Four Statements about the Fourth Generation

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Summary of the "Beyond the 3-generation SM in the LHC era" Workshop, CERN, September 4-5, 2008

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Abstract

This summary of the Workshop "Beyond the 3-generation SM in the LHC era" presents a brief discussion of the following four statements about the fourth generation: 1) It is not excluded by EW precision data; 2) It addresses some of the currently open questions; 3) It can accommodate emerging possible hints of new physics; 4) LHC has the potential to discover or fully exclude it.

Introduction

It is now generally accepted that the Standard Model (SM) consists of three fermion families, or generations. However the number of generations is not fixed by the theory. The asymptotic freedom constraint from QCD only limits the number of generations to be less than 9. Neutrino counting at the Z pole shows that the number of generations with light neutrinos ($m_\nu \ll m_Z/2$) is equal to 3, but neutrino oscillations suggest a new mass scale that is beyond the SM, and the possibility of additional heavier neutrinos cannot be excluded. In the era of the LHC, the possibility of the SM with a fourth generation (SM4) should therefore not be forgotten.

By SM4, we mean a sequential repetition of the existing generation pattern to 4 quark and 4 lepton left-handed doublets and corresponding right handed singlets. We use the commonly known primed notation, i.e. t' and b' for fourth generation quarks, and τ' and ν'_τ for the heavy charged and neutral leptons. The current 95% CL mass limits from the PDG are [1],

$$m_{t'} > 256\,\mathrm{GeV}; \qquad m_{b'} > 128\,\mathrm{GeV}\ (\text{CC decay; 199 GeV for 100\% NC decay}); \tag{1}$$

$$m_{\tau'} > 100.8\,\mathrm{GeV}; \qquad m_{\nu'_\tau} > 90.3\,\mathrm{GeV}\ (\text{Dirac coupling; 80.5 GeV for Majorana coupling}) \tag{2}$$

The following text is a summary of the thematic Workshop "*Beyond the 3-generation SM in the LHC era*", on the physics of the SM with $N > 3$ fermion generations, held at CERN on 4-5 September [2]. Besides reviewing the theory, as well as flavour factory, collider and astroparticle/cosmology aspects, the aim was to stimulate discussions by bringing together theorists and experimentalists working on, or interested in, the subject. The imminent LHC start up placed an emphasis on collider and flavour physics, especially on the preparation for LHC data exploitation.

Statement 1: The fourth generation is not excluded by EW precision data.

EW precision data

The "oblique parameters" S, T and U provide stringent constraints on SM4 [3]. The PDG states that "An extra generation of ordinary fermions is excluded at the 6σ level on the basis of the S parameter alone" [1]. The caution that is often not noted or remembered is that "This result assumes that ... any new families are degenerate", while "the restriction can be relaxed by allowing T to vary as well". [1] The contribution of the 4th generation fermions (much heavier than the Z boson) to S is

$$\delta S = \frac{2}{3\pi} - \frac{1}{3\pi}\left[\log\frac{m_{t'}}{m_{b'}} - \log\frac{m_{\nu'_\tau}}{m_{\tau'}}\right], \tag{3}$$

[1] The issue has also been reopened by a recent study [4].

where the leading term causes trouble with EW precision data for degenerate fermion masses. However, if $m_{t'} > m_{b'}$ and/or $m_{\nu'_\tau} < m_{\tau'}$ then the S parameter constraint can be softened. In fact this points towards a heavier Higgs. As the Higgs mass is raised, a positive contribution to T is required from some other source. Mass splitting between heavy fermion doublets provides such a source and this, from (3), helps to alleviate the problem with S.[2]

When the mass of the heavy neutral lepton ν'_τ is close to $m_Z/2$, threshold effects to the Z boson self energy need to be incorporated. In such an analysis, it is found that the quality of fit for one extra generation can be the same as the 3 generation case for certain mass values, while the upper bound on Higgs mass from the SM fit is largely removed [6].

The above discussion assumes that ν'_τ has a Dirac mass. But ν'_τ could instead have a Majorana mass along with the three much lighter neutrinos (and then all four right-handed neutrinos could have masses well above the electroweak scale). A dynamical Majorana mass for $\nu'_{\tau L}$ produces an additional finite and negative contribution to T [7]. Thus further splitting in the heavy fermion doublets is needed to produce a compensating positive contribution to T. This then has the same effect as increasing the Higgs mass in alleviating the problem with S.

