Why the Fundamental Representations seem enough?

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Talk at Kyoto University

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The SM is (almost) a great theory

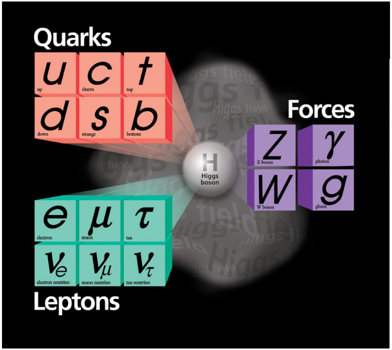
The New Physics Paradigm $\rightarrow$ NHDM, DM and FN singlet

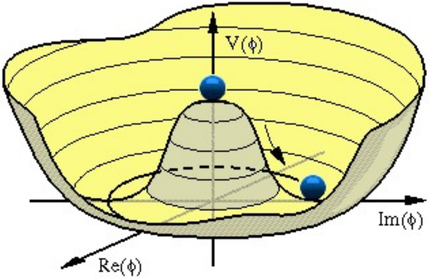
Large representations: where are they?

Conclusions.

I) The SM is a great theory

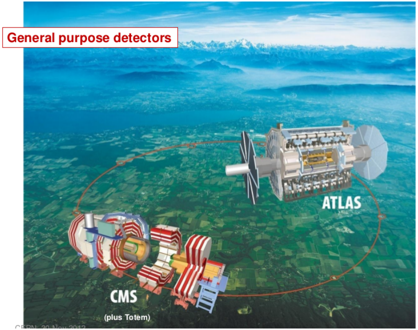
- Matter is made of quarks and leptons (3 families),
- Forces are associated with gauge symmetries ($SU(3)_c \times SU(2)_L \times U(1)_Y$ Yang-Mills),
- Masses arise from spontaneous symmetry breaking (SSB), a light Higgs boson being remmant of such mechanism,

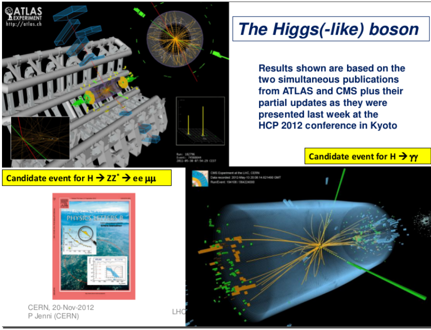


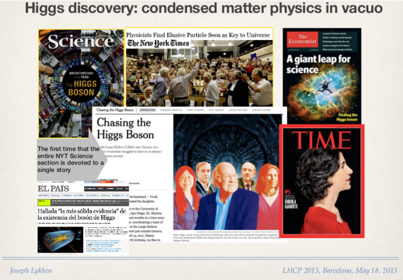


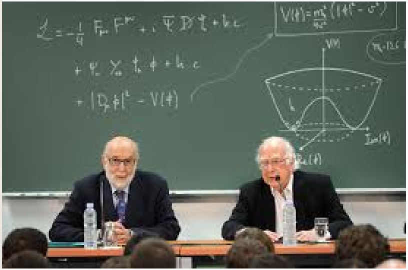
All these 3 aspects have been tested!

