THE LAST DECADE IN EXPERIMENTAL PARTICLE PHYSICS

DP

Abstract. The last decade of particle physics has been largely a time of slow progress, development of basic themes, and a few new discoveries. The latest important discovery is the announcement in July, 2012 that the existence of a new particle resembling the Higgs boson at 125 GeV is firm from both ATLAS and CMS at the LHC. Otherwise, recent history has not been as exciting as say the **"November Revolution"** of 1974 when charmonium was discovered with subsequent realization over the next few years that the quark model was valid and the standard model took shape (e.g., 1974 J/ψ meson, 1975 tau lepton , 1977 Upsilon, 1979 gluon jet, 1983 W and Z weak bosons). However, we are now in the midst of another very interesting **'Neutrino Revolution'** from the observation of flavor changing neutrinos. A primary goal has been the search for new physics beyond the standard model, a search that is still in progress mainly at the CERN Large Hadron Collider (LHC). This 27 km-circumference proton collider was switched on in September, 2008 after 25 years of planning and construction. So far, most new reports say something like, "No excess above the Standard Model expectations is observed." LHC is also performing RHIC type experiments to clarify the nature of the high energy quark-gluon plasma, and some new discoveries have been made in that arena.

1. The Higgs Boson

By the end of 2011, There was yet no firm experimental evidence that the Higgs particle existed. Many possible decay modes had been investigated, $H \to \gamma\gamma, \tau\bar{\tau}$, b$\bar{b}$, W^+W^-, or Z$\bar{Z}$. What was called preliminary data from most major tests and channels indicated that a Higgs boson would be shown to exist near a mass of 125 GeV with confidence level above 3 standard deviations. At least the higher candidate range of $m_H \simeq$ 129-525 GeV had been excluded. During 2012, the LHC was able to run at a slightly higher 4 TeV/beam with about 3 times higher luminosity, and decent Higgs statistics was finally obtained.

July 4, 2012: CERN CMS and ATLAS announced the official existence of a new particle with properties similar to that expected for the Higgs particle and having a mass of 125 GeV with essentially 5-sigma confidence. There are still details to be worked out about all the higgs decay modes and how it fits into expected physics Figure 1 shows the enhancement bump near 125 GeV for the strong-decay di-photon channel for CMS data.

The existence of an $m_H \simeq 125$ GeV definite particle boson resembling the Higgs was the last outstanding piece of the standard model (SM). The Higgs field permeates all space, and its interactions with elementary particles gives them mass by providing a condensate

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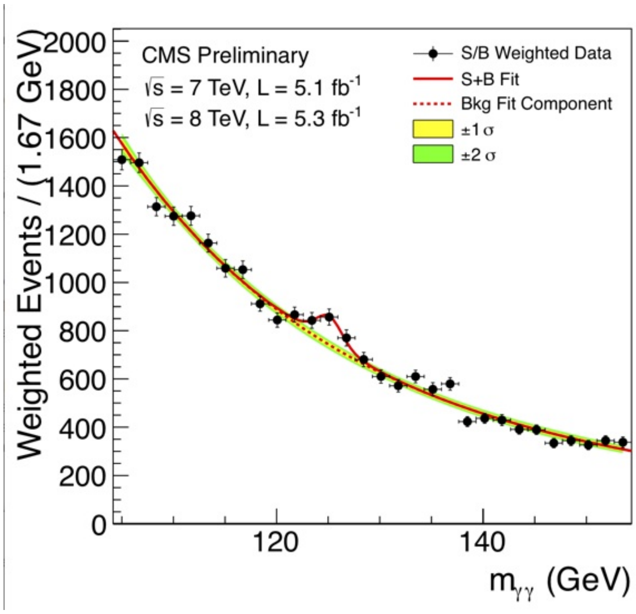

FIGURE 1. "Higgs particle Bump" Experimental results from 2011/2012 LHC proton-proton collision data in the two-gammas (di-photon) channel.

that can break gauge invariance. The Higgs mechanism is a type of weak-force superconductivity of the vacuum (similar to that which gives effective mass to the photon in electrical superconductors). One over-simplified picture of its action is to provide a pool of 'molasses' that can stick to particles traveling through it. Different particles interact with different strengths, but the top quark interacts most strongly (and has a higher mass, $m_t = 177$ GeV, than the Higgs).

