Dmitri Diakonov - life in physics...

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PNPI

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Dmitri Diakonov — founder of Euler Simposium

30.03.1949 — 26.12.2012

Dmitri Diakonov

Dmitri Diakonov **entered PNPI** as PhD student in **1972**. First paper known to QSPIRES is published in **1973**. Last paper published in this year — **2013**. Few more are prepared for publication.

Dmitri Diakonov, 1977

$\sim$ **170** *distinct* papers. According to QSPIRES they have $>$ **7000** citations, **4 papers** have more than **500 citations** each.

Early publications

- Mitya came in physics at a time when field theory in the time when **quantum field theory** was not very popular. The reason — **nullification of the charge** — discovered Landau *et al* in 50s. Many theorists consider field theory being **senseless**. It was the time of **Regge theory**. PNPI Theory Division led by **V.N.Gribov** was **world center of 'reggistics'**.

  Discovery of **Asymptotic Freedom** was still ahead...

- Mitya **strongly believed** in the field theory during **all his life** starting from the very beginning of his scientific career. His advisor was **A.Anselm** who continues the investigation of different quantum field theories. Curiously, A.Anselm observed the asymptotic freedom in few 2-dimensional theories long before 1973 but considered this as an artifact of 2 dimensions.

Early publications

First Mitya's publications were devoted to the complicated **problems of field theories**: (with A.Anselm and alone)

- Properties of 4-fermion model in two dimensions (Gross-Navier model) (**spontaneous breakdown of chiral invariance in perturbation theory**).
- Corrections to **Coleman-Weinberg effective potential** in electroweak theory in different gauges
- Radiative corrections to the **Weinberg angle** in grand unification theories ($SU(5)$, $SO(10)$)

— papers of pure field theorist. However in 1977 he suddenly **changed** the topic. He made this many times in his life...

Perturbative QCD theory: DDT

- Revolution'of 1973-74 brings QCD to existence. Mitya realized immediately that it is **the theory** of strong interaction.
- In 1973 Mitya (together with Mark Strikman) translated the book of **R.Feynman "Interaction of photons and hadrons"**. This book was the Bible of parton physics

He feels that it is a high time to switch to QCD... He remembered that they wanted for the first time **check QCD** not with one or two numbers but with the whole non-trivial function which can be confronted to the experiment

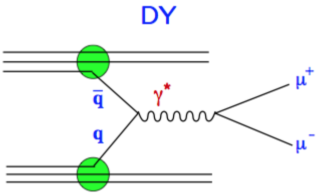
He started to work on together with **D.Dokshitzer** and **S.Troyan** in 1975-1976 and published few papers in the subject which later was called **physics of hard processes in QCD**.

They formulated perturbative approach to 2 most famous hard processes in QCD:

- e^+e^- **annihilation to hadrons**

Perturbative QCD theory: DDT

- **Drell-Yan process**



For the last process they derived famous **DDT** formula:

$$\frac{d\sigma}{dq^2 dq_t^2 dy} = \frac{4\pi\alpha^2}{9}\frac{1}{sq^2 q_t^2}\frac{\partial}{\partial \log q_t^2}$$

$$\left[\sum e_F^2 \mathbf{D_a^F}(\mathbf{x_1}, \mathbf{q_t^2})\mathbf{D_a^F}(\mathbf{x_2}, \mathbf{q_t^2})\mathbf{T_F^2}(\mathbf{q_t^2}, \mathbf{q^2})\right]$$

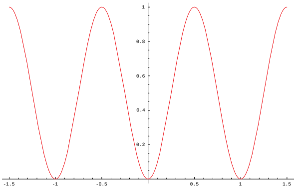
Perturbative QCD theory: DDT

where D are parton distributions (measured in **deep inelastic** scattering) and T is a **Sudakov double logarithmic** formfactor:

$$\mathbf{T} = \exp\left[-\frac{\alpha_s}{3\pi}\log^2\frac{q^2}{q_t^2}\right]$$

It was one the **first non-trivial quantitative** calculations in QCD. They wrote the review in Phys.Rep. which became a classics for QCD. It has ~ 800 ref in QSPIRES and the last ref is of 2013!
It seemed the career of world known perturbative QCD theorist was clear for him. But Mitya **was not satisfied again**. He decided to switch to another topic.
Later he told to me that he thought a lot during these years and understood that perturbative QCD **is unable** to give the answers to the **basic questions** of QCD he was interested in.

