Prospects for light exotic scalar measurements at the e^+e^- Higgs factory

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POLAND

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BSM Physics + Global Interpretation session
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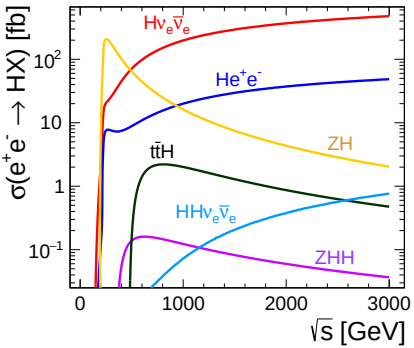
Prospects for light exotic scalar measurements

Outline:

1. Motivation
2. Decay mode independent search
3. Search for $S \to \tau^+\tau^-$
4. Search for $S \to b\bar{b}$
5. Conclusions

e^+e^- Higgs factory

Precision Higgs measurements are clearly the primary target for future Higgs factory.



In the ZH production channel (dominant below 450 GeV) we can use "Z-tagging" for unbiased selection of events.

New channels open at higher energies allowing for direct access to top Yukawa coupling and Higgs self-coupling.

Precision Higgs boson, top quark and electroweak measurements will result in indirect constraints on BSM or possible hints...

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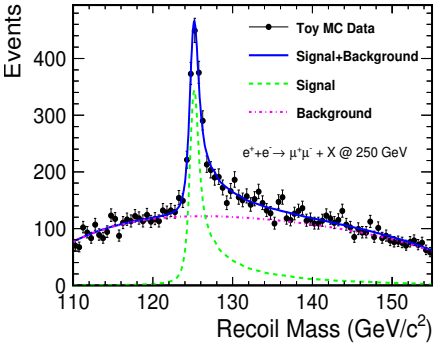
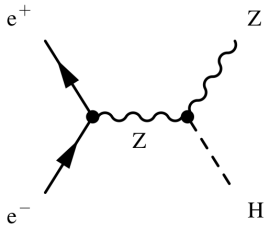


At 250 GeV we will focus on H_{125} production



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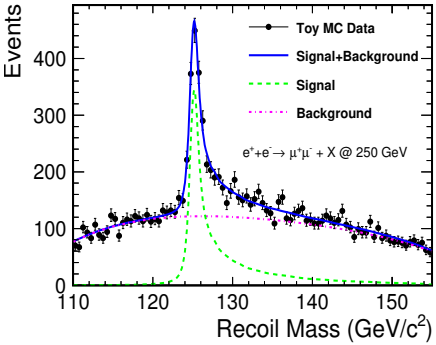

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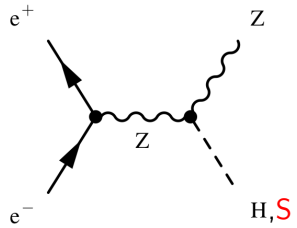

But production of additional, light exotic scalar states is still not excluded by the existing data!

ECFA study

Light scalar searches at future Higgs Factories were only partially studied so far.

More work is clearly needed to understand the experimental challenges and prospects.

Light scalar searches were selected as one of the ECFA study focus topics arXiv:2401.07564

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Theoretical and phenomenological targets (1)

Higgs factories are best suited to search for light exotic scalars in the process:

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

Production of new scalars can be tagged, independent of their decay, based on the recoil mass.

We should look for different scalar decay channels e.g. $b\bar{b}$, $W^{+(*)}W^{-(*)}$, $\tau^+\tau^-$ or invisible
Non-standard decays channels of the new scalar should also be looked for.
For maximum sensitivity, feasibility of including hadronic Z decays should also be explored.

Theoretical and phenomenological targets (2)

Second benchmark scenario: light scalar pair-production in 125 GeV Higgs boson decays

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

Again, different decay channels should be considered, both SM-like and exotic.
While new scalar states could in general be long-lived, only scenarios with prompt decays are included in this focus topic (there is a dedicated topic focusing on LLPs).

