Low Energy Tests of the Standard Model with Spin Degrees of Freedom

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Abstract. After briefly reviewing the status of the standard model, I will focus mainly on polarized electron scattering and other tests of the weak neutral current. I will also address other low energy tests in which polarization degrees of freedom play a crucial role, including precision muon physics and searches for electric dipole moments.

Keywords: Standard model tests; neutral currents; polarized electron scattering; muon physics; electric dipole moments.

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Introduction

The Standard Model (SM) of the strong and electroweak (EW) interactions, based on the gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y$, is well tested up to energies of $O(100 \text{ GeV})$. It is now clear that the SM is correct not only to first (tree-level) order, but also at the level of radiative (loop) corrections. Thus, beyond the SM physics can only be a small perturbation, and is probably of decoupling type. The prospects to eventually find new physics are extraordinarily bright. Most theorists argue that within the SM the EW scale is unstable, because radiative corrections would generally drive the quadratic term of the Higgs potential to very high mass scales (the hierarchy problem) — unless those corrections are controlled by a physical cut-off which is not much larger than the EW scale itself. In addition, observations of dark matter, dark energy, and the matter anti-matter asymmetry in the universe imply modifications of the SM beyond the introduction of neutrino mass.

Most scenarios for physics beyond the SM are guided by the hierarchy problem. Supersymmetry (SUSY) stabilizes the Higgs potential by virtue of non-renormalization theorems. Dynamical symmetry breaking (e.g., technicolor) nullifies the problem by avoiding fundamental scalar fields to start with. Large extra dimensions relate the hierarchy to the geometry of a higher dimensional space-time, but the stability of the latter remains in general an open question. Little Higgs models construct the Higgs as a pseudo-Goldstone boson, postponing the occurrence of quadratic divergences by one or two loop orders. In all cases is it difficult to construct realistic models which are free of problems and consistent with all observations. One usually needs to introduce extra

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degrees of freedom to address those difficulties. This assures a rich phenomenology with implications for low energy physics, as well.

A great deal of experimental information (in several cases with better than per mille precision) has been gained from the Z-factories, LEP 1 and SLC [1]. As a result, the Z boson is now one of the best studied particles of the SM, and its properties are in reasonable agreement with the SM. Nevertheless, there are classes of new physics which do not significantly affect Z boson properties, and which may hide under the Z resonance. As will be reviewed in the subsequent sections, experiments at very low energies — even if their relative precisions are not at the per mille level — can have complementary sensitivities to new physics. The key idea is to exploit the spin degree of freedom to separate the dominant parity conserving electromagnetic force from the parity violating EW interaction, and possibly parity violating new interactions. If in addition, the SM prediction is parametrically suppressed (as frequently turns out to be the case) one has enhanced leverage, allowing to test new physics scales up to the multi-TeV region. Thus, there are generally two complementary strategies to test the SM and its extensions, namely using high energy or high precision. In turn, precision tests can be performed in SM allowed processes (e.g., parity violating scattering) or in SM forbidden (highly suppressed) observables (such as permanent electric dipole moments).

Status of the Standard Model

One of the key parameters of the electroweak SM is the weak mixing angle,

$$\sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2} = 1 - \frac{M_W^2}{M_Z^2}, \quad e = g \sin \theta_W = g' \cos \theta_W,$$

(1)

where g, g', and e are the gauge couplings of SU(2)_L, U(1)_Y, and QED, respectively. The weak Z^0 boson and the photon, A, are then the linear combinations,

$$Z_\mu^0 = \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu, \quad A_\mu = \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu,$$

(2)

of SU(2)_L and U(1)_Y gauge bosons, W^3 and B. Measurements of sin\theta_W currently yield the strongest constraints on the Higgs boson mass, M_H, which is extracted from Higgs loop effects. Fig. 1 shows that there are actually three independent determinations of M_H as functions of m_t. The banana shaped solid (dark green) contour arises from Z boson properties, like total and partial widths and the hadronic peak cross section, but not asymmetry measurements. The latter result in the dotted (brown) lines. The long-dashed (blue) lines are due to the W boson mass measurements, M_W = 80.394 ± 0.029 GeV at LEP 2 [2, 3] (e^+e^-) and the Tevatron [4, 5] (p\bar{p}). These three contours overlap for values of m_t consistent with the Tevatron average (shown as the vertical lines), m_t = 171.4 ± 2.1 GeV [6]. Only the dashed (magenta) contour from low energies driven by the NuTeV result [7] on neutrino deep inelastic scattering (ν-DIS) (to be discussed
FIGURE 1. One-standard-deviation (39.35%) uncertainties in $M_H$ as a function of $m_t$ for various inputs, and the 90% C.L. region allowed by all data. The 95% C.L. direct lower limit from LEP 2 is also shown.