$U(1)$ and Θ problems (with M.Eides, 1980)



It is known that QCD **potential energy** is **periodic** in **Chern-Simons term**:
$\varepsilon_{ijk} \int d^3x \left[A_i \partial_j A_k + \frac{2}{3} A_i A_j A_k\right]$
Instantons — transitions between different ‘vacua‘ (**Gribov**)

D.D. and Eides gave the interpretation of **θ-vacuum of QCD** as the state with **quasi-momentum** in periodic potential and rederive by other method **Witten-Veneziano** formula for the mass of η'-meson

$$m_\eta^2 = 4 \frac{< Q_t^2 >}{F_\pi^2}$$

$U(1)$ and Θ problems

Thus $U(1)$ **problem** (why there are only 8 Goldstone bosons in QCD, while $SU(2) \times U(1)$ is broken is) **is solved**. Instead **Θ-problem** appears — Why QCD vacuum has $\Theta \equiv 0$ while the states with $\Theta \neq 0$ are **stable**.

Mitya and Ludwig Faddeev, 1981

Mechanisms of Θ-vacuum decay invented so far (axions) **contradict the data**, so the problem remains unsolved till now. Meanwhile $\Theta \neq 0$ implies arbitrary ***CP*-nonconservation in the strong interactions**. Searches for such non-conservation are in experimental plans of many labs...

Instantons

Work on $U(1)$-problem + some *phenomenological* considerations (E.Shuryak, 1981) convinced Mutya that **instantons** can play important role in QCD and maybe, they are **the only** non-perturbative **fluctuations in QCD vacuum**.

In 1982 we (**D.D.+V.P.**) started a long-standing project trying to understand all non-perturbative phenomena in QCD from a **point of view**, without any parameter. This project lasts now for 30 year and we walked all the way **from instantons to pentaquarks**, more or less successfully...

First, we prepared some instruments:

- Approximate calculation of quantum determinants in arbitrary fields (together with **,** 1982
- **Feynman variational** principle (analogue of variational principle in quantum mechanics) in field theories, in partiular, gauge theories, 1982

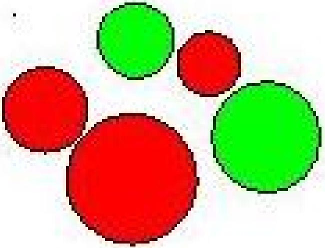
Instantons

These instruments allow to estimate (from below) the contribution of **arbitrary configuration** to the QCD functional integral. We made a single **assumption** that dominating configurations are instantons.

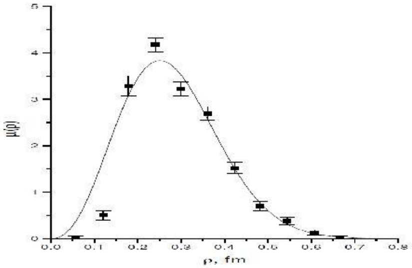
- Statistical sum of instanton vacuum

$$\mathcal{Z} = \int \prod \frac{dz^i_\mu d\rho^{(i)}}{(\rho^{(i)})^5} [\Lambda\rho^{(i)}]^b e^{-\beta U_{int}[\mathbf{z}^{(\mathbf{i})}_\mu, \rho^{(\mathbf{i})}, \mathbf{O}^{(\mathbf{i})}]}$$

is integral in **collective coordinates**.



