1.1 Fields and Particles

Theoretical research in Fields and Particles division in 2003-2004 was carried out in accordance with he following projects:

- The Standard Model and its extensions
- QCD: spin effects and sum rules
- Nonperturbative methods in QFT
- Effective theories and Hadron Physics
- Low-energy Quark Models of Light hadrons
- Symmetries and Gauge Theories

In recent years, following the main tendencies in high energy physics we have started a new activity in neutrino physics and astroparticle physics related to these intensively developing fields. Below one can find a collection of mini reports on various topics which contain a detailed description of the results obtained at BLTP during the last two years. The main ones include:

- Calculation of the anomalous dimensions of the so-called Wilson operators in N=4 supersymmetric gauge theory in higher orders of perturbation theory (A. Kotikov et al). This very advanced calculation allows one to check a hypothesis on the structure of supersymmetric theory.
- Investigation of properties of the QCD vacuum, in particular, the domain model related to the long-standing problem of confinement in QCD (S. Nedelko et al). This model reproduces several main features of QCD vacuum in particular quark condensates.
- The rigorous analysis of QCD nonperturbative coupling in coordinate space is performed (D.V. Shirkov).
- Discussion of the possibility for SUSY searches in space, and investigation of the hypothetical dark matter halo of the Milky way (D. Kazakov, A. Gladyshev et al). This is the first evidence for the indirect manifestation of the dark matter interpreted as SUSY dark matter maid from heavy neutral particle - neutralino.
- Investigation of the spin properties of the proton in semi-inclusive deep inelastic scattering (A. Efremov). A probabilistic model is developed that includes transversity distribution which is the subject of HERMES and COMPASS experiments.
- Elaborative QCD analysis of the pion structure, electromagnetic formfactor and differential pion characteristics (A. Bakulev, S. Mikhailov). Detailed description of the pion is obtained on the basis of the pion distribution amplitude which perfectly explains experimental data.
- Investigation of distribution amplitudes of exotic mesons and meson pairs (I. Anikin, O. Teryaev). The QCD description of ρ^0-meson pair production in L3 experiment and predictions for hard electroproduction of quark-gluon hybrids are obtained.
- Investigation of nonperturbative properties of the QCD vacuum in the instanton liquid model (A. Dorokhov). The transition from perturbative to nonperturbative regime is described which can be used in description of dynamics at intermediate momenta.

– Application of the nonlinear chiral model with nonlocal kernel to the description of meson properties (M. Volkov et al).

– Investigation of cooling of neutron stars on the basis of the nonlocal chiral quark model (D. Blaschke et. al).

– Application of perturbative QCD to the analysis of semi-inclusive deep inelastic scattering data from HERMES and COMPASS experiments (A. Sissakian et al). The method allows one to extract the polarized strangeness content of the nucleon.

– Calculation of the radiative corrections to high energy QED processes at modern colliders (E. Kuraev, A. Arbuzov et al). These corrections, which include electron-positron, electron-photon and electron-proton processes, are vitally important for the calibration of colliders and extracting experimental data.

– Investigation of neutrino interactions with nucleons (V. Naumov). The developed model allows one to describe the processes of neutrino interaction with the target and production of the secondary pion essential for all modern neutrino experiments.

– Investigation of polarization of the electron-positron vacuum by a strong magnetic field in a theory with fundamental mass as a possible option of the physics beyond the Standard Model (V. Kadyshevsky et al).

– High precision calculation of the properties of three-body atoms and molecules (V. Korobov). Record precision is achieved in the calculation of the ground state energies, transition energies and QED radiative corrections in helium atom and hydrogen molecules.

There are also several topics that are not included in this report, but are present in the list of references. They reflect a wide diversity of fields of research in Fields and Particles division of BLTP following the main directions of activity in modern particle physics.

D.I. Kazakov

ANOMALOUS DIMENSIONS OF THE WILSON OPERATORS IN THE N=4 SUPERSYMMETRIC GAUGE THEORY

A.V. Kotikov, L.N. Lipatov[1], A.I. Onishchenko[1], V.N. Velizhanin[1]
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The anomalous dimensions (AD) of the twist-two Wilson operators govern the Bjorken scaling violation for parton distributions in the framework of Quantum Chromodynamics (QCD). expressed through the Mellin transformation

$$\gamma_{ab}(j) = \int_0^1 dx\, x^{j-1} W_{b\to a}(x)$$

of the splitting kernels $W_{b\to a}(x)$ for the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equation which relates the parton densities $f_a(x,Q^2)$ (hereafter $a = \lambda,\, g,\, \phi$ for the spinor, vector, and scalar particles, respectively) with different values of Q^2 as follows:

$$\frac{d}{d\ln Q^2} f_a(x,Q^2) = \int_x^1 \frac{dy}{y} \sum_b W_{b\to a}(x/y)\, f_b(y,Q^2)\,.$$

The anomalous dimensions and splitting kernels in QCD are now well known up to the next-to-next-to-leading order (NNLO) of perturbation theory.

The QCD expressions for AD can be transformed to the case of the $\mathcal{N}=1$ Supersymmetric gauge theory (SUSY) if one uses for the Casimir operators C_A, C_F, T_f the following values $C_A = C_F = N_c$, $T_f = N_c/2$ (the last substitution follows from the fact that each gluino λ_i being a Majorana particle gives half of the contribution for the Dirac spinor). For extended supersymmetric theories the anomalous dimensions cannot be obtained in this simple way, because additional contributions coming from scalar particles should also be taken into account. Recently these anomalous dimensions were calculated in the next-to-leading (NLO) approximation [1] for the $\mathcal{N}=4$ Supersymmetric Yang-Mills theory.

However, it turns out, that the expressions for eigenvalues of the AD matrix in the $\mathcal{N}=4$ SUSY can be derived directly from the QCD anomalous dimensions without tedious calculations by using a number of plausible arguments. The method elaborated in Ref. [2] for this purpose is based on special properties of solutions of the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation in this model (see [3]). In the NLO approximation this method gives the correct results for AD eigenvalues, which were checked by direct calculations in [1].

The NNLO corrections to AD in QCD were calculated recently [4]. Using these results and the above method we derived in [5] the eigenvalues of the AD anomalous dimension matrix for the $\mathcal{N}=4$ SUSY in the NNLO approximation.

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DOMAIN MODEL OF THE QCD VACUUM

S.N. Nedelko

A mechanism which simultaneously provides for confinement of colour, spontaneously broken chiral symmetry, and a resolution of the $U_A(1)$ problem is still to be understood in QCD today. Partial solutions based on specific semi-classical or topologically stable configurations (like instantons, abelian monopoles, center vortices) can go some way to manifest this triplet of phenomena [1] but founder either on generating all three or in allowing for an effective, phenomenologically valuable, hadronization model. The purpose of identifying the typical features of nonperturbative gluonic configurations which can provide for as many gross features of nonperturbative QCD as possible, and preserving simultaneously the well-studied short distance regime can be achieved by studying various models of QCD vacuum and hadronization.

The "domain model", originally proposed in [2], belongs to the class of background field models, shared, for instance, with instanton liquid model. In order to define the QCD functional integral in these approaches one represents general gluon fields as $A = B + Q$ with the background B from the class of fields dominating the integral and Q being small localised fluctuations in this background. The integral over fields B has to be performed exactly, while fluctuations Q can be treated perturbatively. In the domain model the dominating fields $B^a_\mu(x)$ are required to satisfy the condition $F^a_{\mu\nu}(x)F^a_{\mu\nu}(x) = B^2$ almost everywhere in Euclidean space-time ($B =$ const) , which, and this is important, neither forbids space-time variation of the strength tensor and the fields $B^a_\mu(x)$ nor devalues the importance of topological (singular) pure gauge field defects of various dimensions. The role of these defects in the model is to generate boundary conditions for the fluctuations of gluon and quark fields Q and ψ inside domains [2]. In a sense, the model represents a "step-function" approximation to a class of fields with infinite classical action which are assumed to dominate the QCD partition function. The building blocks of this approximation are domains with mean size R and mean action density B^2, whose values are determined from the phenomenological string tension in [2]. The field in domains is taken to be (anti)-self-dual, a mean absolute value q of the integral of the topological charge density over the domain volume is expressed through the mean domain size R and mean action density. This quantity can take any real values. The partition function of the model describes a statistical system of domain-like structures of finite density. Each domain is characterised by a set of internal parameters associated with the covariantly constant abelian mean field B^a_μ (e.g., space and colour orientations, (anti-)self-duality) and with internal dynamics represented by fluctuation gluon Q and quark ψ fields. It relates to the symmetries of QCD since the statistical ensemble is invariant under space-time, colour gauge and chiral symmetries. The model involves two free parameters: the mean field strength B related to the lowest gluon condensate and the mean domain radius R which can be associated with the topological succeptibility of the pure gluodynamics.

Without further tuning the model this setup for the background field B provides for confinement of both static (area law) and dynamic (propagators are entire functions of momentum) quarks [2], spontaneous breaking of the flavour $SU_L(N_f) \times SU_R(N_f)$ chiral symmetry [3], and a resolution of $U_A(1)$ problem without introducing the strong CP problem [4, 5]. These features are seen both at the quark-gluon level and in terms of colourless hadrons. The hadronization procedure of [6] adopted (so far – partially) in the case of the domain model leads to the effective hadron Lagrangian [3] with the spectrum of mesons describing experimental data with good accuracy. Static characteristics of the vacuum (quark and gluon condensates, string constant, and topological succeptibility) are in quantitative agreement with the generally accepted values.