The discovery of the Higgs at LHC7.8 - 2012

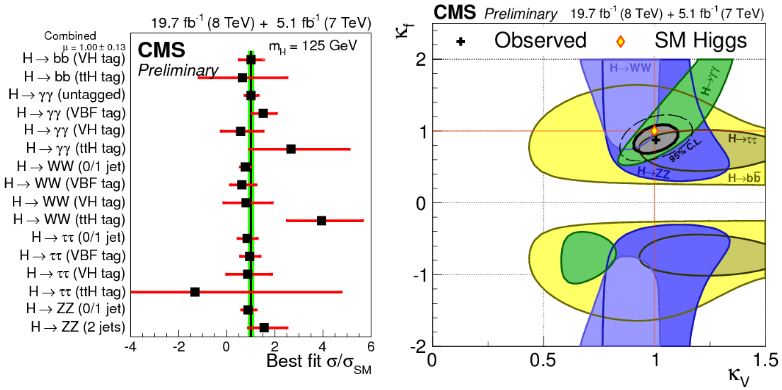








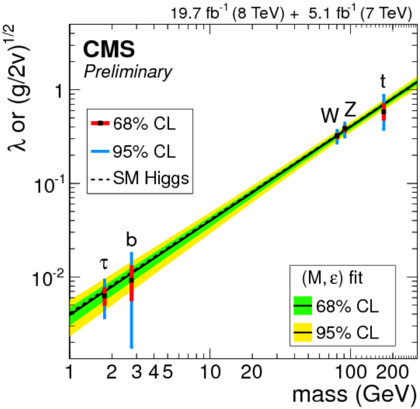
Higgs couplings from LHC



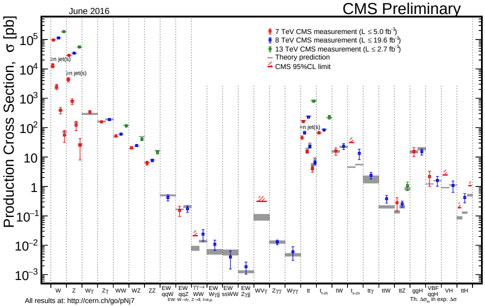
$$g_{hVV} = \kappa_V g_{hVV}^{sm}, \quad g_{hff} = \kappa_F g_{hff}^{sm},$$

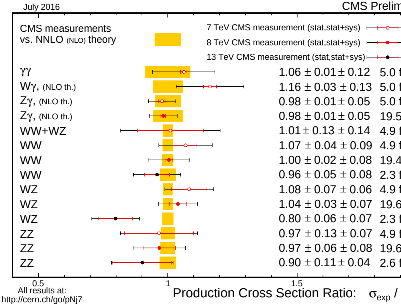
The Higgs identity from LHC

The couplings of the Higgs with particles, as a function of the mass, lays on a single line, which as been tested at LHC, i.e.



Tests of the SM





Agreement between theory and experiment is impressive! (This already includes the Higgs boson)

Questions about the Higgs nature

- Is it the SM Higgs? All couplings lay on a single line?
- How can we test the Higgs couplings with 2nd generation fermions?
  ($B.R.(h \to \mu^+\mu^-) \simeq 2 \times 10^{-4}$,
  $B.R.(h \to (c\bar{c}) + \gamma) \simeq 10^{-6}$)
- Are Higgs signal affected by new physics?
  (Is $h \to \gamma\gamma$ consistent with SM?)
- Signals of Flavor Violating Higgs Couplings
  (LFV Higgs decays: $h \to \tau\mu$?)
  (Top FCNC decay: $t \to c + h$?)
- Could the Higgs couplings with light quarks be extracted from: $\tau \to \mu + (s\bar{s})$?, $e - \mu$ conversion? DM search?
- Is the 125 GeV Higgs part of an extended Higgs Spectrum?
- New Physics BSM at LHC?

Multi-Higgs doublet models- our work

- "The Two Higgs Doublet Model with textures: 2HDM-Tx", J.L. Diaz-cruz, E. Diaz, M. Arrollo, J. Orduz,
- "Higgs couplings and new signals from Flavon-Higgs mixing effects within multi-scalar model", J. L. Diaz-Cruz, U. J. Saldaña-Salazar,
- "Has a Higgs-Flavon with $m_S = 750$ GeV mass been detected at LHC13?", A. Bolanos, J.L. Diaz-Cruz, G. Hernandez-Tome, G. Tavares,
- "Linking Higgs LFV and CPV", E. Barradas, J.L.D.-C., O. Felix, U. Saldana, work in progress,
- "Inert Dark Matter Model with an extra CP violation induced by a complex singlet", arXive: [hep-ph], D. Sokolowska, C. Bonilla, J. L. Diaz-Cruz, N. Darvishi, M. Krawczyk,