later) disagrees. With the latest experimental results, a global fit to all data yields,

$$M_H = 84^{+32}_{-25} \text{ GeV},$$
$$m_t = 171.4 \pm 2.1 \text{ GeV},$$
$$\alpha_s(M_Z) = 0.1216 \pm 0.0017.$$ (3)

The result for $M_H$ is only barely consistent (within 1 $\sigma$) with the 95% C.L. lower search limit from LEP 2 [8], $M_H > 114.4$ GeV. Including the results of these direct searches as an extra contribution to the likelihood function yields the 95% C.L. upper bound,

$$M_H \leq 178 \text{ GeV}.$$ (4)

The value of $m_t$ in Eq. (3) is completely dominated by the Tevatron input. One can also perform a fit to the precision data alone, i.e., excluding the direct $m_t$ from the Tevatron, yielding $m_t = 171.0^{+9.5}_{-7.1}$ GeV, in perfect agreement with the direct determination. The strong coupling constant, $\alpha_s(M_Z)$, is mainly constrained by $Z$ and $\tau$ decays. These correspond to clean determinations of $\alpha_s(M_Z)$ at two very different energy scales and are in perfect agreement with each other. The overall goodness of the global fit is very reasonable, with $\chi^2 = 47.3$ for 42 degrees of freedom and a probability for a larger $\chi^2$ of 27%. However, there are a few observables showing interesting deviations from the SM. Some of these are in the low energy sector and will be discussed below.

**Effective Lepton-Hadron Lagrangian**

The weak neutral current can be tested at low energies by isolating interference effects with the photon amplitude using the parity (P) and charge conjugation (C) symmetry violating nature of the weak interaction. It is sufficient to work with the effective P and
C violating four-Fermi lepton-hadron Lagrangian,
\[
\mathcal{L}_{\text{NC}}^{lh} = \frac{G_F}{\sqrt{2}} \sum_q\left[ C_{1q} \bar{\nu} \gamma^\mu \gamma^5 \ell \gamma_\mu q + C_{2q} \bar{\nu} \gamma^\mu \ell \bar{q} \gamma_\mu \gamma^5 q + C_{3q} \bar{\nu} \gamma^\mu \gamma^5 \ell \bar{q} \gamma_\mu \gamma^5 q \right].
\] (5)

Here \(G_F\) is the Fermi constant, and the \(C_{ij}\) are effective four-Fermi couplings, where,
\[
C_{1q} = -T_3^q + 2Q_q \sin^2 \theta_W, \quad C_{2u} = -C_{2d} = -\frac{1}{2} + 2\sin^2 \theta_W, \quad C_{3u} = -C_{3d} = \frac{1}{2}, \tag{6}
\]
holds at the SM tree level. Notice, that the \(C_{2q}\), as well as the combination \(Q^p_W \equiv 2C_{1u} + C_{1d}\) (relevant for the Qweak experiment discussed later), are proportional to \(1 - 4 \sin^2 \theta_W\). Therefore, one can have enhanced sensitivity to \(\sin^2 \theta_W\) as its numerical value is close to \(1/4\). If the SM tree level contribution is suppressed in this way then loop effects — but also possible new physics contributions — are relatively enhanced. This gives additional leverage to study the TeV scale. In the following sections, past and future low energy measurements constraining the \(C_{ij}\) are reviewed.