These results are consequences of several qualitatively important aspects of the model. An area law appears due to finite range correlations of the background field B^a_μ [2]. Strong mean field inside domains and boundary effects lead to the nonlocal character of dynamics of the quark ψ and gluon Q fluctuations providing for entire quark and gluon propagators [2]. Chiral symmetry realization is due to the specific chiral properties of quark eigenmodes: the discrete spectrum λ_n of the Dirac operator is asymmetric with respect to $\lambda_n \to -\lambda_n$ and zero quark modes are absent, but the local chirality of all nonzero modes at the centre of domains is correlated with the duality of the background field. This asymmetry results in the nonzero quark condensate responsible for the spontaneous breaking of flavour chiral symmetry and for the specific form of the axial anomaly providing for the non-Goldstone character of $U_A(1)$ realisation [3]. The same specific form of the anomaly simultaneously resolves the strong CP-problem in the model if mean value of the unit "topological charge" q takes an irrational value [4, 5]. Nonlocality can potentially lead to the unphysical exponential growth of hadronic amplitudes at high energies. This problem was preliminary studied in [7] within the exactly solvable nonlocal model with confined fundamental fields and Regge spectrum of relativistic bound states. It was found that proper taking into account the finite width of resonances can suppress unphysical growth of observable quantities at high energies.

In conclusion, it should be stressed that being quite a rough approximation of the genuine QCD vacuum the above-described model cannot reproduce certain subtle features of QCD like, for instance, Casimir scaling. The status of approximations and assumptions made in the model requires a further careful investigation.

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TAUBERIAN THEOREM AND QCD EFFECTIVE COUPLING IN THE DISTANCE REPRESENTATION

D.V. Shirkov

We discuss the correlation of some singular long–range asymptotic behaviors to the IR momentum region. This correlation is popular in quantum physics where, one uses the so–called "quantum–mechanical correspondence relation" $r \to 1/Q$ which in the IR case is equivalent to

$$F(Q) \sim f(Q^{-1}) \quad \text{as} \quad Q \to 0\,. \tag{1}$$

Heuristically, this last feature could be simply understood by a change of the integration variable $r \to x = rQ$ in the general linear transformation

$$F(Q) = \int_0^\infty \frac{dx}{x} K(x)\, f\left(\frac{x}{Q}\right)\,. \tag{2}$$

However, for a more rigorous derivation of (1) one needs to specify some asymptotic property of the function $f(r)$ as $r \to \infty$. In short, this can be formulated as the Tauberian theorem[1]: (Here, the symbol " $\sim$ " means "behaves like".)

If function $f(r)$ asymptotically satisfies "the separability condition"

$$f(kr) \sim C\phi(r)\rho(k) \quad as \quad k \to \infty \quad with \quad C \neq 0\,, \tag{S}$$

then, under some additional conditions, its Fourier image obeys the property

$$F(Q) \sim \rho(1/Q) \quad as \quad Q \to 0\,, \tag{T}$$

— that, with some reservation, follows from eq.(2).

Now, for a definite class of functions $\rho(k)$ entering into the condition (S), e.g., of power and/or logarithmic type

$$f(r) \sim \rho(r) \sim r^\beta (\ln r)^\gamma (\ln\ln r)^\delta \ldots \quad \text{as} \quad r \to \infty\,, \tag{3}$$

it is possible to obtain from (T) the correspondence rule (1). Meanwhile, this class of functions is rather narrow. For instance, it does not contain trigonometric functions and exponentials.

In particular, this concerns recent ALPHA collaboration results on the asymptotic behavior of the QCD effective coupling obtained by lattice simulation. There, numerically calculated behavior of effective QCD coupling defined via Schroedinger functional has an exponential form

$$\bar{\alpha}_{SF}(L) \simeq e^{mL}\,.$$

D.V. Shirkov, "On the Fourier transformation of Renormalization Invariant Coupling", *TMP* **136** (2003) 893-907; hep-ph/0210113.

[1] Originally, under the name of Tauberian theorems one implied statements concerning the relation between *summability* and *convergence* of series. More recently, in the middle of XX century, this term started to be used in the context of asymptotic properties of integral transformations. Here, we give only a crude outline of this important theorem for the Fourier transformation, the sketch that is sufficient for our application.

SEARCH FOR SUSY MANIFESTATION IN SPACE

D. Kazakov, A. Gladyshev,
W. de Boer[1], C. Sander[1], M. Herold[1], V. Zhukov[1]
[1] IEKP, Univ. Karlsruhe

1. Search for various manifestations of supersymmetry in Nature was one of the main aims of numerous experiments at colliders and non-accelerator facilities in the previous decade. Theoretical investigation of the Minimal Supersymmetric Standard Model (MSSM) has shown that it is possible to meet different requirements such as a) unification of the strong and electroweak forces, thus providing a prototype theory for a Grand Unified Theory (GUT); b) spontaneous electroweak symmetry breaking (EWSB) by radiative corrections through the heavy t-quark; c) unification of Yukawa couplings resulting in the correct values of the masses of the third generation quarks and leptons; d) small corrections to the rare meson decays allowing one to fill the gap between the SM and experiment; e) data on the muon anomalous magnetic moment, the observed deviation from the SM may be described by additional SUSY contributions and fixes the sign of the Higgs mixing parameter μ, killing half of the parameter space; f) right amount of the Dark matter in the Universe due to the presence of a light stable particle – neutralino, etc.

The constrained MSSM which simultaneously fulfills all the requirements happens to be a very predictive theory. Within the allowed regions in the parameter space it gives the spectrum of superpartners and the Higgs bosons, thus providing the pattern for experimental search. Two main scenarios selected by the above- mentioned requirements are usually referred to as low and high $\tan\beta$ ones, $\tan\beta$ being the ratio of the v.e.v.s of the two Higgs bosons. The first scenario typically predicts relatively light superpartners and the lightest Higgs boson below 100 GeV, and is practically excluded by modern collider data. Search for the light charginos and neutralinos and the Higgs boson at LEP II collider gave no results and increased the bound for $\tan\beta$ up to 4.3. On the contrary, high $\tan\beta$ scenario predicts relatively heavier particles and is under test now. Moreover, the high $\tan\beta$ scenario ($\tan\beta \sim 50$) is favoured by the recent astrophysical data [1, 3].

2. Among the recent nonaccelerator experimental data which attracted much attention are the very precise data on the thermal fluctuations of the Cosmic Microwave Background Radiation provided by the Wilkinson Microwave Anisotropy Probe (WMAP) [2]. The analysis of the data implies the amount of the dark matter in the Universe to be $23 \pm 4\%$.

Supersymmetry provides us with an excellent candidate for the cold nonbaryonic Dark matter, usually assumed to be formed from Weakly Interacting Massive Particles (WIMP). The lightest neutralino (the mixture of superpartners of photon, Z-boson and neutral Higgs bosons) being the lightest supersymmetric particle (LSP) is stable if R-parity is conserved.

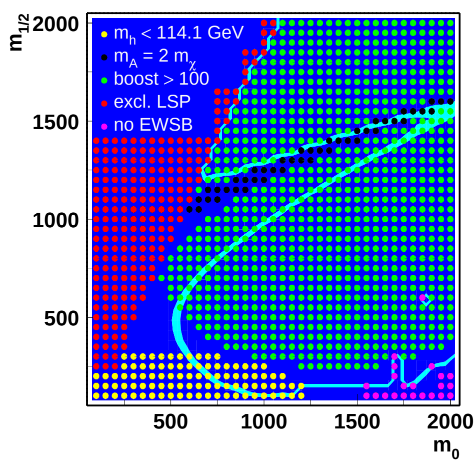

Figure 1: *Allowed regions of the parameter space in the Constrained MSSM*

The cross sections for the neutralino annihilation are typically of the order of the weak ones, so the LSP is "neutrinolike", i.e. it would form halos around the galaxies and, consequently, it is an excellent candidate for dark matter. Having this in mind one gets very severe constraints on the parameter space shown by a narrow blue line in Fig. 1.

3. Galactic gamma rays have been extensively studied during the nine years of data taking by the EGRET satellite on the Compton Gamma Ray Observatory. These data show a clear excess of diffuse gamma rays above the background from conventional galactic sources for energies above 1 GeV [4].

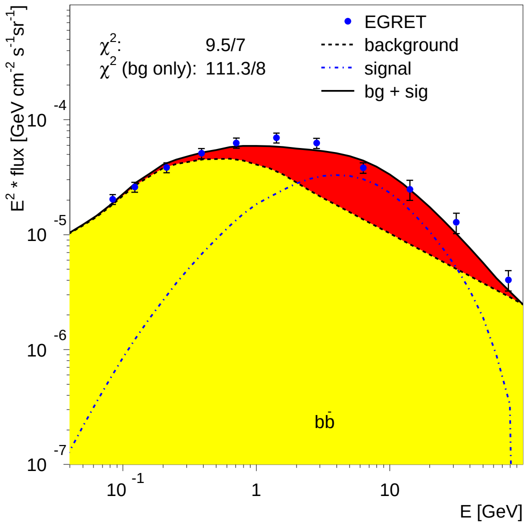

Figure 2: *The diffuse galactic gamma ray energy spectrum*

Of course, there are also many sources of diffuse gamma rays in the galaxy, so disentangling the annihilation signal is at first glance not easy. The main sources of conventional background are: a) decays from π_0 mesons produced in nuclear interactions (mainly inelastic proton-proton or p-He collisions); b) inverse Compton scattering of electrons on photons (e.g. from star light or cosmic microwave background); c) Bremsstrahlung from electrons. WIMP's are expected to annihilate in fermion-antifermion pairs, so a large fraction will annihilate into quark pairs, which produce typically 30-40 photons per annihilation in the fragmentation process (mainly from π_0 decays as in nuclear interactions).

