Sixty Years of Particle Physics at Moriond

(Moriond 60 After Dinner Speech)

Chris Quigg · 16 January 2016

Dear Friends, old and new! How thrilling it is to come together in this splendid venue, to celebrate the *Rencontres de Moriond!* This marvelous scientific institution—now truly venerable as it passes into its seventh decade—has promoted open dialogue and common understanding in the service of search and discovery, friendship and mutual respect. How lucky we are that colleagues from Orsay who found it challenging to cross a road for discussions instead decamped to the Alps in order to learn from each other. Their innovation has become an essential global forum for particle physics and an ever-evolving roster of subjects that nourish each other through their common relevance.

And what a time it has been! The Moriond era encompasses the establishment of two new laws of nature: Quantum Chromodynamics and the Electroweak Theory. These are tested every day in our laboratories as quantum field theories. These fundamental interactions, we now see, are dictated by gauge symmetries, following the insights of Emmy Noether's second theorem of 1918, which took a while to find its most potent application. Think also of the stunning advances in experimental technique and accelerator art!

Dark matter is overwhelmingly likely to be a yet unidentified component of our universe. Gravitation, which first entered the Moriond agenda on the ski slopes, is now in fruitful conversation with nuclear and particle physics through the observation of gravitational radiation and distinct kinds of sources. Cosmology, increasingly a quantitative discipline, has become an essential partner of particle physics since our first speculations about unified theories encountered the early universe.

The implication of those unified theories that protons need not be forever motivated the large-volume detectors that have so far raised the lower bound on the proton lifetime to many times the age of the universe. Those first detectors have taught us about a supernova source and revealed new properties of the neutrinos themselves. It was a great surprise to me, and a testament to the astuteness of experimenters that the discoveries of neutrino oscillations came from natural "found" sources and nuclear reactors, not from accelerator beams.

There are more varieties of matter than the Founders knew at those early meetings. Quarks are real; they come in six flavors, matched by three flavors of neutrinos and three of charged leptons. Hadrons increasingly display novel body plans, beyond the classic quark–antiquark mesons and three-quark baryons. Seventy-nine new hadrons have been discovered at the Large Hadron Collider! And the three quark doublets have made sense of the CP-violation first observed in 1964. We have accumulated rich evidence that spontaneous symmetry breaking is at the root of quark and lepton masses and, we think, of quark mixing angles, but we have not explained the values of those masses and mixings. We don't yet know the masses of the neutrinos, or the detailed role that spontaneous symmetry breaking might play in setting them. We do not know the origin of the Higgs interactions, but it is not a simple gauge symmetry.

Since the 1960s, particle physics and condensed matter physics have both been fascinated—in somewhat different ways—by spontaneous breaking of both global and local symmetries. The kinship among the Meissner effect and its Ginzburg–Landau phenomenology and our understanding of electroweak symmetry breaking is a consequential example, and there are many more.

One of the great discoveries of twentieth century science is the recognition that the human scale—by which I mean our everyday notions of time and distance—is not privileged for understanding nature, and may for many purposes be disadvantaged. I regard this as an insight no less profound than Copernicus's discovery that we are not at the center of the Universe, or Einstein's observation that there is no preferred reference frame. It's a lesson not just for physics, where we are able to give it a precise and powerful mathematical form, but for all of science.

We may wonder at the appearance of a giraffe, so different from our own. But we do not understand what makes a giraffe a giraffe, or how it relates to other creatures, unless we study the giraffe's DNA. Nor do we really understand what a giraffe is until we observe the behavior of herds. We gain understanding by zooming in and zooming out.

Physicists learned in the 1920s that to understand why a table is solid or why a metal gleams, we need to explore a world a billion times smaller than our own: the quantum realm of atoms and molecules. Going there is akin to visiting a foreign land, in which the language and customs do not necessarily follow from what we learned as children, but must be experienced and judged by their internal consistency. It seems weird and wonderful that what happens in the quantum world determines so much of the character of our quotidian world. It is a splendid and rewarding challenge to try to discover, to the extent we can, why our world is the way it is.

