Universität Hamburg
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Off-shell effects in Higgs decays to gauge bosons

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University of Hamburg

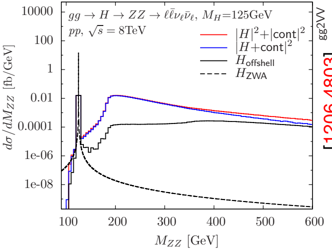
DESY

HELMHOLTZ | GEMEINSCHAFT

Aim of this talk: Discuss LHC inspired effects for linear collider:

▷ 1. Off-shell contributions in $H \to VV^{(*)}$

[1206.4803; Kauer Passarino:
Inadequacy of zero-width approximation
for a light H boson signal]
Further elaboration: [1305.2092, 1310.7011; Kauer]
[1307.4935; Caola Melnikov: Constraining the Higgs
boson width with ZZ production at the LHC]



[1206.4803]

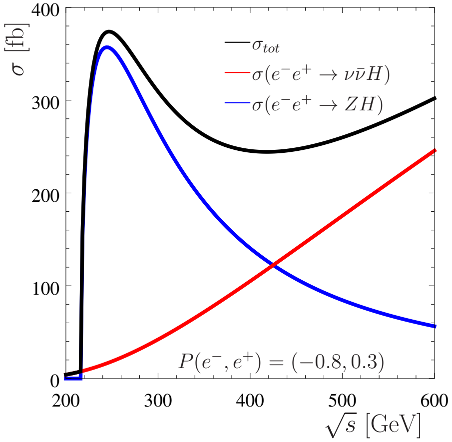
Further elaboration: [1311.3589, 1312.1628; Campbell Ellis Williams]
Application: CMS [CMS-PAS-HIG-14-002, 1405.3455], ATLAS [ATLAS-CONF-2014-042]
$\Longrightarrow$ Obtained bound $\Gamma_H < (5-7)\Gamma_H^{SM}$
Further comments: [1310.1397, 1405.0285, 1405.1925, 1406.1757, 1406.6338]

▷ 2. Interferometry with background in $H \to \gamma\gamma$

[1208.1533, 1303.3342; Martin: Shift in the $H \to \gamma\gamma$ mass peak from interference with background]
Further elaboration: [1303.1397; de Florian et al., 1305.3854; Dixon Li]

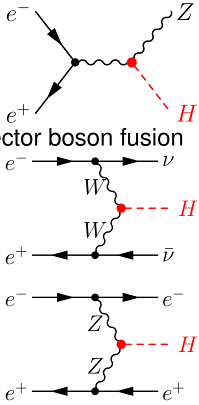
$\to$ Can also be investigated at the (I)LC!

Main production mechanisms of the SM Higgs at the (I)LC:



Higgsstrahlung

Vector boson fusion

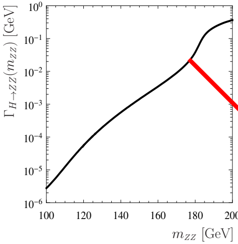


Discussion of off-shell contributions $m_{ZZ} > 2m_Z$ in $H \to ZZ$:

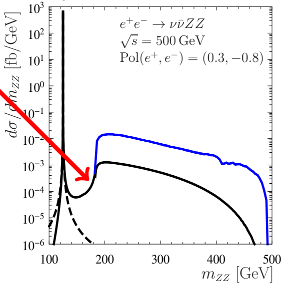
$$\left(\frac{d\sigma^{\nu\bar{\nu}ZZ}_{\text{ZWA}}}{dm_{ZZ}}\right) = \sigma^{\nu\bar{\nu}H}(m_H)\frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2}\frac{m_H\Gamma_{H\to ZZ}(m_H)}{\pi}$$

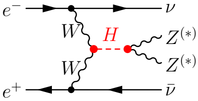
$$\left(\frac{d\sigma^{\nu\bar{\nu}ZZ}_{\text{off}}}{dm_{ZZ}}\right) = \sigma^{\nu\bar{\nu}H}(m_{ZZ})\frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2}\frac{m_{ZZ}\Gamma_{H\to ZZ}(m_{ZZ})}{\pi}$$

Second equation describes the proper calculation of $e^+e^- \to \nu\bar{\nu}ZZ$ at LO!



