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Round Table: Resolving Physics Beyond the Standard Model at Low Energies

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Low-energy precision experiments can reveal physics beyond the standard model through either the observation of the violation of expected fundamental symmetries or an observed deviation from a precision calculation. We offer an overview of the possibilities, thereby illuminating the subfield's essential challenges and themes.

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In our round table discussion we considered the potential of various, low-energy precision experiments to discover physics beyond the standard model (BSM), from both theoretical and experimental perspectives. Our panelists were V. Cirigliano (VC), P. Fierlinger (PF), Ch. Fischer (CF), K. Jansen (KJ), and S. Paul (SP). S. Gardner (SG) served as the moderator, representing the convenors of Section E, namely, SG, Felipe J. Llanes-Estrada, Huey-Wen Lin, and W. Michael Snow.

We eschewed individual presentations per se, but, rather, engaged in a dialogue guided by discussion points, which were shared with the audience and which we reproduce here. In what follows we interweave the panelists' remarks with the apropos discussion points to give an accurate sense of what transpired.

- *If collider searches for new physics prove null, why should low energy experiments fare better? How does precision trade for energy reach?*

VC addressed these questions, noting that he disagreed with the negative spirit of the first as framed, because the energy reach of a sweep of low-energy experiments can exceed that directly accessible at colliders. It is possible to quantify the relationship between the precision to which a particular low-energy effect is probed and the energy scale of the hidden particles which could give rise to it. Suppose new physics is realized through the appearance of new particles and new interactions at some energy scale in excess of $\Lambda_{\rm BSM}$. Then at energies below $\Lambda_{\rm BSM}$, an effective Lagrangian emerges in terms of local operators $O_i^{(d)}$ of mass dimension d with $d > 4$ [1]; namely,

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_i \frac{C_i^{(5)}}{\Lambda_{\rm BSM}} O_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda_{\rm BSM}^2} O_i^{(6)} + \dots\,, \tag{1}$$

where $\mathscr{L}_{\rm SM}$ is that of the standard model (SM). Low energy experiments thus probe combinations of $C_i^{(d)}/\Lambda_{\rm BSM}^{(d-4)}$ once the matrix elements of $O_i^{(d)}$ with respect to SM fields are known. The existing experiments fall into two different classes: (i) one can make precision measurements of non-zero quantities, such as of the muon anomalous magnetic moment $(g-2)_\mu$ and of β decay observables; and (ii) one can search for violations of fundamental symmetries, such as baryon number B, lepton number L, time-reversal T, parity-violation P, or through searches for quark and lepton flavor-changing neutral currents (FCNC). In Fig. 1 the energy reach of different low-energy experiments is summarized and compared with that of direct searches at the Large Hadron Collider (LHC) under the *assumption* that the associated coefficients $C_i^{(d)}$ are universally $\mathscr{O}(1)$. Thus we conclude that the energy reach of certain low-energy experiments can indeed *far exceed* that of direct searches. We refer the reader to a suite of recently completed reviews on the study of fundamental symmetries and neutrinos, probed through low-energy experiments, in the LHC era [2, 3, 4, 5, 6, 7, 8, 9, 10] to consider the possibilities.

- *How can we discover new physics in a complex system (be it nucleon, nucleus, atom, molecule) if its "first-principles" structure is ill-known? What role does theory play here?*

In complex systems, the observation of a violation of a symmetry of the SM constitutes evidence for physics BSM. PF addressed this question through explicit examples, considering searches

*Speaker.

