ABSTRACT

We report on the activities of the Precision Measurements Of Heavy Objects working group of the Very Large Hadron Collider Physics and Detector Workshop.

I. INTRODUCTION

The topics discussed by the Precision Measurements Of Heavy Objects working group spanned a very wide range; consequently, it is impossible to cover each topic in depth. Therefore, in this report we will primarily focus on the issues most relevant to a VLHC machine. In the following, we mention only the highlights, and refer the reader to the literature for more specific questions.

II. PARTON DISTRIBUTIONS FOR VLHC

Global QCD analysis of lepton-hadron and hadron-hadron processes has made steady progress in testing the consistency of perturbative QCD (pQCD) within many different sets of data, and in yielding increasingly detailed information on the universal parton distributions.

We present the kinematic ranges covered by selected facilities relevant for the determination of the universal parton distributions. While we would of course like to probe the full \( \{x, Q\} \) space, the small \( x \) region is of special interest. For example, the rapid rise of the \( F_2 \) structure function observed at HERA suggests that we may reach the parton density saturation region more quickly than anticipated. Additionally, the small \( x \) region can serve as a useful testing ground for BFKL, diffractive phenomena, and similar processes. Conversely, the production of new and exotic phenomena generally happens in the region of relatively high \( x \) and \( Q \).

This compilation provides a useful guide to the planning of future experiments and to the design of strategies for global analyses. Another presentation regarding future and near-future machines is given in the 1996 Snowmass Structure Functions Working Group report.

As we see in Fig. 1, the VLHC will probe an \( \{x, Q\} \) region far beyond the range of present data. To accurately calculate processes at a VLHC, we must have precise PDF’s in this complete kinematic range. Determining the PDF’s in the small \( x \) regime is a serious problem since there will be no other measurement in the extreme kinematic domain required by VLHC. For the large \( x \) and \( Q \) region, the PDF’s at large \( Q \) can, in principle, be determined via the standard QCD DGLAP evolution, but in practice uncertainties from the small \( x \) region can contaminate this region.

In Fig. 2, we display the evolution of the PDF’s for a selection of partons. For the gluon and the valence quarks, we see a decrease at high \( x \) and an increase at low \( x \) with \( x \approx 0.1 \) as the crossing point. In contrast, for the heavy quark PDF’s, we see generally an increase with increasing \( Q \). The momentum fraction of the partons vs. energy scale is shown in Table I. An interesting feature to note here is the approximate “flavor democracy” at large energy scales; that is, as we probe the proton at very high energies, the influence of the quark masses becomes smaller, and all the partonic degrees of freedom carry comparable momentum fractions. To be more precise, we see...
III. HEAVY QUARK HADROPRODUCTION

Improved experimental measurements of heavy quark hadroproduction has increased the demand on the theoretical community for more precise predictions. The first Next-to-Leading-Order (NLO) calculations of charm and bottom hadroproduction cross sections were performed some years ago. As the accuracy of the data increased, the theoretical predictions displayed some shortcomings: 1) the theoretical cross-sections fell well short of the measured values, and 2) they displayed a strong dependence on the unphysical renormalization scale \( \mu \). Both these difficulties indicated that these predictions were missing important physics.

Table I: Momentum fraction (in percent) carried by separate partons as a function of the energy scale \( Q \).

| Q       | g | \( \bar{u} \) | \( \bar{d} \) | s | c | b |
|---------|---|-------------|-------------|---|---|---|
| 3 GeV   | 46| 5           | 7           | 3 | 1 | 0 |
| 10 GeV  | 48| 6           | 8           | 4 | 2 | 0 |
| 30 GeV  | 48| 6           | 8           | 5 | 3 | 1 |
| 100 GeV | 48| 7           | 8           | 5 | 3 | 2 |
| 300 GeV | 49| 7           | 8           | 6 | 4 | 2 |
| 1 TeV   | 49| 7           | 8           | 6 | 4 | 3 |
| 3 TeV   | 49| 7           | 8           | 6 | 4 | 3 |
| 10 TeV  | 50| 7           | 9           | 6 | 4 | 4 |
| 30 TeV  | 50| 7           | 9           | 7 | 6 | 4 |
| 100 TeV | 51| 7           | 10          | 7 | 7 | 4 |

These deficiencies can, in part, be traced to large contributions generated by logarithms associated with the heavy quark mass scale, such as \( \ln(s/m_Q^2) \) and \( \ln(p_T^2/m_Q^2) \). Pushing the calculation to one more order, formidable as it is, would not

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3Based on the presentation by Randall J. Scalise.