However, the photons from the dark matter annihilation (DMA) are expected to have a significantly different spectrum than the ones from nuclear interactions. This can be easily seen as follows: the WIMP's are strongly nonrelativistic, so they annihilate almost at rest. Therefore, quarks from DMA are almost monoenergetic with an energy approximately equal to the WIMP mass. This results in a rather energetic spectrum with a sharp cut-off of the photons at twice the WIMP mass. Fig. 2 shows the diffuse gamma ray data together with the data from the background processes which are shown by the yellow area and clearly fails to describe the EGRET data shown by the points with vertical error bars. The fit to the EGRET data including DMA is shown by red area for a WIMP mass of 90 GeV [3]. Data on positron or antiproton fluxes can also be described in the same framework [5].

4. The neutralino with a mass of around 90 GeV also allows one to describe the rotation curves of the Milky Way (Fig. 3) [3]. The rotation curve of our galaxy shows a peculiar nonflat structure near our solar system, namely at $R = 1.1R_0$ kpc the slope changes the sign, the data are from Refs. [6]. We suggest a model of the dark matter distribution in the Milky Way, assuming that besides the halo surrounding the galaxy, there are two rings with larger dark matter density at $R = 4.3$ and 14 kpc. This two ring model describes the structure of the rotation curve very well, as shown in Fig. 3.

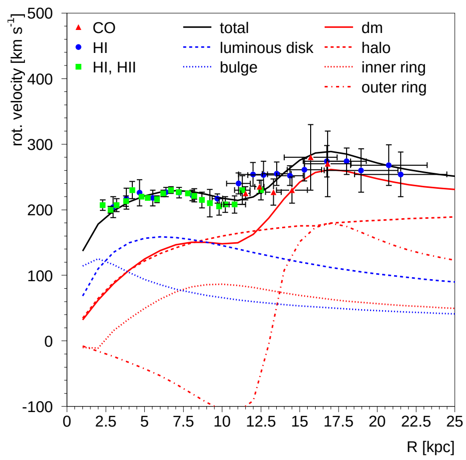

Figure 3: *Milky Way rotation curve*

The contributions from each of the mass terms is shown separately. The basic explanation for the negative contribution from the outer ring is that a tracer star at the inside of the ring at 14 kpc feels an outward force from the ring, thus a negative contribution to the rotation velocity. In order to calculate this more quantitatively, one needs the complete distribution of both the visible and DM mass.

5. The regions consistent with the WMAP constraint are: the first one around $m_0 = 600$ GeV, $m_{1/2} = 400$ GeV and the second one around $m_0 = 1400$ GeV, $m_{1/2} = 180$ GeV.

The latter region is strongly preferred by the EGRET diffuse galactic gamma ray spectrum. The evolution of the sparticle masses for it from the GUT scale values towards lower energies is shown in Fig. 4 [3].

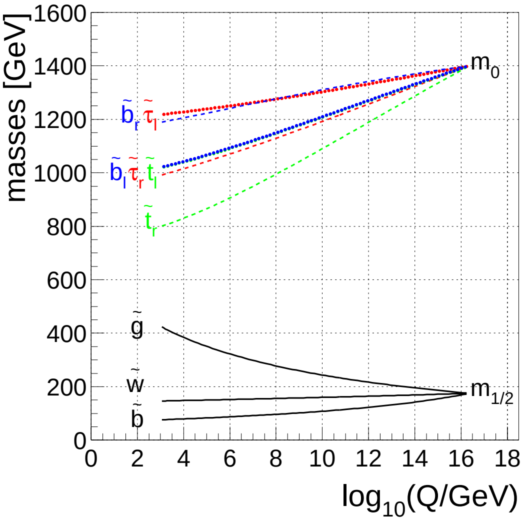

Figure 4: *The evolution of the particle spectrum for $m_0 = 1400$, $m_{1/2} = 180$ GeV*

The large value of m_0 yields squark and slepton masses around 1 TeV, but the gluinos and charginos are relatively light, which would have interesting consequences for searches at future colliders. The compatibility with Supersymmetry implies the possibility that the Dark Matter is the supersymmetric partner of the Cosmic Microwave Background. Future experiments from 2007 onwards at the Large Hadron Collider under construction at CERN will tell, since the predicted sparticle masses from the present analysis are within the range of this accelerator with a center of mass energy of 14000 GeV.

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PROTON TRANSVERSITY AND AZIMUTHAL ASYMMETRIES IN SIDIS

A.V. Efremov

It is well known that three most important (twist-2) Parton Distribution Functions (PDF) in a nucleon are the nonpolarized distribution function $f_1(x)$, helicity distribution $g_1(x)$ and the transverse spin (transversity) distribution $h_1(x)$. The first two have been more or less successfully measured experimentally in classical Deep Inelastic Scattering (DIS) experiments but the measurement of the last one is especially difficult since it corresponds to interference of helicity amplitudes, belongs to the class of the so-called chiral-odd structure functions, and can not be seen in DIS. That is why it was completely unknown experimentally till recent time. The only information comes from the Soffer inequality $|h_1(x)| \leq \frac{1}{2}[f_1(x)+g_1(x)]$ which follows from density matrix positivity and theoretical models.

To access the transversity, one needs either to scatter two polarized hadrons and measure the transversal spin correlation A_{TT} in the Drell-Yan process or to know the transverse polarization of the quark scattered from transversely polarized target. This could be done using a new spin dependent T-odd parton fragmentation function (PFF) responsible for the left-right asymmetry in one particle fragmentation of transversely polarized quark with respect to quark momentum–spin plane. (The so-called "Collins effect".)

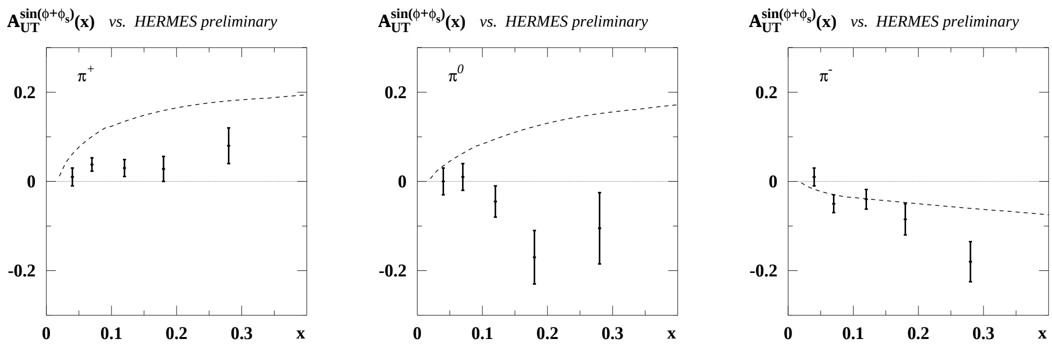

Figure 1: The Collins effect transverse target SSA $A_{0T}^{\sin(\phi+\phi_s)}$ in the production of π^+, π^0 and π^- from a proton target. *Preliminary* data are from HERMES.

Using the parton distribution functions from the chiral quark-soliton model predictions were made [1] for x-dependence of the Single Spin azimuthal Asymmetries (SSA) due to the Collins effect in pion production from Semi-Inclusive Deeply Inelastic Scattering (SIDIS) off transversely polarized targets for the HERMES and COMPASS experiments. The overall normalization of the predicted asymmetries is determined by the information on the Collins PFF extracted from the previous HERMES data on azimuthal asymmetries $A_{UL}^{\sin\phi}$ from a *longitudinally* polarized target where the Sivers effect is shown [2] to be strongly suppressed. The SSA from the *transversely* polarized proton target are found to be about 10% for positive and neutral pions at both HERMES and COMPASS. For a *longitudinally* polarized target for COMPASS the SSA were also predicted: $A_{UL}^{\sin\phi} \sim 0.5\%$ and $A_{UL}^{\sin 2\phi} \sim 1.5\%$. The preliminary data from HERMES more or less agree with predictions for π^- (see Fig.1) but some disagreement is seen for π^+ and especially for π^0. The reason for this could be the clear absence of the x and z factorization in HERMES data, which demands $A(\pi^0) = \frac{\sigma(\pi^+)}{\sigma(\pi^+)+\sigma(\pi^-)}A(\pi^+) + \frac{\sigma(\pi^-)}{\sigma(\pi^+)+\sigma(\pi^-)}A(\pi^-)$, where $\sigma(\pi)$ is unpolarized SIDIS cross section ($\sigma(\pi+)/\sigma(\pi) \approx 1/2$).

The Drell-Yan process remains up to now the theoretically cleanest and safest way to access the nucleon transversity $h_1^a(x)$. The first attempt to study $h_1^a(x)$ by means of the Drell-Yan process is planned at RHIC. Dedicated estimates, however, indicate that at RHIC the access of $h_1^a(x)$ is very difficult since the observable double spin asymmetry A_{TT} is proportional to a product of transversity quark and antiquark. The latter are small even if they were saturated the Soffer upper limit.

This problem can be circumvented by using an antiproton beam. The challenging promising program how to polarize an antiproton beam has recently been suggested in the PAX experiment at GSI. The quantitative estimates for the A_{TT} in the kinematics of the PAX experiment were given [3] on the basis of predictions for the transversity distribution from the chiral quark soliton model (Fig.2a).

