Search for Exotic Scalars at the International Linear Collider

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on behalf of the ILD Concept Group

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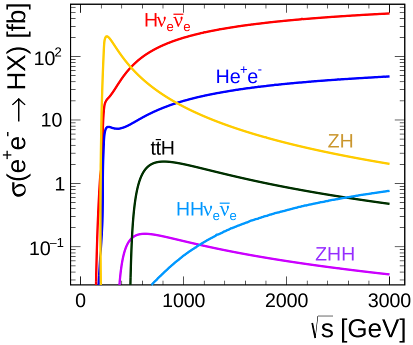
Track 01: Higgs Physics

Outline:

1. Motivation
2. ILC and its experiments
3. Decay mode independent search
4. Search for $S \to \tau^+\tau^-$
5. Search for $S \to b\bar{b}$
6. Prospects and 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...

⇒ see dedicated contributions on Higgs studies and BSM searches at the ILC

e^+e^- Higgs factory

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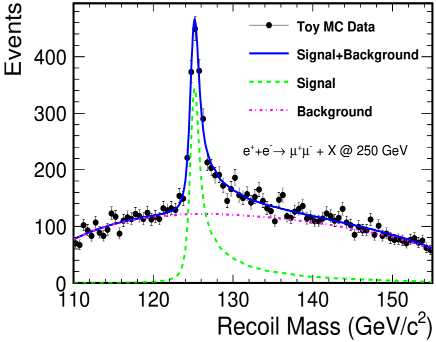
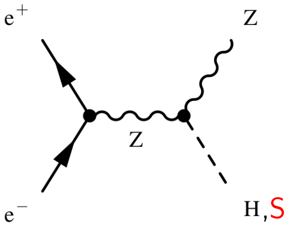


At 250 GeV we will focus on H_{125} production



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

Motivation

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.
Selected as one of the ECFA Higgs/EW/Top factory study focus topics arXiv:2401.07564

EXscalar focus topic

1. Direct light exotic scalar production in the process:

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

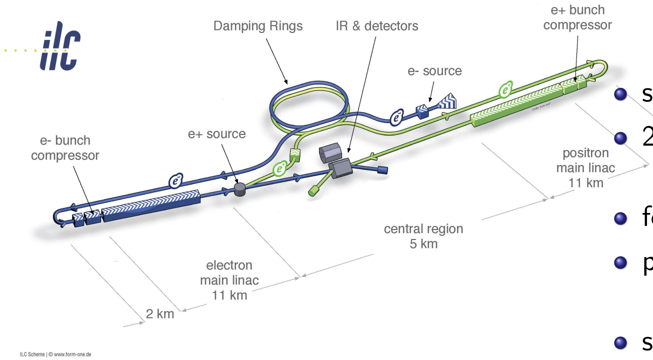
Different scalar decay channels possible e.g. $b\bar{b}$, $W^{+(*)}W^{-(*)}$, $\tau^+\tau^-$ or invisible

In this talk I will focus on the activities related to this EXscalar phenomenological target

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...

International Linear Collider

Technical Design (TDR) presented in 2013 arXiv:1306.6328



- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline),
  1 TeV upgrade possible
- footprint 20 – 31 km
- polarisation for both e^- and e^+ (80%/30%)
  see backup slides for running scenario
- staged construction, arXiv:1903.01629
  starting as 250 GeV Higgs factory

see dedicated contribution on ILC status and plans

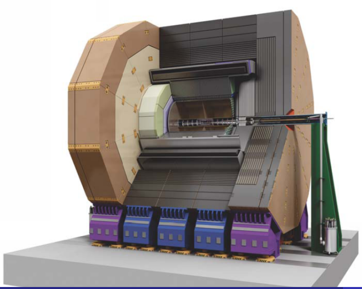
Baseline detector requirements

- Track momentum resolution: $\sigma_{1/p_t} = 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \cdot 10^{-3}/(p_t\ \sin^{1/2}\Theta)$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\,\mu m\ \mathrm{GeV}/(p\ \sin^{3/2}\Theta)$
- Jet energy resolution: $\sigma_E/E = 3-4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

