PROCEEDINGS OF SCIENCE

# Physics Performance and Detector Requirements at an Asymmetric Higgs Factory

**Antoine Laudrain,[a,*] Ties Behnke,[a] Carl Mikael Berggren,[a] Karsten Buesser,[a] Frank Gaede,[a] Christophe Grojean,[a] Benno List,[a] Jenny List,[a] Jürgen Reuter[a] and Christian Schwanenberger[a]**

[a] *DESY,*
*Notkestraße 85, Hamburg, Germany*

*E-mail:* antoine.laudrain@desy.de

Recently, a concept for a Hybrid Asymmetric Linear Higgs Factory (HALHF) has been proposed, where a center-of-mass energy of 250 GeV is reached by colliding a plasma-wakefield accelerated electron beam of 500 GeV with a conventionally accelerated positron beam of about 30 GeV. While clearly facing R&D challenges, this concept bears the potential to be significantly cheaper than any other proposed Higgs Factory, comparable in cost e.g. to the EIC. The asymmetric design changes the requirements on the detector at such a facility, which needs to be adapted to forward-boosted event topologies as well as different distributions of beam-beam backgrounds. This contribution will give a first assessment of the impact of the accelerator design on the physics prospects in terms of some flagship measurements of Higgs factories, and how a detector would need to be adjusted from a typical symmetric Higgs factory design.

*The European Physical Society Conference on High Energy Physics (EPS-HEP2023)*
*21-25 August 2023*
*Hamburg, Germany*

*Speaker





PoS(EPS-HEP2023)556

## 1. Introduction

Studies for designing a Higgs factory are going on full swing. All current projects, linear or circular $e^+e^-$ colliders, are very expensive both financially and environmentally and reducing their cost must come from a reduction in length. For circular colliders, such reduction comes with a penalty in luminosity due to synchrotron radiation, which cannot be easily circumvented. For linear colliders, it means a direct reduction in energy.

The most advanced linear collider project (the ILC) plans on superconducting radio-frequency (SRF) cavities with gradients reaching 31.5 MV/m [1], with potential improvements up to 50 MV/m. However, recent developments in electron-beam-driven plasma wake-field acceleration (PWFA) hint toward the possibility a breakthrough by reaching acceleration gradients of up to 1.5 GV/m [2] in the next ten years.

Current developments focus on the electron acceleration, PWFA for positrons being notably more difficult to achieve. The rest of this proceeding assumes PWFA-based electron acceleration would be available in about ten years but positron acceleration would still be RF-based. Under these assumptions, we discuss here the detector requirements at an Higgs factory using PWFA-based electron acceleration needed to achieve similar physics performances as at the ILC.

## 2. The HALHF concept

Assuming a working PWFA-based electron acceleration, the size of linear Higgs factory could naively be reduced by a factor of almost two by shrinking its electron acceleration arm. The size reduction can be further improved if we allow the electron and positron to have different energies, effectively making the facility asymmetric. Assuming a centre-of-mass energy of 250 GeV (that would allow for $e^+e^- \to ZH$ production), this can be achieved by two beams of 125 GeV, or for example by a beam of 500 GeV and another of 31.3 GeV. In this example, the four-fold more energetic electron beam requires a longer PWFA accelerator, which only has a small impact on the total length of the facility. However, the four-fold less energetic positron beam leads to much a shorter SRF accelerator, which decreases the overall facility size by a sizeable amount.

This concept has been named "HALHF": the Hybrid Asymmetric Linear Higgs Factory, and was first introduced in [3]. A schematic of the facility is presented in Figure 1, and this choice of beam energy parameters ($E_e = 500$ GeV and $E_p = 31.3$ GeV) leads to an overall facility length of about 3 km (to be compared to the 20 km planned for a 250 GeV ILC [1]). It should also be noted that the length of HALHF is dominated by the beam delivery system.

