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Strong Interactions at High Energy: 100 Years of Inquiry

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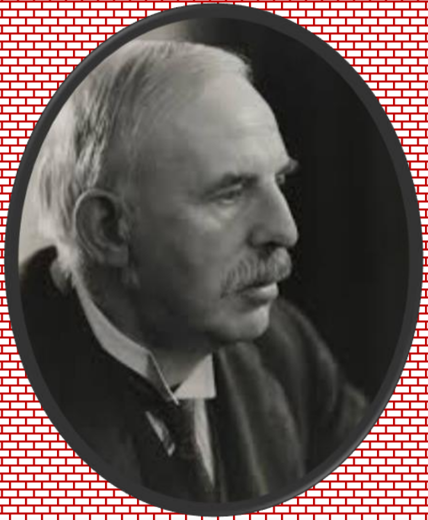
Prehistory: 1923



CHEMISTRY AND INDUSTRY Sept. 14, 1923

THE ELECTRICAL STRUCTURE OF MATTER
By Prof. SIR ERNEST RUTHERFORD

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.

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

Entia non sunt multiplicanda praeter necessitatem.

Plurality should not be posited without necessity

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 Neutron und Proton in einen mit Kerndimensionen vergleichbaren Abstand, so wird — in Analogie zum H_2^+-Ion — ein Platzwechsel der negativen Ladung eintreten, dessen Frequenz durch eine Funktion $\frac{1}{h}J(r)$ des Abstandes r der beiden Teilchen gegeben ist. Die Größe $J(r)$ entspricht dem Austausch- oder richtiger Platzwechselintegral der Molekültheorie. Diesen Platzwechsel kann man wieder durch das Bild der Elektronen, die keinen Spin haben und den Regeln der Bosestatistik folgen, anschaulich machen. Es ist aber wohl richtiger, das Platzwechselintegral $J(r)$ als eine fundamentale Eigenschaft des Paares Neutron und Proton anzusehen, ohne es auf Elektronenbewegungen reduzieren zu wollen.

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.

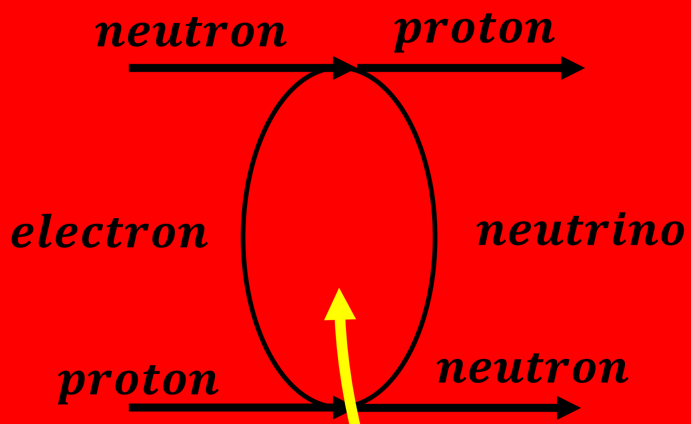
The chief point of interest is how far the neutrons can be considered as elementary particles (something like protons or electrons). It is easy to calculate the number of α-particles, protons, and neutrons for a given nucleus, and form in this way an idea about the momentum of nucleus (assuming for the 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.

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

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



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

IG. TAMM.
Physical Research Institute,
State University,
Moscow.

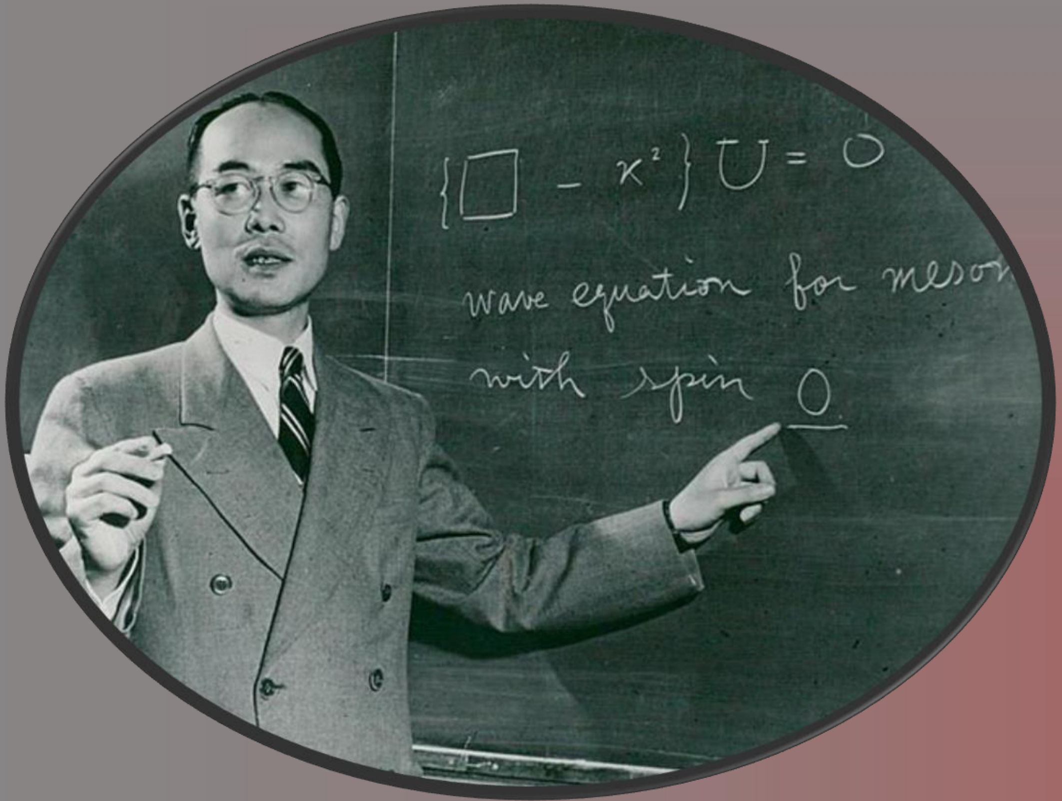
[1] Fermi, *Z. Phys.*, **88**, 161; 1934.
[2] Wick, *Rend. R. Nat. Acad. Lincei*, **19**, 319; 1934.

