LHC–ILC SYNERGY*

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I will begin by making a few general comments on the synergy between the Large Hadron Collider (LHC) which will go in action in 2007 and the International Linear Collider (ILC) which is under planning. I will then focus on the synergy between the LHC and the PLC option at the ILC, which is expected to be realised in the later stages of the ILC program. In this I will cover the possible synergy in the Higgs sector (with and without CP violation), in the determination of the anomalous vector boson couplings and last but not least, in the search for extra dimensions and radions.

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1. Introduction

Historically there has always been feedback and interplay between the hadronic and the leptonic colliders. $Sp\bar{p}S$ saw a handful of W's and Z's, establishing the correctness of the SU(2)× U(1) model, whereas the LEP/SLC tested it to a one per mil precision using the millions of Z's and thousands of W's. The agreement between the "prediction" of the top mass obtained using precision measurements from LEP and the "direct" measurements made at the Tevatron, was indeed a very important step in establishing the Standard Model. But since this synergy has always existed, one may well ask the question as to what is the special need NOW for discussing the LHC/ILC synergy. The need arises from the current state of play in High Energy Physics (HEP) and the high stakes in physics studies at future colliders, both on the physics front and on the economic front; as well as the long time scales which the planning and execution for a new collider require. The LHC is a hadronic collider with pp collisions at $\sqrt{s} = 14\,\mathrm{TeV}$, whose strong point is the larger mass reach for direct discoveries. Even though at the LHC the composite

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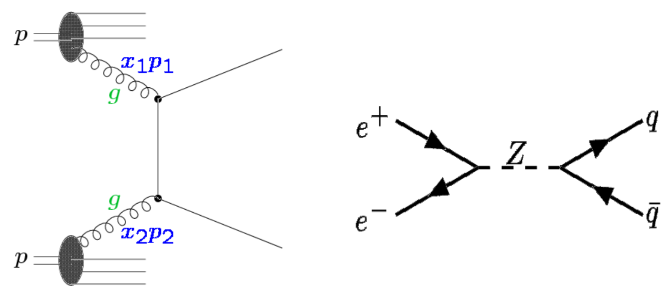

Fig. 1. The LHC and the ILC.

nature of colliding protons gives rise to an underlying event and the $\sqrt{s}$ of the hard interaction is not fixed, one can use conservation of the transverse momentum $P_{\rm T}$ and thus study interesting "hard" physics. Being a hadronic machine all the physics studies at the LHC will have to deal with large QCD backgrounds. The ILC on the other hand is planned to be an e^+e^- collider with $\sqrt{s} = 0.5$–$1.0\,$TeV. Its strong point being the high precision physics. The precisely known initial state kinematics along with possibilities of the initial state beam polarisation, allows accurate and detailed analysis of the decays, precision determinations of masses and couplings *etc.* Since the initial state contains EW particles the QCD backgrounds will be smaller than at the LHC. Further, it will also offer possibilities of various options; such as the $\gamma\gamma$, γe and e^-e^-, opening up a chance to study aspects of physics of the SM as well as physics beyond the SM, that may not be accessible at the LHC or in the e^+e^- option of the ILC. The LHC, however, has the greatest advantage *viz.*, it is all geared to start action in 2007, whereas we still are not sure IF, WHEN and WHERE construction will happen for the ILC. It is heartening, however, that a clear international consensus has emerged on the ILC now and the planning is in full swing.

Fig. 2 shows the expected cross-sections at the LHC and the ILC for different processes. The plots in left panel show us, for example, that in the exploration of the Higgs physics, which would be the focus of studies at the LHC, it is going to be a big challenge to deal with the large physics backgrounds. On the other hand we see from the expected cross-sections at the ILC for the different physics processes, that it is the ILC which will offer the possibility of high precision study of the Higgs sector. Therefore, as a community it is very important for us to assess the desired energy, luminosity and **the timing** of the ILC *vis-à-vis* the physics goals of the LHC/ILC which are set by the current stage of understanding in particle physics. In the context of the PLC it really means making sure that the ILC designs keep the possibilities of the PLC option open.

