

Stefan Liebler

**SM Higgs physics at a LC
(Personal) theory overview**



Belgrade, Serbia - 7 October 2014

University of Hamburg



Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

Particles, Strings,
and the Early Universe

Collaborative Research Center SFB 676

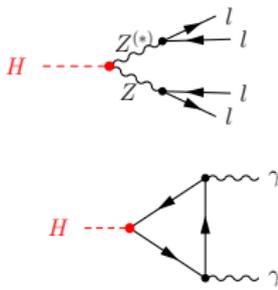
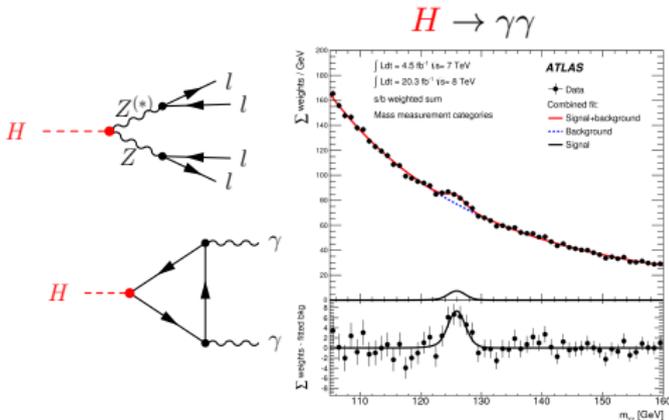
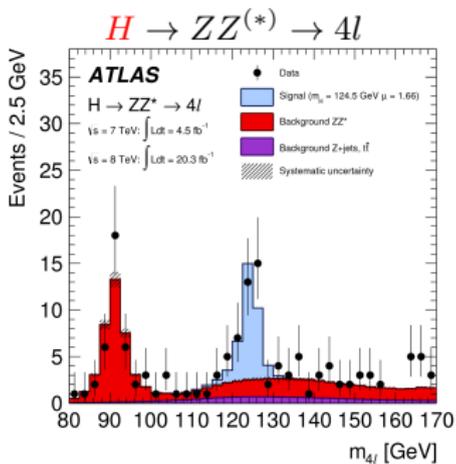


HELMHOLTZ
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Outline

- 1 Introduction
- 2 LC Higgs production and decay at NLO
- 3 Non-resonant Higgs processes
- 4 Event generators at NLO
- 5 Conclusions

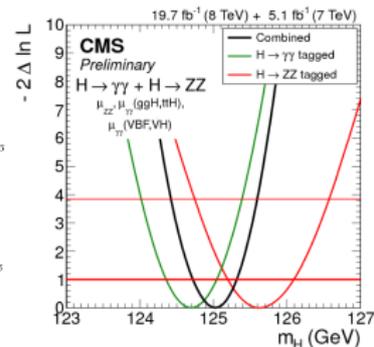
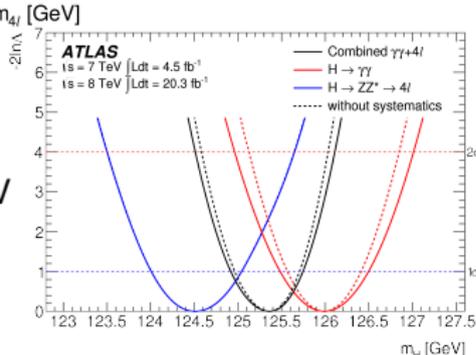
Great success: Run 1 of the LHC - A scalar resonance visible in


 with mass m_H
 $125.4 \pm 0.4 \pm 0.2 \text{ GeV}$

[ATLAS 1406.3827]

 $125.0 \pm 0.3 \pm 0.15 \text{ GeV}$

[CMS-PAS-HIG-14-009]

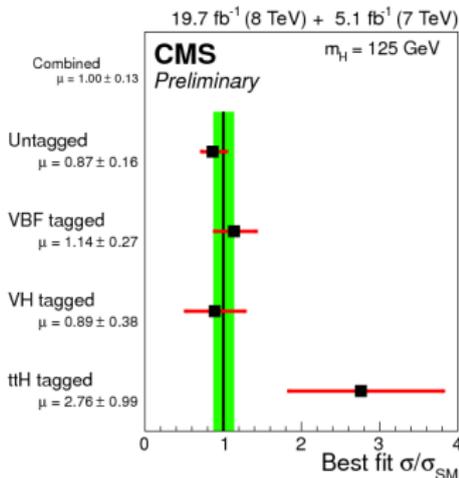


So far compatible with the SM Higgs boson:
 Higgs doublet forming one physical CP-even Higgs boson H
 with one free parameter m_H and couplings (VEV v):

$$g_{Hf\bar{f}} = m_f/v \quad g_{HVV} = 2m_V^2/v$$

$$g_{HHVV} = 2m_V^2/v^2$$

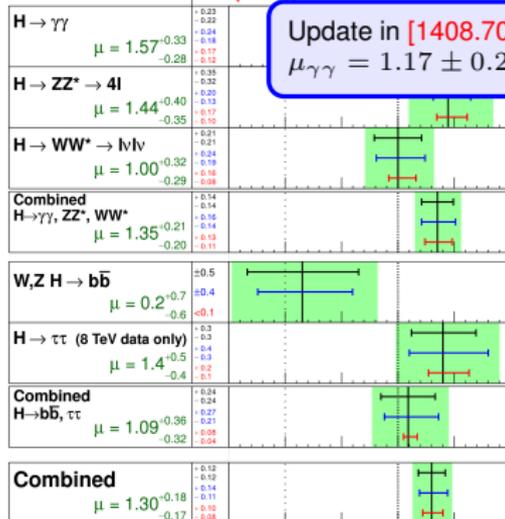
$$g_{3H} = 3m_H^2/v \quad g_{4H} = 3m_H^2/v^2$$



[CMS-PAS-HIG-14-009]

ATLAS Prelim.

