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24 -30 August 2023

Strong Interactions in Historical Perspective: From Nuclear Structure to Multiquarks

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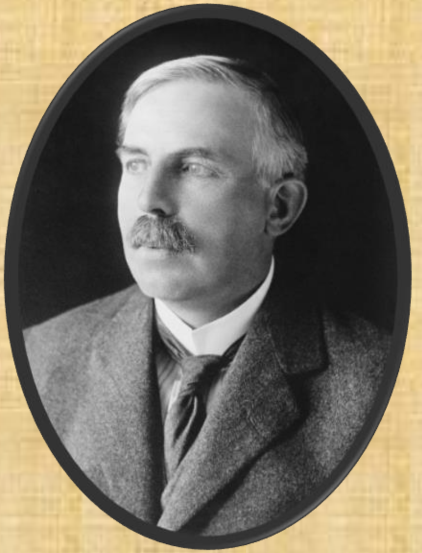
LOGUNOV Institute for High Energy Physics,

Prautvinault, RF

Prehistory: 1920



Bakerian Lecture: *Nuclear Constitution of Atoms.*

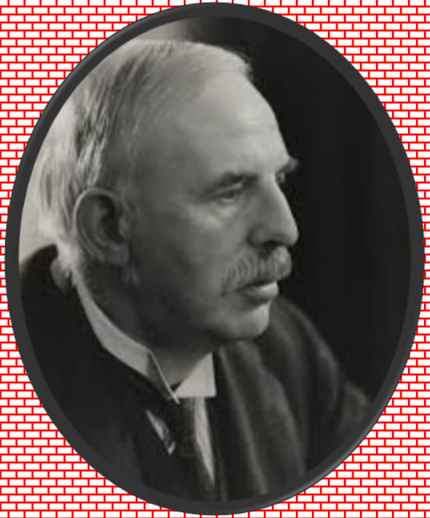
By Sir E. Rutherford, F.R.S., Cavendish Professor of Experimental Physics, University of Cambridge.

(Received June 3,—Lecture delivered June 3, 1920.)

Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope, and it may be impossible to contain it in a sealed vessel. On the other hand, it should enter readily the structure of atoms, and may either unite with the nucleus or be disintegrated by its intense field, resulting possibly in the escape of a charged H atom or an electron or both.

Prehistory: 1913

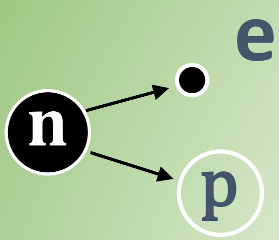
CHEMISTRY AND INDUSTRY Sept. 14, 1923

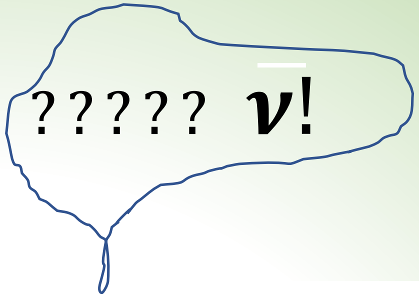


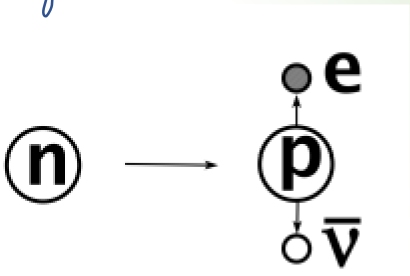
THE ELECTRICAL STRUCTURE OF MATTER
By Prof. SIR ERNEST RUTHERFORD

While it is known that the law of the inverse square holds for the electrical forces some distance from the nucleus, it seems certain that this law breaks down inside the nucleus. A detailed study of the collisions between α particles and hydrogen atoms, where the nuclei approach very close to each other, shows that the forces between nuclei increase ultimately much more rapidly than is to be expected from the law of the inverse square, and it may be that new and unexpected forces may come into importance at the very small distances separating the protons and electrons in the nucleus. Until we gain more information on the nature and law of variation of the forces inside the nucleus, further progress on the detailed structure of the nucleus may be difficult. At the same

While we may be confident that the proton and the electron are the ultimate units which take part in the building up of all nuclei, and can deduce with some certainty the number of protons and electrons in the nuclei of all atoms, we have little, if any, information on the distribution of these units in the atom or on the nature of the forces that hold them in equilibrium.



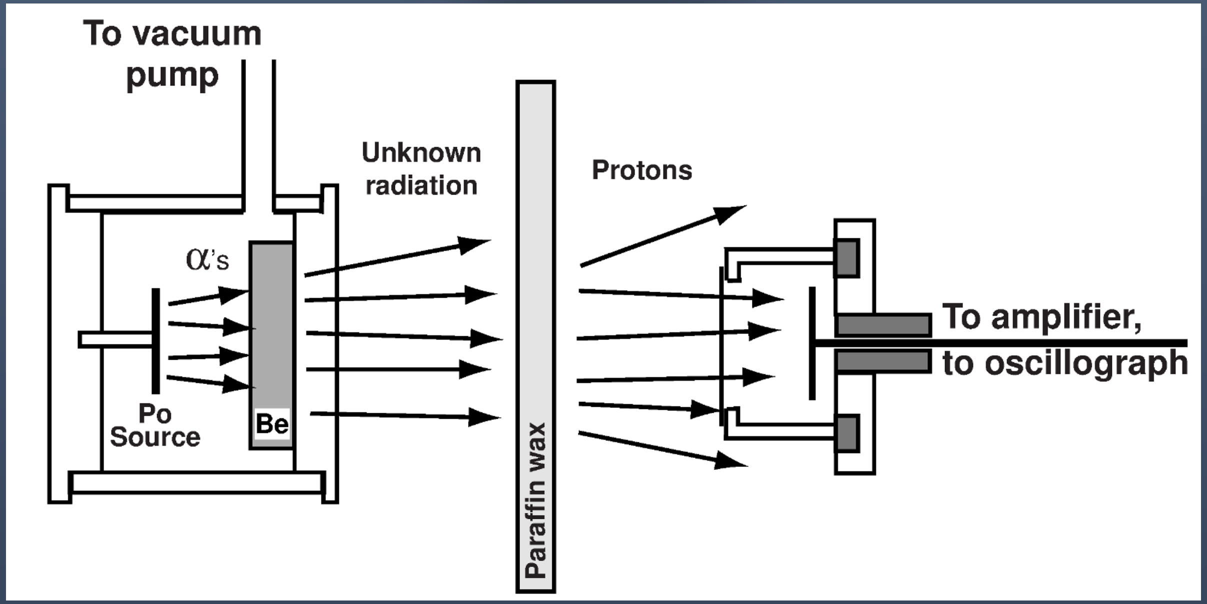




Namely the possibility that electrically neutral particles, which I would like to call neutrons, might exist inside nuclei; these would have spin ½, would obey the exclusion principle

The mass of the neutron ought to be about the same order of magnitude as the electron mass,

…..Now, the question is, what forces act on the neutron?


