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Precision inclusive Higgs physics at e^+e^- colliders with tracking detectors and without calorimetry

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ABSTRACT: A primary goal of a future e^+e^- collider program will be the precision measurement of Higgs boson properties. For practical reasons it is of interest to determine the minimal set of detector specifications required to reach this and other scientific goals. Here we investigate the precision obtainable for the $e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^-X$ inclusive cross section and the Higgs boson mass using the di-muon recoil method, considering a detector that has only an inner tracking system within a solenoidal magnetic field, surrounded by many nuclear interaction lengths of absorbing material, and an outer muon identification system. We find that the sensitivity achievable in these measurements with such a tracking detector is only marginally reduced compared to that expected for a general purpose detector with additional electromagnetic and hadronic calorimeter systems. The difference results mainly from multi-photon backgrounds that are not as easily rejected with tracking detectors. We also comment on the prospects for an analogous measurement of the $e^+e^- \rightarrow Zh \rightarrow e^+e^-X$ inclusive cross section. Finally, we study searches for light scalars utilizing the di-muon recoil method, estimating the projected reach with a tracking or general purpose detector.

KEYWORDS: Higgs Physics, Beyond Standard Model

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1 Introduction

The discovery of the 125 GeV Higgs boson at the Large Hadron Collider (LHC) was a milestone achievement in high energy physics, representing a capstone to the Standard Model (SM) and validating the weakly-coupled Higgs mechanism as the source of electroweak symmetry breaking. Within current measurement precision available at the LHC, all observed properties of the Higgs boson are in agreement with SM predictions. Because of its primary role in the description of electroweak symmetry breaking, the Higgs boson will remain an important target of measurements throughout the remainder of the LHC program.

Looking further into the future, it is highly desirable to put the Higgs boson under a more refined microscope to undertake qualitatively new measurements of its properties and obtain quantitative improvements in experimental precision, beyond what may be achieved at the LHC. Proposed e^+e^- colliders including the ILC, CEPC, FCC-ee, and CLIC, would provide relatively clean, fairly high-statistics samples of Higgs bosons, offering the possibility of (sub)percent-level measurements for many of its most important properties. This would provide an interesting level of discovery potential for signs of new physics beyond the SM connected with electroweak symmetry breaking. The physics case for these colliders

is now broadly established [1–6] with design plans at various stages of development. It remains to be seen which, if any, will be constructed.

In this work we study one of the most important Higgs measurements at e^+e^- colliders, the inclusive σ_{Zh} cross section measurement based on the di-muon recoil method, using a detector with only inner tracking and muon systems, without hadronic or electromagnetic calorimetry. Comparing to a traditional analysis with full calorimetry, we find that the track-based analysis is nearly as sensitive in the di-muon channel as an analysis with a general purpose detector with tracking and calorimetry. The Higgs boson mass can also be measured in this channel, for which again we find only a marginal reduction in sensitivity for tracking detectors without calorimeters. A cartoon of the tracking only and general purpose detectors we consider is shown in figure 1. The small difference in reach for these measurements arises primarily from multiphoton backgrounds, which are more easily vetoed with electromagnetic calorimetry.

Our focus on a detector with the minimum number of components to achieve a specific scientific goal shares some similarities with the motivation behind the Fourth Concept Detector [7] proposed for the ILC, where simplicity and a reduction in the number of detector components was a guiding design principle, and the IDEA detector [4] for circular colliders.

This work is organized as follows. In section 2 we review the σ_{Zh} measurement using the di-muon recoil method and describe our signal and background generation, commenting on several related technical issues. In section 3 we perform a track-based analysis and compare it to an analysis with a general purpose detector with tracking and calorimetry, also commenting on sensitivity to the Higgs mass and simple alternative methods for photon rejection utilizing a conversion tracking layer. In section 4 we discuss the σ_{Zh} measurement in the electron channel, where backgrounds are larger, final state radiation (FSR) and bremsstrahlung are more important, and discriminating charged hadrons from electrons is essential. We do not perform a complete analysis here, but we show that hadronic backgrounds to electron identification can be efficiently rejected with tracking information alone. In section 5 we perform a closely-related analysis of searches for new light bosons mixing with the Higgs using the di-muon recoil method with and without calorimetry. In section 6 we summarize and conclude, commenting on directions for future study.

2 $e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^-X$

One of the primary and most important precision Higgs boson measurements that will be undertaken at a future e^+e^- collider is the inclusive Zh production cross-section, σ_{Zh} . The coupling of the Higgs boson to Z -bosons that determines this cross section can be sensitive to new physics beyond the Standard Model. For example, σ_{Zh} can deviate significantly from its predicted SM value if the Higgs mixes with another scalar, and is generally affected if the Higgs couples to new states through the “Higgs portal” mechanism. Deviations in σ_{Zh} can be tied to solutions to the hierarchy problem, dark matter, or new physics predicting a strong first-order electroweak phase transition [8–14]. Most proposals for future e^+e^- colliders ultimately aim to achieve (sub)percent-level precision in σ_{Zh} [1, 3, 5, 15–18], which would provide unparalleled sensitivity to new physics involving the Higgs boson. It

Figure 1. Cartoon comparing a transverse wedge slice of a general purpose collider detector (left) with a similar slice of a magnetic solenoid tracking detector (right). The inner tracker systems are similar in both detectors. The general purpose detector has electromagnetic and hadronic calorimeter systems outside the inner tracker. The magnitude of the solenoidal magnetic field in the inner tracker region is similar in both detectors. However, the solenoid can be physically smaller in the tracking detector. In the general purpose detector the return yoke for the solenoid is embedded within the muon system. In the tracker detector the return yoke can be part or all of the shielding material outside the solenoid.

is important that any detector design and experimental run plan allow for this level of sensitivity in order to maintain the physics case for these colliders.

The excellent sensitivity to σ_{Zh} achievable at e^+e^- experiments is due to the relatively clean environment and the ability to perform an inclusive recoil measurement to isolate genuine Zh events. The cleanest channel is $Z(\rightarrow \mu^+\mu^-)h$, as muon identification is expected to be very efficient and the corresponding momenta can be measured with high accuracy. Unlike other channels, the acceptance times efficiency for prompt reconstructed muons can also be characterized essentially independent of other activity in the remainder of the event coming from the various Higgs boson decay modes. The electron channel $Z(\rightarrow e^+e^-)h$ is expected to offer slightly less sensitivity, due to additional backgrounds and the effects of final state radiation and bremsstrahlung. The hadronic channel $Z(\rightarrow \bar{q}q)h$ provides larger statistics, but suffers larger backgrounds and less resolution. The acceptance times efficiency for jets in the hadronic channel, and for electrons in the electron channel, depend on the amount of activity in the remainder of the event from Higgs boson decay mainly into hadronic final states, and so do not strictly provide a model independent measurement of the Zh inclusive cross section without additional assumptions about Higgs boson branching ratios.

Here, we study the prospects for measuring σ_{Zh} in the muon channel with and without detector calorimetry. As we review below, such a measurement typically relies primarily on the kinematics of the muons, which can be accurately determined with tracking alone.

2.1 Signal

For the signal, we consider the process

$$e^+e^- \rightarrow Zh \quad \text{with} \quad Z \rightarrow \mu^+\mu^-, \quad h \rightarrow \text{all} \quad (2.1)$$

Measuring the rate for this process and dividing by the well-measured $Z \rightarrow \mu^+\mu^-$ branching ratio yields a direct measurement of σ_{Zh} . To determine the ultimate sensitivity to σ_{Zh} in this channel, we will compare the predicted signal and corresponding backgrounds. We generate $e^+e^- \rightarrow \mu^+\mu^-h$ events using the Monte Carlo event generator **Whizard 2** [19, 20], including the effects of initial state radiation (ISR). The effects of beamstrahlung are not included, as they should be negligible at a circular e^+e^- collider, and are not expected to be a limiting factor at a linear e^+e^- collider. For the Monte Carlo samples we analyze below, only signal events with prompt muons are included, as the contribution from events with muons arising from heavy flavor decays to the signal region is found to be negligibly small. Throughout our study the center-of-mass energy is taken to be $\sqrt{s} = 250$ GeV. Events are passed to **Pythia 6** [21] for final state showering and hadronization. At the generator level, $\sigma_{Zh} \cdot \text{Br}(Z \rightarrow \mu^+\mu^-) \simeq 7$ fb in the Standard Model. Details concerning the reconstruction and selection criteria are described below in section 3.1. All signal and background samples are generated assuming 200 fb^{-1} of integrated luminosity, which could conservatively be achieved within one or two years of running [2, 4, 5].