4Here, \( m_Q \) is the heavy quark mass, \( s \) is the energy squared, and \( p_T \) is the transverse momentum.
necessarily improve the situation since these large logarithms persist to every order of perturbation theory. Therefore, a new approach was required to include these logs.

In 1994, Cacciari and Greco\cite{Cacciari:1994} observed that since the heavy quark mass played a limited dynamical role in the high $p_T$ region, one could instead use the massless NLO jet calculation convoluted with a fragmentation into a massive heavy quark pair to compute more accurately the production cross section in the region $p_T \gg m_Q$. In particular, they find that the dependence on the renormalization scale is significantly reduced.

A recent study\cite{Ferrera:2000} investigated using initial-state heavy quark PDF's and final-state fragmentation functions to resum the large logarithms of the quark mass. The principle ingredient was to include the leading-order heavy-flavor excitation (LO-HE) graph (Fig. 5) and the leading-order heavy-flavor fragmentation (LO-HF) graph (Fig. 6) in the traditional NLO heavy quark calculation.\cite{Ferrera:1998} These contributions can not be added naively to the $O(\alpha_s^3)$ calculation as they would double-count contributions already included in the NLO terms; therefore, a subtraction term must be included to eliminate the region of phase space where these two contributions overlap. This subtraction term plays the dual role of eliminating the large unphysical collinear logs in the high energy region, and minimizing the renormalization scale dependence in the threshold region. The complete calculation including the contribution of the heavy quark PDF's and fragmentation functions 1) increases the theoretical prediction, thus moving it closer to the experimental data, and 2) reduces the $\mu$-dependence of the full calculation, thus improving the predictive power of the theory. (Cf., Fig 7.)

In summary, the wealth of data on heavy quark hadroproduction will allow for precise tests of many different aspects of the theory, namely radiative corrections, resummation of logs, and multi-scale problems. Resummation of the large logs associated with the mass is an essential step necessary to bring theory in agreement with current experiments and to make predictions for the VLHC.

IV. W MASS STUDIES

The W boson mass is one of the fundamental parameters of the standard model; its precision measurement can be used in conjunction with the top mass to extract information on the Higgs boson mass. The W boson mass has already been measured precisely, and the current world average is: $M_W = 80.356 \pm 0.125$ GeV/c$^2$.

Here, we focus on issues which are unique to a VLHC facility, and refer the reader to the literature for details regarding other topics.\cite{Aad:2013,ATLAS:2013,CMS:2013} The question addressed in the working group session was to consider the expected precision for $M_W$ at the VLHC in comparison to what will be available from competing facilities at VLHC turn-on. For our estimates, we use $\sqrt{s} = 100$ TeV, $\Delta t = 16.7$ ns (the bunch spacing), $\sigma_{\text{total}} \approx 120$ mb, and 20 interactions per crossing.

For W events produced in a hadron collider environment there are essentially only two observables that can be measured: $i$) the

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Based on the presentation by Marcel Demarteau.
lepton momentum, and ii) the transverse momentum of the recoil system. The transverse momentum of the neutrino must be inferred from these two observables. The W boson mass can be extracted from either the lepton transverse momentum distribution, or the transverse mass: $M_T = \sqrt{2p_T^el p_T^\nu (1 - \cos \phi^{el\nu})}$, where $\phi^{el\nu}$ is the angle between the electron and neutrino in the transverse plane.