The Higgs boson is the excitation quantum of the Higgs field, and its identification is seen from decays into two photons and into two Z's with predictions agreeing with the standard model for Z's but perhaps somewhat higher than expected for di-photons. Like the Ws, the Higgs decays quickly, and hence its detection 'bump has a wide energy width. Higgs particle production derives mainly from gluon-gluon fusion, $gg \to H$, from loop diagrams mediated by quarks but mainly using the top quark. The decay $H \to \gamma\gamma$ isn't that common and also depends on loop diagrams mainly from W's. Decays into the W's channel and also the tau's and b's weakly seems to be below expectations so far. More data is needed for clarity, and higher energy is needed for self-interaction of the Higgs with itself. Bill Ford (CU) believes that with current statistics, all is within expectation. Details will continue to emerge from CERN over the next two years. The perhaps bigger news from CERN is the apparent absence of supersymmetry (SUSY − again, so far). Physicists are hoping to see the 'stop' or susy-top-quark-superpartner. If the higgs turns out to be too *normal*, then physicists are in a quandary about what might lie around the next bend.

The Weinberg-Salaam ElectroWeak (EW) theory requires four scalar fields − three of which are used up in making the massive W's and Z, and one to give a "Higgs particle," H. A nice presentation of this is given on Matt Strassler's website [22]. The discovery of the Higgs favors actual physical use of EW scalar fields rather than new strong "technicolor forces." "This is why the discovery is important." [Weinberg, July, 2012].

2. Neutrino Oscillations

The **'Neutrino Revolution'** refers to the observation of flavor changing neutrinos after 1998. There are three different types or flavors of neutrinos (ν_e, ν_μ, ν_τ, and their antiparticles: $\bar{\nu_e}$, $\bar{\nu_\mu}$, $\bar{\nu_\tau}$). The existence of the electron neutrino was experimentally verified in 1956 from nuclear reactors, the muon neutrino was seen in 1962, and the tau neutrino in 2000. On earth, the main source of electron neutrinos is from nuclear reactions in the sun. Neutrinos are also produced from inside the earth and in the atmosphere from cosmic rays that also yield muon neutrinos.

Detections of solar electron neutrinos occurred from 1970 to 1994 a mile below ground in an old South Dakota gold mine. Ray Davis (Nobel prize 2002 at age 88) and John Bahcall ran an experiment using 100,000 gallons of dry-cleaning fluid and counted rare individual argon atoms converted from chlorine by the neutrinos from the sun. The mysterious net result was that only a third of the expected count was observed − the "solar neutrino problem." The solution to the mystery is that electron neutrinos from the sun are converted into muon and tau neutrinos so that the net abundance at earth is about the same for all three types. The first proof of neutrino oscillation (transmutations and tiny neutrino masses) occurred in 2001 from an underground detection tank in Canada ("SNO") using 1000 tonnes of heavy water surrounded by 9600 photo-multiplier tubes. It could see all types of neutrinos, and their total flux finally agreed with solar theory. The first SNO (Sudbury Neutrino Observatory) experiments of June 2001 indicated that the solar neutrino problem was due to particle physics rather than solar astronomy. Solar electron neutrinos from the decay of 8-Boron were seen along with elastic neutrino scattering in heavy water which sees all types of neutrinos.

After 2001, a human controlled experiment ("K2K") verified the loss in flight of muon neutrinos at "Super-Kamiokande" Japan. This transmutation loss was verified in 2005 by a Fermilab-to-Minnesota ("MINOS") experiment. The K2K test used muon neutrinos created from the "KEK" synchrotron beamed through the earth over 250 km to a detector using 50,000 tons of water. A different later experiment called T2K (Tokai to Kamioka, Japan) in 2011 showed that some muon neutrinos can interconvert into electron neutrinos[1].

That the electron neutrino survival probability really does oscillate with distance traveled was clearly demonstrated by the experiment "KamLAND" in 2002 (see Fig. 2). Antineutrinos from nuclear power plants showed a sine wave probability with flight distance L (survival versus L/Energy). Neutrinos can be created in the atmosphere from cosmic ray collisions, and muon neutrinos from above are more plentiful than muon neutrinos coming from below. In traveling through the earth, many muon neutrinos seem to change into tau neutrinos $-$ a loss first noted in Japan in 1998. The physics of neutrinos is a work in progress with many unanswered questions. There are many large experiments under construction or awaiting publication and much more to be discovered.