Scrutinizing nature at different size or energy scales—noting at each scale the appropriate degrees of freedom and (perhaps effective) interactions is one of the most fruitful areas of overlap between condensed matter and particle physics. The tool of the renormalization group, both as a mathematical formalism and a framework to develop intuition, has led to lively dialogue (and occasional incomplete communication) between the two groups.

I'll return right away to physics, but I want to give an example of the human qualities and foibles that make Moriond such an enriching experience. Occasionally the organizers import a certified Great Man or Great Woman to leaven the proceedings and bring a little culture. One episode involved the Fields Medalist and developer of "catastrophe theory," René Thom, who presented an informal lecture on the seven elementary catastrophes: smooth behavior that leads to sudden dramatic events. He began in English, but there was a problem with the sound system, which sporadically emitted pops and crackles that interrupted his flow. At the first such event, he switched to French and continued until the next electrical storm, whereupon he switched back to English. The alternation continued several more times. I never knew whether he was such an accomplished showman that he planned the little catastrophes to dramatize his insight.

When she invited me to speak, Monica Pepe-Altarelli planted a subversive thought. She said, conspiratorially, "Not everything presented at Moriond has been true." Since I take her *very* seriously, I started to make a list of discoveries that went away: the high-*y* anomaly, super trimuons, alternating neutral currents, monojets signally supersymmetry, the 42-GeV top quark. Maybe you see a pattern here? Upsilon (6.0) preceded the true Upsilon(9.6) and its excitations. [At least they got the name right.] There were the days when muon g–2 was said to "fit SUSY like a glove." There is another category of effects that seem too good to be true, but that we haven't yet totally ruled out. And finally, to give some attention to Monica's LHCb experiment, there are tantalizing effects at the limit of sensitivity and systematics that can't decide whether to come or go.

Weird effects or dramatic declarations are not necessarily bad for science. They invite us to stretch our minds. And they may even get the attention of the masters of the universe, who may decide to set the record straight. The most dramatic example I know is attributed both to Lord Kelvin and to Albert A. Michelson. Michelson wrote in the 1898–99 University of Chicago catalogue: "While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice …. An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals."

As the ink was drying on these earnest words, Röntgen discovered x rays and published the epoch-making radiograph of his wife's hand, Becquerel and the Curies explored radioactivity, Thomson discovered the electron and showed that the "uncuttable" atom had parts, and Planck noted that anomalies in the *first* place of the decimals required a wholesale revision of the physicist's conception of the laws of Nature.

You can see the temptation to taunt the gods, in hopes of a similar bounty of unanticipated discoveries. I have seen this done on the Moriond platform, where one of our dear colleagues repeatedly proclaimed that the LHC would discover precisely nothing! Normally I consider physics too important for betting, but this provocation seemed to offer a teaching moment. In the unthinkable case that the LHC experiments found nothing, I would pay a bottle of the finest Illinois wine. When, as I believed inevitable, the LHC would deliver a discovery—for example, the Higgs boson—my nemesis would pay a bottle of the finest Dutch wine. It turns out that there is a gold-medal Dutch wine, which I gratefully received. It was *buvable*.

The Moriond years have been glorious for the advancement of our science. We can take great satisfaction in what we have learned, but let us not despair that nature will never be so kind again. When the standard model was just taking form, after the discovery of neutral currents, a Great Man who had been present at the discovery of the pion teased me that we kids would never have it as good as the Pioneers. I poked him in the chest and said, "Just because it's over for you, Old Man, doesn't mean it's over!" To his credit, he laughed even more heartily than I did. And that is my lesson for those who will carry on.

We have much more to learn. It is easy to cite a few Great Questions—what lies behind electroweak symmetry breaking, the nature of dark matter and dark energy, the origin of the matter excess in the universe, whether we live in the best of all possible worlds. As momentous as such questions are, they are far from the whole story of open-ended exploration. I worry that students contemplating only the Great Questions will see the field as narrow, constrained. So I have recently published on the arXiv a more expansive agenda for particle physics (arXiv:2510.06348), containing no fewer than 148 questions. I invite answers—and more questions.

