物理所研習生午餐討論會 2022.8.25

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質子之內，別有洞天 - 次原子世界的驚奇之旅
The Adventure of Exploring Proton's Substructure

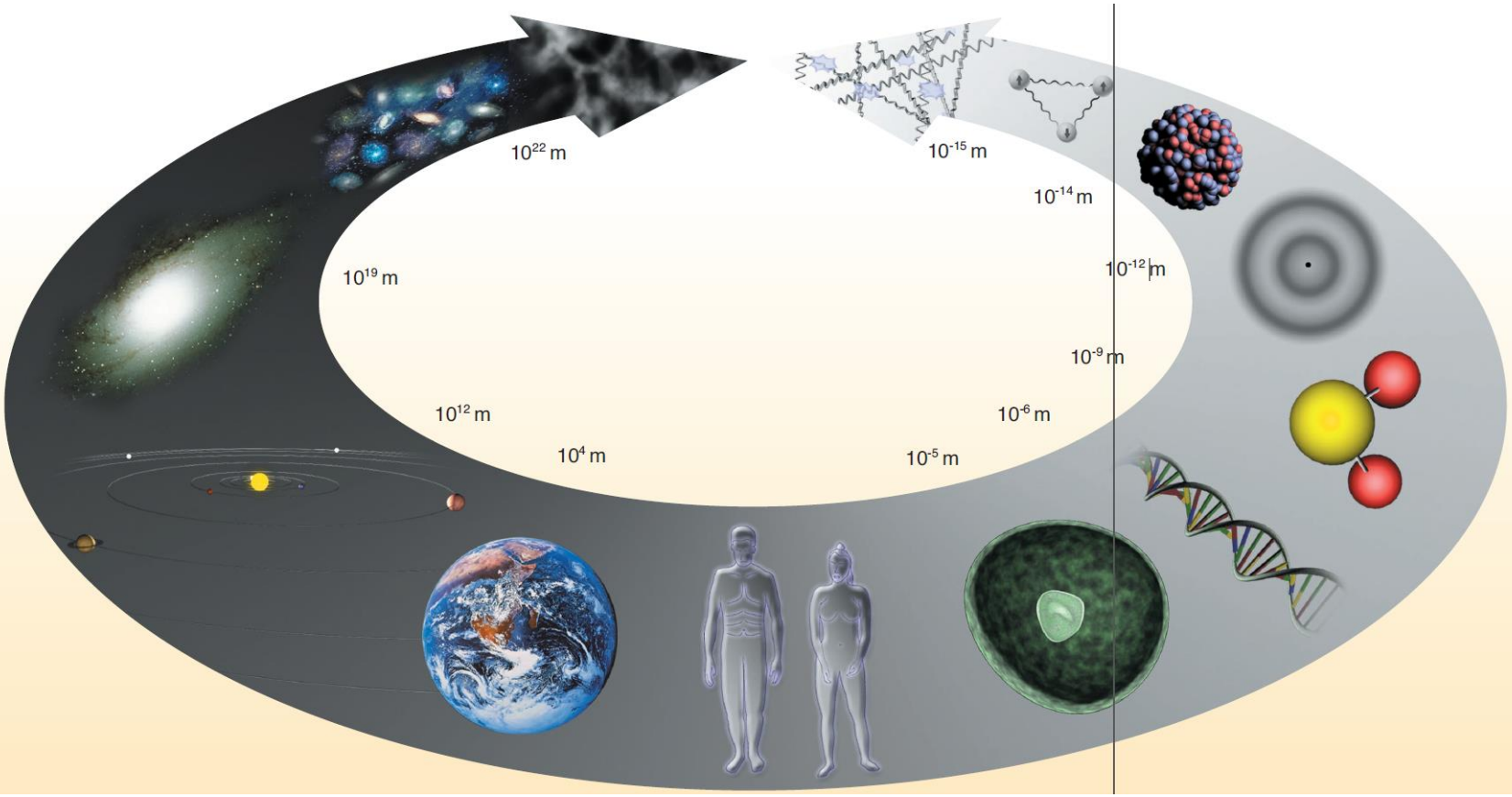
章文箴
中央研究院 物理研究所

物理（大英百科全書）

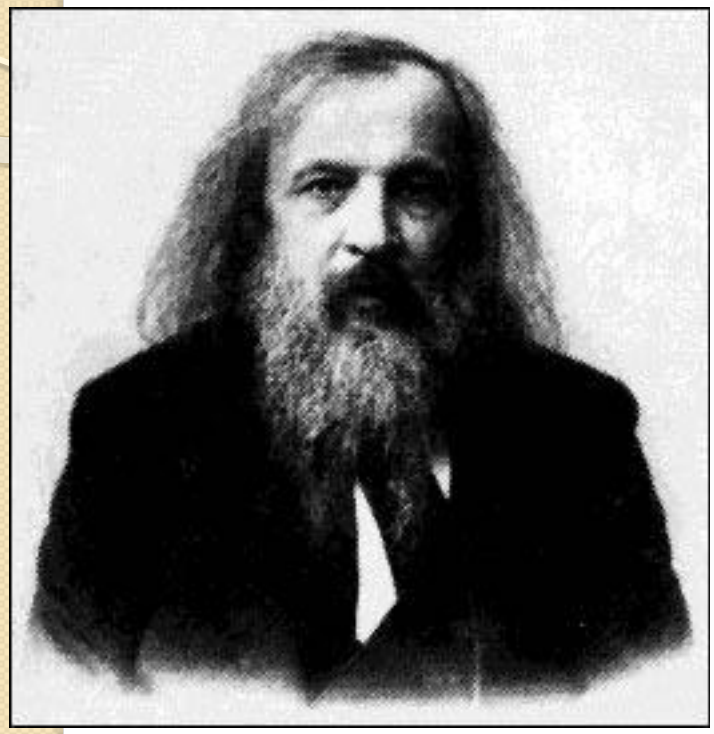
- 探討物質結構，和可觀察宇宙基本成分及其作用方式的科學。
  (science that deals with the structure of matter and the interactions between the fundamental constituents of the observable universe.)

物理學探討模式

- 「化約論」：構成粒子、作用方式



門得列夫（Dmitri Mendeleev）：元素週期表 (1860)



PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

Series	GROUPS OF ELEMENTS								
	0	I	II	III	IV	V	VI	VII	VIII
1	—	Hydrogen H 1·008	—	—	—	—	—	—	
2	Helium He 4·0	Lithium Li 7·03	Beryllium Be 9·1	Boron B 11·0	Carbon C 12·0	Nitrogen N 14·04	Oxygen O 16·00	Fluorine F 19·0	
3	Neon Ne 19·9	Sodium Na 23·05	Magnesium Mg 24·3	Aluminium Al 27·0	Silicon Si 28·4	Phosphorus P 31·0	Sulphur S 32·06	Chlorine Cl 35·45	
4	Argon Ar 38	Potassium K 39·1	Calcium Ca 40·1	Scandium Sc 44·1	Titanium Ti 48·1	Vanadium V 51·4	Chromium Cr 52·1	Manganese Mn 55·0	Iron Fe 55·9 / Cobalt Co 59 / Nickel Ni 59 (Cu)
5		Copper Cu 63·6	Zinc Zn 65·4	Gallium Ga 70·0	Germanium Ge 72·3	Arsenic As 75	Selenium Se 79	Bromine Br 79·95	
6	Krypton Kr 81·8	Rubidium Rb 85·4	Strontium Sr 87·6	Yttrium Y 89·0	Zirconium Zr 90·6	Niobium Nb 94·0	Molybdenum Mo 96·0	—	Ruthenium Ru 101·7 / Rhodium Rh 103·0 / Palladium Pd 106·5 (Ag)
7		Silver Ag 107·9	Cadmium Cd 112·4	Indium In 114·0	Tin Sn 119·0	Antimony Sb 120·0	Tellurium Te 127	Iodine I 127	
8	Xenon Xe 128	Cæsium Cs 132·9	Barium Ba 137·4	Lanthanum La 139	Cerium Ce 140	—	—	—	— — —
9		—	—	—	—	—	—	—	
10	—	—	—	Ytterbium Yb 173	—	Tantalum Ta 183	Tungsten W 184	—	Osmium Os 191 / Iridium Ir 193 / Platinum Pt 194·9 (Au)
11		Gold Au 197·2	Mercury Hg 200·0	Thallium Tl 204·1	Lead Pb 206·9	Bismuth Bi 208	—	—	
12	—	—	Radium Rd 224	—	Thorium Th 232	—	Uranium U 239		

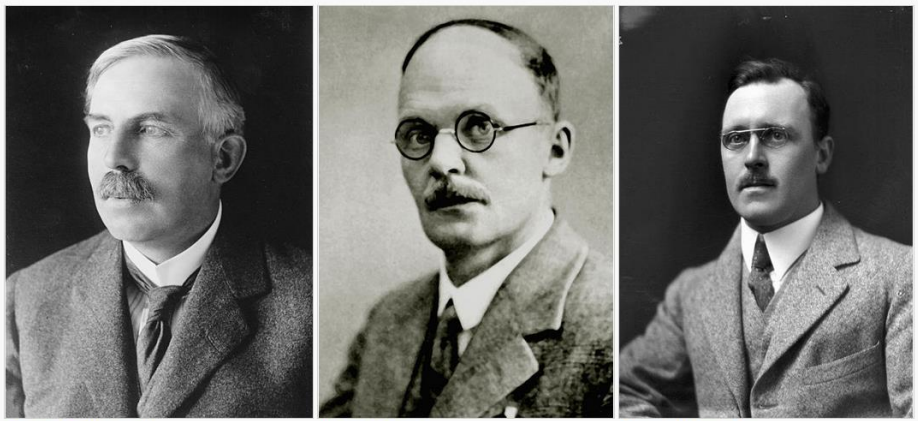
HIGHER SALINE OXIDES

R	R_2O	RO	R_2O_3	RO_2	R_2O_5	RO_3	R_2O_7	RO_4

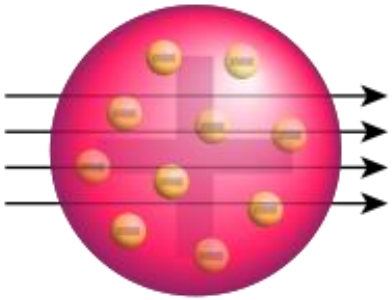
HIGHER GASEOUS HYDROGEN COMPOUNDS

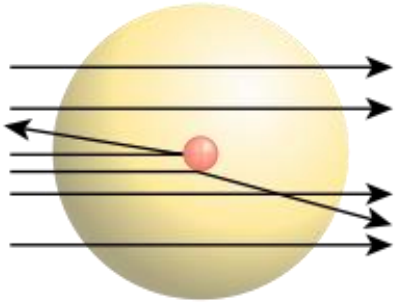
				RH_4	RH_3	RH_2	RH	

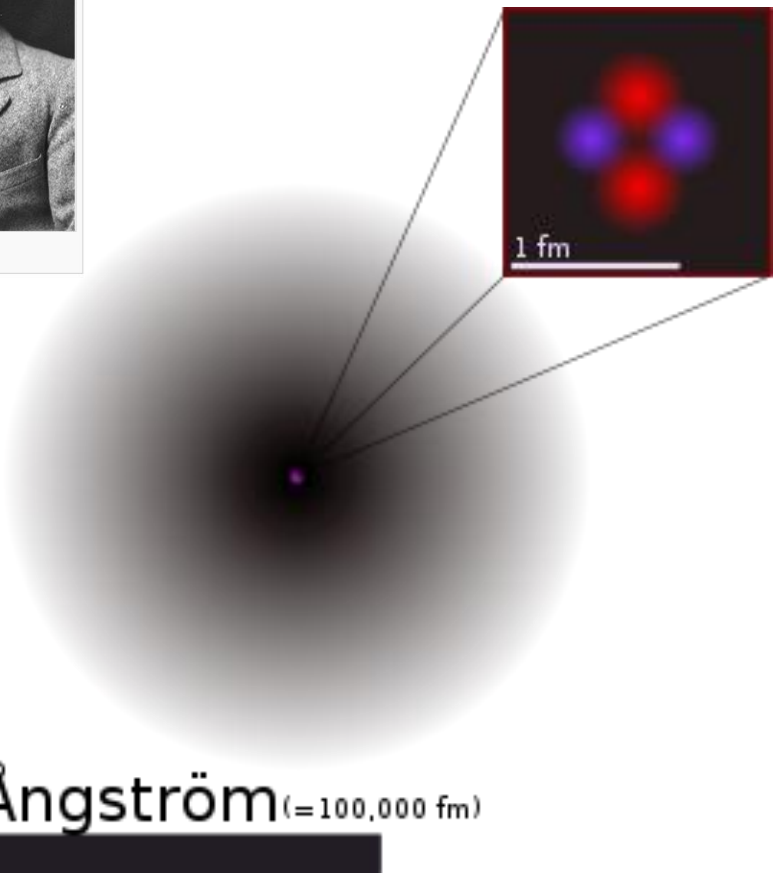
拉塞福散射實驗: 原子結構 (1913)



Ernest Rutherford　Hans Geiger　Ernest Marsden







Robert Hofstadter: 電子散射、原子核結構 (1956)

Robert Hofstadter

The Nobel Prize in Physics 1961

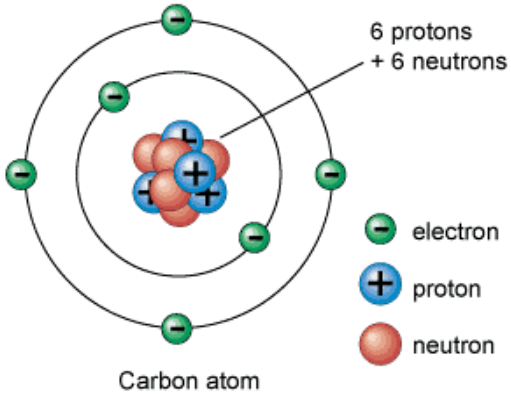
Robert Hofstadter
The Nobel Prize in Physics 1961

Born: 5 February 1915, New York, NY, USA

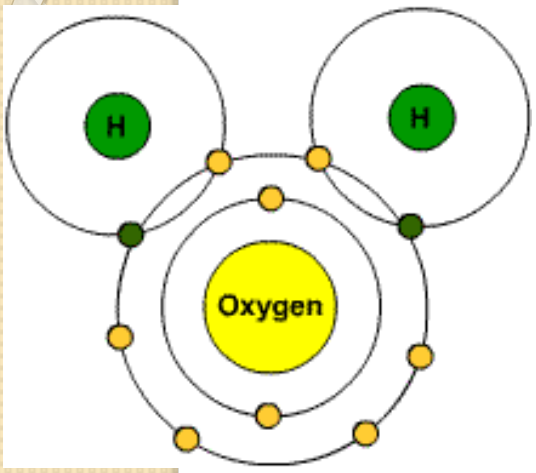
Died: 17 November 1990, Stanford, CA, USA