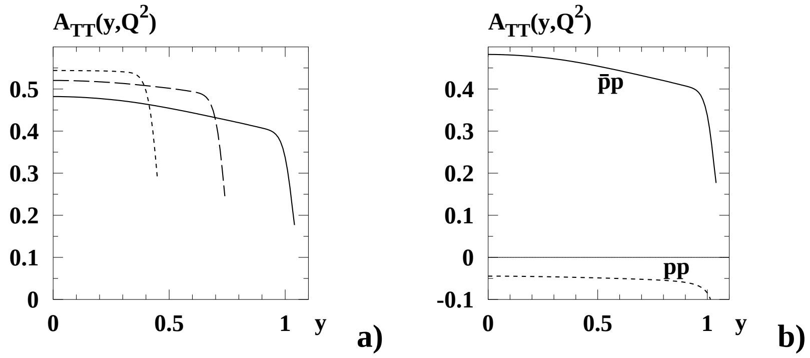

Figure 2: **a)** The asymmetry $A_{TT}(y,M^2)$ at PAX as a function of the rapidity y for $Q^2 = 5\,\mathrm{GeV}^2$ (solid) and $9\,\mathrm{GeV}^2$ (dashed) and $16\,\mathrm{GeV}^2$ (dotted line) for $s = 45\,\mathrm{GeV}^2$. **b)** Comparison of $A_{TT}(y,M^2)$ from proton-antiproton (solid) and proton-proton (dotted line) collisions for $Q^2 = 5\,\mathrm{GeV}^2$.

The advantage of using antiprotons is evident from Fig.2b. The corresponding asymmetry from proton-proton collisions is an order of magnitude smaller. Even if this advantage is compensated by a small antiproton polarization $(5-10)\%$, the counting rates and accuracy are more sizeable.

A probabilistic model of parton distributions, previously developed by one of the authors, was generalized to include also the transversity distribution [4]. It was obtained that when interference effects are attributed to the quark level only, the intrinsic quark motion produces the transversity, which is about twice as large as the usual helicity distribution. The applicability of such a picture is considered and possible corrections accounting for interference effects at the parton-hadron transition stage are discussed.

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DEEP INSIDE THE PION: QCD THEORY VS DATA

A.P. Bakulev, S.V. Mikhailov

Light-cone sum-rule predictions for $F^{\gamma^*\gamma\pi}$ and $F^{\gamma^*\rho\pi}$. Our description of the pion-photon transition form factor, $F^{\gamma^*\gamma\pi}$, emerged from the light-cone sum-rule (LCSR) calculation, is shown in Fig. 1 (right) in comparison with CLEO and CELLO exp. data. This description is based on the Bakulev–Mikhailov–Stefanis (BMS) bunch of the pion distribution amplitude (DA), Fig. 1 (left), and on a complete NLO calculation for the corresponding spectral density. The BMS description (green strip on the right) is inside the 1σ region while the predictions for both asymptotic and Chernyak–Zhitnitsky (CZ) DAs are outside the 3σ region. The $F^{\gamma\rho\pi}$ form factor appears as an inevitable part of the $F^{\gamma\gamma^*\pi}$ transition form factor in this analysis. In

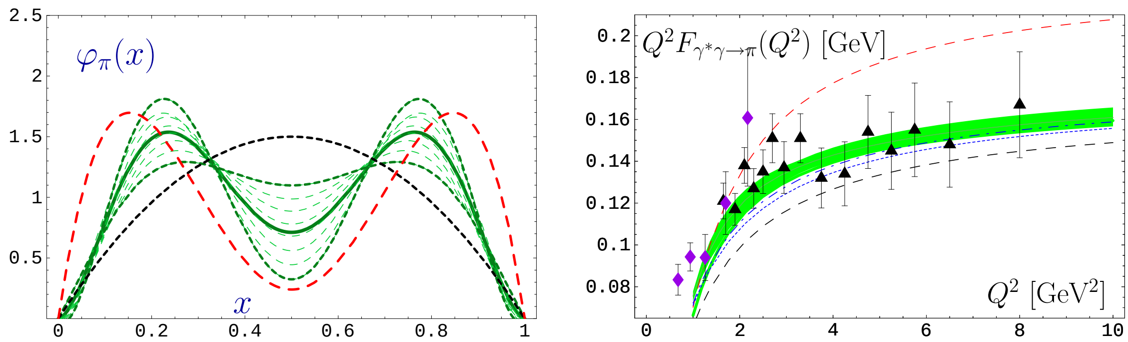

Figure 1: **Left**: BMS "bunch" of the pion DAs contrasted with two extreme alternatives (asymptotic DA—dotted line and CZ model—long-dashed line) at $\mu^2 \approx 1$ GeV^2. **Right**: Light-cone sum-rule predictions for $Q^2 F_{\gamma^*\gamma\to\pi}(Q^2)$ in comparison with the CELLO (diamonds) and the CLEO (triangles) experimental data, evaluated with the twist-4 parameter value $\delta^2_{\text{Tw}-4} = 0.19$ GeV^2. The predictions correspond to selected pion DAs; notably, CZ (upper dashed line), BMS-"bunch" (shaded strip), two instanton-based models (dotted and dash-dotted line), and the asymptotic DA (lower dashed line).

this framework it depends mainly on the *differential* pion characteristic $\frac{d}{dx}\varphi_\pi(x)|_{x=\varepsilon}$, $\varepsilon \sim \frac{s_\rho}{Q^2}$, in the ε-neighborhood of the origin. This feature is opposite to the case of the $Q^2 F^{\gamma\gamma^*\pi}(Q^2)$ form factor which mainly depends on the inverse moment $\langle x^{-1}\rangle_\pi = \int_0^1 \varphi_\pi(x;\mu^2)x^{-1}dx$, i.e., on an *integral* pion characteristic. Therefore $Q^4 F^{\gamma\rho\pi}(Q^2)$ can provide complementary information on the pion DA and help discriminate among different pion DA models. Our predictions for $Q^4 F^{\gamma\rho\pi}(Q^2)$ are presented in Fig. 2 (left) by a shaded strip with the central line denoting the BMS model, their thickness being a practical measure for the allowed variation of the twist-4 parameter $\delta^2_{\text{Tw}-4} = (0.15-0.23)$ GeV^2.

Pion electromagnetic form factor We have calculated the electromagnetic pion form factor $F_\pi(Q^2;\mu_R^2) = F_\pi^{\text{LD}}(Q^2) + F_\pi^{\text{Fact}-\text{WI}}(Q^2;\mu_R^2)$, where the soft part $F_\pi^{\text{LD}}(Q^2)$ is modelled via local duality and the factorized contribution $F_\pi^{\text{Fact}-\text{WI}}(Q^2;\mu_R^2)$ is corrected via a power-behaved pre-factor in order to respect the Ward identity at $Q^2 = 0$. In our analysis $F_\pi^{\text{Fact}}(Q^2;\mu_R^2)$ was computed to NLO using Analytic Perturbation Theory and trading the running coupling and its powers for analytic expressions in the nonpower series expansion, i.e.,

$$\left[F_\pi^{\text{Fact}}(Q^2;\mu_R^2)\right]_{\text{MaxAn}} = \bar{\alpha}_s^{(2)}(\mu_R^2)\,\mathscr{F}_\pi^{\text{LO}}(Q^2) + \frac{1}{\pi}\mathscr{A}_2^{(2)}(\mu_R^2)\,\mathscr{F}_\pi^{\text{NLO}}(Q^2;\mu_R^2)\,,$$

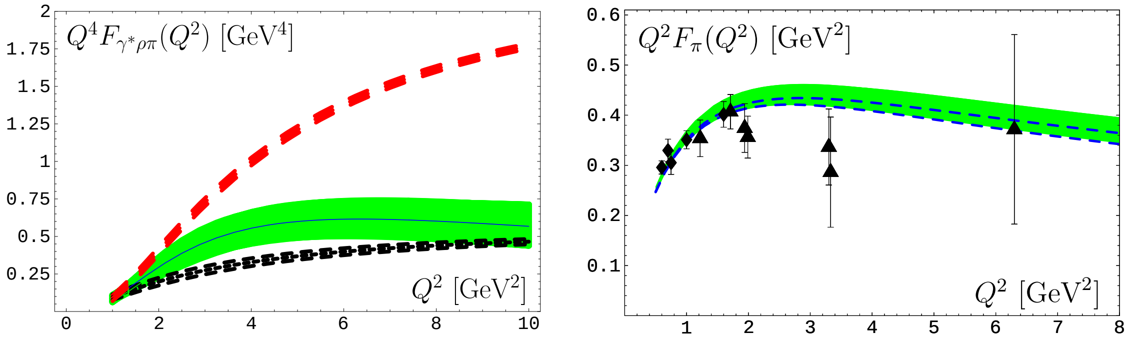

Figure 2: **Left:** Predictions for $Q^4 F^{\gamma\rho\pi}(Q^2)$ for the pion DAs shown on the left. The thickness of the two broken lines corresponds to the variation of the twist-4 parameter in the range $\delta^2_{\text{Tw}-4} = (0.15 - 0.23)$ GeV^2. **Right:** Predictions for the scaled pion form factor calculated with the BMS bunch (green strip) encompassing nonperturbative uncertainties from nonlocal QCD sum rules and renormalization scheme and scale ambiguities at the level of the NLO accuracy. The dashed lines inside the strip restrict the area of predictions accessible to the asymptotic pion DA using the "Maximally Analytic" procedure. The experimental data are taken from JLab (diamonds) and *C. J. Bebek et al.* (triangles).

with $\bar{\alpha}_s^{(2)}$ and $\mathscr{A}_2^{(2)}(\mu_R^2)$ being the 2-loop analytic images of $\alpha_s(Q^2)$ and $\left(\alpha_s(Q^2)\right)^2$, correspondingly, whereas $\mathscr{F}_\pi^{\text{LO}}(Q^2)$ and $\mathscr{F}_\pi^{\text{NLO}}(Q^2;\mu_R^2)$ are the LO and NLO parts of the factorized form factor, respectively. The phenomenological upshot of this analysis is presented in Fig. 2 (right), where we show $F_\pi(Q^2)$ for the BMS "bunch" using the "Maximally Analytic" procedure which substantially reduces the scheme and scale setting uncertainties (the width of the corresponding strip in Fig. 2 (right) is determined by these rather small uncertainties, as well as by those due to the BMS bunch). This new procedure replaces the running coupling and its powers by their own analytic images and provides results in rather good agreement with the experimental data, given also the large errors of the latter. (*Let us note here that the old data due to C. J. Bebek et al. depicted in Fig. 2 (right) are now considered by JLab groups as being underestimated*). One appreciates that the form-factor predictions are only slightly larger than those resulting with the asymptotic DA.