2.2 Backgrounds

In order to determine the precision with which σ_{Zh} can be measured, several background processes mimicking the signal must also be accounted for. The dominant contributions can be grouped into two fermion ($2f$) and four fermion ($4f$) processes, described below. In our analysis we again utilize **Whizard 2** and **Pythia 6** for background event generation and showering/hadronization.

2.2.1 $2f$ +ISR

An important background for the Zh recoil analysis consists of two-fermion events, primarily produced either through a Z -boson or off-shell photon, accompanied by a significant amount of initial state radiation. Two or more ISR photons can provide the necessary “kick” for the recoil mass, m_{reco} (defined below), to fall within the Higgs mass window. While our analysis will include cuts on the lepton p_T , the reconstructed Z mass, and m_{reco} , it is straightforward to see that $2f$ events with at least one sufficiently transverse photon and one hard collinear photon can fall within the signal region. Thus, low- p_T hard ISR photons should be accounted for in our analysis.

Emission of n hard, collinear ISR photons results in logarithmically-enhanced contributions to the inclusive $2f$ cross-section proportional at leading multi-logarithm order to

$$\frac{1}{n!} \alpha_{\text{EM}}^n \log^n \frac{s}{m_e^2} \quad (2.2)$$

These leading multi-logarithm contributions can be accounted for, up to a given n , by electron structure functions in **Whizard**. Although these structure functions marginalize over

the ISR p_T , **Whizard** can also generate events with finite transverse momentum for the recoiling system so that the distributions reproduce the expected leading behavior in p_T . We utilize this feature when generating events. Since the two fermions produced by **Whizard** will be required to yield di-muons reconstructing to near m_Z , we incorporate a generator level cut on the fermion-antifermion invariant mass, $m(f\bar{f}) > 10 \text{ GeV}$. After imposing our selection criteria, we find that the dominant contribution is from events with two prompt muons (throughout muon is used to refer to both muons and anti-muons, except where noted) and so we neglect the non-prompt 2μ background in what follows.

In comparing detectors with and without an electromagnetic calorimeter (ECAL), we will be interested in the effect of a photon veto on this background, since some sufficiently hard transverse ISR is required for 2μ processes to contribute to the signal region. Events with a single hard photon will have $m_{\text{reco}} \simeq 0$ at parton-level, and thus do not fall within the signal region. For $\sqrt{s} = 250 \text{ GeV}$, the effective expansion parameter in eq. (2.2) is not very large, $\alpha_{\text{EM}} \log s/m_e^2 \sim 0.2$, and so the contribution of hard 3γ events is suppressed by $\sim \mathcal{O}(0.1)$ relative to events with two hard photons. We therefore expect the largest background contribution from $e^+e^- \rightarrow \mu^+\mu^- + 2\gamma$. For each event, the **Whizard** approach effectively generates one ISR photon per beam with non-zero p_T , and so should reasonably capture the transverse photon kinematics in the signal region. Note that **Madgraph** [22] can also be used to analyze this background, provided that one includes two photons in the generated process, incorporates non-zero lepton masses (to cut off collinear infrared divergences), and sets a low generator-level photon energy cut.

2.2.2 $4f$

Four-fermion processes ($e^+e^- \rightarrow 4f$) make up another important background for the recoil measurement when the final state involves a $\mu^+\mu^-$ pair, produced directly in the hard process and/or in heavy flavor decays. In the latter case, the muons are generally reconstructed as non-prompt and tend to be produced in close proximity to additional charged tracks with significant p_T . After imposing muon isolation criteria, we find that events with two non-prompt muons contribute negligibly to this background, and so we consider only $e^+e^- \rightarrow \mu^+\mu^- + 2f$ and $e^+e^- \rightarrow \mu^\pm + 3f (\neq \mu)$ in what follows.

Two important contributions to the $4f$ background in the signal region are shown in figure 2. The first corresponds to $e^+e^- \rightarrow (Z/\gamma^*)(Z/\gamma^*)$, with subsequent decays to four fermions including a $\mu^+\mu^-$ pair. This process is resonantly enhanced for $\mu^+\mu^-$ near the Z pole, and features kinematics similar to the Zh signal, making it challenging to eliminate. The multi-peripheral diagrams like that shown in the right panel of figure 2 feature a large collinear enhancement when either of the photons go close to on-shell, $q^2 \rightarrow 0$, where q^μ is the photon 4-momentum. Although these diagrams are accounted for in principle by generating the total $e^+e^- \rightarrow 4f$ background all together, in practice the collinearly-enhanced low q^2 region of the $e^+e^- \rightarrow e^+e^- + 2f$ contribution is challenging to sample in the Monte Carlo integration. We therefore break up the $4f$ event generation into two complementary regions of phase space: we generate four fermion events in **Whizard** requiring

$$(p_{e^\pm, \text{initial}}^\mu - p_{e^\pm, \text{final}}^\mu)^2 > (5 \text{ GeV})^2 \quad (2.3)$$

Figure 2. Example of diagrams contributing significantly to the $4f$ background. Diagrams such as the one on the left feature kinematics similar to the Zh signal and are resonantly enhanced near the Z poles. Multi-peripheral diagrams such as the one on the right with photons can contribute significantly in the small p_{Z/γ^*}^2 regime due to collinear singularities. These multi-peripheral diagrams are double counted if one naively includes both the total $4f$ background and $\gamma\gamma \rightarrow \mu^+\mu^-$ background (in the equivalent photon approximation) without appropriate kinematic cuts.

where $p_{e^\pm, \text{initial}}^\mu$ is the four-momentum of the initial state electron or positron, and $p_{e^\pm, \text{final}}^\mu$ is the four-momentum of any outgoing electron or positron in the event. This cut eliminates $e^+e^- \rightarrow e^+e^- + 2f$ events with small q^2 , but captures nearly the entire contribution from e.g. ZZ diagrams such as those in the left panel of figure 2. We include the effects of ISR during the event generation, as described above for the $2f$ background. We also place loose generator-level cuts requiring $m(f\bar{f}) > 10 \text{ GeV}$ for all fermion-antifermion pairs. This avoids issues with soft and collinear divergences associated with emission of an off-shell photon that splits to a fermion-antifermion pair, but is a modest enough requirement that it should reasonably estimate the corresponding background once invariant mass cuts are imposed in our signal selection.

In the $e^+e^- + 2f$ phase space with smaller values of q^2 , the multi-peripheral contributions such as those in the right panel of figure 2 dominate the $4f$ background. To efficiently sample these contributions, we generate $\gamma\gamma \rightarrow \mu^+\mu^-$ events using the equivalent photon approximation in **Whizard**, discarding events in which the value of q^2 for both photons exceeds $(5 \text{ GeV})^2$ to avoid double counting the phase space sampled by the $4f$ events. We also include the invariant mass cut described above for the $4f$ background, and allow finite p_T to be generated for the scattered electrons in each event. We find that $\gamma\gamma$ -initiated events without prompt muons contribute negligibly to the signal region

3 Sensitivity with and without calorimetry

With the signal and background events generated as described above, we analyze the Monte Carlo samples considering a detector with and without an ECAL or hadronic calorimeter (HCAL) system. In both cases, we assume that there is both an inner tracking and outer muon systems, separated by a layer of shielding, allowing for highly efficient muon identification and momentum determination without a significant muon fake rate, as illustrated

in figure 1. We assume the efficiency and resolution are comparable to that of the proposed CLD detector for FCC-ee, for which the HCAL depth is 5.5 pion interaction lengths [23]. This corresponds to about a meter of iron or lead shielding before the outer muon system in our tracking detector, which is about 60 radiation lengths in iron, and almost 200 radiation lengths in lead. The minimum ionization is similar in these materials and about half what it is for tungsten (utilized in the proposed CLD ECAL). Therefore, we expect that muon efficiency and resolution should be the same or better with our proposed shielding layer.

