PHYSICS AT $e^-e^-$: A CASE FOR MULTI-CHANNEL STUDIES

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Abstract

I argue that it would be crucial to have as many channels as possible to understand the physics of electroweak symmetry breaking (EWSB) in next-generation collider experiments. A historic example of the parity violation and the $V - A$ interaction is used to make this point. An $e^-e^-$ option offers us a new channel in this respect. The usefulness of this channel is exemplified for the case of supersymmetry and of the strongly coupled EWSB sector.

1. Why are we here?

So, here is another workshop on collider physics. Specifically on a rather exotic collider option, $e^-e^-$ collider. Why are we doing this, after all?

The answer to this question is quite simple. We believe that the physics of electroweak symmetry breaking (EWSB) is the most pressing question in particle physics. And it is going to be a challenging task to completely reveal all secrets of EWSB. It will take substantial experimental and theoretical efforts to understand it. For this aim, having as many possible channels as possible will probably be necessary.

Why multi-channel? We heard about the complementarity of hadron and lepton machines so many times. Maybe enough of it. And we are talking here about yet another possible collider option. Why bother?

I would like to remind you of an example in the history of particle physics where it was crucial to attack the same problem from many different channels. It is the $V - A$ form of the charged-current weak interaction.\textsuperscript{a}

The first hint for parity violation came from a purely hadronic process. In cosmic ray and beam-based studies of strange particles, there appeared two particles with

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\textsuperscript{a}Of course, all of this happened before I was born; I rely completely on reviews, a random reading of conference proceedings and private communications. There must have been much more behind-the-scene confusions than I briefly outline here.
opposite parities but with exactly the same mass and lifetime—the famous $\tau$-$\theta$ puzzle. And it took geniuses like T. D. Lee and C. N. Yang (1956) to make a bold step towards the resolution: the parity violation. They pointed out that even though there was a wealth of evidence that parity was a good symmetry of the electromagnetic and strong interactions, there was basically no experimental test whether the weak interaction preserves parity. If it does not, we can identify the $\tau$ and $\theta$ mesons which decay into states with opposite parities.

The evidence for parity violation came from two different channels in 1957: semi-leptonic and purely leptonic. The semi-leptonic channel is the experiment on $^{60}$Co $\beta$ decay (C. S. Wu et al). The correlation between directions of the applied magnetic field and the electron momentum established the violation of parity. The purely leptonic channel is the experiment by Garwin, Lederman and Weinrich, using the sequence of decays $\pi \to \mu \to e$. The angular distribution of the $\mu \to e$ decay showed the stopped muon was highly polarized. It is interesting that both papers were published in the same volume of *Phys. Rev.* 105 side by side.

The violation of parity opened up a big confusion in the community. The Fermi Hamiltonian of the weak interaction had to be reexamined by allowing all possible 40 independent parameters of scalar, vector and tensor Lorentz structures. It also appeared, before 1957, that the scalar and tensor interactions are dominant.

In order to choose $V, A$ over $S, T$ and $P$, different types of nuclei had to be used. In the study of the $(\beta - \nu)$ angular correlation, different nuclei sit at different points on the so-called Scott diagram, depending on the relative magnitude of Fermi and Gamov–Teller transitions and recoil energy spectra. The data using $^{19}$Ne can be explained either by a combination of $V, A$ or of $S, T$. However, the data using the $^{35}$Ar nucleus prefer $V$. The data from $^{23}$Ne and $^6$He prefer $A$. Only after putting all of them together, the choice of $V$ and $A$ comes out preferred over $S$ and $T$. This analysis could not be done without the determination of the negative helicity of the neutrino, evidence for which came from the $K$ capture of $e^- {^{152}Eu} \to \nu {^{152}Sm}$ by Goldhaber, Grodzins, and Sunyar in 1958, which reduced the number of parameters by a factor of two. However, none of these measurements was able to establish precisely the $V - A$ form, because the strong interaction renormalizes the axial-vector coupling even though the CVC hypothesis keeps the normalization of the $V$ part non-renormalized.\(^6\)

In the purely leptonic channel, muon decay was studied in detail. By fitting the energy spectrum and angular correlation with polarized muons, the parameter space was restricted. The Michel parameter $\rho$ and the asymmetry parameter $\xi$ chose the $V - A$ theory by 1960. Even at the present time, this analysis still offers the best evidence for the $V - A$ nature. The 20 parameters were reduced to just one.

And throughout all this, the universality of the weak interaction between muon decay (purely leptonic) and $\beta$-decay (semi-leptonic) played its role as the backbone of the development.