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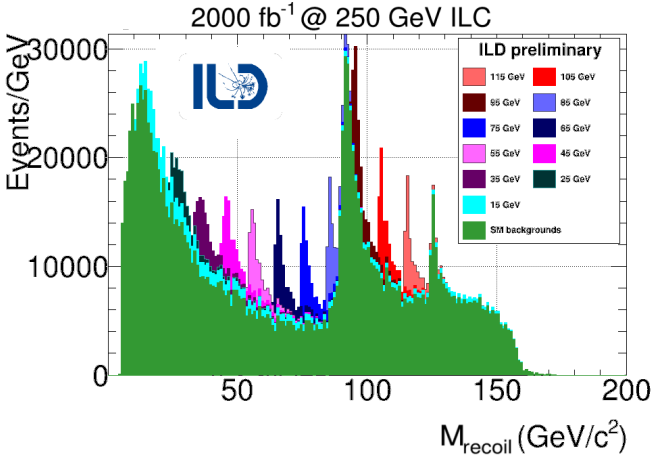
In this talk I will focus on the new activities triggered by the ECFA study on EXscalar focus topic target (1): **direct light Higgs production in the scalar-strahlung process**

Presented studies were carried out in the framework of the ILD concept group
But the results should be quite general, applying to all 240–250 GeV e^+e^- machines...

Decay mode independent search

Previously studied

arXiv:1903.01629 arXiv:2005.06265



ILD full simulation study for

$$e^+e^- \rightarrow Z\,S \rightarrow \mu^+\mu^- + X$$

Search strategy based on the reconstructed recoil mass spectra

Decay mode independent search

Previously studied

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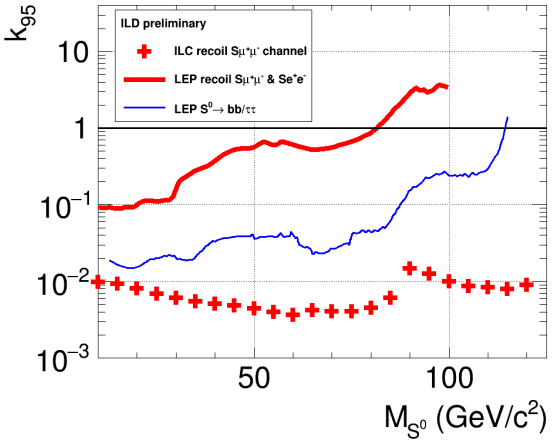


Expected sensitivity for ILC @ 250 GeV
(relative to SM-like Higgs boson production rate)

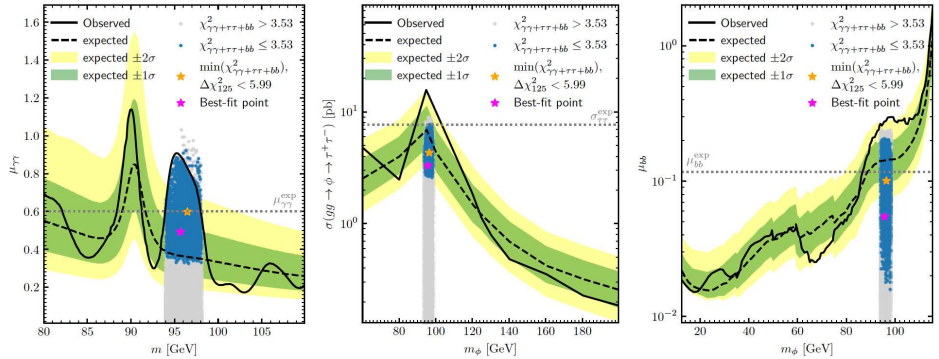
Expected limits are likely to improve further with use of up-to-date simulation, reconstruction and analysis tools
(ongoing effort)

Experimental hints...

T. Biekötter, S.Heinemeyer, G. Weiglein arXiv:2203.13180

Some discrepancies point to new scalar with mass of ∼95 GeV and dominant decay to $\tau\tau$...