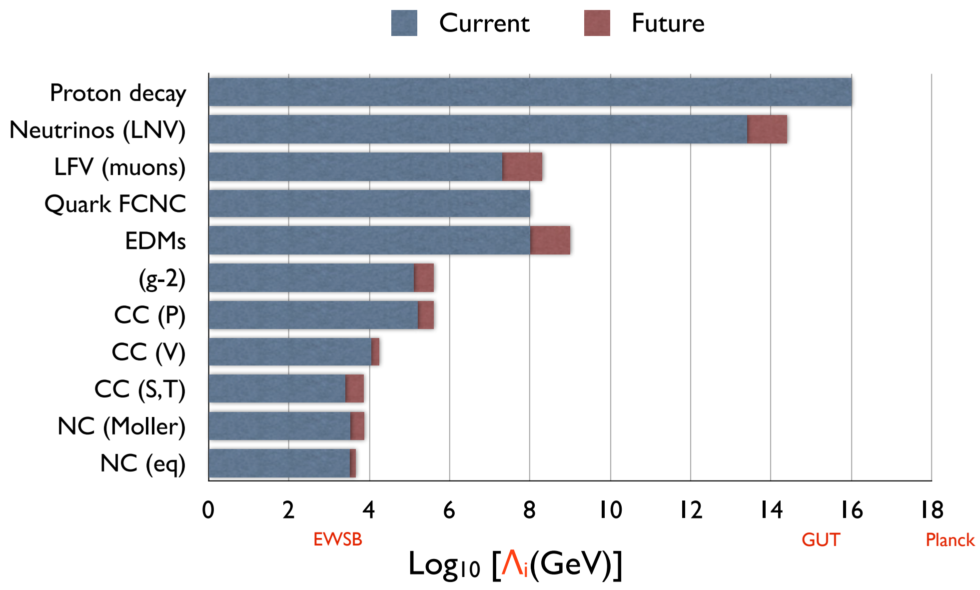

Figure 1: (Color online) Comparison of the new physics reach of current and future experiments which search for physics BSM, assuming universal coefficients $C_i^{(d)}$ of $\mathscr{O}(1)$, noting probes of lepton number violation (LNV), (charged) lepton flavor violation (LFV), (permanent) electric dipole moments (EDMs), the muon $(g-2)$, as well as non-$(V-A)$ currents in charged-current (CC) and neutral-current (NC) processes, taken from Ref. [2]. We refer to Ref. [2] for all details.

for both neutrinoless double β decay [$0\nu\beta\beta$] and EDMs. A discovery of $0\nu\beta\beta$ decay would reveal the existence of lepton number violation, revealing that neutrinos are massive Majorana particles [11]. Typically the sensitivity of a particular experiment is parameterized in terms of the effective Majorana mass, so that the sensitivity of various experiments is also compared in this manner, though we do not know *a priori* the BSM mechanism by which a $0\nu\beta\beta$ matrix element is made non-zero. Indeed a diversity of new-physics scenarios are probed through such experiments; we refer to Ref. [12] for a discussion. Figure 2 shows the range of possible effective $\beta\beta$ masses, given the known empirical constraints on the neutrino mixing matrix, including the current non-zero value of θ_{13} and the possibility of CP-violating Majorana phases [13]. Current limits on the effective $\beta\beta$ mass include $\langle m_{\beta\beta}\rangle < 140-380\,\mathrm{meV}$ at 90% C.L. [14] and $\langle m_{\beta\beta}\rangle < 120-250\,\mathrm{meV}$ at 90% C.L. [15], where each limit employs a range of $0\nu\beta\beta$ nuclear matrix elements. There are more than dozen or so experiments in preparation world-wide, either approved or under construction, with R&D efforts in addition. No efforts currently planned will be able to access a mass scale lower than $\langle m_{\beta\beta}\rangle \sim 20\,\mathrm{meV}$ [4].

Searches for permanent EDMs are being developed in a variety of systems. These tests can

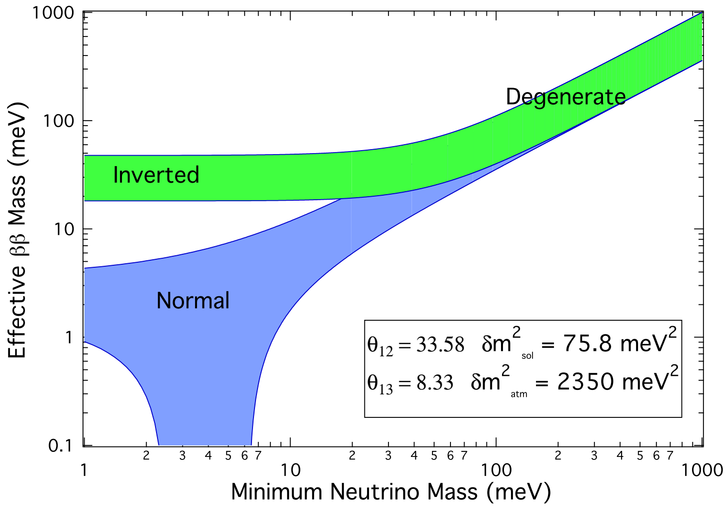

Figure 2: (Color online) Locus of possible effective $\beta\beta$ masses given neutrino mixing constraints, taken from Ref. [13].