CKM unitarity

Current measurement errors of the CKM quark mixing (and similarly PMNS for lepton sector) matrix elements leave ample room for the possible extension from 3×3 to 4×4. For example, the most precisely measured first row gives $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.9999\pm0.0011$ [1]. If this is equated to $1-|V_{ub'}|^2$, one finds (one-sided 95% CL),

$$|V_{ub'}| \quad < \quad 0.04. \tag{4}$$

Note that the bound is much larger than $|V_{ub}| \sim 0.004$ (the value of which did not matter in the above analysis). For the second row, $|V_{cs}|$ is far from well measured. Improvement is made by using W boson leptonic branching ratio (where 3 generation lepton unitarity is typically assumed, which is another cautionary note), giving $|V_{cd}|^2+|V_{cs}|^2+|V_{cb}|^2 = 1.002\pm0.027$. The large errors again tolerate a $|V_{cb'}|$ value considerably larger than $|V_{cb}| \simeq 0.04$. A more rigorous analysis could be performed by studying the τ and W decays, which would yield the correlation between CKM and PMNS matrices [8]. Additionally, an increase of available data would improve the constraints.

Statement 2: SM4 addresses some of the currently open questions.

New CPV source for BAU problem

The B factories have confirmed the source of CP violation (CPV) in the 3 generation KM model. However, it is commonly said that the KM model (hence SM) falls short from what is needed to satisfy the Sakharov conditions for generating the baryon asymmetry of the Universe (BAU), by more than 10 orders of magnitude. This can be seen from the Jarlskog rephasing invariant measure of CPV [9],

$$J \quad = \quad (m_t^2-m_u^2)(m_t^2-m_c^2)(m_c^2-m_u^2)(m_b^2-m_d^2)(m_b^2-m_s^2)(m_s^2-m_d^2)A,$$

where A is twice the area of any triangle formed from the 3×3 SM unitarity condition $V^\dagger V = I$. The CPV triangle area $A \simeq 3\times10^{-5}$ is small, but the stronger suppression factors are the small masses, or Yukawa couplings, of SM quarks other than the top, as compared to the v.e.v. scale.

From the last point, however, it was recently pointed out [10] that, in SM4, most of the mass suppressions can be bypassed in the (generalized) Jarlskog invariant, while bringing in a larger CPV "triangle" area that could impact on $b\to s$ transitions (see below). The cumulative gain is of order 10^{13} to 10^{15}.

While this is not a proof, and issues such as the order of the phase transition remain, it is exciting to note that the KM structure with 4 generations may provide enough CPV for the matter-dominated Universe.

New perspectives on the Higgs naturalness problem

The heavy quark loops will contribute new terms in the running of the quartic coupling that are proportional to powers of the new Yukawa couplings, namely $\mu d\lambda/d\mu \propto \lambda\, y_{q'}^2 - y_{q'}^4 + \dots$. The result is to produce a smaller allowed range for the Higgs mass (increasing lower limit and decreasing upper limit) if one wants the quartic coupling to remain finite and positive at 1 TeV. This allowed range decreases quite quickly as the fourth generation masses are increased. Even more dramatic is the large contribution to the Higgs mass from the heavy fermion loops, $\delta m_h^2 \approx \left[m_{q'}/400\text{ GeV}\right]^2\Lambda^2$. Here Λ represents the scale of new physics needed to cut off these loops, which is at least as large as $m_{q'}$. Finally, there are the large Yukawa couplings themselves that run quickly and lead to Landau poles not far above a TeV. While supersymmetry

[2] After completion of this document, a paper by M. S. Chanowitz [5] appeared, taking CKM mixing into account in electroweak precision constraints. It was found there that a mixing between 3^{rd} and 4^{th} generations of the size of the Cabibbo mixing is allowed.

could be invoked to control the heavy fermion loop effects, the running of the Yukawa couplings is not so easy to control. Given these considerations, we see that the discovery of a 4th generation would impact directly on the likelihood of the simplest realization of electroweak symmetry breaking, namely the Higgs boson. This is especially true if the 4th generation quarks have masses as high as ~ 600 GeV, the so-called unitarity bound. The Goldstone bosons of electroweak symmetry breaking would then couple so strongly to these quarks that the concept of an elementary scalar field is no longer appropriate.

