	$\begin{bmatrix} t \\ b \end{bmatrix}_L$	$+2/3$ $-1/3$	$+1/2$ $-1/2$	$+1/3$ $+1/3$
	$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix}_L$	$\begin{bmatrix} \nu_\mu \\ \mu^- \end{bmatrix}_L$	$\begin{bmatrix} \nu_\tau \\ \tau^- \end{bmatrix}_L$	0 -1	$+1/2$ $-1/2$	-1 -1
$\Psi_+ = \gamma_+\Psi$ right-handed	u_R	c_R	t_R	$+2/3$	0	$+4/3$
	d_R	s_R	b_R	$-1/3$	0	$-2/3$
	e^-_R	μ^-_R	τ^-_R	-1	0	-2
	ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	0	0	0

so that we must choose

$\langle\mathbb{H}\rangle \subset (\mathbf{1},\mathbf{2})_{+1}$

- And then, in fact, the vev is in the lower component, so that
- $\langle\mathbb{H}\rangle = (\mathbf{1},-\tfrac{1}{2})_{+1} = \mathbf{1}_0$, neutral with respect to $Q = I_3 + \tfrac{1}{2}Y$.
- The mass-term with $(\mathbf{1},\mathbf{2},\mathbf{2})$ includes all fermions of a family!

makes $h_u = h_d = h_e = h_\nu$

The Pati-Salam Model

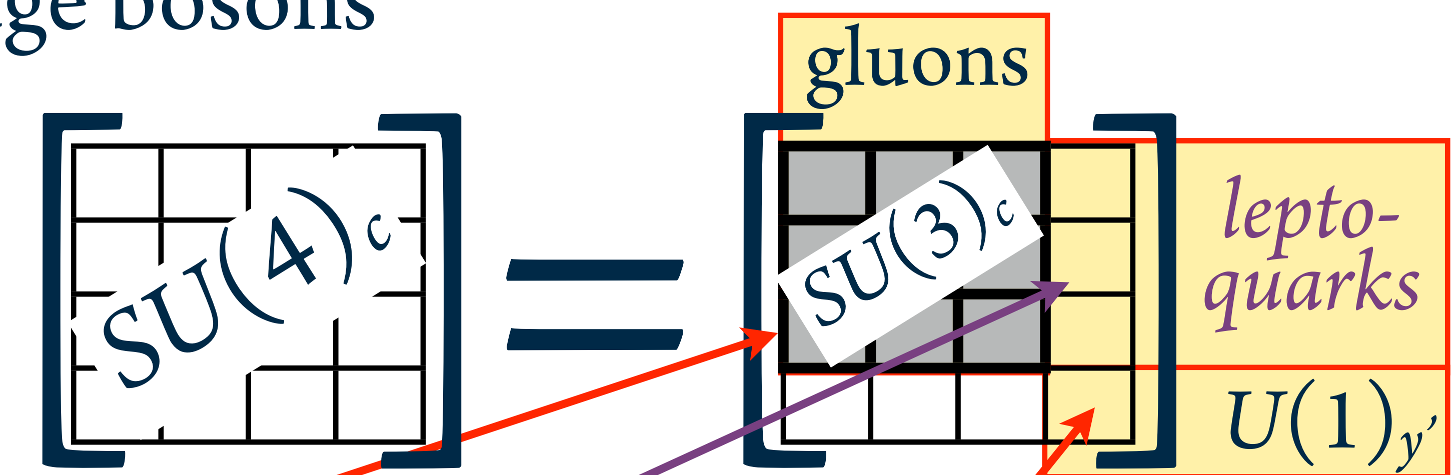
Fermion mass hierarchy & structure

- Since the "electroweak" Higgs $(\mathbf{1}, \mathbf{2}, \mathbf{2})$ gives all fundamental fermions $(\mathbf{4}, \mathbf{2}, \mathbf{1})_L \oplus (\mathbf{4}, \mathbf{1}, \mathbf{2})_R$ of the same family the same mass
- … the mass-hierarchy within a family must be obtained via
  - coupling with another Higgs field, that couples differently to the various components of $(\mathbf{4}, \mathbf{2}, \mathbf{1})_L$ and $(\mathbf{4}, \mathbf{1}, \mathbf{2})_R$
  - such as, e.g., $(\mathbf{15}, \mathbf{1}, \mathbf{2})$ and/or $(\mathbf{15}, \mathbf{2}, \mathbf{2})$ and/or $(\mathbf{1}, \mathbf{1}, \mathbf{2})$.
  - When decomposed in the $SU(3)_c \times SU(2)_L \times U(1)_y$ basis, these introduce (e.g., three) new coupling parameters,
  - …which then afford a degree of structure in the mass hierarchy.
- This showcases a GUT rephrasing of the mass hierarchy issue.
  - The mass hierarchy structure is restricted by the GUT symmetry
  - …even if the number of parameters turns out to be the same.
  - It does require a proliferation of Higgs fields.

