Flavour Physics

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Towards Standard Model

After the fantastic success of Quantum Electrodynamics as a beautiful, precisely tested theory in 1950th, the question of creating a (renormalizable) Quantum Field Theory for the strong and weak interactions became urgent.

It took more than 10 years and a lot of beautiful ideas to come up with a theory of strong and weak interactions built on the similar principles.

After every beautiful idea was suggested, obstacles arose that seemed to kill the idea, but the perseverance of physicists helped to overcome all these obstacles.

Towards Standard Model: idea #1

A transformation from one field configuration to another is called a gauge transformation; the lack of change in the measurable quantities, despite the field being transformed, is a property called gauge invariance.

The first `good idea' was the invention of non-Abelian gauge theories by Yang and Mills in 1954. One hoped to obtain with the isospin as the local symmetry a theory of strong interactions with the ρ-mesons as gauge bosons. After the V – A structure of the weak interactions had been identified, the similar idea was applied to the weak interactions with intermediate vector bosons.

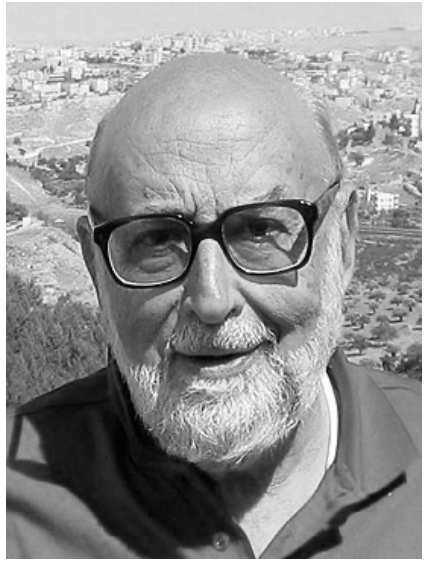
Towards Standard Model: idea #1

But all physical applications of non-Abelian gauge theories seemed to require massive vector bosons because no massless ones had been found, neither in strong nor weak interactions. Such mass terms had to be inserted by hand, breaking explicitly the local gauge symmetry and thereby destroying the rationale for introducing non-Abelian local symmetries in the first place. Moreover, it was realized that non-Abelian gauge theories with mass terms would be nonrenormalizable, plagued by the same divergences as the four-fermion theory of weak interactions.

The idea was good but neither solved any problem, nor found any confirmation in experiment: seems to be good for mathematics, but useless for physics.

Towards Standard Model: idea #2

A further `good idea' was spontaneous symmetry breaking: there can be symmetries of the Lagrangian that are not symmetries of the vacuum. According to the Goldstone theorem there must be a massless spinless particle for every spontaneously broken global symmetry. On the other hand, there is no experimental evidence for any massless scalar with strong or weak interactions.



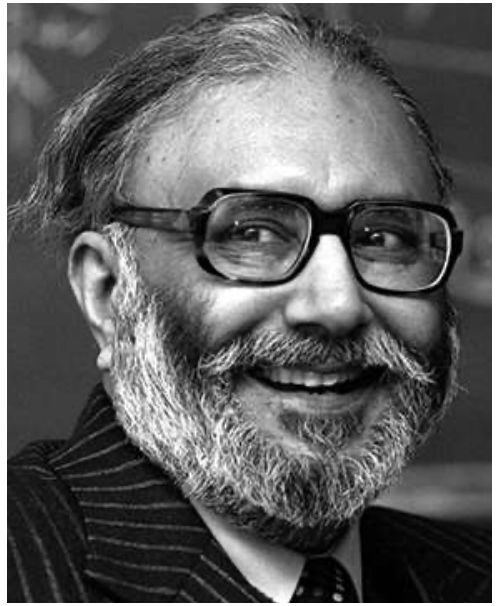
In 1964 Higgs, Englert and Brout found a way to outwit Goldstone's theorem: the theorem is not applicable if the symmetry is a gauge symmetry as in electrodynamics or the non-Abelian Yang-Mills theory. Then the Goldstone boson becomes the helicity-zero part of the gauge boson, which thereby acquires a mass.

Towards Standard Model: idea #3

Another `good idea' was the quark model, proposed in 1964 independently by Gell-Mann and Zweig. The hypothesis that hadrons are made out of three quarks or quark-antiquark pair allowed one to understand their quantum numbers and mass spectrum in terms of an approximate SU(3) flavour symmetry, the `eightfold way'.

Furthermore, the deep-inelastic scattering experiments at SLAC in 1968 could be interpreted as elastic scattering of electrons off point-like partons inside the proton, and it was natural to identify these partons with quarks.

Towards Standard Model: idea #3



But were quarks real or just some mathematical entities? In 1967 Weinberg (he did not believe in quarks) abandoned his attempts to build the chiral $SU(2)_L \times SU(2)_R$ symmetry of strong interactions and then applied the idea of spontaneous symmetry breaking to the weak interactions of the leptons $(\nu_L; e_L)$ and e_R.

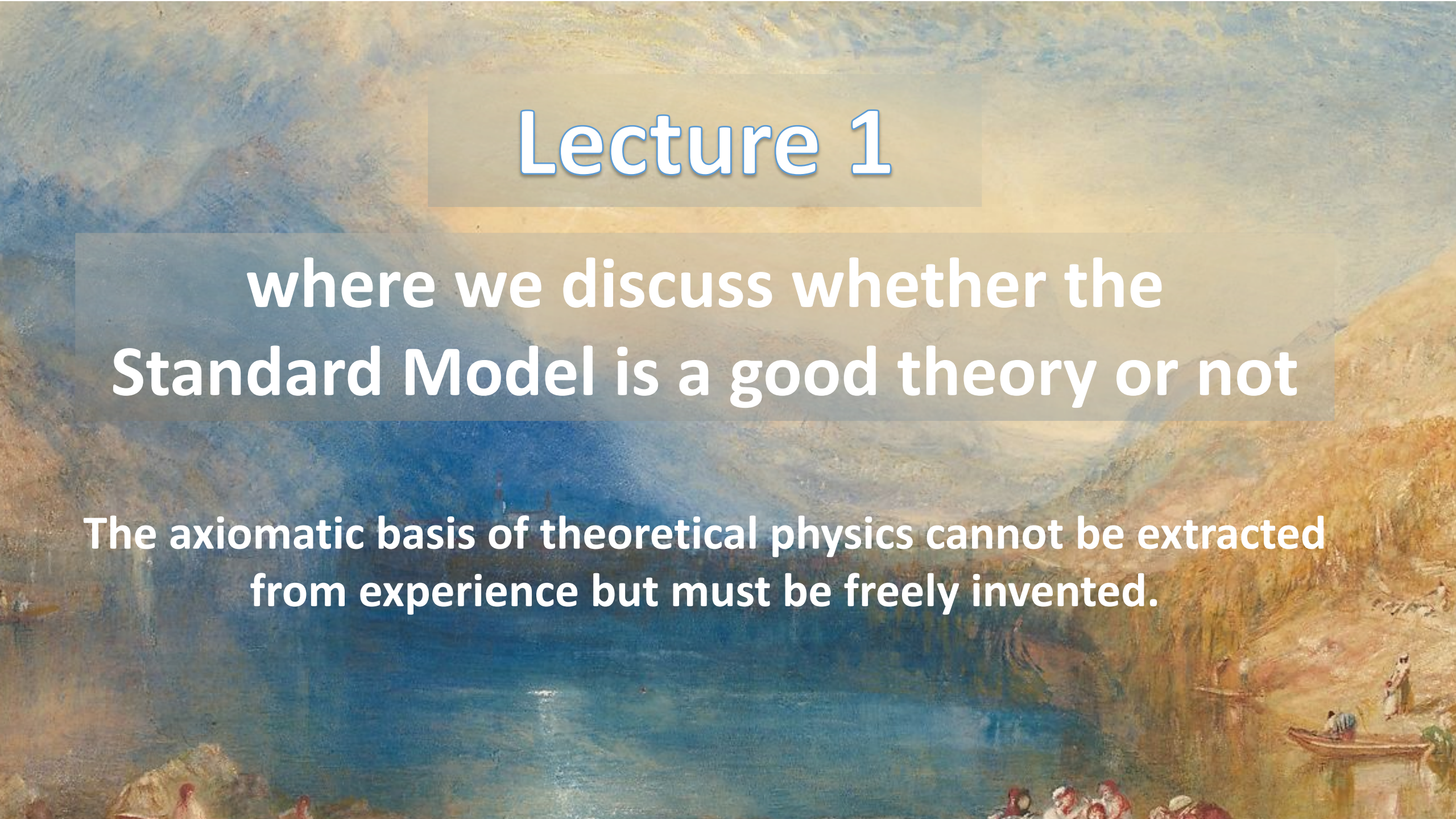
This led to the gauge group $SU(2) \times U(1)$, massive W, Z and Higgs bosons, and a massless photon.