We provide details on the validation of our analysis methods and a comparison with existing studies in appendix A.

3.1 Tracker-only analysis

Let us first perform the analysis with tracker information only. The muons and anti-muons output by `Pythia` are taken to be reconstructed with 95% efficiency provided $|\eta| < 3$ and $p_T > 5$ GeV. The momentum of the muons is assumed to be determined by hits in both the inner and outer tracker. To account for the finite tracker momentum resolution, we first smear all muon inverse transverse momenta, $1/p_T$, by a Gaussian centered on $(p_T/\text{GeV})^{-1}$ with width

$$\sigma_{\text{GeV}/p_T} = 2 \times 10^{-5} \oplus \frac{10^{-2} \text{ GeV}}{p_T} \quad (3.1)$$

where $a \oplus b \equiv \sqrt{a^2 + b^2}$. This resolution formula is similar to others commonly used in the e^+e^- collider literature (see e.g. refs. [16, 24]), and assumes comparable tracking technology as that envisioned for e.g. the International Linear Detector (ILD) [18, 25]. Elsewhere in the literature the second term in eq. (3.1) often appears with some angular dependence, as it arises from multiple scattering within the tracking material. Since it is governed by the detailed tracker geometry considered, we neglect this angular dependence in our analysis, although we have verified that inclusion of angular dependence does not have an important effect on the results. Note that in smearing the muon p_T by eq. (3.1), we keep the invariant mass fixed and adjust the energy accordingly. The angular variables are also held fixed, corresponding to the excellent angular tracking resolution expected at future e^+e^- experiments. This treatment neglects inelastic interactions with the detector material, which are not expected to be significant for muons.

After smearing, identified muons and antimuons are required to satisfy a track-based isolation criterion, taken to be

$$I_{\mu^\pm} = \sum_{\substack{i \in \text{tracks} \\ \neq \mu^\pm}} \frac{p_T(i)}{p_T(\mu^\pm)} \bigg|_{\Delta R_{i\mu^\pm} \leq 0.2} < 0.1 \quad (3.2)$$

where i denotes all charged tracks in the event with $p_T > 0.1$ GeV, excluding other hard muons, within a $\Delta R < 0.2$ cone¹ of the $\mu^\pm$. In this step, all charged particle momenta are also smeared using eq. (3.1) keeping the corresponding invariant masses fixed. Note that the

¹It is more common in the lepton collider literature to use the relative lab frame angle in describing the separation between reconstructed objects, however we do not find a significant difference between this approach and utilizing the longitudinal boost-invariant angular separation ΔR in this analysis.

Figure 3. Distribution of m_{reco} in the di-muon channel for signal and background events with 200 fb^{-1} after cuts (except that on m_{reco}) with a tracking detector (left) and a general purpose detector (right) with tracking and electromagnetic calorimeter. The general purpose detector with calorimetry allows veto of hard ISR photons which removes almost all of the two fermion background, and as well allows FSR and muon momenta to be combined to slightly improve kinematic reconstruction.

calorimeter (energy) information is not used in this isolation criterion in either the tracker or tracker+calorimeter analyses. We find that including a calorimeter-based isolation variable does not significantly affect any of the backgrounds or signal at the level of our analysis.

For each event, we require at least one identified muon and one identified antimuon satisfying $|\eta| < 3$, $p_T > 5 \text{ GeV}$, and the isolation criterion (3.2). If there is more than one muon and/or antimuon in an event, we choose the $\mu^+\mu^-$ pair with invariant mass $m_{\mu^+\mu^-}$ closest to m_Z and then require

$$|m_{\mu^+\mu^-} - m_Z| \leq 5 \text{ GeV} \quad (3.3)$$

to select events consistent with a $Z \rightarrow \mu^+\mu^-$ decay. To isolate events consistent with the decay of a Higgs, we compute the recoil mass

$$m_{\text{reco}} \equiv \sqrt{s + m_{\mu^+\mu^-}^2 - 2E_{\mu^+\mu^-}\sqrt{s}} \quad (3.4)$$

where $E_{\mu^+\mu^-}$ is the sum of the selected muon and antimuon lab-frame energies. Genuine $\mu^+\mu^-h$ events will have $m_{\text{reco}} \simeq m_h$, and so we require

$$120 \text{ GeV} < m_{\text{reco}} < 130 \text{ GeV} \quad (3.5)$$

Since most signal events will feature moderately transverse muons from recoiling against a Higgs, we impose additional transversality cuts on the Z candidate, requiring

$$p_T(\mu^+\mu^-) > 30 \text{ GeV}, \quad p_L(\mu^+\mu^-) < 60 \text{ GeV} \quad (3.6)$$

This significantly reduces many of the backgrounds, especially $2f + \text{ISR}$. Also, since the Z candidate in genuine Zh events tends to be less boosted than for the backgrounds, we place a requirement on the acollinearity of the muons,

$$\cos^{-1} \left(\frac{\mathbf{p}_{\mu^-} \cdot \mathbf{p}_{\mu^+}}{|\mathbf{p}_{\mu^-}| |\mathbf{p}_{\mu^+}|} \right) > 100^\circ \quad (3.7)$$

The distribution of m_{reco} after all cuts (except that on m_{reco}) for the Zh signal and various backgrounds is shown in figure 3. With only tracker information, the Higgs signal peak is distinct. The width of the Higgs signal m_{reco} distribution comes mainly from the experimental uncertainty in muon momentum measurements. The small high-side tail is due mainly to radiation that reduces the measured value of the sum of the muon lab-frame energies, $E_{\mu^+\mu^-}$, compared with the actual value.

For 200 fb^{-1} of integrated luminosity with all the cuts defining the basic Zh signal region (3.3)–(3.7) listed above, there are 634 Zh signal events and 1372 background events. The background is dominated by $4f$ events ($\approx 49\%$), followed by the $\mu^+\mu^- + \text{ISR}$ contribution ($\approx 38\%$); the $\gamma\gamma$ -induced background contributes about 13%. We again emphasize that the requirements imposed so far only make use of tracker information.

The expected statistical uncertainty in σ_{Zh} for signal and background samples binned in m_{reco} may be approximated by

$$\frac{\delta\sigma_{Zh}}{\sigma_{Zh}} \simeq \left(\sum_{i \in \text{bins}} \frac{S_i^2}{S_i + B_i} \right)^{-1/2} \quad (3.8)$$

Summing over bins of 0.5 GeV width in the full range $120 \text{ GeV} < m_{\text{reco}} < 140 \text{ GeV}$ to capture the high-side tail, we find that a statistical uncertainty of 5.9% can be achieved in the measurement of σ_{Zh} with 200 fb^{-1} of integrated luminosity with a single tracking detector. Extrapolating this to 5 ab^{-1} of integrated luminosity yields a statistical uncertainty in σ_{Zh} of 1.1%.

The cuts listed in (3.3)–(3.7) are similar to those appearing in several past analyses in the context of the ILC [17, 26], the FCC-ee [5, 15], CLIC [18], and the CEPC [16, 27] (see also appendix A). Additional requirements can be imposed on the reconstructed Z system that could potentially further reduce backgrounds (e.g. cuts on the acoplanarity of the Z or angular separation of the muons). However, for the $Z \rightarrow \mu^+\mu^-$ channel, we do not find these additional cuts to provide significant gains in sensitivity to σ_{Zh} in our cut-based analysis. Also, more sophisticated multivariate methods have been used in the literature to further reduce some of the remaining backgrounds [18, 27]. However, since these methods typically rely solely on information about the $\mu^+\mu^-$ momenta, obtained from the tracker and muon system, we do not expect these improvements to significantly impact our performance comparison between a tracking detector and a general purpose tracking+calorimeter detector in the di-muon recoil measurement of σ_{Zh} .