The Pati-Salam Model

Consequences: proton decay, phases

- The $SU(4)_c$ gauge bosons



- …besides the gluons and the *L-R* "hyper-photon," $SU(4)_c$ also contains "*lepto-quarks.*"
- Just as $q^r \to q^b + g^r{}_b$, so $q^r \to \ell^\ell + X^r{}_\ell$ allows for quarks to turn into leptons, but conserving the "B+3L" number.
- Thus, the simplest proton decays are
  - $p^+ \to 3\nu_e$ + (mesons$^+$, photons)
  - $p^+ \to 4\nu_e + e^+$ + (mesons^0, photons).

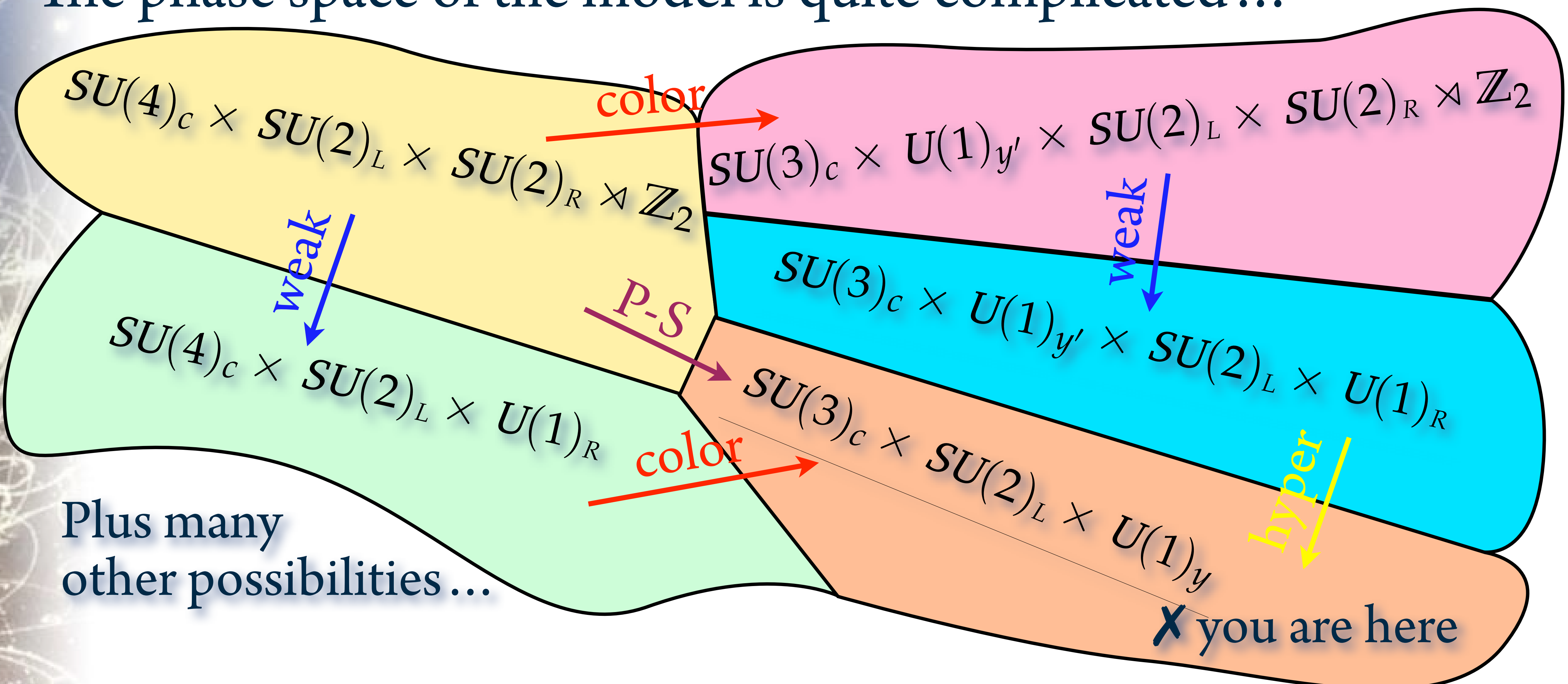
    (must involve a Higgs field)

