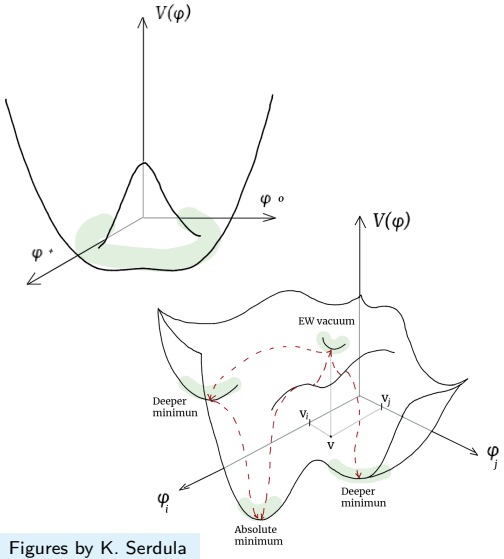
WW-fusion in a ZHH analysis.

Mikael Berggren (DESY), Bryan Bliewert (DESY/UHH), Jenny List (DESY), Dimitris Ntounis (SLAC), Taikan Suehara (U Tokyo), Junping Tian (U Tokyo), Julie Munch Torndal (DESY/UHH), Caterina Vernieri (SLAC)

LCWS2026

November 10, 2026

Higgs potential and Higgs self-coupling



Figures by K. Serdula

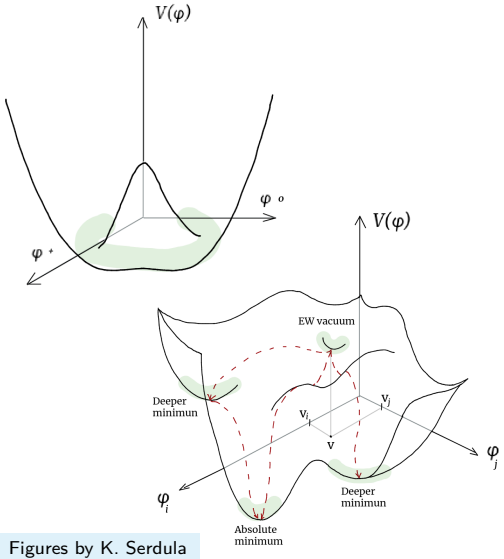
$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_{HHH} \nu h^3 + \frac{1}{4} \lambda_{HHHH} h^4$$

where in SM $\lambda_{HHH} = \lambda_{HHHH} = m_H^2 / 2\nu^2$ Measure $\boldsymbol{\lambda}$

- → **Higgs potential**
- → **Higgs mechanism**

- → new physics in Higgs sector?

Higgs potential and Higgs self-coupling



Figures by K. Serdula

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

where in SM $\lambda_{HHH} = \lambda_{HHHH} = m_H^2/2\nu^2$ Measure $\boldsymbol{\lambda}$

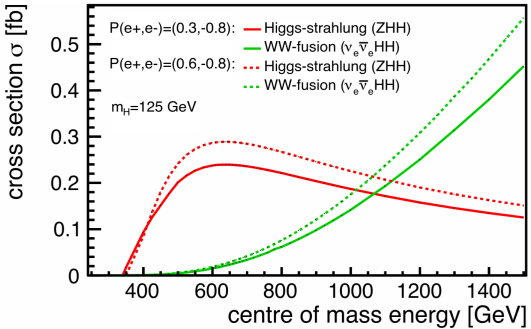
- → **Higgs potential**
- → **Higgs mechanism**

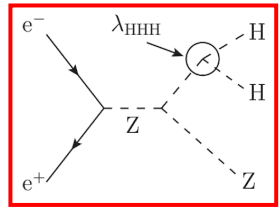
- → new physics in Higgs sector?

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

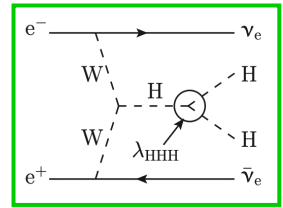
$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = k \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHx}}$$