Instantons **u**ntil effective repulsion stabilizes the swelling. Interaction is **large** enough $e^{\beta U} \sim 1$). but small as compared to action.



distribution in sizes measured on lattice (2000) vs

$$\rho = \rho^{b-5} \exp\left[\nu\left(\rho^2/\bar{\rho}^2\right)\right]$$

where

$$\nu = \frac{b-4}{2} \qquad b = \frac{11}{3} N_c$$

Instanton liquid in 2 loops

- Coupling **freezes** at

$$\beta(\bar{\rho}) \equiv \frac{8\pi^2}{g^2} = \begin{cases} \mathbf{15} & SU(3) \\ \mathbf{12} & SU(2) \end{cases}$$

Theory of instanton liquid (1984)

$$\frac{\bar{R}}{\bar{\rho}} = \begin{cases} \mathbf{4.1} & SU(3) \\ \mathbf{3.1} & SU(2) \end{cases}, \qquad \varkappa \equiv \frac{\pi \bar{\rho}^4}{\bar{R}^4} = \begin{cases} \mathbf{\frac{1}{10}.} & SU(3) \\ \mathbf{\frac{1}{25}} & SU(2) \end{cases}$$

- — **fraction** of the volume occupied by instantons. It is our small parameter.
- **Gluon condensate and condensate of topological charge**

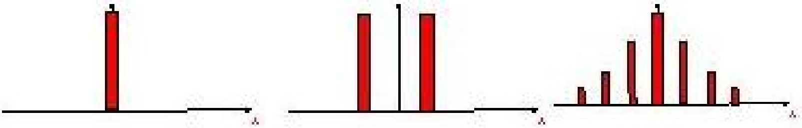
$$< \frac{G^2_{\mu\nu}}{32\pi^2} (\mathbf{(200MeV)^4}) \approx < Q_t Q_t > (\mathbf{(190MeV)^4}) \approx (0.7\Lambda_{P.V.})$$

- Normalzing to experimental $< Q_t Q_t >$ **the only parameter of the theory** $\Lambda_{P.V.} = 280 MeV$.

Quarks in the instanton vacuum, 1986

- Quarks in the instanton background have **zero mode** $\nabla[A]\Psi = 0$. This leads o **new mechanism** of spontaneous breakdown of chiral invariance.
- Eiegenvalues distribution funtion:

$$\nu(\lambda) = \langle\langle \sum \delta(\lambda - \lambda_i) \rangle\rangle$$



overlap of w.f. of quarks. **Chiral condensate**

$$< \bar{\psi}\psi >= -\pi \frac{N}{V} \nu(0)$$

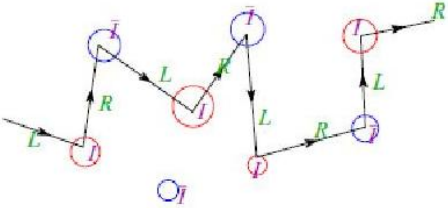
Casher-Banks formula

Quarks in the instanton vacuum

- Chiral condensate

$$< \bar{\psi}\psi >= -(\mathbf{255Mev})^{\mathbf{3}} \; (-(\mathbf{250Mev})^{\mathbf{3}})$$

- Owing to **scattering** on istanton fluctuations

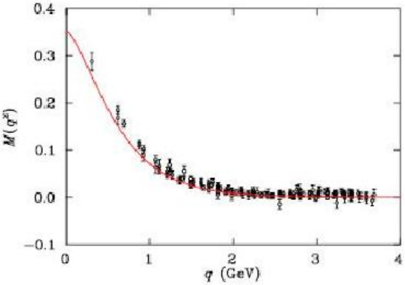


dynamical mass $M(p)$
Parametrically:

$$M(0) = \sqrt{\frac{\mathbf{N}}{\mathbf{VN_c}}\pi^2\bar{\rho^2}}$$

- Condensate is **large** if density **is small** (zero mode)