While keeping the same centre-of-mass energy, this beam energy asymmetry introduces a boost given by $\gamma = \frac{1}{2}\left(\frac{2E_p}{\sqrt{s}} + \frac{\sqrt{s}}{2E_p}\right)$. For the above parameters, the boost is $\gamma \approx 2.13$. In the following, we study the impact of this boosted topology on physics performance and compare to the ILC.

## 3. Physics benchmarks compared to the ILC

The impact of boosted topologies on physics processes have been studied through two benchmarks: the Higgs mass measurement through recoil mass in the $e^+e^- \to Z(\mu^+\mu^-)H$ channel, and the lepton forward-backward asymmetry in the $e^+e^- \to \mu^+\mu^-$ process. In both cases, events are

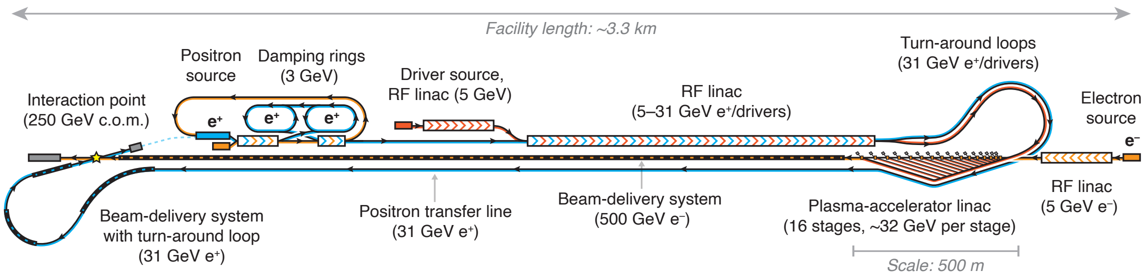


**Figure 1:** Schematic layout of the Hybrid Asymmetric Linear Higgs Factory [3].

generated using Whizard [4]. The studies are performed with the ILD [5] as a baseline detector, simulated using SGV [6]. To cope with the asymmetric collisions, an asymmetric version of the ILD with all barrel subsystems (in particular tracking) extended in the boost direction is also implemented and tested.

The distributions of the simulated $Z \to \mu^+\mu^-$ recoil mass in the case of ILD at the ILC (for reference), ILD at HALHF, and extended asymmetric ILD at HALHF are shown in Figure 2. The width of the recoil mass distribution is around 2.2 times larger for the ILD at HALHF than for the ILC at ILD. At HALHF, the muons are boosted forward and their momentum measurement is hampered by a lower lever arm which decreases the muon momentum resolution. Using the "extended" ILD improves the muon momentum measurement, recovering most of the recoil mass resolution: the width of the distribution is only 20 % larger than the ILD at ILC case. While yielding slightly lower performance, using an asymmetric extended ILD-like detector would allow for a reasonable precision on Higgs recoil mass measurement.

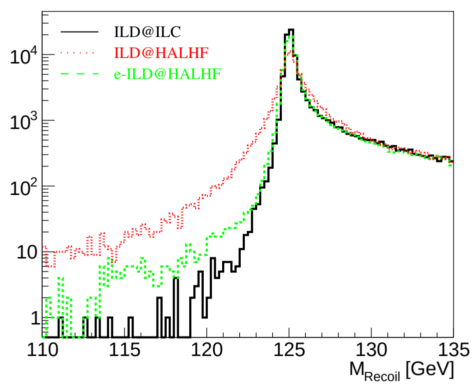


**Figure 2:** Reconstructed Higgs recoil mass in the process $e^+e^- \to Z(\mu^+\mu^-)H$, in black for the ILD at the ILC facility, in red for the same ILD at the HALHF facility and in green for an extended asymmetric version of the ILD at HALHF.