$m_H = 125.5$ GeV



[ATLAS-CONF-2014-009]

$\sqrt{s} = 7$ TeV | Ldt = 4.6-4.8 fb⁻¹
 $\sqrt{s} = 8$ TeV | Ldt = 20.3 fb⁻¹

Signal strength (μ)

Deviations in extended Higgs sectors:

Survey according to Haber's decoupling theorem with $M = 1$ TeV:

Model	Δg_{HVV}	$\Delta g_{Hb\bar{b}}$	$\Delta g_{H\gamma\gamma}$
Singlet Mixing	$\approx 6\%$	$\approx 6\%$	$\approx 6\%$
2HDM	$\approx 1\%$	$\approx 10\%$	$\approx 1\%$
Decoupled MSSM	$\approx -0.0013\%$	$\approx 1.6\%$	$< 1.5\%$
Composite	$\approx -3\%$	$\approx -(3 - 9)\%$	$\approx -9\%$
Top Partner	$\approx -2\%$	$\approx -2\%$	$\approx 1\%$

[ILC TDR, Michael Peskin]

(see e.g. plenary talks by Keisuke Fujii and Philipp Roloff)

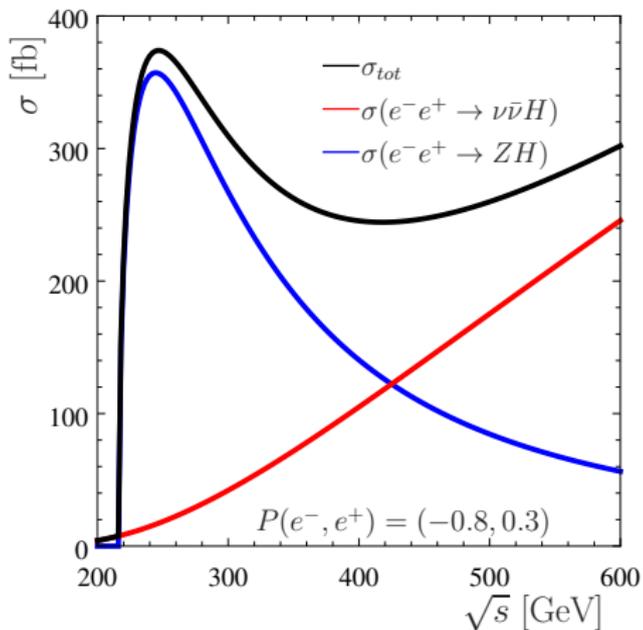
⇒ Need for high precision to discover differences from SM Higgs!

⇒ High order contributions in theoretical calculations required at a LC, although by far smaller than at LHC!

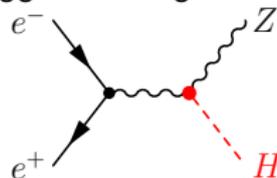
Some predictions are very sensitive to numerical input values:

Variation of m_H by ± 200 MeV \leftrightarrow $\text{BR}(H \rightarrow ZZ^{(*)}/WW^{(*)}) \sim \pm 2.5\%$!

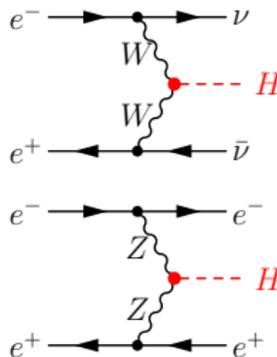
Main production mechanisms of the SM Higgs at a LC:



Higgsstrahlung



Vector boson fusion

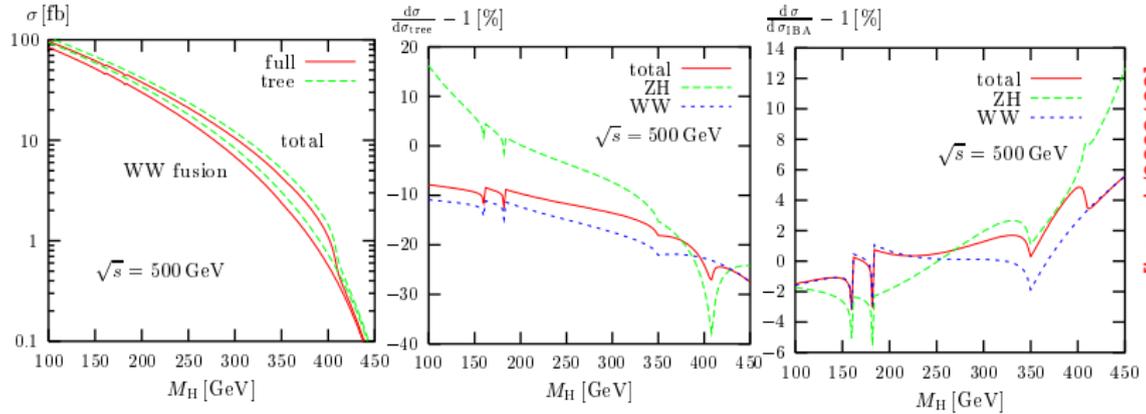


Higher order corrections for Higgs production processes:

▷ $e^+e^- \rightarrow ZH$ (341) [Fleischer Jegerlehner 83; Kniehl 92; Denner et al. 92]

▷ $e^+e^- \rightarrow \nu\bar{\nu}H$ (1350)

[hep-ph/0212261 Belanger et al.; hep-ph/0302198 Denner et al.; hep-ph/0212004 Jegerlehner et al.]



[hep-ph/0302198]

▷ $e^+e^- \rightarrow e^+e^-H$ (4470)

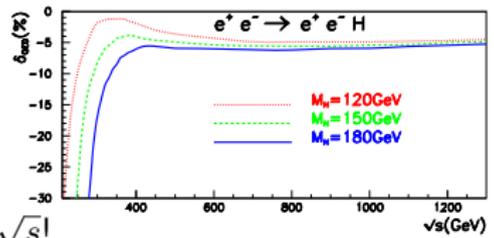
[hep-ph/0407065 Boudjema et al.]

Take away message:

Typical size of EW corrections: (5 – 10)%

↔ ISR includes quite some bit!

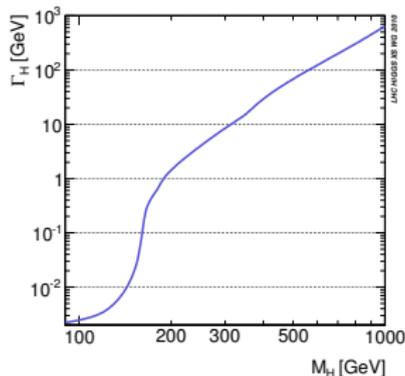
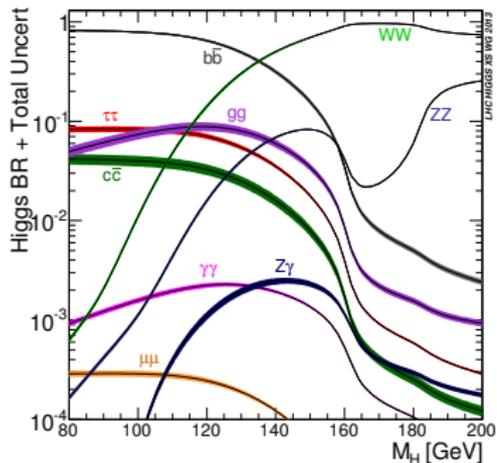
Be careful at thresholds and with increasing \sqrt{s} !



