

Higgs self-coupling via double Higgs production at future e^+e^- colliders.

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Higgs 2026

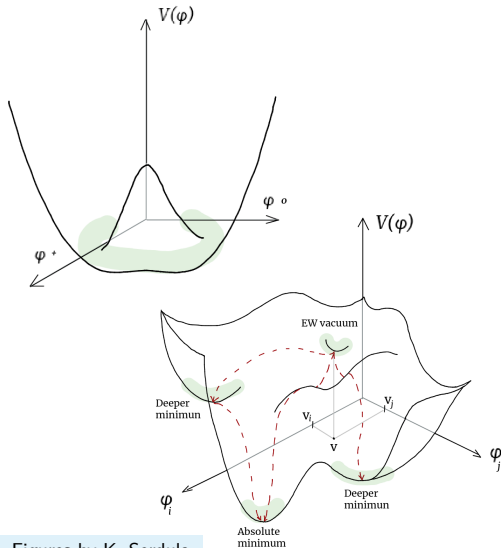
October 27, 2026



HELMHOLTZ



Higgs potential and Higgs self-coupling

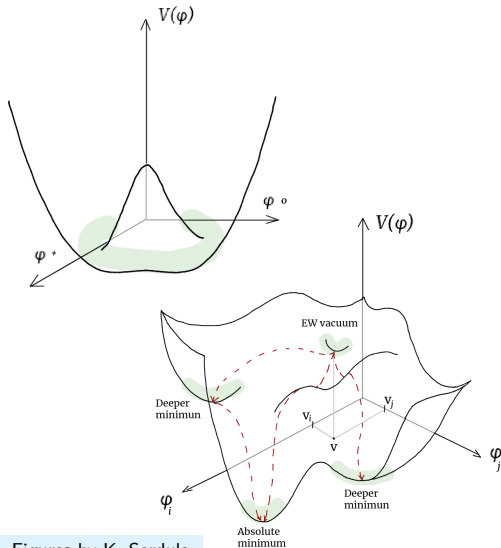


$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_{HHH} h^3 + \frac{1}{4}\lambda_{HHHH} h^4$$

where in SM $\lambda_{HHH} = \lambda_{HHHH} = m_H^2/2v^2$ Measure λ

- **Higgs potential**
- **Higgs mechanism**
- new physics in Higgs sector?

Higgs potential and Higgs self-coupling



Figures by K. Serdula

$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_{HHH} \nu h^3 + \frac{1}{4}\lambda_{HHHH} h^4$$

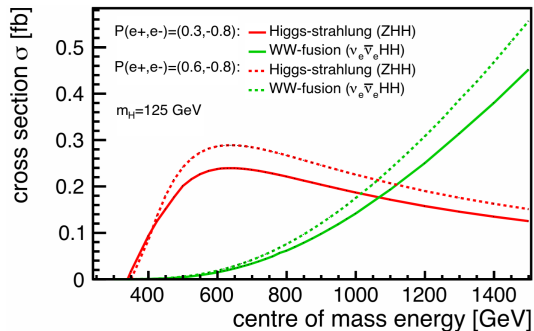
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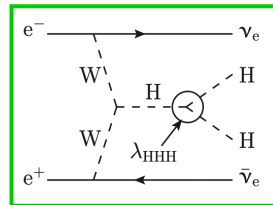
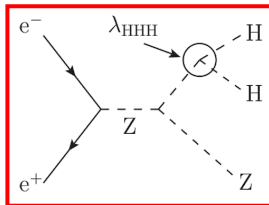
"Direct" access at tree-level:
through double-Higgs production

$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = k \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHx}}$$

