ECFA Higgs Factory Focus Topics

ECFA
European Committee for Future Accelerators

ECFA workshops on e+e- Higgs/EW/Top factory

Jenny List
A detector for a Higgs Factory and beyond: ILD
CERN
16 January 2023

DESY.

Reminder

Previously on the ECFA Higgs Factory Study

https://indico.cern.ch/event/1044297/

- created in spring 2021, final report in 2025
- activities comprise: annual workshops, topical workshops & mini-workshops, seminar series, *focus topics*
- communication via CERN e-groups, for details cf https://indico.cern.ch/event/1044297/page/27821-e-groups
- *everybody* is welcome to join!

Overview and Activities

Based on the recommendations of the European Strategy for Particle Physics Update, the European Committee for Future Accelerators (ECFA) has launched a series of workshops on physics studies, experiment design, and detector technologies towards a future electron-positron Higgs/EW/Top factory. The aim is to bring together the efforts of various e^+e^- projects, to share challenges and expertise, to explore synergies, and to respond coherently to this high-priority strategy item.

To set up the relevant structures and to define a path towards such workshops, an International Advisory Committee (IAC) was formed, which established three Working Groups led by conveners from both experiment and theory.

For information on the ECFA study activities, please see the wiki pages:

https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories

Motivation

What can ECFA HiggsFactory Study add beyond state-of-the-art?

- Unclear which project will be built - but to get any, a strong e+e- community is required!
  => How can HEP community engage in e+e- Higgs Factory studies after Snowmass?
- Most can only spend only a small fraction of their time on “future topics”

  => lower threshold to contribute as far as possible
  => avoid duplication
- ECFA Study is not tied to a specific e+e- project:
  - for people who hesitate to “sell their soul” to FCC or ILC or … this could be the ideal place!
  - forum to present work and discuss science and detector requirements across projects
  - **trigger actual joint work => defined 14 focus topics**
    They are NOT meant to be a comprehensive representation of the physics case, but selected examples where work is needed. The final report will contain MUCH more!
  - support the use of common software and exchange of data-sets via Key4HEP

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Focus Topic Document (short, ~3 page description per topic) on the arXiv today:

Focus Topic Overview

Many of you contributed - many thanks!

- started with a list of topics, iterated with IAC
- formed “Expert Team” for each topic
  - charge:
    - capture state-of-the-art (science / tools)
    - define future work needed

=> “Focus Topic Document” arXiv:2401.0xxx submitted yesterday - but will only appear tomorrow: “Apparently there was some sort of arxiv holiday yesterday (Martin Luther King day) which delays the announcement to tomorrow. Just annoying for Jenny who won't have an id for her talk at ILD today.”

- ILD contributed a lot
  => should be well aligned with ILD plans
- NOW:
  - FORM TEAMS who actually DO THE WORK
  - ideal point in time for new students etc to join!
  - check out https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics for “living” information
  - **never hesitate to contact Jenny and/or Filip!**

	Topic	Lead group	Relevant $\sqrt{s}$ [GeV] 91	161	240–250	350–380	≥ 500
1	HtoSS	HTE			✓	✓	✓
2	ZHang	HTE (GLOB)			✓	✓	✓
3	Hself	GLOB			✓	✓	✓
4	Wmass	PREC		✓	✓	✓	✓
5	WWdiff	GLOB			✓	✓	✓
6	TTthres	GLOB (HTE)				✓	✓
7	LUMI	PREC	✓	✓	✓	✓	✓
8	EXscalar	SRCH			✓	✓	✓
9	LLPs	SRCH	✓	✓	✓	✓	✓
10	EXtt	SRCH				✓	✓
11	CKMWW	FLAV		✓	✓	✓	✓
12	BKtautau	FLAV	✓				
13	TwoF	HTE (PREC)	✓	✓	✓	✓	✓
14	BCfrag and Gsplit	PREC (FLAV)	✓	✓	✓	✓	✓

1 e+e− → Zh with h → ss (Z → anything) at √s = 240..250 GeV

HtoSS, HTE

Theoretical, phenomenological and MC generator targets

Expanding the BSM interpretations of the studies that have already been performed or developing new simulation-based analyses targeting specific BSM scenarios would enlarge the physics case for strange tagging at future colliders. In particular, we welcome studies in the following areas:

- Detailed understanding of how to extract the Higgs-strange coupling strength from a BR($h \to s\bar{s}$) measurement, given contributions from Dalitz decays, e.g, $h \to g^*(\to s\bar{s})g$ or $h \to \gamma^*(\to s\bar{s})\gamma$.
- BSM models predicting deviations in $h \to s\bar{s}$, e.g., SUSY or composite Higgs — see Refs. [36, 37];
- BSM models predicting, for example, charged Higgs bosons with large branching ratios in final states including strange quarks, e.g., 2HDM $H^+ \to cs$ BR $\approx 50\%$;
- $s\bar{s}$ vs. $b\bar{b}$ in BSM models: gain from $s\bar{s}$;
- BSM flavour structure and $h \to s\bar{s}$ signal.

Target physics observables

Several physics quantities will be investigated:

- $e^+e^- \to Zh$ with $h \to ss$ ($Z \to$ anything) at $\sqrt{s} = 240/250\,\text{GeV}$ (this has been the only target so far, but it will be relevant to explore also higher centre-of-mass energies, which, in turn, enable different Higgs production modes);
- projected precision on the branching fraction and the differential cross-section in $\cos\theta_s$;
- flavour-changing decays are very rare in the SM, for example, BR($h \to bs$) $\simeq 10^{-7}$. New physics models, which can be encapsulated by an EFT, allow larger values.

Target analysis techniques

The performed proof-of-concept studies [49, 51] showed that to improve the results there will be a large need for more powerful background rejection techniques as well as a potentially more global approach in the extraction of the Higgs couplings. Two areas of particular interest will be:

- diboson background suppression;
- signal extraction (fit discriminant variables, counting experiments, etc.).

Target methods to be developed

In collaboration with the Reconstruction and Detector groups, the impact from the following features will have to be evaluated when estimating the analysis sensitivity reach, including:

- control of strange-tagging related systematic uncertainties;
- reconstruction of in-flight decays, e.g., $K^0_S \to \pi^+\pi^-$;
- strangeness-tagging with ML techniques and compared with anti-b-tagging techniques;
- s vs $\bar{s}$ separation;
- complementarity of particle identification (ID) techniques for charged hadrons in momentum reach (from dN/dx, dE/dx, ToF, RICH);
- understanding the contribution from $g \to s\bar{s}$ (from single jets) to strange-tagging performance and analysis sensitivity.

Target detector performance aspects

The obtained results will inform the community on two crucial aspects:

- dependence of the precision on physics observables on particle ID, strange-tagging, and reconstruction capabilities;
- technology benchmarks for sub-detectors.

Generation and Simulation needs

Full simulation samples will be needed to perform the studies listed above. Samples for $e^+e^- \to f\bar{f}h$ at $\sqrt{s} = 240/250\,\text{GeV}$ and $350/380/550\,\text{GeV}$ are available as indicated in the general samples listed in the motivation. In the years to come, it will be important to iterate with simulation experts on $s\bar{s}$ correlations and fragmentation uncertainties in order to account for more realistic systematic uncertainties.