#NLO diagrams with GRACE - by Y. Yasui

Higher order corrections for branching ratios:

→ profit from the LHC Higgs XS Working Group! [\[Handbook 1307.1347\]](#)



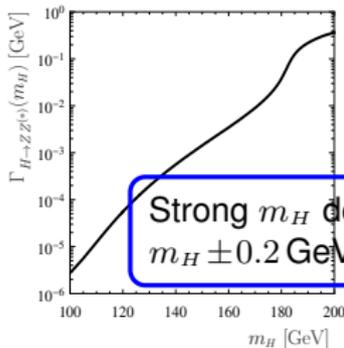
$$H \rightarrow ZZ^{(*)}/WW^{(*)} \rightarrow 4l$$

with PROPHECY4f

[\[Bredenstein Denner Dittmaier Weber\]](#)

- ▷ $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ included
- ▷ complex mass scheme for W/Z
- ▷ distributions

(HDECAY [\[Spira\]](#))



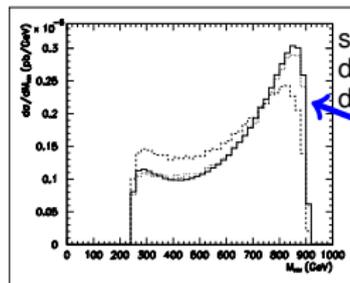
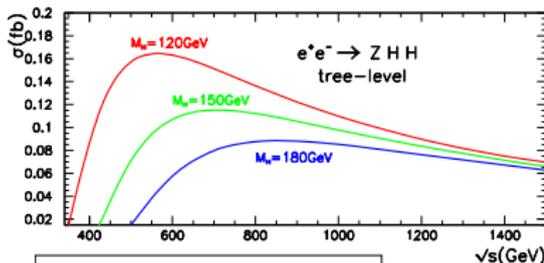
Strong m_H dependence
 $m_H \pm 0.2 \text{ GeV} \leftrightarrow \text{BR} \sim \pm 2.5\%$

Higher order corrections for processes involving Higgs couplings:

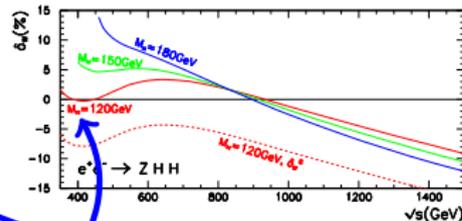
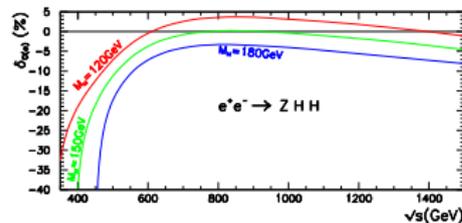
▷ Double Higgsstrahlung [Barger Han 90; hep-ph/9507396 Boudjema Chopin]

$e^+e^- \rightarrow ZHH$ (5417) [hep-ph/0309010 Belanger et al.; hep-ph/0308203 Chen et al.]

$e^+e^- \rightarrow \nu\bar{\nu}HH$ (19638) [Boudjema et al. 05]



solid: tree
dotted: genuine EW
dashed: full $\mathcal{O}(\alpha)$



Inclusion of ISR at tree-level

[hep-ph/0309010]

▷ $e^+e^- \rightarrow WWH$ [0808.3018 Song et al.]

Higher order corrections for processes involving the top Yukawa coupling:

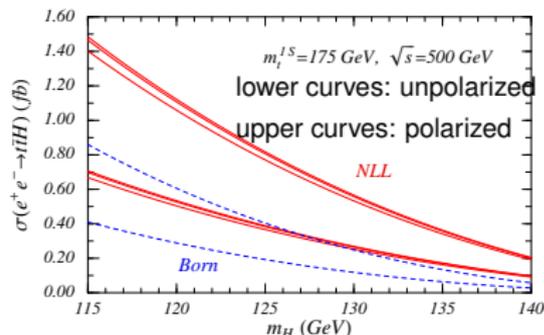
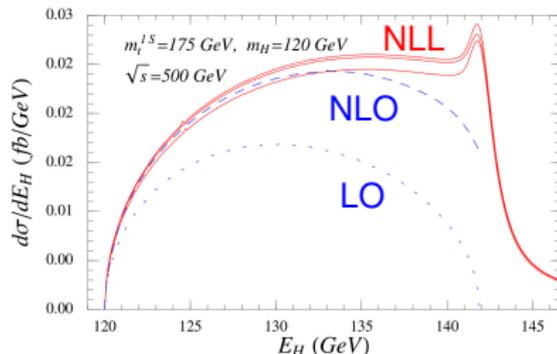
▷ $e^+e^- \rightarrow t\bar{t}H$ (2327)

QCD: [hep-ph/9808443 Dawson Reina; hep-ph/9808433 Dittmaier et al.]

EW: [hep-ph/0307193 Denner et al.; hep-ph/0307029 Belanger et al., hep-ph/0309106 You et al.]

Of particular importance in the threshold region around $\sqrt{s} = 500$ GeV:

NRQCD@NLL: [hep-ph/0504220 hep-ph/0604166 Farrell Hoang]



For $m_H = 120 \text{ GeV}$, $\sqrt{s} = 500 \text{ GeV}$, $m_t = 175 \text{ GeV}$:

$$E_H^{\max} = (s + m_H^2 - 4m_t^2)/(2\sqrt{s}) \sim 141.9 \text{ GeV}$$

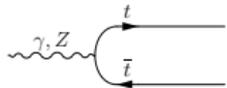
Recycled $e^+e^- \rightarrow t\bar{t}$ result by matching with NLO [hep-ph/0307193 Denner et al.]

Higher order corrections for processes involving the top Yukawa coupling:

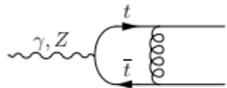
$$\triangleright e^+e^- \rightarrow t\bar{t}$$

Threshold region with non-relativistic $t\bar{t}$: NRQCD with $v \approx \alpha_s < 1$

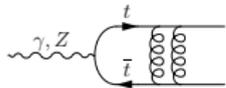
$$\sim 1$$



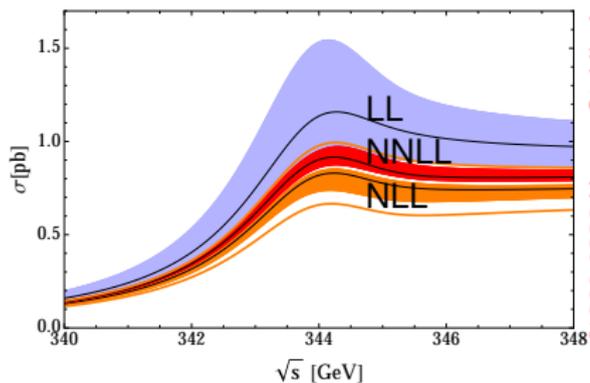
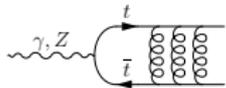
$$\sim \alpha_s/v$$



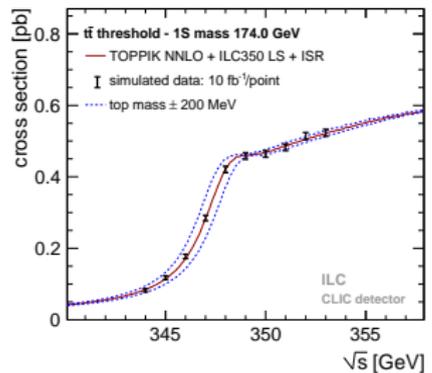
$$\sim (\alpha_s/v)^2$$



$$\sim (\alpha_s/v)^3$$



[1309.6323 Hoang Stahlhofen]

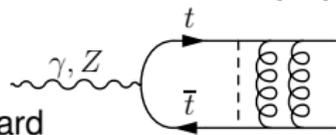


[1303.3758 Seidel et al.]

