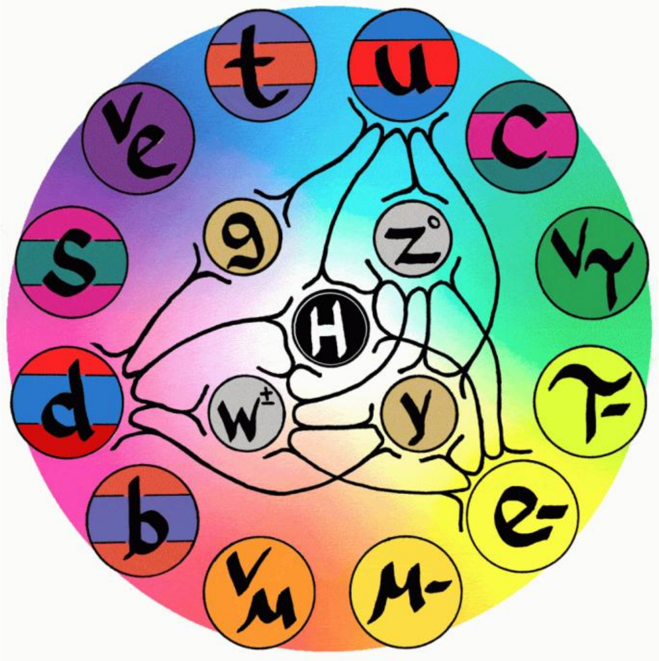
粒子物理大事记

milestones of particle physics

邢志忠
xingzz@ihep.ac.cn
高能所

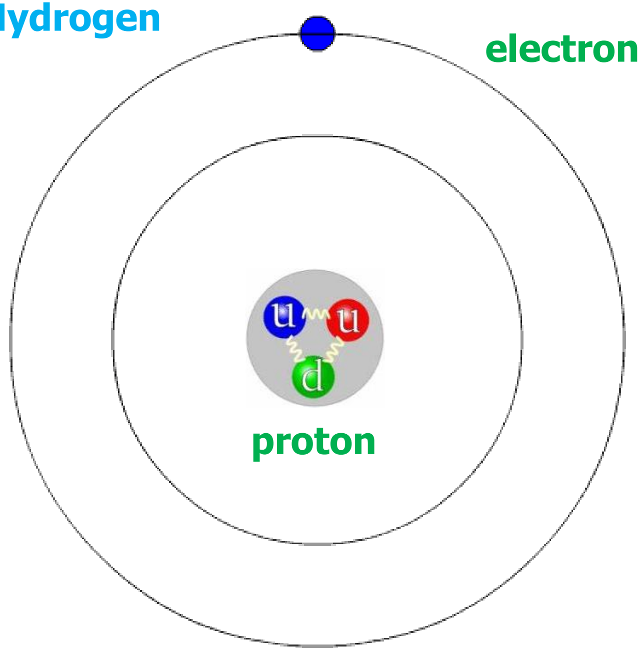


TeV 高能实验物理暑期学校（iSTEP2025），10—17.8.2025，中山大学深圳校区

Milestones towards the SM (1)

	EX discovery or TH breakthrough	Main contributors (★ Nobel laureates)	
1897	electron	J.J. Thomson ★	
1905	photon	A. Einstein ★	(a TH prediction)
1905	relativity	A. Einstein	
1912	cloud chamber	C.T.R. Wilson ★	
1914	beta decays	J. Chadwick	
1917	proton (u + d quarks)	E. Rutherford	
1923	Compton scattering	A.H. Compton ★	(1st US laureate)
1925	QM (matrix)	W. Heisenberg ★, M. Born, P. Jordan	
1926	QM (wave)	E. Schrödinger ★	
1928	Dirac equation	P.A.M. Dirac ★	
1929	Abelian gauge symmetry	H. Weyl	(foreshadowing)
1930	neutrino hypothesis	W. Pauli	(weak, isn't he?)
1931	cyclotron	E.O. Lawrence ★, M.S. Livingston	
1932	neutron	J. Chadwick ★	
1933	positron	C.D. Anderson ★	

Titbit 1: do you belong to a school?



- 1897: J.J. Thompson electron
- 1917: E. Rutherford proton
- 1932: J. Chadwick neutron
- 1905: A. Einstein photon

Four renowned schools in particle physics:

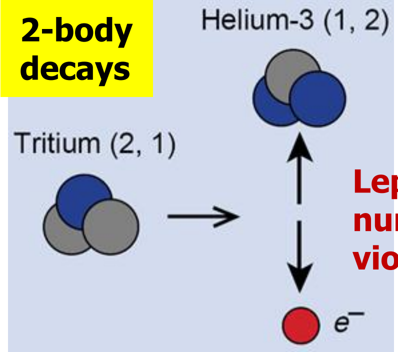
- J.J. Thomson
- A. Sommerfeld
- H. Yukawa
- E. Fermi

S.S. Chern: You must always put yourself amid people who are better than you, so you can become better.

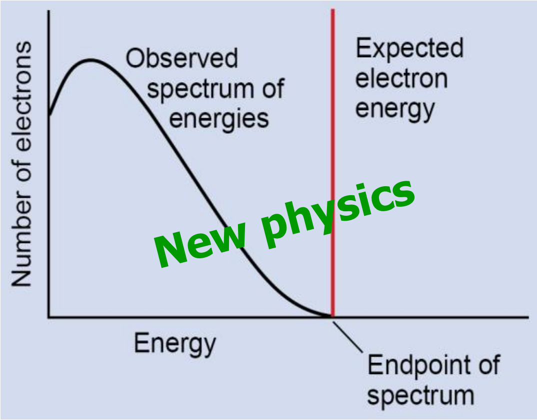
Titbit 2: why was Pauli unhappy?