Keep in mind that great discoveries sometimes arise from what seem to be prosaic measurements. In the late 1990s, some of our astronomical colleagues set out to measure the cosmic deceleration parameter, which everyone knew would have the value one-half. If you doubted, you would be betting against Einstein, never a good strategy. But hidden in the expectation was the belief, based on inferences from the inflationary paradigm, that the matter density of the universe equals the critical density. The astonishing result was that the matter density is considerably less than the critical density, and that the rate of expansion of the universe is accelerating.

The extraordinary *romancier*, Victor Hugo, was a bit of a science groupie, especially fascinated by astronomy. He composed an excellent slogan:

Au delà du visible l'invisible. Au-delà de l'invisible l'inconnu.

To which I would add,

Au-delà de l'inconnu, l'imaginaire!

Beyond the visible, the invisible. Beyond the invisible, the unknown. Beyond the unknown, imagination!

Because we are engaged in a profoundly human adventure, I'd like to share with you some words with which Bob Cahn and I concluded our recent book, *Grace in All Simplicity*.

Humanity's place in the universe is even less central than Victor Hugo and his astronomical muse, Camille Flammarion, could conceive. We are, as they knew, exponentially smaller than the reaches of their 19th-century *cosmos, but that is not all. There is much more to the natural world than we can see and touch. The extraordinarily ancient universe that we inhabit is expanding, and it evolved from conditions that do not at all resemble its current state. Even as our instruments and our imagination take us back billions of years in time and out farther than we can ever hope to travel, we are also exploring nature's inner workings at sizes a billion-billion times smaller than our own. We are studying phenomena so ephemeral that they transpire in a trillionth of a trillionth of the blink of an eye.*

Titans on the scale of electrons or quarks, we humans do not have dominion over that world of the infinitesimal; instead, what takes place there, so remote from everyday experience, makes the rules that shape our existence. The more closely we examine the submicroscopic realms, the better we understand the human scale and beyond. The uncertainties that come into play at very short distances and fleeting time intervals, expressed in probabilities and quantum fluctuations, seem increasingly likely to have seeded the large-scale structure of the universe. Perhaps we are subjects rather than monarchs!

And yet . . . though nature elicits in us a sense of awe and humility, the understanding we have earned instills in us a sense of purpose that lifts us above languishing in our insignificance. What an understanding it is! Building on the working hypothesis that nature is reliable, not capricious, and the expectation that cause must precede effect, we humans have come to comprehend a great deal about the two infinities—surpassingly large and small—and about our own in-between existence.

We celebrate the elegance and economy of today's picture of particle physics—the standard model. We need only identify a handful of basic constituents plus a few symmetries that dictate the fundamental interactions, recognize that concealed symmetries foster richness and diversity, and we can derive the essential features of the physical world. We can read some outcomes from the patterns themselves, expressed in a few acts of the particle play. Others—such as the confinement of quarks and gluons, the collisions of heavy nuclei at high energies, the properties of an ensemble of atoms or molecules acting collectively—are emergent phenomena that require analysis of a different sort.

We delight in the phenomena understood, the mysteries resolved, the hints of a more complete understanding, but what animates our work is all that we don't know. We and our colleagues live for the questions still unanswered, the puzzles that remain, the mysteries not yet encountered, the questions we don't know enough to ask. Many in this room have been lucky to come of age as physicists when the standard model came together, when the two infinities met and merged as never before, when technological innovations made possible new instruments to help physicists explore the *boundless horizons of our science. We have had the good fortune to work together as experimenters, instrument makers, accelerator builders, theorists, computational scientists, and technologists of many sorts.*

Particle physics is a planetary undertaking. It brings together people of different backgrounds and diverse styles who are curious about nature and driven to explore. Professional and personal lives are enriched by teachers and students, colleagues and friends, from many countries and cultures. Together, we elevate experimental test over attachment to received truths. We welcome uncertainty not as motivation to be cynical, but as incentive to open our minds and investigate. As individuals and as teams, we compete and collaborate. Our science thrives in a culture in which standing is measured by knowledge shared, not secrets withheld. For that tradition of openness, we thank the citizens of the world, who provide material support and active encouragement for the explorations we undertake together. What we discover is for all to share.

With that, I thank the guardian angels of the secretariat, the program committees, the *gentils organisateurs,* and all the founders, with a special mention to Kim and Van, and salute the 12,057 participants, who have helped to create and sustain *l'esprit de Moriond!*