- The proof by 't Hooft and Veltman that non-Abelian gauge theories are renormalizable;
- The discovery of asymptotic freedom by Gross, Wilczek and Politzer;
- Understanding that the infrared properties of non-Abelian gauge theories lead to the confinement of quarks and massless gluons.

The making of the Standard Model was completed by 1973!

Since 1973 many experiments have confirmed the Standard Model

- 1973: discovery of neutral currents;
- 1979: discovery of the gluon;
- 1983: discovery of the W and Z bosons;
- 1975-2000: discovery of the third family;
- 1990-2001: precision test at LEP, SLC, Tevatron
- 2012: discovery of the Higgs boson



Lecture 1

where we discuss whether the Standard Model is a good theory or not

The axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented.

many people not related to science have expressed their (in)valuable opinion what the true theory should be

Ignorance can be educated;
Crazy can be medicated;
But there is no cure for stupid.

The theory should be based on a broad philosophical generalization of the ontogenesis and phylogenesis of cognition.

V. Lenin

It would be godless to look for laws of Nature in the vulgar and crude matter, of which our bodies are composed, serving as a temporary prison for us.

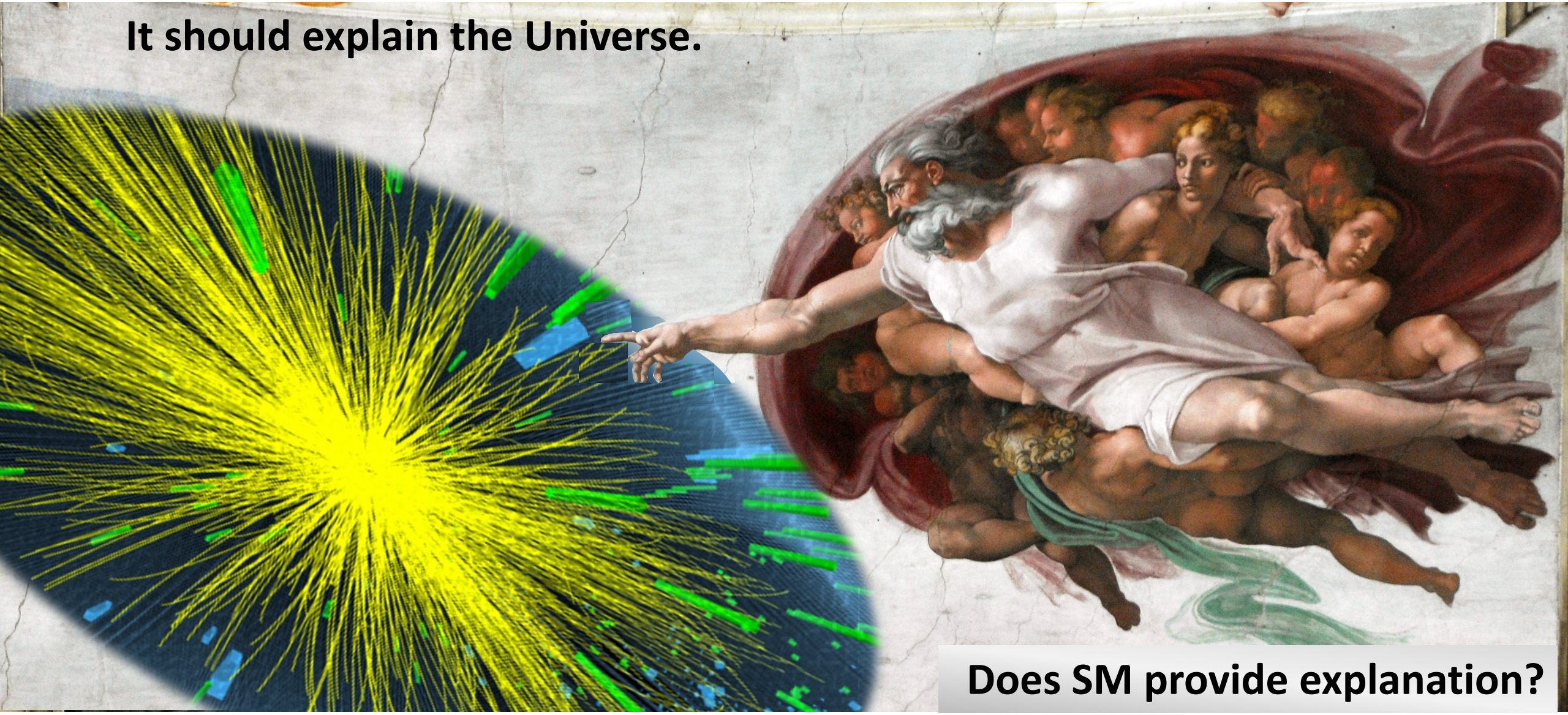
unnamed theologian from Orthodox almanac

Higher mathematics kills creativity… I did not study higher mathematics at school, and at the same time I am not stupider than others… Politicians cannot be suspected of being idiots.

A. Fursenko

- SM is an ideological bomb!
- SM is the eight deadly sin!
- SM is a product of uncreative LGBT mathematicians.

Just a general idea, what should do physical theory:



SM, a table of contents:

Standard Model: pragmatism

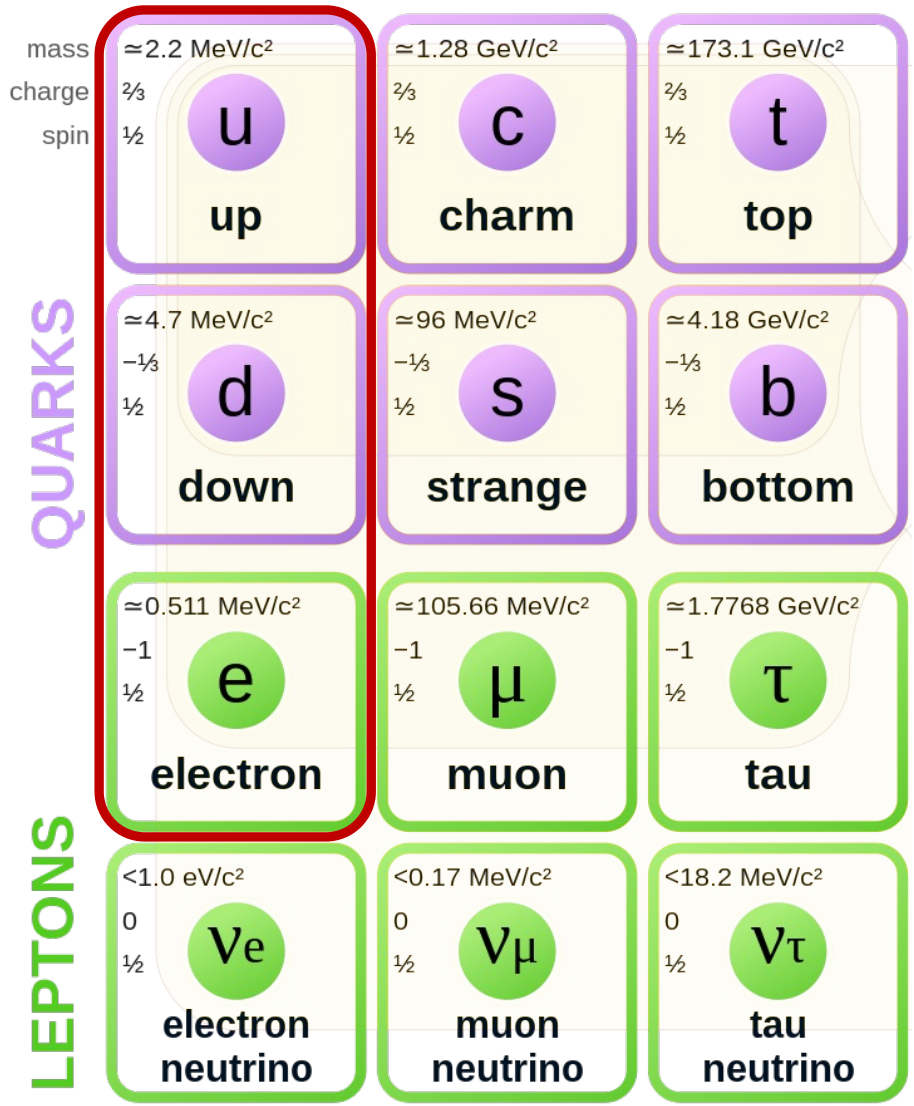
Matter, spin = 1/2 *Forces, spin = 1* *Vacuum, spin = 0*

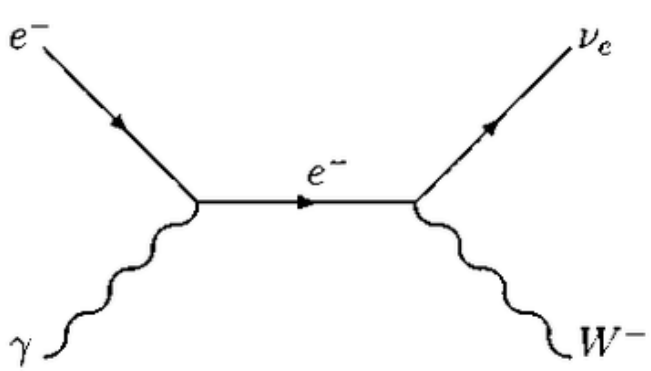
mass	≃2.2 MeV/c²	≃1.28 GeV/c²	≃173.1 GeV/c²	0	≃124.97 GeV/c²
charge	⅔	⅔	⅔	0	0
spin	½	½	½	1	0
	u	c	t	g	H
	up	charm	top	gluon	higgs
QUARKS	≃4.7 MeV/c²	≃96 MeV/c²	≃4.18 GeV/c²	0	SCALAR BOSONS
	−⅓	−⅓	−⅓	0	
	½	½	½	1	
	d	s	b	γ	
	down	strange	bottom	photon	
	≃0.511 MeV/c²	≃105.66 MeV/c²	≃1.7768 GeV/c²	≃91.19 GeV/c²	GAUGE BOSONS VECTOR BOSONS
	−1	−1	−1	0	
	½	½	½	1	
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
LEPTONS	<1.0 eV/c²	<0.17 MeV/c²	<18.2 MeV/c²	≃80.39 GeV/c²	
	0	0	0	±1	
	½	½	½	1	
	νe	νμ	ντ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	

SM is a very practical theory:

It provides all ingredients to build a beautiful world

Fermions are the best bricks





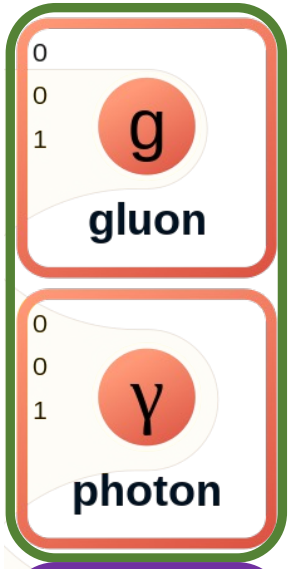
Fermions can transform into each other, but they cannot vanish or appear out of void.

This is a good building material - it will ensure the stability of our constructure.

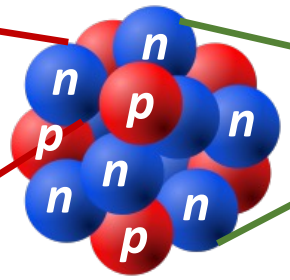
A danger: antifermions can knock out our fermion building blocks and destroy our structure. Nature must ensure that antifermions are not around. And Nature really took care of this: antimatter is not near us (probably there is just no much antifermions in our Universe at all).

Gauge bosons are cement mortar

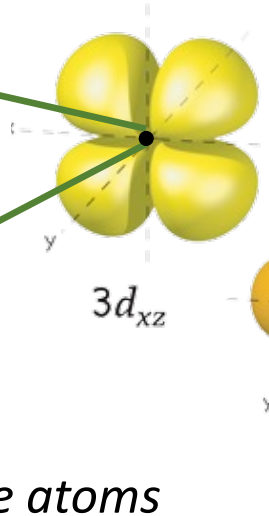
Strong force is to build nucleons and nuclei



nucleon



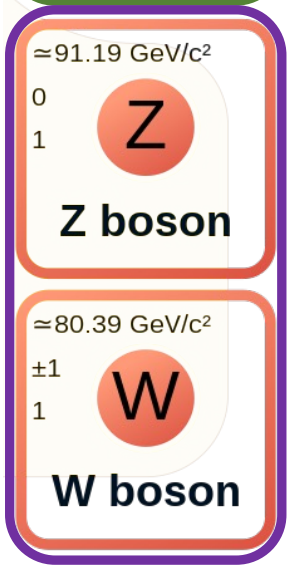
nucleus



atomic electron clouds

the whole variety of chemical elements is due to electromagnetic interactions, quantum mechanics and the Pauli principle.

Electromagnetic force is to complete atoms



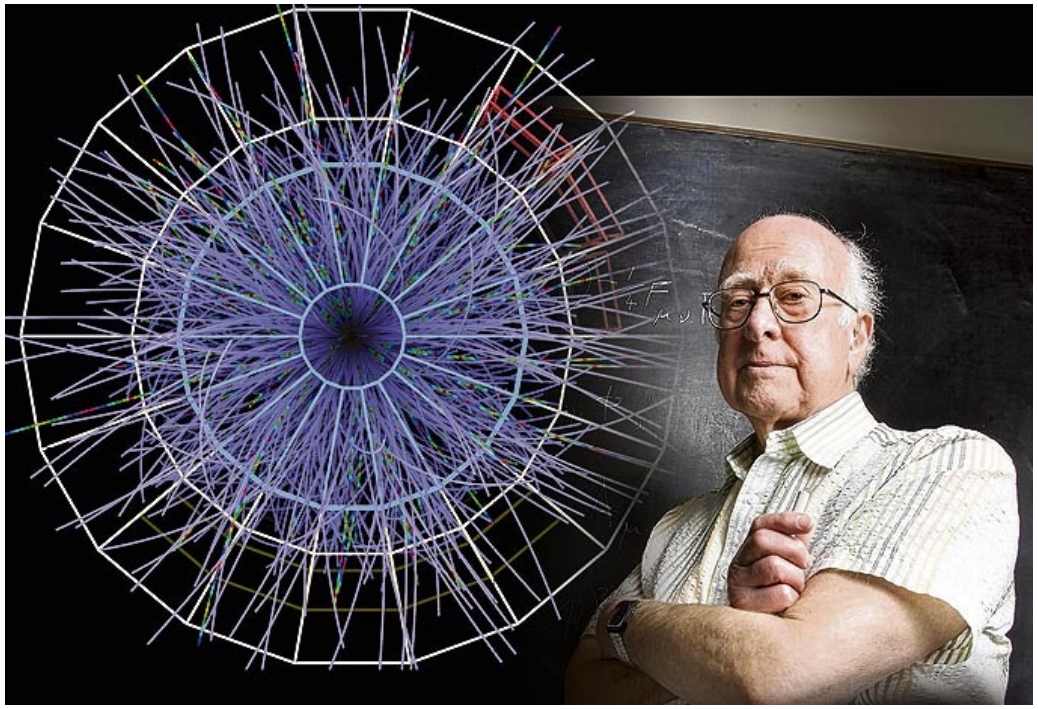
… or energy suppliers

Weak force seems not being used for construction, but supplies energy.