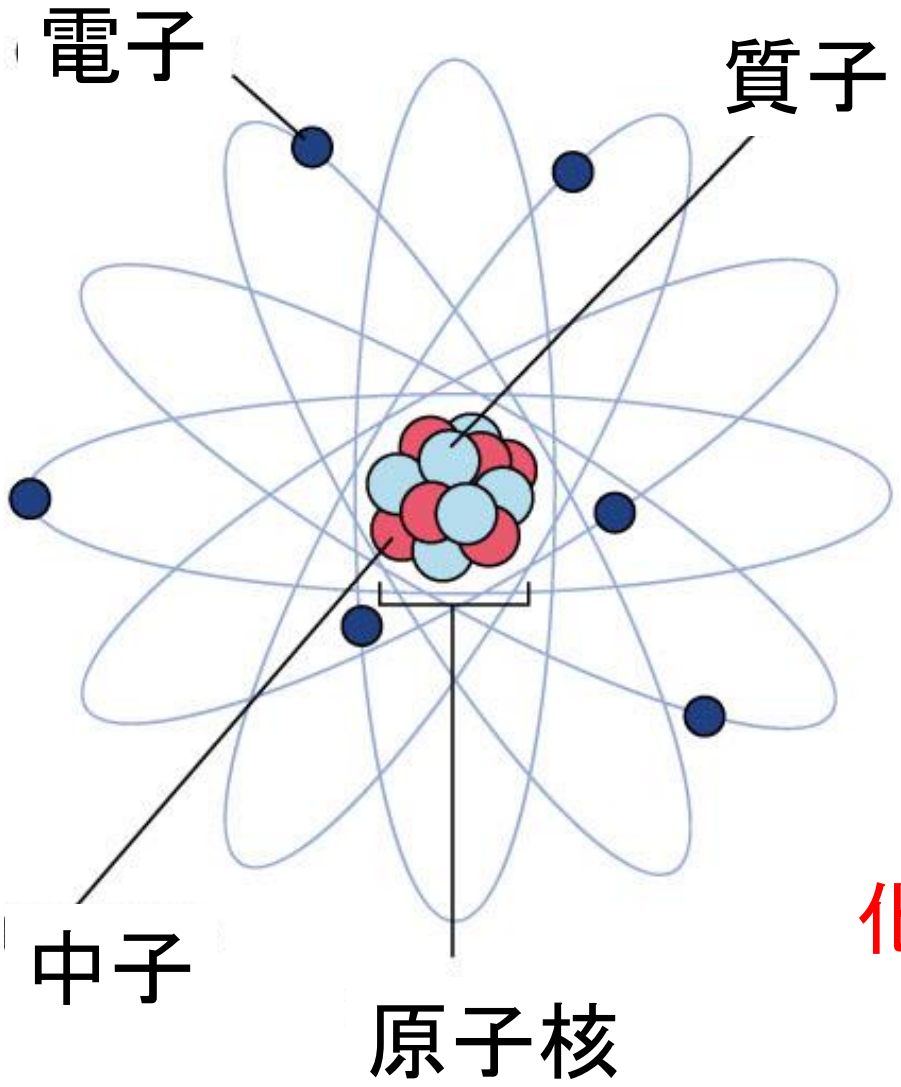
Affiliation at the time of the award: Stanford University, Stanford, CA, USA

Prize motivation: "for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons."



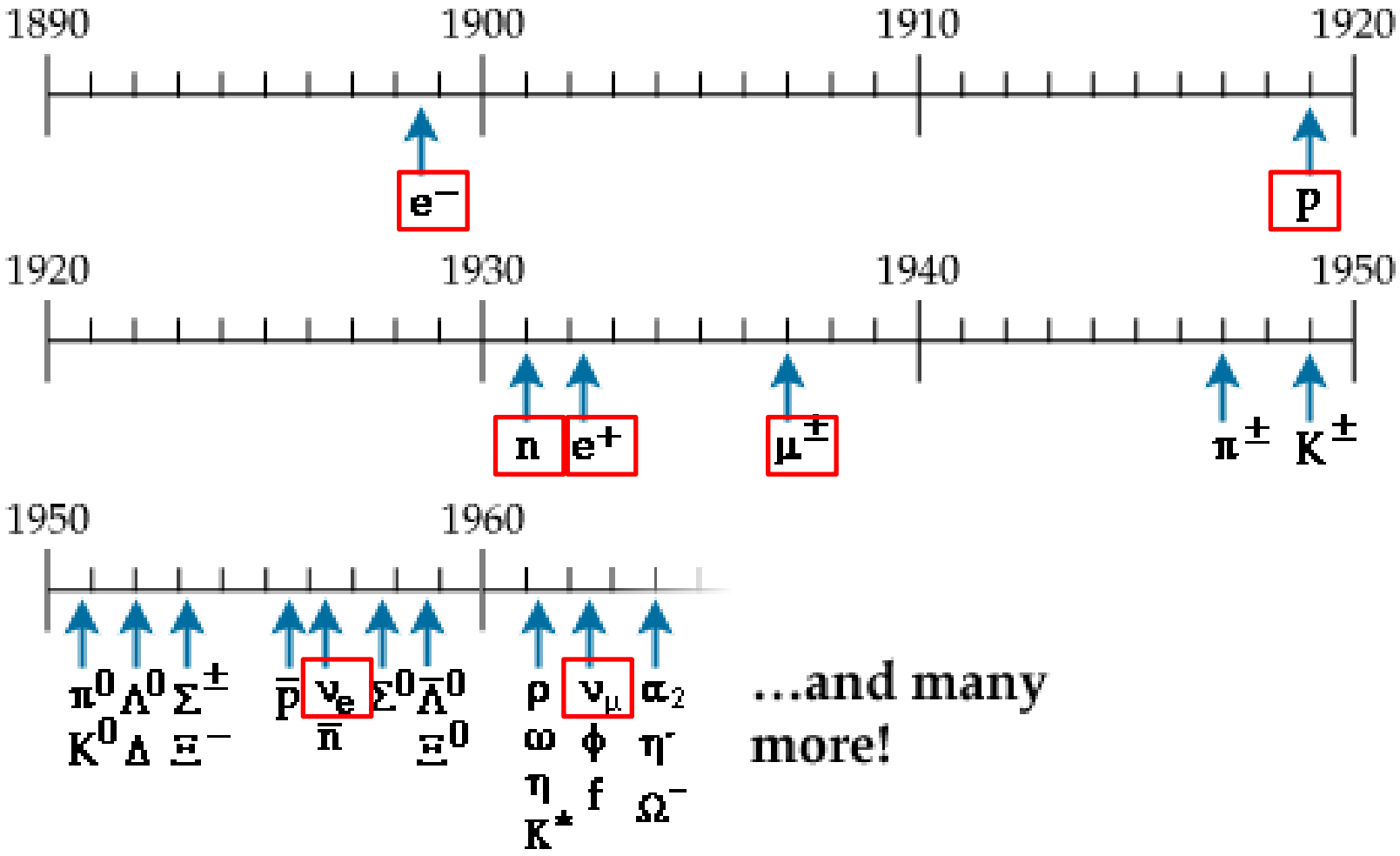
原子結構和化學性質





化繁為簡

基本粒子: 1898 -1964



Murray Gell-Mann: 夸克模型 (1964)

Physics

The Nobel Prize in Physics 1969

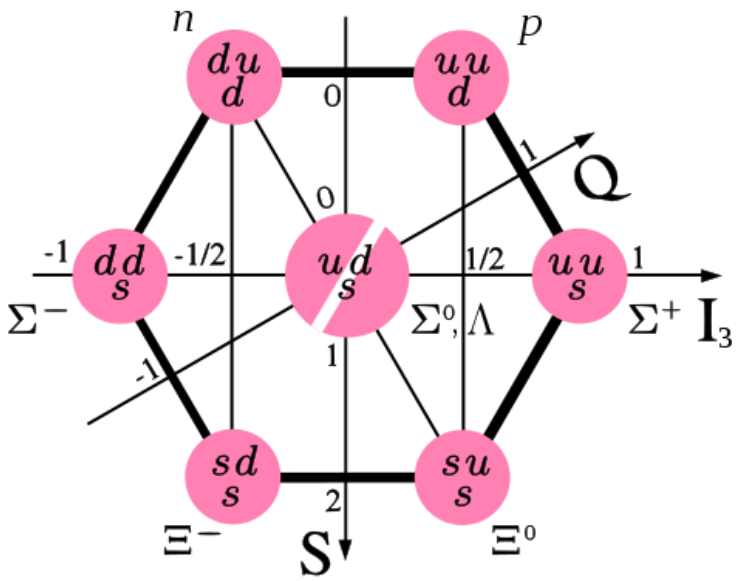
"for his contributions and discoveries concerning the classification of elementary particles and their interactions"

Murray Gell-Mann

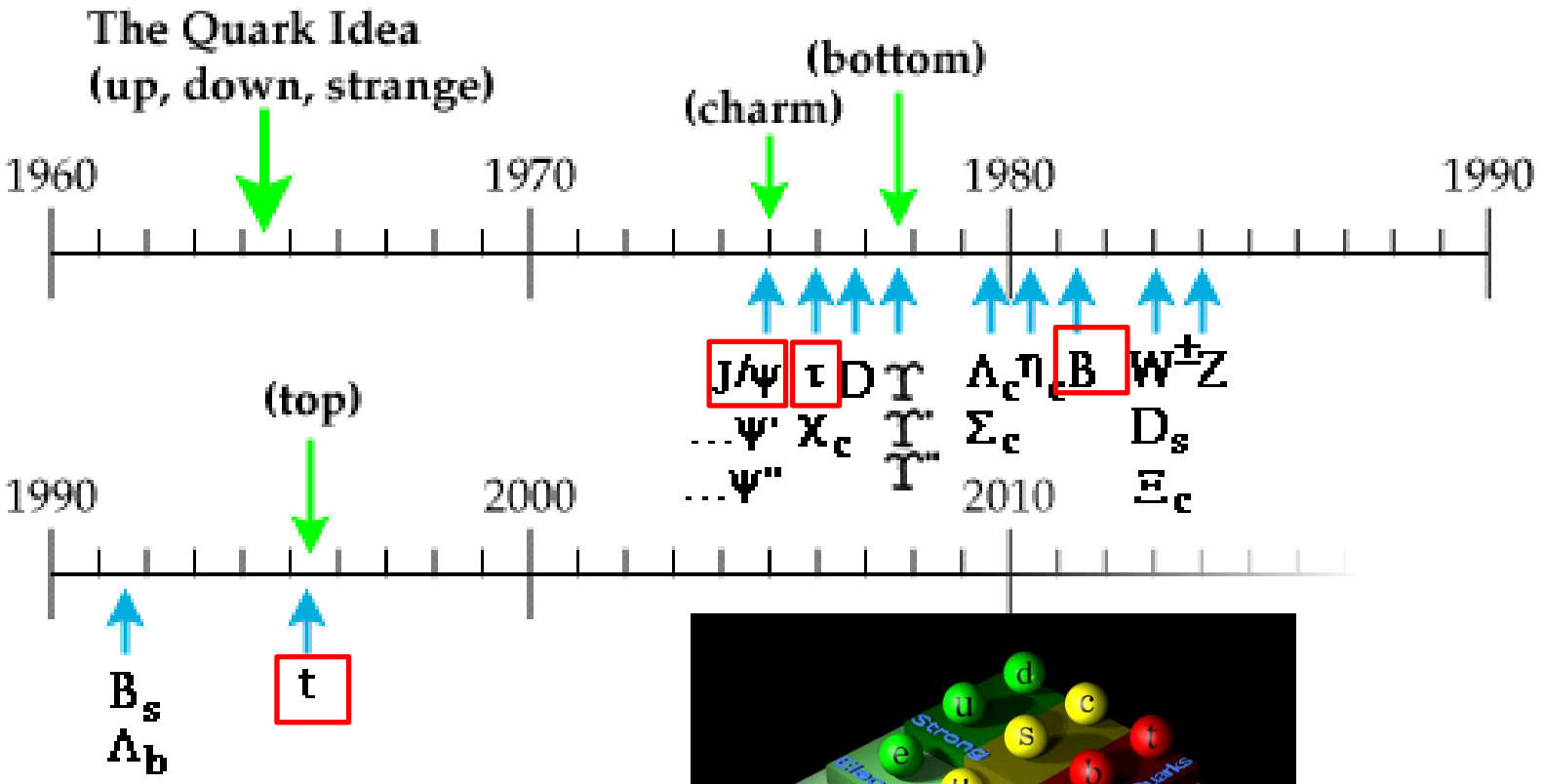
USA

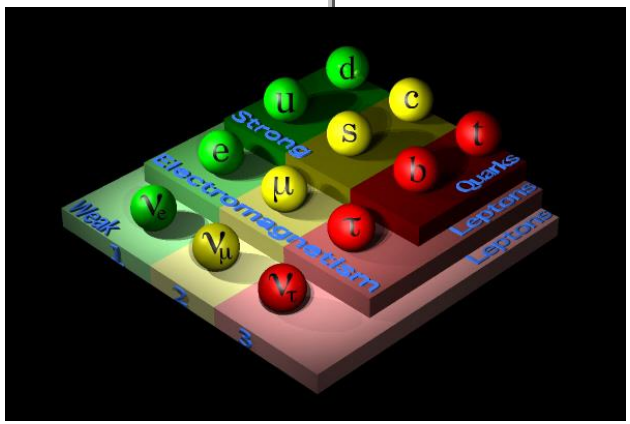
California Institute of Technology (Caltech)
Pasadena, CA, USA