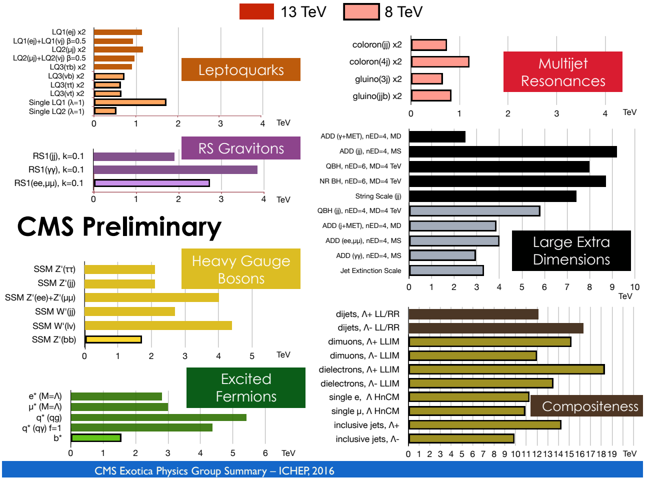
Open problems in the SM $\to$ New Physics

Trying to understand the SM structure (Parameters, gauge unification, DM, BAU, etc) have motivated the search for extensions of the SM,

- Large/Little hierarchy problem (T), Strong CP problem (T),
- Flavor problem: q, l, ν masses, CKM, CPV (T),
- Unification of all forces (T),
- Dark Matter (E), Cosmological constant (Dark energy) (E),
- Matter-Antimatter asymmetry of the Universe (E)
- Some deviations from the SM, e.g. Δa_μ, etc. (E)

So far, the use of symmetries have illuminated the understanding of elementary particles and their interactions.

LHC search for new physics



→ The SM rules up to O(TeV) scales!

Vanishing Hints of new physics

- Early data from LHC (ATLAS) suggested an excess on the rate for $h \to \gamma\gamma$, which seemed to open the room for new light particles (charged Higgs, stops, ...)
- Similarly, CMS7,8 reported hints of LFV Higgs decay $h \to \tau\mu$ with $B.R. \simeq 10^{-2}$,
- There was also the di-photon signal at 750 GeV which produced initial excitement ...
- Other fluctuations appear here and there...
- But sadly, all of them are gone,

A crisis in HEP?

Hints of 750 GeV signal caused lots of controversy, partly because more than 500 theory papers (including one from us! ... err)

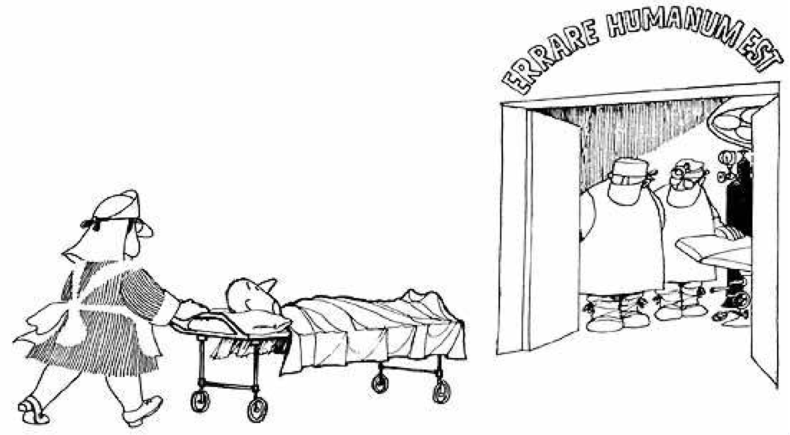
From Resonaances (A. Falkowski): Given that for 30 years we have been looking for BSM theory, our reaction was not disproportionate... Excitement is an inherent part of physics research. And so is disappointment, apparently.

Comments from the blog:

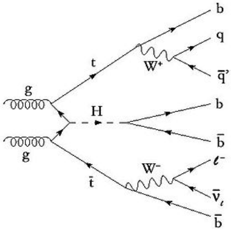
- "Seriously: young people: get out of here and don't look back."
- "Accusing the entire hep-th community of engaging in a deceitful enterprise is outrageous."
- "This is the end of particle physics."