For more details and complete references see:

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QCD LIGHT CONE DISTRIBUTIONS OF HADRONIC SYSTEMS AND EXOTIC STATES

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1. The current development of high energy physics includes the "renaissance" of hadron spectroscopy (see e.g. [1] and Ref. therein). The hadrons which cannot be included in the standard scheme of $q\bar{q}$ mesons and qqq baryons became the object of rigorous theoretical and experimental studies. This may be an important step in understanding the nonperturbative QCD.

A special role in relating the theory and experiment is played by the QCD factorization for hard processes when both perturbative and nonperturbative ingredients are well-defined and provide suitable objects for perturbative and nonperturbative calculations, respectively. The maturity of this approach results in the variety of the nonperturbative ingredients describing various semi-inclusive and exclusive [2] hadronic processes.

2. The simplest and known hadronic light-cone distribution is that of the pion that manifested itself in the scaling behaviour of the transition form-factor studied in the collisions of real and virtual photons. It was proved that the production of two or three mesons should be described in a similar way [3, 4]. This prediction was confirmed when such a scaling behaviour was found [5] in the production of two $\rho-$mesons. It marked the experimental discovery of the first multimeson distribution amplitudes. The detailed theoretical analysis [6] showed that the meson spin does not affect the resulting Q^2-dependence when the average over final particles angular distribution is performed. The good quantitative description of the data is achieved (see Fig. 1).

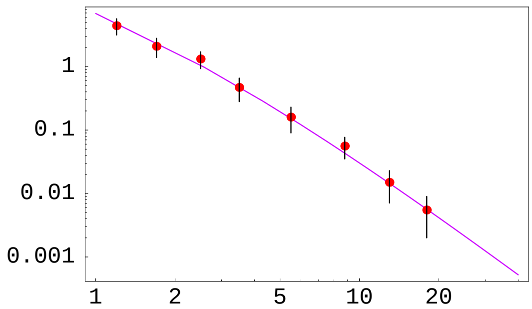

Figure 1: Cross-section $d\sigma/dQ^2[pb/GeV^2]$ as a function of $Q^2[GeV^2]$

3. Light-cone distributions generally provide the description of hadronic states different from the one in terms of nonrelativistic quark wave functions. This brings the problem of the lightcone distributions of exotic states, namely, to which extent the operators on the light cone follow the content defined by the low energy structure. The detailed analysis of the quark-gluon hybrid state [7] shows that the quantum numbers may be carried by gluons associated with the string required by the colour gauge invariance. This results in the leading twist amplitude of the hybrid meson production, contrary to the naive expectations. Hybrid production may be studied through its interference with nonexotic states, resulting in the angular asymmetries in production of the meson pair consisting of one pion and one η meson [8].

4. The specific case when low-energy and light-cone structures are intimately related -is provided by the $I = 2$ four-quark state which does not have a projection to a quark-antiquark state. Its existence was suggested [9] in order to explain the relative production of charged and neutral ρ mesons in real photon collisions. The generalization of this approach to the case of virtual photons naturally explains the observed experimental features like a twice larger production of charged mesons at large Q^2 due to the leading twist $I = 0$ state, while its interference with the twist-4 $I = 2$ state should explain the intersection of cross-sections of charged and

neutral mesons at the transition point $Q^2 \sim 1GeV^2$ [10]. The detailed theoretical analysis [11] of this effect will allow a first direct study of a four-quark state via a higher twist light-cone distribution.

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NONLOCAL $SU(2) \times SU(2)$ SYMMETRIC MODEL WITH QUARK CONFINEMENT

A.E. Dorokhov, A.E. Radzhabov, and M.K. Volkov

Masses and interactions of light mesons are described in the framework of the model with the chiral invariant $SU(2) \times SU(2)$ four-quark interaction [1, 2]. The nonlocal kernel of the interaction is chosen in the form that ensures the absence of ultraviolet divergences in the Feynman diagrams and poles in the quark propagator. This form of kernel is motivated by the instanton interaction. This model is a nonlocal extension of the well-known Nambu–Jona-Lasinio (NJL) model with local quark interaction. However, with nonlocal form-factors, quark loops are free of ultraviolet divergences and it is possible to implement the quark confinement. The use of a covariant nonlocal low-energy quark model based on a self-consistent approach to the dynamics of quarks has many attractive features: it preserves gauge invariance, it is consistent with the low-energy theorems as well as takes into account the large-distance dynamics controlled by bound states.

The pseudoscalar, scalar, vector, and axial-vector mesons are considered in the model. The σ, a_1 meson masses and the widths of main strong decays $\sigma \to \pi\pi$, $\rho \to \pi\pi$ and $a_1 \to \rho\pi$ are estimated.

Nonlocal models, in contrast with the local NJL model, can be successfully used for the description of the constant part of amplitudes of meson interactions as well as the momentum dependence of amplitudes at small energies. It becomes possible to describe a set of important meson properties: electromagnetic radii, electric and magnetic polarizabilities, meson-meson scattering lengths, slope parameters of different processes and so on. In some cases (for example, the pion radii [3]) the standard local NJL model may lead to incorrect results. In nonlocal models, the contribution of the diagrams with intermediate vector mesons is shown to be suppressed and the electromagnetic radius of charged pion and the transition radius of the neutral one are in good agreement with experimental value. At the same ρ-meson diagrams play a very important role for description of the form-factor of the process $\gamma^* \pi^+ \pi^-$ in the time-like region. It is shown that the pion polarizability in a nonlocal model is noticeably smaller than in the local NJL model and is very sensitive to the form of nonlocality [4].

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CORRELATORS OF VECTOR AND AXIAL-VECTOR CURRENTS IN THE INSTANTON LIQUID MODEL

A.E. Dorokhov

The transition from perturbative regime of QCD to nonperturbative one has yet remained under discussion. At high momenta the fundamental degrees of freedom are almost massless quarks. At low momenta the nonperturbative regime is adequately described in terms of constituent quarks with masses dynamically generated by spontaneous breaking of chiral symmetry. The instanton model of QCD vacuum provides the mechanism of dynamical quark dressing in the background of instanton vacuum and leads to generation of the momentum dependent quark mass that interpolates these two extremes. Still it is not clear how an intuitive picture of this transition may be tested at the level of observables. In order to clarify the problem we considered the correlators of vector and axial-vector currents in channels with different quantum numbers [1]-[4].

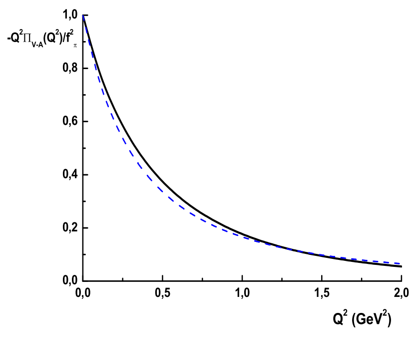

Figure 1: Normalized $V-A$ correlation function constructed in the NχQM (solid line) and reconstructed from the ALEPH experimental spectral function (dashed line).

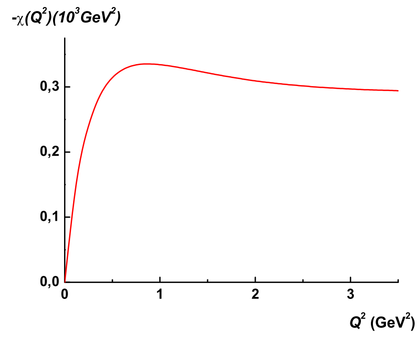

Figure 2: Topological susceptibility versus Q^2 predicted by the NχQmodel.

The behavior of nonperturbative parts of the isovector-vector and isovector axial-vector correlators at Euclidean momenta was studied in the framework of a covariant chiral quark model with instanton-like quark-quark interaction (NχQM). The gauge covariance is ensured with the help of the P-exponents, with the corresponding modification of the quark-current interaction vertices taken into account[1]. The low- and high-momentum behavior of the correlators is compared with the chiral perturbation theory and with the QCD operator product expansion, respectively. The V-A combination of the correlators obtained in the model reproduces quantitatively the ALEPH data on hadronic τ decays transformed into the Euclidean domain via dispersion relations (Fig. 1). The predictions for the electromagnetic $\pi^{\pm} - \pi^0$ mass difference and for the pion electric polarizability obtained from the chiral sum rules are also in agreement with experimental values [2].

The topological susceptibility of QCD vacuum (the correlator of the isosinglet axial-vector currents) was studied within the same approach as a function of momentum transfer $\chi(Q^2)$ [3] (Fig. 2). Its first moment was predicted to be $\chi'(0) \approx (50MeV)^2$ and this value is in accordance with one of the predictions of QCD sum rule calculations. In addition, the fulfillment of the Crewther theorem was demonstrated ($\chi(0) = 0$). The relation of the first moment of topological susceptibility $\chi'(0)$ and the 'spin crisis' problem were briefly discussed. It was shown, in particular, that one always gets the inequality $\chi'(0) > \chi'_{OZI}$, thus discarding the mechanism explaining the 'spin crisis' based on anomalous smallness of $\chi'(0)$.