b. 1929

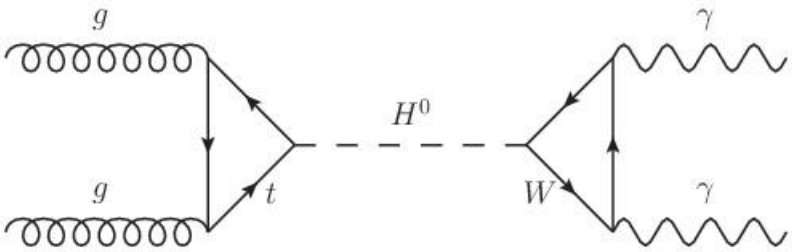


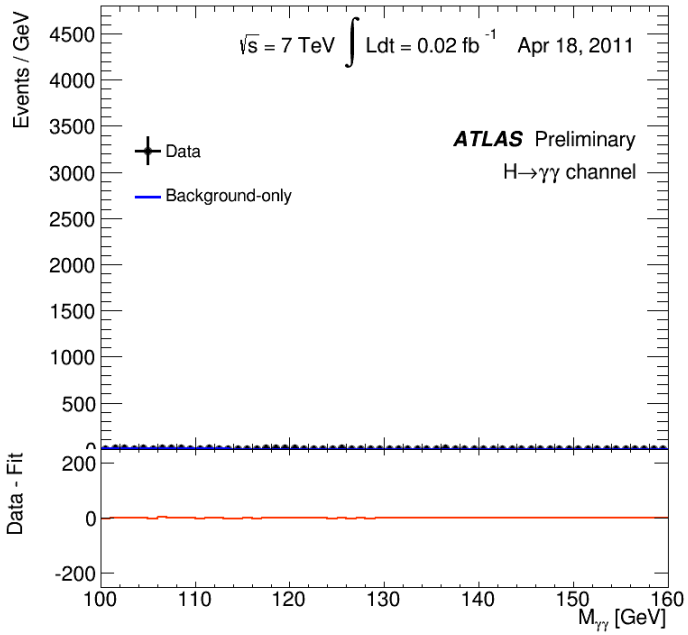
基本粒子和新種類夸克: 1964 - 2010

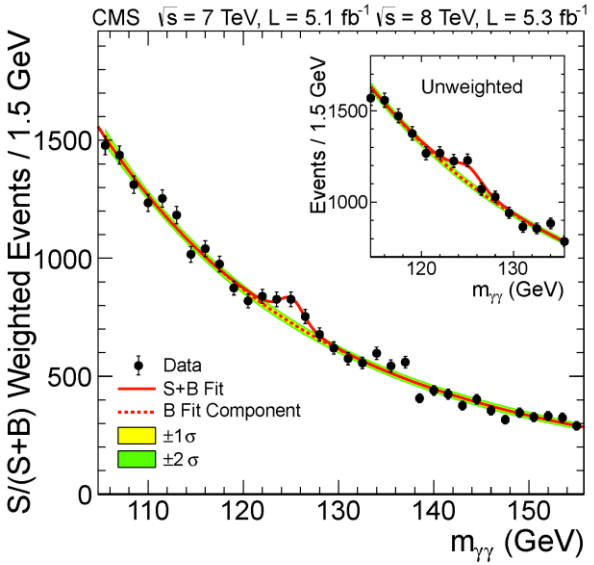




希格氏粒子的發現（2012）







The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

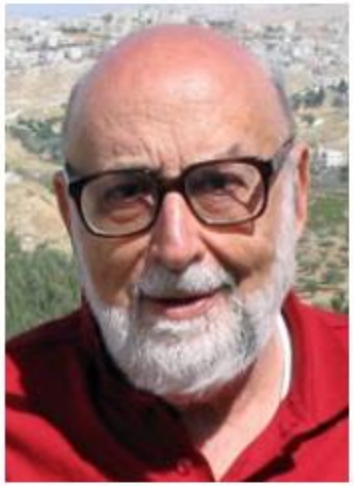


Photo: Pnicolet via Wikimedia Commons

François Englert

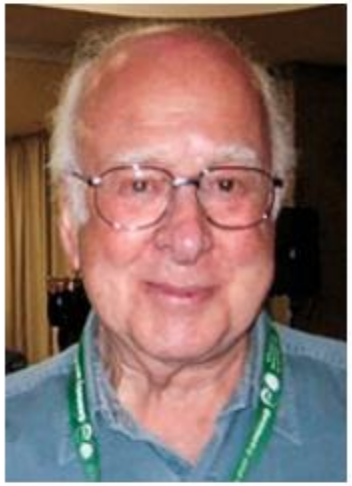
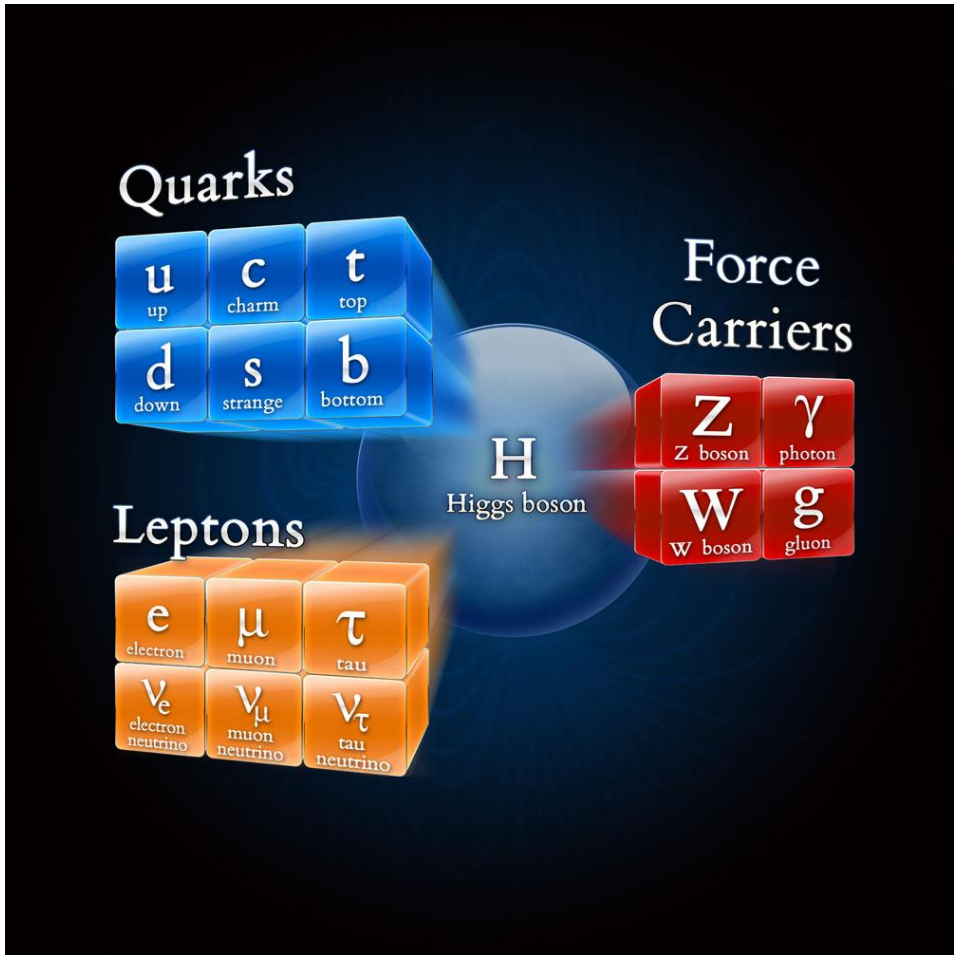


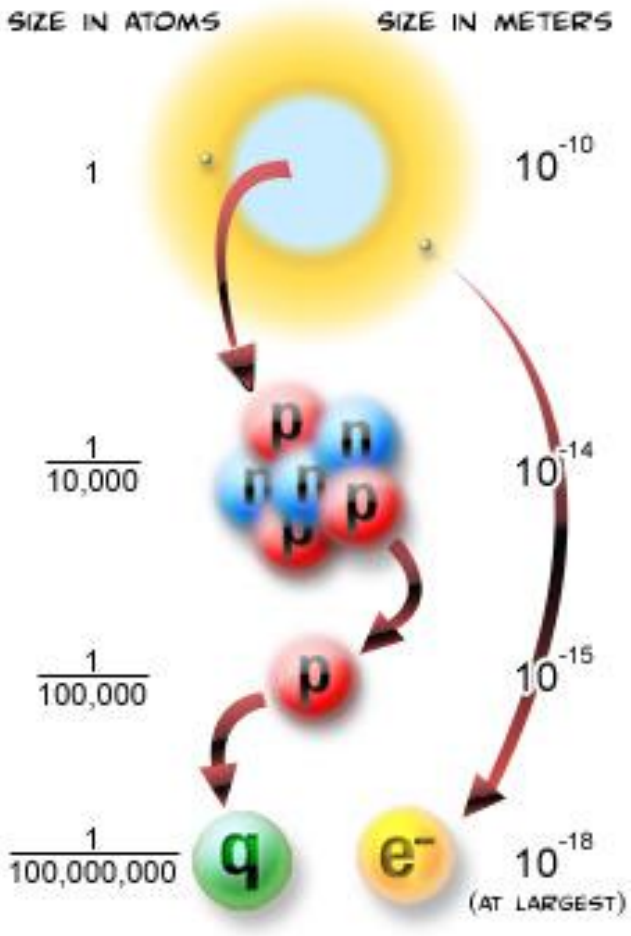
Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs ***"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"***

基本粒子標準模型


Quarks
u up
c charm
t top
d down
s strange
b bottom
Leptons
e electron
μ muon
τ tau
νe electron neutrino
νμ muon neutrino
ντ tau neutrino
H Higgs boson
Force Carriers
Z Z boson
γ photon
W W boson
g gluon


SIZE IN ATOMS
SIZE IN METERS
1
10^-10
1/10,000
10^-14
1/100,000
10^-15
1/100,000,000
10^-18
(AT LARGEST)
p
n
q
e⁻

夸克系統—強子Hadron

重子

介子

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u\bar{d}}$	+1	0.140	0
$\mathbf{K^-}$	kaon	$\mathbf{s\bar{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u\bar{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d\bar{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c\bar{c}}$	0	2.980	0

Hadron is the effective degree of freedom of all quark systems.

描述強作用力的量子色動力學

Quantum Chromodynamics (QCD) for the Strong Interaction

Quantum Chromodynamics (QCD), the gauge field theory that describes the strong interactions of colored quarks and gluons, is the SU(3) component of the SU(3)×SU(2)×U(1) Standard Model of Particle Physics.

The Lagrangian of QCD is given by

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu} , \qquad (9.1)$$

where repeated indices are summed over. The γ^μ are the Dirac γ-matrices. The $\psi_{q,a}$ are quark-field spinors for a quark of flavor q and mass m_q, with a color-index a that runs from $a = 1$ to $N_c = 3$, *i.e.* quarks come in three "colors." Quarks are said to be in the fundamental representation of the SU(3) color group.

Parameters:

m_q: quark mass

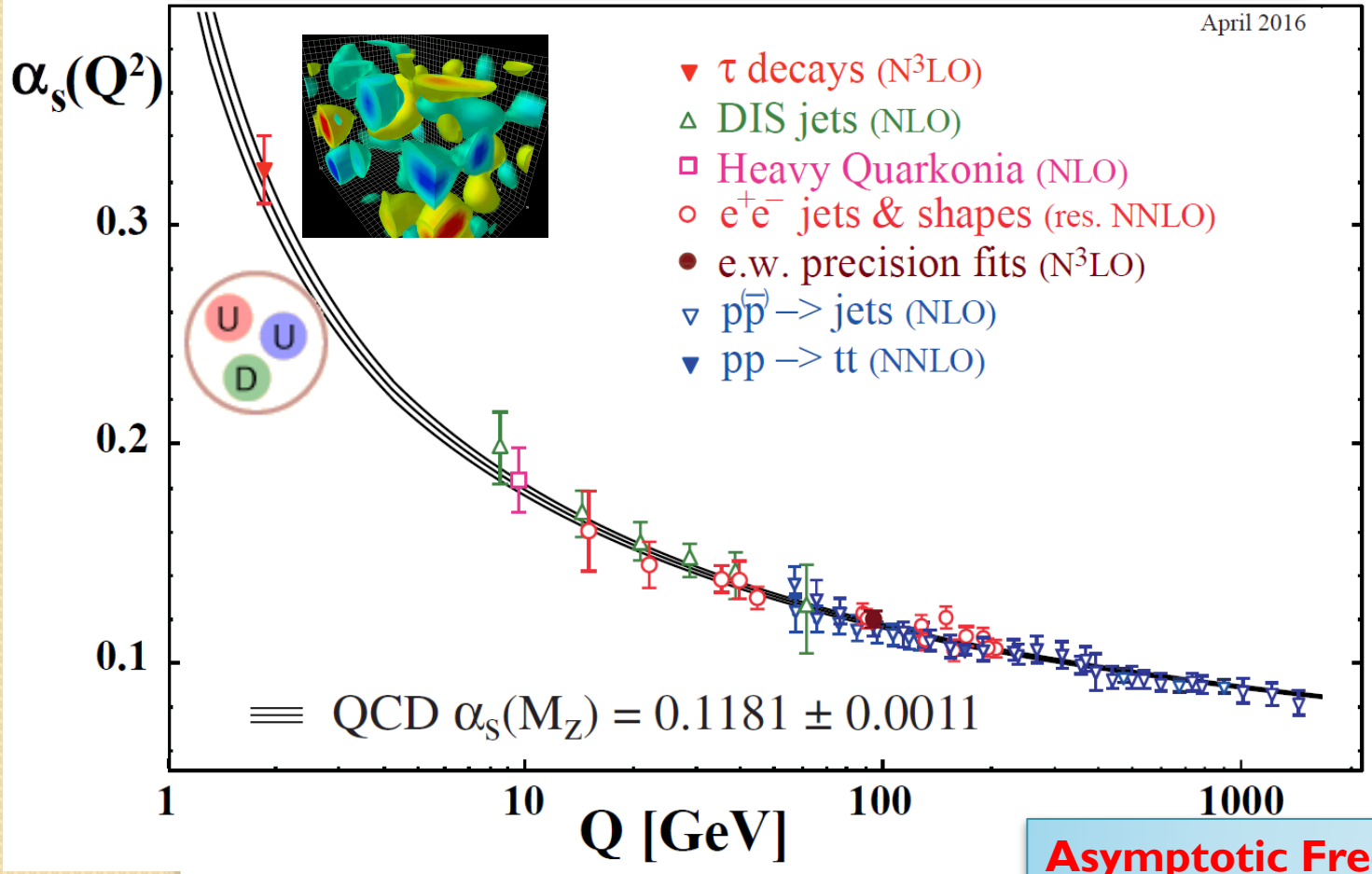
g_s:coupling constants

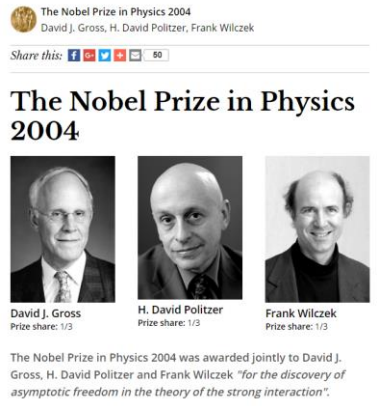
http://pdg.lbl.gov/2017/reviews/rpp2017-rev-qcd.pdf

強作用力的性質

$\alpha_s = \frac{g_s^2}{4\pi}$

Quark Confinement（夸克禁閉）: no isolated quarks.

