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Summary of the Very Large Hadron Collider Physics and Detector Workshop

Physics at the high energy frontier beyond the LHC

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Fermi National Accelerator Laboratory, Batavia, Illinois

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Abstract

One of the options for an accelerator beyond the LHC is a hadron collider with higher energy. Work is going on to explore accelerator technologies that would make such a machine feasible. This workshop concentrated on the physics and detector issues associated with a hadron collider with an energy in the center of mass of the order of 100 to 200 TeV.

I. INTRODUCTION

The Very Large Hadron Collider Physics and Detector workshop took place at Fermilab in March 1997. In this paper we summarize the activities of the working groups during the workshop.

This workshop was motivated by the accelerator work [1] [1] that has been started on new technologies for a post-LHC Very Large Hadron Collider (VLHC). 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.

As is well known, the last largely unexplored sector of the Standard Model (SM), the Higgs sector, will be investigated over the next decade or so by the Tevatron, HERA, LEP, and LHC. 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 any specific accelerator beyond the LHC. Therefore, our goal is to make the case for accelerator and detector developments that would allow us to build a hadron collider for a lower cost than with current technologies.

Some preliminary work was done during the Snowmass 96 [2] workshop, where the EHLQ [3] paper was used as a guide. Contrary to what is sometimes assumed, it is not necessary to increase the luminosity proportionally to the square of the energy. In fact for the production of heavy objects, each time the accelerator energy is increased by a factor of 2, the cross section increases by more than a factor of 10. For this to be true, the heavy object has to be detectable at the lower energy accelerator. The increase in cross section is due to the simple fact that the average Bjorken-x probed is decreased when the accelerator energy is increased and that the parton distribution function are larger at smaller x.

For this workshop it was therefore decided to concentrate on a center of mass energy (E_{cm}) between 100 TeV and 200 TeV and a luminosity ($\mathcal{L}$) between $10^{34} cm^{-2} s^{-1}$ and $10^{35} cm^{-2} s^{-1}$. These ranges are testing the limits of the detector and accelerator capabilities and allow one to investigate the tradeoff between E_{cm} and $\mathcal{L}$. The increase in E_{cm} and $\mathcal{L}$ from the LHC to the VLHC are about the same as the increase between the Tevatron and the LHC. We will see that with these parameters the scales of physics beyond the SM that can be probed are about an order of magnitude larger than the scales probed at the LHC.

One of the conclusions reached during the Snowmass 96 workshop was that it would be interesting to concentrate on scenarios of physics beyond the SM that have a chance to reveal themselves before the VLHC and study their implications for a VLHC. This was done in several studies during this workshop.

Due to the discovery nature of the VLHC, it is clear that we need to consider multipurpose detectors. No major problems with detector design were uncovered during the Snowmass 96 study.

About 150 participants attended the workshop which consisted of one day of plenary talks, one day of working group meetings and one half day of working group summaries by the conveners. Before going to the summary of the different working groups we provide here a brief synopsis of the plenary talks.

P. Sphicas (MIT) started with a broad sweep from the first hadron collider, the ISR, to the VLHC. He summarized the impresssive achievements of hadron colliders over the last 25 years and the current outstanding questions. G. Dugan (Cornell University) summarized the activity of the accelerator group during the Snowmass 96 workshop. Both the low and high field options were considered, with a center of mass energy of 100 TeV, a peak luminosity of $10^{34} cm^{-2} s^{-1}$ and 16ns bunch spacing. It is currently believed that there is an overall luminosity upgrade potential for the low and high field options of a factor of 5 and 10, respectively. P. Bloch (CERN) reviewed the main components of the LHC detectors. C. Hill (Fermilab) summarized the basic principles of the SM and possible scenarios of physics beyond the SM (e.g., SUSY, Technicolor, Topcolor.). F. Wilczek (IAS, Princeton) gave his view of the future of particle physics, describing the success and deficiencies of the SM and the wonders of unification and SUSY. P. Grannis (SUNY Stony Brook) closed the workshop with a talk entitled:" The Future Beckons". He analysed lessons of the past and drew morals for future decisions. He presented both depressing and optimistics scenarios, and warned us against the danger of hasting our decision to support a specific machine before Nature gives us some clues of what the appropriate machine is. [2]

We now turn to the working group summaries.

[1] The references for the introduction and conclusions are at the end of the paper, the references for the working group summaries are at the end of the respective sections.

[2] The collection of transparencies of the plenary talks and working group summary talks is available, please send your request for a copy to vlhc@fnth32.fnal.gov.

II. NEW STRONG DYNAMICS WORKING GROUP

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The New Strong Dynamics working group considered what a VLHC could reveal about new strong interactions, such as might be involved in electroweak symmetry breaking (EWSB). We tried to identify new physics that would be uniquely visible at a VLHC (as opposed to the LHC, NLC, or a muon collider). We also considered the appropriate center of mass energy and luminosity for a hadron collider intended to explore this physics and whether the traditional 'rules of thumb' about energy-luminosity trade-offs hold.

The working group met for a total of four hours during the VLHC workshop. Group discussions were initiated (and ultimately summarized) by the following presentations:

- Introduction and Overview (J. Womersley)
- Non-Standard Higgs (V. Koulovassilopoulos)
- Multiple W Production (W. Kilgore)
- Strong WW Scattering (K. Cheung)
- Deca-TeV Unified Compositeness (Y. Pirogov)
- Summary (E. Simmons)

Many other physicists including S. Chivukula, P. Grannis, C. Hill, T. LeCompte and F. Paige also made valuable contributions.

One thread of our discussion centered around the feasibility of using the VLHC to study a 'non-standard Higgs': a scalar boson with a mass of 400 to 800 GeV with non-standard couplings to weak gauge bosons and fermions[1]. Looking in the decay channel $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$, it appears that this scalar can be discovered as easily as a standard Higgs. A careful measurement might then make it possible to distinguish whether the width of the discovered object differed from that of the standard model prediction by more than a few percent. Both the discovery and identification capabilities of a VLHC would be superior to those of the LHC; a muon collider of the right energy might also do a reasonable job. The relatively low mass of this scalar makes it easier to study at a lower-energy (60-100 TeV) VLHC than at a higher-energy (200 TeV) machine.

In particular, Koulovassilopoulos *et al.* studied the possibility that the WWH coupling is rescaled relative to the standard model value by a factor ξ. The decay width of the heavy Higgs is proportional to ξ^2, and a collider's ability to detect the non-standard nature of the Higgs can be described in terms of its sensitivity to deviations of ξ from 1.0. Their results for the LHC and several possible VLHC accelerators are listed in Table I.

$\sqrt{s}$, $\mathcal{L}(\mathrm{cm}^{-2}s^{-1})$	Sensitivity to ξ, m_H (GeV): 400	600	800
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%

Table I: Sensitivity to the parameter ξ at the LHC and VLHC for various value of the luminosity and CM energy. The starred entries indicate that the value given applies only for $\xi > 1$, whereas for $\xi < 1$ the sensitivity is substantially worse.

Another topic was production and detection of multiple (longitudinal) weak gauge bosons at high energies. The idea is that just as pion scattering above the ρ resonance is dominated by multiple pion production, so might $W_L W_L$ scattering (in a strongly-interacting regime) result at high energies in multi-W_L final states. Kilgore[2] estimates the total cross section σ_{WW} to be $\sim$ 100 fb at the "ρ" peak and $\sim$ 20 fb asymptotically at higher $\sqrt{\hat{s}}$. If the acceptance is of order 50%, then the observable cross section of $\sim$ 10 fb would imply that it is not reasonable to require more than $\sim$ 1 of the W's to decay leptonically. If one of the W's is required to decay leptonically and each of the others becomes a single 'fat' hadronic jet, the dominant background will arise from standard production of one W plus multiple gluon jets. Unlike multiple W production the cross section for this process would fall rapidly with increasing jet multiplicity and the multiple-W signal might become apparent above $n_{\rm jets} \sim 5-8$. The current rough estimate is that with an integrated luminosity of 100 fb^{-1}, about 100 signal events (and almost no background) might remain after all cuts and branching ratios are included. Other suggestions for reducing background and improving signal included allowing more than one W to decay leptonically or identifying tau leptons resulting from $W \rightarrow \tau\nu_\tau$ decays.

A third focus was on how well the VLHC compares with the LHC in studying strong $V_L V_L$ scattering in the gold-plated modes where the vector bosons decay leptonically and the silver-plated modes where two Z bosons are produced and one decays to neutrinos[3]. Since (at tree level) the only hadronic activity in the detector in the signal events would result from the spectator quarks that radiated the $W_L's$, a forward jet tag and central jet veto can reduce background. It appears that the VLHC would do much better than the LHC at detecting the simple excess of $V_L V_L$ final states that would indicate the presence of a strongly-coupled electroweak symmetry-breaking sector. Furthermore, the VLHC would more clearly determine which specific final states ($W^\pm W^\pm, ZZ, W^+W^-, WZ$) showed the largest excesses – information that would help distinguish among competing models of the strong electroweak interactions. It is interesting to note that, based on these studies, cutting on measured missing E_T may not be required for W identification. This is potentially important for detector design.

Mode	σ_B	$\sigma_S(S/\sqrt{B})$	
		1 TeV Higgs	Rescaled $\pi\pi$
$\sqrt{s} = 14$ TeV, 100 fb^{-1}			
$W^\pm W^\pm$	0.037	0.065(3.4)	0.2(11)
ZZ	0.006	0.042(5.1)	0.0085(1.0)
W^+W^-	0.13	0.18(5.0)	0.05(1.3)
$W^\pm Z$	0.05	0.016(0.7)	0.04(1.8)
$\sqrt{s} = 60$ TeV, 100 fb^{-1}			
$W^\pm W^\pm$	0.83	1.4(15)	4.9(54)
ZZ	0.2	1.3(29)	0.3(6.9)
W^+W^-	5.2	7.3(32)	3.5(15)
$W^\pm Z$	1.1	0.38(3.6)	1.5(14)
$\sqrt{s} = 100$ TeV, 100 fb^{-1}			
$W^\pm W^\pm$	1.9	2.9(21)	10(72)
ZZ	0.5	2.8(40)	0.68(9.6)
W^+W^-	12	16(45)	9.4(27)
$W^\pm Z$	3.2	0.7(3.9)	4.0(22)
$\sqrt{s} = 200$ TeV, 100 fb^{-1}			
$W^\pm W^\pm$	4.9	6.8(31)	2.4(110)
ZZ	1.3	6.2(52)	1.8(15)
W^+W^-	40	40(62)	28(43)
$W^\pm Z$	10	3.1(6.6)	15(47)

Table II: Signal and background cross sections σ_S and σ_B (in femtobarns), and signal significance $S/\sqrt{B}$, for two models of vector-boson pair production in various final states, for the LHC and for various VLHC options.

For instance, Cheung *et al.* examined the signal of a strong EWSB sector at the LHC and VLHC in several longitudinal diboson final states. They employed the general type of cuts described above and evaluated the significance $S/\sqrt{B}$ (where S and B are the number of signal and background events) assuming an integrated luminosity of 100fb^{-1}. Table II shows their results for two models of strong EWSB: a 1 TeV Higgs and a rescaled $\pi\pi$ scattering model (including chirally coupled ρ, σ and f_0 states) scaled from QCD.

Finally, it was acknowledged that the existence of compositeness at scales of order 10 TeV, as discussed in [4], might give rise to new interesting resonances at energies accessible to the VLHC.

Drawing any firm conclusions about the physics of the VLHC is currently impossible, because we do not know what underlies electroweak symmetry breaking. For the purposes of this working group we assume that it involves some new strong dynamics. It then seems reasonable to conclude that:

- The VLHC should be designed to probe the TeV scale in detail, since the physics associated with electroweak symmetry breaking will be there. This is the only scale at which we can currently say much about the possibilities for new physics. If the LHC has discovered this physics, the VLHC will be able to explore it in depth. If this physics lies just beyond the reach of the LHC, we will nonetheless know it must exist, and the VLHC will catch it.

- At the same time, the VLHC should have an ultimate reach of 10 TeV or more at the partonic scale, so that it can be sensitive to any relatively low-lying phenomena associated with flavor physics.

- The VLHC detector(s) will need to be capable of identifying final states involving multiple vector bosons. This will require good capability for measuring the charge and momentum of leptons, and the energy and direction of hadronic jets (including forward jets associated with spectator quarks). It is not clear if missing E_T measurement will have a high priority. Tagging the jets associated with high-energy top quarks or taus would also be very useful, because the physics of flavor-symmetry breaking might be expected to give top- and tau-enriched signals. Tagging heavy flavor in the environment of the VLHC will be an interesting challenge!

- While a compelling case for studying the TeV scale exists, far less is known about what might lie at higher scales. A challenge to theorists is to identify the possibilities for 10 TeV-scale physics. For instance, it would be interesting to know the extent to which specific classes of experimental results at lower energies (e.g. observing a particular spectrum of technipions at the LHC) would help narrow the options at higher scales.