The energy crisis in β decays

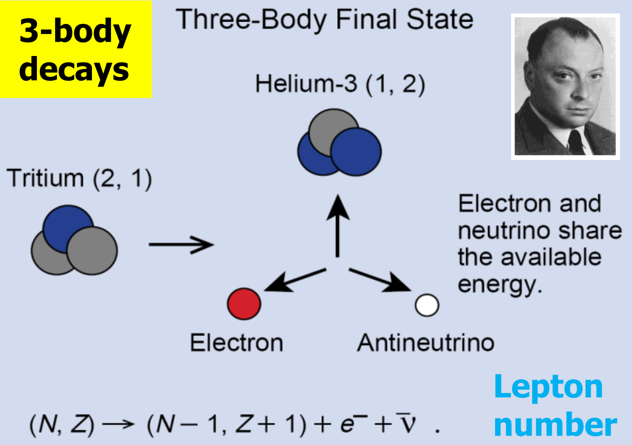
J. Chadwick 1914 , C. Ellis 1920~1927



Lepton number violation

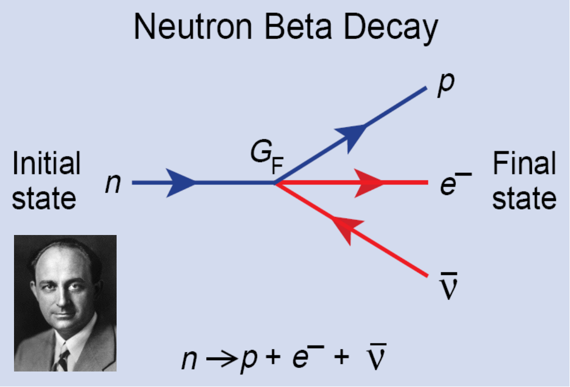


Wolfgang Pauli's new idea (1930)



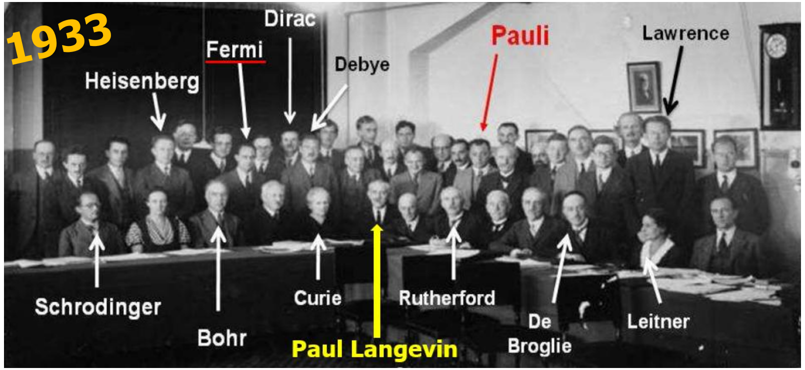
Lepton number conservation

Enrico Fermi's β-theory (1933)



"I will be remembered for this paper!"

Solvay 1933



泡利是个胆小鬼

Titbit 3: how QED arises from U(1)

The Lagrangian of a free electron keeps invariant under a global phase transformation:

$$\psi \to e^{i\theta}\psi \quad \longrightarrow \quad \mathcal{L}_{\mathrm{Dirac}} = i\hbar c\,\overline{\psi}\gamma^\mu\partial_\mu\psi - mc^2\,\overline{\psi}\psi$$

(θ : arbitrary real)

Weyl: what happens if the phase factor is spacetime-dependent? The Lagrangian of a free electron under a local phase transformation changes as

$$\psi \to e^{i\theta(x)}\psi \quad \longrightarrow \quad \mathcal{L}_{\mathrm{Dirac}} \to \mathcal{L}_{\mathrm{Dirac}} - \underline{\hbar c\,(\partial_\mu\theta)\,\overline{\psi}\psi}$$

To recover the Lagrangian's form invariance as a guiding principle, the electron is not free anymore, but has to interact with the electromagnetic field:

$$\mathcal{L}_{\mathrm{Weyl}} = \underbrace{\left[i\hbar c\,\overline{\psi}\gamma^\mu\partial_\mu\psi - mc^2\,\overline{\psi}\psi\right]}_{\text{electron}} - \underbrace{\left[\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} + Q\,\overline{\psi}\gamma^\mu\psi A_\mu\right]}_{\text{electromagnetic field}}$$

$$\psi \to e^{i\theta(x)}\psi \quad + \quad A_\mu \to A_\mu + \partial_\mu\lambda \quad \text{with} \quad \lambda(x) \equiv -\frac{\hbar c}{Q}\theta(x)$$