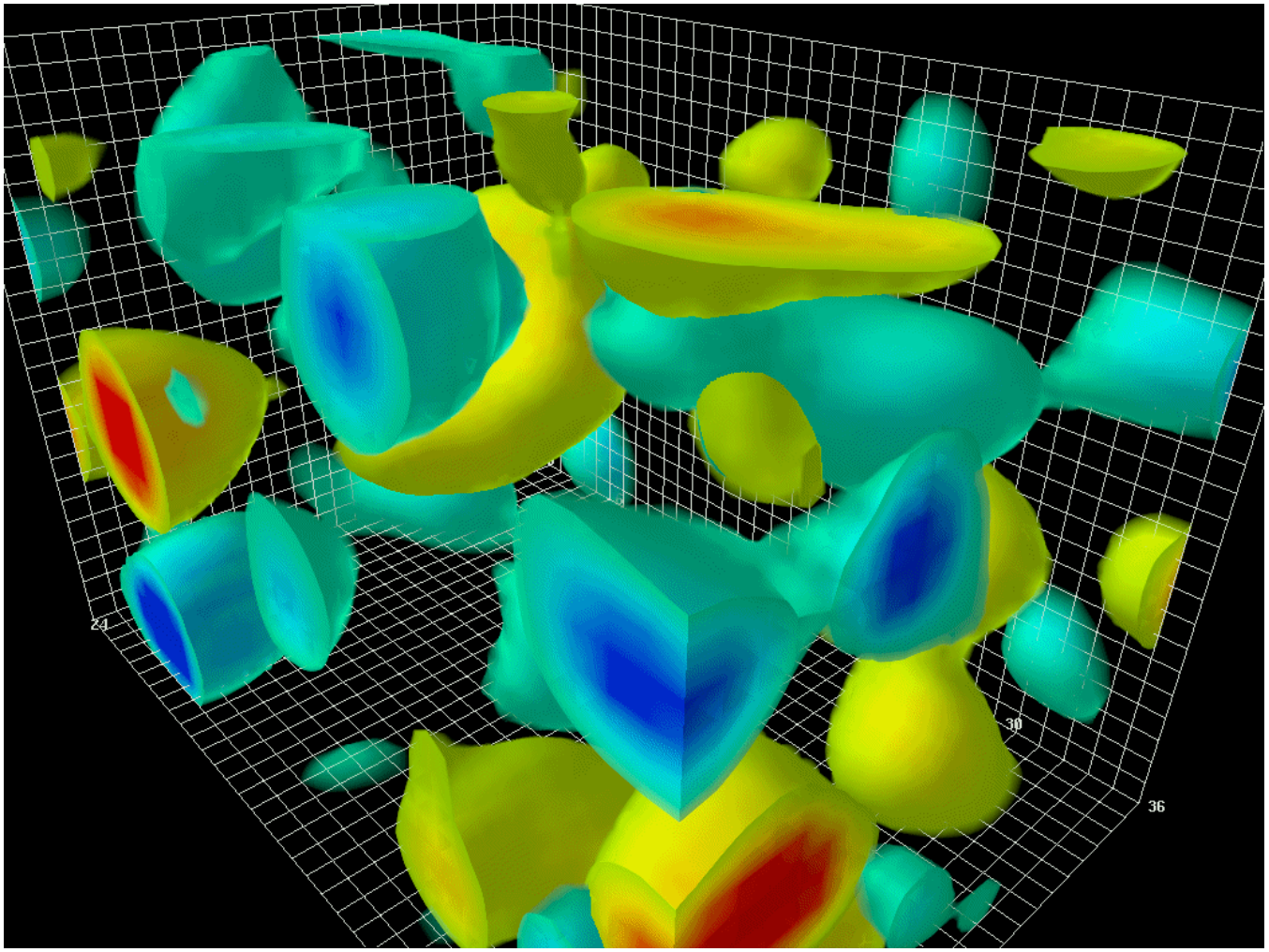




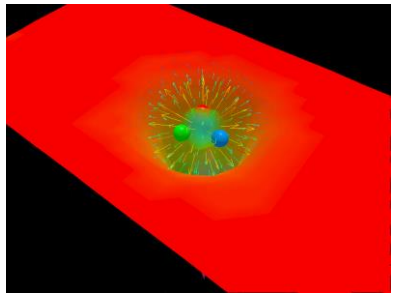
Asymptotic Freedom（漸近自由）

http://pdg.lbl.gov/2017/reviews/rpp2017-rev-qcd.pdf

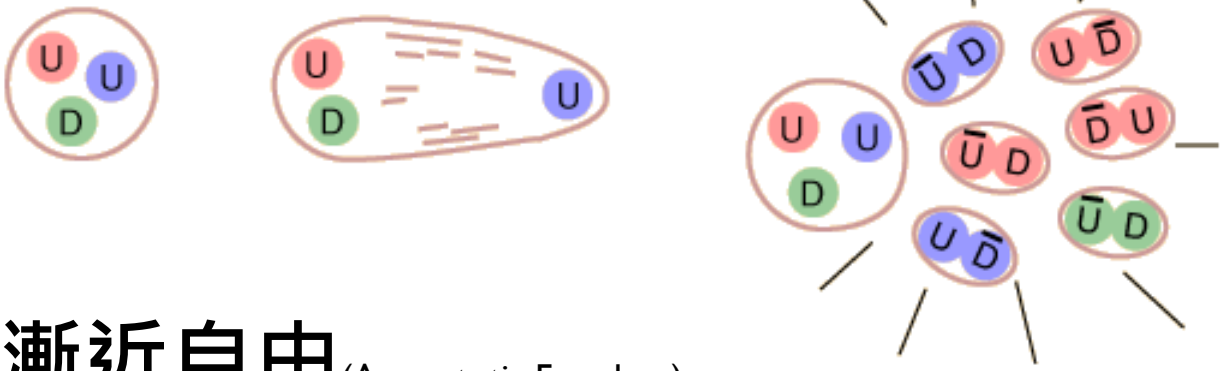
膠子（強交互作用的交換粒子）



強作用力



- **夸克禁閉**(Quark Confinement): 無單獨夸克存在



- **漸近自由**(Asymptotic Freedom):

$$\alpha_s(E) = \frac{12\pi}{(33 - 2n_f)\ln\left[\frac{E^2}{\Lambda^2}\right]}$$

n_f = number of quarks active in pair production (up to 6)

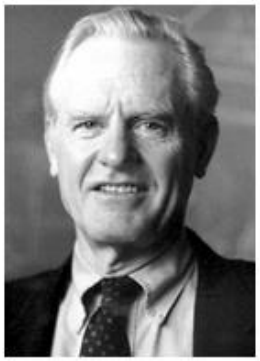
Λ = experimentally determined parameter, ≈ 0.2 GeV

$$E \to \infty,\ \alpha_s \to 0.$$

夸克存在的實驗證據：
電子深度非彈性散射 (Deep Inelastic Scattering)

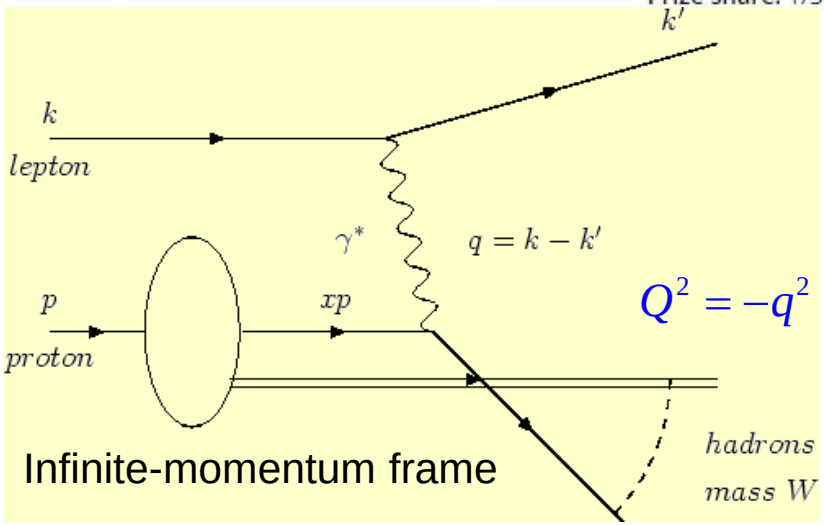
The Nobel Prize in Physics 1990

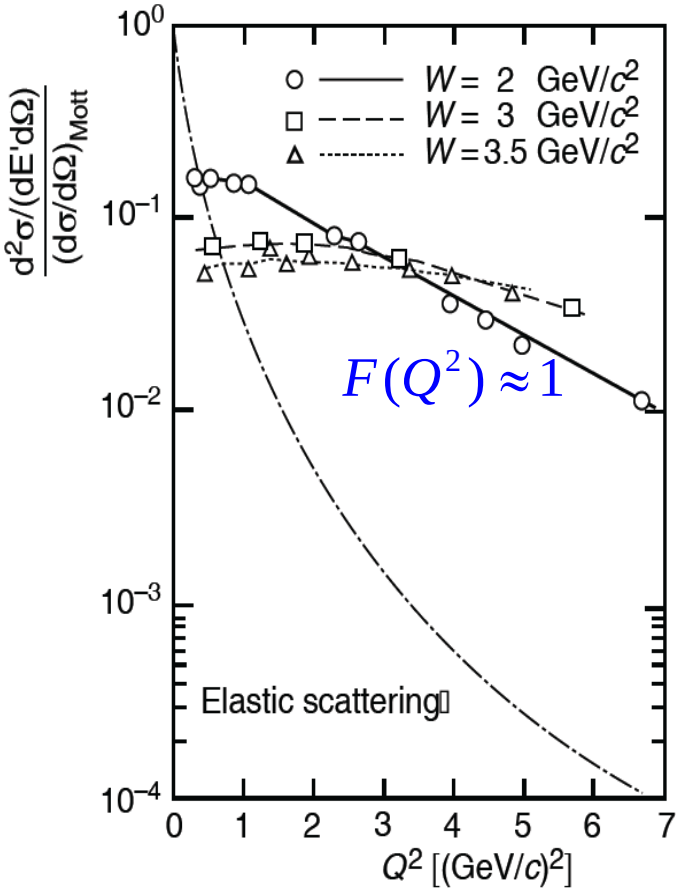
Jerome I. Friedman
Prize share: 1/3



Henry W. Kendall
Prize share: 1/3

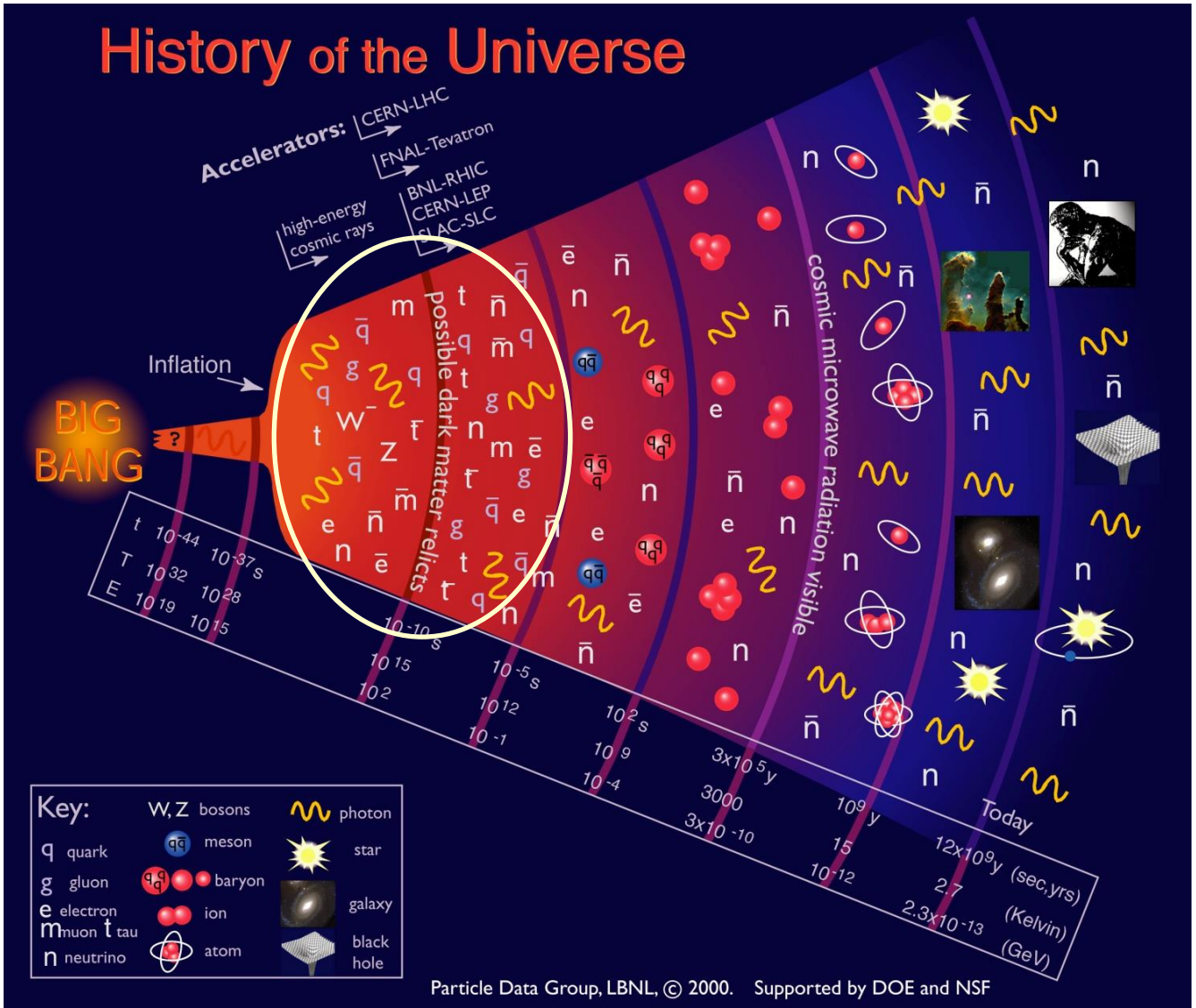
Photo: T. Nakashima
Richard E. Taylor
Prize share: 1/3