The lepton forward/backward asymmetry provides another interesting case study as the asymmetry from the facility might interplay with the intrinsic asymmetry of the physics process. As seen in Figure 3 left, in the case of symmetric collisions, the pseudo-rapidity distribution of muons (anti-muons) is tilted in the electron (positron) beam direction. The two distributions are nevertheless expected to be the mirrored image of one another with regard to the $\eta = 0$ line. In asymmetric collisions such as at HALHF, all events are boosted further in the electron beam direction, breaking the symmetry around $\eta = 0$ and making the physical asymmetry not as straightforward to extract. However, if the coordinates are boosted back in the centre-of-mass frame (Figure 3 right) one almost recovers the mirror-image behaviour and resolution: the peak is now found at the same position and has the same width as in the symmetric collision case. Nevertheless, the distributions are cut in the boost direction (up to $\eta \approx +1.8$ instead of $\eta \approx +3.1$) while extending in the opposite direction (down to $\eta \approx -4.5$ instead of $\eta \approx -3.1$): events being "lost" in the forward direction while other being "gained" in the backward direction, the final impact on a forward/backward analysis cannot be simply established from this observation and requires more detailed investigations.

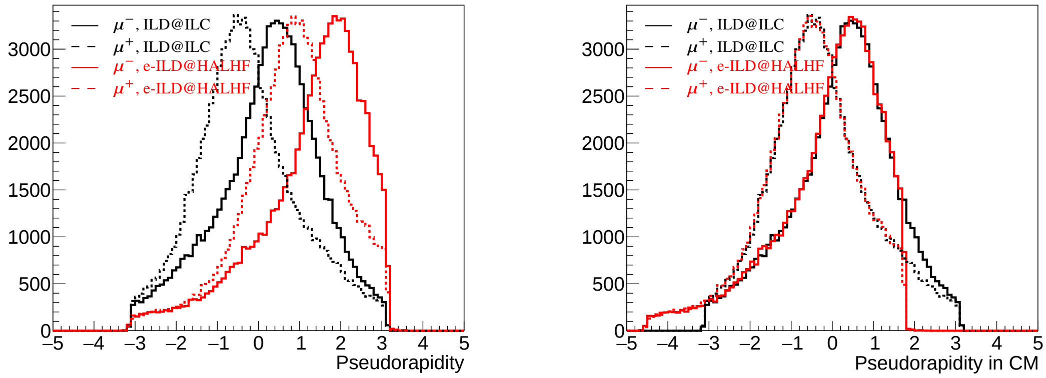


**Figure 3:** Muon (solid) and anti-muon (dashed) $\eta$ coordinate distribution in the lab frame (left) and in the centre-of-mass frame (right). Black corresponds to the ILD detector at the ILC facility, red to an extended-ILD at the HALHF facility.

## 4. Power efficiency and beam-induced backgrounds

While the cost of the facilities is driven by their construction, care should also be given in optimising their running cost. An asymmetric facility will always prove less efficient than a symmetric one as some of the collision energy is used to boost the system instead of participating in the hard-scatter process. The power efficiency compared to a symmetric facility is computed by $\frac{P}{P_{\text{sym}}} = \frac{E_e N_e + E_p N_p}{\sqrt{N_e N_p}\sqrt{s}}$. Plugging in the numbers planned for the ILC [1] but with asymmetric beam energies ($E_e = 500\,\text{GeV}$, $E_p = 31.3\,\text{GeV}$ and $N_e = N_p = 2 \times 10^{10}$ particles/bunch), we get $\frac{P}{P_{\text{sym}}} = 2.13$. An efficiency of 1 could theoretically be achieved by having $N_e = 0.5 \times 10^{10}$ and $N_p = 8 \times 10^{10}$. However, such a large asymmetry induces positron production issues and beam backgrounds, as discussed in the following.

Beam-induced backgrounds emanate from electron-positron pairs created in the high electric field of the crossing beam. These are simulated using Guinea-Pig [7], which additionally computes the luminosity for each bunch crossing. Particles created with a large transverse momentum can reach the beam pipe or even the inner layers of the detector, creating backgrounds in the detector or even damaging it if the deposited energy is too high. Figure 4 shows the distribution of electrons and positrons from pair creation (in the $(p_T, \theta)$ space), for a scenario where all beam quantities except for the energy are symmetric (see above). The lines represent what particle kinematic is needed to hit various subsystems of the detector. In this case, the pairs distributions are symmetric in the forward and backward region, and reach far outside the beam pipe (black line), hitting parts of the inner vertex detector. The energy deposited reaches a few TeV, quickly damaging the detector.