be regarded as "null" tests as well because a nonzero EDM at current levels of sensitivity would attest to the existence of physics beyond the electroweak SM. The SM without neutrino masses nominally has two sources of CP violation: through a single phase δ in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, as well as through the T-odd, P-odd product of the gluon field strength tensor and its dual, the latter product being effectively characterized in the full SM by the parameter $\bar{\theta}$. The CKM mechanism of CP violation does give rise to nonzero EDMs, and the neutron EDM d_n, e.g., is estimated to be $d_n \sim 10^{-31} - 10^{-33}$ e·cm [16, 17, 18] in size, making it several orders of magnitude below the current experimental upper limits and experimentally inaccessible for the next decades. We note in passing that additional enhancements arising from the nucleon's intrinsic flavor structure may exist [19] and that the lepton moments from the CKM mechanism are also nonzero, but are smaller still [20]. The second mechanism, termed strong CP violation, appears with an operator of mass dimension four; consequently, it is unsuppressed by any mass scale and need not be small, though it is bounded experimentally to be $\bar{\theta} < 10^{-10}$ [21]. The lack of an established explanation for the small size of $\bar{\theta}$ is termed the "strong CP problem." Possible explanations must be compatible, too, with $\delta \sim \mathscr{O}(1)$, which experimental measurements of CP-violating observables in B-meson decays demand [22, 23, 24]. The manner of its resolution can also impact the possible numerical size of non-CKM sources of CP violation, see Ref. [25] for a discussion. If the Peccei-Quinn mechanism operates, so that there is indeed a new continuous symmetry [26] which is spontaneously and mechanically broken at low energies, then we could win on two counts. There would be a new particle, the *axion* [27, 28], which we may yet discover [29, 30], and non-CKM sources of CP violation could also be of $\mathscr{O}(1)$ in size.

A variety of well-motivated extensions of the SM, including models with an extended Higgs sector, with manifest left-right symmetry at sufficiently high energy scales, with extra spacetime dimensions, and with weak-scale supersymmetry, can generate EDMs substantially in excess of the predictions of the CKM model [25, 3]. Models with weak-scale supersymmetry are particularly appealing in that they can potentially resolve a variety of theoretical problems at once, yielding a

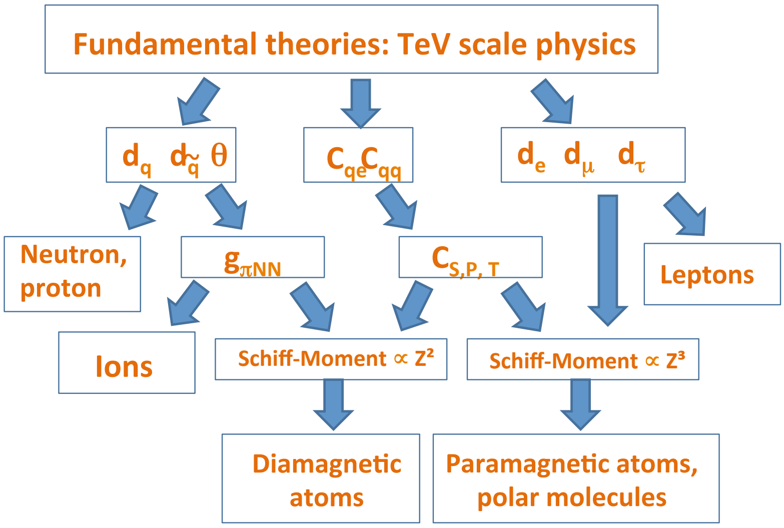

Figure 3: (Color online) New sources of CP violation at the TeV scale filter through the parameters of effective Lagrangians at ever lower energy scales to give rise to non-zero lepton, nucleon, nuclear, atomic, and molecular EDMs. Figure loosely adapted from Ref. [25].