$$p + p \rightarrow {}^2D + e^+ + \nu_e + 0.4 \text{ МэВ}$$

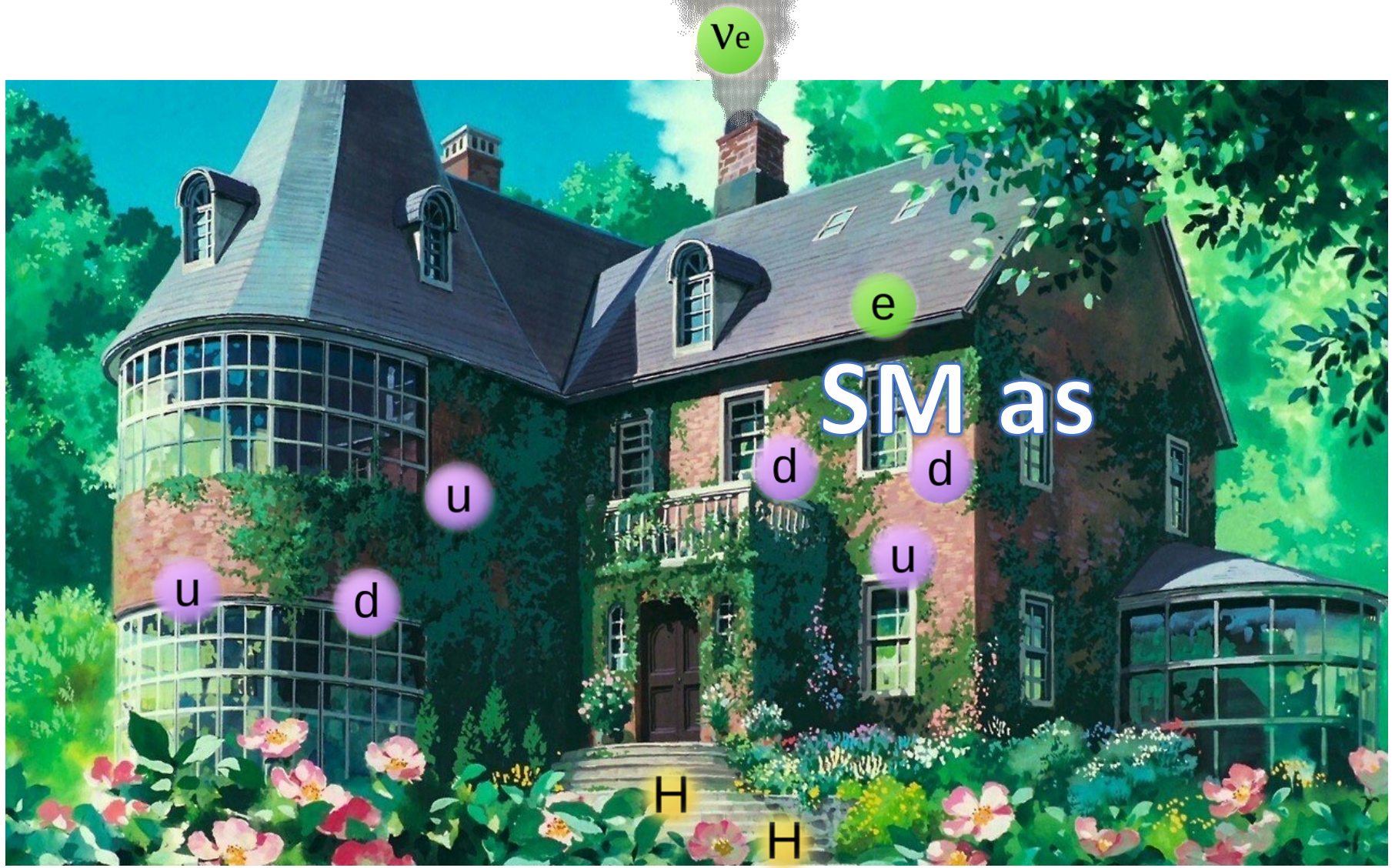
Scalar boson is footing

Ether was the postulated medium for the propagation of light. This idea (rejected in the 19th century) was revived in the 20th, although not in the form in which it was originally invented.



Higgs condensate plays a role of medium, where all other SM ingredients put in. Many of them (fermions and weak bosons) interact with Higgs field and thus are fixed in space, rather than senselessly run through it, like photons.

Does SM provide explanation for Universe?

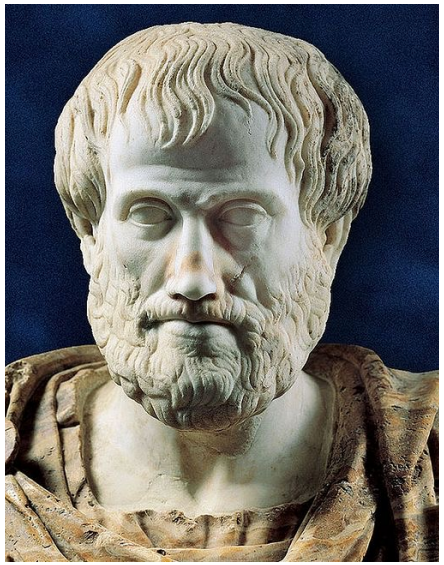


… seems to provide good training. We likely can build all objects that we see around from this small set of fundamental particles.

… and why are we unhappy?

Aristotle's principle

***Nature does nothing in vain* (NDNIV)**



Does SM satisfy NDNIV?