Quarks in the instanton vacuum



Dependence on momentum is given by **zero mode**

$$M(0) \approx 350 Mev$$

mass of **constituent** quark

- **Averaging** in instanton ensemble leads to **interaction** between quarks.
- Bosonizing this interaction at large N_c **(Witten)** one gets effective meson Lagrangian
- There is massless π-, Goldstone particle

Quarks in the instanton vacuum

- Axial constant

$$F_\pi^2 = 4N_c \int \frac{d^4p}{(2\pi)^4} \frac{M^2(p)}{p^2 + M^2(p)} \sim \frac{M^2}{4\pi^2}$$

numerics: $F_\pi = 98 MeV$ (**94 MeV**)

- Different scales:

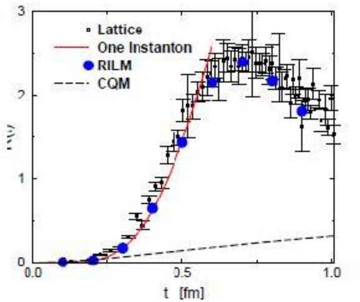
$$\rho \sim \frac{1}{600 MeV}, \qquad R \sim \frac{1}{200 MeV}$$

$$M \sim \frac{1}{\sqrt{\rho R}} \sim 350 MeV, \qquad \frac{F_\pi^4}{< \frac{G^2}{32\pi^2} >} \sim \left(\frac{\rho}{R}\right)^4$$

- $U(1)$-**problem** is solved and **Witten-Veneziano** formula is reproduced:

$$m_{\eta'}^2 = \frac{4N_f N}{V F_\pi^2}$$

Quarks in the instanton vacuum



Coincidence with experiment is **satisfatory**, (not in all channels)

$$\frac{\Pi_{scalar}(q^2) - \Pi_{pseudoscalar}(q^2)}{\Pi_{scalar}(q^2) + \Pi_{pseudoscalar}(q^2)}$$

- Typical meson mass is $m_h \sim 1/\rho = 600 MeV$

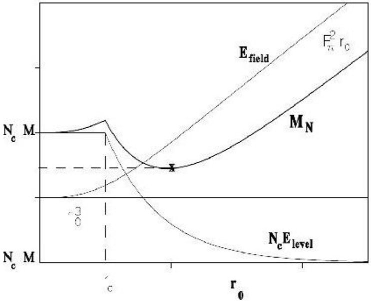
Baryons: Quark-soliton model, 1988, together with V.P.and P.Pobylitsa

- At $N_c \to \infty$ nucleon has a mass N_c, it can be found as **soliton of meson lagrangian** (Witten, 1983).
- If the size of nucleon is $1/M$ then only **relevant** degrees of freedom are **pions and constituent quarks**. Lagrangian can be obtained from the **instanton vacuum**.

$$\mathcal{L} = \mathfrak{D}et \left[i\hat{\partial} + iMe^{i\pi_a\tau_a\gamma^5} \right]$$

- Nucleon is a bound state of N_c quarks in **self-consistent** pion field (Thomas-Fermi, $Z \gg 1$)

Baryons: properties



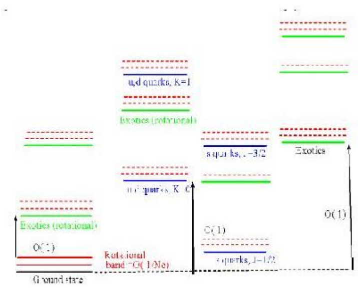
Pion field has **hedgehog** symmetry. Mass:

$$\mathcal{M}_N = N_c E_{level} + E_{field}[\pi]$$

- One can calculate all properties of the nucleon and its excited states. (**1988-1994**), **static Formfactors**, etc.
- construct $SU(3)$ theory, calculate mass **splittings**, decay constants, etc **1990**
- **parton distributions**, **wave functions on the light cone**, **generalized (skewed) parton distributions** (1991-1995)
- **Accuracy** of the theory (no parameter!) is about 10%