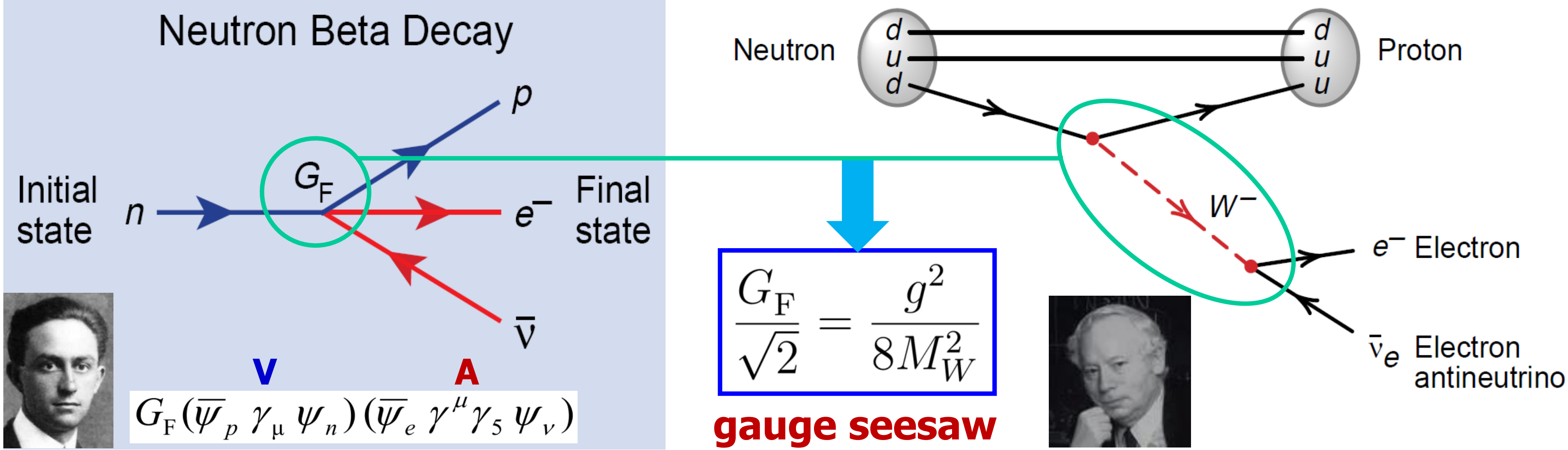
$$F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$$

Milestones towards the SM (2)

	EX discovery or TH breakthrough	Main contributors (★ Nobel laureates)	
1933	EFT for beta decays	E. Fermi	(1st EFT of the SM)
1935	Yukawa meson theory	H. Yukawa ★	(1st work = Nobel)
1936	muon	C.D. Anderson, S.H. Neddermeyer	
1946	QED	S. Tomonaga ★	
1947	pion	C. Powell ★, et al.	
1947	kaon (s quark)	G.D. Rochester, C.C. Butler	
1947	Lamb shift	W.E. Lamb ★, R.C. Retherford	
1948	magnetic moment of electron	H.M. Foley, P. Kusch ★	
1948	QED + Feynman diagrams	J. Schwinger ★; R. Feynman ★	
1952	bubble chamber	D.A. Glaser ★	
1954	non-Abelian gauge symmetry	C.N. Yang, R. Mills	(publishing is king)
1955	antiproton	O. Chamberlain ★, E. Segrè ★, et al.	
1956	electron antineutrino	C.L. Cowan, F. Reines ★, et al.	
1956	parity violation (TH)	T.D. Lee ★, C.N. Yang ★	
1957	parity violation (EX)	C.S. Wu, et al.; L. Lederman, et al.	

Titbit 4: behind Fermi's imagination

It's S. Weinberg who untied E. Fermi's knot (1934) by introducing a new degree of freedom (1967):



$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

gauge seesaw

Fermi coupling constant

$$G_F \simeq 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

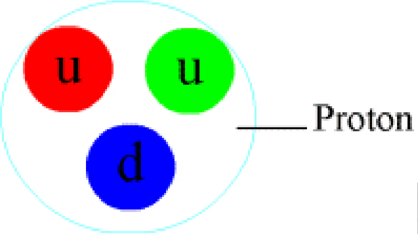
Weak interaction coupling constant

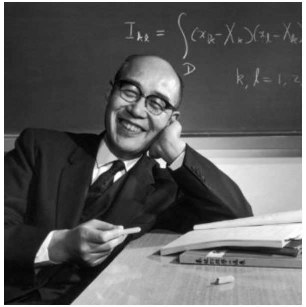
$$g \simeq 0.65 \quad \textbf{vs} \quad M_W \simeq 80.4\ \mathrm{GeV}$$

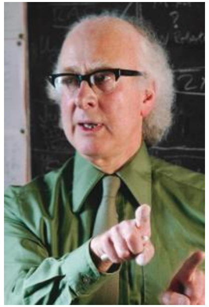
A good lesson: some effective quantities at low energies are very likely to originate from new heavy degrees of freedom in a more fundamental theory at much higher energy scales.

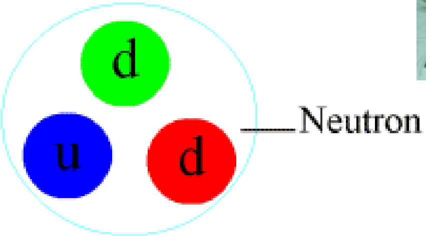
Titbit 5: the Yukawa interactions

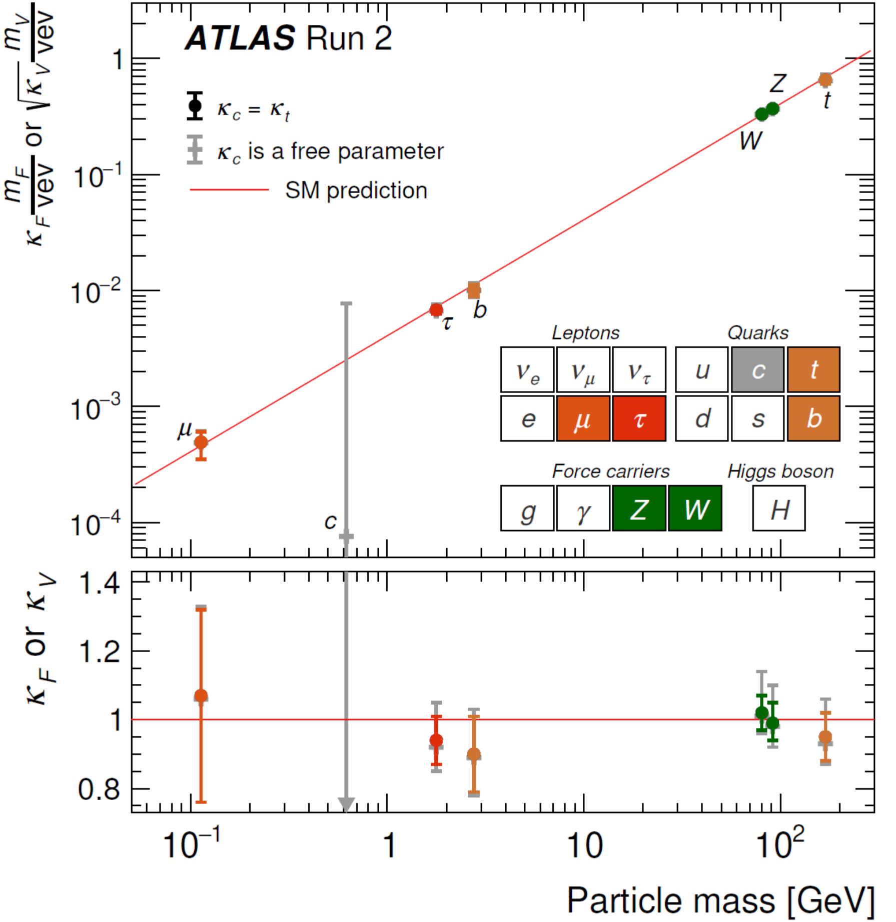
The Yukawa interaction between 2 nucleons (1935):