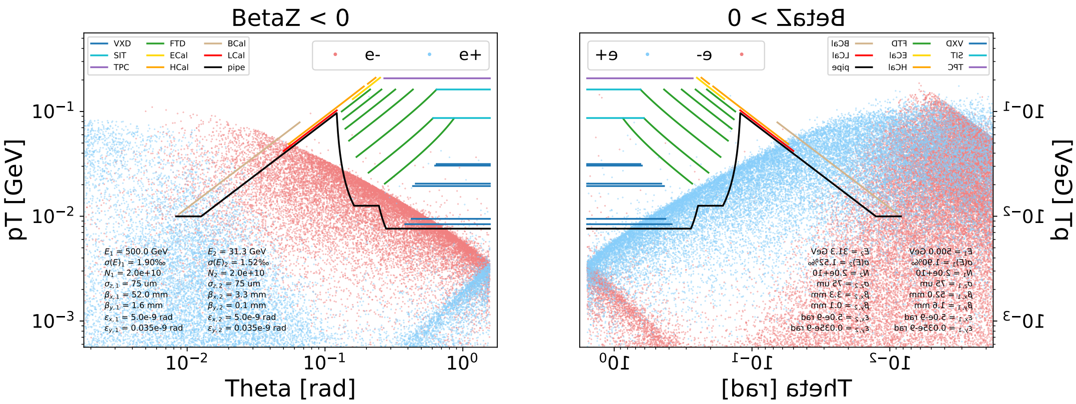


**Figure 4:** Electron (red) - positron (blue) pairs created in beam-beam interaction in case of symmetric beams ($E_e = 500\,\text{GeV}$, $E_p = 31.3\,\text{GeV}$, $N_e = N_p = 2 \times 10^{10}$ and $\sigma_{z,e} = \sigma_{z,p} = 75\,\mu\text{m}$). The lines represent elements of an ILD-like detector (symmetric) with a magnetic field of 3.5 T.

Two of the beam parameters can be used to remedy the situation. The first is to increase the bunch length of the SRF-accelerated beam to 300 µm, as for the ILC design (75 µm for the PWFA-accelerated beam is already at the current estimated limit). The second is to simultaneously decrease the bunch charge of the short-bunch beam (electrons) while keeping $N_e \times N_p$ constant (to preserve luminosity).

Optimisation of the detector solenoid magnet design can also help to improve the situation. The default ILD is fitted with a 3.5 T solenoid, but increasing its magnetic field to 5 T (as forecast for the SiD [8]) would improve the containment of the pairs. The pairs distribution using an combined asymmetric bunch length of $\sigma_{z,e} = 75\,\mu\text{m}, \sigma_{z,p} = 300\,\mu\text{m}$ and asymmetric charge of $N_e = 1.33 \times 10^{10}, N_p = 3 \times 10^{10}$, as well as an asymmetric detector with an increased magnetic field of 5 T for the solenoid is shown in Figure 5. With this beam and detector configuration, the detector is almost completely safe from beam backgrounds while yielding a power efficiency $\frac{P}{P_{\text{sym}}} = 1.52$ and a luminosity about 30 % lower than at the ILC. Additional fine tuning of the beam parameters are expected give further improvements.