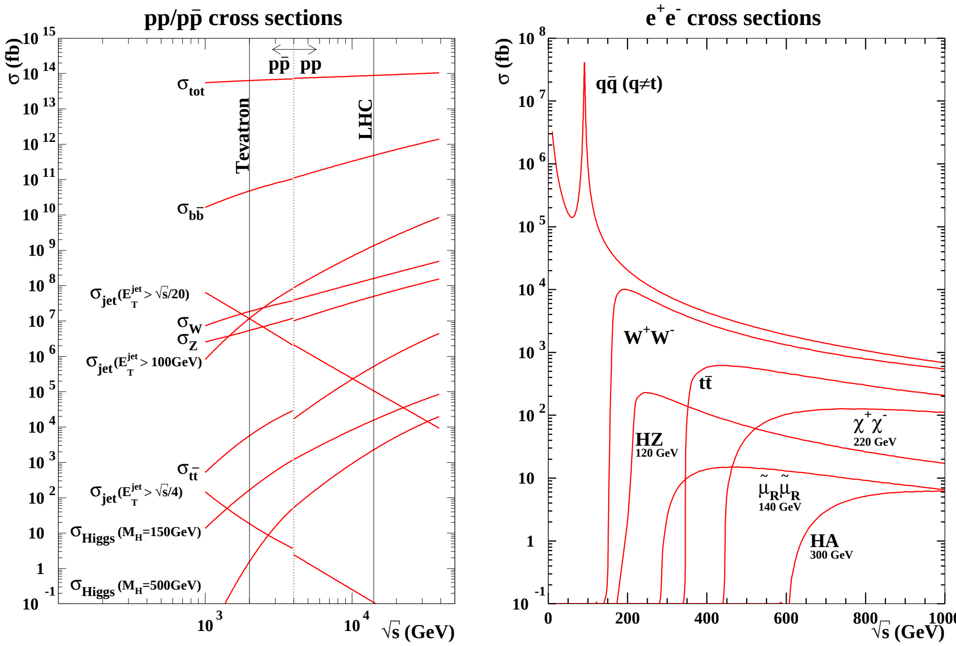

Fig. 2. Expected cross-sections for the physics process of interest at the LHC and the ILC [2].

2. LHC–ILC interplay

Till about 2002 or so there was not much interaction between the LHC and the LC community. LHC/ILC study group was first formed in the context of an ECFA LC group and then became a worldwide affair. It has been a collaborative effort of the Hadron Collider (the LHC) and the Leptonic Linear Collider (ILC) community. At the time of the formation of the group the LHC was well on its way and the physics case of an ILC had been clearly made. (Incidentally for the PLC this exercise needs to be cemented beyond the studies that have already been made [1].) The aim of the LHC/ILC study group was NOT to compare which of the two colliders can do better but rather how the two can complement each other and further whether one can identify areas where the cross-talk between the two colliders can increase the utility of *both*. It is clear that LHC will have higher reach in energy and hence can perhaps create directly new particles expected in the extensions of the SM. The ILC on the other hand can make precision measurements and can be sensitive to the indirect effects of the same particles even if masses are much higher than the energy of the ILC. Thus information from a lower energy ILC can still feedback into studies at the LHC. This is the simplest form of synergy between the two colliders. We have seen an example of this in comparison between the mass of the top quark as estimated from the precision EW measurements and as measured directly from the Tevatron data. Now we see similar interplay for the prediction of the (SM) Higgs mass, being sharpened by knowledge of the top mass from Tevatron. Precision measurements from the ILC may therefore sometimes be able to tell the LHC where to focus the effort. Precision measurements at the LHC are difficult if not impossible, but will be possible only after a few years after the beginning of its operation. These studies can definitely benefit due to the feedback from the ILC. Of course, the ability of the ILC is not restricted to precision measurements alone but also to making possible discoveries which at times will be difficult or impossible at the LHC. These qualitative statements are almost obvious to practising phenomenologists and experimentalists, but quantitative studies are necessary. Various examples of such studies and possible cross-talks are present in the document [2].

