彭桓武高能基础理论研究中心

Colloquium

强相互作用物质微观结构的探索

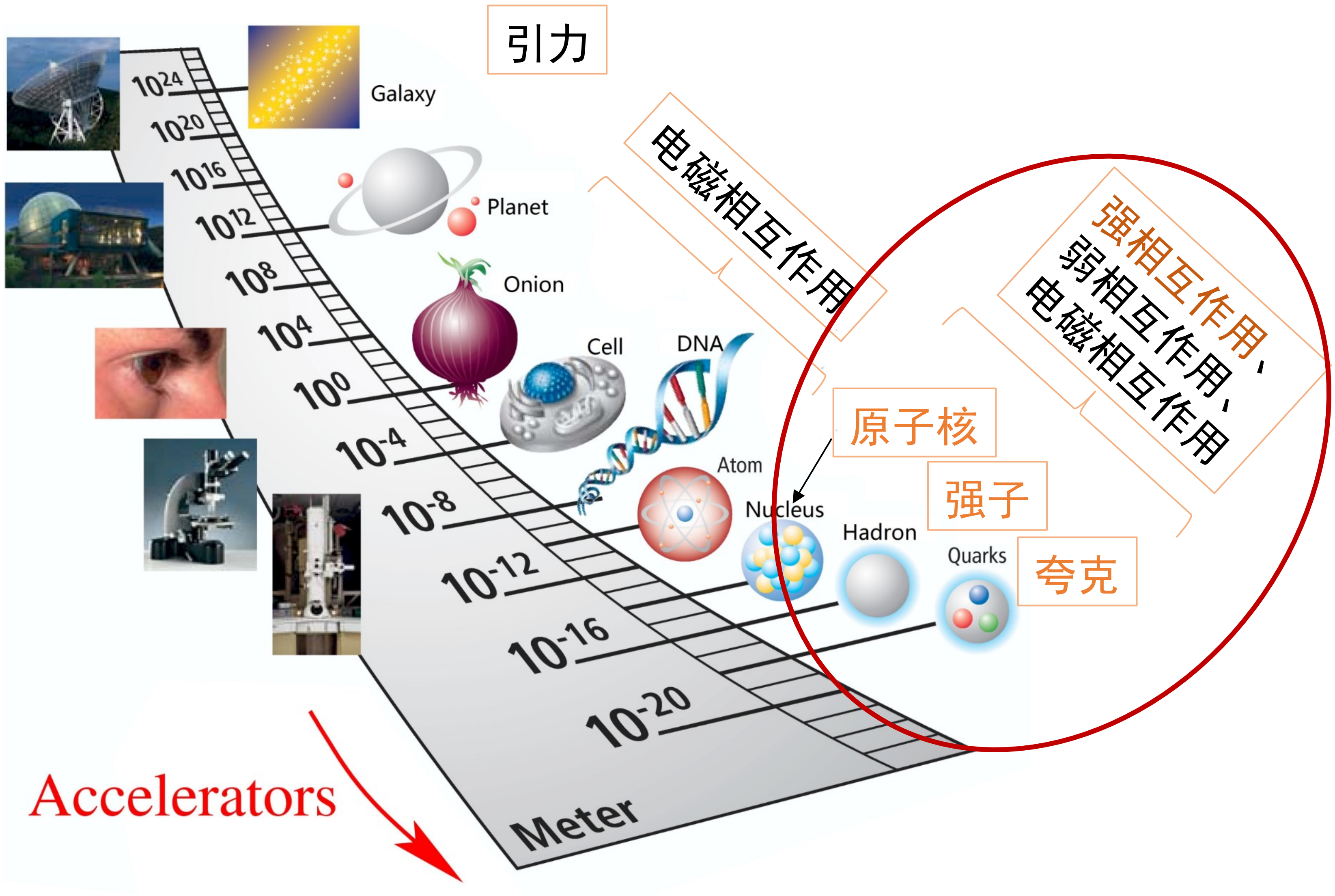
——从质子到X(3872)

郭奉坤

中国科学院理论物理研究所

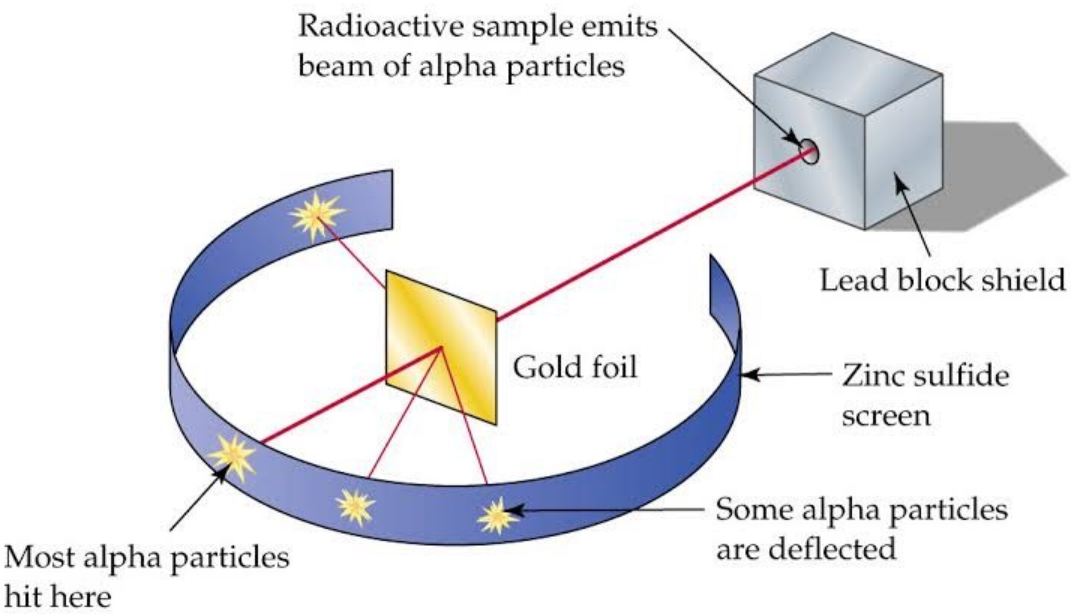
2023.12.01

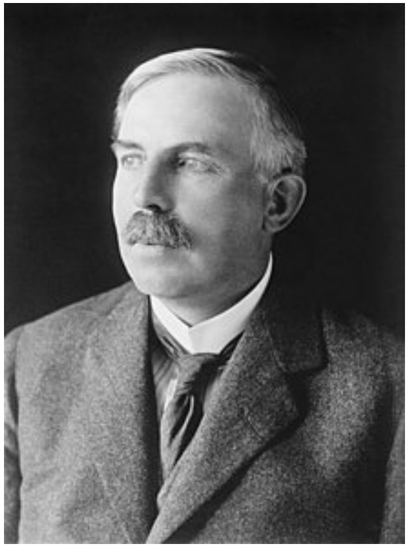
基本相互作用



引力
电磁相互作用
强相互作用、
弱相互作用、
电磁相互作用
原子核
强子
夸克
Galaxy
Planet
Onion
Cell
DNA
Atom
Nucleus
Hadron
Quarks
10^24
10^20
10^16
10^12
10^8
10^4
10^0
10^-4
10^-8
10^-12
10^-16
10^-20
Meter
Accelerators

原子核的发现



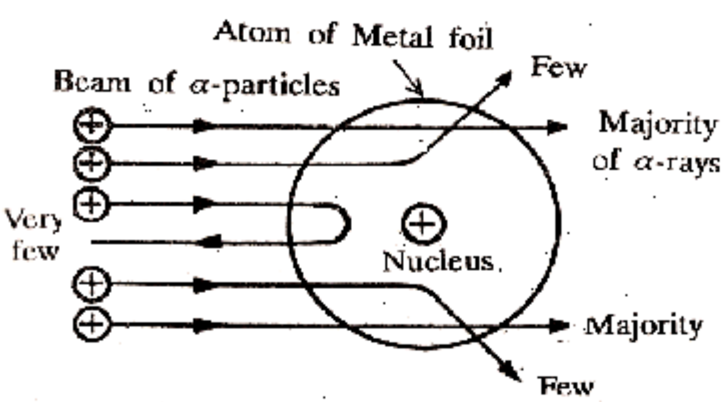


Ernest Rutherford (1871-1937)
1908年诺贝尔化学奖(放射性)

1908年, 卢瑟福用α粒子轰击金箔

1911年, 提出卢瑟福模型:

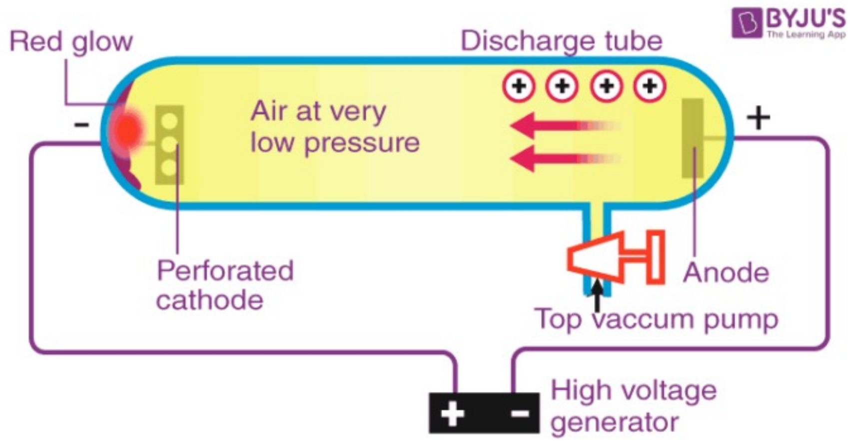
原子 = 原子核 + 核外电子

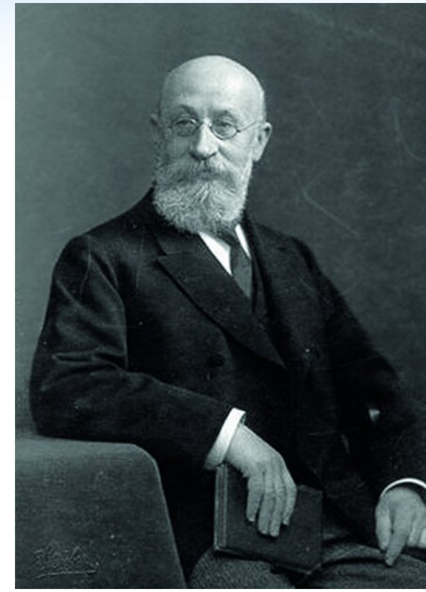


质子的发现

质子质量： 1.67×10^{-24} g = 938 MeV

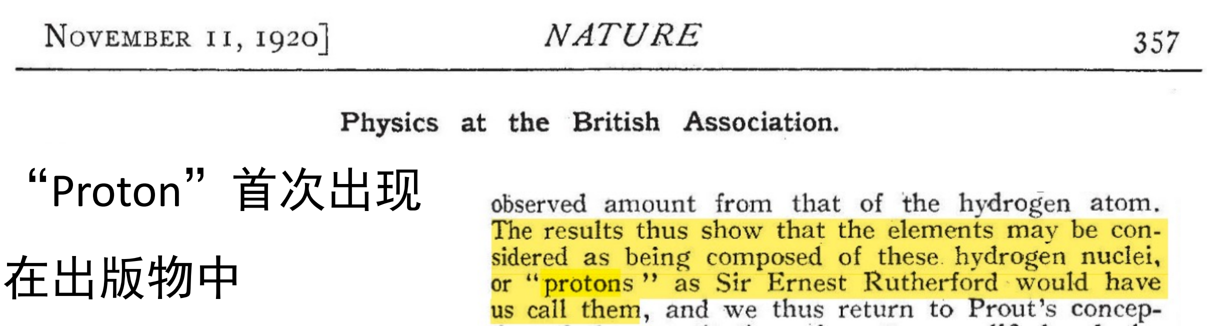
- 1886年，Eugen Goldstein 发现阳极射线





Eugen Goldstein (1850-1930)

- 1919年, 卢瑟福用α粒子打氮气 $({}^{14}N + \alpha \to {}^{17}O + p)$, 产生氢原子核, 即质子, 说明氢原子核是所有原子的一部分, 之后质子被接受



NOVEMBER 11, 1920] NATURE 357

Physics at the British Association.

observed amount from that of the hydrogen atom. The results thus show that the elements may be considered as being composed of these hydrogen nuclei, or "protons" as Sir Ernest Rutherford would have us call them, and we thus return to Prout's concep-

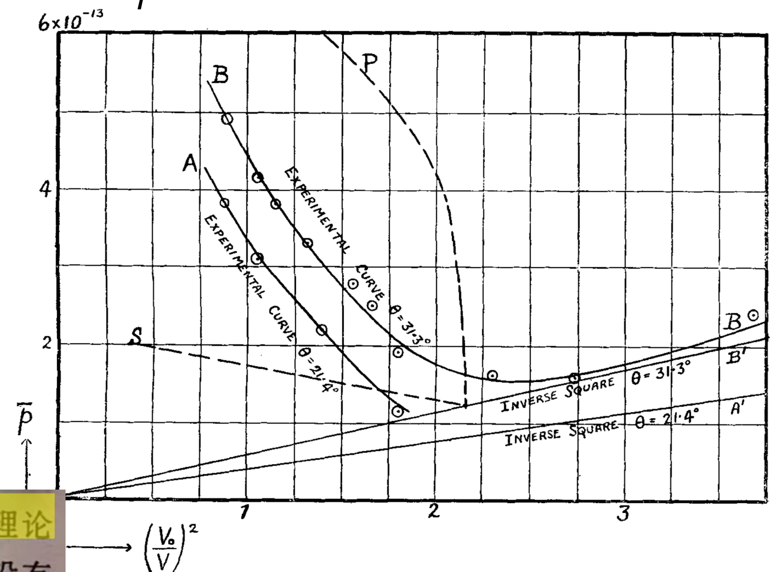
“Proton”首次出现

在出版物中

强相互作用的诞生

核物理的传统目标：通过研究核子之间的相互作用来理解原子核的性质

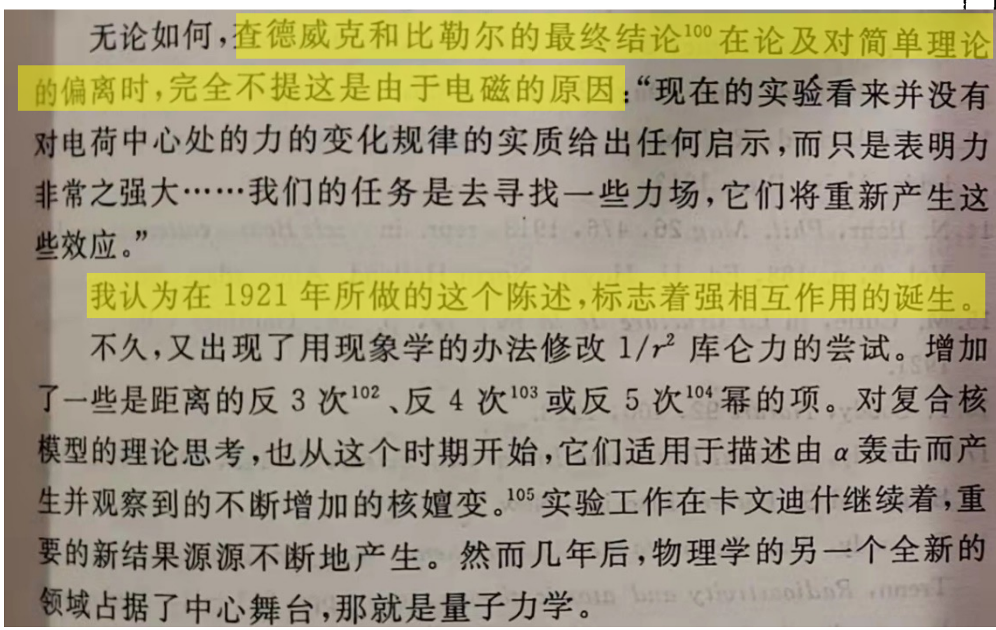
- 卢瑟福认为核力是电磁力，1919年观察到对假设核力$\propto \frac{1}{r^2}$的偏离，但认为可能是对点结构的偏离带来的
- 1921年，查德威克和他的学生E.S. Bieler 研究 α−氢散射



C. *The collisions of α particles with hydrogen nuclei*

J. Chadwick Ph.D. & E.S. Bieler M.Sc

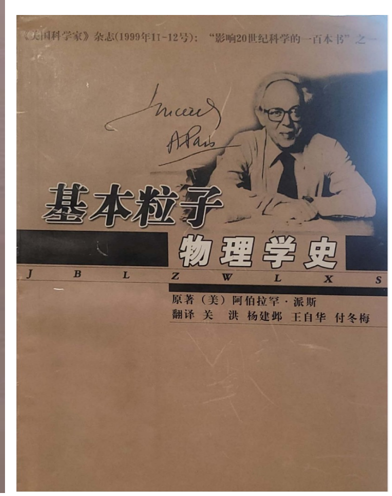
Pages: 923-940



无论如何，查德威克和比勒尔的最终结论[100]在论及对简单理论的偏离时，完全不提这是由于电磁的原因："现在的实验看来并没有对电荷中心处的力的变化规律的实质给出任何启示，而只是表明力非常之强大……我们的任务是去寻找一些力场，它们将重新产生这些效应。"

我认为在 1921 年所做的这个陈述，标志着强相互作用的诞生。

不久，又出现了用现象学的办法修改 $1/r^2$ 库仑力的尝试。增加了一些是距离的反 3 次[102]、反 4 次[103]或反 5 次[104]幂的项。对复合核模型的理论思考，也从这个时期开始，它们适用于描述由 α 轰击而产生并观察到的不断增加的核嬗变。[105]实验工作在卡文迪什继续着，重要的新结果源源不断地产生。然而几年后，物理学的另一个全新的领域占据了中心舞台，那就是量子力学。



氘核的发现 质子-中子的束缚态

A Hydrogen Isotope of Mass 2

Harold C. Urey, F. G. Brickwedde, and G. M. Murphy

Phys. Rev. **39**, 164 – Published 1 January 1932

1931年底， Urey, Brickwedde, Murphy 通过蒸发液氢，从原子光谱上发现了氘（deuterium），

氢的质量数为2的同位素

Harold Urey and the discovery of deuterium

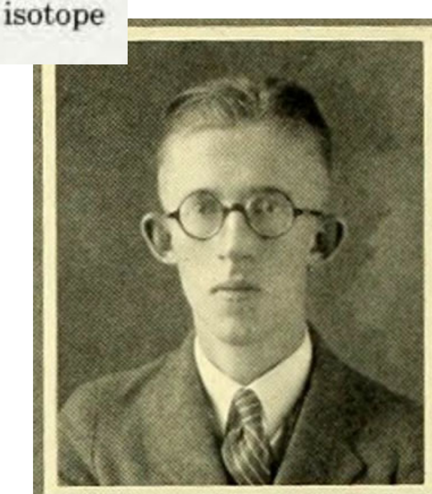
Chemistry, nuclear physics, spectroscopy and thermodynamics came together to predict and detect heavy hydrogen before the neutron was knowı

Ferdinand G. Brickwedde

Although George M. Murphy and I coauthored with Urey the papers[1–3] reporting the discovery, it was Urey who proposed, planned and directed the investigation. Appropriately, the Nobel Prize for finding a heavy isotope of hydrogen went to Urey.