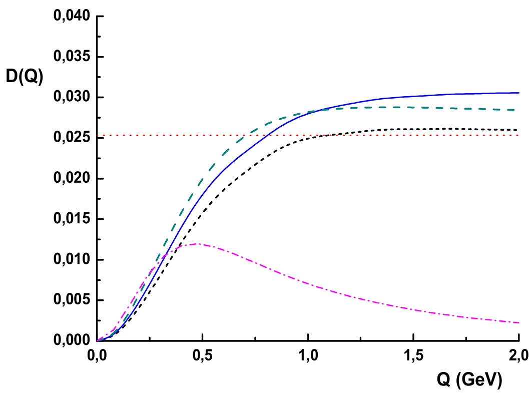

Figure 3. The Adler function from the NχQM contributions: dynamical quark loop (short dashed), quark + chiral loops + vector mesons (full line) versus the ALEPH data (dashed). The dash-dotted line is the prediction of the constituent quark model and the dotted line is the asymptotic freedom prediction, $1/4\pi^2$.

We demonstrated that the Adler function depending on spacelike momenta may serve as an appropriate quantity to show the transition from perturbative regime of QCD to nonperturbative one. This function defined as a logarithmic derivative of the current-current correlator can be extracted from experimetal data of ALEPH and OPAL collaborations on inclusive hadronic τ decays. From a theoretical point of view it is well known that in high-energy asymptotically free limit the Adler function calculated for massless quarks is a nonzero constant. On the other side, in the constituent quark model (suitably regularized) this function is zero at zero virtuality. Thus, the transition of the Adler function from its constant asymptotic behaviour to zero is very indicative concerning the nontrivial QCD dynamics at intermediate momenta. In [4], we showed that the instanton-like nonlocal chiral quark model extended by inclusion of the vector and axial-vector mesons describes this transition correctly. In particular, we analyzed the correlator of vector currents and the corresponding Adler function in the framework of NχQM that allows us to draw a precise and unambiguous comparison of experimental data with the model calculations (Fig. 3). The use in the calculations of a covariant nonlocal low-energy quark model based on the self-consistent approach to the dynamics of quarks has many attractive features as it preserves the gauge invariance, is consistent with the low-energy theorems and takes into account the large-distance dynamics controlled by the bound states.

As an application we estimated the leading order hadronic vacuum polarization contribution to the muon anomalous magnetic moment,$a_{\mu}^{hvp,1}$, which is expressed as a convolution integral over spacelike momenta of the Adler function and confront it with the recent results of the measurements by the Muon $(g-2)$ collaboration.

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COOLING OF NEUTRON STARS WITH COLOR SUPERCONDUCTING QUARK CORES

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We reinvestigated the cooling of neutron stars [1] and demonstrated that modern cooling data in the form of temperature vs. age can be well explained within the *nuclear medium cooling scenario* [2] when suppression of the $^3P_2$ neutron gap is adopted. This investigation revealed that once the conditions for the onset of the very efficient direct Urca (DU) process were met within a neutron star (central densities ρ_c exceeding the critical one ρ_{DU} for DU onset) this led to a very fast cooling. Therefore, we formulated as a condition to the nuclear equation of state that the critical neutron star mass above which the DU process was allowed should be larger than that of a typical neutron star which should be in the range of measured masses of binary radio pulsars (BRP) $M_{BRP} = 1.35 \pm 0.04\ M_\odot$ [3]. While stars with ρ_c slightly below ρ_{DU} still cool rather slowly, a small increase of ρ_c above this threshold makes the cooling dramatically faster. In the case of hadronic matter the onset of this process is determined by the density dependence of the asymmetry energy. The latter dependence is an important issue for the analysis of heavy ion collisions, especially within the new program for investigation of compressed baryon matter (CBM experiment) to be realized at the future accelerator facility FAIR at the GSI Darmstadt.

Our assumption about the mass distribution of neutron stars can be developed into a more quantitative test of cooling scenarios when these are combined with population synthesis models [4].

We demonstrated [5] that within a recently developed nonlocal chiral quark model (see [6] and Refs. therein) the critical densities for a phase transition to color superconducting quark matter could be low enough for these phases to occur in compact star configurations with masses below M_{BRP}. For the choice of the Gaussian formfactor the 2SC-normal quark matter mixed phase arises at $M \simeq 1.21 M_\odot$. We showed that without a residual pairing the 2SC quark matter phase could describe the cooling data only if compact stars had masses in a very narrow band around the critical mass for which the quark core could occur. Since there are observations of neutron stars with higher and essentially different masses, such a scenario should be disfavored.

In order to bring the hybrid star cooling scenario in accordance with the modern cooling data, we had to assume that all quarks had to be paired. This means that also those quarks unpaired within the 2SC phase should be paired with a small gap $\Delta_X < 1$ MeV (2SC+X pairing) which is density dependent, according to $\Delta_X(\mu) = \Delta_c \exp[-\alpha(\mu - \mu_c)/\mu_c]$ where the parameters are chosen such that at the critical chemical potential $\mu_c = 330$ MeV for the onset of the deconfinement transition the X-gap has its maximal value of $\Delta_c = 1.0$ MeV and at the highest attainable chemical potential $\mu_{\max} = 507$ MeV, i.e., in the center of the maximum mass hybrid star configuration, it falls to a value of the order of 10 keV. We chose the value $\alpha = 10$ for which $\Delta_X(\mu_{\max}) = 4.6$ keV.

We show in Fig. 1 that the present day cooling data could be well explained by hybrid stars though when assuming a complex pairing pattern, where the quarks are partly strongly paired within the 2 … < 1 MeV.

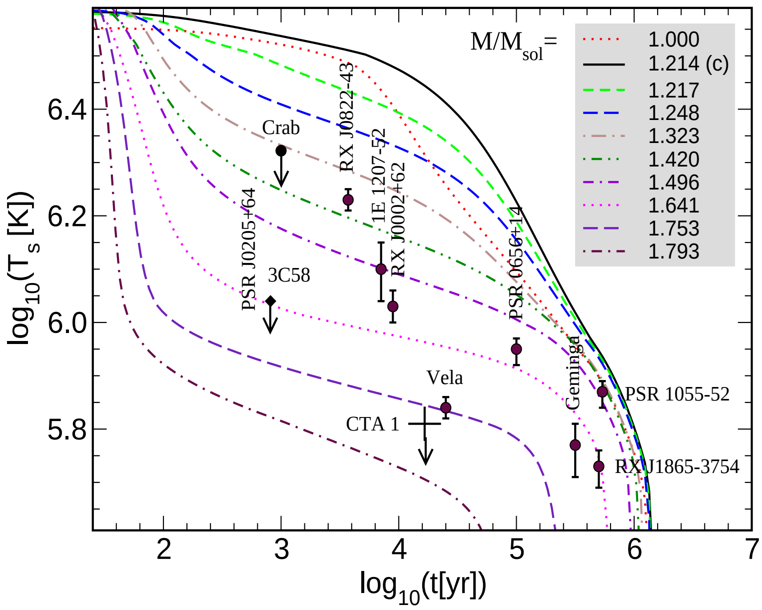

Figure 1: Surface temperature vs. age for different thermal X-ray sources (data points with error bars) compared with theoretical cooling curves for hybrid star configurations with quark matter core in the 2SC+X phase with density dependent small diquark pairing gap Δ_X [5]. The labels correspond to the gravitational masses of the star configurations in units of the solar mass.

However, as was discussed in [7], the 2SC phase was most unlikely in compact stars. If 2SC does not occur, this excludes the 2SC+X phase and other patterns of diquark pairing satisfying color and charge neutrality can become energetically more favorable than normal quark matter. As a viable alternative the color-spin-locking (CSL) phase [8] was suggested, for which the pairing gaps are so small that the EoS is well described by a bag model.

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NLO QCD METHOD OF SIDIS DATA ANALYSIS

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The main points of interest for modern semi-inclusive deep inelastic scattering (SIDIS) experiments with a longitudinally polarized beam and target are the strange quark, light sea quark, and gluon contributions to the nucleon spin. Of special importance is also a still open question whether the polarized light quark sea is symmetric or not, i.e., if the quantity[2] $\Delta_1\bar{u}-\Delta_1\bar{d}$ is equal to zero or not.

At the same time it was shown [1] that to get reliable results on such tiny quantities as Δs and $\Delta_1\bar{u}-\Delta_1\bar{d}$ from the data obtained at a relatively small average Q^2 available to modern SIDIS experiments (such as HERMES and COMPASS), a simple leading order analysis is not sufficient and a next-to- leading order analysis is necessary. A new method of $\Delta_1 q$ extraction in the next-to-leading (NLO) QCD order was proposed in ref. [2]. The main advantage of the proposed method is that it is a *direct* extraction method. It is free of additional assumptions which are required for all other known today NLO extraction procedures.

