A Derivation of the Standard Model

``String Phenomenology 2015", Madrid, June 12, 2015

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discrete structure of the

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(not including the
number of families)

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A Derivation of the Standard Model

(in a class of intersecting brane models)

Towards

(not including the
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discrete structure of the

A Derivation of the Standard Model

(in a class of intersecting brane models)

Inspiration

- Clash between two points of view:
  - The traditional “Einstein” point of view of top-down determination from some fundamental principle or theory (perhaps involving GUTs)
  - The landscape point of view: the SM originates from some ensemble with a distribution of physical quantities and anthropic constraints
- The current situation in particle physics: the SM is structurally complete, perhaps only SM singlets are still needed.

The Standard Model

Gauge Group $SU(3) \times SU(2) \times U(1)$

Quarks and leptons

$$(3, 2, \frac{1}{6}) + (3^*, 1, -\frac{2}{3}) + (3^*, 1, \frac{1}{3}) + (1, 2, -\frac{1}{2}) + (1, 1, 1)$$

Higgs $(1, 2, -\frac{1}{2})$ Gives masses to all quark and leptons

Charge Quantization!

Candidate derivations
(and why they fail)

- **Grand Unification**
  Higgs doesn't fit in SU(5)
  SU(3) x SU(2) x U(1) not uniquely selected
  Why SU(5) or SO(10)?
  Why (5*)+(10) or (16)?
  No evidence for the Susy-GUT scenario

- **Anomalies***
  Does not select gauge group
  Relies on "minimality"
  Argument fails for non-chiral matter, more than 15 Weyl fermions

- **String Theory**
  Landscape!

(*) Geng, Marshak, Minahan, Ramond, Warner, Babu, Mohapatra, Foot, Joshi, Lew, Volkas

Anthropics

vs.

Aesthetics

Anthropics

(concerns existence of observers)

vs.

Aesthetics

Anthropics
(concerns existence of observers)

vs.

Aesthetics
(concerns happiness of observers)

Anthropic assumptions

- Sufficiently rich “atomic” physics (at least one massless photon and some (meta)stable charged particles)
- Hierarchy between the scale of the atomic mass scales and gravity

We are not demanding carbon, stars, galaxies, nucleosynthesis, abundances, weak interactions(*)….

cf. Harnik, Kribs, Perez, “A universe without weak interactions”

The Hierarchy Problem

Renormalization of scalar masses

$$\mu^2_{\text{phys}} = \mu^2_{\text{bare}} + \sum_i a_i \Lambda^2$$

Computable statistical cost of about 10^{-34} for the observed hierarchy. This is the "(technical) hierarchy problem".

Renormalization of fermion masses

$$\lambda_{\text{phys}} = \lambda_{\text{bare}} \left(\sum_i b_i \log(\Lambda/Q) \right)$$

Statistical cost determined by landscape distribution of λ_{bare}

The Hierarchy Problem

If we accept the current status quo, apparently nature has chosen to pay the huge price of a single scalar that creates the hierarchy.

It remains to be shown that is cheaper than having fundamental Dirac particles with small masses, or than solutions to the technical hierarchy problem (susy, compositenes, ….) but we will assume that it is.

Then this price is going to be payed only once: there should be just one Higgs.

String Theory Input

We would like to enumerate all QFT's with a gauge group and chiral matter. All non-chiral matter is assumed to be heavy, with the exception of at most one scalar field, the Higgs. We demand that after the Higgs gets a vev, and with all possible dynamical symmetry breakings taken into account, at least one massless photon survives, and all charged leptons* are massive.

Otherwise photons will pair-produce massless charged leptons, turning the entire universe into an opaque lepton-antilepton plasma.
(C. Quigg, R. Shrock, Phys.Rev. D79 (2009) 096002)

This is very restrictive, but still has an infinite number of solutions in QFT.

So at this point we invoke string theory. Its main rôle is to restrict the representations. It also provides a fundamental reason for anomaly cancellation.