Harold Urey (1893-1981)
1934年诺贝尔化学奖

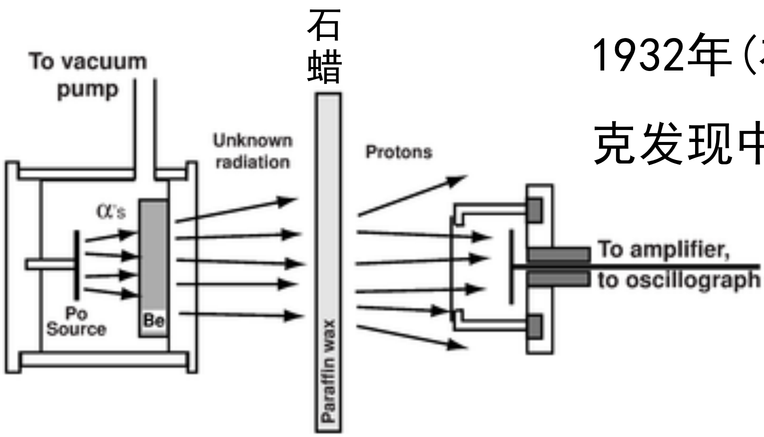
Ferdinand Brickwedde (1893-1981)



George Murphy (1903-1968)

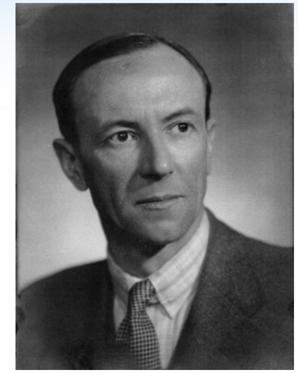
中子的发现

中子质量： 939.6 MeV



1932年（在氘核发现十周后），查德威克发现中子，质量与质子差不多

$$^{9}\text{Be} + \alpha \rightarrow {}^{12}\text{C} + n$$



James Chadwick (1891-1974)
1935年诺贝尔物理奖

此前，约里奥–居里夫妇（1935年诺贝尔化学奖，人工放射性）做了实验，以为发现的是 γ 射线

312 *NATURE* [FEBRUARY 27, 1932

Letters to the Editor

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of* NATURE. *No notice is taken of anonymous communications.*]

Possible Existence of a Neutron

This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a

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The Existence of a Neutron.

By J. CHADWICK, F.R.S.

(Received May 10, 1932.)

702 J. Chadwick.

The masses are $B^{11} = 11\cdot00825 \pm 0\cdot0016$; $He^4 = 4\cdot00106 \pm 0\cdot0006$; $N^{14} = 14\cdot0042 \pm 0\cdot0028$. The kinetic energies in mass units are α-particle = 0·00565; neutron = 0·0035; and nitrogen nucleus = 0·00061. We find therefore that the mass of the neutron is 1·0067. The errors quoted for the mass measurements are those given by Aston. They are the maximum errors which can be allowed in his measurements, and the probable error may be taken as about one-quarter of these.* Allowing for the errors in the mass measurements it appears that the mass of the neutron cannot be less than 1·003, and that it probably lies between 1·005 and 1·008.

原子核 = 质子 + 中子

- 1932年，查德威克发现中子后， Iwanenko 和海森堡立刻提出原子核由质子和中子构成
- 此前的模型：质子+电子（原子核的β衰变放出电子）

1932年4月

The Neutron Hypothesis

Dr. J. Chadwick's explanation[1] of the mysterious beryllium radiation is very attractive to theoretical physicists. Is it not possible to admit that neutrons play also an important rôle in the building of nuclei, the nuclei electrons being *all* packed in α-particles or neutrons? The lack of a theory of nuclei makes, of course, this assumption rather uncertain, but perhaps it sounds not so improbable if we remember that the nuclei electrons profoundly change their properties when entering into the nuclei, and lose, so to say, their individuality, for example, their spin and magnetic moment.

The chief point of interest is how far the neutrons can be considered as elementary particles (something like protons or electrons). It is easy to calculate the number of α-particles, protons, and neutrons for a given nucleus, and form in this way an idea about the momentum of nucleus (assuming for the neutron a moment $\frac{1}{2}$). It is curious that beryllium nuclei do not possess free protons but only α-particles and neutrons.

D. Iwanenko.

Physico-Technical Institute,
Leningrad, April 21.

Nature, 129, 312, Feb. 27, 1932.

Dmitri Ivanenko
(1904-1994)

D. Ivanenko, P.A.M. Dirac and W. Heisenberg (Berlin, 1958)

原子核 = 质子 + 中子 质子和中子统称核子 (nucleon: Møller, 1941)

1932年6月

海森堡的原子核模型：

- 非相对论量子力学
- 假设中子自旋为1/2（第3篇文章中持保留态度）
- 引入同位旋的概念：质子和中子相转换
- 假设新的短程相互作用：交换力(电子)

Über den Bau der Atomkerne. I

W. Heisenberg　　论原子核的结构

Zeitschrift für Physik **77**, 1–11 (1932) | Cite this article

Über den Bau der Atomkerne. II

W. Heisenberg

Zeitschrift für Physik **78**, 156–164 (1932) | Cite this article

Über den Bau der Atomkerne. III

W. Heisenberg

Zeitschrift für Physik **80**, 587–596 (1933) | Cite this article

Werner Heisenberg (1901-1976)
1932年诺贝尔物理奖 (量子力学)

	自旋交换	电荷交换
海森伯力(1932 年)[104]	是	是
维格纳力(1932 年)[117]	否	否
马约拉纳力(1933 年)[116]	否	是
巴特勒特(J. H. Bartlett)力(1936 年)[118]	是	否

1933年索尔维会议的讨论焦点

被广泛假设的短程势的形式：

$J(r) = ae^{-br}$ or $J(r) = ae^{-br^2}$

INSTITUT INTERNATIONAL DE PHYSIQUE SOLVAY

SEPTIÈME CONSEIL DE PHYSIQUE -- BRUXELLES. 22-29 OCTOBRE 1933

Photo Benjamin Couprie

28. avenue Louise, Bruxelles

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P. LANGEVIN Th. DE DONDER L. de BROGLIE

Absents : A. EINSTEIN et Ch.-Eug. GUYE

量子场论的早期发展

Über die Wechselwirkung von zwei Elektronen.

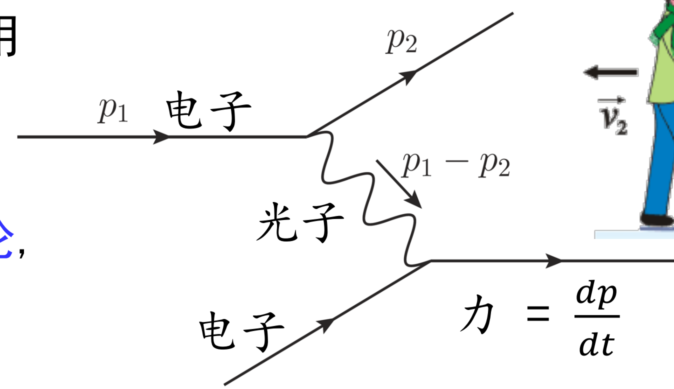
Von **H. Bethe** und **E. Fermi** in Rom.

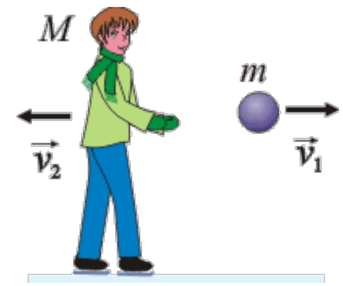
(Eingegangen am 9. Juni 1932.)

- 1932年, 贝特和费米: 带电粒子之间的相互作用通过交换虚光子;

  经典观点: 通过带电粒子的电磁场相互作用

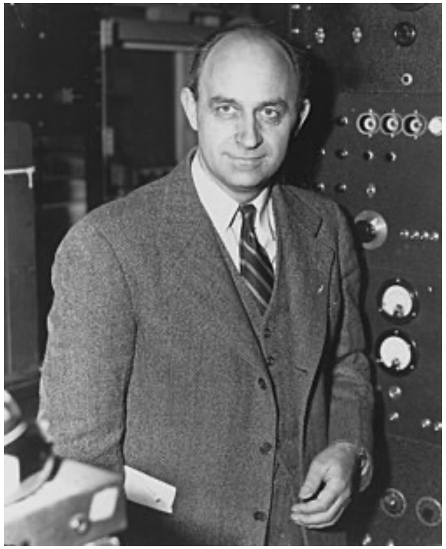
- 交换其它粒子可以给出别的力





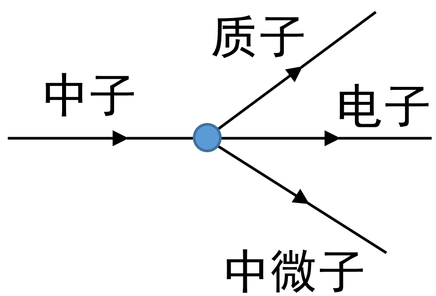
- 1933, 1934年, 费米: β 衰变的四费米子理论,

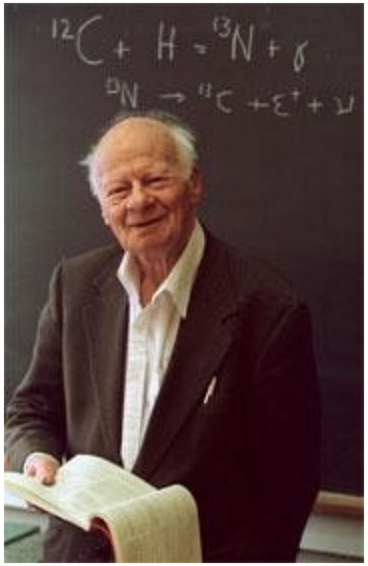
  相对论量子场论, 粒子数不守恒, 电子不存在于原子核中, 衰变的时候才产生出来



Enrico Fermi (1901-1954)

1938年诺贝尔物理奖 (慢中子诱发核反应)





Hans Bethe (1906-2005)

1967年诺贝尔物理奖 (恒星核合成理论)

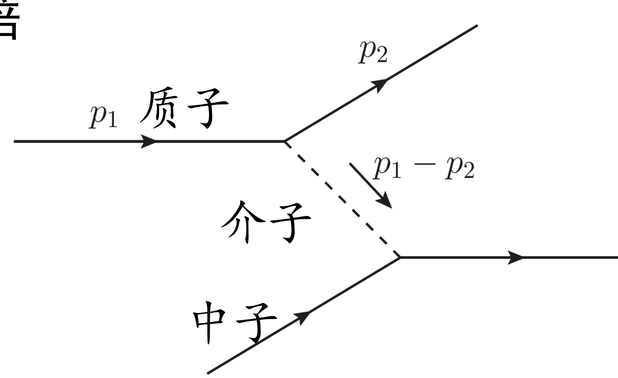
汤川力和π介子

1934年11月，汤川秀树 (Hideki Yukawa) 的核力的介子交换理论

- 不再纠结于电子交换
- 提出存在一个新的零自旋的重粒子（1939年开始被称为介子meson），质量大约是电子的两百倍

汤川势：

$$J(r) = -g^2 \frac{e^{-\lambda r}}{r}$$



汤川秀树 (1907-1981)
1949年诺贝尔物理奖

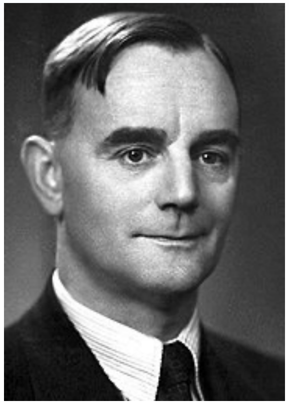
On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov. 17, 1934)

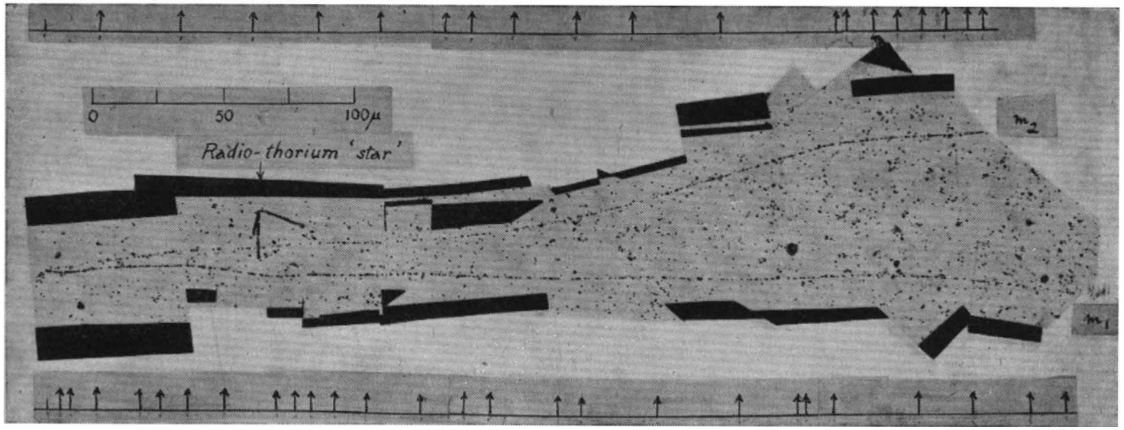
π介子的发现

- 1936年, Carl Anderson 和 Seth Neddermeyer 在宇宙线中发现 μ子, 大约是电子的两百倍, 被误以为是π介子
- 1945年, M. Conversi 等发现其与核的相互作用比汤川介子弱 10 到 12 个量级
- 1947年, C. F. Powell 用感光乳胶发现了π介子, 来源于宇宙线



Cecil Powell (1903-1969)
1950年诺贝尔物理奖

694 NATURE May 24, 1947 Vol. 159



Grain-counts indicate that the masses of the primary particles in Figs. 1 and 2 are 350 ± 80 and 330 ± 50 m_e, respectively; and of the secondary

现在的结果: $m_{\pi^\pm} = 274\, m_e$

π介子的发现

- D. Bose 和 B. Choudhuri 于1940-1942年可能就看到了π介子的迹象

302 NATURE MARCH 14, 1942, VOL. 149

A Photographic Method of Estimating the Mass of the Mesotron

WE have described[1] a method of estimating the

values of mesotron masses found with plates B and C are probably due to the presence of proton tracks in these plates, due to collision of primary neutrons with hydrogenous matter. This is further evidence

Mean grain spacing 10^{-4} cm.		6–5	5–4	4–3	3–2	Mean value
Value of mesotron mass μ in units of m_0	Plate A	221	160	236	(1723)	217 ± 30
	B		316	355		336 ± 19·5
	C	278	318	342	(1743)	313 ± 18·6

Plate A was kept under air, and B under 20 cm. of water at Sandakphu, and plate C at Phari Jong, Tibet, in the Post Office building under a roof thickness of 2½ ft. of mud and wood. The consistently high

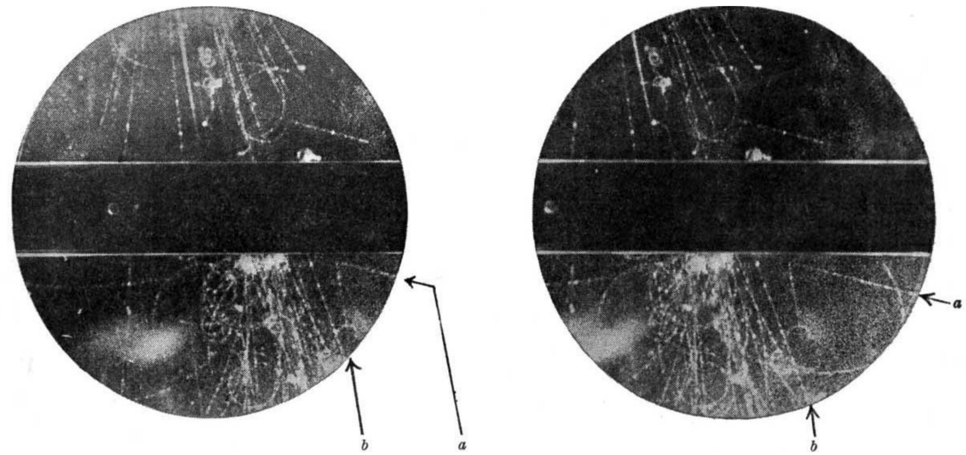
西藏帕里镇

Debendra Mohan Bose (1885-1975)

Bibha Chowdhuri (1913-1991)

更多“基本”粒子在宇宙线中的发现

- 1944年, L. Leprince-Ringuet (1901-2000), M. L'Heritier 带电K介子
- 1947年, G. Rochester (1908-2001), C. Butler (1922-1999) 发现中性K介子, 确认带电K介子
- 1951年, R. Armenteros 等和 R. Thompson 等发现Λ^0超子 (hyperon, Leprince-Ringuet 1953)
- 1952年, R. Armenteros 等发现带电 Ξ^- 超子
- 1952年, C. York 等发现带电Σ^+超子



No. 4077 December 20, 1947 NATURE

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER AND Dr. C. C. BUTLER

Physical Laboratories, University, Manchester

Photo-graph
1
2

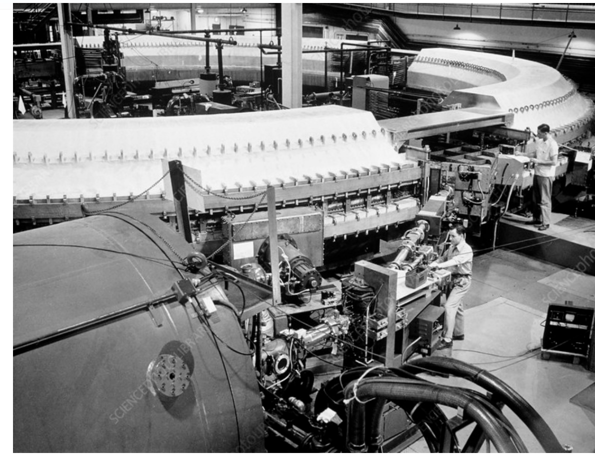
case is

We conclude from all the evidence that Photograph 1 represents the decay of a neutral particle, the mass of which is unlikely to be less than 770*m* or greater than 1,600*m*, into the two observed charged particles. Similarly, Photograph 2 represents the disintegration of a charged particle of mass greater than 980*m* and less than that of a proton into an observed penetrating particle and a neutral particle. It may be noted that no neutral particle of mass 1,000*m* has yet been observed; a charged particle of mass 990*m* ± 12 per cent has, however, been observed by Leprince-Ringuet and L'héritier[2].