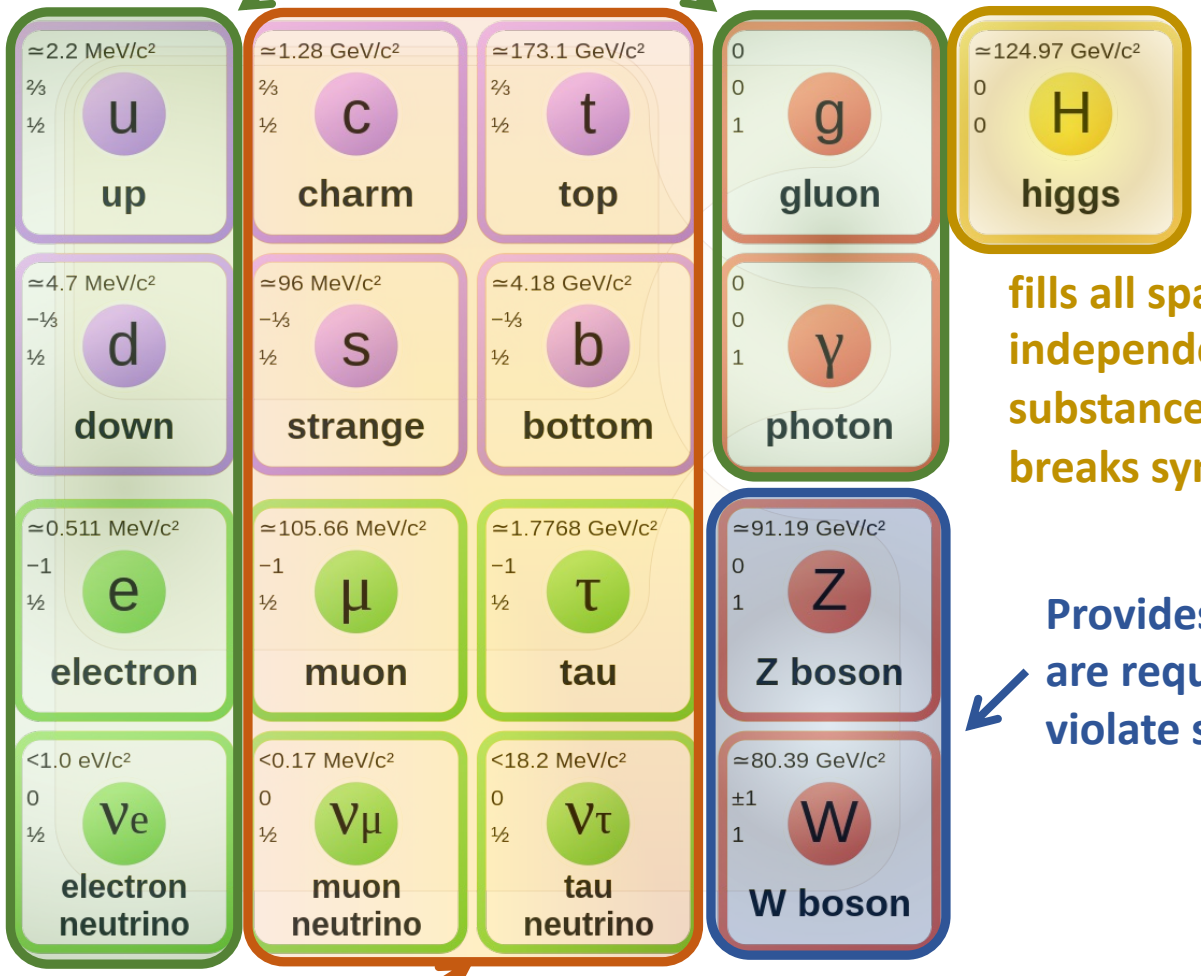
We used almost the entire contents of the SM particle table, but two fermion generations (and all antifermions) remain unused…

As for the macroscopic role of the particles of the second and the third generations, it seems at first glance trifling. These particles resemble the rough sketches, which the Creator has thrown out as unsuccessful, and which we with our sophisticated equipment dug in his wastebasket. Now we are starting to understand that these particles play an important role in the first moments of the Big Bang…

Lev Okun

Aristotle's principle

Are constituents of stars, planets and all we can see



Are required to remove antimatter

It turns out that two extra generations are needed to remove antimatter. Natural question: Why did antimatter even have to be created, and then to be removed in such a complicated way?

fills all space, provides an independent 'transmission' substance, gives masses, breaks symmetries

Provides energy, are required to violate symmetries

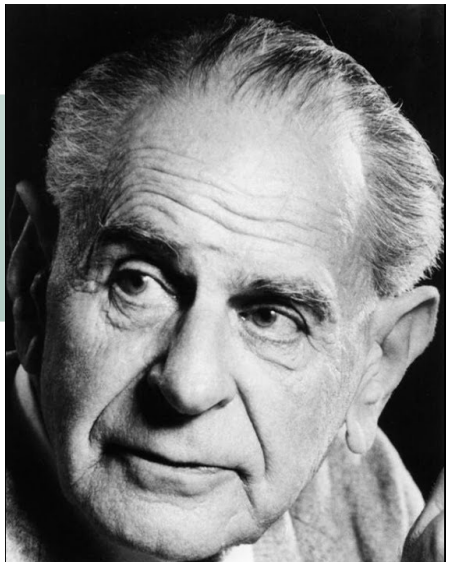
SM is free of unnecessary meaningless components and thus, satisfies NDNIV!

This table seems to be necessary and sufficient for our Universe.

… and why are we unhappy?

According to Falsification Principle, proposed by Karl Popper,

the theory considered as scientific one must be able to be tested and conceivably proven false.



- If theory **T** is true, then we should observe **O**, but **O** is not ensured (even better if **notO** does seem to be ensured)
- We do not observe **O**
- So, the theory **T** is wrong

for 50 years, the SM has been subjected to such thorough (and the most expensive) testing from all possible sides as no other theory, and …

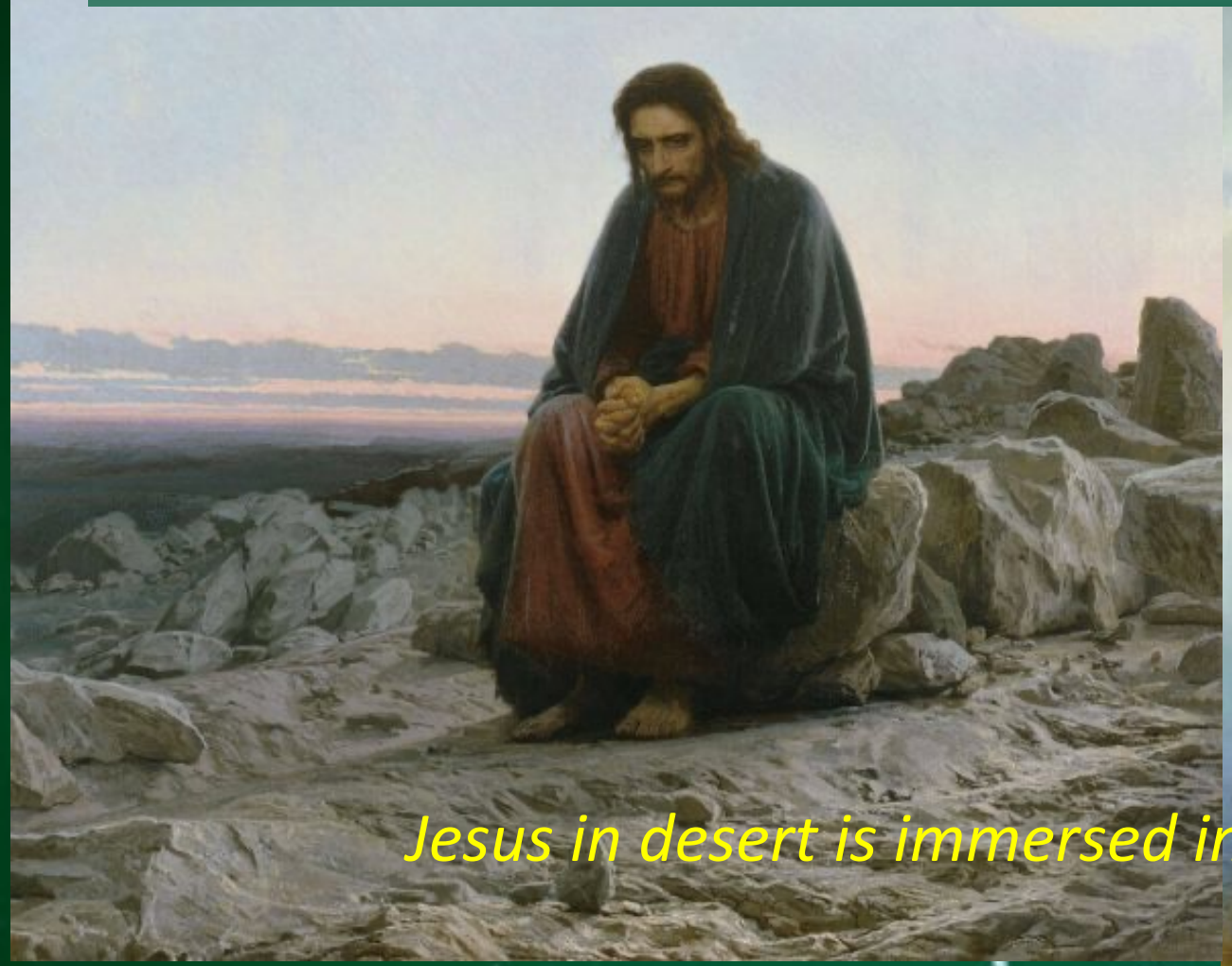
… all tests confirm the SM

Since 1967 SM describes all experiments!