In the SM a Yukawa coupling measures the strength of a fundamental fermion interacting with the Higgs field, from which it gets its finite mass.

Titbit 6: birth of Yang-Mills theory

The 2 × 2 unitary matrix can always be expressed as the product $U = e^{i\theta}e^{i\tau\cdot\mathbf{a}}$ with θ a real phase, τ the vector of Pauli matrices, and "a" a real vector.


Global SU(2) transformation: $\psi \to e^{i\tau\cdot\mathbf{a}}\psi$

Local SU(2) transformations: $\psi \to S\psi$, $S \equiv e^{-iq\tau\cdot\lambda(x)/\hbar c}$, $\lambda(x) \equiv -\frac{\hbar c}{Q}\mathbf{a}(x)$

proton-neutron isospin symmetry

$$\mathcal{L}_{\text{Dirac}} = i\hbar c\overline{\psi}\gamma^\mu\partial_\mu\psi - mc^2\overline{\psi}\psi$$

This free term isn't invariant under the local transformation $\partial_\mu\psi \to S\partial_\mu\psi + (\partial_\mu S)\,\psi$, but it will be invariant after the derivative is replaced by a covariant derivative and the gauge fields are assigned to simultaneously transform in a proper way:

$$\partial_\mu \to \mathcal{D}_\mu \equiv \partial_\mu + i\frac{Q}{\hbar c}\tau\cdot\mathbf{A}_\mu$$

$$\mathbf{A}_\mu \to \mathbf{A}'_\mu \quad \text{with} \quad \tau\cdot\mathbf{A}'_\mu = S\left(\tau\cdot\mathbf{A}_\mu\right)S^{-1} + i\frac{\hbar c}{Q}\left(\partial_\mu S\right)S^{-1}$$

泡利的内心很挣扎

1954

A complete SU(2) Yang-Mills Lagrangian:

$$\mathbf{F}^{\mu\nu} \equiv \partial^\mu\mathbf{A}^\nu - \partial^\nu\mathbf{A}^\mu - \frac{2Q}{\hbar c}\left(\mathbf{A}^\mu \times \mathbf{A}^\nu\right)$$

$$\mathcal{L}_{\text{YM}} = \mathcal{L}_{\text{Dirac}} - \left[\frac{1}{16\pi}\mathbf{F}^{\mu\nu}\cdot\mathbf{F}_{\mu\nu} + \left(Q\overline{\psi}\gamma^\mu\tau\psi\right)\cdot\mathbf{A}_\mu\right]$$

Milestones towards the SM (3)

	EX discovery or TH breakthrough	Main contributors (★ Nobel laureates)
1958	V-A structure of weak interactions	G. Sudarshan, R. Marshak; R. Feynman, M. Gell-Mann
1960	pioneering idea of flavor mixing	M. Gell-Mann, M. Levy (milestones' milestone)
1961	Nambu-Goldstone boson	Y. Nambu ★, G. Jona-Lasinio; J. Goldstone
1962	muon neutrino	L. Lederman ★, M. Schwartz ★, J. Steinberger ★, et al.
1963	Cabibbo flavor mixing angle	N. Cabibbo
1964	SU(3) quark model	M. Gell-Mann ★; G. Zweig
1964	CP violation in kaon decays	J.W. Cronin ★, V.L. Fitch ★, et al.
1964	BEH mechanism	R. Brout, F. Englert ★; P. Higgs ★
1967	electroweak theory	S. Weinberg ★, A. Salam ★ (epitomize all knowns)
1968	multiwire proportional chamber	G. Charpak ★, et al.
1969	DIS of electron on protons	J.I. Friedman ★, H.W. Kendall ★, R.E. Taylor ★, et al.
1969	Bjorken scaling + Feynman's partons	J. Bjorken; R. Feynman
1970	GIM mechanism	S. Glashow ★, J. Illiopolous, L. Maiani
1971	renormalization of EW theory	G. 't Hooft ★, M. Veltman ★ (killing all divergence)
1973	weak neutral-current interactions	Gargamelle Collaboration

