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Summary of the Very Large Hadron Collider Physics and Detector Subgroup[1]

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Abstract

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ABSTRACT

We summarize the activity of the Very Large Hadron Collider Physics and Detector subgroup during Snowmass 96. Members of the group: M. Albrow, R. Diebold, S. Feher, L. Jones, R. Harris, D. Hedin, W. Kilgore, J. Lykken, F. Olness, T. Rizzo, V. Sirotenko, and J. Womersley.

I. INTRODUCTION

Considering the long lead time for accelerator projects it is important for us to investigate possible options for colliders beyond the LHC. This subgroup was motivated by the accelerator work [1] that has been started on new technologies for a post-LHC Very Large Hadron Collider (VLHC) [2].

The goal of this subgroup was to start the discussion on physics and detector issues associated with a VLHC with an energy in the center of mass of the order of 100 to 200 TeV and a luminosity up to $10^{34-35} cm^{-2} s^{-1}$. Obviously, physics and detector issues, along with accelerator technology and budget constraint, must guide us to select appropriate and realistic energy and luminosity for such a machine. Defining the physics goals of a post-LHC accelerator is not trivial. As is well known, the last largely unexplored sector of the Standard Model (SM), the Higgs sector, will be investigated over the next decade by the Tevatron, LEP, and LHC. It is therefore likely that any post-LHC machine will be built to explore Physics beyond the SM. At this point in time, we do not have any experimental evidence for the physics beyond the SM, and it is therefore difficult to make the case for a specific accelerator beyond the LHC. Our goal is to make the case for R&D on accelerator and detector technologies that would allow us to build a VLHC with a lower cost than current methods.

We have to investigate different models/scenarios of physics beyond the SM and understand their implications for a VLHC. It is important to provide luminosity requirement versus the energy of the machine for fixed physics goal(s). It seems that to be successfull any new accelerator will need to probe physics at a scale at least an order of magnitude larger than the LHC.

We had a few meetings before Snowmass where we defined possible topics to work on during Snowmass. For the physics issues we used the EHLQ [3] paper as a guide. As the physics that will be probed by this machine is not yet known, a multipurpose detector was discussed.

II. SUMMARY OF WORK DONE AT SNOWMASS

In this section, we briefly summarize the work that was done during the workshop by the different members of the group.

F. Olness: "Can we use the current distribution function sets?". The upper limit for the factorization scale, Q, of the parametrized version of CTEQ3M is 10TeV. The set still can return values at higher value of Q. The Bjorken-x and Q variation behave as expected, with the $q\bar{q}$, qg, and gg fluxes dominating at high, intermediate, and low Bjorken-x, respectively. Only the valence d-quark distribution seem to behave abnormaly: it starts rising at 10TeV for $x \sim .5$. The other distributions appear to be fine in that range. The momentum sum rule is a good check that can be performed. It is off by about 5% at 10TeV and by about 15% at 100TeV. In conclusion, for the current level of accuracy needed, CTEQ3M seems to be adequate. It would be convenient if, in the future, CTEQ and other groups would generate sets that can be used up to 100 TeV.

S. Keller: "W' production". This simple example can be used to illustrate the basic features of going to higher energy. The same couplings as for the W are used, only the mass is changed. Using the narrow width approximation one can easily derive the following expression for the cross section:

$$\sigma(E_{cm}) \sim \frac{1}{E_{cm}^2} \sum_{a,b} \int_{\frac{M_{W'}^2}{E_{cm}^2}}^{1} \frac{dx_1}{x_1} F_a(x_1, Q) F_b(x_2, Q), \qquad (1)$$