We can also estimate the statistical sensitivity of a tracking detector to measurement of the Higgs mass. To do so, we characterize the statistical uncertainty in the mean value of the Higgs signal reconstructed mass binned in m_{reco}

$$\langle m_h \rangle \simeq \frac{\sum_{i \in \text{bins}} m_{\text{reco},i} S_i}{\sum_{i \in \text{bins}} S_i} \quad (3.9)$$

The core of the m_{reco} distribution near the true Higgs mass is expected to be approximately Gaussian. The statistical uncertainty in this Gaussian core, binned in m_{reco} , may be approximated by

$$(\delta m_h)^2 \simeq \frac{\sum_{i \in \text{bins}} (S_i + B_i) (m_{\text{reco},i} - \langle m_h \rangle)^2}{\left(\sum_{i \in \text{bins}} S_i \right)^2} \quad (3.10)$$

	$\delta\sigma_{Zh}/\sigma_{Zh}$		δm_h	
	200 fb ⁻¹	5 ab ⁻¹	200 fb ⁻¹	5 ab ⁻¹
Tracking Detector	5.9%	1.2%	56 MeV	11 MeV
General Purpose Detector	4.9%	1.0%	47 MeV	9 MeV

Table 1. Projected statistical uncertainties that can be achieved at a 250 GeV e^+e^- collider for the Zh inclusive cross section and Higgs boson mass using the di-muon recoil method with either a single tracking detector or general purpose detector with 200 fb⁻¹ or 5 ab⁻¹ of integrated luminosity. The moderate reduction in uncertainties for these important Higgs boson measurements with a general purpose detector compared with a tracking detector comes mainly from the ECAL of the general purpose detector that allows for a veto on hard ISR photons which reduces $2f$ backgrounds, and as well allows the recovery of final state photons (produced as final state radiation through `Pythia` in our analysis) which improves the signal reconstruction slightly.

Summing over bins of 0.5 GeV width in the range $123.5 \text{ GeV} < m_{\text{reco}} < 126.5 \text{ GeV}$ within the approximately Gaussian core, we find that a statistical uncertainty on the Higgs reconstructed mass of $\delta m_h \simeq 56 \text{ MeV}$ can be achieved with 200 fb⁻¹ of integrated luminosity with a single tracking detector. Extrapolating this to 5 ab⁻¹ of integrated luminosity yields a statistical uncertainty in the Higgs mass of $\delta m_h \simeq 11 \text{ MeV}$. This result does not depend significantly on the bin size. The statistical uncertainty in the Zh inclusive cross section and Higgs mass that can be achieved with a single tracking detector are summarized in table 1. As we show in the next section these uncertainties are comparable to the precision achievable by a single general purpose detector that includes calorimeters.

3.2 Adding calorimeters

So far, the entire analysis described above can apply to a detector with or without an ECAL/HCAL. Since the recoil measurement is specifically designed to be independent of the Higgs decay mode, the cuts defining the basic Zh signal region (3.3)–(3.7) depend only on the muon four-momenta, which can be measured to excellent precision with the inner tracker and outer muon system. So how can this analysis benefit from calorimetry?

The most important handle an ECAL can provide in this analysis is the identification and reconstruction of photons. This can improve the analysis with only tracking in two main ways. First, reconstructed FSR photons can be used to slightly improve the efficiency for identifying Z bosons. Second, and more importantly for this analysis, identification of ISR photons can be used to suppress backgrounds in the Higgs signal region.

Photons radiated by FSR internal Bremsstrahlung off of the Z candidate muons can be incorporated in a radiative reconstruction to slightly improve the efficiency for identifying the Z . To investigate this effect, we re-analyze our Monte Carlo events combining final state muon and photon four-momenta for photons within $\Delta R < 0.2$ of the $\mu^\pm$ reconstructing the Z , and subsequently removing the corresponding photons from the event record. Photon momenta would be measured by the ECAL with finite resolution, and so following previous studies that utilized photon energy resolution at a future e^+e^- collider [16, 24], we smear

photon energies by a Gaussian centered on E_γ/GeV with width

$$\sigma_{E/\text{GeV}}^{\text{ECAL}} = 0.16 \sqrt{\frac{E}{\text{GeV}}} \oplus 0.01 \frac{E}{\text{GeV}} \quad (3.11)$$

keeping the momentum direction and vanishing invariant mass fixed. The signal peak is somewhat increased due to the improved reconstruction efficiency, as can be seen in the right panel of figure 3 which displays the m_{reco} distributions incorporating calorimetry. However, the resulting improvement is not very significant because of the small internal Bremsstrahlung rate. Note that our analysis does not include the effects of energy loss from interactions of muons with the material (occurring through e.g. ionization, atomic excitations, and external Bremsstrahlung), however these effects are expected to be small for muons. Accounting for FSR and external Bremsstrahlung can be important for electrons in the $e^+e^- \rightarrow Zh \rightarrow e^+e^- + X$ analysis, however, as discussed briefly below in section 4.

Sensitivity to photons also allows for the reduction of backgrounds in the muon analysis. As mentioned above, the large $2f + \text{ISR}$ background can only contribute to the signal region provided there are at least two photons, at least one of which has substantial transverse momentum. In a detector with an ECAL, it is possible to veto on sufficiently hard, transverse photons to partially mitigate this background. This approach was taken in the TLEP/FCC analysis of inclusive Higgs measurements [5, 15]. To investigate the utility of an ECAL in reducing such backgrounds, we analyze photons generated in events passing the signal criteria above and exclude events from our tracker+ECAL analysis if they have any photons with

$$p_T(\gamma) > 30 \text{ GeV}, \quad |\eta| < 5 \quad (3.12)$$

Note that recovered FSR photons discussed above are not considered in this veto.

The effect of these two improvements on the $e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^- + X$ analysis is reflected in the second row of table 1. The signal efficiency is increased slightly, owing to the improved reconstruction of the Z by combining the FSR and muon momenta. More importantly, the total background is reduced by about 40%, due primarily to the reduction in the $2f + \text{ISR}$ contribution, which becomes negligible in the signal region, as illustrated in the right panel of figure 3. The photon veto reduces the signal by only $< 1\%$. We find that a sensitivity of $\delta_{Zh}/\sigma_{Zh} \simeq 4.9\%$ can be achieved with these improvements made possible by an ECAL, assuming 200 fb^{-1} . This corresponds only to a 17% improvement over the tracker-only projection. Sensitivity to m_h can also be characterized as given in eq. (3.10) and compared to the results of our tracker-only analysis. We find that with the improvements afforded by an ECAL discussed above, a precision of

$$\delta m_h \simeq 47 \text{ MeV} \quad \text{for} \quad 200 \text{ fb}^{-1} \quad (3.13)$$

can be achieved. This corresponds only to a modest 16% improvement over the analysis with a tracking detector.

Another potential benefit of both an ECAL and HCAL in the muon recoil analysis is the ability to measure the total visible energy and momentum in an event. Some previous studies impose requirements on the polar angle of the missing momentum, θ_{miss} (see

e.g. [26]). By placing a lower bound on θ_{miss} , events with hard ISR photons outside of the detector acceptance can be rejected. We have investigated this effect in our analysis, and do not find a significant improvement over the results without missing momentum cuts once the photon veto and final state photon recovery are taken into account.

Apart from photon identification and reconstruction, and measuring missing momentum, we are not aware of any additional information coming from calorimetry that would significantly improve $\delta\sigma_{Zh}/\sigma_{Zh}$ in the muon channel. We are also not aware of any additional backgrounds that would become relevant without calorimetry (provided high muon ID and fake rejection efficiencies can be achieved with the tracker alone).

