Testing Grand Unification at the (S)LHC

D. Rainwater and T.M.P. Tait

1Dept. of Physics and Astronomy, University of Rochester, Rochester, NY, USA
2High Energy Physics Division, Argonne National Lab, Argonne, IL, USA

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Abstract

We examine the possibility of measuring the three gauge couplings at high scales at the LHC, in order to see the first steps as they run toward Grand Unification at much higher energies. Using the MSSM with sparticle masses of several hundred GeV as an example of a theory in which the couplings do unify at very high energies, we find that the processes $pp \rightarrow \ell^+\nu$, $pp \rightarrow \ell^+\ell^-$ and $pp \rightarrow \gamma j$ can be useful to discriminate the SM from the MSSM with masses at the few hundred GeV scale, and determine that the couplings are converging at better than the SM prediction toward the GUT scale. Such measurements indirectly probe the existence of lower mass states, charged under the SM gauge groups, but which may be difficult to produce directly or extract from backgrounds at the LHC.
The Standard Model (SM) of particle physics is an extremely successful description of nature at the subnuclear level, although it is also generally regarded as an effective theory, likely not valid beyond the TeV scale. For example, the exact mechanism of electroweak symmetry breaking remains undetermined. The SM explanation contains a minimal weakly-coupled Higgs sector, which introduces a number of theoretical loose ends, including the gauge hierarchy problem, and the lack of a compelling theory to determine the pattern of flavor. In addition, there is strong evidence for the existence of large amounts of non-baryonic “dark” matter in the universe, which the SM does not include. These and other puzzles have led to the development of numerous extensions to the SM, varying greatly in their underlying structure and new particle content. A common theme, however, is the presence of new heavy states in the sub-Tev to few-TeV mass range. The LHC at CERN will soon study the TeV mass scale, and is expected to probe these mysteries at a level previously unobtainable in particle physics.

One of the primary goals in exploring higher energy scales is the hope that simpler organizing principles can be revealed and understood. In the same way that QCD took the effective theory of mesons and baryons, described by a huge number of states each with its own mass and couplings, and allowed (at least) a qualitative understanding of the pattern in terms of a gauge theory with a small handful of parameters, it is hoped that at higher energies we will understand how to predict the structure and parameters of the SM in terms of simpler principles and fewer input parameters. Chief among these potential triumphs is the idea that we will be able to understand the $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge structure of the SM (and the representations of the fermions under it) in terms of a single grand unified theory (GUT) with a single coupling constant. The minimal simple group containing the SM gauge structure, $SU(5)$, has some remarkable successes: naïve extrapolation of the SM gauge couplings does seem to move toward convergence as one considers physics at smaller distances, and the known SM matter fields precisely fill out complete $SU(5)$ representations.

However, despite these encouragements, grand unification in the SM does not quite work. The couplings do converge, but they fail to meet one another at a single scale, as shown in Fig. 1. The amount of discrepancy is large ($\sim 20\%$) compared with any expected correction from thresholds of heavy fields at the GUT scale itself. Thus, in order for the couplings to actually meet at high energies, one must include some correction associated with a lower energy scale, to alter the running and induce a log-enhanced shift in the coupling with respect to the SM prediction. This argues that the new states responsible for unification of the couplings should be relatively light\(^1\) (though it does not guarantee that they will be within the reach of the LHC).

In particular, the minimal supersymmetric standard model (MSSM), is a well-motivated extension of the SM, which stabilizes the electroweak scale with respect to quantum corrections from higher scales, and (usually) contains a viable dark matter candidate with an appropriate relic density. In addition, when one includes the full MSSM particle content and extrapolates the gauge couplings to large energies, one finds remarkable convergence\(^2\) at a scale of order $10^{16}$ GeV (see Fig. 1). While previous searches for supersymmetric particles

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\(^1\) However, see Ref. [1], which claims that very light supersymmetric particles (in a simplistic framework) are already indicated by comparison of couplings at the $Z$ pole with those at energies of order 200 GeV.