Instead, one would conclude that some strong interaction is responsible for electroweak symmetry breaking via a condensation of the fourth generation fermions. What this dynamics is and how it links to the light fermions remains to be determined. For instance, dynamically broken gauge interactions could not only be responsible for the condensation, but could also connect different generations and feed mass from heavy to light fermions [11]. In this case the new flavour physics should range from a TeV up to about 1000 TeV, and the new physics has large (small) impact on heavy (light) fermions. Sufficiently light masses for three neutrinos can follow if right handed neutrinos masses are ~ 1000 TeV. A light remnant of these new flavour interactions, the X boson, should also couple to the third generation, and can be searched for at the LHC via, e.g. $b\bar{b} \to X \to \tau^+\tau^-$ [12].

Alternatively, in a model with fermions propagating in a five-dimensional AdS space, it is possible to break the electroweak symmetry via the condensation of the fourth generation, driven by their interactions with the Kaluza-Klein gauge bosons and by the presence of bulk higher-dimensional operators [13]. This dynamical mechanism results in a heavy composite Higgs which is highly localized towards the infrared boundary (brane). The localization of the fermions in the 5D bulk gives rise to the Yukawa couplings. This picture is complementary, and may provide insight to, the 4D view of strong interactions.

New perspectives into the fermion mass hierarchy problem

In the Standard Model, the Yukawa couplings spread over an unnaturally wide range of values, exhibiting a similar hierarchy for different type of fermion charges. It may be more natural to assume that all the fermion-Higgs couplings are of the same order, yielding a single non-zero eigenvalue, M_{44}, of the fermionic mass matrix M. This idea is known as the flavour democracy or Democratic Mass Matrix (DMM) approach [14]. In such a scenario, the observed masses of fermions in the first three generations arise from perturbations to M. The mass differences among the third generation charged fermions do not allow such a parameterization for a 3×3 mass matrix. Therefore, flavour democracy requires a 4th SM generation [15]. This would also favor smaller masses for the known neutrinos [16].

New inroads into the Dark Matter problem

In a number of models, like the Pati-Salam model or in simpler phenomenological approaches, there are additional fermions such as mirror fermions, singlets and sterile neutrinos, even stable quarks [17]. The new fermions could provide answers to a number of astrophysics problems such as Dark Matter (DM), pulsar kicks etc. There are group theoretical arguments based on spin-charge unification or spin-generation considerations that predict the number of SM like generations as 8, with the additional fermions as DM candidates [18]. These additional fermions could either decouple completely from their SM counterparts and serve as cold DM, or they may be stable particles that form bound neutral atomic states and serve as composite DM.

For example, some heavy charge $+2/3$ quarks, denoted as U to emphasize their stability, could remain in the early Universe after BBN. Such quarks could form $\overline{UUU}$ hadrons, which could bind with primordial helium into atom-like "O-helium" states. In this scenario, O-helium atoms decouple from plasma and radiation before recombination, and play the role of warm DM [19]. Although the interaction of O-helium with terrestrial matter would slow it down to below the underground DM direct search threshold, it can be searched for in ground-based experiments and in space. Annual modulations of ionization signal from $\overline{UUU}$ captured by $^{53}I_{127}$ and $^{82}Tl_{205}$ can explain the results of DAMA/NaI and DAMA/Libra experiments [20], while positrons from de-excitation of O-helium, excited in its mutual collisions in the galactic bulge, could explain the excessive positron annihilation line observed by the Integral experiment.

Searches for new fermions at the upcoming accelerators could check the validity of these models, hence probe DM.

Statement 3: SM4 can accommodate emerging possible hints of new physics.

Tevatron direct search

Fourth generation quarks continue to be searched for at the Tevatron by the CDF and D∅ collaborations, as they continue to collect data. CDF has searched for t' in the charged current decay $t' \to qW$, i.e. without invoking b-tagging [21]. The $p\bar{p} \to qqWW$ event gives rise to the signature of $\ell+$ jets $+$ MET (missing transverse mass). The observed slight excess of events at high m_{reco} (jargon for “reconstructed” mass) values could hint at a new quark heavier than the top, although such an interpretation would require a production cross section larger than expected from purely SM couplings of the t'. Both experiments have also searched for new quarks in the neutral current decay channels [22]. The searches yielded null results consistent with the non-existence of the FCNCs in the SM.

One should note that the experimental searches usually assume 100% branching fraction of the mode under study, and tacitly that the heavy quark is unstable. The exclusion is clearly softened when the branching fraction or lifetime is affected by mixing angles, and e.g. the b' and t' mass difference. In principle, one heavy quark could even become stable in certain special cases, such as a mixing angle of the order of 10^{-8}. Such small angles could be motivated by a broken discrete symmetry between generations that only gets restored at the Planck scale. When quoting the experimental results, the assumptions made have to be kept in mind [23].