3.3 Alternative methods for photon identification

Even without detector calorimetry, it may be possible to infer the presence of photons in an event and effectively reject events with hard photons from the signal region, mimicking a photon veto. For example, a photon conversion layer consisting of material a few radiation lengths thick could be added just outside the inner tracker, along with an additional outer tracking element comprised of very few tracking layers outside the conversion layer, all contained within the solenoid. Photons impinging on the conversion layer would convert with relatively high efficiency into e^+e^- pairs, that would be detected in the outer tracking element. Photon identification would be achieved by the observation of an opposite sign charged track pair in the outer tracking element emanating from the conversion layer, without an associated proximate track in the inner tracker. A jet comprised predominantly of neutral hadrons could also give such a signal. However, the fraction of hadronic jets without any associated charged tracks is expected to be small. For the $\mu^+\mu^-h$ signal, we have verified that for $p_T(j) \gtrsim 5 \text{ GeV}$, the fraction of trackless jets is negligible, while for lower p_T the fraction can be at the percent level. Thus, converted e^+e^- pairs with significant p_T observed in the outer tracking element, without associated tracks in the inner tracker likely indicates the presence of a hard photon, and the corresponding event can be vetoed.

A more detailed analysis of this strategy would involve a simulation of photon interactions within the inner tracker and conversion layer, and is beyond the scope of this work. Nevertheless, it appears possible to obtain some information about the presence of photons using a variation of this approach. If so, with the relatively simple addition of a conversion layer and outer tracking element to allow for photon identification and rejection, the sensitivity of a tracking detector to $\delta\sigma_{Zh}$ could approach that suggested in the second row of table 1 and the r.h.s. of figure 3 even without calorimetry.

3.4 Summary of $e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^-X$

With tracker information alone, a future e^+e^- collider with 200 fb^{-1} of integrated luminosity could probe σ_{Zh} to a precision of around 5.9% (1.2%) with 200 fb^{-1} (5 ab^{-1}) of integrated luminosity, compared to around 4.9% (1.0%) with FSR recovery and a photon veto allowed by including calorimetry. The Higgs mass can also be measured with a precision of $\delta m_h \simeq 56 \text{ MeV}$ (47 MeV) without (with) calorimetry, for 200 fb^{-1} . Sensitivities similar to that of our tracking+calorimetry analyses might be achieved without an ECAL by adding a conversion layer between the inner detector with an additional outer tracking

Figure 4. Comparison of the m_{reco} distribution for the $Z(\rightarrow e^+e^-)h$ signal and $q\bar{q} + \text{ISR}$ background for track only-based electron candidates with no isolation requirements for 200 fb^{-1} of integrated luminosity. The lack of any isolation requirement results in a large $q\bar{q} + \text{ISR}$ contribution where charged hadrons within jets fake track based electron candidates. This background can be substantially reduced by the track isolation requirements discussed in the text.

element to allow for photon identification and veto. Thus, we conclude that an early stage of tracker-only operation of a detector at a future e^+e^- collider could come close to the sensitivity afforded by a full detector for important Higgs boson measurements, and already significantly improve over what can be done at the LHC, at least in the $\mu^+\mu^-$ channel.

4 Comments on $e^+e^- \rightarrow Zh \rightarrow e^+e^- X$

We have shown that relatively high precision can be obtained for the Zh recoil measurement in the muon channel without calorimeters. This is because the most important selection criteria, cuts, and observables depend only on the kinematics of the muons, which can be accurately identified and measured with the tracking system alone. Here, we comment briefly on the prospects for performing an electron recoil measurement without calorimeters, deferring a full analysis of the electron recoil measurement to possible future work.

Consider the process

$$e^+e^- \rightarrow Zh \quad \text{with} \quad Z \rightarrow e^+e^-, \quad h \rightarrow \text{all} \quad (4.1)$$

The situation without detector calorimetry is more complicated for electrons than for muons. With tracking information only, an electron track is essentially indistinguishable from a charged hadron track with the same relativistic momentum. The main handle that can be used to distinguish electrons from charged hadrons in the Higgs measurements considered here is the isolation of the track from other tracks within the event. Electrons from Z boson decay tend on average to be isolated from other tracks, while charged hadrons are mainly within jets and so tend to be close to other charged hadron tracks.

As a first step in addressing the utility of using track isolation as a means to distinguish electron track candidates from charged hadrons we simulate $e^+e^- \rightarrow e^+e^-h$ events, as well

Figure 5. Track isolation information for the $Z(\rightarrow e^+e^-)h$ signal and $q\bar{q} + \text{ISR}$ background for 200 fb^{-1} of integrated luminosity. The distribution on the left shows the total number of charged tracks with $p_T > 0.5 \text{ GeV}$ within a cone of $\Delta R = 0.5$ around a track based electron candidate passing all other cuts (including the m_{reco} window requirement). Note that all such track based electron candidates in the $q\bar{q} + \text{ISR}$ background with 200 fb^{-1} of integrated luminosity have at least two charged tracks within $\Delta R < 0.5$, reflecting the non-trivial track multiplicity of QCD jets that is not present for isolated electrons. The distribution on the right shows the distance between the least isolated electron candidate and the nearest charged track with $p_T > 0.5 \text{ GeV}$. Genuine electrons tend to be more isolated, whereas the track based electron candidates in the $q\bar{q} + \text{ISR}$ background with 200 fb^{-1} of integrated luminosity always have another charged track within $\Delta R \lesssim 0.2$.

as $e^+e^- \rightarrow q\bar{q} + \text{ISR}$. The $q\bar{q}$ background is large, and could potentially bury the Zh recoil signal if electrons cannot be adequately distinguished from charged hadrons within jets. We perform an analysis similar to that described in section 2 for muons. First, we define electron (and positron) object candidates simply as tracks with $p_T > 10 \text{ GeV}$, $|\eta| < 3$, and with no corresponding hit in the muon system. At this level, all track p_T output by *Pythia* are smeared using eq. (3.1). Note that the effects of inelastic interactions of the charged particles with the tracking material (e.g. bremsstrahlung) are neglected in what follows, but would be important to address in a full analysis. After smearing, we proceed as before, requiring at least two electron candidates per event, then reconstruct the Z out of the candidates that minimizes $|m_{e^+e^-} - m_Z|$, and require

$$p_T(e^+, e^-) > 30 \text{ GeV}, \quad p_L(e^+, e^-) < 60 \text{ GeV}, \quad \cos^{-1} \left(\frac{\mathbf{p}_{e^-} \cdot \mathbf{p}_{e^+}}{|\mathbf{p}_{e^-}| |\mathbf{p}_{e^+}|} \right) > 100^\circ \quad (4.2)$$

in analogy with our selection criteria in the muon case. We compute m_{reco} from eq. (3.4) with muon quantities replaced by electron track candidate quantities, and require $120 \text{ GeV} < m_{\text{reco}} < 130 \text{ GeV}$. The corresponding m_{reco} distributions for the Zh signal and $q\bar{q}$ background are shown in figure 4 after all cuts except those on m_{reco} . The signal peak is still evident, but lies beneath the $q\bar{q}$ background at this stage. At this stage, no track isolation requirements have been imposed on the electron candidates.