No confirmed p^+-decay yet…

The Pati-Salam Model

Consequences: proton decay, phases

- The phase space of the model is quite complicated…

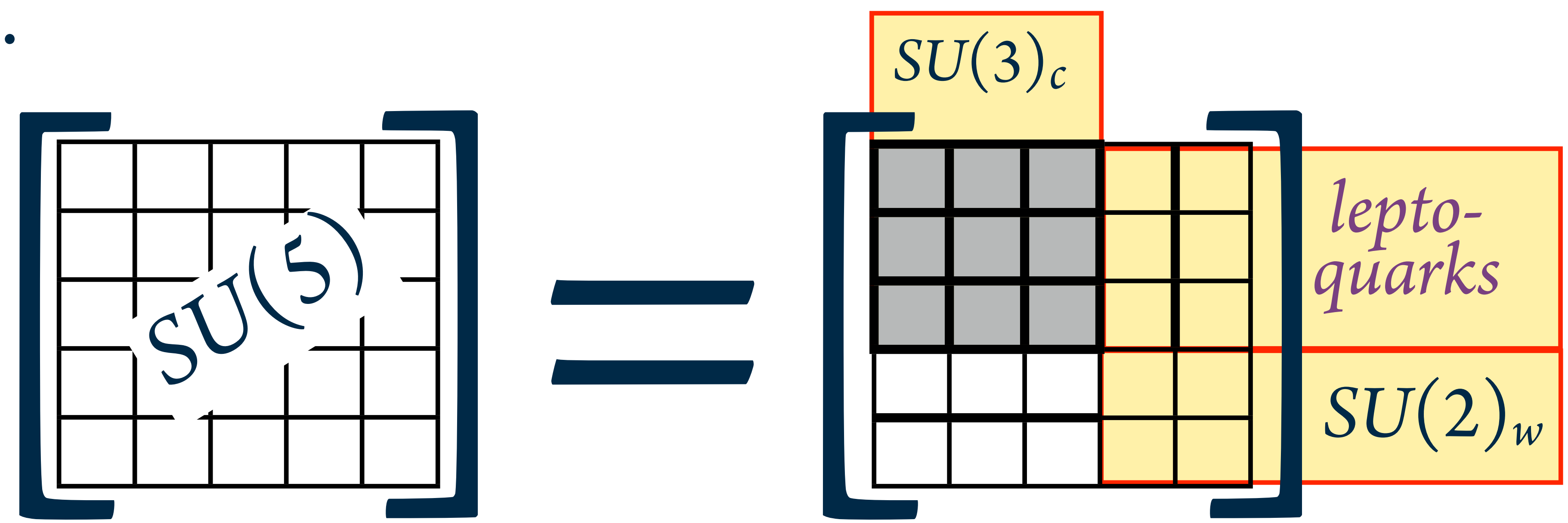


- The $SU(4)_c$ and the $SU(2)_L \times SU(2)_R$ gauge coupling charges remain unrelated: α_c and α_w .

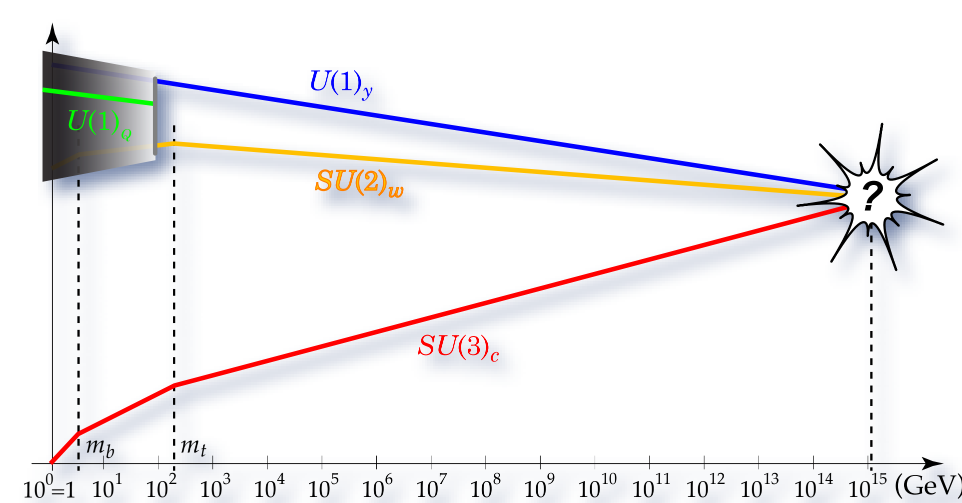
The Georgi-Glashow Model

Unification of gauge interactions

- The smallest Lie group containing $SU(3)_c \times SU(2)_w \times U(1)_y$ is $SU(5)$.