To vacuum
pump
Unknown
radiation
Protons
α's
Po
Source
Be
Paraffin wax
To amplifier,
to oscillograph

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.

Über den Bau der Atomkerne. I.

Von **W. Heisenberg** in Leipzig.

Mit 1 Abbildung. (Eingegangen am 7. Juni 1932.)

Dieses Ergebnis legt die Annahme nahe, die Atomkerne seien aus Protonen und Neutronen ohne Mitwirkung von Elektronen aufgebaut[3]). Ist diese

[2]) J. Chadwick, Nature **129**, 312, 1932.
[3]) Vgl. auch D. Iwanenko, ebenda S. 798.

Um nun die Hamiltonfunktion des Atomkerns aufzuschreiben, erweisen sich folgende Variablen als zweckmäßig: Jedes Teilchen im Kern wird charakterisiert durch fünf Größen, die drei Ortskoordinaten $(x, y, z) = \mathfrak{r}$, den Spin σ^z in der z-Richtung und durch eine fünfte Zahl ϱ^ζ, die der beiden

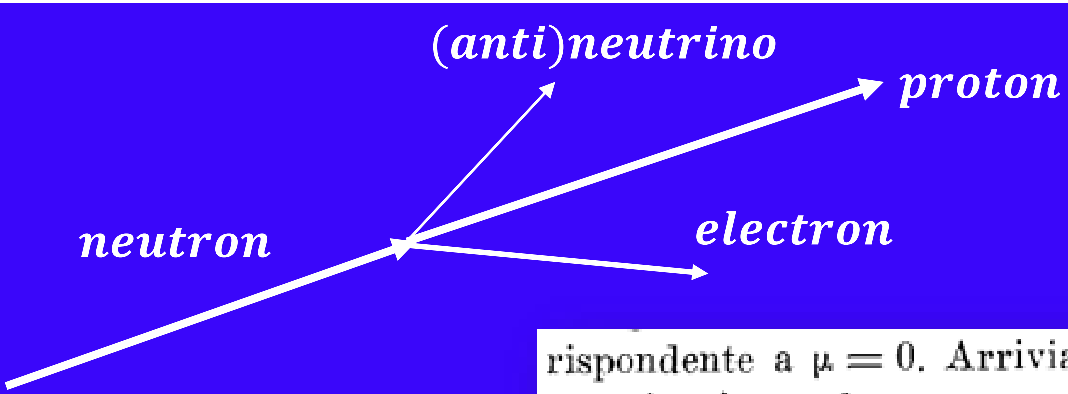
Werte $+1$ und -1 fähig ist. $\varrho^\zeta = +1$ soll bedeuten, das Teilchen sei ein Neutron, $\varrho^\zeta = -1$ bedeutet, das Teilchen sei ein Proton. Da in der

TENTATIVO DI UNA TEORIA DEI RAGGI β

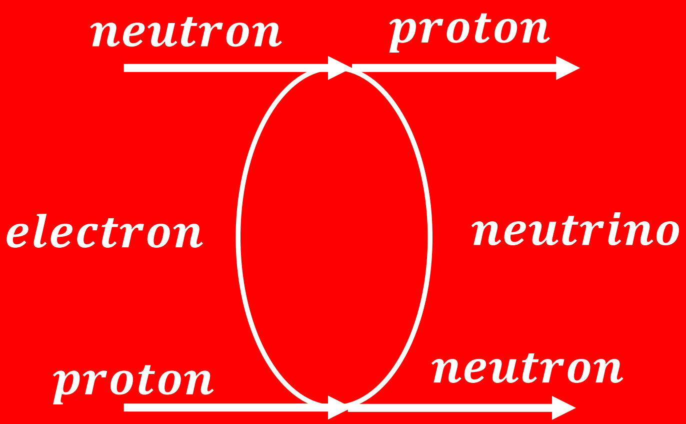
Nota [1] di Enrico Fermi

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.*

January 1934



rispondente a $\mu = 0$. Arriviamo così a concludere che la massa del neutrino è uguale a zero o, in ogni caso, piccola in confronto della massa dell'elettrone [1]. Nei calcoli che seguono porremo per semplicità $\mu = 0$.



Exchange Forces between Neutrons and Protons, and Fermi's Theory

IG. TAMM.

Physical Research Institute,
State University,
Moscow.