However nature has chosen to construct the world, we can be sure that if it involves new strong dynamics the VLHC will have a rich spectrum of new physics to explore.

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III. SUPERSYMMETRY WORKING GROUP

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Assessing the role of a VLHC as a tool for studying supersymmetry at this point in time is a problematic enterprise. This question depends largely and significantly on what is and is not seen in future collider experiments. As a candidate for physics just beyond the standard model, supersymmetry presents us with a large variety of models and frameworks. Still, in this context, it is reasonable to ask "under what circumstances would a very high energy collider like the VLHC further, or possibly complete, our understanding of weak-scale supersymmetry?" The principal scenarios which could require a very high energy accelerator fall into two classes: Models with a multi-scale superpartner spectrum, and models with gauge mediated supersymmetry breaking. [3]

If the physics just beyond the standard model is supersymmetric, naturalness requires an abundance of superpartners with masses below a few hundred GeV[1]. These new spectra should be well within the range of the LHC and a 1.5 TeV NLC, and it is likely the lighter of these particles will be accessible at the Tevatron and perhaps LEP-II. If no evidence of supersymmetry is seen by the time the LHC is in operation, supersymmetry will have little motivation as the physics just beyond the weak-scale. In this case, it is supersymmetry and not the VLHC which is lacking motivation and one would expect new dynamics of the type discussed by other groups in the VLHC study. If SUSY does appear at the weak-scale, it will be discovered by the next generations of accelerators (Tevatron, LEP-II, LHC). Moreover, the LHC and a 1-1.5 TeV NLC could provide us with considerable information about the spectroscopy and interactions of superparticles. What might we learn about SUSY at these colliders that would argue for a higher energy machine such as the VLHC?

It is possible that pre-VLHC experiments would only uncover part of the supersymmetric spectrum. Although the simplest formulations of weak-scale supersymmetry would place *all* of the superpartners below a few–several hundred GeV, it is tenable for some superpartners to appear at a higher scale[2]. Because the first two generations of squarks and sleptons couple less strongly to the Higgs sector, it is possible for them to have masses of several TeV without violating naturalness unacceptably. Supersymmetry requires at least two Higgs doublets, and if the multi-TeV scale involves new dynamics, it is also conceivable for part of the Higgs sector to have masses as heavy as a few TeV[2]. Evidence for a multi-scale superpartner spectrum would be inferred from the absence of some modes of superpartner production. Moreover, the radiative effects of multi-TeV superpartners would induce a non-decoupling violation of the equality between the gauge couplings of bosons and gauginos. This violation can occur at the $1 - 10\%$ level for multi-TeV scale superpartners [3].

The most compelling case for a VLHC would arise if future collider experiments could probe the dynamics of supersymmetry breaking. Any supersymmetric theory of physics beyond the standard model must contain a mechanism for breaking supersymmetry and a method (messenger) for communicating this breaking to the superpartners of the standard model particles. Hence, any SUSY discovery immediately implies the existence of two, possibly distinct, scales beyond the weak-scale: the fundamental scale of SUSY breaking and the messenger scale. A typical superpartner mass $\tilde{m}$ is related to the messenger scale M and the dimension-two supersymmetry breaking vev F by:

$$\tilde{m} \propto \eta \frac{F}{M} \tag{1}$$

here we include a parameter η as a placeholder for additional suppressions which can be supplied by dimensionless couplings. If supersymmetry breaking is mediated by gravitational interactions, $M = M_{Pl}$, requiring $\sqrt{F} \sim 10^{10} GeV$ a scale so high as to be irrelevant for conceivable collider experiments. If supersymmetry breaking is communicated by gauge interactions, M is replaced by the mass of heavy vector-like messenger fields and the parameter η contains a factor $\alpha/4\pi$. For $\sqrt{F} \sim M$, it is possible that the messengers of supersymmetry breaking and the fundamental scale of SUSY breaking itself are as low as $10-10^2$ TeV. However even with gauge mediation these relatively low scales are not inevitable. Anything resembling a "no-lose" theorem for the VLHC would rely both our ability to determine that supersymmetry breaking has been communicated by gauge interactions, and on our ability to place an upper bound on the messenger scale.

We have at least two ways of distinguishing gauge-mediated SUSY breaking from gravitationally mediated SUSY breaking. In their simplest forms, these two mechanisms for mediating SUSY breaking lead to rather different patterns of superpartner masses (see for example Figs. 10–11 of Ref. [4]). A more dramatic diagnostic comes from the decays of superpartners. In gravitationally mediated models, the lightest superpartner–LSP, typically the lightest neutralino – $\tilde{\chi}_1^0$ is stable. [4] In gauge mediated models, the gravitino, with a mass typically on the scale of eV's takes on the role of the LSP. In this case, distinctive decays of the next to lightest superpartners–NLSP, into the gravitino *e.g.*, $\tilde{\chi}_1^0 \to \gamma + \tilde{G}$ may occur inside the detector, leading to signatures with two-photons, missing energy and various combinations of jets and leptons[5, 6, 7, 8]. (For other possibilities see for example [9]).

The more challenging task is determining if the messenger sector and/or the fundamental scale of supersymmetry breaking is within reach of the VLHC. We can hope to learn something about a potential multi-TeV messenger scale from the mass spectra of superpartners and from their decays to gravitinos.

The field(s) responsible for SUSY breaking, whether fundamental or composite may have both supersymmetry preserving and dimension-two supersymmetry breaking vevs which we denote by S and F_S respectively. In the simplest models, if the

[3] Of course, other possible motivations for a VLHC, including extended gauge groups, extended heavy Higgs sectors, or additional heavy exotic-particles are compatible with weak-scale SUSY, but these augmentations are not specific to SUSY models, and these subjects are treated in detail by the New Strong Dynamics, and Exotics groups.

[4] Assuming R-parity conservation.

field responsible for supersymmetry breaking couples to a pair of messengers with a Yukawa coupling λ, each supermultiplet of messengers will split into a pair of heavy and light scalars along with an intermediate mass fermion. In this case messenger masses can be written in terms of two parameters[7]:

$$\begin{aligned} M_f &= \frac{\Lambda}{x} \\ M_{\ell,h} &= \frac{\Lambda}{x}\sqrt{1 \mp x} \end{aligned} \qquad (2)$$

The scale $\Lambda = F_S/S$, is roughly a factor of 10^2 larger than a typical superpartner mass, and will be determined once the magnitudes of superpartner masses are measured *e.g.*, $m_{\tilde{g}}, m_{\tilde{q}} \sim \frac{\alpha_s}{4\pi}\Lambda$. The residual uncertainty in the values of messenger masses is parameterized by $x = F_S/\lambda S^2 = \lambda^{-1}\Lambda^2/F_S$. For simplicity we neglect variations in λ across different messenger representations. In order to avoid unwanted breaking of color, x is bounded from above by one. For fixed superpartner masses, as $x \to 0$, messenger particles become inaccessibly heavy, even for a VLHC.

The appearance of heavy messenger representations, induce soft supersymmetry breaking masses for the SM superpartners through loop corrections. At a renormalization group scale $\mu \sim M_f$ the induced gaugino masses, M_a and scalar superpartner masses $\tilde{m}$ take the form: [7, 10, 11]:

$$\begin{aligned} M_a &= \frac{\alpha_a}{4\pi}\Lambda \sum_i n_a(i) g(x_i) \\ \tilde{m}^2 &= 2\Lambda^2 \sum_a \left(\frac{\alpha_a}{4\pi}\right)^2 C_a \sum_i n_a(i) f(x_i), \end{aligned} \qquad (3)$$

where C_a is the quadratic Casimir invariant of the MSSM superpartner field, and $n_a(i)$ is the Dynkin index of the i-th messenger pair. For the minimal $\mathbf{5} + \bar{\mathbf{5}}$ model, the sum over messenger representations: $\sum_i n_1(i) = \sum_i n_2(i) = \sum_i n_3(i) = 1$.

The superpartner mass spectrum depends on x in two ways, so a precise measurement of the superpartner spectrum can in principle be used to place an upper-bound on the messenger sector. The masses in Eq. 3 must be renormalized down to low energy. This induces a logarithmic dependence of the superpartner masses on x. However, the softness of this logarithmic dependence makes the prospect of obtaining an upper bound on messenger masses low enough to provide a guarantee for the discovery at a VLHC appear quite challenging.

In the fortunate circumstances that x is close to one, and upper-bound on the messenger scale could be achieved by examining the ratio of gaugino and scalar superpartner masses. For small x, the functions $g(x)$ and $f(x)$ are very close to one, and the only dependence of superpartner masses on the messenger scale is the logarithmic dependence discussed above. As x approaches 1 the functions $f(x)$ and $g(x)$ depart from values close to one. In this case examination of scalar superpartner–gaugino mass ratios may provide a quantitative measure of the messenger scale. The relevant quantity is $\sqrt{f}/g$, which is always less than unity and approaches 1 for $x \to 0$. $\sqrt{f}/g \lesssim .8\ (.9)\ ((.95))$, requires $x \gtrsim .9\ (.72)\ ((.54))$ respectively. This approach also appears quite challenging, unless x is quite close to one. Moreover, the simple dependence of the superpartner mass ratios on $\sqrt{f}/g$ occurs at messenger energy scales, and this contribution must be disentangled from renormalization effects, the dependence on the messenger content, and other effects. However, these fortuitously large values of x also coincide with the light messenger masses we have the best chance of probing. Our ability to use superpartner mass measurements to place an upper bound on the messenger scale which lie within the reach of a VLHC requires that future colliders make reasonably precise measurements of superpartner masses.

Recent studies of the potential for superpartner mass measurements at the LHC appear quite promising. For example, Hinchliffe *et.al*, [12] were able to extract superpartner mass measurements at the level of $\sim 10\%$ and $\sim 20\%$ for Snowmass LHC study. However, the precision of these measurements depends on were one is in SUSY parameter space, and these analyses are not model independent. How precisely, and model-independently we will be able to measure superpartner masses at the LHC is not yet known. More detailed analyses have been made concerning precision measurements achievable at an NLC [13]. If at all possible, bounding the messenger scale significantly may require a future lepton collider, but whether this is a necessity will not be clear for some time.

An upper bound on the messenger scale could also be inferred from upper bounds on the displaced vertex in NLSP decay. The gravitino coupling to superpartners diminishes significantly as the scale supersymmetry breaking increases. Accordingly, a shorter lifetime for the NLSP requires a lower scale of supersymmetry breaking and lighter messenger masses. Rewriting Eq. 2 for the messenger fermion mass, a bound on F can be translated into a bound on the messenger scale M:

$$M_f = \lambda \frac{F_S}{\Lambda} < \lambda \frac{F_{tot}}{\Lambda} \lesssim \frac{F_{tot}}{\Lambda} \qquad (4)$$

here we make a distinction between F_S and F_{tot} because there may be other sources of supersymmetry breaking in addition to the SUSY breaking field coupled to messenger fields. Because Λ can be in principle determined by measurements of superpartner masses, an upper-bound on the messenger scale can be found if we can place and upper bound on F_{tot} or equivalently an upper bound on the distance to the displaced vertex. The decay width for the lightest neutralino into a gravitino in gauge mediated models is

$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}\gamma) = 20\kappa \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{\sqrt{F}}{10\ \mathrm{TeV}}\right)^{-4} \mathrm{eV} \qquad (5)$$

where κ is the photino content of $\tilde{\chi}_1^0$. The probability that the neutralino travels a distance x before decaying in the detector is $P(x) = 1 - e^{-x/L}$, where

$$L = \frac{9.9 \times 10^{-3} \mu m}{\kappa} \left(\frac{m_{\tilde{\chi}_1^0}}{100 GeV}\right)^{-5} \left(\frac{\sqrt{F_{tot}}}{10\ \mathrm{TeV}}\right)^4 \left(E_{\tilde{\chi}_1^0}^2 / m_{\tilde{\chi}_1^0}^2 - 1\right)^{\frac{1}{2}}. \qquad (6)$$

Leading to the bound:

$$M_f \lesssim 10 \text{ TeV} \left(\frac{100 \text{ TeV}}{\Lambda}\right)\left(\frac{\kappa L}{0.99\ \mu\text{m}}\right)^{1/2} \left(\frac{100 \text{ GeV}}{m_{\tilde{\chi}_1^0}}\right)^{5/2}\left(E^2_{\tilde{\chi}_1^0}/m^2_{\tilde{\chi}_1^0}-1\right)^{-\frac{1}{4}} \quad (7)$$

So this method will challenge our ability to resolve relatively small displaced vertices as well.

