Hadronic Physics: an Outlook

Eric S. Swanson

Dept of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA 15260.

Abstract. A brief outlook, in two senses, is presented for hadronic physics. The likely near term future for experiment and lattice effort is sketched and I speculate on future directions in theory. I also look out at other fields, presenting a short review of QCD ideas in “Beyond the Standard Model” physics.

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OUTLOOK (I)

We have seen a lot of particles come (and some go) since Hadron 1993 in Como. Amongst these are $\xi(2220)$ (Como, 93); $f_0(1500)$ (Manchester, 95), $\pi_1(1400)$ (BNL, 97); $\pi_1(1600)$ (Beijing, 99); $X(3872)$, $D_s(2317)$, $\Theta(1540)$, $\eta'$, $D_{s1}(2630)$, $\pi_1(1900)$ (Aschaffenburg, 03); $Y(4260)$, h_t, $X(1835)$, $D_s(2860)$ (Rio de Janeiro, 05); Z(4430), $Y(4660)$ (Frascati, 07); $\eta_b$, $X(1500)$ (Tallahassee, 09).

What can we expect in the future? Because experiments tend to be large they have long funding lead-in times, and one can approximately anticipate where effort will lie. A good part of this conference was dedicated to current and future effort at experimental facilities. Thus the next section, which deals with future experiment, is largely pilfered from talks at this meeting.

Experiment

We are fortunate to have a global and robust experimental program in hadronic physics. This is due, in part, to the fact that the world is made up of hadrons, and hence those interested in nonhadronic physics must decouple hadrons in a controlled manner. Of course, it is also due to the many experiments dedicated to understanding hadrons and their beguiling underlying theory.

The upgrade is underway at Jefferson Lab. This $300 million effort will add another pass to the accelerator, build a new experimental hall that will house the GlueX experiment, and upgrade the existing halls. Thus CLAS will become CLAS-12[1] and a new era in holographic measurements of nucleon structure will begin. GlueX, alternatively, will be chiefly concerned with mapping out the properties of light hybrid mesons[2].

Brookhaven National Lab continues to pursue a luminosity upgrade (RHIC II) and an electron-heavy ion collider (eRHIC) as possible upgrades. The eRHIC facility would “be the world’s foremost facility for the study of gluon-dominated matter”[3]. Of more immediate interest are plans to look for glueballs in central production via double pomeron exchange with the STAR detector[4]. This could be the only experiment focussed on glueballs in the world.

Although CLEO has terminated operations, many new results have appeared in the past two years, and it was pleasing to learn that analysis of data still continues[5].

The BESIII upgrade is operational and the collaboration has collected 220 million $J/\psi$ and 100 million $\psi(2S)$ events. They will take $\psi(3770)$ data for five months and then move on to collect 10 billion $J/\psi$ events and 3 billion $\psi(2S)$ events. Several upgrades are in planning, including increasing the beam energy from 4.6 to 5.0 GeV[6]. The collaboration plans to continue investigating charm and charmonium physics, tau physics, light hadron spectroscopy, and rare decays.

After nearly a decade of construction, J-PARC has started its operational phase. An extensive experimental program covering the range of hadronic physics is planned. Currently approved experiments include an investigation of the properties of vector mesons in medium, a search for the pentaquark $\Theta^+$, precision spectroscopy of kaonic atoms, and a study of $\Xi$ hypernuclei[7].
The COMPASS experiment at CERN has spent considerable effort investigating the $\pi_1$ resonances seen at BNL, VES, and the Crystal Barrel, along with a program in nucleon structure and chiral dynamics[8]. The next two years will be devoted to muon physics, after this the collaboration will apply to continue research on hadrons.

The 1.3 billion euro expansion of GSI is underway. An important portion of this will be the PANDA experiment at FAIR (Facility for Antiproton and Ion Research), which is devoted to studying hadron spectroscopy, in-medium properties of hadrons, nucleon structure, and hypernuclei. Expect it all to start in 2016[9].

The German baryon experiments, CB-ELSA at Bonn and MAMI at Mainz, continue to collect high quality data[10]. The current funding cycle is drawing to a close, and plans are to apply for five more years of running[11].

