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Summary of Lepton-Photon 2011

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ABSTRACT

In this lecture, I summarize developments presented at the Lepton Photon 2011 conference and give my perspective on the current situation in high-energy physics.

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1 Introduction

I am grateful to the organizers of Lepton Photon 2011 for providing us a very pleasant and simulating week in Mumbai. This year's Lepton Photon conference has covered the full range of subjects that fall within the scope of high-energy physics, including connections to cosmology, nuclear physics, and atomic physics. The experiments that were discussed detect particles ranging in energy from radio frequencies to EeV. Other speakers thanked the organizers for inviting them to lecture at the Lepton Photon conference, but I have to regret that the organizers of LP11 have given me an impossible task – to summarize the results presented and make sense of them.

This review will then necessarily cover only a subset of what was presented at the conference. I will emphasize results in which I have some personal interest or on which I would like to state a sharp opinion or perspective. I apologize to those speakers whose work is not discussed here. This review was completed in October 2011. The situation in high-energy physics, especially in topics involving TeV energies and LHC, is evolving rapidly. I am sure that some of the opinions expressed here will soon be out date.

This conference is the biennial festival of the enthusiasts of leptons and photons – and of quarks and gluons. This year, we have much to celebrate. The Large Hadron Collider at CERN is finally launched. The machine and its experiments are performing beyond expectations and are carrying us into new and unexplored realms of physics at short distances. At the other extreme, the links between the two most fundamental sciences, particle physics and cosmology, are stronger than ever and are leading us to new insights at the largest accessible distances, and even beyond.

And yet, we are apprehensive. Our field seems to be approaching a definite point of reckoning. We are headed somewhere at breakneck speed, but are we racing toward enlightenment, or to disillusionment and chaos?

In reviewing the highlights of LP11, I cannot avoid this question.

First, though, I will discuss some of the wonderful things that we have learned in Mumbai.

2 The Universe

The cosmological Standard Model – the flat expanding universe containing 5% baryons, 20% dark matter, and 75% dark energy – continues to be put on a firmer

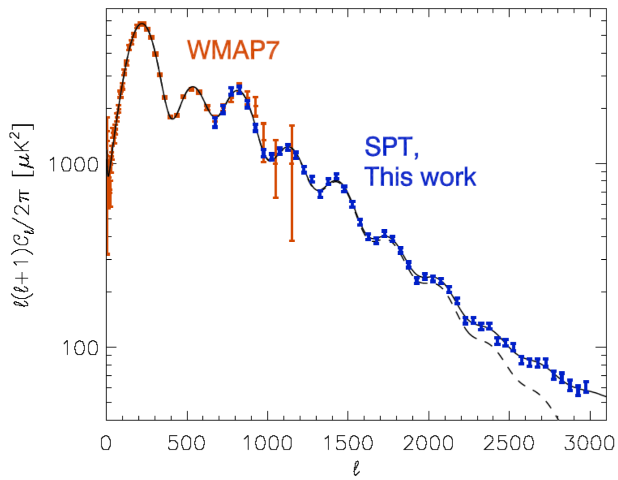

Figure 1: The 2011 measurement of the fluctation spectrum of the Cosmic Microwave Background by the South Pole Telescope [3].

footing. I refer you to Scott Dodelson's lecture [1] for a review of the current experimental programs aiming to clarify the nature of dark energy. For me, dark energy is a total mystery. It seems to be a nonzero cosmological constant. The mystery is not why this cosmolgical constant is constant or nonzero, but rather why it is not at least 60 orders of magnitude larger.

Another piece of the mystery is the success of inflationary cosmology. Observations of cosmic structure require that the initial conditions for our universe contained an almost scale-invariant spectrum of adiabatic perturbations, whose parameters were uniform far outside the horizon. The theory of inflation predicted such a spectrum and continues to be the only straightforward explanation of it. Inflation links to the dark energy problem in a puzzling way. Inflation requires that the universe actually contained a cosmological constant 100 orders of magnitude greater than the present one early in its history. The exit from this state of exponential expansion and the consequent heating of the universe is what we call the Big Bang. We do not understand how this prior state is related to the dark energy that we see today.

However mysterious it might be, inflation has predictions that agree with observations. The most striking effects are in the spectrum of fluctuations of the cosmic microwave background. We will soon have much more precise observations of the cosmic microwave background from the Planck spacecraft. At LP11, Francois Bouchet [2] reviewed the design of Planck and the expectations for its physics program. However, the main cosmological results from Planck will not be available until Lepton Photon 2013.

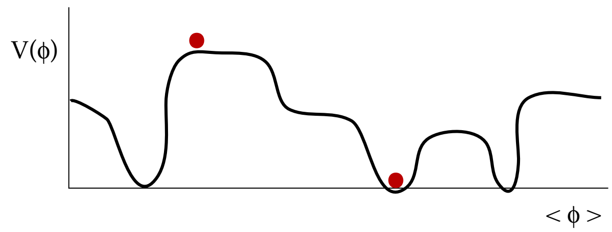

Figure 2: Typical scalar field potential of a quantum field theory model of inflation. The energy density at the plateau is $V = \lambda M^4$, where M is a very high energy scale, perhaps as large as the Planck mass $m_{\rm Pl}$. The Hubble constant during inflation is $H_0 = (8\pi\lambda/3)^{1/2} M^2/m_{\rm Pl}$.

In the meantime, though, we have a new result on the Cosmic Microwave Background from the South Pole Telescope [3], shown in Fig. 1. The South Pole Telescope has extended the observation of acoustic peaks in the CMB observed by WMAP and other detectors by another 6 peaks, reinforcing the agreement with astrophysical calculation. One sees by eye that the peaks are not uniform in size. The first, third, fifth peaks, and so on, are slightly higher than the general trend; the second and fourth peaks are slightly lower. This observation has a simple and well-known explanation: The primordial plasma that radiated the CMB had two components, a gas of Hydrogen and Helium, and a gas of weakly interacting dark matter. At the first and the other odd peaks, these components slosh coherently, at the even peaks, they are sloshing in opposite directions. This picture was the basis for the measurement of the dark matter density of the universe by WMAP [4], and it remains one of the compelling arguments for existence of dark matter. With new results from the Atacama Cosmology Telescope [5], Dodelson explained, all aspects of the current synthesis of cosmology — the flatness, the baryons, the dark matter, the dark energy, and the scale-invariant spectrum of perturbations – are independently observed and measured in the CMB data [1].

This is truly excellent, but it comes with a shadow, one emphasized since the 1980's by Andrei Linde [6]. To have inflation, there must be ranges of scalar field values in which the scalar potential is very flat, as shown in Fig. 2. Regions of space with such flatness inflate exponentially and dominate the volume of the universe. Regions exit inflation by falling off the plateaus. If the theory of Nature has multiple vacuum states – all attractive theories of grand unification have potentials with multiple minima – all of these vacua will be populated somewhere in the universe. It is very important to us which of these minima our local universe sits in. This choice determines the particles and couplings that we see in particle physics. But the perspective of inflation tells us that that choice could be dictated by *history* rather than by *necessity*.

The conclusion brings us to the great divide that cut through nineteenth-century science between physics and chemistry on one side and biology and geology on the other. Physicists, exemplified by Laplace, believed that Nature is described by fundamental equations which have a unique solution and therefore lead to definite predictions. Biologists, after Darwin, believed that Nature is the logical result of random processes, with the final solution determined by accidents of history. Linde argues that, even for physics, there are basic limits to Laplacian thinking about the ultimate laws of Nature. We do not know where these limits will appear, but, eventually, we must run up against them.

I will return to this point at the end of the lecture.

3 Cosmic Rays

The origin of cosmic rays is naturally a subject that should intrigue high-energy physicists. For a long time, however, most research in high-energy physics ignored the products of cosmic accelerators, preferring to concentrate on results from artificial accelerators. More recently, some fascinating problems involving cosmic rays have brought this subject back into the mainstream.

The first of these problems is the identity of the highest energy cosmic rays. The cosmic ray spectrum above the 'knee' at 10^{16} eV is well known to fall roughly as $dN/dE \sim E^{-3}$. There is no known mechanism for producing such high energy cosmic rays within the galaxy, so cosmic rays in this range are assumed to be of extragalactic origin. Ralph Engel [7] explained to us that the story of this region of the cosmic ray spectrum has changed dramatically over the past 4 years.

In 2007, the Pierre Auger Collaboration announced evidence for a correlation between the arrival directions of extremely high energy cosmic rays, above 10^{18} eV, and the directions to nearby Active Galactic Nuclei [8]. Given the strength of intergalactic magentic fields, these rays would point back to their sources only if they were of charge $Z = 1$, that is, protons rather than heavy nuclei. The spectrum of cosmic ray protons is cut off by the GKZ effect [9]: A sufficiently energetic proton sees cosmic microwave background photons boosted to 300 MeV gamma rays, where they can excite the Δ resonance and thus cause the proton to lose energy by emission of a pion. The cutoff in the proton spectrum is predicted to be at $E = 3 \times 10^{19}$ GeV. Indeed, a sharp cutoff in the cosmic ray spectrum is seen at this location, as shown in Fig. 3.

Over the past few years, this beautiful and coherent picture has fallen apart. First, the correlation of high-energy cosmic rays with AGNs has decreased, as shown

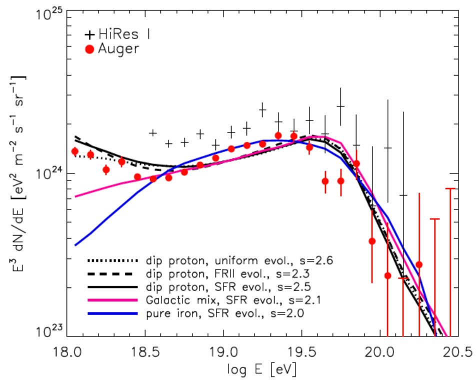

Figure 3: The energy spectrum of the highest energy cosmic rays, $E^3 dN/dE$, showing the observed cutoff at the highest energies, from the review [10].

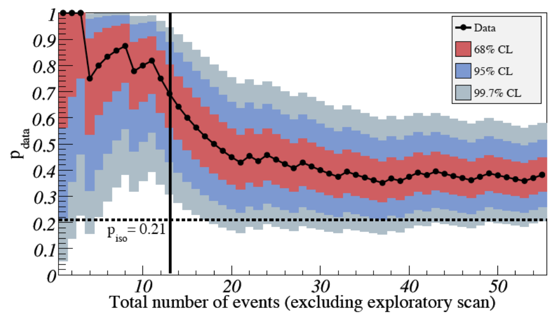

Figure 4: The degree of correlation of the arrival directions of cosmic rays above an energy of 10^{18} GeV, as observed by the Pierre Auger Collaboration, shown as a function of time [11]. The vertical line marks the date of the Auger paper [8].

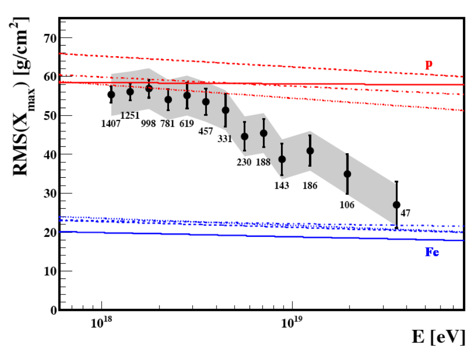

Figure 5: Dependence of the RMS fluctuation of the depth of the shower maxima of high energy cosmic rays, from [12]. This parameter is predicted to be much smaller for showers initiated by protons than for those initiated by heavy nuclei.

in Fig. 4 [11]. The Telescope Array in the Nothern Hemisphere did not support the earlier Auger result but rather gave a weak correlation similar to that found by Auger now [7]. The Auger experiment has also tried to measure the composition of high-energy cosmic rays directly by measuring the position in the atmosphere of the shower maximum (X_{max}) and using this to estimate the cross section of the species initiating the shower. Auger and the HiRes Collaboration disagree on the interpretation of the results for the shower maximum, even though the actual measurements are not very different [12,13]. However, Auger also reports a marked decrease in the RMS fluctuation of X_{max} between 3×10^{18} and 3×10^{19} eV, shown in Fig. 5. Heavy nuclei have a more uniform shower development from event to event, so this is evidence that the composition of the cosmic rays changes from protons to Fe nuclei over this range.

There is no simple theory such as that of GKZ for the energy cutoff in Fe nuclei. Detailed calculations estimate the cutoff as happening as the same point as for protons, 3×10^{19} eV *per nucleus*. The energy loss mechanism is the disruption of nuclei by excitation of the giant dipole resonance. However, because the energies of individual nucleons are lower by a factor 56, the cosmic microwave background is not sufficiently energetic to excite this resonance. The dominant effect is expected to come from the Cosmic Infrared Background, which is not of cosmological origin. If the cutoff did result from this mechanism, the highest energy cosmic rays reaching earth would be the light nuclei that are the results of this disruption process. A more likely hypothesis is that cosmic accelerators, for example, shock fronts in large clusters of galaxies, are limited in the energy they can pump into cosmic rays. If the energy limit for protons is 10^{18} GeV, the energy limit for Fe will be 26 times higher, and Fe nuclei will dominate at the highest energies [7].

To resolve this problem, we not only need higher-statistics measurements of cosmic rays air showers but also a more accurate theory of the proton-nucleus and nucleus-nucleus cross section at very high energy. LHC data on the proton-proton cross sections at 7 and 14 TeV and on the multiplicity distribution in minimum-bias events will provide important information for modelling these effects.

