Do we need a Linear Collider to see BSM Physics?

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Summary. — The current LHC results have discovered a SM-like Higgs boson with $m_H \sim 126$ GeV, but do not yet show further hints for physics beyond the Standard Model. Therefore one also has to critically review the physics for a future Linear Collider. In the talk a short review about the current status of the ongoing Linear Collider activities are given. A personal choice of tricky new scenarios in BSM physics are presented and the capabilities of the ILC how to resolve such secrets of nature are presented.

1. – Introduction

With the discovery of a Higgs boson with a mass of about $m_H \sim 126$ GeV a completely new type of particle has been discovered and its properties have to be thoroughly investigated in best experimental conditions. Still it is not clear whether this particle shows a pure Standard Model (SM) character. A precise knowledge on couplings, branching ratios and the total width will clarify this question. Therefore experiments at an e^+e^- collider ideally prepared for precision physics in the Higgs sector are in the focus of current discussions and several machine options are under discussion. The most mature design for an e^+e^- LC is the ILC with different tunable energy stages from $\sqrt{s} = 90$, 250, 350, 500 GeV up to 1 TeV, where just recently the Technical Design Report (TDR) [2] has been published and sent to the Particle Accelerator Committee (PAC) awaiting comments.

As can be see from Fig 1a [1], the expected achievable accuracy in the determination of the different Higgs couplings beats by far the expected precision at the LHC and even at the high luminosity upgrade HLHC. A determination of the different branching ratio's is achievable at the $3 - -10\%$ (depending on the channel), the total width can be determined up to $\Gamma_H = 6\%$, the top Yukawa coupling $\Delta c_{ttH} \sim 6.5\%$, the trilinear Higgs coupling λ should be measurable with a precision of $\sim 24\%$ and even CP-mixed eigenstates can be resolved. With the full physics programme at the ILC up to 1 TeV it will therefore be possible to measure the mass dependence of the Higgs couplings that will be an important check of the Higgs mechanism, see Fig 1b [2].

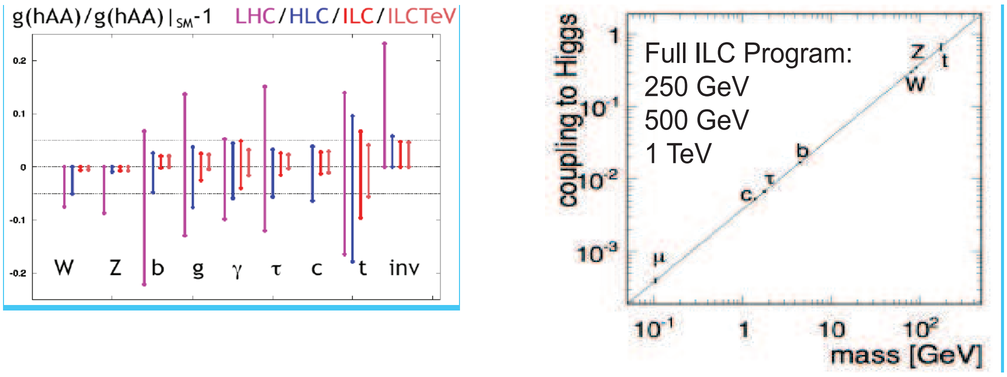

Fig. 1. – Left panel: Expected precision of Higgs couplings to bosons and fermions at the LHC, high luminosity LHC (HLC), ILC and ILC(1TeV)[1]. Right panel: Testing the linearity of the Higgs couplings and their expected precision in a staged approach of the full programme at the ILC [2].

Another discussed e^+e^- concept is that one for a multi-TeV design CLIC whose Conceptual Design Report (CDR) has been published in 2012[3] as well as ideas for several circular e^+e^- options as, for instance a circular Higgs factory. Current strong engagement of the Japanese community to host the ILC as a global project supports strongly further LC activities.

However, so far no further discoveries have been released, the current bounds for supersymmetric (SUSY) particles, for instance, are for the 1st and 2nd generation of coloured sparticles close to the TeV range. Limits to additional gauge bosons Z', W' are already in the 2 TeV range as well as limits for large extra dimension etc. The further LHC run with higher energy and luminosity are eagerly awaited. Therefore one has to critically ask whether enough physics space is currently left to decide already now at this stage about the next high energy physics collider.