*lepton: a fermion not coupling to any non-abelian vector boson

Intersecting Brane Models

We will assume that all matter and the Higgs bosons are massless particles in intersecting brane models. Then the low-energy gauge groups is a product of $U(N)$, $O(N)$ and $Sp(N)$ factors.

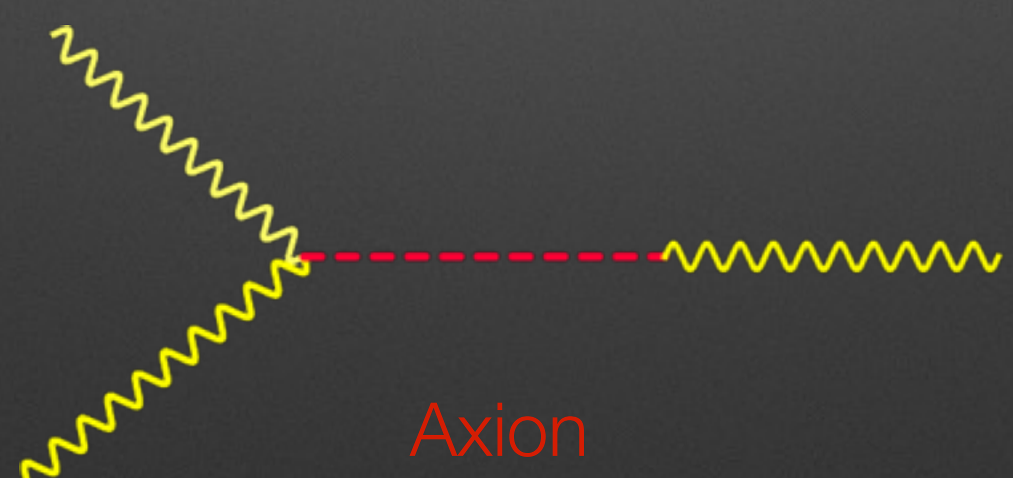
The low energy gauge group is assumed to come from S stacks of branes.
There can be additional branes that do not give rise to massless gauge bosons: $O(1)$ or $U(1)$ with a massive vector boson due to axion mixing.

All matter (fermions as well a the Higgs) are bi-fundamentals, symmetric or anti-symmetric tensors, adjoints or vectors (open strings with one end on a neutral brane)

We start with $S = 1$, and increase S until we find a solution.

Intersecting Brane Models

- Brane multiplicities are subject to tadpole cancellation (automatically implies absence of triangle anomalies in QFT).
- Massless vector bosons may mix with axions and acquire a mass.



Intersecting Brane Models: Single Stack

Chan-Paton group can be $U(N)$, $O(N)$ or $Sp(N)$, but only $U(N)$ can be chiral.

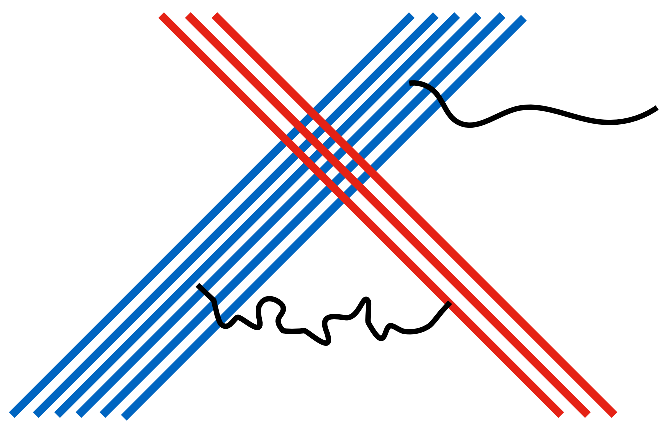
Matter can be symmetric or anti-symmetric tensors or vectors.
Chiral multiplicities $S,\ A,\ K$; charges $2q,\ 2q,\ q$.