The B factories have contributed in a spectacular way to hadronic physics in the past seven years. Two new B factories are in the planning stages, SuperKEKB in Japan, and SuperB in Italy. SuperB is part of the European high energy physics strategic plan and has been approved by INFN as a ‘special project’. The Lazio government has allocated 20 M euro for R&D. Right now the Italian Ministry of Science and Education is awaiting a funding endorsement from the Economy Ministry. In Japan, the government has allocated $32M for upgrade R&D as part of its economic stimulus plan. KEK has also submitted a budget request for $350M for construction, and a decision is expected imminently[12].

After a few ‘issues’, the LHC is up and running (it appears to be cooling down in preparation for its winter 2010 runs[13]). Although the word ‘hadron’ appears in its name, hadronic physics is not mentioned often in CERN press releases. Nevertheless, a substantial hadronic physics program is planned[14]. In rough chronological order ATLAS and CMS intend to perform charmonium and bottomonium ‘measurements’ (presumably calibrations on the $J/\psi$ and $\Upsilon$), measure bottomonium production cross sections, measure lifetime and other properties of $B$ mesons, measure $B_s$ oscillations and CP violation, and measure rare decays such as $B_s \rightarrow \mu^+ \mu^-$. Alternatively, you will search the LHCb web site in vain for a mention of hadronic physics[15]. We are nonetheless assured that the experiment is interested in hadrons[16] and we have seen how collaborations interested in New Physics have found their attention drifting toward hadronic properties in the past! Finally, if one is still worried about the possibility that the LHC will suck the universe into a black hole, I recommend following the link at Ref. [17].

In short, the next decade of experiments will bestow upon us millions of $J/\psi$s, $\Upsilon(2S)$s, $Y$s, bottom mesons, and charm mesons. Baryon spectroscopy will continue at JLab, MAMI, COSY, and ELSA and there will be a two-pronged attack on hybrid mesons. Countering this, it appears that heavy baryon spectroscopy and glueballs will be orphaned. Finally, the era of nucleon structure holography will begin.

**Lattice Infrastructure**

Progress in lattice gauge theory is driven by improved algorithms and faster machines. Algorithms will be discussed in the next section, here we focus on machines, which are relatively easy to track since they must be planned well into the future.

Current large machines operate with a peak performance of around 100 teraflops, and have a sustained performance two orders of magnitude lower. The next generation is represented by the Blue Waters machine at the National Center for Supercomputing Applications at UIUC, which is due to come online in 2011[18]. Blue Waters will achieve sustained performance at greater than 1 petaflop with more that 200,000 IBM power7 processors. It will have nearly a petabyte of RAM and more than 10 petabytes of disk storage[19].

Funding agencies are already looking at the goals and costs of exascale computing. A recent workshop sponsored by the DOE lists several milestones judged to be achievable at the exascale[20]:

- the spectrum and properties of mesons, especially exotic mesons
- the gluonic content of the nucleon, low moments of the gluon distribution functions $g(x)$ and $\Delta g(x)$
- three-nucleon interactions, the alpha particle
- the neutron electric dipole moment
- $^{132}$Sn structure
- $0\nu\beta\beta$ rates for $^{76}$Ge
- nuclear fission for hot nuclei
- transport properties for neutron star crusts
A few of these estimates seem low-balled. For example, exotic meson properties are already being computed with reasonable accuracy at JLab. On the other hand, some things seem impossibly far away, such as obtaining accurate predictions of nuclear properties directly from QCD.

The lattice community (specifically the USQCD collaboration) is also pursuing imaginative use of graphics processing units[21]. In a sort of reverse spin off effect, we can be thankful that the multibillion dollar computer gaming industry is helping to drive hadronic physics forward!

It is a good time to be doing lattice gauge theory, infrastructure and research are well supported by the funding agencies. In 2008 the Scientific Discovery through Advanced Computing (SciDAC) program allocated more than 1/4 billion processor hours. By 2009 this had doubled to 1/2 billion processor hours[22].

How long can exponential growth persist in a finite planet? The Blue Waters facility occupies around 100,000 square feet of Illinois real estate, clearly an exascale facility requires much more than simply increased processor speed. Indeed, Michael Strayer, SciDAC’s director, issued an alarming warning[22]:

We can see that the gigaflops and teraflops era was a regime where we were following Moore’s law through advances in clock speed. In the current regime, we’re introducing massive parallelism... in order to reach [the] exascale [regime], extrapolations talk about machines that require 100 megawatts of power.