Sensitivity to the top Yukawa:

$$\Delta g_{Ht\bar{t}} \sim (5 - 10)\% \text{ [1310.0563 Horiguchi et al.]}$$

→ Further theory improvement/to be incl. in Whizard



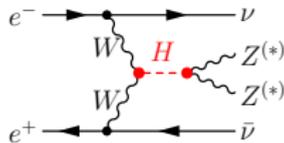
Discussion of off-shell contributions $m_{ZZ} > 2m_Z$ in $H \rightarrow ZZ^{(*)}$

Breit-Wigner improved ZWA

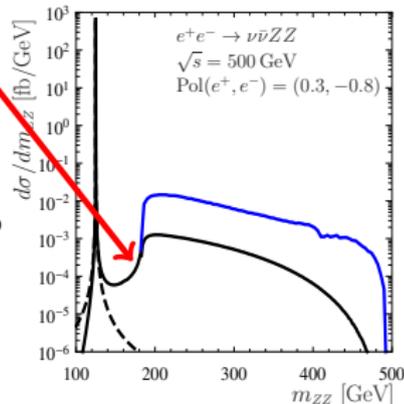
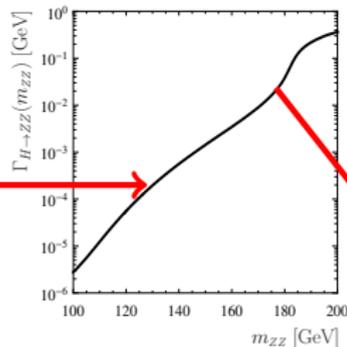
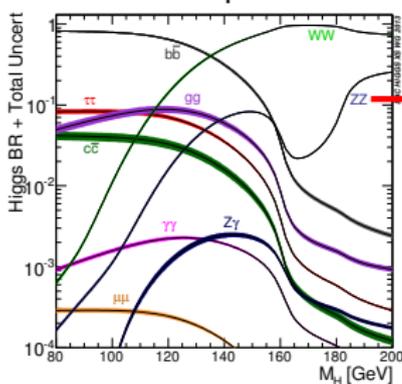
$$\left(\frac{d\sigma_{\text{ZWA}}^{\nu\bar{\nu}ZZ}}{dm_{ZZ}} \right) = \sigma^{\nu\bar{\nu}H}(m_H) \frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2} \frac{m_H\Gamma_{H \rightarrow ZZ^{(*)}}(m_H)}{\pi}$$

$$\left(\frac{d\sigma_{\text{off}}^{\nu\bar{\nu}ZZ}}{dm_{ZZ}} \right) = \sigma^{\nu\bar{\nu}H}(m_{ZZ}) \frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2} \frac{m_{ZZ}\Gamma_{H \rightarrow ZZ^{(*)}}(m_{ZZ})}{\pi}$$

Second equation describes $e^+e^- \rightarrow \nu\bar{\nu}ZZ^{(*)}$ at LO!



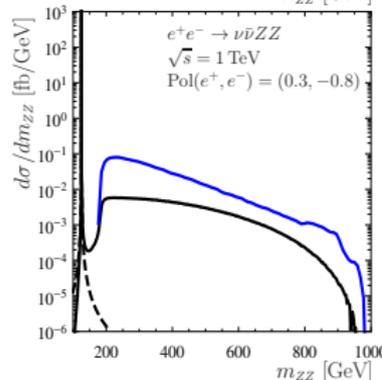
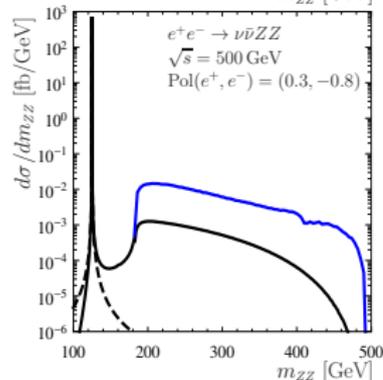
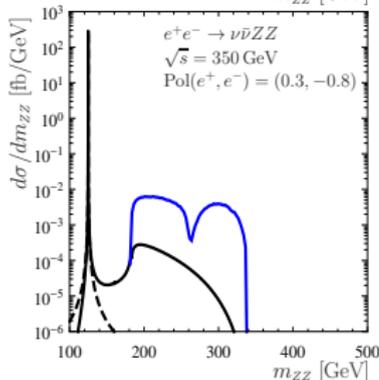
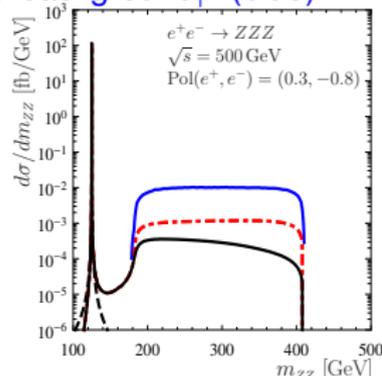
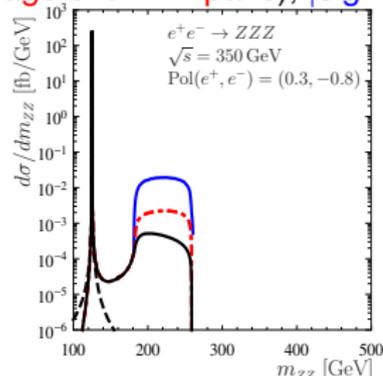
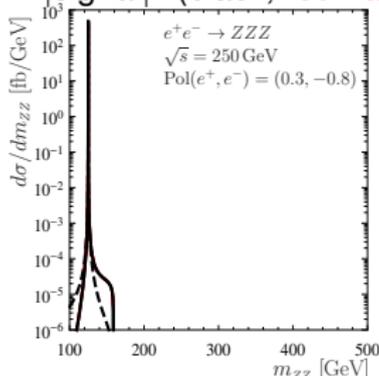
Consequences:



for LHC: [1206.4803 Kauer Passarino]