cosmic baryon asymmetry through an electroweak phase transition more efficiently than in the SM [31], as well as providing a dark-matter candidate [32]. These models have and have had significant implications for flavor physics, and limits from the non-observation of EDMs and, more generally, of new chirality-changing interactions, constrain the appearance of new degrees of freedom [33, 34]. Such models can generate EDMs through dimension-five operators, which upon imposing $SU(2)_L \times U(1)$ gauge invariance are of dimension-six in numerical effect. Under dimensional analysis, the EDM of a fermion with mass m_f is $d_f \sim e \sin\phi_{\rm CP}\, m_f/\Lambda^2$, where $\phi_{\rm CP}$ is a CP-violating phase [35]. A prominent example of an EDM search is for that of the neutron, but also nuclei and electrons can have permanent EDMs [36]. The currently best measured limit (at 90% C.L.) of the neutron EDM is $d_n < 2.9 \cdot 10^{-26}$ e·cm [37], whereas that of the electron is $d_e < 1.05 \cdot 10^{-27}$ e·cm [38]. If $\sin\phi_{\rm CP} \sim 1$, as $\sin\delta$ is in the CKM mechanism, then the current experimental limits on the electron and neutron imply that $\log_{10}[\Lambda({\rm GeV})] \sim 5-6$. Thus, crudely, energy scales in excess of 10 TeV are probed by current experiments, with the next generation of EDM experiments, typically with factors of 100 increased sensitivity, improving the energy reach by a factor of 10.

Atoms differ from fundamental particles such as electrons, muons, and taus, as well as from neutrons, protons, deuterons, and indeed nuclei, in that their composite nature guarantees that their EDMs vanish in the point-like, nonrelativistic limit even if their constituents have nonzero EDMs [39]. This effect suppresses the visibility of an EDM in their measurement, but enhancements also arise because the cancellation can be strongly violated by relativistic and finite-size effects. The latter effect can give rise to a nonzero EDM though a P-odd, T-odd nuclear moment termed a "Schiff moment," whereas the former effect can give such an experiment sensitivity to d_e as well. We refer to Ref. [40] for a detailed exposition. Tracking the manner in which TeV-scale sources of CP violation, noting that we implicitly assume that CPT is inviolate throughout, emerge in the low-energy theoretical frameworks appropriate to the descriptions of nuclei, atoms, and molecules is a richly complex task; we illustrate it, crudely and incompletely, in Fig. 3 and refer to Ref. [3] for a recent review. Different sources of CP violation may be visible differently in the various experimental searches for EDMs at the hadronic, nuclear, atomic, or molecular scale [40, 25, 3], making the study of these various systems highly complementary. Although the EDMs of atomic systems, notably ^{199}Hg [21], can be measured with much higher accuracy, these results currently probe the underlying physics at a level crudely commensurate to that of the neutron limit (to the extent that they are comparable). Another recent development includes an enhancement through the deformation of the atomic shell in an external field [41].

A variety of EDM experiments are being planned or are ongoing, and PF reviewed the possibilities. At the SNS [42], PSI [43], ILL [44], and TUM [45] there are different, ongoing efforts to measure the neutron EDM with a sensitivity below 10^{-27} e·cm. The techniques use either ultracold neutrons (UCN) produced and stored in superfluid helium or UCN provided by a dedicated source, with the experiment at room temperature. As a measurement technique, Ramsey's method of separated oscillatory fields [46, 36] is used with spins precessing in a magnetic field with an electric field applied externally, either parallel or anti-parallel. A cohabitating magnetometer finally provides a good enough handle on systematic effects, in particular the so-called geometric phase. This is crucial to make the step below 10^{-26} e·cm. Also to achieve the required statistical accuracy, new UCN-sources are being realized that provide 10^3 UCN cm^{-3}. However, these have turned out to be technically more challenging than anticipated, thus any milestones in improved sensitivity will require another 3-5 years.

EDM experiments with protons and deuterons have recently gain increased attention, as these systems can provide competitive results. Here, the technical challenge is to search for a tiny *aspheric* electric charge distribution in the particle, noting that the particle is electrically charged itself. The proposed technical solutions by BNL [47] and Jülich [48] are frozen-spin storage rings, where the spin-rotation due to an EDM is decoupled from the Larmor-precession in the magnetic field. This is a conceptually new approach with its potential reach possibly exceeding experiments with neutrons. However, the implementation time would prove to be rather larger due to the required development of new techniques for, e.g., controlling magnetic fields in a 40 m radius ring.