One of the most important mixing angles in the neutrino sector, θ_{13}, "has been shrouded in mystery for a long time." [7]. But then the experiments called T2K, Double Chooz, and MINOS hinted at a large $\sim 10^o$ non-zero PMNS matrix angle angle associated with loss of 'inverse beta decay' signals between near and far detectors of electron anti-neutrinos from nuclear reactors (using $\bar{\nu_e} + p \rightarrow e^+ + n$ reaction). Finally, in March, 2012, a precise measurement was achieved: "The Daya Bay Reactor Neutrino Experiment at Guangdong, China has measured a non-zero value for the neutrino mixing angle θ_{13} with a significance of 5.2 standard deviations [20] using antineutrinos from six reactors with 55 days of data. The latest result is $\theta_{13} \simeq 8.8 \pm 0.8^o$ ($\pm 1\sigma$ range). This very interesting non-preservation is much stronger than the CKM quarks case ($\theta_{13} \simeq 0.2^o$). The neutrino matrix 'describes a fundamental mismatch between the weak-interaction (flavor) and mass eigenstates of six leptons.'

In the CKM case, there was a relationship between angles and the strong hierarchies of quark masses (e.g., Cabibbo $\sin\theta_c \simeq \sqrt{m_d/m_s} = \sqrt{4.79MeV/92.4MeV}$) $[\theta_c = \theta_{12}^{CKM} \sim 13.1^o]$. A similar analogy for leptons might say $\sin\theta_{23} \simeq \sqrt{m_\mu/m_\tau} + \sqrt{m_2/m_3} \simeq 0.65-$ actual result $\theta_{23} \simeq 45^o$. Also note that $\theta_{13}^{PMNS} \sim \theta_c/\sqrt{2}$, as suggested by several GUT models beyond the standard model [21]. It could also be that $\theta_{12}^{PMNS} + \theta_c = 45^o$.

At present, neutrinos are only left handed with no evidence for right handed spins ('sterile' neutrinos, ν_s) [4]. That is, if your left hand fingers curl in the direction of spin, then your thumb points in the direction of motion near the speed of light. Anti-neutrinos are only right handed, and the ability to convert directly from muon neutrinos to electron neutrinos is not yet established. It is established that only three light neutrinos can exist $-$ but possible heavy neutrinos are not eliminated. It is not known whether massive neutrinos are also their own antineutrinos (Majorana neutrinos) or whether CP (charge-parity) violation occurs. It does now seem likely that Majorana particles will soon turn up in solid state physics.

Some Other Dates:

Aug 16, 2007: First real time detection of Be7 $\rightarrow$ Li7 solar neutrinos by Borexino! (Gran Sasso underground laboratory in Italy).

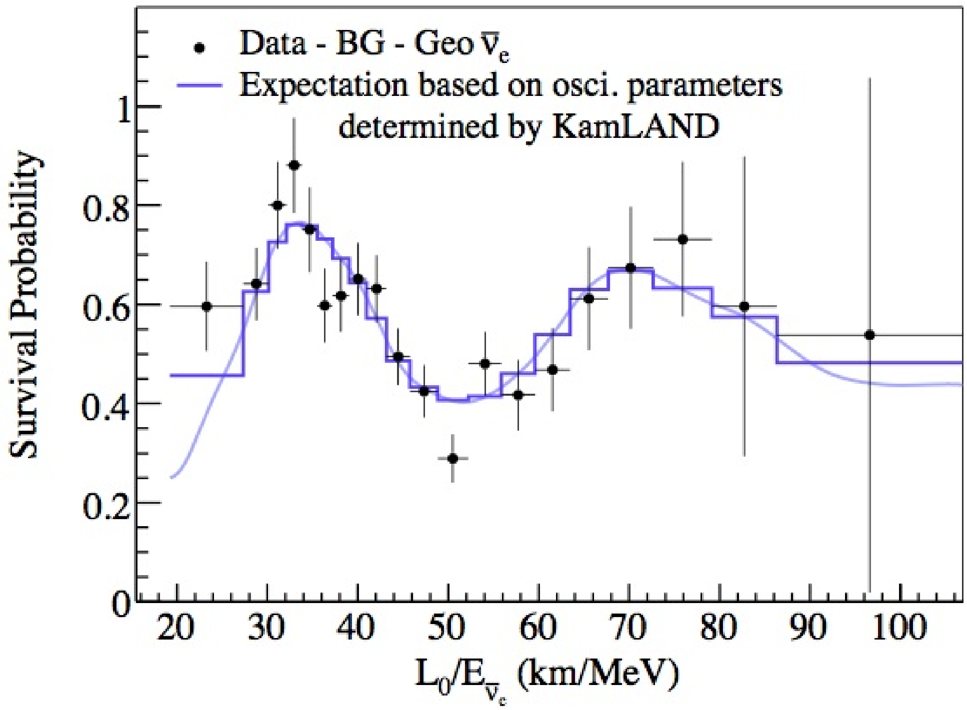

FIGURE 2. Neutrino Oscillation: Comparison of experimental data in Japan against that expected by theory. L is distance traveled in km. [4]