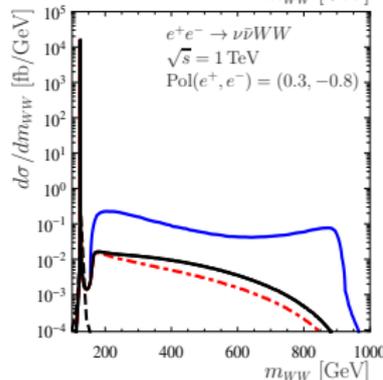
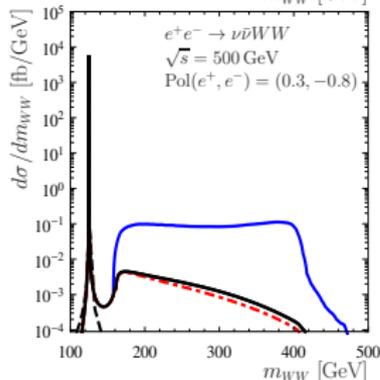
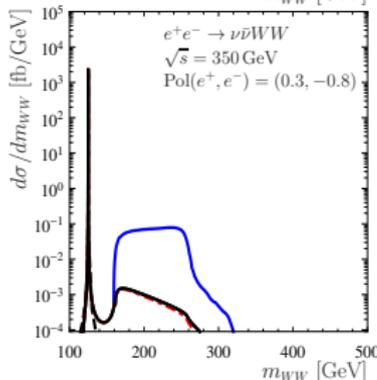
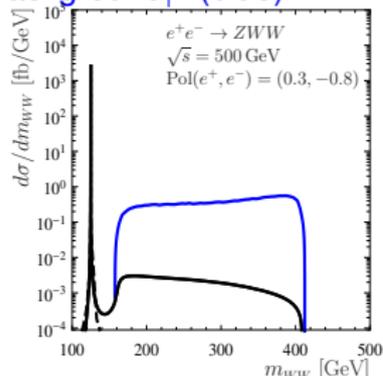
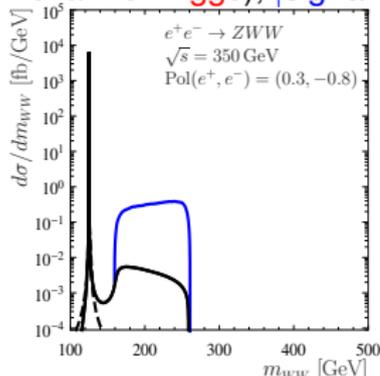
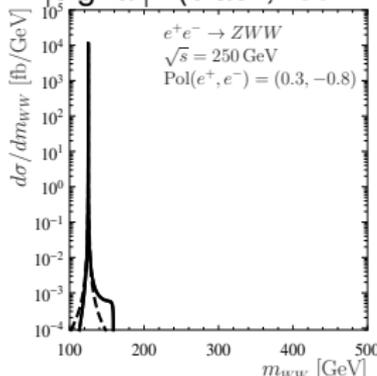
Quantification for $H \rightarrow ZZ^{(*)}$ as function of \sqrt{s} :

$|\text{signal}|^2$ (black, red - average over ZZ pairs), $|\text{signal} + \text{background}|^2$ (blue)



Quantification for $H \rightarrow WW^{(*)}$ as function of \sqrt{s} :

$|\text{signal}|^2$ (black, red - with t -channel Higgs), $|\text{signal} + \text{background}|^2$ (blue)



Relative contribution: $\text{Pol}(e^+, e^-) = (0.3, -0.8)$

With $\sigma_X(m_{VV}^d, m_{VV}^u) = \int_{m_{VV}^d}^{m_{VV}^u} dm_{VV} \left(\frac{d\sigma_X}{dm_{VV}} \right)$ we define

$$\Delta_{\text{off}}^{ZVV} = \frac{\sigma_{\text{off}}^{ZVV}(130\text{GeV}, \sqrt{s} - m_Z)}{\sigma_{\text{off}}^{ZVV}(0, \sqrt{s} - m_Z)} \quad \text{and} \quad \Delta_{\text{off}}^{\nu\bar{\nu}VV} = \frac{\sigma_{\text{off}}^{\nu\bar{\nu}VV}(130\text{GeV}, \sqrt{s})}{\sigma_{\text{off}}^{\nu\bar{\nu}VV}(0, \sqrt{s})}$$

\sqrt{s}	$\sigma_{\text{off}}^{ZZZ}$	$\Delta_{\text{off}}^{ZZZ}$	$\sigma_{\text{off}}^{\nu\bar{\nu}ZZ}$	$\Delta_{\text{off}}^{\nu\bar{\nu}ZZ}$
250 GeV	3.12(3.12) fb	0.03(0.03) %	0.490 fb	0.12 %
350 GeV	1.71(1.82) fb	1.82(7.77) %	1.91 fb	0.88 %
500 GeV	0.802(0.981) fb	7.20(24.1) %	4.78 fb	2.96 %
1 TeV	0.242(0.341) fb	30.9(50.9) %	15.0 fb	13.0 %
\sqrt{s}	$\sigma_{\text{off}}^{ZWW}$	$\Delta_{\text{off}}^{ZWW}$	$\sigma_{\text{off}}^{\nu\bar{\nu}WW}$	$\Delta_{\text{off}}^{\nu\bar{\nu}WW}$
250 GeV	76.3 fb	0.03 %	3.98(3.99) fb	0.13(0.12) %
350 GeV	41.4 fb	0.92 %	15.5(15.5) fb	0.49(0.43) %
500 GeV	18.6 fb	2.61 %	38.1(38.1) fb	1.21(0.96) %
1 TeV	4.58 fb	11.0 %	110.8(108.9) fb	4.45(2.78) %

Comments:

- ▷ Δ_{off} independent of the polarisation.
- ▷ Important: On-shell XS strongly dependent on Higgs mass, off-shell not!
- ▷ Z recoil method at $\sqrt{s} = 250$ GeV not affected (at 350 GeV 0.3% effect)!

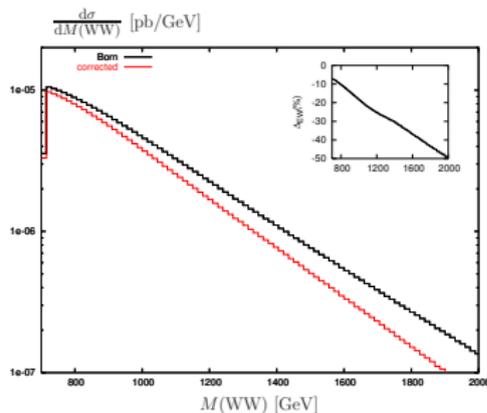
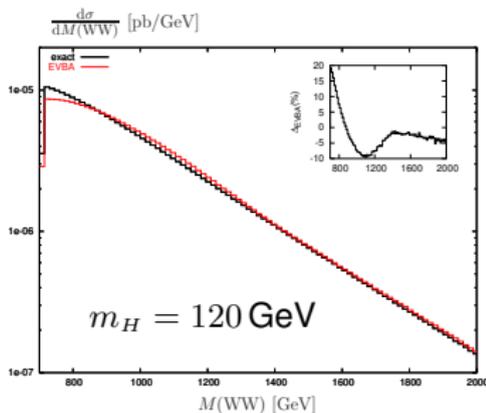
What are these off-shell contributions useful for?