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.

TOO WEAK!!!



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...

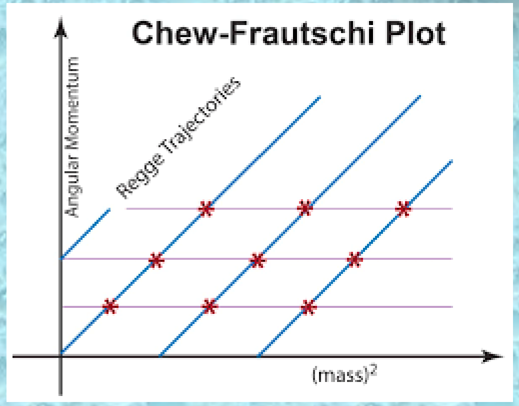
The ψ operators which contain unobservable information must disappear from the theory and, since a Hamiltonian can be built only from ψ operators, we are driven to the conclusion that the Hamiltonian method for strong interaction is dead and must be buried, although of course with deserved honour.....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

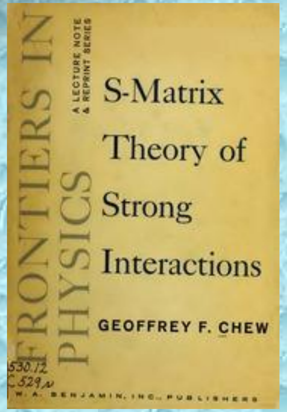
...on the basis of approximations, it is dangerous to make any conclusions about the situation taking place in the exact problem (1959)

New age: Analytic S-matrix & Regge Revolution

Prelude/ Intermezzo: Regge poles (1959)

Adaptation to relativistic case (1961)

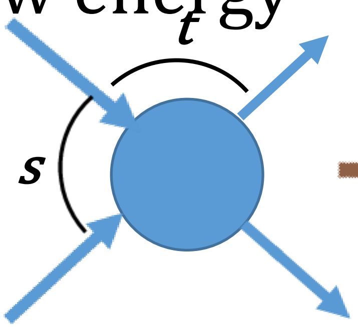


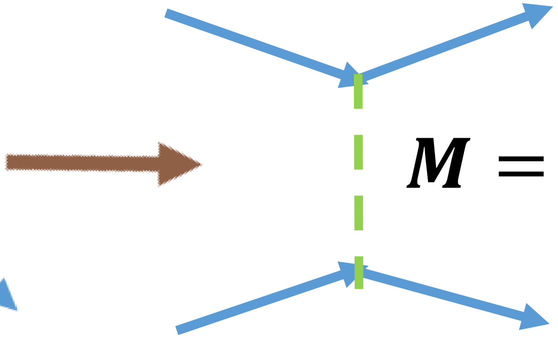


Nuclear Democracy:
no hadron is more elementary than any other!

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

Low energy





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

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

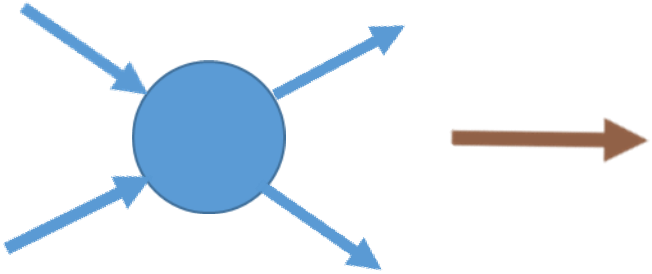
$$A_J(s,t) = g_J^2 \frac{s^J}{M_J^2 - t}$$

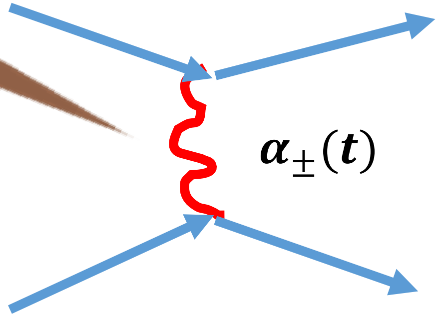
$$\rightarrow V(r) = \pm\, g_J^2 \frac{s^{J-1} e^{-M_J r}}{4\pi r} \qquad \langle r \rangle \sim 1/M_J$$