As this situation has become murkier, our understanding of lower-energy cosmic rays created by galactic sources has become clearer. An interesting type of source to study is a supernova remnant lying close to a molecular cloud. Cosmic rays from the source irradiate the cloud, producing gamma rays that point back to the cloud and identify the system. As Simona Murgia explained to us [14], the spectrum of these gamma rays is characteristicly different for sources in which the primary radiation is protons, which produce gammas by π^0 decay, or electrons, which produce gammas by inverse Compton scattering. The difference is especially clear in the GeV energy range that can be studied by the Fermi Gamma-ray Space Telescope. For example, Fig. 6 shows the Fermi gamma ray spectrum of the supernova remnant RX J1713.–

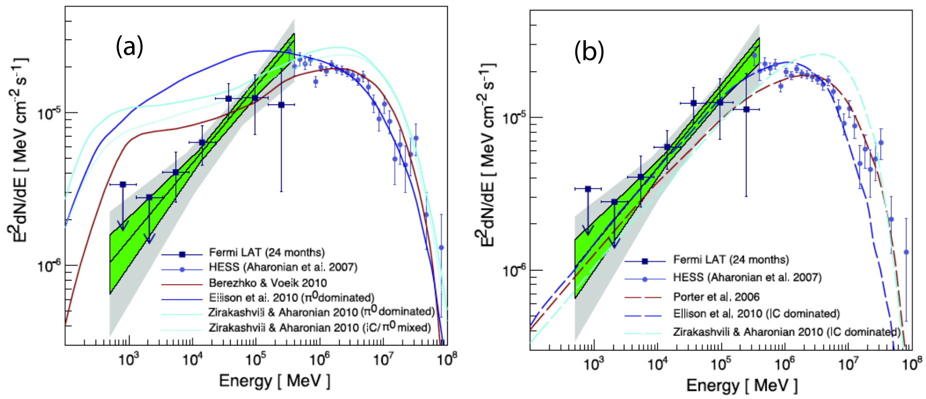

Figure 6: Test of the spectrum of gamma rays from the supernova remnant RX J1713.–3946 measured by the Fermi GST and the Hess Telescope against models in which (a) protons and (b) electrons are the primary species accelerated by this object, from [15].

3946, together with HESS data on the same object [15,16]. The observations clearly favor a model in which the primary species accelerated is electrons. Fermi has also identified sources for which the primary species accelerated is protons.

There is one more very interesting result this year from Fermi. Despite the fact that Fermi is a non-magnetic detector, the Fermi LAT Collaboration was able to measure the position/electron ratio in cosmic rays by comparing time intervals of the orbit in which the Earth's magnetic field dominantly throws positively charged particles into the satellite to time intervals in which the Earth's magnetic field dominantly selects negatively charged particles [17]. The results confirm the celebrated results from PAMELA [18] showing a rise in the e^+/e^- ratio in the 100 GeV region; see Fig. 7.

4 Heavy Quark Physics

In the study of CP violation, we are coming to the end of an era, with the BaBar and Belle experiments preparing their final results. It is hard to remember that, as recently as 1999, we had hardly any evidence on the mechanism of CP violation in hadronic weak interactions. In that year, we only knew that the value of the K^0 decay parameter ϵ' was nonzero, and that there was a first indication of CP violation in $B \to J/\psi K^0_S$ from CDF.

The KEK and SLAC B-factories have totally changed this situation. We now have a long list of CP-violating effects measured in B meson decays. Up to a few

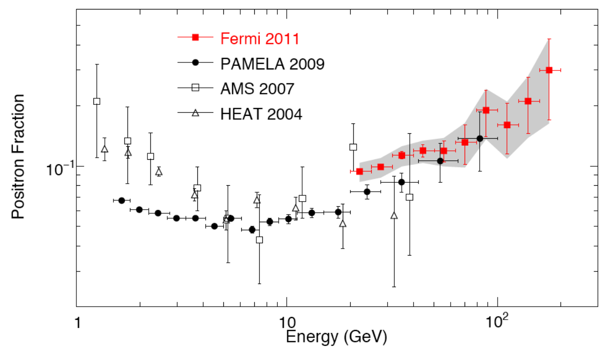

Figure 7: Comparision of the 2011 measurement of the e^+/e^- ratio in cosmic rays by the Fermi GST to the earlier measurement by the PAMELA satellite [18], from [17].

discrepancies and tensions, all of this data is explained by a single CP-violating parameter, the Kobayashi-Maskawa phase in the weak interaction mixing matrix. The current status of determinations of the Cabibbo-Kobayashi-Maskawa matrix was beautifully reviewed at this conference by Tim Gershon [19]. The overall situation is summarized by the global fit to the parameters (ρ, η) of this mixing matrix by the CKMfitter group shown in Fig. 8 [20]. In this figure, we see that six different high-precision data sets from B decay and the ϵ parameter from the K^0 system are mutually consistent with a specific parameter choice $\rho \approx 0.2$, $\eta \approx 0.3$.

Over the course of the B factory program, a number of measurements that seemed to indicate anomalies have come into line as statistics have accumulated. An example is shown in Fig. 9. The amplitude of time-dependent CP violation in $b \to s\bar{s}s$ penguin decays is expected in the CKM to agree with the amplitude $\sin 2\beta$ observed in $B \to J/\psi K^0_S$. At the 2003 Lepton Photon conference, there seemed to be a large discrepancy between these values [21], but now the B factory measurements are in good agreement with the well-determined value $\sin 2\beta = 0.68$ [22].

One discrepancy that still remains is in the rate of the decay $B \to \tau\nu$. This is an interesting channel, since it could receive a contribution from the tree-level decay of a b quark through charged Higgs boson exchange. The measurement of this decay was reviewed at this conference by Younghoon Kwon [23]. The current rate is 2.6 σ larger than the prediction of the global CKM fit. A similiar, though still less signficant, excess is seen in $B \to D\tau\nu$. These are very difficult processes to detect. One of the final fits from the Belle $B \to \tau\nu$ analysis is shown in Fig. 10 [24]. However, there are independent and compatible results from Belle and BaBar [25–27]. The measurement of $B \to \tau\nu$ is extraordinarily difficult for the LHCb experiment, but it might be possible for that experiment to study $B \to D\tau\nu$ with higher statistics.

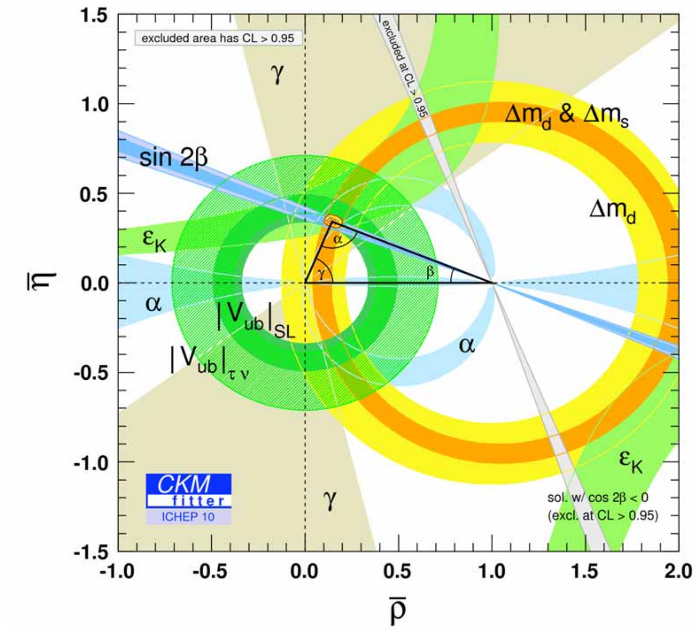

Figure 8: Current status of the global fit to the parameters (ρ, η) of the CKM modelCKM, from [20]. The bands show the primary contributing measurements.

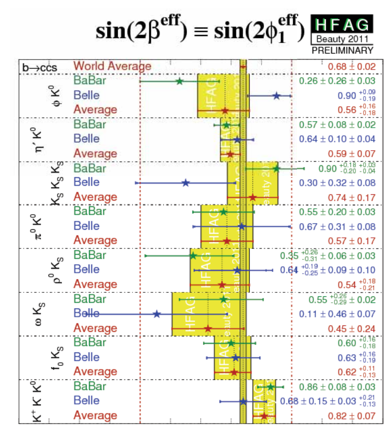

Figure 9: Current status of determinations of $\sin 2\beta_{eff}$ governing the time-dependent CP asymmetry in $b \to s\bar{s}s$ decays, fom [22]. The results should be compared to the prediction that this parameter should agree closely with the parameter $\sin 2\beta$ measured in $b \to c\bar{c}s$ decays.

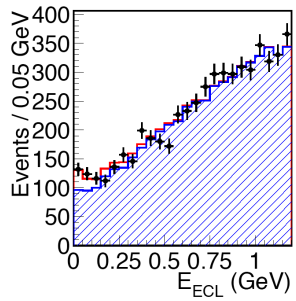

Figure 10: Signal (red) and estimated background (blue) in one of the Belle measurements of the rate of $B \to \tau\nu$, from [24].

The B factories have also contributed important results in other domains, including the discovery of D^0–$\overline{D}^0$ mixing and the exotic states X, Y, Z of the charmonium system. Hai-Bo Li spoke at LP11 on the current status of hadron spectroscopy, presenting many new results from the B factories, KLOE, and BES [28]. I do not have space to do justice to the details, but I would like to present two particularly beautiful plots in Fig. 11. The top plot show the reconstruction by BaBar of two final states of η_C decay, observed in $\gamma\gamma$ collisions [29]. Both $\eta_c(1S)$ and $\eta_c(2S)$ are clearly visible. The bottom plot shows the missing mass spectrum in $\Upsilon(5S) \to \pi^+\pi^- + X$, as observed by Belle [30]. The entire spectrum of $C = -1$ $b\bar{b}$ states appears, including the 1D state and the first two C odd P states. We will miss such striking and illustrative plots as the major results in heavy quark physics come increasingly from hadron colliders.

I now turn to the one truly anomalous result in B physics, the observation by the DØ experiment of a nontrivial asymmetry between $\mu^+\mu^+$ and $\mu^-\mu^-$ production in proton-antiproton collisions. The kinematics of the muons suggests that the anomaly is dominated by B and B_s meson decays. In the CKM model, such inclusive, time-integrated asymmetries are predicted to have values very close to zero. However, at LP11, Rick van Kooten [31] reported an asymmetry

$$A^b_{s\ell} = (-0.787 \pm 0.172 \pm 0.093)\ \% \ , \tag{1}$$

a value 3.9σ discrepant from the small CKM expectation [32].

The measurement by DØ is elegant. Among other features, it uses the fact that DØ frequently reverses the polarity of its magnet to collect independent data samples that cancel some systematic errors. Unfortunately, there is a systematic asymmetry, also at the 1% level, due to the fact that the DØ detector is made of matter rather than antimatter. This is more difficult to reverse and cancel. By separating the data into two samples by impact parameter, DØ shows that the bulk of the effect is

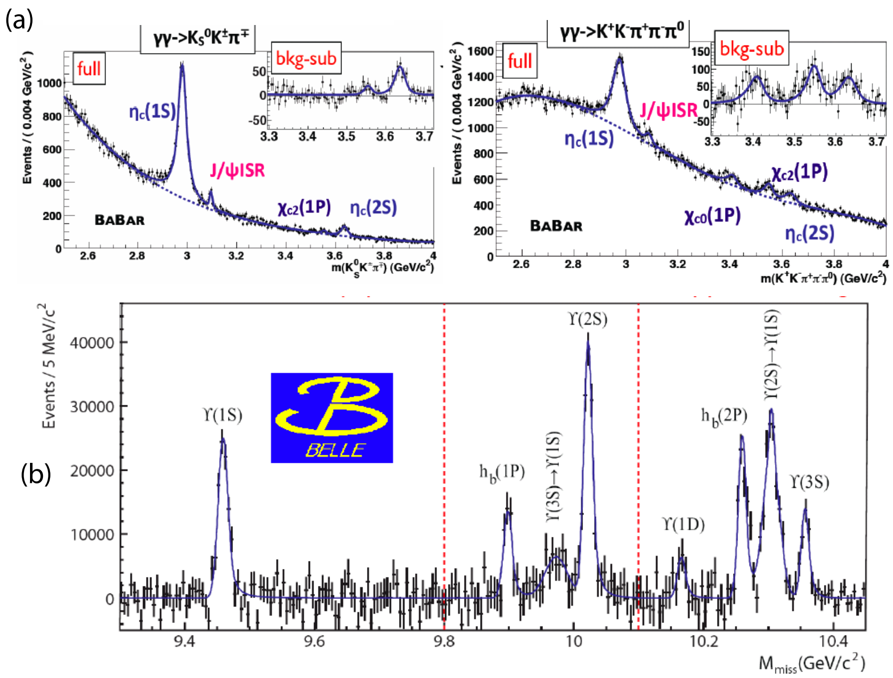

Figure 11: (a) The BaBar measurement of the mass distribution in two $K\overline{K}$ final states in $\gamma\gamma$ collisions, showing the $C = +1$ states of the charmonium system, from [29,28]. (b) The Belle measurement of the missing mass distribution in $\Upsilon(5\mathrm{S}) \to \pi^+\pi^- + X$, showing the $C = -1$ states of the Υ spectrum, including the P-wave state $h_b(1\mathrm{P})$, $h_b(2\mathrm{P})$, from [30,28].

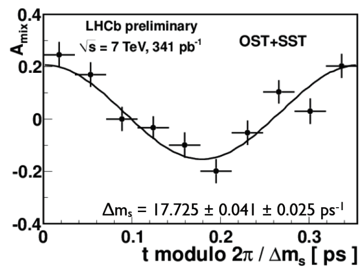

Figure 12: The particle-antiparticle oscillation in B_s–$\overline{B}_s$ mixing, as observed by the LHCb experiment [33].