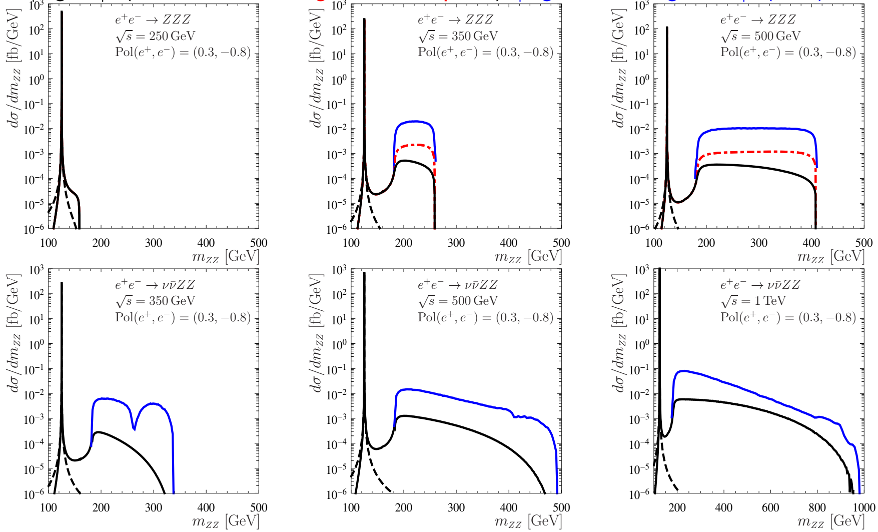
Consequences:



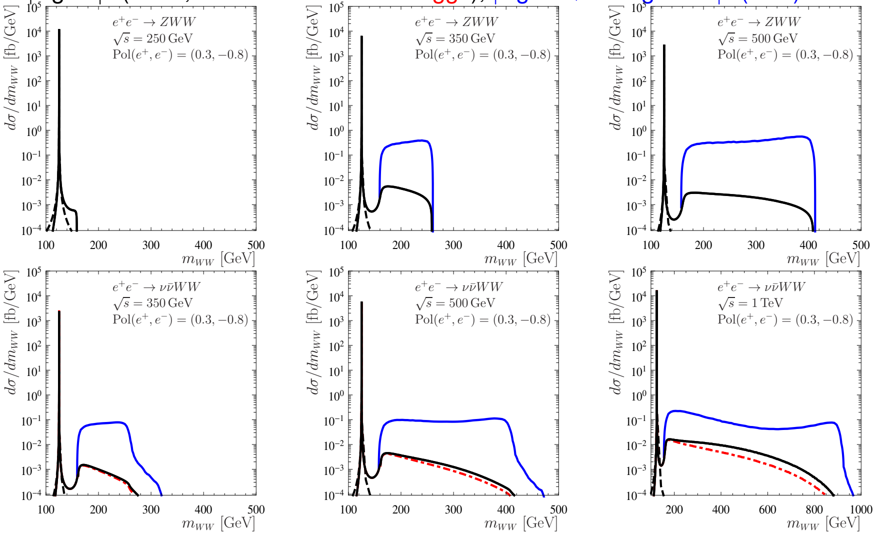


On-shell:
$\sigma \propto g^{\text{on},4}_{HVV}/\Gamma_H$
Off-shell:
$\sigma \propto g^{\text{off},4}_{HVV}$
Access width Γ_H if g^{on}_{HVV} and g^{off}_{HVV} scale identically

Quantification for $H \to ZZ^{(*)}$ as function of $\sqrt{s}$:
$|\text{signal}|^2$ (black, red - average over ZZ pairs), $|\text{signal} + \text{background}|^2$ (blue)