Aug 21, 2008: Measurement of the solar 8-B neutrino flux with 246 live days of Borexino and observation of the 'MSW' [1] vacuum-matter transition.
Mar 01, 2010: Observation of Geo-Neutrinos (from deep inside the earth). Borexino pseudocumene (trimethylbenzene) scintillator which has a much higher light output than mineral oil based liquid scintillators.
2008-2012: finally verified 'sun-like' fusion of proton+proton + electron 'pep' reactions with 1.44 MeV ν's at Borexino − in agreement with theory.

Since 1990, solar neutrino physics has evolved into a precision science. Data from the many neutrino experiments over the past decade is being assembled into a special 3x3 matrix checkerboard of key values. This is bit of a stretch to understand. Some of the neutrino oscillation data is in the form of mixing angles between the various types of neutrinos. We also need to know the tiny masses associated with the various neutrinos − but it is hard to get these directly. Neutrino conversion experiments are revealing Δm^2 differences not between e, mu, tau neutrinos themselves (called the three electroweak eigenstates) but

[1]Mikheyev-Smirnov, Wolfenstein 1978 matter electrons effect

rather their 'massive base states' labeled 1, 2, and 3 (called the mass-eigenstates). That is, neutrinos and antineutrinos are produced as ν_e, ν_μ, ν_τ together with the named charged leptons $\ell = e$, μ, τ. However, neutrinos of definite masses are something more primitive: ν_1, ν_2, ν_3. Similar to the 'CKM' matrix for quarks, these are connected by the 3x3 unitary transformation matrix and called the "PMNS" matrix (standing for Pontecorvo-Maki-Nakawaga-Sakata). One difference between this and the older CKM (Cabibbo, Kobayashi, Maskawa) quark matrix is that non-diagonal values are large (that is, wider mixings are more common). Like the neutrino case, the CKM quark matrix describes 'a Unitary rotation between the flavor eigenstates and the mass eigenstates.' PMNS shows the ability to mix generations or flavors. Again, its key working parameters are differences in mass-squared, 'mixing' angles, and also Dirac 'CP phase angle,' δ. The PMNS matrix form (there are others) just uses sines and cosines of mixing angles θ's and δ. For solar neutrinos involving loss of electron neutrinos, the 1 vs 2 difference is measured. For atmospheric muon neutrinos, the 2 vs 3 difference is measured. (For a little more detail, see Appendix at end).

3. Quark Gluon Plasma:

During the first few microseconds of the universe, the temperature was near 4 trillion degrees Celsius, and quarks and gluons existed as a plasma prior to forming protons and neutrons. The Brookhaven Relativistic Heavy Ion Collider, "RHIC," discovered in April 2005 that the quark-gluon plasma (QGP) behaved as an unexpectedly perfect liquid without friction or viscosity. High energy gold (Au) nuclei colliding on gold nuclei produce what is sometimes called the 'little big bang. Strange results continued to occur through 2010, and then the LHC did its own lead-on-lead Pb nuclei collisions in 2011 at twice the temperature (2.76 TeV per nucleon pair). This high temperature is still not yet hot enough to decompose the most tightly bound Upsilon particle (bottom, anti-bottom quarks) but does break apart their less tightly bound states. The J/ψ particle does break up (charm, anti-charm meson). Also the resulting back-to-back jet sprays are reduced on sides of the plasma with greater density $-$ their energy is sapped by the plasma (this is called 'Jet Quenching). On the other hand, photons and Z bosons get through easily because they are not strongly interacting particles.

On 3/10, the "STAR" detector at Brookhaven found the 'antihypertriton' (antiparticle nuclei of $p + n + \Lambda$ [quark structure 'sud']) with a lifetime of 2×10^{-10} seconds. They had previously seen anti-deuterium, anti-tritium, and anti-He-3. Strange quarks, s, are not rare in the quark-gluon plasma. Another observation is that the "fields created by gluons can twist, forming vortex-like structures in the all pervasive vacuum of space and when quarks loop through these vortices, they gain energy making them heavier." Off-center collision produce powerful magnetic fields causing charge separations with + charges moving in one direction and negative charges moving in another direction. The gluon created vortices are called "instantons." Recently, physicists in the RHIC/STAR collaboration observed that copper-copper collisions produce about 25% more strange quarks per nucleon than do gold-gold collisions [19]. Every new test is a learning experience.