- ▷ Test of **unitarity** (vector boson scattering)
- ▷ Probe **higher dimensional operators** and thus **composite Higgs scenarios**
- ▷ Probe **anomalous HVV couplings** and extended Higgs sectors
- ▷ Under specific assumptions **extraction of the Higgs width** (as done by LHC)

Higher order corrections for off-shell Higgs production of importance:

Corrections to $e^+e^- \rightarrow \nu_e \bar{\nu}_e W^+ W^-$ in Equi. Vector-Boson-Approx. (EVBA)

↔ Corrections to $WW \rightarrow WW$ [[hep-ph/0611289](https://arxiv.org/abs/hep-ph/0611289) Accomando Denner Pozzorini]



Take away message: ▷ EVBA improves with increasing energy, i.e. m_{WW}

▷ Corrections are growing with increasing energy (up to 50%! (same@LHC))

Event generators yielding results at NLO are desirable and on the way:

Different methods for virtual contributions (**Codes**):

▷ Tensor reduction (**Golem**)

[[Passarino Veltman 79](#); [hep-ph/0509141 Denner Dittmaier](#); [0810.0092 Binoth et al.](#)]

▷ Integrand reduction (OPP method) (**CutTools, Samurai**)

(Coefficients to known loop integrals) [[hep-ph/0609007 Ossola Papadopolulos Pittau](#); [hep-ph/0404120 del Aguila Pittau](#); [1006.0710 Mastrolia et al.](#)]

▷ Generalized unitarity (**BlackHat, Rocket**)

(Cutting diagrams to tree-level diagrams)

[[hep-ph/9403226 Bern et al.](#); [0708.2398 Ellis Giele Kunstz](#); [0806.3467 +Melnikov](#)]

Remarks/Challenges:

▷ Soft/Colliner singularities (e.g. by FKS [[hep-ph/9512328 Frixione Kunstz Signer](#)])

▷ Matching with parton showers (e.g. MC@NLO [[hep-ph/0204244 Frixione Weber](#)])

▷ Issue for NLO processes due to computing time: Find a good deal between intermediate unstable particles and full processes

- ▷ HAWK for LHC processes $pp \rightarrow HZ \rightarrow Hll'$ and $pp \rightarrow H + 2 \text{ jets}$ with QCD/EW corrections [0707.0381 0710.4749 1112.5142 Denner Dittmaier Kallweit Mück]
 - ▷ Automatization: MadGraph5_aMC@NLO [1405.0302 Alwall et al.]
- MadGraph (Tree-level generator) & MadLoop (CutTools)
& MadFKS & MC@NLO

Process	Syntax	Cross section (pb)			
		LO 1 TeV		NLO 1 TeV	
j.1 $e^+e^- \rightarrow t\bar{t}H$	$e^+ e^- > t \bar{t} h$	$2.018 \pm 0.003 \cdot 10^{-3}$	+0.0% -0.0%	$1.911 \pm 0.006 \cdot 10^{-3}$	+0.4% -0.5%
j.2* $e^+e^- \rightarrow t\bar{t}Hj$	$e^+ e^- > t \bar{t} h j$	$2.533 \pm 0.003 \cdot 10^{-4}$	+9.2% -7.8%	$2.658 \pm 0.009 \cdot 10^{-4}$	+0.5% -1.5%
j.3* $e^+e^- \rightarrow t\bar{t}Hjj$	$e^+ e^- > t \bar{t} h j j$	$2.663 \pm 0.004 \cdot 10^{-5}$	+19.3% -14.9%	$3.278 \pm 0.017 \cdot 10^{-5}$	+4.0% -5.7%
j.4* $e^+e^- \rightarrow t\bar{t}\gamma$	$e^+ e^- > t \bar{t} a$	$1.270 \pm 0.002 \cdot 10^{-2}$	+0.0% -7.9%	$1.335 \pm 0.004 \cdot 10^{-2}$	+0.5% -0.4%
j.5* $e^+e^- \rightarrow t\bar{t}\gamma j$	$e^+ e^- > t \bar{t} a j$	$2.355 \pm 0.002 \cdot 10^{-3}$	+9.3% -7.9%	$2.617 \pm 0.010 \cdot 10^{-3}$	+1.6% -2.4%
j.6* $e^+e^- \rightarrow t\bar{t}\gamma jj$	$e^+ e^- > t \bar{t} a j j$	$3.103 \pm 0.005 \cdot 10^{-4}$	+19.5% -15.0%	$4.002 \pm 0.021 \cdot 10^{-4}$	+5.4% -6.6%
j.7* $e^+e^- \rightarrow t\bar{t}Z$	$e^+ e^- > t \bar{t} z$	$4.642 \pm 0.006 \cdot 10^{-3}$	+0.0% -0.0%	$4.949 \pm 0.014 \cdot 10^{-3}$	+0.6% -0.5%
j.8* $e^+e^- \rightarrow t\bar{t}Zj$	$e^+ e^- > t \bar{t} z j$	$6.059 \pm 0.006 \cdot 10^{-4}$	+9.3% -7.8%	$6.940 \pm 0.028 \cdot 10^{-4}$	+2.0% -2.6%
j.9* $e^+e^- \rightarrow t\bar{t}Zjj$	$e^+ e^- > t \bar{t} z j j$	$6.351 \pm 0.028 \cdot 10^{-5}$	+19.4% -15.0%	$8.439 \pm 0.051 \cdot 10^{-5}$	+5.8% -6.8%
j.10* $e^+e^- \rightarrow t\bar{t}W^+jj$	$e^+ e^- > t \bar{t} wpm j j$	$2.400 \pm 0.004 \cdot 10^{-7}$	+19.3% -14.9%	$3.723 \pm 0.012 \cdot 10^{-7}$	+9.6% -9.1%
j.11* $e^+e^- \rightarrow t\bar{t}HZ$	$e^+ e^- > t \bar{t} h z$	$3.600 \pm 0.006 \cdot 10^{-5}$	+0.0% -0.0%	$3.579 \pm 0.013 \cdot 10^{-5}$	+0.1% -0.0%
j.12* $e^+e^- \rightarrow t\bar{t}\gamma Z$	$e^+ e^- > t \bar{t} a z$	$2.212 \pm 0.003 \cdot 10^{-4}$	+0.0% -0.0%	$2.364 \pm 0.006 \cdot 10^{-4}$	+0.6% -0.5%
j.13* $e^+e^- \rightarrow t\bar{t}\gamma H$	$e^+ e^- > t \bar{t} a h$	$9.756 \pm 0.016 \cdot 10^{-5}$	+0.0% -0.0%	$9.423 \pm 0.032 \cdot 10^{-5}$	+0.3% -0.4%
j.14* $e^+e^- \rightarrow t\bar{t}\gamma\gamma$	$e^+ e^- > t \bar{t} a a$	$3.650 \pm 0.008 \cdot 10^{-4}$	+0.0% -0.0%	$3.833 \pm 0.013 \cdot 10^{-4}$	+0.4% -0.4%
j.15* $e^+e^- \rightarrow t\bar{t}ZZ$	$e^+ e^- > t \bar{t} z z$	$3.788 \pm 0.004 \cdot 10^{-5}$	+0.0% -0.0%	$4.007 \pm 0.013 \cdot 10^{-5}$	+0.5% -0.5%
j.16* $e^+e^- \rightarrow t\bar{t}HH$	$e^+ e^- > t \bar{t} h h$	$1.358 \pm 0.001 \cdot 10^{-5}$	+0.0% -0.0%	$1.206 \pm 0.003 \cdot 10^{-5}$	+0.9% -1.1%
j.17* $e^+e^- \rightarrow t\bar{t}W^+W^-$	$e^+ e^- > t \bar{t} w^+ w^-$	$1.372 \pm 0.003 \cdot 10^{-4}$	+0.0% -0.0%	$1.540 \pm 0.006 \cdot 10^{-4}$	+1.0% -0.9%