$pp \to h_{95} \to \gamma\gamma$ $\quad gg \to h_{95} \to \tau^+\tau^-$ $\quad e^+e^- \to Zh_{95} \to Zb\bar{b}$



Sven Heinemeyer @ First ECFA WS on e^+e^- Higgs/EW/top factories, October 2022

Timeline

LCWS'2023 First results on the 96 GeV scalar search
Delphes simulation, cut-based analysis of combined data

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Delphes simulation, BDT used for event selection, limits from combined data

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LCWS'2024 New analysis approach
Delphes simulation, multiple event categories (signature/polarization),
limits based on BDT response distribution

Event samples

Signal and background samples generated with WHIZARD 3.1.2 using built-in SM_CKM model.

Signal generated by varying H mass in the model and forcing its decay to $\tau^+\tau^-$ (or $b\bar{b}$).

All relevant four-fermion final states considered as background.
SM-like Higgs boson contribution included in the background estimate.
Contribution from two-fermion and six-fermion processes found to be small.

ISR and luminosity spectra for ILC running at 250 GeV taken into account

Total lumionsity of $2\,\mathrm{ab}^{-1}$, with $\pm 80\%/\pm 30\%$ polarisation for e^-/e^+ (H-20 scenario).

Fast detector simulation with Delphes ILCgen model.

Event categories

Five event categories, according to number of isolated leptons and τ-tagged jets

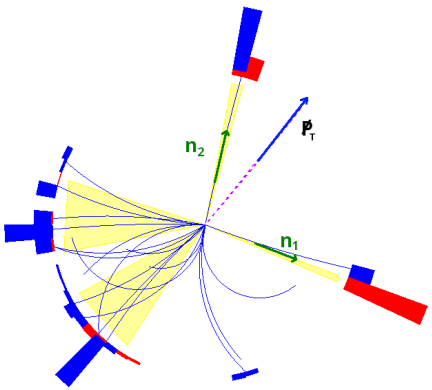
category	isolated leptons	tight	loose
hadronic	zero	4 jets including 2 with τ-tag	4 jets, 1 with τ-tag and other lightest jet as second τ- tag jet
semi-leptonic	one	3 jets including 1 with τ-tag	3 jets with no τ-tag, lightest jet as τ- tag jet
leptonic	two	two jets without τ-tag	

Event classification was considered separately for each category and polarization!

Event reconstruction

arXiv:1509.01885

Example signal event with hadronic tau decays



Tau leptons are very boosted $\Rightarrow$ collinear approximation

Assume tau neutrinos are emitted in the tau jet direction.

Their energies can be found from transverse momentum balance:

$$\vec{p}_T \;=\; E_{\nu_1} \cdot \vec{n_1} + E_{\nu_2} \cdot \vec{n_2}$$

where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

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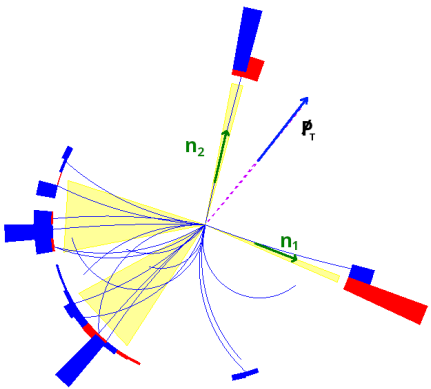

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Unique solution !

Works also for semi-leptonic and leptonic events!

