November 28, 2013

MITP Workshop on Low-Energy Precision Physics

Summary of Afternoon Discussion Sessions

Organizers:
Krishna Kumar, Michael Ramsey-Musolf (U. Mass., Amherst),
Harvey Meyer, Hubert Spiesberger (U. Mainz),
Jens Erler (UNAM Mexico and MITP)

Dates: September 23 - October 11, 2013

We summarize the most important topics which have been addressed in discussion sessions during the MITP Workshop on Low-Energy Precision Physics. For the individual contributions we refer to the documents that have been uploaded to the conference web-page at
`http://indico.cern.ch/conferenceDisplay.py?confId=248072`

1 Theory of parity violating elastic ep scattering (week 1)

The main theme of the first week was the theory of low-energy parity violating ep scattering. Presentations and discussions included various aspects of electroweak loops, $\gamma\gamma$ and γZ box diagrams, 2-loop corrections, QED, structure functions, form factors, new physics, and PVES probes of hadron structure (higher twist, charge symmetry violation).

1.1 How should experiments quote their results? (Tu., 24. 9.)

Measurements in Møller scattering, elastic electron-proton scattering, electron-ion scattering, PVDIS, and APV should quote results in such a way that they are easily comparable with each other with respect to

- the weak mixing angle,
- the weak charge, or other universal couplings,
- Λ-parameters for new contact interactions.

Running parameters should be quoted at the (average) energy scale relevant for each experiment, and (i) for the weak mixing angle and the weak charge also at $\mu = 0$ where they can be unambiguously defined, (ii) for the weak mixing angle also at $\mu = M_Z$. In the latter case the running from low to high scales might change by a tiny amount in the future, for example when hadronic input, quark mass thresholds etc., change.

- The analysis sequence can be ordered like this:
  $A_{PV}^{raw} \longrightarrow A_{PV}^{phys} \longrightarrow C_{2e}, C_{1q}, C_{2q} \longrightarrow g_{AV}^{eq} \longrightarrow \sin^2\theta_w(\mu)|_{\overline{MS}}$.
- The first step $A_{PV}^{raw} \longrightarrow A_{PV}^{phys}$ involves experiment-dependent corrections and is part of the experimental analysis.
- The second step is based on expressions for the observables with the usual definition of coupling constants C_{2e}, C_{1q}, C_{2q} in terms of effective 4-fermion operators. This step involves QED radiative corrections to be applied by the experimentalists and subtraction of hadronic or nuclear effects. This is done through experiment-specific Monte-Carlo simulation programs and experimentalists will need close guidance by theorists in this step.
- The next step is based on the definition of chiral couplings g_{AV}^{eq} described in [1] and Jens Erler's talk. This involves subtraction of a number of corrections, including, for example, those parts of γZ box graphs that go beyond the parton-level expression cut off at the hadronic mass scale $\Lambda_{\text{had}} = m_p$. Details and clear prescriptions needed to achieve a reproducible extraction of electroweak parameters from data are to be worked out.

In previous attempts to extract Λ-parameters as a measure of the mass scale of new physics, the underlying definitions have not always included factors of $\sqrt{2}$ in the same way. No extra stretching by assuming specific models with more than one chiral combination of 4-fermion couplings should be used. Specific model assumptions can be described by considering "rotations" in the space of V and A couplings (and in the flavor space), but should be based on the common normalization using $g = 4\pi$. See Jens' talk for more details.

1.2 Theory needs for the next generation experiments (We., 25. 9.)

Oleksandr Tomalak presents preliminary results of ongoing work about 2-photon exchange corrections in elastic ep scattering in a dispersive framework. 2γ box graph corrections will be needed to get the correct normalization of the PV asymmetry.
In terms of the weak charge, the precision of planned measurements are 2 % for MOLLER, 1.5 % for P2 at MESA, 0.3 % for a ^{12}C experiment, $5\,\%$ for $2C_{2u} - C_{2d}$ at SoLID. APV in very heavy Ra or Fr isotopes using trapped atoms or ions are very promising. No concrete numbers were given for the expectations of atomic structure calculations needed to allow for a conclusive interpretation of

the data, but it will be important to improve over what has been achieved in Cs. Hadronic uncertainties in the running of α_{em} and $\sin^2\theta_w(\mu)|_{\overline{MS}}$ have to be reduced by about a factor of two; see for example [2] ($\delta\sin^2\theta_w(0) = 7\times 10^{-5}$). A comparison with Fred Jegerlehner's approach should be done (see `http://www-com.physik.hu-berlin.de/~fjeger/software.html`) and other independent studies are called for.