… and why are we unhappy?

This only proves that SM is scientific, but not that it's true

God does not govern the world with equations and formulas.



Jesus in desert is immersed in thought, not in calculations.

He rules by ideas and principles because he was probably bad at maths at school.

Another physical principle: principles are more important than equations

remember a struggle around Newton's laws, which eventually led to the stationary-action principle (principle of least action)

Aristotle (~350BC): All nature's manifestations choose the shortest or easiest way.

Pierre de Fermat (1662): Principle of least time for a light beam in optics.

Pierre de Maupertuis (1744): Path followed by a physical system is the one of least length.

Leonhard Euler (1744): The curve described by the body to be the curve that minimizes $\int mv\, ds$.

Joseph-Louis Lagrange, Leonhard Euler (~1750): Euler–Lagrange equation $\frac{\partial L}{\partial f} - \sum_{i=1}^{n} \frac{\partial}{\partial x_i} \frac{\partial L}{\partial f_{x_i}} = 0$

Is the SM built on principles rather than equations?

Keystone principles of SM

Lorentz invariance: We do not have any reason to believe that at the presently available energies this symmetry is broken. However, the coupling constants in the SM depend on the energy scale of the process.

Quantum mechanics: SM is based on quantum field theory. To quantize the system, one replaces the coordinate and the momentum by operators with commutation relation related to Planck's constant.

Gauge symmetries: Local gauge symmetry is an internal symmetry of the SM Lagrangian. This leads through Noether's theorem to the conservation of charges.

Symmetry breaking: the SM Lagrangian is symmetric but the physical vacuum does not conserve the symmetry. Then one or several massless spin-0 particles emerge (in SM they directly absorbed into the longitudinal degrees of freedom of the massive gauge bosons).

Based on these principles, we can derive almost all terms of the SM Lagrangian.
***Almost** all, but **not all**.*

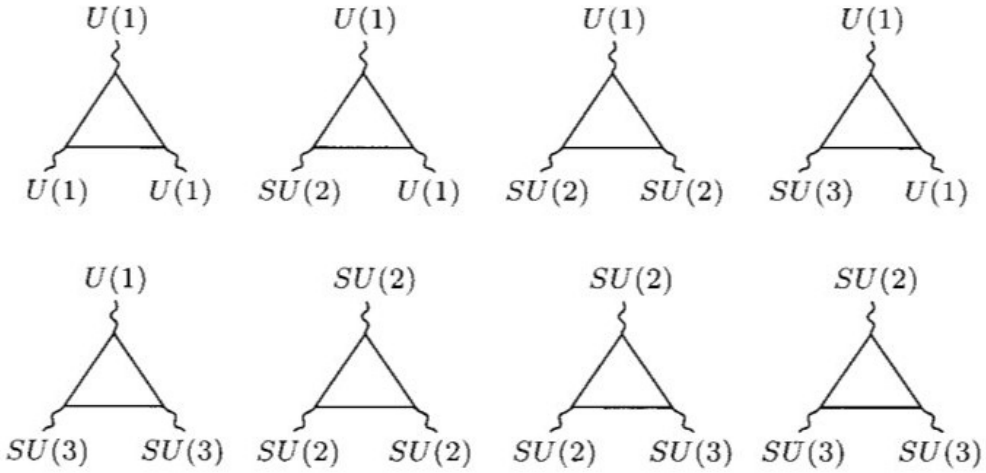
The gauge symmetries

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

3 free parameters: dimensionless coupling constants (g_1~0.3, g_2~0.6 ,g_3~1)

Gauge fields in interacting with fermions and scalar look relatively natural

For Hypercharge assignments there is nearly unique solution by demanding cancellation of all SM anomalies within one generation



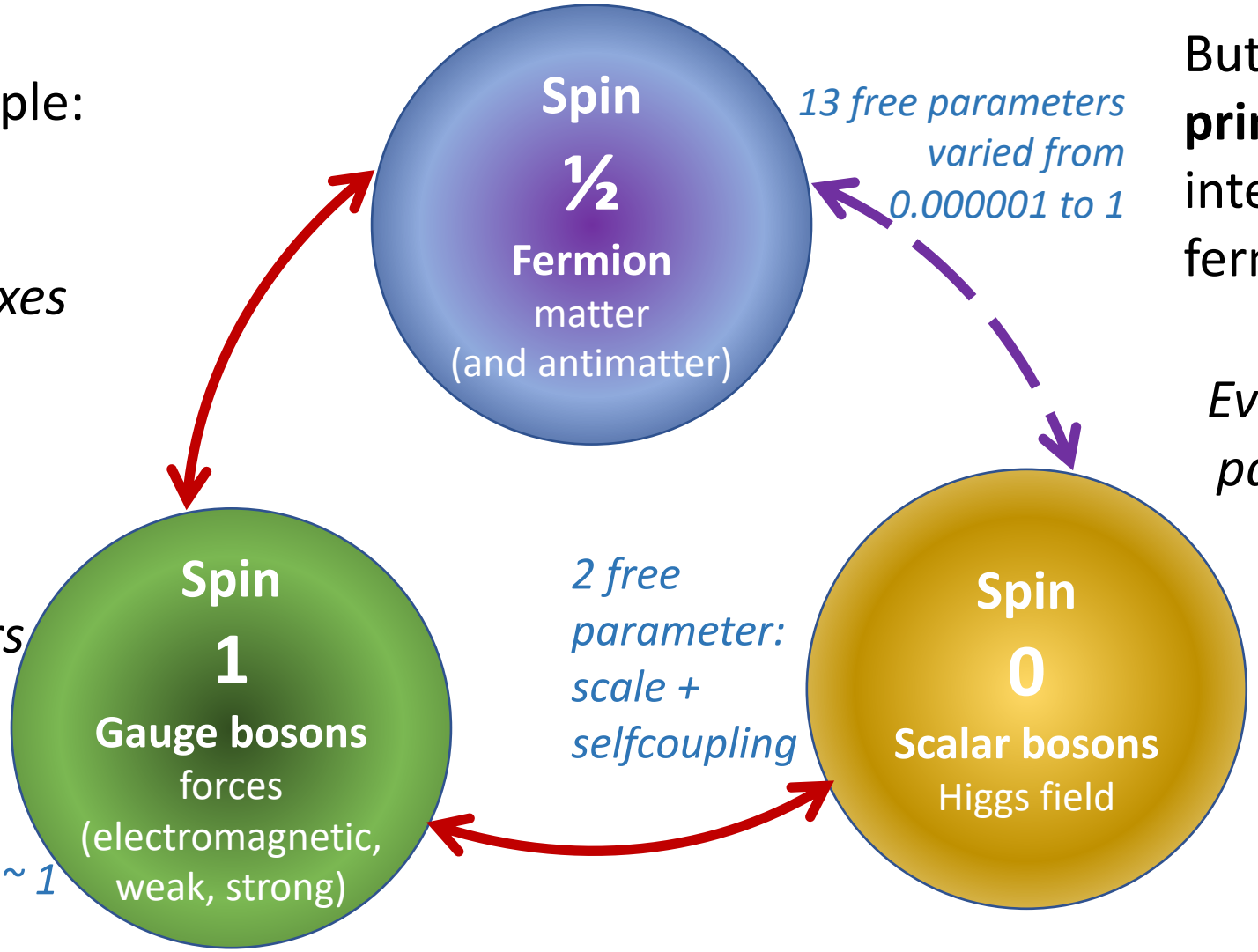
	e_R	l_L	u_R	d_R	q_L
$SU(3)$	0	0	1	1	1
$SU(2)$	0	1	0	0	1
$U(1)$	-2	-1	$+4/3$	$-2/3$	$+1/3$

Ideally, we have to accept one scale parameter, and expect that dimensionless parameters are some geometrical constants; there is a hint that three gauge constants are related to each other...