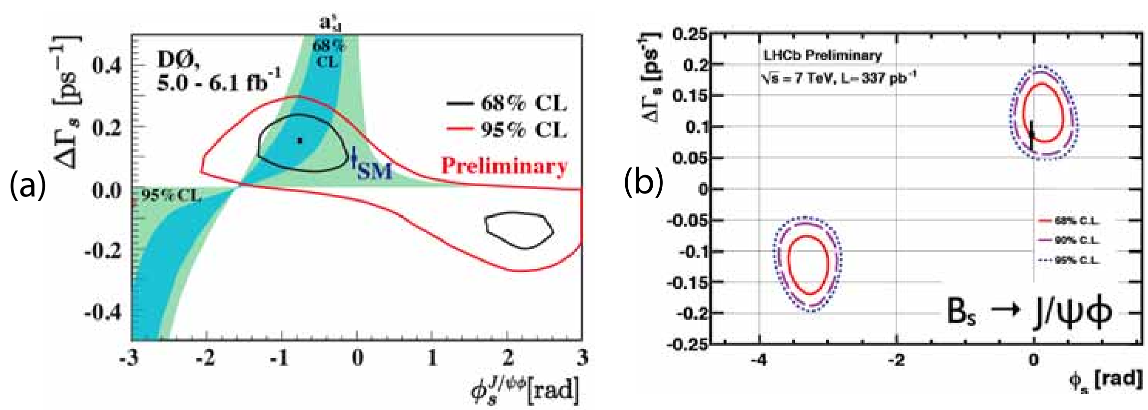

Figure 13: (a) Regions of the $(\phi_s, \Delta\Gamma_s)$ parameter space for B_s–$\overline{B}_s$ mixing consistent with measurements of the mixing by the DØ experiment (contours), and consistent with the DØ value of A^b_{sl}, from [34]. (b) Regions of the $(\phi_s, \Delta\Gamma_s)$ parameter space for B_s–$\overline{B}_s$ mixing consistent with the new LHCb measurement, from [35].

associated with small impact parameter. This means that the anomaly is mainly due to B_s decays—or to uncancelled prompt backgrounds.

Is it reasonable that there are no anomalies in the B_d system while order-1 anomalies appear in the B_s system? Theory favors the idea that the B_d system should be more sensitive to new physics. But this is only a generic statement. It is possible that the BaBar and Belle experiments were unlucky, while the LHCb experiment will be extremely lucky.

At LP11, Gerhard Raven presented the first results from LHCb [33], including a remarkable new measurement of the B_s–$\overline{B}_s$ mixing parameters. The time-dependent mixing amplitude is shown in Fig. 12. For those of us who are used to seeing B_s–$\overline{B}_s$ mixing as a rapid oscillation that must be Fourier-analyzed to be observed, this is a very impressive improvement of the state of the art [35]. From these results, LHCb has extracted values of the mixing phase ϕ_s and the off-diagonal width $\Delta\Gamma$. If the origin of the DØ anomaly were to come from B_s–$\overline{B}_s$ mixing—though it could also arise from a non-standard direct decay amplitude—the values of these parameters should be in the region shaded blue in Fig. 13(a) [34]. Instead, LHCb data favors the parameter region shown in Fig. 13(b). The result is consistent with the CKM model expectation. Please note also that the scale in the LHCb plot is magnified by about a factor 2 from that in the DØ plot. Over the next year, we will see whether other studies of the B_s system will reveal another source of non-standard behavior or will refute DØ's claim of an anomaly.

5 Neutrinos

There are many open problems in the area of neutrino masses and mixings. I will concentrate on only one issue, but one that is especially relevant to the new developments presented at LP11: *Has θ_{13} been observed?* This is a crucial question for the future of neutrino physics. All CP-violating effects in neutrino oscillations are multiplied by $\sin\theta_{13}$, so all prospects for measuring CP violation in neutrino oscillations depend on this parameter being large enough.

Up to now, we have only had limits on θ_{13},

$$\sin^2\theta_{13} < 0.12 \qquad (95\% \ \ \text{conf.}) \tag{2}$$

from the Chooz [36] and MINOS [37] experiments. At LP11, however, we saw tantalyzing evidence for $\theta_{13} \neq 0$ from MINOS and T2K.

The T2K result, described at LP11 by Hiro Tanaka [38], is quite elegant and persuasive. The experiment runs a muon neutrino beam from the JPARC laboratory in Tokai to Kamiokande, where events are examined for electron appearance in charged-current reactions. The experiment uses an off-axis beam that provides a neutrino spectrum of low energy with a relatively narrow energy spread. The angle and energy are tuned to put the first oscillation maximum at the location of the Super-Kamiokande detector. The beam has measured small ν_e contamination and the solar neutrino oscillation mixing θ_{12} makes only a minor contribution, so it is only necessary to demonstrate that electrons are actually being produced above background.

The most dangerous background is the neutral-current process $\nu N \to \nu\pi^0 N$, with the π^0 decay giving an electromagnetic shower similar to that of an electron. Fortunately, the π^0s are produced at relatively low momentum ($p_{\pi^0} < 200$ MeV), so most π^0 decays produce two distinct Cherenkov rings. This signature is cleanly

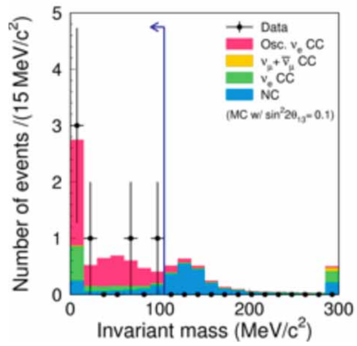

Figure 14: Invariant masses obtained for events in the T2K sample classified as single-ring (candidate e^-) events, then reanalyzed as two-ring (two-photon) events, from [38].

separated from the single-ring electron events in Super-K. The background rejection claimed is

$$18 \text{ events} \rightarrow 6 \text{ single-ring} \rightarrow 0.6 \text{ final background} \tag{3}$$

The total background expected, including also events from ν_e contamination in the beam, is 1.5 ± 0.3 events, and 6 events are observed [39]. The invariant mass distribution of the electromagetic component observed for the 6 events is shown in Fig. 14; the pink region shows the prediction for the best-fit oscillation model.

The total background is nontrivial; the 6 events could be the result of a fluctuation. The p-value for $\theta_{13} = 0$ is 0.7%, corresponding to exclusion at 2.5 σ.

The MINOS experiment has reported a similar result [40], described at LP11 in the lecture by Jenny Thomas [41]. MINOS is not at the oscillation maximum and has no clean technique for e/π^0 separation but does benefit from much higher statistics. Using a multivariate discriminant to select a region with highest probability for electron appearance, MINOS observes 62 events with $49.5 \pm 7.0 \pm 2.8$ expected background. There is a small excess, giving a p-value for $\theta_{13} = 0$ of 11%, corresponding to exclusion at 1.2 σ.

In his summary of the complete world situation for neutrino mixing, Thomas Schwetz-Mangold described a global fit to the data, adding all sources of evidence, that excludes $\theta_{13} = 0$ at 3.2 σ [42,43]. The lecture was followed by an animated discussion of what the criteria should be for discovery in neutrino physics. The chair, Young-Kee Kim, asked me to include my opinion on this issue in the summary talk.

My position is quite conservative. I take seriously the good advice given by Jenny Thomas in her lecture that 2%, even 1%, is a substantial probability for a fluctuation that should not be ignored. My advice is:

1. Even to announce "evidence for ...", we must demand 3σ observation in a single analysis with systematics under the control of one experimental group. Only when this criterion is reached should corroborating evidence be piled on.

2. A 3σ observation still needs corroboration. The criterion for "discovery" should be 5σ, as it typically is in collider experiments.

I was eager to report the observation of $\theta_{13} \neq 0$ in my summary talk, but we are not there yet. In the next two years, we are expecting additional data from MINOS, a new large data set from T2K, and the first results from three reactor experiments—Double Chooz, RENO, and Daya Bay [44]. If the current hints are correct, we will have discovery of θ_{13} by the time of Lepton-Photon 2013. At that meeting, I hope, a luckier community will celebrate this achievement.

I was grateful for another piece of news in Tanaka's talk. JPARC, KEK, and Kamiokande have survived the Tohoku earthquake in good order and are preparing for new experiments in 2012. Our whole community sends these labs our best hopes for the future.

6 Muons

Andreas Hoecker reviewed a variety of experiments on the charged leptons [45]. I will briefly discuss two of these.

The first is the measurement of the muon $(g-2)$. The actual value of the muon $(g-2)$ was measured with better than a part per billion precision by an elegant BNL experiment that presented its final results in 2006 [46]. The experimental result deviates from the Standard Model expectation by more than 3 parts per billion, well outside the experimental error. However, the interpretation of that experiment has been clouded by the fact that the Standard Model prediction for the muon $(g-2)$ depends on low-energy hadronic amplitudes that are difficult to evaluate accurately. The most troublesome of these is the simple lowest-order hadronic vacuum polarization diagram shown in Fig. 15(a). It is not possible to compute the required hadronic amplitude from QCD, so this amplitude must be obtained from a dispersion integral over the measured cross section for the process $e^+e^- \to$ hadrons. To match the accuracy of the BNL experiment, the e^+e^- cross section must be given to an accuracy of parts per mil. Unfortunately, most of the world's data comes from experiments that were not designed for this level of accuracy.

A new development in the past two years is the addition of two high-precision data sets from the radiative return process $e^+e^- \to \gamma + \pi^+\pi^-$, one from BaBar [47],

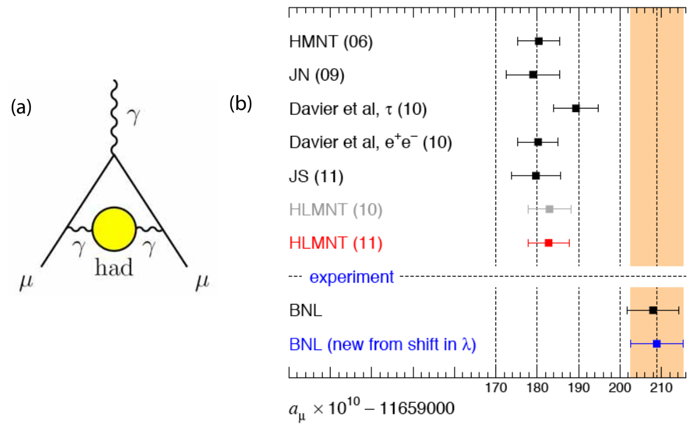

Figure 15: (a) The lowest order hadronic vacuum polarization contribution to the muon $(g-2)$. (b) The last few significant figures of the predictions of the muon $(g-2)$ by the groups [49–51], and comparision to the experimental measurement [46], from [51].

one from KLOE [48]. Three teams of experts have tried to turn the corpus of e^+e^- data into a precision determination of the hadronic vacuum polarization diagram [49–51]. The final results of the analyses are shown in Fig. 15(b). The final value of the hadronic vacuum polarization contributions is about $(685 \pm 4) \times 10^{-10}$, with some variation in the last significant figure among the three groups. About half of the error comes from the uncertainly in QED radiative corrections that must be applied to the measurements. An additional error of 2×10^{-10} is estimated for the hadronic light-by-light-scattering diagram.

The results of these analyses show a persistent discrepancy between the BNL result and Standard Model theory, the level of 3.3–3.6 σ. If this effect is real, it could indicate interesting effects from beyond the Standard Model, due to light sleptons or other exotic lepton partners. However, the threshold for claiming this as a discovery is high. There is now a proposal to repeat the muon $(g-2)$ experiment at Fermilab [52]. However, without a method to increase the precision on the hadronic matrix elements, it is not clear to me that that a higher statistics measurement of $(g-2)$ will improve our level of understanding.

In the area of lepton flavor violation, the MEG experiment on $\mu \to e\gamma$ has announced a new result, adding a new data set from 2010 with double the statistics of their previous 2009 result [53]. For the 2010 run, the apparatus was improved in several ways, most notably, with sharper time resolution. A cluster of candidate events found in 2009 was not confirmed in the 2010 data. My interpretation is that this is actually good news, giving a real prospect that the MEG experiment can explore for this lepton flavor violating process down to a branching ratio of 10^{-13}.

7 The Large Hadron Collider

I echo the sentiments of many speakers at LP11 by congratulating Steve Myers and his team for a very successful year of operation of the CERN Large Hadron Collider at 7 TeV. The LHC experiments have now accumulated large and interesting data sets. I will describe results from that data in the remainder of this lecture. First, though, I would like to make two more general observations about the LHC.

The first of these follows Thomas Friedman's phrase, "the world is flat" [54]. The construction and commissioning of the LHC experiments has been a global effort. Now we are seeing the fruits of that process. The experitise on how the experiments work is distributed worldwide. The experimental data is available to all members of each detector collaboration through a global computer network. And, we are all connected by 21st-century communication systems. The distribution of data and expertise implies a new era for high-energy physics. Experimenters no longer need to travel to the accelerator. Working in their home labs, they *are already* at the accelerator. Any group, anywhere, could make the crucial breakthrough that leads to a discovery. All that is needed is eager students and patient faculty.

As an illustration, I show in Fig. 16(a) the CMS group of the Tata Institute for Fundamental Research. This is one of many groups around the world working aggressively to mine the data from the LHC. The Lepton Photon meetings have traditionally been located at the electron accelerator laboratories. The hosting of LP11 in Mumbai is a new direction that celebrates this state of affairs.

However, there is another side to the story. A flat world revolves around a center. For the LHC, the center is CERN. It is of course true that a major accelerator project requires billions of dollars, forefront technological expertise, and a huge construction project. But an enterprise the size of the LHC requires even more.

The LHC was imagined in the early 1980's. The first data is arriving only now. The project has then required an institution whose goals could be coherent over all of that time—a period of more than a generation. Throughout this period, CERN has worked constantly, on a global scale, with governments, with the scientific community, and with the public to move the LHC project forward to its realization. It is a unique achievement. Our whole community must be grateful to CERN as an institution for making it possible.

As an illustration, I show in Fig. 16(b) the picture from the LHC First Beam Day in 2008 [55] of the five DGs of CERN who presided over the design and construction of the LHC.

Frederick Bordry described to us the commissioning and current status of the

Figure 16: (a) The CMS group of the Tata Institute for Fundamental Research, key participants, in the flat world, in the CMS supersymmetry searches. (b) The five Directors General of CERN who presided over the design and construction of the LHC, (from the left) Robert Aymar, Luciano Maiani, Chris Llewellyn-Smith, Carlo Rubbia, and Herwig Schopper, the creators of our flat world, from [55].