\(^2\) Unification at a similar level also occurs by adding vector-like quarks [2].
FIG. 1: Evolution of the three gauge couplings $\alpha_1$ ($SU(5)$ normalized, as the dashed line), $\alpha_2$ (dotted line) and $\alpha_3$ (solid line) in the SM (upper set of curves) and MSSM (lower set of curves), assuming superpartner masses are all close to the top quark mass.

have had null results [3], it seems likely that if TeV-scale supersymmetry is realized in nature, the LHC will be able to discover it. In particular, the LHC is expected to copiously produce the colored superpartners in large numbers [4]. The discovery of superpartners would be a strong hint that the couplings do unify, and that a GUT is realized in nature.

In this article we explore the possibility that the LHC could find at least the first hints of Grand Unification, by measuring the gauge couplings from observation of ordinary SM processes at high scales. If new particles exist at the weak scale, they will influence the evolution of these couplings at energies larger than their masses, and the couplings will begin to run away from the SM extrapolations. While the LHC has the potential to see only the first step in eventual unification of the couplings, we will see that it can make a statement as to whether the couplings seem to be coming together as in the MSSM, or missing each other, as in the SM. We will use the MSSM with masses of several hundred GeV as our test example, though one of the virtues of the approach is that it is not very sensitive to the underlying model itself.

The corrections that cause the coupling to run differently amount to a class of higher-order virtual corrections from the new states running in the loops. At energy scales of order the mass of the new particles, such corrections are complicated, and not described sufficiently by simply running the coupling. We envision that at the highest energies the LHC probes (the multi-TeV region), we are sufficiently above the new mass thresholds that the log-enhanced terms dominate the corrections, and the description in terms of a running coupling captures the bulk of the effect of the new physics. Of course, this implies that the LHC has enough energy to produce the new states directly and would likely have seen at least some of them. Even so, a direct extrapolation including the new states explicitly may not be possible. It is well known in the MSSM that while the colored superpartners
are produced in large numbers, the electroweakly interacting sparticles will in most cases be visible only if they form part of an observable decay chain from the colored objects; in most regions of MSSM parameter space, some of the electroweak objects will end up being missed. Even when they are visible, the representations under $SU(2)_W \times U(1)_Y$ are obscured by electroweak symmetry breaking, and the representation content is likely to be impossible to determine using LHC data alone.

We identify three processes at LHC which could potentially provide such a measurement. They naturally must be observable with good statistics at large invariant mass, in particular above the mass thresholds of SUSY particles, and with systematic uncertainties much smaller than the change in rate due to altered coupling evolution. The obvious candidates are: Drell-Yan (DY) production of mixed charged-neutral lepton pairs (off-shell $W$ production), sensitive at leading order (LO) only to the $SU(2)$ coupling; DY charged lepton pairs (through off-shell $Z/\gamma^*$), sensitive at tree level to both the $SU(2)$ and $U(1)_Y$ couplings; and photon-jet ($\gamma j$) production, which is sensitive to both QCD’s $SU(3)$ coupling as well as the $U(1)_{EM}$ coupling, itself a combination of both the $SU(2)$ and $U(1)_Y$ couplings: $\alpha_{EM} = \alpha_1 \alpha_2 / (\alpha_1 + \alpha_2)$.

We review the running of gauge couplings and give our input parameters in Sec. II, then calculate the cross sections expected at LHC for the three processes in Sec. III, along with our estimates for how accurately the MSSM rates could be distinguished from those of the SM. Finally, we discuss the prospects and for performing these measurements at LHC, and the uncertainties of greatest concern.

II. RUNNING OF THE GAUGE COUPLINGS

In an effective theory approach, we capture the leading log corrections from higher orders by employing a set of running couplings,

$$\alpha_i(Q^2) = \frac{\alpha_i(\mu^2)}{1 - \beta_i \alpha_i(\mu^2)/4\pi \ln(Q^2/\mu^2)} ,$$  \hspace{1cm} (1)

where $\alpha_i = g_i^2 / 4\pi$ is the analog of the fine structure constant for each of the SM’s three gauge groups ($U(1)_Y$, $SU(2)$, and $SU(3)$), $\mu$ is a reference scale at which the coupling has already been measured (usually $M_Z$ is a convenient choice) and $Q$ is the scale of the physical process in question. The coefficients $\beta_i$ ($i = \{1, 2, 3\}$ for $\{U(1)_Y, SU(2)_W, SU(3)_C\}$) are determined by the particle content active at scales of order $Q$: those species whose masses are less than $Q$. Mass thresholds appear (at this order) as changes in $\beta_i$, resulting in a change in the slope of $d\alpha_i/d\ln Q$. We take our reference inputs at the $Z$ mass ($M_Z = 91.188$ GeV) from global fits to precision data, $\alpha_{EM} = 1/128.9 \alpha_s = 0.1185$, and $\sin^2 \theta_W = 0.2312$ [5].