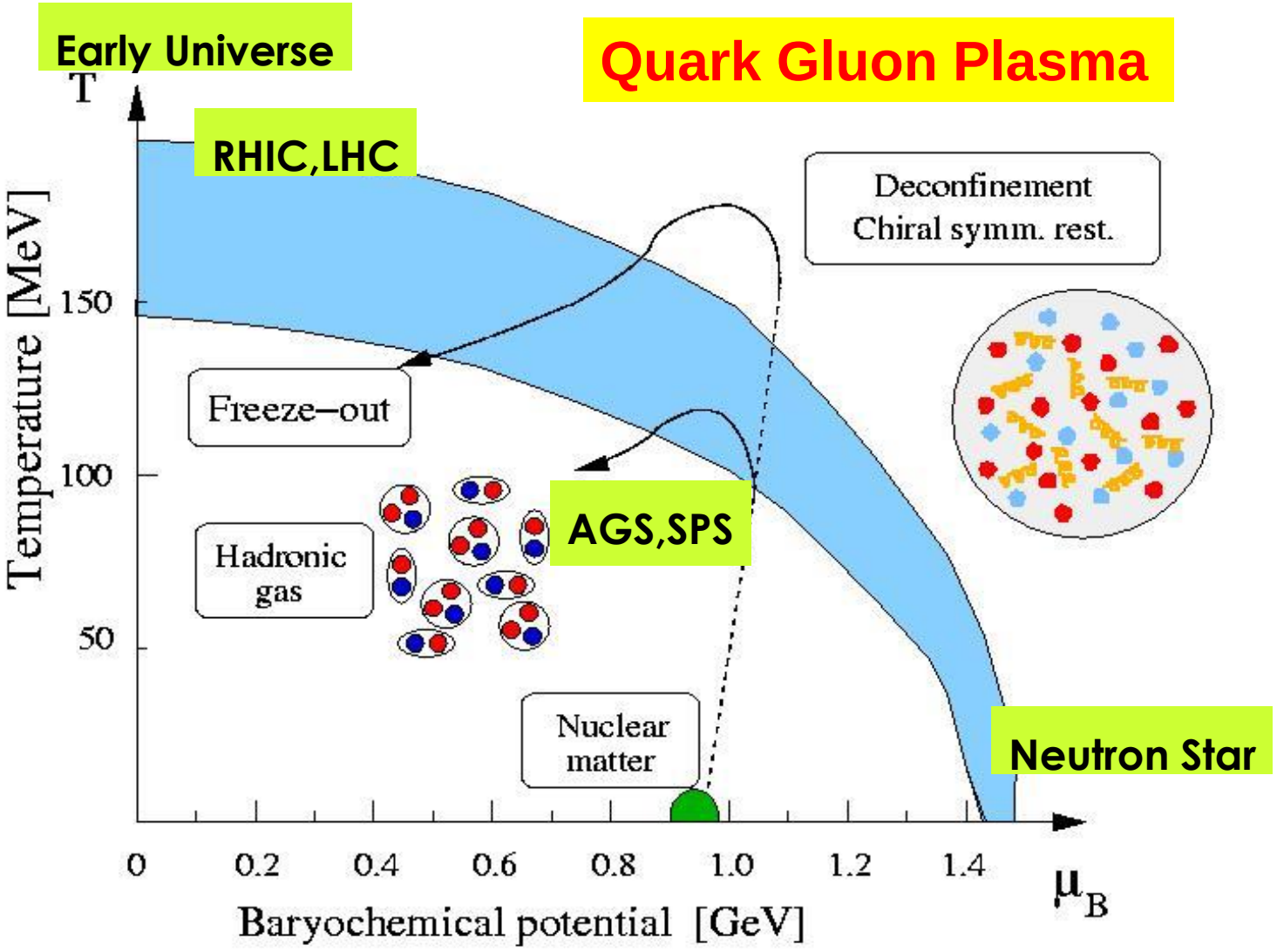


Parton 部分子

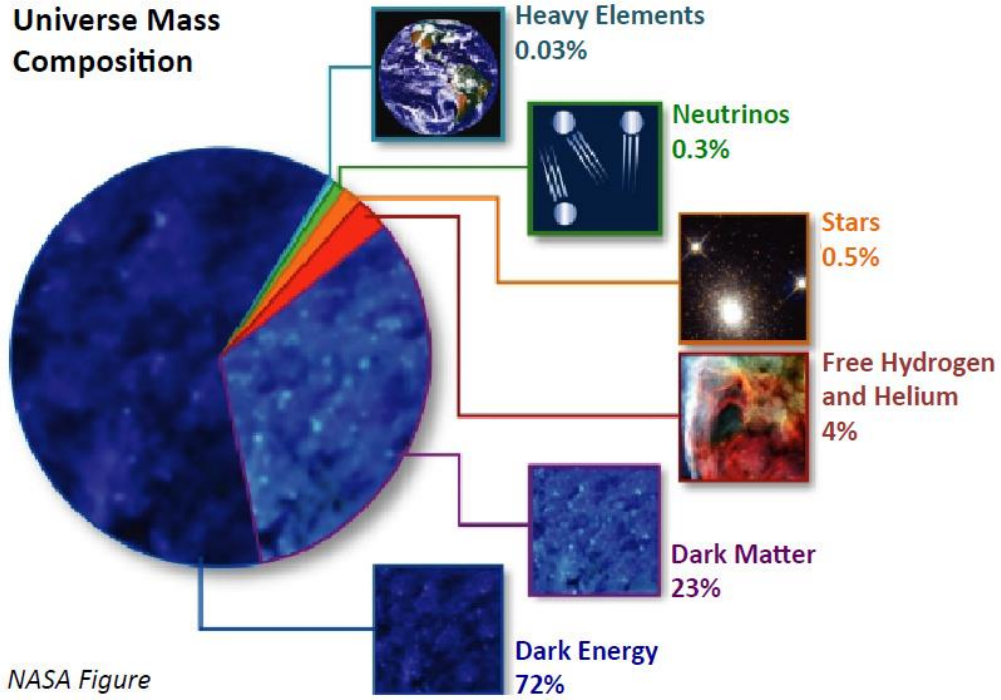
宇宙大爆炸理論

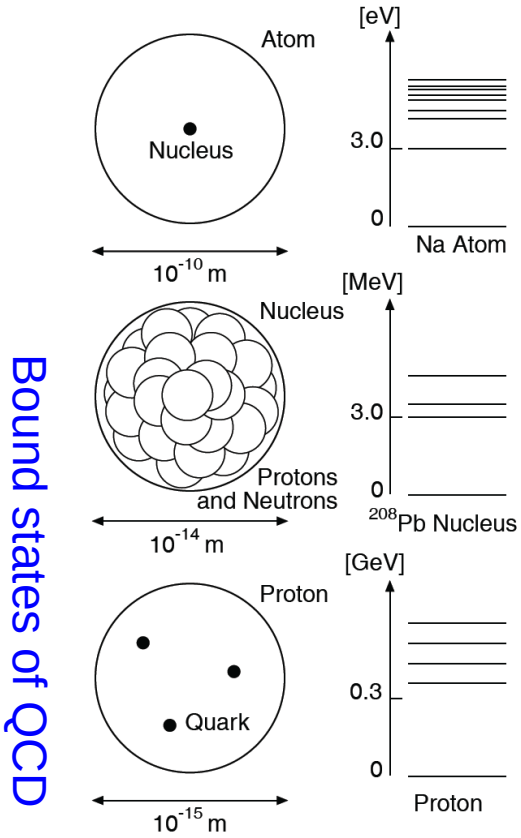

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
W,Z bosons
photon
quark
meson
star
gluon
baryon
galaxy
electron
ion
muon
tau
atom
black hole
neutrino
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

QCD Phase Diagram



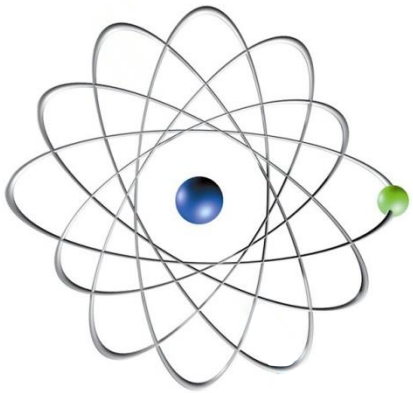
Composition of the Universe





組合系統的質量

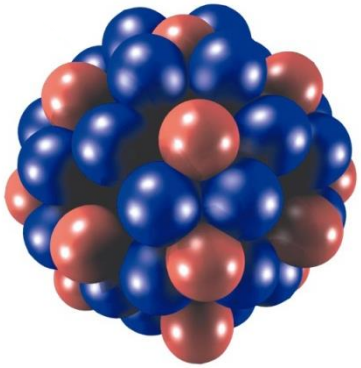
原子
10^{-10} m



$M \approx \Sigma m_i$

binding energy
effect $\approx 10^{-8}$

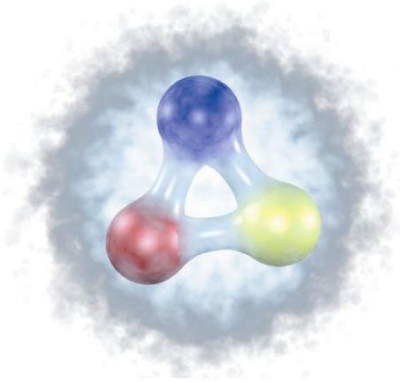
原子核
10^{-14} m



$M \approx \Sigma m_i$

binding energy
effect $\approx 10^{-3}$

質子
10^{-15} m

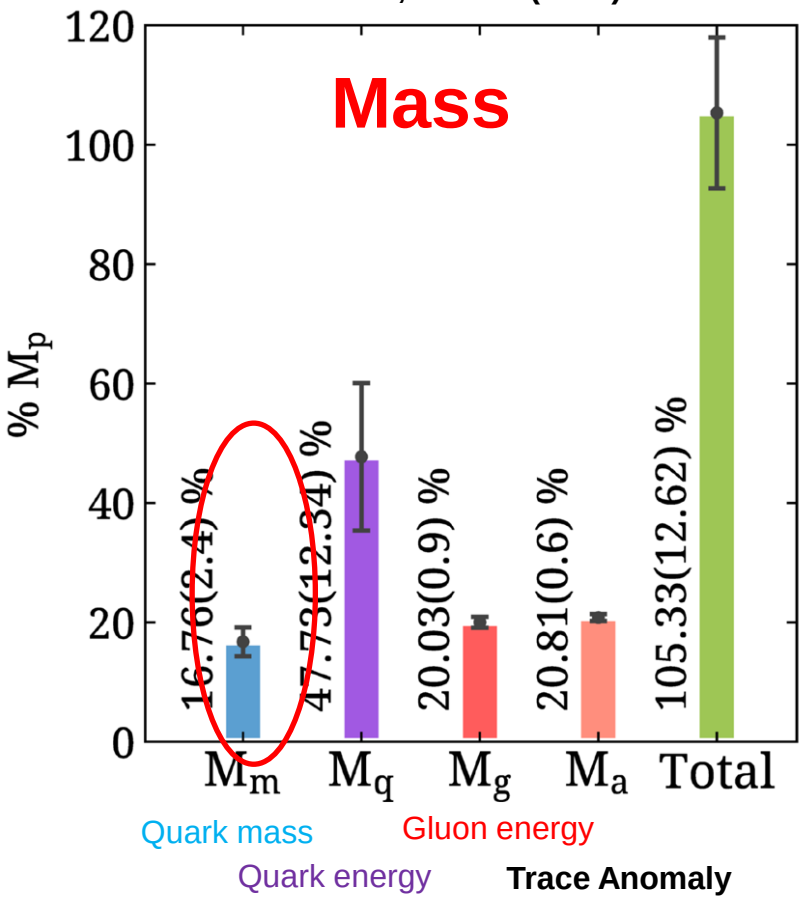


$M \gg m_i$

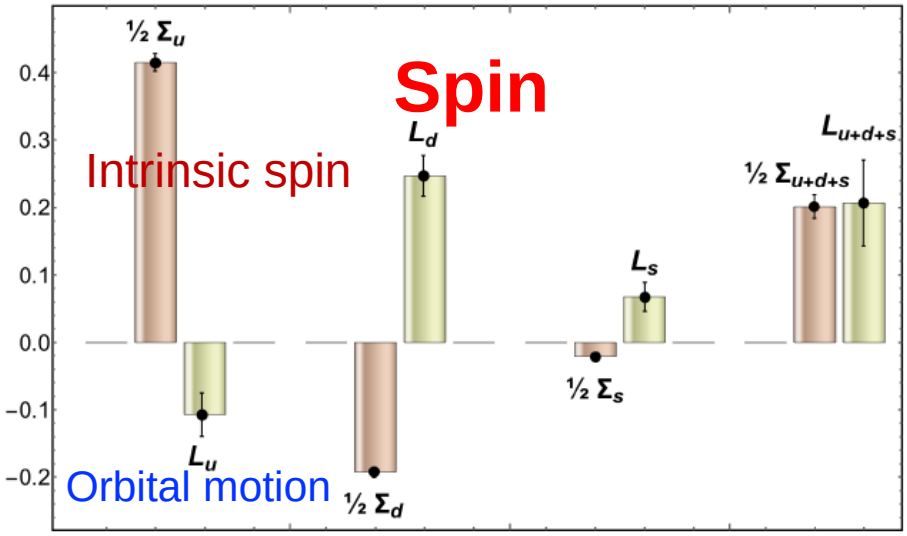
質子的質量為 980 MeV，但 u, d夸克的質量卻只有5-10 MeV?
"mass without mass" (Wilczek)

Mass/Spin Decomposition of Proton (Lattice QCD)

PRL 116, 252001 (2016)
PRL 119, 142002 (2017)



PRL 119, 142002 (2017)

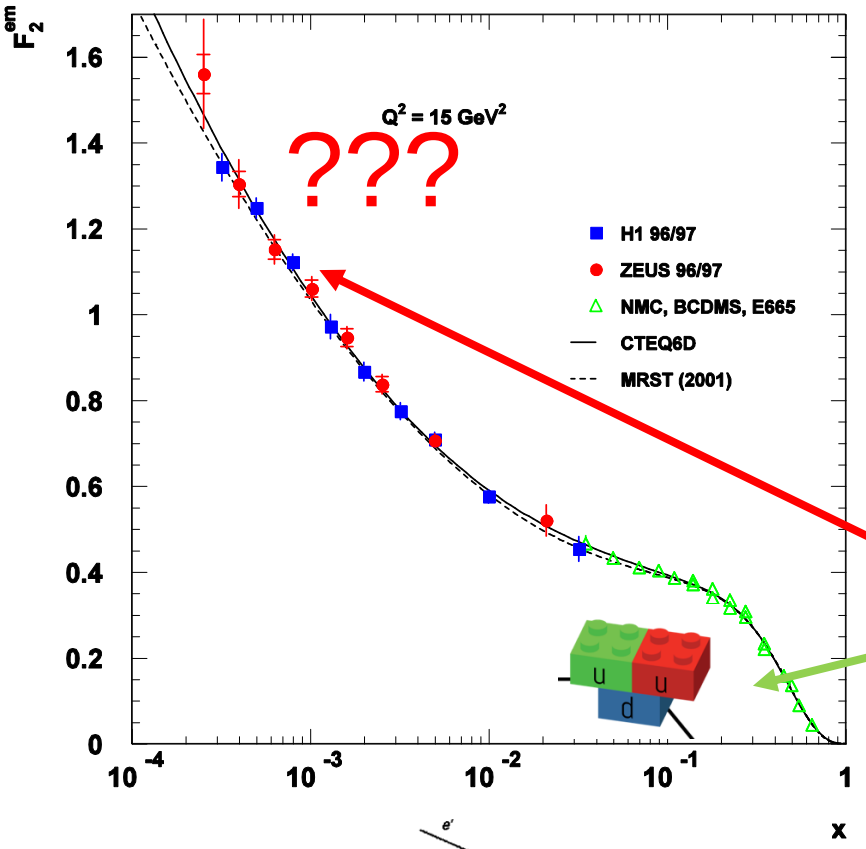


Quark orbital angular momentum extracted indirectly ($L_q = J_q - \Sigma_q$)

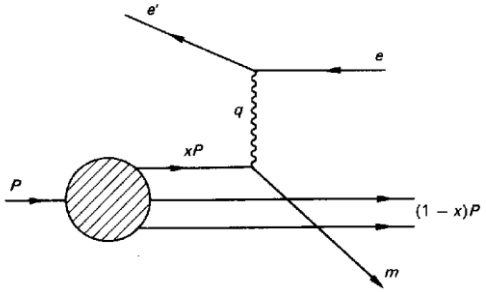
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{Q+G}$$

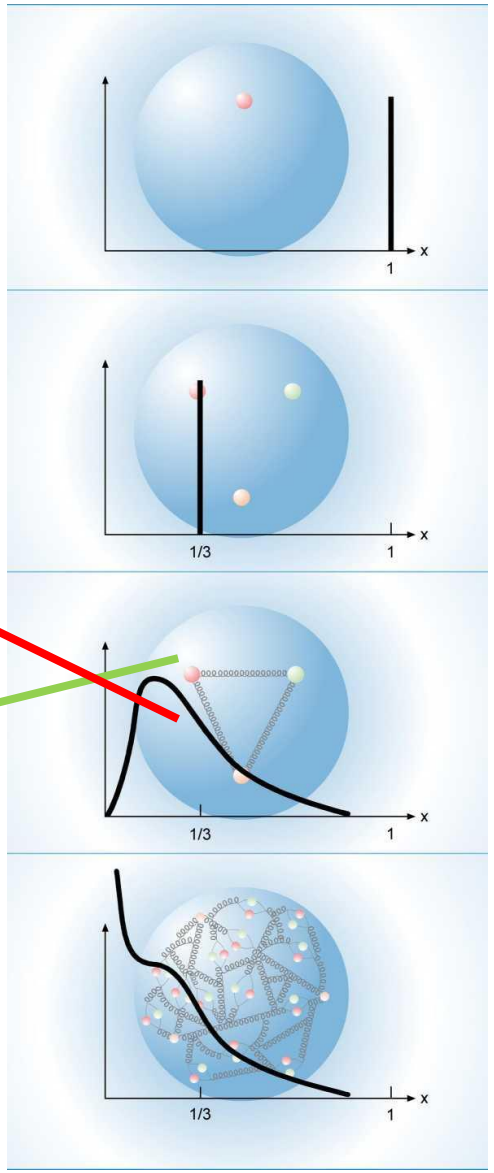
Can the origin of nucleon mass and spin be understood by its partonic structure?