In the study group report [2] possibilities were analysed assuming that the LHC will run for 20 years and that the ILC can kick off after the LHC has been running a few years. The specific questions that were addressed in this document were as follows:

1. How information obtained at both the colliders can be put **together** so that the basic physics questions being asked by the HEP community can be answered more **conclusively and effectively**.
2. Can the combined studies give pointers to new benchmarks for measurements at the LHC.
3. Can the results obtained at a lower energy ILC affect the analysis at the LHC if **not** the triggering. Can it affect the luminosity/detector upgrades and also provide yet more focus to the LHC studies.
4. What are the physics needs and advantages of concurrent running of the LHC and the ILC.
5. What are the physics arguments to make a strong case for keeping the door for PLC open in the ILC designs under consideration.

One can think of various possible scenarios for the cross-talk:

(1) LHC + ILC: ILC data help clear up the underlying structure of new physics of which Tevatron and the LHC will give us some glimpses.

(2) **LHC ⊕ LC > LHC + LC**: A combined interpretation of LHC/ILC data can help use both the data more effectively to learn about the TeV scale physics beyond the SM; in particular such an analysis can reduce possible model dependencies.

(3) **LHC ⊗ LC > LHC ⊕ LC**: If the machines have some overlap in time, and a combined analysis of the LHC/ILC data were to be possible then the ILC results could influence the second phase of the LHC, just like some of the LEP-II results have affected the Tevatron upgrades. Similarly, the ILC results could provide inputs to the upgrade options for the LHC machines and detectors.

A few comments are in order here: While no examples could be found such that the "triggering" at the LHC could be affected by what the ILC will see, certainly very good case can be made for aiming at a combined interpretation of the data and some time overlap so that the ILC could affect the upgrades at LHC. Many examples for the latter were found particularly in the context of SUSY studies. In the context of analysis in the Higgs sector, it was shown that a reduction of model dependencies may be achieved through a combined LHC/ILC analysis. We will look at one example each from the Higgs and the SUSY sector and then go over to the case of a PLC.

2.1. Higgs studies

The LHC will be able to observe the SM Higgs and afford measurements of its various properties such as width, relative couplings to some accuracy (about 15–20%) by the end of the high luminosity run [3, 4]. As far as the ILC is concerned it can, of course, profile a Higgs most accurately even in the low energy, moderate luminosity option [5], except for the measurement of the $t\bar{t}H$ coupling and the reconstruction of the Higgs potential. At the ILC, a precision measurement of $t\bar{t}H$ coupling requires $\sqrt{s} = 800$–1000 GeV. The LHC measures $\sigma\times$ BR into different channels. One question that can be

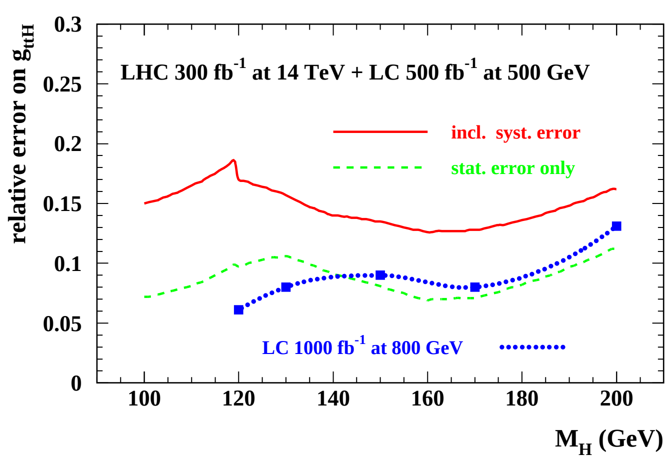

Fig. 3. LHC–ILC cross talk for the $t\bar{t}$ Higgs coupling determination [6].