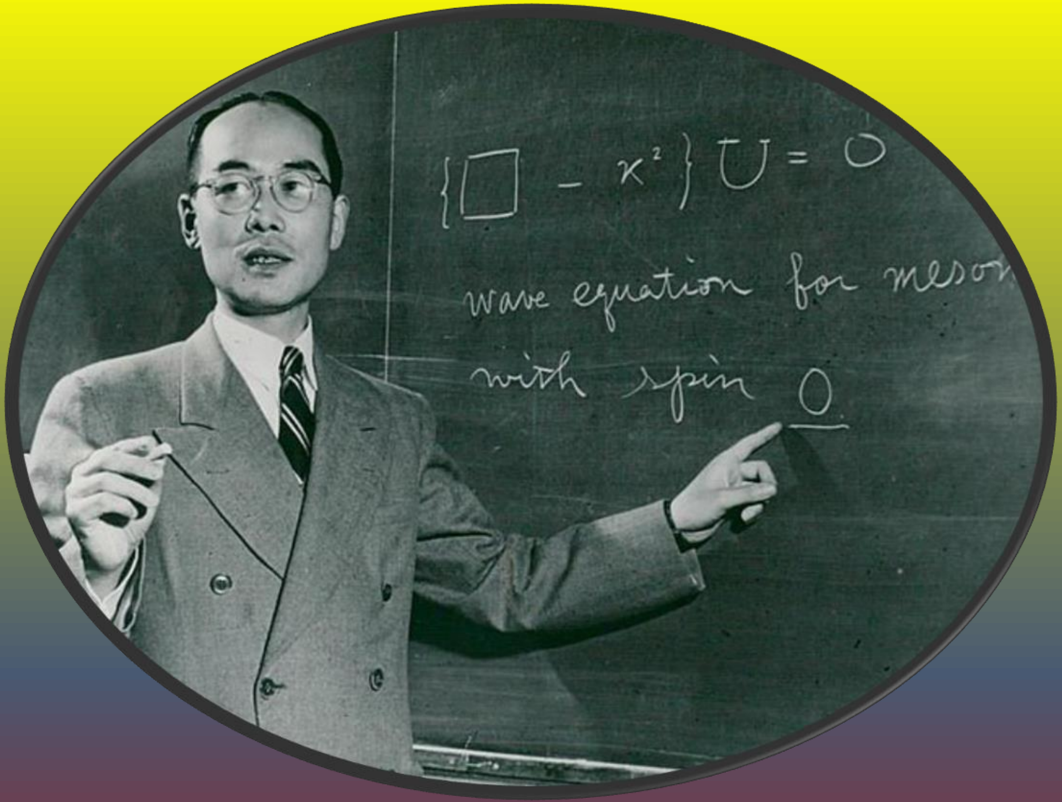
[1] Fermi, *Z. Phys.*, **88**, 161 ; 1934.
[2] Wick, *Rend. R. Nat. Acad. Lincei*, **19**, 319 ; 1934.

Interaction of Neutrons and Protons

D. IWANENKO.

Physical-Technical Institute,
Leningrad.

[1] cf. D. Iwanenko, *C.R. Ac. Sci. U.S.S.R.*, Leningrad, **2**, No. 9, 1934.



On the Interaction of Elementary Particles. I.

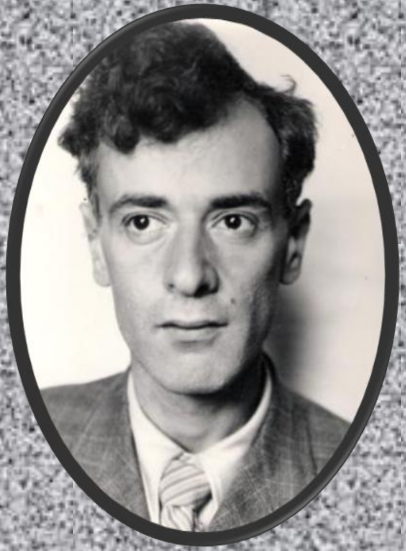
By Hideki YUKAWA.

(Read Nov. 17, 1934)

(3) Ig. Tamm, Nature **133**, 981 (1934); D. Iwanenko, ibid. 981 (1934).

$$g^2 \frac{e^{-\lambda r}}{r}$$

20 years of painful field-theoretical searches: perturbative, strong coupling, Tamm-Dankov etc...

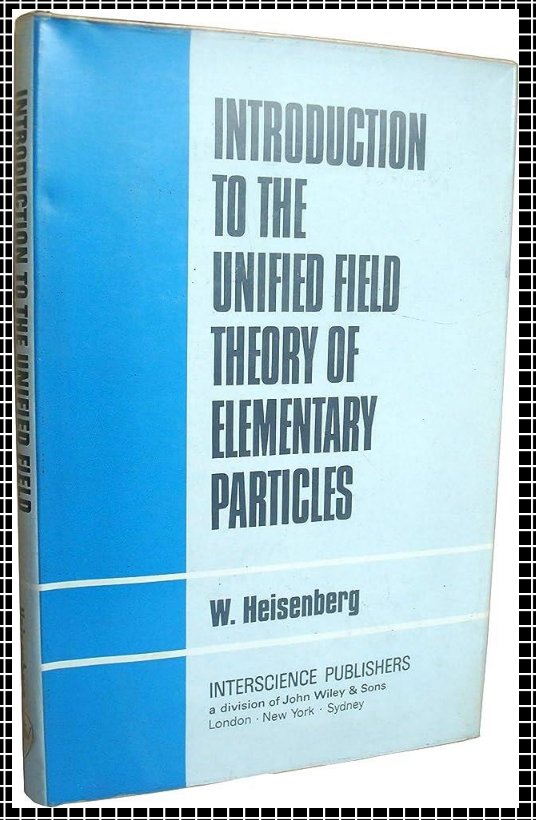


The ψ operators which contain unobservable information must disappear from the theory and, since a Hamiltonian can be built only from ψ operators, we are driven to the conclusion that **the Hamiltonian method for strong interaction is dead and must be buried, although of course with deserved honour... (1959)**

...on the basis of approximations, it is dangerous to make any conclusions about the situation taking place in the exact problem (1959)

«Old-believers»...

$$i\sigma^{\nu}\frac{\partial\chi(x)}{\partial x^{\nu}}+l^{2}\sigma^{\nu}:\chi(x)(\chi^{*}(x)\sigma_{\nu}\,\chi(x)):=0$$

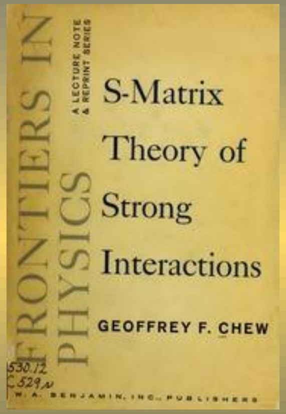


We are all agreed that your theory is crazy. The question which divides us is whether it is crazy enough to have a chance of being correct.