In ref. [2] it was shown that the proposed NLO method could be successfully applied to solve such an important problem (for understanding the proton spin puzzle) as the symmetry of the light quark polarized sea. To this end, using the proposed NLO procedure, one should first extract from the special SIDIS asymmetries (so-called “difference asymmetries”) the first moments of the polarized valence distributions $\Delta_1 u_V$, $\Delta_1 d_V$ and then, applying the respective form of the Bjorken sum rule, one can get the quantity (polarized sea asymmetry) $\Delta_1\bar{u}-\Delta_1\bar{d}$ which indicates the symmetry of the polarized sea in nucleon, broken or not. The equations [2] for $\Delta_1 u_V$, $\Delta_1 d_V$ and $\Delta_1\bar{u}-\Delta_1\bar{d}$ obtained in ref. [2] have a very simple form

$$\Delta_1 u_V = \frac{1}{5}\frac{A_p^{exp}+A_d^{exp}}{L_1-L_2}; \quad \Delta_1 d_V = \frac{1}{5}\frac{4A_d^{exp}-A_p^{exp}}{L_1-L_2}, \tag{1}$$

for valence distributions and

$$\Delta_1\bar{u}-\Delta_1\bar{d} = \frac{1}{2}\left|\frac{g_A}{g_V}\right| - \frac{2A_p^{exp}-3A_d^{exp}}{10(L_1-L_2)} \tag{2}$$

for the polarized sea asymmetry. All the quantities in the right-hand sides of these equations contain already measured unpolarized quark distributions and pion fragmentation functions (favored and unfavored, entering into the coefficients L_1 and L_2, respectively), known NLO Wilson coefficients and the experimental input, difference asymmetries $A_p^{\pi^+-\pi^-}$ and $A_d^{\pi^+-\pi^-}$ (entering into the quantities A_p^{exp} and A_d^{exp}), extracted from the SIDIS data for the pion production on the proton and deuteron targets. Thus, the pair of difference asymmetries is the only unknown input which should be measured to find the quantities $\Delta_1 u_V$, $\Delta_1 d_V$ and $\Delta_1\bar{u}-\Delta_1\bar{d}$ using Eqs. (1) and (2).

The validity of the proposed NLO procedure was confirmed by the respective simulations. To this end the peculiarities of HERMES and COMPASS experiments were considered. The analysis performed in [2] confirms that for both HERMES and COMPASS kinematics the proposed NLO QCD extraction method meets the main requirement: to reconstruct the quark moments in the Bjorken x region accessible to measurement.

[2]The notation $\Delta_1 q \equiv \int_0^1 dx \Delta q$ is used for the first moments of the local in Bjorken x quark helicity distributions $\Delta q(x)$.

At present, the proposed NLO QCD method is successfully applied to all types of measured by HERMES and COMPASS semi-inclusive asymmetries. In particular, it gives the possibility to extract such important quantity as the polarized strangeness content in nucleon. All numerical tests performed for all used SIDIS asymmetries demonstrate that the proposed method works very well and can be applied in the real conditions of the running and planed SIDIS experiments.

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RADIATIVE CORRECTIONS TO HIGH-ENERGY QED PROCESSES AT ELECTRON-POSITRON, ELECTRON-PROTON, ELECTRON-PHOTON AND ION COLLIDERS. CALIBRATION PROCESSES ON COLLIDERS

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Radiative corrections (RC) to the Compton scattering cross section are calculated in the leading and next-to leading logarithmic approximation to the case of colliding high energy photon-electron beams [1]. RC to the double Compton scattering cross section in the same experimental set-up are calculated in the leading logarithmic approximation. We consider the case when no pairs are created in the final state. We show that the differential cross section can be written in the form of the Drell-Yan process cross-section. Numerical values of the K-factor and the leading order distribution on the scattered electron energy fraction and scattering angle are presented.

We considered RC to the virtual Compton scattering in the high-energy limit including additional hard photon emission in the leading logarithmical approximation [2]. Our result is consistent with the Drell-Yan picture of the process and is expressed in terms of electron structure function. The comparison with the previous work on DVCS is made.

The process of the muon (pion) pair production with small invariant mass in the electron–positron high–energy annihilation, accompanied by emission of hard photon at large angles, is considered [3]. We find that the Drell–Yan picture for the differential cross section is valid in the charge–even experimental set–up. Radiative corrections for both electron block and final state block are taken into account.

The lowest order radiative corrections to the differential cross-section of the muon pair production with emission of hard photon at high energy electron-positron annihilation are calculated [4]. Taking into account the emission of additional soft and hard photon the cross-section can be put in the form of the Drell-Yan process in the leading logarithmical approximation. Applying the crossing transformation we obtain the cross section of radiative electron-muon high-energy scattering process. Virtual and soft photon emission contributions of the nonleading form are tabulated for several typical kinematic points. The limit of small invariant mass of a muon pair is in agreement with our previous analysis.

The recent analysis of nuclear distortions in DIS off nuclei revealed a breaking of the conventional hard factorization for a multijet observable. The related pQCD analysis of distortion effects for jet production in nucleus-nucleus collisions is as yet lacking. As a testing ground for such an analysis we consider the Abelian problem of higher order Coulomb distortions of the spectrum of lepton pairs produced in peripheral nuclear collisions [5]. We report an explicit calculation of the contribution to the lepton pair production in the collision of two photons from one nucleus with two photons from the other nucleus, $2\gamma + 2\gamma \to l^+l^-$. The dependence of this amplitude on the transverse momenta has a highly nontrivial form the origin of which can be traced to the mismatch of the conservation of the Sudakov components for the momentum of leptons in the Coulomb field of the oppositely moving nuclei. The result suggests that the familiar eikonalization of Coulomb distortions breaks down for the oppositely moving Coulomb centers which is bad news from the point of view of extensions to the pQCD treatment of jet production in nuclear collisions. On the other hand, we notice that the amplitude for the $2\gamma + 2\gamma \to l^+l^-$ process has a logarithmic enhancement for the lepton pairs with large transverse momentum which is absent for $n\gamma + m\gamma \to l^+l^-$ processes with $m,n > 2$. We discussed the general structure of multiple exchanges and showed how to deal with higher order terms which cannot be eikonalized.

The calibration QED process cross sections for experiments on planned electron-photon and photon-photon colliders for detecting small-angle scattered particles are calculated [6]. These processes describe the creation of two jets moving sufficiently close to the beam axis directions. The jets containing two and three particles including charged leptons, photons and pseudoscalar mesons are considered explicitly. Considering the pair production subprocesses we take into account both bremsstrahlung and double photon mechanisms. The obtained results are suitable for further numerical calculations.

Processes with creation of pair charged particles with emission of hard photon and two pairs of charged particles [7] are considered for colliding partially polarized photon photon beams. The effects of circular and linear polarization of the initial photons are discussed in more detail.

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NEW TRENDS IN HIGH-ENERGY COLLIDER PHYSICS

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Two new sum rules are derived relating Dirac radii and anomalous magnetic moments of the considered strongly interacting fermions with the convergent integral over a difference of the total proton and neutron, as well as He^3 and H^3, photoproduction cross-sections [1].

Starting with very high energy inelastic electron-nucleon scattering with production of a hadronic state X to be moved closely in the direction of the initial nucleon, then utilizing analytic properties of parts of the forward virtual Compton scattering amplitudes on proton and neutron, one obtains the relation between nucleon form factors and a difference of proton and neutron differential electroproduction cross-sections [2]. In particular, in the case of small transferred momenta, one finally derives sum rule, relating Dirac proton mean square radius and anomalous magnetic moments of proton and neutron to the integral over a difference of the total proton and neutron photoproduction cross-sections.

The charge asymmetry induced by interference of amplitudes with σ and ρ mesons decaying into the $\pi^+\pi^-$ pair created in the fragmentation region of proton suggests to be a test of degeneration hypothesis of ρ and σ mesons [3]. Some numerical estimations are given.

Introducing such a notion as ”excitation of physical vacuum” we make an attempt to explain some strange experimental facts such as large value of σ-term measured in pion-nucleon low-energy scattering, the $\Delta T = 1/2$ rule in kaon-two pion decay modes, the ratio of strange to nonstrange yield in low energy proton-antiproton annihilation, and excess of soft photons in hadron collisions [4]. As a test of our approach we suggest that multiparticle production processes and decays of heavy virtual objects be measured.

The effective kinematic diagram technique is applied to study inelastic form factors of electron and quark in QED and QCD [5]. The explicit expressions for these form factors in the double-logarithmic approximation are presented. The self-consistency of the results is shown by demonstrating the fulfillment of the Kinoshita-Lee-Nauenberg theorem.

Starting with the gauge invariant effective action in the quasi-multi-Regge kinematics (QMRK), we obtain the effective reggeized gluon (R) – particle (P) vertices [6] of the following types: *RPP*, *RRP*, *RRPP*, *RPPP*, *RRPPP*, and *RPPPP*, where the *on*-mass-shell particles are gluons, or sets of gluons with small invariant masses. The explicit expressions satisfying the Bose-symmetry and gauge invariance conditions are obtained. As a comment to the Feynman rules for derivation of the amplitudes in terms of effective vertices we present a “vocabulary” for practitioners.

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RADIATIVE CORRECTION TO THE RADIATIVE PION DECAY MODES

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We find the contribution of a constituent quark loop mechanism to the branching ratio $B_{4\gamma} = \Gamma_{\pi^0\to 4\gamma}/\Gamma_{\pi^0\to 2\gamma}$ to be less $\leq 10^{-16}$ for the reasonable choice of constituent quark mass $m \approx 280 MeV$ [1]. This result is in agreement with vector-dominance approach result obtained years ago. The main contribution arises from the QED mechanism $\pi^0 \to \gamma(\gamma^*) \to \gamma(3\gamma)$ including light-light scattering block with an electron loop. This last one was investigated in paper of one of us and gave $B_{4\gamma} \sim 2.6 \cdot 10^{-11}$.