Anomaly cancellation:

$$KNq^3 + \tfrac{1}{2}N(N+1)S(2q)^3 + \tfrac{1}{2}N(N-1)A(2q)^3 = 0$$
$$KNq + \tfrac{1}{2}N(N+1)S(2q) + \tfrac{1}{2}N(N-1)A(2q) = 0$$
$$Kq + (N+2)S(2q) + (N-2)A(2q) = 0$$

Solutions: $K{=}S{=}A{=}0$ or $q{=}0$. In the former case, there is no chiral spectrum, in the latter case no electromagnetism.

Two stack models



$$SU(M) \times SU(N) \times U(1)$$

(We have only considered unitary branes so far)

$$Y = q_a Q_a + q_b Q_b$$

$q_a, \;\; q_b$ determined by axion couplings

Q	$(M, N, q_a + q_b)$
U	$(A, 1, 2q_a)$
D	$(\overline{M}, 1, -q_a)$
S	$(S, 1, 2q_a)$
X	$(M, \overline{N}, q_a - q_b)$
L	$(1, \overline{N}, -q_b)$
T	$(1, S, 2q_b)$
E	$(1, A, 2q_b)$

Anomalies

$SU(M) \times SU(N) \times U(1)$

S W Y

There are six kinds of anomalies:

SSS
WWW

$\Big\}$ From tadpole cancellation: also for $M,\ N < 3$

YYY

SSY

WWY

GGY Mixed gauge-gravity

At most one linear combination of the $U(1)$'s is anomaly-free

Anomalies

$$\begin{aligned}
(S+U)\tilde{q}_a &= C_1 \\
(T+E)\tilde{q}_b &= -C_2 \\
(D+8U)\tilde{q}_a &= (4+M)C_1 + NC_2 \\
L\tilde{q}_b + D\tilde{q}_a &= 0 \\
2E\tilde{q}_b + 2U\tilde{q}_a &= C_1 - C_2
\end{aligned}$$

$$\tilde{q}_a \equiv Mq_a,\ \tilde{q}_b \equiv Nq_b$$

$$C_1 = -(Q-X)\tilde{q}_b$$

$$C_2 = (Q+X)\tilde{q}_a$$

($q_a = 0$ and/or $q_b = 0$ must be treated separately)

Abelian theories

Single $U(1)$: Higgs must break it, no electromagnetism left

$U(1) \times U(1)$: No solution to anomaly cancellation for two stacks

So in two-stack models we need at least one non-abelian factor in the high-energy theory.

Strong Interactions

It is useful to have a non-abelian factor in the low-energy theory as well, since the elementary particle charge spectrum is otherwise too poor. We need some additional interaction to bind these particles into bound states with larger charges (hadrons and nuclei in our universe).

For this to work there has to be an approximately conserved baryon number.
This means that we need an $SU(M)$ factor with $M \geq 3$, and that this $SU(M)$ factor does not become part of a larger group at the “weak” scale.

Note that $SU(2)$ does not have baryon number, and the weak scale is near the constituent mass scale. We cannot allow baryon number to be broken at that scale.

But let’s just call this an additional assumption.

Higgs Choice

This implies that at least one non-abelian factor is not broken by the Higgs. We take this factor to be $U(M)$.

Therefore we do not consider bi-fundamental Higgses breaking both $U(M)$ and $U(N)$. We assume that $U(N)$ is the broken gauge factor. Then the only Higgs choices are **L**,**T** and **E**.

We will assume that $U(M)$ it is strongly coupled in the IR-regime and stronger than $U(N)$.

$SU(M) \times U(1)$ $(i.e.\ N{=}1)$

Higgs can only break $U(1)$, but then there is no electromagnetism.

Hence there will be a second non-abelian factor, broken by the Higgs.

$$M = 3,\ N = 2$$

Higgs = L

Decompose L, E, T: chiral charged leptons avoided only if

$$L = E,\ T = 0$$

Substitute in anomaly equation:

$$S\tilde{q}_a = \left(\frac{5 - N - M}{2M}\right) C_1$$

For $M = 3,\ N = 2$: $S = 0$

Therefore we get standard QCD without symmetric tensors.