**PV-DIS**

The right-left asymmetry, \(A_{RL}\), in parity violating deep inelastic electron scattering (PV-DIS) is given by,
\[
A_{RL} = \frac{3G_F Q^2}{10\sqrt{2}\pi \alpha(Q^2)} \left[ (2C_{1u} - C_{1d}) + g(y)(2C_{2u} - C_{2d}) \right], \tag{7}
\]
where \(\alpha(Q^2)\) is the electromagnetic coupling at squared momentum transfer, \(Q^2\), and \(g(y)\) is a function of the fractional energy transfer, \(y\), from the electron to the hadrons. The relative weights of up and down quarks is given by their electric charge ratio — a consequence of interfering individual quarks with the photon amplitude as is typical in the deep-inelastic regime. The first experiment of this type was the celebrated E–122 experiment at SLAC [9] which was crucial to establish the SM even before the discovery of the \(W\) and \(Z\) bosons (searches for atomic parity violation at the time gave conflicting results). The NA–004 experiment at CERN [10] is the only experiment to date to have replaced positive muons with negative ones simultaneously with the reversal of the muon polarization. This resulted in unique sensitivity to the coefficients \(C_{3j}\).

An experiment at JLab [11] is approved to use the current 6 GeV CEBAF beam to repeat the SLAC experiment on deuterium with greater precision. One hopes to be able to collect more data points after the 12 GeV upgrade [12]. This would improve the SLAC result and the current world average by factors of 54 and 17, respectively. The issues to be addressed are higher twist effects and charge symmetry violating (CSV) parton distribution functions (PDFs). Since higher twist effects are strongly \(Q^2\) dependent and CSV should vary with the kinematic variable, \(x\), while contributions from beyond the SM would be kinematics independent, one can separate all these possible effects by measuring a large array of data points. Thus, a great deal can be learned about the strong and weak interactions at the same time. The measurements are expected to be limited experimentally by the determinations of the polarization and the \(Q^2\) scale.
Polarized Møller Scattering

An experiment free of QCD issues has been completed recently by the E–158 Collaboration [13] located in End Station A at SLAC. They obtained the first measurement of the parity violating Møller asymmetry,

\[ A_{PV} = -\mathcal{A}(Q^2, y)Q^\text{W}_e = (-1.31 \pm 0.14 \pm 0.10) \times 10^{-7}, \]  

(8)

where \( \mathcal{A} \) is the analyzing power and \( Q^\text{W}_e \) is the so-called weak charge of the electron which contains all the weak physics. The experiment used the SLC beam delivering \( 89 \pm 4\% \) polarized electrons. The beam energies were at 45 and 48 GeV, but the small electron mass turned this into a low \( Q^2 = 0.026 \text{ GeV}^2 \). Although \( Q^\text{W}_e \) is not in the sector giving rise to \( C_{ij} \) measurements, it is another example of a quantity proportional to \( 1 - 4\sin^2 \theta_W \). The resulting \( Q^\text{W}_e = -0.0403 \pm 0.0053 \), which is in reasonable agreement with the SM prediction, can thus be used to extract a precise value for the weak mixing angle defined at the \( Z \) scale. Including one-loop radiative corrections [14] one arrives at,

\[ \sin^2 \theta_W(M_Z) = 0.2330 \pm 0.0014. \]  

(9)

The world’s best measurements of the weak mixing angle [1] have been provided by SLD (\( \pm 0.00029 \) from the left-right cross section asymmetry) and the LEP groups (\( \pm 0.00028 \) from the forward-backward asymmetry for \( b \)-quark final states). These two measurements contribute greatly to our current knowledge of \( M_H \). However, they disagree from each other by 3.1 \( \sigma \). It is important to resolve this discrepancy. Notice that their uncertainty is about 5 times smaller than the one in Eq. (9). Thus, a factor of 5 improvement in the precision of the Møller asymmetry would make this kind of measurement fully competitive with the \( Z \) factories which could shed some light on the discrepancy. Precisely this kind of improvement is currently under discussion at JLab [15].