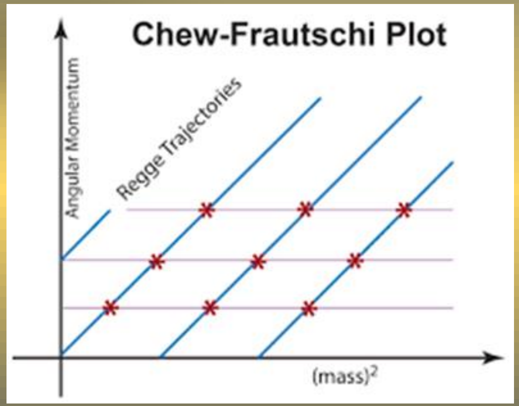
New age: Analytic S-matrix & Regge Revolution

Prelude/ Intermezzo: Regge poles (1959)

Adaptation to relativistic case (1961)

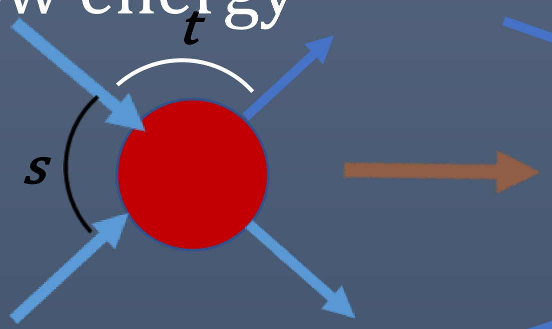


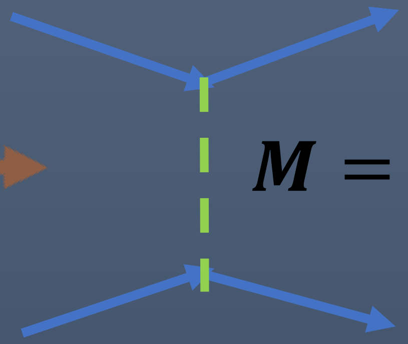
Nuclear Democracy:
no hadron is more elementary than any other!



From the "Yukawa paradigm" to the "Regge paradigm"

Low energy





$M = \pi, \rho, \omega, f, \ldots .$

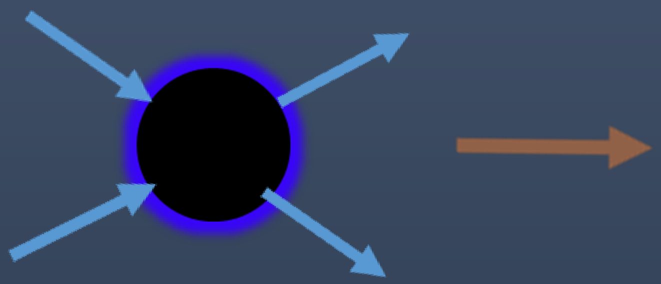
$$\frac{g_{\pi NN}^2}{4\pi} = 14.2 \leftrightarrow \frac{e^2}{4\pi} = 7.3 \cdot 10^{-3}$$