In both cases, establishing that messengers lie within reach of a VLHC requires relatively large values of x, relatively light values of F, and reliable measurements of superpartner masses. On one hand combining these fortunate circumstances may appear to be wishful, but the fortunate circumstances under which we would be able to identify and place reliable upper-bounds messenger scale overlap with those where multi-TeV messenger states are light enough to be accessible at a VLHC. Good luck is when preparation and opportunity meet, and we should be prepared to exploit this opportunity if it arises.

We conclude with a few remarks about the collider signatures of the messenger sector. If light enough, messenger particles would be pair produced at the VLHC. Heavy messenger scalars will decay to messenger fermions by radiating gauginos and messenger fermions will decay to the lighter messenger scalars by radiating gauginos as well. Renormalizable Yukawa interactions between messenger fields and standard model fields potentially introduce flavor changing neutral currents, spoiling the principle motivation for low energy 10–100 TeV SUSY breaking. In the absence of such couplings the lightest messenger fields contain conserved quantum numbers and are stable. The presence of nonrenormalizable operators may induce messenger decay, but not on time scales relevant to collider searches. Planck mass suppressed dim-5 operators, would for example lead messengers to decay with lifetimes of $\sim 10^{-1}$–10^{-2} s[10].

The apparent unification of gauge couplings at high energies $\sim 10^{16}$ GeV is most naturally accommodated by messenger representations in complete $SU(5)$ representation. In the minimal messenger model, the messengers are contained in the $\mathbf{5}+\bar{\mathbf{5}}$ representation of $SU(5)$. Under the standard model gauge group $SU(3)\times SU(2)\times U(1)$. The $\bar{\mathbf{5}}$ representation decomposes as:

$$\bar{\mathbf{5}} = (\bar{\mathbf{3}}, \mathbf{1}, \frac{\mathbf{1}}{\mathbf{3}}) + (\mathbf{1}, \mathbf{2}, -\frac{\mathbf{1}}{\mathbf{2}}). \quad (8)$$

Together with the 5, the lightest scalar messenger states will these states will have the quantum numbers of and has the same quantum numbers as $SU(2)$-singlet down squarks– D^c, and left handed slepton doublet – L respectively. The colored scalar messenger states hadronize to form multi-TeV objects with the same quantum numbers as a neutron or proton, and would look like a canon ball in the detector.

In the absence of a discovery of supersymmetry at or before the LHC SUSY provides little motivation for a VLHC. However, it should be understood in this case that it is supersymmetry and not the VLHC which is lacking motivation.

If the world is supersymmetric above the weak scale and supersymmetry breaking is transmitted to the standard model superpartners by gauge interactions, the VLHC may be a logical step in the worlds future high energy physics program. However, this is not inevitable. Supersymmetry could be found at the several hundred GeV scale without giving us any compelling reason to expect another layer of structure at the multi-TeV scale. The case for such a machine will rest on what nature provides for us, and on our ability to exploit the Tevatron, LEP-II and the LHC.

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IV. EXOTICS WORKING GROUP

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A. Introduction

We summarize the reach of the VLHC for contact interactions and new heavy particles in non-supersymmetric extensions of the Standard Model.

The Standard Model (SM) of strong and electroweak interactions, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, has been extremely successful phenomenologically. It has provided the theoretical framework for the description of a very rich phenomenology spanning a wide range of energies, from the atomic scale up to the Z boson mass. However, the SM has a number of shortcomings. In particular, it does not explain the origin of mass, the observed hierarchical pattern of fermion masses, and why there are three generations of quarks and leptons. It is widely believed that at high energies deviations from the SM will appear, signaling the presence of new physics.

Many theoretical models which attempt to overcome the shortcomings of the SM either involve new gauge symmetries, or predict that quarks and leptons are composite objects. A common feature of these models are new interactions and new heavy particles. The mass of these objects is in general given by the energy scale of the new interaction. At low energies, their existence is signalled by four fermion contact interactions. A hadron collider with a center of mass energy of 100 TeV or more (VLHC) would offer an excellent chance to search for contact interactions and also, directly, for the new heavy particles associated with new interactions.

In this brief report, we discuss the potential of the VLHC to search for contact interactions associated with quark and lepton compositeness, and illustrate the discovery mass reach for new heavy states by describing the search for excited quarks [1] in some detail. In addition, we list benchmark results for additional gauge bosons [2] and leptoquarks [3], which are predicted by many grand unified models. We also briefly comment on the discovery mass reach for colorons [4] and axigluons [5] which appear in models with extended strong interaction gauge symmetries. Supersymmetric and technicolor particle searches at the VLHC are described in Refs. [6] and [7] and are therefore not discussed here.

B. Contact Interactions

The repetition of the three generations of quarks and leptons suggests that they are bound states of more fundamental fermions, and perhaps bosons, bound together by a new interaction which is characterized by an energy scale Λ^+. At energies much smaller than Λ^+, the substructure of quarks and leptons is signalled by the appearance of four fermion contact interactions which arise from the exchange of bound states of the subconstituents [8]. The lowest order contact terms are dimension 6 four-fermion interactions which can affect jet and Drell-Yan production at a hadron collider. Compared with the SM terms, they are suppressed by a factor $1/\Lambda^{+2}$. The signature for four-quark contact interactions, for example, would be an excess of events at large transverse energy, E_T, similar to that observed by CDF in inclusive jet production at the Tevatron in Run 1a [9].

However, from the CDF measurement of the jet inclusive cross section it is apparent that it is difficult to discover a signal for contact interactions by looking for an excess of events at high transverse energies, due to uncertainties in the parton distribution functions, ambiguities in QCD calculations, and systematic uncertainties in jet energy measurements [10]. Another signal for quark – quark contact interactions, which is not very sensitive to theoretical or jet energy uncertainties, is the dijet angular distribution which is more isotropic than that predicted by QCD if contact terms are present. Both CDF [11] and DØ [12] have found good agreement with the shape predicted by QCD. The DØ dijet angular distribution is shown in Fig. 1. The quantity χ shown here is related to the scattering angle in the center of mass frame, θ^*, by $\chi = (1 + |\cos\theta^*|)/(1 - |\cos\theta^*|)$. Using a model with left-handed contact interactions, DØ sets a preliminary 95% confidence level (CL) limit on the interaction scale, Λ^+, of $\Lambda^+ > 2.0$ TeV [12]. CDF obtains a 95% CL limit of $\Lambda^+ > 1.8$ TeV [11]. From the inclusive jet analysis, the dijet angular distribution and other searches for contact interactions at the Tevatron [13], as well as searches at the CERN $p\bar{p}$ collider [14] and simulations carried out for the LHC [15], we conclude that the compositeness scale reach of a hadron collider is roughly equal to its center of mass energy, $\sqrt{s}$. Detailed simulations for the VLHC, however, have not been carried out so far.

C. Excited Quarks

Conclusive evidence for a new layer of substructure would be provided by the direct observation of excited states of the known quarks and leptons. In the following we shall concentrate on excited quarks with spin 1/2 and weak isospin 1/2. The coupling between excited spin 1/2 quarks, ordinary quarks and gauge bosons is uniquely fixed to be of magnetic moment type by gauge invariance. Excited quarks decay into quarks and a gluon, photon or a W/Z boson, or, via contact interactions into $\bar{q}qq'$ final states [16]. Subsequently, only decays via gauge interactions are considered. Excited quarks are then expected to decay predominantly via strong interactions; radiative decays and decays into a quark and a W/Z boson will typically appear at $\mathcal{O}(\alpha/\alpha_s)$, *i.e.* at the few per cent level [17].

In hadronic collisions, excited quarks can be produced singly via quark gluon fusion. The subsequent $q^* \to qg$ decay leads to a peak in the two jet invariant mass distribution located at $m(jj) = M^*$, where M^* is the excited quark mass. UA2 [18], CDF [19, 20] and DØ [21] have searched for q^* production in the dijet invariant mass distribution. Figure 2 shows the region of the excited quark coupling $f = f' = f_s$ versus M^* plane excluded by those experiments. Here, f, f' and f_s are the strength of the $SU(2)_L$, $U(1)_Y$ and $SU(3)_C$ couplings of the q^* to quarks and the SM gauge fields when the scale of the magnetic moment coupling is set equal to M^*. For $f = f' = f_s = 1$,

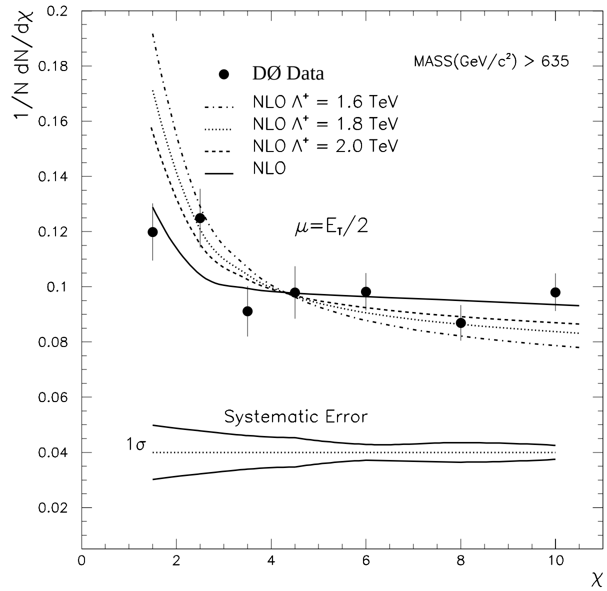

Figure 1: The DØ dijet angular distribution (points) for dijet masses larger than 635 GeV compared to predictions of NLO QCD (solid line), and NLO QCD with a quark contact interaction for various values of Λ^+.

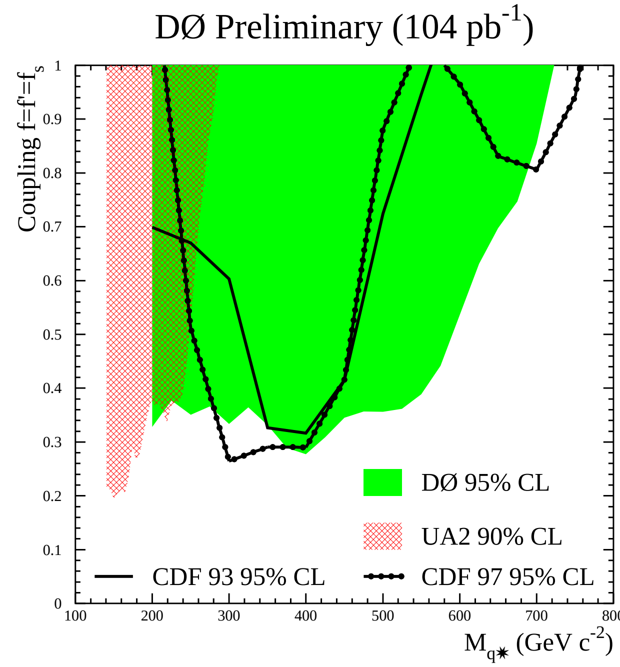

Figure 2: The region of the excited quark coupling versus mass plane excluded by UA2, CDF and DØ measurements.

CDF sets a lower 95% CL limit of $M^* > 760$ GeV (with the exception of the region $570\ \text{GeV} < M^* < 580$ GeV), whereas DØ finds a (preliminary) bound of $M^* > 725$ GeV (95% CL). Only first generation excited quarks, u^* and d^*, are considered. The u^* and d^* are assumed to be degenerate in mass.

The discovery reach of the VLHC in this model has been studied in Ref. [1], assuming a Gaussian dijet invariant mass resolution of $\sigma = 0.1\,m(jj)$, which is similar to that of the CDF detector. Since $\Gamma(q^*) \approx 0.04\,M^*$ in the model considered, approximately 90% of the two jet events from an excited quark will be in the mass window $0.84\,M^* < m(jj) < 1.16\,M^*$. To estimate the mass reach, the differential cross section is integrated within this window for both the q^* signal and the QCD background. The QCD background rate is then used to find the $5\,\sigma$ discovery cross section. This is defined as the cross section which is above the background by $5\,\sigma$, where σ is the statistical error on the measured cross section.

The discovery mass reach for excited quarks at the VLHC is shown in Fig. 3 for three different machine energies as a function of the integrated luminosity. For an integrated luminosity of 10^4 fb^{-1}, the mass reach at a pp collider with center of mass energy of 50 TeV (200 TeV) is $M^* = 25$ TeV (78 TeV). However, an excited quark with a mass of 25 TeV would be discovered at a pp collider with $\sqrt{s} = 100$ TeV with only 13 fb^{-1}. In this case, doubling the collider energy is equivalent to an increase in integrated luminosity of almost a factor 1000. A similar result is obtained from other heavy particle searches.