If the SM remains valid, at energies above the top mass, the couplings will evolve with $\beta$-functions,

$$\beta_i = \left\{ \frac{41}{6}, -\frac{19}{6}, -7 \right\} ,$$  \hspace{1cm} (2)

while in the MSSM, above the masses of all the superpartners they are

$$\beta_i = \{11, 1, -3\} .$$  \hspace{1cm} (3)

Note the change in sign of $\beta_2$, which takes the $SU(2)$ gauge coupling from being asymptotically free to asymptotically enslaved, an indication of a qualitative difference between
the SM and MSSM at high energies. The MSSM predictions for the gauge couplings are model-dependent in that they are sensitive to the mass spectrum, and thus the mechanism by which supersymmetry breaking is communicated to the superpartners of SM fields. We will assume that the electroweakly interacting superpartners (charginos, neutralinos, sleptons, and Higgs) have degenerate masses of 120 GeV, safely above the LEP II and Tevatron bounds $^3$, and modify the coupling evolution from the SM to include the SUSY states at that energy. However, the Run II bounds on colored superpartners are already somewhat better than this $^3$, so we will assume their masses are 500 GeV, also beyond the current limits$^3$. This implies that the electroweak couplings have a threshold at 120 GeV from the electroweak gauginos, sleptons, and Higgses; one at the top mass from the top quark; and one at 500 GeV from the squarks, whereas the shift in the evolution of the $SU(3)$ coupling away from the SM begins at 500 GeV.

### III. CROSS SECTIONS AT THE LHC

Ideally, one would like to observe purely QED, weak and QCD interactions to separately measure their gauge couplings. In practice, this is quite difficult. For example, diphoton production is on the order of only 10 fb for invariant masses above 1 TeV, and more than an order of magnitude smaller for 2 TeV, where the lever arm from running approaches usable size. This gives far too few events to perform a measurement. Similarly, purely QCD processes suffer the worst systematic uncertainties, mostly due to detector effects but also on the theoretical side.

However, there is a purely weak process which is very easy to observe and experimentally “clean”: $pp \rightarrow W^* \rightarrow \ell \nu$, $\ell = e, \mu$. This manifests itself as a highly energetic (“hard”) charged lepton and missing energy in the transverse direction; one cannot reconstruct the center-of-mass frame as the longitudinal momentum information of the neutrino is lost. The downside of this final state is that only the transverse mass ($M_T$) can be measured, not the true invariant mass, although they do track each other reasonably well. We make theoretical predictions for the transverse mass distribution using a running coupling to calculate the differential cross section. After convolution with simulated detector effects, it could then be compared with the data distribution. Being forced to use the transverse mass will weaken the measurement slightly, but not precipitously.

Drell-Yan charged lepton pairs, $pp \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^-$, allow for complete reconstruction of the kinematics and thus determination of the invariant mass, but occur at a much smaller rate than $W^*$ events. In addition, the $Z$ coupling to fermions is an admixture of QED and the weak sector. Nevertheless, it could potentially add weight to the weak sector measurement via $W^*$.

To measure the QCD gauge coupling we choose a mixed QCD–QED process out of necessity: gamma–jet production, $pp \rightarrow \gamma j$. QCD jet energies are not particularly well-measured by LHC detectors, making comparison with theory of energy-scale observables more difficult due to scale uncertainty. By requiring the QCD jet to be balanced by a photon, perhaps the worst detector effects can be mitigated. We discuss this issue further in the relevant

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$^3$ This pattern of lighter weakly interacting superpartners compared to heavier colored superpartners is also common to most popular mechanisms of supersymmetry breaking, and is largely induced by the renormalization group evolution of the masses.
subsection below.