$$A_J(s,t) = g_J^2 \frac{s^J}{M_J^2 - t}$$

$$\rightarrow V(r) = \pm g_J^2 \frac{s^{J-1} e^{-M_J r}}{4\pi r}$$

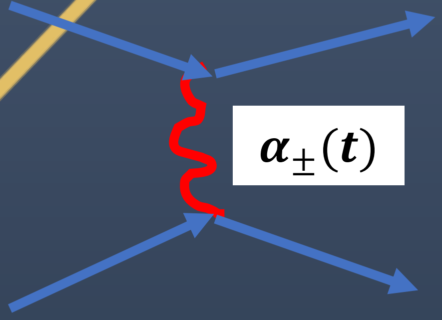
$\langle r \rangle \sim 1/M_J$

High energy



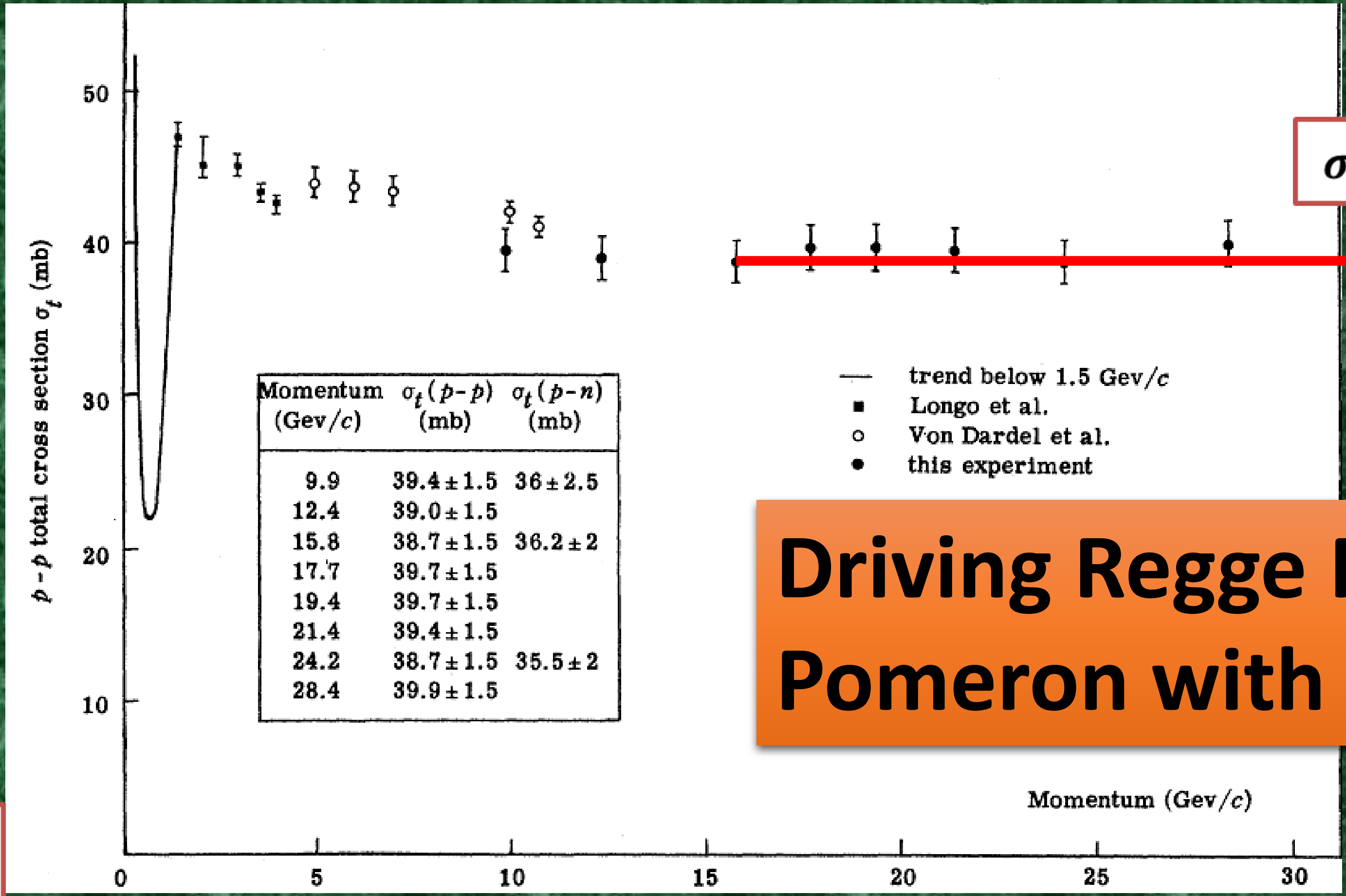
$-t(IR) \ll s(UV)$

$\sum_J A_J(s,t) \rightarrow \pm s^{\alpha_\pm(t)}$ (L. Van Hove)



$\alpha(M_J^2) = J \qquad \langle r \rangle \sim \sqrt{\alpha' \ln s}$

Experiment: Prehistory (1953-70)



Momentum (Gev/c)	$\sigma_t(p-p)$ (mb)	$\sigma_t(p-n)$ (mb)
9.9	39.4 ± 1.5	36 ± 2.5
12.4	39.0 ± 1.5	
15.8	38.7 ± 1.5	36.2 ± 2
17.7	39.7 ± 1.5	
19.4	39.7 ± 1.5	
21.4	39.4 ± 1.5	
24.2	38.7 ± 1.5	35.5 ± 2
28.4	39.9 ± 1.5	

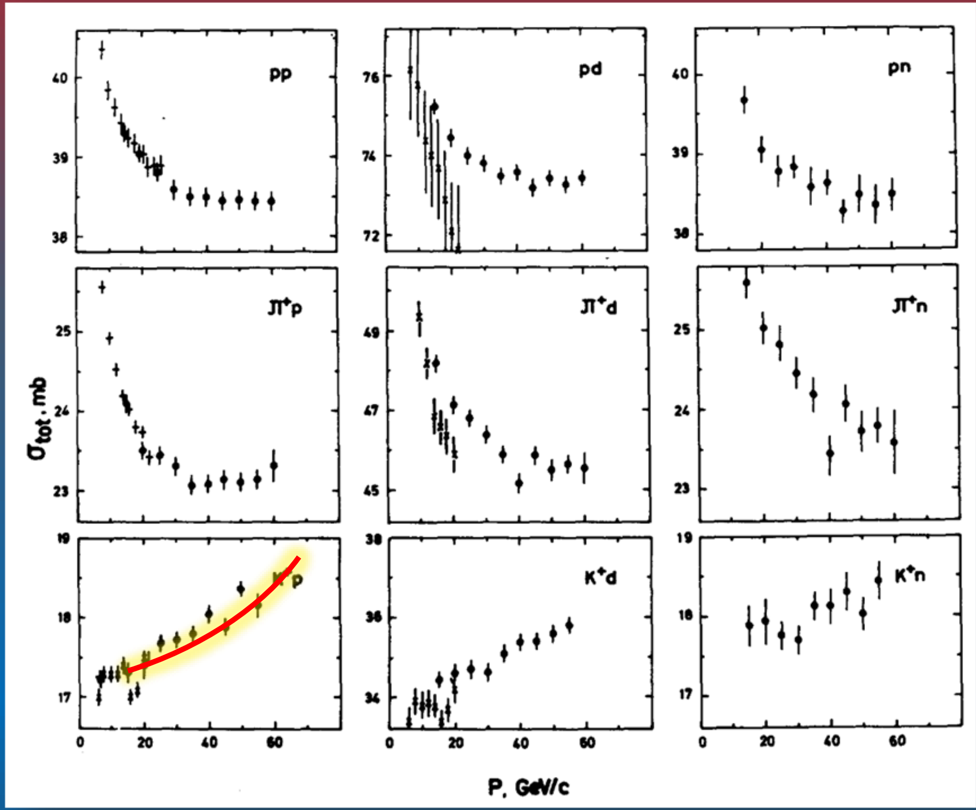
$$\sigma_{\bar{A}B}^{tot} - \sigma_{AB}^{tot} \to 0, \qquad E \to \infty$$

?