The $q\bar{q}$ background typically results in electron track candidates that are actually charged hadron constituents of jets with several other nearby charged hadron tracks. In contrast, genuine electrons from Z boson decay tend on average to be isolated from other hard charged particles. We can therefore distinguish between genuine electrons and charged

hadrons by considering tracker-based isolation criteria. To characterize the isolation, we consider observables that depend on the longitudinal boost-invariant angular distance ΔR instead of the more conventional relative lab frame angle, since $q\bar{q}$ events contributing to the signal region can feature a substantial longitudinal boost. On the left side of figure 5, we show the total number of charged tracks with $p_T > 0.5 \text{ GeV}$ within a cone of $\Delta R = 0.5$ around either electron track candidate within a pair of candidates with invariant mass consistent with the Z boson in each event passing all other cuts (including the m_{reco} window requirement). With 200 fb^{-1} of integrated luminosity, all generated $q\bar{q}$ events passing cuts turn out to have at least 2 additional charged tracks within $\Delta R < 0.5$ of the electron track candidates, reflecting the fact that most charged hadrons from this source lie within jets that have a multiplicity of charged hadrons. In contrast most electron track candidates passing cuts in the e^+e^-h signal have no tracks within $\Delta R < 0.5$. On the right hand side of figure 5, we show the minimum distance between either of the electron track candidates within a pair of candidates with invariant mass consistent with the Z boson, and a charged track with $p_T > 0.5 \text{ GeV}$, again after all cuts. With 200 fb^{-1} of integrated luminosity, the simulated $q\bar{q}$ background always features a charged track within $\Delta R \lesssim 0.2$ of one of the electron track candidates, while $\approx 90\%$ of the signal features more isolated electrons. Therefore, requiring e.g. $\Delta R_{\text{nearest track}} > 0.2$ would significantly reduce the $q\bar{q} + \text{ISR}$ background, while only marginally affecting the signal. We expect similar conclusions for the other multi-jet backgrounds. Therefore it may indeed be possible to obtain good sensitivity to $\delta\sigma_{Zh}$ in the electron channel without detector calorimetry, although a more detailed analysis is required to draw firm conclusions.

There are other challenges associated with a tracker-only analysis of $e^+e^- \rightarrow Zh \rightarrow e^+e^- + X$ that should be kept in mind. For one, the backgrounds are larger than for the muon case, since there are many more topologies with an e^+e^- pair in the final state (although this is true for the analysis with calorimetry as well). Also, electrons tend to produce more final state radiation and bremsstrahlung photons than muons, decreasing the Z boson reconstruction efficiency slightly and somewhat degrading the Higgs signal peak if the radiated photons are not accounted for [18, 26]. Properly analyzing the latter effect requires accounting for inelastic interactions of electrons in the material, which we have not included. Addressing these issues with a more definitive analysis of $e^+e^- \rightarrow Zh \rightarrow e^+e^- + X$ with and without calorimetry would be an interesting follow on to the present work.

5 Light scalar searches

It is also worthwhile to consider the detector capabilities required in searching for light scalars beyond the SM Higgs at future e^+e^- colliders. A scalar decay mode-independent search can be performed using the recoil method in analogy with the Zh measurement (see e.g. [28, 29] for similar studies for the ILC). This strategy was used at LEP by the OPAL collaboration to set limits on light scalars coupled to the Z boson [30]. Here, we compare the sensitivities achievable in the $Z \rightarrow \mu^+\mu^-$ channel with and without calorimetry. Note that in concrete models involving new light scalars, other searches targeting specific decay

Figure 6. Distributions of m_{reco} for light scalars in the $(Z \rightarrow \mu^+\mu^-)\phi$ channel for 200 fb^{-1} after cuts with a tracking detector (left) and a general purpose detector (right) with tracking and electromagnetic calorimeter. Results are shown for several scalar masses with $\kappa = 1$.

modes of the Z and Higgs can be more sensitive than the decay mode-independent search (see e.g. [31–33]).

For our analysis, we consider a scalar ϕ with mass $m_\phi < m_h$ that couples to the Z with strength reduced by κ with respect to the SM Higgs, so that σ_{Zh} is reduced by κ^2 relative to that expected for a SM Higgs of the same mass. For models in which ϕ inherits its couplings to the SM by mixing with the Higgs, $\kappa^2 = \sin^2 \theta$, where θ is the $\phi - h$ mixing angle. For the recoil analysis we can remain agnostic about the decay modes of ϕ , although in our Monte Carlo we allow it to decay as a SM-like Higgs of the same mass for simplicity. As for the SM case, we generate signal events in **Whizard 2** incorporating the effects of ISR, and use **Pythia 6** for showering and hadronization. To estimate sensitivities, we make use of the background sample from the Zh analysis.

Our selection criteria mimic those of the $Z(\rightarrow \mu^+\mu^-)h$ measurement, only now we focus on $m_{\text{reco}} < 120\text{ GeV}$ and loosen the acollinearity cut, as lighter scalars are produced with larger characteristic boost

$$\cos^{-1} \left(\frac{\mathbf{p}_{\mu^-} \cdot \mathbf{p}_{\mu^+}}{|\mathbf{p}_{\mu^-}| |\mathbf{p}_{\mu^+}|} \right) > 40^\circ \quad (5.1)$$

To estimate the sensitivities to κ , we use eq. (3.8) with $\sigma_{Zh} \rightarrow \sigma_{Z\phi}$, the $e^+e^- \rightarrow \phi Z$ cross-section at a given m_ϕ , to determine the value of κ such that $\delta\sigma_{Z\phi}/\sigma_{Z\phi} \leq 20\%$. If we restrict the sum in the analog of eq. (3.8) to a single bin, this requirement corresponds to $S/\sqrt{S+B} \geq 5$. In determining sensitivities, the sum is taken over 0.5 GeV bins in $m_{\text{reco}} \in [20, 150]\text{ GeV}$ for which both $S_i, B_i > 0$ for a given m_ϕ . This analysis neglects systematic uncertainties, but provides a reasonable comparison of the statistical sensitivities achievable with and without calorimetry.

The recoil mass distributions for the SM background and signal for various values of m_ϕ and $\kappa = 1$ are shown in figure 6 after applying all cuts. The plot on the right (left) shows the distributions with (without) an ECAL. Note that we only consider scalar masses down to 30 GeV , as going below this requires looser cuts than those assumed above. The signal peak is wider at lower masses, corresponding to the decreased p_T resolution for more boosted

Figure 7. Discovery reach for the coupling strength squared of new light scalars coupled to the Z -boson in a $Z(\rightarrow \mu^+\mu^-)\phi$ recoil search at a future Higgs factory with 200 fb^{-1} and 5 ab^{-1} of integrated luminosity. The solid curves show the sensitivity for a tracking detector and the dashed curves for a general purpose detector with tracking and electromagnetic calorimeter. In the tracking-only detector the reach is degraded at low masses due to the significant $2\mu + \text{ISR}$ background, which could be largely eliminated by a photon veto afforded by a photon conversion layer and outer tracking element described in section 3.3. Also shown for reference are the analogous decay mode-independent bounds from OPAL [30].

muons, reflected in eq. (3.1). In the tracker-only case, the background is significantly larger below m_Z , due to the $2\mu + \text{ISR}$ contribution. This degrades the sensitivity to scalars with $m_\phi \lesssim m_Z$, as shown in figure 7, which illustrates the corresponding discovery potential in the $Z(\rightarrow \mu^+\mu^-)\phi$ recoil search with and without calorimetry. Also shown for reference are the current limits from the analogous decay mode-independent search at OPAL [30]. Although the sensitivity to light scalars below $\sim m_Z$ is reduced without a photon veto, the alternative photon ID method discussed in section 3.3 could be used to improve the tracker-only reach so that it is comparable to that afforded by calorimetry. Therefore, we conclude that tracking detectors at a Higgs factory could still be capable of providing excellent sensitivity to new light scalars beyond the Standard Model coupling to the Z boson.

6 Discussion

A high-precision determination of the inclusive Zh cross section and Higgs boson mass with the recoil method are among the most important physics targets for future e^+e^- Higgs factories. It is of practical interest to know what minimum detector elements are required to perform these measurements. In this work we have shown that measurements of σ_{Zh} and the Higgs boson mass in the $Z \rightarrow \mu^+\mu^-$ channel utilizing a tracking detector can achieve nearly the same precision as a measurement with a conventional general purpose detector with tracking and full calorimetry. The primary advantage of including calorimetry in this analysis is the ability to identify photons. Recovering photons radiated from final state muons increases the signal efficiency slightly, while rejecting events with hard ISR photons

results in better background reduction. A tracker-only detector might also be supplemented by a simple photon veto conversion tracking layer to achieve comparable performance, but in any case the improvement from photon identification in the expected sensitivity is small in this analysis.

The $Z \rightarrow e^+e^-$ channel is more challenging due to an increase in backgrounds, larger bremsstrahlung effects, and the difficulty of distinguishing electrons from charged hadrons without calorimetry. We have not performed a complete study of this channel, but we have shown that in a tracker detector electrons can be very effectively discriminated from charged hadrons escaping jets by utilizing track isolation requirements.