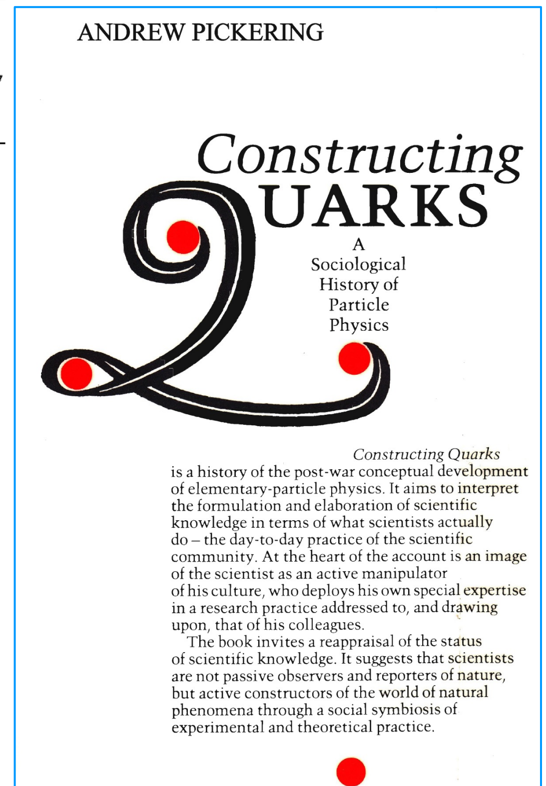
加速器时代开启

1952年, 美国 Brookhaven 国家实验室的加速器

Cosmotron 开始运行

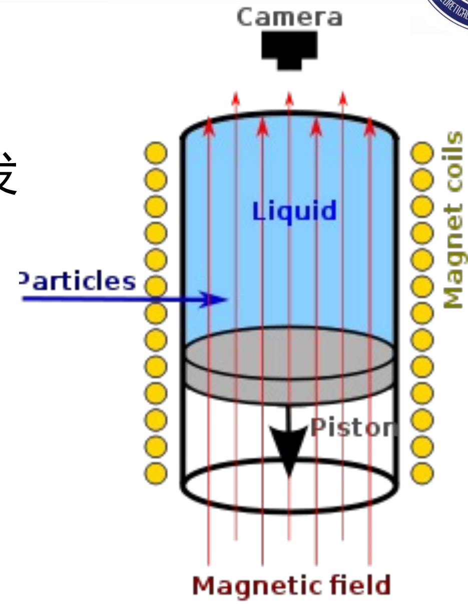


Accelerator	Date of first operation	Particles accelerated	Beam energy (GeV)	CM energy (GeV)
Cosmotron, Brookhaven	1952	Protons	3	2.8
Bevatron, Berkeley	1954	Protons	6.2	3.5
Dubna	1957	Protons	10	4.5
CERN PS	1959	Protons	28	7
AGS, Brookhaven	1961	Protons	33	8
CEA, Cambridge, MA	1962	Electrons	6	3.5
ZGS Argonne	1963	Protons	13	5
NIMROD, Rutherford Lab.	1963	Protons	7	3.7
DESY, Hamburg	1964	Electrons	7	3.8
NINA, Daresbury	1966	Electrons	5	3.2
SLAC, Stanford	1966	Electrons	22	7
Yerevan, USSR	1967	Electrons	6	3.5
Cornell	1967	Electrons	12	5
Serpukhov	1967	Protons	76	12
Fermilab, Chicago	1972	Protons	500	32
CERN SPS	1976	Protons	450	30
KEK, Tsukuba, Japan	1977	Protons	12	5
Tevatron, Fermilab	1985	Protons	1000	43
UNK, Serpukhov	Late 1980s	Protons	3000	76



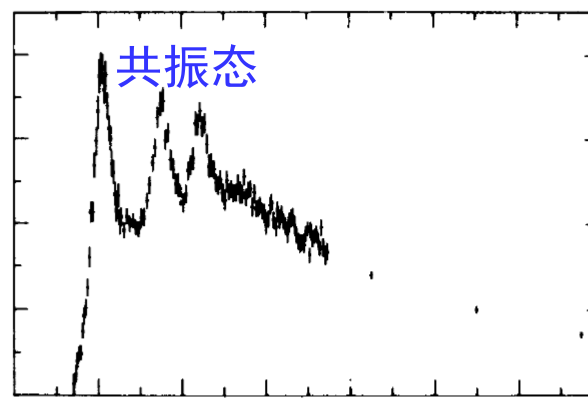
新的探测技术

- 1952年, Donald Glaser 发明气泡室 (乙醚)
- 随后, Luis Walter Alvarez 发展液氢气泡室和数据分析技术, 发现了大批共振态



Donald Glaser (1926-2013)
1960年诺贝尔物理奖

Luis Alvarez (1911-1988)
1968年诺贝尔物理奖



“基本”粒子太多了

TABLE I

MASSES AND LIFETIMES OF ELEMENTARY PARTICLES

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)	Mass difference (Mev)	Mean life (sec)	Decay rate (number per second)
光子 tons	γ	1	0		stable	0.0
轻子 tons and ıtileptons	$\nu, \bar{\nu}$	$\frac{1}{2}$	0		stable	0.0
	e^-, e^+	$\frac{1}{2}$	0.510976*		stable	0.0
	μ^-, μ^+	$\frac{1}{2}$	105.70 $\pm$0.06*		$(2.22\pm0.02)\times10^{-6}$*	0.45×10^{6}
强子 / 介子 ons	$\pi^\pm$	0	139.63 $\pm$0.06*	4.6*	$(2.56\pm0.05)\times10^{-8}$*	0.39×10^{8}
	π^0	0	135.04 $\pm$0.16*		$(0.0<\tau<0.4)\times10^{-15}$ (O)	$>2.5\times10^{15}$
	$K^\pm$	0	494.0 $\pm$0.20 (a)		$(1.224\pm.013)\times10^{-8}$ (b)	0.815×10^{8}
				1 ± 5	K_1: $(0.95\pm.08)\times10^{-10}$ (P)	1.05×10^{10}
	K^0	0	493 $\pm$5 (Th)		K_2: $(3<\tau<100)\times10^{-8}$ (L)(P)	$(>0.01<0.3)\times10^{8}$
强子 / 重子 ᐧons†	p	$\frac{1}{2}$	938.213$\pm$0.01*		stable	0.0
	n	$\frac{1}{2}$	939.506$\pm$0.01*		$(1.04\pm0.13)\times10^{+3}$ *	0.96×10^{-3}
	Λ	$\frac{1}{2}$?	1115.2 $\pm$0.13 (B)		$(2.77\pm0.15)\times10^{-10}$ (d)	0.36×10^{10}
	Σ^+	$\frac{1}{2}$?	1189.3 $\pm$0.35 (B)	7.1 ± 0.4	$(0.78\pm0.074)\times10^{-10}$ (e)	1.28×10^{10}
	Σ^-	$\frac{1}{2}$?	1196.4 $\pm$0.5 (B)	7.6_{-2}^{+3}	$(1.58\pm0.17)\times10^{-10}$ (f)	0.64×10^{10}
	Σ^0	$\frac{1}{2}$?	1188.8_{-3}^{+2} (g)		$(<0.1)\times10^{-10}$ (A)	$>10\times10^{10}$
					theoretically $\sim10^{-19}$	theoretically $\sim10^{19}$
	Ξ^-	?	1321 $\pm$3.5*		$(4.6<\tau<200)\times10^{-10}$ (Tr)	$(>0.005,<0.2)\times10^{10}$
	Ξ^0	?	?		?	

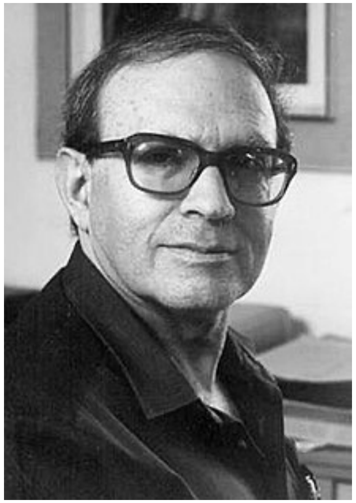
PDG 粒子性质综述 1957版, M. Gell-Mann, A. Rosenfeld

强子分类的探索

- 1949年, 杨振宁和 Fermi 猜想 π 介子由正反核子构成
- 1956年, 坂田昌一 (Shoichi Sakata) 提出坂田模型: 强子都由质子, 中子和 Λ 及其反粒子组成; 1959年, 两组日本物理学家阐明其模型中的 U(3) 对称性
- 1961年, Gell-Mann 和 Ne'eman 分别独立提出八正法 (Eightfold way) 分类强子, SU(3) 对称性

坂田昌一 (1911-1970)

Murray Gell-Mann (1929-2019)
1969 年诺贝尔物理奖



Yuval Ne'eman (1925-2006)

- 对如何区分基本粒子和复合粒子的讨论
（Howard, Jouvet, Nishijima, Salam, Dowker, Weinberg, …）

SU(3) 对称性

- 关于十重态质量的预言

Glashow, Sakurai, Nuovo Cim. 25 (1962) 337; Nuovo Cim. 26 (1962) 622

$$8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus \overline{10} \oplus 27$$

The 27-fold Way and Other Ways: Symmetries of Mesons-Baryon Resonances (*).

S. L. Glashow

Institute for Theoretical Physics and Department of Physics, Stanford University - Stanford, Cal.

J. J. Sakurai

Enrico Fermi Institute for Nuclear Studies and Department of Physics, University of Chicago - Chicago, Ill.
Department of Physics, California Institute of Technology - Pasadena, Cal.

$$(27;\ Y = -2,\ T = 1),$$
$$(10;\ Y = -2,\ T = 0)^-$$

On the Tenfold Way (*).

S. L. Glashow (**) and J. J. Sakurai (*,*)

Institute for Theoretical Physics, University of Copenhagen - Copenhagen

Sheldon Glashow (1932-)
1979年诺贝尔物理奖

樱井纯 (1933-1982)

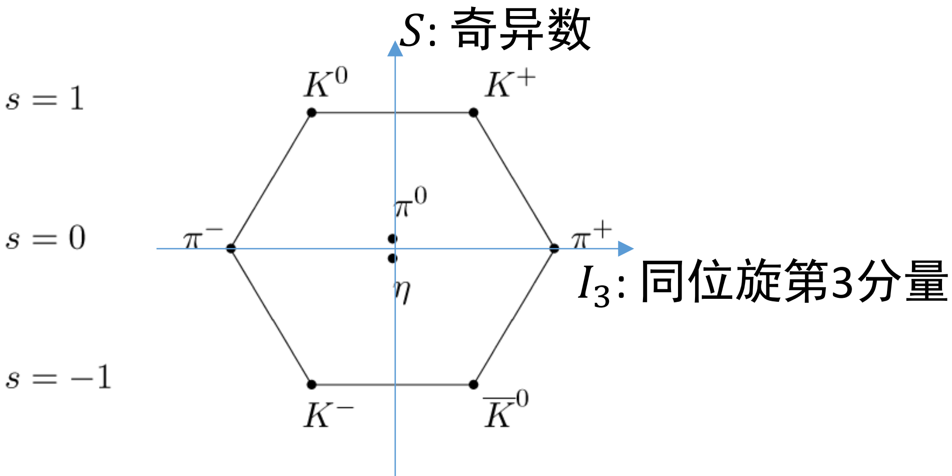
附录

Fitting the mass of $(10; 1, \frac{3}{2})$ to 1240 MeV, the mass of the $\mathcal{N}^*_{\frac{3}{2}}$, we find for the masses of the other members of the 10 fold way:

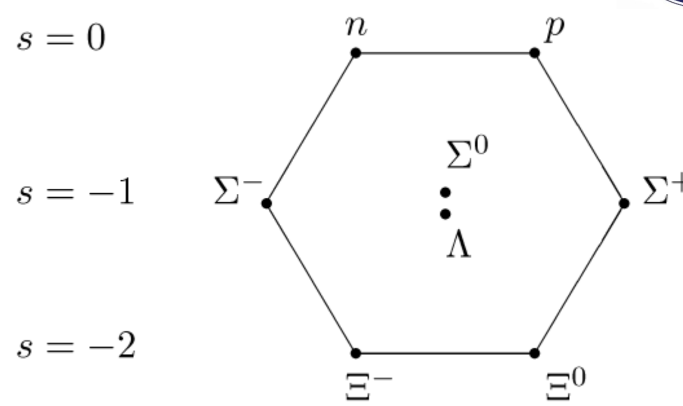
$$m_{0,1} = 1390 \text{ MeV},$$
$$m_{-1,\frac{1}{2}} = 1520 \text{ MeV},$$
$$m_{-2,0} = 1640 \text{ MeV}.$$

实验发现：
$\Sigma(1385)$
$\Xi(1530)$
$\Omega(1670)$

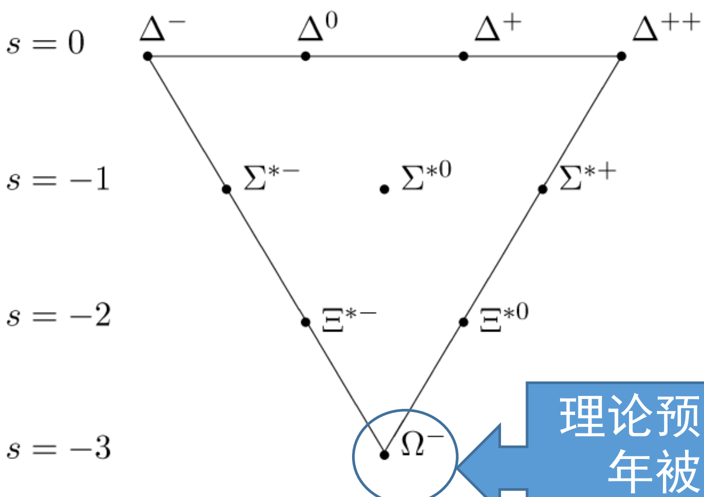
八正法的确立



赝标介子

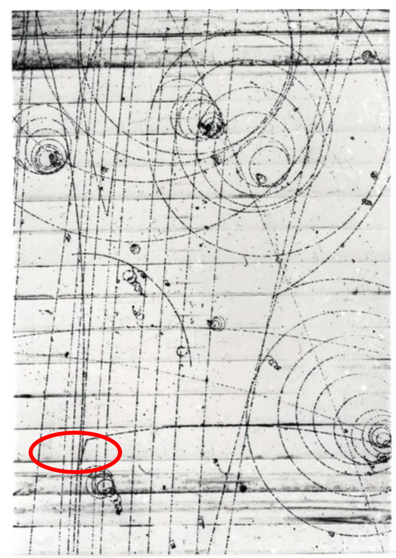


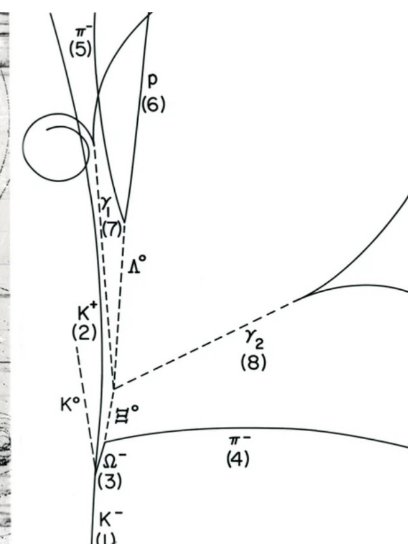
$J^P = \frac{1}{2}^+$ 的重子



理论预言，1964年被发现；结束了坂田模型

$J^P = \frac{3}{2}^+$ 的重子





27重态无法容纳 $S=-3, I=0$ 的Ω^-

夸克模型

- 1964年, Gell-Mann 和 Zweig 独立提出夸克模型 (Gell-Mann: quark; Zweig: ace)
  - 夸克自旋 $\frac{1}{2}$, 带分数电荷

    $$\left(u{:}\,\frac{2}{3};\quad d{:}-\frac{1}{3};\quad s{:}-\frac{1}{3}\right)$$

    3味: 上夸克; 下夸克; 奇异夸克
  - 介子: $\bar{q}q, qq\bar{q}\bar{q}, \ldots$
  - 重子: $qqq, qqqq\bar{q}, \ldots$

