(1) An overview on low mass scalars at future lepton colliders

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based on

arXiv:2203.08210; Universe 8 (2022) 286

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(2) Typical processes at Higgs factories

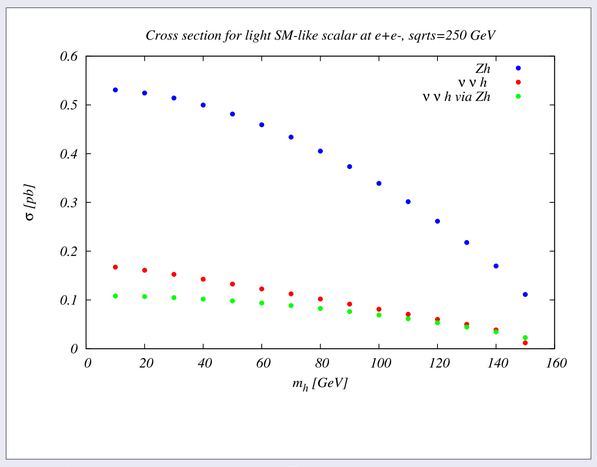
various production modes possible

- 1) **easiest example:** $e^+ e^- \to Z h_1$, onshell production interesting up to $m_1 \sim 160\,\mathrm{GeV}$
- 2) in **models with various scalars:** e.g. also $e^+ e^- \to h_1 h_2$ (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587
  again: for onshell production, $\sum_i m_i \leq 250\,\mathrm{GeV}$
- 3) another (final) option: **look at** $e^+e^- \to h_i Z,\ h_i \to h_j h_k$

already quite a few studies for 1), 3) available

(3) Possible production modes and rates

$e^+ e^- \to Z^* \to Zh,\ e^+ e^- \to \nu\bar{\nu} h$ **(VBF)**



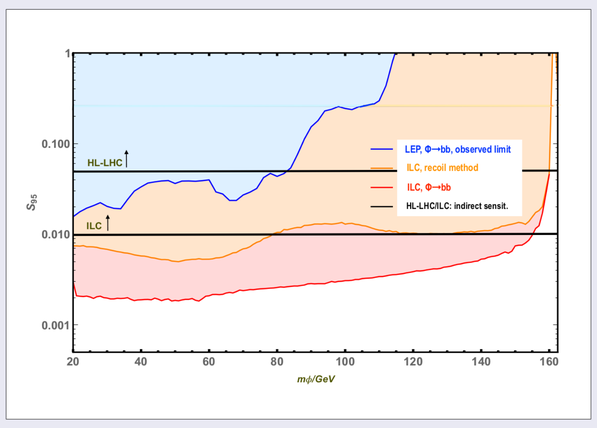
[cross sections for $e^+ e^-$ at $\sqrt{s} = 250\,\mathrm{GeV}$ using Madgraph5;

LO analytic expressions e.g. in Kilian ea, Phys.Lett.B 373 (1996) 135-140]

- rule of thumb: **rescaling** $\lesssim 0.1$
- $\Rightarrow$ maximal production **cross sections around 50 fb**
- $\sim 10^5$ **events using full luminosity**

(4) Projections for additional scalar searches

[P. Drechsel, G. Moortgat-Pick, G. Weiglein, Eur.Phys.J.C 80 (2020) 10, 922]