High energy

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

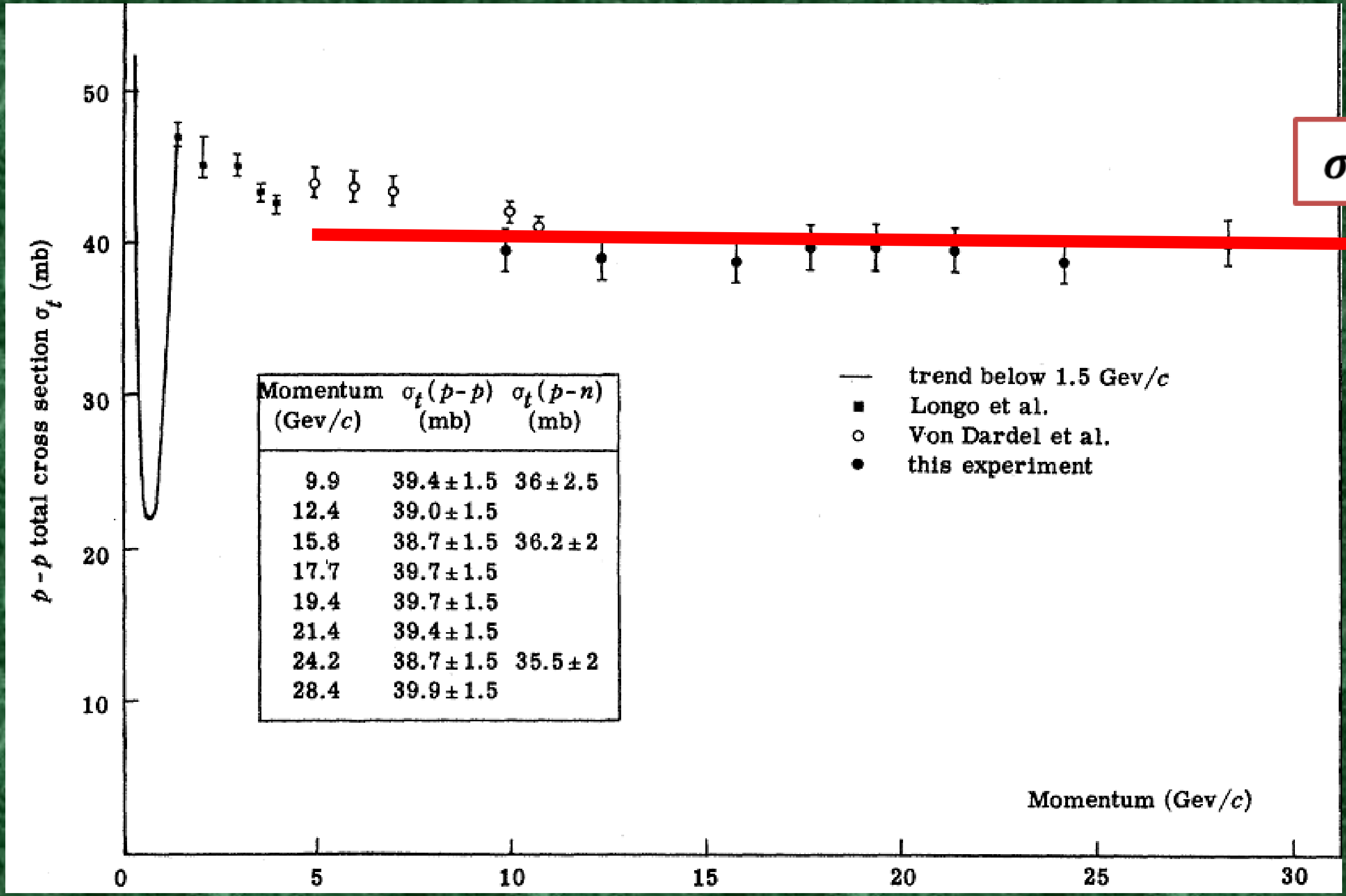
$\sum_J A_J(s,t) \rightarrow \pm\, s^{\alpha_\pm(t)}$ (**L.Van Hove)**