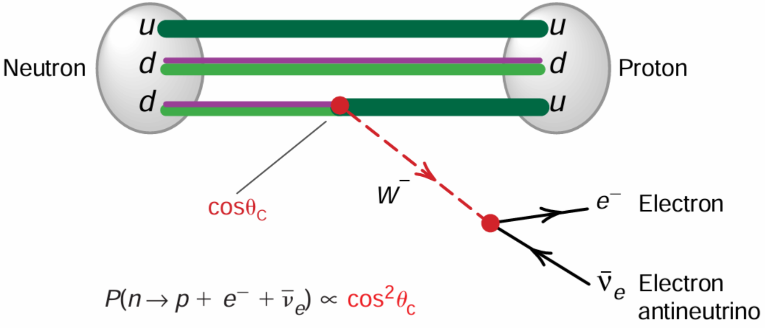
Titbit 7: an invaluable footnote

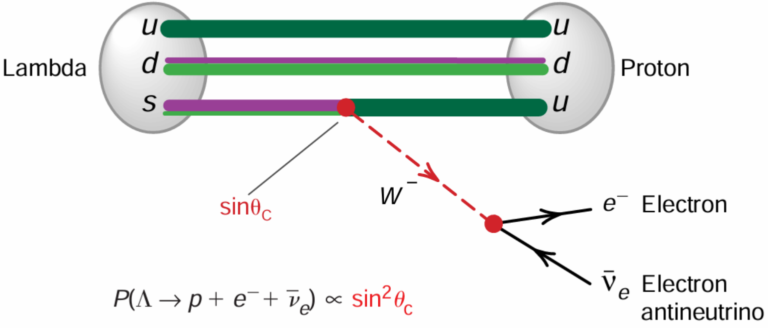
M. Gell-Mann, M. Levy: the axial current in beta decay (Nuovo Cim. 16, 705, 1960):

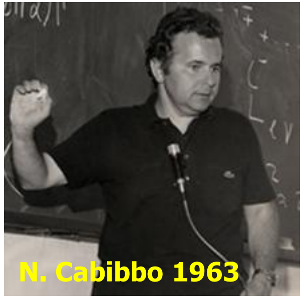
(*) *Note added in proof.* – Should this discrepancy be real, it would probably indicate a total or partial failure of the conserved vector current idea. It might also mean, however, that the current is conserved but with $G/G_\mu < 1$. Such a situation is consistent with universality if we consider the vector current for $\Delta S = 0$ and $\Delta S = 1$ together to be something like:

$$GV_\alpha + GV_\alpha^{(\Delta S=1)} = G_\mu \bar{p}\gamma_\alpha(n + \varepsilon\Lambda)(1+\varepsilon^2)^{-\frac{1}{2}} + \dots ,$$

and likewise for the axial vector current. If $(1+\varepsilon^2)^{-\frac{1}{2}} = 0.97$, then $\varepsilon^2 = .06$, which is of the right order of magnitude for explaining the low rate of β decay of the Λ particle. There is, of course, a renormalization factor for that decay, so we cannot be sure







Titbit 8: Basic structures of the SM

- **Foundations**: quantum mechanics + special relativity.
- **Local gauge symmetry groups** $SU(3)_c \times SU(2)_L \times U(1)_Y$: strong + weak + electromagnetic forces.
- **BEH mechanism**: electroweak gauge symmetry breaking.
- **Renormalizability**: to make infinities disappear and predictions reliable.

电弱统一理论部分的拉式量

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm fermion} + \mathcal{L}_{\rm Yukawa}$$

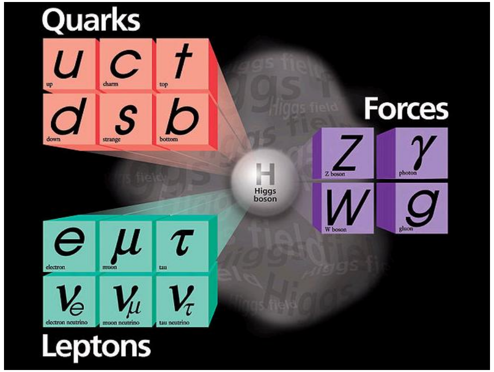
$$\mathcal{L}_{\rm G} = -\frac{1}{4}\left(W^{i\mu\nu}W^{i}_{\mu\nu} + B^{\mu\nu}B_{\mu\nu}\right)$$

$$\mathcal{L}_{\rm H} = (D^{\mu}H)^{\dagger}(D_{\mu}H) - \mu^{2}H^{\dagger}H - \lambda(H^{\dagger}H)^{2}$$

$$\mathcal{L}_{\rm F} = \overline{Q_{\rm L}}{\rm i}\not{D}Q_{\rm L} + \overline{\ell_{\rm L}}{\rm i}\not{D}\ell_{\rm L} + \overline{U_{\rm R}}{\rm i}\not{\partial}'U_{\rm R} + \overline{D_{\rm R}}{\rm i}\not{\partial}'D_{\rm R} + \overline{E_{\rm R}}{\rm i}\not{\partial}'E_{\rm R}$$

$$\mathcal{L}_{\rm Y} = -\overline{Q_{\rm L}}Y_{\rm u}\widetilde{H}U_{\rm R} - \overline{Q_{\rm L}}Y_{\rm d}HD_{\rm R} - \overline{\ell_{\rm L}}Y_{l}HE_{\rm R} + {\rm h.c.}$$

neutrinos are massless



Titbit 9: what is renormalizability?

A great success of the SM in fitting precision data——it is a renormalizable theory.