The dominating 2-loop corrections for Møller scattering have been calculated by W. Marciano and collaborators and are of order 2 %. Results are not yet published. It should be relatively easy to translate this calculation to the case of ep scattering. A. Aleksejevs has estimated the quadratic one-loop corrections and found $O(4)\,\%$. Details must be compared. Aleksejev's group plans to attack the project of calculating the complete 2-loop corrections for the weak charge of the electron and subsequently of the proton.

For the SoLID experiment, i.e. parity violating deep inelastic scattering, a Monte Carlo event generator (HERACLES) as well as public code for numerical calculations (HECTOR) including the full one-loop electroweak corrections are available.

1.3 Auxiliary measurements (Th., 26. 9.)

Krishna Kumar provides information about measurements done or planned at Qweak, SoLID, and MOLLER (some of them are auxiliary measurements primarily for calibration and background estimates). Among them are: form factors (Qweak), d/u ratio, higher twist and charge-symmetry violation (SoLID), ep elastic + radiative tail (MOLLER).

The extraction of the weak charge of the proton at zero momentum transfer from the measured PV asymmetry at Qweak is discussed in detail [3]. It is emphasized that a good knowledge of the Q^2 dependence of form factors and γZ box graph corrections is required since this will affect the size and the correlation of the errors assigned to the individual points entering the fit. There seems to be too little information available at the moment to scrutinize the validity of the underlying assumptions about the Q^2 dependence.

1.4 γZ box graph contributions (Th., 26. 9.)

Mikhail Gorchtein opens the discussion about the published theory predictions for the γZ box graph contributions. The details of this session, including perspectives for future work on γZ box graphs, have been collected in a separate document [4].

1.5 Potential PV asymmetry measurements on C-12 at MAMI/MESA (Fr., 27. 9.)

The case of a measurement of the parity-violating asymmetry with a carbon target was discussed in the morning session by O. Moreno. In order to pin down uncertainties specific to the carbon target, additional auxiliary measurements will be needed. The dominating effects are due to the strange form factor and isospin breaking effects with an unknown Q^2 dependence. During the discussion, two additional kinematic points were identified for which the measurements can be carried out simultaneously at two different scattering angles with a single run of about 100 days. It must be determined what precision would be optimal in order to use these higher Q^2 measurements to constrain hadronic uncertainties with a leading Q^2 dependence, such as the strangeness radius, to the required level to interpret a 0.3% C-12 weak charge measurement at a Q of 60 or 70 MeV.

Concerning isospin (charge-symmetry) breaking effects, the question was raised whether all possible physical mechanisms are taken into account in O. Moreno's approach (nuclear isospin mixing). The contribution from γZ box graphs, estimated from calculations for a deuterium target, seem to be smaller than $0.1\,\%$. Calculations for carbon to confirm this expectation are possible and will be done (M.G.).

T-odd effects in elastic ep scattering can be searched for in the transverse-spin asymmetry. Such effects occur at relative order α and involve a spin flip, thus are of the order 10^{-5} for a beam energy of 1 GeV. Such measurements seem possible, but it must be investigated whether they will provide new insights into the interplay between dispersion corrections and Coulomb distortions.

2 Proton radius and atomic parity violation (week 2)

2.1 Theory of proton radius measurements from spectroscopy (Mo., 30. 9.)

Details of theoretical predictions for the energy shift of hydrogen energy levels (both electronic and muonic hydrogen) are discussed: possible double counting, hyper-fine splitting, strong field effects, long-range forces related to terms in the perturbative calculation with a branch cut starting at zero-momentum transfer. No effect, no term could be identified which was not already discussed by the experts and excluded or found to be too small to explain the large required energy shift.