Finally, in the $\mu^+\mu^- + X$ channel a bump-hunt in the recoil mass can provide a decay-independent search for new light scalars that couple to the Z , for example through mixing with the Higgs. The tracker-only search offers comparable sensitivity for $m_\phi \gtrsim m_Z$ and sensitivity within a factor of a few of the full detector analysis at lower masses. The latter is dominated by backgrounds from ISR photons, which could be largely controlled in a track-only detector by inclusion of a photon veto conversion tracking layer.

By carrying out these analyses, we do not mean to suggest that a tracking detector is either an omni-purpose detector or a replacement for such. Our goal is more limited in scope: we believe it is worthwhile to study the utility of minimal detector designs for specific measurements, as has been done in the past, in order to fully streamline, simplify, and prioritize detector subsystems capable of reaching the essential set of physics goals for a future lepton collider. In this sense our motivation is similar in spirit to that of the Fourth Concept Detector [7] and the IDEA detector [4]. Furthermore, such studies may be useful for considering a staged approach to detector construction and deployment. We have focused here on the $ZH \rightarrow \mu^+\mu^- + X$ inclusive cross section, the Higgs mass measurement in this channel, the corresponding $e^+e^- + X$ channel, and a search for new scalar resonances, but it would be of considerable interest to assess a larger set of measurements. We view our results as motivation for these studies.

Our results suggest several specific avenues for immediate follow-up work. It would be of interest to perform a full study of the e^+e^- channel, as well as exclusive channels. The process $e^+e^- \rightarrow Zh \rightarrow b\bar{b}jj$ is another interesting case where there is enough kinematic information (given the Z and h masses) to reconstruct the event, even if the neutral component of hadronic energy goes unmeasured, as would be the case in a tracking detector. The reconstruction of $h \rightarrow b\bar{b}$ is also an important ingredient of the measurement of the total Higgs width at e^+e^- colliders. Analysis of the $e^+e^- \rightarrow Zh \rightarrow b\bar{b}jj$ channel is underway, and preliminary results indicate that with good tracker-based b-tagging, the cross section sensitivity with a tracking detector is comparable to the reach with a full detector. It would also be worthwhile to consider modifications of other detector subsystems and their impact on the science reach at e^+e^- Higgs factories. We suspect that further study along these lines may reveal new practically and economically advantageous approaches to detector design for Higgs boson measurements at next-generation lepton colliders. New ideas for reducing complexity and costs in other aspects of an e^+e^- collider project, including tunneling and magnet design and construction, may also be required before a Higgs factory can become a reality.

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A Validation and comparison with existing studies

In this appendix, we provide some additional details about the comparison and validation of our results against existing analyses in the Higgs factory literature. Our specific choices for the detector parameters (e.g. the smearing in p_T , isolation requirements, etc) were made in light of these comparisons. As a first step, we validated against the TLEP/FCC-ee projections for $Z(\rightarrow \ell^+\ell^-)h$ detailed in refs. [5, 15]. These results are often referenced in the present-day FCC-ee literature, feature a full **GEANT-4** [34]-based simulation of the CMS detector, and incorporate realistic tracking and reconstruction algorithms used by the CMS collaboration. Our results are found to be in good agreement with those of the TLEP/FCC-ee studies for both signal and background at and below the Higgs peak, as shown on the left in figure 8. In producing this figure, we have imposed the cuts and selection criteria outlined in refs. [5, 15] using the muon/electron identification criteria and tracking resolution described in sections 3–4. We verified that the slight excess in our background and signal for high masses is due to the inclusion of ISR effects in our simulation using **Whizard**, not included in the Monte Carlo simulations of [5, 15].

We also compared results obtained using our simplified treatment of the detector against several more recent analyses that incorporate sophisticated tracking system and full **GEANT**-based detector simulation and found good agreement for both the signal and background rates. For example, a comparison of our results to the CEPC $Z(\rightarrow \mu^+\mu^-)h$ analysis of ref. [27] is shown on the right hand side of figure 8. The total number of events is compared for the signal and different background processes (our results are extrapolated from our 200 fb^{-1} event samples to 5 ab^{-1}). The gray shaded columns correspond to requiring at least one $\mu^+\mu^-$ pair with $120\text{ GeV} \leq m_{\text{reco}} \leq 150\text{ GeV}$, $80\text{ GeV} \leq m_{\mu^+\mu^-} \leq 100\text{ GeV}$, and $p_T(\mu^+\mu^-) > 20\text{ GeV}$ (fifth row of table 2 in [27]). The white columns show our results incorporating all selection criteria and cuts in section 3 compared to the results of [27] at the final stage of analysis (final row of table 2 in [27]). Note that we labeled the combined $\mu^+\mu^- + 2f$ and $\mu^\pm + 3f$ background as ‘4f’ in figure 8. In our analysis, the $2f$ +ISR background in figure 8 comprises the $\mu^+\mu^-$ +ISR events. We also show error bars in figure 8 corresponding to the rounding uncertainty from the reported results in [27]. Figure 8 shows that at both stages of the analysis our results for the signal and background rates agree with those of ref. [27] to within a few tens of percent. This suggests that we are indeed

Figure 8. Left: comparison of our analysis with the TLEP/FCC design study in refs. [5, 15]. Note that $\sqrt{s} = 240$ GeV in this plot. Right: comparison of our signal and background rates to the CEPC study of ref. [27]. The gray shaded columns labeled ‘Selection + p_T cuts’ correspond to requiring at least one $\mu^+\mu^-$ pair with $120 \text{ GeV} \leq m_{\text{reco}} \leq 150 \text{ GeV}$, $80 \text{ GeV} \leq m_{\mu^+\mu^-} \leq 100 \text{ GeV}$, and $p_T(\mu^+\mu^-) > 20 \text{ GeV}$ (fifth row of table 2 in [27]). The white columns labeled ‘All cuts’ show our results incorporating all selection criteria and cuts listed in section 3 compared to the results of [27] at the final stage of analysis (final row of table 2 in [27]). The error bars on the data points from ref. [27] correspond to the rounding uncertainty in the results of their table 2, which only tabulates the number of events at the precision of 0.01% of the total number of generated events. In some cases, the error bars are too small to be evident on the plot.

capturing all relevant backgrounds and that our simple parametrization of detector effects provides a valid theory-level estimate of what can be achieved in Zh recoil measurements with a tracking detector at future circular e^+e^- colliders.

Our light scalar analysis also yields results consistent with projections in the literature. For example, the signal and background rates in figure 7 can be compared to the ILC projections in ref. [29]. The rates presented in figure 1 of ref. [29] do not account for the ISR veto cuts, and so the most relevant comparison is with our tracker-only analysis (l.h.s. of figure 7). Ref. [29] finds a background rate that is roughly ~ 5 times larger than ours for low masses. However, a similar difference is reflected in the signal rate comparing between the two approaches. The difference is likely attributable to a combination of the beam polarization assumed in the ILC study, the different signal-background discrimination methods used (the BDT of [29] outperforms our cut-and-count), the difference in p_T resolution assumed (the ILD detector features better resolution than our assumption in eq. (3.1) for Z candidates more than $\sim 20^\circ$ off the beam axis), and the different methods used to select the Z candidate muon pair (we apply the same analysis as in section 3, while ref. [29] minimizes a χ^2 in both $m_{\mu^+\mu^-}$ and m_{reco}). The latter two effects are especially evident in our signal m_{reco} distributions, which are significantly more smeared out than ref. [29]. Since both our signal and background are reduced relative to [29] due to these differences, we are likely under-estimating the sensitivity that can be achieved. This is consistent with the results of our figure 7: the sensitivity we obtain is weaker by about a factor of 1–2 in κ ($= \sqrt{\kappa_{95}}$) compared to figure 2 of [29] and would likely be improved by a more optimized analysis. Nevertheless, we believe that our approach is capturing the relevant physics and again provides a reasonable estimate of the sensitivity achievable by tracking detectors at Higgs factories.