Sin-Itiro Tomonaga

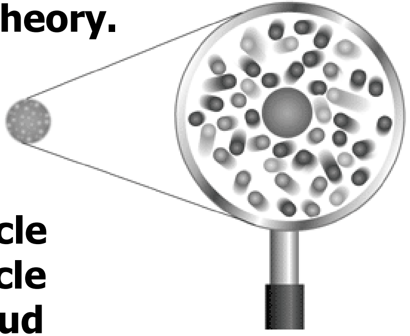

Julian Schwinger

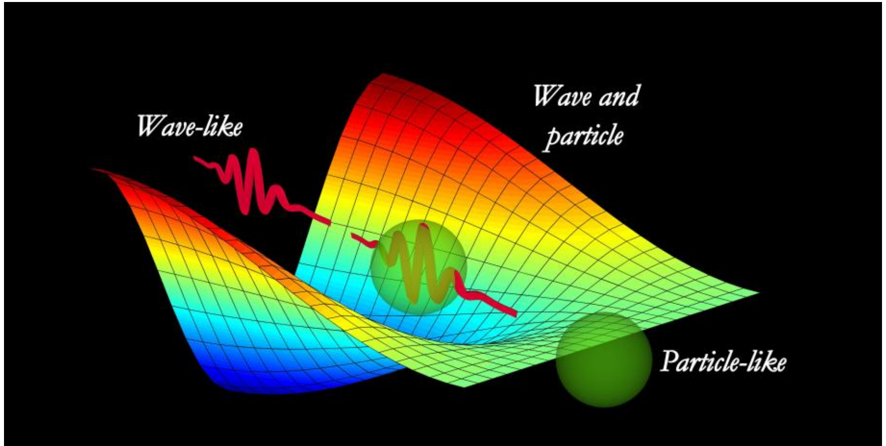

Richard P. Feynman

A **real** particle

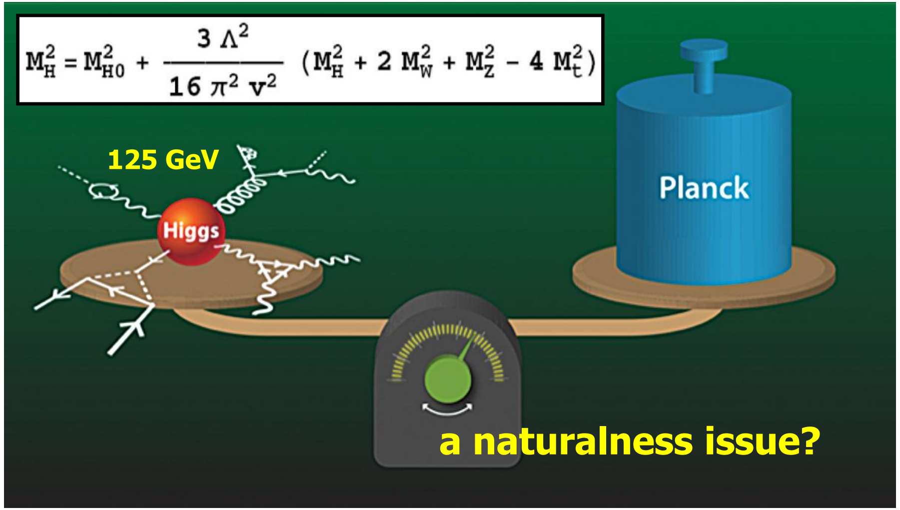
⇓

The **bare** particle
+ **virtual** particle
(**quantum**) cloud





A trouble from the **point-like** particles in QF theories



Milestones towards the SM (4)

	EX discovery or TH breakthrough	Main contributors (★ Nobel laureates)
1973	KM mechanism of CP violation	M. Kobayashi ★, T. Maskawa ★ (nontrivial CPV phase)
1973	asymptotic freedom of Yang-Mills theory	D. Gross ★, F. Wilczek ★; D. Politzer ★
1973	QCD	H. Fritzsch, M. Gell-Mann, H. Leutwyler
1974	charmonium (charm quark)	S.C.C. Ting ★, et al.; B. Richter ★, et al.
1975	tau	M.L. Perl ★, et al. (Sarma-Xing theorem)
1977	bottomonium (bottom quark)	L. Lederman, et al.
1979	gluons	TASSO Collaboration; et al.
1983	W and Z bosons	C. Rubbia ★, S. van der Meer ★, et al.
1995	top quark	CDF Collaboration; D0 Collaboration
2000	tau neutrino	DONUT Collaboration
2001	CP violation in b-quark decays	BaBar Collaboration; Belle Collaboration
2012	Higgs boson	ATLAS Collaboration; CMS Collaboration

- I am sorry for having missed some milestones, especially in accelerator + detector technologies.
- Some of the milestones listed above are more or less a reflection of my personal favorites.

Titbit 10: the only phase of the SM

In QFTs: • non-observable phase → a possible symmetry; • observable phase → symmetry breaking.

In 1973, M. Kobayashi and T. Maskawa proposed a mechanism of CP violation in the SM.

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

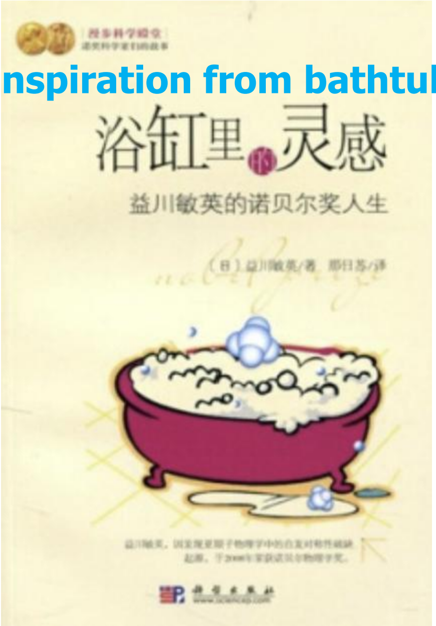
Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Inspiration from bathtub



It is the nontrivial KM phase that determines all the phenomena of CP violation in the quark sector.

This is the only phase parameter in particle physics that has so far been observed. More to be seen?

Titbit 11: the Sarma-Xing theorem

In the 1980s and 1990s, many theorists published many papers on the possibilities of 4 G fermions.

when will the 4th charged lepton be discovered?

NOBEL LEPTONS [1]

arXiv:hep-ph/9512420v1 25 Dec 1995

K. V. L. Sarma
Tata Institute of Fundamental Research
Homi Bhabha Road, Bombay 400 005, India
(E-mail: *kvls@theory.tifr.res.in*)

The 1995 Nobel Prize in Physics is shared equally by the American physicists Frederick J. Reines and Martin L. Perl for their pioneering experimental contributions to lepton physics. Following is a brief account of their discoveries.