2.2 Proton radius and new physics (Tu., 1. 10.)

A large number of suggestions made in the literature, collected by P. Indelicato and including serious as well as highly speculative ideas, are discussed one by one. None was found convincing, none stands the tight constraints from other observations.

2.3 Proton radius and dark photons (We., 2. 10.)

Talk by T. Beranek: “Theoretical framework for the analysis of searches for hidden light gauge bosons”.

Additional clarification of some properties of dark photons, dark Z bosons, parity violation in the dark sector by W. Marciano.

No mechanism involving a dark photon is known which could affect the proton radius measurements in different ways for the electron and the muon.

Theory of proton radius determinations from ep scattering

The statistical analysis of the Mainz measurement of elastic ep scattering and its proton radius determination is discussed in detail: error correlations and significance, quality of form factor fits, dependence on variations of the fit ansatz.

Future measurements with deuterium are underway, results expected within the next year; muonic helium, highly-charged ions are difficult, but seem feasible.

Lattice calculations of the proton polarizabilities are unlikely to be feasible.

2.4 Prospects for extracting weak charges from APV (Fr., 4. 10.)

Future APV experiments, e.g. with Ra^+, seem to be as good as the existing ones, but the accuracy of an extraction of the weak charge and the weak mixing angle does not seem to be much better. It remains unclear whether one can get atomic uncertainties under control.

Measurements with isotope chains are discussed. Here, one can get rid of atomic uncertainties by taking ratios. However, sensitivity to new physics that would modify the ρ-parameter is also lost. Therefore one should try to identify isotopes with a large lever-arm, i.e. where the difference of the neutron number, ΔN, is as large as possible to get the highest sensitivity to $\sin^2\theta_w$.

Returning to the proton radius puzzle, the workshop participants get convinced that there is a real discrepancy. A vote shows that the majority considers missing effects in the theory prediction as the most likely cause. Nobody votes for the possibility that either hydrogen, muonic hydrogen or ep scattering experiments are wrong, or that new physics beyond the Standard Model has shown up in the proton radius measurements.

3 Electric dipole moments (week 3)

Electric dipole moments in molecules, atoms, nucleons, light nuclei, electron; EDMs from BSM scenarios.

The discussions of this week focused on three questions:

- What are the broader implications of EDM searches for cosmology, studies at the energy frontier, and other precision probes of physics beyond the Standard Model?
- What are the primary theoretical challenges and strategies for addressing them?

- What do we learn from existing and planned experiments and what are the most compelling new experimental directions ?

The talks throughout the week highlighted aspects of these questions:

- An overview of the broader context of EDMs and an introduction of the key questions by M. Ramsey-Musolf
- The opportunities for an experimental program at Fermilab by A. Kronfeld
- Implications of EDMs and the Higgs observation for electroweak baryogenesis by J. Shu (remotely from Beijing)
- Possible higher order transverse electric corrections to Schiff screeing by S. Inoue
- Complementary implications of EDMs and “fifth force” probes for new parity- and time-reversal violating interactions by S. Mantry
- The status and prospects for nuclear Schiff moment computations by J. Engel (remotely from North Carolina)
- EDMs of few body systems by J. de Vries and J. Baissou
- EDM of the rho meson using Dyson-Schwinger methods by M. Pitschmann
- Lattice QCD computations of EDMs by E. Shintani

We also heard two talks on topics not directly related to EDMs but still of interest to the broader theme of the three-week workshop:

- Atomic physics effects in probes of neutrino magnetic moments by C.-P. Liu
- The phenomenology of Dyson Schwinger for QCD observables by I. Cloet

With regard to the questions for the week, it was generally agreed that EDMs are vital for testing electroweak baryogenesis and that they have the potential to probe mass scales well above what will be accessible at the LHC, given the anticipated sensitivity of the next generation experiments. The bulk of the discussion highlighted the open problems in computing hadronic matrix elements as needed to derive robust limits on underlying CPV parameters from EDMs of hadronic and diamagnetic systems. The challenge is that for several sources of CPV that may be generated by BSM physics, such as the quark chromo EDM (CEDM), the hadronic computations of the induced neutron EDM and parity and time reversal violating (PVTV) pion-nucleon coupling have an order of magnitude or more uncertainty. This level of uncertainty makes it challenging for EDMs to provide the most conclusive tests of BSM scenarios, particularly as needed to test electroweak baryogenesis.