Driving Regge Pole:
Pomeron with $\alpha_P(0) = 1$

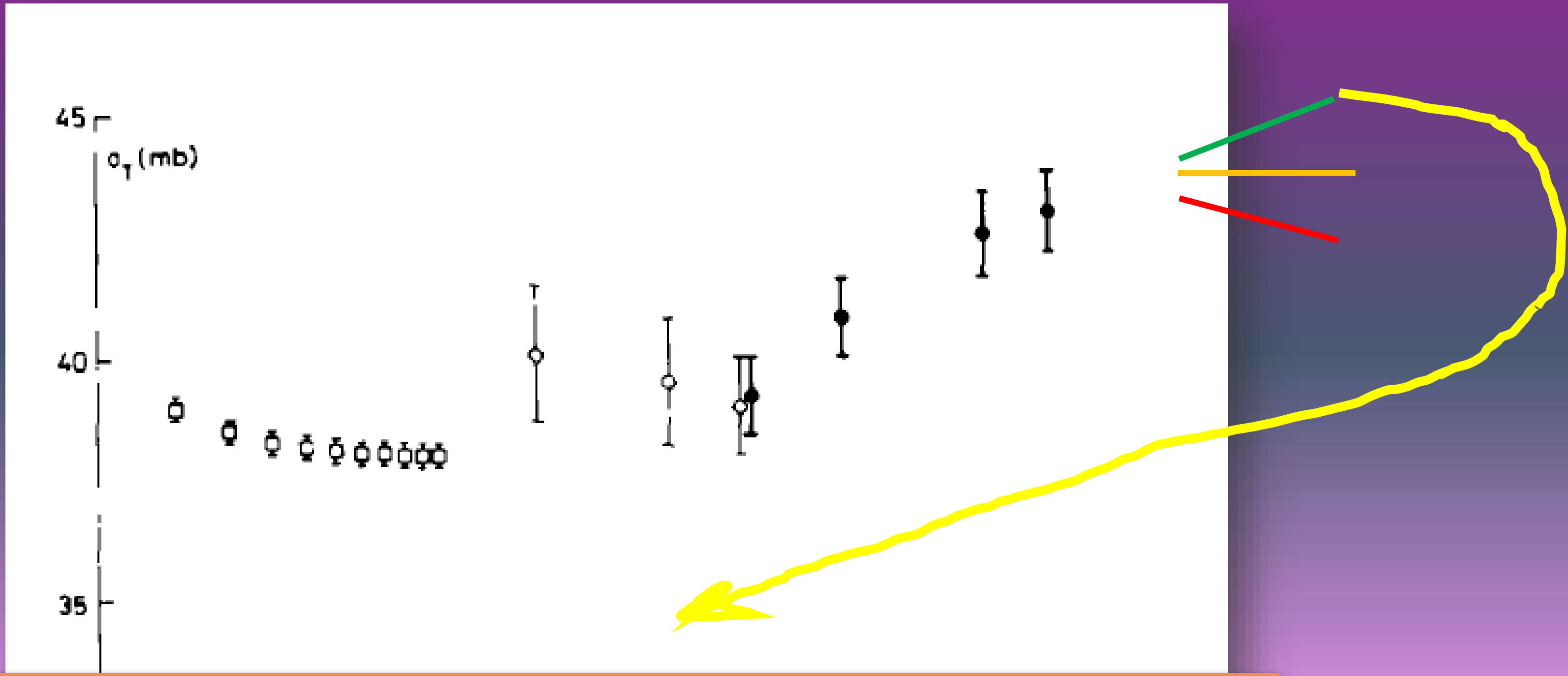
$$\frac{\sigma_{AB}^{tot}}{\sigma_{CD}^{tot}} \to 1, \qquad E \to \infty$$

Middle Age (1971-73)
(Serpukhov proton synchrotron)



S. P. Denisov et al. (1971)

New Era (1973-…) (+ FNAL + ISR)



Driving Regge Pole: Pomeron.

Now with $\alpha_P(0) = 1 + \Delta, \Delta > 0$

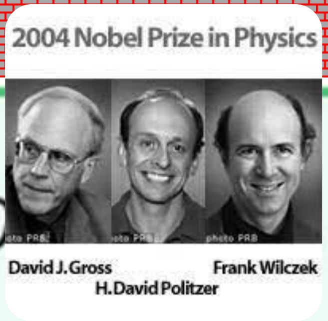
Aristocracy takes over?

"Quark Counterrevolution":

Scaling (1968-69): Rehabilitated QFT

Parton model

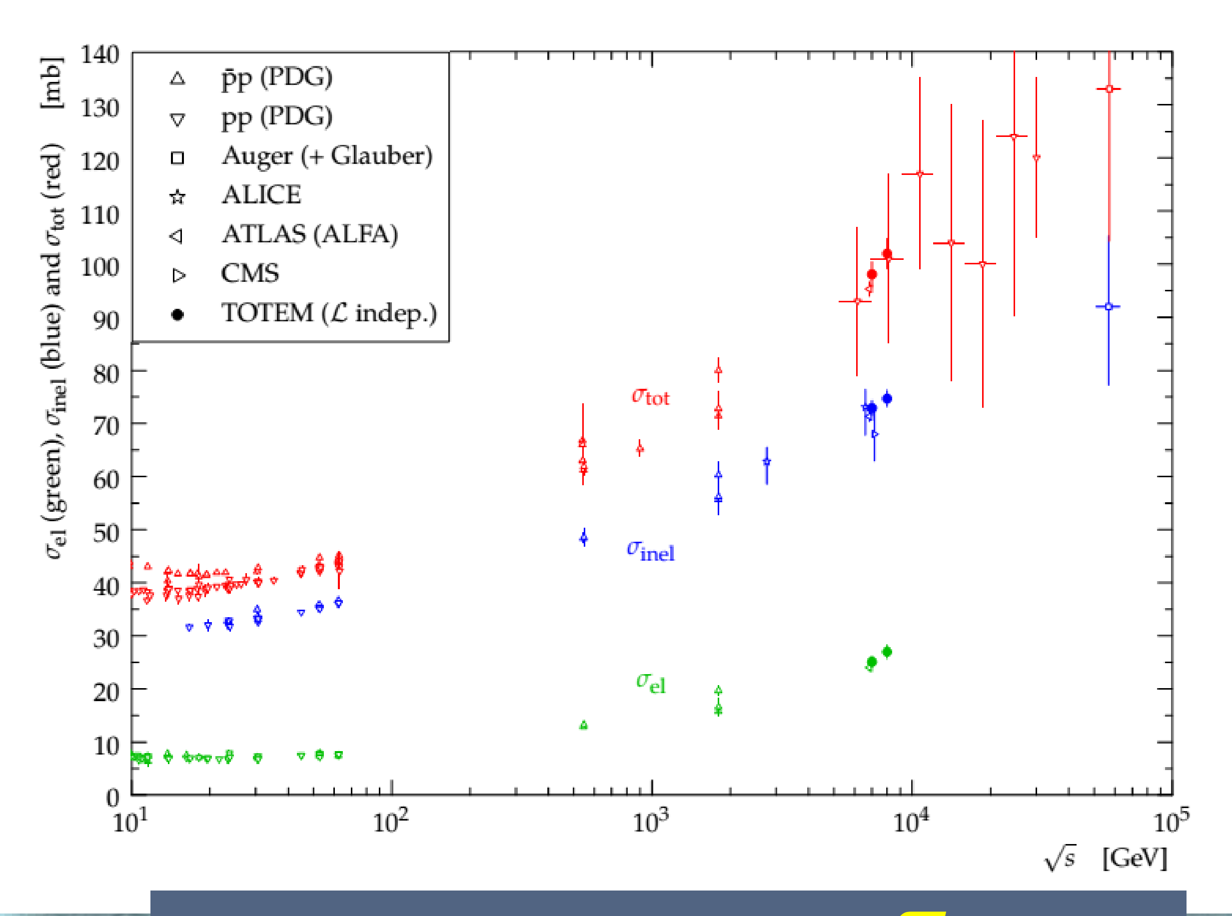
QCD :
Official theory of strong interactions (since 1973)