Qweak

A very similar experiment, in fact using the same kind of target (hydrogen), will measure the analogous weak charge of the proton, \( Q^\text{p}_W = 2C_{1u} + C_{1d} \). The combination of a smaller beam energy of 1.165 GeV and the larger target mass (protons) relative to E–158 results in virtually the same \( Q^2 = 0.03 \text{ GeV}^2 \), corresponding to elastic scattering. Thus, one scatters from the proton as a whole, so that the relative weight of up and down quarks is given by the valence quark composition. With an expected polarization of \( 85 \pm 1\% \) the Qweak Collaboration anticipates to measure the parity violating asymmetry,

\[ A_{PV} = 9 \times 10^{-5} \text{ GeV} (Q^2 Q^\text{p}_W + Q^4B) \sim (-2.68 \pm 0.05 \pm 0.04) \times 10^{-7}, \]  

(10)

where the first uncertainty is experimental. The second uncertainty is from the leading form factor contribution, the \( Q^4B \) term, which will be determined experimentally by means of a fit to existing and future measurements at various \( Q^2 \) points. The actual Qweak experiment [16] is the one with the lowest lying \( Q^2 \). The anticipated errors in
$Q_{W}^p$ and the corresponding $\sin^2 \theta_W$ are $\pm 0.003$ and $\pm 0.0007$, respectively. Notice, that the (expected) asymmetry (10) is about twice as large as the Møller asymmetry (8). The reason is that neither the form factor term (suppressed by $Q^2/m_p^2$) nor the one-loop $WW$-box (of order $\alpha/\pi$ and enhanced by a factor of 7 relative to $Q_{eW}^p$) enter with the $1 - 4 \sin^2 \theta_W$ suppression factor, so that on balance these contributions are roughly comparable with the tree level. The one-loop radiative corrections [17] have the form,

$$Q_{W}^p = [\rho_{NC} + \Delta_c] [1 - 4 \sin^2 \hat{\theta}_W(0) + \Delta'_c] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}, \quad (11)$$

a structure which also applies to $Q_{eW}^p$, as well as to APV discussed below. $\rho_{NC} - 1$, $\Delta_c$, and $\Delta'_c$ are due to self-energy and vertex corrections, and $\sin^2 \hat{\theta}_W(0)$ is an effective low energy weak mixing angle. The $\gamma Z$-box, $\Box_{\gamma Z}$, is plagued by long-distance QCD effects of the form $\ln M_Z^2/\Lambda_{QCD}^2$, where $\Lambda_{QCD}$ is the strong interaction scale. The precise value of $\Lambda_{QCD}$ to be used here is difficult to estimate, but fortunately, these effects are suppressed by $1 - 4 \sin^2 \theta_W$. On the other hand, the relatively large $WW$-box contribution, $\Box_{WW}$, of about 26% requires inclusion of two-loop mixed EW-QCD corrections, which in this case (and also for the $ZZ$-box, $\Box_{ZZ}$) are of short-distance type and given by [18],

$$\Box_{WW} = \frac{\hat{\alpha}(M_W)}{4\pi \sin^2 \hat{\theta}_W(M_W)} \left[ 2 + 5 \left( 1 - \frac{\alpha_s(M_W)}{\pi} \right) \right]. \quad (12)$$

The two weak charges, $Q_{W}^p$ and $Q_{eW}^p$, are complementary not only because of their very different experimental systematics, but also due to their different sensitivities to new physics [18]. E.g., supersymmetric loop contributions and many types of extra neutral $Z'$ bosons would affect them in a strongly correlated way. By contrast, SUSY models with so-called R-parity violation typically produce anti-correlated effects. And leptoquarks could strongly contribute to $Q_{W}^p$, but not to the purely leptonic electron weak charge.

