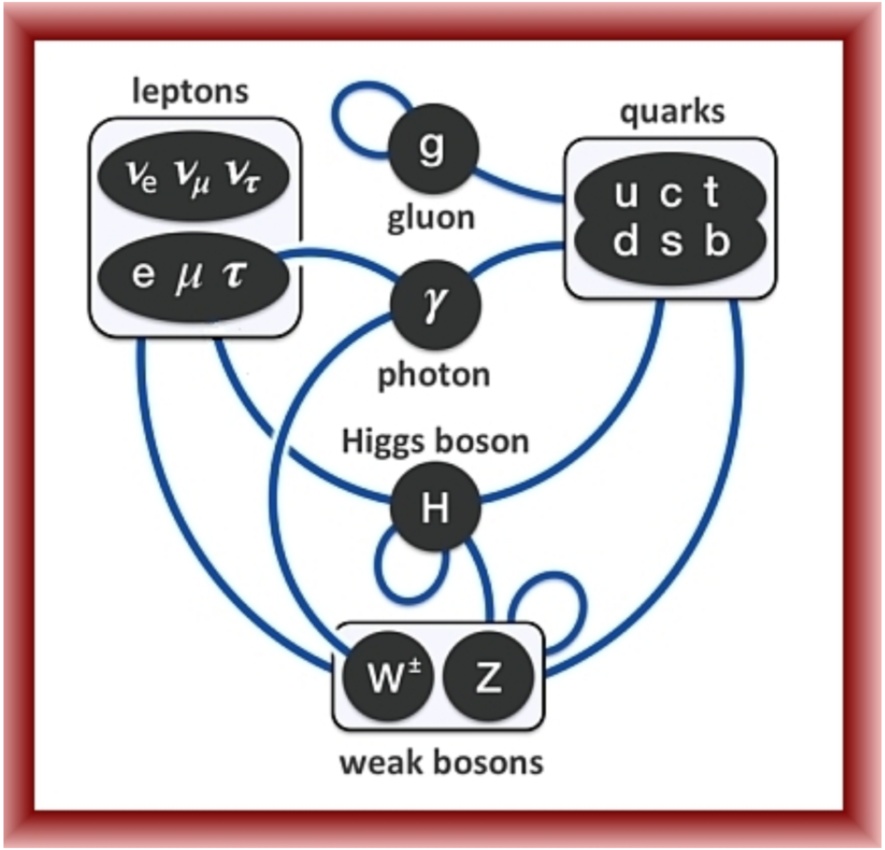
The Standard Model

Yesterday, Today, and Tomorrow

Howard Georgi

Harvard

What is the standard model



johncarlosbaez.wordpress.com

The RISE of Particle Physics?

There was great particle physics experiment and theory in the 1950s and 1960s

Highlights from the timeline

1950 Bjorklund, Crandall, Moyer, York observed the $\boldsymbol{\pi}^0$

1951 Petermann, Stueckelberg renormalisation group

1952 Courant, Livingston, Snyder invented strong focusing principle for particle accelerators

1952 Glaser invented the bubble chamber

1952 Pais hypothesized associated production

1953 Gell-Mann and Nishijima connected strangeness, charge and isospin

1954 Yang and Mills constructed non-abelian gauge theory

1954 Low and Gell-Mann revisted the renormalisation group

1955 Gell-Mann and Pais disentagled the $K_L - K_S$ puzzle

1955 Chamberlain, Segre and Wiegand discovered the anti-proton

1956 Reines and Cowan detected neutrinos

1956 Goldhaber, Grodzins and Sunyar showed that neutrinos have negative helicity

1956 Cork, Lambertson, Piccioni, Wenzel found evidence for anti-neutron

1956 Block, Lee and Yang argued that weak interaction could violate parity

1956 Reines and Cowan detected anti-neutrinos

1957 Marshak, Sudarshan, Feynman, Gell-Mann predicted that weak interactions would be $V - A$

1957 Wu and Friedman, Lederman, Telegdi observed parity violation in weak decays

1958 Goldberger, Treiman their relation

1958 Gary Feinberg (Schwinger) predicted that muon neutrino is distinct from electron neutrino

1959 Regge worked out the theory of his poles

1960 Gell-Mann and Levy constructed the sigma model of pions and nucleons

1961 Nambu and Jona-Lasinio connected dynamical symmetry breaking and the pion

1961 Good etal (LBL) observed regeneration and macroscopic quantum interference in $\boldsymbol{K}$s

1961 Glashow introduced the $\boldsymbol{Z}$ and weak mixing angle

1961 Goldstone analyzed his bosons

1961 Gell-Mann and Ne'eman found the eightfold way

1961 Robert Hofstadter found internal structure in nucleons

1961 Geoffrey Chew espoused nuclear democracy and the bootstrap model

1962 Lederman, Steinberger, Schwartz found evidence for two neutrinos

1962 Gell-Mann and Ne'eman predicted the Omega minus particle

1963 Samios detected the Omega mimus Baryon

1963 Anderson showed that gauge theories can evade the Goldstone theorem

1963 Cabibbo described flavor mixing

1963 Gell-Mann and Zweig invented quarks

1964 Brout, Englert, Higgs, Guralnik, Hagen, Kibble constructed U(1) Higgs theories

1964 Christenson, Cronin, Fitch, Turlay observed CP violation

1964 Gell-Mann formulated current algebra

1964 Gursey, Pais, Radicati discussed SU(6)

1964 Bjorken and Glashow suggested charm

1964 Salam, Ward wrote down SU(2)xU(1) without Higgs

1964 Bell analyzed quantum entanglement

1965 Greenberg, Han, Nambu connected SU(3) color and quark statistics

1966 Kibble generalized the Higgs mechanism to Yang-Mills theory

1966 Weinberg calculated pion scattering lengths

1967 Weinberg constructed a nonlinear realization of chiral symmetry

1967 Weinberg published famous model of leptons

1967 Davis found the solar neutrino problem

1968 Veneziano initiated string theory with his dual resonance model

1968 Bjorken suggested scaling in Deep Inelastic Scattering

1968 Feynman built his parton model of DIS

1969 Adler, Jackiw discovered chiral anomalies

1969 Kendall, Friedman, Taylor found hard structure inside protons

1969 Wilson formulates the operator product expansion

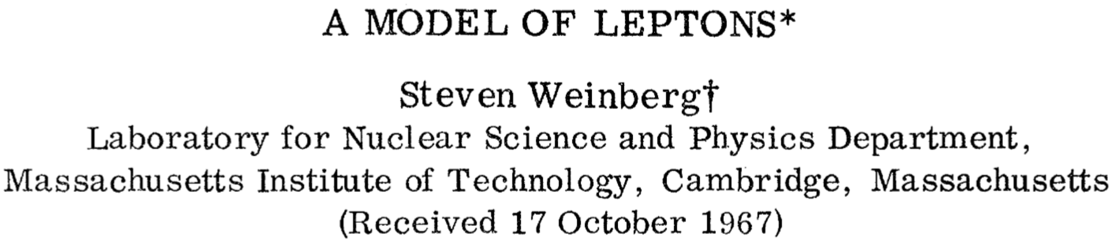
So why were particle physicists depressed?

These fantastic experimental discoveries and theoretical breakthroughs created as many puzzles and frustrations as they solved.

puzzles

The suppresion of FCNC? — Why approximate SU(3)? And why is isospin symmetry so much better? — Partons=Quarks? — Why don't we see quarks/partons if they are almost free? — How can DIS and $e^+e^- \rightarrow$hadrons be reconciled? — If quarks can have fractional charges, why the don't we see them, and more generally why is the hydrogen atom neutral in the first place? — Why are current algebra quark masses so different from constituent masses? — Why doesn't the η' look like a Goldstone boson (chiral U(1) problem)? — Why is CP violation so small? — $\cdots$

Frustrations — Current algebra seemed to work sometimes but was not very systematic. — Strong interaction dynamics was completely unknown.