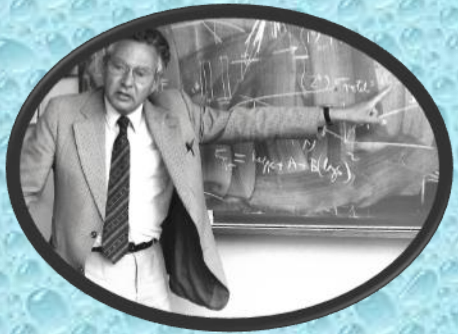


$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D \ldots \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

Breakthrough to new frontiers

Froissart, 1961
Martin, 1963





$$\sigma_{inel} \leq \frac{\pi}{4m_\pi^2} ln^2 s$$

Martin 2005

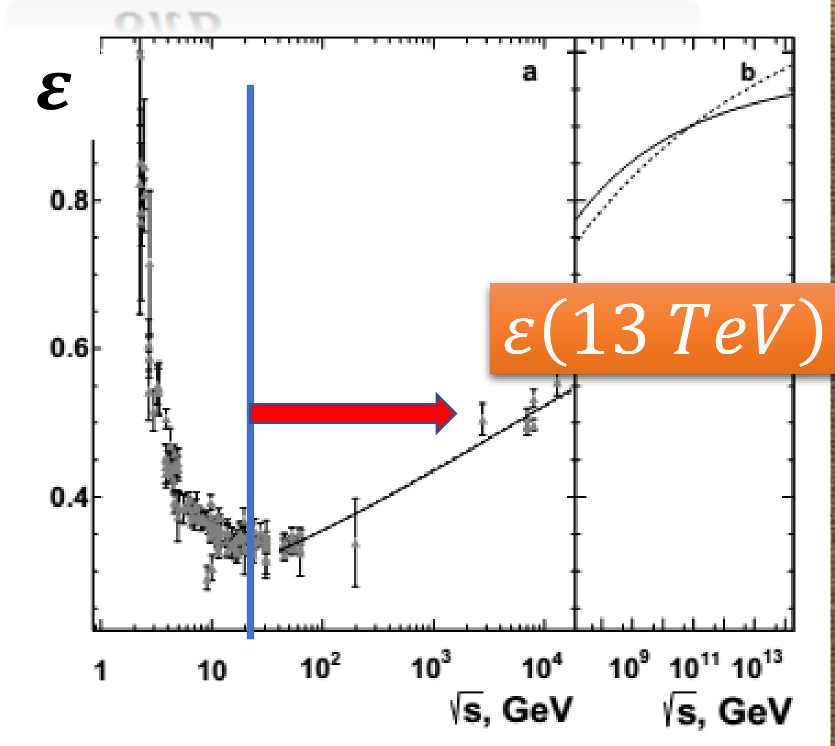
$$\sigma_{inel} = \frac{\pi}{4m_\pi^2} ln^2 s,$$

Heisenberg, 1952

$$\sigma_{tot} = \sigma_{inel} + \sigma_{el} \leq \frac{\pi}{m_\pi^2} ln^2 s$$

« Asymptoticity Index » : $\varepsilon = \dfrac{\sigma_{tot}}{8\pi B}$

$$\varepsilon = \frac{\sigma_{tot}}{8\pi B} \to 1 \text{ при } \sqrt{s} \to \infty$$



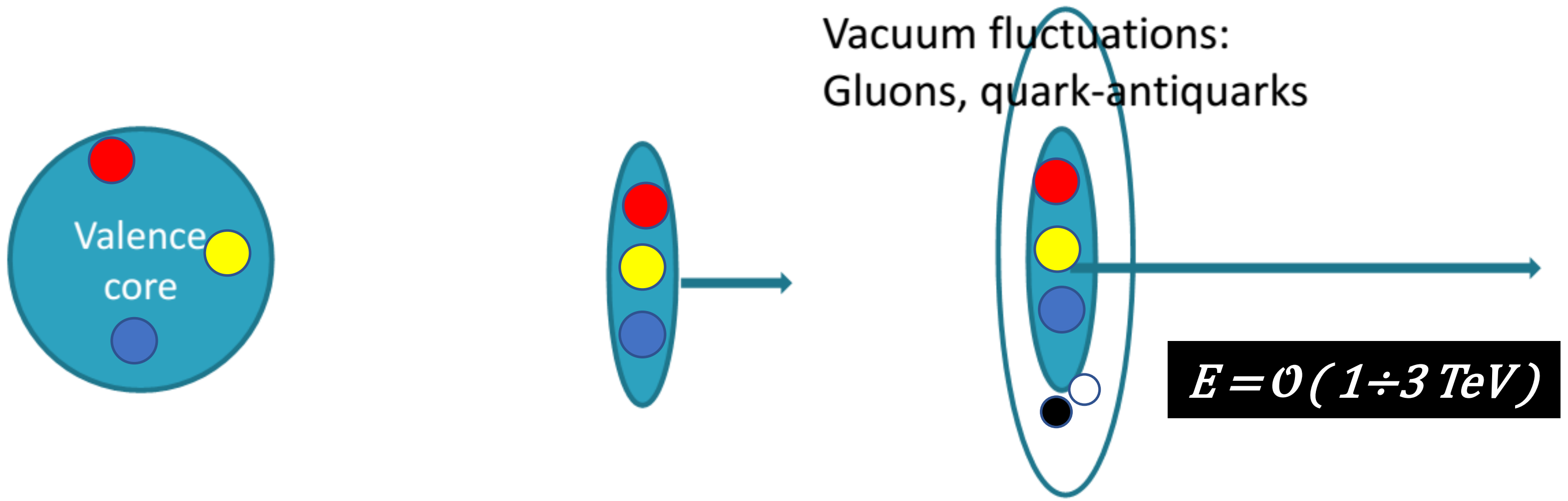
$\varepsilon(13\ TeV) \approx 0.5$

$$\frac{\langle b^2 \rangle}{2} \approx B(s) \gg \langle b^2 \rangle(proton) \approx 11 GeV^{-2}$$