Access to the Higgs self-coupling





Di-Higgs strahlung:
dominant below 1 TeV



WW fusion:
dominant above 1 TeV

"History" of the ZHH analysis

More on the ZHH analysis in Bryan's talk

2014 ZHH analysis DESY-THESIS-2016-027

- **@ 500 GeV, only ZHH**
- $\Delta\lambda_{SM}/\lambda_{SM} = 26.6\%$

→ 8σ observation of $e^+e^- \to ZHH$

→ 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

➔ **@ 550 GeV, ZHH + WBF**

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

"History" of the ZHH analysis

More on the ZHH analysis in Bryan's talk

2014 ZHH analysis DESY-THESIS-2016-027

- **@ 500 GeV, only ZHH**
- $\Delta\lambda_{SM}/\lambda_{SM} = 26.6\%$

→ 8σ observation of $e^+e^- \to ZHH$

→ 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

➔ **@ 550 GeV, ZHH + WBF**

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

2026 EPPSU extrapolations

- Discovery reach with better reconstruction tools

  ILC@ 500 GeV: $\Delta\lambda_{SM}/\lambda_{SM} \to 18\%$

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

  ILC/C^3@ 550 GeV: $\Delta\lambda_{SM}/\lambda_{SM} \to 15\%$

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

  LCF@ 550 GeV: $\Delta\lambda_{SM}/\lambda_{SM} \to 11\%$

"History" of the ZHH analysis

More on the ZHH analysis in Bryan's talk

2014 ZHH analysis DESY-THESIS-2016-027

- **@ 500 GeV, only ZHH**
- $\Delta\lambda_{SM}/\lambda_{SM} = 26.6\%$

→ 8σ observation of $e^+e^- \to ZHH$

→ 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

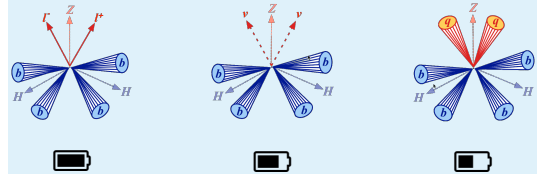
➔ **@ 550 GeV, ZHH + WBF**

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

2026 EPPSU extrapolations

- Discovery reach with better reconstruction tools
  ILC@ 500 GeV: $\Delta\lambda_{SM}/\lambda_{SM} \to 18\%$
- and with 10% more $\sqrt{s}$
  ILC/C^3@ 550 GeV: $\Delta\lambda_{SM}/\lambda_{SM} \to 15\%$
- and with ambitious $\mathcal{L}$ and |P(e^+)|
  LCF@ 550 GeV: $\Delta\lambda_{SM}/\lambda_{SM} \to 11\%$

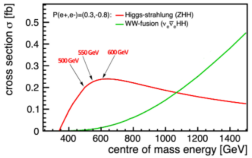
Next: confirm extrapolations in analysis



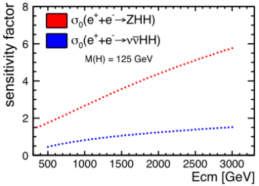
Studies on Centre-of-Mass Energy

MC production in 2022 of ZHH and ZZH samples at **500 GeV**, **550 GeV**, and **600 GeV**

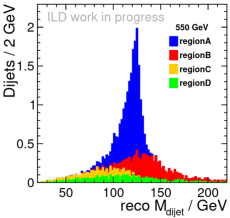
$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = k \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHx}}$$



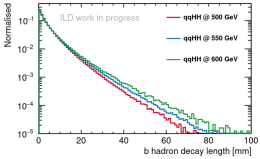
- better precision on cross section $\Delta\sigma_{HHx}/\sigma_{HHx}$



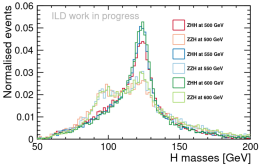
- but less sensitivity with growing k



- less misclustering with increasing E_{CM}



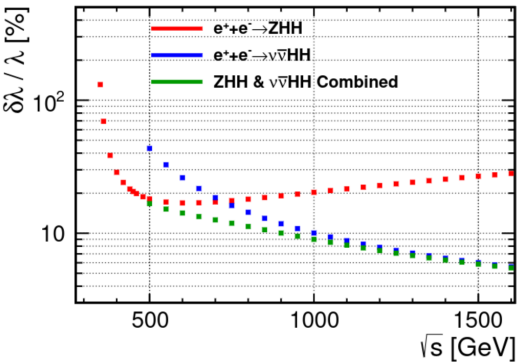
- increased b-hadron decay lengths for better flavor tagging