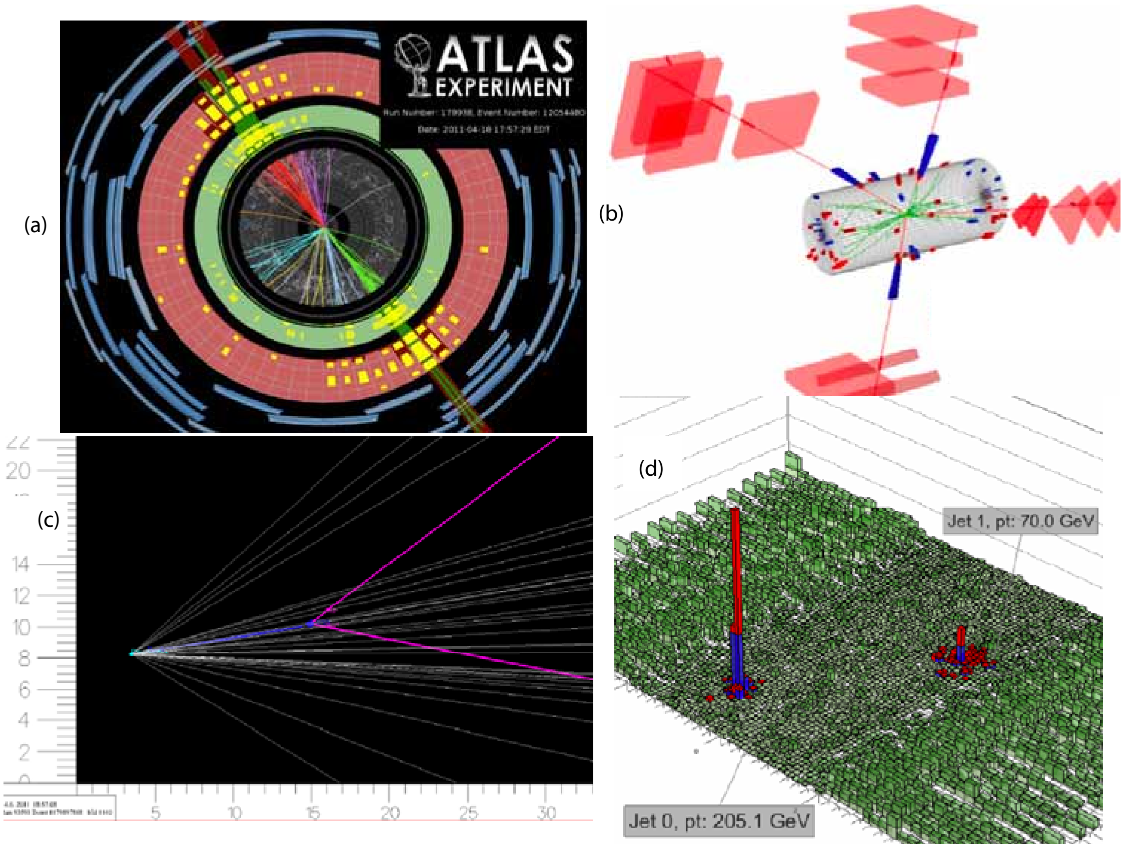

Figure 17: A montage of LHC events shown at LP11: (a) the highest-mass jet pair observed so far ($m_{jj} = 4$ TeV), (b) a candidate $h^0 \to Z^0 Z^0 \to 4\mu$ event from CMS, (c) a candidate $B_s \to \mu^+\mu^-$ event from LHCb, (d) an event display from the heavy ion program showing quenching of a jet of transverse momentum 200 GeV.

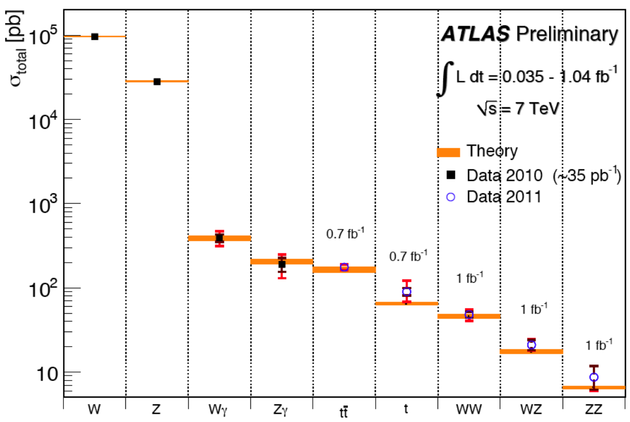

Figure 18: Rediscovery of the Standard Model: ATLAS measurements of cross sections for production of 2 massive Standard Model particles [57].

LHC, which is now running routinely at luminosities above 2×10^{33}/cm^2/sec [56]. As of LP11, the ATLAS and CMS experiments had collected over 2.4 fb^{-1} of data. Many of the analyses shown at LP11 were based on more than 1.0 fb^{-1} of data. In Fig. 17, I show a collection of images from the first year of the LHC. These include, from ATLAS, the highest-mass jet pair recorded to date, with $m(jj) = 4.0$ TeV, from CMS, the first Z^0Z^0 to four muon event, from LHCb, a candidate event for $B_s \to \mu^+\mu^-$, and, from the heavy ion program, an event display from CMS showing quenching of a jet of transverse momentum 200 GeV.

Fig. 18, from ATLAS [57], shows the current status of the rediscovery of the Standard Model. Cross sections for all of the key two-body processes have now been measured, all the way down to Z^0Z^0 production. The stage is set for the discovery of new processes not included in the Standard Model.

I found a pleasant surprise in the poster session of LP11. A majority of posters from ATLAS and CMS showed analyses involving the τ lepton. Indeed, it is finally true that the τ, the last major physics object to be developed at the LHC, has come of age. Fig. 19 shows an important calibration plot for the τ, the reconstruction of the Z^0 in $Z^0 \to \tau^+\tau^-$, with one muonic and one hadronic τ, from the posters presented by the graduate students Michael Trottier-McDonald and Raman Khurana [58,59].

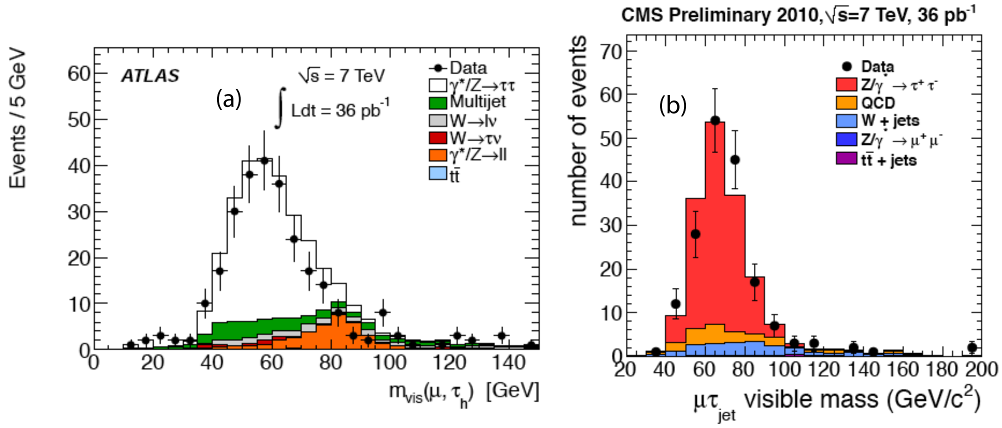

Figure 19: From the poster session at LP11: Reconstruction of the Z^0 resonance in the decay $Z^0 \to \tau^+\tau^-$, with one τ decaying to a muon and the other decaying hadronically [58,59].

8 Quantum Chromodynamics

The startup of the LHC has triggered tremendous progress in many aspects of QCD. Although, already for many years, the data from the Fermilab Tevatron has called for very sophisiticated calculations in perturbative QCD, the higher energy of the LHC and the increased precision of its detectors has raised the standard for the required level of QCD predictions. Theorists have answered with a stream of new methods and results. At LP11, Jim Pilcher reviewed the remarkable progress in theory and experiment [60]. I will now highlight a few topics from that discussion.

As an introduction, I show in Fig. 20 the measurement by CMS of the inclusive jet cross section at 7 TeV in bands of rapidity up to $|y| = 3$ [61]. The detailed agreement of theory and experiment is obscured somewhat by the very compressed log scale on the vertical axis. Nevertheless, the level of understanding achieved already at this early stage of the LHC program is very impressive.

Part of the credit for the good agreement shown is an improved level of sophistication in the extraction of Parton Distributions Functions. At LP11, Katja Krüger reviewed the current status of PDFs, with special emphasis on the new HERAPDF 1.5 set based on a combined analysis of the H1 and ZEUS deep inelastic scattering results [62,63]. The results from this analysis refute the expectation that direct data on gluon-gluon scattering is needed to pin down the gluon PDF well enough to account for the form of large p_T jet cross sections. Figure 21 shows the HERAPDF 1.5 set in good accord with PDF sets based on global fits, and in good accord with early ATLAS data, even though this PDF uses no hadron collider data at all [64]. The

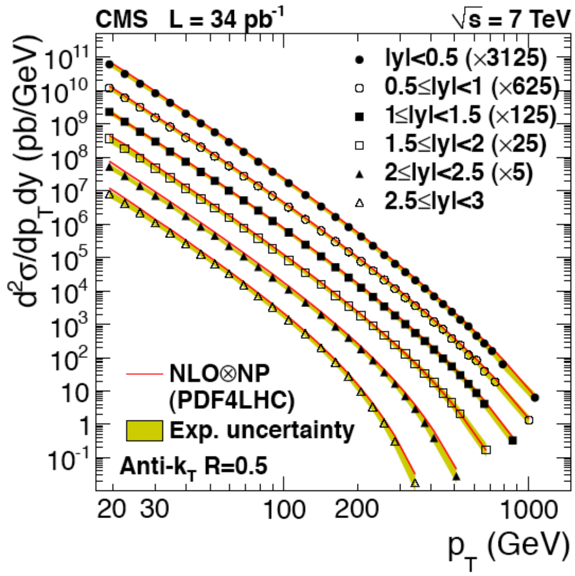

Figure 20: Comparison of NLO QCD theory and experiment for the inclusive jet cross section at 7 TeV, from [61].

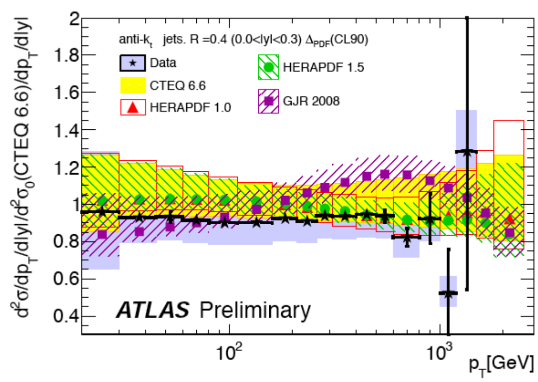

Figure 21: Comparison of the inclusive jet differential cross section at 7 TeV for $|y| < 1.0$ with predictions from a number of parton distribution functions, from [64]. The HERAPDF 1.5 predictions are shown as the green circles.

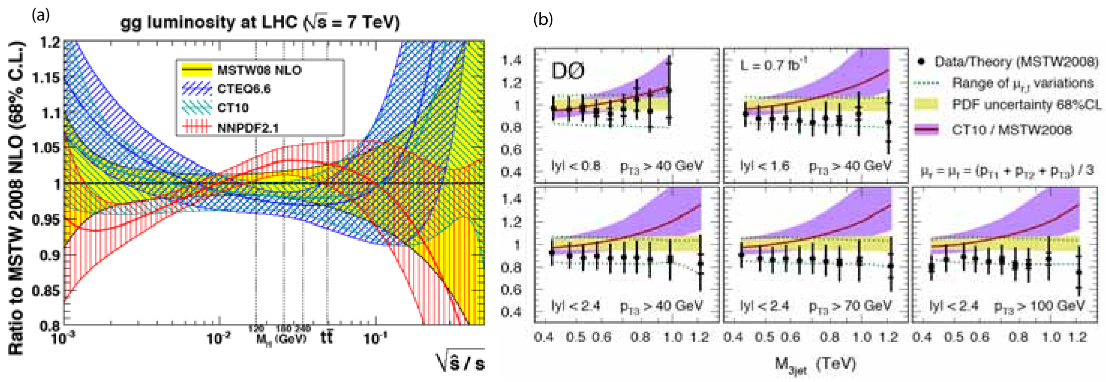

Figure 22: (a) Prediction for the gluon-gluon luminosity function at the 7 TeV LHC from various PDF sets, as a function of $\sqrt{\hat{s}/s}$. The predictions are normalized to the central value of the prediction from the MSTW08 PDF, from [68]. (b) Measurements of the $p\bar{p} \to 3$ jet cross section by the DØ experiment, and predictions from the CT10 PDF set, normalized to the to the central value of the prediction from the MSTW08 PDF, from [69].

form of the gluon distribution is extracted from Bjorken scaling violation at high x, measured using the long lever arm provided by HERA.

Pilcher showed, however, that this is not the end of the story for the determination of the gluon PDF. Recent Tevatron data from DØ on the 3-jet cross section makes a more sensitive probe of the high-x behavior of this distribution and highlights the different behavior predicted by the two leading global fits, MSTW08 [65] and CTEQ 2010 [66]. Figure 22(a) shows the ratio of predicted values for the gluon-gluon luminosity at 7 TeV for these and other PDF sets [68]. The behavior above $\sqrt{\hat{s}/s} = 0.1$ is constrained only a little by data and depends more on the way that the gluon PDF is parametrized as $x \to 1$. These differences can be compared to the PDF dependence of the observable studied by DØ, shown in Fig. 22(b) [69]. The trend of the DØ data favors MSTW08. But this behavior will need to be pinned down further by data before we can make the most sensitive searches for high-mass gluon resonances and quark compositeness that will be possible at the LHC.

Figure 23, from ATLAS [67] shows the remarkable depth of the study of the $W+$ jets process that is already available at the LHC. This process is the major background to new physics searches and must be understood with high precision.