SM contains three sectors: fermions, gauge and scalar bosons

Important SM principle:
gauge invariance

Gauge invariance fixes all interaction of gauge bosons: selfinteraction and interaction with fermions and scalars



But there is **no known principle** on interaction between fermions and scalar

Even knowing all the parameters of these interactions with high accuracy, we cannot guess the principle.

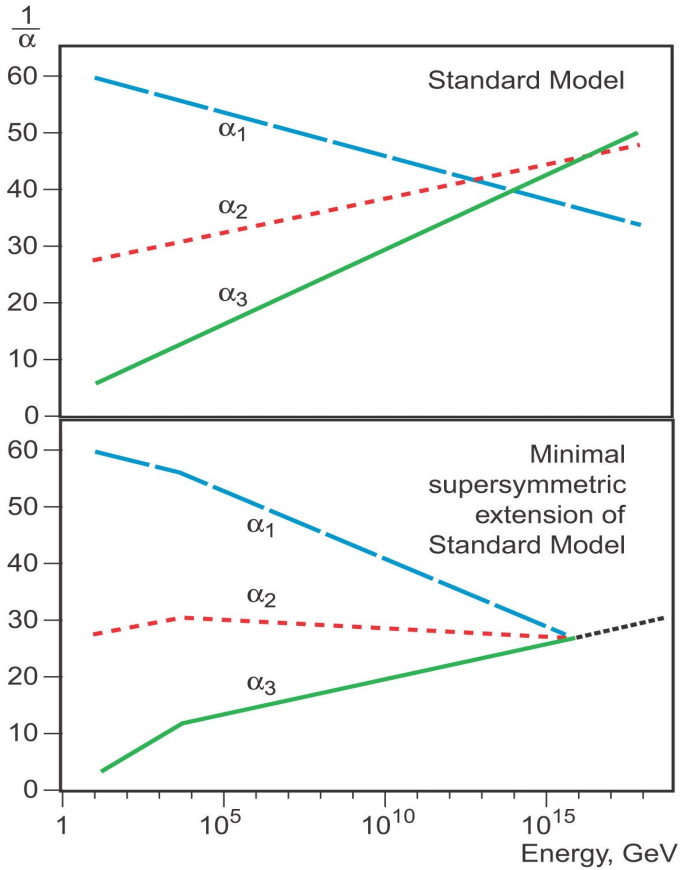
SM is really built on few keystone principles, but we haven't grasped some principles yet

This is not the SM problem – this is likely a problem of lack of our creativity due to overloaded with math

Parameters of the Standard Model

- 3 gauge couplings (of the same order ~1, moreover, they are running and seem to be trending to the same value)
- 2 Higgs parameters (one is scaling parameter – we can't avoid this, another is selfcoupling ~1)
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

= 18 (+7)



after 50 years of thinking, we still have no ideas.

() = with Dirac neutrino masses

… that's why are we unhappy?

This large number of free parameters is behind several of the mysteries of the SM:

- Why are there so many different fermions?
- What is responsible for their organization into generations?
- Why are there 3 (nor 2, neither 37) generations each of quarks and leptons?
- Why are there flavour symmetries?
- What breaks the flavour symmetries?
- What causes matter – antimatter asymmetry?

Unfortunately, these mysteries will not be answered in these lectures

FLAVOUR PHYSICS | FEATURE

The flavour of new physics

8 May 2019

We use term “flavour” when consider fermions beyond one generation. Only the weak interaction has a power to change flavour.

Just as ice cream has color and flavour so do quarks

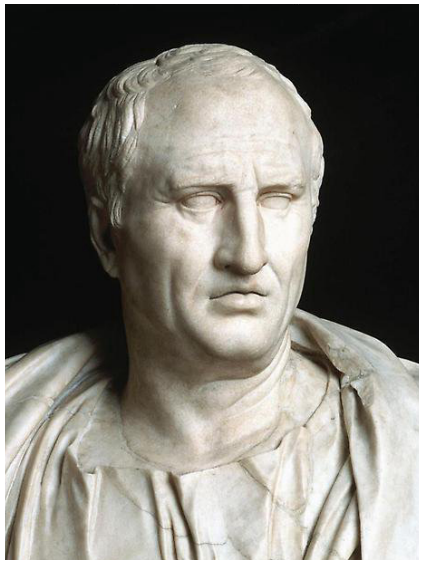
In 1971, at a Baskin-Robbins ice-cream store in Pasadena, California, Murray Gell-Mann and his student Harald Fritzsch came up with the term “flavour” to describe the different types of quarks. From the three types known at the time – up, down and strange – the list of quark flavours grew to six. A similar picture evolved for the leptons: the electron and the muon were joined by the unexpected discovery of the tau lepton at SLAC in 1975 and completed with the three corresponding neutrinos. These 12 elementary fermions are grouped into three generations of increasing mass.

In 1967 the new theory: SM unified the weak and electromagnetic interactions (by mixing weak $SU(2)$ and hypercharge $U(1)$). The strong interaction stands alone, as its principles were not known well that time (Well, let it be). The unification of two interactions looked great!
SM accommodated fermions. But in 1967 only the first generation was known. Strange quark and muon (and muon neutrino) considered as a mistake of Nature. All problems solved, the great theory created!

Our ignorance has blinded us and made us admire imperfection

But then, together with success in testing, comes disillusionment. New phenomena (more quark generations, neutrino mixing) inflated SM to a clumsy monster, while some new observations (dark matter, dark energy, early Universe inflation) did not find their place in this theory… Some intrinsic problems still not solved: strong CP problem, ultraviolet divergencies. Strong interaction, while based on the same gauge principle still stands alone, but even worse with gravity: it can not stand even nearby with the SM.

The closer the collapse of an Empire, the crazier its laws

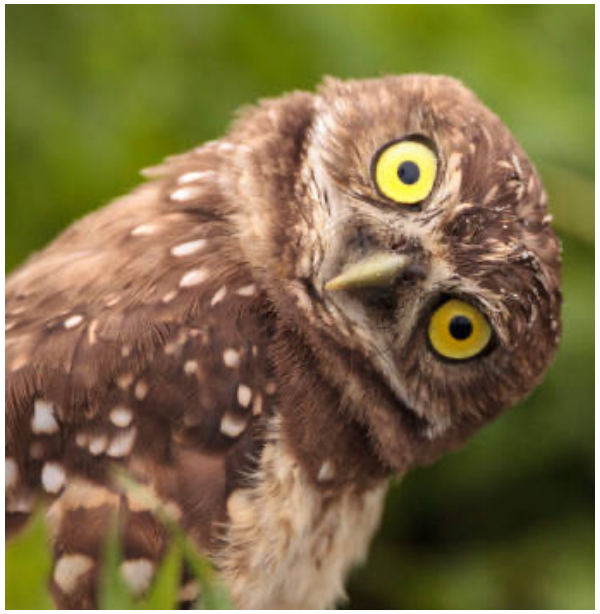


Marcus Tulius Cicero

The same is true for the Theory: during 50 years, SM has to accommodate many new features: half of the second and the third generations of quarks, mixed with a complex matrix, neutrino masses, Higgs-top masses at the edge of vacuum stability, etc. These double the number of free parameters and likely indicate the sooner transition to a new Theory.