質子的結構粒子動量分布



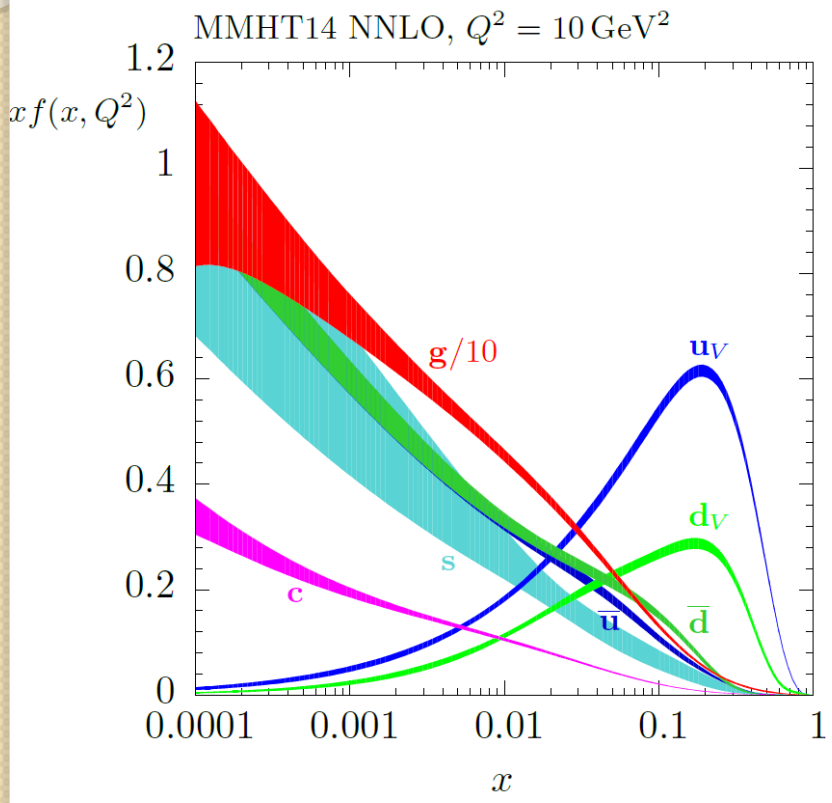
Parton model

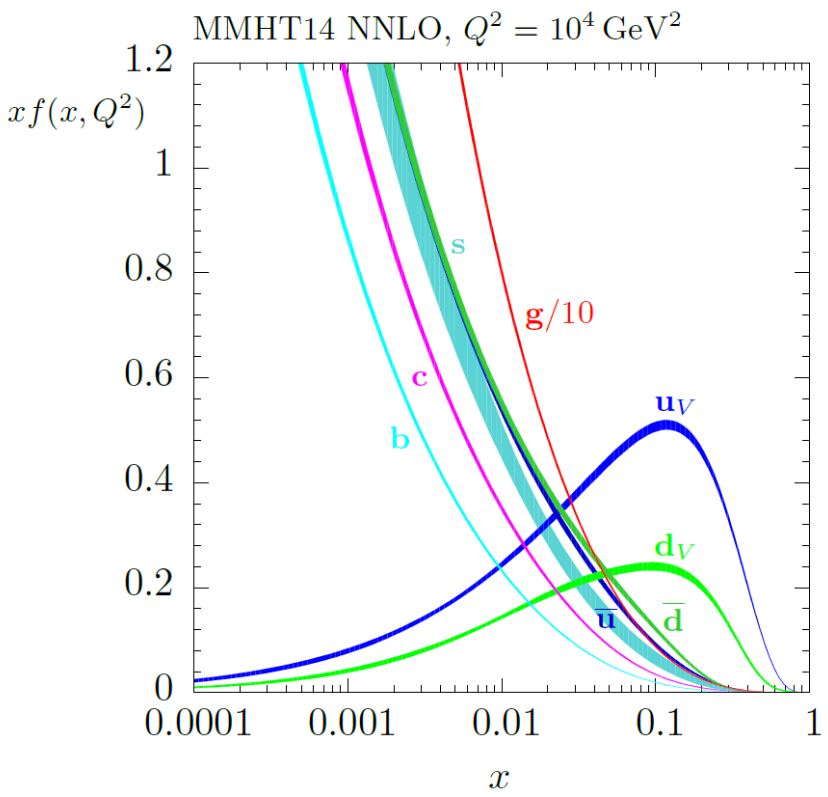




Q^2 提高解析度

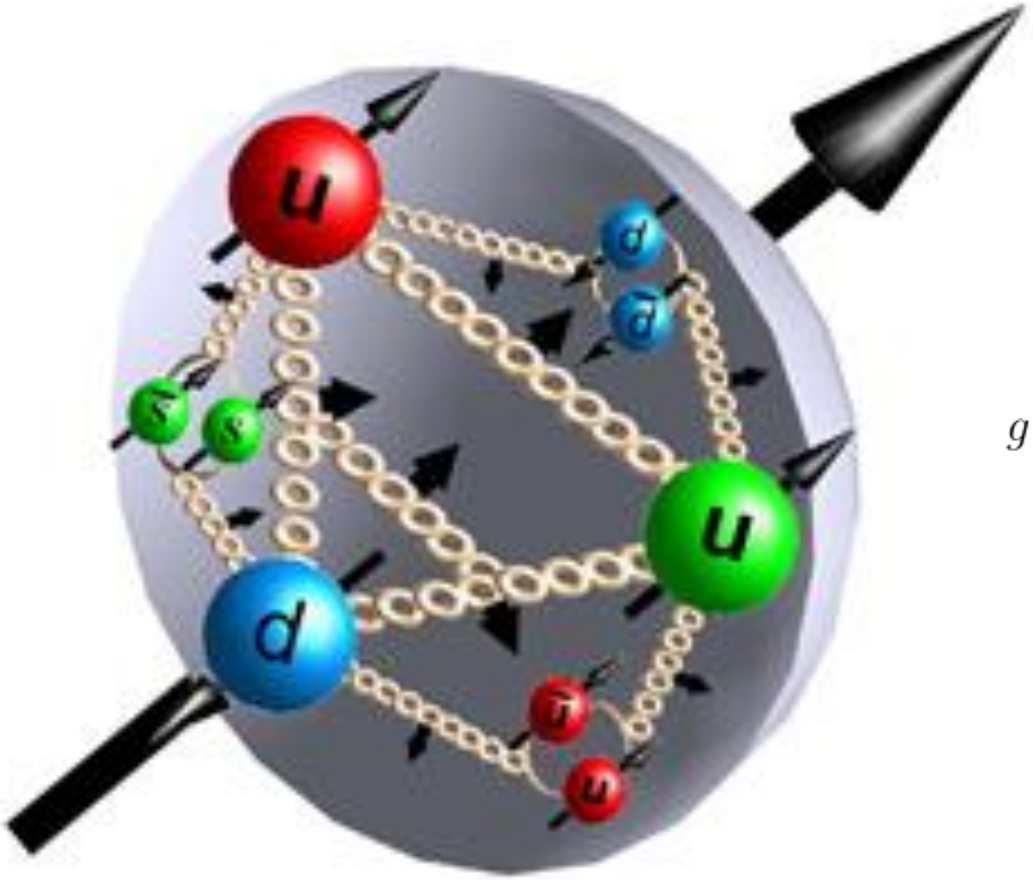
質子內部成分
Parton Distribution Function (PDF)

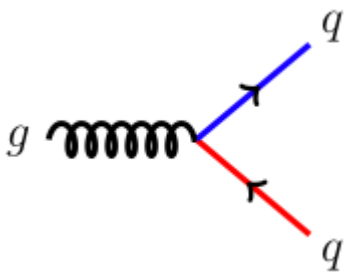




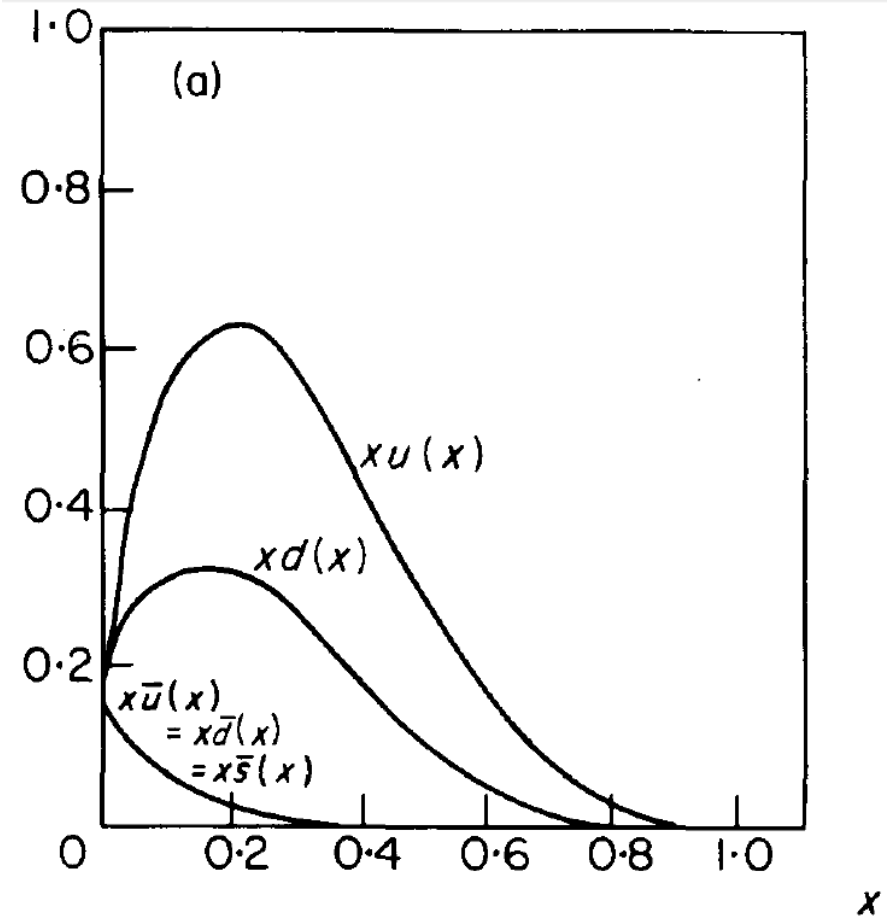
L. A. Harland-Lang, A. D. Martin, P. Motylinski, R.S. Thorne, arXiv:1412.3989

質子內部的反夸克 $(\bar{u}, \bar{d}, \bar{s}, \ldots)$



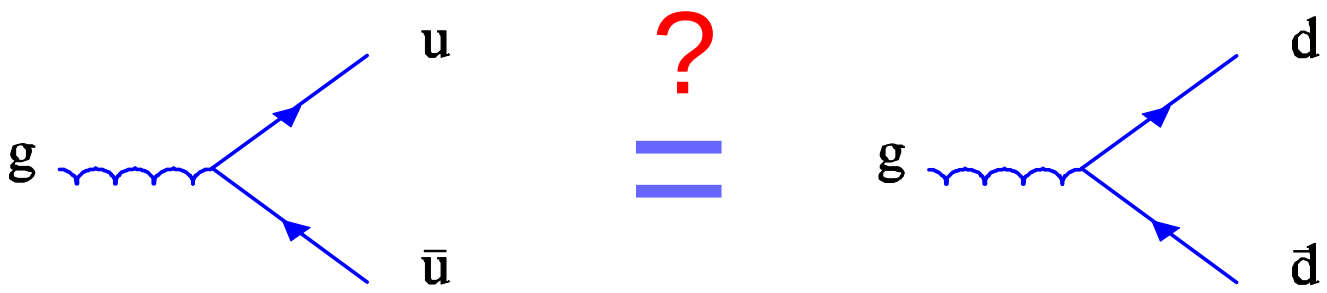


質子內部的反夸克 $(\bar{u}, \bar{d}, \bar{s}, \ldots)$



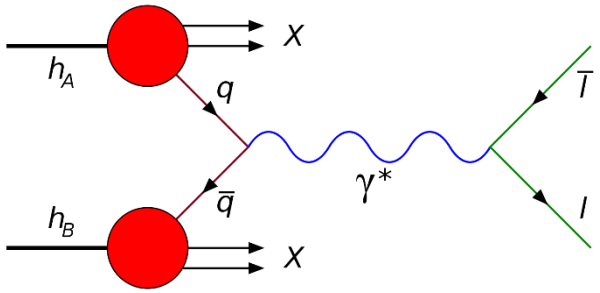
F.E. Close, “An Introduction to Quarks and Partons”

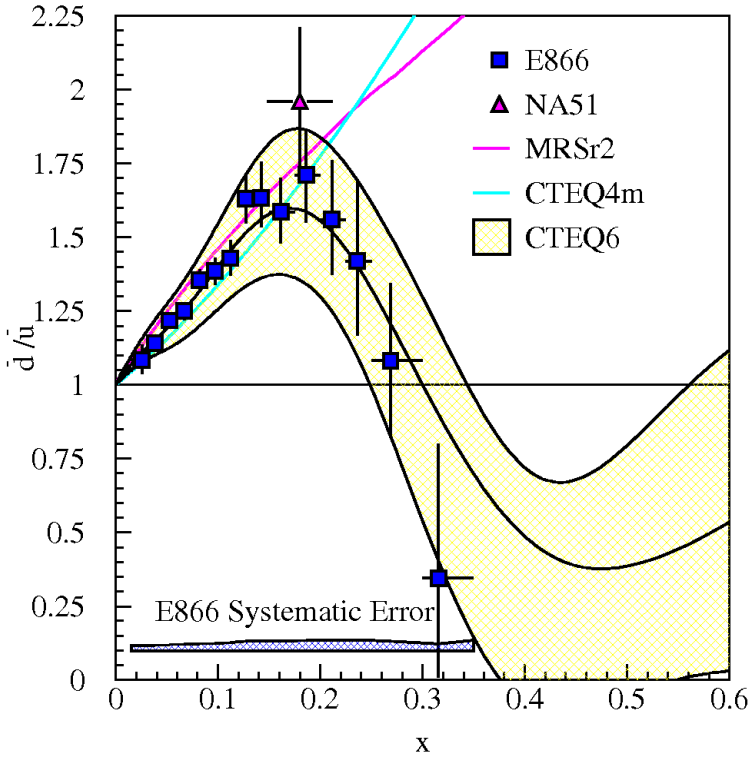
$\bar{u}$和$\bar{d}$有完全相同的分布狀態嗎？



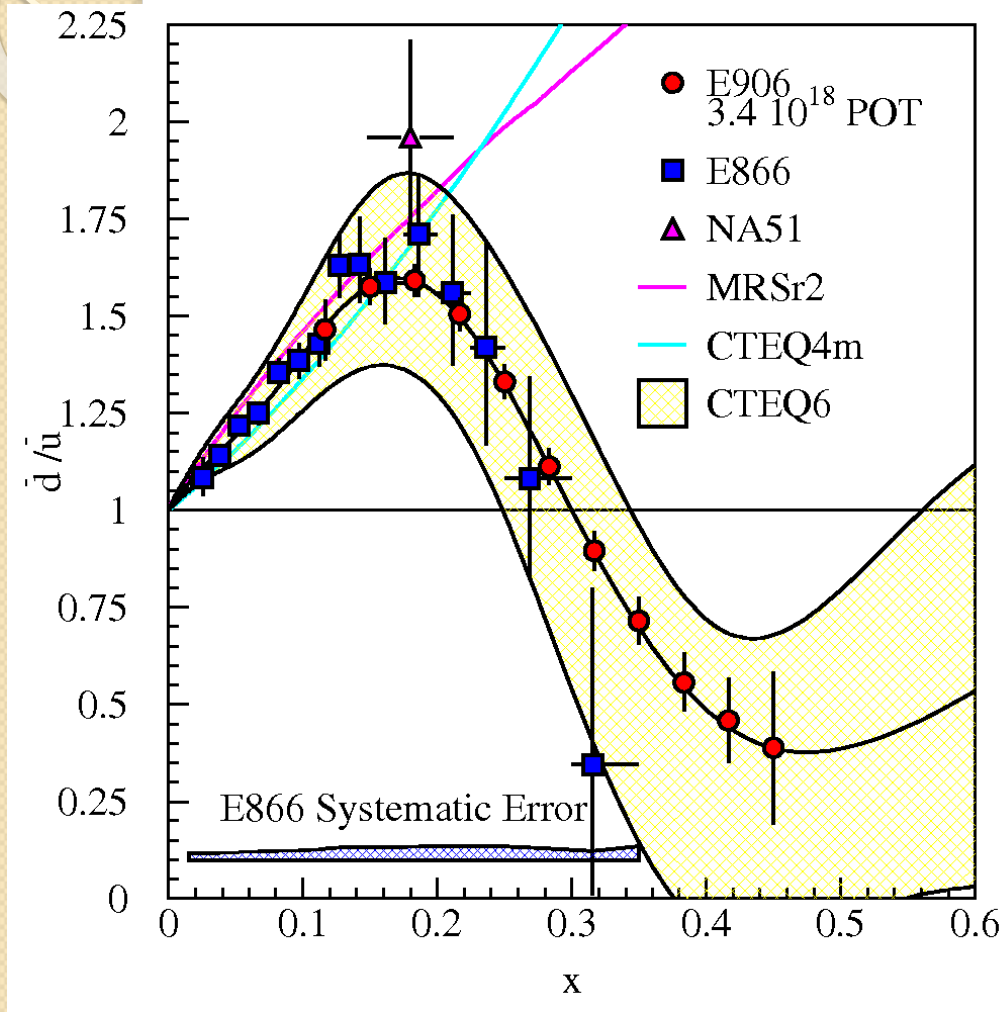
反夸克分布差異測定

- Naïve Assumption: $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule):
  $\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$
- NA51 (Drell-Yan, 1994):
  $\bar{d} > \bar{u}$ at $x = 0.18$
- E866/NuSea (Drell-Yan, 1998):
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$