4. Matter-AntiMatter Asymmetry (CP Violation):

A long-term interest for particle physicists has been why our universe is mainly made up of matter with very little antimatter. Three important operators in high energy physics are called 'C' for reversing the sign of charge, P for reversing parity, and T for time reversal. Parity refers to mirror image symmetry between left-ness and right-ness: should basic physics be the same in its mirror image? It turned out that the answer was, definitely "No!" Parity conservation was experimentally shown to be overthrown by weak interactions such as beta decay (Madame Wu, 1956) . In Feynman's view, an antiparticle is a particle moving backwards in time; and generally, basic physics looks the same under time reversal, T. It is still believed that the product of CPT operators is never violated (although tests are still ongoing to verify it). CP (charge parity) violation was first seen in 1964 in K-meson (kaon) measurements (resulting in a Nobel prize for Cronin and Fitch in 1980). That in turn implies that T must also be violated meaning that the rate for a particle interaction is different for the time-reversed process (matter antimatter asymmetry).

After the discovery of the bottom quark, it was anticipated that CP violation would be much stronger in b-meson decays. Much data has now been gathered on B-factory tests with bottom-quark containing mesons like the B's. And indeed, measurement of large CP violation in the B^o system was first observed in 2001 (at BABAR and Belle). Fermilab detectors in 2006 verified a mixing oscillation over time between B_s^o, $\bar{B}_s^o$ after long efforts (i.e., $s\bar{b}$, $b\bar{s}$ particle and antiparticle). CP violation in the decays of neutral 'charmed D-mesons' was seen by CERN in 2011 (the 'LHCb' experiment). LHCb made the first 5σ statistics observation of a CP asymmetry at the LHC in the mode $B_o \to K\pi$. The decays of bottom-mesons is a very lively arena awaiting a great many more publications.
The 'Belle collaboration' of Japan ended in June 2010 after gathering short of a billion Upsilons ($b\bar{b}$, 4S) from electron-positron collisions. They studied bottom quark decays into charmonium (b $\to c\bar{c}s, : c\bar{c}d$, e.g., $B_o \to J +$ kaons or D+D-s [6]). Flavor changing neutral current radiative decays can also occur (b $\to s\gamma$). CP asymmetry is about 0.6%. The B $\to$ Charmonium K_o decays mediated by $b \to c\bar{c}s$ are experimentally clean and are called the 'golden modes' for seeing CP violation. The explanation for CP violation in the standard model is contained in a complex phase-angle in the CKM matrix describing quark mixing. But it probably comes from weak interactions rather than from QCD. The stronger cosmological matter-antimatter asymmetry probably depends mainly on some new physics beyond the Standard Model.

5. General:

The **strong force coupling constant** α_s is a major parameter of the standard model (SM). It has been generally claimed that its value is near unity for energies below a GeV.

However, we know that α_s is actually not constant but rather decreases in value with energy (or momentum transfer, p_T). The decay in the curve is predicted by the "renormalization group equation" (and negative 'beta function'). The mass of the neutral Z-boson, $M_Z \simeq 91$ GeV, is a convenient reference energy to use for current particle physics, and at this energy $\alpha_s(M_Z) \simeq 0.116 < 1$ [13]. An up-to-date plot of the values of the strong coupling is shown in Figure 2. Why is this strength decay important? Recall that with high energies approaching the 'GUT' (Grand Unified Theory) scale, the strong, weak, and electromagnetic coupling constants are supposed to be comparable. We know that the electromagnetic coupling constant, α_{EM}, is weaker than the strong coupling but also increases in value when viewed at increasing energy (getting inside the electron-positron cloud surrounding an electron). Here the strong coupling gets weaker − making it easier to imagine that they might converge. The predicted convergence is supposed to be assisted by supersymmetry. However, there is some recent debate about being able to continue this sort of graph above the top quark mass ($M_t \simeq 173$ GeV). In addition, surprisingly, it might be the case that the curve declines again below about 200 MeV or so (low energy where peak $\alpha_s > 1.0$). This was recently modeled by Lattice-QCD [15]. Ongoing debate: − does computer modeling count as an experiment?
Some discussion of the Weak Force Coupling Constant is given in the Appendix at end.