Our proposed relative gauge coupling measurement is thus a deconvolution of the altered running on one pure- and two mixed-coupling rates, with varying associated uncertainties. We describe in the following subsections the individual channels and their likely expected uncertainties. In all cases, we rely on leading order estimates for the rates (provided by MADGRAPH\cite{6}, with the only improvement coming from the running coupling. While this is probably not sufficient to match an experimental result with theory to the desired accuracy, it should be sufficient to provide an estimate of the statistical uncertainties, and we discuss systematic and theoretical uncertainties below. We use the CTEQ6L1 LO parton distribution functions (PDFs)\cite{7} for our LO calculations. We present results assuming a combination of two detectors, each of which will collect 300 fb$^{-1}$ at the LHC, and 3000 fb$^{-1}$ at the SLHC, running at $\sqrt{s} = 14$ TeV center of mass proton-on-proton collisions.

In all cases, the dominant uncertainties come from our knowledge of the PDFs (primarily the gluon), higher-order QCD and electroweak corrections, the integrated collider luminosity associated with the data sample, and reconstruction of the event kinematics from detector observables. Fortunately for the Drell-Yan rates, the higher-order QCD corrections are known to NNLO\cite{8} and have percent-level attendant uncertainties. The gluon PDF is the least well-known, especially at the large values of Feynman $x$ for multi-TeV partonic collisions — on the order of 10%. Various measurements can perhaps improve this at LHC, for example by DY itself at lower invariant mass\cite{9}, but we propose to eliminate some of the PDF (and all of the luminosity) uncertainty by measuring not absolute rates, but rates at large invariant mass relative to those at lower invariant mass, below the scale where the MSSM content significantly alters gauge coupling running. Thus, our proposal is to measure the gauge couplings at high energy relative to those known at or close to the $Z$ pole.

A. Drell-Yan $\ell\nu$ Pair Production

Drell-Yan production of one charged and one neutral lepton takes place at tree level through the process $q\bar{q} \to W^* \to \ell\nu$. The missing neutrino implies that the invariant mass of the $W$ cannot be uniquely reconstructed at the LHC, but the transverse mass still correlates well with the $W$ off-shellness, and shows the effect of the different running coupling hypotheses at large transverse masses, as shown in Figure 2. We estimate our rates from LO matrix elements; in a final analysis one should take advantage of NNLO QCD\cite{8} and NLO EW\cite{10} corrections, but these effects are on the order of 10% at the transverse masses of interest, and thus will not affect our estimate of the statistical analyzing power. To simulate the acceptance of the detector, we require the charged lepton to be central, with high $p_T$,

$$|y_\ell| \leq 2.5, \quad p_T^{\ell} > 100 \text{ GeV},$$

(though in practice for such large transverse masses the $p_T$ cut is irrelevant). We apply an efficiency to identify a charged lepton of 95%. As we shall see below, the measurement of the lepton energy is crucial to have a sensitivity, and we thus consider only electrons, which can potentially be measured more precisely, and not muons.

In order to estimate how well the large transverse mass $\ell\nu$ rate can be used to distinguish the Standard Model gauge couplings from those in the MSSM, we assume that the low transverse mass region has been matched to a SM calculation, which should remove the overall luminosity uncertainty and the dominant PDF uncertainties. We estimate using the
FIG. 2: On the left is the rate of $pp \rightarrow \ell \nu$ assuming SM gauge coupling evolution (solid curve) and MSSM evolution (dashed curve) as a function of the cut on the minimum of the transverse mass. On the right is the significance as a function of a cut on the transverse mass (including systematic uncertainties explained in the text) for the LHC (lower curves) and SLHC (upper curves). The solid curves assume an electron energy resolution of 0.5%, whereas the dashed curves assume 0.1%.

NLO inclusive rate [16] that the residual PDF uncertainty should be of order 1%, and we assume, based on the fact that NNLO calculations are available, that the residual uncertainty from higher order, uncomputed QCD corrections is negligible. We assume a 0.5% energy scale uncertainty for the electron, and translate this back into a resultant uncertainty in the cross section at that scale. This assumption is optimistic, but may be possible with enough collected luminosity. Adding these uncertainties in quadrature with the statistical uncertainty, we compute the significance of the difference between SM and MSSM as a function of the cut on the minimum of the transverse mass in Fig. 2 for the LHC and SLHC. We see that the dominant limitation is from systematics, especially at $M_T \sim 1$ TeV, and that for transverse mass cuts around $1-2$ TeV, the SM and MSSM can be distinguished at about 1σ at the (S)LHC. In order to examine the importance of the electron energy resolution, we also consider a 0.1% energy scale uncertainty, and find that this could raise the significance to 2σ or more.