- Since the generators of $SU(5)$, $SU(3)_c$ and $SU(2)_w$ are all traceless, $SU(5)$ contains also one diagonal element: $U(1)_y$.
- Since all generators are united into a single algebra, there is a single gauge coupling, α_5.



The Georgi-Glashow Model

Unification of gauge interactions

- The fermions however fit into:

$$(f_{\mathbf{10}})^{[AB]} = \begin{bmatrix} 0 & e^{+} & u^{r} & u^{y} & u^{b} \\ & 0 & d^{r} & d^{y} & d^{b} \\ & & 0 & \overline{u}_{b} & \overline{u}_{y} \\ & & & 0 & \overline{u}_{r} \\ & & & & 0 \end{bmatrix}_L , \quad (\overline{f}_{\mathbf{5}^*})_A = \begin{bmatrix} e^{-} \\ \nu_e \\ \overline{d}_r \\ \overline{d}_y \\ \overline{d}_b \end{bmatrix}_L , \quad f_{\mathbf{1}} = (\overline{\nu}_e)_L,$$

anti-symmetric rank-2 tensor

$$\mathbf{1} \to (\mathbf{1},\mathbf{1})_0$$

- which decompose:

$$\mathbf{10} \to (\mathbf{3},\mathbf{2})_{\frac{1}{3}} \oplus (\mathbf{3}^*,\mathbf{1})_{-\frac{4}{3}} \oplus (\mathbf{1},\mathbf{1})_{2}, \quad \mathbf{5}^* \to (\mathbf{3}^*,\mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_{-1},$$

- The lepto-quarks now come as an $SU(2)_w$-doublet:

$$\begin{Bmatrix} X^r \\ Y^r \end{Bmatrix}, \quad \begin{Bmatrix} X^y \\ Y^y \end{Bmatrix}, \quad \begin{Bmatrix} X^b \\ Y^b \end{Bmatrix} : \qquad \begin{matrix} I_3(X) = +\tfrac{1}{2}, & Q(X) = \tfrac{4}{3}, \\ I_2(Y) = -\tfrac{1}{2}, & Q(Y) = \tfrac{1}{3}. \end{matrix}$$

The Georgi-Glashow Model

Consequences: proton decay, phases

- The SU(5) lepto-quarks now directly mediate proton decay:

$$p^+ = (u+u+d) \to (u+u+(\overline{X}+e^+)) \to (u+(u+\overline{X})+e^+)$$
$$\to (u+\overline{u}+e^+) \to \pi^0+e^+ \quad \to \quad 2\gamma+e^+.$$

- …conserving the “B–L” number.
- With M_X, M_Y ~10^{15} GeV/c^2, τ_p ~ 10^{28}–10^{29} years
- Waiting experiments: $\tau_p > 6.6 \times 10^{33}$ years
- Higgs: **24** of $SU(5)$ does have an $SU(3)_c \times SU(2)_w \times U(1)_y$-invariant component: the diagonal generator of $U(1)_y$.
  - But, **24** also has an $SU(4) \times U(1)$-invariant component…
  - …so there are at least those three phases.
  - Alternatively, a **75** of $SU(5)$ does an $SU(3)_c \times SU(2)_w \times U(1)_y$-invariant component, no $SU(4) \times U(1)$-invariant one, but also an $SO(5)$-invariant one…

Grand Unification Model Building Yarn

Consequences

... zoom-out

- Unification of quarks and leptons leads to proton-decay
- ... preserving some "αB+βL" number.
  - "B+3L" number for the Pati-Salam model
  - "B–L" number for the Georgi-Glashow model

Particulars of unifying quarks and leptons

- Phases/regimes of the model depend on
  - the grand-unification (Lie) group
    - Subalgebra chains of Lie groups — classic results, used recursively
  - the Higgs fields employed
    - Representation decomposition w.r.t. subgroup — tables trick-or-treat
- Mass hierarchy:
  - Typically a hierarchy of Higgs fields
    - One w/ $\langle\mathbb{H}_1\rangle \sim 10^{15}$ GeV, the GUT scale — beyond Standard Model masses
    - one w/ $\langle\mathbb{H}_2\rangle \sim 10^{2}$ GeV, the electroweak scale — Standard Model masses

junk

More Complex Models

Unification of fundamental fermion families

- As the P-S model fully unifies fermions but not gauge fields
- And the G-G model fully unifies gauge fields but not fermions
- … seek a bigger model that unifies them all.
- "Next" in size:

$$SO(10) \to \begin{cases} \overset{SO(6)}{SU(4)_c} \times \overset{SO(4)}{SU(2)_L \times SU(2)_R}, \\ SU(5) \times U(1)', \end{cases}$$

$$\mathbf{16}_L \to \begin{cases} (\mathbf{4},\mathbf{2},\mathbf{1})_L \oplus (\mathbf{4}^*,\mathbf{1},\mathbf{2})_L, \\ (\mathbf{10}_{-1})_L \oplus (\mathbf{5}^*{}_3)_L \oplus (\mathbf{1}_{-5})_L. \end{cases}$$