Quantification for $H \to WW^{(*)}$ as function of $\sqrt{s}$:
$|\text{signal}|^2$ (black, red - with t-channel Higgs), $|\text{signal} + \text{background}|^2$ (blue)



Relative contribution to the total signal cross section: Pol$(e^+, e^-) = (0.3, -0.8)$

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

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

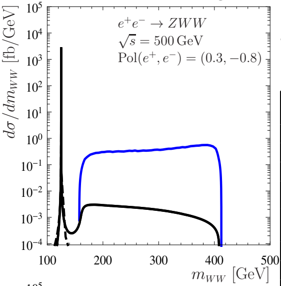
$\sqrt{s}$	$\sigma^{ZZZ}_{\text{off}}$	$\Delta^{ZZZ}_{\text{off}}$	$\sigma^{\nu\bar{\nu}ZZ}_{\text{off}}$	$\Delta^{\nu\bar{\nu}ZZ}_{\text{off}}$
250 GeV	$3.12(3.12)$ fb	$0.03(0.03)$ %	0.490 fb	0.12 %
350 GeV	$1.71(1.82)$ fb	$1.82(7.77)$ %	1.91 fb	0.88 %
500 GeV	$0.802(0.981)$ fb	$7.20(24.1)$ %	4.78 fb	2.96 %
1 TeV	$0.242(0.341)$ fb	$30.9(50.9)$ %	15.0 fb	13.0 %

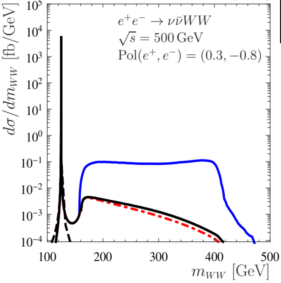
$\sqrt{s}$	$\sigma^{ZWW}_{\text{off}}$	$\Delta^{ZWW}_{\text{off}}$	$\sigma^{\nu\bar{\nu}WW}_{\text{off}}$	$\Delta^{\nu\bar{\nu}WW}_{\text{off}}$
250 GeV	76.3 fb	0.03 %	$3.98(3.99)$ fb	$0.13(0.12)$ %
350 GeV	41.4 fb	0.92 %	$15.5(15.5)$ fb	$0.49(0.43)$ %
500 GeV	18.6 fb	2.61 %	$38.1(38.1)$ fb	$1.21(0.96)$ %
1 TeV	4.58 fb	11.0 %	$110.8(108.9)$ fb	$4.45(2.78)$ %

Comments:

- ▷ Δ_{off} independent of the polarisation.
- ▷ For $H \to ZZ \to 4l$ off-shell contributions accessible by m_{4l}.
- ↔ For $H \to WW \to 2l2\nu$ not directly accessible! ↔ Coupling extraction!
- ▷ Important: On-shell XS strongly dependent on Higgs mass, off-shell not!

Comment on the background:





Inclusive cross sections for $m_{VV} > 130\,\text{GeV}$ for 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 $WW \to WW$!

What can be done with the (basically m_H independent) off-shell contributions?

- They are needed for and allow to test unitarity in $WW \to WW$!
- They allow to test the influence of higher dimensional operators and thus can probe composite Higgs scenarios!
  see e.g. [hep-ph/0301097, Barger Han et al.]
  Current study with e.g. $e^+e^- \to \nu\bar{\nu} + 4$ jets: [1309.7038, Contino Grojean et al.]

- They can test extended Higgs sectors!

- In the pure SM (without NLO effects) they allow to set a bound on Γ_H!
  Note: Precise Higgs width determination from Z recoil method is safe from off-shell effects for low $\sqrt{s}$!