SM in 1967: elegant, fresh, natural, logical.

SM in 2022: old, contradictory, unnatural, ugly.

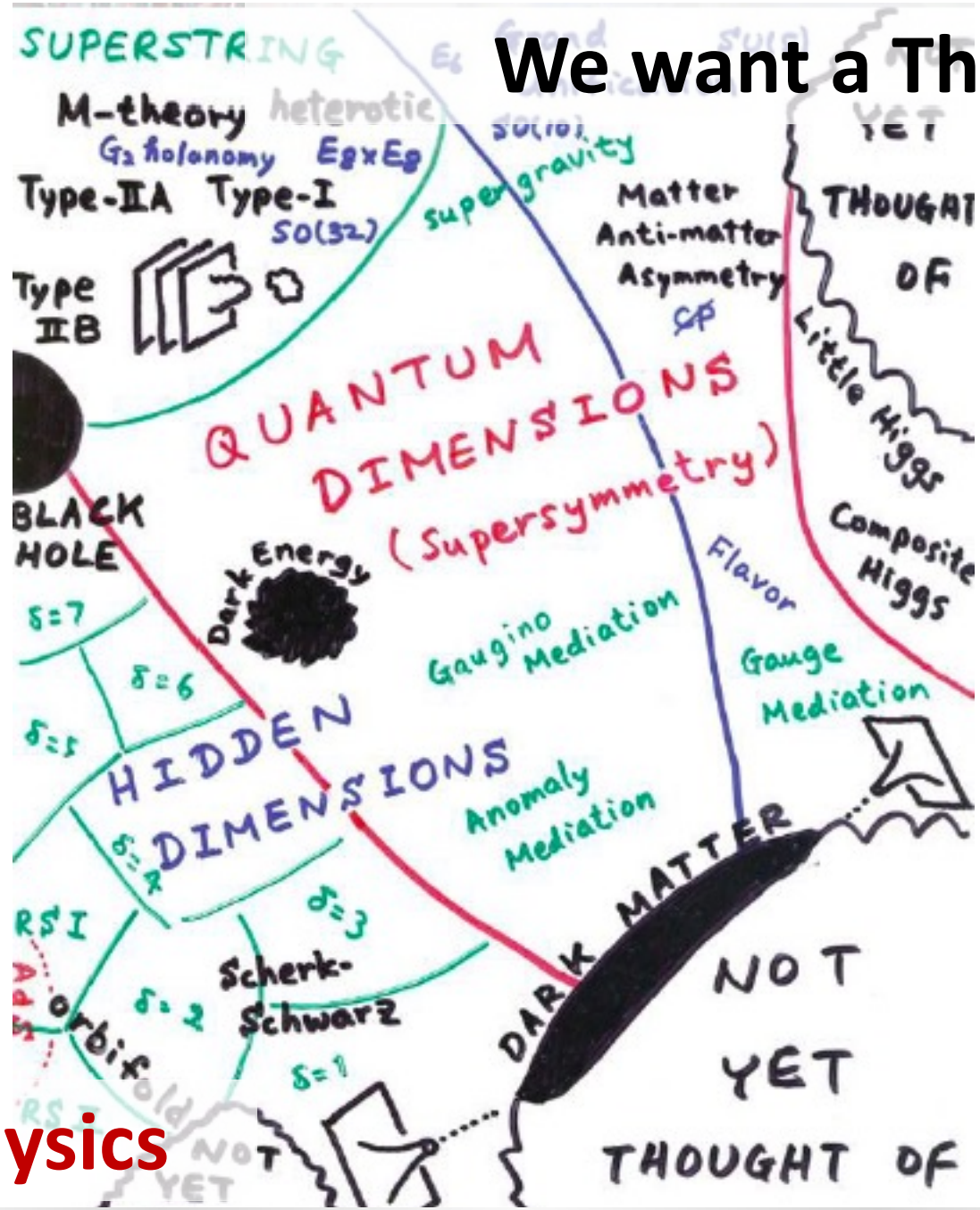


perhaps, we are too greedy…

Well, give us at least something beyond the Standard Model.

We want a Theory of Everything

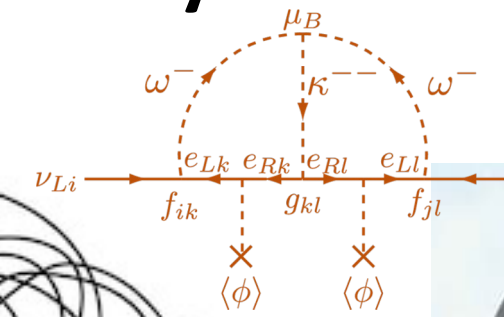
that answers all questions and resolves all mysteries

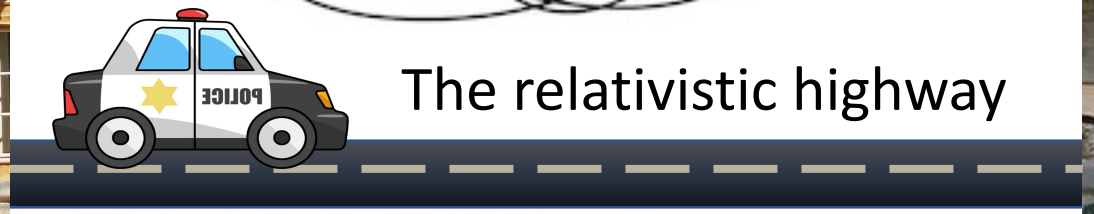


We want New Physics

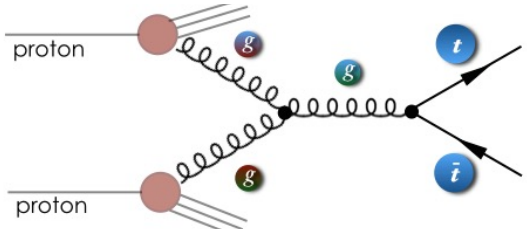
How to reach New Physics?

The quantum path

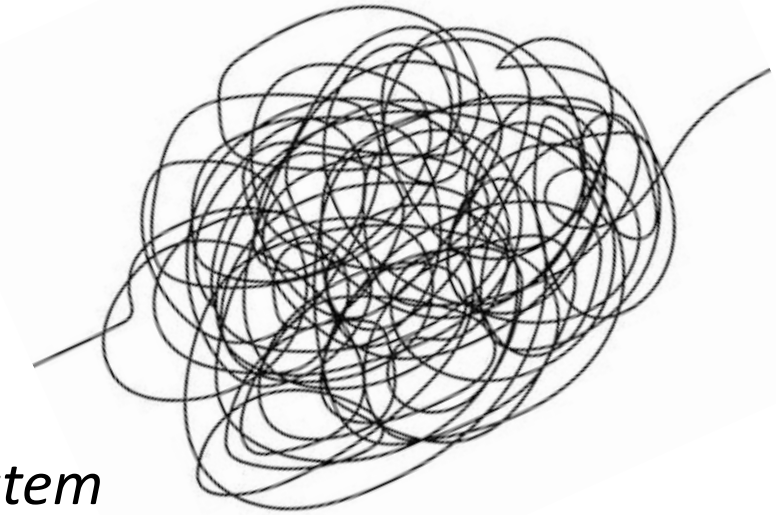




The relativistic highway



Quantum path is easy?



Requires:

precise measurements

+ good idea to explain them

+ routine math work

- *Charm discovery by the observation rare FCNC in the Kaon system*
- *3rd quark family seen by CPV in Kaon system*
- *the heaviness of the top quark … seen by B physics*
- *Nonobservation of many proposed/suspected NP phenomena at TeV scale from B-physics*
- *Anomalous muon magnetic moment wants to say us something…*

At least succeful!