asked is whether a cross talk between the LHC and the ILC can improve this situation? The strategy is to use the ILC precision information on the other branching ratios of the Higgs and thus get information on the $t\bar{t}H$ coupling in a model independent way, using BOTH the ILC and the LHC data. As can be seen from Fig. 3 the combined use of the LHC and a 500 GeV ILC with 500 fb^{-1} integrated luminosity, will allow a determination of the $t\bar{t}H$ coupling to an accuracy of 10%–15%. Further, the accuracy expected taking into account the statistical errors alone is about 5% which is comparable to that expected for a 800 GeV ILC with 1000 fb^{-1}. This clearly shows that the combined analysis of the LHC and the ILC data gives better value for money [6].

2.2. Supersymmetry studies

Next to Higgs searches and study of its properties, Supersymmetry (SUSY) searches [7] will form an important part of the physics program of any collider, be it hadronic, leptonic or photonic. Supersymmetry is certainly broken since we do not see the superpartners of the particles of the SM, differing in spin by 1/2 from them and with the same mass as them. In the unconstrained minimal supersymmetry standard model, MSSM, there exist 105 new parameters in the form of the masses of the superpartners and mixing angles. Normally, while investigating the prospect of SUSY studies at the LHC, one reduces the number of these parameters by working in the framework of one of the SUSY breaking models. These are named after the mechanism used for SUSY breaking. These are: (a) Gravity mediated (MSUGRA), (b) Gauge mediated SUSY breaking, (c) Anomaly mediated SUSY breaking *etc.* If TeV scale SUSY should exist then the probability that the LHC will see some signal is very high. The current studies of the LHC potential in the context of SUSY not only look at the prospects of discovering it but focus also on the possible measurements of masses and mixing angles. These in turn may be used for SUSY parameter and consequently the SUSY breaking mechanism determination. So far most of the studies of the LHC potential have been model dependent, now they move to **model independent** ones. At the LHC masses will be not determined with very high precision but mass differences will be. In the commonly used R-parity conserving SUSY scenarios, all the final states corresponding to a decay chain of a given sparticle contains at least one lightest supersymmetry particle (LSP) which appears as "missing" energy. Thus the sparticle mass determined is highly correlated with the mass of the LSP. This is illustrated in Fig. 4 for the determination of the $\tilde{b}_1$ mass. The dots in Fig. 4 indicate the results achievable using the LHC data alone. On the other hand, at the ILC an accurate determination of $m_{\tilde{\chi}_1^0}$ is possible. The vertical bands in Fig. 4 show the results if one were to restrict the $m_{\tilde{\chi}_1^0}$ to within

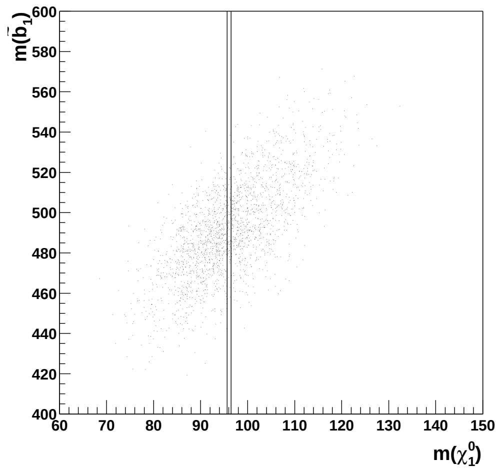

Fig. 4. Mass correlation plots, where the dots show possibilities using the LHC result alone and the vertical bands the precision possible on the LSP mass determination at the LSP [8].

$\pm 2\sigma$ with the ILC input ($\sigma = 0.2\%$). So the suggested strategy is to use the accurate mass determination of $\tilde{\chi}_1$ from the ILC and feed it in LHC sparticle mass determination. The second column in the Table I shows that indeed the ILC input can reduce the errors in the sparticle mass determina-

TABLE I

The improvement in the possible precision in the sparticle mass determination due to the combined use of the LHC and the ILC data. The errors quoted are in GeV and are for the point SPS1a [8].