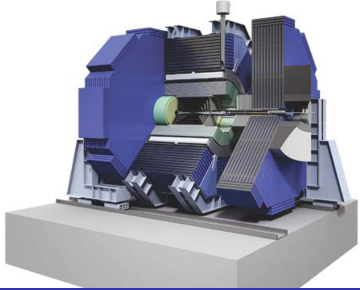
Two detailed ILC detector concepts optimized for particle flow event reconstruction

see dedicated contribution on ILD detector concept

ILD

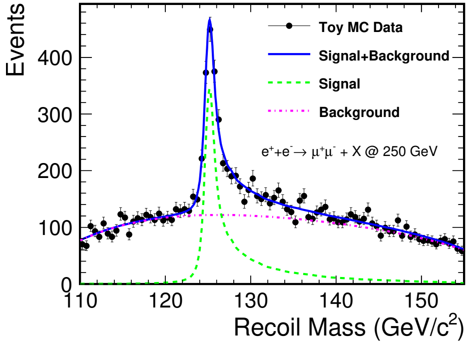


SiD



Event reconstruction

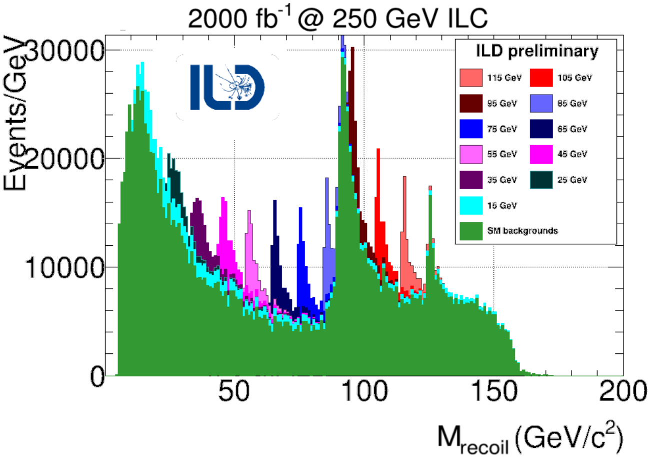
Follow the approach used in the SM-like Higgs boson analysis in the ZH production channel: use "Z-tagging" with $Z \rightarrow e^+e^-/\mu^+\mu^-$ for unbiased selection of scalar production events



We avoid any possible dependence on the scalar decay channels (could be exotic or invisible)!

Analysis

arXiv:1903.01629 arXiv:2005.06265



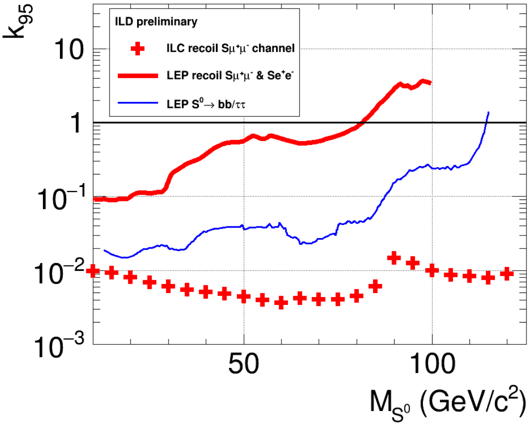
ILD full simulation study for

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

Search strategy based on the reconstructed recoil mass spectra

Results

arXiv:1903.01629 arXiv:2005.06265



Search sensitivity for ILC @ 250 GeV

expected 95% C.L. limits on the cross section ratio

$$k = \frac{\sigma\left(e^+e^- \to Z\ S\right)}{\sigma^{SM}\left(e^+e^- \to Z\ H\right)\big|_{m_H=m_S}}$$

scalar production cross section relative to SM Higgs boson production cross section at given mass

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

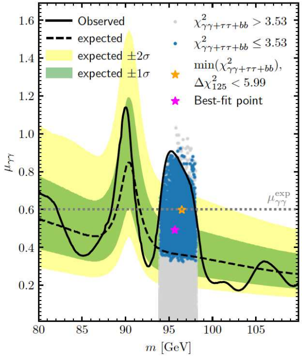
$S \to \tau^+\tau^-$

Experimental hints...