- better jet pairing for di-jet mass reconstruction

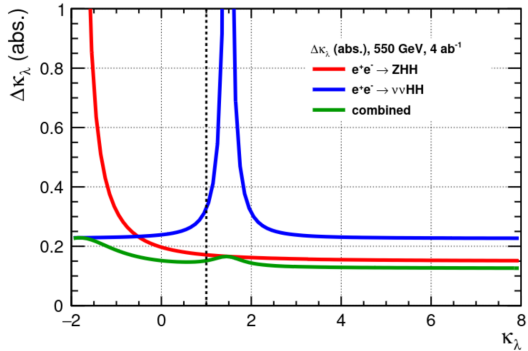
Choice of Centre-of-Mass Energy

Precision as a function of energy

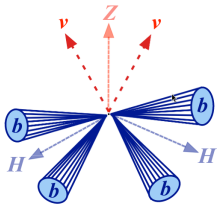


- The precision on λ grows with energy aided by the WW fusion but for ZHH 550-650 GeV is optimal

Precision as a function of lambda

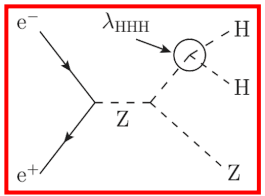


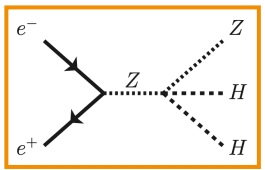
- ZHH crucial if the value of λ realised in nature is slightly above 1

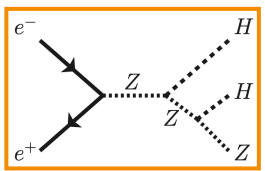


Neutrino channels

Interlude: Higgs self-coupling extraction







Single-parameter extraction via sensitivity factor (k) translation

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

λ-dependency:

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

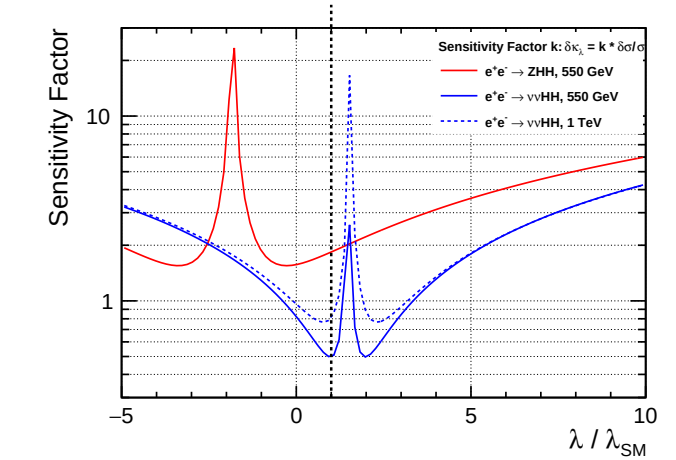
Error propagation:

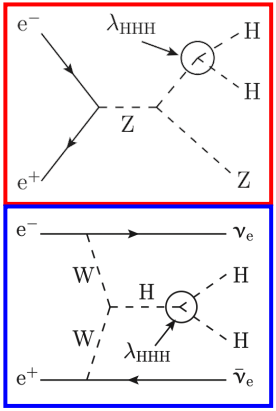
$$\Delta\sigma = 2S\lambda\Delta\lambda + I\Delta\lambda HHH$$

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

DESY.

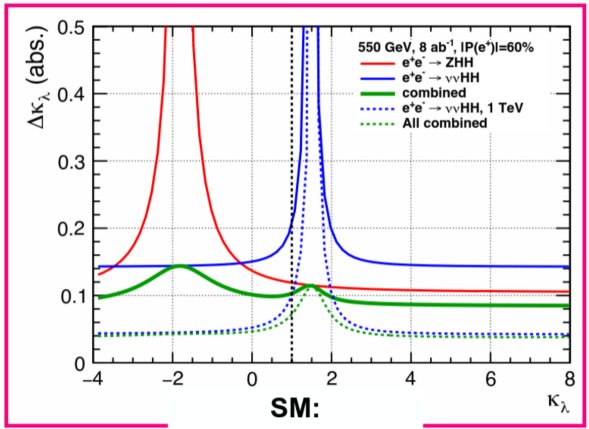
Sensitivity factors beyond the SM





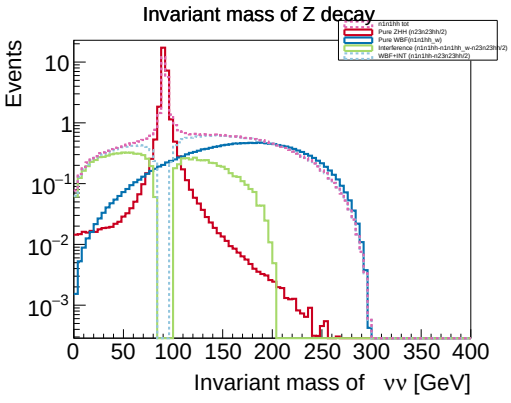
- Effects of different interference patterns versus $\kappa_\lambda = \lambda_3/\lambda^{SM_3}$
- Sensitivity factor (k) varies strongly with $\lambda_3 \otimes$ "non-λ_3" diagrams