	LHC	LHC+ILC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (ILC input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23
$\Delta m_{\tilde{l}_{\rm R}}$	4.8	0.05 (ILC input)
$\Delta m_{\tilde{l}_{\rm L}}$	5.0	0.2 (ILC input)
$\Delta m_{\tilde{\tau}_1}$	5–8	0.3 (ILC input)
$\Delta m_{\tilde{q}_{\rm L}}$	8.7	4.9
$\Delta m_{\tilde{q}_{\rm R}}$	7–12	5–11
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{g}}$	8.0	6.5

tion substantially. These investigations brought out an interesting feature, that the jet measurement seems to be the limiting factor for the accuracies possible with a combined analysis of the LHC and the ILC data. *This is an example where the study has isolated a feature of the LHC analysis which, if improved upon, can add to the accuracy of the sparticle mass determination at the LHC in a big way.* This thus is a very good example of the LHC–ILC synergy.

3. PLC and LHC/ILC(e^+e^-) synergy

3.1. Higgs and SUSY

To begin with, the accurate ($\sim 2\%$) measurement of the $\gamma\gamma$ decay width of a light Higgs boson possible at the PLC [1], allows a probe of high scale physics, as the heavy particles affect this decay width through loop effects. The availability of polarised photon spectra and a democratic mechanism for production of CP-even and CP-odd Higgs, makes the PLC an ideal tool to probe CP violation in the Higgs sector. Further, the s-channel production mechanism allows for single-Higgs production and hence increases the reach compared to the e^+e^- option by about a factor of 1.6. As a matter of fact, in the MSSM for $\tan\beta \simeq 4$–10, $M_A, M_H > 200$–250 GeV, the LHC will see only one spin 0 state and the H, A are not accessible for the first generation, 500 GeV, ILC. The PLC offers possibilities of probing the H/A in this so called "LHC wedge" region [9–12] through their s-channel production and decay into a $b\bar{b}$ and WW/ZZ final states. For larger values of $\tan\beta$, where the $b\bar{b}$ final state cannot be used effectively, the decays into a neutralino pairs can be used too [9]. The PLC also offers a possibility of pinning down the Higgs structure of a theory in a general Two Higgs Doublet Model (2HDM). Some aspects of this have already been discussed elsewhere in the proceedings [13, 14].

Krawczyk and collaborators [15] have discussed an example where the measurement of $\gamma\gamma$ width of the Higgs is essential to determine whether a Higgs seen at the LHC is indeed a SM Higgs. These authors have identified realisations of the 2HDM with a SM-like light Higgs boson. In case of Model A, considered by the authors, the gg width is the same as that in the SM whereas in Model B it differs by about 30%–40 % from it. The first panel in Fig. 5 shows the gg width in Model B, whereas the other two panels show the expected $\gamma\gamma$ widths for the two cases in comparison with the SM. One sees clearly that the accurate measurement of $\Gamma_{\gamma\gamma}$ possible at the PLC will indeed supplement the LHC data substantially towards getting a more complete understanding of the spontaneous symmetry breaking.

For a heavier Higgs which can decay to a pair of gauge bosons, it is possible at the PLC to measure the phase of the $H \to \gamma\gamma$ amplitude through interference effects. This phase carries information about the couplings of