The FermiLab Tevatron collider in Illinois began operation in 1985 but was permanently shut down on 9/30/2011. There will be no more TeV colliding proton beams in America. However, 'Fermilab' itself as an overall laboratory will continue to operate and will be doing important neutrino physics experiments (if adequate funding continues to be available).
Older high-energy collision data from Fermilab is still being analyzed. The CDF and D0 collaborations at the Tevatron experimentally discovered the top quark, t, in 1995. This is the most massive elementary particle known today (near 173 GeV) and couples very strongly with the Higgs boson, H. Because the Tevatron was a proton-antiproton collider, the $t\bar{t}$ resonances occur mainly by quark-antiquark annihiliation (center of mass energy near 2 TeV). The higher energy LHC is a pp collider so far near $\sqrt{s} = 7 - 8$ TeV center-of-mass energy giving it 22 times higher probability of $t\bar{t}$ production instead formed 85% by 'gluon fusion' $gg \to t\bar{t}$ [12]. In the standard mode, t decays nearly 100% of the time into a W and a b-quark. Gluon fusion is also believed to be a major way of producing the Higgs boson, $gg \to H$.

The LHC high energy 7 TeV inelastic pp 'cross section' implies a size of 0.86 fm (square, i.e., 73 mb [where 'b' = 'barn' = $10^{-24} cm^2$]) [2]. Total cross section rises with energy. Note that nuclear density is $n \sim 0.16\, fm^{-3}$ (or a square 1.84 fm − but proton diameter is 1.56 fm − intuitively not much wiggle room for motion of protons and neutrons − yet they do move fairly freely).

[2] "Big as a barn" for nuclear reactions. Integrated Luminosity is measured in inverse-femto-barns, fb^{-1} hinting at how many collisions occurred for a data base.

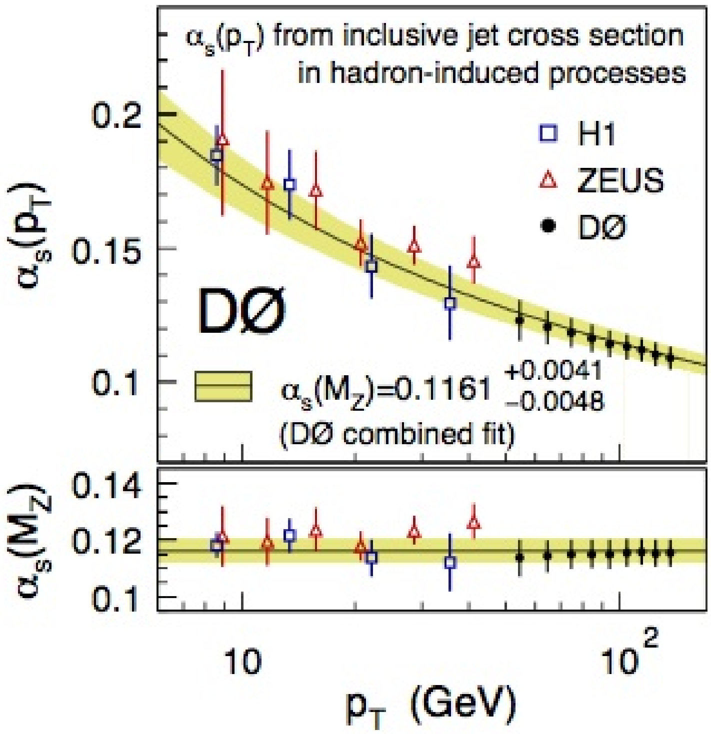

FIGURE 3. Experimental results for the declining coupling 'constant' α_s of the strong force versus energy. Earlier plots show $\alpha_s \simeq 0.4$ near 1 GeV to the far left.

ATLAS (LHC, Oct-2011) has measured the probability of forming t-tbar (top +anti-top) but has not yet been able to distinguish single top quark production. Forward/Backwards motion asymmetry is not yet explained in CMS studies.

The status of "Weak Charge, Q_w:" Most fermions have a special non-electric charge that can contribute to the formation of weak bosons. This is measured by a parameter which is set approximately to minus one for the neutron, the source of natural beta decay, $Q_w(n) \simeq -1$. Although the B boson couples to fermions according to 'weak hypercharge' Y (where $Q = T_3 + Y/2$, and T_3 is 'weak-isospin'), the W and Z interact with anything that has non-zero Q_w. The weak vector bosons also carry weak charge and interact among themselves. Weak charge has chirality or 'handedness' that can lead to parity violation.