## 5. Conclusion

Assuming the ten years of PWFA R&D prove successful, building more compact accelerator might become a reality a few years later. As PWFA-based positron acceleration is not yet realistic, designing asymmetric factories with a high-energy PWFA-based electron arm and lower energy SRF-based positron arm would yield the best accelerator compactness, and therefore lowest facility cost. Physics benchmarks using Higgs recoil mass and lepton forward/backward asymmetry measurements show that an extended detector would recover most of the sensitivity lost due to boosted topologies from the asymmetric beam energies. Beam-induced backgrounds risk damaging the

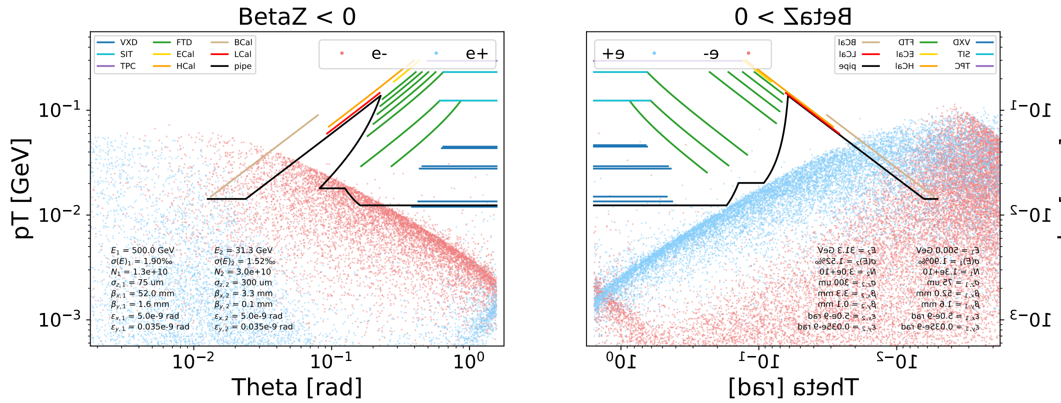


**Figure 5:** Electron (red) - positron (blue) pairs created in beam-beam interaction in case of asymmetric beams ($E_e$ = 500 GeV, $E_p$ = 31.3 GeV, $N_e = 1.33 \times 10^{10}$, $N_p = 3 \times 10^{10}$ and $\sigma_{z,e}$ = 75 µm, $\sigma_{z,p}$ = 300 µm). The lines represent elements of a forward-extended barrel ILD-like detector with a magnetic field of 5 T.

detector but a careful choice of beam parameters and optimised detector (geometry and magnetic field) should maintain the backgrounds pairs within the beam-pipe volume. Additionally, luminosity measurement in asymmetric collisions are challenging and require a detailed study. This studies are preliminaries and a full-simulation of an optimised, asymmetric detector with additional experimental magnets is needed to bring definitive answers to these questions.

## Acknowledgments

We thankfully acknowledge the support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy EXC 2121 "Quantum Universe" 390833306.

## References

[1] C. Adolphsen et al., *The International Linear Collider Technical Design Report - Volume 3.II: Accelerator Baseline Design*, 1306.6328.

[2] R. D'Arcy et al., *Recovery time of a plasma-wakefield accelerator*, *Nature* **603** (2022) 58 [2203.01571].

[3] B. Foster, R. D'Arcy and C.A. Lindstrom, *A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration*, *New J. Phys.* **25** (2023) 093037 [2303.10150].

[4] W. Kilian, T. Ohl and J. Reuter, *WHIZARD: Simulating Multi-Particle Processes at LHC and ILC*, *Eur. Phys. J. C* **71** (2011) 1742 [0708.4233].

[5] ILD Concept Group collaboration, *International Large Detector: Interim Design Report*, 2003.01116.

[6] M. Berggren, *SGV 3.0 - a fast detector simulation*, in *International Workshop on Future Linear Colliders (LCWS11)*, 3, 2012 [1203.0217].

[7] D. Schulte, *Study of Electromagnetic and Hadronic Background in the Interaction Region of the TESLA Collider*, dissertation, Universität Hamburg, 1997.

[8] M. Breidenbach, J.E. Brau, P. Burrows, T. Markiewicz, M. Stanitzki, J. Strube et al., *Updating the SiD Detector concept*, 2110.09965.