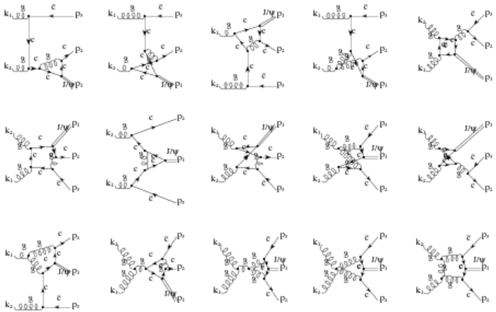
Other Physics "gone with the wind"

- Higgs boson of 7 GeV (also 98 GeV, 115 GeV, 140 GeV)
- Top quark of 45 GeV,
- Neutrinos faster than light,
- Tensor modes/inflation...
- Cold fusion, ... etc, etc, etc,

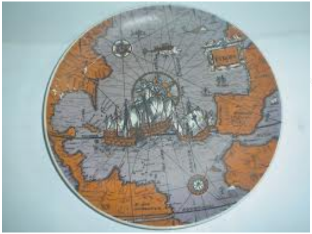


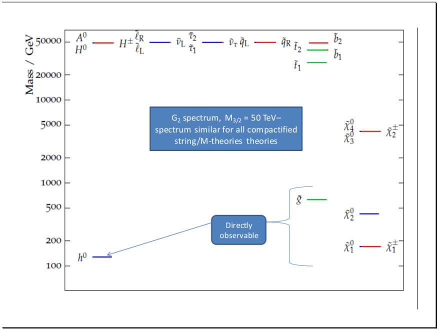
"Shut up and calculate" (R Feynman)



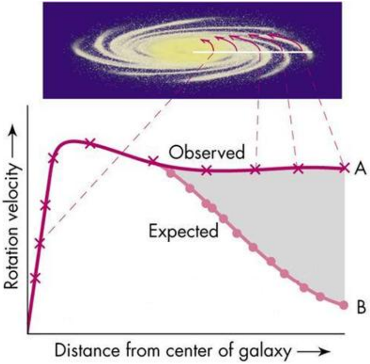


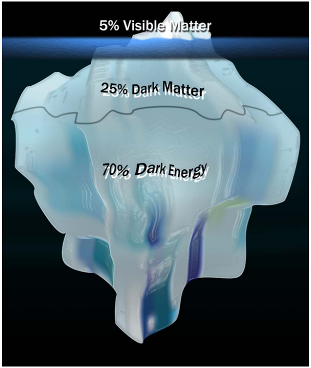
Search for new physics - keep looking!





Dark Matter - WIMPS

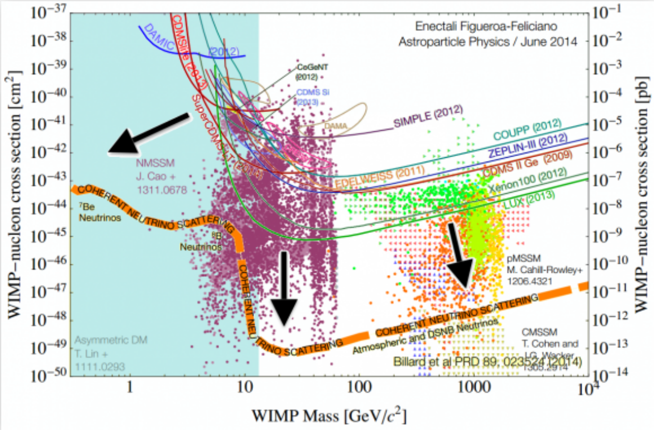




Many models of Physics Beyond the SM are motivated because they include a discrete symmetry (ex Z_2), such that a Z_2-odd particle is stable and could be a viable DM candidate (WIMP).

Dark Matter searches (wimp-direct)

The search for WIMPS involves both cosmology and energy frontiers.

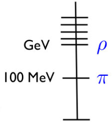


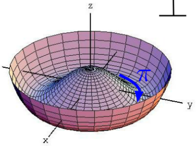
Higgs- Dark matter connection

Composite PGB Higgs

Inspired by QCD where one observes
that the (pseudo) scalars are the lightest states

Spectrum:





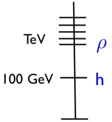
Are Pseudo-Goldstone bosons (PGB)

Mass protected by the global QCD symmetry!

$$\pi \longrightarrow \pi + \alpha$$

The light Higgs can be a kind of pion from a new strong sector

The spectrum of the new strong sector could be:



Pseudo-Goldstone bosons (PGB)

Mass protected by the global symmetries!

