The Pati-Salam Supersymmetric SM (PSSSM)

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Abstract. Grand Unified Theories based on an $E_6$ gauge group embed all Higgs- and matter fields within one $27$ dimensional fundamental representation. In addition each $27$ contains a right handed neutrino, an NMSSM-like standard model singlet and a pair of exotic particles, that couple quarks to leptons. The extended particle content spoils simple gauge unification as in the MSSM. By embedding the SM into a Pati-Salam gauge group above $10^{16}$ GeV, one obtains a unification below the Planck-scale. We present a Markov chain Monte-Carlo algorithm to systematically scan the high dimensional parameter space and calculate low-energy spectra, as well as first results of our studies of the LHC phenomenology of leptoquarks and leptoquarkinos with the event generator WHIZARD.

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$E_6$ GUT WITH INTERMEDIATE PATI-SALAM SYMMETRY

Grand unified theories (GUT) in the framework of supersymmetry have been investigated for decades. Under the assumption of a minimal supersymmetric extension (MSSM) of the standard model (SM), the SM gauge couplings unify at approximately $10^{16}$ GeV. At higher energies, the known interactions might be described by a single simple gauge group. However, the choice of the unified gauge group is not unique and potentially interferes with the low-energy theory, as shall be illustrated in the following.

Throughout this note, we assume a GUT with the rank 6 exceptional Lie-group $E_6$ as gauge group. Decomposing the $27$ dimensional fundamental representation under its SM subgroup, one observes that the $27$ contains, in addition to one full generation of SM quarks and leptons, a right-handed neutrino as well as a full MSSM Higgs-sector, augmented by a SM singlet $S$ as in the NMSSM. Furthermore there is a pair of exotic particles $D, D^c$ that may couple quarks to leptons and shall be denoted as leptoquarks.$^1$

Without the introduction of a further mechanism to render the exotic particle heavy at the $E_6$-breaking scale, the full particle content remains in the spectrum down to the TeV-scale $^1$.

The extra matter changes the renormalization group equations and hence the running of the couplings: Simple unification of all three SM couplings as in the MSSM is spoiled.

As proposed in $^1$ and furtherly investigated in $^2$, unification to a simple gauge group can be achieved by introducing an intermediate semi-simple gauge group, namely a Pati-Salam symmetry $^3$:

$$SU(4) \times SU(2)_L \times SU(2)_R[\times U(1)_X]$$

$^1$ These particles could also have diquark couplings - only one should be allowed, in order to prevent the proton to decay. In this work, we focus on the leptoquark case.
In this regime there are only two independent couplings left to intersect, as $SU(2)_L$ and $SU(2)_R$ have identical particle content.

A suitable breaking of the intermediate gauge symmetry $\mathfrak{e}_6$ to the SM gauge group is achieved by introducing some Higgs fields $H', \bar{H}'$ that transform as $27, \bar{27}$ under $E_6$ and acquire a Vev in the direction of the right-handed neutrino. This generates Majorana masses for the right-handed neutrinos, arising from the effective operator $(27\bar{7}8\bar{27})^2$ which trigger a see-saw mechanism to account for naturally small neutrino masses. The SM hypercharge group becomes a linear combination of the Cartan generators $T_{15} \propto (B-L)/2$ of $SU(4)$ and $T^3_R: Y = (B-L)/2 + T^3_R$. The $SU(3)_c$ group is just the evident subgroup of $SU(4)$. Finally, $U(1)'$ corresponds to the unbroken linear combination of $(B-L)/2, T^3_R$ and $Q_{\chi}$ orthogonal to $Y$ at the scale where the PS-group is broken down to the SM.

The full unification scenario is shown in Figure 1.