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\(^6\)The PCAC, however, related the axial-vector coupling to the pion-nucleon coupling (Goldberger–Treiman relation) in 1958.
I am telling students in my particle physics course that the discovery of the 
$V-A$ nature led to a major paradigm shift in the way we understand the elementary 
particles. This is not much emphasized, but it is a fundamental change. Since the 
days of Pauli, the spin of the electron used to be an additional degree of freedom 
attached to a non-relativistic electron. However, the $V-A$ nature forced us to 
go to a totally different idea. The distinction of the left-handed and right-handed 
helicity states is fundamental; these are different particles! And this fundamental 
distinction does not allow the electron to stop, because then the helicity would lose 
its meaning. The elementary particles are chiral. And only because of the Higgs 
bigon condensate, the left-handed and right-handed states can convert to each other 
and the electron can peacefully “sit” at rest.

I anticipate that the experimental study of the physics of EWSB will be as 
confusing and complex. In order to fully reveal all the secrets, we are likely to need 
as many channels as possible. This is why we would like to have an $e^+e^-$ machine 
in addition to the already-approved LHC project. As an added bonus, an $e^+e^-$ 
machine will offer an $e^-e^-$ option at minimum cost and give us a handle on yet 
another channel in the study.

Of course, at this point we do not know how having different channels will help 
us to understand the physics of EWSB, because we do not yet know what the physics 
is. But we can do a case study using the known proposed mechanisms of EWSB 
and associated new particles in order to study how an $e^-e^-$ option would help us. 
In the next sections we will see the cases of supersymmetry (weakly interacting 
EWSB) and strongly interacting EWSB from this point of view.

2. Characteristics of $e^-e^-$ Experiments

In a review on $e^+e^-$ physics Michael Peskin and I listed the three important 
characteristics of an $e^+e^-$ collider: cleanness, “holism,” and democracy. The cleanness 
refers to the fact that the event rate at an $e^+e^-$ machine is low and offers 
a desirable environment for detectors and physics. Since the initial state is well- 
defined, including the polarization of at least the $e^-$ beam, we know what we are 
doing. And the background is calculable. The “holism” refers to the capability to 
capture the entire event. Since the kinematics is well-defined, we can use the beam 
energy constraint to facilitate the reconstruction of the event. Lastly, democracy 
means that all final states, both signal and background, have comparable cross sec-
tions; hence, the experiment is suitable for studying many different types of particles 
and interactions simultaneously.

By switching to the $e^-e^-$ option, we retain cleanness and “holism”, but we lose 
democracy. Basically, almost all final states cannot be produced, both the signals 
and the backgrounds. There is no annihilation between $e^-$ and $e^-$, which makes 
the level of the background even lower. However, this opens up a new channel in the 
experiment. There are some signals which can be studied with this option—there

A possible di-lepton resonance is an exception.
may be some exotic and/or rare final states. I will give a few relevant examples later. As emphasized earlier, we do not know what specifically would be the best signal to study in this new channel. But it is likely that there are some signals arising from the complexity in the physics of EWSB.

3. Supersymmetry

Let us take the superpartner of the electron, the selectron, for the purpose of this discussion. At the LHC, the selectron can be studied in detail if it appears in the decay of the second neutralino, $\tilde{\chi}_2^0 \approx \tilde{W}^0$, with its possible decay into $\tilde{e}^\pm e^\mp$. It is not always possible to study the selectron, however, depending on the precise pattern of the superparticle spectrum.

At an $e^+e^-$ machine, the study of the selectron is more-or-less trivial as long as it exists within kinematic reach. Furthermore, the use of a polarized right-handed electron beam suppresses the $W$-pair background, and many details, such as the mass of the selectron, the neutralino in its decay product, and the electron-selectron-neutralino coupling can be studied.

At an $e^-e^-$ collider, the selectron can be studied in even greater detail. One reason is that the destructive interference between $s$-channel $\gamma$, $Z$ exchange and $t$-channel $\tilde{B}$ exchange in the $e^+e^-$ annihilation is gone in $e^-e^-$ collisions, because of the absence of the $s$-channel diagram. This results in larger cross sections (see Fig. 1). Second, there is no $W$-pair background even with the left-handed electron beam. Third, one can control the polarization of both of the beams, which can effectively turn on or off the final states of interest. The $e^-_Le^-_R$ initial state produces only the $\tilde{e}^-_Le^-_R$ final state. Similarly, $e^-_Le^-_R$ leads to $\tilde{e}^-_Le^-_R$ and $e^-_Re^-_R$ to $\tilde{e}^-_R\tilde{e}^-_R$. The experimental verification of this simple selection rule would tell us that the scalar particles can carry chirality, which is the very reason why supersymmetry protects scalar masses against radiative corrections. And the threshold behavior of $e^-_Re^-_R \rightarrow \tilde{e}^-_R\tilde{e}^-_R$ is $\propto \beta$, as opposed to the $\beta^3$ behavior in $e^+e^-$ annihilation. This is suitable for an accurate determination of the selectron mass.