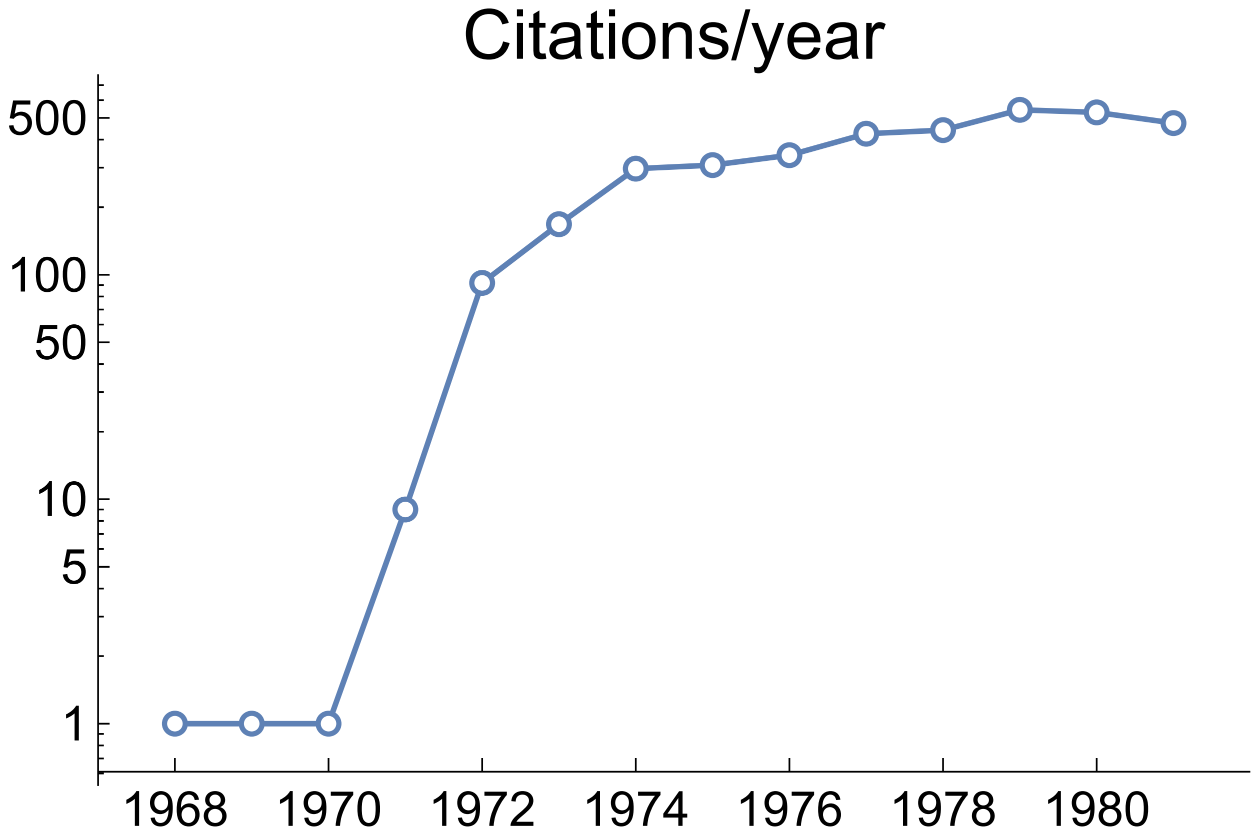
A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

The renormalizability of Weinberg’s model of leptons was just a speculation.

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields. And if this model is renormalizable, then what happens when we extend it to include the couplings of $\vec{A}_\mu$ and B_μ to the hadrons?

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields. And if this model is renormalizable, then what happens when we extend it to include the couplings of $\vec{A}_\mu$ and B_μ to the hadrons?


Citations/year
500
100
50
10
5
1
1968
1970
1972
1974
1976
1978
1980

https://www.cntraveler.com/story/iceland-new-era-of-volcanic-tourism

Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†

Having introduced four quarks, we must consider strong interactions which admit the algebra of chiral $SU(4)$. Does this mean we should expect $SU(4)$ to be an approximate symmetry of nature? Nothing in our argument depends on how much $SU(4)$ is broken; the divergences are necessarily properly ordered. However, for the higher-order nonleading divergences to be as small as they must be, the breaking of $SU(4)$ cannot be too great: The limit on the cutoff Λ is replaced by a limit on Δ, a parameter measuring $SU(4)$ breaking; and from the observed K_1K_2 mass difference we now conclude that Δ must be not larger than 3–4 GeV.

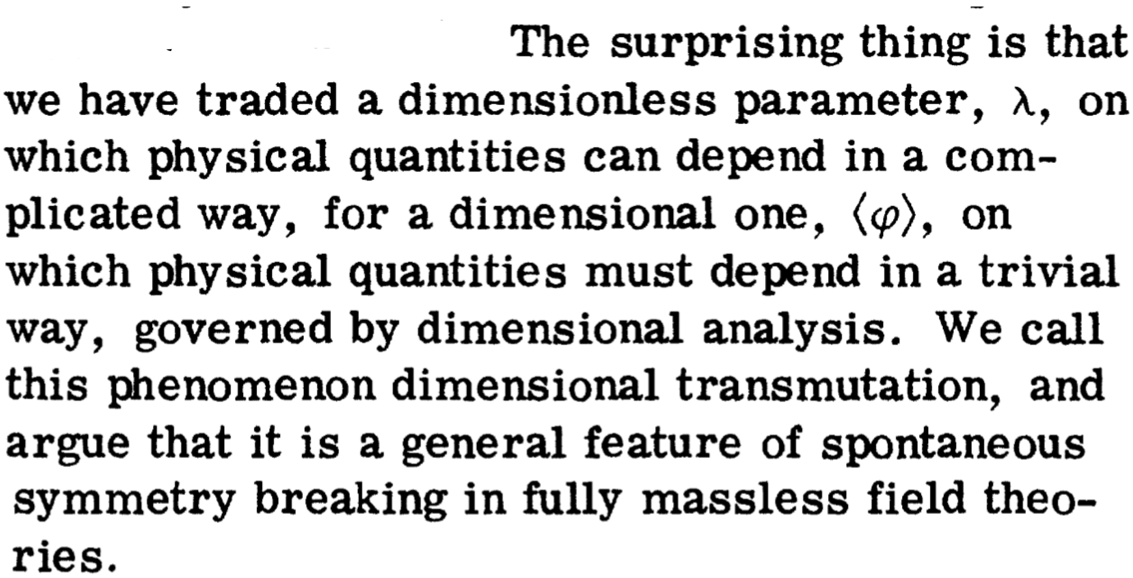
RENORMALIZABLE LAGRANGIANS FOR MASSIVE YANG-MILLS FIELDS

G.'t HOOFT

Our result is a large set of different models with massive, charged or neutral, spin one bosons, photons, and massive scalar particles. Due to the local symmetry our models are renormalizable, causal, and unitary. They all contain a small number of independent physical parameters.