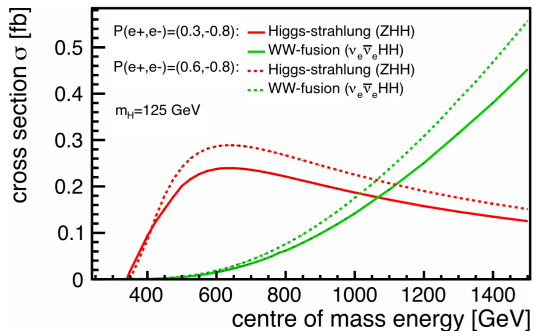
Access to the Higgs self-coupling



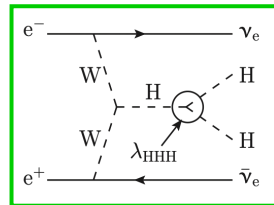
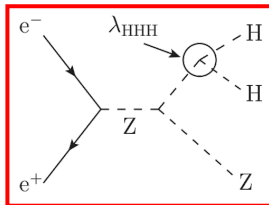
Collider	$\mathcal{L}$ [ab^{-1}]	$ P(e^-, e^+) $	$\sqrt{s}$ [GeV]
ILC	4	(80%, 30%)	500/550
C ³	4	(80%, 30%)	550
LCF	8	(80%, 60%)	550



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2014 ZHH analysis DESY-THESIS-2016-027

- $\Delta\lambda_{SM}/\lambda_{SM} = 26.6\%$

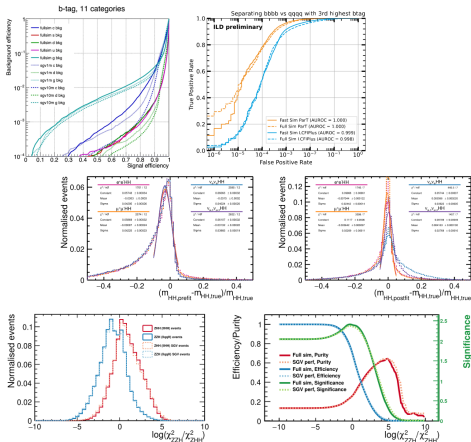
→ 8σ observation of $e^+e^- \rightarrow ZHH$

→ only $3.x\sigma$ observation of λ_3^{SM}

2022 ZHH analysis ongoing

- advancements in event reconstruction and analysis algorithms (often with ML)
- revision of running scenarios in e^+e^- colliders

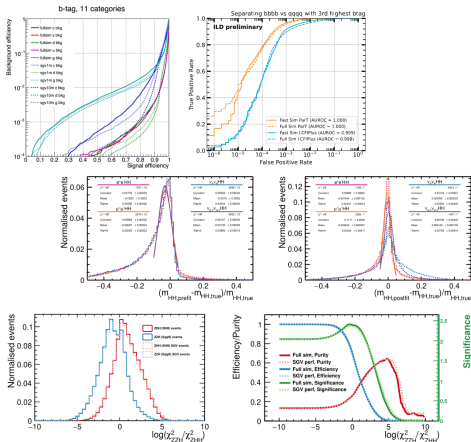
Event Reconstruction Highlights for Extrapolations



Key observations:

- b-tagging: (10% efficiency increase)³ for 4b
- kinematic reconstruction: 10% higher event selection efficiency
- $S/\sqrt{S+B}$: scale S and keep B

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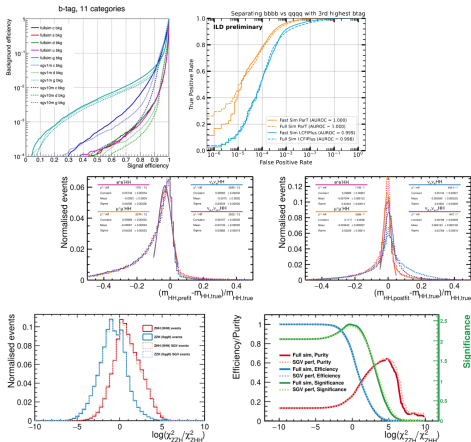
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Discovery reach with better reconstruction tools:

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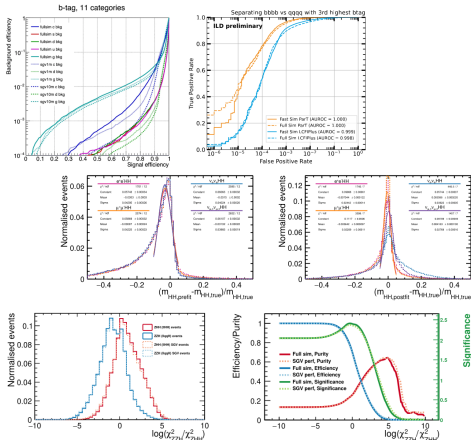
$$\Delta\lambda_{SM}/\lambda_{SM} \rightarrow 18\%$$

and with 10% more $\sqrt{s}$:

ILC/C³@ 550 GeV:

$$\Delta\lambda_{SM}/\lambda_{SM} \rightarrow 15\%$$

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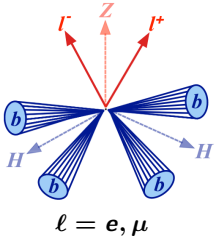
ILC/C³@ 550 GeV:

$$\Delta\lambda_{SM}/\lambda_{SM} \rightarrow 15\%$$

and with ambitious $\mathcal{L}$ and $|P(e^+)|$:

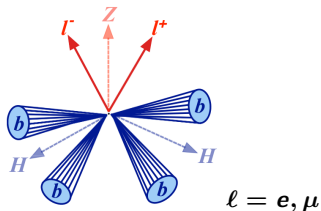
LCF@ 550 GeV:

$$\Delta\lambda_{SM}/\lambda_{SM} \rightarrow 11\%$$



Lepton channels

Event selection in lepton channels: $eeHH$ & $\mu\mu HH$

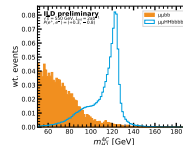
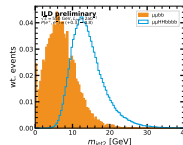
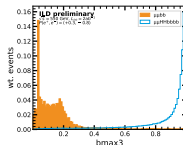


Preselection:

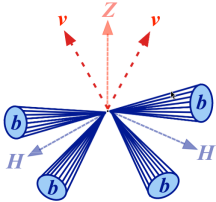
Cut-based, modified from 2014 analysis

Event selection:

- Multiclass BDT (XGBoost)
- 2 signal classes: $HH \rightarrow 4b$ + non- $4b$
- 4 background classes
- Optimised with scan over hyper parameters
- Applied to **full SM 4f+6f** bkgs

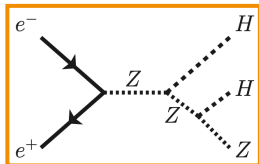
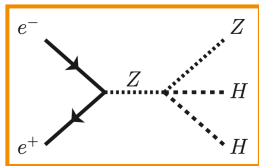
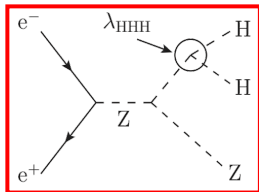


$S/\sqrt{S+B}$	2014	Extrapol.	2025	2026
$eeHH$ ($HH \rightarrow 4b$)	0.84	1.2	1.28	??
$eeHH$ (incl.)	1.14	1.5		??
$\mu\mu HH$ ($HH \rightarrow 4b$)	0.82	1.1	1.39	1.47
$\mu\mu HH$ (incl.)	1.36	1.7		1.92



Neutrino channels

Interlude: Higgs self-coupling extraction



Single-parameter extraction via sensitivity factor (k) translation

$$\frac{\Delta\lambda}{\lambda} = \textcircled{k} \cdot \frac{\Delta\sigma}{\sigma}$$

λ -dependency:

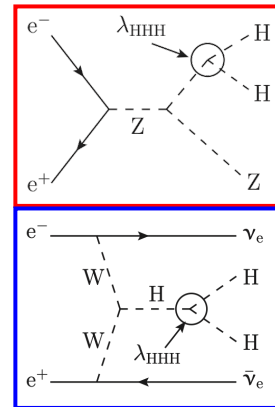
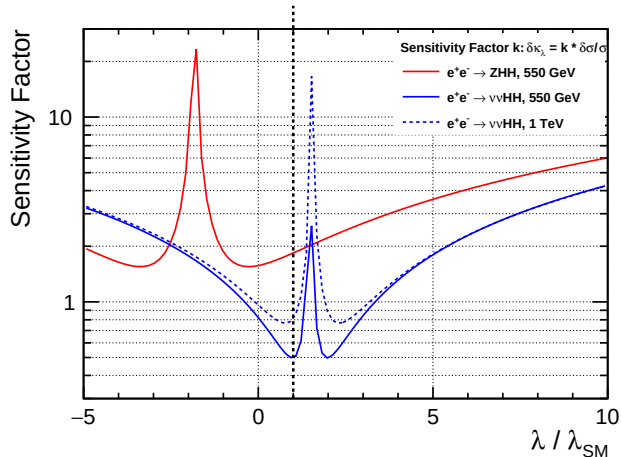
$$\sigma = S\lambda^2 + I\lambda + B$$