Workshop participants identified several important directions in this regard:

- Chiral symmetry provides a robust prediction for the dependence of the isocalar PVTV pion-nucleon coupling in terms of the QCD θ parameter, given knowledge of the up- and down-quark mass difference and the contribution of this difference to the neutron-proton mass splitting. Computation of this dependence in other scenarios and comparison with the chiral result provide an important benchmark.
- Computations of the quark EDM contribution to the neutron EDM also provide an important benchmark.
- Additional and concerted lattice QCD efforts are needed, particularly focusing on computations of matrix elements arising from dimension six CPV operators, such as the CEDM or Weinberg three-gluon operator.
- Formulating the dimension-six operator problem for the lattice is a new challenge, though the quark EDM contribution can be obtained from calculations of the nucleon matrix elements of the tensor charge.
- State-of-the-art lattice configurations generated with mesonic quantities in mind should be used for nucleons quantities to compute benchmark quantities such as g_A and the electromagnetic form factors, as well as the theta induced neutron EDM.
- There exists a need for quenched chiral perturbation theory calculations for the dimension six operator problem in order to facilitate extrapolation to physical quark masses and large volumes.
- A calculation of the electric dipole charge radius would provide an important consistency check as it depends only on the isocscalar PVTV pion-nucleon coupling at lowest order and is free from additional low-energy constants.
- Raising the awareness of the lattice QCD community as to the importance of the EDM matrix element problem is needed.
- Extending Dyson-Schwinger calculations beyond the rainbow-ladder truncation and “contact interaction” framework would provide new insight, though is a labor-intensive challenge.
- Obtaining a more robust Standard Model CKM prediction for the nucleon EDM could become important if the 10^{-29} e-cm sensitivity is reached with future neutron and storage ring proton EDM experiments.

The nuclear and atomic problems also present ongoing challenges. From the talks by Engel, de Vries, Inoue, and Bsaisou, we concluded that

- Strategies for testing calculations of many-body nuclear Schiff moment calculations are needed. Among the ideas proposed are the use of hadronic PV: taking the leading order effective PV NN interaction from the few-body experiments and using it to compute the PV observables in many-body systems could shed light on the renormalization of four-nucleon operators in nuclei. It would also be useful to find an experimental probe that is correlated with some aspects of the nuclear Schiff moment or PVTV potential.
- The combined effect of successive J=1 and J=2 transverse electric interactions between the atomic electrons and nucleus appears to be potentially significant when compared with the nuclear Schiff moment. Resolving this question could have substantial implications for the interpretation of diamagnetic atom EDMs.
- Few-body nuclei (deuteron and ^{3}He) offer potential advantages. The impact of chiral symmetry-breaking d=6 operators is particularly exposed in the deuteron EDM, while both the deuteron and ^{3}He may allow access to the two lowest order PVTV short range interaction.
- Additional work needed in the few-body systems includes refining the computation of the four nucleon matrix elements in chiral potentials and inclusion of the three-pion vertex-induced three-body PVTV force in ^{3}He.

Finally, with regard to additional future experimental directions, it was emphasized that paramagnetic EDMs test a linear combination of d=6 operators, the electron EDM and a semileptonic operator. Consequently, there exists a need for a direct measurement of the electron EDM. Efforts are underway to investigate the possibility of an electron storage ring experiment at Fermilab.

References

[1] J. Erler and S. Su, Prog. Part. Nucl. Phys. **71** (2013) 119 [arXiv:1303.5522 [hep-ph]].

[2] J. Erler and M. J. Ramsey-Musolf, Phys. Rev. D **72** (2005) 073003 [hep-ph/0409169].

[3] D. Androic *et al.* [Qweak Collaboration], arXiv:1307.5275 [nucl-ex].

[4] M. Gorchtein, J. Erler, T. Hurth, H. Spiesberger, K. Kumar, M. J. Ramsey-Musolf and H. B. Meyer, arXiv:1311.4586 [hep-ph].