Radiative Corrections as the Origin of Spontaneous Symmetry Breaking

Sidney Coleman and Erick Weinberg



The surprising thing is that we have traded a dimensionless parameter, λ, on which physical quantities can depend in a complicated way, for a dimensional one, $\langle\varphi\rangle$, on which physical quantities must depend in a trivial way, governed by dimensional analysis. We call this phenomenon dimensional transmutation, and argue that it is a general feature of spontaneous symmetry breaking in fully massless field theories.

the Z, the mixing angle, and algebraic charge quantization

SO(3) [HG+SLG] motivated by experiments that failed to see the expected neutral currents. Charged leptons in triplets

$$\begin{pmatrix} E^+ \\ \cos\phi\,\nu_e + \cdots \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} E^+ \\ \cdots \\ e^- \end{pmatrix}_R \quad + \quad \begin{matrix} e^- \to \mu^- \\ E^+ \to M^+ \end{matrix}$$

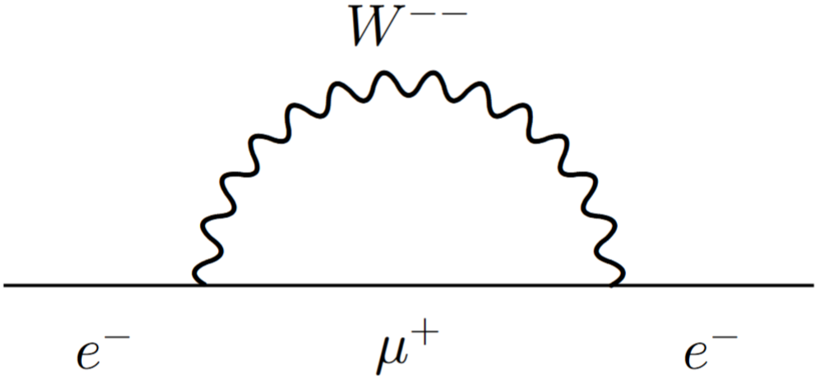
Higgs SO(3) triplet — we liked charge quantization

the Lee-Prenki-Zumino model had no neutral heavy leptons but put RH leptons in singlets - so they needed a Z

Mixing Angle in Renormalizable Theories of Weak and Electromagnetic Interactions*

Steven Weinberg

$$\begin{pmatrix} e^- \\ \nu_e \\ \mu^+ \end{pmatrix}_L \qquad \begin{pmatrix} \mu^- \\ \nu_\mu \\ e^+ \end{pmatrix}_L \qquad \langle \phi \rangle = \begin{pmatrix} V & 0 & 0 \\ 0 & V & 0 \\ 0 & 0 & -2V \end{pmatrix}$$



AN ANOMALY-FREE VERSION OF WEINBERG'S MODEL

C. BOUCHIAT, J. ILIOPOULOS and Ph. MEYER

cancellation of SU(2)×U(1) gauge anomalies for 3 colors of fractionally charged quarks.

Gross and Jackiw prove renomalizability but for some reason don't mention that fractional charges and 3 colors works.

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

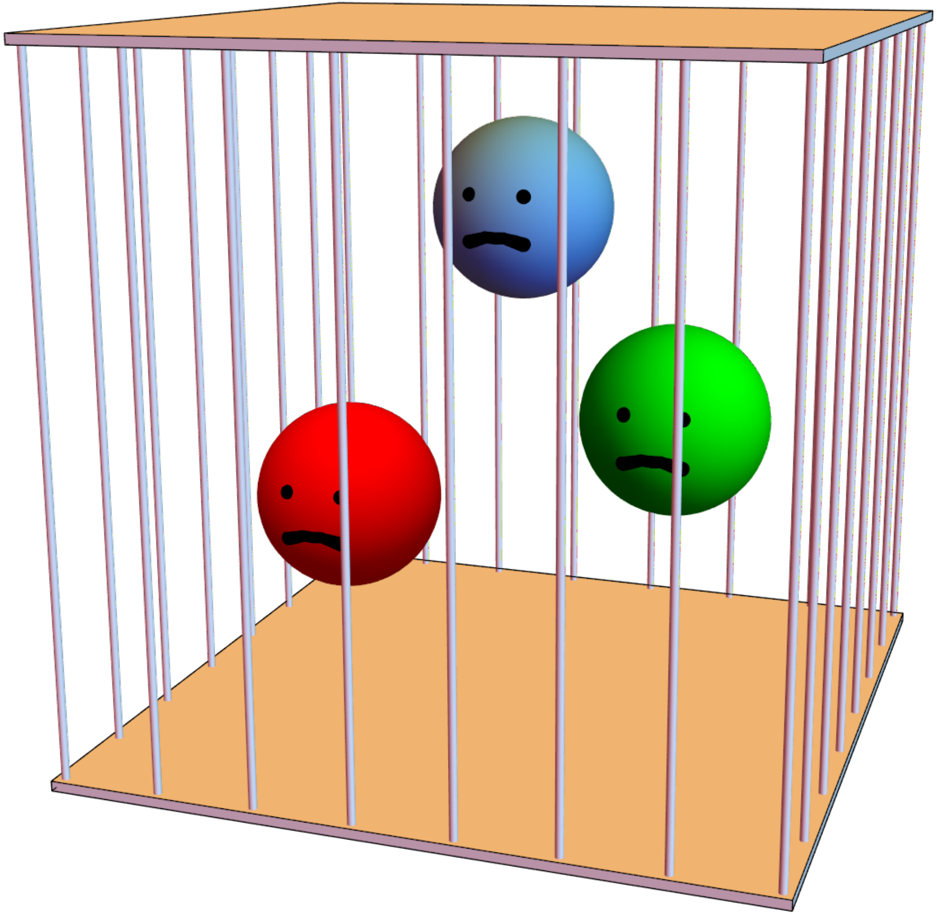
Lepton number as a 4th color — Pati-Salam

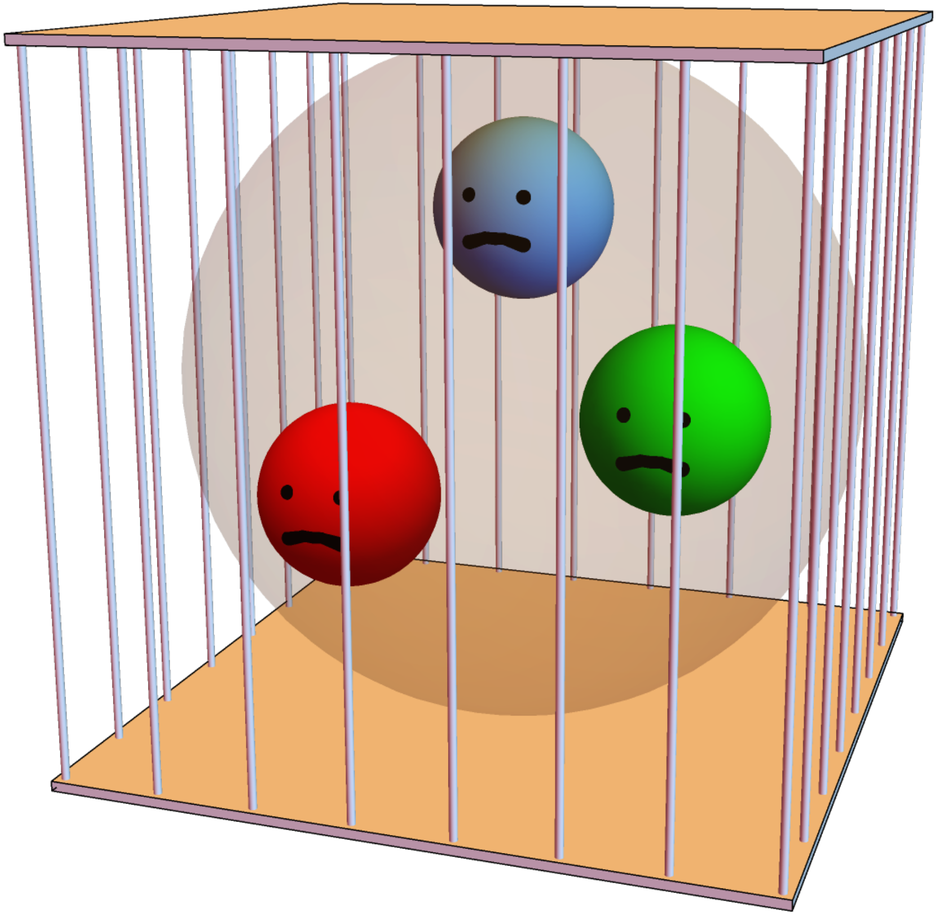
$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{SU}(4)$

$$SU(2)_L \left\{ \overbrace{\begin{pmatrix} u_{rL} & u_{gL} & u_{bL} & \nu_L \\ d_{rL} & d_{gL} & d_{bL} & e^-_L \end{pmatrix}}^{SU(4)} \right.$$

$$SU(2)_R \left\{ \overbrace{\begin{pmatrix} u_{rR} & u_{gR} & u_{bR} & \nu_R \\ d_{rR} & d_{gR} & d_{bR} & e^-_R \end{pmatrix}}^{SU(4)} \right.$$