A useful formula for weak charge for nuclei is $Q_w(Z,N) \simeq Z(1 - 4\sin^2\theta_w) - N$, where theta is the Weinberg angle so that $x = \sin^2\theta_w \simeq 0.238$. [3] This is not actually a constant but varies somewhat with energy and with Z bosons versus W's. For Z's, it drops to near 0.23 near the mass of the bosons (the Z-pole). For the proton, $Q_w(p) = Q_w(1,0) \simeq 1(1 - 4(0.238)) = 0.048$. Since the square of the Weinberg angle is nearly one-fourth, the weak charge plays almost no role for protons. For the neutron however, $Q_w(n) = Q_w(0,1) \sim 0 - 1 = -1$, which has a large effect. These values have actually not yet been directly experimentally measured (the proton measurement is in progress). The 'Qweak' experiment at Jefferson Lab will measure the cross-sections for positive and negative helicity electrons in polarized elastic e-p scattering. There will be an asymmetry due to interference of photon and Z boson exchange. But large nuclei for cesium, thorium, bismuth, and lead have already been studied, and mesurements agree with SM and the formula and help pin down the Weinberg angle for those cases.

The most important measurement so far is the SLAC experiment 'E158' from 2003 in California. This is a measure of parity violation in Møller e-e scattering near 50 GeV using longitudinally polarized electrons scattering from unpolarized electrons in a 1.5 meter long liquid hydrogen target. The result is a left-right handed asymmetry near 0.14 ppm − small but definitely there and proportional to the weak charge. The weak charge for the electron now measured to be $Q_w(e) \simeq -0.04$. All of the quarks have weak charge with d being larger and positive while u is smaller and negative.

6. What Has Not Yet Happened (as of 2012):

Glueballs have not yet been found. The strong interaction mediated by gluons is 'non-abelian' meaning that gluons interact with other gluons. They should be able to get together to form a particle consisting of just glue, and there should be many mass states of these particles. "Nothing is more symbolic of the difficulty of solving QCD than the fact that, while glueballs are central to the understanding of non-perturbative QCD, there is currently no definite experimental evidence for their existence" [23]. This is largely a difficult signal-to-noise problem for experimenters.

A fourth neutrino has not yet been found [e.g., ν_s using ν_4 and m^2_{41}]. So, the mechanism of giving small masses to the neutrinos is still unknown (although there are a variety of possible 'seasaw' mechanisms − often mentioning right-handed neutrinos [all 'normal' neutrinos are left-handed]). There is also talk of a possible fourth generation of quarks, t' and b'. "The exploration of Terascale physics has only just started!"

QCD-Confinement: There is still no proof of confinement for quantum chromodynamics in the continuum limit (single quarks cannot escape from baryons) [15]. This problem is so difficult and so interesting that confinement is a Millennium Prize Problem from the Clay Mathematics Institute. How is it that massless Yang-Mills gluons enable ultimately

[3] Here, 'Z' is total proton count, and N is neutron number in a given nucleus.

massive bound states of gluons – the "mass gap. 'Establish rigorously the existence of the quantum Yang-Mills theory and a mass gap.' [Note that the short list of Millennium problems include the Poincaré Conjecture which was recently solved by Grigori Perelman].

SUSY: Repeated phrase from LHC publications: "No evidence is found for physics beyond the Standard Model." Supersymmetry is called SUSY, and its minimal supersymmetric extension onto the standard model is called 'MSSM.' Neither SUSY nor MSSM has yet been found where it was supposed to be at the LHC – it was NOT just around the corner as some had previously claimed. One more recent example is an LHC CERN ATLAS summary of supersymmetry (SUSY) data which said, No excess above the Standard Model expectations is observed.. [8] Exploration will have to continue now at higher energy.

nucleon spin: There is still a "spin crisis" that only about 30% of nucleon spin is carried by quark spins [missing spin: ArXiv 1111.2562]. A lot of experimental and theoretical efforts for the last 20 years were devoted to search for the rest of the nucleon spin, without obvious success. "It is quite possible that much of the remaining nucleon spin will be found in the orbital motion of the valence quarks" [Jefferson Lab].

Cosmic Rays: "The mystery of the origin of cosmic rays is celebrating its 100th, anniversary in 2012"[14]. Charged cosmic rays should point toward their origin when their energy is $> 10^{20}\, eV -$ multiple EeV! (the highest energy so far detected). Energies beyond 10 PeV (peta $= P = 10^{15}$) are rare and are largely believed to originate within our galaxy from shock acceleration in supernova remnants. A variety of modern and special instruments is needed to cover over 8 orders of magnitude in energy and 24 in cosmic ray flux.

Dark Energy and Dark Matter have not yet been identified – and our WIMP experiments are not close to being able to pin down the nature of dark matter particles – if they indeed exist. And neither particle physics or astro-physics can succeed on its own – this is a joint venture.