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Holographic Dark Matter and Higgs Models

J. Lorenzo Díaz-Cruz

Phys. Rev. Lett. **100**, 221802 – Published 5 June 2008

A Gauge Origin for SM parameters?

- The SM includes 19 parameters, of which only 3+1 are associated with gauge principle, what about the rest?
- In SUSY QFT: Quartic Higgs and "Yukawa" interactions fermion-sfermion and gaugino, are related to gauge couplings ($\rightarrow$ SUSY-induced radiative fermion masses),

J. LORENZO DÍAZ-CRUZ, *Mod. Phys. Lett. A* **20**, 2397 (2005). DOI: http://dx.doi.org/10.1142/S0217732305017949

TRACING THE GAUGE ORIGIN OF YUKAWA AND HIGGS PARAMETERS BEYOND THE STANDARD MODEL

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We discuss possible realizations of the hypothesis that all the fundamental interactions of the elementary particles should be of gauge type, including the Yukawa and Higgs ones. In the minimal SUSY extension of the standard model, where the quartic Higgs couplings are "gauged" through the D-terms, it is also possible to generate radiatively the Yukawa matrices for the light generations, thus expressing them as functions of gauge couplings. The program can also be applied to the SUSY LR model, where the possibility to induce radiatively the mixing angles, can help to make viable the parity solution to the strong CP problem. The superpotential of the model still includes some non-gauge couplings, namely, the Yukawa constants for the third generation and the trilinear terms $\lambda\chi_L\Phi\chi_R$ and $\lambda'\chi_L^c\Phi\chi_R^c$, involving the Higgs bi-doublet (Φ) and two pairs of doublets (χ_L, χ_R and their conjugates). Additional progress to relate these parameters to gauge couplings, can be made by embedding the LR model within a SUSY model $SU(4)_W \times U(1)_{B-L}$ in five dimensions, where the Higgs bi-doublet is identified as the extra component of the 5D gauge field.

Keywords: Meson; mass relation; Regge phenomenology
PACS: 12.40.Yx, 14.40.-n, 11.55.Jy

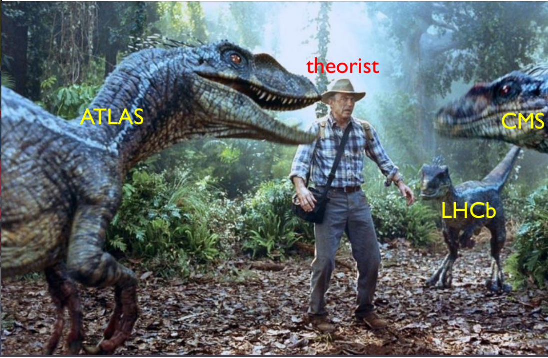
But if nothing else is found at LHC, Then what?

May be is time to go back to study the fundamental principles that support the SM

Back to the roots of HEP and the SM

We should remind that HEP theory includes

1. Formal aspects / QFT,
2. Model building,
3. Phenomenology,



Foundations of the SM

Formal developments are perhaps the area with far reaching goals, which could have influence even in other areas of physics,

(a) Gauge principle (Yang-Mills): It provides a rationale for the origin of interactions,

(b) SSB: After the works of Englert-Brout, Higgs, particle physics had a general method to provide masses to gauge vector bosons. From these, it has to be a matter of experiments and model building to find out which model was chosen by nature.

(c) Renormalization of Gauge Theories: 't Hooft and Veltman provided a general method to build renormalizable gauge theories with massive vector bosons.

(d) Anomalies $\rightarrow$ Geometry and QFT.

The Matter Representations within the SM

- Experimental data (from beta-decay to discovery of top quark) have restricted matter representations,
- Weak interactions require chiral QFT,
- Known matter appears, at most, in the Fundamental Representations of the SM gauge group,
- Known leptons are either siglets or doublets of $SU(2)_L$,
- The known quarks are in addition triplets of $SU(3)_c$,

Who ordered that?

Spin, Isospin and Reprs.

T / S	0	1/2	1	3/2	2
0	?	Neutrinos-R	gluon	?	?
1/2	Higgs	electron quarks	?	?	?
1	?	?	W, Z	?	?

Where have all the large representations gone?

What are the known limits for larger reprs.?