Is it possible that we are reaching the end of the computing line? If so, we must face the prospect that some things may never be numerically computable.

**Theory**

It is much more difficult to project theoretical developments into the future. Nevertheless, one can make guesses based on the current interests of the community. Of course any such list will be dependent on the limited purview of the lister. With this caveat in mind, I offer the following:

- effective field theory: the development of a formalism capable of describing states high in the spectrum will be achieved. Ambiguities in the separation of short range and long range physics will be addressed.
- potential models: similarly, attempting to incorporate continuum channels into the potential quark model is a priority in the subfield.
- gluonics: models of the nonperturbative behaviour of glue will improve with the advent of experimental confirmation of heavy and light hybrid mesons.
- Schwinger Dyson formalism: improved technique will permit computing three point functions and beyond; computations will move beyond the rainbow-ladder approximation; gluonics will begin to be incorporated.
- lattice gauge theory: algorithmic improvements will permit the computation of hair pin and all-to-all correlators. Computing multiparticle operators will become feasible, permitting accurate extraction of resonance information. A coupled channel Lüscher formalism will be developed.
- data analysis: a consistent, gauge invariant description of coupled $\pi N$ and $\gamma N$ experiment will be made.

**OUTLOOK (II)**

Here we interpret *outlook* as looking outward from hadronic physics. Doing so reveals intense interest in the properties of strongly interacting Yang-Mills field theory. It worth remembering, in spite of the modern focus on the Standard Model as an effective field theory, that QCD is a "perfect" field theory in that it is self-consistent (as opposed to QED, which suffers from Landau poles).

**Mass Hierarchy**

Quark and lepton masses array themselves over eleven or twelve orders of magnitude. How are we to understand this? In terms of naturalness, it is certainly not satisfactory to regard the mass scale hierarchy as due to happenstance with Yukawa couplings.
An attractive alternative is that large ratios of scales can be generated dynamically. It was with goal in mind that Appelquist and Pisarski suggested examining the properties of QCD (or QED) in three dimensions[23]. The theory is superrenormalisable, which is a fancy way of saying that the coupling carries (positive mass) units. Setting quark masses to zero implies that the coupling sets the scale unless spontaneous chiral symmetry breaking occurs. In this case it is possible that the generated scale is much different from that of the coupling. And in fact, studies of QED3 reveal that this is precisely what happens[24]. One finds that the generated mass is strongly dependent on the number of quark flavours. One quark yields \( m_{\text{gen}}(N_f = 1) \approx e^2 \) while \( m_{\text{gen}}(N_f = 2) \approx e^2/10 \), and \( m_{\text{gen}}(N_f = 3) \approx 10^{-8} e^2 \). Thus it is possible to leverage the nonperturbative properties of strongly interacting field theory to generate enormous mass ratios with \( \theta'(1) \) changes in model parameters.

**Electroweak Symmetry Breaking**

It is widely held that the Higgs sector of the Standard Model is simply an effective description of more complex dynamics[25]. This would, for example, do away with the fine tuning problem associated with the Higgs mass. Not long after the advent of QCD, Weinberg suggested that a version of QCD, scaled up to the TeV range, could provide this dynamics[26]. Weinberg dubbed this model ‘hypercolor’ and suggested that dynamical chiral symmetry breaking would generate hyper-Goldstone bosons that are eaten by the \( W \) and \( Z \), providing the mechanism for generating a viable electroweak (EW) force.

Hypercolor has problems: there are other light hyper-Goldstone bosons and there is no mechanism to generate the fermion masses. A way forward was postulated by Dimopoulos and Susskind, who introduced extra gauge interactions to raise the fermion and hyper-Goldstone boson masses[27]. The theory, renamed ‘extended technicolor’ (ETC), is broken at the ETC scale giving rise to effective four-fermion operators at the EW scale[28]. Calling \( Q \) a techniquark and \( q \) a quark, these operators are of the form \((\bar{Q}Q)/(\bar{Q}Q)/A_{\text{ETC}}^2, (\bar{Q}Q)/(\bar{q}q)/A_{\text{ETC}}^2\) and \((\bar{q}q)/(\bar{q}q)/A_{\text{ETC}}^2\). Spontaneous symmetry breaking allows one to replace \((\bar{Q}Q)\) with \((\bar{Q}Q)\). Thus the first operator raises ETC Goldstone boson masses and the second generates fermion masses. Unfortunately, the third generates flavour changing neutral currents, which are strongly suppressed in nature, implying that \( \Lambda_{\text{ETC}} \sim 1 \text{ TeV} \). This in turn implies that fermion masses are smaller than desired.