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- extraction of h-ss coupling strength
- BSM!

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- projected precision on BR and diff. x-sec
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ZHang, HTE

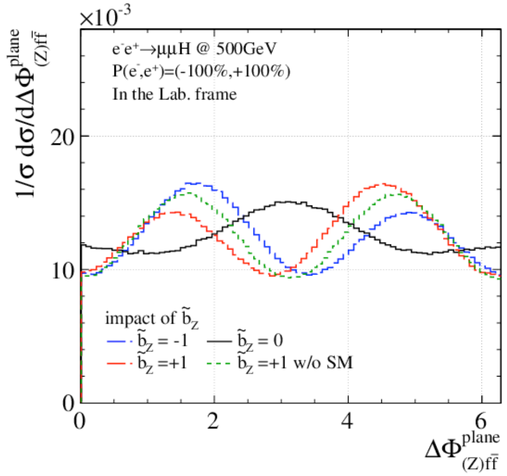
Use differential cross-section to constrain CP-odd and CP-even (self-coupling!) interactions

- CP odd:

Potential studies

The sensitivity of an e^+e^- collider to the CP structure of several Higgs interactions has been established. Further studies can determine whether there is scope to improve the sensitivity, or to extend it to additional interactions. Possibilities include:

- a complete implementation of the Zh analysis including all Z decays and backgrounds into an existing experimental framework;
- using angular information or an optimal observable to improve sensitivity to the CP structure of the hZZ vertex;
- a joint constraint on the CP-even and CP-odd components of the hZZ vertex using pseudo-observables or the SM effective field theory (SMEFT), rather than just the CP-odd fraction;
- analysis of the CP sensitivity to the hZZ vertex in an asymmetric collider, as in the HALHF design [56]; and
- improvements in sensitivity from exploiting beam polarisation.



- CP even:

Potential studies

The existing studies can be extended to a global SMEFT analysis to determine the generality of the $e^+e^- \to Zh$ process sensitivity to the Higgs self-coupling. Several specific activities are possible:

- determine whether angular or other observables can target the sensitivity to the self-coupling, possibly in conjunction with different centre-of-mass energies and beam polarisations;
- perform a complete NLO analysis of the ZH process within the context of a global SMEFT analysis, including constraints from other measurements; and
- extend the global SMEFT analysis to dimension-8 operators and all terms at order $1/\Lambda^4$.

The extension of the SMEFT analysis to order $1/\Lambda^4$ is particularly valuable given that both CP-odd and CP-even operators contribute to many observables at this order. The optimisation of the analysis to SMEFT interactions can include the use of quantum information observables, which have been shown to provide sensitivity at order $1/\Lambda^4$ for diboson processes [65]. Finally, concrete models such as those motivated by baryogenesis can be used to validate the SMEFT analysis and to directly compare the sensitivity of various observables to these models.

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- vertexing, jet charge,
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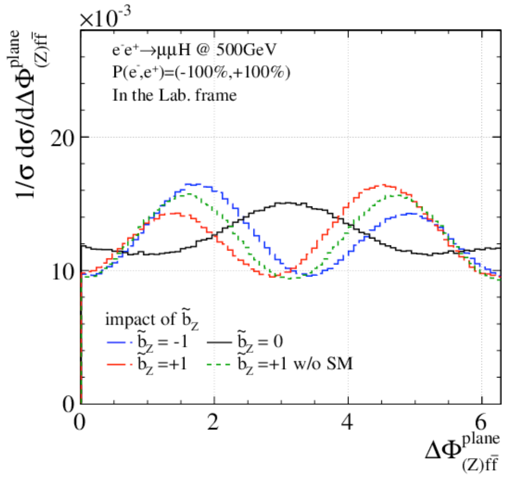

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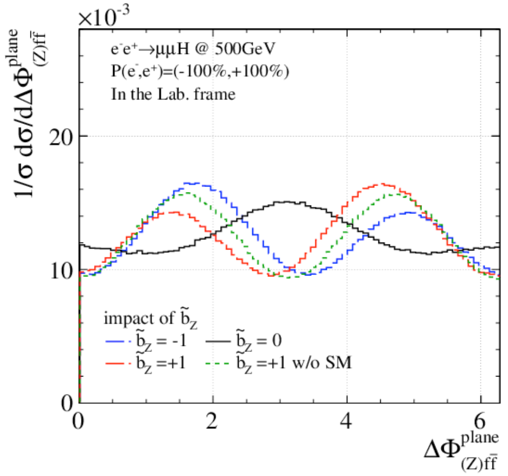

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- ZH differential x-sections (angles, pt etc)
- SMEFT analysis at NLO (with Hself)
- dim-8 SMEFT (with Hself)

3 Determination of the Higgs self-coupling

HSelf, GLOB

Single-Higgs: lifting the degeneracies

The key goal is to isolate out the effects of λ_{hhh} from many others as mentioned above.