2. – SUSY at the Linear Collider

2·1. *Implications from LHC results on SUSY models.* – Supersymmetry is one of the best motivated extensions of the Standard Model, fully renormalizable and therefore with a high predictive power up to the quantum level. Since it can cure several of the open questions of the SM as the hierarchy problem, gauge unification and provides several dark matter candidates, one has to take a careful look to understand why so far no significant hints of SUSY at the LHC have been shown up so far.

Since SUSY provides a rich spectrum of new parameters (about 105 in the minimal model), simplifying assumptions have to be done in the complicated experimental analyses at the LHC. Therefore usually constrained models with only a few parameters have been studied.

In Fig2a bounds on the mSUGRA parameters m_0, $m_{1/2}$ based on 5.8 fb^{-1} at 8 TeV in the same–sign dilepton+multi-jets+$E_T^{\rm miss}$ channel at ATLAS are presented and are in the range of $m_{1/2} = 400 - 500$ GeV. In Fig2b the current exclusion limits on the cross section for squark pair production at CMS are given in the $m_{\rm LSP} - m_{\tilde{q}}$ projection. One should note that the analysis is only based on simplified models where a 100% branching ratio of $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ has been assumed. Turning to more realistic branching ratios in the

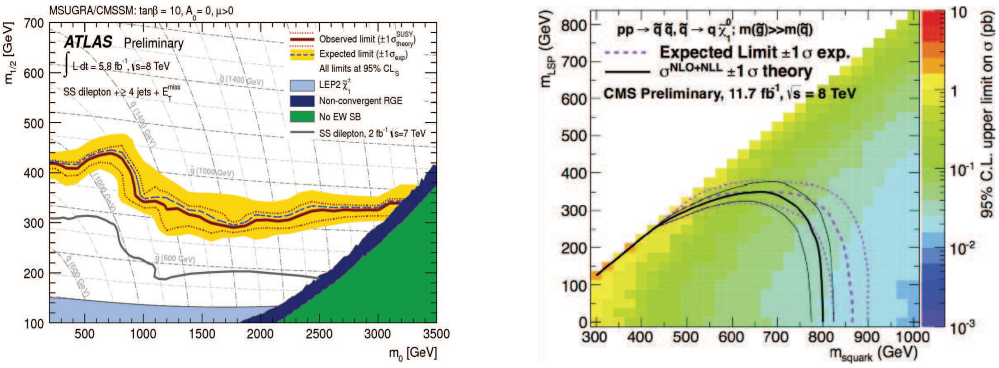

Fig. 2. – Left panel: Current bounds from ATLAS data based on 5.8 fb^{-1} at $\sqrt{s}$ =8 TeV in the mSUGRA parameter space $m_0 - m_{1/2}$–plane with a fixed $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$[4]. Right panel: CMS Cross section exclusion bounds in squark pair production based on 11.7 fb^{-1} at $\sqrt{s}$ =8 TeV in a simplified model with a 100% BR in $\tilde{q} \to q\tilde{\chi}^0_1$[5] .

model usually leads to much less sensitivity.

2˙2. *Motivation for low-energy SUSY scales.* – The deviations between the measured and predicted anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$, which are sensitive to new physics proportional to$(\frac{m_\mu}{M_{BSM}})^2$[6], prefer a rather light electroweak SUSY scale. To combine this with the rather heavy bounds from LHC in the coloured sector, motivates to study SUSY models where the coloured and non-coloured sector are decoupled. In this regard, many new benchmark scenarios for LC studies in SUSY have been made that are consistent with $m_H = 125$ GeV, see for instance[7]. Usually one get an heavy coloured sector but a rather light electroweak sector in the range of 100-500 GeV with a rich spectrum of phenomenological applications at the LC and LHC in order to reveal the underlying model and determine the parameters unambiguously.