One could imagine improving the significance by considering bins of transverse mass. The fact that the cross section falls very rapidly with $M_T$ implies that a higher $M_T$ cut sample is essentially uncorrelated with a lower $M_T$ cut sample, and thus one could potentially make more than one measurement with similar statistical significance in different bins of $M_T$, improving the overall significance. We leave such refinements to future work.

B. Drell-Yan $\ell^+\ell^-$ Production

Charged lepton pair production is mediated by both the photon and $Z$ boson. Both couplings are a combination of the $SU(2) \times U(1)$ couplings $g_1$ and $g_2$, and in this case we are able to directly reconstruct the virtuality of the bosons from the charged pair invariant mass. We once again restrict ourselves to electrons and impose the same acceptance cuts on
FIG. 3: On the left is the rate of $pp \to \ell^+\ell^-$ assuming SM gauge coupling evolution (solid curve) and MSSM evolution (dashed curve) as a function of the cut on the minimum of the transverse mass. On the right is the significance as a function of a cut on the transverse mass (including systematic uncertainties explained in the text) for the LHC (lower curves) and SLHC (upper curves). The solid curves assume an electron energy resolution of 0.5%, whereas the dashed curves assume 0.1%.

The lepton as before, Eq. (4) with an identification efficiency of 95% per lepton, and once again assume a 0.5% (0.1%) energy resolution for (both) electrons, and 1% PDF uncertainty. The SM and MSSM rates and MSSM versus SM significance are shown in Fig. 3 and are considerably smaller than for the corresponding charged current case. This is partially because the effect of the running coupling is less, but also because the process is more sensitive to the energy resolution on the charged leptons, and the corresponding uncertainty thus larger. Our conclusion is that this process is unlikely to be useful in its own right, though it could perhaps be included in a more global analysis based on either charged-neutral production or $\gamma$–jet production to add some information. Again, the cross section falls rapidly, and one could imagine a binned analysis with small correlation between bins and improved overall significance.

C. Photon-jet production

The photon-jet production rate will be the least well-measured/predicted of any that we propose, due to the initial-state gluon PDF at LO and the jet and photon energy scale uncertainty (detector capability) in the multi-TeV regime. However, these drawbacks can be balanced by a larger rate (thus smaller statistical error), and sensitivity to $g_3$ which evolves faster than $g_2$ or $g_1$. Ideally, one would prefer to examine the dijet rate at large invariant mass, because it is a purely QCD process, and also has approximately twice the rate enhancement in the MSSM case compared to the photon-jet cross section. (This is because $\alpha_{\text{EM}}$ runs very little compared to $\alpha_s$.) However, the dijet rate suffers from twice the gluon uncertainty, and prohibitively large jet energy uncertainties.

Photons, in contrast, tend to be much better-measured than jets, because they shower electromagnetically in the detector and can be calibrated by comparison with electrons,
whose momentum can be measured by their trajectory in the magnetic field as observed by the tracking system. (In fact, the jet energy scale is calibrated in experiment using photons, in turn calibrated from electrons.) Our idea is that in high \( p_T \) photon-jet events, one would assume that the jet balances the photon in transverse momentum, then use the well-measured flight direction of the jet to completely reconstruct the system.

However, the dearth of multi-TeV electrons leads to the naïve estimate that the photon energy scale in our region of interest will not be better than about 3%, about the same as jets. This would immediately kill our proposal. The solution is to rely on photons at very high transverse momenta using the (well-known rate of) electron-conversion photons, which provides a source of equally high-energy electrons for “self-calibration” \[13\]. This is likely to allow for at least 1% energy scale uncertainty, and possibly 1/2%, over the lifetime of the first LHC run. This could be reduced by about a factor of about 3 (i.e., \( \sqrt{10} \)) using the ten times statistics available at the LHC luminosity upgrade, the SLHC \[14\].