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

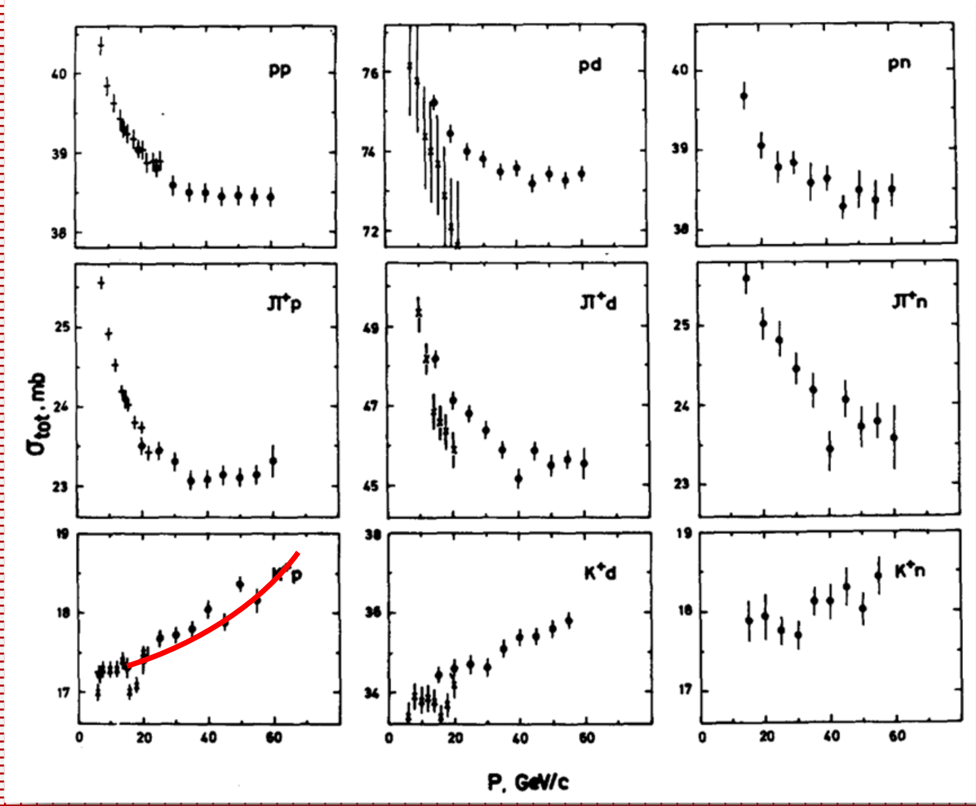
Experiment: Prehistory (1953-70)



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

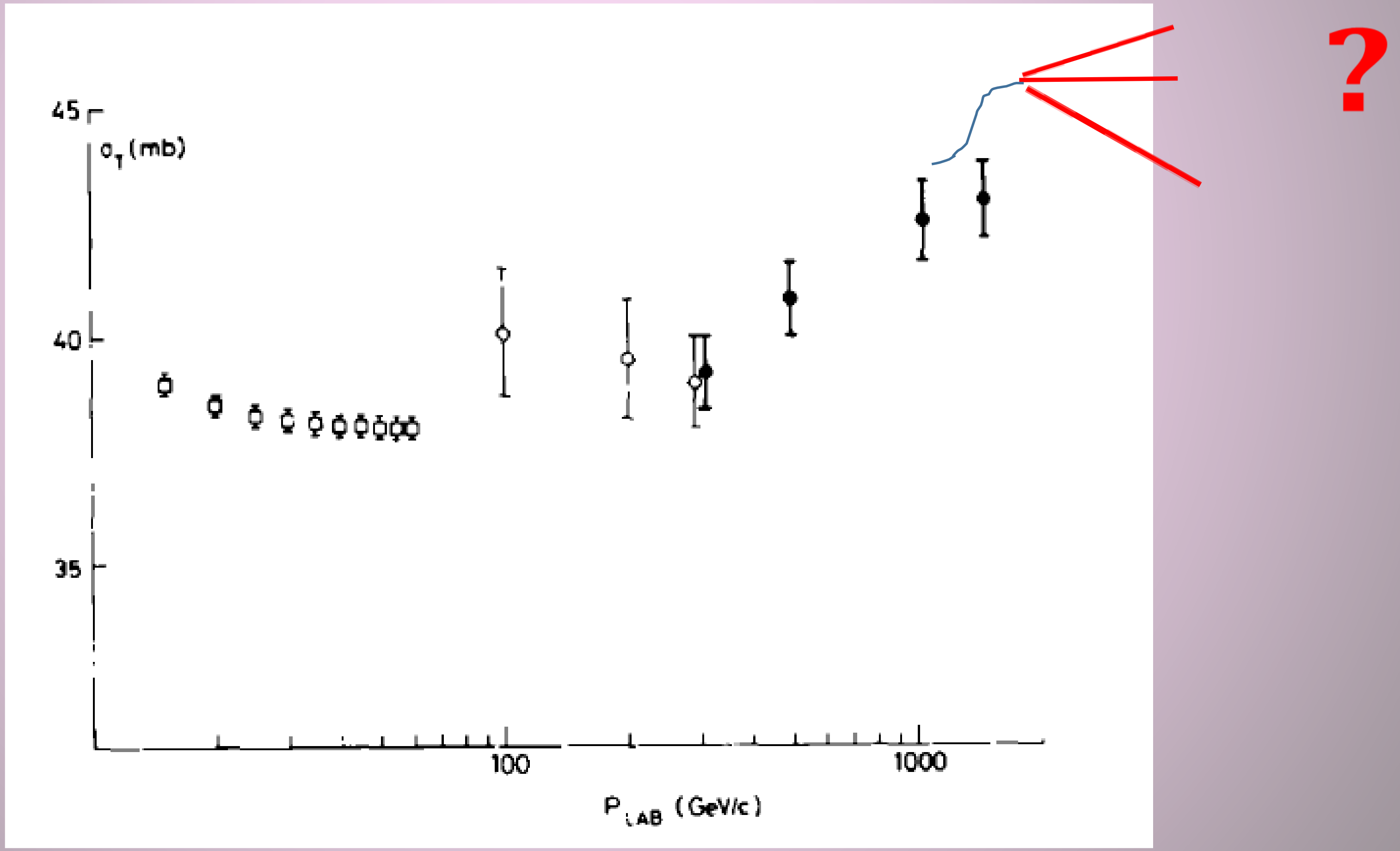
$$\frac{\sigma^{tot}_{AB}}{\sigma^{tot}_{CD}} \to 1, \qquad E \to \infty$$

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



S. P. Denisov et al. **(1971)**

New Era (1973-…)
(+ FNAL + ISR)



Scaling (1968-69): Rehabilitated QFT takes over?