From a theoretical point of view a light SUSY scale is preferred in order to keep electroweak fine-tuning up to a reasonable amount, to stay at a 'natural' level. The minimization of the Higgs potential reads at 1–loop

$$\frac{M_Z^2}{2} = \frac{m^2_{H_d} + \Sigma^d_d - (m^2_{H_u} + \Sigma^u_u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

and can be approximated to $-(m^2_{H_u} + \Sigma^u_u) - \mu^2$. Corresponding 'naturalness' a rather light $\mu \sim 200$ GeV is required [8, 9]. In this regard scenarios with a light $\tilde{t}_1$ as well as light higgsino-like $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^\pm_1$ are 'natural' leading to challenging phenomenology for colliders.

2˙3. *SUSY with light $\tilde{t}_1$.* – Light $m_{\tilde{t}_1}$ masses are not excluded, neither from supersymmetric fits, see Fig3a,b [10], nor from LHC searches, see Fig4a.

Due to the strong relation between the Higgs mass and the stop sector in SUSY, the Higgs mass of 125 GeV drives m_{tildet_1} to large values. However, the crucial parameter is the mixing angle. The off-diagonal mixing matrix element is given by $X_t = A_t\mu\cot\beta$. For a large mixing even a rather light $\tilde{t}_1$ is not excluded, see Fig3a. This fact is in concordance with the current LHC results, see Fig4, where large stop masses are preferred

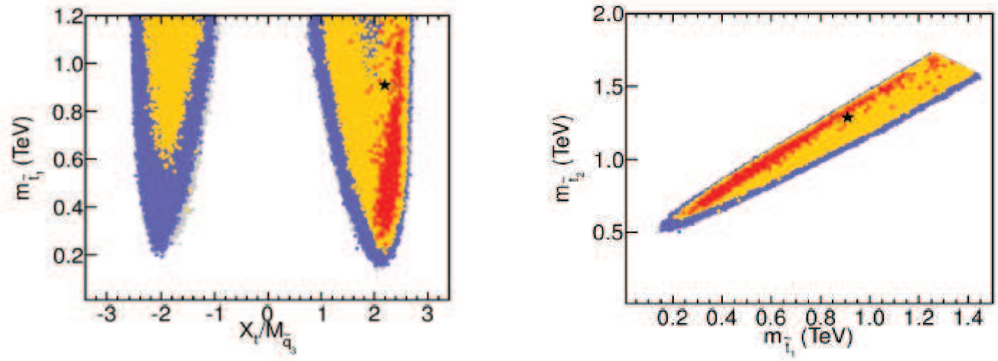

Fig. 3. – Left panel: Light stop mass eigenvalue $m_{\tilde{t}_1}$ consistent with $m_{\text{Higgs}} = 125$ GeV in dependence of the stop mixing parameter $X_t = A_t - \mu \cot\beta$[10]. Right panel: Stop mass eigenvalues $m_{\tilde{t}_{1,2}}$ consistent with $m_{\text{Higgs}} = 125$ GeV [10].

but light stops cannot be excluded since the bounds depend crucially on the made mass assumptions on $m_{\tilde{1}^0}$, $m_{\tilde{\chi}_1^\pm}$.

The crucial dependence on the Higgs sector shows the importance of determining the stop mixing angle which can be measured with very high accuracy at the LC. In particular important is the availability of high luminosity and polarized beams. In particular with respect to the mixing angle, polarized e^+ simultaneously to polarized e^- are very powerful, see TabI and Fig4b [11]: 5-times the luminosity reduces the error to 1/2 but only switching on positron polarization with 60% reduces the uncertainty by 60% at fixed luminosity[11].

A high accuracy in $\Delta \cos\theta_{\tilde{t}}$ is mandatory to achieve a precise determination of ΔX_t: $\Delta X_t \sim 10\%$ causes $\Delta m_H = \pm 1.5$ GeV which is a too big uncertainty for checking the consistency of the model. Only a precise of $\Delta X_t = \pm 1\%$ results in $\Delta m_H = \pm 0.2$ GeV