Error propagation:

$$\Delta\sigma = 2S\lambda\Delta\lambda + I\Delta\lambda$$

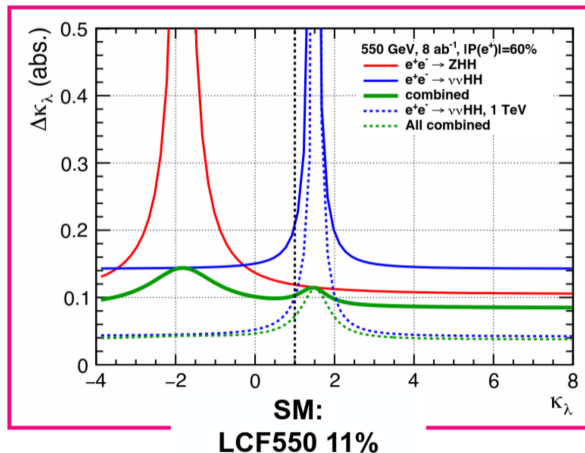
$$\Rightarrow \frac{\Delta\lambda}{\lambda} = \textcircled{\frac{\sigma}{2S\lambda^2 + I\lambda}} \cdot \frac{\Delta\sigma}{\sigma}$$

Sensitivity factors beyond the SM



- Effects of different interference patterns versus $\kappa_\lambda = \lambda_3/\lambda^{SM_3}$
- Sensitivity factor (k) varies strongly with $\lambda_3 \otimes$ “non- λ_3 ” diagrams

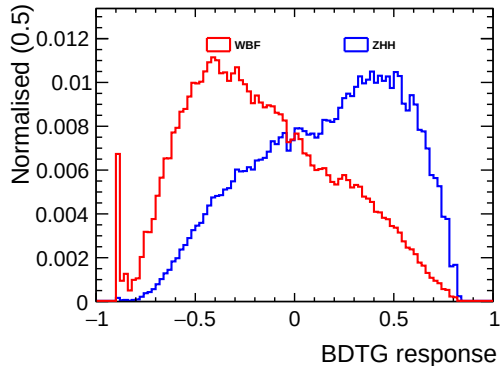
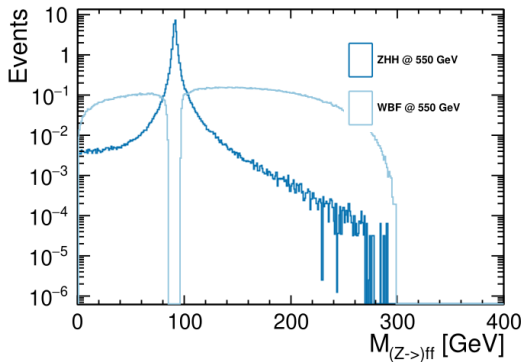
Precision on Higgs self-coupling beyond the SM



- Dependence on λ_3 of cross sections (precision) and of sensitivity factors
- 🔑 key to cover range of λ_3 with projected precision at $\sim 10 - 15\%$ level at LCF550
- Further improvements with run at 1 TeV ($\sim 5 - 10\%$)

WBF/ZHH separation - Proof-of-principle

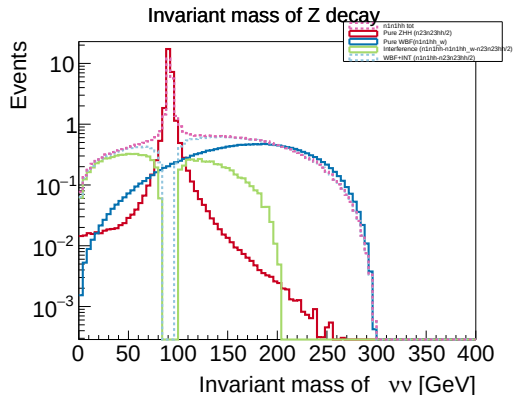
- WBF/ZHH separation $\rightarrow$ enhance λ_3 sensitivity due to very different interference patterns