Papers are hard to read because Salam didn’t believe in fractionally charged quarks





Pati-Salam SU(2)$_L$×SU(2)$_R$×SU(4)

$=$ SO(4)×SO(6) $\rightarrow$ SO(10)

16 dimensional spinor

$\langle \phi_{16} \rangle$ breaks SO(10)$\rightarrow$SU(5)

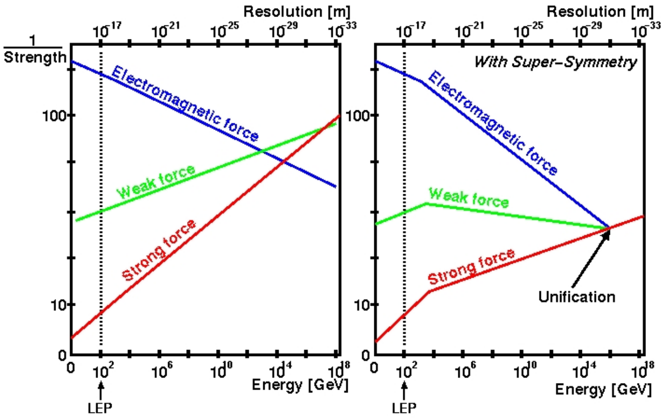
PERFECT FIT

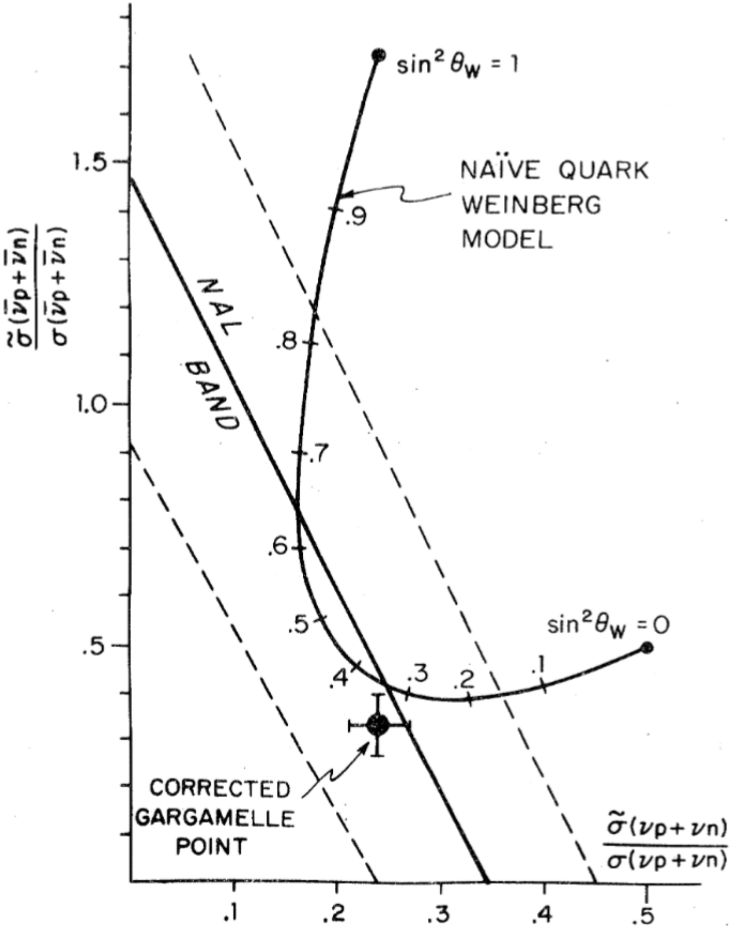
Hierarchy of Interactions in Unified Gauge Theories*

H. Georgi,† H. R. Quinn, and S. Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

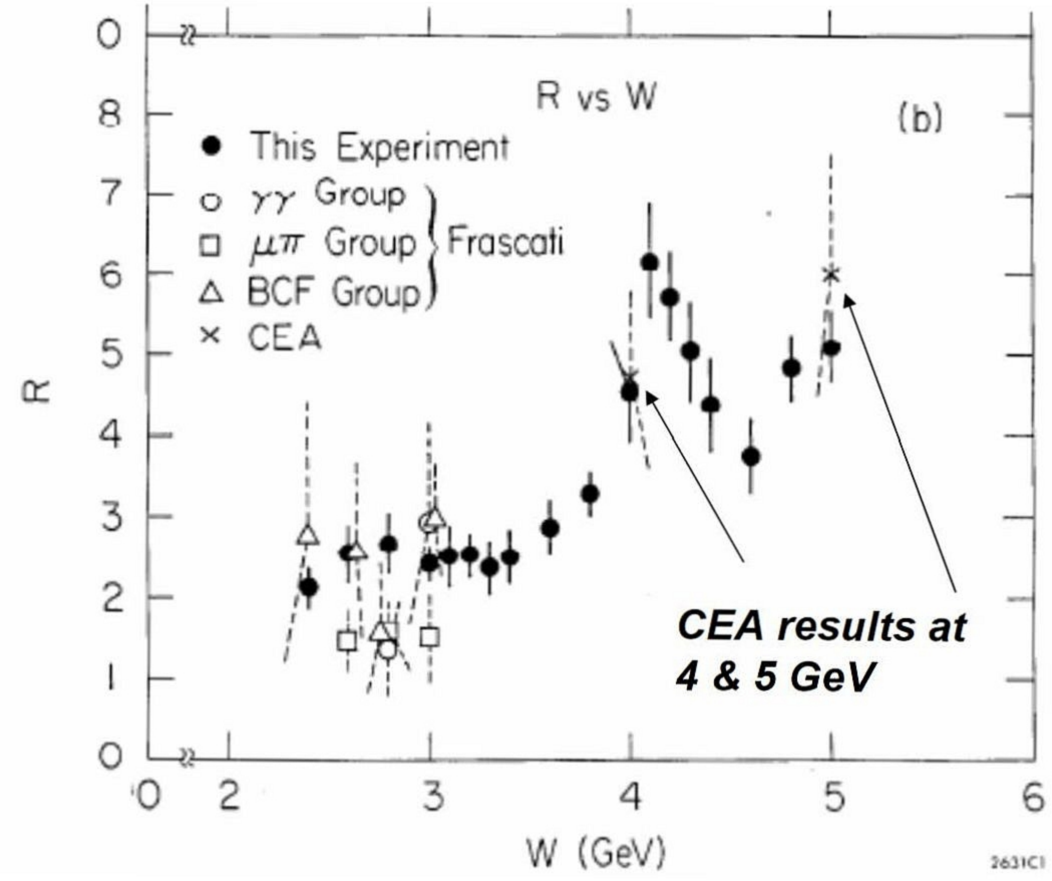
(Received 15 May 1974)

We present a general formalism for calculating the renormalization effects which make strong interactions strong in simple gauge theories of strong, electromagnetic, and weak interactions. In an SU(5) model the superheavy gauge bosons arising in the spontaneous breakdown to observed interactions have mass perhaps as large as 10^{17} GeV, almost the Planck mass. Mixing-angle predictions are substantially modified.