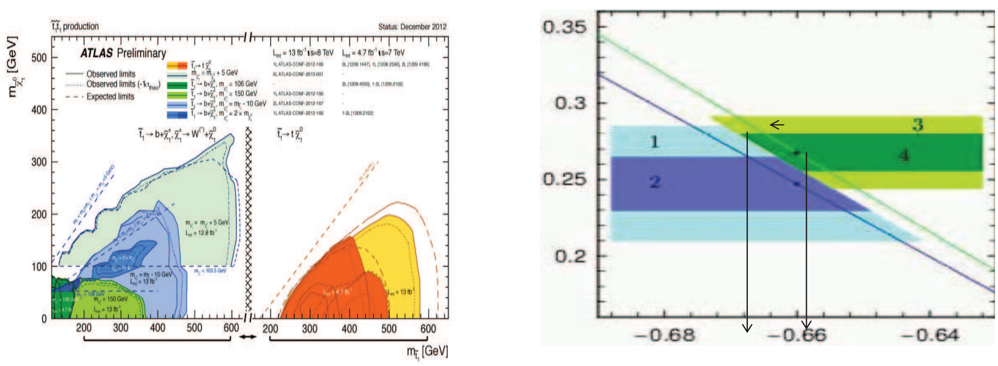

Fig. 4. – Left panel: ATLAS $m_{\tilde{t}_1}$ exclusion bounds on basis of 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV and 13 fb^{-1} at $\sqrt{s} = 8$ TeV at LHC. Right panel: Determining the mixing angle $cos\theta_{\tilde{t}}$ via the left-right asymmetry in $e^+e^- \to \tilde{t}_1\tilde{t})1$ at $\sqrt{s} = 500$ GeV for different luminosities and different beam polarizations $P_{e^-} = \mp 90\%$ w/o $P_{e^+} = \pm 60\%$ at the ILC[11].

TABLE I. – *Achievable accuracy for the stop mass and the stop mixing angle at the ILC based on different luminosioty assumptions and with different beam polarization configurations, only* $P_{e^-} = \pm 90\%$ *and simultaneously* $P_{e^-} = \pm 90\%$, $P_{e^+} = \mp 60\%$ *[11].*

$\mathcal{L}_{\rm int}$	P_{e^-}	P_{e^+}	$\Delta m_{\tilde{t}_1}$	$\Delta \cos\theta_{\tilde{t}}$
100 $\rm fb^{-1}$	∓ 0.9	0	1.1%	2.3%
500 $\rm fb^{-1}$	∓ 0.9	0	0.5%	1.1%
100 $\rm fb^{-1}$	∓ 0.9	± 0.6	0.8%	1%
500 $\rm fb^{-1}$	∓ 0.9	± 0.4	0.4%	0.7%

that matches the long-term precision at the LHC.

2·4. *SUSY with light higgsino-like*$\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^\pm_1$. – Very interesting and challenging SUSY scenarios are cases with the parameters $\mu \ll M_2$ which lead to strongly mass degenerated scenarios between the light neutralinos and charginos. Easily such scenarios can also be embedded within SUSY breaking models, namely hybrid-models, where large M_2- values are driven by gauge-mediation and small values by μ originating from gravity mediation. However, resulting even in $m_H \sim 125$ GeV requires very high values of M_2 in the large multi-TeV range[12].

In the examples the light masses $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^\pm_1$ are in the range of 165 GeV, but with a very small mass difference $(m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1})$ of only about 1 GeV. This small mass difference results in many π's, soft γ's in the detector. How can one resolve such scenarios? The LHC would have substantial problems if not even impossible to detect such signals.

At a Linear Collider one can, however, use the ISR method, i.e. one takes only events of this process that are accompanied by a hard photon from initial state radiation (ISR). Measuring chargino production at two different energies $\sqrt{s} = 350$, 500 GeV offers more observables and exploiting the semihadronic channel and using the recoil mass method allows to determine the mass difference $\Delta M(\tilde{\chi}^\pm_1, \tilde{\chi}^0_1) \sim 0.8 \pm 0.02$ GeV, where the true mass difference is 0.77 GeV[12].

2·5. *Sensitivity to heavy virtual particles.* – Measuring the masses even in such challenging cases as shown before, with a high accuracy, using polarized cross sections and different asymmetries, often at two different energies, allows to determine the fundamental SUSY parameters without assuming a specific breaking scheme. Due to the high achievable precision in mass and cross sections measurement at the LC, one can determine the parameters M_1, M_2, μ, $\tan\beta$ up to the per cent level, i.e. one is sensitive to the quantum level and higher-order corrections have to be incorporated in the theoretical calculations[13] (and refernces therein).