Quark nuclear physics (together with V.P. and A.Vladimirov, 2009-2012)

It is possible to give the complete classification of **all** baryons **under 2 GeV** and calculate their properties...



quark levels	rotational bands	$(I_1)^{-1}$, MeV	$\tilde{a}_K$
$K^P = 0^+$, ground state	$(8, 1/2^+, 1152)$ $(10, 3/2^+, 1382)$	153	
$0^+ \to 0^+$ 482 MeV	$(8, 1/2^+, 1608)$ $(10, 3/2^+, 1732)$	83	
$0^+ \to 2^+$ 722 MeV	$(8, 3/2^+, 1865)$ $(8, 5/2^+, 1873)$ $(10, 3/2^+, 2087)$ $(10, 5/2^+, 2071)$ $(10, 7/2^+, 2038)$	131	-0.050
$0^+ \to 1^+$ $\sim$780 MeV	$N(1/2^+, 1710)$ $N(3/2^+, 1900)$ $\Delta(1/2^+, 1910)$ $\Delta(3/2^+, \sim 1945)$? $\Delta(5/2^+, 2000)$		
$0^+ \to 1^-$ 468 MeV	$(8, 1/2^-, 1592)$ $(8, 3/2^-, 1673)$ $(10, 1/2^-, 1758)$ $(10, 3/2^-, 1850)$	171	0.336
$0^+ \to 0^-$ 563 MeV	$(8, 1/2^-, 1716)$	155(fit)	
$0^+ \to 2^-$ 730 MeV	$(8, 3/2^-, 1896)$ $(8, 5/2^-, 1801)$	155(fit)	-0.244

Contrary to the **quark model** there are **no extra** states and no state **is missing**

Prediction of exotic antidecuplet, together with V.P. and M.Polyakov

One of the most **dramatic** events in the history of the hadron physics

- Our theory predicted antidecuplet of particles with lightest Θ^+
- Properties were very **unusual**
- Parity **plus**
- mass 1540 MeV, and **very narrow** $\Gamma < 15 Mev$

- Mitya managed **to convince experimentalists** to look for it
- Θ was **discovered** by 3 groups on the level of 5σ in 2003. During the year at least **dozen** of other groups confirmed this on different level of accuracy.

Prediction of exotic antidecuplet

- During 2005-2006 many other group repeated experiments with higher statistics and in different conditions and **did not observe** Θ. At last, in 2007 after the second experiment of CLAS collaboration common wisdom accepted that Θ^+ **is dead...**
- However few groups **did not refuse** from their results. They made new experiments and confirmed Θ^+ again with higher statistics. Subgroup of CLAS found Θ^+ in the same data... Last paper with **observation of** Θ^+ appeared a week ago. They see Θ^+ on the level 6.3σ. Also there are evidences in existence of another particle from antidecuplet — $N(1685)$.
- Situation **remains indefinite**

Confinement in the dyon vacuum, 2004-2007, together with V.P.

- **There are no confinement in the instanton vacuum**. Confinement is related to **long range correlations**
- **Main role** in **average** vacuum fluctuations and **bulk properties** of hadrons is played by spontaneous breaking of **chiral symmetry**. However, always there are properties **dominated** by confinement.
- One has **to marry** instanton vacuum and confinement

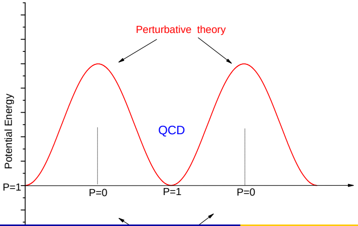
t'Hooft and Mitya: discussing confinement

Confinement

- Polyakov: **order parameter** for confinement is given by Polyakov's loop:

$$\mathcal{P}\exp\left[i\int_0^\beta A_\mu dx_\mu\right] = \begin{cases} \neq 0 & \text{no confinement} \\ = 0 & \text{confinement} \end{cases}$$