In SUSY/2HDM with $\tan\beta = v_2/v_1$ two Higgs doublets H_1 and H_2 form:

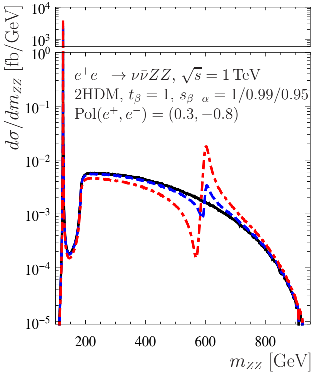
- light and heavy Higgs h and H (with Higgs mixing angle α)
- pseudoscalar A.

It yields: $g_{hVV} = \sin(\beta - \alpha) \quad \leftrightarrow \quad g_{HVV} = \cos(\beta - \alpha)$

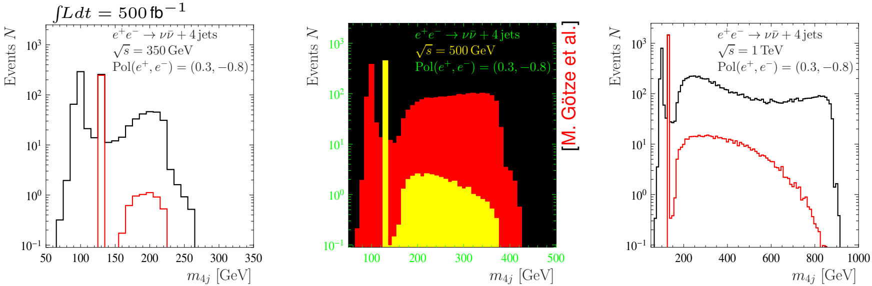
For $\sin(\beta-\alpha) \lesssim 1$ on-shell H interferes with the off-shell contributions of h.

For large m_{VV} combination of h and H guarantees unitarity.

Example: 2HDM
with $m_h = 125$ GeV, $m_H = 600$ GeV



Bounding the Higgs width using e.g. $e^+e^- \to \nu\bar{\nu} + 4\,$jets:
`MadGraph` with $\Delta_{R,j} > 0.4$, $|y_j| < 5$, $p_{T,j} > 20\,$GeV, $p_{T,4j} > 75\,$GeV



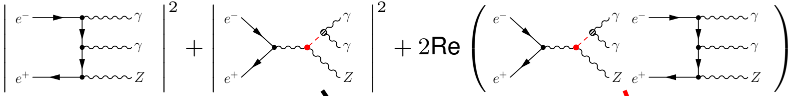
Rescaling couplings and the width (assuming pure SM!!!):

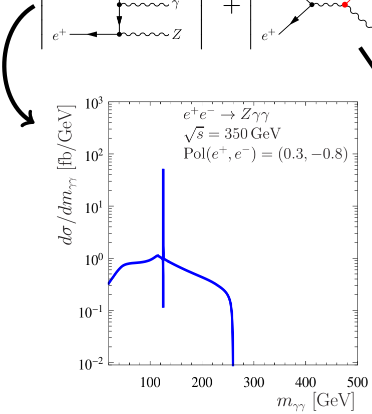
$$N(r) = N_0(1 + R_1\sqrt{r} + R_2 r) + N_B \quad \text{with} \quad r = \Gamma_H/\Gamma_H^{SM}$$

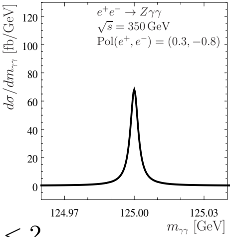
$\sqrt{s}$	350 GeV	500 GeV	1 TeV
N_0 ($\int L dt = 500\,\text{fb}^{-1}$)	263	1775	8420
R_1	-0.017	-0.010	-0.098
R_2	0.026	0.019	0.048
Limit on r ($\int L dt = 500\,\text{fb}^{-1}$)	4.1	2.5	2.3
Limit on r ($\int L dt = 1\,\text{ab}^{-1}$)	3.2	2.1	2.0

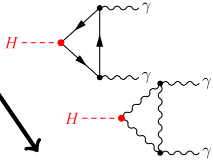
Main limitation:
Negative interference!
In contrast to LHC:
Pure tree-level processes!