In our example, see TabII, next-leading-order corrected masses, polarized cross sections at $\sqrt{s} = 350$ and 500 GeV and in addition the forward-backward asymmetry has been exploited in $e^+ L, Re^-_{R,L} \to \tilde{\chi}^+_1 \tilde{\chi}^-_1$. Concerning the experimental uncertainties for $m_{\tilde{\chi}^\pm_1}$, $m_{\tilde{\chi}^0_1}$ two cases have been compared: the achievable precision via threshold scans versus that one expected from measurements in the continuum. The dominant virtual effects in loops come from the stop sector $\tilde{t}_1$, $\tilde{t}_2$. The fundamental parameters as well as the stop masses have been extracted from these observables based on loop-corrected predictions using an on-shell renormalization scheme[14]. As can be seen from TabII, M_1, M_2, μ can be determined with an accuracy better than 1%, $\tan\beta$ up to 5%. Also excellent precision is achievable concerning the unobservable sneutrino with $\Delta m_{\tilde{\nu}} \sim$ 2-

TABLE II. – *Fit results (masses in GeV) at the 1-loop level for input light chargino/neutralino masses obtained from threshold scans as well as from continuum measurements at the LC[13]. An on-shell renormalization scheme has been applied[14].*

Parameters	Threshold fit	Continuum fit
M_1	125 ± 0.3	125 ± 0.6
M_2	250 ± 0.6	250 ± 1.6
μ	180 ± 0.4	180 ± 0.7
$\tan\beta$	10 ± 0.5	10 ± 1.3
$m_{\tilde{\nu}}$	1500 ± 24	1500 ± 20
$m_{\tilde{t}_1}$	400^{+180}_{-120}	–
$m_{\tilde{t}_2}$	800^{+300}_{-170}	800^{+350}_{-220}

3%. Due to the incorporation of loop effects one is even sensitive to the stop sector. However, in this case it becomes clear, why threshold scans are so important: only the achievable precision via such scans allows to predict both $\tilde{t}_1$ and $\tilde{t}_2$ rather accurately[13].

Such an accuracy in the determination of the gaugino/higgsino parameters has also impact on the dark matter predictions: the uncertainties of the NLO corrected parameters cause 5% uncertainty in the dark matter prediction (with an overall uncertainty of about 10%)[13].

2·6. *Challenge of extended BSM model: NMSSM*. – A very important question for collider physics is how to determine the underlying physics model?

A very precise model parameter determination is mandatory to reveal inconsistencies between the model assumptions. In the NMSSM the additional Higgs singlet offers surprising opportunities for embedding a SM-like $m_H \sim 125$ GeV. Since the new Higgs singlet should also have new higgsinos as superpartners such an extended SUSY model is often believed to lead to a characteristic distinguishable phenomenology. However, there are tricky scenarios where the Higgs sector leads to a very similar phenomenology and the corresponding SUSY partner provide a similar mass spectrum so that a model distinction at the LHC is not expected. For instance, choosing the SUSY partner of the new Higgs singlet to be the second lightest neutralinos provides, for instance, with the parameters $M_1 \sim 370$ GeV, $M_2 \sim 150$ GeV, $\mu \sim 360$ GeV and $x \sim 900$ GeV a very similar gaugino/higgsino mass spectrum in the MSSM and NMSSM. However, the mixing character differs, in particular in the heavier states[15]. Therefore a very accurate but model-independent parameter determination might be mandatory to reveal the underlying structure of the extended model.

Performing now an accurate fundamental MSSM parameter determination as explained before would predict a strongly higgsino-like heavier $\tilde{\chi}^0_3$-state, that should not be observable at the LHC. However, in the typically chosen NMSSM scenario, the heavier $\tilde{\chi}^0_3$ would have a sufficient gaugino-like component leading to a dilepton edge at the LHC, see Fig5a. Combining therefore mass edge results from LHC with high precision parameter determination strategies at the ILC could immediately point to a model inconsistency between the theoretical predictions and the experimental results and clarify therefore the true underlying model[15].

