Executive Summary of the MITP Topical Workshop

"Hadronic contributions to the muon anomalous magnetic moment: strategies for improvements of the accuracy of the theoretical prediction"

April 1-5, 2014, at Schloss Waldthausen (near Mainz)

Organized by:
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The anomalous magnetic moment of the muon provides stringent tests for the electroweak Standard Model (SM) and is an excellent monitor for new physics. Being one of the most precisely measured and at the same time very precisely predictable observable in elementary particle physics, the present persisting deviation between theory and experiment is likely the best established indication of physics beyond the SM. Theoretical predictions are limited by the uncertainties of non-perturbative hadronic contributions. The workshop was focused on how to reduce theoretical uncertainties to match the precision of forthcoming experiments at Fermilab in the US and possibly also at J-PARC in Japan.

About 30 participants set out to answer the questions:

1) To what extent will we be able to improve the evaluation of the Hadronic Vacuum Polarization (HVP) based on Data, Lattice QCD Calculations and/or Models.

2) How can we improve the reliability and reduce the uncertainty of the predictions of the Hadronic Light-by-Light (HLbL) contributions based on Models, Data, and/or Lattice simulations.

At present, experimental and theoretical uncertainties are of comparable size. The new muon $g-2$ experiments at Fermilab and J-PARC are expected to be able to reduce the error by a factor 4. A reduction of the present hadronic uncertainties by a factor 2 could turn the presently estimated deviation $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm the} = 3$ to $4\,\sigma$ to a $\Delta a_\mu = 7.7\,\sigma$ effect.

That's what we hope to achieve in time: to be prepared for an adequate interpretation of the new experimental results to come.

One major achievement of the workshop was that we were able to attract many new researchers to actively participate in the field and indeed a number of new ideas and approaches to tackle the difficult problems have been presented and have been lively debated in the discussion sessions.

While HVP contributions are usually evaluated using $e^+e^- \to$ hadrons cross sections and Dispersion Relations (DR), HLbL calculations have been based on low energy effective QCD hadronic models. Viable models are extensions of chiral perturbation theory by including vector meson dominance ideas in a way which is compatible with the chiral structure of QCD. Variants are the Extended Nambu-Jona-Lasinio Model (ENJL) the Hidden Local Symmetry (HLS) model or other effective Resonance Lagrangian variants. Operator Product Expansion (OPE) constraints thereby play a crucial role. Different approaches usually do not lead to very different results, although they usually differ in the bookkeeping of the various typical virtual sub processes which contribute. Application of such models to the much simpler HVP problem provide useful crosschecks for the effective theories. In any case data on $\gamma\gamma \to$ hadrons processes in various channels play a key role for further progress.

In contrast to common folklore that HLbL cannot be evaluated in a model independent way via DRs in terms of appropriate experimental data, among the highlights of the workshop have been the demonstrations that a closer inspection actually shows that a DR approach also here is able to provide a direct data driven access to the problem. Two alternate approaches have been presented. One based on a DR evaluation of HLbL inside the muon $g-2$ itself (Mainz Group) and the other by evaluation of the more complicated $\gamma\gamma \to \gamma\gamma$ amplitudes (Bern group).

The key point: we need much more experimental data, either as an input for the disperion relations approach or to constrain the effective theories. The workshop provided an excellent opportunity for very intense interactions between experimentalists and theorists which are mandatory to substantially improve the control of low-energy hadronic effects.

Data for HVP summary:

- The dominating 2π channel is measured with accuracy better than 1%, however, the most precise ISR measurements (KLOE, BABAR) are in conflict with each other. Fortunately, cross check by BES III - ISR and VEPP-2000 aim for unprecedented accuracy about 0.3%.

- Higher multiplicities in the range between 1.4 GeV and 2.4 GeV are dominated by BABAR ISR measurements. This region giving a substantial contribution to the HVP, at present, gives the largest uncertainty. Again, cross check and improvement are expected by VEPP-2000, BES III and possibly by BELLE-II in intermediate future.

- Issues in this context are radiative corrections, precise form factor models in MC generators, hadronic final state radiation modeling.

Data for HLbL summary:

- Huge experimental progress in all kinematic ranges under way.

- KLOE-II and BES III will measure pseudo-scalar meson transition form factors in low Q^2 range (no data so far).

- Hadronic models need to be validated by data. At present the experimental accuracy in most cases not yet precise enough.

- A new approach admitting a model independent data driven (via dispersion relations) HLbL calculation possible provides an interesting interplay between theory and experiment. This method makes new improved measurements of $\gamma\gamma \to$ hadrons processes more important than ever.

Lattice for HVP summary:

- Lots of interest, work on hadronic contributions, especially HVP

- Statistical errors (sub) 1% have been achieved.

- Several groups have done or do physical $m_\pi(m_{\text{quark}})$ simulations.

- Much effort on understanding systematics.

- Workshop was very helpful to encouraging cooperation!

- 2-3% total error on connected HVP in 2 years possible; may be achievable for disconnected HVP. too.

Lattice QCD for HLbL summary:

- At present, one active collaboration (Blum et al.): QCD+QED promising, but significant systematics. They are now running with $m_\pi = 170$ MeV and investigating excited state contamination. Feasibility studies look very promising.
- Dynamical QED+QCD is coming, too.
- Need more groups working on it!
- Study of four-point correlator would be very interesting, but also simpler objects like the pion transition form factor are important.

Besides the 'from first principles" lattice QCD approach, another ambitious numerical QCD approach discussed is based on the attempt to solve the HLbL problem by a numerical solution of coupled truncated Schwinger-Dyson/Bethe-Salpeter equations; results are quite compatible with results obtained by low-energy effective hadronic models.

Conclusion: the workshop was very useful and successful in promoting a number of new ideas to a larger group of people working actively on muon $g-2$ topics. Also the interplay between theoretical and experimental aspects have been lively discussed. Close collaboration between theory and experiment is mandatory in high precision physics and helps to motivate people to intensify their efforts to contribute to progress in the field. The highly appreciated discussion sessions actually helped a lot to streamline previously controversial issues. The mini-proceedings of the workshop, which are available on the hep-archive, actually give a good short overview on the different topics covered.