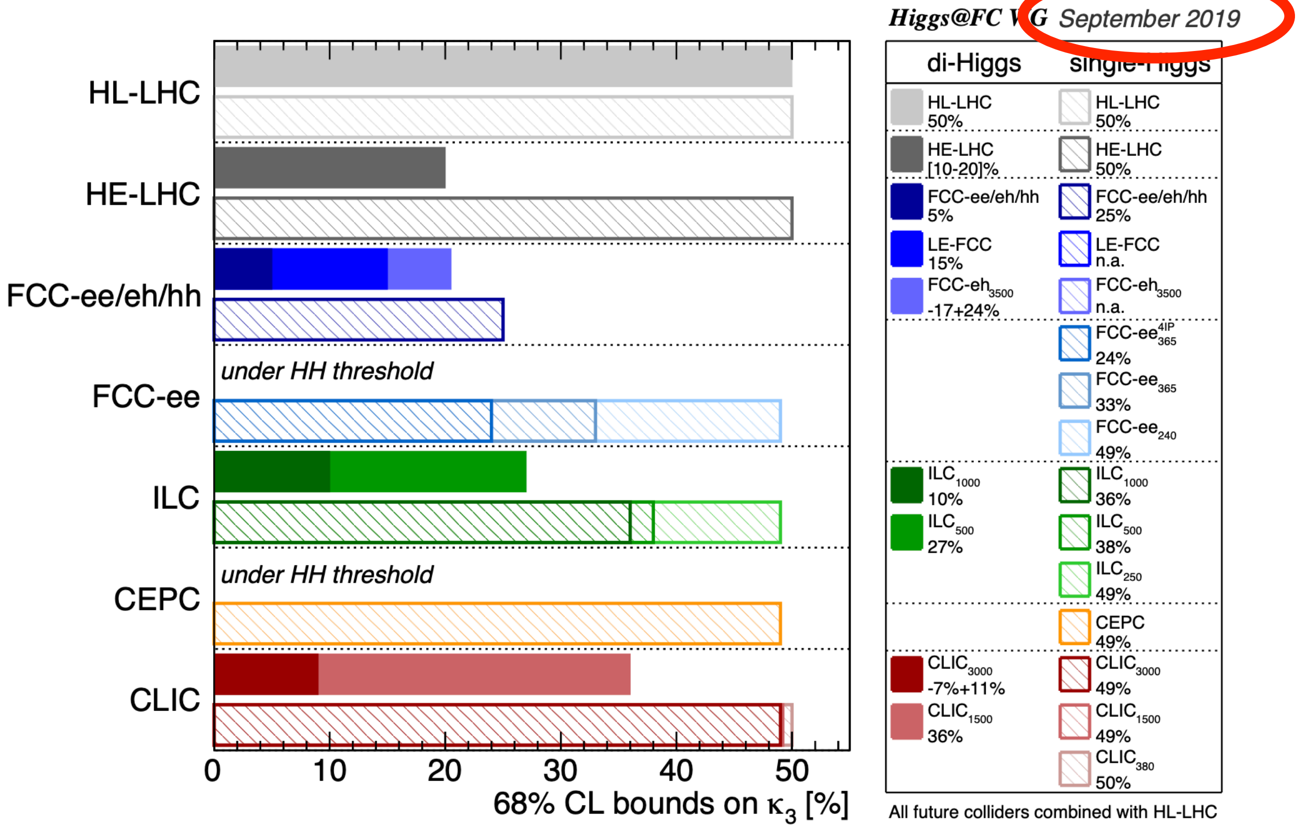
- Can we lift the degeneracies by employing new observables other than σ_{Zh}? E.g., using the angular distributions in Zh.
- Can we take advantage of initial state radiation to realise multiple effective $\sqrt{s'}$ which may help lift the degeneracies? Or how would energy scan just around one nominal $\sqrt{s}$ help?
- What if we include other NLO effects as well, e.g. 4-fermion contact interaction from electron and top-quark?
- Can we clarify the importance of each input measurement for the λ_{hhh} in the global fit?
- Do we expect any update from experimental analyses about single-Higgs observables?
- Combination of single-Higgs and double-Higgs sensitivity to λ_{hhh} at $\sqrt{s} \geq 500$ GeV.

Di-Higgs production: advancing the analysis technique

The di-Higgs production has a substantially smaller challenge from degeneracies. The main questions are related to how we can improve experimental analyses either for $\lambda_{hhh} = \lambda_{hhh}^{\mathrm{SM}}$, or for values of $\lambda_{hhh} \neq \lambda_{hhh}^{\mathrm{SM}}$, or for the case with contributions from new light scalars. It has been realised [73] that there is a huge room for potential improvement by comparing the projections based on current full simulation analysis and idealised theoretical expectation (no background and 100% efficiency) as shown in Fig. 2. The limiting factors in current simulation analysis dominantly come from the algorithms for jet-clustering and flavour tagging. In general more efficient analysis methods which can better suppress background or utilising more signal channels will be helpful, such as employing more sophisticated kinematic fitting [74], matrix element method [75], or machine learning [76], and analysing $Z \to \tau\tau$ signal. Some details about the potential impact to λ_{hhh} precision from those improvements can be found in Ref. [66].

Other than improving the analysis techniques, it would be also interesting to address following questions:

- Would the use of centre-of-mass energies slightly above 500 GeV help the analysis, e.g. from more boosted jets?
- The event shapes are strongly influenced by the value of λ_{hhh} as well as by tree-level contributions of additional light scalars (where a BSM triple Higgs coupling, here denoted as λ_{hhH} enters the prediction) [77].
  - Can we do some simulation analysis with non-SM value of λ_{hhh}?
  - Can we do some simulations taking into account the effects of λ_{hhH}?
  - Can we investigate new event shapes that are more suitable to analyse these effects?



Update this plot!

4 W Mass from Threshold and Continuum

WMass, PREC

Further work and open questions

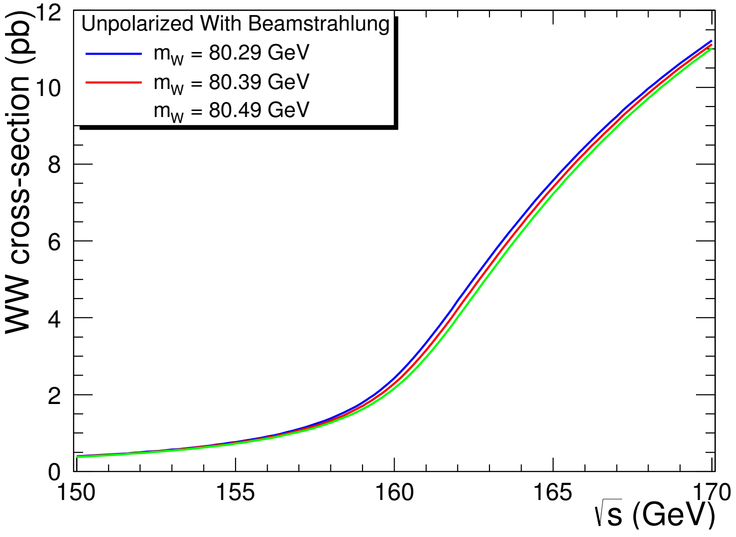
In the following we provide an incomplete list of work packages with possible large impact on the precision estimates. The results can provide important input to future theory developments and detector design.

Pair-production threshold

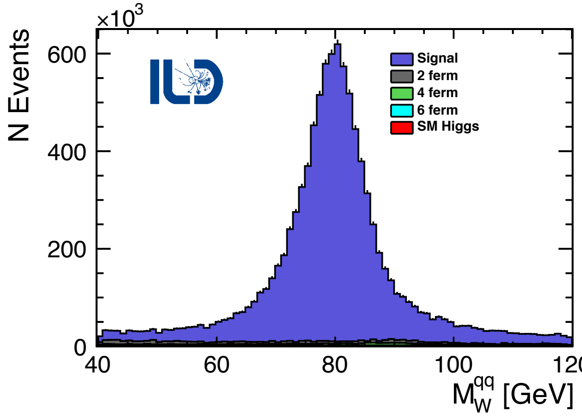
- Explore in more detail the systematic uncertainties with multi-point ($n \geq 3$) cross section measurements from a WW threshold scan. The reduction and cancellation of point-to-point correlated systematic uncertainties as acceptance, luminosity and background, are of particular interest.
- Design and implement a modern analysis, using event classifiers based on machine learning and/or a profile likelihood fit with nuisance parameters to describe and constrain systematic uncertainties.
- Use state-of-the-art generators to evaluate the impact of the various systematic uncertainties and overall performance, for each channel and their combination.
- Evaluate model-independent approaches in which the theory uncertainties, as outlined above, could be constrained directly from the data.
- For intermediate and high energies, a full NNLO calculation for W-pair production in DPA would be most desirable, a task that should be achievable in the next decade, anticipating further progress at the frontier of loop calculations.