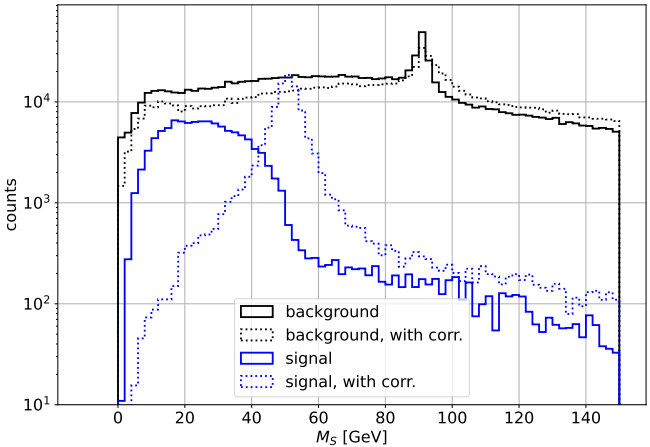
Because of small tau mass ⇒ small invariant mass of neutrino pair

Event reconstruction

Impact of the neutrino energy correction on the reconstructed di-tau mass distribution ⇒

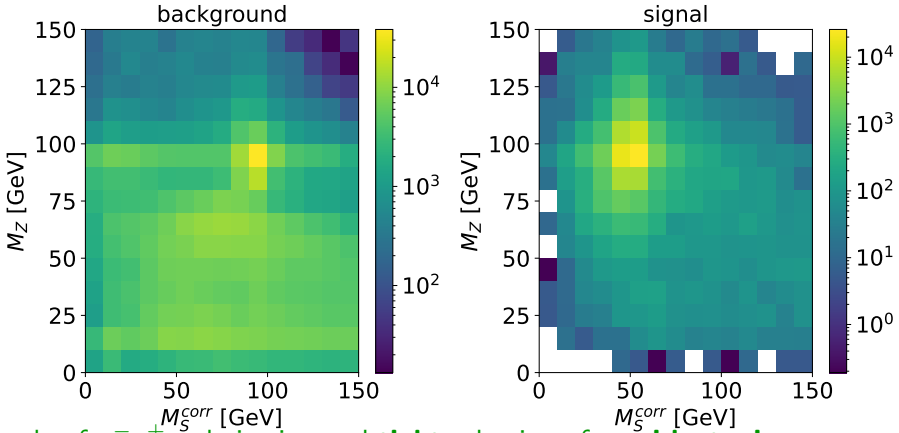
Signal for scalar mass of **50 GeV**. Normalized to 1% of the SM production cross section for the considered scalar mass.

Example of $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight** selection of **semi-leptonic** events.



Event reconstruction

Corrected scalar mass vs reconstructed Z mass for 50 GeV scalar and SM background



Example of $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight** selection of **semi-leptonic** events.

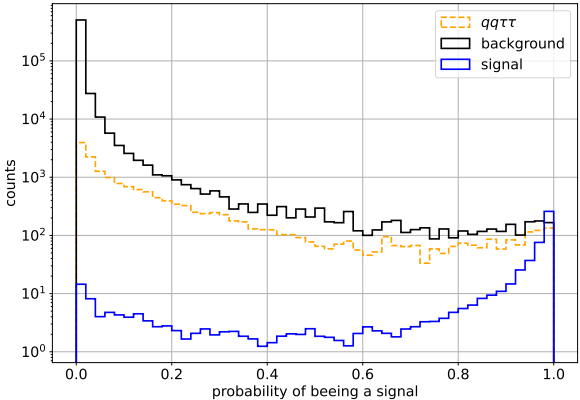
Event classification

XGBoost BDT classifier response distributions for signal and background
dominant $qq\tau\tau$ background indicated

Example for $\mathbf{e}_L^-\mathbf{e}_R^+$ polarisation and **tight semi-leptonic** event selection.

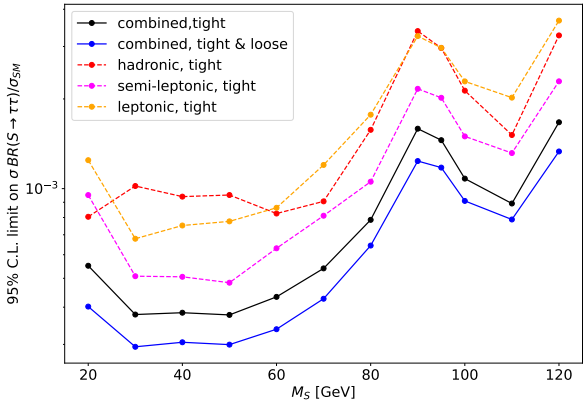
Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