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7. Appendix:

More on the Neutrino Matrix:

Some neutrino oscillation parameters are beginning to be pinned down [4] [21]. A current list of known values is:

$$\begin{array}{ll}
\Delta m^2_{12} \simeq 7.6 \times 10^{-5}\, eV^2, & \theta_{12} = \theta_{Solar} \simeq 34.0^o \pm 1.1^o(1\sigma)\ . \\
|\Delta m^2_{23}| \simeq 2.4 \times 10^{-3}\, eV^2 & \theta_{23} = \theta_{Atmospheric} \simeq 46.1 \pm 3.4^o(1\sigma). \\
\Delta m^2_{13} \simeq 2 \times 10^{-3} eV^2 & \theta_{13} = 8.8 \pm 1.0^o(1\sigma) \quad > 0!\ .
\end{array}$$

$\Delta m^2_{32} \simeq \Delta m^2_{31}$, and $|\Delta m^2_{31} - \Delta m^2_{32}| = |\Delta m^2_{21}|$. Presently, the sign of Δm^2_{atm} is unknown. A current puzzle is that we do not yet know the masses of the base states (eigenstates): ν_1, ν_2, ν_3 [8]. We know that $m_2 > m_1$ but don't know if m_3 is larger than these or smaller (heirarchy problem). It is expected that eventually double-beta decay experiments may provide the answer − in case neutrinos are 'Majorana' particles (their own antiparticle). Equally promising are long-baseline neutrino accelerator experiments, provided $\sin 2\theta_{13} \sim 0.001$. Also a 100 Megaton detector for neutrinos may give the answer if $\sin^2 2\theta_{13} > 0$. The optimal test length for θ_{13} is L = 0.5 km E/MeV; so do 1-2 km short range testing. The 'Chooz' reactor in France used 1 km, and 'Double Chooz' is next.

As a simple example of a 2x2 subset of 3x3 matrix, consider the case of two neutrino avours ν_μ, ν_τ and two mass eigenstates ν_2, ν_3. One has a superposition of states:
$\nu_\mu = \nu_2 \cos\theta_{23} + \nu_3 \sin\theta_{23}$; $\nu_\tau = -\nu_2 \sin\theta_{23} + \nu_3 \cos\theta_{23}$.

If the masses m_2 and m_3 are dfferent, quantum mechanical time evolution of an initial ν_μ state induces a non-zero transition probability to ν_τ. The survival probability for the muon neutrino is:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2[1.27\Delta m^2_{23}\, L[GeV]/E_\nu[eV^2\, km]]. \tag{1}$$

where L (in km) is the distance travelled by the neutrino, E_ν (in GeV) its energy, and $\Delta m^2_{32} = m^2_3 - m^2_2$ (in eV^2). Notice that the division by energy means that the oscillation is fast and wild at low energy, but most testing is done in the GeV's range.

The present estimation of the PMNS Unitary matrix is: [11]

$$|U| = \begin{vmatrix} 0.8-0.9 & 0.5-0.6 & 0.0-0.2 \\ 0.3-0.6 & 0.3-0.7 & 0.6-0.8 \\ 0.1-0.5 & 0.5-0.8 & 0.6-0.8 \end{vmatrix} \tag{2}$$

If there are neutrinos lying beyond the basic three, then their masses are constrained by cosmological requirements to sum to less than a total of 0.6 eV.

<u>The Weak Coupling Constant:</u>
The coupling constant for the weak force is often presented as the historically old 1932 Fermi Coupling, G_F which has the tiny value $G_F/(\hbar c)^3 = 1.166\times10^{-5} GeV^{-2}$ [16]. In 2010, this value was measured to better than a part-per-million accuracy based on the mean life of positive muons $\tau \simeq 2.197\mu s$ [18]. When people say that the weak force is about a million times weaker than the strong force, they are referring to this Fermi constant. But another more currently relevant form is $\alpha_w = {g_w}^2/4\pi \simeq 1/30$. The g-coupling is attached to each vertex of the Weak exchange Feynman diagram; and $g_w \simeq 0.65$ is related to the mass of the charged W vector boson, $m_w \simeq 80.4$ GeV (the mass itself is contained in what is called the propagator).

$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}\, g^2}{8{m_w}^2} \tag{3}$$

Since the electromagnetic coupling $\alpha_{EM} \simeq 1/137$, we note that α_w is in fact nearly four times stronger than EM! The weakness of the weak interaction is due to its having a low probability of occurrence which in turn is due to the large mass of the relevant W boson. And, at high energies where momentum transfer is near the W mass, then the weak interaction is comparable in strength to the electromagnetic interaction [17].