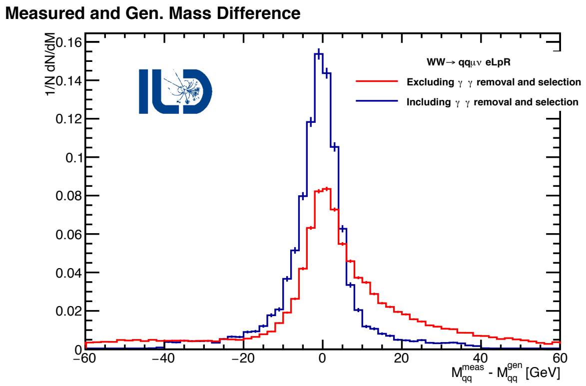
W-pair decay kinematics

- Study a LEP2-style W mass measurement. Estimate the statistical precision of data at different centre-of-mass energies. Study the impact of the systematic uncertainties in detail.
- Explore simultaneous analysis and fit of diboson events (WW, ZZ and $Z\gamma$) to extract m_W/m_Z with potential cancellations of systematic uncertainties both theoretical and experimental. The simultaneous fit of Z peak data for the calibration of lepton and jet energies will also be necessary.
- Clarify the usefulness of high-precision cross section measurements in the continuum (see e.g. section 4.5 in Ref. [113]).



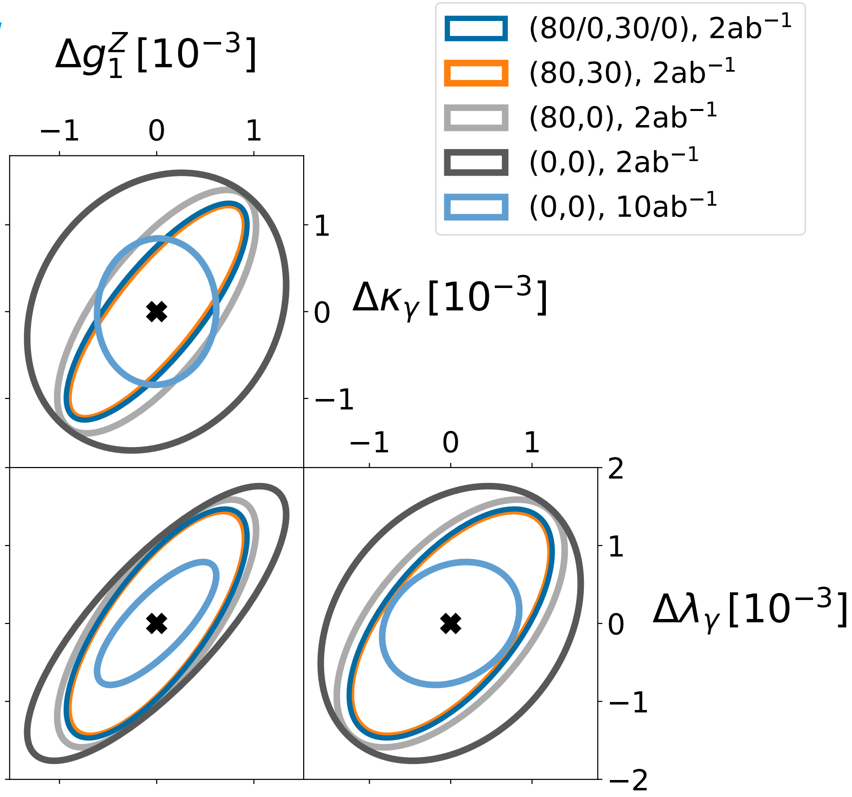
- theory predictions and MC generators
- detector-level studies including mass reconstruction techniques
- systematic limitations and calibration strategies





5 Differential cross-sections in WW / eνW

WWdiff, GLOB



Goals of this Focus Topic

Therefore the main objective of this focus topic is to understand the full potential of e^+e^- colliders with respect to gauge boson interactions, using the full differential information from W-pair and single-W events to extract CP-even and CP-odd couplings, based on detailed detector simulation with assessments of systematic uncertainties, at all centre-of-mass energies.

It is also important to establish the complementarity of these studies with similar studies of anomalous triple gauge couplings (aTGC) at the HL-LHC and to clarify gain in precision that is expected at future e^+e^- colliders.

Proposed Study Targets

– Detector-level projections for differential cross-section measurements with respect to production and decay angles, at all centre-of-mass energies with and without beam polarisation.
– Detector-level projections for optimal observables for CP-even and CP-odd anomalous gauge couplings, again at all centre-of-mass energies with and without beam polarisation.
– Reduction of systematic uncertainties by inclusion of nuisance parameters in the combined interpretation of various data sets.
– Estimation of residual systematic uncertainties and their incorporation in formalism.
– Inclusion in the studies of single-W production, to establish its role of in co interactions, when combined with di-boson production.

- comparision of theory predictions and MC generators
- detector-level studies including full differential angular information
- reconstruction of CP angles
- optimal observables
- interface to global interpretations
- CP violating operators and other effects beyond “standard” TGCs

6 Detector-level simulation study at a typical ttbar threshold energy & ttbar threshold scan optimisation

TTthres, HTE + GLOB

The expert team aims to provide a firm basis for the projected precision of the top quark mass and width measurements, including a realistic estimate of systematic uncertainties from theory and experiment. This includes, importantly, a full-simulation study of the top quark cross-section measurement at the threshold. Detector-level studies of top physics exist mainly at centre-of-mass energies of $380 - 500\,\mathrm{GeV}$ and above, focusing on precision determinations of the electroweak couplings of the quarks. Threshold scans have been studied so far based on toy measurements of the total cross-section near threshold. These considered simultaneous extractions of top mass, width, Yukawa coupling and strong coupling α_s, but included neither differential information nor polarisation.

Discussion among theorists and experimentalists are needed to establish exactly which corrections and cuts to the data are expected to be applied by the experimental collaboration, and which effects can instead be included in the theoretical prediction.

Finally, the expert team hopes to provide a perspective for the top quark mass measurement by comparing the expected precision to the HL-LHC prospects, and by embedding the top quark prospects in the global electroweak precision fit, together with the projections for other measurements, such as that of the W-boson mass, the strong coupling, etc.

Beyond the top quark mass, studies of the top quark width measurement from a threshold scan should be compared to projections of HL-LHC and to the predictions of new physics scenarios that involve non-standard "invisible" decays of the top quark. New ideas are required to turn the extraction of the strong coupling and the top quark Yukawa coupling from the threshold scan into competitive results.