Separate BDT trained for each event class and polarization combination



Results

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
for different event categories and combined analysis

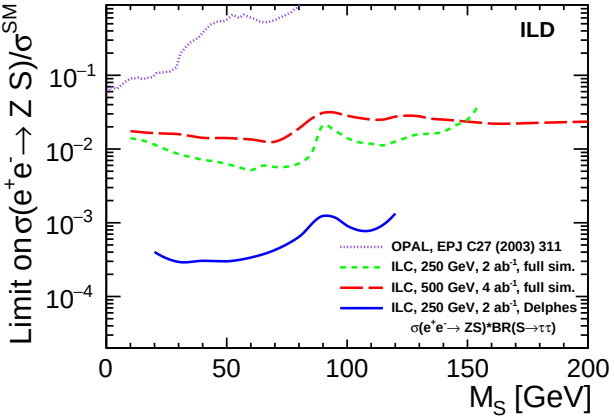


Semi-leptonic sample most sensitive to new scalar production

Significant improvement when including loose-selection categories

Results

Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
compared with decay-mode independent limits on σ/σ_{SM} from earlier studies



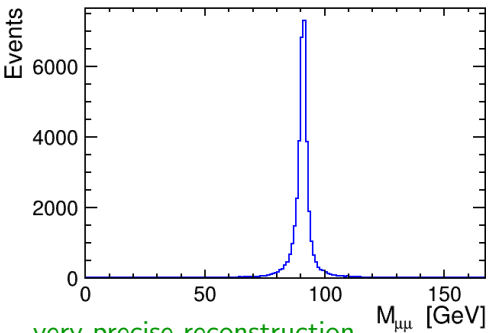
Targeted analysis results in over order of magnitude increase in sensitivity...

Possible gain in discovery reach depends on the BR!

Event reconstruction

Focusing on leptonic decays, $Z \to e^+e^-/\mu^+\mu^-$; huge W^+W^- background for hadronic decays

Z mass from leptonic decays:



very precise reconstruction...

Direct reconstruction of the scalar mass much more problematic. Invariant mass of two b jets poorly reconstructed, large impact of energy losses in semi-leptonic heavy meson decays.

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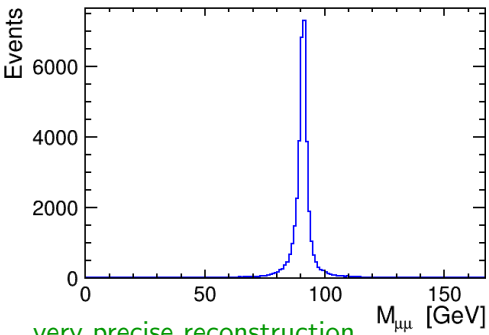

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However, conservation of transverse momentum can be used to reconstruct jet energies from leptonic final state and jet angles.

ILD-PHYS-PUB-2019-001

Event reconstruction

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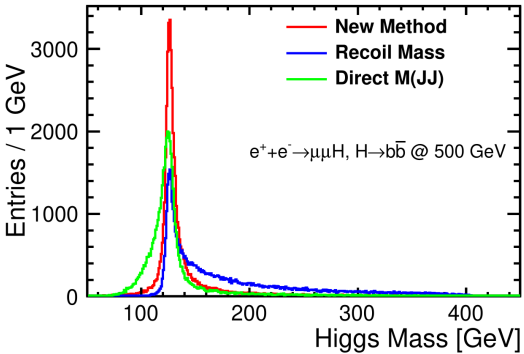
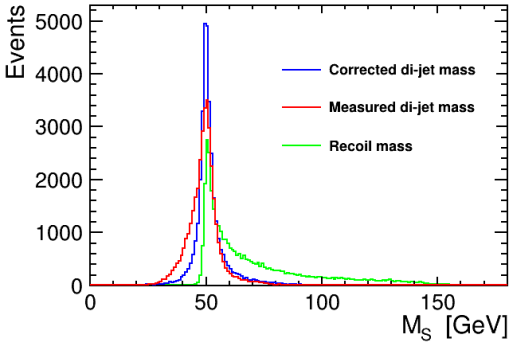
Full simulation for H_{125} at 500 GeV