$$R^{\perp}_{interaction} \gg 3\ fm$$

$$R^{\perp}_{interaction}(13\ TeV) \cong 4\ fm$$

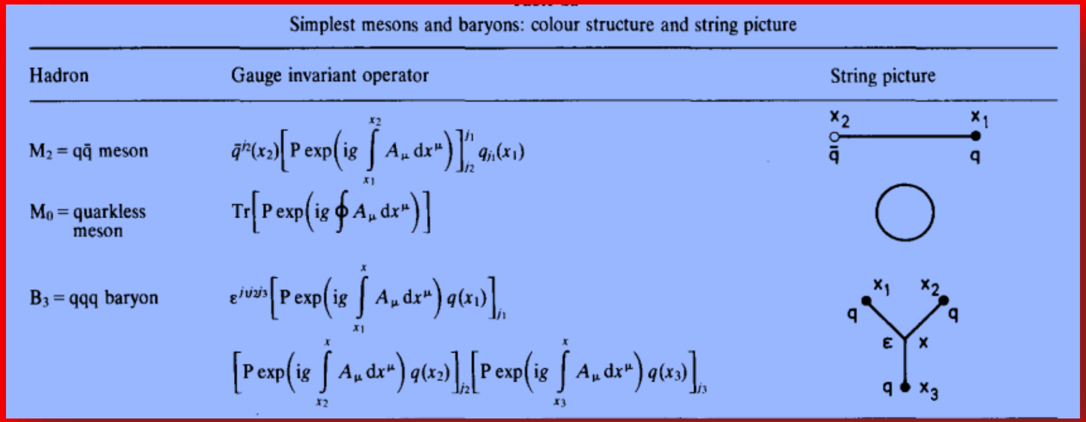
- **Moving nucleon's spatial structure**



What QCD gives for Strong Interactionat High Energies?

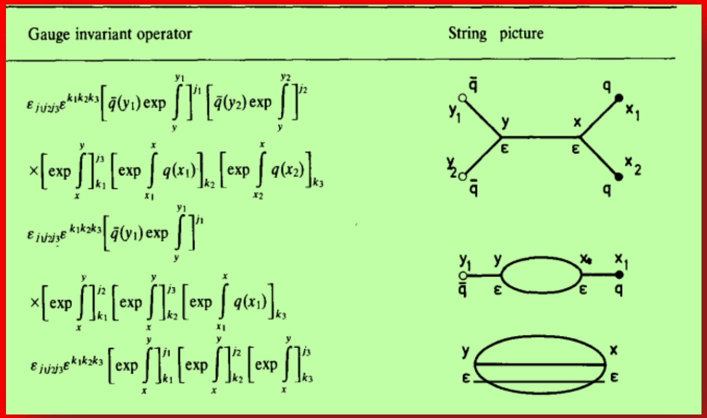
- C-odd partner of the Pomeron, the "Odderon" is allowed
- The Strong Interaction Amplitudes - ?
- Regge residues - ?
- Pomeron (Odderon) slope $\alpha'_{P/O}(0)$?
- Pomeron (Odderon) intercept $\alpha_{P/O}$? $(\alpha_P(0) \geq \alpha_O(0))$
- Regge trajectories are non linear and flat at $t \to -\infty$.
- $\alpha_{P/O}(t) \to 1$ at $t \to -\infty$,
- $\alpha_{P/O}(0) > 1$ and does not depend on the gauge coupling.

Glueball and multiquark states in QCD



Simplest mesons and baryons: colour structure and string picture

Hadron	Gauge invariant operator	String picture
$M_2 = q\bar{q}$ meson	$\bar{q}^{j_2}(x_2)\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu dx^\mu\right)\right]^{j_1}_{j_2} q_{j_1}(x_1)$	
$M_0 =$ quarkless meson	$\mathrm{Tr}\left[P\exp\left(ig\oint A_\mu dx^\mu\right)\right]$	
$B_3 = qqq$ baryon	$\varepsilon^{j_1j_2j_3}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu dx^\mu\right)q(x_1)\right]_{j_1}\left[P\exp\left(ig\int_{x_2}^{x} A_\mu dx^\mu\right)q(x_2)\right]_{j_2}\left[P\exp\left(ig\int_{x_3}^{x} A_\mu dx^\mu\right)q(x_3)\right]_{j_3}$	



Gauge invariant operator	String picture
$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar{q}(y_1)\exp\int_y^{y_1}\right]^{j_1}\left[\bar{q}(y_2)\exp\int_y^{y_2}\right]^{j_2} \times\left[\exp\int_x^y\right]^{j_3}_{k_1}\left[\exp\int_{x_1}^x q(x_1)\right]_{k_2}\left[\exp\int_{x_2}^x q(x_2)\right]_{k_3}$	
$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar{q}(y_1)\exp\int_y^{y_1}\right]^{j_1} \times\left[\exp\int_x^y\right]^{j_2}_{k_1}\left[\exp\int_x^y\right]^{j_3}_{k_2}\left[\exp\int_{x_1}^x q(x_1)\right]_{k_3}$	
$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\exp\int_x^y\right]^{j_1}_{k_1}\left[\exp\int_x^y\right]^{j_2}_{k_2}\left[\exp\int_x^y\right]^{j_3}_{k_3}$