QCD :
Official theory of strong interactions (since 1973)

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

"If you are out to describe the truth, leave elegance to the tailor."
— Ludwig Boltzmann

Heisenberg: σ_{inel} should grow as $\sim \frac{\pi}{4m_\pi^2} ln^2 s$!

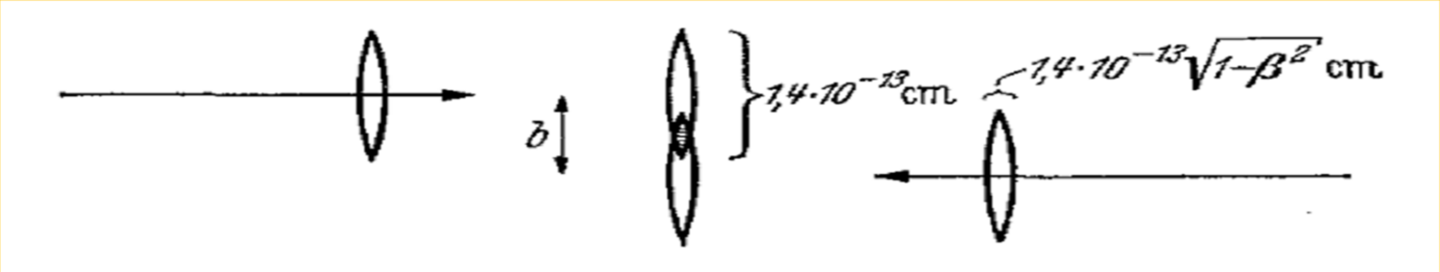
Mesonenerzeugung als Stoßwellenproblem.

Von

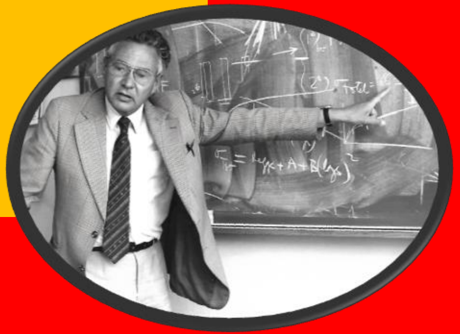
W. HEISENBERG.

Mit 6 Figuren im Text.

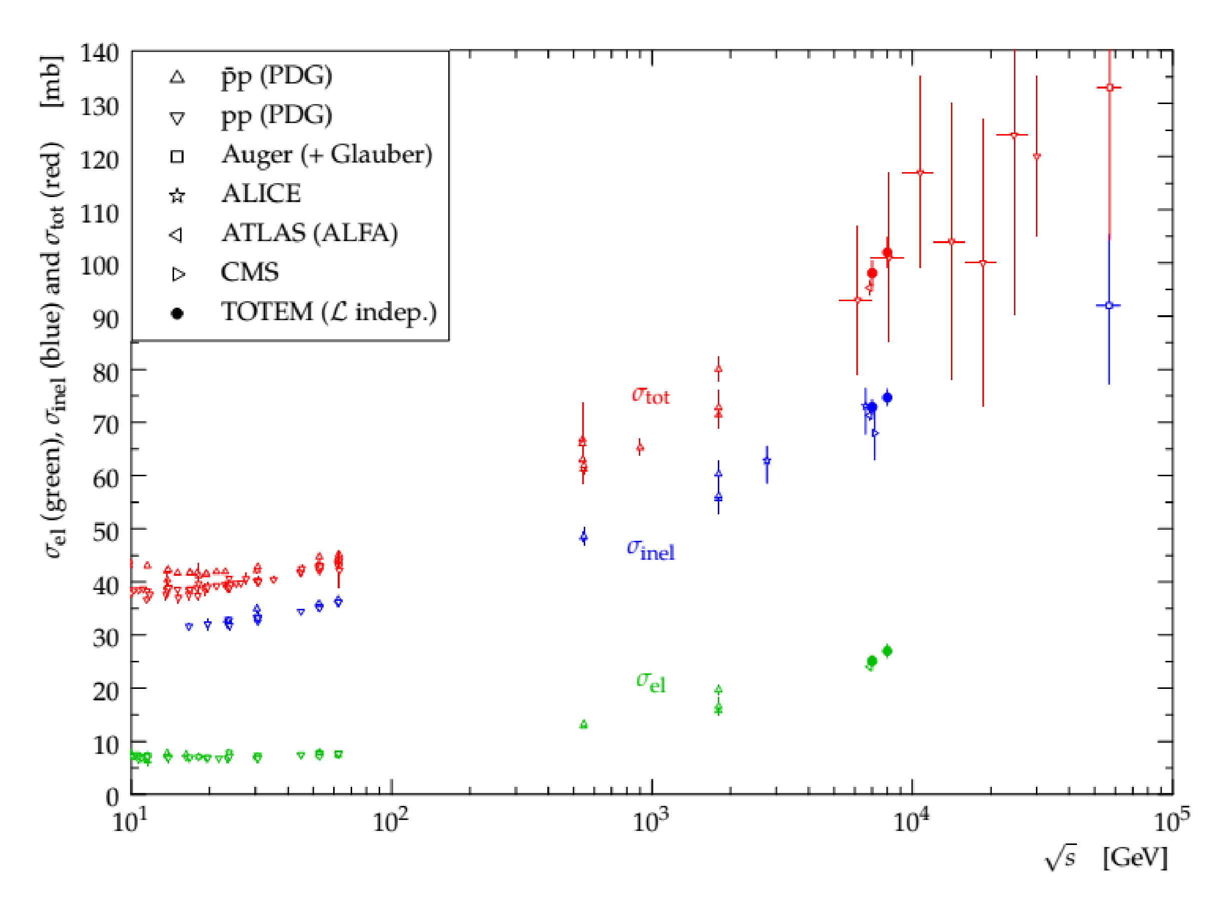
(Eingegangen am 5. Mai 1952.)