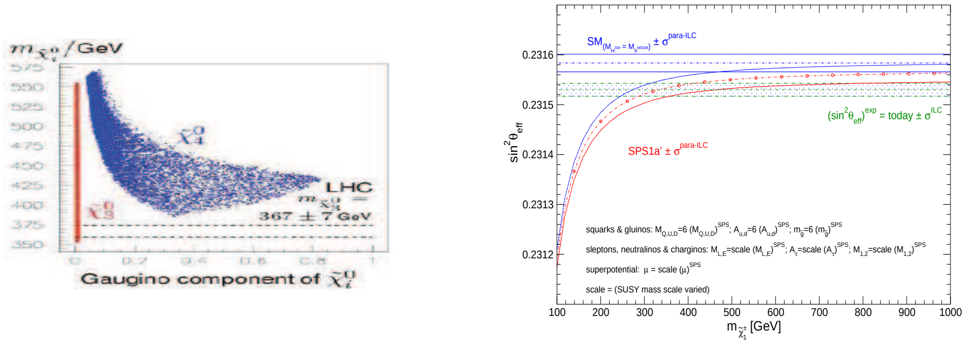

Fig. 5. – Left panel: Predicted mixing character of the heavier neutralino states based on the accurately determined parameters M_1, M_2, μ, $\tan\beta$ in the MSSM. The underlying NMSSM would lead to a contraction in the predicted mixing character for the heavier neutralino. Combining results at the LHC with the expected precision outcome at the ILC would therefore immediately point to a model inconsistency of the underlying assumed SUSY model. Right panel: Theoretical prediction for $\sin^2\theta_{\rm eff}$ in the SM and the MSSM (including prospective parametric theoretical uncertainties) compared to the experimental precision at the ILC with GigaZ option. An SPS 1a' inspired scenario is used, where the squark and gluino mass parameters are fixed to $6\times$ their SPS 1a' values. As can see from the figure, one is still sensitive to the mass differences between both models, even if the on-shell particles are beyond the kinematic range.

3. – Traces for new physics: electroweak precision tests

Another tricky case to face is if the LHC only finds the SM-like Higgs but no other trace for physics beyond the SM.

However, one should remind that there exists a strong relation between the measured Higgs mass and the electroweak mixing angle $\sin^2\theta^{\rm lept}_{\rm eff}$, see Fig6a [16]. The currently still most accurate high precisions analyses still offer a more than 2σ-discrepancy between the derived $\sin^2\theta^{\rm lept}_{\rm eff} = 0.23221\pm0.00029$ at LEP and 0.23098 ± 0.00026 at SLC, see Fig6a. The world average is given by $\sin^2\theta^{\rm lept}_{\rm eff} = 0.23153\pm0.00016$. At GigaZ, the high luminosity option for running at the Z-pole, offers to determine the mixing angle up to a precision of 1.3^{-5}[11].

Electroweak precision tests are a very powerful tool to check the model and reveal inconsistencies. However the achievable precision is still driven by parametric uncertainties from Δm_Z, $\Delta\alpha_{\rm had}$ and $\Delta m_{\rm top}$. A top precision of $m_{\rm top} = 0.1$ GeV is mandatory to achieve the goals[17]. However, the top quark does not appear as an asymptotic state and is strongly dependent on the renormalization scheme. Only the definition of the threshold top mass meets stability requirements and offers a unique matching to the renormalization scheme and allows a determination up to the desired precision [18, 2].

On basis of such a precision of $\Delta m_{\rm top} = 0.1$ GeV one could apply the ultimate precisions tests at GigaZ at the ILC, see Fig5b and would be sensitive to SUSY scenarios that have a multi-TeV coloured sector beyond the kinematic range of the LHC[19]. Such a measurement would give an important hint whether only the SM model or also BSM is at the horizon and would outline the expected BSM scale.