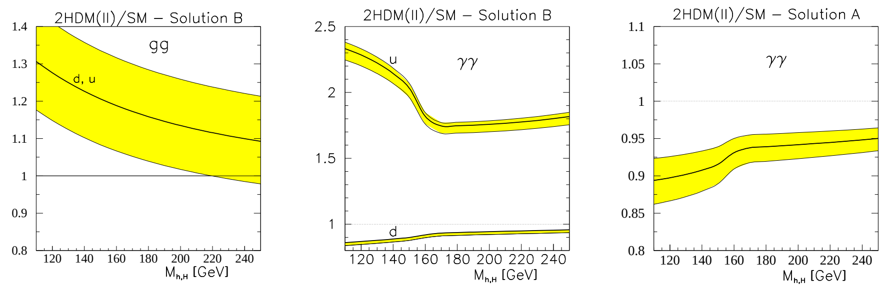

Fig. 5. The discrimination between a 2HDM and the SM using the $\gamma\gamma$ width at the PLC [15].

the H to the gauge bosons as well as to a $t\bar{t}$ pair. On the other hand the LHC measurements can give better information on the $t\bar{t}H$ coupling whereas the ILC ones on the hVV couplings. Hence combining the information from the PLC along with the LHC and the ILC measurements, the couplings of a Heavy Higgs boson can be pinned down too. This is illustrated in the left panel of Fig. 6 taken from Ref. [16]. One sees clearly that the $\phi_{\gamma\gamma}$ measurement possible at the PLC will play an absolutely essential role

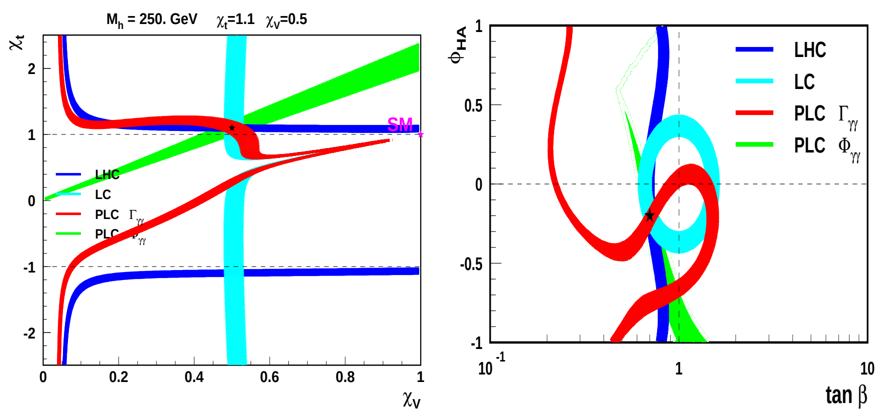

Fig. 6. The left panel shows the synergy between the LHC/ILC and the PLC in precise determination of the Higgs Boson couplings in a general 2 Higgs Doublet Model [16]. The star at $(1, 1)$ indicates the SM point and the "star" at the centre of the plot corresponds to a particular set of parameters for the general 2HDM for which the light Higgs has a SM-like phenomenology. The plot in the right panel shows an example of the same synergy for the case of he Higgs Boson couplings in a CP-violating 2HDM [17]. The plot shows that the measurements at the all three colliders will be needed to determine conclusively whether the CP-violating phase is nonzero.

in lifting the sign ambiguity which cannot be resolved using the LHC and the ILC. In case of CP-violating 2HDM, the CP-violating phase will affect the phase of the amplitudes $H\gamma\gamma$ and HWW, which can be measured via interference effects in the angular distributions of the decay W's. The plot in the right panel of Fig. 6 shows clearly again the crucial role that the PLC can play in removing the ambiguities in the determination of the mixing angle in the H–A sector.

Some more aspects of this synergy in the context of SUSY have been discussed in the proceedings elsewhere [14].

3.2. Anomalous couplings and extra dimensions

One of the simplest ways to look for new physics related to EW symmetry breaking is through measurements of the anomalous couplings of the gauge bosons [5], due to the contribution of the t-channel diagrams. Fig. 7 [18] shows a comparison of the potential of the different colliders for measurements of these anomalous couplings for the photon. We see that while for the anomalous coupling λ_g the PLC would perform better than a 500 GeV ILC, the situation is different for the case of κ_g. This is somewhat representative in this context.