The lowest order radiative corrections (RC) to the width and spectra of the radiative $\pi e2$ decay are calculated [2]. We take into account virtual photon emission contribution as well as soft and hard real photon emission one. The result turns out to be consistent with the standard Drell-Yan picture for the width and spectra in the leading logarithmical approximation which permits us to generalize it to all orders of perturbation theory. Explicit expressions of nonleading contributions are obtained. The contribution of short distance is found to be in agreement with the Standard Model predictions. It is presented as a general normalization factor. We check the validity of the Kinoshita-Lee-Nauenberg theorem about cancellation in the total width of the mass singularities at the zero limit of electron mass. We discuss the results of the previous papers devoted to this problem. The Dalitz plot distribution is illustrated numerically.

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EXTENDED REIN-SEHGAL MODEL FOR SINGLE-PION NEUTRINOPRODUCTION

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The Rein–Sehgal (RS) model [1] is undoubtedly one of the most circumstantial and approved phenomenological tools for description of single-pion production through baryon resonances in neutrino and antineutrino interactions with nucleons. It is incorporated into essentially all MC neutrino event generators developed for both accelerator and astroparticle experiments. However, the RS model is not directly applicable to the ν_τ and $\overline{\nu}_\tau$ induced reactions since it neglects the final lepton mass. Due to the same reason, the model is not suited for studying the lepton polarization phenomenon. These faults were removed in the extended RS model (ExRS hereafter) [2] which takes into account both the final lepton mass and spin and automatically satisfies the positivity constraints (see, e.g., Ref. [3] and references therein).

The extension is based upon a covariant form of the charged leptonic current j_λ with definite lepton helicity λ which allows us to express the components j_λ^α of the current in the resonance rest frame (RRF) through the kinematic variables (and λ) measured in the laboratory frame. Since the leptonic current j_λ can be treated as the intermediate W boson polarization 4-vector, it can be decomposed (in RRF) into three polarization 4-vectors $e_{L,R,S}$ corresponding to the left-handed, right-handed, and scalar polarizations.

However, the vector e_S has to be modified with respect to that of the original RS model and, consequently, its inner products with the vector and axial charged hadronic currents $F^{V,A}$ has to be recalculated. To do this, the explicit form was used for the currents $F^{V,A}$ of the Feynman–Kislinger–Ravndal (FKR) relativistic quark model [4] adopted in the original RS approach. As a result, some structures involved into the description of the FKR dynamics are also modified. After that, the lepton polarization density matrix $\rho = \|\rho_{\lambda\lambda'}\|$ can be written as the superposition of the partial cross sections $\sigma_i^{\lambda\lambda'}$ $(i = L,R,S)$,

$$\rho_{\lambda\lambda'} = \frac{\Sigma_{\lambda\lambda'}}{\Sigma_{++} + \Sigma_{--}}, \quad \Sigma_{\lambda\lambda'} = \sum_{i=L,R,S} c_i^\lambda c_i^{\lambda'} \sigma_i^{\lambda\lambda'},$$

and the differential cross section for single-pion production is given by

$$\frac{d^2\sigma}{dQ^2 dW^2} = \frac{G_F^2 \cos^2\theta_C Q^2}{2\pi^2 M |\mathbf{q}|^2} \left(\Sigma_{++} + \Sigma_{--}\right).$$

The partial cross sections $\sigma_i^{\lambda\lambda'}$ are found to be bilinear combinations of the CC amplitudes referring to one single resonance in a definite state of isospin, charge and helicity. The coefficients c_i^{λ} are explicitly defined through the components j_λ^α written in RRF. The remaining kinematic variables and constants in the above equation have their standard meaning.

One of the most exciting consequences of the ExRS model is an essential suppression of the differential cross sections for single-pion production due to the finite lepton mass [5]. The major effect is, of course, due to the τ lepton production threshold but accounting for the mass in the lepton current ("dynamic correction") gives rise to a significant additional decrease of the cross section: the effect can be as large as 300% at low neutrino energies and remains important up to rather high energies.

Note that the dynamic mass correction for the ν_μ and $\overline{\nu}_\mu$ induced reactions is typically at a few per cent level or less and the purely kinematic correction for the muon mass is sufficient.

The ExRS model was tested with all available data on single-pion neutrinoproduction as well as with the data on the total $\nu_\mu N$ and $\overline{\nu}_\mu N$ cross sections. In the latter case, the quasielastic contribution was taken into account, according to the recent result of Refs. [6, 7] while the deep-inelastic (DIS) contribution, according to the Bodek-Yang model for the nucleon structure functions [8]. In these calculations, the same set of 18 interfering baryon resonances with the central masses below 2 GeV/c^2 was used, as in Ref. [1]. However, all relevant input parameters were updated according to the most recent data [9]. The factors estimated in Ref. [1] numerically were corrected by using the new data and a more accurate algorithm for numerical integration. The transition form factors $G^{V,A}\left(Q^2\right)$ adopted in the RS model are not modified but the today's standard values for the axial mass and coupling constant are used. In contrast with the original RS model prescription, the nonresonance background was assumed to be part of the DIS contribution. Nuclear effects (most important at low energies) were taken into account within the standard relativistic Fermi gas model. The agreement with all the data is quite satisfactory through the whole available kinematic region.

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POLARIZATION OF ELECTRON-POSITRON VACUUM BY A STRONG MAGNETIC FIELD IN THE THEORY WITH A FUNDAMENTAL MASS

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Within the framework of the approach based on the use of exact solutions to the quantum equations of motion of charged particles it is shown that an essential reduction of distances in strong fields can result in effects with a new scale of a length peculiar to a formalism of the modified quantum electrodynamics –*QED with a fundamental mass*. In particular, effects of polarization of electron-positron vacuum by a strong magnetic field H in traditional QED accounting AMM of particles and a new QED with a fundamental mass M are investigated. In the one-loop approximation, Lagrangian of an intensive constant magnetic field, which generalizes Lagrangian of traditional QED, is calculated. The important difference between modified Lagrangian and Heisenberg-Euler Lagrangian of traditional QED consists in that the generalized expression contains an additional field scale $F^* = M^2c^3/e\hbar$. Within the framework of the theory with a fundamental mass the field F^* can naturally be named a *fundamental field*. It is established that the generalized Lagrangian and meanwhile an energy density of the polarized vacuum are real, which confirms the stability of the vacuum in the modified theory at any values of a magnetic field. It is also shown that in the weak field limit ($H \ll F^*$) the calculated Lagrangian coincides with the known Heisenberg-Euler formula. On the other hand, for extremely strong fields ($H \gg F^*$) the Lagrangian is completely independent of a field. In this limit the new Lagrangian tends to a constant which is determined by the relation of fundamental and lepton masses. It is well known that the estimation is performed of the observable difference between theoretical calculations of a lepton AMM $a_\mu(SM)$ derived within the framework of the Standard Model and precision experimental results on measurement of AMM positive muons $a_{mu}(exp)$ recently obtained at the Brookhaven National Laboratory. It is shown that at values of the fundamental mass $M \sim 1$ TeV in the modified theory a lepton initially possesses AMM the value of which is about the observable difference $\Delta_\mu = a_\mu(SM) - a_\mu(exp)$. Thus, a solution of the muon $(g-2)$ problem can give rise to a new theory beyond the scope of the Standard Model, in particular – *Standard Model with a fundamental mass*.

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NONRELATIVISTIC QED AND PRECISE SPECTROSCOPY OF THREE–BODY ATOMS AND MOLECULES

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It is known that quantum electrodynamics is well developed for the two–body bound systems [1].

On the other hand, the major part of the proposed methods, such as the Bethe-Salpeter equation or the effective Dirac equation, do not extend well to systems of three and more particles. It seems that the formalism of the nonrelativistic quantum electrodynamics (NRQED), as it was formulated in [2], is the most suitable for that purpose. An energy of a bound state in NRQED is searched for as a series expansion in terms of the coupling constant α. At present, explicit expressions and methods for their evaluation have been obtained for the contributions up to and including terms of an order of $\alpha^5 \ln^2 \alpha \cdot \mathrm{Ryd}$.

The three–body problem with the Coulomb pairwise interaction is one of the nonintegrable problems in the quantum mechanics. At the same time, it allows "arbitrarily" accurate numerical solutions at modern computers. For example, the nonrelativistic energy of the ground state for a helium atom with infinite nuclear mass can be obtained with as much as 26 significant digits [4]:

$E(^\infty\mathrm{He}) = -2.903724377034119598311159\,4(4)$ a.u.

These accurate variational solutions make feasible precise studies of different three–body systems such as helium and helium-like atoms or molecular ions of hydrogen isotopes H_2^+, HD^+, etc. Application of this high precision calculations is usually found in the metrology of fundamental constants. Thus, the fine structure intervals of $^4\mathrm{He}(2^3P_J)$ state may become an alternative way for determination of the fine structure constant α. A study of vibrational transitions in H_2^+ is considered as the most efficient way to improve the proton to electron mass ratio.

Results obtained within the last few years are:

1. The ground-state ionization energy of the ^{4}He atom is found [3], this result includes all effects of relative order α^4, $\alpha^3 m_e/m_\alpha$, and $\alpha^5 \ln^2 \alpha$. The Bethe logarithm for a range of S and P states in helium has been calculated with the highest precision of about 10 significant digits [6], this quantity has been a source of major theoretical uncertainty until recently.
2. Transition energies between metastable states of an antiprotonic helium atom have been obtained with about 1 ppb (part per billion) precision [5]. That uncertainty allows determination of the antiproton/electron mass ratio to a level of 0.5 ppb, which competes with the CODATA02 recommended value for the proton/electron mass ratio.
3. The first *ab initio* calculation of the leading order radiative corrections for the hydrogen molecular ions H_2^+, HD^+ have been performed [7].

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