D. Additional Vector Bosons and Leptoquarks

The discovery of new gauge bosons, W', Z', would signal an extension of the SM gauge group by an additional factor such as $U(1)$ or $SU(2)$. Z' bosons appear in most Grand Unified Theories. W' bosons are typical for models which restore the left-right symmetry at high energies. The mass reach of a hadron collider for new gauge bosons is model dependent due to the variations in their couplings to quarks and leptons. At hadron colliders, new gauge bosons can be produced directly via quark – antiquark annihilation, $q\bar{q}' \to W'$ and $q\bar{q} \to Z'$. CDF [22] and DØ [23] have searched for W' (including righthanded W bosons) and Z' bosons in a variety of models. The limits obtained vary between 565 GeV and 720 GeV. The discovery reach of the VLHC for new gauge bosons has been investigated in Ref. [2]. Only the leptonic decays of the W' and Z' bosons, which are virtually background free, were used in this analysis. At a 200 TeV pp collider, with an integrated luminosity of 1000 fb^{-1}, Z' bosons with mass up to $M_{Z'} = 40 - 50$ TeV can be detected [2], whereas the mass reach for W' bosons is 50 – 60 TeV, depending on the details of the model considered.

Many Grand Unified Theories predict the existence of leptoquarks, LQ, which are spin 0 (scalar) or spin 1 (vector) color triplet objects coupling to a quark – lepton pair. Searches for leptoquarks have been performed at LEP [24], HERA [25] and the Tevatron [26]. The most stringent bounds presently come from Tevatron data which exclude, at 95% CL, scalar (vector) first generation leptoquarks with $B(LQ \to eq) = \beta = 0.5$ if their mass is $M_{LQ} < 192$ GeV (270 GeV) [27]. Leptoquarks can be produced either singly or in pairs at a hadron collider. The cross

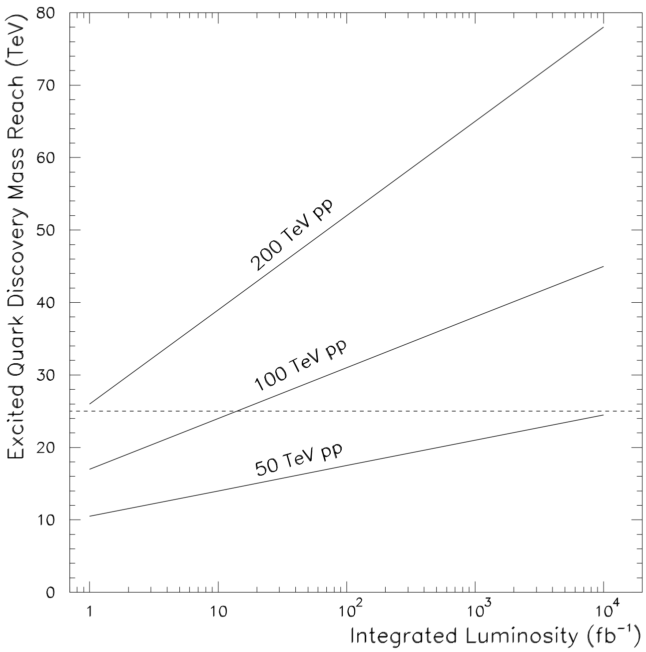

Figure 3: The $5\,\sigma$ discovery mass reach for $pp \to q^* \to jj$ is shown as a function of the integrated luminosity for a VLHC with center of mass energy of 50 TeV, 100 TeV and 200 TeV (solid lines). The horizontal dashed line illustrates what integrated luminosity is necessary to discover an excited quark with mass $M^* = 25$ TeV.

section for single production depends on unknown Yukawa couplings of the leptoquark. Pair production, on the other hand, proceeds via QCD interactions, and therefore depends only on the leptoquark spin. Unless the Yukawa couplings are large, pair production dominates. The discovery reach of the VLHC for leptoquarks has been studied in Ref. [3]. At a proton – proton collider with $\sqrt{s} = 200$ TeV and an integrated luminosity of 1000 fb^{-1}, one should be able to detect scalar (vector) leptoquarks with a mass up to $M_{LQ} \approx 14$ TeV ($M_{LQ} \approx 23$ TeV), if $\beta = 0.5$. For $\beta = 1$, the mass reach is higher by about 1 TeV.

If leptoquarks are sufficiently light, the VLHC will make it possible to probe the Yukawa couplings of leptoquarks. At a 100 TeV proton – proton collider, Yukawa couplings as small as $\lambda/e = 10^{-3}$ ($\lambda/e = 10^{-5}$) [e is the electric charge unit] can be probed for $M_{LQ} = 2$ TeV ($M_{LQ} = 1$ TeV) [28].

At a $p\bar{p}$ collider, the search limits for new gauge bosons and leptoquarks are both about 20 – 30% higher than those found for pp collisions with the same center of mass energy [2, 3].

E. Colorons and Axigluons

In the coloron [4] model, the symmetry group of the strong interactions, $SU(3)_C$, is replaced by a $SU(3)_1 \times SU(3)_2$ group, which is spontaneously broken to $SU(3)_C$ at an unknown scale v. The corresponding color octet of massive gauge bosons (colorons) couples vector-like to quarks. In the axigluon [5] model, the gauge group is $SU(3)_L \times SU(3)_R$, and the coupling of the massive color octet vector bosons (axigluons) to quarks is axial vector-like. Colorons and axigluons can be produced via $q\bar{q}$ annihilation, and lead to a peak in the two jet invariant mass distribution, very much like an excited quark. CDF has searched for these particles in the dijet channel, and places a lower limit of 980 GeV (95% CL) on their mass [19]. The discovery reach of the VLHC for these particles has not been estimated yet. It is expected that colorons and axigluons in the multi-ten TeV range can be discovered at a 200 TeV pp collider.

F. Conclusions

In this brief report, we have discussed the search for contact interactions and new heavy particles, which appear in popular non-supersymmetric extensions of the SM, at the VLHC. The search potential of the VLHC for these new states is truly enormous; for a collider with a center of mass energy of 100 TeV or more, the limits are in general in the multi-ten TeV region. To maximize the heavy particle search potential, the VLHC should strive to the highest energy possible. It should be emphasized, however, that there are no models which firmly predict the existence of new particles in the region of interest for the VLHC. On the other hand, in a situation where first signs of new physics are observed at the LHC in the form of contact interactions, but the scale of new physics is too high to allow production of the associated new states directly, the VLHC will be a perfect tool for an in-depth investigation of the beyond the Standard Model frontier.

G. Acknowledgments

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V. FULL RAPIDITY PHYSICS WORKING GROUP

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Particle production at a VLHC operating at $\sqrt{s} = 100$ TeV will span some 24 units of rapidity. Such an accelerator should include a detector and interaction region optimized for full acceptance[1]. Design goals for such a detector should include:

- all charged particles, photons and neutrons of generic p_t should be observed and their energies/momenta well measured over all of phase space
- diffractive and elastically scattered protons should be well measured
- muon identification should be extended into the far forward regions
- the physics of rapidity gaps should not be compromised

While no full acceptance detector has ever operated at collider energies, such a detector, FELIX, is being proposed for the LHC[2]. The lessons learned in the design and operation of FELIX will provide the basis for a full acceptance detector at the VLHC.

The need for a full acceptance detector at the VLHC follows from basic kinematics. Physics on the energy frontier is necessarily central and will largely be the domain of optimized central detectors, conversely, any physics not on the energy frontier is forward physics, and will benefit from a full acceptance detector.

A second point is that a full acceptance detector should operate in an environment of ~ 1 interaction per beam crossing. This ensures that global event structure can be determined, event by event. In contrast, central detectors operating on the energy frontier will also be operating on the luminosity frontier, with many collisions per beam crossing. This observation also has a corollary: any precision physics or standard physics will likely be done well by a full acceptance detector.

Finally, one should state the obvious: a central detector, optimized for high-p_t physics at the energy frontier in messy environments will only be sensitive to a small fraction of the kinematically allowed phase space. The discovery potential of a full acceptance detector operating in unexplored regions of phase space should thus be noted.

A few examples illustrate the scope of a full acceptance detector at the VLHC.

A. The small-x frontier

Hard processes at the VLHC span a kinematically allowed region in (x, Q^2) given by

$$x_1 x_2 \geq \frac{4E_t^2}{s}, Q^2 \geq E_{tmin}^2 \tag{9}$$

where x_1, x_2 are the momentum fractions of the two partons involved in the hard scattering, and E_{tmin} is the minimum transverse energy needed to identify the process. Thus, at $\sqrt{s} = 100$ TeV, for scattering to two jets with $E_{tmin} \sim 10$ GeV, one can probe the proton structure down to $x \sim 4 * 10^{-8}$. This is some 4 orders of magnitude smaller than the HERA limit, and will be an extremely interesting domain of QCD[3].

B. Forward particle tags

Particle production in the fragmentation region has never been studied at collider energies. A full acceptance detector, with complete coverage for neutral particles down to zero degrees, and with complete charged particle tracking, will not only measure such production exquisitely, it will also be able to tag leading particles. For example, detecting leading deltas or neutrons tags the rest of the event as a collision between a beam nucleon with the exchanged non-strange meson. The VLHC thus becomes an effective meson-proton collider. One can similarly tag on both sides, defining meson-meson interactions, tag on strange meson exchange, and so on. Aside from the rich physics program that this capability will allow, it is also necessary for total cross section measurements which are crucial for determining the cross sections for all physics processes.

C. Rapidity gap phenomena

While perturbative QCD has been extremely successful at describing and predicting many aspects of the strong interactions, many fundamental processes cannot yet be calculated in this language. Processes such as elastic and diffractive scattering are instead still understood in terms of Regge theory, with elusive objects like the “Pomeron” playing a central role in current phenomenology. The study of such processes, in particular hard diffractive processes, has expanded dramatically in recent years[4], with pioneering work at UA8, followed by important ongoing studies at HERA and the Tevatron. It should be noted that all of these current or past experiments would have benefited tremendously from increased coverage. A full acceptance detector at the VLHC will be able to do all of this physics superbly, allowing a continuous transition from the clearly perturbative regime into the non-perturbative regime in a controlled manner.

D. Cosmic ray phenomena

All experimental information about particle interactions at the highest energies comes from cosmic ray experiments. LHC energies correspond to primary cosmic rays of about 100 PeV (10^{17} eV); particles with energies of 10^{20} eV have been observed. While fraught with problems of limited statistics and complicated systematics, cosmic ray experimentalists can point with pride to a number of important discoveries, including a prediscovery of charm. It is thus important to take note of the fact that there are a number of anomalies reported in studies of cosmic ray interactions hinting at unusual physics, not anticipated in the standard model. These anomalies are observed at energies beyond the reach of current accelerators. Further, since cosmic ray experiments track energy flow, their sensitivity is typically in the fragmentation region, beyond the reach of current (central) collider detectors. A full acceptance detector should be designed keeping these anomalies in mind. The list of anomalies includes reports of anomalous mean free paths, anomalous forward heavy flavor production, anomalous attenuation of secondary hadrons, anomalies in the energy fraction of air showers, scaling anomalies, anomalies in the charged to neutral ratio (Centauros and anti-Centauros), and anomalously parallel multi-muon bundles. Only detectors with good acceptance in the very forward direction can test these claims in an accelerator environment.

E. Summary

The task of designing a full acceptance detector for the VLHC is non-trivial, and requires careful coordination with the design of the machine itself. The starting point is necessarily the magnetic architecture, which must be integrated into the machine lattice. The design of FELIX, a possible full acceptance detector for the LHC, should serve as a prototype for discussing the design of a full rapidity detector at the VLHC.

Important features of the FELIX design which may translate to the VLHC include:

1. The relatively low luminosity should permit an insertion in which focusing quadrupoles are located a large distance from the collision point. In FELIX, this distance is more than 100 m.

2. The requirement of complete calorimetric coverage for neutrals demands a precision zero degree calorimeter. This requires that the beams be separated by a significant transverse distance (in FELIX, 42 cm) at the location of the zero degree calorimeter. The beam separation is defined in FELIX by the requirement that the experiment co-habit with the RF cavities, located 140 m from the beam.

3. The dipole fields needed to move the beams through the experimental area within the above constraints will play a dual role as spectrometer analysis magnets and consequently should have the largest possible aperture.

4. While the central region is not the focus of the proposed experiment, it should nevertheless have a good central detector. Such a detector might be built around elements of the preceeding generation of collider detectors. It need not be of the quality of the high p_t central VLHC detector, but should also not be neglected.

Although it is premature to begin detailed work on possible optics for an insertion at the VLHC, the need for a long straight section is clear and should be built into any VLHC design at the earliest stage. Simple scaling with the beam energy (which seems reasonable given constants such as transverse shower sizes in calorimeters) would suggest that the zero degree calorimeter should be located at least 700 m from the collision point. The required beam separation at this point would imply that a straight section with a total length of 2.8–4 km seems appropriate.

A full acceptance detector will provide a powerful tool for the study of physics at the VLHC. While low in cost compared to detectors concentrating on physics at the energy frontier in the central region, a full acceptance detector will combine a strong program of physics complementary to other detectors with a substantial discovery potential, particularly for the "unexpected".