Figure 24(a) shows a new result from ATLAS on the internal structure of jets observed at the LHC [70]. The quantity on the vertical axis is a measure of the width of the jet. Jets of larger p_T are narrower for two reasons, first, because the QCD radiation from the parent quark or gluon is more collimated, second, because, quark

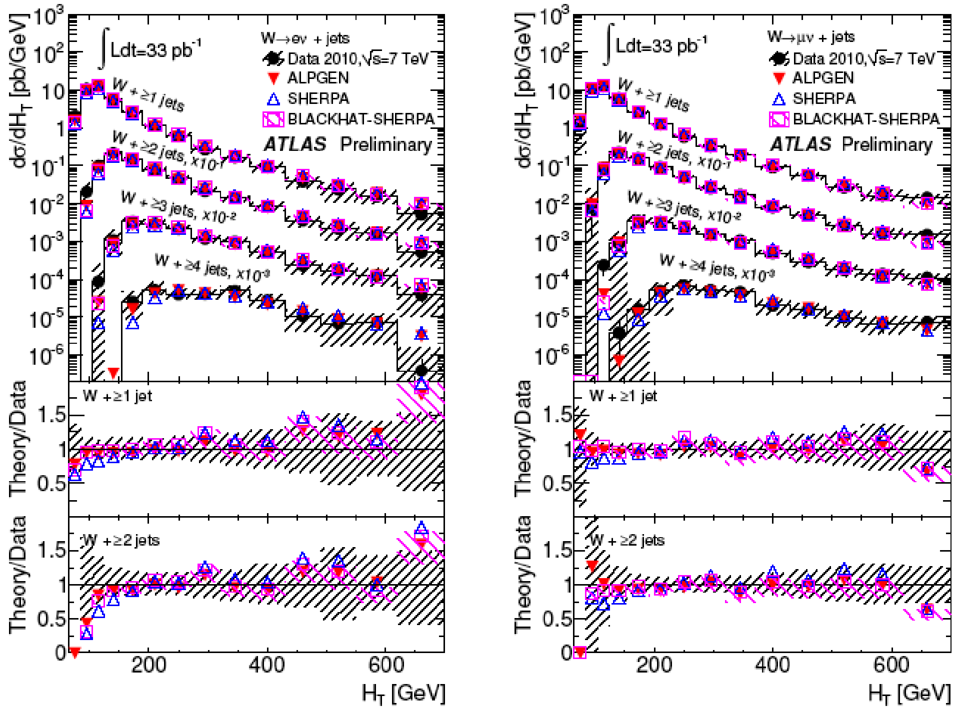

Figure 23: Measurement by the ATLAS experiment of the cross section for production of $W + n$ jet events as a function of the total transverse energy H_T, for $n = 1, 2, 3, 4$, and comparison to the predictions of QCD event generators, from [67].

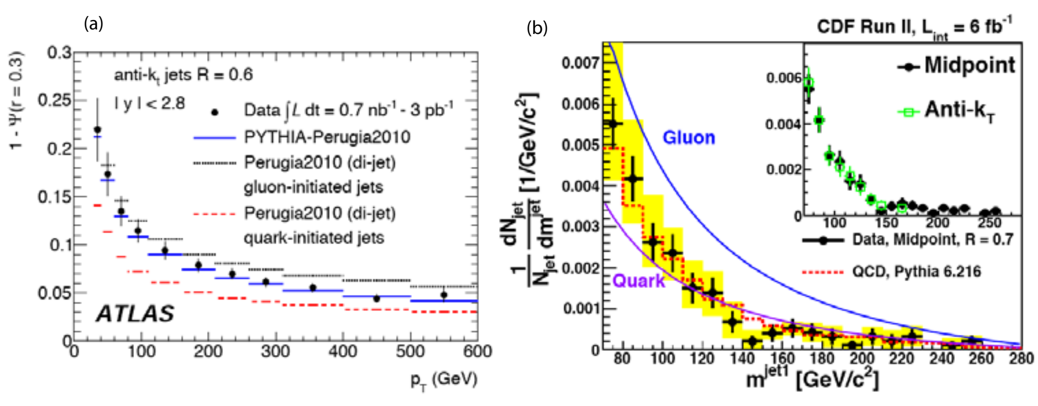

Figure 24: Two 2011 measurements of jet shape in hadron-hadron collisions: (a) from ATLAS, the fraction of the jet energy contained within a cone of radius $R = 0.3$ as a function of the jet p_T [70]; (b) from CDF, the distribution of single-jet masses [72].

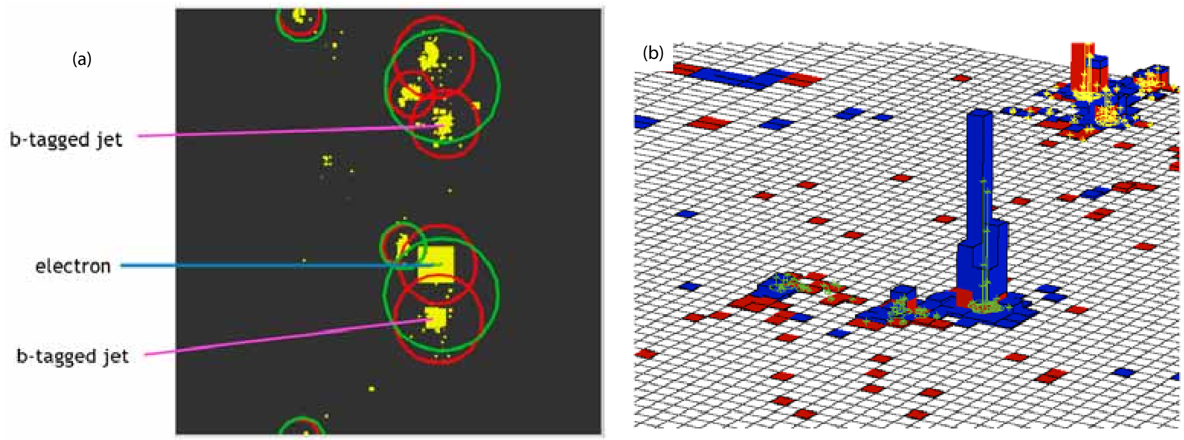

Figure 25: Events from (a) ATLAS and (b) CMS showing candidate $t\bar{t}$ events with highly boosted top quarks [79,80]. Both events resolve the internal structure of the top quark jet in terms of three subjets corresponding to the products of top quark decay.

jets, which are narrower than gluon jets, become a larger fraction of the sample at large p_T. Both behaviors are modelled by PYTHIA in good agreement with the data. The analysis in Fig. 24(a) repeats a classic analysis from CDF [71]. At LP11, we saw a more sophisticated version of this analysis from CDF, showing the spectrum of the measured jet mass [72]. This result is reproduced in Fig. 24(b).

Given the excellent understanding of jet shapes shown in the figure, it is realistic to use jet shape variables to identify unusual jets that are unlikely to arise from QCD. Reactions that produce heavy particles, including the Higgs boson and the top quark, often give these particles boosts large enough that all of the decay products of the particle end up within a single jet cone. Many years ago, Michael Seymour suggested that the properties of heavy particle decay could be used to search for these particles in high-p_T jet samples [73]. More recently, a number of groups have built effective algorithms to search for heavy particles against the forbidding background of QCD gluon jets [74–77]. This rapidly developing field is reviewed in [78]. In the next few years, the selection of heavy particles by these methods will be a major theme in studies of reactions involving Higgs bosons and in searches for new physics effect from beyond the Standard Model.

As enticement to this study, I show in Fig. 25 some of the first examples of boosted top quarks [79,80], showing the internal structure that distinguishes the heavy quark origin of these exotic jets.

The complexity of QCD processes at the Tevatron and the LHC that must be explained by QCD have stimulated new developments in the art of QCD computation.

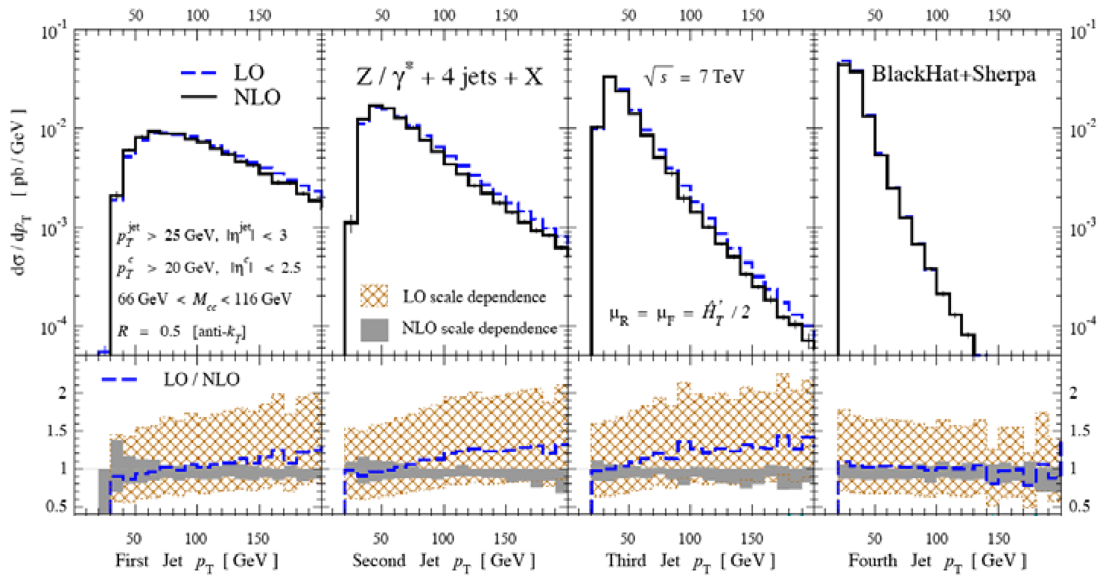

Figure 26: NLO QCD calculation by the BlackHat Collaboration of the p_T spectrum of the leading four jets in $pp \to Z+$ jets, from [90]. In the lower boxes, the comparison of the brown hatched and grey shaded regions shows the decrease in the theoretical error in going from LO to NLO.

Following the invention in the early 1990's of methods that allowed the computation of the rates of $2 \to 3$ processes at the next-to-leading order (NLO), the art of QCD computation progressed in deliberate stages. The pace of the advances changed in 2003, when a remarkable paper of Witten [81] introduced a radical new perspective. The new perspective quickly led to new methods for the computation of tree amplitudes [82]. Another outcome was the transformation of the unitarity method pioneered in the 90's by Bern, Dixon, Dunbar, and Kosower [83] into a robust method applicable to reactions of practical interest in QCD [84–86]. The final result of that development, the method of Ossola, Papadapoulos, and Pittau (OPP) [87], has given us a effective method not only for NLO computations of $2 \to 4$ processes but also for processes of arbitrarily higher complexity. This set of theoretical developments, was reviewed at LP11 in the lectures of Frank Petriello and Giulia Zanderighi [88,89]. It is, in my opinion, the most important development in theoretical particle physics of the past few years.

Many authors have contributed to this progress. I hope that I may be excused by referring to Petriello's lecture [88] for a more complete bibliography and concentrating here on three projects on the leading edge: BlackHat, HELAC, and the POWHEG Box.

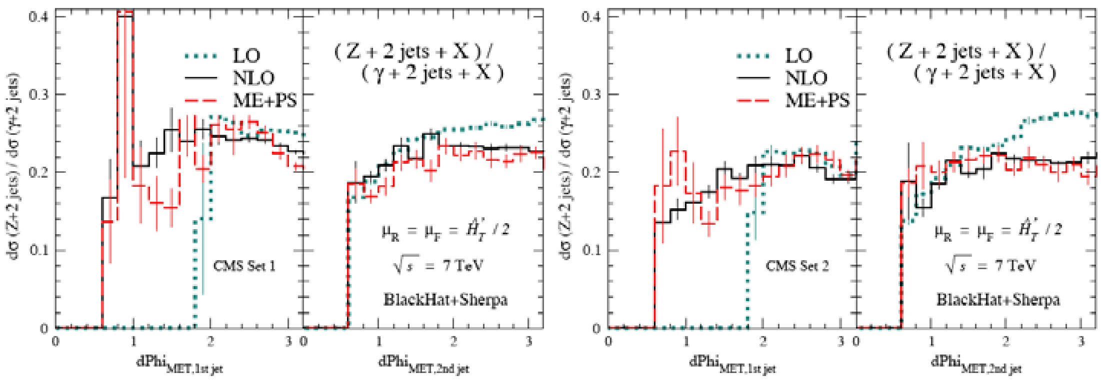

Figure 27: Correction factors for the conversion of measured differential cross sections for $pp \to \gamma +$ jets to cross sections for $pp \to Z^0 +$ jets, computed in NLO QCD by the BlackHat Collaboration, from [93].

BlackHat, the product of a collaboration led by Zvi Bern, Lance Dixon, and David Kosower, has been the most aggressive in incorporating the new theoretical methods into phenomenological computation. As a result, this collaboration has presented results for the most complex processes, most recently the NLO contributions to the production of Z^0+ 4 jets at the LHC. The computed p_T spectra for the first, second, third, and fourth jets are shown in Fig. 26 [90]. The difference between the hatched and grey shaded areas in the insets shows the reduction in theoretical error with the inclusion of the NLO amplitudes. The calculation reflects a smooth merger of the BlackHat methods for loop amplitude computation with the sophisticated handling of multi-leg tree amplitudes in the Sherpa Monte Carlo program [91]. This combination of methods will eventually lead to the integration of multijet NLO computations with the complete event description by parton showers [92].

Figure 27 shows a second interesting output of BlackHat. An important background to supersymmetry searches is the process of Z^0+ jets production with the Z^0 decaying invisibly to $\nu\overline{\nu}$. In principle, it is possible to estimate this background from data by measuring the same process with Z^0 decay to charged leptons. However, this reaction has a cross section 6 times less than the invisible decay. An alternative is to measure the cross section for production of a direct photon plus jets. This process has much higher statistics, but the kinematics is somewhat different from that of Z^0 production, requiring a nontrivial correction factor to convert the measured cross section to a background estimate. The figure shows this correction factor, computed to NLO accuracy by BlackHat [93].