LOW-ENERGY SPECTRA AND LHC PHENOMENOLOGY

The superpotential is obtained from decomposing an $E_6$-symmetric superpotential $W_{E_6} \propto 27^3$, omitting the terms involving the right handed neutrinos as well as the baryon-number violating interactions of the exotic particles $D, D^c$:

$$W = W_{\text{MSSM}} + Y^{SH }SH^d + Y^{SD }SDD^c + Y^{D1 }D_u e^c + Y^{D2 }D d^c + Y^{D3 }D^c LQ. \quad (2)$$

A priori, all Yukawa couplings are rank three tensors in family space. However, in order to avoid flavor changing neutral currents, we introduce a so-called H-parity [4], that only allows one Higgs generation to acquire a Vev and couple to matter. This parity renders the lightest “un-Higgs” stable and hence introduces a possible additional type of dark matter.

As in most SUSY models (in fact all BSM models without a theory about flavor), the model contains a huge number of free parameters in the SSB sector. Assuming the trilinear soft couplings to be proportional to the corresponding Yukawas, the latter to be diagonal and neglecting complex phases, we arrive at a set of 16 parameters (see Table 1). Three of those are be fixed by the minimization of the Higgs-potential. From this parameter set, a code generates a spectrum by solving the RGEs, minimizing the Higgs potential and iterating in the dependent parameters. Throughout a run, it checks for perturbativity of the theory up to the unification scale and negative scalar mass-squares. In the end, the spectrum is compared to the current direct experimental bounds.

This algorithm is integrated into a Monte-Carlo Markov-Chain (MCMC), in order to efficiently scan the high-dimensional parameter space. Using this method, we hope to find a somewhat representative set of scenarios to characterize the phenomenology of this model.

General phenomenological features of this model are: a more or less hierarchical structure of leptoquarks in the range from 500 GeV to several TeV as their masses

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2 The requirement of the orthogonality to $Y$ yields non-rational charges $Q'$. Furthermore, the RGE evolution of the two $U(1)$ couplings introduces a non-trivial mixing among these groups, which can be taken into account by redefining $Q'$. 

\[ m_D \propto \langle S_3 \rangle \] are proportional to the singlet vev. This has to be big enough (which comes more or less for free on the other hand, driven by a possibly large leptoquark singlet Yukawa coupling) in order to have a \( Z' \) above the current Tevatron limits and electroweak precision data limits. For the very same reason, the so-called un-Higgses (two of the three CP-even), the charged as well as the CP-odd Higgses are rather heavy, i.e. \( M_H \gtrsim 1 \) TeV. In contrast, the lightest Higgs boson runs quite often in the NMSSM parameter channel where it can be as light as 90 GeV in some regions of the parameter space. As in the NMSSM, the decays via the lightest pseudoscalars into four \( b \) jets which already excluded discovery at LEP, render a discovery at LHC very intricate. Another very distinct feature is a rather light gluino not much heavier than weak inos, because the QCD beta function vanishes at first order.

Drawing a completely general conclusion from sparse scans through such a high-dimensional parameter space is difficult, so we shall concentrate in the following on a sample scenario, obtained by the MCMC and discuss some phenomenological features in a little more detail. Fig. 2 shows on the left a sample spectrum, for which the leptoquark states are rather light, order 600 GeV. The lightest Higgs has a mass around 110 GeV, whereas the remaining two Higgs particles are heavier are far in the decoupling limit at 1 TeV or more. The \( Z' \) mass lies at order 2 TeV, such that should also be discovered at an early stage of the LHC. But the really spectacular feature are the light leptoquarks, which yield cross section in the picobarn range. With an integrated luminosity of 100 fb\(^{-1}\), around 100,000 signal events could be collected in the area of parameter space presented here. This would allow a spectroscopy of the leptoquark sector, and maybe even a determination of the Yukawa couplings.

We implemented this Pati-Salam symmetric Supersymmetric Standard Model (PSSSM) into the multi-purpose event generator WHIZARD [5], which has been designed especially for BSM analyses, and many SUSY phenomenology projects have been performed [6]. Here, we followed basically the conventions in [7]. As a prime example for the LHC phenomenology of this model we show here the \( p_T \) distribution of single leptoquark production in that model. The chosen parameter point yields a spectacular signal-to-background ratio of 127.

In summary, we analyzed both the high-dimensional parameter space of the PSSSM and its LHC phenomenology, which might give striking signals already at an early LHC stage. More phenomenology has been studied here [8].
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