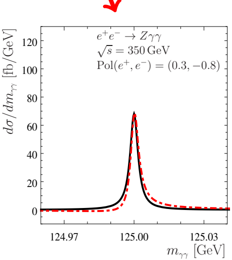
2. Interferometry with the background in $H \to \gamma\gamma$











Applied cuts: $E_\gamma > 20$ GeV, $|\eta_\gamma| < 2$

Interferometry with the background in $H \to \gamma\gamma$

$$\frac{d\sigma^{sig}}{dm_{\gamma\gamma}} = \frac{S}{(m_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2} \to \sigma^{sig} = \frac{\pi S}{2m_H^2\Gamma_H}$$

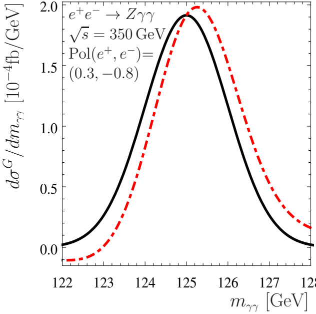
$$\frac{d\sigma^{int}}{dm_{\gamma\gamma}} = \frac{(m_{\gamma\gamma}^2 - m_H^2)R + m_H\Gamma_H I}{(m_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2\Gamma_H^2} \to \sigma^{int} = \frac{\pi I}{2m_H}$$

Relevant part: R induces shift of the peak without changing the incl. XS!

Smearing due to detector resolution:
Gaussian G with e.g. $\hat{\sigma}^G = 1\,\text{GeV}$

$$\frac{d\sigma^G}{dm_{\gamma\gamma}} = \int_0^\infty dm'_{\gamma\gamma} G(m_{\gamma\gamma} - m'_{\gamma\gamma}, \hat{\sigma}^G) \frac{d\sigma}{dm'_{\gamma\gamma}}$$

$\to$ Visible shift Δm_H of the mass peak!
Depending on $\hat{\sigma}^G$, E_γ, η_γ, $\sqrt{s}$, δ_γ, (Pol).

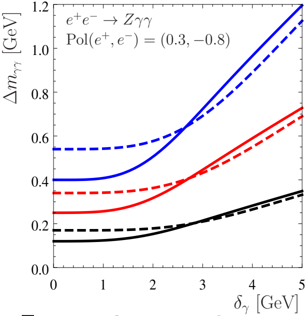


Mimic the method of peak extraction:

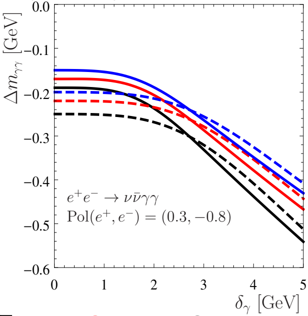
$$\langle m_{\gamma\gamma}\rangle_{\delta,X} = \frac{1}{N}\int_{m_p-\delta}^{m_p+\delta} dm_{\gamma\gamma} m_{\gamma\gamma} \frac{d\sigma_X^G}{dm_{\gamma\gamma}} \quad \to \Delta m_{\gamma\gamma} = \langle m_{\gamma\gamma}\rangle_{\delta_\gamma,S+I} - \langle m_{\gamma\gamma}\rangle_{\delta_\gamma,S}$$

Obtain $\langle m_{\gamma\gamma}\rangle_{\delta_\gamma,S}$ from different cuts or other final states.