Fast simulation for 50 GeV scalar at 250 GeV



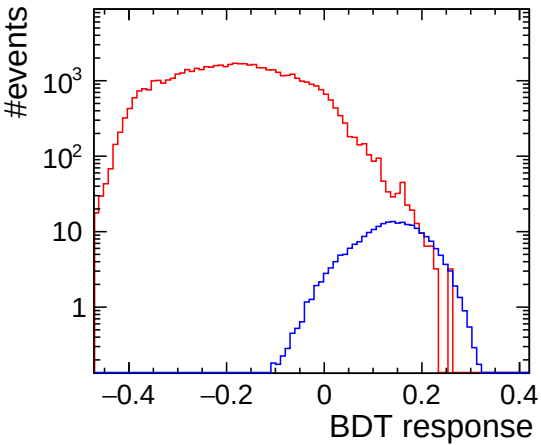
ILD-PHYS-PUB-2019-001

Work in progress...

Event classification

First results from the BDT classifier used on the preselected event samples (two electrons or muons, two b-tagged jets)

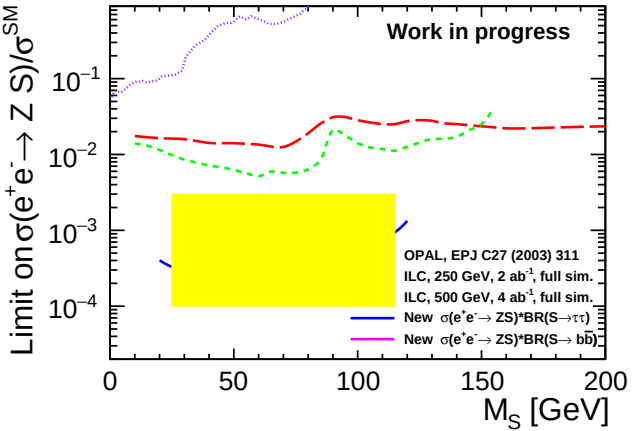
Example for $e_R^- e_L^+$ polarization, scalar mass $M_S = 80\,\text{GeV}$ scenario normalized to 1% of the $\sigma_{SM}(M_S)$



Still waiting for the first results

Work in progress!

Expected 95% C.L. limits on the scalar production cross section $\sigma \cdot BR(S \to b\bar{b})/\sigma_{SM}$ assuming $Z \to e^+e^-,\ \mu^+\mu^-$



Conclusions

BSM scenarios with light scalars still not excluded by existing data

Sizable production cross sections for new scalars can coincide with non-standard decay...

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Over order of magnitude limit improvement of search sensitivity expected.

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Search for light scalar decays to $b\bar{b}$ is a must!
Fast simulation study ongoing, first sensitivity estimates expected very soon...

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Results for the ECFA study report need to be completed by the end of the year!
More results should be available already for October workshop...
Still not all possible discovery channels covered...


Thank you!

ILC running scenario

The unique feature of the ILC is the possibility of having both electron and positron beams polarised! This is crucial for many precision measurements as well as BSM searches.

Four independent measurements instead of one:

- increase accuracy of precision measurements
- more input to global fits and analyses
- remove ambiguity in many BSM studies
- reduce sensitivity to systematic effects

Integrated luminosity planned with different polarisation settings [fb^{-1}]

H-20	$\mathrm{sgn}(P(e^-), P(e^+))$				Total
$\sqrt{s}$	$(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	
250 GeV	900	900	100	100	2000
350 GeV	135	45	10	10	200
500 GeV	1600	1600	400	400	4000

arXiv:1903.01629