Searches in atomic systems are typically of table-top scale but will have nevertheless a very-high-energy physics reach in the next 1-3 years. Whereas many diamagnetic atoms show a suppression of an EDM associated with the atomic nucleus, very heavy atoms such as Ra (at ANL) [49] and Rn (at TRIUMF) [50] show enhancements of the Schiff moment by a factor of 1000 over that of ^{199}Hg [51] due to octupole deformations. The latter has been recently observed in ^{224}Ra [52]. Efforts to measure these effects require a strong supply of radioactive ions and, for the case of radium, highly sophisticated atomic trapping techniques. In contrast, in atomic systems such as ^{199}Hg or ^{129}Xe, where the EDM is suppressed, measurement techniques combined with high available densities of the particles enable highly precise measurements. Here, the availability of sophisticated technology will likely enable improvements in sensitivity to below 10^{-29} e·cm in the next 2 years. Another class of systems with high potential in the near future are polar molecules which show strong internal electrostatic fields of GV/cm. Recently, the limit of the electron EDM could already be matched with such a technique in YbF to $\sim 1.05^{-27}$ e·cm [38]. Using ThO, the

ACME experiment [53, 54] is expected to produce a highly competitive result very soon.

In these systems theory is important to determining the experiments most sensitive to fundamental physics, and to helping to identify its nature. Nevertheless, the first nonzero results would be “discovery” experiments and in establishing that in itself theory would play little role.

- *We can also discover new physics through the comparison of non-null experimental results with precision theory. This is the domain of collider physics, but we can offer first-row CKM unitarity, as well as the muon $(g-2)_\mu$ as highly non-trivial tests. What are the future prospects here?*

SP offered an overview of the low-energy experiments designed to probe BSM physics. They are diverse in nature. Classifying by *process* one can study charged LFV in rare decays such as $\mu \to e\gamma$ or $\mu \to ee^+e^-$ or in $\mu - e$ conversion on nuclei. One can also search for enhanced branching ratios or CP asymmetries in B meson decays, e.g., or for novel particle properties such as EDMs, which can be probed in neutrons, deuterons, electrons, atoms, and/or molecules. One can also measure particle properties such as the $(g-2)_\mu$, the neutron electric charge, and the neutrino mass. Finally one can search for novel interactions, such as $0\nu\beta\beta$ decay, new short range forces, gravity at short distances (extra dimensions tests), right-handed currents, or anti-hydrogen spectroscopy, e.g., to realize CPT-tests. The spectrum of possibilities is vast. Classifying by *prediction*, then some experiments can be connected to SM predictions, though these may be much smaller than the experimental sensitivity, and have, moreover, robust BSM model predictions. Particular examples include rare decays, EDMs, right-handed currents, and studies of CP violation in the K and $B_{(s)}$ systems. Another example in which the SM prediction is low and the computation of QCD corrections difficult is CP violation and mixing in the D-system. Finally there are “dark” searches in that there is no real guidance as where to look, namely, searches for extra dimensions, $n-\bar{n}$ oscillations, mirror neutrons, dark photons, as well as tests of neutron and atom neutrality, which probe the quantization of electric charge [55].

New facilities are being opened, are under construction, or are being planned which focus on precision experiments at the high intensity frontier at low energies (as compared to those at the LHC). Facilities and/or corresponding experiments are listed in Table 1. The table is meant as an overview, and we disclaim any completeness. These facilities cover new beams and sources for slow or ultracold neutrons, respectively (FRMII (Munich), PSI, ILL, TRIUMF, SNS...), new very high intensity muon beams (PSI, JPARC, Osaka...), and new beams of kaons and sources for B and D-meson production or electron machines for dark photon searches. The latter are also used to search for new physics through precision measurements of parity-violating electron scattering [56]. New technologies and experimental schemes are being developed to address many of the relevant questions and to push the precision to the frontier desired. It should be noted that findings beyond expectations from SM will often have no unique interpretation, thus requiring several of the above experiments to be successful to pin down the origin of BSM effects.

Let us consider the possibility of discerning physics BSM from the precision measurement of quantities which are nonzero in the SM more carefully. In this we consider the measurement of $(g-2)_\mu \equiv a_\mu$ as a paradigm of sorts. In this class of BSM observable, theory is essential. The SM