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

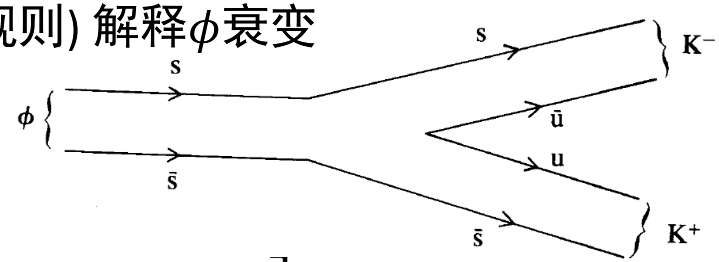
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

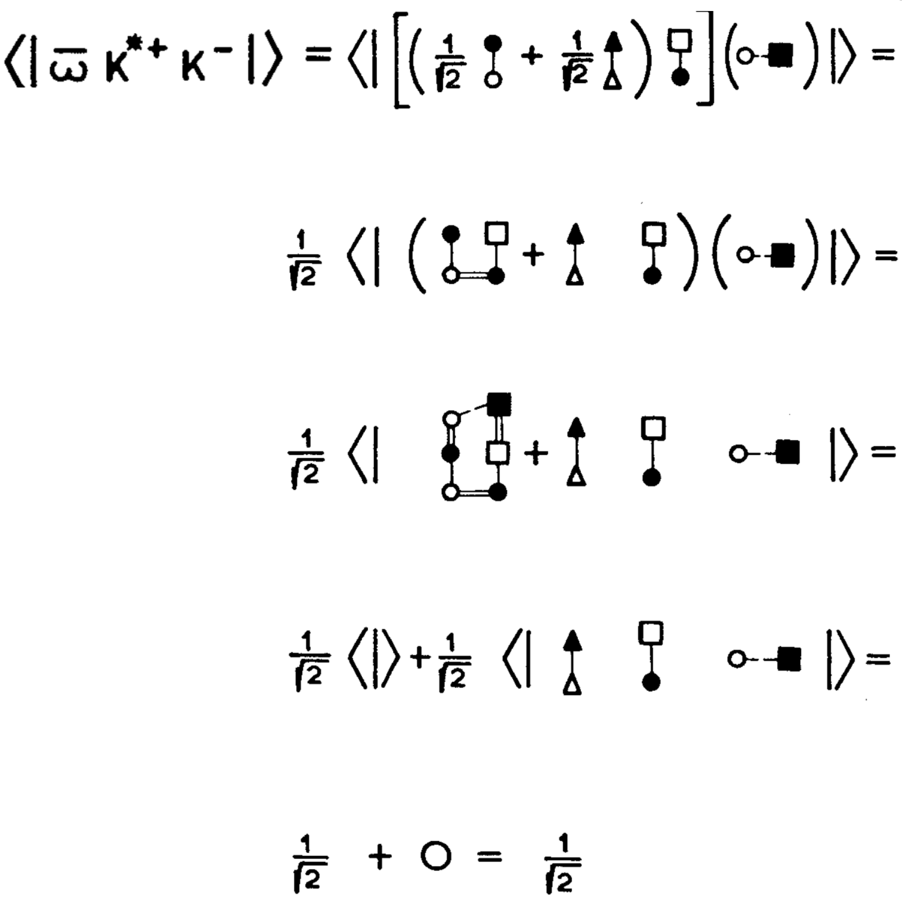
- Gell-Mann: 不确信夸克是实体粒子

interactions, much as Λ goes into N. Ordinary matter near the earth's surface would be contaminated by stable quarks as a result of high energy cosmic ray events throughout the earth's history, but the contamination is estimated to be so small that it would never have been detected. A search for stable quarks of charge $-\frac{1}{3}$ or $+\frac{2}{3}$ and/or stable di-quarks of charge $-\frac{2}{3}$ or $+\frac{1}{3}$ or $+\frac{4}{3}$ at the highest energy accelerators would help to reassure us of the non-existence of real quarks.

夸克模型

- Zweig: 组分夸克模型
- Zweig 规则 (OZI 规则) 解释ϕ衰变





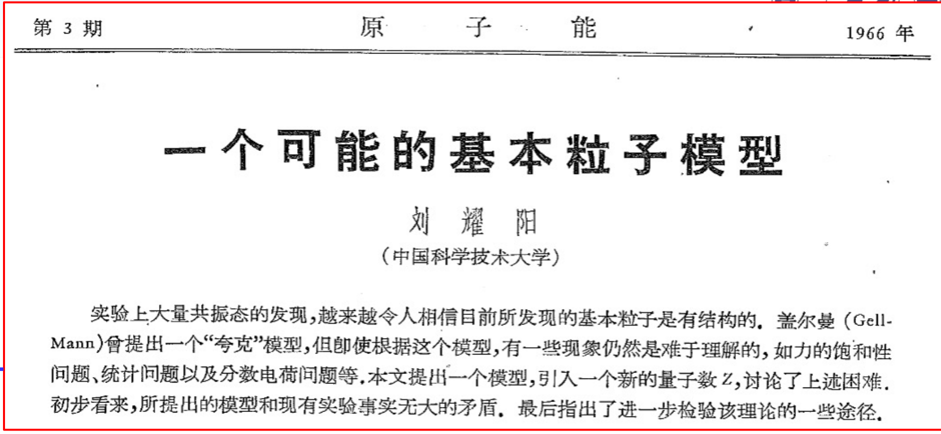
George Zweig (1937-)

Ace		Quark
●	p_0	u
▲	n_0	d
■	λ_0	s

- Zweig 回忆1963年的情况: "粒子分类也是困难重重，因为许多(共振)峰…是不真实的. 在这个介子表里列了 26 个态, 其中 7 个是'奇特态', 现在知道这 26 个态里的 19 个是不存在的!"

Zweig, Baryon 1980

夸克模型



第 3 期　原　子　能　1966 年

一个可能的基本粒子模型

刘　耀　阳

（中国科学技术大学）

实验上大量共振态的发现，越来越令人相信目前所发现的基本粒子是有结构的。盖尔曼（Gell-Mann）曾提出一个"夸克"模型，但即使根据这个模型，有一些现象仍然是难于理解的，如力的饱和性问题、统计问题以及分数电荷问题等。本文提出一个模型，引入一个新的量子数 Z，讨论了上述困难。初步看来，所提出的模型和现有实验事实无大的矛盾。最后指出了进一步检验该理论的一些途径。

- 夸克模型的困难:
  - 没观测到分数电荷的粒子
  - Δ^{++}, Ω^{-} 不满足费米-狄拉克统计
  - 实际上暗含还可能有 $qq\bar{q}$ 等类型的强子
- 色 (color) 量子数的提出

Color first appeared in Bardeen, Fritsch, Gell-Mann (1972)

  - 1964, O. Greenberg: 夸克是 3 阶的仲费米子 (parafermions), 遵从格林统计
  - 1965, 南部阳一郎 (Yoichiro Nambu) 和韩武荣 (Moo Young Han) 提出双重 SU(3)方案 (flavor⊗color [当时称为 charm]), 夸克带整数电荷
    - 统计问题, 夸克分数电荷问题
    - 解释为何没有 $qq\bar{q}$ 等: 建议无色的是质量的基态

南部阳一郎 (1921-2015)
2008年诺贝尔物理奖
(对称性自发破缺)

韩武荣
(1934-2016)

  - 1966 , 刘耀阳: 至少 3 套夸克, 新量子数作为力的媒介

(一个可能的基本粒子模型，原子能，1966 (3): 232-235)

$$H_i = \sum_{j \neq k} Z_j Z_k V(r_{j,k}).$$

刘耀阳
(1934-2023)

原子能 1966年 第3期

目 录

人的正确思想是从那里来的？是从天上掉下来的嗎？不是。是自己头脑里固有的嗎？不是。人的正确思想，只能从社会实践中来，只能从社会的生产斗爭、阶級斗爭和科学实驗这三項实践中来。

——毛泽东《人的正确思想是从那里来的？》

馬克思主义的哲学认为，对立統一規律是宇宙的根本規律。这个規律，不論在自然界、人类社会和人們的思想中，都是普遍存在的。矛盾着的对立面又統一，又斗爭，由此推动事物的运动和变化。矛盾是普遍存在的，不过按事物的性质不同，矛盾的性质也就不同。对于任何一个具体的事物說来，对立的統一是有条件的、暫时的、过渡的，因而是相对的，对立的斗爭则是絕对的。

——毛泽东《关于正确处理人民內部矛盾的問題》

我們看事情必須要看它的实质，而把它的現象只看作入門的向导，一进了門就要抓住它的实质，这才是可靠的科学的分析方法。

——毛泽东《星星之火，可以燎原》

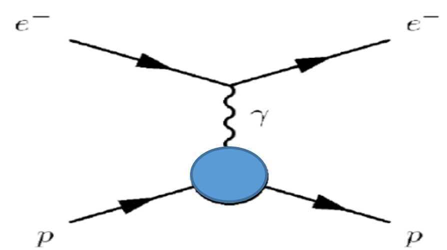
宇宙，从小的方面說，也是无穷无尽的。原子里头分为原子核和电子，它們是对立面的統一。原子核里头又分为质子和中子，它們也是对立面的統一。质子又有和反质子的对立的統一。中子又有和反中子的对立的統一。质子、反质子、中子、反中子，等等，这些基本粒子还是可分的。物质是无限可分的。

——摘自"紅旗"杂志发表坂田昌一《关于新基本粒子观的对話》一文的編者按

质子有大小

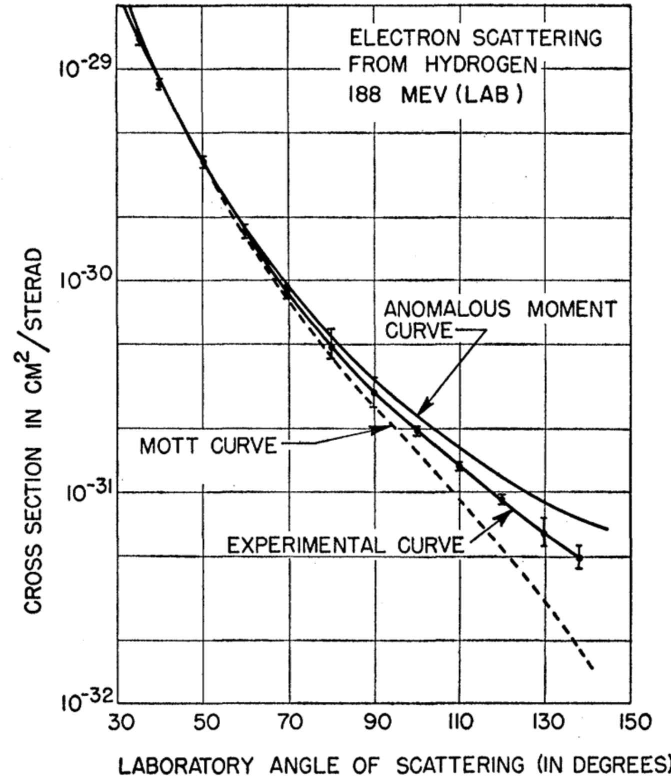
- R. Hofstadter 发展电子散射技术, 研究核和核子结构:

质子不是类点粒子



Robert Hofstadter (1915-1990)
1961 年诺贝尔物理奖

well by the following choices of size. At 188 Mev, the data are fitted accurately by an rms radius of $(7.0\pm2.4)\times10^{-14}$ cm. At 236 Mev, the data are well fitted by an rms radius of $(7.8\pm2.4)\times10^{-14}$ cm. At 100 Mev the data are relatively insensitive to the radius but the experimental results are fitted by both choices given above. The 100-Mev data serve therefore as a valuable check of the apparatus. A compromise value fitting all the experimental results is $(7.4\pm2.4)\times10^{-14}$ cm. If the proton were a spherical ball of charge, this rms radius would indicate a true radius of 9.5×10^{-14} cm, or in round numbers 1.0×10^{-13} cm. It is to be noted that if our interpretation is correct the Coulomb law of force has not been violated at distances as small as 7×10^{-14} cm.



Electron Scattering from the Proton

Robert Hofstadter and Robert W. McAllister
Phys. Rev. **98**, 217 – Published 1 April 1955

质子半径~0.84 fm

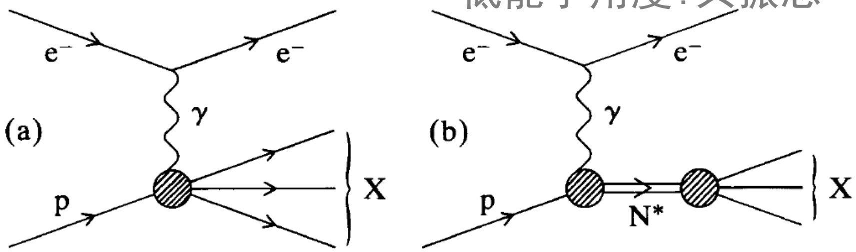
1 fermi (fm) = 10^{-15}m

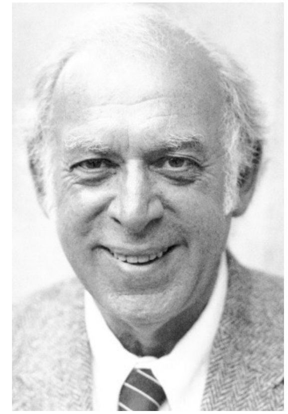
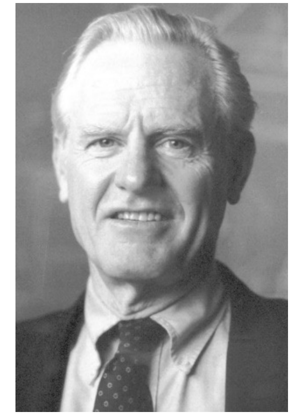
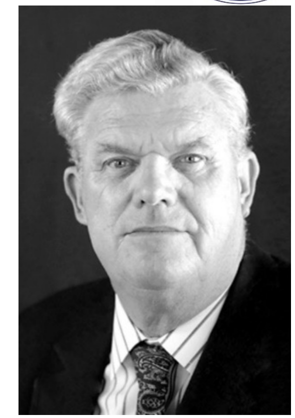
Hofstadter (1956)

深度非弹性散射与标度律

1968, SLAC-MIT 电子–质子非弹性散射

低能小角度：共振态

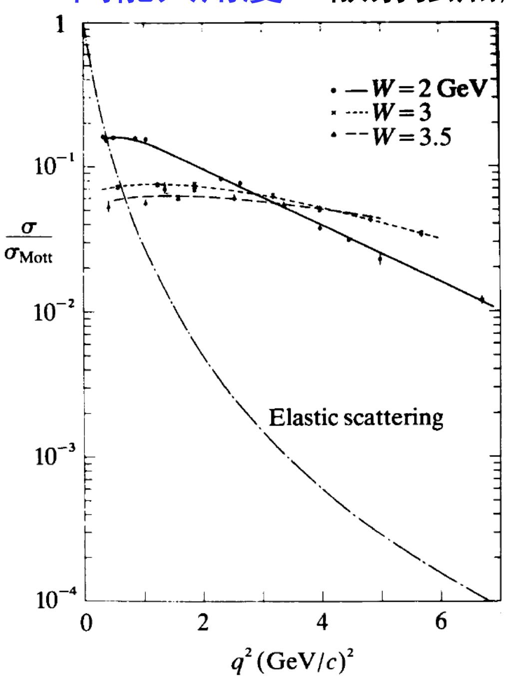


Jerome Friedman, Henry Kendall, Richard Taylor

1990年诺贝尔物理奖

高能大角度：散射强烈，类似于卢瑟福实验



实验家按照 Bjorken 的建议分析数据，发现

标度无关性：质子内部有类点结构

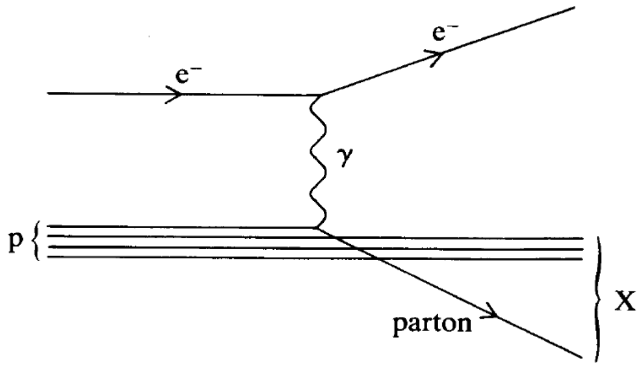
1967-1968, J. Bjorken 提出标度律

James Bjorken (1934-)

部分子模型

1968年, 费曼提出部分子(parton)模型: 强子是由无数粒子构成的云, 称之为部分子 (不假设其为夸克或介子)

- 高能碰撞: 个别部分子之间
- 强子内部: 部分子相互作用可忽略



Richard Feynman (1918-1988)

1965年诺贝尔物理奖 (QED)

SLAC-MIT 的进一步实验表明:

- 部分子自旋为1/2, 被认为是夸克
  - 价夸克: 给出 SU(3) 分类的量子数
  - 海夸克: 无穷多对$q\bar{q}$
- 还需引入额外的成分: 胶子 (gluon, 首次出现在 Gell-Mann 1962 年关于八正法的文章中)

group. We chose the algebraic structure by analogy with the case of leptons and we saw that the simplest field theory model embodying the structure is just the Fermi-Yang model, in which p and n fields are treated just like the ν and e fields for the leptons, except that they are given a mass and a strong "gluon" coupling.