$M = 3,\ N = 2$

Quark sector

$$Q(3, q_a) + Q(3, q_a + 2q_b) + X(3, q_a) + X(3, q_a - 2q_b) - U(3, -2q_a) - D(3, q_a)$$

$$Q + X - D = 0$$

$Q = U$ **if and only if** $q_a + 2q_b = -2q_a$

or

$X = U$ **if and only if** $q_a - 2q_b = -2q_a$

In both cases we get an $SU(5)$ type charge relation, and hence standard charge quantization

$$M = 3,\ N = 2$$

Quark sector

$$Q(3, q_a) + Q(3, q_a + 2q_b) + X(3, q_a) + X(3, q_a - 2q_b) - U(3, -2q_a) - D(3, q_a)$$

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$$M = 3, \; N = 2$$

Quark sector

$$Q(3, q_a) + Q(3, q_a + 2q_b) + X(3, q_a) + X(3, q_a - 2q_b) - U(3, -2q_a) - D(3, q_a)$$

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In both cases we get an $SU(5)$ type charge relation, and hence standard charge quantization

$$M = 3,\ N = 2$$

Hence either $Q = 0$ ***or*** $X = 0$; the choice is irrelevant.

Take $X = 0$.

Then $D = Q = U,\ T = 0,\ L = E$

Remaining anomaly conditions: $L = Q$

Hence the only solution is a standard model family, occurring Q times.

The branes **a** and **b** are in principle unrelated, and can generally not be combined to a $U(5)$ stack

$M = 3,\ N = 2$

Higgs = T

The symmetric tensor can break $SU(2)\times U(1)$ in two ways, either to $U(1)$, in the same way as **L**, or to $SO(2)$.

Breaking to $U(1)$ (same subgroup as L)

No allowed Higgs couplings to give mass to the charged components of L, E and T, so we must require $E = L = T = 0$. Then there is no solution.

Breaking to $SO(2)$

Then $SO(2)$ must be electromagnetism. Y-charges forbid cubic T couplings, so $T = 0$ to avoid massless charged leptons. Quark charge pairing (to avoid chiral QED, broken by QCD) requires $Q = -X$. **If we also require $S = 0$, everything vanishes.**

Note: stronger dynamical assumption: $S = 0$

$M > 3$ and/or $N > 2$

- No solution for quark pairing for $M{>}3$
- Non-trivial solutions with quark and lepton pairing exist for $M{=}3,\ N{>}2$

  (This involves considering the most general $Q{+}\Lambda$, where Q is the external $U(1)$, and Λ a generator in the flavor group, left unbroken by dynamical symmetry breaking)

- All of them satisfy standard model charge quantization, even though $M{+}N \neq 5$
- But massless charged leptons can be avoided only for $N{=}2$

Conclusions

- The Standard Model is the only anthropic solution within the set of two-stack models.
- Family structure (and hence family repetition), charge quantization, the weak interactions and the Higgs choice are all derived.
- Standard Model charge quantization works the same way, for any value of N, even if $N+3 \neq 5$.
- The GUT extension offers no advantages.
- Only if all couplings converge (requires susy), GUTs offer an advantage.


AIA

Couplings

The $U(3)\times U(2)$ structure of this class of models implies one relation among the SM couplings, instead of the two of $SU(5)$

$$\frac{1}{\alpha_Y} = \frac{2}{3}\frac{1}{\alpha_s} + \frac{1}{\alpha_w}$$

see also:
Ibañez, Munos, Rigolin, 1998;
Blumenhagen, Kors, Lüst, Stieberger, 2007

Extrapolation this to higher energies we see that this is satisfied at $5.7\times 10^{13}\ \mathrm{GeV}$ $(1.4\times 10^{16}\ \mathrm{GeV}$ for susy).

Proton decay by SU(5) vector bosons would be far too large, but generically we do not have such bosons in the spectrum. There is no SU(5) in any limit.