- $\beta = 1/T$, **T -temperature**. We do not understand what happens at $T = 0$, perturbative regime — **large T** Potential energy at $T \neq 0$ depends on **logarithm of Polyakov's loop** (Gross,Pisarsky, Jaffe)

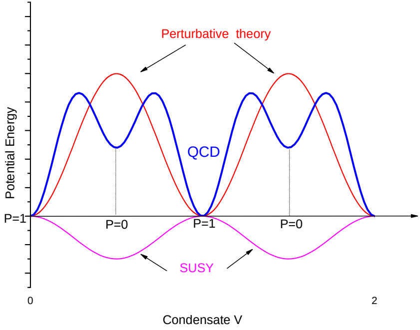


Periodic function with minimum at **loop =0**

Confinement

- At non-zero Polyakov's loop **instanton melts** — classical solution corresponds 2 **dyons** ($SU(2)$) at some distance (P.Baal, Kraan, 2001). In $SU(N_c)$ instanton decay into N_c **dyons**
- **Dyon** — particle with equal ± 1 color **electric and magnetic** charges
- Theory of **dyon vacuum** is constructed analogous to the instanton vacuum theory. However it has specifics due to **long range interaction** of dyons (D.I.Diakonov& V.P., 2005)
- One can calculate effective **non-perturbative** potential for Polyakov's loop due to **dyons**. It has mnimum at $<\mathcal{P}>=0$

Confinement



Perturbative potential grows with T, non-perturbative remains constant. At some T minimum moves to $\mathcal{P} = 0$ - this means **confinement-deconfinement phase transition**

- In $N = 1$ SUSY Yang-Mills theory **only non-perturbative potential exists** (known exactly!). There are no phase transition in this theory — **it has confinement at any temperature**

Confinement

Theory based on dyons **reproduces correctly**

- Phase transition is of the 2nd order for $SU(2)$, **and first order for $SU(N_c)$**
- gives non-zero **string tension** σ and reproduces correctly **the ratio** $\frac{\sqrt{\sigma}}{T_c}$ for different N_c
- Predicts for string tension in**representations**

$$\sigma_k = \sigma_0 \sin\left(\frac{\pi k}{N_c}\right)$$

  ($k = J$ in $SU(2)$ group). This formula **better than Casimir scaling** coincides with lattice data.
- Below phase transition $\sigma_{el} = \sigma_{mag}$ (σ_{mag} — string tension determined with space Wilson loop) . At $T > T_c$ $\sigma_{el} = 0$ and σ_{mag} **practically do not change**

Confinement

- Reproduce correctly gluon condensate

$$< \frac{G_{\mu\nu}^2}{32\pi^2} >= (255 MeV)^4$$

  and topological charge condensate ($O(1)$, and not $O(N_c)$ as in instanton vacuum)

$$< Q_t Q_t >= (181 MeV)^4$$

  (string tension is fixed)
- This theory should proceed smoothly to **the instanton vacuum**. However at small T **the theory is not under control**.

Mitya's papers which I do not mention

- at high energies in the Standard Model. Calculation of **'holy Graal'** function in 1 and 2 loops

- Yang-Mills theory in gauge invariant terms. Theory **dual** to pure QCD is equivalent to **gravitational theory**. For $SU(2)$ and in $d = 3$ it is Einstein gravity, in other cases lead to **more general relativity**. This symmetry **mixes** particles of different spins (like SUSY) but only integer ones. The dual QCD can be formulated as **deformation of topological theory**
- Method of **singular classical solutions** for semi-classical **baryon number violation**

Mitya's papers which I do not mention

- Representation of Polyakov and Wilson loops in the Yang-Mills and gravity theory with functional integral
- ....

- Calculations of primordial **baryon asymmetry washing** due to **sphaleron** transitions
- Effective potential in perturbation theory for Polyakov's loop, kinetic energy terms.
- Instanton vacuum at non-zero temperature and density, restoration of chiral symmetry at large baryon density.
- Spinor gravity on the lattice