To clarify it even more why such a measurement is important, one studies, for instance, the measured central values of the mixing angles at LEP and SLC separately, see Fig7a,b. The current central value from the LEP measurement would rule out immediately the

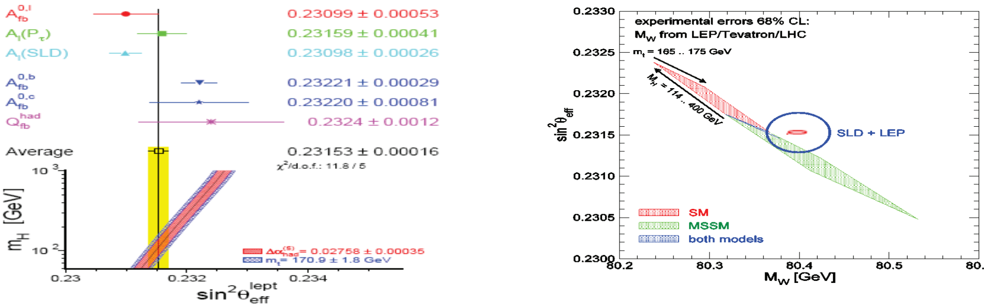

Fig. 6. – Left panel: Mass of a SM Higgs in dependence of the electroweak mixing angle $\sin^2\theta_{\rm eff}$ measured via different observables and the central value (yellow area)[16]. Right panel: $\sin^2\theta_{\rm eff}$ in dependence of m_W for the SM and the MSSM. The blue circle denotes the 1σ uncertainty around the current central value, the red circle denotes the 1σ uncertainty expected at GigaZ[19, 20].

SM as well as the MSSM, see Fig7a. Contrary the measured central value at SLC would point to the MSSM, see Fig7b and would immediately rule out the SM[21].

In summary: in case that the LHC finds only the Higgs but no hints for BSM physics in the near future the option of the ILC to go back in energy and exploit first the high luminosity run at the Z-pole before upgrading to higher energy may be the wise key player in outlining the high scale of a possible new physics.

4. – Landscape vision for 2030 and beyond

In twenty years time we maybe could tell the following story: Once upon a time –it was July, 4th, 2012– the success story of the Higgs boson started in Geneva and was followed by intense high precision Higgs physics at the ILC Higgs factory at $\sqrt{s} = 250$ GeV in Japan. All properties of the two heavy elementary particles, Higgs and top quark, were measured in the years after at the energy stages $\sqrt{s} = 350$ GeV and $\sqrt{s} = 500$ GeV. The precision measurements of the width and couplings gave first hints whether it was a pure SM Higgs or belonged to a BSM model. With the help of successfully applied ISR

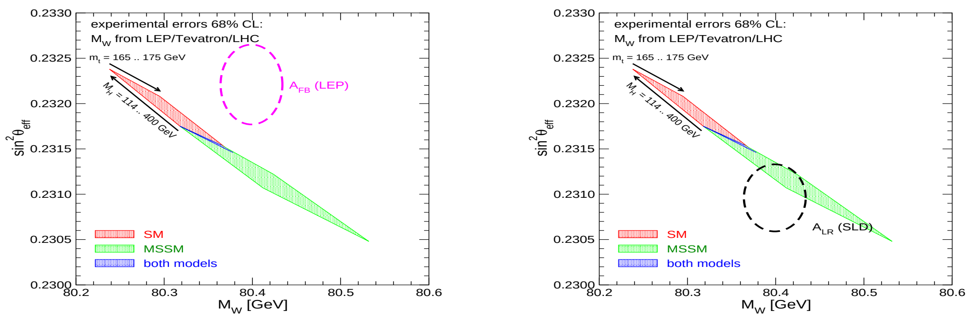

Fig. 7. – Left panel: The 1σ uncertainty area of $\sin^2\theta_{\rm eff}$ depicted at the measured value at $A_{\rm FB}$ at LEP in dependence of m_W for the SM and the MSSM. Both models would be excluded. Right panel: The 1σ uncertainty area of $\sin^2\theta_{\rm eff}$ depicted at the measured value at $A_{\rm LR}$ at SLC in dependence of m_W for the SM and the MSSM. The MSSM would be favoured.

methods at the LC higgsino-like charginos and neutralinos were found. From that time on, the Higgs was identified as SUSY Higgs. The LC upgrade to higher energies to the TeV regions together with high luminosity LHC runs was accompanied by the discovery of many new members within the SUSY family and many LHC and LC theorists and experimentalists worked happily together on the common path towards a grand unified theory.

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GMP would like to thank the organizer for the welcoming and warm atmosphere and all the great inspiring discussions and talks at the meeting. Furthermore a big thank you for their patience with this proceedings contribution.

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