Precision on Higgs self-coupling beyond the SM



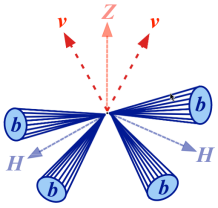
- Dependence on λ_3 of cross sections (precision) and of sensitivity factors
- key to cover range of λ_3 with projected precision at $\sim 10-15\%$ level at LCF550
- Further improvements with run at 1 TeV ($\sim 5-10\%$)

Analysis strategy of $\nu\nu HH$



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

→ estimate interference effects



Preselection:
Cut-based, modified from 2014 analysis

Event selection:

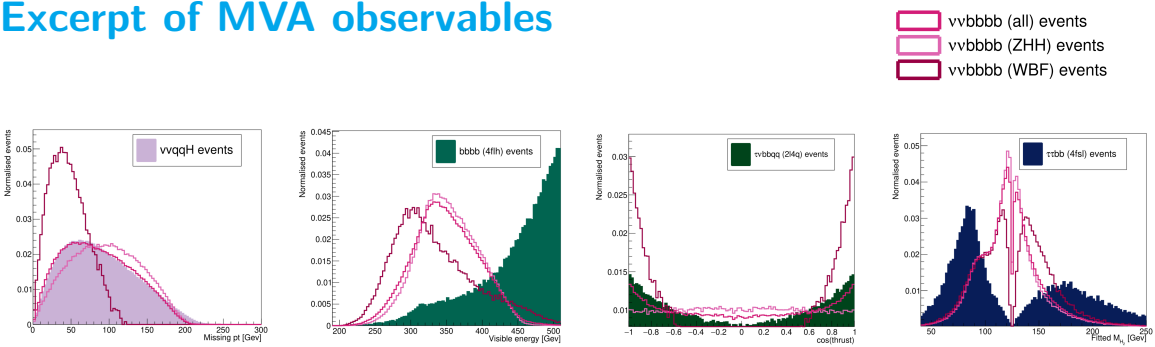
- Multiclass BDT (XGBoost)
- 2 signal classes: Pure ZHH + pure WBF ($HH \to 4b$)
- 6 background classes
- Optimised with scan over hyper parameters
- Applied to **full SM 4f+6f+ttH+ttZ** bkgs