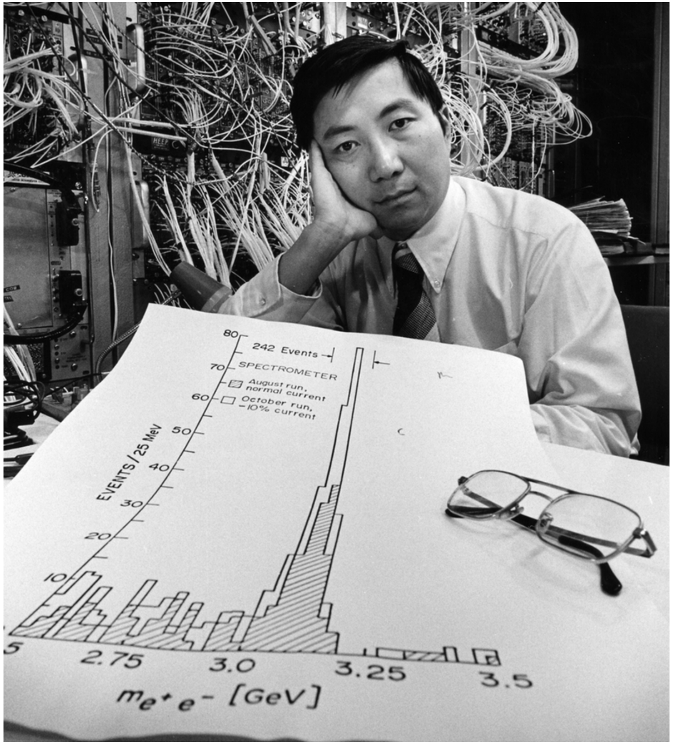


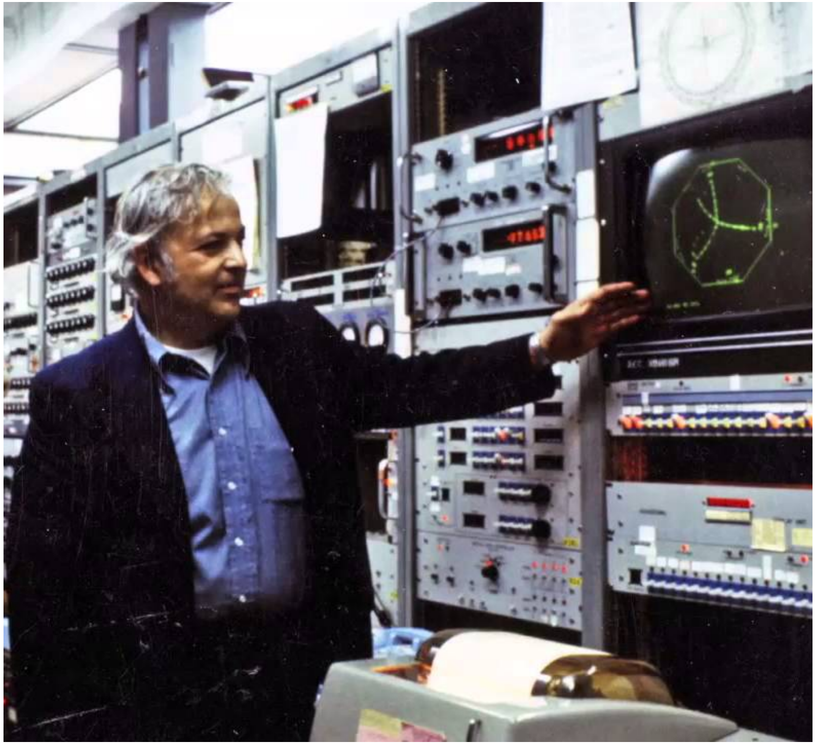
$\sin^2\theta_W = 1$
NAÏVE QUARK
WEINBERG
MODEL
.9
.8
.7
.6
.5
.4
.3
.2
.1
$\sin^2\theta_W = 0$
NAL
BAND
CORRECTED
GARGAMELLE
POINT
$\frac{\tilde{\sigma}(\bar{\nu}p+\bar{\nu}n)}{\sigma(\bar{\nu}p+\bar{\nu}n)}$
$\frac{\tilde{\sigma}(\nu p+\nu n)}{\sigma(\nu p+\nu n)}$
1.5
1.0
.5
.1
.2
.3
.4
.5



CEA results at 4 & 5 GeV

SLAC-PUB-1520, LBL-3621; January 1975





Physical Review Letters 6 January 1975 — 8 theory articles

Are the New Particles Baryon-Antibaryon Nuclei?

Alfred S. Goldhaber and Maurice Goldhaber

Baryon-antibaryon bound states and resonances could account for the new particles, as well as narrow states near nucleon-antinucleon threshold, which were reported earlier. [no comment]

Interpretation of a Narrow Resonance in e+e- Annihilation

Julian Schwinger

A previously published unified theory of electromagnetic and weak interactions proposed a mixing between two types of unit-spin mesons, one of which would have precisely the characteristics of the newly discovered neutral resonance at 3.1 GeV. With this interpretation, a substantial fraction of the small hadronic decay rate can be accounted for. It is also remarked that other long-lived particles should exist in order to complete the analogy with ρ^0, ω, and ϕ. [no comment]

Possible Explanation of the New Resonance in e+e- Annihilation

S. Borchardt, V. S. Mathur, and S. Okubo

We propose that the recently discovered resonance in e+e- annihilation is a member of the $15 \oplus 1$ dimensional representation of the SU(4) group. This hypothesis is consistent with the various experimental features reported for the resonance. In addition, we make a prediction for the masses of the charmed vector mesons belonging to the same representation. [mentions charm but completely misses the point]

Model with Three Charmed Quarks

R. Michael Barnett

The spectroscopy and weak couplings of a quark model with three charmed quarks are discussed in the context of recent results from Brookhaven National Laboratory, Stanford Linear Accelerator Center, and Fermi National Accelerator Laboratory. [no comment]

Possible Interactions of the J Particle

H. T. Nieh, Tai Tsun Wu, and Chen Ning Yang

We discuss some possible interaction schemes for the newly discovered particle J and their experimental implications, as well as the possible existence of two $\boldsymbol{J^0}$'s like the $\boldsymbol{K_S}$-$\boldsymbol{K_L}$ case. Of particular interest is the case where the J particle has strong interactions with the hadrons. In this case J can be produced by associated production in hadron-hadron collisions and also singly in relative abundance in ep and $\boldsymbol{\mu}$p collisions. [no comment]

Is Bound Charm Found?

A. De Rújula and S. L. Glashow

We argue that the newly discovered narrow resonance at 3.1 GeV is a $^3S_1$ bound state of charmed quarks and we show the consistency of this interpretation with known meson systematics. The crucial test of this notion is the existence of charmed hadrons near 2 GeV. [correct interpretation]

Remarks on the New Resonances at 3.1 and 3.7 GeV

C. G. Callan, R. L. Kingsley, S. B. Treiman, F. Wilczek, and A. Zee

This is a collection of comments which may be useful in the search for an understanding of the recently discovered narrow resonances at 3.1 and 3.7 GeV. [not stupid - but doesn't commit to charm]

Heavy Quarks and e+e- Annihilation

Thomas Appelquist and H. David Politzer

The effects of new, heavy quarks are examined in a colored quark-gluon model. The e+e- total cross section scales for energies far above any quark mass. However, it is much greater than the scaling prediction in a domain about the nominal two-heavy-quark threshold, despite e+e- being a weak-coupling problem above 2 GeV. We expect spikes at the low end of this domain and a broad enhancement at the upper end. [brilliant prediction - sadly submitted too late]