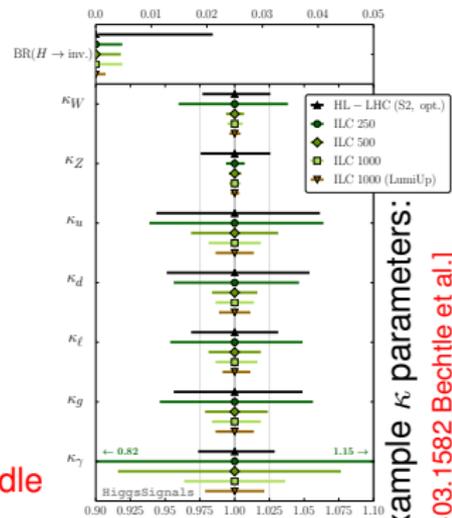
QCD corrections
automatized
for up to $2 \rightarrow 5$
[1405.0302]

- ▷ Whizard [hep-ph/0102195 0708.4233 Moretti Kilian Ohl Reuter]
(see Jürgen Reuter's talk on Wednesday 14:40)

This talk could not cover all the sophisticated inclusive, but also exclusive(!) simulation studies related to the extraction of the Higgs couplings and the Higgs mass and width. Accordingly I did not talk about Higgs couplings sensitivity, which is also a function of energy staging (see e.g. plenary talks by Keisuke Fujii and Philipp Roloff)

Looking forward to an interesting Higgs parallel session at LCWS 14:

- ▷ Higgs couplings and mass:
Tian Kurata Redford Simon Ishikawa Randle-Conde
- ▷ Higgs decays, specific decay channels:
Szalay Liebler Milutinovic-Dumbelovic Pandurovic Müller Kawada Roloff
- ▷ Recoil mass of the Higgs:
Watanuki Barklow Tomita
- ▷ Criticality, Unitarity, Scattering:
Reuter Oda Machida
- ▷ Extended Higgs sectors:
Kanemura Yokoya Nagai Moortgat-Pick Dubey Tsumura



Example κ parameters:
[1403.1582 Bechtile et al.]

Conclusions:

- ▷ Higher order corrections for all SM Higgs production processes in good shape (partially since quite a bit) and needed to reach full LC potential
→ sufficiently accurate for LC performance predictions

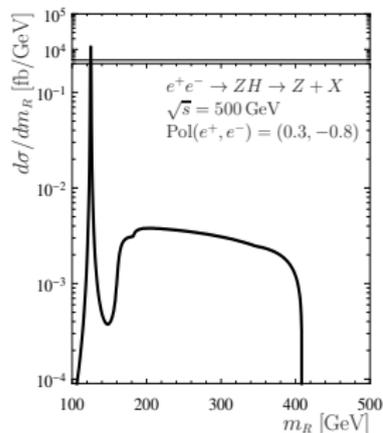
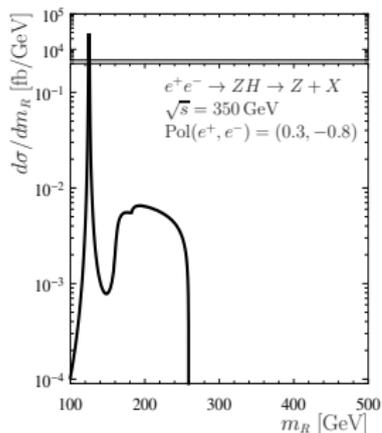
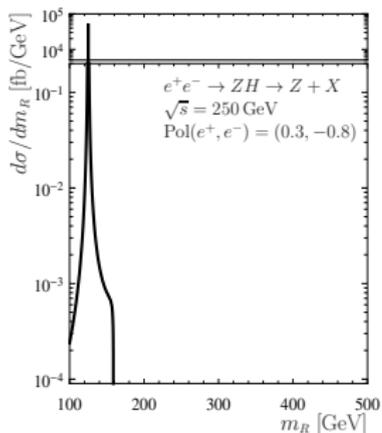
- ▷ Future theory steps:
 - Event generators including higher orders (first QCD, then EW)
(MadGraph5_aMC@NLO, Whizard)
 - Maybe further improvements w.r.t. $e^+e^- \rightarrow t\bar{t}(H)$ (within generators)
 - Exploit large off-shell Higgs contributions
including higher order corrections (not visible at circular e^+e^- collider)
 - Distributions at higher orders and Higgs flavour violating decays

- ...

Thank you for your attention!

(Slides partially copied from Marcus Weber and Max Stahlhofen - Thanks!)

Off-shell contributions in the Z recoil method:

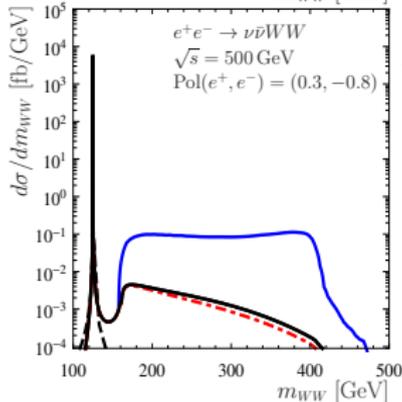
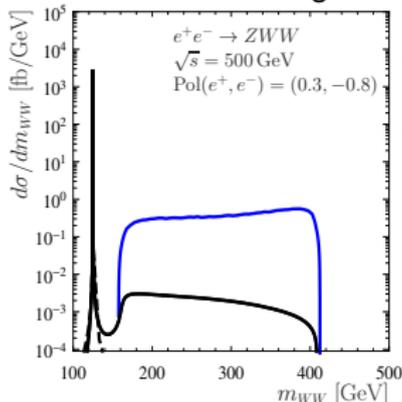