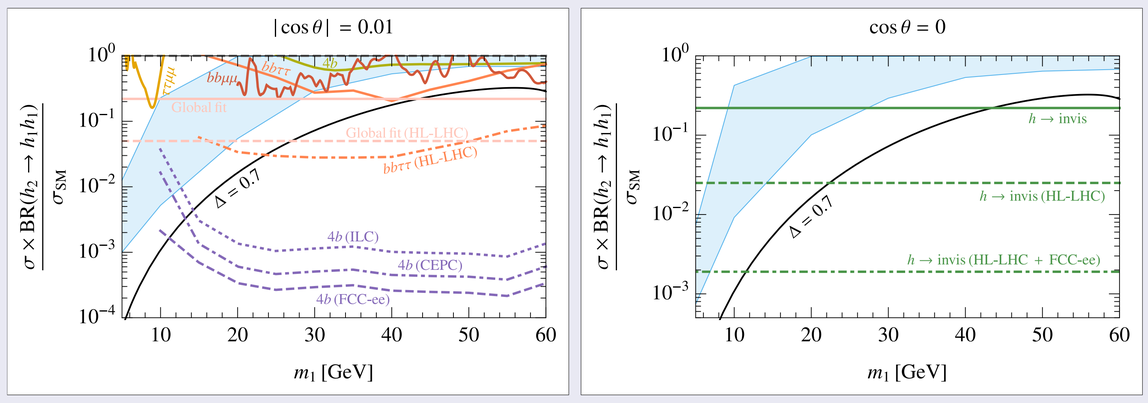


estimate of ILC sensitivity based on validation using LEP results

ILC: $\sqrt{s} = 250\,\mathrm{GeV}$, $\int \mathcal{L} = 2\,\mathrm{ab}^{-1}$; S95: rescaling limit

(5) Singlet extension, with connection to strong first-order electroweak phase transition

[J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, Phys.Rev.D 101 (2020) 11, 115035] [see also M. Carena, Z. Liu, Y. Wang, JHEP 08 (2020) 107]



blue band = strong first-order electroweak phase transition

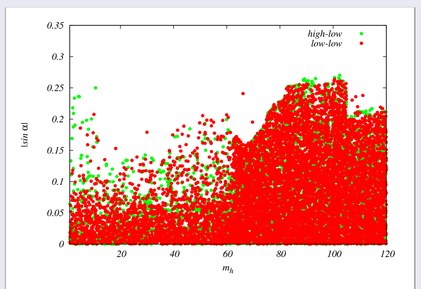
comment: **current constraints lead to prediction** $\lesssim 10^{-1}$

[invisible BR, signal strength, assumes SM-like decay to bs]

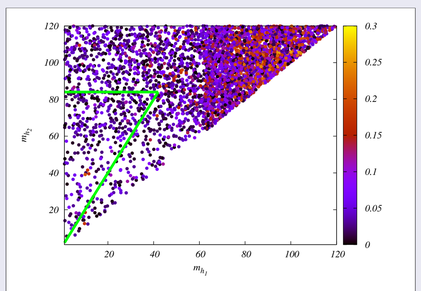
[projections taken from Z. Liu, L.-T. Wang, and H. Zhang, Chin. Phys. C 41, 063102 (2017)]

(6) Singlet extensions

TRSM: 2 real singlets [TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151]



mass and mixing angle



case with two light scalars;

color coding: h_1 rescaling

- **low-low:** both additional scalars below 125 GeV; **high-low:** one new scalar above 125 GeV

cross sections for $e^+e^- \to h_{125} \to h_1 h_2$ **and** $e^+e^- \to h_2 \to h_1 h_1$ $\mathcal{O}(10 - 20\mathrm{fb})$ **@ 250 GeV**

(7) Production modes in 2HDMs

[notation on this slide $h \equiv h_{125}$]

$e^+e^- \to h/HZ,\ hA,\ HA,\ H^+ H^-$

- for on-shell production: **need** $\sum_i m_i \lesssim \sqrt{s}$

requires relatively light scalars, typically $m \lesssim 160\,\mathrm{GeV}$

- include suppression/ alignment, and mass range: HZ, hA **supressed by** $\cos(\beta - \alpha)$
- $H^+ H^-$ **production: kinematic limit only**

need light(ish) $H^\pm$, $m_A + m_H \lesssim 250\,\mathrm{GeV}$

(8) Aligned 2HDM

[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005; V. Miralles, private communication]