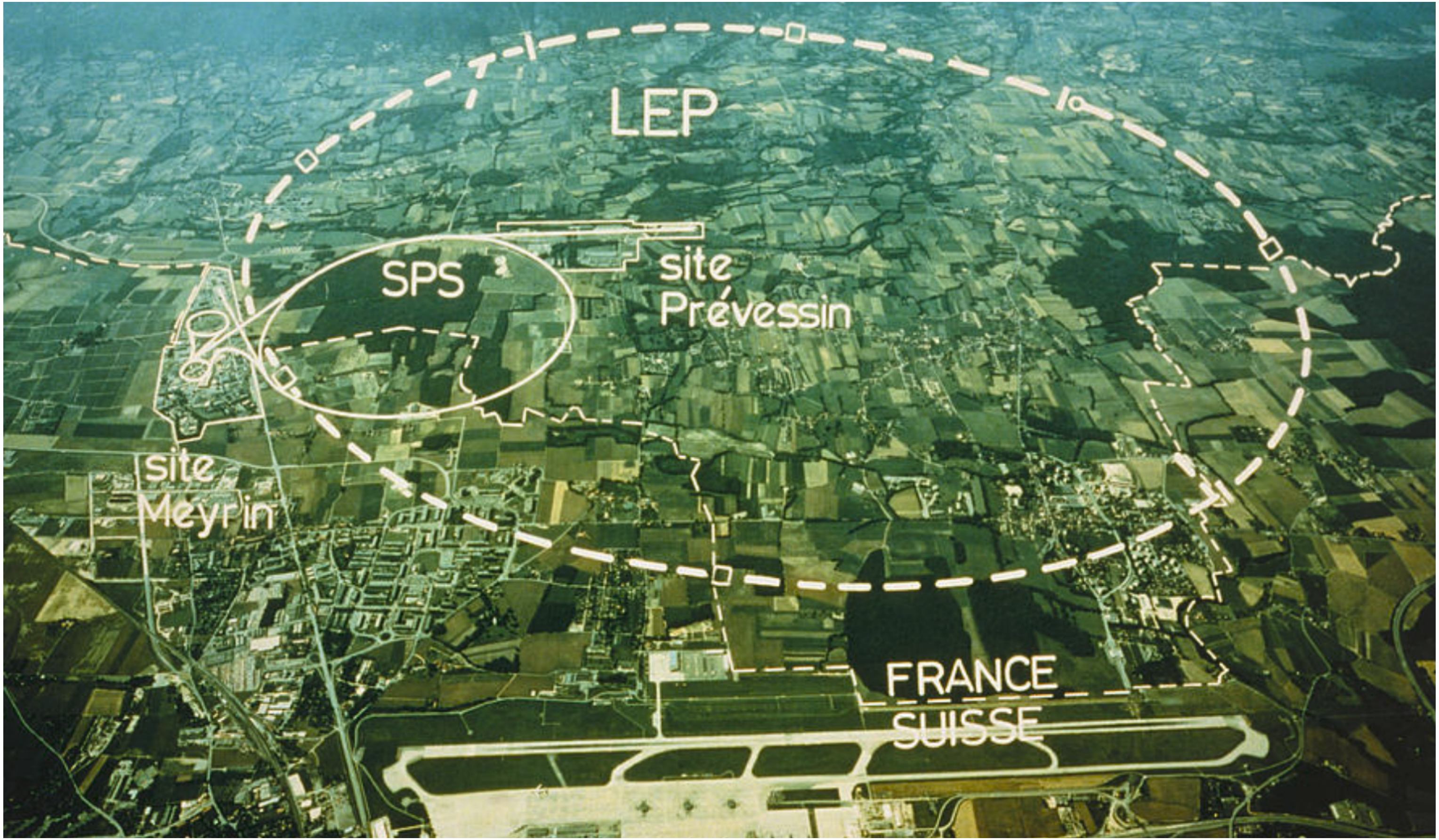
Stable Particle Table *(cont'd)*

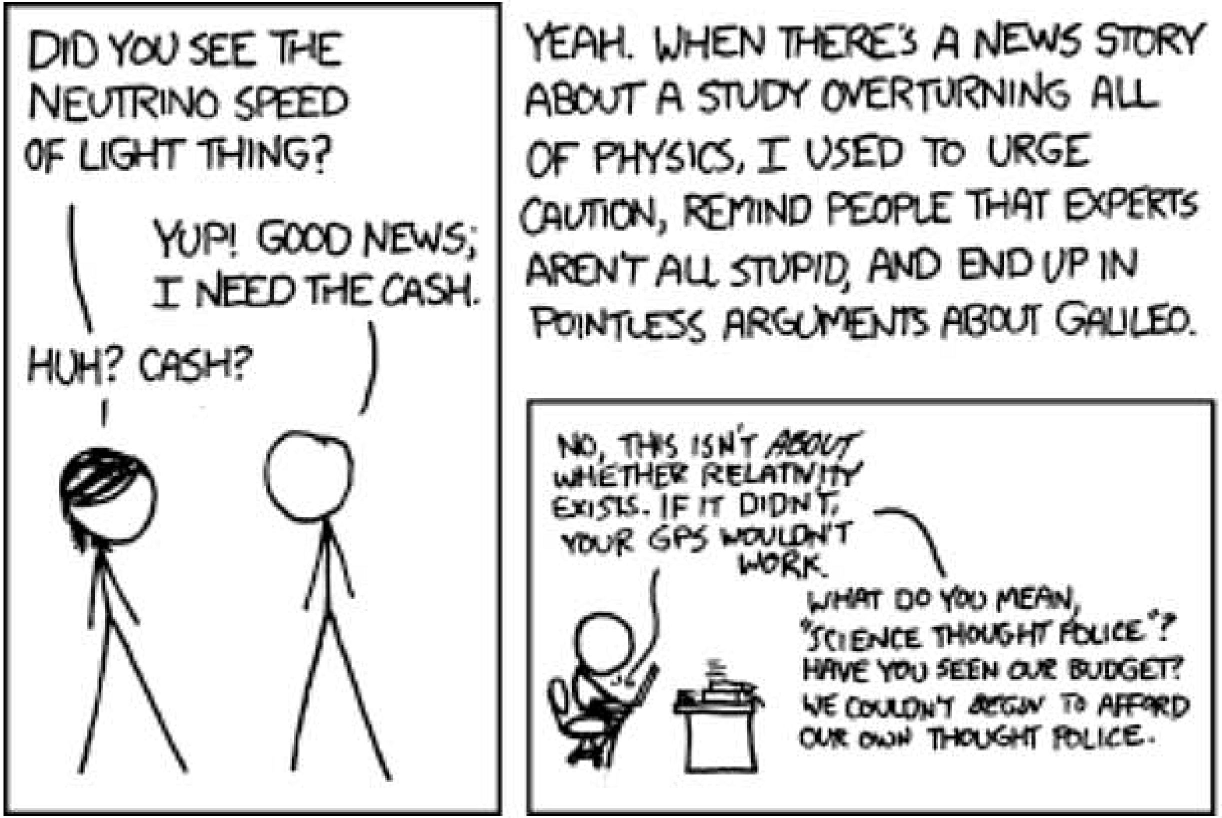
Particle	$I^G(J^P)C_n$	Mass (MeV) Mass^2 (GeV)^2	Mean life (sec) cτ (cm)	Partial decay mode: Mode	Fraction[a]	p or p_{max}[b] (MeV/c)
K^0	$\frac{1}{2}(0^-)$	497.70 ±0.13 S=1.1* m^2=0.248	50% K_{Short}, 50% K_{Long}			
K^0_S	$\frac{1}{2}(0^-)$		0.886×10^{-10} ±.007 S=2.4* cτ=2.66	$\pi^+\pi^-$	(68.77 ±0.26)% S=1.1*	206
				$\pi^0\pi^0$	(31.23)%	209
				$\mu^+\mu^-$	(< 0.3) 10^{-6}	225
				e^+e^-	(<35) 10^{-5}	249
				$\pi^+\pi^-\gamma$	c(2.0 ±0.4) 10^{-3}	206
				$\gamma\gamma$	(< 0.4) 10^{-3}	249
K^0_L	$\frac{1}{2}(0^-)$		5.179×10^{-8} ±0.040 cτ=1553	$\pi^0\pi^0\pi^0$	(21.3 ±0.6)% S=1.1*	139
				$\pi^+\pi^-\pi^0$	(*11.9* ±*0.4*)% S=2.2*	133
				$\pi\mu\nu$	(27.5 ±0.5)% S=1.1*	216
				$\pi e\nu$	(39.0 ±0.6)% S=1.1*	229
				$\pi e\nu\gamma$	c(1.3 ±0.8)%	229
				$\pi^+\pi^-$	(*0.177 ± 0.018*)% S=4.9*	206
				$\pi^0\pi^0$	(0.093±0.019)% S=1.5*	209
				$\pi^+\pi^-\gamma$	c(< 0.4) 10^{-3}	206
				$\pi^0\gamma\gamma$	(< 2.4) 10^{-4}	231
				$\gamma\gamma$	(4.9± 0.4) 10^{-4}	249
				$e\mu$	(< 1.6) 10^{-9}	238
				$\mu^+\mu^-$	i(< 1.6) 10^{-8}	225
				e^+e^-	(< 1.6) 10^{-9}	249
				$e^+e^-\gamma$	(< 2.8) 10^{-5}	249