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VI. PRECISION MEASUREMENTS OF HEAVY OBJECTS WORKING GROUP

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A. Introduction

We report on the activities of the Precision Measurements of Heavy Objects working group. The following people contributed to the writing of this summary: Marcel Demarteau, Vassilis Koulovassilopoulos, Joseph Lykken, Stephen Parke(convener during the workshop), Erich Varnes, G. P. Yeh (convener during the workshop).

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.

B. 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.[5]

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 [1].

Here we will simply mention a few features which are particularly relevant for such a very high energy facility as a VLHC.

As we see in Fig. 4, 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

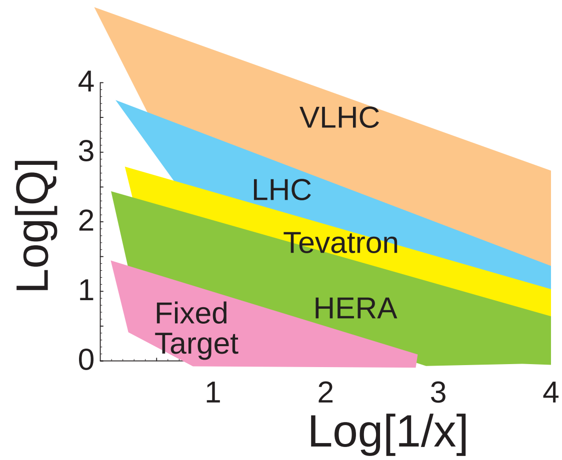

Figure 4: Kinematic range of various machines. Note the small x range is clipped in this plot. The Q scale is in GeV and the logs are base 10.

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.

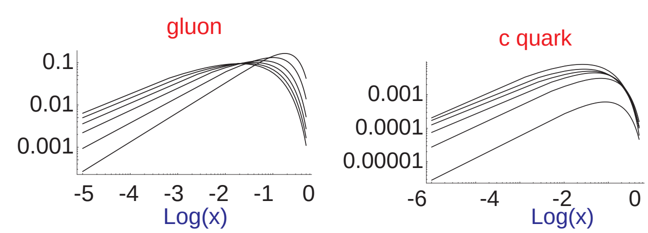

Figure 5: Evolution of the a) gluon and b) charm PDF's in Q *vs.* x. We display $x^2 f_{i/P}(x, Q)$ for $Q = \{2, 10^1, 10^2, 10^3, 10^4, 10^5\}$ GeV.

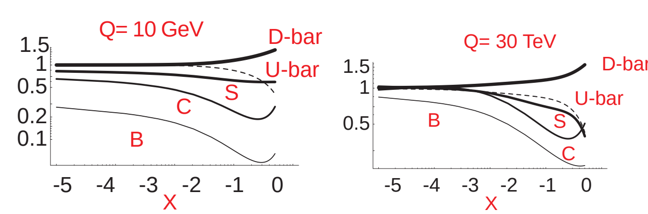

Figure 6: Flavor democracy at a) 10 GeV and b) 30 TeV. We compare the individual parton distributions $f_{i/P}(x, Q)$ to that of the average sea, $(\bar{u} + \bar{d})/2$.

In Fig. 5, 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 $x \sim 0.1$ as the crossing point. In contrast, for the heavy quark PDF's, we see

[5] PDF sets are available via WWW on the CTEQ page at http://www.phys.psu.edu/∼cteq/ and on the The Durham/RAL HEP Database at http://durpdg.dur.ac.uk/HEPDATA/HEPDATA.html.

generally an increase with increasing Q. The momentum fraction of the partons *vs.* energy scale is shown in Table III. 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 that at the very highest energy scales relevant for the VLHC, the strange and charm quark are on par with the up and down sea, (while the bottom quark lags behind a bit). This feature is also displayed in Fig. 6 where we show these contributions for two separate scales. In light of this observation, we must dispense with preconceived notions of what are "traditionally" heavy and light quarks, and be prepared to deal with all quark on an equal footing at a VLHC facility. This approach is discussed in the following section.

Table III: 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	5	4
30 TeV	50	7	9	7	6	4
100 TeV	51	7	10	7	7	4

C. Heavy Quark Hadroproduction

Improved experimental measurements of heavy quark hadroproduction has increased the demand on the theoretical community for more precise predictions [2, 3, 4, 5, 6]. The first Next-to-Leading-Order (NLO) calculations of charm and bottom hadroproduction cross sections were performed some years ago [3]. 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 μ. Both these difficulties indicated that these predictions were missing important physics.

These deficiencies can, in part, be traced to large contributions generated by logarithms associated with the heavy quark mass scale, such as[6] $\ln(s/m_Q^2)$ and $\ln(p_T^2/m_Q^2)$. Pushing the calculation to one more order, formidable as it is, would not 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.

[6]Here, m_Q is the heavy quark mass, s is the energy squared, and p_T is the transverse momentum.

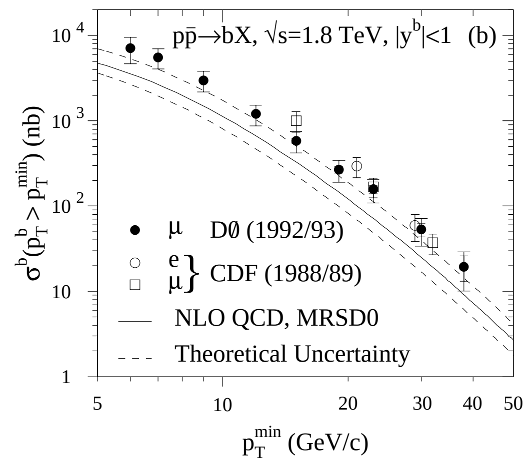

Figure 7: Heavy quark hadroproduction data. *Cf.*, Ref. [2].

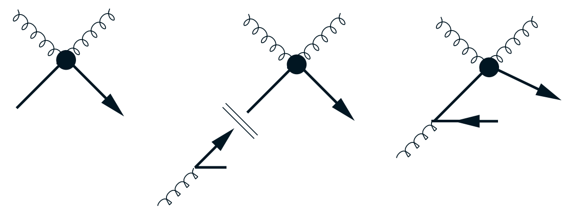

Figure 8: a) Generic leading-order diagram for heavy-flavor excitation (LO-HE), $gQ \to gQ$. b) Subtraction diagram for heavy-flavor excitation (SUB-HE), ${}^1f_{g\to Q} \otimes \sigma(gQ \to gQ)$. c) Next-to-leading-order diagram for heavy-flavor creation (NLO-FC).

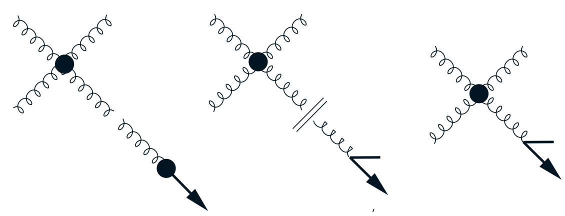

Figure 9: a) Generic leading-order diagram for heavy-flavor fragmentation (LO-HF), $\sigma(gg \to gg) \otimes D_{g\to Q}$. b) Subtraction diagram for heavy-flavor fragmentation (SUB-HF), $\sigma(gg \to gg) \otimes {}^1d_{g\to Q}$. c) Next-to-leading-order diagram for heavy-flavor creation (NLO-FC).

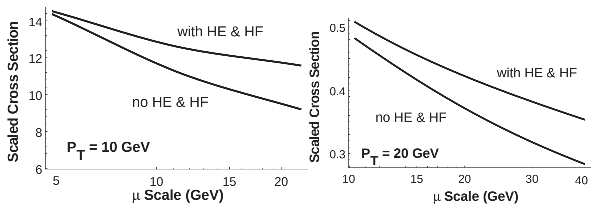

Figure 10: The scaled differential cross section $p_T^5\, d^2\sigma/dp_T^2/dy$ at $p_T = 10, 20\,\mathrm{GeV}$ and $y = 0$ in $(pb - \mathrm{GeV}^3)$ *vs.* μ. The lower curves are the heavy quark production cross sections *ignoring* heavy-flavor excitation (HE) and heavy-flavor fragmentation (HF). The upper curves are the heavy quark production cross sections *including* HE and HF. *Cf.*, Ref. [6].

In 1994, Cacciari and Greco[5] 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[6] 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. 8) and the leading-order heavy-flavor fragmentation (LO-HF) graph (Fig. 9) in the traditional NLO heavy quark calculation [3]. These contributions can not be added naively to the $\mathcal{O}(\alpha_s^3)$ 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 μ-dependence of the full calculation, thus improving the predictive power of the theory. (Cf., Fig 10.)

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.

D. 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: $M_W = 80.356 \pm$

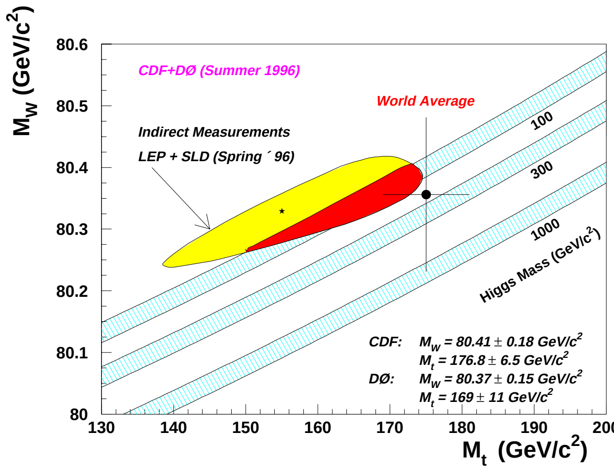

Figure 11: Plot of M_W *vs.* M_t with DØ and CDF preliminary measurements of the W boson and top quark masses. Bands indicate the Standard Model constraints for different Higgs mass values. Indirect measurements from LEP I are also shown. (June, 1997) Taken from Ref. [9].

$0.125\,\mathrm{GeV}/c^2$.

Here, we focus on issues which are unique to a VLHC facility, and refer the reader to the literature for details regarding other topics [7, 8, 9, 10]. 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), $\sigma_{tot} \simeq 120$ 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 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: $M_T = \sqrt{2p_T^e p_T^\nu(1 - \cos\phi^{e\nu})}$, where $\phi^{e\nu}$ 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 (η) can be estimated by scaling results from the CERN $Sp\bar{p}S$ and the Fermilab Tevatron. The shoulder of the pseudorapidity plateau is ~ 3 for $\sqrt{s} = 630\,\mathrm{GeV}$, and ~ 4 for $\sqrt{s} = 1.8$ TeV. This yields an estimate in the range of ~ 5 to 9 for a $\sqrt{s} = 100$ TeV VLHC. Assuming coverage out to $|\eta| \leq 4$, we obtain ~ 1400 charged tracks in the detector calorimeter with which we must contend for the missing E_T calculation, ($\not{E}$). 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 $\not{E}_T$ resolutions of $\sim 4 - 5\,\mathrm{GeV}$, we estimate $\sigma(\not{E}_T) \simeq 25 - 30\,\mathrm{GeV}$ 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, δM_W. For a luminosity of 2 fb^{-1}, δM_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 IV, 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 IV: Anticipated limits on δM_W from present and future facilities. (This compilation is taken from Ref. [9].)

FACILITY	δM_W (MeV/c^2)	$\mathcal{L}$
NuTeV	$\sim$ 100	—
HERA	$\sim$ 60	1000 pb^{-1}
LEP2	$\sim$ 35-45	500 pb^{-1}
Tevatron	$\sim$ 55	1 fb^{-1}
Tevatron	$\sim$ 18	10 fb^{-1}
LHC	$\lesssim$ 15	10 fb^{-1}
VLHC	$\sim$ 20	1 fb^{-1}
VLHC	$\sim$ 15	10 fb^{-1}

E. The Top Quark

The mass of the recently discovered top quark is determined by the CDF and D∅ 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 V, 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 naively 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 γ + 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 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.

Table V: Anticipated accuracy on the top quark mass, as estimated by the TeV2000 report.

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

F. Probing a nonstandard Higgs boson at a VLHC

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 ($\mathcal{L} = 10^{33} - 10^{35} cm^{-2} s^{-1}$) and compared to those obtained for the LHC in [16].

Our analysis is based on the gold-plated channel $H \to ZZ \to l^+l^-l^+l^-$ and assumes cuts on the final-state leptons, which are given by $|\eta^l| < 3$, $p_T^l > 0.5 \times 10^{-3}\sqrt{s}$. 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 ξ 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 ξ, y_t and $\mathcal{L}$ 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 Γ_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 [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 SM width are distributed. Postulating that a nonstandard Higgs boson is "distinguishable" if its width differs from the SM value by at least 3σ, we were able to determine the precision with which the parameter ξ can be measured at the LHC and a VLHC. This is summarized in Table I 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 collider parameters.