The impact of top quark coupling measurements in operation of the e^+e^- collider above threshold has been studied in detail [139–141]. The e^+e^- prospects are compared to current LHC results and expected HL-LHC bounds on operator coefficients involving top quarks in a global fit of the top sector of the SMEFT [113,142,143]. These studies are being extended to include a complete NLO parametrisation of the dependence of top quark production processes on all operator coefficients for hadron colliders. Future work may include extension to the imaginary parts of the relevant Wilson coefficients and —

- full simulation studies of total & differential cross-section, asymmetries, CP observables
- realistic estimate of theory and exp. systematics
- exp <-> theory interface (corrections, cuts…)
- backgrounds, polarisation, energy-step optimisation
- extract mass, width, Yukawa, α_s as well as electroweak coupling parameter extraction, also CPV
- interplay with HL-LHC
- SMEFT fit of top sector

7 Luminosity measurements from Small-Angle Bhabha Scattering & Di-photons

LUMI, PREC

Open Questions

In the following we point out a few concrete questions which should be addressed with high priority:

1. Di-photon production may be a promising candidate for a robust high-precision determination of the total integrated luminosity. A detailed study of the luminosity calibration using this process is still lacking and would be very important.
2. SABS is preferred for the point-to-point luminosity control, due its higher yields. Some leading systematic uncertainties should drop out in the point-to-point comparison. More studies on this last point are needed, in particular for the understanding of correlations between luminosity measurements at different centre-of-mass energies.
3. Detailed designs for LumiCal detectors are needed for different collider setups and different detector concepts.
4. Radiative production of additional fermion pairs is currently not implemented in typical MC programs for SABS and $\gamma\gamma$ production. What is their impact in the experimental analysis of the luminosity measurements?
5. What is (quantitatively) the impact of beamstrahlung on the overall luminosity determination? Will the beamstrahlung spectrum need to be obtained from simulation, or can be determined from in-situ measurements?
6. Are there other processes besides $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ that could be useful for luminosity measurements?

8 New Exotic Scalars

EXscalar, SRCH

Scalar-strahlung

Higgs factories are best suited to search for light exotic scalars, here denoted as ϕ, in the process similar to the Higgs-strahlung:

$$e^+e^- \to Z\phi \,.$$

As for the SM Higgs boson, the production of new scalars can be tagged, independent of their decay, based on the recoil mass technique [174]. Similar analysis methods can be used, looking for corresponding light scalar decay channels (e.g. $b\bar{b}$, $W^{(*)+}W^{(*)-}$, $\tau^+\tau^-$ or invisible decays), but relaxing the constraint imposed by the SM Higgs boson mass. Non-standard decays channels of the new scalar (e.g. decays to long-lived particles) can also be looked for, similarly as they should be addressed for the 125 GeV Higgs. For maximum sensitivity, the feasibility of including hadronic Z decays should be explored.

Higgs decays to Extra Scalars

In addition to the associated production of the new scalar with the Z boson, other production channels can also be considered, including production processes involving decays of heavier particles (SM gauge bosons, Higgs boson, top quark or new exotic particles). As as second benchmark scenario for the EXscalar focus topic, light scalar pair-production in 125 GeV Higgs boson decays is proposed:

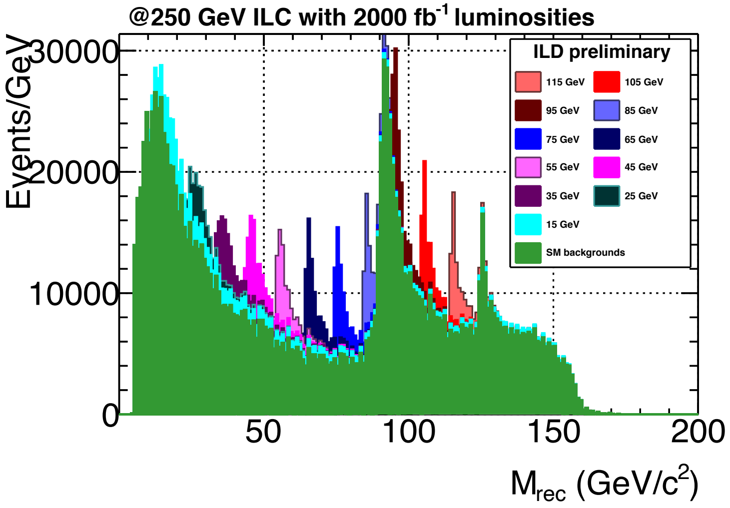
$$e^+e^- \to ZH \to Z\phi\phi \,.$$

Here again, different decay channels of the new scalar state should be considered, both SM-like decays (e.g. $b\bar{b}$, $\tau^+\tau^-$) and exotic ones (e.g. invisible decays) should be considered. While new scalar states could in general be long-lived, only scenarios with prompt decays are included in this focus topic (while a dedicated topic focuses on LLPs).

Target detector performance aspects and reconstruction methods to be developed

Many reconstruction algorithms for the studies proposed here exist in KEY4HEP. In the areas below, performance improvements are expected from developments of more sophisticated approaches:

1. Recoil mass reconstruction is the primary method for identification of the SM-like Higgs boson production events and can also be used for new scalar searches. In fact, precision of the recoil mass reconstruction is expected to be the leading factor determining the search sensitivity in the scalar-strahlung scenario, as well as for the exotic Higgs decays.
2. Resolution in the reconstruction of the invariant mass from the hadronic decays of the produced heavy objects (Z boson, Higgs boson, exotic scalar) is also very important.
3. Invariant-mass reconstruction can also be improved, using the appropriate corrections for semi-leptonic decays of heavy flavours, for scalar decays to $b\bar{b}$ and $c\bar{c}$ [176].
4. Reconstruction of the invariant mass for scalar decays to $\tau^+\tau^-$ is the key issue for scenarios where these decays dominate (see e.g. Ref. [167]). This has already been considered in the past for the SM Higgs boson [177], but should probably be developed further.
5. Finally, efficient tagging of ISR photons is also important for proper reconstruction of event kinematics and background suppression.



9 Long-lived particles

LLPs, SRCH

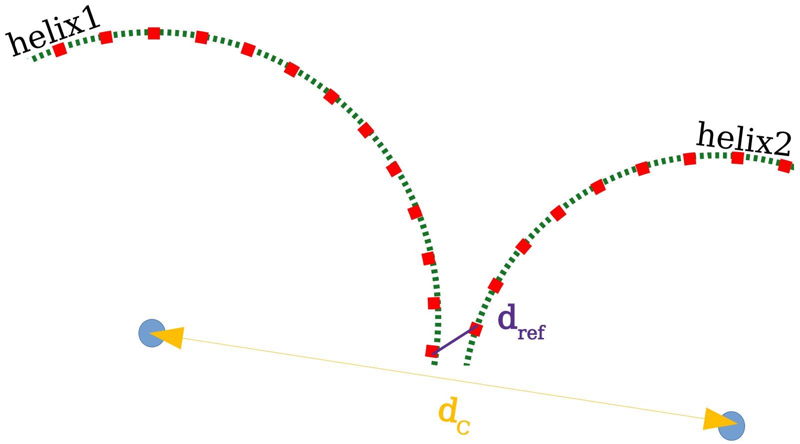
Heavy Neutral Leptons, Axions, LLPs in Higgs Decays

Target physics observables and signatures

In all cases, the target physics observables comprise the discovery (and exclusion) reach in terms of cross-sections, masses and lifetimes of the LLPs, as well as the precision to which these and other properties of the LLPs can be determined in case of a discovery.