HELAC is a program that combines the OPP method with a more robust recursive method for tree amplitude generation, developed by a collaboration led by

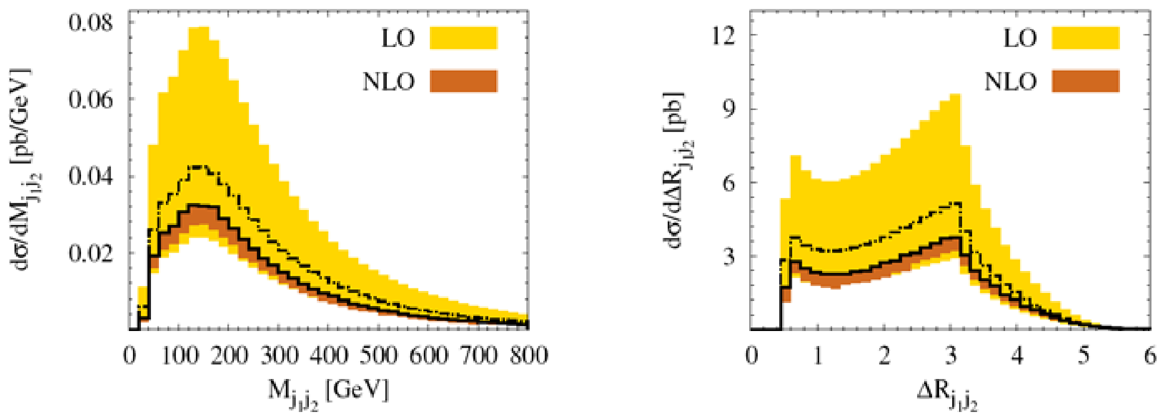

Figure 28: Observables of the 2-jet mass distribution in $pp \to t\bar{t} + 2$ jets, computed in NLO QCD by the HELAC group [95].

Papadopoulos and Pittau [94]. The products of this method have so far been limited to $2 \to 4$ processes, but have included processes with heavy particles such as top quarks in intermediate states. Figure 28 shows the HELAC computation of observables for the process $pp \to t\bar{t}jj$ [95]. This is important progress toward the complete understanding of $t\bar{t}+$ jets reactions that dominate LHC backgrounds to new physics searches with leptons and large numbers of jets.

The POWHEG Box is an innovative supplement to these computational methods. Nason originally developed the POWHEG method for integrating NLO calculations with parton shower Monte Carlo programs [96,97]. With this method, one uses standard NLO QCD to calculate the inclusive distribution of the hardest partons, then adds further partons from an iterative parton shower, restricting the emission phase space so that the computed inclusive distributions are not affected. In an important insight, Alioli, Nason, Oleari, and Re conceived the idea that the method could be formulated as an *interface* between NLO computations and existing parton shower programs such as PYTHIA and HERWIG [98]. They built a computational environment that is open for any NLO calculator to turn his or her calculations into a simulation code useful for experimenters. In [99], for example, the NLO calculation of a very complex $2 \to 4$ process is successfully integrated with parton showers using the POWHEG Box.

These advances in QCD calculation are of practical importance, but, as I have already emphasized, they are also intertwined with developments on the formal mathematical side of quantum field theory. One way to express this is to explain that computations in QCD are simplified if QCD is replaced by a similar theory with higher symmetry, the $N = 4$ supersymmetric version of Yang-Mills theory. $N = 4$

supersymmetric Yang-Mills is a fascinating theory in its own right with many special properties. Shiraz Minwalla reviewed these developments in an energetic and exciting lecture at LP11 [100].

For all values of its parameters, 4-dimensional $N = 4$ supersymmetric Yang-Mills theory is a theory of gluons and fermions with exact scale invariance. However, in the limit in which the number of QCD colors becomes large, it has additional unexpected properties. The theory has a dual description as a gravity theory in 5-dimensional anti-de Sitter space [101]. The duality maps the strong-coupling region of the original theory into a region of the gravity theory corresponding to small background curvature and classical dynamics. Under duality, scattering amplitudes map to Wilson loops with lightlike edges. The full symmetry of the theory includes conformal symmetry in the original space, plus a second conformal invariance acting on Wilson loops in the dual description [102]. The weak-coupling scattering amplitudes seem to have another alternative, nonlocal description in terms of integrals over a space of Grassmannians [103].

By making use of these features, it is possible to solve for the S-matrix of theory both at weak and at strong coupling [104,105]. It is very likely that the exact S-matrix of $N = 4$ super-Yang-Mills theory for a large number of colors will be found in the next few years. This is an exciting prospect that will undoubtedly bring surprising and useful insights both for mathematical quantum field theory and for practical application to QCD.

9 The Higgs Boson

I now turn to searches for new phenomena at the LHC. First of all, I will discuss the search for the Higgs boson.

At the first Lepton Photon conference that I attended—1981—the final talk was given by Lev Okun [106]. Hearing Okun was a memorable experience for me, and one important for the development of my own ideas about particle physics. Here are some excerpts from the talk:

> Instead of giving a general overview of the prospects, I decided to choose and discuss in some details just one problem, which could be considered as problem No. 1 in particle physics. To be No. 1 this problem has to be theoretically advanced and urgent. It should also be experimentally accessible.
>
> It seems to me that the problem No. 1 of high energy physics are scalar particles.

> Painstaking search for light scalars should be considered as the highest priority for the existing machines ... and even more so for the next generation of accelerators ...

Thirty years later, this question is still unresolved, and still No. 1.

This summer, we have seen tantalyzing hints of a Higgs boson of mass about 140 GeV. Both ATLAS and CMS have seen excess events in the channel $pp \to \ell^+\nu\ell^-\overline{\nu}$ that might signal Higgs production with the decay $h^0 \to WW^*$. The excesses are not yet significant, but ATLAS and CMS expect that a Higgs boson in this mass range could actually be discovered (at 5σ) with about 5 fb^{-1} of data. If the LHC continues to perform as it has, data samples of this size should be available before the end of this year.

It is hard not to be impatient. However, as I discussed above in the section on neutrino physics, it is important not to allow our expectations to substitute hints for discovery. This is especially true for the discovery of the long-awaited Higgs boson. As a way to analyze this issues I would like to propose five criteria for the discovery of a Higgs boson of mass 140 GeV:

1. A clear excess of events in $pp \to \ell^+\nu\ell^-\overline{\nu}+$ (0,1) jets, with careful attention to the background from $t\overline{t}$ production.
2. Correlation of the excess with variables indicating that the parent is a 0^{++} state.
3. Corroboration by a pileup of $pp \to ZZ^* \to 4\ell$ events in a single bin of width 4 GeV.
4. Corroboration by an excess of events in $pp \to \gamma\gamma$.
5. Corroboration by observation of a similar excess of $\ell^+\nu\ell^-\overline{\nu}$ at the Tevatron.

If the Higgs boson mass turns out to be lower, for example, 120 GeV, the list of criteria for discovery will be different but, I hope, no less rigorous.

How far had we come toward the goals of discovering a 140 GeV Higgs boson by LP11? Figure 29 shows the $pp \to \ell^+\nu\ell^-\overline{\nu}$ events recorded at the LHC, as presented by Aleandro Nisati for ATLAS [107,108] and Vivek Sharma for CMS [109,110],plotted in the variable $\Delta\phi(\ell\ell)$. The distribution in this variable, the polar angle between the two charged leptons, peaks at low values for a spin 0 Higgs boson but at high values for at least one of the relevant backgrounds, continuum WW production. The data is presented in 0-jet and 1-jet bins. Bins with higher numbers of jets are seriously contaminated by background from $t\overline{t}$. The data sets presented are of size 1.7 fb^{-1} for

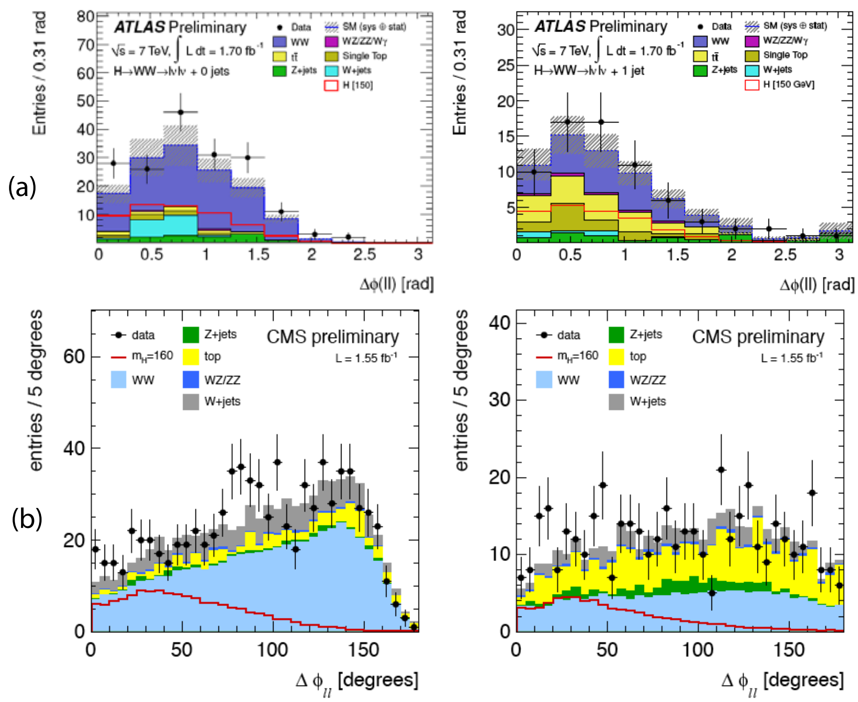

Figure 29: Current status of the measurment of the cross section for $pp \to \ell^+\ell^-\nu\bar{\nu} + 0,1$ jets, from (a) ATLAS and (b) CMS, from [108,110]. The colored histograms show various backgrounds expected from QCD. The red line histogram shows the expectation for a Standard Model Higgs boson of mass 150 GeV. The data is plotted as a function of the azimuthal angle between the two leptons.

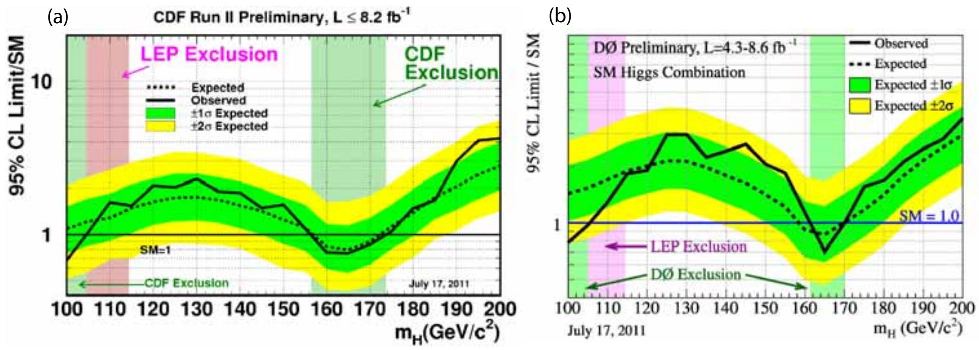

Figure 30: Upper limits on the cross section for production of a Standard Model Higgs boson at the Tevaton, as a ratio to the Standard Model expectation, from (a) CDF and (b) DØ, from [111].

ATLAS, 1.55 fb^{-1} for CMS. Small excesses are seen: 93 events over 76 ± 10 expected background for ATLAS, 140 events over 120.3 ± 10.8 for CMS. The correlation of these excesses with small values of $\Delta\phi(\ell\ell)$ is certainly not obvious from the figures. Both ATLAS and CMS see $pp \to ZZ^*$ events roughly covering the range of masses from 120 GeV to 450 GeV. Near 140 GeV, ATLAS has a candidate at 144., CMS has candidates at 139.3 and 144.9. There is no significant peak in $pp \to \gamma\gamma$. The Tevatron limits on the Standard Model Higgs boson, presented by Marco Verzocchi [111,112], are shown in Fig. 30. DØ sees a substantial excess of events in the mass region $140 - 150$ GeV; CDF does not.

It is not possible now to make a persuasive case for the appearance of the Higgs boson. But the current situation is quite consistent with the expected signals a Higgs boson of mass about 140 GeV. We can hope that the picture will become clearer when the full 2011 data set has been accumulated.

ATLAS and CMS have also *excluded* the Standard Model Higgs boson over a broad range of higher masses. In most of the higher-mass range, the on-shell decays $h^0 \to W^+W^-, Z^0Z^0$ would be obvious in several channels if they were in fact present. These same channels typically dominate in the high-mass region in models with multiple or non-standard Higgs. The union of the ATLAS and CMS 95% exclusion regions covers the entire range from 145 to 446 GeV, except for a small interval from 288 to 296 GeV. Thus, we already know from the LHC that *either* the Higgs boson is light, with a mass within 30 GeV of the direct lower limit from LEP, *or* the Higgs boson is very heavy and strongly self-coupled.

The precision electroweak predictions strongly favor a light Higgs boson, with mass close to the LEP limit. The Minimal Supersymmetric Standard Model predicts that the Higgs boson mass is below 130 GeV, and many other theoretical models also favor a light Higgs boson. So, as a theorist, I see no reason to be worried that the Higgs boson will be excluded. The situation is quite the reverse: The Higgs boson is now being restricted by the LHC results to the narrow mass region in which it is most strongly expected to appear. If the true Higgs boson of Nature is similar to the one in the Standard Model, and if it is in the low-mass range, this particle should be discovered using the 15 fb^{-1} LHC data set that, hopefully, will be accumulated in 2012. If the Higgs boson is not found in this search, the reason can only be because of other new physics, outside of the Standard Model, that should also be discoverable at the LHC.

There is one further point to be made about the Higgs boson. This was nicely expressed by Abdelhak Djouadi in his theoretical review of Higgs physics [113]: "Finding the Higgs is only the first part of our contract." Much more work will be needed to establish experimentally that the particle discovered in Higgs boson searches is indeed the Higgs boson and that it plays the role required in the Standard Model of generating the masses of quarks, leptons, and gauge bosons.

10 The Top Quark

It is remarkable that the LHC experiments have now accumulated as many top quarks as the Tevatron experiments. So far, the properties of the top quark observed at the LHC have been in accord with the Standard Model. That picture could well change, though, as we go to still higher statistics.

The measurement of the top quark pair production total cross section at the LHC was presented in the talk of Albert de Roeck [114]; the result is shown in Fig. 31. The result is a remarkable one. The LHC at 7 TeV has an energy only a factor of 3.5 higher than that of the Tevatron and has the relative disadvantage of using pp rather than $p\overline{p}$ collisions, yet the cross section is higher than that at the Tevatron by a factor of 25. The effect is understood within the Standard Model as signalling the transition from $q\overline{q}$ to gg production, and the measured result is in good agreement with QCD estimates [115,116].