A possible finesse was suggested by Holdom[29]: if the technicolor coupling ran sufficiently slowly it would enhance condensates while keeping the technipion decay constant stable (it is the latter that sets the EW scale, while the former sets the technihadron mass scale). Exploring the properties of ‘walking technicolor’ is thus a high priority for model builders.

Coulplings run slowly near fixed points and it is thus natural to examine the beta function of QCD-like theories. In particular, one seeks the conformal window, which is the range of \( N_f \) for which the theory is asymptotically free and has no infrared fixed point. The theory walks just below the conformal window. For example, to two-loop order and for three colours, the conformal window is \( N_f \in (7.75, 16.5) \)[30]. Recent lattice computations imply that there is an IR fixed point for \( N_c = 3, N_f = 12 \), but no IR fixed point for \( N_c = 3, N_f = 8 \)[31].

Other constraints on model building exist. For example, one can parameterise extensions to the Standard Model in terms of ‘Peskin–Takeuchi parameters’, \( S, T, \) and \( U \). Nature tells us that \( S \) and \( T \) are very small, and ETC models need to obey this constraint[32]. The expression for \( S \) is roughly given by

\[
g_{\mu\nu} S \sim \frac{d}{dq^2} \left[ \langle V^\mu(q)V^\nu(0) \rangle - \langle A^\mu(q)A^\nu(0) \rangle \right]_{q^2=0}.
\]

where the matrix elements are vector-vector and axial-axial correlators in the new theory. It is remarkable that something as prosaic as \( \rho \) and \( \alpha_1 \) spectral densities enter the discussion!

**Dark Matter**

The advent of the Concordance Model of cosmology has led to several interesting theoretical issues. For example, why is the density of dark matter about five times that of baryonic matter? If dark matter consists of WIMPS, its interactions with the Standard Model must be weak. How, then, is the WIMP mass generated? Strong Yang-Mills theory to the rescue!

Many years ago Nussinov suggested that a natural way to generate a dark matter abundance of the same order as the baryon abundance is to invoke the same Standard Model mechanism that generates baryon matter asymmetry in the
technibaryon sector[33]. Thus the same nonperturbative physics that results in the predominance of matter will give rise to dark matter. Again, nonperturbative field theory may provide the way forward in a difficult problem.

Technibaryons that are charge and electroweak neutral would also provide a natural explanation for the second problem since they would have suppressed Standard Model couplings[34]. Alternatively, it has been proposed that dark matter is ‘quirky’, namely scalar baryonic bound states of a new nonAbelian force that becomes strong below the electroweak scale[35]. The baryon is made of chiral quarks that transform under the new force and in chiral representations of the electroweak group. Interestingly, the authors of the latter paper note that the decay of quirky glueballs to photons can disrupt the successes of nucleosynthesis. Thus understanding glueball decays takes on cosmological significance.

**CONCLUSIONS**

BESIII and RHIC continue their labours; LHC starts in earnest soon; JLab at 12 GeV is set to start in 2014; PANDA in 2016; and perhaps a super B factory or two some time after that. Thus it appears that many hadrons, old and new, will be created in labs around the world. In the meantime, theoretical understanding and technique continue to improve, aided greatly by massive investment in computational resources. Furthermore, it seems very possible that a high energy version of QCD is what is required to bring the Standard Model into a state of ‘naturalness’.

Eberhard Klempt opened this conference by discussing the nature of mass and baryons. At the start of the LHC era we have heard many times how the ‘God Particle’ creates mass for all other particles. But it is worth remembering that quarks contribute only 1/2% of the mass of baryons, and hence almost all the mass of all the matter we understand (ie, not dark energy or dark matter) is generated by gluons. I therefore propose that the true location of divinity in the Standard Model should be shifted from the electroweak sector to the strong sector. As we have seen, many people are working on effecting this shift for the entire Standard Model.

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28. It is worth remembering something Dimopolous and Susskind said, “… we must warn the reader that we will deal with complicated systems of interacting gauge sectors, some of which are strongly interacting. Thus we can only guess the patterns of spontaneous symmetry breaking which occur.”