CPV in $B_s \to J/\psi\phi$ at Tevatron

A potentially exciting development emerged at the Tevatron during 2008: there is now a hint for mixing-dependent CPV in $B_s \to J/\psi\phi$ [24]. CDF and D∅ have altogether conducted three measurements so far, all of which indicate that $\sin 2\Phi_{B_s} = -\sin 2\beta_s$ is large and negative, with central value around -0.6 and a significance of roughly 2.8σ. The SM expectation is -0.04. If the central value stays, it seems that the Tevatron could establish the effect with the 2010 dataset.

In SM4, with strong $m_{t'}$ dependence (called nondecoupling) in the box diagram just like the top, and with the new CKM product $V_{t's}^* V_{t'b}$ bringing in a new CPV phase, the 4th generation offers the simplest explanation for large deviations of $\sin 2\Phi_{B_s}$ from the SM prediction. In fact, two predictions [25, 26] were made beforehand for $\sin 2\Phi_{B_s} < 0$. The stronger prediction [26] of -0.5 to -0.7 was put forth with the CDF observation of B_s mixing in 2006. The argument was that, because typical $f_{B_s}\sqrt{B_{B_s}}$ values give rise to Δm_{B_s} values that are larger than observed, together with the nondecoupling effect of the t' quark, large and negative $\sin 2\Phi_{B_s}$ would generally follow.

Hints from B-factories

The difference in direct CPV (DCPV) measured [27] in $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$ decays by the B-factories, is now established beyond 5σ level. It is larger than the -10% found in the latter mode. Since the two processes differ only in the "spectator" quark, this dramatic difference was not anticipated. "In the mind of many [28, 29, 30], however, a large enhancement of the color-suppressed amplitude could reduce the usefulness of this mode as a probe of New Physics".

It was pointed out [25, 31], nevertheless, that if the electroweak or Z penguin is any fraction of a culprit, then New Physics is necessary in the bsZ penguin loop (the Z can produce a π^0 but not the π^-). From the insight that the top quark is nondecoupled in this loop, just like in the B_s mixing box diagram, introducing the t' quark brings in new CPV phase via $V_{t's}^* V_{t'b}$. The link to B_s mixing led to the first prediction, in 2005, that $\sin 2\Phi_{B_s} = -\sin 2\beta_s$ would be large and negative, a prediction that is in better agreement with recent CDF and D∅ measurements discussed earlier, compared to 3-generation SM expectations.

Statement 4: LHC has the potential to discover or fully exclude SM4.

ATLAS and CMS discovery prospects

Since the heavy quark pair production cross section at the LHC is rather large, the ATLAS and CMS experiments have the potential to discover the 4th generation quarks if they exist. Since partial wave unitarity gives an upper bound of about 1 TeV to the 4th generation fermion masses [32], a non-discovery could also mean full exclusion of the SM4 model, assuming usual decays and mixings [23].

The prominent decay channels depend on the 4×4 CKM matrix, as well as the b' and t' mass difference. The case with dominant mixing between the 3rd and 4th generations has been investigated in the ATLAS TDR, and more recently by the CMS experiment. The decay channels studied are $t' \to bW$ and $b' \to tW^- \to bW^+W^-$. With 100 fb^{-1} data, ATLAS claimed 61 (13.5) σ discovery by reconstructing the hadronic decay of the t' quark pairs of mass of 320 (640) GeV [33]. The study found the fully hadronic mode of t' and the reconstruction of b' to be rather difficult. A recent study by CMS aimed for early physics, searching for same sign dilepton or trilepton signals from $b'\bar{b}' \to b\bar{b}W^+W^-W^+W^-$. Using the HT variable (HT$\equiv \sum p_T^i$) and incorporating systematical errors, the study found 7.5 (2.0) σ significance for a b' quark of mass 300 (400) GeV, with just 100 pb^{-1} at 14 TeV [34]. The significance would of course weaken for 10 TeV.

If the fourth generation quarks prefer to mix with the first two generation members, the decays $Q \to qW$ where $Q = t'$, b' and q is a light quark (jet), should be considered. Note that the DMM approach implies nearly equal t' and b' masses, which is supported by the precision data. If t' and b' are within 50 GeV of each other, they could be hard to distinguish, and the signal is doubled. Such t' and b' quarks with mass ~ 500 GeV can be discovered at 5σ significance with 400 pb^{-1} data [35].

Similar to the boosted top, for W bosons with $p_T \sim 250$ GeV or higher, one should consider the new tool of reconstructing the W boson invariant mass as a “single jet” [36].