What principle dictates the SM structure?

Bounds on large representations

1. EWPT (S, T, U limits).
   To keep T UV finite (H.H. Zhang et al, MPLA 23, 2008):
$$\sum_{l}(j^2 + j - 3l^2)m_j^2 = 0 \qquad (1)$$
2. Collider searches:
   LHC has searched for new exotics, e.g. For gluino: $M > O(1)$ TeV,
3. Unitarity bounds:
   H. Logan et al, find that for complex scalar multiplet: $T \leq \frac{7}{2}$

EWPT and Unitarity bounds (K. Earl et al.,PRD 90,2014)

$Y = 2T = n - 1$

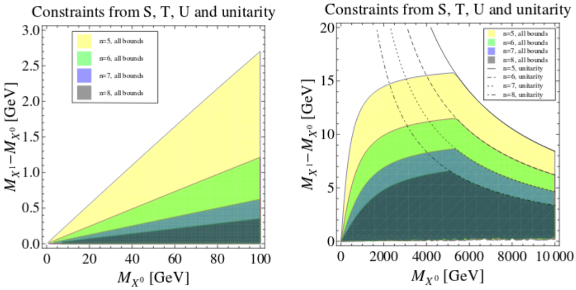


FIG. 1. The 95% confidence level constraints on $\Delta m \equiv m_{\chi^{+1}} - m_{\chi^0}$ as a function of m_{χ^0} from the S, T, and U parameters, for the scalar multiplets with $n = 5$, 6, 7, and 8 and $Y = 2T = n - 1$. Dashed lines indicate the upper limit on Δm from the unitarity bound on λ_3. The left panel shows the low-m_{χ^0} region while the right panel extends to higher masses.

Current approaches to problem of reprs.

Some work has been done on absence of large reprs, or rather why only small reprs. appear in nature

1. Effective selection rules (H. Nielsen et al),
2. Discrete symmetries (L. Bento),
3. Composite quarks and leptons (JLDC et al),
4. Unification and minimal complexity (JLDC)

Effective selection rules (H. Nielsen et al)

- SM gauge group is rather special, it shows a minimal degree of "skeweness",
- The gauge groups has associated some quantity that gets maximized and singled out the $S(U(2) \times U(3)$ gauge group.
- Defined as ratio of quadratic Casimir invariant for the adjoint representation and that for the smallest (matter) representation.
- Furthermore, this quantity also helps to single out the fundamental reprs. for quarks, leptons and Higgs,
- Similarly, possible to find a related quantity that singles out: $D = 4$.

SM gauge group wins a group competition

$$\text{“goal quantity”} = \left(\prod_{\text{simple groups } i} \left(\frac{C_A}{C_F}\right)_i^{d_i} * \prod_{\text{Abelian factors } j}^{J} \left(\frac{e_A^2}{e_F^2}\right)_j \right)^{1/d_G}.$$

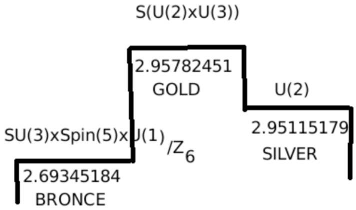


Figure 1: This figure illustrates the three Lie groups getting in our game the highest scores for our “goal quantity” as were the sportsmen winning gold silver and bronze medals.

Discrete symmetries (L. Bento, PLB,1992)

- Bento studied discrete symmetries as away to look for some constrait on the size of the allowed represenntations,
- Idea is to find which representations use consistently the same definition for the discrete symmetry.
- Similarly, using invariance under change of basis restricts possible reprs.,
- Conclusion: Only fundamental reprs of SU(N) are consistent,

Compositeness

- It could happen that we only observe the small representations because of a dynamical reason. Namely, that quarks and leptons are composite.
- Use nuclear physics analogy: only nucleus with $Z \lesssim 120$ are obseved in nature, because of limit when nuclear attractive force between nucleons ($p\,\&\,n$), wins over the electromag. repulsion. Namely, when $F_{em} = k\frac{Z^2e^2}{r^2} \sim \frac{e^{-mr}}{r}$.
- If quarks and leptons are composites, then only doublets of $SU(2)_L$ and triplets of $SU(3)_c$ exist, because a repulsive force among constituents makes impossible to form bound states with large values of isospin.
- Possible that some imprint would be left on the SM fermion properties by the composite dynamics, for instance on the anomalous magnetic coments.