- separation on generator level to a good approx. with $m_{\nu\nu}$ cut

- Proof-of-principle of separation on reco level with a BDT using p_T , M , E_{vis} , M_{vis} , thrust

Analysis strategy: Neutrino channel



- Pure ZHH in $\nu_{\mu,\tau}\nu_{\mu,\tau}HH$ events
- Pure WBF in dedicated event generation
- estimate interference effects

Preselection: (Modified from 2014 analysis)

- $\#\ell_{\text{ISO}} = 0$
- $\sum \text{b-tags} > 1.8$
- $60\text{GeV} < M_{H1}^{4C} < 180\text{GeV}$
- $40\text{GeV} < M_{H2}^{4C} < 250\text{GeV}$
- $\text{thrust} < 0.93$
- $E_{\text{vis}} < 530\text{GeV}$
- $M_{\text{vis}} < 200\text{GeV}$

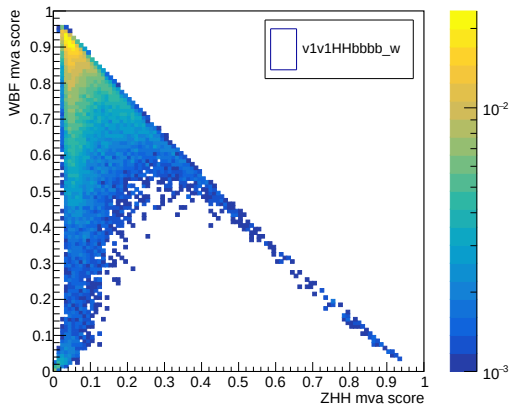
Event selection:

- Multiclass MVA using XGBoost
- Signal classes:
 - Pure WBF events
 - Pure ZHH events
- Background classes:
 - $\nu\nu qqH$
 - $\nu\nu bb$
 - $bbbb$
 - $\nu\nu bbbb$
 - $\ell\nu bbqq$
 - $bbqqqq$

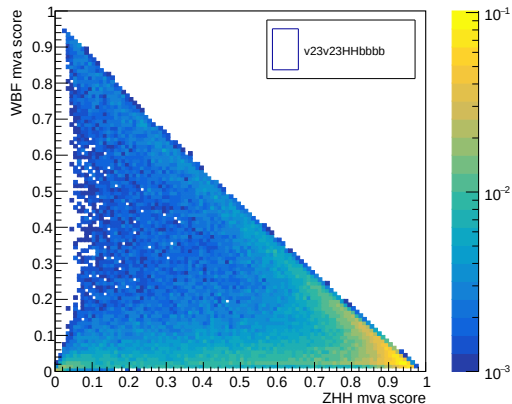
ZHH versus WBF classification

Testing training

Pure WBF events:

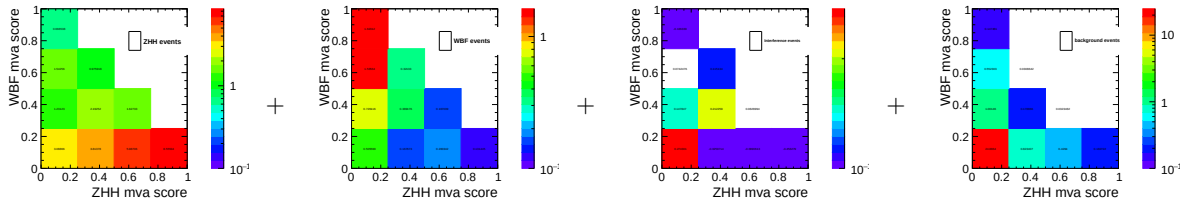


Pure ZHH events:



- MVA responds well to the two types of events that it was trained on

Template fit with toy models



Template:

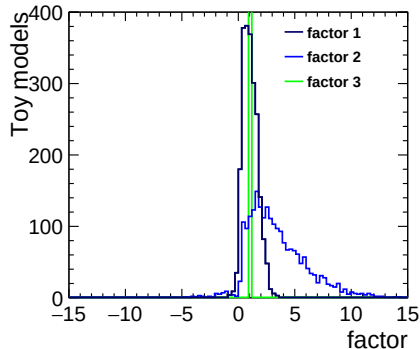
$$\text{hist}_{\text{template}} = f_1 \cdot \text{hist}_{\text{ZHH}} + f_2 \cdot \text{hist}_{\text{WBF}} + \sqrt{f_1 \cdot f_2} \cdot \text{hist}_{\text{int}} + \text{hist}_{\text{bkg}}$$

Fit model: 2D log-likelihood with 10K toy models

$$LLH = \sum_i \sum_j \text{Log}(\text{Poisson}(\text{data}_{i,j}, \text{temp}_{i,j}))$$

Template fit with toy models (continued)

Preliminary:



Results (mean and rms):

$$f_1 \simeq 1.1 \pm 0.6, \quad f_2 \simeq 3.4 \pm 2.5$$

$$(f_3 \simeq 0.9999 \pm 0.0019)$$

- assuming $P(e^-, e^+) = (-0.8, 0.3)$ and 2 ab⁻¹

with 6x6 bins:

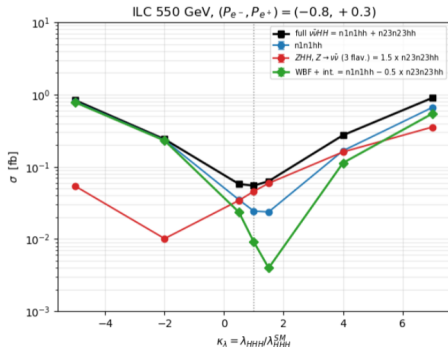
For comparison, extrapolations assumed

- $\delta\sigma/\sigma \sim 50\%$ for ZHH events $(-0.8, 0.3)$ as well as for $(0.8, -0.3)$, with 2 ab⁻¹ each
- $\delta\sigma/\sigma \sim 120\%$ for WBF events $(-0.8, 0.3)$ with 2 ab⁻¹

Event Generation with $\kappa_\lambda \neq 1$

Cross section vs κ_λ

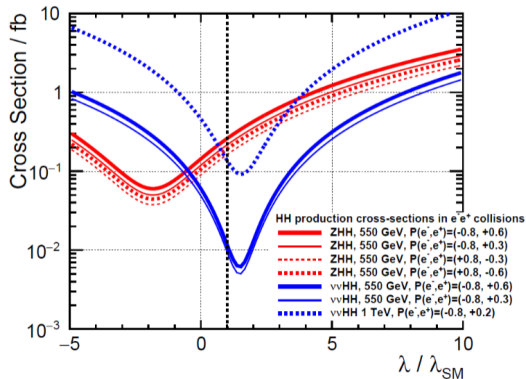
$e^+e^- \rightarrow \nu\bar{\nu}HH$ cross section vs. κ_λ at $\sqrt{s} = 550$ GeV



- Event generation for $\kappa_\lambda \in \{-5, -2, 0.5, 1.0, 1.5, 4, 7\}$
- Next steps:
 - Test if template fit factors varies as expected with cross sections
 - Test if template fit can extract value of λ directly

Reference*

*Without interference



From [2509.14148v1]

Conclusion

- Extrapolations to estimate projections for ESPPU:
- **ILC550 @ $\mathcal{L} = 4 \text{ ab}^{-1}$: $\Delta\lambda_{SM}/\lambda_{SM} \rightarrow 15\%$**
- **LCF550 @ $\mathcal{L} = 8 \text{ ab}^{-1}$: $\Delta\lambda_{SM}/\lambda_{SM} \rightarrow 11\%$**
- with LCF550 projections at $\sim 10\text{-}15\%$ level across range of λ_3

- ✓ Lepton channel analysis confirms and exceeds extrapolations made for EPPSU
 - ! with further improvements from a multiclass MVA and fine-tuning hyper parameters
- ✓ Separation of ZHH and WBF events in neutrino channel
 - ! for the first time below 1 TeV
 - 🔧 extraction of λ underway
- 🔧 Re-analysis of hadron channels also underway
- With Bryan's hep-workflow (luigi+law) for faster event generation, simulation and reconstruction

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See also:

- [ZHH ILD note](#)
- [LC Vision document](#)
- [Physics Briefing Book](#)

Thank you.