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



Breakthrough to new frontiers



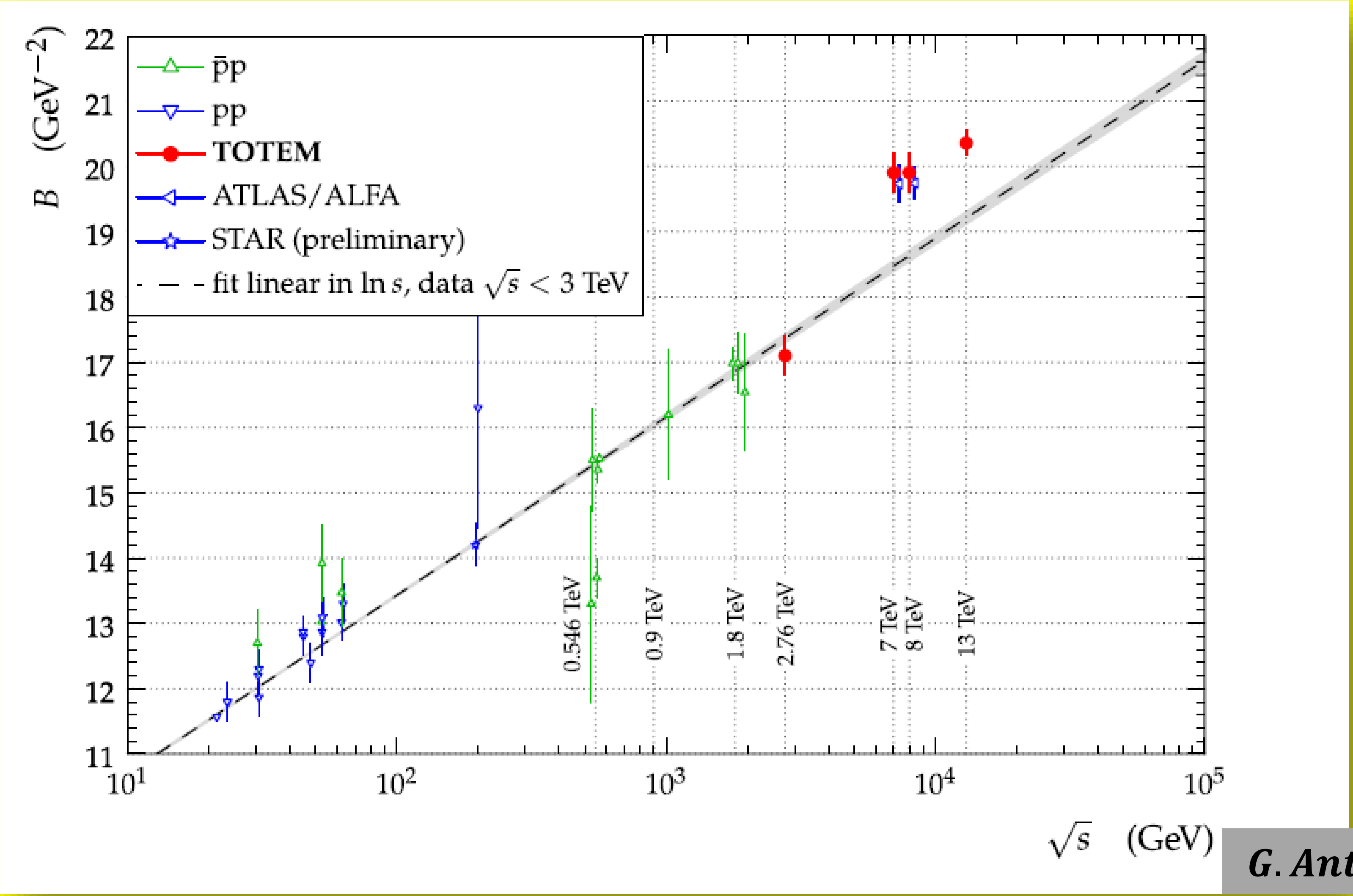
$d\sigma/dt \sim e^{B(s)t}$

$\langle b^2/2 \rangle \approx B(\sqrt{s} = 2.76\ \text{TeV}) = 17.10 \pm 0.26\ \text{GeV}^{-2}$