The Tevatron experiments have reported an anomalously large forward-backward asymmetry in $t\overline{t}$ production. The results deserve discussion. They represent a large deviation from the Standard Model expectation. It is difficult to imagine an experimental problem that would lead to a false measurement. Among several Tevatron anomalies presented at LP11, I consider this the most likely to survive, and the most puzzling.

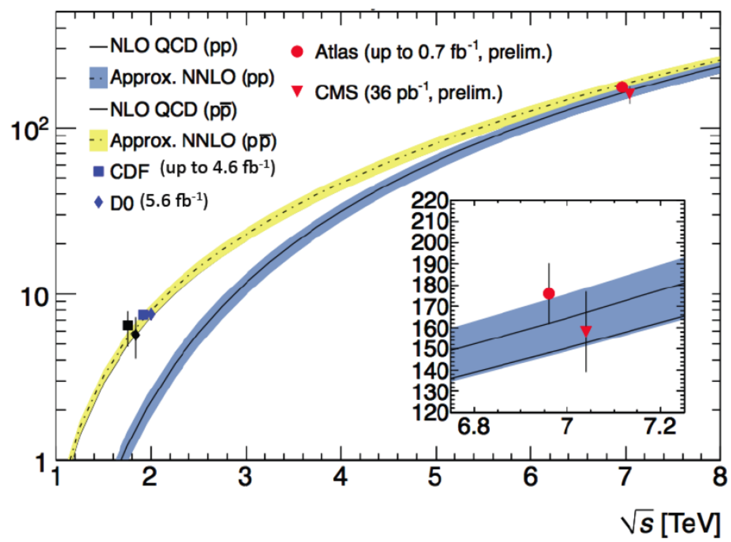

Figure 31: Measured values of the cross section for $t\bar{t}$ production at the Tevatron and the LHC, compared to QCD theory, from [114].

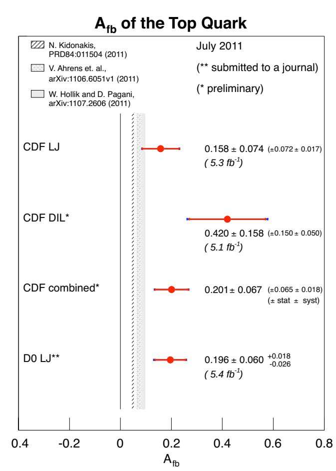

Figure 32: Measurements of the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron, and comparison to theoretical predictions, from [117].

A summary of the measurements is shown in Fig. 32 [117]. The numbers in the figure are to be compared to an expectation from QCD of 6%, plus an extra 1% from electroweak effects. The effect is strictly zero in $gg \to t\bar{t}$, but it can appear in $q\overline{q} \to t\bar{t}$ from the interference between 1- and 2-gluon production diagrams. The measured value of the asymmetry is $(20 \pm 6)\%$ in each of the two Tevatron experiments.

It is tempting to say that the effect must be due to new physics in the $q\overline{q}t\bar{t}$ interaction. This necessarily implies one or more new particles contributing to this interaction in the s, t, or u channel. The various possibilities are reviewed comprehensively by Gresham, Kim, and Zurek [118]. Many of these possibilities are already excluded by the higher-energy measurements at the LHC. For example, a new particle in the s-channel would be a color octet vector particle coupling to $q\overline{q}$ and $t\bar{t}$. If the coupling to $q\overline{q}$ is sufficiently large—unitarity in the $t\bar{t}$ system gives a lower bound—this particle should appear as a resonance in the 2-jet mass distribution at the LHC similar to the signature of an axigluon [119]. ATLAS and CMS exclude resonances in the dijet mass distribution up to 3.3 TeV [120,121] and thus, at least for a narrow resonance, exclude the entire relevant parameter space. A new particle in the t channel would be a Z' boson coupling to $q\bar{t}$. If there is only one such particle, the exchange of this boson mediates the reaction $qq \to tt$. A CMS search for tt production at 7 TeV eliminates the entire parameter space of this model [122]. Some possibilities do remain, including an interesting suggestion by Tavares and Schmaltz that the anomaly is due to a broad resonance at 400 GeV that decays mainly to 3-jet final states [123]. These should be tested in the near future.

In his talk at LP11, Frank Petriello expressed the opinion that the anomaly could be explained within the Standard Model [88]. As I have already explained, the forward-backward asymmetry in $q\overline{q} \to t\bar{t}$ appears for the first time at NLO, and therefore the estimate cited above, from one-loop diagrams, is only a leading-order result. It is not uncommon that QCD effects are enhanced by a factor of 2 due to next-to-leading corrections. To verify this hypothesis, an NNLO calculation of the $t\bar{t}$ cross section is needed. This has not yet been done. However, several groups, beginning with Almeida, Sterman, and Vogelsong [124], have done calculations that resum terms with large logarithms that typically give the largest contributions to the next order result. These calculations give only small corrections to the forward-backward asymmetry.

I find, at this moment, no persuasive explanations of the $t\bar{t}$ forward-backward asymmetry either from Standard Model physics or from new physics. This is a problem that needs attention and new ideas.

11 Beyond the Standard Model

The first 1 fb^{-1} of data from the LHC has shown no evidence for new physics beyond the Standard Model. Experimenters, I have noticed, are not disturbed by this. We are still at a very early stage in the LHC program. We have seen only 0.1% of the eventual LHC data set, and only the first year of a program that will last 15 years or longer.

And, it should be said, many experimenters believe that the Standard Model is literally correct. ("If only we could find that Higgs boson ...") I will comment on this possibility in the next section.

Theorists feel differently. This statement applies doubly to those of us who have written for many years about the incompleteness of the Standard Model and the necessity of its extention, and to those of us who have championed specific models of new physics such as supersymmetry. As the LHC experiments become sensitive to hypothetical new particles with TeV masses, we are reminded of the phrase from the Latin Requiem Mass.

Confutatis maledictis, flammis acribus addictis, voca me cum benedictus.

A loose translation is: Thousands of theory papers are being tossed into the furnace. Please, Lord, not mine!

The territory explored by ATLAS and CMS in 2011 has already excluded many possibilities for physics beyond the Standard Model. I will now discuss what it is that, in my opinion, we have learned from these exclusions. At LP11, Henri Bachacou gave a beautiful summary of the new LHC limits on a variety of new physics models [125]. I will discuss only a few of these limits that follow the main lines of my argument.

First, the idea of a sequential fourth generation of quarks and leptons is in serious trouble. If there exist new heavy quarks U and D that couple to the Standard Model as a conventional quark doublet, the cross section for the production process $gg \to h^0$ is multiplied by a factor of 9. Given the fact that Higgs limits are now within a factor of a few of the Standard Model expectation, this excludes fourth generation models over the entire range of Higgs mass, excepting only high values above 550 GeV. It is important to note that other types of exotic fermions are still in play and are even interesting; I will discuss one particular example below.

Before the startup of the LHC, I expected early discovery of events with the jets + missing transverse energy signature of supersymmetry. It did not happen. A particularly striking comparison is shown in Fig. 33. On the left, I show the expectation given in 2008 by De Roeck, Ellis, and their collaborators for the preferred

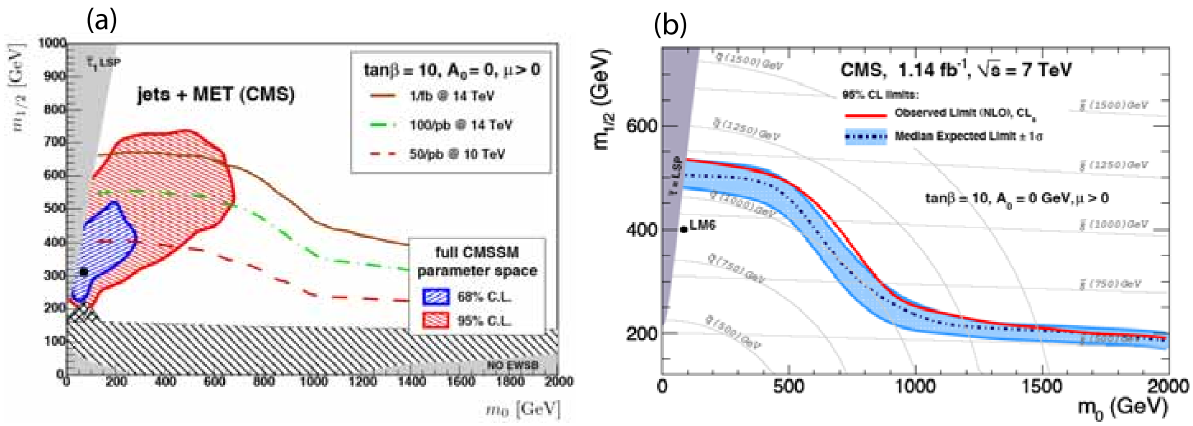

Figure 33: (a) Prediction of [126] at 68% and 95% confidence of the unified supersymmetry-breaking parameters $(m_0, m_{1/2})$ of the constrained Minimal Supersymmetric Standard Model. (b) 95% confidence exclusion region in the parameters $(m_0, m_{1/2})$ in the α_T search for supersymmetry presented by CMS at LP11 [127].

region of the parameter space of the constrained Minimal Supersymmetric Standard Model (the cMSSM, also known as MSUGRA) [126]. The red region is the 95% confidence expectation. On the right, I show the 95% confidence *excluded region* from one of the many supersymmetry search analyses presented by CMS at LP11 [127]. No reasonable person could view these figures together without concluding that we need to change our perspective. But, what new perspective is called for?

There was a good reason to expect that SUSY would be found at a relatively low energy. We postulate supersymmetry to provide a natural explanation of the mass scale of electroweak symmetry breaking. In most models of supersymmetry, the SUSY mass scale is very closely tied to the mass scale of the Higgs vacuum expectation value. In SUSY models with the minimal content of Higgs fields, there is a relation

$$m_Z^2 = 2\frac{M_{H_d}^2 - \tan^2\beta M_{H_u}^2}{\tan^2\beta - 1} - 2\mu^2 \ , \tag{4}$$

where $M_{H_d}^2$, $M_{H_u}^2$ are the SUSY-breaking masses of the two Higgs doublets and μ is the Higgsino mass term. It is difficult to understand how the μ parameter could be even as large as 1 TeV if the Higgs vacuum expectation value is small enought to put the Z boson mass at 91 GeV.

The simplest possibility is that all SUSY mass terms are of the order of a few hundred GeV. In some types of SUSY models, it is possible that only a few of the SUSY mass terms are small. But this is not an option over most of the parameter space of the cMSSM. In the cMSSM, μ is an output parameter and typically is computed to be one of the largest masses in the theory. Then the squarks and gluinos have masses comparable to μ or smaller, leading to very large production cross sections at the LHC. These predicted large cross sections are not observed.

Despite the lack of evidence for SUSY at the LHC so far, SUSY remains a very attractive possibility for physics at the TeV scale. The important questions about the TeV scale—the mechanism of electroweak symmetry breaking and the origin of dark matter—have not gone away. Supersymmetry offers solutions to these problems within a theory that includes only weak couplings, so that all aspects of the theory can be computed in detail. Supersymmetry has the additional advantage of providing simple avenues for connecting to grand unified theories and string theory at very high mass scales [128,129].

However, realizations like the cMSSM or MSUGRA, or, in another class of models, minimal gauge mediation, are tiny subspaces within the whole class of supersymmetry models. They reflect very simple assumptions about the parameters that break SUSY—assumptions that represent the first guesses people made decades ago. Now the data tells us that these guesses were incorrect. We thus need to abandon them and acknowledge that, to test SUSY, we must search over the full parameter space of the model.

I find strong motivation to consider SUSY parameter regions in which the natural expectation from (4) that the Higgs mass parameters are near the 100 GeV scale does not force the strongly interacting superpartners to have masses of a few hundred GeV. Actually, SUSY models with this property have been studied for many years. In 1996, Cohen, Kaplan, and Nelson introduced the 'more minimal supersymmetric Standard Model' [130], in which only the third generation sfermions and the gauginos are light, while the first and second generation quark and lepton partners are very heavy. Additional models that share the property of having naturally light Higgsinos along with very heavy squarks have been introduced regularly ever since that time [131–133].

To discuss the experimental signatures of this and related regions of SUSY parameter space, it is useful to view SUSY models using the general schema shown in Fig. 34. There are three ways to produce SUSY particles. First, if the squarks and gluinos are sufficiently light, these particles can be pair-produced in gg and qg collisions with cross sections of the order of 1 pb. The squarks and gluinos provide a *gateway* into the SUSY world. Other, color-singlet SUSY particles are found in the decays of these particles. By this mechanism, the exotic signatures of SUSY such as missing transverse energy and like-sign dileptons are also produced with pb cross section. This large production is apparently not taking place at the 7 TeV LHC, although we could still see it at the 14 TeV LHC.

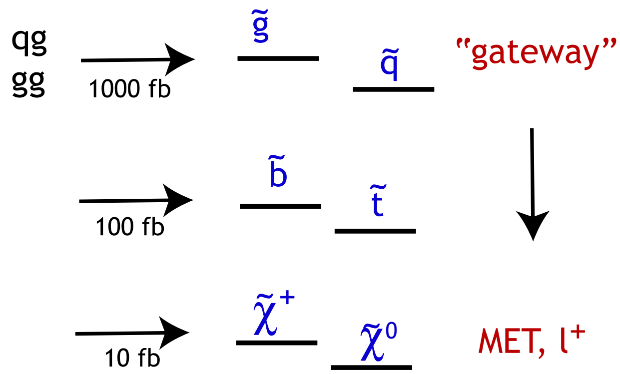

Figure 34: Schematic diagram illustrating the SUSY phenomenology at the 7 TeV LHC. Quark-gluon reactions can create pairs of SUSY particles, dominated by particles the highest cross sections that are kinematically allowed. Eventually, all of these particles decay to charginos and neutralinos, generating missing transverse energy and other characteristic signatures.

Second, the primary means of SUSY particle production could be the production of heavy particles with suppressed cross sections. The examples relevant here are top or bottom scalars. It is possible that only a single spin-0 color triplet boson (for example, the $\tilde{t}_L$) is light. Then the cross section for SUSY particle production would be at the 100 fb level. At luminosities sufficient to access this cross section, SUSY signatures such as jets plus missing energy will appear.