Although the QCD NLO results are known for photon-jet production, and are large at low invariant mass \[15\], the results for higher invariant masses are not readily available. We neglect fragmentation processes, and do not apply a K-factor to our LO results, which we believe to be a conservative approximation to the available rate at LHC. We also do not consider “background” from dijet production, as the rate for misidentifying a jet as a photon occurs at about the \( 10^{-4} \) level, while the cross section ratio is more on the order of \( 10^2 \)–\( 10^3 \). Naturally these approximations should be investigated further, when detector simulation is added. To simulate the detector acceptance, we require both the photon and the jet to be central:

\[ |\eta_j| < 4.0 \; , \quad |\eta_\gamma| < 2.5 \; ; \] (5)

and include an 80% efficiency factor to identify a photon \[11, 12\].

FIG. 4: Left: the leading-order photon-jet cross section at the LHC, in the SM (lower curve) and MSSM (upper curve) as a function of photon-jet invariant mass. The cross section falls off a little slower than \( m_{\gamma j}^4 \). Right: the ratio of MSSM to SM cross sections at the LHC, also as a function of \( m_{\gamma j} \). The logarithmic deviation due to the running coupling is readily apparent.

We first show the LO cross section and MSSM/SM cross section ratio in Fig. 4 as a function of photon-jet invariant mass. The former gives one an idea of what event statistics
FIG. 5: Results for the expected significance of MSSM-running gauge couplings v. the SM at LHC (left) and SLHC (right). The solid curve at LHC is for the more pessimistic assumptions of 4% relative PDF uncertainty and 1% photon energy scale uncertainty, which dashed is for 0.5% photon energy scale uncertainty, and dotted is further reducing the relative PDF uncertainty to 2%. The curves are the same at SLHC, except that the corresponding photon energy scale uncertainties are $\sqrt{10}$ smaller than those at the LHC, due to the larger available sample sizes for calibration. For two detectors, the LHC assumes 300 fb$^{-1}$ each, and the SLHC ten times that.

will be available at LHC, while the latter distinctly shows the dominant logarithmic behavior of including the MSSM spectrum in the gauge coupling running. Approximately 85% of the running is due to the evolution of $\alpha_s$, the remaining part due to the QED coupling.

Our results are summarized in Fig. 5 for the LHC and SLHC. The curves represent the signal significance, i.e. the deviation of the MSSM rate from the expected SM rate. Keep in mind this will ultimately be done as a relative measurement of the rate at large invariant masses to that at around 200 GeV. The significance is calculated as the MSSM–SM rate separation in terms of SM rate uncertainty, adding in quadrature the uncertainties from statistics, photon energy scale and PDFs (dominantly the gluon, although the high-$x$ quark uncertainties would also have to be known more precisely than at present). At the moment, high-$x$ gluons are known to only 10–15% in our region of interest; quite poorly. How much uncertainty exists in the relative measurement at high invariant mass to low is not well-studied \[16, 17\]. However, it should be possible to improve this using Drell-Yan lepton data over a range of invariant mass and rapidity to tighten up the uncertainty bands considerably \[17\]. To illustrate the range of potential, we first start with a pessimistic but reasonable 4% PDF uncertainty at high $x$, and 1% on the photon energy normalization. This is shown by the solid lines. The dashed lines are the result of reducing the photon energy scale uncertainty by a factor two, to half a percent. The dotted curves are additionally a reduction of the PDF uncertainty by a factor two, from 4% to 2%. This represents the most optimistic scenario.

It is clear that at the LHC the limiting factor is the PDF uncertainty at high $x$, dominantly the gluon, although improving the photon energy scale calibration results in a significant
increase of analysing power, from about a 2σ observation to almost 3σ. LHC could achieve 4σ if the convoluted PDFs at high x can be brought under control to the 2% level, relative to those as lower x where the lower invariant mass cross section is made, which is not a totally unreasonable assumption. At the SLHC, the much higher event rate available for photon energy scale calibration largely removes that as a large source of uncertainty. Instead, the gluon PDF dominates. If a 2% uncertainty can be achieved, not only would this measurement result in a beautiful observation of altered running of the gauge couplings, it would allow for a first measurement of the actual gauge coupling values (primarily αs), somewhere in the 20% range at SLHC.