$\langle r^2 \rangle \approx 3\,B = 51.3 \pm 0.78\ \text{GeV}^{-2}$ ⟷ $1/(m(\pi^0))^2 = 54{,}88\ \text{GeV}^{-2}$

$1/(m(\pi^\pm))^2 = 51{,}33\ \text{GeV}^{-2}$

Accidental coincidence ?

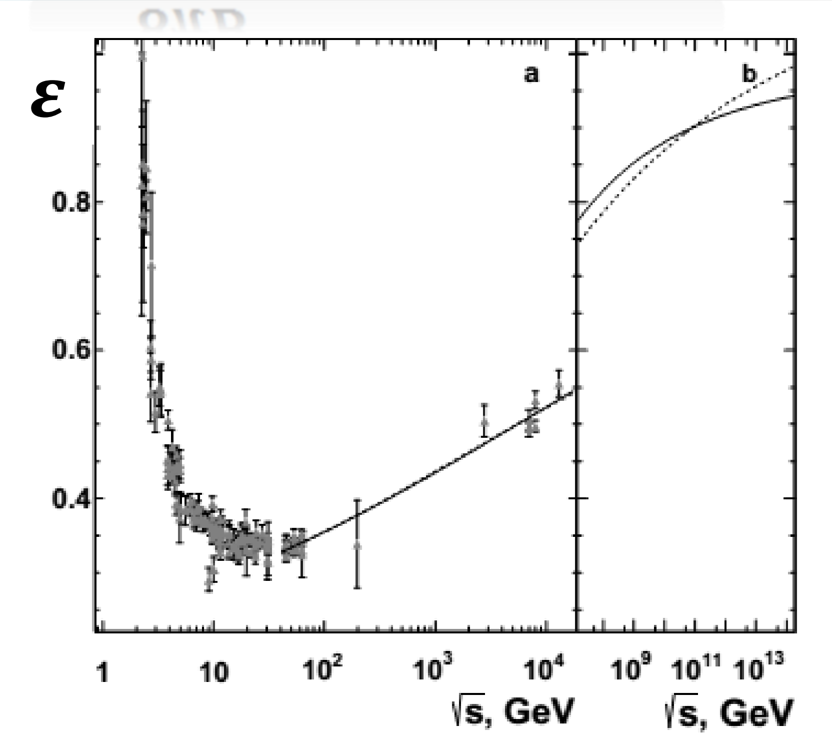


***G. Antchev et al.* (2019)**

« Asymptoticity Index »