Finally, it is possible that all of the possible gateway particles are too heavy to be produced at the 7 TeV LHC. Then the primary reactions for production of SUSY particles will be the electroweak production of gauginos and Higgsinos in $q\bar{q}$ annihilation. The relevant cross sections are 10-100 fb. If the Higgsinos are light, below 200 GeV as we expect from (4), we should see pair production of charginos and neutralinos, yielding trilepton and like-sign dilepton signals, in the 2012 LHC data set.

The current limits on models of the second type just described, with only third generation squarks light, are quite weak. The limits presented by ATLAS are shown in Fig. 35. For models in which gluinos decay to a b jet plus missing energy, Fig. 35(a), the gluino mass can be anywhere above 700 GeV [134]. The vertical cutoff of the exclusion region shown in the figure indicates that we are not yet sensitive to direct squark pair production. In scenarios with a lepton in the final state (for example, from gluino decay to $\tilde{t} + \bar{t}$), the limits on the gluino mass are even weaker, only 500 GeV, as shown in Fig. 35(b) [135]. The current LHC limits do not yet probe the expected regions of parameter space in these scenarios.

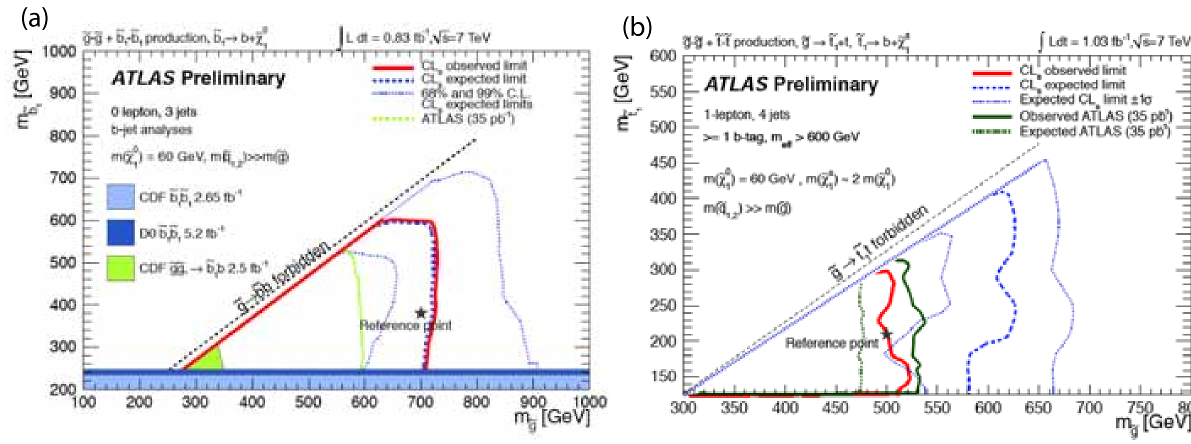

Figure 35: 95% exclusion regions in the plane of the gluon mass $m_{\tilde{g}}$ and the bottom or top quark mass presented by ATLAS at LP11 [134,135].

As an alternative to exploring new regions of SUSY parameter space, we can explore alternatives to SUSY. As I have explained above, the main advantage of SUSY is that it gives a complete description of the physics of electroweak symmetry breaking by weak-coupling interactions that can be treated using perturbation theory. If we give up this property and allow composite or strongly interacting Higgs bosons, more possibilities open up. These were described at LP11 in the lecture of Gautam Bhattacharya [136].

It is difficult to make a model of strong Higgs interactions at the TeV scale consistent with the constraints of precision electroweak measurements. It is easier to make a model in which Higgs bosons are composite at the 10 TeV scale. There are several schemes for the construction of such models. The most direct approach is that of Little Higgs models [137,138]. Alternatively, one can construct Randall-Sundrum models [139], in which a fifth dimension of space, with constant negative curvative, serves as a dual representation of new strong interactions above the TeV scale [140]. Extra-dimensional theories with *gauge-Higgs unification*, in which the Higgs bosons arise as the higher-dimensional components of gauge fields [141], share many features and can be considered within the same class of models. In all of these models, there is a light composite Higgs boson with properties similar to those of the Standard Model Higgs, plus new exotic particles with masses about 1 TeV.

Bhattacharya explained the general structure of the Higgs potential that is found in models of these types. At the first level of approximation, the composite Higgs has a flat potential. A perturbation generates a stabilizing $|\phi|^4$ potential for the Higgs field. The mass term for the Higgs is generated in the second order of perturbation theory.

There are specific mechanisms—based on loop corrections involving the top quark and the large value of the top quark Yukawa coupling—that produce a *negative* value for the induced mass term [138,143], giving a dynamical explanation for electroweak symmetry breaking. The final Higgs potential has the form

$$V = -\frac{m_t^4}{(16\pi^2)^2 F^2}|\phi|^2 + \frac{\alpha_w}{4\pi}|\phi|^4 \ , \tag{5}$$

where $F \sim 1$ TeV is a parameter similar to pion decay constant f_π arising from the strong interactions that bind the composite Higgs particles.

All of these models possess symmetries that forbid the generation of a Higgs boson mass in leading order. This means that they must include new particles that cancel the usual Standard Model quadratic divergences in the Higgs mass due to W, Z, and top quark loops. The models we are discussing now have no fermion-boson symmetry, so these are massive particles with the quantum numbers of the Standard Model states. In extra-dimensional models, they are the Kaluza-Klein excitations of the W, Z, and t fields.

Among these particles, a very interesting target for searches is the partner T of the top quark. This particle is not a member of a sequential fourth generation; instead, it is a vectorlike massive fermion of hypercharge $\frac{2}{3}$, or a member of a vectorlike doublet. Because this particle does not obtain its mass from electroweak symmetry breaking, there is no rigorous upper bound to the mass, in contrast to the expectation for a fourth-generation quark. However, to cancel divergences in the Higgs boson self-energy, the mass of the T should be of the order of 1 TeV. A typical decay pattern found in models is

$$T \to bW^+, \ tZ^0, \ th^0 \ , \tag{6}$$

with branching ratios close to (50%, 25%, 25%). It is possible that the Higgs boson could be discovered in decays of the T by searching for events with $W \to \ell\nu$ and multiplet b-tagged jets. At the moment, the LHC experiments have only weak constraints on such a particle; for example, CMS constrains a particle decaying by $T \to tZ^0$ only to be above 400 GeV [146].

The W and Z partners predicted by these theories have a suppressed coupling to light fermions. Current search limits on heavy W bosons are usually quoted for sequential Ws [144,145]. In the models I am discussing now, the W and Z partners typically couple to light quarks with 10% of the $SU(2)$ coupling strength, giving single resonance production rates of the order of 1% of those for full-strength coupling. The ATLAS and CMS limits for a W boson with a cross section at 1% of the standard value are about 1.0 TeV, leaving much parameter space to explore but giving a good prospect for thorough searches for these particles.

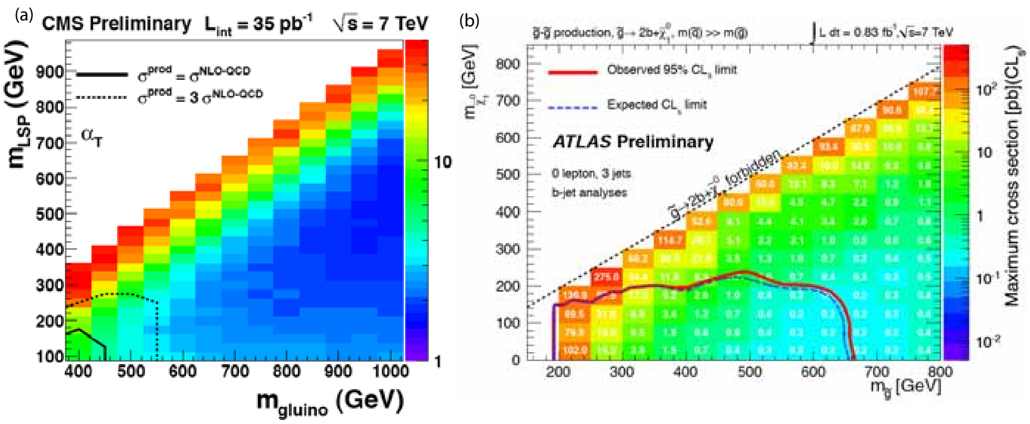

Figure 36: Two examples of LHC search analyses giving cross section limits using the parameters of simplified models: (a) CMS missing energy plus jets search [149], (b) ATLAS missing energy plus b jet search [134].

The supersymmetric and non-supersymmetric scenarios that I have discussed in this section are just a few examples of plausible model of electroweak symmetry breaking that are just beginning to be constrained by the LHC data. In the next year, we will explore possibilities far beyond the most commonly discussed models of new physics. We can only guess what is there.

Before concluding this section, I would like to describe a useful innovation in the presentation of limits on searches for new particles. Searches based on specific signatures constrain or, in time, will give evidence for, a wide variety of models. It would be of great advantage if the limits or nonzero signals could be presented in a manner that is as model-independent as possible. In a very interesting paper, Alwall, Schuster, and Toro have proposed creating *simplified models* that contain only the particles responsible for the particular signature being studied [147]. They showed that this approach can be used to analyze more complete and realistic models of new physics by demonstrating that the full complexity of supersymmetry models can be built up by constructing a sequence of simplified models that increase in complexity as more signatures are included. In the current situation, where there are no observed signals of new physics and no preferred models, it makes sense to analyze searches in simplified models with the very minimum number of particles and parameters. A compilation of simplified models covering a wide variety of possible signatures of new physics has been presented in [148].

Figure 36 shows the presentation of limits on supersymmetry cross sections given in the context of simplified models, from CMS [149] and ATLAS [134] analyses. The very simple models considered have two relevant masses. The figures show limits on the observed cross section in the various mass intervals. The CMS result is reported in detail as a set of Root files posted at [150]. Results presented in this way can be translated into limits on any other model, supersymmetric or not, that leads to final states of the particular topology under study.

12 The Path Forward

There is one more issue to discuss: *Couldn't it just be the Standard Model?*

The answer to this question is, unfortunately, yes. We know that there are phenomena in Nature that the Standard Model cannot explain, most prominently, the dark matter of the universe and the nonzero values of neutrino masses. However, there exist very plausible models in which the explanations for those phenomena lie ten or more orders of magnitude above the reach of current accelerators. Within the realm that we can explore directly with particle physics experiments, there is no hint or anomaly we see today that could not simply disappear with improved measurements, leaving the Standard Model unchallenged. If the Higgs boson mass is above the LEP lower bound of 114 GeV and below the upper limit from the LHC quoted in Section 9, the Standard Model is self-consistent up to very high energies, all the way to the Planck scale [151]. Thus, a possible outcome of the LHC experiments could be the end of experimental particle physics. The LHC experiments would confirm the predictions of the Standard Model at accessible energies, and would give no guidance as to the location of a higher energy scale at which the Standard Model might break down.

This would leave us in a terrible situation. All of the questions that we have today about the properties of particles within the Standard Model would not only be left unanswered but would be unanswerable. In the Standard Model, the parameters of the theory are renormalizable couplings. This means that, as a matter of principle, these parameters are not computable within the model. The most obvious difficulty of the model is our inability to understand the value of the Higgs field vacuum expectation value, or even, as the famous naturalness problem is stated [152], to understand why this value is not 16 orders of magnitude larger. However, within the Standard Model, we also cannot understand the values of the gauge boson couplings, or the values of any of the quark and lepton masses and mixing angles.

Those who choose to believe that the Standard Model is literally true should understand that this is what they are buying. There is no fundamental objection to this point of view. As I have explained in Section 2, this viewpoint is made intellectually respectable by theory of inflation, in particular, the idea that the equations of motion that we observe are true only locally in our small patch of the universe. The path that led to the Standard Model could have been determined in the very early history of the universe through mechanisms that are invisible to us today.

This is a thoroughly deplorable prospect. But every particle physicist needs to confront these ideas and ask: Do I think that this is how Nature works?

There is an alternative point of view. We do not know whether it correct. Nature will choose.

That point of view is the optimism that the physics of the Higgs field and electroweak symmetry breaking has a mechanism, and that that mechanism will be visible to our experiments at the TeV scale. There is a compelling justification for accepting this idea: Only people who believe in it can make the discovery that it is true.

It is a good time for optimism. With the LHC, we have a new engine that will produce the data that we need to find the explanations. The LHC gives us the power, over the course of its long program to 1000 fb^{-1} luminosity samples and beyond, to uncover evidence of any variant of physics explanations for the TeV scale. We can harness this power to look in every corner, under every stone, to find the clue that will unlock the secrets of the Higgs boson and its partners.

The measurements that will turn out to be the most important might not be the ones that we expect. We will need persistence and patience. But, if we are right, we have the chance before us to discover an entirely new level in the fundamental laws of physics.

I leave you with the image in Fig. 37. This is Manjusri, in Buddhist teaching, the bodhisattva associated with wisdom triumphant over all obstacles. In his traditional portrait, he has an impassive expression, above all trivial concerns, and he rides on a lion. We also have a lion, the LHC, to carry us forward.

We will meet again at the Lepton Photon conference of 2013. We look forward to the prospect that the many issues left unsettled in this year's report will be informed by the new data that is about to appear. We wait expectantly to see what next year's experiments will say.

ACKNOWLEDGEMENTS

I am grateful to Naba Mondal, Rohini Godbole, and the other organizers of LP11 for inviting me to this very stimulating conference and for providing very pleasant arrangements in Mumbai for all of the participants. I thank the speakers at LP11 and others whose work is reviewed here for patiently answering my questions, however

Figure 37: Manjusri, the bodhisattva of indomitable wisdom, protrayed riding on a lion [153].

persistent. I am grateful to my colleagues at SLAC for discussions of many of the points raised in this lecture. These people tried as hard as they could to give me the best perspective, so whatever errors remain are my responsibility. Finally, I thank the US Department of Energy for supporting me and the SLAC HEP Theory Group, under contract DE–AC02–76SF00515.

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