The absence of the $W$-pair background and the increase in the cross section allows us to study rare processes better than in an $e^+e^-$ collision. One interesting example will be discussed by Jonathan Feng later in this workshop. What he pointed out together with Nima Arkani-Hamed, Hsin-Chia Cheng, and Lawrence Hall, is that the selectron may have a small mixing with the smuon; this mixing then results in a phenomenon similar to the neutrino oscillation. When, for instance, $\tilde{e}^+\tilde{e}^-$ is produced from $e^+e^-$ annihilation, the produced $\tilde{e}$ is in its “interaction eigenstate”, which may differ from its mass eigenstate. Then the $\tilde{e}$ can oscillate to a mixture of $\tilde{e}$ and $\tilde{\mu}$ and can decay into muon as well. This results in a final state of $e^+\mu^\mp \tilde{e}^-_R$. A search for this phenomenon can be done quite well in the $e^+e^-$ environment, but much more efficiently in $e^-e^-$ collisions, as seen in Fig. 2, because of the absence of the $W$-pair background and of the higher cross section.

Another important example is the following precision measurement: By studying
Fig. 1. The total selectron pair production cross sections for the $e^+_R e^-_R$ and $e^+_R e^-_R$ modes with $m_{\tilde{e}_R} = 150$ GeV and $\sqrt{s} = 500$ GeV, as functions of the Bino mass $M_1$.4

Fig. 2. Contours of constant $\sigma(e^+_R e^-_R \rightarrow e^\pm \mu^\mp \tilde{\chi}^0)$ (left) and $\sigma(e^-_R e^-_R \rightarrow e^- \mu^+ \tilde{\chi}^0)$ (right) in fb for the NLC, with $\sqrt{s} = 500$ GeV, $m_{\tilde{e}_R}, m_{\tilde{\mu}_R} \approx 200$ GeV, and $M_1 = 100$ GeV (solid). The thick gray contour represents the experimental reach in one year. Constant contours of $B(\mu \rightarrow e\gamma)$ are also plotted for left-handed sleptons degenerate at 350 GeV.4
the selectron in detail, the $\tilde{e}-\tilde{e}-\tilde{B}$ coupling can be measured precisely in the $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$ process. Again, thanks to the lower background and the higher cross section, this measurement can be done better with an $e^-e^-$ option. Since this coupling is supposed to be the same as the $U(1)_Y$ gauge coupling $g' = g/\cos\theta_W$ because of supersymmetry, this would be an important quantitative test if the interactions preserve supersymmetry. If a small violation were seen, it could be interpreted as the violation of supersymmetry due to the heaviness of squarks—which can modify the $\tilde{e}-\tilde{e}-\tilde{B}$ coupling at the one-loop level. The small violation could be used to determine roughly how massive the squarks are. This effect is called a super-oblique correction, in analogy to the determination of the top quark and Higgs boson masses from electroweak precision measurements. The better accuracy achievable at an $e^-e^-$ option could prove essential in this type of study.

One may also look for some exotic physics with an $e^-e^-$ option. For instance, the $R$-parity violating interactions

$$\lambda_{132}L_1L_3\mu^e + \lambda_{231}L_2L_3e^e$$

do not generate $\mu \rightarrow e\gamma$ or $\mu-e$ conversions because of the conserved $L_e + L_\mu$ quantum number. The best bound on these couplings come from muonium conversion, $\mu^+e^- \leftrightarrow \mu^-e^+$, and $e-\mu-\tau$ universality; it is of the order of 0.1 for $m_\mu \sim 200$ GeV. These interactions can cause the reaction $e^-_Le^-_R \rightarrow \mu^-_L\mu^-_R$ with essentially no background. The event rate is given roughly by

$$\frac{\#(\text{event})}{20 \text{ fb}^{-1}} \approx 10^6 \times \lambda^4 \times \left(\frac{200 \text{ GeV}}{m_\mu}\right)^4 \left(\frac{\sqrt{s}}{200 \text{ GeV}}\right)^2.$$ 

One can see more than 5 events if $\lambda \geq 0.05$, which is below the current limits.