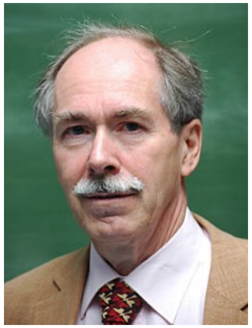
非阿贝尔规范场论

- 1954年, 杨振宁和 R. Mills 提出核子相互作用的 SU(2) 非阿贝尔规范理论

杨振宁 (1922-)
1957年诺贝尔物理奖 (宇称破坏)

Robert Mills
(1927-1999)

- 强作用: 通过核子和介子构建的场论非微扰, 困扰多年
- 渐近自由: 能量越高, 作用越弱; 一大类非阿贝尔规范场论具有
  - G. ‘t Hooft 1972年首先指出, 但未发表
  - 1973年, D. Gross 和 F. Wilczek 以及 D. Politzer (S. Coleman 的学生) 独立发现
  - 可解释 Bjorken 标度律: 强作用理论可能是非阿贝尔规范场论



G. ‘t Hooft (1946-)
1999年诺贝尔奖 (重整化)

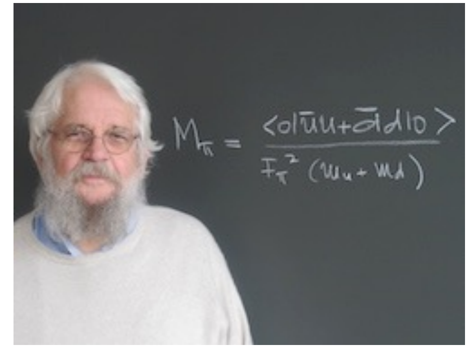
Frank Wilczek (1955-), David Gross (1941-), David Politzer (1949-)
1999年诺贝尔奖

量子色动力学 (QCD)

- 1973年, Fritzsch, Gell-Mann 和 Leutwyler 写出 quantum chromodynamics (QCD) 的拉氏量

Harald Fritzsch

(1943-2022)



Heinrich Leutwyler

(1938-)

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$SU(3)_c$, 夸克 : 色3重态

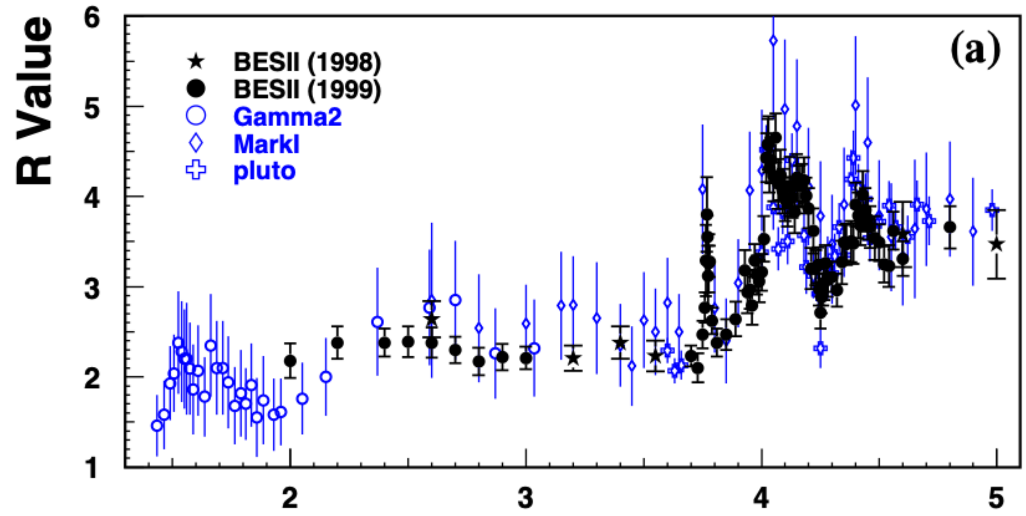
胶子 : 色8重态

量子色动力学 (QCD)

- 夸克色的数目 $N_c = 3$ 的实验证据:
  - ✓ R值测量

$$R = \frac{\sigma(e^+e^- \to q\bar{q} \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \approx N_c \times \left(\sum_{\text{夸克味}} Q_q^2 \right)$$

$$N_c \times \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} \right) = \frac{2N_c}{3}$$



BES, PRL 88 (2002) 101802

□ 教科书经常出现的另一个"证据": π 介子衰变

$$\Gamma(\pi^0 \to \gamma\gamma) \propto N_c^2 \left(Q_u^2 - Q_d^2\right)^2$$

但 $Q_u = (\frac{1}{N_c} + 1)/2$, $Q_d = (\frac{1}{N_c} - 1)/2$, 导致 $N_c\left(Q_u^2 - Q_d^2\right) = 1$

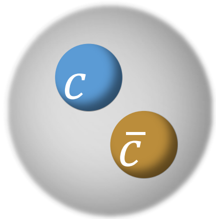
从而 $\Gamma(\pi^0 \to \gamma\gamma)$ 与N_c 无关

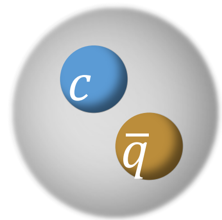
S. Rudaz, PRD 41 (1990) 2619; A. Abbas, PLB 238 (1990) 344; O. Bär, U.-J. Wiese, NPB 609 (2001) 225

更重的夸克

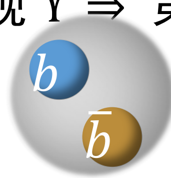
1976年诺贝尔奖

- 十一月革命: 1974年11月, 丁肇中和 B. Richter (SPEAR组) 发现 J/ψ, 紧接着, SPEAR组发现ψ'
- 1970年, S. Glashow, J. Iliopoulos, L. Maiani (GIM) 机制: 存在更重的夸克: 粲 (charm) 夸克
- 各种理论解释:
  - 粲偶素 (charmonium):
  - 色模型: 预言带电J/ψ
  - W玻色子
  - 胶子
  - ……

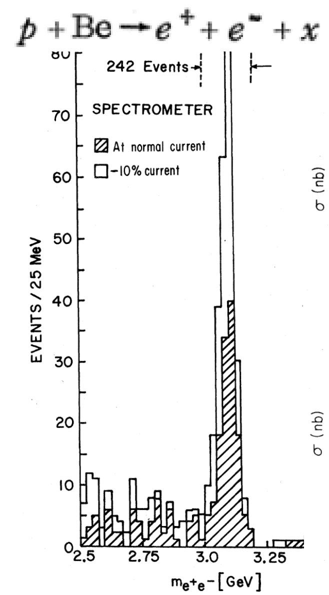




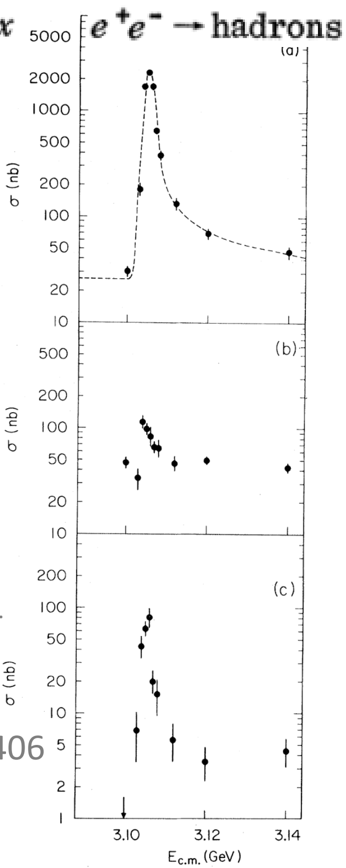
- 1976年, SPEAR组发现D介子, 粲夸克得到确认; 确认了夸克作为真实粒子的观念
- 1977年, Fermilab 发现 Υ ⇒ 第5种夸克: 底 (bottom)



- 1995年, CDF 和D0合作组发现第6种夸克: 顶 (top)



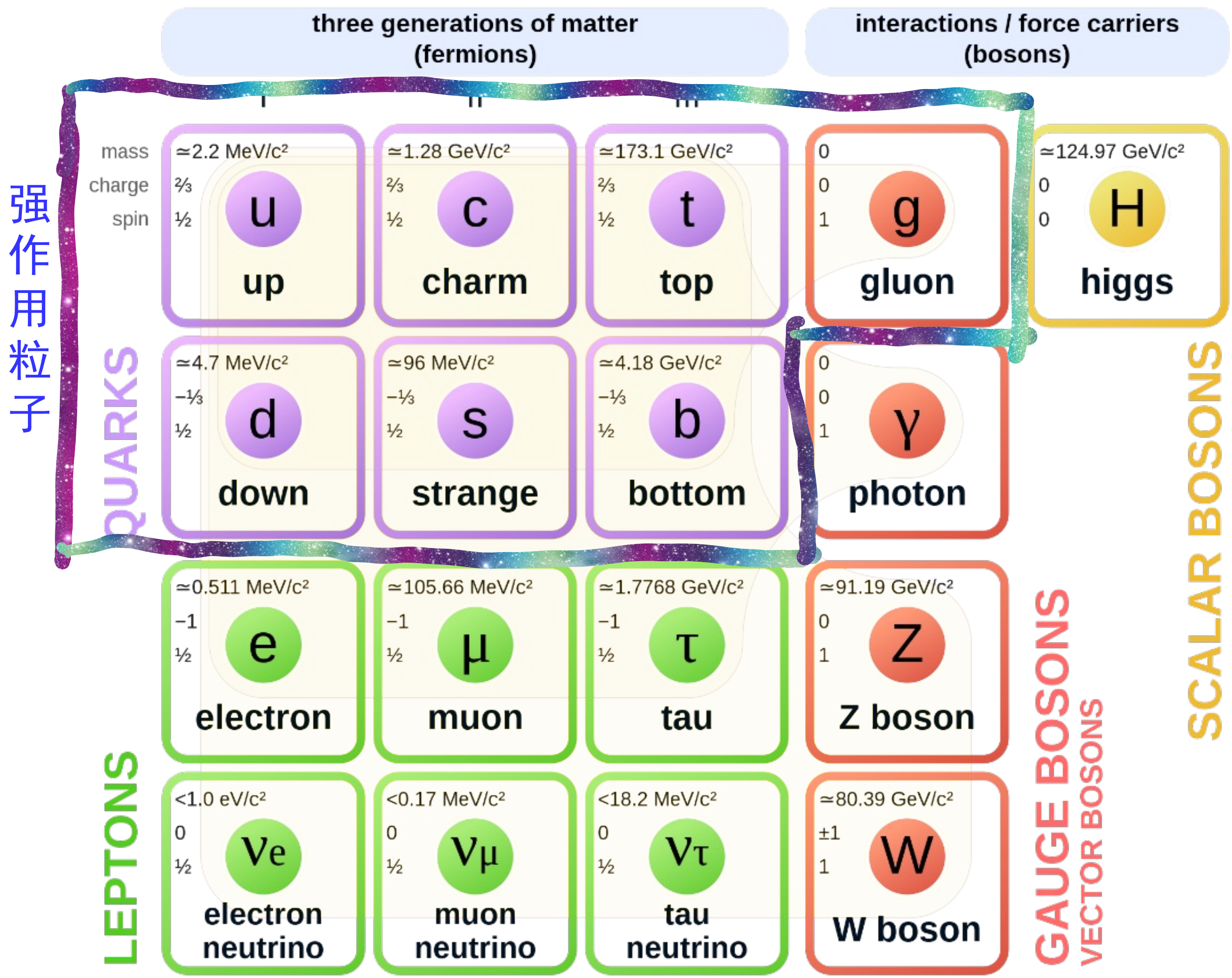
PRL33(1974)1404



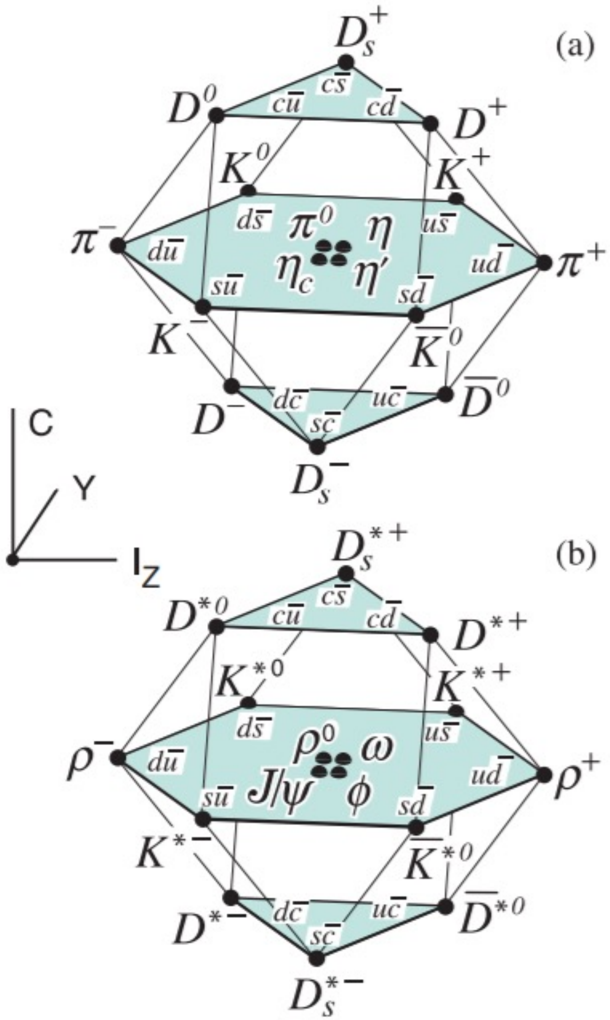
PRL33(1974)1406

标准模型里的基本粒子

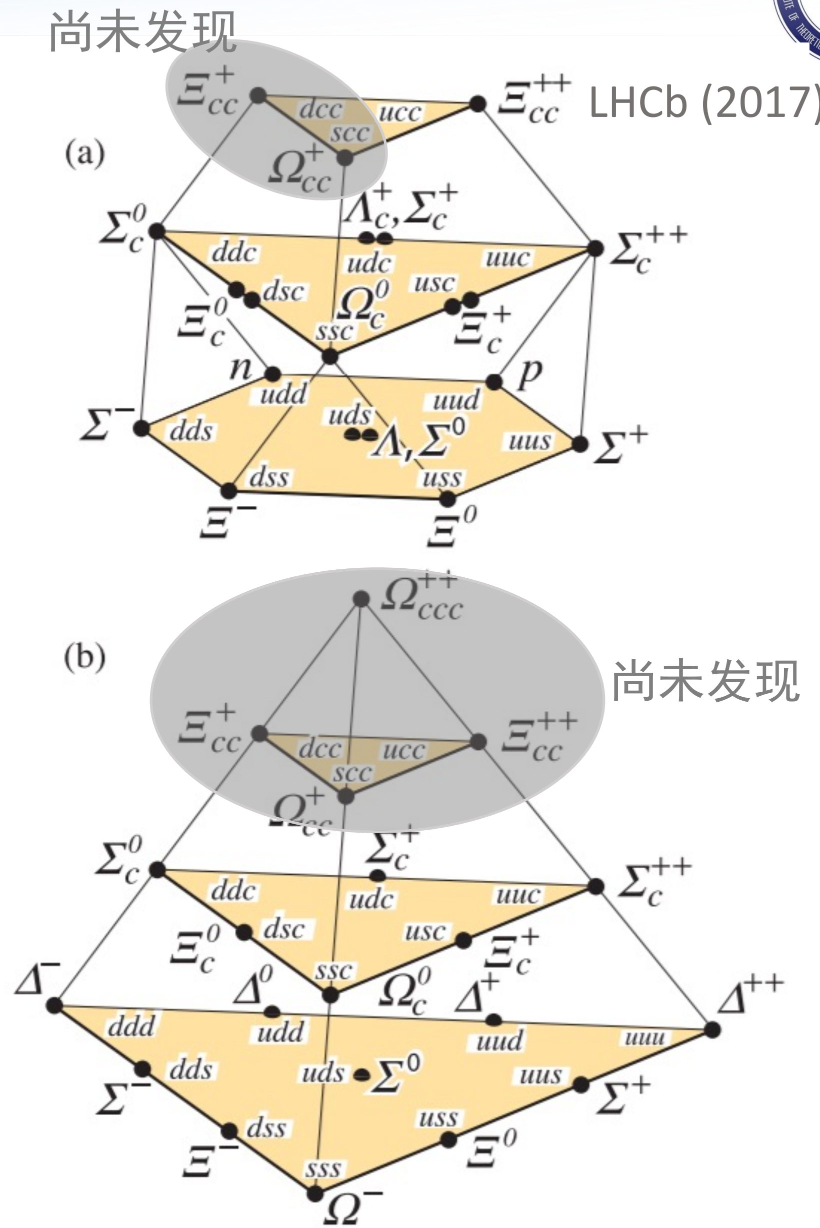
Standard Model of Elementary Particles



强子味道多重态的扩充

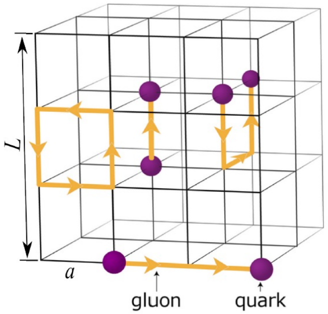


Amsler, DeGrand, Krusche, review on Quark Model by the Particle Data Group (PDG)