Recoil mass:

$$m_R^2 = s + \hat{m}_Z^2 - 2E_Z\sqrt{s}$$

\sqrt{s}	250 GeV	300 GeV	350 GeV	500 GeV	1 TeV
Δ_{off}	0.02%	0.12%	0.30%	0.91%	1.84%

Comment on the background:


 Inclusive cross sections for $m_{VV} > 130$ GeV
 for $\text{Pol}(e^+, e^-) = (0.3, -0.8)$:

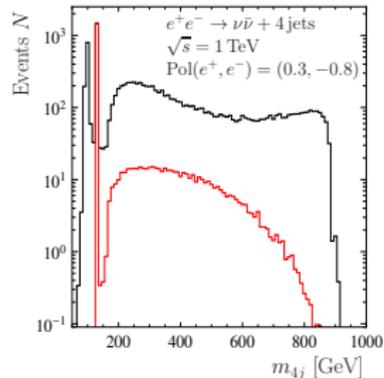
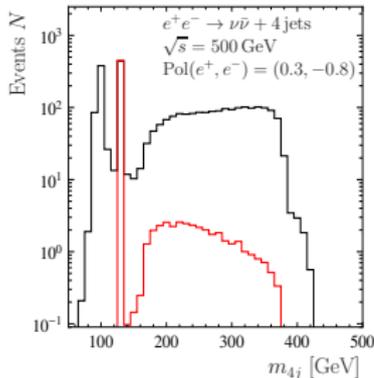
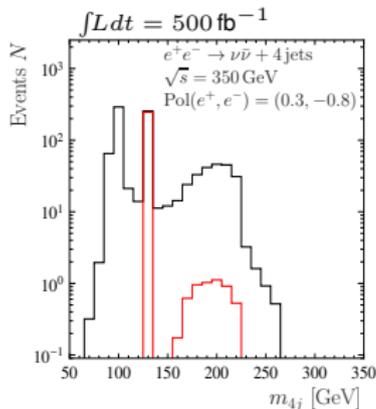
\sqrt{s}	$\sigma_{\text{all}}^{ZZZ}$	Δ_{SB}^{ZZZ}	$\sigma_{\text{all}}^{\nu\bar{\nu}ZZ}$	$\Delta_{\text{SB}}^{\nu\bar{\nu}ZZ}$
250 GeV	---	---	1.51 fb	0.04 %
350 GeV	1.19 fb	2.62(11.9) %	1.66 fb	1.01 %
500 GeV	2.06 fb	2.83(11.6) %	2.85 fb	4.96 %
1 TeV	1.71 fb	4.40(10.2) %	16.7 fb	11.6 %
\sqrt{s}	$\sigma_{\text{all}}^{ZWW}$	Δ_{SB}^{ZWW}	$\sigma_{\text{all}}^{\nu\bar{\nu}WW}$	$\Delta_{\text{SB}}^{\nu\bar{\nu}WW}$
250 GeV	---	---	0.05 fb	9.87(9.87) %
350 GeV	29.2 fb	1.30 %	6.44 fb	1.18(1.03) %
500 GeV	91.8 fb	0.53 %	22.4 fb	2.05(1.63) %
1 TeV	136.7 fb	0.37 %	67.3 fb	7.31(4.49) %

 $\Delta_{\text{SB}} \leftrightarrow$ Signal/Background in off-shell region.

 Naturally: Very large interference term
 guarantees unitarity in $WW \rightarrow WW$!

Bounding the Higgs width using e.g. $e^+e^- \rightarrow \nu\bar{\nu} + 4\text{jets}$:

MadGraph with $\Delta_{R,j} > 0.4$, $|y_j| < 5$, $p_{T,j} > 20$ GeV, $p_{T,4j} > 75$ GeV



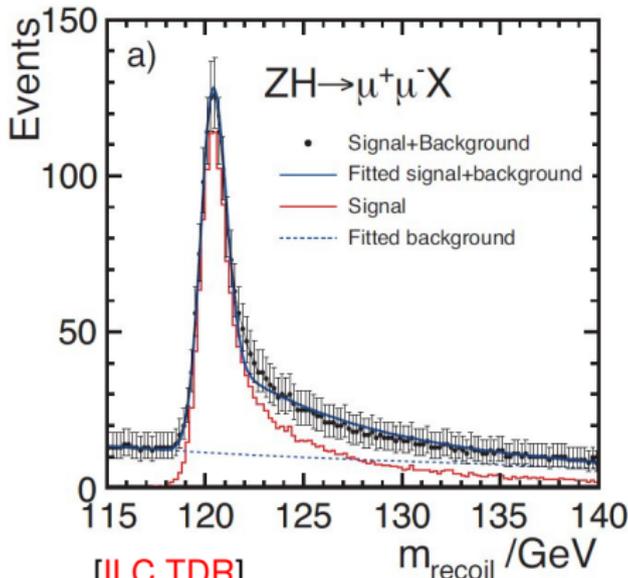
Rescaling couplings and the width (assuming pure SM!!!):

$$N(r) = N_0(1 + R_1\sqrt{r} + R_2r) + N_B \quad \text{with} \quad r = \Gamma_H/\Gamma_H^{SM}$$

\sqrt{s}	350 GeV	500 GeV	1 TeV
N_0 ($\int L dt = 500 \text{ fb}^{-1}$)	263	1775	8420
R_1	-0.017	-0.010	-0.098
R_2	0.026	0.019	0.048
Limit on r ($\int L dt = 500 \text{ fb}^{-1}$)	4.1	2.5	2.3
Limit on r ($\int L dt = 1 \text{ ab}^{-1}$)	3.2	2.1	2.0

Main limitation:
 Negative interference!
 In contrast to LHC:
 Pure tree-level processes!

Higgs width Γ_H through the Z recoil at $\sqrt{s} = 250$ GeV (free from off-shell H)



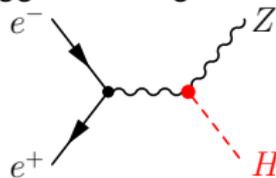
[ILC TDR]

$250 \text{ fb}^{-1} @ 250 \text{ GeV}$

$\Delta\sigma_P / \sigma_P = 2.5\%$

$\Delta m_H = 30 \text{ MeV}$

Higgsstrahlung



Observe: $Z \rightarrow \mu^+ \mu^-$

$Z \rightarrow q\bar{q}$ [1311.2248 Miyamoto]

Reconstruct:

$\sigma_P = \sigma(e^+e^- \rightarrow HZ) \propto g_{HZZ}^2$
(needs defined initial state)

Obtain absolute BR:

$\text{BR}_{H \rightarrow X} = (\sigma_P \text{BR}_{H \rightarrow X}) / \sigma_P$

Reconstruct (example):

$\Gamma_H \propto \Gamma_{H \rightarrow ZZ} / \text{BR}_{H \rightarrow ZZ}$
 $\propto g_{HZZ}^2 / \text{BR}_{H \rightarrow ZZ}$

Details: [1311.7155 Han Liu Sayre]