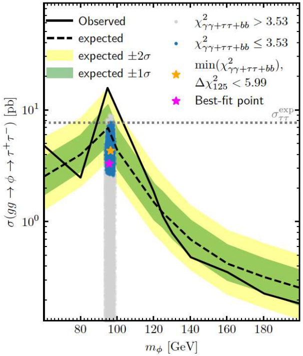
T. Biekötter, S.Heinemeyer, G. Weiglein arXiv:2203.13180

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

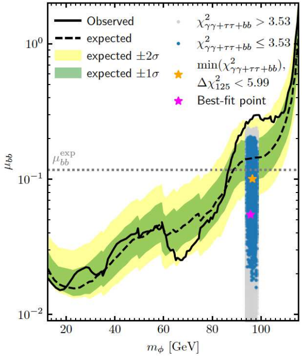
$pp \to h_{95} \to \gamma\gamma$



$gg \to h_{95} \to \tau^+\tau^-$



$e^+e^- \to Zh_{95} \to Zb\bar{b}$



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

Analysis framework

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 $\tau^+\tau^-$

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

Fast detector simulation with Delphes ILCgen model.

$S \to \tau^+\tau^-$

Event categories

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

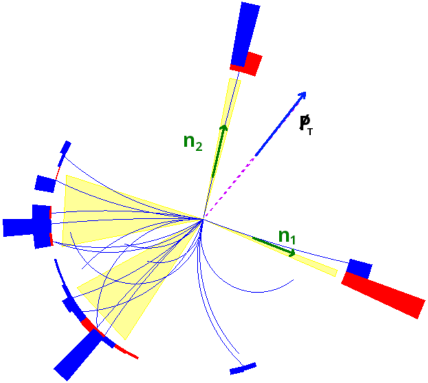
category	isolated leptons	tight selection	loose selection
hadronic	zero	4 jets including 2 with τ-tag	4 jets, 1 with τ-tag and other lightest jet as second τ- tag jet
semi-leptonic	one	3 jets including 1 with τ-tag	3 jets with no τ-tag, lightest jet as τ- tag jet
leptonic	two	two jets without τ-tag	

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:

$$\vec{\not{p}}_T \quad = \quad E_{\nu_1} \cdot \vec{n_1} + E_{\nu_2} \cdot \vec{n_2}$$

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

Unique solution !

Event reconstruction

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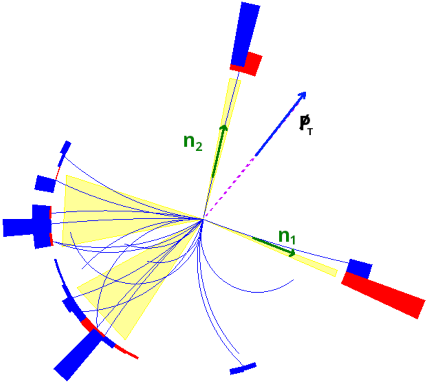

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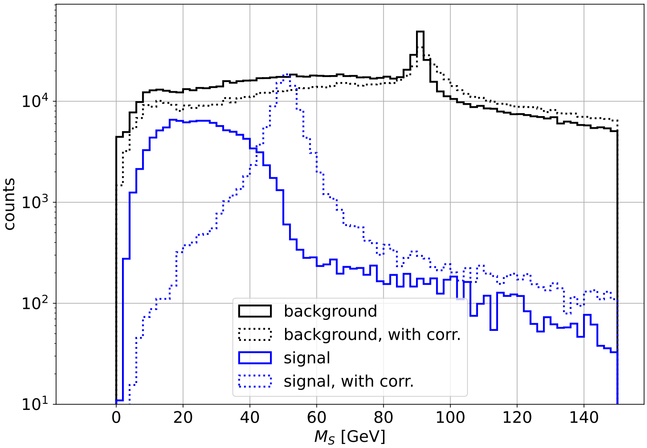
Unique solution !

Works also for semi-leptonic and leptonic events!