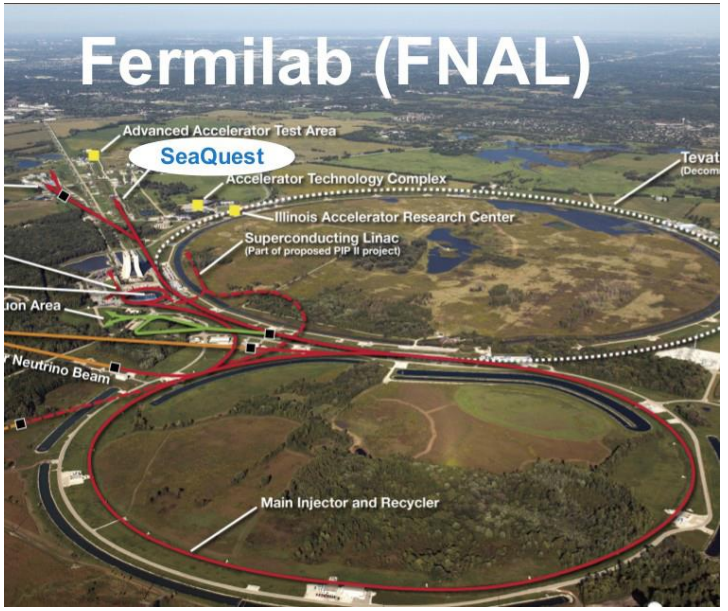
FNAL E906/SeaQuest Experiment



$(\bar{d}(x)/\bar{u}(x))$ up to $x_T \sim 0.45$

Fermilab E906

- $x_B x_T = \frac{M}{s}$; smaller s, larger x_T
- Unpolarized Drell-Yan using 120-GeV proton beam from Main Injector
- ^{1}H, ^{2}H, and nuclear targets



反夸克分布差異測定

Article

The asymmetry of antimatter in the proton

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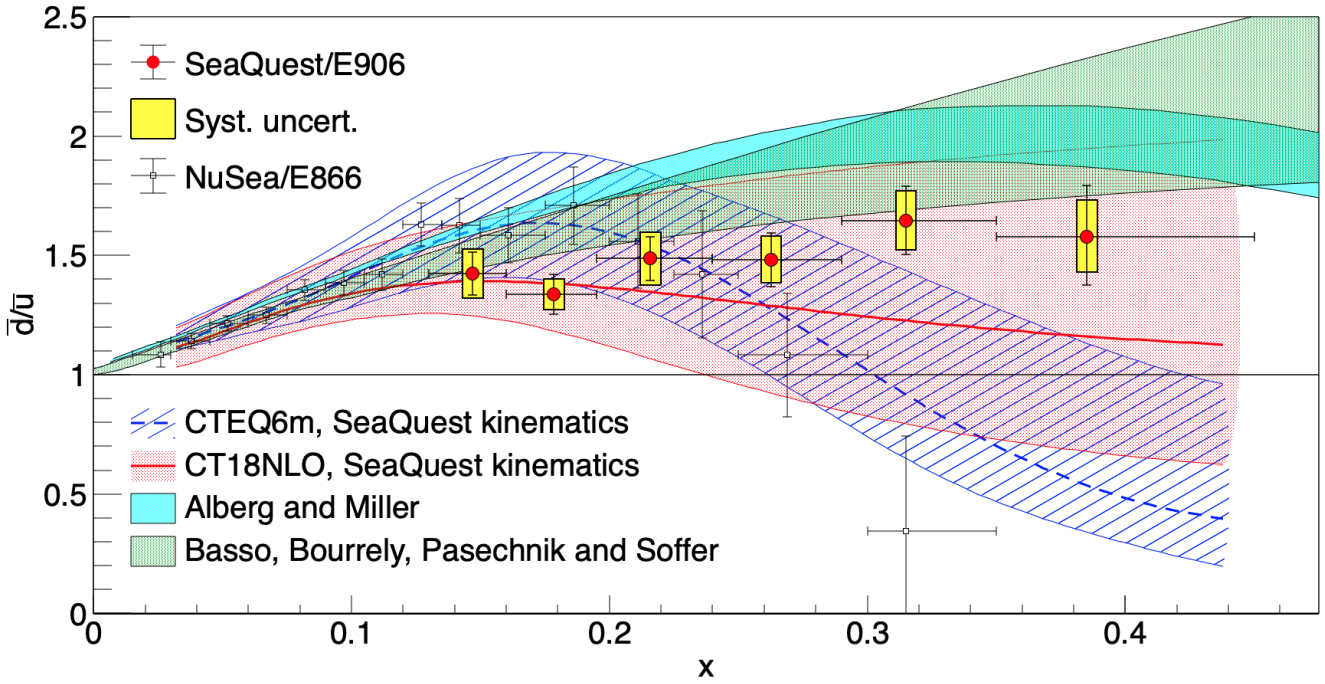
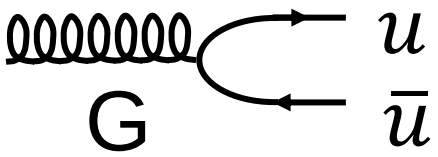
J. Dove[1], B. Kerns[1], R. E. McClellan[1,18], S. Miyasaka[2], D. H. Morton[3], K. Nagai[2,4], S. Prasad[1], F. Sanftl[2], M. B. C. Scott[3], A. S. Tadepalli[5,18], C. A. Aidala[3,6], J. Arrington[7,19], C. Ayuso[3,20], C. L. Barker[8], C. N. Brown[9], W. C. Chang[4], A. Chen[1,3,4], D. C. Christian[10], B. P. Dannowitz[1], M. Daugherity[8], M. Diefenthaler[1,18], L. El Fassi[5,11], D. F. Geesaman[7,21], R. Gilman[5], Y. Goto[12], L. Guo[6,22], R. Guo[13], T. J. Hague[8], R. J. Holt[7,23], D. Isenhower[8], E. R. Kinney[14], N. Kitts[8], A. Klein[6], D. W. Kleinjan[6], Y. Kudo[15], C. Leung[1], P.-J. Lin[14], K. Liu[6], M. X. Liu[6], W. Lorenzon[3], N. C. R. Makins[1], M. Mesquita de Medeiros[7], P. L. McGaughey[6], Y. Miyachi[15], I. Mooney[3,24], K. Nakahara[16,25], K. Nakano[2,12], S. Nara[15], J.-C. Peng[1], A. J. Puckett[6,26], B. J. Ramson[3,27], P. E. Reimer[7] ✉, J. G. Rubin[3,7], S. Sawada[17], T. Sawada[3,28], T.-A. Shibata[2,29], D. Su[4], M. Teo[1,30], B. G. Tice[7], R. S. Towell[8], S. Uemura[6,31], S. Watson[8], S. G. Wang[4,13,32], A. B. Wickes[6], J. Wu[10], Z. Xi[8] & Z. Ye[7]

The fundamental building blocks of the proton—quarks and gluons—have been known for decades. However, we still have an incomplete theoretical and

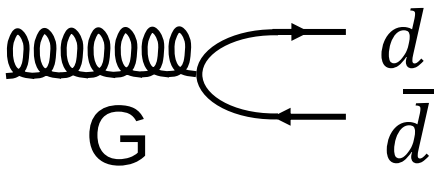
Nature 590, 561–565 (2021)

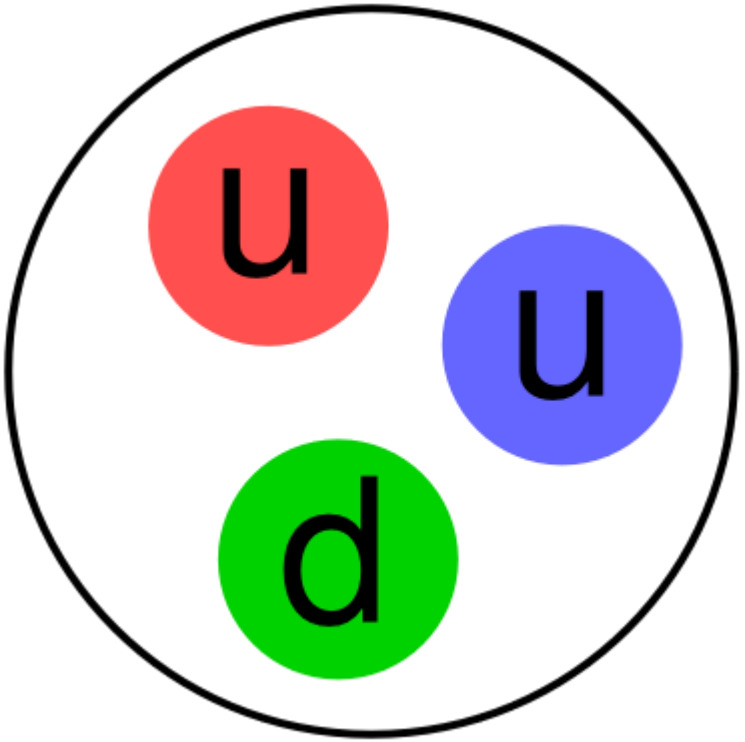


為何 $\bar{u}(x) \neq \bar{d}(x)$？價夸克影響



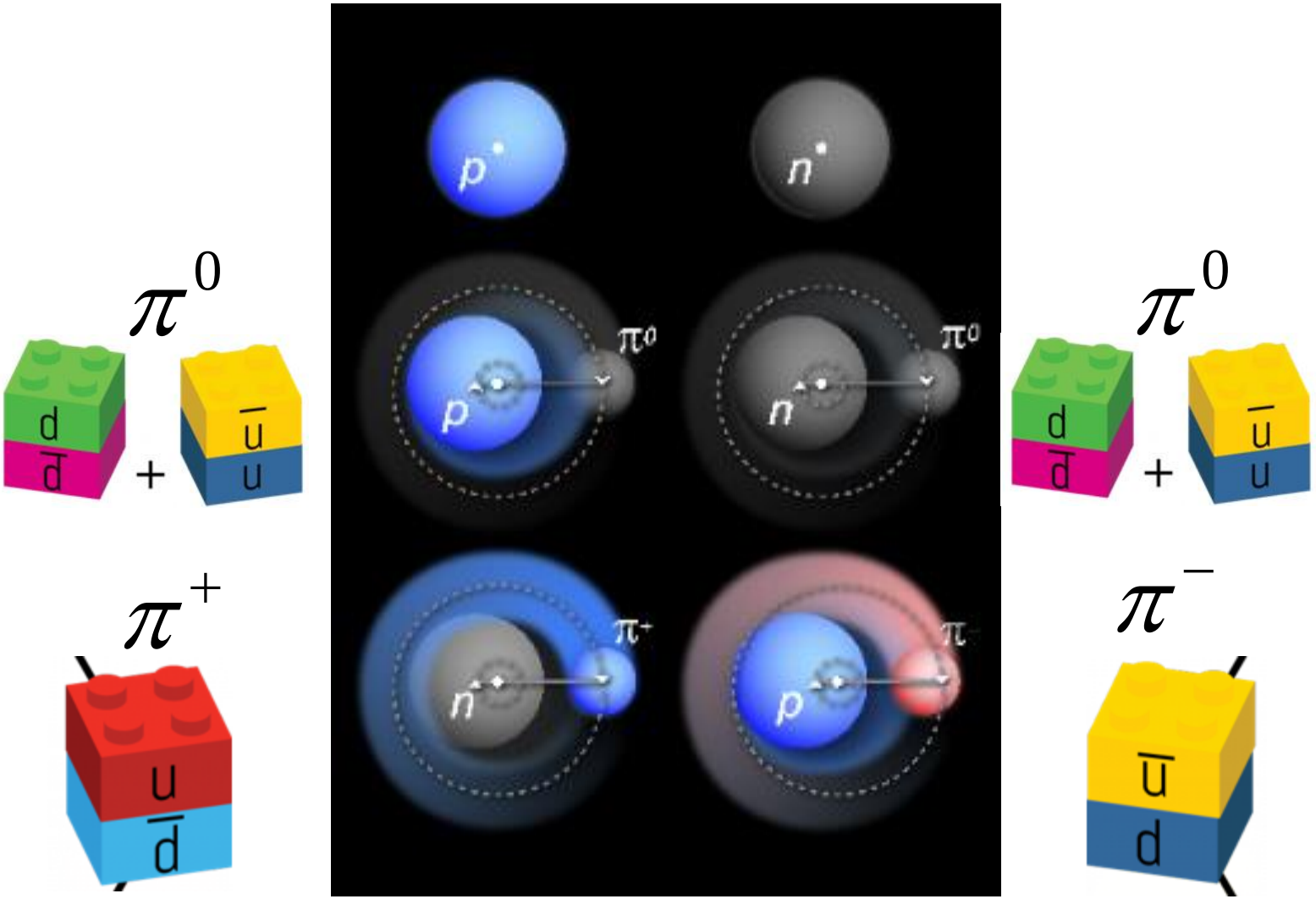
庖立不相容效應



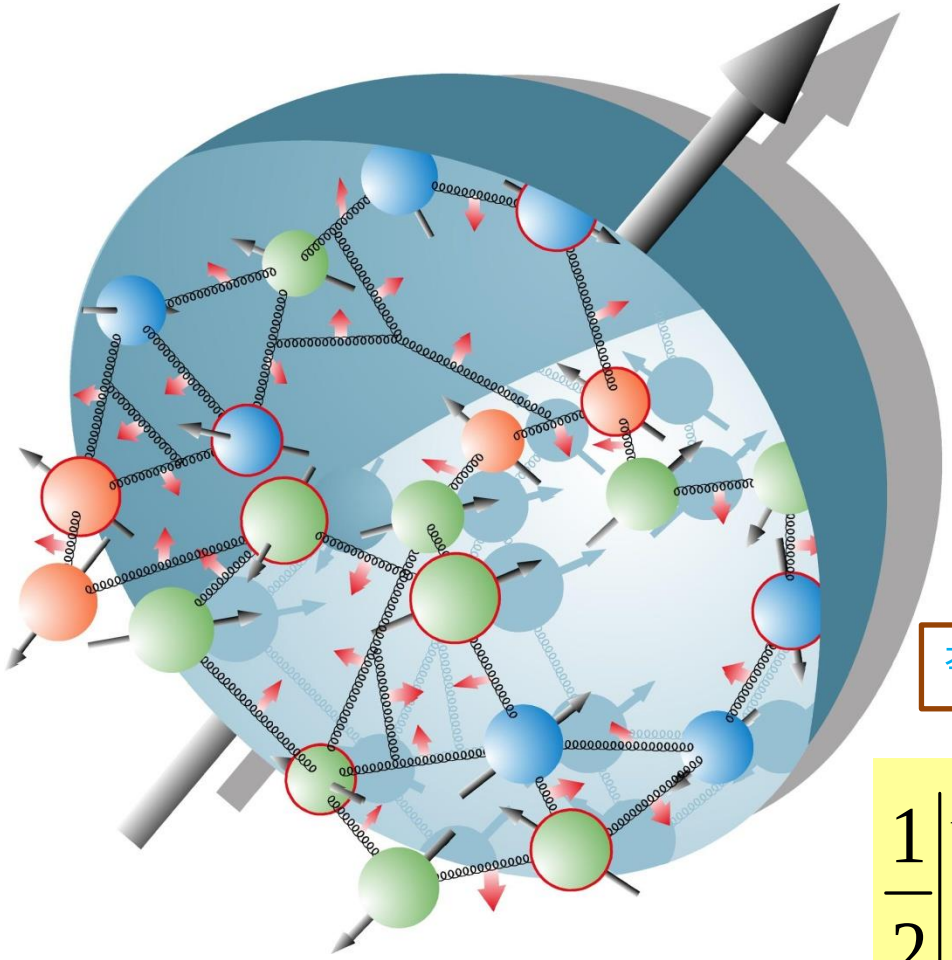


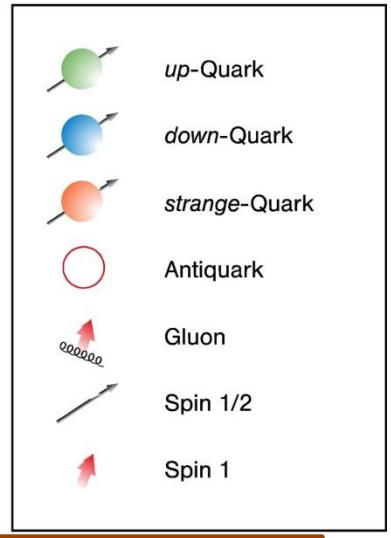
為何 $\bar{u}(x) \neq \bar{d}(x)$？介子雲

$$p \to N\pi;\ \pi^+ : \pi^0 : \pi^- = 2:1:0$$



質子自旋(s=1/2)