G. Supersymmetry

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 $\gtrsim$ 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 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 [19]. While the gauginos and the third generation squarks and sleptons would be within reach of the LHC, investigation of $\{\widetilde{u}, \widetilde{d}, \widetilde{e}, \widetilde{\nu}_e,\}$ and $\{\widetilde{c}, \widetilde{s}, \widetilde{\mu}, \widetilde{\nu_\mu}\}$ 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 efficiently of b-tagging and high p_t lepton detection, for example, are crucial to suppressing the backgrounds.

H. 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 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 $\not{E}$.

In contrast, the strong suit of the VLHC is clearly its kinematic reach. Should there be unexpected sparticles in the $\gtrsim$ 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 TeV regime which will be explored in the near-future; however what we discover in this energy range can provide important clues as to where we should search with a VLHC.

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VII. MULTIPLE INTERACTIONS WORKING GROUP

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The Multiple Interactions working group was charged with investigating issues related to the large number of interactions per crossing envisioned for the VLHC at design luminosity. Presentations and discussions focused on the following topics: corrections to the calorimetric measurements of single-particle and jet energies in the presence of many interactions, multiple interaction corrections to luminosity measurements at the Tevatron, and the measurement of the luminosity in the VLHC environment. As the Tevatron luminosity increased into the range 10^{31} cm^{-2} s^{-1} during Run I, the CDF and DØ experiments learned to cope with increasing, yet small number (1 – 5) of interactions per crossing. The LHC at CERN will provide a more difficult training ground since there will be in average 17 interactions per crossing at the design luminosity of 10^{34} cm^{-2} s^{-1}.

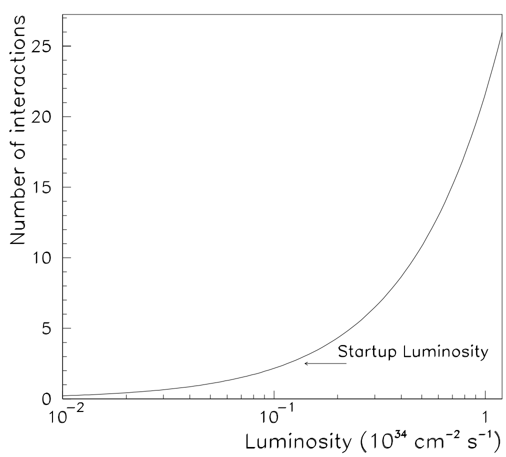

Figure 12: Average number of interactions per crossing as a function of luminosity at the VLHC. The horizontal axis is a log scale labeled in units of 10^{34} cm^{-2} s^{-1}.

The problem with multiple interactions at the VLHC will be worse, yet comparable to the situation at the LHC. The design luminosities are identical (10^{34} cm^{-2} s^{-1}) and the luminous region for a given bunch crossing will be a few cm longitudinally for both machines. While the time between bunch crossings is 25 nsec at the LHC and the bunches are separated by 7.5 m, these numbers are 17 nsec and 5 m, respectively, for the VLHC. Fig. 12 shows the number of interactions per bunch crossing expected at the VLHC as a function of luminosity, assuming an inelastic proton-proton cross section of 130 mbarn. At design luminosity, each beam crossing will yield about 22 interactions.

Both the LHC and the VLHC will likely come online with instantaneous luminosities at least a factor of 10 lower than the design luminosity. Fig. 12 shows that at start-up luminosity, there will only be a few interactions per crossing, so the multiple interaction problem will be similar to that faced at the Tevatron. As discussed below VLHC will benefit from low-luminosity running at start-up, both for physics and detector calibration reasons.

The much higher center-of-mass energy of the VLHC, however, will make the underlying event problem more difficult than at the LHC, since the particle multiplicity and average minimum-bias E$_T$ will be higher. Still an average E$_T$ density of 10's of GeV per unit $\eta - \phi$ at the VLHC design luminosity is manageable if one is searching for high mass particles and jets at $\sqrt{s}$ = 100 TeV.

A precise knowledge of the proton-proton luminosity at a VLHC interaction region is an essential ingredient in the measurement of absolute cross sections in a VLHC experiment. Monitoring the instantaneous luminosity is also important for making corrections to the data for detector effects related to the number of interactions per beam crossing.

The "counting zeros" technique is used by the DØ and CDF experiments at the Fermilab Tevatron collider and leads to an uncertainty of order 5%. A modified version of this technique is expected to yield similar precision at the VLHC even in the presence of large numbers of interactions per bunch crossing.

The counting zeros technique works as follows [1]. Two sets of luminosity monitors, symmetrically located on each side of the interaction region, count the fraction of times a given bunch crossing results in no detected particles on either side. The luminosity is inferred from the rate of such zeros.

The probability of having an empty crossing where a forward/backward coincidence is not recorded is given by:

$$P(0) = e^{-\overline{n}_1}\,(2\,e^{-\overline{n}_2/2} - e^{-\overline{n}_2})$$

where $\overline{n}_1$ is the average number of forward/backward coincidences and $\overline{n}_2$ is average number of one-side hits (but not both). $\overline{n}_1$ and $\overline{n}_2$ are related to the instantaneous luminosity L via:

$$\overline{n}_1 = (\epsilon_1^{sd}\sigma^{sd} + \epsilon_1^{dd}\sigma^{dd} + \epsilon_1^{hc}\sigma^{hc})\,\tau\,L$$

and

$$\overline{n}_2 = (\epsilon_2^{sd}\sigma^{sd} + \epsilon_2^{dd}\sigma^{dd} + \epsilon_2^{hc}\sigma^{hc})\,\tau\,L$$

Here, $\sigma^{sd}, \sigma^{dd}, \sigma^{hc}$ are the cross sections for single-diffractive, double-diffractive, and hard-core scattering, $\epsilon_1^{sd}, \epsilon_1^{dd}, \epsilon_1^{hc}$ are the acceptances for forward/backward coincidences for these processes, $\epsilon_2^{sd}, \epsilon_2^{dd}, \epsilon_2^{hc}$ are the corresponding acceptances for one-side hits, and τ is the bunch crossing time.

In order to track the luminosity as it decreases through the lifetime of an accelerator store (typically from a few hours to a day), for example, one would like to monitor the luminosity with a

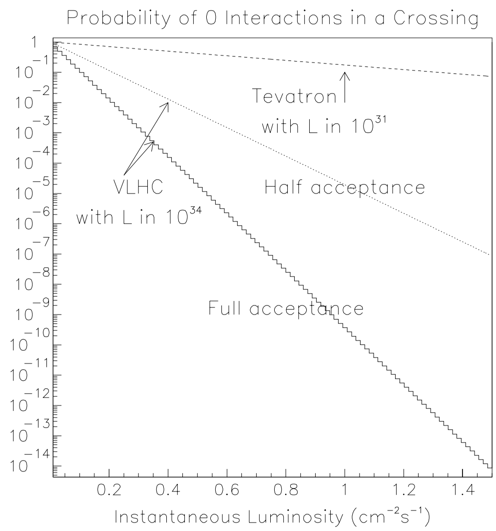

Figure 13: The probability of detecting zero interactions in a crossing vs. instantaneous luminosity for the Tevatron (full acceptance Level-0 array) and the VLHC (full and half acceptance arrays).

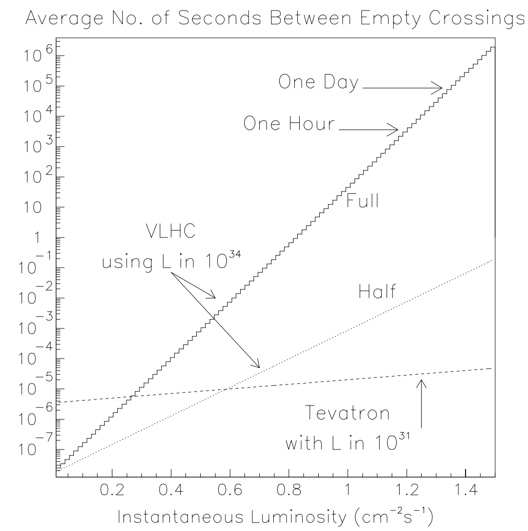

Figure 14: The average number of seconds between detected empty crossings vs. instantaneous luminosity for the Tevatron (full acceptance Level-0 array) and the VLHC (full and half acceptance arrays).

statistical uncertainty of about 1% every few seconds or minutes. This calls for counting of order 10^4 zeros in this period. These rates are achieved in the DØ experiment with the fine-grained Level-0 array of scintillation counters [2] which subtend the high-η region on both sides of the interaction region. The Level-0 counters are nearly 100% efficient for detecting a forward/backward coincidence from a hard-core scattering event, the dominant process among those listed above, since the two beam jets almost always send particles into the two arrays.

Fig. 13 shows the probability of detecting zero interactions per crossing as a function of luminosity for the DØ configuration and for a similar high-acceptance, high-efficiency "Level-0" array located in a VLHC experiment. Fig. 14 shows the same information in an alternate way – the average number of seconds between empty crossings vs. luminosity. One sees that a full-acceptance array at the VLHC results in having to wait several minutes between empty crossings at the design luminosity. The rates of detected zeros can be effectively increased, however, by decreasing the ϵ_1 and ϵ_2 terms in the above relations. This can be achieved by using an array of luminosity counters which have a smaller geometric acceptance or are less efficient for detecting minimum-ionizing particles, accomplished by raising discriminator thresholds.

Fig. 12 and 13 also show that the VLHC situation for a half-acceptance array starts to approach that of the Tevatron. Extrapolating further, the figures indicate that acceptance terms of order 10% those used at the Tevatron will result in zero-counting rates which give negligible statistical uncertainty in the luminosity measurement at the VLHC design luminosity. Fast timing for such counters will be necessary to distinguish between the bunch crossings separated by 17 nsec. Tevatron Level-0 counters, with 200 psec time resolution, have already demonstrated the ability to distinguish particles in neighboring buckets which are separated by about 15 nsec.

The calibration of the luminosity counters at the VLHC will require running the VLHC at low luminosity, where there is an average of one interaction per crossing. This will likely be the default scenario during the start-up of the machine. Many physics measurements require low-luminosity running as well: studies of elastic scattering and diffraction dissociation, studies of rapidity gaps between jets, etc. Another important step in calibrating the luminosity counters will be to run the VLHC at a lower center-of-mass energy where the total proton-proton cross section and its components (hard-core, elastic, single-diffractive, and double-diffractive) have been accurately measured. The LHC center-of-mass energy of 14 TeV would be the obvious low-energy target. Hence, the VLHC machine designers should incorporate into their planning the possibility of running the machine stably at this energy. Running the VLHC at the LHC center-of-mass energy will be useful for cross checking other ingredients in cross-section calculations besides luminosity, as well as studying the $\sqrt{s}$-dependence of many physics processes.

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VIII. TRACKING WORKING GROUP

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A. Introduction

Good tracking has been and will continue to be a key ingredient for high energy physics experiments. Good tracking will require an inner tracker which can achieve precise measurements of the vertex positions for both the initial and displaced vertices. This good tracking will also require an outer tracker which can supply a precision position at large lever arm for momentum measurements and which can be used as a seed for track finding into the inner tracker. The tracker must be resistant to radiation damage particularly in its inner layers which are closest to the beam.

The machine parameters specify 100 TeV center of mass energy and a peak luminosity of $10^{34} cm^{-2} sec^{-1}$. With a bunch spacing of 17ns there will be about 20 interactions per crossing. Extrapolations of the minimum bias cross section are uncertain but indicate that each collision will generate about 10^2 particles for central ($\eta < 1.5$) and of the same order for each of forward and backward ($1.5 < \eta < 3$) regions. This produces some 4x10^3 charged tracks on average per crossing. For tracking to work well the occupancy needs to be kept to about 1% which leads to a requirement of 4x10^5 channels per tracking layer.

It is important to have a precision determination of the momenta of very high energy charged leptons (as discussed by T. Han [1]). For one meter of tracking in a four Tesla field, using fifteen planes, each with 50 μm resolution, the $\frac{\sigma_p}{p}$ resolution for a 10 TeV particle is 25%. For two meters of tracking this drops to 10%. Getting to 2.5% in one meter requires 5 μm resolution. Remember that 50 μm resolution is the 'goal' for the LHC detectors. Also needed is effective second vertex detection. For a two plane system the impact parameter resolution is a function of the ratio of the inner to outer radius. Therefore the inner radii must be small, close to the beam, or the outer radii becomes very large.

B. Inner Tracking with Pixels

For the high radiation levels and instantaneous rates of the VLHC the best choice for inner tracking appears to be pixels (as discussed by S. Kwan [2]). Even at $\sqrt{s}$ = 100 TeV but with a luminosity of about that at the LHC the requirements placed on the pixels by rate considerations are about the same. There pixel detectors of the order of 10^8 channels are planned with r-ϕ hit resolutions of about 15 μm. But at the VLHC the momentum of the high momentum tracks will be almost a factor of ten higher. One way to preserve momentum resolution is to improve tracker resolution by a factor of ten. Some work has been done which suggest that this factor of ten is possible, but reading out the many more smaller pixels could remain a problem [3].