$$\varepsilon = \frac{\sigma_{tot}}{8\pi B}$$

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

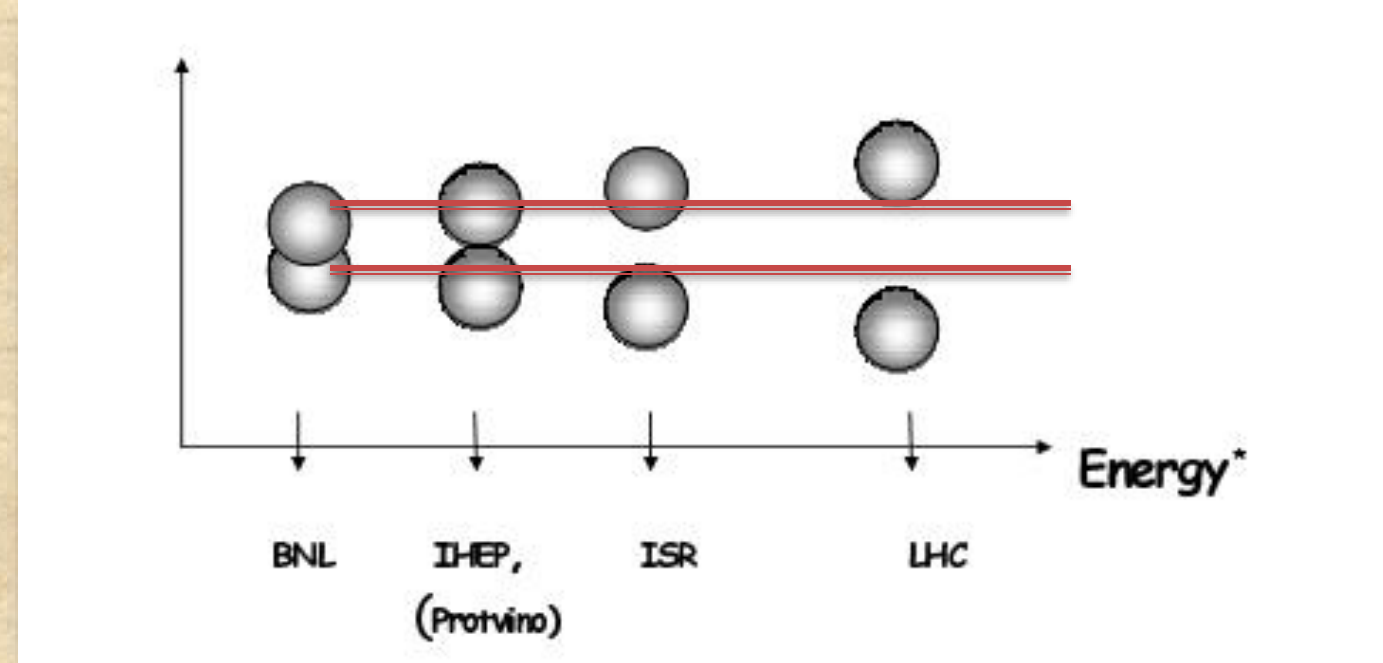


$$\frac{\langle b^2 \rangle}{2} \approx B(s) \gg \langle b^2 \rangle (proton) \approx 11 GeV^{-2}$$

?

$$\frac{\langle b^2 \rangle}{2} \approx 3B(s) \text{ при } \sqrt{s} = 10^4 \text{ TeV}$$

IT'S A LONG WAY TO "ASYMPTOPIA"…



$$\langle b^2 \rangle^{\frac{1}{2}}(10^{-2}\ \mathrm{TeV}) \approx 0.88\ fm$$

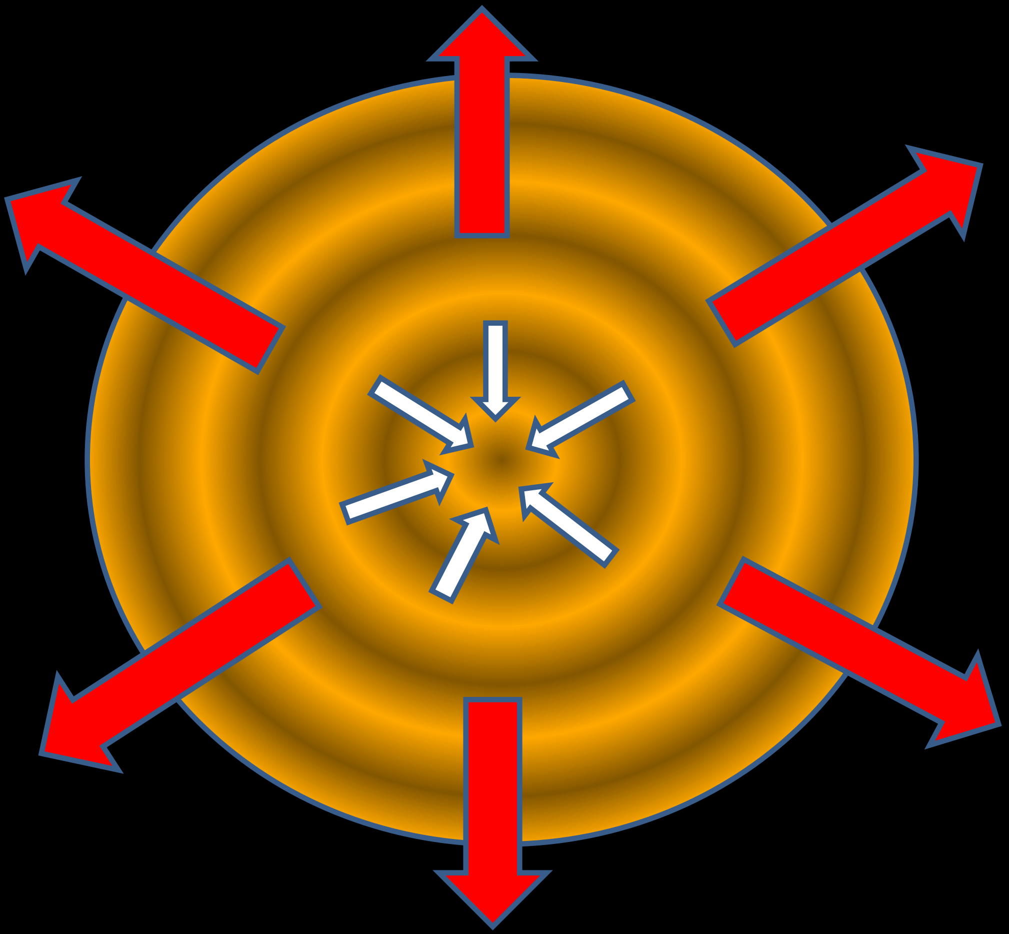
$$\langle b^2 \rangle^{\frac{1}{2}}(13\ TeV) \approx 1.28\ fm$$

Incredible stubbornness of the vacuum

What QCD gives for High Energy Diffractive Scattering ?

- Odderon is allowed
- The Strong Interaction Amplitudes - ?
- Regge residues - ?
- Pomeron (Odderon) slope $\alpha'_{P/O}(0)$?
- Pomeron (Odderon) intercept $\alpha_{P/O}(0)$? $(\alpha_P(0) \geq \alpha_O(0))$
- 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.

QUO VADIS ?



$$1 fm\,(100\ MeV) \neq 1\ fm(1TeV)$$