where E_{cm} is the center of mass energy of the collider, F_a is the parton distribution function of parton a inside of the proton (or anti-proton) and x_i the Bjorken-x of the partons. From this expression the scaling rule that is often used can be explained: an increase of the energy by a factor n require an increase in the luminosity by a factor of n^2 (due to the factor $1/E_{cm}^2$) in order to maintain a constant number of events. The luminosity must be increase by a factor of about 200 when going from the LHC energy of 14 TeV to a VLHC at 200 TeV! However, this is only true if the rest of the expression in Eq. 1 is kept constant, in other word if $M_{W'}/E_{cm}$ is kept constant and the Q evolution of the distribution function is neglected. Keeping the ratio $M_{W'}/E_{cm}$ constant is synonymous of maximizing the machine potential: with a luminosity 200 times bigger than at the LHC, a VLHC at 200 TeV would also investigate a mass of the W' that is about 14 times bigger than at the LHC. On the other hand, if the goal is to compare the physics potential of different machines then the physics goal ($M_{W'}$ in this case) should be fixed. Increasing the energy then reduces the value of Bjorken-x probed. This dramatically increases the cross section because of the increase in the distribution function at small x. For example, for $M_{W'} = 25TeV$, with each doubling of the energy from 50 to 200 TeV, there is roughly an increase in the cross section by a factor of 10 and therefore a reduction by a factor of 10 in the integrated luminosity needed to discover the W' at that fixed mass. For this particular process, a VLHC at $E_{cm} = 200TeV$ and a luminosity $\mathcal{L} = 10^{34}cm^{-2}s^{-1}$ is equivalent to a VLHC at $E_{cm} = 100TeV$ and $\mathcal{L} = 10^{35}cm^{-2}s^{-1}$. Obviously, even without increasing the luminosity compared to the LHC, a VLHC with a center of mass energy in the 100 to 200 TeV range will probe physics at a scale higher than at the LHC.

W' production is also a usefull example to compare the pp and $p\bar{p}$ options. W' is produced through a $q\bar{q}$ pair and it is therefore expected that for large values of $M_{W'}$ the $p\bar{p}$ will have the advantage over the pp option, because the valence-valence flux is bigger than the valence-sea flux at high Bjorken-x. The cross section is at most 3–4 times larger in $p\bar{p}$ than in pp at high Bjorken-x, for $M_{W'} \sim E_{cm}/2$.. The luminosity for the $p\bar{p}$ option can therefore be decreased at most by the same factor, but this advantage should be gauged against the potential loss for other processes.

J. Lykken: "Supersymmetry and the VLHC". There is a consensus opinion that if weak-scale SUSY exists, the LHC will see it and that the LHC and a 1-1.5 TeV NLC are sufficient to do a good job on s-particle spectroscopy. On the other hand, any SUSY discovery immediately implies the existence of at least two new physics scales beyond the weak scale: the dynamical SUSY breaking scale (hidden sector) and the messenger scale. In SUGRA models these scales are close to the Planck scale and not accessible, but in gauge-mediated models the hidden sector scale can be in the range $10^2 - 10^4$ TeV and the messenger scale is likely in the range $10 - 100$ TeV if one assumes that the gluino mass is in the 100-1000 GeV range. If SUSY is discovered, we will know if it is gauge-mediated versus gravity-mediated from distinctive signatures like $\chi_1^0 \rightarrow \gamma + gravitino$, which can be seen at LEPII or the Tevatron. Measuring the χ_1^0 lifetime from displaced vertices at LHC can tell us the scale of the messenger. If this scenario is correct, we may get a "no-loose" theorem for a VLHC.

W. Kilgore (with M. Peskin): "Multiple Production of W's and Z's". In the event of a strongly coupled electroweak symmetry breaking sector, multiple W and Z production could be large enough to dominate the $W + n$ jets cross section at large n at a VLHC. This would be similar to multiple pion production in QCD but would involve the "pions" (*i.e.* longitudinal W's and Z's) of the strongly interacting symmetry breaking sector and would help to characterize that sector.