$\hat{\sigma}^G = 1$ GeV (solid), 1.5 GeV (dashed)



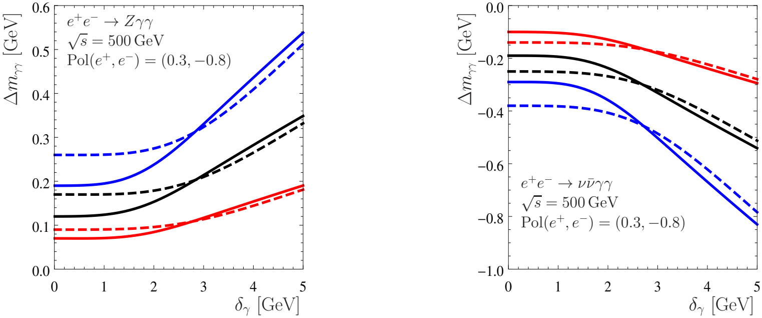
$\sqrt{s} = 250$ GeV, 350 GeV, 500 GeV



$\sqrt{s} = 350$ GeV, 500 GeV, 1 TeV

Higgs width dependence?
Perform similar rescaling of the couplings $g_{HZZ}, g_{HWW}, g_{HAA}$ and the width Γ_H to keep σ_{ZWA} constant.

$\hat{\sigma}^G = 1$ GeV (solid), 1.5 GeV (dashed)
$\Gamma_H = 1$ MeV, 4.07 MeV, 15 MeV



Further studies: Perform analysis with detector simulation?!

Conclusions:

- Off-shell contributions in $H \to VV^{(*)}$ are naturally large at a linear collider (except $\sqrt{s}$ is below 300 GeV). Dependent on the assumptions, they can be used to test unitarity, higher dimensional operators, extended Higgs sectors or to set a bound on Γ_H.
- Lepton collider offers unique possibility to measure Higgs width through Z recoil method in $e^+e^- \to ZH$ at 250 GeV, which is safe from off-shell contributions.
- Signal-background interference in $H \to \gamma\gamma$ shifts the mass peak by a few 100 MeV! The shift also allows to access Γ_H.
- For all purposes a well determined Higgs mass is necessary.

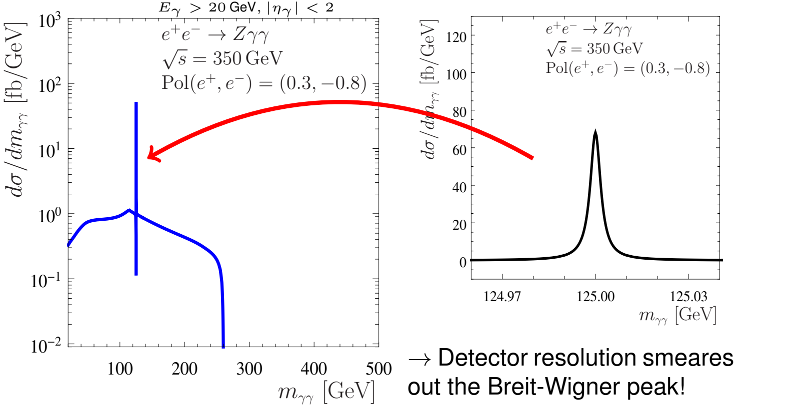
Conclusions II: Precision machine LC now or never!

Thank you for your attention!

How to obtain information about the total Higgs width Γ_H?
$\rightarrow$ Measure the Breit-Wigner peak e.g. in $H \rightarrow \gamma\gamma$?

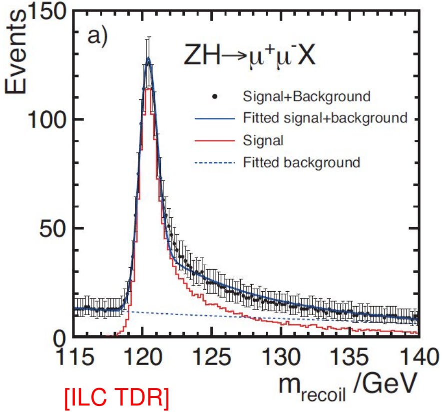
$$\frac{d\sigma^{Z\gamma\gamma}_{\text{ZWA}}}{dm_{\gamma\gamma}} = \sigma^{ZH}(m_H)\frac{2m_{\gamma\gamma}}{(m^2_{\gamma\gamma}-m^2_H)^2+m^2_H\Gamma^2_H}\frac{m_H\Gamma_{H\rightarrow\gamma\gamma}(m_H)}{\pi}$$

Problem: $m_H = 125$ GeV $\leftrightarrow \Gamma_H = 4.07$ MeV $\quad \rightarrow \sigma^{Z\gamma\gamma}_{\text{ZWA}} = \sigma^{ZH}\frac{\Gamma_{H\rightarrow\gamma\gamma}}{\Gamma_H}$



$\rightarrow$ Detector resolution smeares out the Breit-Wigner peak!