But what happens at that scale?

If it is the string scale, one would still expect quantum-gravity related proton decay, which would be much too large.

But there are many ways out.

Complete list of solutions

Nr.	M	N	q_a	q_b	Higgs	Q	U	D	S	X	L	E	T
1	1	2	2	-3	$\mathbf{L}$	3	6	3	3	0	1	1	0
2	1	2	4	-1	$\mathbf{L}$	2	1	1	0	0	2	3	1
3a	1	2	2	-1	$\mathbf{L}$	3	4	1	3	-4	1	0	-1
3b	1	2	2	-1	$\mathbf{L}$	2	2	1	1	-1	1	1	0
3c	1	2	2	-1	$\mathbf{L}$	4	5	0	3	-4	0	1	-1
4	1	3	3	-2	$\mathbf{L}$	2	3	2	1	0	1	1	0
5	1	3	3	-1	$\mathbf{E}$	0	0	-2	-1	1	-2	1	0
6	1	4	4	-1	$\mathbf{L}$	1	1	1	0	0	1	1	0
7	M	2	1	ρ	$\mathbf{T}$	1	$-\rho$	$2M\rho$	$-\rho$	-1	$2M$	0	0
8	2	3	3	-2	$\mathbf{L}$	1	1	1	0	0	1	1	0
9	3	2	2	-3	$\mathbf{L}$	1	1	1	0	0	1	1	0

All chiral spectra without massless charged free leptons that can be obtained for all M and N with $q_a \neq 0$ and $q_b \neq 0$. Here $M = 1,2$ and ρ is a free integer parameter.

Complete list of solutions

Nr.	M	N	q_a	q_b	Higgs	Q	U	D	S	X	L	E	T
6	1	4	4	-1	**L**	1	1	1	0	0	1	1	0

This realizes the $SU(4)\times U(1)$ subgroup of SU(5).
The Higgs boson breaks this to $SU(3)\times U(1)$, QCD × QED.

But this implies $SU(5)$-type proton decay at the weak scale.

A family constitutes a single, complete $SU(4)$ Higgs multiplet.

Complete list of solutions

Nr.	M	N	q_a	q_b	Higgs	Q	U	D	S	X	L	E	T
8	2	3	3	-2	**L**	1	1	1	0	0	1	1	0

This is the same $SU(3)\times SU(2)\times U(1)$ subgroup of $SU(5)$ that gives rise to the Standard Model, but with a triplet Higgs instead of a doublet Higgs.

At low energies, there is a non-abelian $SO(4) \approx SU(2)\times SU(2)$ gauge group without conserved Baryon number.

The special case $q_a = 0$ (all M,N)

Anomaly cancellation:

$SU(M) \times SU(N) \times U(1)_Y$

$Q[(V, V, 1) + (V, \overline{V}, -1)] + \text{flavor-neutral } \mathbf{U}, \mathbf{D}, \mathbf{S} \text{ matter}$

For $M = 1{,}2$ this is vectorlike (hence massive)
For $M > 3$ there is no $U(1)$ in the flavor group that is non-chiral with respect to $SU(M)$, hence no electromagnetism.

Note: we treat Higgs and dynamical breaking on equal footing

The special case $q_b = 0$ (all M,N)

Anomaly cancellation:

$SU(M) \times SU(N) \times U(1)_Y$

$Q[(V,V,1) + (\overline{V},V,-1)] + Y\text{-neutral } \mathbf{L},\ \mathbf{E},\ \mathbf{T} \text{ matter}$

For $N = 1$,2 this is vector-like, and hence massive

For N ≥ 3 the candidate Higgses do not break $U(1)_{\mathrm{Y}}$

Hence the Higgs just has to break $SU(N)$ to a real group, and this is indeed possible, for example Higgs = **T**, breaking $SU(N)$ to $SO(N)$

$Q[(V,V,1) + (\overline{V},V,-1) + 2M(1,V,0)]$

No charged leptons; Baryon number is gauged, so baryogenesis would be problematic.