Because of small tau mass $\Rightarrow$ small invariant mass of neutrino pair

Event reconstruction

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

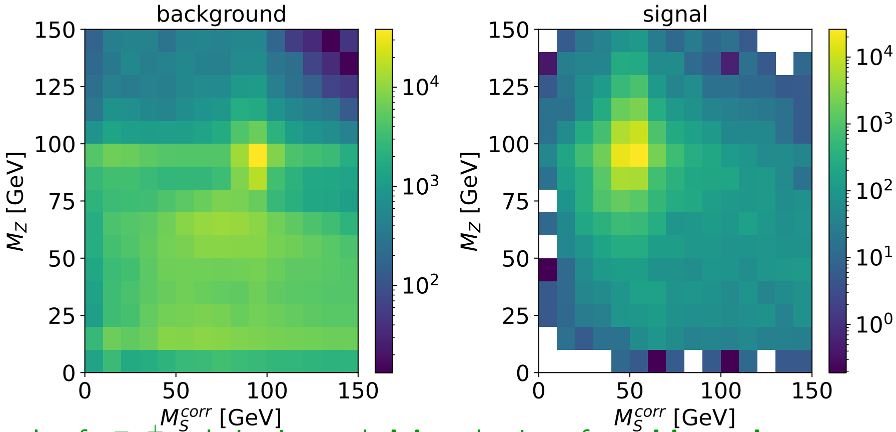


Signal for scalar mass of **50 GeV**. Normalized to 1% of the SM production cross section for the considered scalar mass.

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.

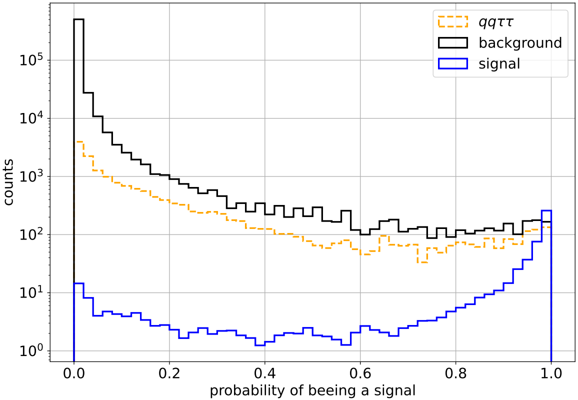
Event classification

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.

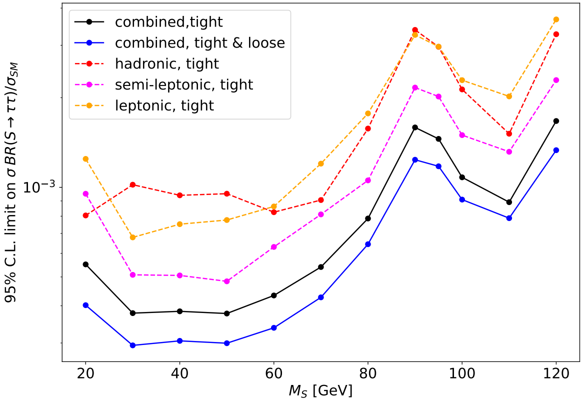
Signal for scalar mass of **50 GeV** normalized to 1% of SM cross section.

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

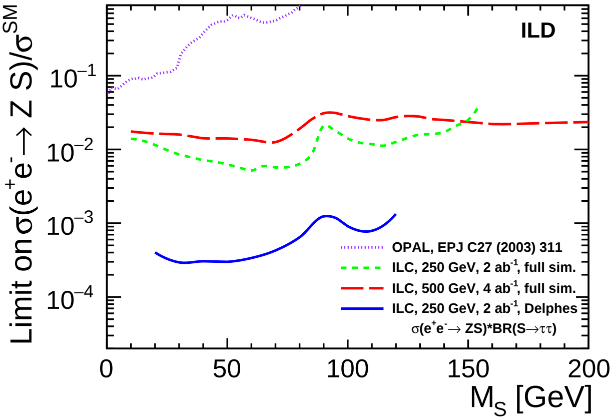


Semi-leptonic sample most sensitive to new scalar production

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



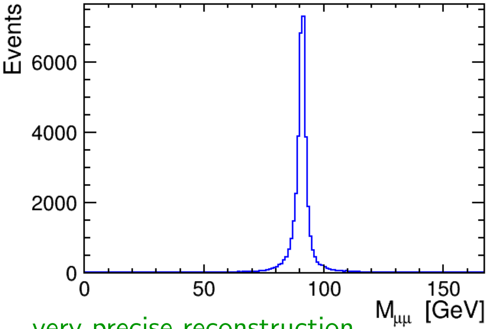
Targeted analysis results in over order of magnitude increase in sensitivity...