→ LC unique method: Higgs width Γ_H through the Z recoil at $\sqrt{s} = 250\,$GeV



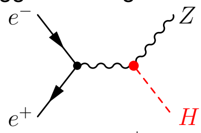
[ILC TDR]

$250\,\mathrm{fb}^{-1}$@$250\,$GeV

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

$\Delta m_H = 30\,$MeV

Higgsstrahlung



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

Reconstruct:
$\sigma_P = \sigma(e^+e^- \to HZ) \propto g^2_{HZZ}$
(needs defined initial state)

Obtain absolute BR:
$\mathrm{BR}(H \to X) = (\sigma_P \mathrm{BR}_X)/\sigma_P$

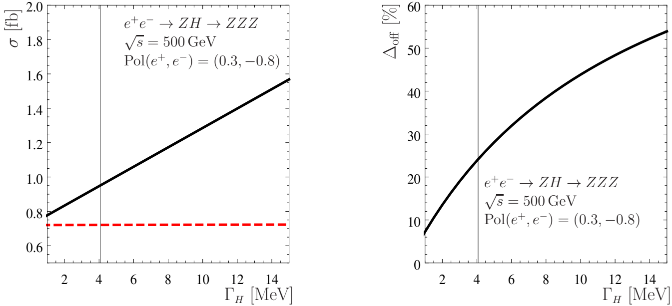
Reconstruct (example):
$\Gamma_H \propto \Gamma(H \to ZZ)/\mathrm{BR}(H \to ZZ)$
$\propto g^2_{HZZ}/\mathrm{BR}(H \to Z)$

Details: [1311.7155: Han, Liu, Sayre]

How can the width be determined from off-shell contributions?

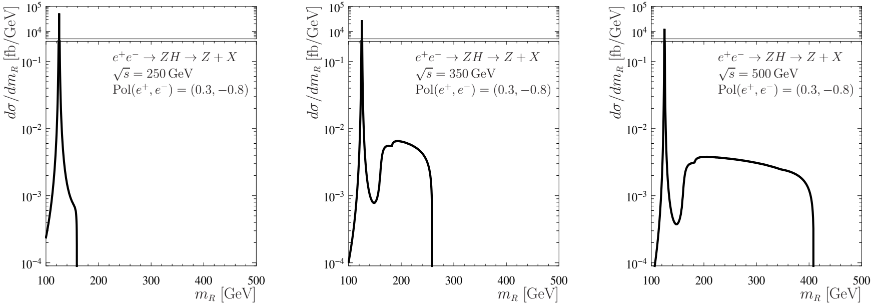
$$\sigma^{ZZZ}_{\text{ZWA}} = \sigma^{ZH}(m_H)\frac{\Gamma_{H\to ZZ}(m_H)}{\Gamma_H} \propto \frac{g^4_{HZZ}}{\Gamma_H}$$

Rescaling $g'_{HZZ} = \xi g_{HZZ}, \Gamma'_H = \xi^4\Gamma_H$ does not change $\sigma^{ZZZ}_{\text{ZWA}}$!
$\to$ Vary Γ_H (in reasonable interval!) and leave σ_{ZWA} constant!
$\to$ Off-shell contributions $\propto g^4_{HZZ} \to \Delta_{\text{off}}$ changes!.



Can the off-shell cont. be discriminated from the background?

Off-shell contributions in the Z recoil method:



Recoil mass:

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

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