Preselection of $\nu\nu HH$

	expected	$Isolatedleptons = 0$	$\Sigma_{bTags} \geq 1.8$	$60.0 \leq m^{4C}_{H1}/GeV \leq 180.0$	$40.0 \leq m^{4C}_{H2}/GeV \leq 250.0$	$thrust \leq 0.93$	$E_{vis}/GeV \leq 510$	$M_{vis}/GeV \geq 200$
evbbqq	$2.27 \cdot 10^5$	$7.94 \cdot 10^3$	$5.60 \cdot 10^3$	$5.42 \cdot 10^3$	$5.29 \cdot 10^3$	$5.27 \cdot 10^3$	$5.14 \cdot 10^3$	$5.12 \cdot 10^3$
μvbbqq	$2.25 \cdot 10^5$	$9.94 \cdot 10^3$	$7.06 \cdot 10^3$	$6.86 \cdot 10^3$	$6.74 \cdot 10^3$	$6.72 \cdot 10^3$	$6.60 \cdot 10^3$	$6.55 \cdot 10^3$
τvbbqq	$2.26 \cdot 10^5$	$2.02 \cdot 10^5$	$1.31 \cdot 10^5$	$1.26 \cdot 10^5$	$1.22 \cdot 10^5$	$1.22 \cdot 10^5$	$1.21 \cdot 10^5$	$1.21 \cdot 10^5$
ννbbbb	132	131	130	128	126	126	126	109
bbqqqq	$6.52 \cdot 10^5$	$6.42 \cdot 10^5$	$3.73 \cdot 10^5$	$1.99 \cdot 10^5$	$1.66 \cdot 10^5$	$1.66 \cdot 10^5$	$6.74 \cdot 10^4$	$6.74 \cdot 10^4$
ννbb	$3.35 \cdot 10^5$	$3.32 \cdot 10^5$	$2.60 \cdot 10^5$	$1.10 \cdot 10^5$	$3.45 \cdot 10^4$	$3.12 \cdot 10^4$	$3.12 \cdot 10^4$	$4.40 \cdot 10^3$
ττbb	$2.79 \cdot 10^4$	$2.26 \cdot 10^4$	$1.71 \cdot 10^4$	$1.55 \cdot 10^4$	$1.32 \cdot 10^4$	$6.62 \cdot 10^3$	$6.47 \cdot 10^3$	$5.83 \cdot 10^3$
bbbb	$2.44 \cdot 10^4$	$2.37 \cdot 10^4$	$2.33 \cdot 10^4$	$2.18 \cdot 10^4$	$2.00 \cdot 10^4$	$1.45 \cdot 10^4$	$8.63 \cdot 10^3$	$8.49 \cdot 10^3$
bbqq	$2.94 \cdot 10^5$	$2.87 \cdot 10^5$	$1.81 \cdot 10^5$	$1.71 \cdot 10^5$	$1.52 \cdot 10^5$	$8.42 \cdot 10^4$	$4.46 \cdot 10^4$	$4.37 \cdot 10^4$
ttH	$2.64 \cdot 10^3$	$1.45 \cdot 10^3$	$1.10 \cdot 10^3$	297	260	260	217	217
ttZ	$6.75 \cdot 10^3$	$3.81 \cdot 10^3$	$2.20 \cdot 10^3$	988	916	916	813	805
ννqqH	837	750	422	416	407	406	405	381
Total background	$6.36 \cdot 10^7$	$4.30 \cdot 10^7$	$1.14 \cdot 10^6$	$7.14 \cdot 10^5$	$5.54 \cdot 10^5$	$4.50 \cdot 10^5$	$3.01 \cdot 10^5$	$2.69 \cdot 10^5$
ννHH	72.5	52.2	30.8	30.2	29.7	29.6	29.6	27.9
(v23v23bbbb)	20.6	20.3	20.1	20.0	19.9	19.9	19.9	19.8
(v1v1bbbb)	16.5	16.4	16.2	16.1	16.0	16.0	15.9	15.9
Total signal	110	88.9	67.1	66.3	65.6	65.4	65.4	63.7

- Preselection modified from 2014 analysis
- Optimised for signal efficiency → more signal for training in MVA
- With equal signal efficiency between $\nu_e\nu_e HH$ and $\nu_{\mu,\tau}\nu_{\mu,\tau} HH$
- Backgrounds in MVA: $\nu\nu qqH$, $\nu\nu bbbb$, $\nu\nu bb$, $\ell\nu bbqq$, $bbbb$, $bbqqqq$

Excerpt of MVA observables

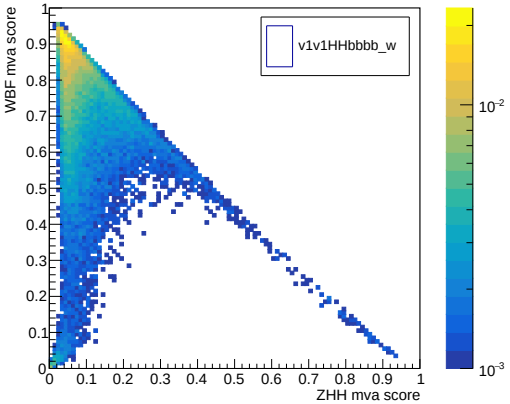


- Similarities and differences between ZHH and WBF events against a few select backgrounds

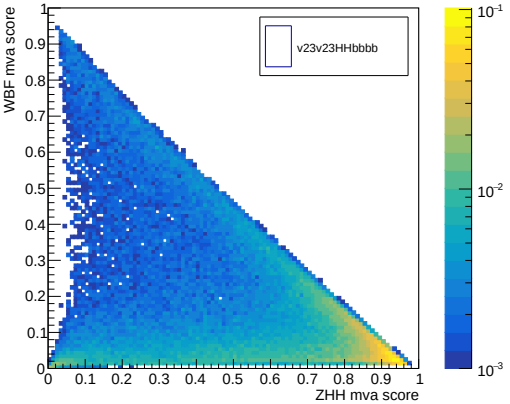
ZHH versus WBF classification

Testing training

Pure WBF events:

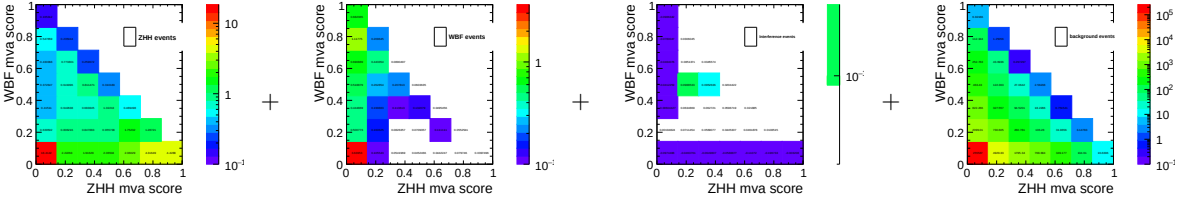


Pure ZHH events:



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

Template fit with toy models



Template:

$$\text{hist}_{template} = f_1 \cdot \text{hist}_{ZHH} + f_2 \cdot \text{hist}_{WBF} + \sqrt{f_1 \cdot f_2} \cdot \text{hist}_{int} + f_3 \cdot \text{hist}_{bkg}$$

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

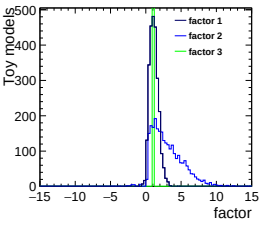
$$LLH = \sum_i \sum_j Log(Poisson(data_{i,j}, temp_{i,j}))$$

Promising results with comparable precision to extrapolations

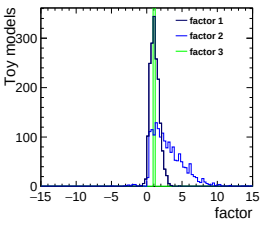
Preliminary results

$$\text{hist}_{template} = f_1 \cdot \text{hist}_{ZHH} + f_2 \cdot \text{hist}_{WBF} + \sqrt{f_1 \cdot f_2} \cdot \text{hist}_{int} + f_3 \cdot \text{hist}_{bkg}$$

incl. interference term: $\sqrt{f_1 \cdot f_2} \cdot \text{hist}_{int}$

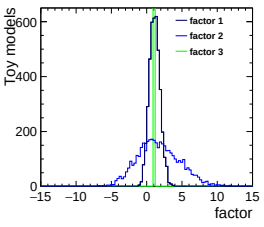


f_1, f_2, f_3 fitted

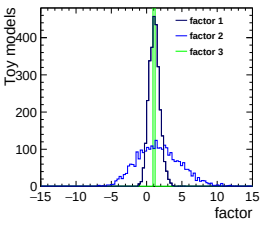


f_1, f_2 fitted, f_3 fixed

ignore interference term: ~~$\sqrt{f_1 \cdot f_2} \cdot \text{hist}_{int}$~~



f_1, f_2, f_3 fitted



f_1, f_2 fitted, f_3 fixed

- fit best when fitting background and including interference term, fixing the WBF to positive values
- In progress: closure test with $\kappa_\lambda \neq 0$ ($\kappa_\lambda \in \{-5, -2, 0.5, 1.0, 1.5, 4, 7\}$)

Conclusions

- Centre-of-mass energy targeting ZHH revised to 550 GeV

→ Small contribution from WBF events accesible in ZHH analysis

- Complementarity of ZHH and WBF in BSM scenarios

→ LCF550 projections at $\sim$10-15% level across range of λ_3

☑ Separation of ZHH and WBF events in neutrino channel achieved
- ❗ for the first time below 1 TeV
- 🔧 extraction of λ underway

Conclusions

- Centre-of-mass energy targeting ZHH revised to 550 GeV

➔ Small contribution from WBF events accesible in ZHH analysis

- Complementarity of ZHH and WBF in BSM scenarios

➔ LCF550 projections at ∼10-15% level across range of λ_3

☑ Separation of ZHH and WBF events in neutrino channel achieved
- ❗ for the first time below 1 TeV
- 🔧 extraction of λ underway

See also:

- Bryan's talk
- ZHH ILD note
- LC Vision document
- Physics Briefing Book

Thank you.