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Physics observable	facilities	gain factor in sensitivity
	neutrons (cold beams & UCN sources)	
EDM	FRMII, PSI, ILL, SNS, TRIUMF	10-100 ($6 \cdot 10^{-26}$ at present)
n electric charge	FRMII, Mainz	10-100 (10^{-21} at present)
right handed currents	FRMII, ILL, LANL	10
$V_{\rm ud}$	FRMII, ILL, LANL	$>$10, also $0^+ \to 0^+$ transitions and theory input
new short range forces	FRMII, ILL	10-100 (strength, distance scale)
new spin dependent forces		
	LFV	
$\mu \to e\gamma$, $\mu \to 3e$	PSI, Osaka (MUSIC)	1000 (?)
B-decays	BELLE II	50-100
$\mu + N(A,Z) \to e + N(A,Z)$	JPARC (COMET), FNAL (Mu2E)	$10^{11}\mu/s$ (factor 1000 PSI_{2012})
	PRISM (storage ring)/PRISME	$10^{12} - 10^{13}\mu/s$
	EDMs	
deuteron	Jülich	
proton	FNAL (?)	$10^{-29}\mathrm{e} \cdot \mathrm{cm}$
atoms	Argonne, TRIUMF, Groningen	
e^-, molecules	various labs	
μ	new high power μ sources	factor $10^4 - 10^5$
	(PSI, PRISM)	$2 \cdot 10^{-19}\mathrm{e} \cdot \mathrm{cm}$
	g-2	
$(g-2)_\mu$	FNAL	5
	Rare Decays	
$K_L \to \pi^0 \nu\overline{\nu}$	JPARC	
$K^+ \to \pi^+ \nu\overline{\nu}$	CERN (NA62)	$V_{\rm td}$ to 10%
$B(_s) \to \mu\mu$	B-FACTORES, LHCB	
	dark photons	
	Mainz (MAMI, MESA), JLAB, B-factories...	

Table 1: Overview of physics observables on various intensity frontiers. Gain factors are rough estimates.

prediction for a_μ comes from various sources, noting

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HLO} + a_\mu^{\rm HHO}\,, \quad (2)$$

where a succinct, descriptive summary of the pieces can be found in Ref. [57]. The QED contribution is relatively large and well-established; the smaller contributions from electroweak (EW) and hadronic effects, both leading- (HLO) and higher-order (HHO), drive the uncertainty in the SM prediction. In what follows we note the leading order hadronic vacuum polarization contribution "HVP-LO" is just the "HLO" contribution, whereas the "HHO" contribution is the sum of the next-to-leading order hadronic vacuum polarization "HVP-NLO" and hadronic light-by-light "HLBL" contributions. The second such HLBL contribution has been used to determine $\delta a_\mu^{\rm TH}$. The dominant contributions to the theory error budget as per Ref. [57] are

$$a_\mu^{\mathrm{EW}} = 154(2)\times 10^{-11} \quad (3)$$
$$a_\mu^{\mathrm{HVP-LO}} = 6894(40)\times 10^{-11} \quad (4)$$
$$a_\mu^{\mathrm{HVP-NLO}} = -98(1)\times 10^{-11} \quad (5)$$
$$a_\mu^{\mathrm{HLBL}} = 116(39)\times 10^{-11} \quad (6)$$
$$= 105(26)\times 10^{-11} \quad (7)$$
$$\delta a_\mu^{\mathrm{TH}} = \pm 48\times 10^{-11} \quad (8)$$
$$\delta a_\mu^{\mathrm{EXP}} = \pm 63\times 10^{-11}, \quad (9)$$

where the experimental error $\delta a_\mu^{\mathrm{EXP}}$ is that of the BNL E821 experiment. A new realization of this experiment, planned for Fermilab [58], and an experiment with new technology [59] can reduce the experimental error by a factor of four. Our panellists KJ and CF discussed the possibility of further controlling the theoretical uncertainties through nonperturbative calculations.

- *What do we do if theoretical calculations of non-perturbative quantities, computed with grossly different methods, disagree? Consider the context of the muon g-2....*

KJ discussed the hadronic vacuum polarization contribution to $(g-2)_\mu$ from lattice QCD. The focus of lattice computations has been the leading order hadronic contribution to $(g-2)_\mu$, i.e., $a_\mu^{\mathrm{had,LO}}$. Unfortunately, in the past it turned out that the final error of such calculations were rather large, almost an order of magnitude larger than required from experiment and SM analyses. The reason for the large uncertainty originates mainly from the uncertainty to extrapolate to the physical value of the pion mass. However, in [60] a modification of the observable to calculate $a_\mu^{\mathrm{had,LO}}$ on the lattice has been proposed. This modification led to a much improved and better controlled pion mass dependence of $a_\mu^{\mathrm{had,LO}}$ as can be seen in Fig. 4. Here, the two upper sets of data points belong to the suggested improved lattice observables which allow for a linear extrapolation to the physical point with a corresponding much reduced error. The lowest data points are obtained with the standard method, and it is clear that for those values such an extrapolation would be very difficult.