T. G. Rizzo [4]: "Searches for Scalar and Vector Leptoquarks, Searches for New Gauge Bosons, and Constraints on $q\bar{q}\gamma\gamma$ Contact Interactions". 1) Both scalar and vector leptoquarks should easily be discovered at the LHC if their masses are not in excess of the 1–2 TeV range. A VLHC (pp collider) with an energy of 200TeV in the center of mass and a integrated luminosity of $10^3 fb^{-1}$ would increase the search significantly by an order of magnitude to the 10–20 TeV range. 2) The search reaches for new gauge bosons are summarized for a variete of extended gauge models. Here too a VLHC would increase the mass search reach by an order of magnitude from the $\sim$ 5TeV range at the LHC to the $\sim$ 50 TeV range. 3) High p_t diphoton events with large invariant masses put constraints on flavor-independent $q\bar{q}\gamma\gamma$ contact interactions. Constraints on the corresponding $e^+e^-\gamma\gamma$ contact interaction already exist from LEP. Constraints on the scale associated with these contact interactions are improved by a factor of about 8 and 5 compared to the bounds provided by the LHC for the case of constructive and destructive interference, respectively. In the three cases studied, the signal is initiated by $q\bar{q}$ such that there is an improvement in the mass or scale reach of about $20 - 40\%$ when switching to a $p\bar{p}$ collider.

R. M. Harris [5]: "Discovery Mass Reach for Excited Quarks at Hadron Colliders". If quarks are composite particles then excited states are expected. For an integrated luminosity of $100 fb^{-1}$ ($10^{34}cm^{-2}s^{-1}$ for a year) the mass reach is increased from 6TeV at the LHC to 18 (31, 52) at the VLHC for an energy in the center of mass of 50TeV (100TeV, 200 TeV). Suppose that the LHC sees a classic signal of new physics: an excess of high energy transverse energy jets (assuming that we can rule out the excess as due to the parton distribution functions). This would be strong evidence of new physics, but the nature of this new physics would not be that clear. If the source of new physics is compositeness, we would then expect to see excited quark. Let's assume that we expect an excited quark at a mass around 25TeV. We would then need to decide wich machine to build to find that excited quark. Although a 50TeV machine would require a luminosity of about $10^4 fb^{-1}$, a 100 TeV and 200 TeV would only require about $10 fb^{-1}$ and $1 fb^{-1}$. The current wisdom that a factor of 2 in energy is worth a factor of 10 in luminosity is valid between the two higher energy machine. The factor is much bigger between the lowest and the two highest.

D. Hedin: "Thoughts on Designing Detectors for the VLHC". Simple scaling rules require a general purpose detector which is larger than LHC detectors. However, considering that the cost of a detector is roughly proportional to its (size)^3 it is difficult to imagine how detectors larger than CMS or ATLAS can be built. However, large portion of the project cost is actually hidden within physicists and engineers salaries. In order to minimize these costs we should not start from scratch, but consider to recycle the detector(s) with appropriate changes. If we consider CMS as an example, elements such as the magnet, muon iron, muon chambers and maybe even the calorimeters can be used at a VLHC, while DAQ, electronics, inner tracking and trigger systems would have to be replaced.

V. Sirotenko: "QCD jets at a VLHC". As usual, soft processes will be a background to many processes of interest. Due to the large cross section, these soft interactions determine the detector environment: occupancy, radiation doses, etc. PYTHIA 5.7 was used in order to simulate proton-proton collisions with a center of mass energy of 200TeV with cut parameter $P_t(min) > 25GeV$. The following results have been obtained:

a) charged particle multiplicity: 170 for all $|\eta|$ and 50 for $|\eta| < 3$ per event;

b) the P_t spectra of charged particles is as expected very soft, the average value is around 0.8 GeV;

c) total energy flow for $|\eta| < 3$ is around 250GeV per event. In the central region energy flow in a 0.1×0.1 tower is 0.03GeV per event. Energy fluxes vs detector rapidity were simulated. There are concerns about the accuracy of PYTHIA at such high center of mass energy and about the sensitivity of the results on the choice of the $P_t(min)$ cut parameter.