A summary of the discoveries made in the world of leptons is given in Table 1. We see that the third generation has started getting Nobel prizes. It is amusing that the charged-leptons crop up with a 39-year gap and may be the 4th one would show up in the year 2114. For the present, the available experimental information implies that there are no charged leptons which are heavier than tau and lighter than 45 GeV.

- **1897：发现 电子**
- **1936：发现 缪子**
- **1975：发现 陶子**

预言1975 + 39 = 2114：发现 4G

我当年读了这位老兄的文章后，给他写了一封邮件：三哥，你的算术是体育老师教的？1975 + 39 = 2014。他回复表示尴尬，但也没修改论文…

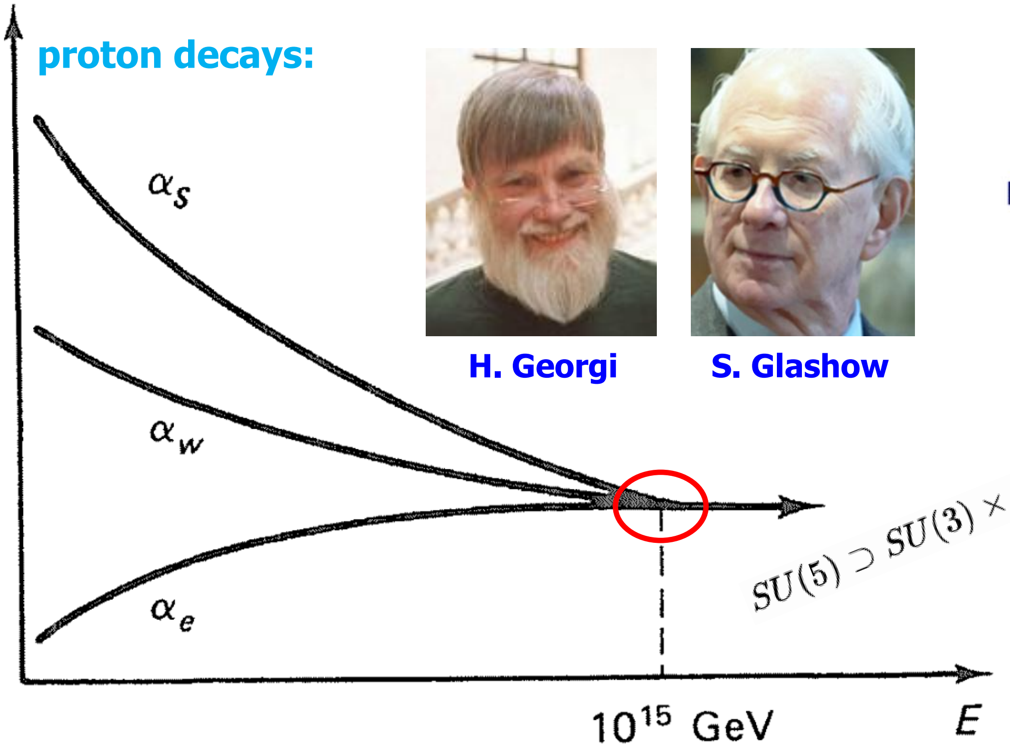
Beyond the SM: massive neutrinos

	EX discovery or TH breakthrough	Main contributors (★ Nobel laureates)	
1937	Majorana fermion	E. Majorana	
1957	neutrino-antineutrino transitions	B. Pontecorvo	
1962	neutrino flavor mixing	Z. Maki, M. Nakagawa, S. Sakata	
1967	formulation of neutrino oscillations	B. Pontecorvo	
1968	solar neutrino deficit	R. Davis ★, et al.	
1974	SU(5) GUT + proton decays	H. Georgi, S.L. Glashow	(who was motivated?)
1977	Minkowski (seesaw) mechanism	P. Minkowski	(most likely to ν mass)
1986	leptogenesis	M. Fukugita, T. Yanagida	
1987	supernova neutrinos	M. Koshiba ★, et al.	
1998	atmospheric neutrino oscillations	T. Kajita ★, et al.	
2001	solar neutrino oscillations	A.B. McDonald ★, et al.	
2002	reactor long-baseline oscillations	KamLAND Collaboration	
2002	accelerator disappearance oscillations	K2K Collaboration	
2011	accelerator appearance oscillations	T2K Collaboration	
2012	reactor short-baseline oscillations	Daya Bay Collaboration	

Titbit 12: search for proton decays

- The GUT idea (1974) was motivated by a proof of asymptotic freedom of Yang-Mills theory (1973)

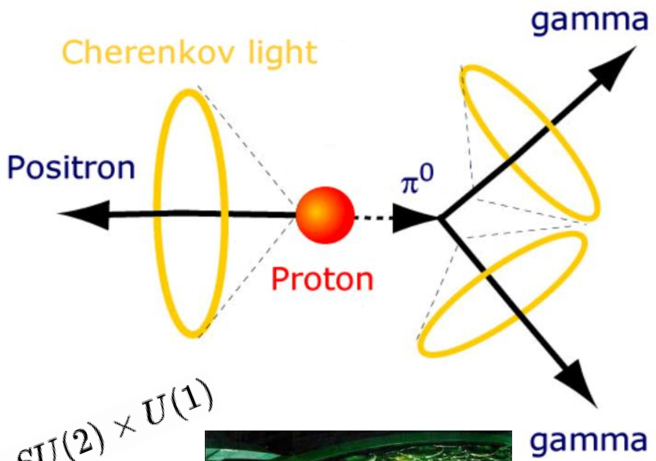
proton decays:



H. Georgi

S. Glashow

$SU(5) \supset SU(3) \times SU(2) \times U(1)$



M. Koshiba

Kamiokande (supernova ν's)
Super-K (atmospheric ν's)
Hyper-K (leptonic CPV?)