$m_{K_L} - m_{K_S} = 0.5403\times10^{10}\,\hbar\ \mathrm{sec}^{-1}$ ±0.0035

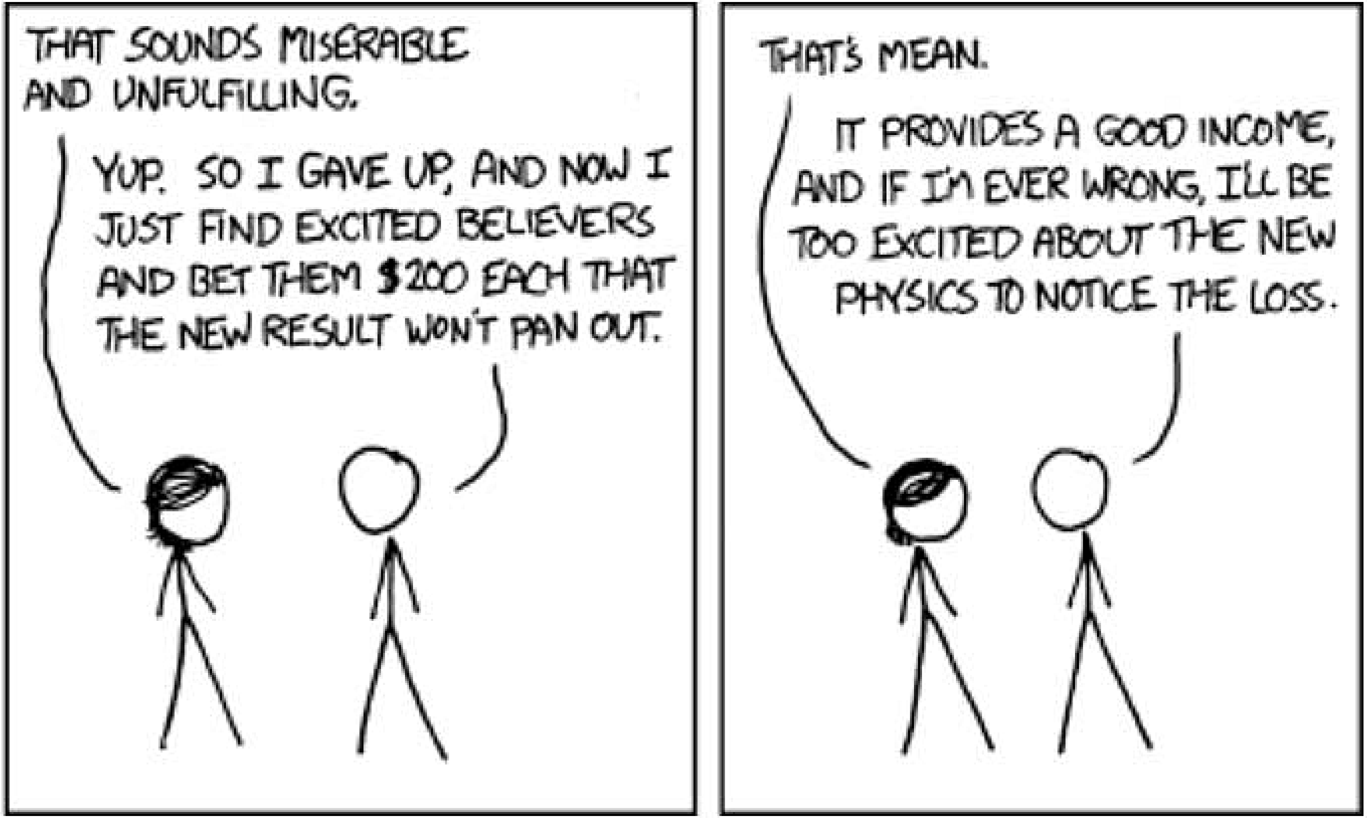
Lattice gauge theories
P-wave charmonium states
EFT of charm
τ lepton discovered
Charmed particles seen
EFT of Weak Interactions
Υ discovered
ε'/ε in KM model
Axions
Technicolor

CKM mixing and CP violation
Monopoles
Charmed particle masses
Systematic $c\bar{c}$ calculations
Chiral U(1)
The QCD parton model
Peccei-Quinn Symmetry
Parity violation in DIS
Gluon jets
Effective Chiral Theory