C. Outer Tracking with Gas Chambers

A promising approach to solving these difficult problems appears to be the combination of the tried and true proportional mode gas avalanche counter and new techniques of surface treatments and photo lithography (as discussed by P. Rubinov [4]). This is already a very active field which has produced ideas such as the Micro Strip Gas Chambers (MSGCs), Micro Gap Chambers (MGCs), Gas Electron Multiplier (GEM) and more. Already one of the LHC detectors (CMS) has committed to developing the MSGCs for tracking as the most promising path of achieving the required performance. For the VLHC, only incremental improvements beyond the LHC application would be required. Gas detectors created with micro technology offer the following parameters:

- Spatial resolution - 40 μm is achievable without difficulty.
- Timing resolution - The very short charge collection times allow a timing resolution of approximately 10ns with current technologies.
- Low mass - Intrinsically, a 3mm gas gap at 1 atm is sufficient for the detection of minimum ionizing particles with full efficiency, but in practice all the material is in the support.
- High rate capability - Up to 10^6 particles/mm^2/sec is currently achievable (r $>$ 190mm at VLHC).
- Segmentation - Strips of as long as 30cm can be used, or they can be as small as 200 μm for MSGCs or even less for MGCs.
- Radiation hardness - Able to withstand several megarads of ionizing radiation. With current technologies, MSGCs can be made to work for up to 10 years in an LHC environment.

Gas detectors is a very active field that is in the process of rapid evolution. Some promising ideas, such as the GEM are only now beginning to be explored. Currently the following parameters can be achieved simultaneously using MSGCs:

- 40 μm spatial resolution
- 10^6 particles/mm^2/sec rate capability
- up to 100mC/cm of collected charge without aging with good control of the gas purity.
- 11ns RMS time resolution.

Further developments such as combining the MSGC with the Gas Electron Multiplier are expected to extend the performance by allowing much higher gains and significantly improved reliability as well as extending the rate capability by another order of magnitude.

D. Scintillating Fibers

Scintillating fibers are a viable technology at high luminosity (as discussed by F.Borcherding [5]). A fiber tracker could start at an inner radius of 1.6m if that layer is segmented into 10 sections in z and the fiber diameter is as small as 0.5mm. A fiber tracker for the VLHC then could have eight layers each with 2x10^5 channels located at radii of 1.5 to 3.0m.

The Upgrade DØ detector at FNAL will use VLPCs to convert photons seen in its fiber tracker and has a total channel count of just under 10^5 in eight layers [6]. It is not unreasonable to expect to build a detector eight to ten times as large for about the same cost in over a decade from now. A modest extrapolation of the VLPC technology indicates that the channel count could be increased 4-fold with no increase in the number of VLPC chips. There is some evidence that 0.5mm diameter fibers will produce enough photons to work with the present VLPCs [7]. A major factor would be in the cost and room needed for the 16 fold increase in clear wave guide fibers. This would be greatly reduced if the VLPCs which must operate at about 6.5 degrees K could be moved closer to the fiber tracker. The electronics could be greatly streamlined over the DØ design by requiring only one bit of information for each channel. The present front end pick off chip for DØ does this for 16 channels. This chip could be evolved up to 64 or 128 channels and a pipelined output stage added.

E. 3D Pixels

Today's silicon strips and tomorrow's pixels are 2-D technology with the electrodes etched on the surface of a silicon wafer (as discussed by S. Parker [8]). In 3-D technology the electrodes would extend through the wafer thickness. Here the n- and p-strips instead of laying on the surface are columns extending through the 300 μm wafer thickness. The depletion voltage for 3-D pixels is very much smaller than that for 2-D pixels. The signal amplitude is also very much greater and arrives within 1ns. The chip industry in the past has been focused on surface features. In the future, however, it will probably move into 3-D structures in its quest for denser and denser circuits. In such an industry 3-D pixel manufacture could become economically viable.

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IX. CALORIMETRY WORKING GROUP

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A. Introduction

The calorimetry looks as the most feasible part of the detector, even with the VLHC luminosity of $10^{34} cm^{-2} s^{-1}$. The radiation doses in the calorimeters and their occupancies increase very modestly with the collider energy. Based on the phenomenology developed by D.E. Groom [1], the calorimetry radiation doses at the collider energy of 100 TeV are only 2 times higher of those at the LHC with the same luminosity. Similar conclusions are followed from N. Mohov's calculations [2]. There are many calorimetry techniques which potentially fit the VLHC conditions, as it was demonstrated at this Workshop.

B. Scintillator calorimeters

This well established technique can be used for the barrel part of the detector in spite of its limited radiation resistance (about 4 Mrad, according to estimations of A. Pla-Dalmau [3]). However, chances to use scintillator for the forward/backward parts of the detector (pseudorapidity $\eta > 2$) do not look realistic even at the luminosity of $10^{34} cm^{-2} s^{-1}$.

Performance of the CMS scintillator hadronic calorimeter in combination with the $PbWO_4$ crystal electromagnetic (EM) calorimeter was discussed by J. Freeman [4]. The problem with this combination is a non-uniform response to the hadronic and EM parts of the shower (e/h $\neq$ 1) which causes non-linear amplitude versus energy dependence for hadrons and a degradation of the hadronic energy resolution (increase of the constant term). However, this degradation is relatively small, and author concludes that it is less important than non-gaussian tails in the calorimeter response function due to cracks and dead areas in real calorimeters.

C. $PbWO_4$ crystal calorimeters

The CMS crystal EM calorimeter was reported by R. Rusack [5]. The lead tungstate crystals ($PbWO_4$) allow to construct a compact EM calorimeter (the radiation length is 0.89 cm, Moliere radius is 2 cm) with excellent energy resolution:

$$\frac{\sigma_E}{E} = \frac{2\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.15}{E} \text{ (E in GeV)}.$$

The long term radiation resistance of the crystal is also good, 10 Mrad has been demonstrated. Nevertheless, the ability of the $PbWO_4$ calorimeter to work in high radiation fields still is not clear. First, there is so called 'short term' radiation damage which may vary the crystal light output in some unpredictable way, thus deteriorating the calorimeter resolution. Another point of concern is the radiation resistance of the silicone avalanche photodiode (APD), which was accepted by CMS as a photodetector for the crystals.

Both, the $PbWO_4$ crystals and especially the APD, are very sensitive to the temperature variations. However, with the proper temperature monitoring, corrections could be made and the calorimeter energy resolution should not suffer.

Apparently, we will have more data on this promising technique in the near future due to intensive studies for CMS.

D. Quartz fiber calorimeters

This new type of calorimetry was presented by O. Ganel [6]. The calorimeter is a kind of 'spaghetti' calorimeter with fibers made of quartz (amorphous silica) instead of scintillator plastic. Pure quartz is very radiation hard, 30 Grad is achievable. Quartz fibers detect Cherenkov light which yields low-intensive but extremely fast signal, an output signal of several nanosecond width has been observed.

The calorimeter EM energy resolution is determined by the photo-electron statistics (yield is 0.8 ph.e./GeV):

$$\frac{\sigma_E}{E} = \frac{(100-140)\%}{\sqrt{E}}.$$

Since the quartz fibers pick up only Cherenkov light from fast electrons the calorimeter is practically non-sensitive to the hadronic energy. Nevertheless, it can be used for the hadron energy measurements at very high energies, due to high EM component in the hadronic shower which logarithmically increases with energy. Clearly, the hadronic energy resolution is not very good, basically, it is 2 - 3 times worse than that for the conventional (scintillator, liquid argon) calorimeters.

Another feature of the quartz fiber calorimeter is narrow hadronic shower (64 mm diameter), because it detects the EM core of the hadronic shower only. This feature may be used for better jet-jet resolution at very high rapidity regions where radius of jet cone is less than the width of the hadronic shower.

E. Diamond calorimeters

Diamond detectors (presented by R. Stone-Rutgers [7]) allow to construct very compact, radiation hard ($\rangle$ 100 Mrad), robust, and very fast ($\sim$ 1ns readout) sampling calorimeters. One such calorimeter has been constructed and tested with a reasonable EM energy resolution:

$$\frac{\sigma_E}{E} \sim \frac{20\%}{\sqrt{E}} \oplus 1.5\% \oplus \frac{8\%}{E}.$$

The main problem with this technique is the diamond price. Presently, the cost of the diamond calorimeter is one or two order of magnitude higher than other types of calorimeters. However, the technology development may change the situation.

F. High pressure tube gas calorimeters

Although the first calorimeter with gas ionization readout has been tested back in 1979 [8] this technique has never been used in physics experiments by one reason: small signal. At low energies electronic noise dominates calorimeter energy resolution. However, with the energy increase and with the electronics improvement this technique presents very attractive option for the future colliders [9].

Gas ionization calorimeters are very radiation hard (⟩ 1 Grad) and fast (20 ns total width output signal has been demonstrated [10]). Due to high ion mobility in gases these calorimeters can work in high intensity radiation fields (100 rad/s) without signal degradation. Due to the lack of the gain the calorimeters are linear and stable. Finally, the gas ionization calorimeters are inexpensive, since their basic design is carbon steel tubes filled with argon based gas mixtures.

The tube design of the high-pressure (100 atm) gas-ionization calorimeters was presented by D. Khazins [11]. A tested hadronic calorimeter made of 0.5 inch diameter tubes had the energy resolution:

$$\frac{\sigma_E}{E} = \frac{70\%}{\sqrt{E}} \oplus 7.4\%.$$

Using a weighting procedure for the e/h compensation, authors managed to reduce the constant term to ⟨3%. (It is not clear, however, how this or similar procedure could be beneficial in the case of jets.) The electronic noise of the tested calorimeter was equivalent to 4 GeV (r.m.s) per hadronic shower. Authors believe it could be reduced to 1 GeV or less.

An EM calorimeter made of ‘wiggling’ tubes had the energy resolution:

$$\frac{\sigma_E}{E} \sim \frac{32\%}{\sqrt{E}} \oplus 3\%.$$

It is somewhat worse than the expected value of $\frac{20\%}{\sqrt{E}} \oplus$ 1%, which implies that the wiggling calorimeter needs more R&D work. The EM calorimeter electronic noise was 0.3 GeV.

G. Moderate pressure gas calorimeters with planar electrode geometry

Another approach to the gas ionization calorimeters is being developed by a Serpukhov group (S. Denisov et al. [12]). They employ the standard sandwich geometry. A hadronic calorimeter filled with 90%Ar + 10%CF_4 gas mixture at 40 atm pressure has been tested. They are now looking for heavy carbon-fluorine gases to reduce the pressure to several atmospheres.

In the process of the calorimeter investigation the group discovered that they can control the calorimeter e/h ratio by adjusting the width and delay of the ADC gate signal. As the result they obtained a very low constant term in the hadronic energy resolution: 2.5% with the absorber made of steel and 0.1% with the lead absorber. This discovery opens possibilities for a really good hadronic and jet energy resolution at VLHC, because at those energies the constant term will dominate energy resolution.

H. Liquid argon calorimeters

The liquid argon calorimeters have not been presented at the Workshop. However, this well established and solid technique, undoubtedly, would be one of the main options for the VLHC detector. It is intrinsically radiation hard, linear, and stable. Energy resolution is very good for both hadrons and EM particles. The H1 group [13] obtained the hadronic resolution:

$$\frac{\sigma_E}{E} = \frac{51\%}{\sqrt{E}} \oplus 1.6\%,$$

using a weighting procedure for the e/h compensation. (Again, the low constant term may be not applicable for jets because of difference in energy distribution in jets and hadronic showers.)

The ATLAS group [14] has tested an accordion EM calorimeter with the resolution:

$$\frac{\sigma_E}{E} = \frac{7.7\%}{\sqrt{E}}$$

with a negligible constant term.

The drawback of the liquid argon technique is the low mobility of both electrons and ions. The big electron collection time, which is presently about 0.5 μsec, creates serious pileup problems for calorimetry. The positive ions build up a volume charge in the liquid argon gap which considerably distorts electric field in the gap at the dose rate about 1 rad/s. However, both these limitations strongly depend on the calorimeter design parameters (the gap size and voltage) and could be improved.

I. Calorimeter in situ calibration

At the last talk of the calorimetry group R. Vidal [15] considered several processes for the calorimeter in situ calibration. Decays J/$\psi \rightarrow \mu^+\mu^-$ and Z $\rightarrow e^+e^-$ can be used for the EM calorimeter calibration. The hadronic calorimeters may be calibrated with (Z + jets) events and with b-tagged W-bosons (decaying into two jets) from tt-bar events. The challenge is the in situ calibration at energies exceeding the weak boson masses.