- No "extra" (junk) fermions (except ν_{eR}), but extra gauge bosons: 45 = ((8+3+1)+ 6+3)+24 = ((8+3+1)+12)+20+1
- Still does not unify the three families of fermions.

More Complex Models

Unification of fundamental fermion families

- The simplest idea: add an $SU(3)$ gauge group that transforms any one family into a linear combination of all three
- Breaking the symmetry in stages
  - All 48 fermions → three families of 16
  - Left-right breaking
  - electroweak → weak + electromagnetism

Needs a Higgs hierarchy, which could reproduce the fermion hierarchy

- $SU(3)$ is *ad hoc* [“for this”], and there are no exp. signs of any such family *gauge* interactions — no family gauge group.
- “Familial symmetry” may well be
  - a broken global symmetry
  - a symmetry that is broken at a higher yet scale
  - an “artifact” of the structure of a higher GUT symmetry

More Complex Models

Other gauge symmetry groups

- Trinification (Georgi, Glashow and de Rujula)
  - Gauge group: $SU(3)_c \times SU(3)_L \times SU(3)_R$,
  - with fermions $(\mathbf{3}, \mathbf{3}^*, \mathbf{1}) \oplus (\mathbf{3}^*, \mathbf{1}, \mathbf{3}) \oplus (\mathbf{1}, \mathbf{3}, \mathbf{3}^*) = 27$
  - with a Higgs $(\mathbf{1}, \mathbf{3}, \mathbf{3}^*)$ and perhaps its conjugate
  - a maximal subgroup of E_6, with fermions in **27** — *(string theory)*
- Really big: $SO(18) \supset SO(10) \times SO(8)$, the latter – "familial"
  - Fundamental fermions: $\mathbf{256} = (\mathbf{16}, \mathbf{8}_s) \oplus (\mathbf{16}^*, \mathbf{8}_c)$
  - Georgi-Bagger "no-go theorem": no way to remain with 3 families
    - w.r.t. orthogonal subgroups, fermions always split in powers of 2
  - D.Chang, T.H., R.Mohapatra: SO(8) has a triality: $\langle \mathbf{8}_v, \mathbf{8}_s, \mathbf{8}_c \rangle$
    - $SO(8) \supset SO(5) \times SO(3)$: $\mathbf{8}_s \to \mathbf{8}_v = (\mathbf{5}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{3})$, $\mathbf{8}_c \to \mathbf{8}_s = (\mathbf{4}, \mathbf{2})$
    - Found a Higgs: $(\mathbf{16}, \mathbf{8}_s) \cdot \langle \mathbb{H} \rangle \cdot (\mathbf{16}^*, \mathbf{8}_c) \neq 0$ for $(\mathbf{16}, (\mathbf{5}, \mathbf{1}))$, — *massive!*
    - …leaving $(\mathbf{16}, (\mathbf{1}, \mathbf{3}))$ massless, along with 3 of $(\mathbf{16}^*, (\mathbf{4}, \mathbf{2}))$ — *mirrors!*
    - …thus breaking the familial $SO(5) \times SO(3)$ gauge symmetry *to an $SU(2)$*

loophole

The Grand Unification Model Building Yarn

Concerns

- To unify both all fundamental fermions (a single family) and also all (Yang-Mills) gauge interactions: $SO(10)$
  - 33 *XS* gauge bosons! — *typically, extra unbroken $U(1)$*
  - Higgs fields typically in the hundreds!
- To unify the three families with a single group, need $SO(18)$
  - 141 *XS* gauge bosons!!
  - mirror fermions!! — *both massive and massless*
  - Higgs fields typically in the (tens of) thousands!!
- The structures that are being introduced (Higgs, *XS* gauge)
  - are *ad hoc* [“for this”]
  - turn out to be more complicated and plentiful
  - …than the structure they supposedly “explain”: Standard Model

Thanks!

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http://homepage.mac.com/thubsch/