A large variety of non-mainstream signatures can be considered: In the tracking system, Uncommon energy loss patterns in dE/dx as well as displaced tracks and vertices can be pursued, or even "disappearing tracks" (in silicon trackers, in continuous tracking even the mini-curler of very soft decay products could be seen). Non-pointing and/or delayed photons will be of interest in the calorimeters, and in these cases, calorimeter timing would be important. Likewise, non-standard jets, such as emerging jets, trackless jets, or jets with unconventional energy distributions in the calorimeters can be explored. Furthermore, jets with out-of-time decays, such as in later or empty bunch crossings, can be a signature of slowly-moving or stopped particles with a long lifetime. In the muon system, displaced particles forming a vertex is a signature worth pursuing. In addition, boosted neutral LLPs could give rise to pairs of collimated muons with no tracks in the inner detector. Finally, unusual time-of-flight measurements in the muon system and/or the calorimeters could be targeted as well.

Reconstruct anything that does weird stuff - anywhere in the detector :)



Target methods to be developed

Following on the previous list of signatures, there are a few core methods to be developed for this focus topic. First, the reconstruction of displaced tracks and vertices, both in the inner detector and the muon spectrometers, must be well established. Then, tracking algorithms should be able to reconstruct anomalous dE/dx patterns. Timing capabilities in the calorimeters and for tracks should be developed. Jets must be well-reconstructed and jet taggers explored. For all of these, basic algorithms exist in KEY4HEP, in particular via the MARLINWRAPPER functionality. However they all need significant development to fully explore the physics potential in the area of LLPs. Conceptual, DELPHES-based studies of displaced vertices and tracks and, to a lesser extent displaced photons are described in Ref. [185].

Finally, the estimation of unusual backgrounds must be developed. These backgrounds include instrumental backgrounds such as beam-induced background, pileup, and cavern noise, as well as backgrounds from cosmic-ray muons.

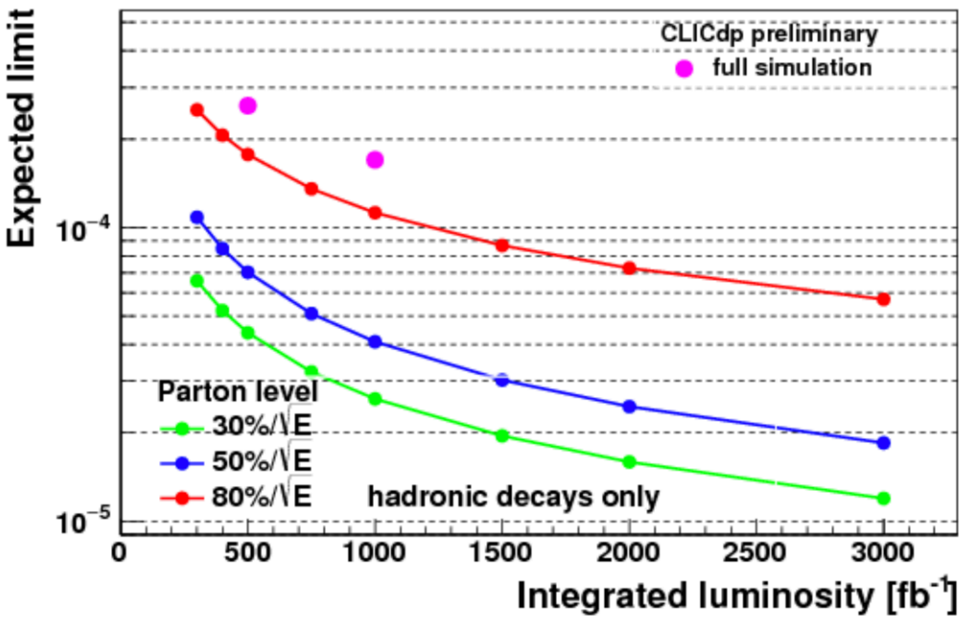
Target detector performance aspects

This focus topic set requirements on all subsystems of collider detectors, with an emphasis on tracking, timing, and calorimetry. In particular, gaseous main trackers have advantages in specific energy loss measurements and pattern recognition which might be difficult to compensate with all-silicon trackers. Analogously, the timing capabilities and the granularity of the chosen ECAL technology might have significant impact on the ability to reconstruct displaced photons and out-of-time signatures.

Additional experiments following those proposed or running at the LHC and HL-LHC should also be considered, from additional detectors on and off-axis to beam dump experiments, depending on the considered facility.

10 Exotic Top decays

EXtt, SRCH



Theory and phenomenological targets

Most $t \to \phi q$ searches so far have focused on $\phi = h$, for instance at CLIC [200]. However it is highly motivated to consider other scalars than the SM Higgs boson h. In particular, the possibility to consider scalars other than the Higgs boson frees up from constraints from other observables related to the properties of the Higgs boson and other tests of the SM. In any case a "generic scalar" search will encompass the Higgs boson as a sub-case, thus allows to obtain results for the SM Higgs at little or no cost at all.

From this starting point the **main phenomenological target** is to quantify the discovery reach of the HET factory below the HL-LHC limits at $\mathrm{BR}(t \to \phi q) \lesssim 10^{-4}$ in the channel $\phi \to bb$ in the mass range $m_\phi \in [10, 172]$ GeV, and to study the obtainable precisions on mass and other properties of the ϕ.

In addition, the search in other decay modes of ϕ, e.g. $\phi \to \gamma\gamma, c\bar{c}, s\bar{s}, gg,$ and invisible , especially for $m_\phi < 10$ GeV, which are also very challenging for LHC. Each of this can provide a new target for detector performances and reconstruction methods.

Detector Performances and Methods

The search for the exotic top decay eq. (3) hinges around reconstruction performances for multi-jet events. A key development concerns methods for b tagging for a kinematics different from the typical $t \to bW$ and $Z \to b\bar{b}$, in particular for "soft" and/or "small-opening-angle" b-jets from a light ϕ. These methods can be explored for ϕ search in top decay, but also for a number of other scenarios where light sources of heavy flavours emerge, e.g. $h \to \phi_1\phi_2$ of interest in the **EXscalar** Focus Topic (Sec. 8).

Considering the fact that each event will contain two top quarks, there will be up to six jets in the event, which can lead to significant jet clustering errors. Thus the development of jet algorithms and kinematic fitting will be essential for a realistic performance estimate.

Extending the scope from $\phi \to b\bar{b}$ to $\phi \to c\bar{c}, s\bar{s}, \gamma\gamma,$ invisible will add the need for corresponding tagging algorithms, especially for the lower-mass cases.

11 CKM matrix elements from WW

CKMWW, FLAV

Target physics observables

A starting point for computing the achievable precision on each CKM matrix element is the total number of W boson produced, which can then decay to each specific hadronic channel. The total hadronic branching ratio of a W boson is [79]

$$\mathrm{BR}(W^- \to \text{hadrons}) = (67.41 \pm 0.27)\% \; . \tag{4}$$

The branching ratio for each quark channel can be approximated by (we neglect quark mass effects) $\mathrm{BR}(W^- \to \bar{u}_i d_j) \approx \frac{1}{2}|V_{ij}|^2 \mathrm{BR}(W^- \to \text{hadrons})$, with the result shown in Table 2. In the bottom row we show the number of events in each channel assuming a total number $N_W = 10^8$ of $W^\pm$ pairs produced and the lower limit for the statistical uncertainty in $|V_{ij}|$ assuming an unrealistic reconstruction efficiency of 100%, computed as $\delta^{\mathrm{th}}_{V_{ij}} = \frac{1}{2} N_{\mathrm{ev}}^{-1/2}$.