It is important to note that the following estimates necessitate a large extrapolation from $\sqrt{s} = 1.8$ TeV to $\sqrt{s} = 100$ TeV. For the W decays, the observed number distribution in pseudorapidity ($|\eta|$) can be estimated by scaling results from the CERN SppS and the Fermilab Tevatron. The shoulder of the pseudorapidity plateau is $\sim 3$ for $\sqrt{s} = 630$ GeV, and $\sim 4$ for $\sqrt{s} = 1.8$ TeV. This yields an estimate in the range of $\sim 5$ to $9$ for a $\sqrt{s} = 100$ TeV VLHC. Assuming coverage out to $|\eta| \leq 4$, we obtain $\sim 1400$ charged tracks in the detector calorimeter with which we must contend for the missing $E_T$ calculation, $<$\(E_T$>. Scaling the $\langle p_T \rangle$ up to $\sqrt{s} = 100$ TeV we estimate $\langle p_T \rangle \simeq 865$ MeV for minimum bias tracks. Assuming $N_{ch}/N_{\gamma} = 1$ yields an average $E_T$ flow of 2 TeV in the detector. Using current $E_T$ resolutions of $\sim 4 - 5$ GeV, we estimate $\sigma(E_T) \simeq 25 - 30$ GeV for VLHC.

Two fundamental problems we encounter at a VLHC are multiple interactions and pile-up. Multiple interactions are produced in the same crossing as the event triggered on. The effects are “instantaneous”; i.e., the electronic signals are added to the trigger signals and subjected to the same electronics. Pile-up effects are out-of-time signals from interactions in past and future buckets caused by “memory” of the electronics. Both cause a bias and affect the resolution, but in different ways. The effect of pile-up is strongly dependent on the electronics used in relation to the bunch spacing.

The bottom line is the estimation of the total uncertainty on the W mass, $\delta M_W$. For a luminosity of 2 fb$^{-1}$, $\delta M_W$ is about 20 MeV for both the transverse mass and lepton transverse momentum fits. For an increased luminosity of 10 fb$^{-1}$, the transverse mass fit might improve to $\delta M_W \sim 15$ MeV, with minimal improvement for the determination from the lepton transverse momentum distribution. It should be noted that these estimates have quite a few caveats—additional study would be required before taking these numbers as guaranteed predictions. In Table II, we compare these estimations with the anticipated uncertainty from upcoming experiments. Clearly the VLHC will not greatly improve the determination of $M_W$. The situation becomes more difficult when one insists that the VLHC detectors be capable of precisely measuring the relatively low energy leptons from the $M_W$ decay.

Table II: Anticipated limits on $\delta M_W$ from present and future facilities. (This compilation is taken from Ref. [9].)

| FACILITY | $\delta M_W$ (MeV/c^2) | $\mathcal{L}$ |
|----------|-----------------------|---------------|
| NuTeV    | $\sim 100$            | ---           |
| HERA     | $\sim 60$             | $150$ pb$^{-1}$ |
| LEPT2    | $\sim 35$−$45$        | $500$ pb$^{-1}$ |
| Tevatron | $\sim 55$             | $1$ fb$^{-1}$  |
| Tevatron | $\sim 18$             | $10$ fb$^{-1}$ |
| LHC      | $\sim 15$             | $10$ fb$^{-1}$ |
| VLHC     | $\sim 20$             | $1$ fb$^{-1}$  |
| VLHC     | $\sim 15$             | $10$ fb$^{-1}$ |

V. THE TOP QUARK

The mass of the recently discovered top quark is precisely determined by the CDF and D0 collaborations from $t\bar{t}$ production at the Tevatron. For the details of this discovery and measurement, we refer the reader to Refs. [11, 12, 13, 14].

In Table II, we display the anticipated accuracy on the top quark mass at the Tevatron as estimated in the TeV2000 report [15]. Since this report, statistical techniques have been improved such that one would expect a precision of $\delta m_t \sim 1.5$ GeV with $10$ fb$^{-1}$, assuming other sources of systematics are negligible.

Moving on to the LHC, the top production cross section is $\sim 100$ times greater than at TeV2000, so with a luminosity of $\sim 100$ fb$^{-1}$/year, we expect $\sim 1000$ more top events after one LHC year. Assuming naïvely that the errors scale as $1/\sqrt{N}$ (where N is the number of events), we would obtain $\delta m_t \sim 50$ MeV.