IV. DISCUSSION AND CONCLUSIONS

We propose using three different high momentum-transfer scattering processes at LHC, Drell-Yan lepton pairs (charged and mixed charged-neutral) and photon-jet events, to study the running of the SM gauge couplings at high energy. Our motivation is the well-known observation that the gauge couplings appear to almost converge at about 10^{15} GeV, and are predicted to do so in many models of new physics that respect a GUT symmetry at that scale. The generic prediction is additional particle content at or near the electroweak scale which alters the gauge couplings’ evolution such that they converge at a single energy scale, at which point they become one coupling. Our proposal suggests that one use these processes as a probe of the GUT hypothesis, and we show that in the specific case of the MSSM, we are able to distinguish the MSSM from the SM using the evolution of the gauge couplings alone. While this is not in itself a proof of unification of couplings, it is at least suggestive of the first step. Further, the combination of this indirect effect of the new physics with direct detection of some of the spectrum can reveal states which may be difficult to see directly, and provides a measure of the sum of the electroweak charges active in the evolution, which may be obscured by electroweak symmetry breaking in direct observation.

We have examined three processes involving Standard Model external states at high momentum transfer, and have shown that we find a potentially very significant difference between SM and MSSM extrapolations to high Q^2 in the case of the semi-weak production of a jet and a photon, moderately significant differences in the charged DY production of an electron and a neutrino, and not very significant differences in the DY e^+e^- channel. We have made optimistic but not impossible assumptions about the potential to measure jet and electron energies at the LHC detectors, and have shown that in each case this is the limiting factor to realize the idea.

Our results demonstrate that the (S)LHC is potentially more of a precision measurement machine than is normally credited. For these measurements, and prospects for adding other channels that are purely QCD, the limiting factors are likely to be the gluon PDF uncertainty at large values of Feynman x, and the precise measurement of energies of jets, photons, and leptons. We have chosen optimistic (but hopefully achievable) estimates of the detector capabilities and PDF uncertainties, and the results are tantalizing. They provide strong encouragement to the continued heroic effort toward reducing these uncertainties via other measurements and creative experimental and theoretical techniques, both those ongoing at Tevatron and those that can be performed over the lifetime of LHC.
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[1] D. Bourilkov, AIP Conf. Proc. 842, 634 (2006).
[2] D. Choudhury, T. M. P. Tait and C. E. M. Wagner, Phys. Rev. D 65, 053002 (2002); D. E. Morrissey and C. E. M. Wagner, Phys. Rev. D 69, 053001 (2004); G. F. Giudice and A. Romanino, Nucl. Phys. B 699, 65 (2004) [Erratum-ibid. B 706, 65 (2005)].
[3] See e.g.: http://www-cdf.fnal.gov/physics/exotic/exotic.html for CDF and http://www-d0.fnal.gov/public/new/new_public.html for DØ.
[4] S. Dawson, E. Eichten and C. Quigg, Phys. Rev. D 31, 1581 (1985).
[5] S. Eidelman et al. [Particle Data Group], Phys. Lett. B 592, 1 (2004).
[6] T. Stelzer, F. Long, Comput. Phys. Commun. 81 (1994) 357.
[7] J. Pumplin et al., JHEP 0207, 012 (2002)
[8] C. Anastasiou, L. J. Dixon, K. Melnikov and F. Petriello, Phys. Rev. D 69, 094008 (2004); K. Melnikov and F. Petriello, Phys. Rev. Lett. 96, 231803 (2006); K. Melnikov and F. Petriello, arXiv:hep-ph/0609070.
[9] S. Alekhin, K. Melnikov and F. Petriello, arXiv:hep-ph/0606237.
[10] S. Dawson, E. Eichten and C. Quigg, Phys. Rev. D 31, 1581 (1985).
[11] U. Baur and D. Wackeroth, Phys. Rev. D 70, 073015 (2004).
[12] ATLAS TDR, report CERN/LHCC/1999-15 (1999).
[13] CMS TDR, report CERN/LHCC/2006-001 (2006).
[14] Tom LeCompte, private communication.
[15] S. Catani, M. Fontannaz, J. P. Guillet and E. Pilon, JHEP 0205, 028 (2002);
    P. Aurenche, M. Fontannaz, J. P. Guillet, E. Pilon and M. Werlen, arXiv:hep-ph/0602133.
[16] C. Balazs and C. P. Yuan, Phys. Rev. D 56, 5558 (1997).
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[17] Frank Petriello, private communication based on Ref. [8].