4. Strongly-Interacting EWSB Sector

The strongly-interacting EWSB sector will pose a great challenge at next-generation collider experiments. The signal is a rather featureless enhancement in the interaction between $W$- and $Z$-bosons at very high energies, $\sqrt{s} \geq 1$ TeV. The TeV-scale experiments in this case are regarded as the “low-energy limit” of the true dynamics of EWSB, which is analogous to pion scattering in the low-energy limit of the QCD, described by the chiral Lagrangian. A better manifestation of the dynamics of EWSB may show clearer at yet higher energies, such as at a 4 TeV muon collider. Until we can reach such a high center-of-mass energy, all we can do is to study the “low-energy” interaction of $W$-bosons in detail and speculate on the dynamics. For this purpose, it is necessary to determine the size of the interaction (scattering lengths) in all possible channels. Table 4 shows the relative merit of different channels for different scenarios.

One possibility which has not been studied is the $ZZ \rightarrow ZZ$ channel. Due to a magical cancelation, there is no strong interaction in this channel according to the Low-Energy Theorem (LET). However, there is likely to be a strong interaction
Table 1. Statistical significances of strong EWSB signals at the NLC and LHC.

| Collider | Process | $\sqrt{s}$ (TeV) | $\mathcal{L}$ (fb$^{-1}$) | $M_\rho =$ 1.5 TeV | $M_H =$ 1 TeV | LET |
|----------|---------|-----------------|-----------------|-----------------|-----------------|-----|
| NLC      | $e^+e^- \rightarrow W^+W^-$ | 0.5  | 80  | $7\sigma$  | $-\sigma$ | $-\sigma$ |
| NLC      | $e^+e^- \rightarrow W^+W^-$ | 1.0  | 200 | $35\sigma$ | $-\sigma$ | $-\sigma$ |
| NLC      | $e^+e^- \rightarrow W^+W^-$ | 1.5  | 190 | $366\sigma$ | $-\sigma$ | $5\sigma$ |
| NLC      | $W^+W^- \rightarrow ZZ$ | 1.5  | 190 | $-\sigma$ | $22\sigma$ | $8\sigma$ |
| NLC      | $W^-W^- \rightarrow W^-W^-$ | 1.5  | 190 | $-\sigma$ | $4\sigma$ | $6\sigma$ |
| LHC      | $W^+W^- \rightarrow W^+W^-$ | 14  | 100 | $-\sigma$ | $14\sigma$ | $-\sigma$ |
| LHC      | $W^+W^+ \rightarrow W^+W^+$ | 14  | 100 | $-\sigma$ | $3\sigma$ | $6\sigma$ |
| LHC      | $W^+Z \rightarrow W^+Z$ | 14  | 100 | $7\sigma$ | $-\sigma$ | $-\sigma$ |

turning on at order $(s/v^2)^2$ and hence it uniquely picks up the model-dependent piece at the next-to-leading order in the derivative expansion. The feasibility of this study has to be examined. It is certain, however, that the $e^-e^-$ option is best suited for this study, using right-handed electron beams $e_R^-e_R^- \rightarrow e_R^-e_R^-ZZ$, because of the absence of the $WW$ fusion mechanism.

5. Many More

I will not go into the other possible interests in the $e^-e^-$ option as discussed in the literature, because they are covered by other speakers in this workshop. It includes the Higgs production from $ZZ$ fusion (Minkowski), $t$-channel $Z'$-exchange (Rizzo), doubly-charged Higgs $H^-$ from $W^-W^-$ fusion (Gunion), $H^-H^-$ production from $W^-W^-$ fusion (Haber), supersymmetry signatures (Peskin, Thomas, Feng, Cheng), strong EWSB (Han), anomalous triple-gauge-boson vertices (Choudhury), dilepton resonance (Frampton), compositeness (Barklow), leptoquarks (Rizzo), $e^-e^- \rightarrow W^-W^-$ from right-handed Majorana neutrino $t$-channel exchange (Greub, Minkowski, Heusch), $\gamma\gamma \rightarrow tt$ (Hewett), $\gamma\gamma \rightarrow H$ (Takahashi). Many of the signatures employ the new channel available only in an $e^-e^-$ collision.

6. Conclusions

The physics of EWSB is likely to produce rather messy and confusing data. In order to sort these out, we would like to have as many channels as possible. This is the most convincing argument behind the complementarity between the LHC and an $e^+e^-$ linear collider. A further extrapolation of this argument raises the interest in the $e^-e^-$ option as a natural sibling to the $e^+e^-$ machine. It offers new channels and hence new observables.

We do not know how exactly data from various channels will collude to reveal the secrets of the physics of EWSB, because we do not know the physics yet. But in
many examples that we know, the $e^-e^-$ option offers new, interesting, and valuable observables.

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