The challenges of the VLHC are quite similar to the LHC regarding this measurement. A precision measurement of the top quark mass at this level (or better) places stringent demands on the jet calibration. Even with large control samples of $Z +$ jets and $\gamma +$ jets, uncertainties due to the ambiguous nature of jet definitions will persist. The large number of multiple interactions at LHC and VLHC complicates this analysis (in a manner

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$^6$Based on the presentation by Erich Varnes.
similar to that discussed for the W boson mass measurement). Therefore, in order to improve upon existing measurements, the VLHC detectors will need to be extremely well designed and understood—certainly a heroic task.

Table III: Anticipated accuracy on the top quark mass, as estimated by the TeV2000 report.\[15\]

| Source                | 70 pb\(^{-1}\) | 1 fb\(^{-1}\) | 10 fb\(^{-1}\) |
|-----------------------|----------------|--------------|--------------|
| Statistics            | 25             | 6.2          | 2            |
| Jet Scale             | 11             | 2.7          | 0.9          |
| Backgrounds           | 4              | 1            | 0.3          |
| **Total**             | **27.6**       | **6.9**      | **2.2**      |

VI. PROBING A NONSTANDARD HIGGS BOSON AT A VLHC\[7\]

We have studied the potential of a VLHC to observe a nonstandard Higgs boson (i.e. a spin-0 isospin-0 particle with nonstandard couplings to weak gauge bosons and possibly fermions) and distinguish it from the Standard Model Higgs boson. Results are presented for different options for the energy (\(\sqrt{s} = 50, 100, 200\) TeV) and luminosity (\(L = 10^{33} - 10^{35} cm^{-2} s^{-1}\)) and compared to those obtained for the LHC in Ref. [13].

Our analysis is based on the gold-plated channel \(H \rightarrow ZZ \rightarrow l^+l^-l'^+l'^-\) and assumes cuts on the final-state leptons, which are given by \(|\eta_l| < 3\), \(p_T > 0.5 \times 10^{-3}\sqrt{s}\). We studied Higgs masses in the range from 400 to 800 GeV (600-800 GeV for \(\sqrt{s} = 200\) TeV), where the lower limit is due to the cuts and the upper limit is theoretically motivated.

The two relevant parameters that encode the deviations from the Standard Model (SM) are \(\xi\) and \(y_t\), the \(HW^+W^- (HZZ)\) and \(Ht\bar{t}\) couplings relative to the SM respectively. We found that a nonstandard Higgs should be detected for practically all values of \(\xi, y_t\) and \(L\) in the entire mass range studied, a situation which is not so clear for the LHC, particularly for the larger masses.

A nonstandard Higgs boson can be distinguished from the SM one by a comparison of its width \(\Gamma_H\) and the total cross-section. Due to theoretical uncertainties in the latter, we chose to use as a criterion only the measurement of the width. Following the procedure of ref. [16] we quantified the statistical significance of a deviation from the SM prediction by constructing the probability density function according to which the possible measurements of the Standard Model width are distributed. Postulating that a nonstandard Higgs boson is “distinguishable” if its width differs from the SM value by at least \(3\sigma\), we were able to determine the precision with which the parameter \(\xi\) can be measured at the LHC and a VLHC. This is summarized in Table IV for the case of \(y_t = 1\). We deduce that, for the purpose of precision measurements of the Higgs couplings, a lower energy VLHC with higher luminosity is preferred to that of a higher energy with lower luminosity — a conclusion that is due to the low-mass character of the physics of interest.

Consequently, we find that for Higgs masses in the range from 400 to 800 GeV, the Higgs-Z-Z coupling can be measured to within a few percent at the VLHC, depending on the precise mass and collision parameters.