J. Womersley: "Physics and detector issues for an O(100TeV) pp collider". If we assume that a luminosity of $\mathcal{L} = 10^{36} cm^{-2} s^{-1}$ will be required for the physics, and a bunch spacing time of 20 ns, then we will have 2000 interactions per crossing or around 10^5 charged tracks in $|\eta|$<2.5. Therefore of order 10^7 tracking elements would be required to obtain an occupancy of a few percent; at a radius of 1 m, this would mean 1 mm^2 pixels, or 100 μm^2 at 10 cm radius. For 10 tracking layers the total channel count would be 10^8 and so even with a few $/channel, the cost would be very high. Electron identification in the presence of this large charged particle flux will be very difficult: the probability to find a "track stub" in front of an electromagnetic calorimeter energy cluster is 20-100%, so almost all π^0's would look like electrons. A central magnetic field is then an advantage to bend slow particles and provide an E/p match. To determine muon momenta, the sagitta must be measured. Since it is propotional to $B * L^2$/p, to have a momentum resolution comparable with the LHC detectors at 10 times higher momentum one could improve the coordinate precision by a factor of 10 (but the ATLAS/CMS goal is already 50 micron), increase the magnetic field by a factor of 10 (to ~40 T!) or increase the detector size by a factor of 3. Some combination of the above three possibilities is probably the best option.

D. Denisov: "Detector issues for 100-200TeV pp collider". A high P_T general purpose detector which can be built based on today technology is considered. Heavy objects are produced almost at rest and the acceptance for their detection is proportional to the covered solid angle. The total cross section at 100TeV is about 150mb with an average number of charged particles per collision around 10^2 ($|\eta|$<3). There are three major elements in modern detectors: tracking, calorimetry and muon system. Tracking is required for electron identification. Occupancy and aging are two major problems for tracking. For $\mathcal{L} = 10^{35} cm^{-2} s^{-1}$ there would be of the order of 10^4 tracks per crossing, assuming bunches are 20ns apart. About 10^7 detector elements would be needed to keep occupancy low for a 10 layers tracking detector. A magnetic field in the central region could bend soft particles away from the central region and reduce occupancy and radiation doses on the central tracker. Calorimetry resolution is just getting better with the increase in energy and thickness has to increase only as the logarithm of the energy. The aging is the most serious problem for the calorimetry, along with underlying minimum bias events fluctuations. High pressure gas ionization calorimetry looks very promizing for VLHC applications, its radiation hardness is very good. Muon detection is not at all trivial. Utilization of muon radiation at such high energy may be a better choice than the standard saggita measurement. Typical parameters for the interaction region should be in the following range: 10 micron perpendicular to the beam axis, 1 m along the beam, and 10-20 ns interval between beam crossings.

R. Diebold [6]: "Physics per buck". A simple model to characterize the cost-benefit ratio, the "physics per buck", for the energy of future accelerator is described. The new physics capability is assumed to be proportional to the logarithm of the ratio of the beam energies for the new and old facilities, whereas the cost is assumed to have a fixed component plus one that is linear with the energy of the beam. The production of heavy "W'" (the same W' model already mentioned in this section) is used as a benchmark for the physics goal. The optimization model is insensitive to details and shows a broad maximum as a function of accelerator energy, with a slow dependence on the ratio of fixed to linear costs for the facility. The model supports the common wisdom and past choices of energy increases by a factor of roughly 3 to 15. Different aspects of the approval process for a machine beyond the LHC are also discussed. The need to have a successfull LHC program is stressed, along with the need for internationalization, and the careful control of costs.

M. Albrow and L. W. Jones [7]: "Forward Physics with the Pipetron". It is argued that provision should be made for a detector engineered to cover the complete final-particle phase space, i.e. to be sensitive to all rapidity including small angle, forward physics. The agenda of such a detector would include a full range of physics topics, mostly related to QCD. Rapidity gap physics should not be compromised, including hard single diffraction, and especially the study of multi-TeV pomeron-pomeron interactions. The physics goals also relate to ultra high energy cosmic ray observations. Such a detector would require a long straight section ($\pm \sim 2$ km) in the accelerator design, and would work at a relative low luminosity ($\approx 10^{31} cm^{-2} s^{-1}$) with on average one (or less) interaction per crossing. The CDF and/or DO detectors could be recycled as central detectors, and a series of forward detectors would cover large rapidities. Such a detector should be included in the planning at an early stage as it influences the lattice and tunnel design.