- 小柴昌俊的自传《我不是好学生》特别值得一读。他也不是好老师?
- 小柴昌俊的最大特点之一是喜欢和顶级的理论家一起耍，获取灵感。

Titbit 13: the Minkowski mechanism

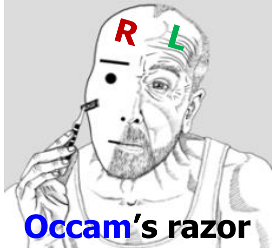
♦ Neutrinos surely have the *right* to be *right* (-handed) to keep a similar kind of left-right symmetry as charged leptons and quarks —— small animals' fair play?

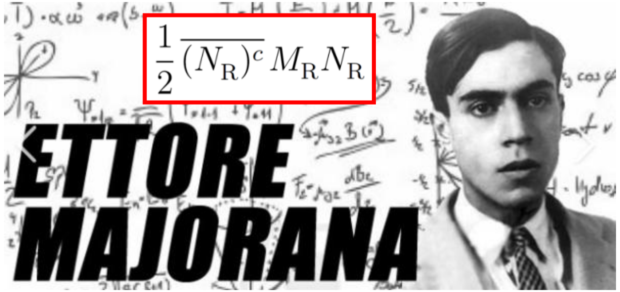
♦ Then neutrinos are allowed to couple to the SM Higgs doublet —— the Yukawa interactions. Why not?

♦ But the gender of neutrinos (neutral) makes it very fair to add a Majorana mass term with *N* and N^c, which is fully *harmless* to all the fundamental symmetries of the SM.

♦ Then we are led to the Minkowski/seesaw mechanism (1977).

$$\begin{pmatrix} u_{\rm L} \\ d_{\rm L} \end{pmatrix} \Longleftrightarrow \begin{matrix} u_{\rm R} \\ d_{\rm R} \end{matrix} \qquad \begin{pmatrix} \nu_{e\rm L} \\ e_{\rm L} \end{pmatrix} \Longleftrightarrow \begin{matrix} ? \\ e_{\rm R} \end{matrix}$$





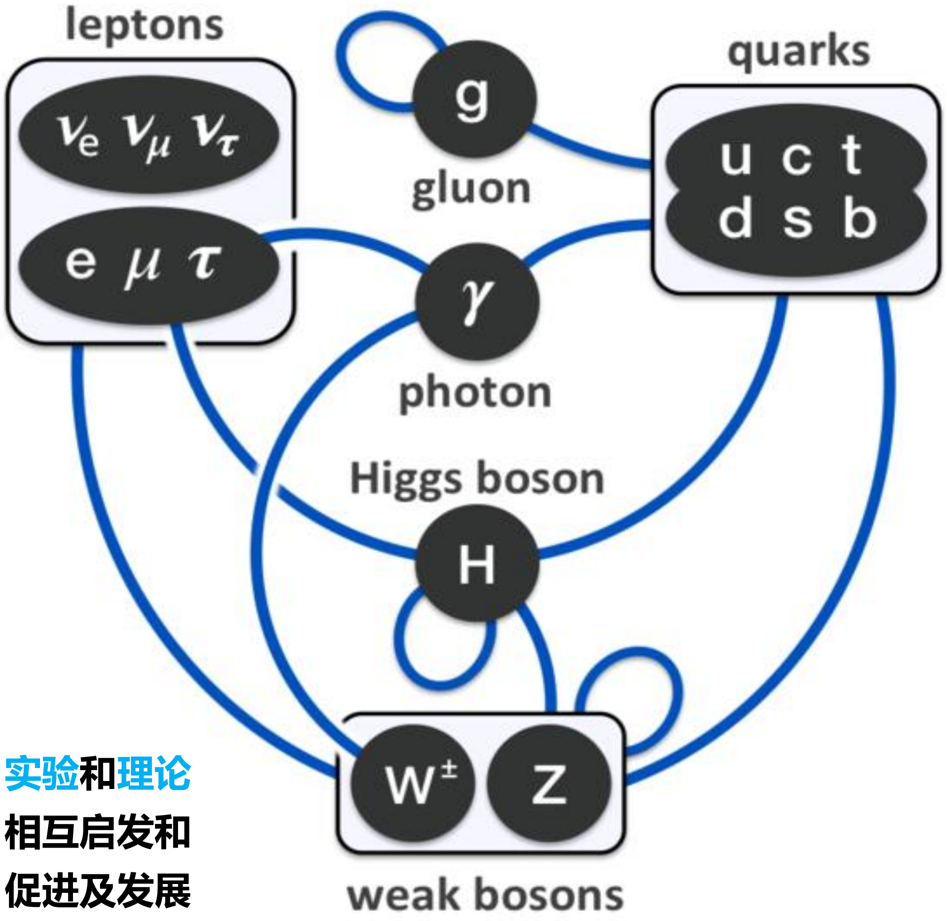
consistent with S. Weinberg's SMEFT (1979) → Seesaw EFT

"unique"
d=5
operator

$$\mathcal{O}_{\rm W} = \frac{\overline{\ell_{\rm L}}\widetilde{H}\widetilde{H}^T\ell^c_{\rm L}}{\Lambda}$$

- tiny neutrino masses !
- the Majorana nature ?

Conclusions



基础研究带动**技术进步**，反之亦然：

体重 2 mg 的蚊子以 0.2 m/s 的速度飞行，其动能约为 4×10^{-8} J ~ 250 GeV，约等于 CEPC 的质心能量。关键在于怎样实现蚊子的稳定飞行和对撞。

实验和**理论**
相互启发和
促进及发展