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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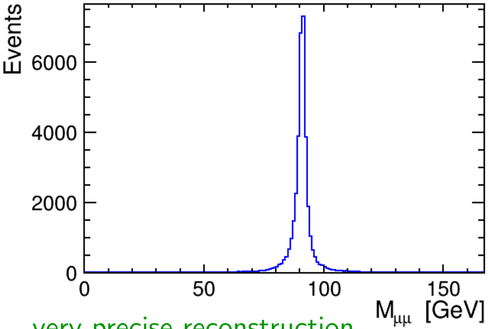

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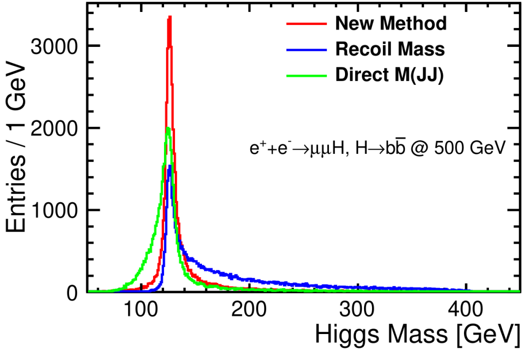
However, conservation of transverse momentum can be used to reconstruct jet energies from leptonic final state and jet angles.

ILD-PHYS-PUB-2019-001

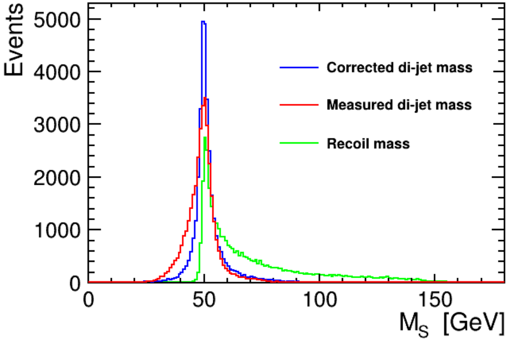
Event reconstruction

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

Full simulation for H_{125} at 500 GeV



Fast simulation for 50 GeV scalar at 250 GeV



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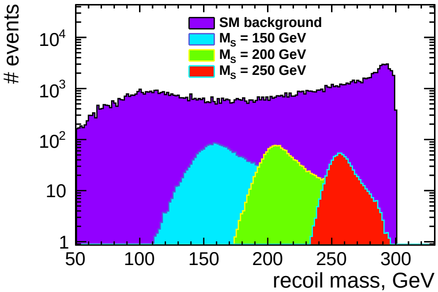
Work in progress...

Prospects

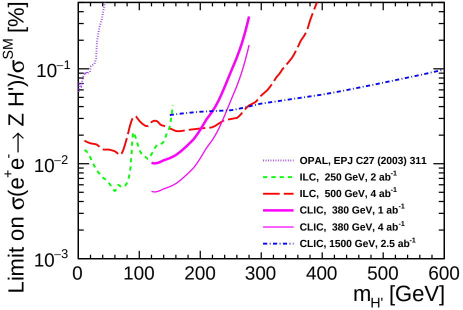
$S \to$ **invisible** fast simulation study just starting...

Previously only studied for CLIC @ 380 GeV arXiv:2002.06034 arXiv:2107.13903

Reconstructed recoil mass spectra



Expected sensitivities of CLIC @ 380 GeV and 1.5 TeV



hadronic Z decays for maximum sensitivity

compared with decay independent limits from LEP and ILC

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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Light scalar decays to tau pairs seem a challenging scenario
and a good testing ground for different detector concepts and analysis methods
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 $\sqrt{s}$	$\mathrm{sgn}(P(e^-), P(e^+))$ $(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	Total
250 GeV	900	900	100	100	2000
350 GeV	135	45	10	10	200
500 GeV	1600	1600	400	400	4000

arXiv:1903.01629