**APV**

Observations of atomic parity violation (APV) can be used to extract the weak charges of heavy nuclei. These are defined analogous to $Q_{eW}^p$ and $Q_{W}^p$, but come with entirely different experimental and theoretical issues. In particular, one needs a solid understanding of the structure of many-electron atoms [19]. At present, only in $^{133}$Cs [20, 21] and $^{205}$Tl [22, 23] are both the experimental and atomic theory errors at the %-level, yielding $Q_{W}^{C_6} = -72.62 \pm 0.46$ and $Q_{W}^{Tl} = -116.4 \pm 3.64$, respectively. Future directions include measurements in Fr (using atom traps), and Ba$^+$ (which has a Cs-like atomic structure) may be studied in ion traps. An alternative could be the study of isotope ratios in which most of the atomic theory uncertainties cancel. Effects from the poorly known neutron distributions contribute an uncertainty at the 0.15%-level [24]. This would be a problem for the isotope ratios unless our understanding of the neutron density can be improved. If this turned out to be impossible, one may conversely use APV to study nuclear structure. The weak charges of single isotopes (but not of isotope ratios) yield very different linear combinations of the coefficients $C_{1j}$ than $Q_{W}^p$, so that with $Q_{\text{weak}}$ it will be possible to constrain the individual $C_{1j}$ precisely. For a recent global fit to the $C_{ij}$, see Ref. [25].
FIGURE 2. The weak mixing angle in the \( \overline{\text{MS}} \) renormalization scheme as a function of momentum transfer, \( \sqrt{Q^2} \). The width of the line indicates the uncertainty in the SM prediction [34]. \( A_{PV} \) is the result from the Möller asymmetry [13], \( A_{FB} \) is the lepton forward-backward asymmetry from the Tevatron [35].

\textbf{NuTeV}

The NuTeV experiment [7] in \( \nu \)-DIS finds for the on-shell definition of the weak mixing angle, \( \sin^2 \theta_W = 0.2277 \pm 0.0016 \), which is 3.0 \( \sigma \) higher than the SM prediction. The discrepancy is in the left-handed effective four-Fermi coupling,

\[ g_L^2 = 0.3000 \pm 0.0014 \sim \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W, \tag{13} \]

which is 2.7 \( \sigma \) low. Within the SM, one can identify five categories of effects that could cause or contribute to this effect: (i) an asymmetric strange quark sea, although this possibility is constrained by dimuon data [26]; (ii) CSV PDFs at levels much stronger than generally expected [27]; (iii) nuclear physics effects [28, 29, 30]; (iv) QED and electroweak radiative corrections [31, 32]; and (v) QCD corrections to the structure functions [33]. The NuTeV result and the older \( \nu \)-DIS data should therefore be considered as preliminary until a re-analysis using PDFs including all experimental and theoretical information has been completed. It is well conceivable that various effects add up to bring the NuTeV result in line with the SM prediction. It is likely that the overall uncertainties in \( g_L^2 \) (and \( g_R^2 \)) will increase, but at the same time the older \( \nu \)-DIS results may become more precise when analyzed with better PDFs than were available at the time. The \( \nu \)-DIS results are compared with other determinations of \( \sin^2 \theta_W \) in Fig. 2.

\textbf{\( \mu \)-decay}

The muon lifetime, \( \tau_\mu \), yields a precise value for the Fermi constant with negligible theoretical uncertainty, \( G_F = 1.16637 \pm 0.00001 \text{ GeV}^2 \). There are two new efforts at
TABLE 1. Results on the Michel parameters for muon decay.

| parameter | comment | SM | pre-TWIST | TWIST |
|-----------|---------|----|----------|-------|
| $\rho$    | spectral shape | 3/4 | 0.7518 ± 0.0026 | 0.7508 ± 0.0010 |
| $\delta$  | asymmetry shape | 3/4 | 0.7486 ± 0.0038 | 0.7496 ± 0.0013 |
| $P_{\mu\zeta}$ | asymmetry | 1 | 1.0027 ± 0.0085 | 1.0003 ± 0.0038 |
| $\eta_{\zeta}$ | $m_e/m_{\mu}$-suppressed | 0 | $-0.007 ± 0.013$ | $-0.0036 ± 0.0069$ |

* See [38] for details.

PSI (FAST [36] and $\mu$LAN [37]) with the goal to improve $\tau_\mu$ by a factor of 20 to $\sim 1$ ppm. The TWIST Collaboration at TRIUMF improved our knowledge of the model independent Michel parameters for $\mu$-decays. As shown in Tab. 1, various parameters have already improved by about a factor of three, with further improvements expected.