III. CONCLUSIONS

Obviously, the work that was done during Snowmass is not in any way completed, it is a start. The following conclusions should be considered within that context.

As the EHLQ [3] paper pointed out in its conclusions more than a decade ago, there is no specific landmark in sight beyond the 1 TeV electroweak scale. We still don't have any experimental evidence for physics beyond the SM, and therefore no clear-cut physics goal(s) for an accelerator beyond the LHC.

To be succesfull any post-LHC accelerator should explore scales at least an order of magnitude larger than the LHC. For the examples studied during this workshop, a Very Large Hadron Collider with an energy in the center of mass of 200 TeV and a luminosity of $10^{34} cm^{-2} s^{-1}$ would achieve that goal, probing scales 5–10 times larger than the LHC (14 TeV and $10^{34} cm^{-2} s^{-1}$).

For the collider energy range considered, a doubling of the energy is equivalent or better than an increase in the luminosity by a factor of 10. This seems to contradict one of EHLQ conclusions that stated the exact oposite for energy in the center of mass above 40 TeV. However, the scales considered in that work were an order of magnitude smaller than here. As the scale considered increases, an increase in the energy becomes more important than an increase in luminosity and of course at the limit of that argument ”no increase in luminosity can compensate for center of mass energy below the treshold for new phenomena” (cf. EHLQ).

The advantages of $p\bar{p}$ collisions over pp collisions is limited to the production of heavy objects through a quark–antiquark initial state. The question here is wether or not the large luminosity required can be achieved for the $p\bar{p}$ option.

The physics studies can be separated in two groups. The first was centered around production models, comparing the reach of different colliders for the discovery of new particles. The second considered different scenarios of physics beyond the Standard Model that have a chance to reveal themselves over the next decade (before a VLHC) and studied their implications for a VLHC. For future studies, we think that it will be more interesting to concentrate on the second group.

VLHC detectors seem feasible using known technologies. There are many challenges, like keeping the total number of tracks per crossing down to a manageable level, measuring multi–TeV muons and finding materials that can sustain the large radiation doses (possibly up to Trad in the forward region). Considering the projected cost of LHC detectors, it is clear that detectors should not be ignored in the overall cost of the project. If the cost of the VLHC detectors stays at the same level than for the LHC, there is even an optimization to do: an increase in the accelerator energy increases its cost, but allows to decrease the luminosity (for fixed physics goal(s)) and therefore more than likely to decrease the cost of the detectors.

The effort started at this workshop will continue. Since the workshop we had a few meetings [8] and a first workhop specifically adressing the physics and detector issues associated with a Very Large Hadron Collider will be held at Fermilab on March 13-15 1997 [9].

IV. REFERENCES

[1] Mini-symposium “New low-cost approaches to high energy hadron colliders at Fermilab” at the May 3, 1996 APS Annual Meeting. G. Dugan, P. Limon, and M. Syphers, “Really Large Hadron Collider Working Group Summary”, these proceedings. E. Malamud, “ New Technologies for a Future Superconducting Proton Collider at Fermilab”, these proceedings.

[2] Some groups at this workshop called this option the Really Large Hadron Collider (RLHC).

[3] E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. 56:579-707,1984; Addendum-ibid. 58:1065-1073, 1986.

[4] T. Rizzo, these proceedings.

[5] R. Harris, these proceedings and Fermilab-Conf-96/285-E, hep-ph/9609319.

[6] R. Diebold, these proceedings.

[7] L. W. Jones, M. Albrow, H. R. Gustafson, and C. C. Taylor, these proceedings.

[8] See our web page: http://www-theory.fnal.gov/vlhc/vlhc.html

[9] For more information and to register see: http://fnphyx-www.fnal.gov/conferences/vlhc/VLHCworkshop.html or send e-mail to: denisovd@fnal.gov or keller@fnal.gov.