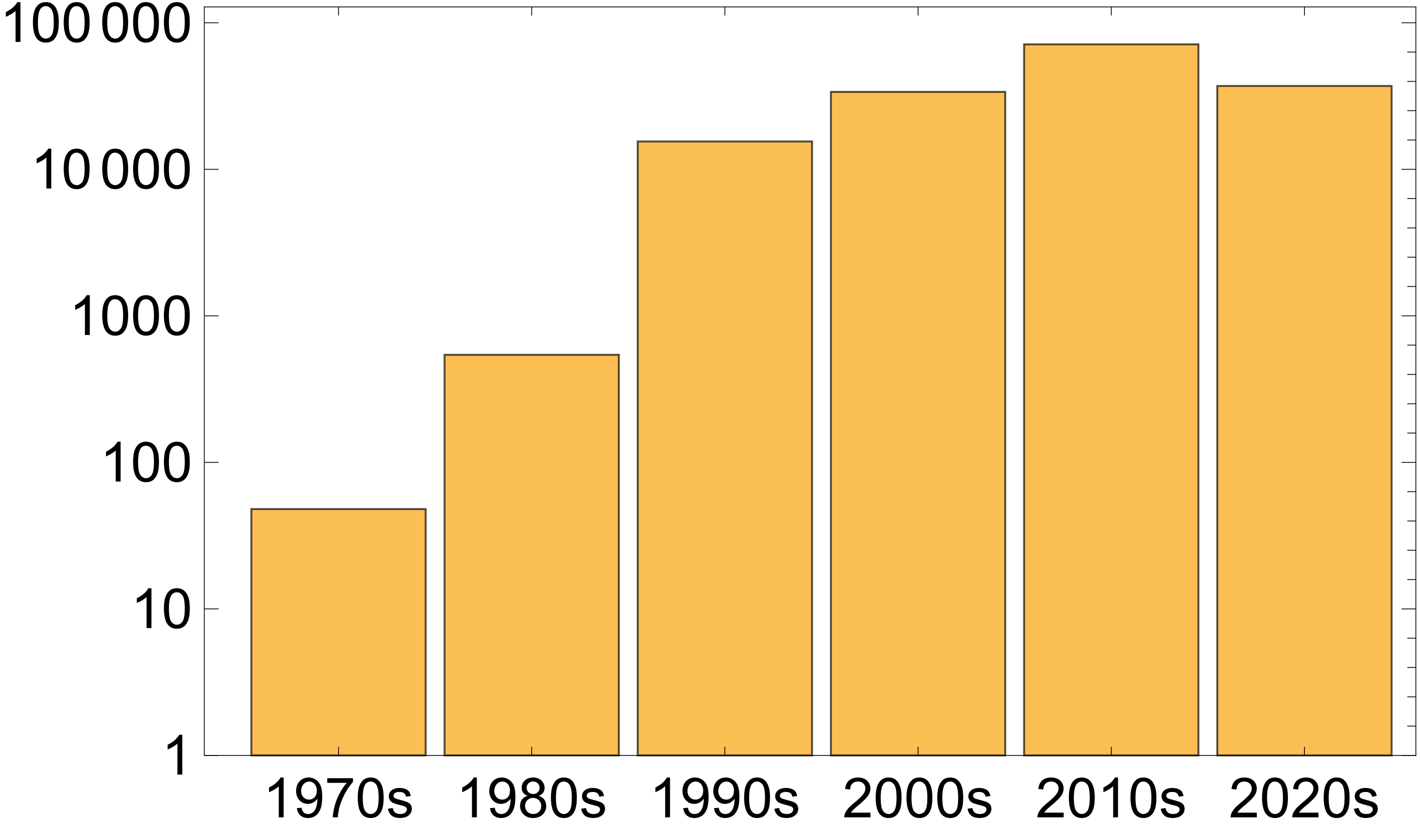

LEP
SPS
site Prévessin
site Meyrin
FRANCE
SUISSE



Randall Munroe: XKCD



Randall Munroe: XKCD


100 000
10 000
1000
100
10
1
1970s
1980s
1990s
2000s
2010s
2020s

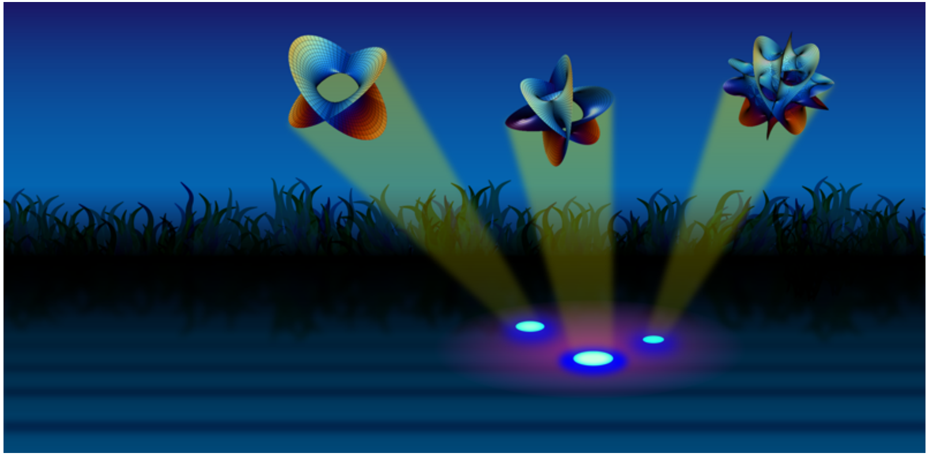


Figure 1: In string theory, high-energy solutions in higher dimensions (shown above) are compacted into four-dimensional quantum field theories that belong to the "landscape" (shown as blue dots). Outside of the landscape is the "swampland," where reside four-dimensional quantum field theories that are not consistent with gravity.

https://physics.aps.org/articles/v12/115

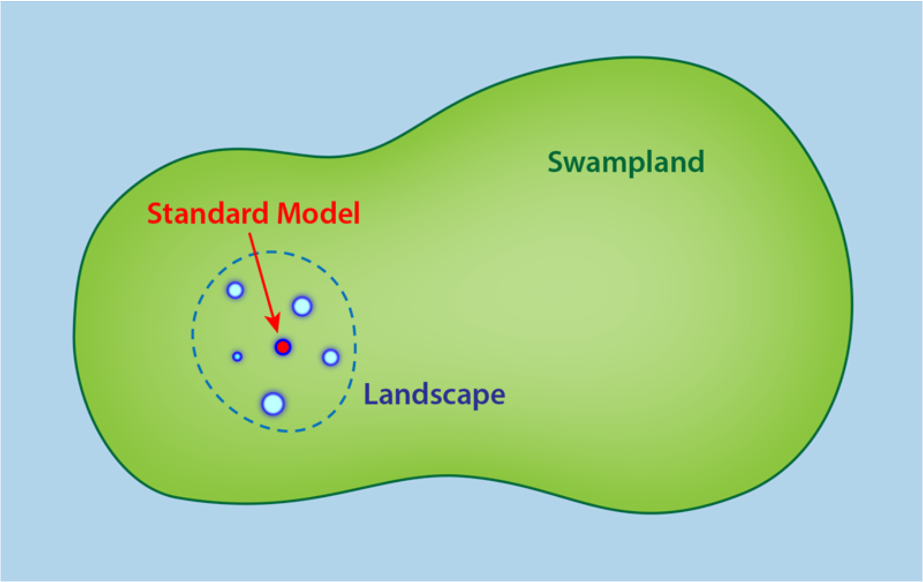


Figure 2: A Venn diagram showing how the swampland encompasses the landscape. The standard model is located within the landscape.

https://physics.aps.org/articles/v12/115 potential, and therefore an AdS minimum can be formed, as shown in Fig. 5. If there are enough fermionic degrees of freedom in the neutrinos and if they are sufficiently light (and thus start to contribute to the potential at large enough radius) they can lift the potential before it crosses zero, otherwise an AdS vacuum will form. If this lower-dimensional AdS vacuum was stable, the Non-susy AdS Conjecture would be violated and the SM would be in the swampland. Since the Standard Model is a good low energy effective theory, unless one assumes there are additional light fermionic degrees of freedom beyond those of the Standard Model, we conclude that neutrinos must be (pseudo-)Dirac. Furthermore, one also obtains an upper bound for their masses in terms of the cosmological constant

$$m_\nu \lesssim \Lambda_4^{1/4} \tag{3.4}$$

https://arxiv.org/abs/1903.06239

H. Georgi escapes from hadron dynamics

Original drawing by Michael Peskin

Scale-invariant Instantons and the Complete Lifetime of the Standard Model

Anders Andreassen[*], William Frost[†], and Matthew D. Schwartz[‡]

With these problems solved, we produce the first complete calculation of the lifetime of our universe: 10^{161} years. With 95% confidence, we expect our universe to last more than 10^{65} years. The uncertainty is part experimental uncertainty on the top quark potential, and therefore an AdS minimum can be formed, as shown in Fig. 5. If there are enough fermionic degrees of freedom in the neutrinos and if they are sufficiently light (and thus start to contribute to the potential at large enough radius) they can lift the potential before it crosses zero, otherwise an AdS vacuum will form. If this lower-dimensional AdS vacuum was stable, the Non-susy AdS Conjecture would be violated and the SM would be in the swampland. Since the Standard Model is a good low energy effective theory, unless one assumes there are additional light fermionic degrees of freedom beyond those of the Standard Model, we conclude that neutrinos must be (pseudo-)Dirac. Furthermore, one also obtains an upper bound for their masses in terms of the cosmological constant

$$m_\nu \lesssim \Lambda_4^{1/4} \tag{3.4}$$

https://arxiv.org/abs/1903.06239

H. Georgi escapes from hadron dynamics

Original drawing by Michael Peskin