Grand Unification and representations

- Another possible reason for the appearence of fermions in small representation, could be based on the unification paradigm.
- Namely, it is rather remarkable that known quarks and leptons fit into almost-small reprs. of Grand Unified gauge group, e.g. 5 and 10 of $SU(5)$,
- Then, we could ask wheather the addition of larger multiplets, could still be unified in some gauge group, without adding much complications,
- More ambitius program would include finding group theory reason for replication of families,

A principle of minimal complexity

"When a multiplet of certain dim. is added to SM, in order to have a complete multiplet under some GUT gauge group, no repr. of larger dimension should be allowed"

[Principle can be strengthened when combined with requirement of Anomaly cancellation, (JL DC et al, PRD80, 2009)]

Branching rules for $SU(5)$

Dim $[SU(5)]$	$SU(2)$	$SU(3)$	$6Y$
5	2	1	3
	1	3	-2
10	1	1	6
	1	3	-4
	2	3	1
15	3	1	-
	2	3	-
	1	6	-
24	1	1	-
	3	1	-
	2	3	-
	2	$\bar{3}$	-
	1	8	-
45	2	1	-
	1	3	-
	3	3	-
	1	$\bar{3}$	-
	2	3	-
	1	6	-
	2	8	-

The case of EW Triplets

Fermion triplets have been used extensively in models of neutrino masses, how do they fare with minimal complexity principle?

- For instance, in the case of $SU(5)$ GUT group, adding a weak triplet requires adding extra matter, e.g. one needs to add a 6 when useing the 15-dim. repr.
- Better fate for weak triplets appear in trinified models $SU(3)_c \times SU(3)_L \times SU(3)_R$, (JLDC, E. Ma, PLB695, 2011)

<u>*E_6 origin*</u> : As listed in Eqs. (1) to (4), there are 27 chiral fermion fields per generation in this model. This number is not an accident, because it comes from the fundamental representation of E_6 or $[SU(3)]^3 = SU(3)_C \times SU(3)_L \times SU(3)_R$. Under the latter which is the maximal subgroup of the former, these fields transform as $(3,3^*,1)+(1,3,3^*)+(3^*,1,3)$, i.e.

$$\begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} + \begin{pmatrix} N & E^c & \nu \\ E & N^c & e \\ \nu^c & e^c & n^c \end{pmatrix} + \begin{pmatrix} d^c & d^c & d^c \\ u^c & u^c & u^c \\ h^c & h^c & h^c \end{pmatrix}. \tag{11}$$

The decomposition of $SU(3)_L \to SU(2)_L \times U(1)_{Y_L}$ is completely fixed because of the standard

Gauge-Family Unification

Look at family problem using properties of orthogonal Lie groups (See A. Zee, Kyoto lectures, 1981),

- Consider gauge group $\mathcal{G}$ containing a single repr. $\mathcal{R}$,
- This group breaks to the GUT gauge group: $\mathcal{G} \to G$,
- Also $\mathcal{R} \to R + R + R + \ldots$, with R being one family,
- The group $SO(2(n+m))$ enjoy the property that spinor reprs. break into 2^m reprs. of $SO(2n)$,
  e.g. For $n = 5, m = 4$, $SO(18)$ gives 8 families of $SO(10)$ (V-A) + mirror fermions (V+A),
- It could be interesting to ask if the structure of the group $\mathcal{G}$ is such that it only allows a unique representation.

Conclusions.

- LHC is testing properties of SM-like Higgs ($m_h = 125$ GeV), "...the higgs boson could had not been discovered by accident" (J. Wells, arXiv:1609.04268 [hep-ph]) "The discovery of the Higgs boson will remmain as one of the major physics discoveries of our time"(G. Altarelli)
- There are strong motivations for BSM Physics, but so far nothing else has been found, then what?
- May be it is the time to look again at the roots of the SM,
- Why only small reprs.? May be there is a deep reason that explains so.
  $\rightarrow$ Grand Unification and Minimal Complexity could restric the possible reprs.