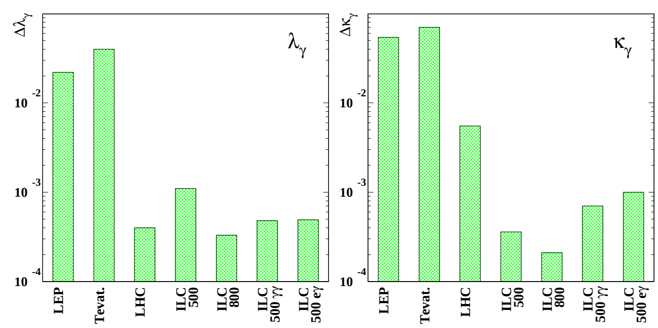

Fig. 7. A compilation of the reach of various colliders for the anomalous couplings of the photon [18].

The PLC has interesting possibilities for the models with extra dimensions since gravitons have large couplings to gluons and photons, the polarisation of photons can also be used for spin determination. Studies in the context of a $\gamma\gamma$ collider do exist [1, 19]. However, to my mind much more detailed analysis needs to be done in this case. One of the examples of things that still need to be done is discussed below. For example, $t\bar{t}$ production in the process $\gamma\gamma \to t\bar{t}$ can be used very effectively [20] to probe the large extra dimensions. It receives the usual QED t/u channel contribution and the s-channel exchange of the tower of virtual Kaluza–Klein particles. The ADD [21] model has two parameters: effective string scale $M_{\rm s}$ and effective

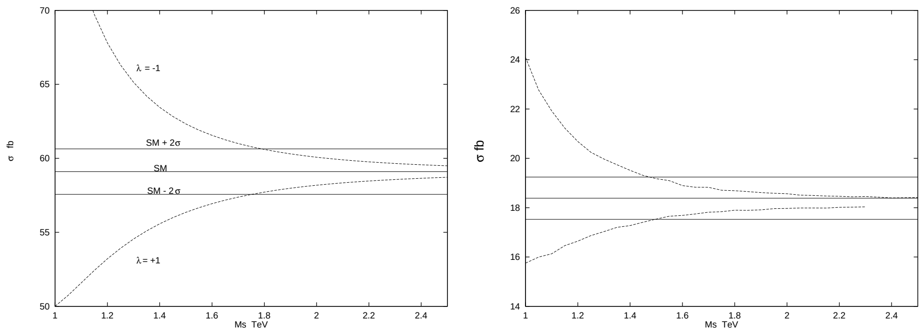

Fig. 8. Comparison of the limits obtained using the ideal backscattered photon spectrum [22] (left panel) and the realistic ComPAZ [24] (right panel).

coupling λ up to a sign ambiguity. The reach in $M_{\rm s}$ can be already quite large just using rates. For a 500 GeV machine, the reach, *e.g.*, is 1.6 TeV. This can be further maximised by use of rapidity distributions and polarisation. However, this and similar other analyses are all done using the ideal backscattered laser spectrum [22], which however, gets modified due to multiple interaction effects which have been, calculated in a Monte Carlo simulation [23]. A convenient parametrisation of the realistic spectrum is available [24]. The more realistic spectrum has a peak at low energies of the photon and the flux of the hard photon also gets smaller by about a factor 2. I present the update of the analysis [20], using the more realistic spectrum [23, 24]. Thus we see that this realistic spectrum does affect the limit substantially. We can see from the right panel that the sensitivity goes down from 1.7 TeV to 1.3 TeV, with the realistic spectrum.

4. Conclusions

It is clear from the above short discussion that there is a large potential for the LHC–ILC synergy and the study group document [2] has scratched only the surface so far. However, various good examples of the synergy have been established quantitatively. There are certainly more ideas waiting to be thought about and studied. It is hard to believe, after these studies, that after the ILC turn on no new questions will be asked of the LHC. It seems also clear that some overlap between LHC/ILC will therefore be necessary. More work is still necessary in the context of PLC, particularly the use of its unique abilities in context of Extra Dimensional models.

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