A study of the particle reconstruction capabilities of each detector design will allow to derive reconstruction efficiencies for each decay channel, enabling an evaluation of the possible reach for the CKM matrix elements. A first estimate for the sensitivity reach in V_{cb} can be found in Ref. [204], where a precision $\delta_{V_{cb}} \approx 0.4\%$ is projected for 10^8 W pairs, a substantial improvement on the expected precision from B meson decays.

$W^- \to$	$\bar{u}d$	$\bar{u}s$	$\bar{u}b$	$\bar{c}d$	$\bar{c}s$	$\bar{c}b$
BR	31.8%	1.7%	4.5×10^{-6}	1.7%	31.7%	5.9×10^{-4}
N_{ev}	64×10^6	3.4×10^6	900	3.4×10^6	63×10^6	118×10^3
$\delta^{\mathrm{th}}_{V_{ij}}$	0.0063 %	0.027 %	1.7 %	0.027 %	0.0063 %	0.15 %

- O(10^8) Ws at FCCee and ILC
- use to extract Vcs, Vcb, Vub
- complementary to B factories
- jet flavour and charge tagging crucial
- systematics
- ….

12 B0 -> K0*tau+tau-

BKtautau, FLAV

Target physics observables

The $B^0 \to K^{*0}\tau^+\tau^-$ decay was considered in Ref. [212] as a mode to test the $b \to s\tau^+\tau^-$ transition. While the two neutrinos emitted from τ decays complicate the experimental search, an excellent reconstruction of all the vertices, considering hadronic τ decays, can help to close the kinematics of the process. Ref. [212] also considers τ polarisation as a further observable to disentangle the Standard Model from possible New Physics contribution.

To study the $b \to s\nu\bar{\nu}$ transition, branching fraction measurements of $B^0 \to K^0_S\nu\bar{\nu}$, $B^0_s \to \phi\nu\bar{\nu}$, $B^0 \to K^{*0}\nu\bar{\nu}$ and $\Lambda^0_b \to \Lambda\nu\bar{\nu}$ decays have been considered. Given the interest in the Belle II measurement, the $B^+ \to K^+\nu\bar{\nu}$ decays should also be considered, although this is experimentally more challenging due to the lack of a secondary decay vertex.

Target detector performance aspects

Precise vertexing is essential to most of the heavy-flavour measurements: time-dependent B^0_s CP asymmetries studies, for instance, require to resolve the B^0_s proper-time significantly better than the $\sim$350 fs oscillation period of the B^0_s meson. State-of-the-art vertex detectors envisaged for a Tera-Z factory are likely to fulfil this requirement, with resolutions of a few microns for multi-track vertices [14]. The reconstruction of the decay modes of interest in this Section impose more challenging detector requirements and would benefit from even better performance. Various improvements can be envisaged and tested with these modes as a case in point. These include, but are not limited to:

- shortening the distance of the first tracking layer to the interaction point (beam-pipe radius);
- reducing the overall material in the detector, as well as assessing the cooling system, and the use of bent sensors;
- understanding the impact of improving hit resolution.

- vertex detector benchmark
- opportunity to get flavour colleagues interested?
  => talk to your LHCb / Belle II colleagues eg at your institute!

13 Two-fermion final states (MZ and beyond)

TwoF, HTE (PREC)

Target physics observables

- Total and differential cross sections as well as asymmetries at different energies for two-fermion inclusive final states; in the case of τ leptons, including the τ polarisation.
- Combination of Z-pole and off-pole measurements to study the energy dependence of EW interactions: separate EW couplings and four-fermion interactions.
- Final states with one isolated γ, interpreted as Z decay to neutrino, or as a new physical signal
- τ spin correlations for CP violation, EDM, a_τ, Bell's inequality, at the Z pole and at higher energies.

Target detector performance aspects

- Design of inner tracking detector systems and their influence on vertex finding, with a focus on the forward region (the most important region for physics sensitivity).
- Charged hadron identification detectors, especially of kaons for b, c, s tagging and charge measurement using dE/dx, dN/dx, time-of-flight detectors, RICH detectors, etc.
- impact of ECAL design (e.g. granularity an energy resolution) on tau decay mode identification.
- Impact of high-energy photon identification. This will be needed for measurements in the continuum where the return to the Z pole contributes to the background but not to the signal. These photons tend to be found in the forward regions.
- Hermeticity of detectors: to study Z-couplings at 240/250 GeV with radiative return events, we will have to look at events in which the ISR photon has escaped the detector through the beam pipe. Proper estimations of the missing energy (via angular measurements, for example) are required, and these depend on the detector hermeticity.
- Typical 2f signatures are back-to-back; detectors often have an even-fold symmetry in ϕ. Would eliminating back-to-back detector cracks (e.g. by adopting an odd-fold symmetry) help reduce systematic effects?

The optimisation of the detector concepts should also address the difference of challenges associated with the different operation scenarios: high-energy vs low-energy scenarios, high-rates (Z pole) or lower rates (HZ threshold and above).

Target methods to be developed

- Strange tagging (see FT **HtoSS**, Sec. 1).
- Separating lightest families (u and d) using final state photon radiation?
- Improved b and c jet identification, for example using Machine Learning techniques [240–242].
- Improved distinguishing of quark and anti-quarks ($b-\bar{b}, c-\bar{c}, s-\bar{s}$) by displaced vertex charge measurement, charged lepton and kaon identification.
- Full τ lepton reconstruction making use of all detector information (esp. impact parameters, high granularity ECAL for neutral pions); optimal extraction of polarimeter information in many decay modes.

13 Two-fermion final states (MZ and beyond)

TwoF, HTE (PREC)

Target physics observables

- Total and differential cross sections as well as asymmetries at different energies for two-fermion inclusive final states; in the case of τ leptons, including the τ polarisation.
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- Final states with one isolated γ, interpreted as Z decay to neutrino, or as a new physical signal
- τ spin correlations for CP violation, EDM, a_τ, Bell's inequality, at the Z pole and at higher energies.

- total & diff x-sections for all fermions
- tau polarisation, CPV, EDM, Bell's inequaloty, …
- many detector and reconstruction questions…

Target detector performance aspects

- Design of inner tracking detector systems and their influence on vertex finding, with a focus on the forward region (the most important region for physics sensitivity).
- Charged hadron identification detectors, especially of kaons for b, c, s tagging and charge measurement using dE/dx, dN/dx, time-of-flight detectors, RICH detectors, etc.
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- Full τ lepton reconstruction making use of all detector information (esp. impact parameters, high granularity ECAL for neutral pions); optimal extraction of polarimeter information in many decay modes.