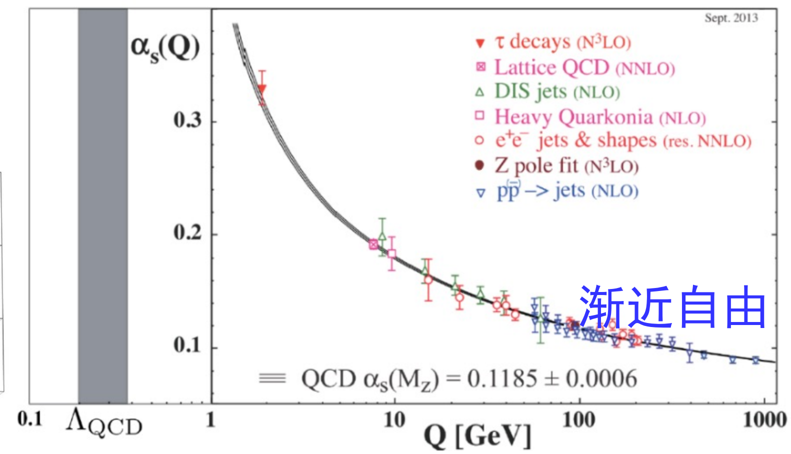


色禁闭

- 然而, 实验上仍然没有观测到自由夸克和胶子!
- 色禁闭 (color confinement): 仍未解决的重大问题!!!
- 1974年, K. Wilson: 格点规范场论



非微扰



渐近自由

Kenneth Wilson (1936-2007)
1982年诺贝尔奖 (重整化群研究临界现象)

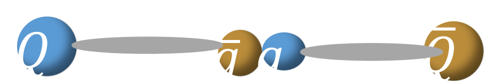
PHYSICAL REVIEW D VOLUME 10, NUMBER 8 15 OCTOBER 1974

Confinement of quarks*

Kenneth G. Wilson
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 12 June 1974)

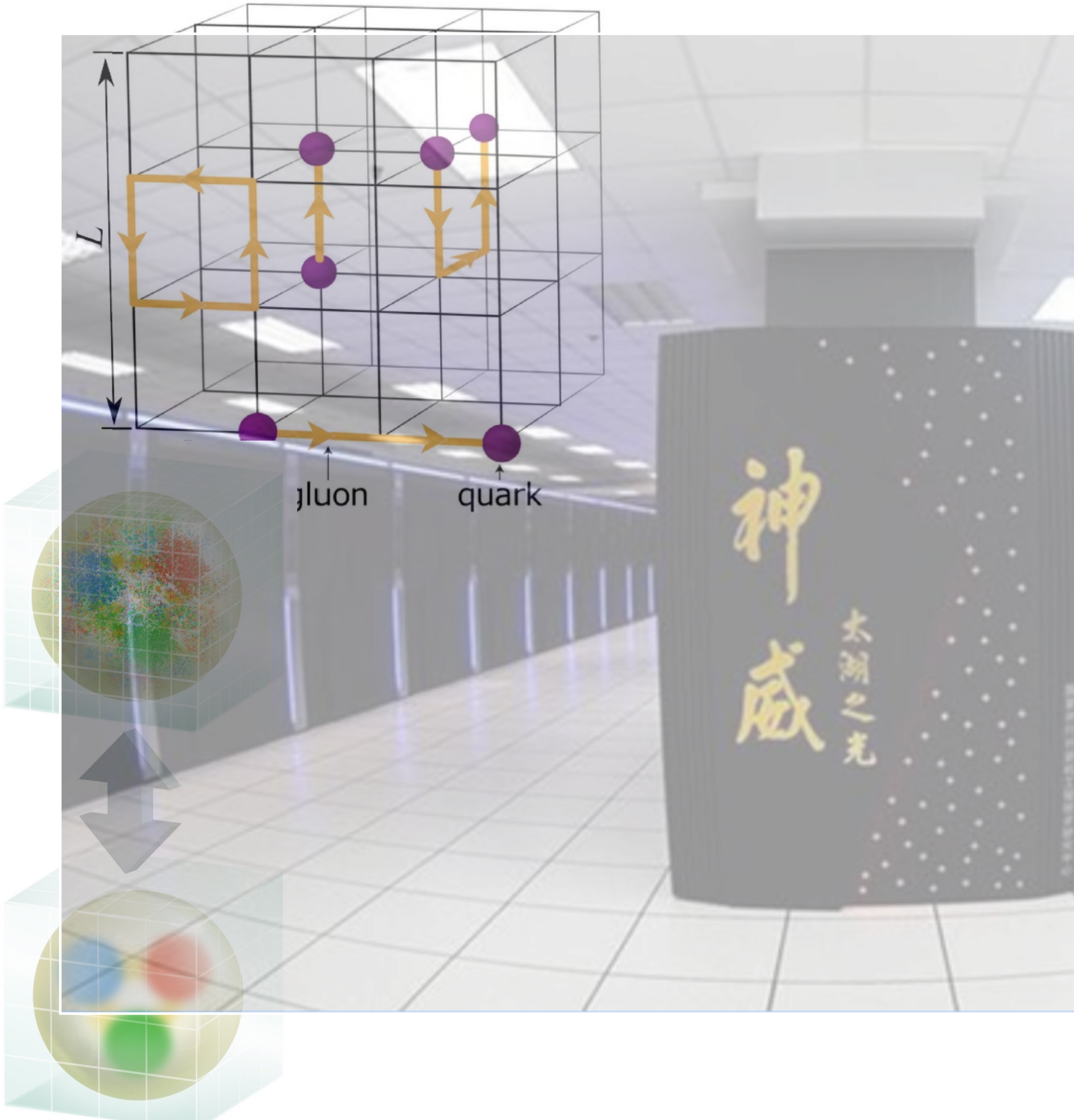
A mechanism for total confinement of quarks, similar to that of Schwinger, is defined which requires the existence of Abelian or non-Abelian gauge fields. It is shown how to quantize a gauge field theory on a discrete lattice in Euclidean space-time, preserving exact gauge invariance and treating the gauge fields as angular variables (which makes a gauge-fixing term unnecessary). The lattice gauge theory has a computable strong-coupling limit; in this limit the binding mechanism applies and there are no free quarks. There is unfortunately no Lorentz (or Euclidean) invariance in the strong-coupling limit. The strong-coupling expansion involves sums over all quark paths and sums over all surfaces (on the lattice) joining quark paths. This structure is reminiscent of relativistic string models of hadrons.

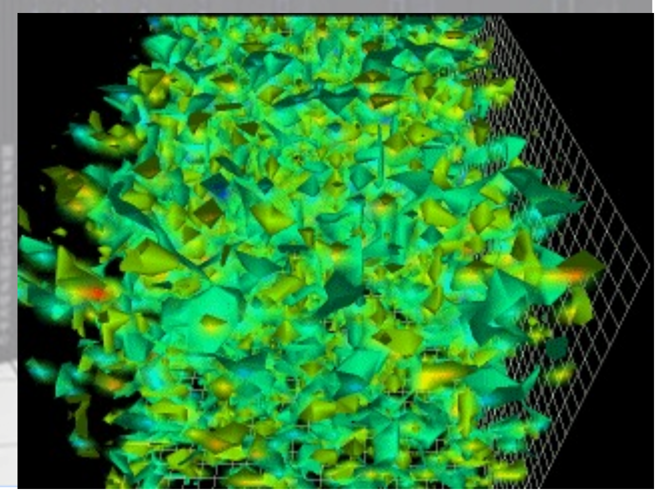
无穷重夸克(纯杨-Mills场): 线性禁闭



格点QCD

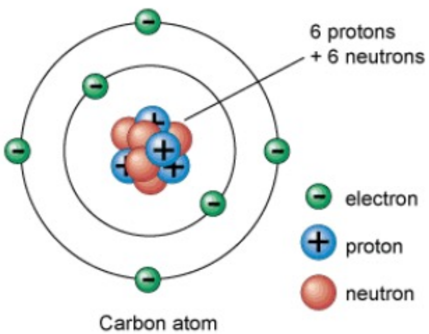
- 时空离散化，利用超级计算机模拟

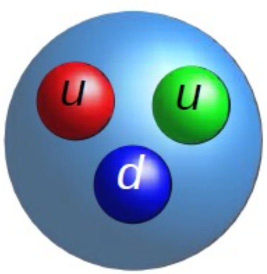


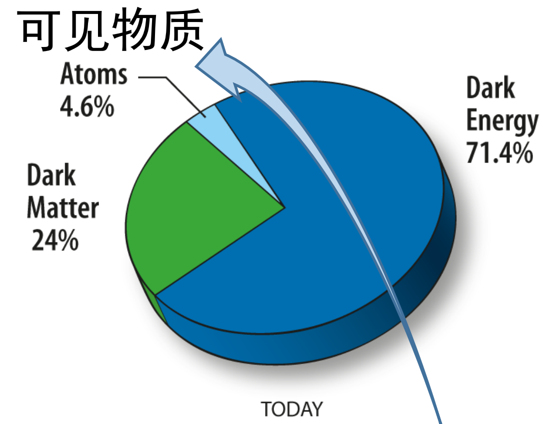


不平静的真空： D. Leinweber

物质质量的起源：强相互作用





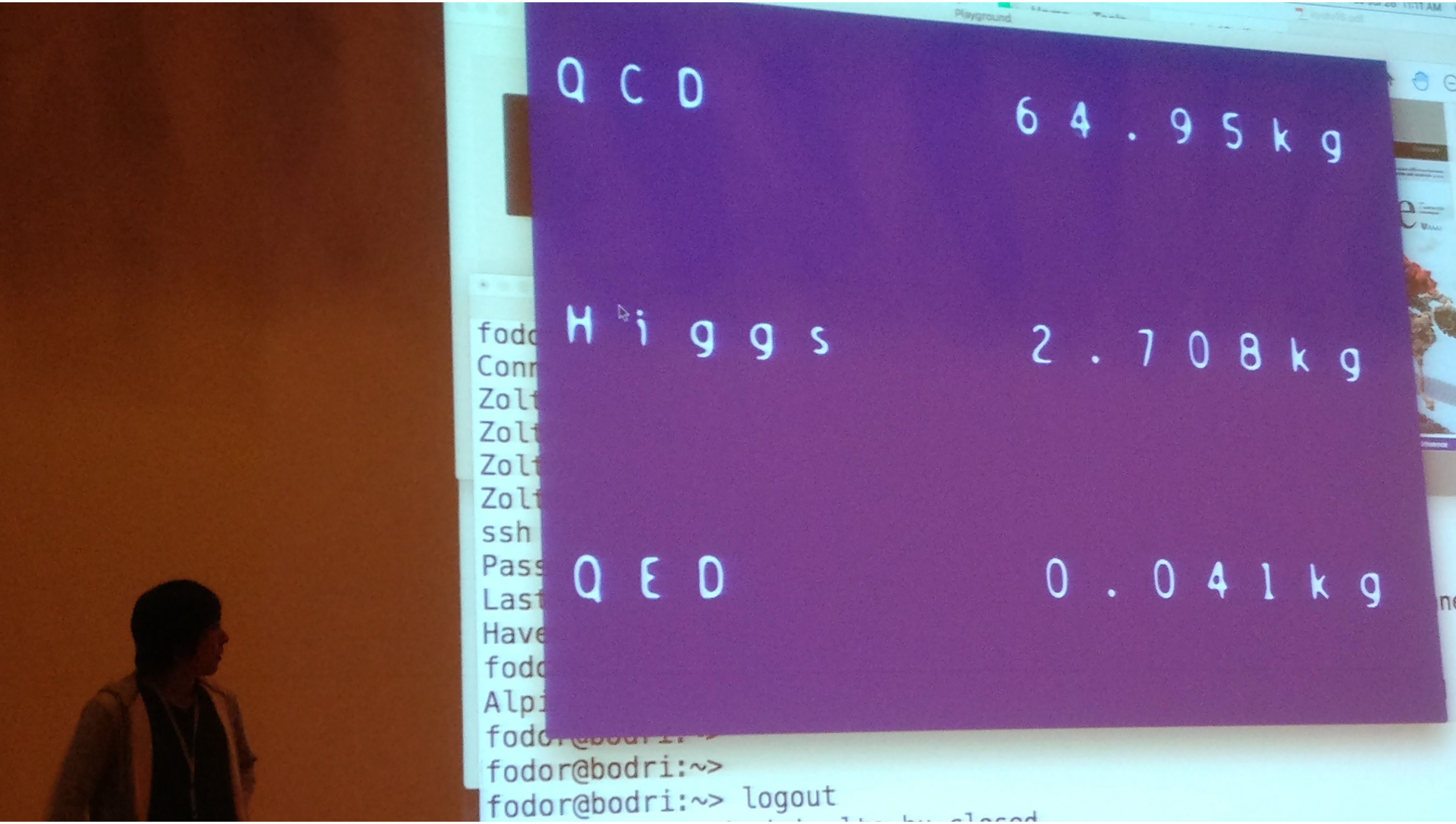


$$M_{\text{diamond}} \simeq \sum M_{C\text{atom}}$$

$$M_{C\text{atom}} \simeq 6(M_{\text{proton}} + M_{\text{neutron}} + M_{\text{electron}})$$

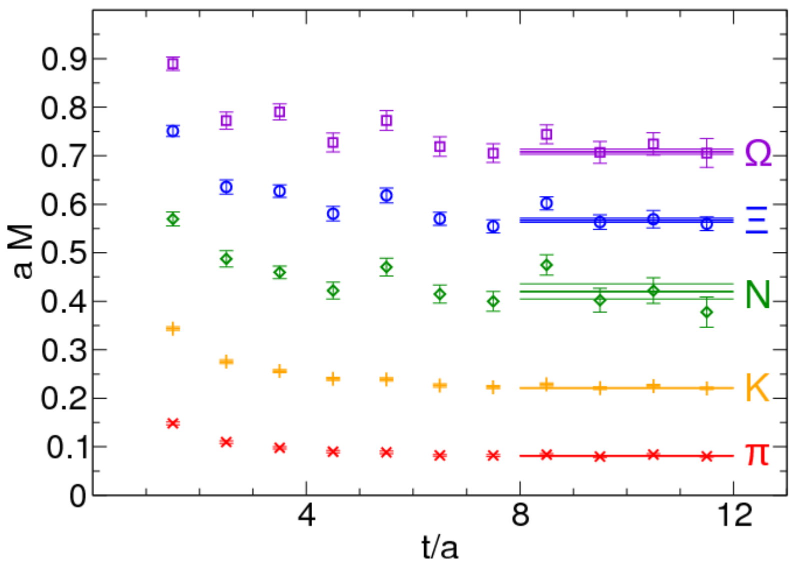
$$\underbrace{M_{\text{proton}}}_{938\ \text{MeV}} \simeq 100(2m_u + m_d) \simeq \sum_q \sigma_q m_q + 850\ \text{MeV}$$

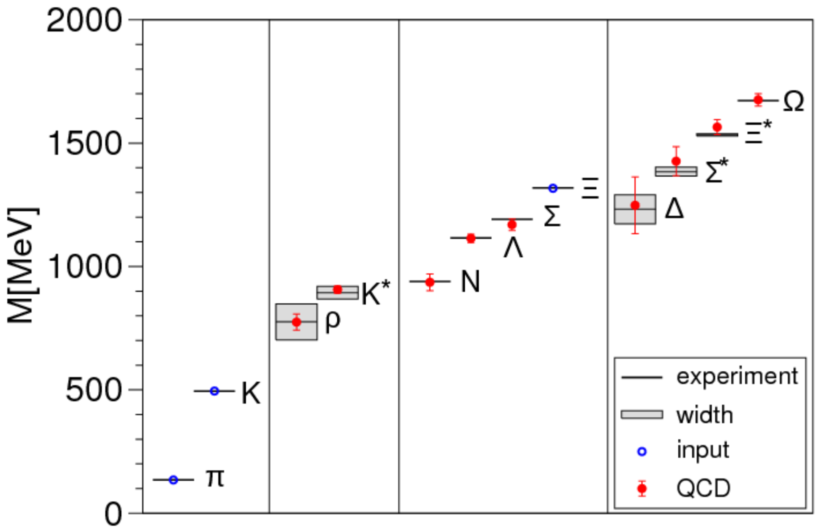
物理学家的秤


QCD 64.95kg
Higgs 2.708kg
QED 0.041kg
fodor@bodri:~>
fodor@bodri:~> logout

强子谱：格点QCD

- 基态（如质子、中子）可精确计算



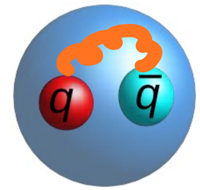


S. Dürr et al. (BMW), Science 322 (2008) 1224

- 革命尚未成功，激发态仍很困难

强子谱：组分夸克模型的回归

- QCD 提供夸克间的动力学
- Cornell 模型: 粲偶素
- Godfrey-Isgur 模型: 所有介子



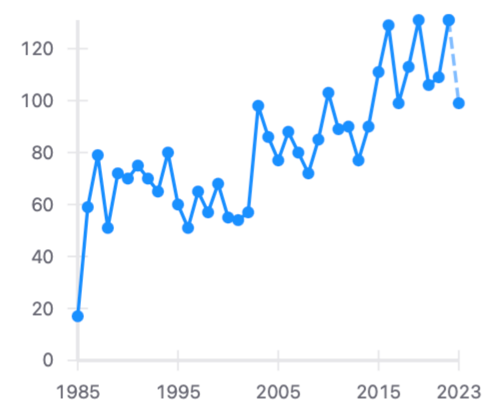
Mesons in a Relativized Quark Model with Chromodynamics

S. Godfrey (Toronto U.), Nathan Isgur (Toronto U.)

1985

43 pages
Published in: *Phys.Rev.D* 32 (1985) 189-231
DOI: 10.1103/PhysRevD.32.189
View in: OSTI Information Bridge Server