Other LHC searches

The resonant production of t' and b' quarks are studied via the anomalous processes $gq^i \to t'$ and $gq^j \to b'$ (where $q^i = u, c$ and $q^j = d, s, b$) at the LHC. Such processes are rather suppressed in SM, but could be induced by the large mass of the fourth generation quarks. With 10 fb^{-1} of integrated luminosity, the sensitivity to anomalous couplings, namely the minimum value of κ/Λ that can be probed, is 0.01 TeV^{-1} [37].

The aforementioned stable U quark, or other exotic possibilities for stable heavy quarks, could form heavy hadrons. Then the detection prospect could be enhanced or suppressed by their interactions with detector material [38].

Impact on Higgs searches at LHC and Tevatron

The dominant production mechanism of the Higgs boson at hadron colliders, gluon-gluon fusion, probes heavy quarks in a triangular loop. The 4th generation quarks lead to an enhancement of this process. However, to make a full analysis one should also recalculate the Higgs branching ratios. Above the $t'\bar{t}'$ or $b'\bar{b}'$ threshold, the 4th generation final state would dominate over the $t\bar{t}$, WW, ZZ. If below threshold, while the same enhancement persists, it is possible to have a Higgs boson decaying dominantly to “invisible” 4th generation neutral leptons [39]. The branching ratio for the $H \to \gamma\gamma$ channel, however, is in general reduced, since the extra fourth generation quarks in the loop tend to cancel the vector boson contribution.

It is possible to even discover ν'_τ through its coupling to the Z and (heavy) Higgs bosons, namely via $pp \to Z/h \to \nu'_\tau \bar{\nu}'_\tau \to \mu W \mu W$. This analysis has also the potential to reveal the Dirac or Majorana nature of ν'_τ, with the Majorana case more promising with few fb^{-1} luminosity [40].

The LHC experiments can discover the Higgs via the "golden mode" ($gg \to h \to ZZ \to 4\ell$) for most of the mass range with ~ 1 fb^{-1}, because of the enhanced cross section due to SM4 [41]. The measured enhancement would provide indirect evidence about the existence of the fourth generation. This effect also increases the importance of the $gg \to H \to WW \to \ell\nu\ell\nu$ search channel at the Tevatron. The enhancement due to fourth generation quarks is about a factor of 8 for $100 < m_H < 200$ GeV. Although the latest data has not yet been combined, the Higgs boson is excluded at 95% level in the range 130 to 190 GeV by CDF alone if the 4th generation exists [42].

LHCb prospects

With tantalizing hints for deviation from SM in the time-dependent CPV measurement of $B_s \to J/\psi\phi$ at the Tevatron, the LHCb experiment is awaiting data to confirm the effect or reject it. Even if the SM value of $\sin 2\Phi_{B_s} = -\sin 2\beta_s \simeq -0.04$ is correct, LHCb is expected to measure it with just 0.5 fb^{-1} data [43], and in the process, explore the full range of New Physics possibilities. Another approach would be to measure the closure of the unitarity triangle, namely the measurement of γ/ϕ_3 in the SM. Again, LHCb can play here a conclusive role.

There is another slight hint of a deviation from the SM at the B factories, namely the forward-backward asymmetries in $B \to K^*\ell^+\ell^-$ [27, 44, 45]. With the B factories drawing to a close, here again LHCb could make dramatic impact. With about 1 fb^{-1} data, LHCb could measure [46] the SM expectation for $A_{\rm FB}$ in $B_d \to K^*\mu^+\mu^-$ (in particular, check the zero), or confirm that one again has a deviation. Already with $2-3 fb^{-1}$ a full angular analysis of this mode will allow for the measurement of the recently proposed new observables [47] with even higher NP sensitivity.

It should be clear that the indirect path of probing the fourth generation through virtual effects cannot provide all information. Once again, the direct search prowess of the LHC should be highlighted.

Prospects for future colliders

Future linear e^+e^- colliders are especially important for understanding the leptonic sector of the fourth generation, and for making precision measurements [48]. If kinematics allows, fourth generation fermions would be pair-produced. For example, an LC operating at 500 GeV would give very powerful complements for finding the fourth generation leptons, and for investigating the light Higgs case [49]. If sufficiently high $E_{\rm CM}$ cannot be made available, one may have to search for single production, such as $e^+e^- \to \tau'\bar{\tau}$ [50]. But the cross section is not promising, unless one brings in further New Physics such as 2HDM.

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