It is important to stress that there are a number of lattice collaborations tackling the problem of $a_\mu^{\mathrm{had,LO}}$, see Refs. [61, 60, 62]. This a very fortunate situation since in this way a cross-check of the lattice results can be obtained and thus confidence in correctly estimated systematic uncertainties of lattice computations can be obtained. Another impoprtant point is that with the improved method of Ref. [60] also other hadronic contributions to electroweak observables can be calculated with an improved precision. This comprises the electron and τ anomalous magnetic moment, the running of the electromagnetic coupling α_{QED}, the weak mixing angle, the Adler function, and the Lamb-shift for muonic atoms, see Ref. [63].

Lattice computations are now also performed for four flavours, including a dynamical strange and charm quark, and a first result for $a_\mu^{\mathrm{had,LO}}$ is already available [64]. The lattice community is also actively looking into the problem of the hadronic light-by-light contribution. This is still a clear challenge, and it needs to be seen whether this quantity can be obtained on the lattice with the desired precision. Here, an interaction with different approaches such as Dyson-Schwinger equations, as discussed below, could be very helpful. In any case, with improved lattice technologies

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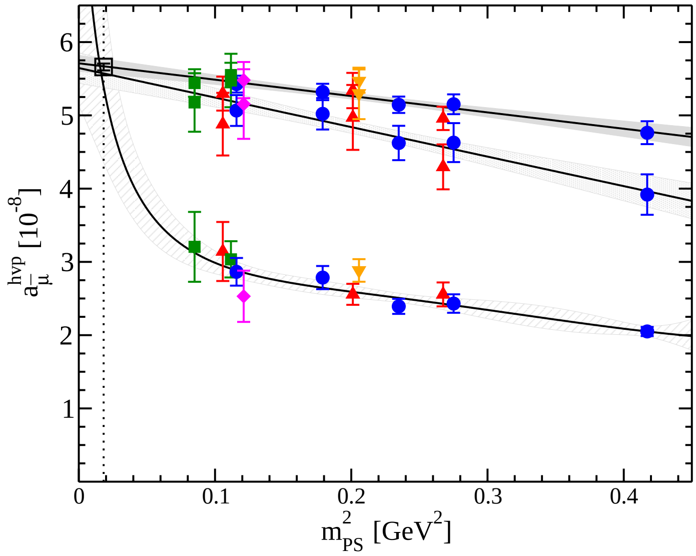

Figure 4: (Color online) Result of a two-flavour computation using the improved observables introduced in Ref. [60]. The lowest data points belong to the standard way of computing $a_\mu^{\rm had,LO}$ while the two most upper sets of points correspond to using the improved observables which allow for a linear and controlled extrapolation to the physical point, leading to a significantly reduced error for $a_\mu^{\rm had,LO}$. Figure taken from Ref. [60].

and the prospect to have calculations directly at the physical point, the lattice is on a promising road to match eventually the precision of the newly planned experiments at Fermilab and J-PARC.

CF discussed the Dyson-Schwinger (DSE) approach to the hadronic vacuum polarization computation [65] and showed that that approach could bracket the result determined from dispersive analyses. Using a well-established model for the quark-gluon interaction the approach is able to reproduce the dispersive result at the two-percent level. Furthermore, the dependence of HLO on the bare quark masses determined from the DSE approach nicely matches corresponding lattice results. While the overall precision of the current DSE calculation is certainly not good enough to improve the dispersive result, it indicates the feasibility of the approach also with respect to HLBL.

CF also discussed hadronic light-by-light contributions. Partly using effective degrees of freedom these may be split into a quark-loop diagram, a contribution from meson exchange and diagrams involving closed pion loops. The latter ones contain also a pion polarizability contribution [66], which were also discussed by M. J. Ramsey-Musolf at the conference [67]. While there is more or less general agreement among different model calculations on the size of the meson exchange contributions, the quark-loop and pion-loop contributions are currently under debate. For the quark-loop contribution the DSE approach delivers a considerably larger value than conventional model approaches; see Ref. [68] for a detailed study of why this is the case. For the pion-loop contribution Ramsey-Musolf argued that chiral effective theory may converge poorly and consequently one has to expect large (negative) corrections from higher-order contributions. This is indeed seems to be the case [66]. In order to work towards a reliable calculation of HLBL from non-perturbative methods a systematic comparison between the different approaches, DSEs, effective theories, and future lattice calculations, is necessary and promising.