Citations per year

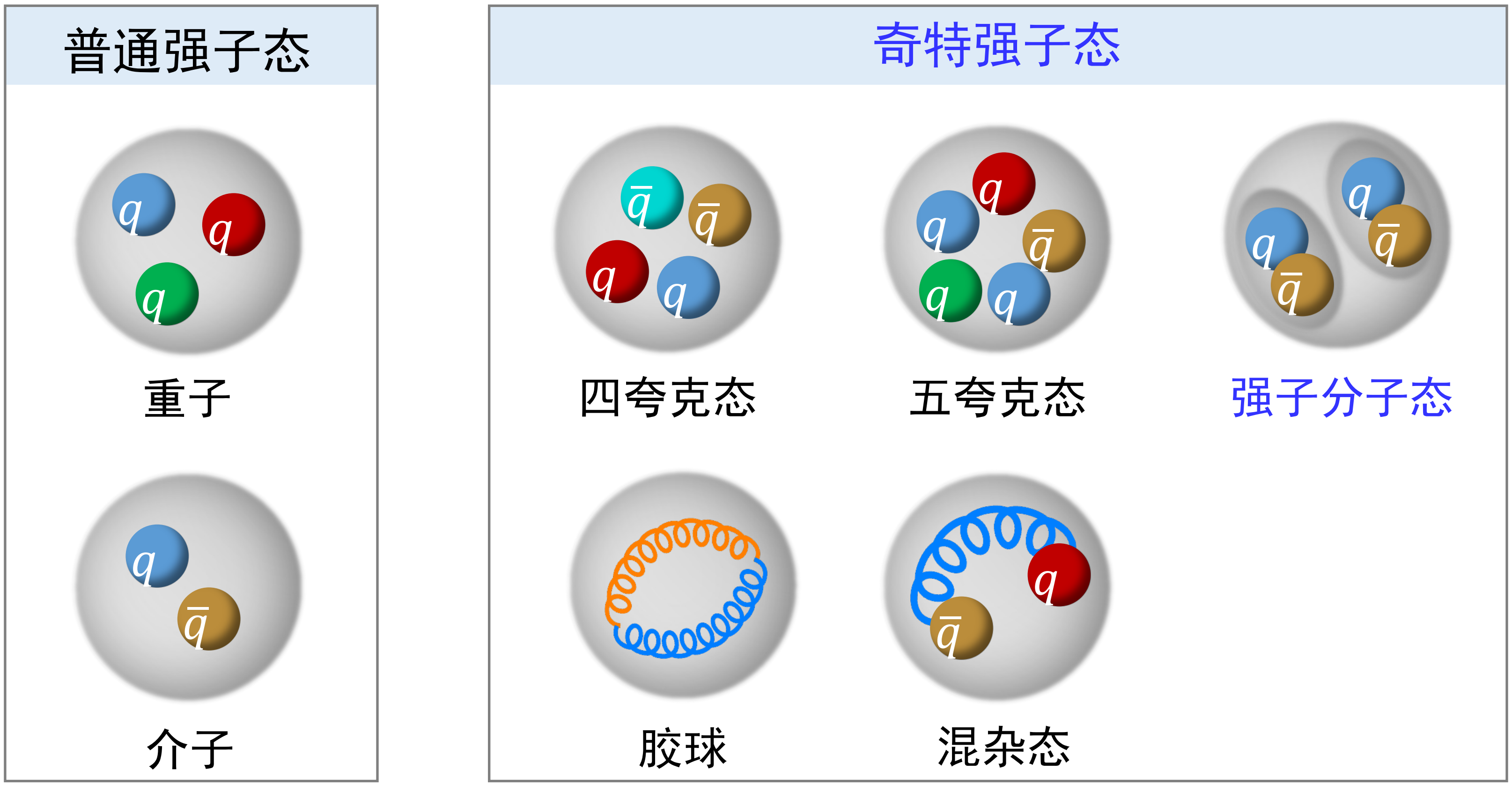


薛定谔方程：

$$\left(\sqrt{m_1^2+p^2}+\sqrt{m_2^2+p^2}+V\right)|\Psi\rangle = E|\Psi\rangle$$

相互作用势：单胶子交换 + 线性禁闭

普通强子态与奇特强子态



- 大科学装置上的实验持续寻找奇特强子态, 但是…

强子谱研究的复兴

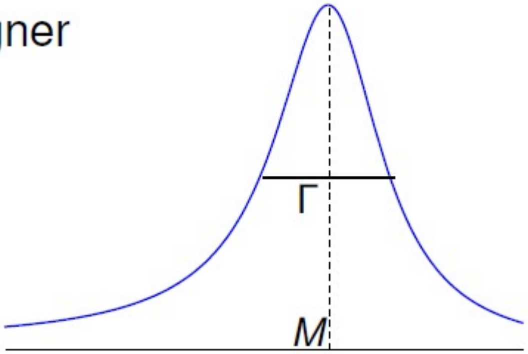
New discoveries since 2003

Many new hadron resonances observed in experiments

- Inactive: BaBar, Belle, CDF, CLEO-c, D0, ...
- Running: Belle-II, BESIII, COMPASS, LHCb, ...
- Under construction/discussion: PANDA, EIC, EicC,

Common strategy: search for peaks, fit with Breit–Wigner

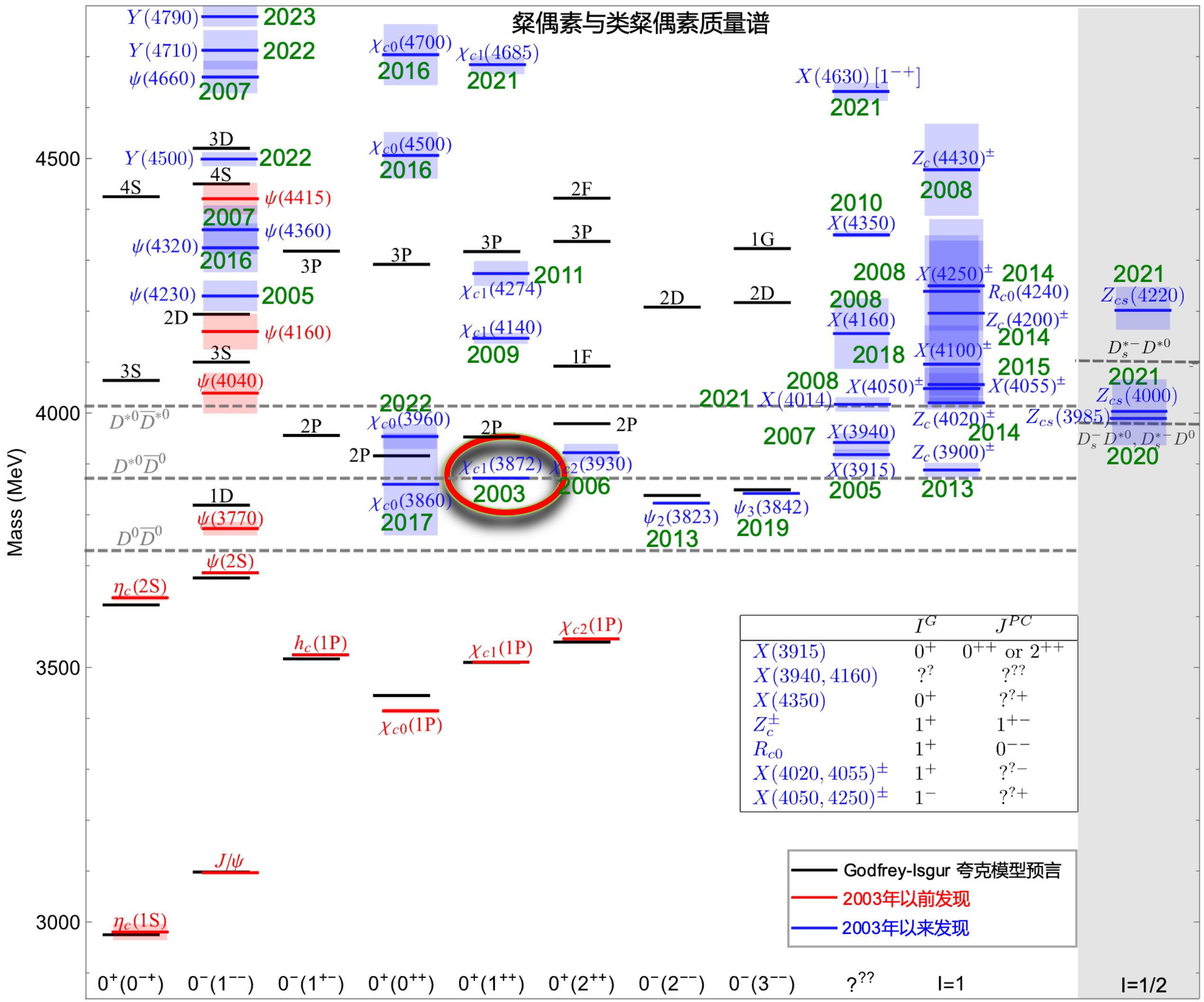
$$\propto \frac{1}{(s-M^2)^2 + s\,\Gamma^2(s)}$$



Lots of mysteries right now ...

粲偶素与类粲偶素

- 2003 年以来，实验上观测到大量类粲偶素 (XYZ 态)，奇特强子态的候选者
- 大科学装置：北京正负电子对撞机、日本Belle(II)、欧洲LHC、美国Tevatron等



	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^{\pm}$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^{\pm}$	1^+	$?^{?-}$
$X(4050, 4250)^{\pm}$	1^-	$?^{?+}$

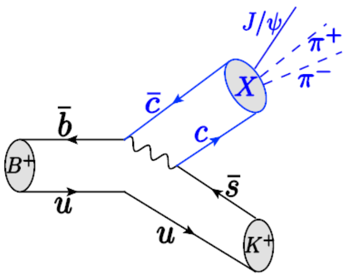
Godfrey-Isgur 夸克模型预言
2003年以前发现
2003年以来发现

类聚偶素的发现

- XYZ 态中最受关注的是 $X(3872)$，其最有意思的性质：

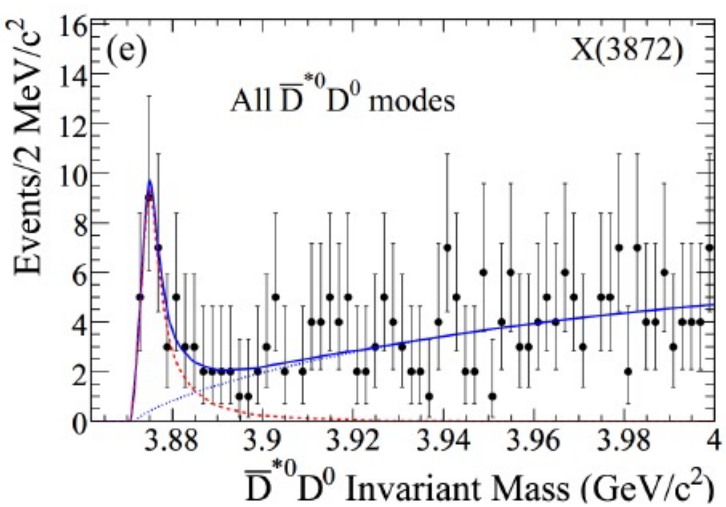
$$M_{D^0} + M_{D^{*0}} - M_X = (0.01 \pm 0.14)\text{MeV}$$ LHCb, PRD102(2020)092005

包含了$X(3872)$内部结构的重要信息

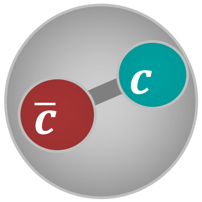


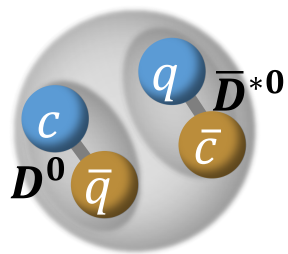
- $X(3872)$ 与 $D\bar{D}^*$ 耦合极强 (S 波)：

$\mathcal{B}(X \to D^0\bar{D}^{*0}) > 30\%$ Belle, PRD81(2010)031103

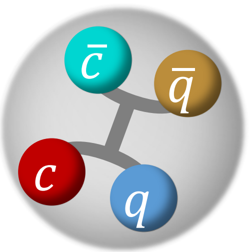


BaBar, PRD77(2008)011102





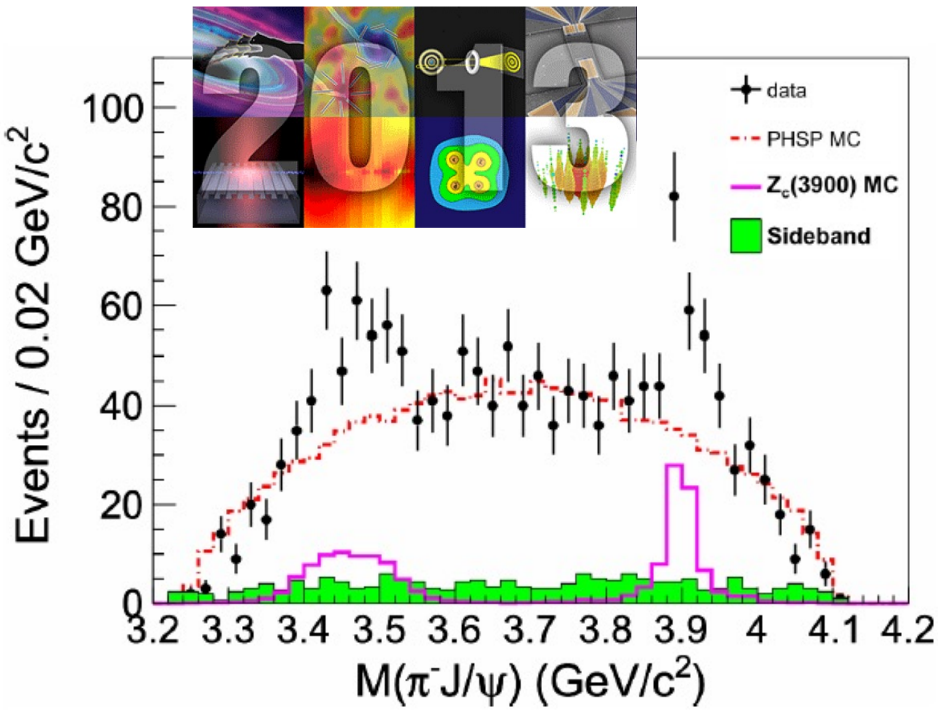
类似于氘核

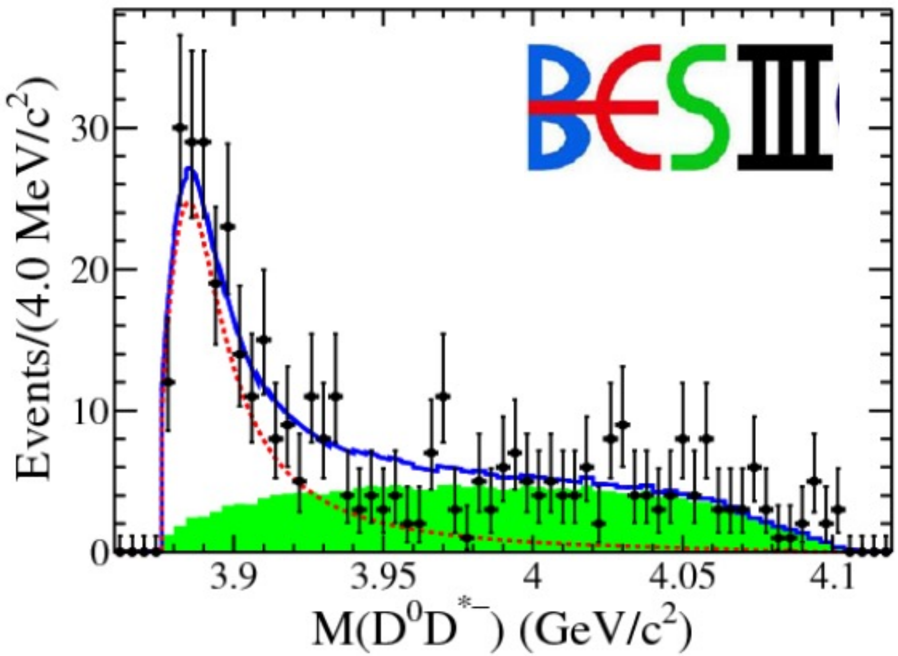


$\mathcal{B}(X \to D^0\bar{D}^{*0} + c.c.) = (52.4^{+25.3}_{-14.3})\%$ C.-H. Li, C.-Z. Yuan, PRD 100 (2019) 094003

带电类粲偶素：四夸克态最佳候选者的发现

- $Z_c(3900)^{\pm}$: structure around 3.9 GeV seen in $J/\psi\pi^{\pm}$ by BESIII and Belle in $Y(4260) \to J/\psi\pi^{+}\pi^{-}$, BESIII, PRL110(2013)252001; Belle, PRL110(2013)252002
  and in $D\bar{D}^{*}$ by BESIII in $Y(4260) \to \pi^{\pm}(D\bar{D}^{*})^{\mp}$ BESIII, PRD92(2015)092006





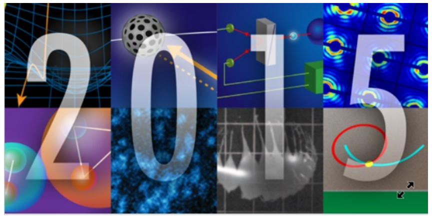
- $Z_c(4020)^{\pm}$ observed in $h_c\pi^{\pm}$ and $(\bar{D}^{*}D^{*})^{\pm}$ distributions