14 B-/C-fragmentation functions, hadronisation rates, gluon splitting

BCfrag & Gsplit, PREC (FLAV)

14.1 Relevance for the physics program of a Higgs/Top/EW Factory

Jets and in particular heavy-flavour jets play an important role in many of the flagship measurements of Higgs/Top/EW Factories. As examples, we highlight here the connection to other ECFA Focus Topics:

Precise study of $h \to gg/b\bar{b}/c\bar{c}$: (HtoSS, Sec. 1, and ZHang, Sec 2). Future Higgs Factories will provide sensitivity to these topologies providing capabilities to fully explore the second generation of Yukawa couplings, which is out of reach at the LHC. However, current uncertainties in gluon splitting into heavy quarks would introduce large systematic uncertainties in the measurements. The questions arising are: how to consistently implement gluon splitting in parton shower tools (modelling and free parameters)? and how to evaluate the impact of incomplete modelling of the gluon splitting when determining the $h \to gg/b\bar{b}/c\bar{c}$ couplings? This issue is discussed in the **HtoSS** focus topic (Sec. 1).

Precise determination of W-mass and cross section: (Wmass, Sec. 4, Wdiff, Sec. 5, and CKMWW, Sec. 11). W mass measurements at future Higgs factories are expected to deliver statistical accuracies at the MeV level [87, 89]. To match this unprecedented precision, the control of systematic uncertainties is crucial. At LEP2, the modelling of non-perturbative QCD effects in W boson hadronic decays was a dominant source of systematic uncertainties. Further theoretical and experimental studies are required to estimate the size of such uncertainties at future colliders. This issue is discussed in the **Wmass** focus topic.

Z-b/c couplings: (TwoF, Sec. 13). What would be the impact of these uncertainties on the extraction of Z-b/c couplings at the Z-pole? In Ref. [257] it is demonstrated that hadronisation uncertainties have a significant impact on determinations of the partial widths normalised to total hadronic width ($R_{b,c}$), the forward-backward asymmetries ($A_{\mathrm{FB}}^{b,c}$) (or left-right asymmetries) at e^+e^- colliders, even after application of cuts to reduce their impact. The size of these uncertainties could be a limiting factor when operating at the Z-pole in the high luminosity scenarios of FCC-ee. This issue is discussed in the **TwoF** focus topic.

14.4 Target detector performance, analysis methods and tools

- Large tracker acceptance as well as very good vertexing and flavour tagging capabilities (including light quarks and gluon quarks)
- Jet charge measurements, including charge hadron identification capabilities (see above), and fit a representative set of observables for hadronisation calibration (see above).
- Samples for hadronic observables using different hadronisation models and parameters. Full simulation is required to understand flavour tagging capabilities. Existing tools are e.g. the generators PYTHIA [263], HERWIG [264, 265], SHERPA [266] and the tuning tools PROFESSOR [267], RIVET [268].
- Access to LEP Archived Data. LEP data (and simulations) have been partially archived to allow their use for physics analyses after the closure of the collaboration. The use of archived data is authorised to former members of the collaboration and collaborators. However, the understanding and reprocessing of analysis is still challenging and depends on the safeguarding of the different collaboration's analysis frameworks and mini-data at CERN. Recent efforts [269] have been driven to re-analyse these data by exporting the data and simulations to more modern and accessible formats, for instance, the MIT Open Data format. A systematic approach for the exportation of such archived data and software tools to the KEY4HEP environment should be considered by the Higgs Factory community. This would allow the validation of newer calculations and MC tools with existing data.

14.5 Summary and open questions

1. How can the recent progress in the Perturbative FF framework, supplemented by the fits of the non-perturbative component, be implemented and used in practice, e.g. in PS Monte Carlo?
2. What is the quantitative impact of uncertainties from parton-shower, fragmentation and hadronisation on flagship Higgs/Top/EW measurements - and which level of precision will be required?
3. Which measurements of particle rates, species, distributions are needed in order to constrain fragmentation and hadronisation models to the required level of precision?
4. Which detector capabilities are required and to which extend do the proposed detector concepts provide these?
5. To which extend could LEP data be useful and how could they be made accessible to test new calculations and MC tools?

Observable	e^+e^-	pp
Event shapes and angular distributions		
Inclusive B/D production cross section	primary production is well known from theory, so any "excess" is from gluon splitting	combines primary production, gluon splitting, and MPI (multiparton interactions) contributions, each with significant theoretical uncertainties
Flavour composition as far back in decay chains as can be traced (even equal D^{*0} and D^{*+} rates gives unequal D^0 and D^+ ones)	we do not expect sizeable momentum dependence, but interesting to contrast mesons and baryons for smaller ones	significant p_T dependence observed and to be studied further, also high- vs. low-multiplicity events, rapidity, ..., which is important for development/tuning of colour reconnection models
Particle-antiparticle production asymmetries	none expected, except tiny from CP-violation in oscillations	asymmetries expected and observed from p flavour content, increasing at larger rapidities; relates to how string (and cluster?) fragmentation connects central rapidities to beam remnants
Momentum spectra	dn/dx_E with $x_E = 2E_\mathrm{had}/E_\mathrm{cm}$; basic distribution for tuning of "fragmentation function"	dn/dp_T and dn/dy give basic production kinematics, but the many production channels give less easy interpretation
Energy flow around B/D hadrons, excluding the hadron itself, as a test that dead cone effects are correctly described	$dE/d\theta$ where θ is the distance from B/D on the sphere	dp_T/dR where R is the distance in (η, ϕ) or (y, ϕ) space, only applied for B/D above some p_T threshold
B/D hadron momentum fraction of total E or p_T in a jet, with $x = p_\mathrm{T}^\mathrm{had}/p_\mathrm{T}^\mathrm{jet}$, as a test of the fragmentation function combined with almost collinear radiation, suitably for some slices of p_T (and in addition with a veto that no other B/D should be inside the jet cone, so as to suppress the gluon splitting contribution)	draw a jet cone in θ around B/D and measure x	draw a jet cone in R around B/D and measure x
B/D hadron multiplicity, as a measure of how often several pairs are produced		
Separation inside B/D pairs, where large separation suggests back-to-back primary production, while small separation suggests gluon splitting	separation in θ	separation both in ϕ and in R, since for primary production $\phi = \pi$ is hallmark with η/y separation less interesting, while gluon splitting means R is small while ϕ and y/η individually are less interesting
Hardness difference within (reasonably hard) pairs, $\Delta = (p_\mathrm{T}^\mathrm{max} - p_\mathrm{T}^\mathrm{min})/(p_\mathrm{T}^\mathrm{max} + p_\mathrm{T}^\mathrm{min})$, where for gluon splitting $x^2 + (1-x)^2$ translates to $1 + \Delta^2$	separately for small or large θ	separately for large or small ϕ

Next steps

There's a lot to do - get involved!

- NOW:
  - FORM TEAMS who actually DO THE WORK
  - ideal point in time for new students etc to join!
  - check out https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics for "living" information
  - **never hesitate to contact Jenny and/or Filip!**

- later today and tomorrow we will discuss the ILD priorities
- I hope that these topics will feature prominently
- all of them need more people -> ideal to also draw new people into ILD!

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2024 ECFA Workshop: ~Oct in some nice place (deadline for applications about ~now, at least one ILD institute applying :)