**Muon Anomalous Magnetic Moment**

One of the most precisely measured observables is the anomalous magnetic moment of the muon, $a_\mu$ [39]. It is also easily affected by new physics contributions and therefore an important probe of physics beyond the SM. However, the interpretation of $a_\mu$ is complicated by hadronic contributions. One can use $e^+e^- \to$ hadrons cross section data to estimate the two-loop vacuum polarization (VP) effect. The most recent evaluation yields, $a^{(2,\text{VP})}_\mu = (68.94 \pm 0.46) \times 10^{-9}$ [40], implying a 3.4 $\sigma$ discrepancy between SM and experiment [41]. If one assumes isospin symmetry (which is not exact and appropriate corrections [42] have to be applied) one can also make use of $\tau$ decay spectral functions [43] which yields instead [44], $a^{(2,\text{VP})}_\mu = (71.10 \pm 0.58) \times 10^{-9}$, and would remove the discrepancy. It is not clear that the conflict between $e^+e^-$ and $\tau$ data originates from larger-than-expected isospin violations: Ref. [45] shows on the basis of a QCD sum rule that the $\tau$ decay data are consistent with values of $\alpha_s(M_Z) \gtrsim 0.120$ (in agreement with the result (3)), while the $e^+e^-$ data prefer lower (disfavored) values. Fortunately, as far as $a^{(2,\text{VP})}_\mu$ is concerned, due to a suppression at large $Q^2$ (from where the conflict originates) this problem is less pronounced. An additional uncertainty is induced by hadronic three-loop light-by-light-type graphs. A recent evaluation [46] resulted in $a^{\text{LBS}}_\mu = (1.36 \pm 0.25) \times 10^{-9}$. This is higher than previous evaluations [47, 48, 49], but consistent with the simple quark level estimate of Ref. [50]. The latter can also be used to bound $a^{\text{LBS}}_\mu$ from above, $a^{\text{LBS}}_\mu < 1.5910^{-9} (95\% \text{ C.L.})$. If more experimental and theoretical work will be dedicated to these hadronic issues, a new and more precise experiment [39] of $a_\mu$ would very well be worth the effort.

**Electric Dipole Moments**

A very powerful probe of physics beyond the SM are searches for CP and time reversal symmetry (T) violating permanent electric dipole moments (EDMs) of electrons, muons,
neutrons, and neutral atoms. EDM searches are of interest for several reasons: (i) The SM (CKM) predictions for the magnitudes of EDMs fall well below the sensitivity of present and prospective measurements. Consequently, the observation of a non-zero EDM would signal the presence of physics beyond the SM or CP violation in the SU(3)$_C$ sector of the SM. The latter arises via a term in the Lagrangian [51],

$$\mathcal{L}^{\text{strong CP}} = \theta_{\text{QCD}} \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu},$$

(14)

where $G_{\mu\nu}$ ($\tilde{G}_{\mu\nu}$) is the (dual) SU(3)$_C$ field strength tensor. (ii) The observed predominance of matter over anti-matter in the universe conflicts with expectations based on the SM alone. On the other hand, candidate extensions of the SM that could provide new CP violation of sufficient strength to account for the matter anti-matter asymmetry could also generate EDMs large enough to be seen. (iii) Recent experimental developments [19, 52] have put the field on the verge of a revolution. The experimental sensitivities are poised to improve by factors of 100 to 10,000 during the next decade. (iv) The various EDM searches provide complementary probes of new CP violation. E.g., the observation of a non-zero neutron or atomic EDM in conjunction with a null result for the electron EDM at a comparable level of sensitivity would point toward the interaction of Eq. (14) as the likely source. In contrast, a non-zero lepton EDM would be a smoking gun for CP violation outside the SM, and a comparison with neutron and atomic studies would be essential for identifying the particular scenario responsible.

**Conclusions**

A network of high precision polarized electron scattering experiments will study the TeV scale in a network of measurements, especially at JLab. Next generation $\mu$-decay experiments will improve the precision of the muon lifetime and are looking for deviations from the $V-A$ structure of the SM. The anomalous magnetic moment of the muon deviates at the 3 $\sigma$ level from the SM prediction and is well worth further investments on both the theoretical and experimental sides, considering that very many types of new physics scenarios can affect this observable. Searches for permanent EDMs are highly motivated, and is an area with spectacular experimental developments.

I hope that this survey (although necessarily incomplete) serves to demonstrates that low energy measurements — almost all of which using spin degrees of freedom in an essential way — will remain indispensable even in the LHC era.

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