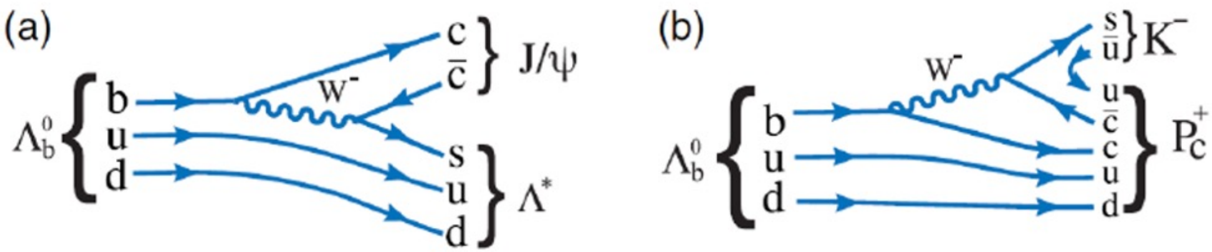
  BESIII, PRL111(2013)242001; PRL112(2014)132001

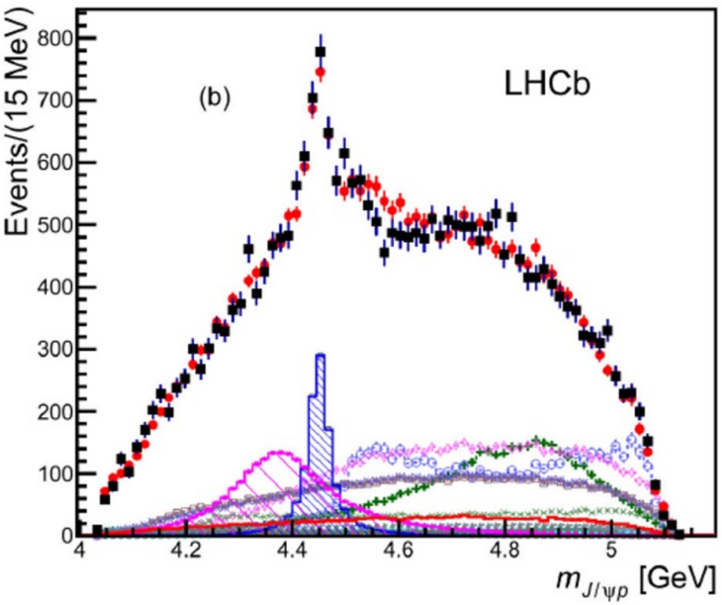
- $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$ very close to $D\bar{D}^{*}$ and $D^{*}\bar{D}^{*}$ thresholds

五夸克态最佳候选者的发现

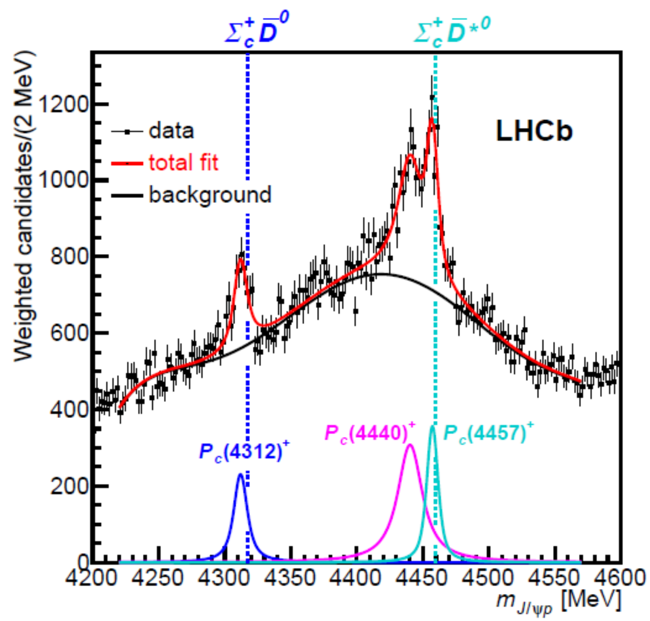
Discovered in $\Lambda_b^0 \to J/\psi p K^-$





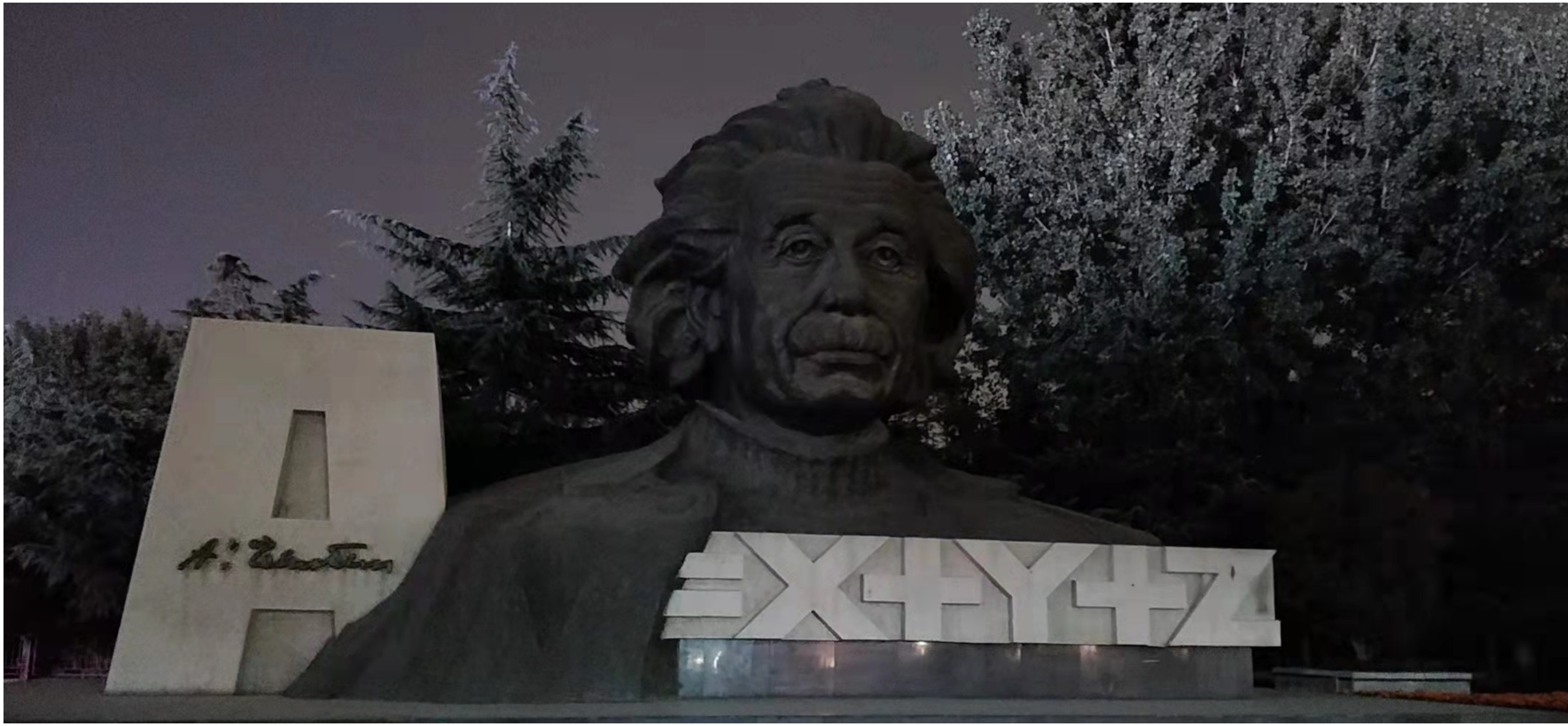


LHCb, PRL 115 (2015) 072001



LHCb, PRL122(2019)222001

XYZ是什么？



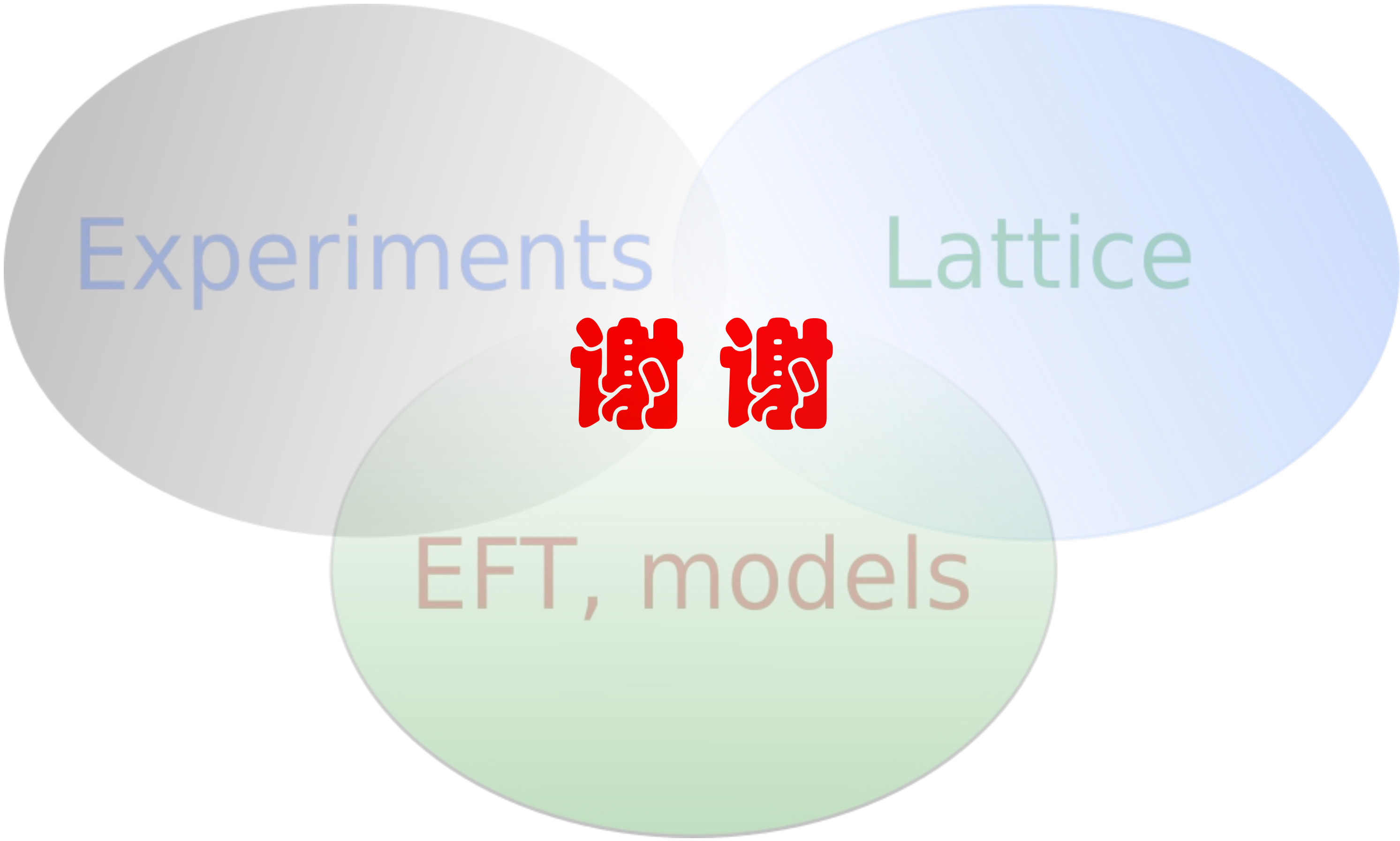
Einstein:

If A is success in life, I should say the formula is $A = X + Y + Z$. X is work, Y is play, and Z is keeping your mouth shut.

超级陶粲装置 (STCF)

近几年的综述不完全列表

- H.-X. Chen, W. Chen, X. Liu, S.-L. Zhu, *The hidden-charm pentaquark and tetraquark states*, Phys. Rept. 639 (2016) 1 [arXiv:1601.02092]
- A. Hosaka, T. Iijima, K. Miyabayashi, Y. Sakai, S. Yasui, *Exotic hadrons with heavy flavors* $-X, Y, Z$ *and related states*, Prog. Theor. Exp. Phys. 2016, 062C01 [arXiv:1603.09229]
- R. F. Lebed, R. E. Mitchell, E. Swanson, *Heary-quark QCD exotica*, Prog. Part. Nucl. Phys. 93 (2017) 143 [arXiv:1610.04528]
- A. Esposito, A. Pilloni, A. D. Polosa, *Multiquark resonances*, Phys. Rept. 668 (2017) 1 [arXiv:1611.07920]
- F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, *Hadronic molecules*, Rev. Mod. Phys. 90 (2018) 015004 [arXiv:1705.00141]
- S. L. Olsen, T. Skwarnicki, *Nonstandard heavy mesons and baryons: Experimental evidence*, Rev. Mod. Phys. 90 (2018) 015003 [arXiv:1708.04012]
- M. Karliner, J. L. Rosner, T. Skwarnicki, *Multiquark states*, Ann. Rev. Nucl. Part. Sci. 68 (2018) 17 [arXiv:1711.10626]
- C.-Z. Yuan, *The XYZ states revisited*, Int. J. Mod. Phys. A 33 (2018) 1830018 [arXiv:1808.01570]
- Y.-R. Liu, H.-X. Chen, W. Chen, X. Liu, S.-L. Zhu, *Pentaquark and tetraquark states*, Prog.Part.Nucl.Phys. 107 (2019) 237 [arXiv:1903.11976]
- N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.-P. Shen, C. E. Thomas, A. Vairo, C.-Z. Yuan, *The* XYZ *states: experimental and theoretical status and perspectives*, Phys. Rept. 873 (2020) 154 [arXiv:1907.07583]
- F.-K. Guo, X.-H. Liu, S. Sakai, *Threshold cusps and triangle singularities in hadronic reactions*, Prog. Part. Nucl. Phys. 112 (2020) 103757 [arXiv:1912.07030]
- G. Yang, J. Ping, J. Segovia, *Tetra- and penta-quark structures in the constituent quark model*, Symmetry 12 (2020) 1869 [arXiv:2009.00238]
- H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, *An updated review of the new hadron states*, Rept. Prog. Phys. 86 (2023) 026201 [arXiv:2204.02649]
- L. Meng, B. Wang, G.-J. Wang, S.-L. Zhu, *Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules*, Phys. Rept. 1019 (2023) 1 [arXiv:2204.08716]
- …


Experiments
Lattice
谢谢
EFT, models

量子场论的早期发展

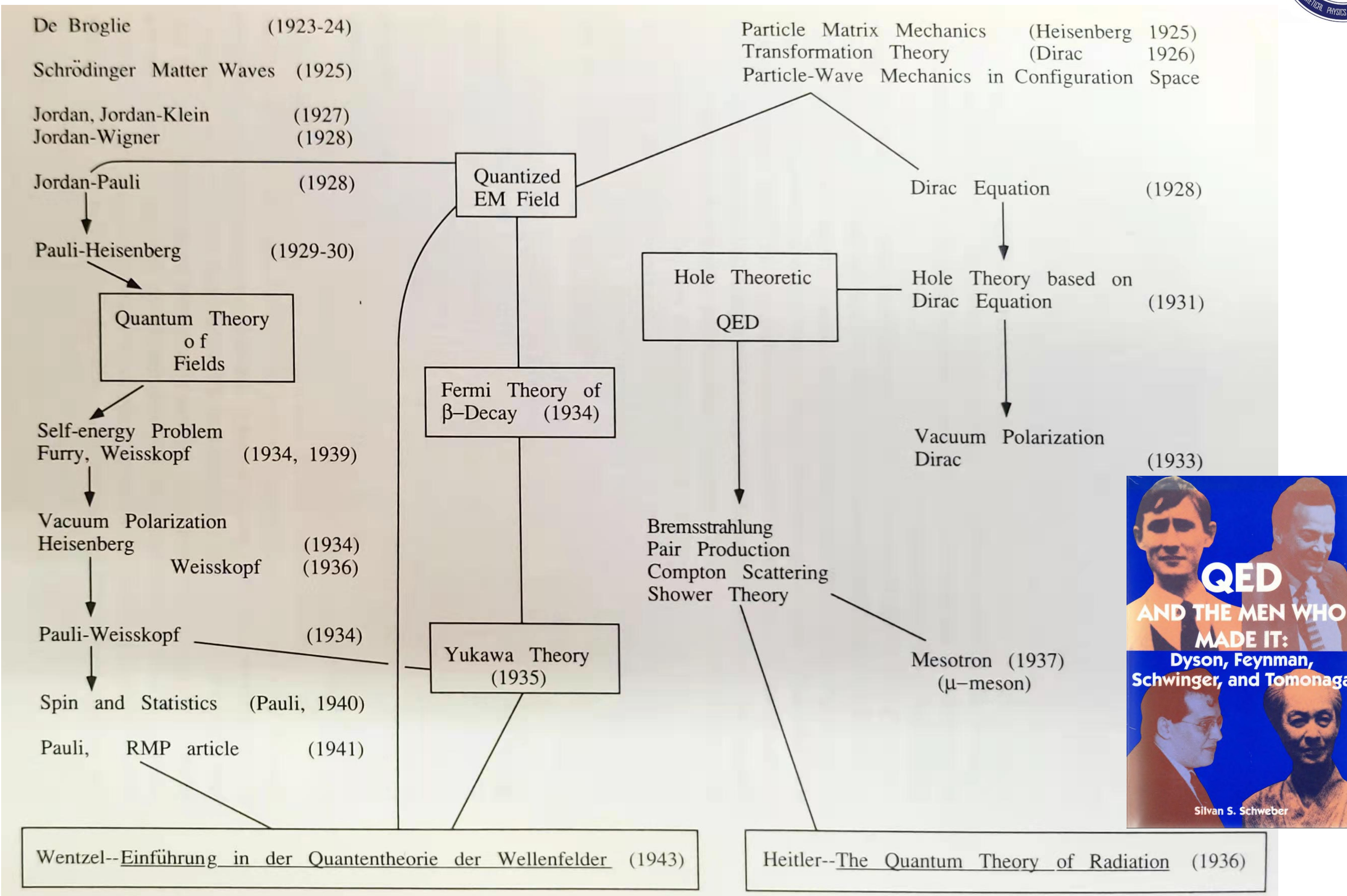


Figure I.1