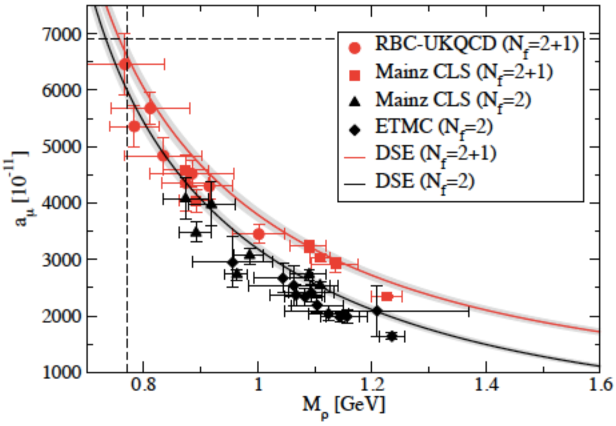

Figure 5: (Color online) The HVP contribution to a_μ as a function of the ρ mass [69]. Compared are DSE results for $N_f = 2$ (black) and $N_f = 2+1$ (red) flavors with corresponding lattice results [61, 60, 62]. The grey bands represent the numerical uncertainty.

- *The LHC has found a Higgs-like boson. Can low-energy experiments help refine the nature of the scalar sector?*

As of this writing the Higgs-like boson has been declared by ATLAS and CMS a "Higgs" [70], though studies of its quantum numbers and couplings are definitely ongoing. SG remarked that certain rare branching ratios are expected to be enhanced in theories with extended scalar sectors. A particularly prominent example is that of the $B_s \to \mu^+\mu^-$ decay rate [71]. Evidence for this decay has finally been found, but at a rate in the ballpark of SM expectations [72], though other observables should also be considered [73]. More generally, interconnections exist between theories with extended scalar sectors and flavor physics observables: existing EDM constraints limit the CP-violating aspects of the former [74], whereas the portion of the MSSM parameter space compatible with a Higgs of some 125 GeV in mass are further constrained by the latter [75]. As a separate tack, scalar (and tensor) interactions at low energies can also be identified, and the SM thereby falsified, through a concerted study of neutron β decay observables [76].

- *What "exotic" experimental searches are important?*

PF addressed this question and presented the possibility of gravity resonance spectroscopy to study the existence of new forces at micrometer distances, as well as to set a 100 times stronger limit on the neutron electric charge. The latter probes the existence and nature of Grand Unified Theories (GUTs) at very high energy scales.

As important "exotic" searches PF would consider fields where new techniques are developed. Here the new gravity resonance technique [77] should be pointed out. A neutron can be vertically trapped on a highly reflective mirror, forcing the formation of bound energy states on the peV scale in the presence of the potential barrier of the mirror and the linearly increasing gravitational potential. By vibrating a mirror, various states of excitation can be selected. This concept is the first precision spectroscopy method that does not require electromagnetic interactions and can be developed towards an interferometric scheme, thus opening up a new window to a variety of precision measurements at quasi-zero energy. Possible applications could be the test of spin-dependent and spin-independent interactions at $< 100\ \mu$m distances, probing gravity as well as axion- or dark-matter-like particles as mediators of forces at short distances. Further, the electric neutrality of the neutron can be tested with this technique with potentially significant improvements, thus probing energies that are hardly accessible with other techniques. Another "exotic" test that probes high energies is the $n-\overline{n}$ transition. Here, many improved measurement concepts have been revived recently [78] in combination with improved theoretical motivations that could strongly be tested with such improvements [79].

- *Your "5 cent" bet: in what (low energy) system will we first establish the existence of dynamics beyond the standard model?*

VC bet on the observation of charged LFV in $\mu \to e\gamma$ and $\mu \to e$ conversion. PF picked gravity experiments. SP picked the $(g-2)_\mu$, possibly, and EDMs. KJ picked the $(g-2)_\mu$, whereas CF picked the $(g-2)_\mu$ and EDMs. SG bet on the "dark horse" $n-\overline{n}$. May at least one of us be right!

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