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References

- [1] H. Baer et al. eds., *The International Linear Collider technical design report — volume 2: physics*, [arXiv:1306.6352](https://arxiv.org/abs/1306.6352) [[INSPIRE](#)].
- [2] K. Fujii et al., *Physics case for the 250 GeV stage of the International Linear Collider*, [arXiv:1710.07621](https://arxiv.org/abs/1710.07621) [[INSPIRE](#)].
- [3] M. Ahmad et al., *CEPC-SPPC preliminary conceptual design report. 1. Physics and detector*, IHEP-CEPC-DR-2015-01, (2015) [IHEP-TH-2015-01] [IHEP-EP-2015-01] [[INSPIRE](#)].
- [4] CEPC STUDY GROUP collaboration, *CEPC conceptual design report: volume 2 — physics & detector*, [arXiv:1811.10545](https://arxiv.org/abs/1811.10545) [[INSPIRE](#)].
- [5] TLEP DESIGN STUDY WORKING GROUP collaboration, *First look at the physics case of TLEP*, *JHEP* **01** (2014) 164 [[arXiv:1308.6176](https://arxiv.org/abs/1308.6176)] [[INSPIRE](#)].
- [6] L. Linssen, A. Miyamoto, M. Stanitzki and H. Weerts, eds., *Physics and detectors at CLIC: CLIC conceptual design report*, [arXiv:1202.5940](https://arxiv.org/abs/1202.5940) [[INSPIRE](#)].
- [7] D. Barbareschi et al., *Detector outline document for the fourth concept detector (“4th”) at the International Linear Collider*, FERMILAB-PUB-06-619-PPD, (2006) [[INSPIRE](#)].
- [8] N. Craig, C. Englert and M. McCullough, *New probe of naturalness*, *Phys. Rev. Lett.* **111** (2013) 121803 [[arXiv:1305.5251](https://arxiv.org/abs/1305.5251)] [[INSPIRE](#)].
- [9] N. Craig, M. Farina, M. McCullough and M. Perelstein, *Precision Higgsstrahlung as a probe of new physics*, *JHEP* **03** (2015) 146 [[arXiv:1411.0676](https://arxiv.org/abs/1411.0676)] [[INSPIRE](#)].
- [10] N. Craig, H.K. Lou, M. McCullough and A. Thalapillil, *The Higgs portal above threshold*, *JHEP* **02** (2016) 127 [[arXiv:1412.0258](https://arxiv.org/abs/1412.0258)] [[INSPIRE](#)].
- [11] D. Curtin, P. Meade and C.-T. Yu, *Testing electroweak baryogenesis with future colliders*, *JHEP* **11** (2014) 127 [[arXiv:1409.0005](https://arxiv.org/abs/1409.0005)] [[INSPIRE](#)].
- [12] K. Assamagan et al., *The Higgs portal and cosmology*, FERMILAB-FN-1010-E-PPD, (2016) [[arXiv:1604.05324](https://arxiv.org/abs/1604.05324)] [[INSPIRE](#)].
- [13] P. Huang, A.J. Long and L.-T. Wang, *Probing the electroweak phase transition with Higgs factories and gravitational waves*, *Phys. Rev. D* **94** (2016) 075008 [[arXiv:1608.06619](https://arxiv.org/abs/1608.06619)] [[INSPIRE](#)].
- [14] C.-Y. Chen, J. Kozaczuk and I.M. Lewis, *Non-resonant collider signatures of a singlet-driven electroweak phase transition*, *JHEP* **08** (2017) 096 [[arXiv:1704.05844](https://arxiv.org/abs/1704.05844)] [[INSPIRE](#)].
- [15] P. Azzi et al., *Prospective studies for LEP3 with the CMS detector*, [arXiv:1208.1662](https://arxiv.org/abs/1208.1662) [[INSPIRE](#)].
- [16] F. An et al., *Precision Higgs physics at the CEPC*, *Chin. Phys. C* **43** (2019) 043002 [[arXiv:1810.09037](https://arxiv.org/abs/1810.09037)] [[INSPIRE](#)].
- [17] D.M. Asner et al., *ILC Higgs white paper*, in *Community summer study 2013: Snowmass on the Mississippi*, Minneapolis, MN, U.S.A., 29 July–6 August 2013 [[arXiv:1310.0763](https://arxiv.org/abs/1310.0763)] [[INSPIRE](#)].

- [18] H. Abramowicz et al., *Higgs physics at the CLIC electron-positron linear collider*, *Eur. Phys. J. C* **77** (2017) 475 [[arXiv:1608.07538](#)] [[INSPIRE](#)].
- [19] W. Kilian, T. Ohl and J. Reuter, *WHIZARD: simulating multi-particle processes at LHC and ILC*, *Eur. Phys. J. C* **71** (2011) 1742 [[arXiv:0708.4233](#)] [[INSPIRE](#)].
- [20] M. Moretti, T. Ohl and J. Reuter, *O'Mega: an optimizing matrix element generator*, [hep-ph/0102195](#) [[INSPIRE](#)].
- [21] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [22] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [23] FCC collaboration, *FCC-ee: the lepton collider. Future Circular Collider conceptual design report volume 2*, *Eur. Phys. J. ST* **228** (2019) 261 [[INSPIRE](#)].
- [24] Z. Liu, L.-T. Wang and H. Zhang, *Exotic decays of the 125 GeV Higgs boson at future e^+e^- lepton colliders*, *Chin. Phys. C* **41** (2017) 063102 [[arXiv:1612.09284](#)] [[INSPIRE](#)].
- [25] H. Abramowicz et al., *The International Linear Collider technical design report — volume 4: detectors*, [arXiv:1306.6329](#) [[INSPIRE](#)].
- [26] J. Yan et al., *Measurement of the Higgs boson mass and $e^+e^- \rightarrow ZH$ cross section using $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$ at the ILC*, *Phys. Rev. D* **94** (2016) 113002 [[arXiv:1604.07524](#)] [[INSPIRE](#)].
- [27] Z. Chen et al., *Cross section and Higgs mass measurement with Higgsstrahlung at the CEPC*, *Chin. Phys. C* **41** (2017) 023003 [[arXiv:1601.05352](#)] [[INSPIRE](#)].
- [28] Y. Wang, J. List and M. Berggren, *Search for light scalars produced in association with muon pairs for $\sqrt{s} = 250$ GeV at the ILC*, in *International workshop on future linear collider*, Strasbourg, France, 23–27 October 2017 [[arXiv:1801.08164](#)] [[INSPIRE](#)].
- [29] INTERNATIONAL LARGE DETECTOR CONCEPT GROUP collaboration, *Search for extra scalars produced in association with muon pairs at the ILC*, in *International workshop on future linear colliders*, Arlington, TX, U.S.A., 22–26 October 2018 [[arXiv:1902.06118](#)] [[INSPIRE](#)].
- [30] OPAL collaboration, *Decay mode independent searches for new scalar bosons with the OPAL detector at LEP*, *Eur. Phys. J. C* **27** (2003) 311 [[hep-ex/0206022](#)] [[INSPIRE](#)].
- [31] LEP WORKING GROUP FOR HIGGS BOSON SEARCHES, ALEPH, DELPHI, L3 and OPAL collaborations, *Search for the Standard Model Higgs boson at LEP*, *Phys. Lett. B* **565** (2003) 61 [[hep-ex/0306033](#)] [[INSPIRE](#)].
- [32] W.-F. Chang, T. Modak and J.N. Ng, *Signal for a light singlet scalar at the LHC*, *Phys. Rev. D* **97** (2018) 055020 [[arXiv:1711.05722](#)] [[INSPIRE](#)].
- [33] W.-F. Chang, J.N. Ng and G. White, *Prospects for detecting light bosons at the FCC-ee and CEPC*, *Phys. Rev. D* **97** (2018) 115015 [[arXiv:1803.00148](#)] [[INSPIRE](#)].
- [34] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].