夸克自旋(~30%)

膠子自旋(~0)

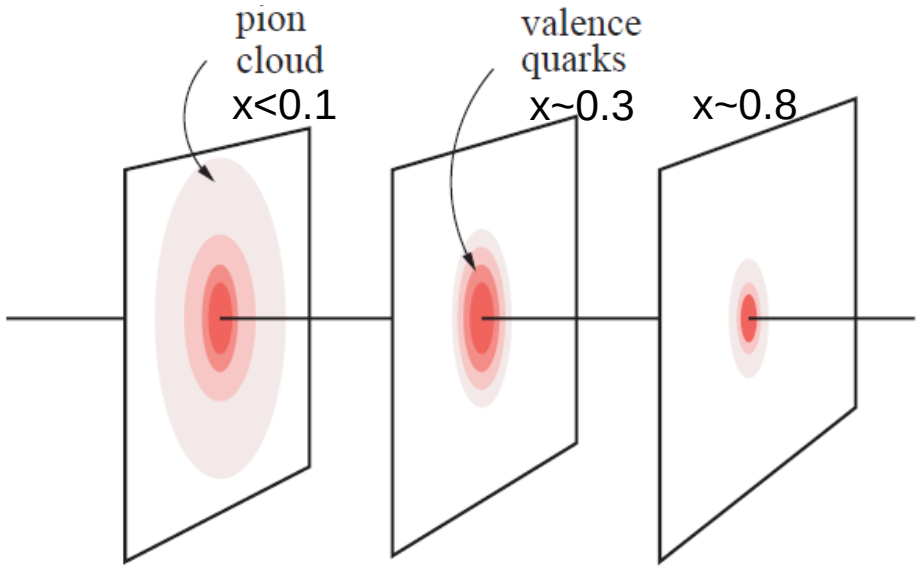
$$\frac{1}{2}\Big|^{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q$$

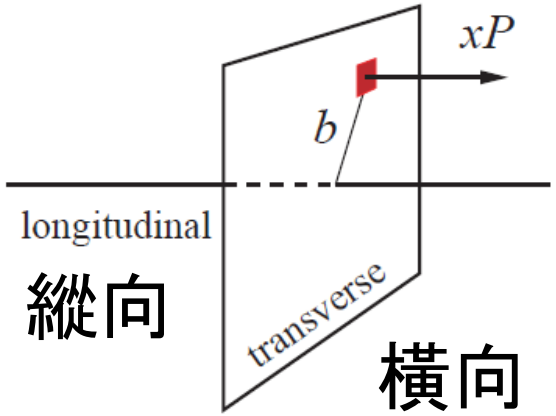
軌道角動量

$$\overrightarrow{L_Z} = \overrightarrow{r_T} \times \overrightarrow{P_T}$$

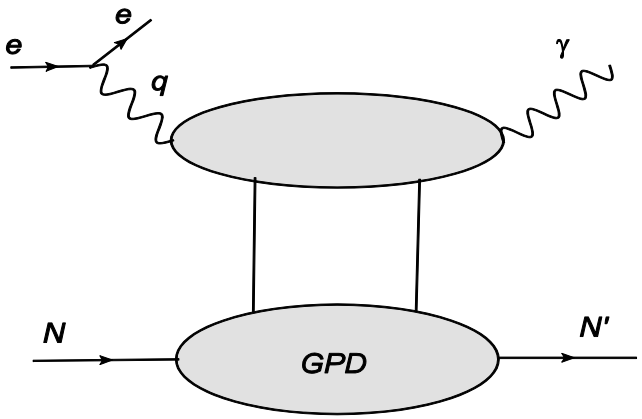
質子構成粒子的橫向位置分布 $\vec{r_T}$

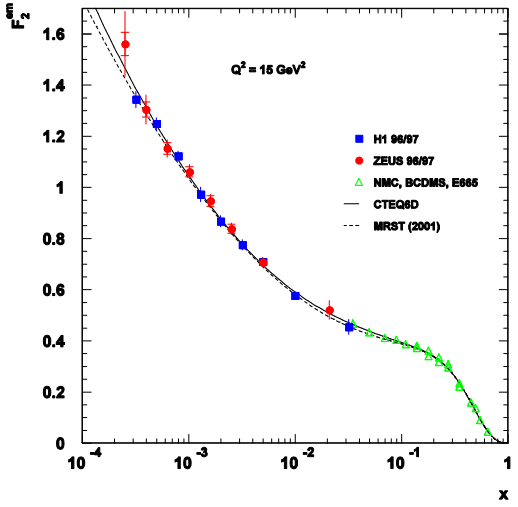
介子雲　價夸克



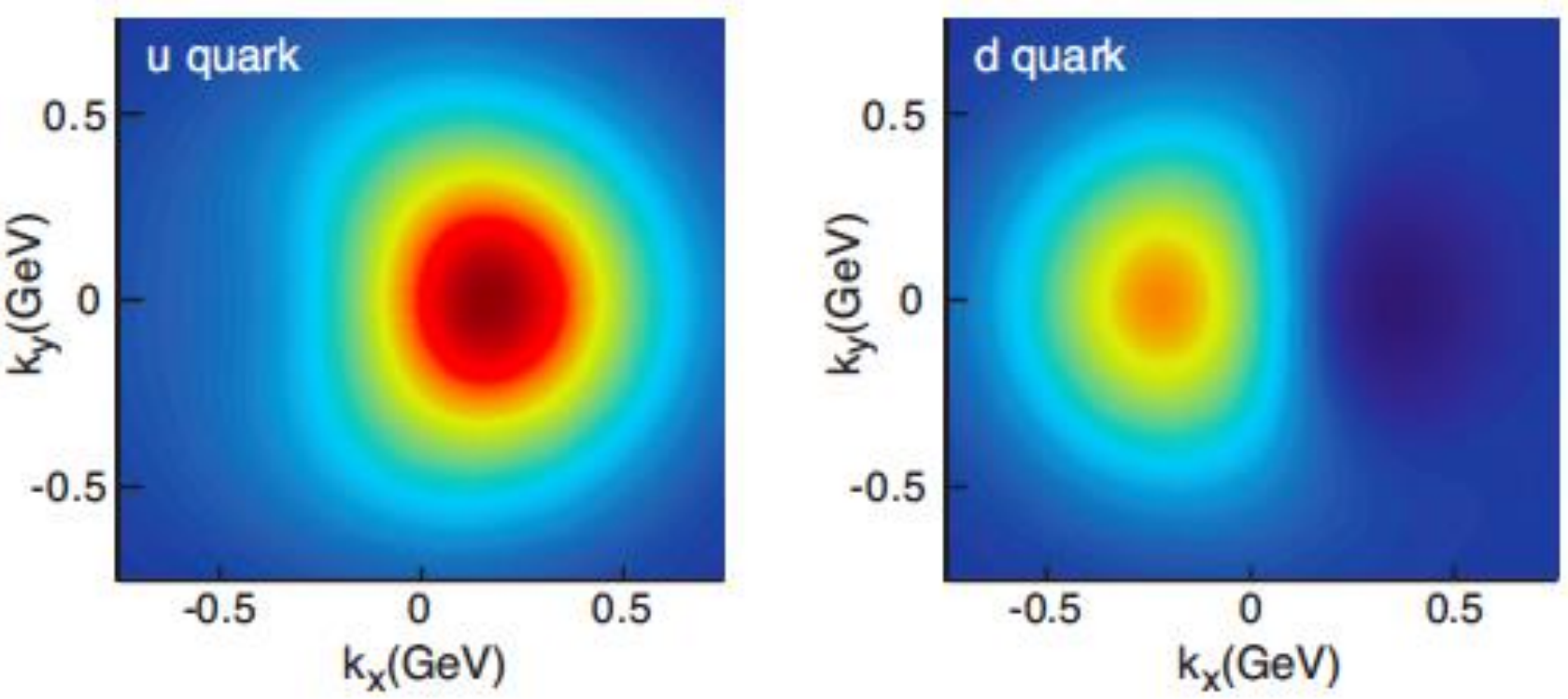


Deeply Virtual Compton Scattering



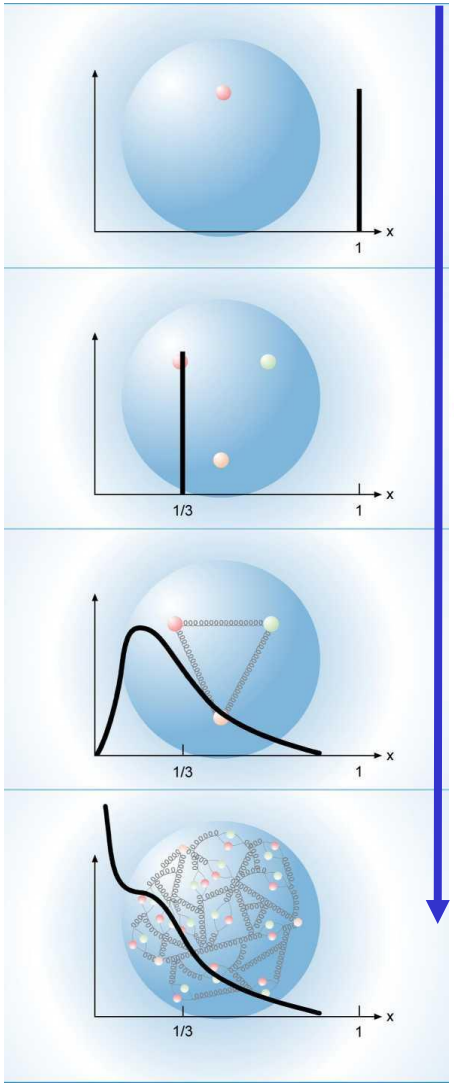


質子構成粒子的橫向動量分布 $\overrightarrow{P_T}$



橫向極化靶實驗

質子構成粒子的多維度分布



Wigner Distributions

$f(x,k_\perp)$

$W(x, k_\perp, r_\perp)$

$f(x,\xi,t)$

Transverse Momentum Dependent Distributions (TMDs)

Generalized Parton Distributions (GPDs)

$d^2r_\perp$

$d^2k_\perp$

Q^2

$\delta z_\perp \sim 1/Q$

$d^2k_\perp$

$d^2r_\perp$

dx

Parton Distribution Functions

$f(x)$

Form Factors

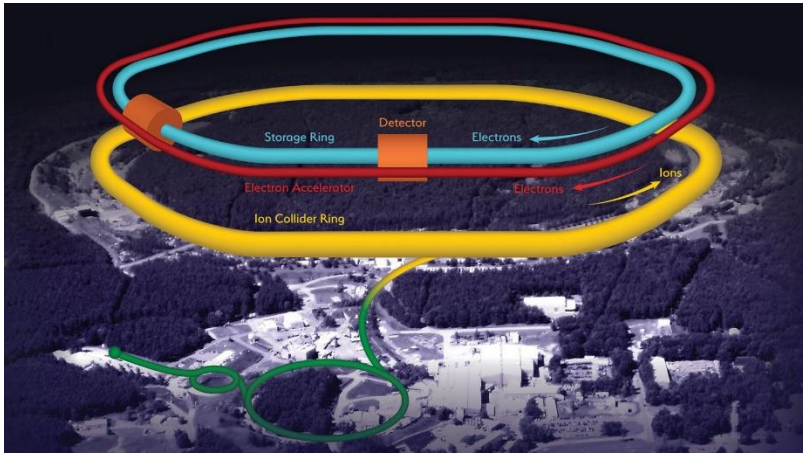
$F_{1,2}(t)$

http://www.int.washington.edu/PROGRAMS/17-3/

Electron-Ion Collider @ Taiwan

- 6 institutes (AS, NCU, NCKU, NTU, NTHU, NSYSU) in Taiwan have the consensus to form a strong team to participate the EIC in the coming future
- Mainly focus on physics, silicon-based detector (sensor development and mechanical structure design)

EOI for the **ECCE** Collaboration (2021)



NTU

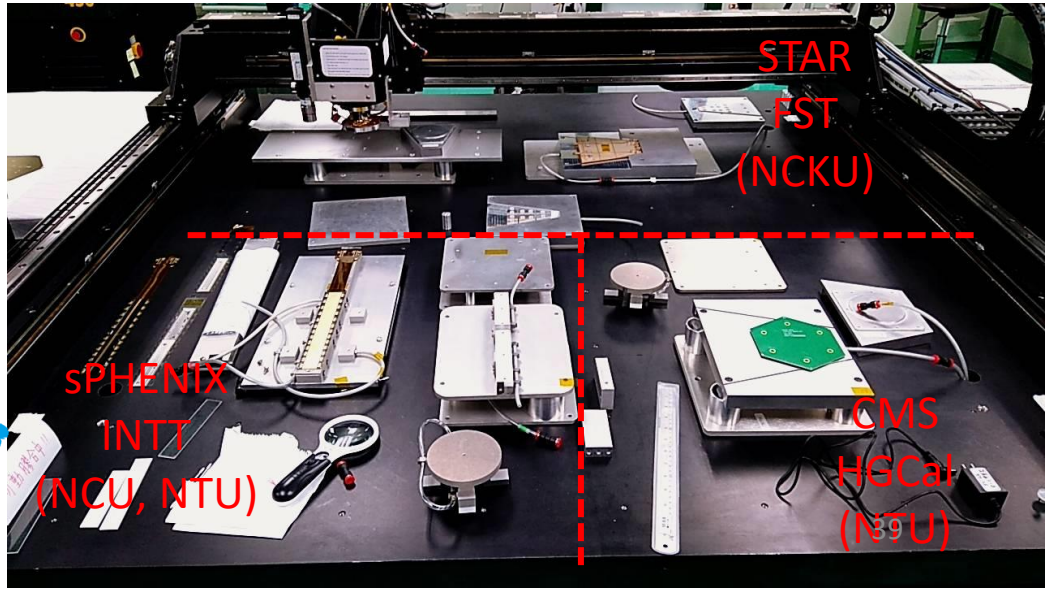
AS

NCU

NTHU

NCKU

NSYSU



結論

- 高能物理是基礎科學的前沿，透過探索最小尺度下基本構成粒子和作用方式，期盼達到「化繁為簡」。
- 質子是一個夸克系統；它的內部除了夸克外，還有豐富多樣的膠子和反夸克成分。由於質子自旋的問題，我們對於質子結構粒子分布的認識，正從"一維"進入"多維"。
- 高能物理仍有許多未解之謎，我們相信這會是一趟「驚奇之旅」，歡迎加入！

台灣高能實驗團隊

- 台大物理：LHC CMS, 大亞灣微中子, KEK Belle-II
- 中央物理：LHC CMS, sPHENIX
- 交大物理：大亞灣微中子
- 清華物理：LHC ATLAS
- 成大物理：RHIC STAR, AMS
- 中研院物理所：LHC ATLAS, AMS, 台灣微中子,CERN COMPASS, J-PARC, KGARA & LIGO