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X. MUON WORKING GROUP

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A. Introduction

Lepton identification is at the core of hadron collider physics. Leptons indicate the presence of an electroweak boson, either real or virtual. Electrons and muons (and to a lesser extent taus) can be identified at the trigger level, allowing these interesting events to be selected against the enormous background of QCD events.

Muons are simple to identify. Their long lifetime and high penetrating power virtually independent of energy makes them very distinctive: any charged particle that penetrates several meters of material is a muon. Unlike electrons, which can have their momenta measured by calorimetry, muons have to have their momentum measured in tracking, which becomes increasingly difficult at high p_T. The critical issue is not whether or not we can identify muons at the VLHC - we can. It's whether or not we can accurately measure their momentum.

B. Theoretical Issues: Which Muons Are We Looking For?

There are several processes of interest that can generate muons as signatures:

• Compositeness or a new contact interaction: here one signature is an increase in the Drell-Yan cross section at high $m(\mu^+\mu^-)$, and $p_T(\mu)$ can be several TeV.

• New gauge bosons, such as $Z' \to \mu^+\mu^-$. Again, $p_T(\mu)$ can be several TeV. Additionally, measuring the forward-backward asymmetry A_{FB} of this new Z' provides information on its couplings. This technique requires large η coverage for muons, and good resolution is needed since the asymmetry varies with $m(\mu^+\mu^-)$.

• Heavy squarks and gluinos. Weak scale supersymmetry (SUSY) will presumably be discovered at the LHC if not before. However some of the heavier states might be too heavy to be seen at the LHC or be produced in insufficient numbers to allow a detailed study of the complicated cascade decay. These particles can be pair produced at the VLHC, and many of these have muons as daughters, and these muons are expected to have $p_T(\mu)$ in the 100's of GeV range.

• Strongly Interacting Electroweak Symmetry Breaking: A hadron machine with the energy envisioned here is a "gauge boson collider," since the production mechanisms involving electroweak gauge bosons from the initial state partons becomes increasingly important. Any evidence uncovered at the LHC for a strongly interacting sector that breaks the electroweak symmetry would motivate a higher energy machine for study of the new interactions. Good charge determination for very energetic muons would allow the identification of various isospin channels in strong vector boson scattering. This is especially the case in the mode $W^+W^+ \to W^+W^+$ where the like-sign lepton signal must be separated from the unlike-sign Standard Model background.

• Multi-W production: While these W's tend to be at high p_T (and therefore generate high p_T muons), we would also like to measure the cross section for single W, WW, etc. production, and this means detection in some cases (when one of the W's is not highly boosted with respect to the lab frame) down to a few 10's of GeV.

• Other new particles: Other scenarios include the possibility of pair-producing leptoquarks which decay into a lepton and a quark jet or pair-producing vector-like quarks which have leptonic decays. New heavy particles exist in the messenger sector of gauge-mediated SUSY breaking models. If light enough some of these particles could be produced at the VLHC. One possible signal involving muons in the final state would be the production of a pair of (charged) messenger scalars which decay into a W and its (absolutely stable or relatively long-lived) neutral electroweak doublet partner, i.e. $\phi^+ \to \phi^0 W^+$. More generally the presence of new particles could enhance the number of muons observed at the VLHC.

This brings up the question of the purpose of a VLHC experiment: does it emphasize doing 10 TeV scale physics, or does it emphasize doing high statistics 1 TeV scale physics? The answer to this question depends on what the LHC does and does not discover, but it does have implications for detector design. For very massive objects, the acceptance is proportional to solid angle coverage, but for less massive objects, it is proportional to rapidity. A detector optimized for 10 TeV scale physics will invest more resources into the best momentum resolution in the central region, whereas a detector optimized for 1 TeV physics will opt to cover a larger region, with less emphasis on resolution. This increases the yield, but also makes A_{FB} measurements possible.

The best momentum measurement possible is desirable. The better the momentum resolution, the narrower peaks become, and the smaller the signal that can be identified over the background. Additionally, should (e.g.) a new Z' boson be discovered, measuring the width $\Gamma(Z')$ would be of intense interest. For intrinsic widths smaller than the detector resolution, this becomes extremely difficult.

C. Experimental Issues: How Do We Find Them?

The dynamic range of the VLHC muon system is unprecedented, ranging from a few 10's of GeV to a few 10's TeV. Even if one were to stipulate that muons from low p_T W bosons were uninteresting, it is impractical to build a detector with a thick enough muon absorber to be blind to these muons: approximately a meter of iron is required for a muon to lose 1 GeV via dE/dx.

Three strategies are commonly employed in measuring the momentum of muons: measure the momentum in a central tracker, measure the momentum in instrumented magnetized shielding, and measure the momentum in a special muon spectrometer outside the shielding.

It is unlikely that an independent muon tracker could measure the momentum better than a central tracker. An independent muon outer tracker covers a substantially larger volume, which increases the channel count for a given number of measurements of a given resolution, and also reduces the practical magnetic field allowed because of stored energy considerations. The tracking group believes that an inner tracker using a large bore high field magnet and existing tracking technologies can reach momentum resolution of 10% or better for a 10 TeV track, which corresponds to a 3σ charge measurement for a 30 TeV muon. Although improved momentum resolution is always better, this is believed to be adequate to probe a broad range of physics.

It is expected that the dominant source of apparent high p_T muons will be low p_T muons that somehow get mismeasured to appear to be much straighter than they really are. While this is unlikely to happen to any particular muon, there are so many more low p_T muons than high p_T muons that non-Gaussian tails on the resolution could pose substantial problems. This is especially true at the trigger level, where only a subset of the detector information is available.

Clearly a second (and possibly even a third) momentum measurement to confirm the central tracker is desirable. It is certainly possible to build a tracking system inside the absorber (as DØ has done) or beyond the absorber (as ATLAS has done), at some cost. Additionally, properties of very energetic muons can be exploited.

A 2 TeV muon has the same velocity as a 10 GeV electron. Muons, therefore, begin to show features normally associated with electrons in their passage through matter. For example, a 1 GeV muon deposits (an average of) 3.5 GeV in 3m of iron. A 1 TeV muon deposits 9 GeV. If a VLHC detector built a 1 foot deep "muon calorimeter" at the extreme outer radius of the muon detector, this calorimeter would only need $30\%/\sqrt{E}$ resolution to provide 3σ separation. The main difficulty with this technique is shower fluctuations. Thicker calorimeters are less sensitive to fluctuations, although they are more expensive: to reduce the fluctuations by a factor of two requires a calorimeter four times thicker.

A second property that can be exploited is that muons of this velocity exhibit transition radiation, with an intensity proportional to γ. Historically, TRD's do not have the best track record, although most problems that have been experienced arise from trying to make TRD's that are lightweight and/or thin, so as not to degrade the track unnecessarily before its next measurement. Since the muon detectors are the last element to measure a particle, there is no incentive to make a TRD too thin. Relatively thick detectors with correspondingly large signals can be built. TRD's cannot be made arbitrarily thick, however, because a showering muon produces electrons, which have large γ. The TRD's would then respond to these electrons and (correctly) identify them as high velocity particles.

For a VLHC operating at luminosities of $10^{34} cm^{-2} s^{-1}$, muon identification and momentum measurement to better than 10% for a 10 TeV muon seems possible by simple extrapolation from known technologies. Non-Gaussian tails causing lower p_T muons to appear as higher p_T muons is a concern, which can be addressed by an additional momentum measurement and/or a velocity measurement using transition radiation or dE/dx.

A critical issue that has not yet been addressed is that of triggering. Experience has shown that triggering on muons is a more difficult problem than offline reconstruction; how much more difficult depends on the bandwidth limitations. Detector design may be driven by ease of triggering.

XI. CONCLUSIONS

Different scenarios of physics beyond the SM were investigated by the physics working groups and each time the potential of the VLHC was clearly demonstrated. Let us review the conclusions of the different working groups.

New Strong Dynamics Working Group. If strong dynamics is involved in electroweak symmetry breaking, the physics associated with it will first appear at the 1 TeV scale, and the VLHC will have the opportunity to explore it in more depth than the LHC. For example, if a Higgs is discovered in the 400-800 GeV range, the VLHC would be able to differentiate between a SM Higgs and a non-SM Higgs much better than the LHC. New strong dynamics as well as any phenomena associated with flavor physics would also give a rich structure in the 1-10 TeV range. A challenge to theorists is to identify the possibilities for 10 TeV-scale physics.

Supersymmetry Working Group. If SUSY is discovered at low energy, as many suspect it will be, and is gauge-mediated, one could then expect new gauge bosons in the 10-100 TeV range. A VLHC would be the right place to study these new particles as well as the heavy part of the SUSY spectrum.

Exotics Working Group. It is likely that not all outstanding questions will be answered by the LHC. Why are there three generations? What is the origin of the quark mixing matrix? Are there any connections between quarks and leptons? We can therefore expect some new phenomena that might manifest themselves by contact interactions and/or by new massive particles. The search potential of the VLHC for these new phenomena is truly enormous and the limits are in general in the multi-ten TeV region. We might never get any clues for these before the VLHC.

Full Rapidity Physics Working Group. A full acceptance detector will provide a powerfull tool and investigate physics complementary to the central, high Pt detector. The long straight section that is needed to insert such a detector should be included right from the start in the VLHC design.

Precision Measurements of Heavy Objects Working Group. The VLHC will not be competitive for precision measurements in the few 100 GeV mass scale, the competition from lower energy machines is too big in that region. The strong suit of the VLHC is clearly its kinematic reach.

Multiple Interaction Working Group. The average number of interactions per crossing at a luminosity of $10^{34} cm^{-2} s^{-1}$ should be about 22 for 17ns bunch spacing. The situation will be worse than, yet comparable to the situation at the LHC. The higher energy of the VLHC, however, will make the underlying event problem more difficult. This problem should be manageable if one is searching for relatively high energy particles and jets. The VLHC will benefit from low-luminosity running at start-up, both for physics and detector calibration reasons. Luminosity callibration would also require to operate the VLHC at the LHC energy.

Tracking Working Group. The total number of detector elements needed per tracking layer is estimated to be 4x10^5 in order to keep the occupancy down to 1%. To keep the momentum resolution of 10 TeV charged leptons in the few percent range will require a tracking resolution which is below the LHC goal, a challenging task. Different types of tracking detectors and their potential applications to the VLHC were discussed: two and three dimensional pixels for inner tracking, micro strip and micro gap gas chambers for outer tracking, and scintillating fibers.

Calorimetry Working Group. The calorimetry appears to be the most feasible part of the detector. The calorimetry radiation doses at E_{cm}=100 TeV are only 2 times higher than those at the LHC, with the same luminosity, and of course the energy resolution improves with energy. There are many calorimetry techniques which might fit the VLHC requirements of good time resolution, high radiation hardness and fine segmentation. The in situ calibration at high energies will be a challenge.

Muon Working Group. Muons are the signatures of many processes generated by physics beyond the SM and are simple to identify. Momentum measurement of 10 TeV muons to better than 10% seems possible with reasonable extrapolation from current technology. Non-Gaussian tails causing lower p_T muons to appear as higher p_T muons is a concern. This could be addressed by a second momentum measurement using transition radiation or the (relatively large at these energies) energy loss in a calorimeter. Triggering will be a serious challenge and will be limited by bandwidth consideration. Detector design may be driven by ease of triggering.

We note that the conclusions reached during the Snowmass 96 [2] workshop were confirmed by the specific studies done during the workshop.

The VLHC will be designed to investigate the unknown physics beyond the SM. It should be capable of investigating a broad spectrum of models which go beyond the SM. Much work remains to be done even though progress has been made during this workshop. We can however draw the following general conclusions. With the center-of-mass energy and luminosity considered at this workshop, the VLHC will be able to probe in detail the physics that will hopefully be discovered by the LHC at the 1 TeV mass scale. It will furthermore allow us to investigate scales that are about an order of magnitude larger (in some cases even larger) than the scales probed at the LHC. It will, however, be difficult for the VLHC to achieve competitive measurements at the 100 GeV mass scale.

For a luminosity comparable to the LHC luminosity, VLHC detectors seem feasible. There are however many challenges and new and/or old technologies should be pushed with the idea of decreasing the cost. Considering the cost of LHC-like detectors, it is clear that detectors should not be ignored in the overall cost optimization of the project. An increase of the accelerator energy increases its cost, but allow a decrease in luminosity (for fixed physics goal(s)) which more than likely will decrease the cost of the detector. The VLHC detector R&D effort should logically start once the LHC effort slows down.

We believe that the physics potential of a Very Large Hadron Collider warrants a strong R&D effort on accelerator technologies that would enable us to reach the necessary energy and luminosity within a reasonable cost.

Since the workshop we have started a VLHC Study Group; for more information see [4]. This workshop was sponsored by

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