Table IV: Approximate sensitivity to the parameter \(\xi\) at the LHC and the VLHC for various values of the luminosity and CM energy. The starred entries indicate the value given applies only to \(\xi > 1\), whereas for \(\xi < 1\) the sensitivity is substantially worse.

| \(\sqrt{s}, L (cm^{-2} s^{-1})\) | \(m_H = 400\) GeV | 600 GeV | 800 GeV |
|-------------------|-----------------|---------|---------|
| \(14\) TeV, \(10^{33}\) | \(60\%\) *      | —       | —       |
| \(14\) TeV, \(10^{34}\) | \(20\%\) *      | \(40\%\) * | —       |
| \(50\) TeV, \(10^{34}\) | \(7\%\)         | \(12\%\) | \(20\%\) |
| \(50\) TeV, \(10^{35}\) | \(3\%\)         | \(4\%\)  | \(7\%\)  |
| \(100\) TeV, \(10^{34}\) | \(6\%\)         | \(8\%\)  | \(12\%\) |
| \(100\) TeV, \(10^{35}\) | \(2-3\%\)       | \(3\%\)  | \(5\%\)  |
| \(200\) TeV, \(10^{34}\) | —               | \(25\%\) | \(30\%\) |
| \(200\) TeV, \(10^{35}\) | —               | \(8\%\)  | \(12\%\) |

VII. SUPERSYMMETRY\[8\]

Supersymmetry (SUSY) is a dominant framework for formulating physics beyond the standard model in part due to the appealing phenomenological and theoretical features. SUSY is the only possible extension of the spacetime symmetries of particle physics, SUSY easily admits a massless spin-2 (graviton) field into the theory, and SUSY appears to be a fundamental ingredient of superstring theory. Given the large number of excellent recent reviews and reports on SUSY,[17, 18, 19] we will focus here on the issues directly related to the VLHC.

One specific question which was addressed in the working group meeting was: Is the VLHC a precision machine for standard weak-scale SUSY with sparticle masses in the range 80 GeV to 1 TeV? Probably not, for the following reasons.

- An order of magnitude increase in sparticle production rates will yield minimal gains, except for sparticles in the range \(\lesssim 1\) TeV.
- Multiple interactions, degraded tracking, calibration, and b-tagging issues complicate reconstruction of the SUSY decay chains.

On the contrary, VLHC looks best if SUSY has some heavy surprises in store such as \(\gtrsim 1\) TeV squarks, or \(\sim 10\) TeV SUSY messengers.

One example of a plausible SUSY scenario would be heavy first and second generation squarks and sleptons (to suppress FCNC’s) with a characteristic mass in the range of \(\sim 3\) TeV.

\[7\] Based on the presentation by Vassilis Koulouvassilopoulos.

\[8\] Based on the presentation by Joseph Lykken.
(Cf. Ref. [9]) While the gauginos and the third generation squarks and sleptons would be within reach of the LHC, investigation of $\{\tilde{u}, d, \tilde{c}, \tilde{\nu}_e\}$ and $\{\tilde{s}, \tilde{t}, \tilde{\nu}_\mu\}$ in the multi-TeV energy range would require a higher energy facility such as the VLHC.

An estimate of the heavy squark signal over the weak-scale SUSY background and conventional channels (such as $t\bar{t}$) indicates that a VLHC can observe heavy quarks in the $\sim 3$ TeV mass range; such a heavy squark is difficult to reach at the LHC. One might expect on order of $10^3 - 10^4$ signal events/year. Of course, background rejection is a serious outstanding question, and the efficiency of b-tagging and high $p_t$ lepton rejection, for example, are crucial to suppressing the backgrounds.

**VIII. CONCLUSIONS**

While these individual topics are diverse, there are some common themes we can identify with respect to a VLHC machine. First, a very high energy hadron collider does not appear to be the machine of choice for precision measurements in the energy range $\lesssim 500 \text{ GeV}$. The competition from Tevatron, HERA, LEP, and LHC are formidable in this region. To obtain comparable precision, the VLHC is handicapped by numerous factors including multiple interactions, large multiplicity, and large $E_T$. Designing a detector to operate in the VLHC environment while achieving the precision of the lower energy competition is a challenging task.

In contrast, the strong suit of the VLHC is clearly its kinematic reach. Should there be unexpected sparticles in the $\gtrsim 10 \text{ TeV}$ range, the VLHC would prove useful in exploring this range. Of course our intuition as to what might exist in the $\sim 10$ TeV regime is not as refined as the $\lesssim 1 \text{ TeV}$ regime which will be explored in the near-future; however what we do discover in this energy range can provide important clues as to where we should search with a VLHC.

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