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Off-shell effects in Higgs decays to gauge bosons at a LC



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University of Hamburg



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

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

[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]

Further elaboration: [1311.3589, 1312.1628; Campbell Ellis Williams]

Application: CMS [CMS-PAS-HIG-14-002, 1405.3455], ATLAS [ATLAS-CONF-2014-042]

⇒ Obtained bound $\Gamma_H < (5 - 7)\Gamma_H^{SM}$

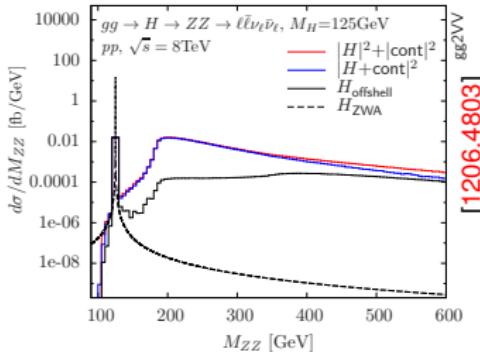
Further comments: [1310.1397, 1405.0285, 1405.1925, 1406.1757, 1406.6338]

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

[1208.1533, 1303.3342; Martin: Shift in the $H \rightarrow \gamma\gamma$ mass peak from interference with background]

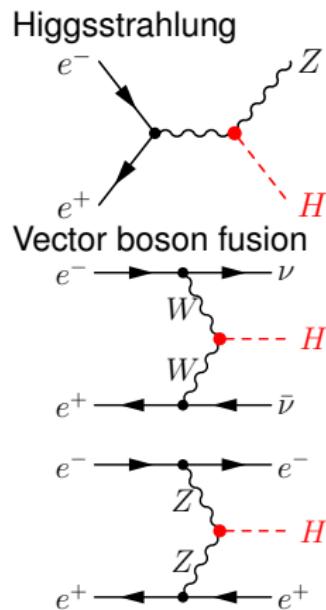
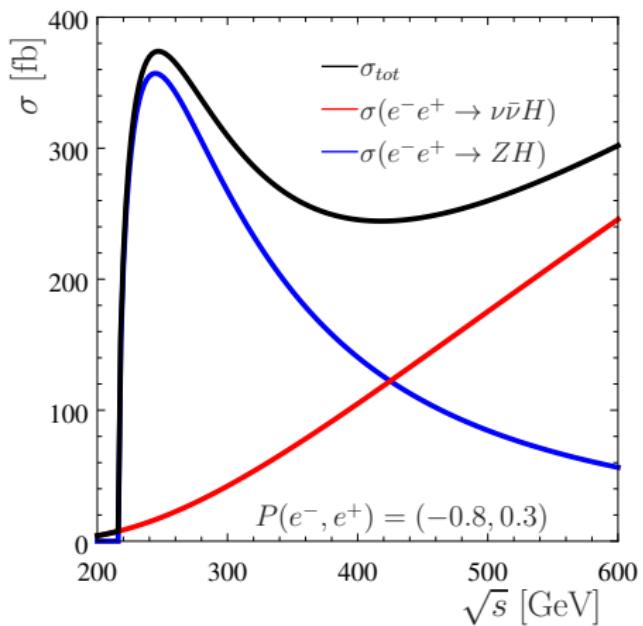
Further elaboration: [1303.1397; de Florian et al., 1305.3854; Dixon Li]

→ Can also be investigated at a LC!



[1206.4803]

Main production mechanisms of the SM Higgs at a LC:

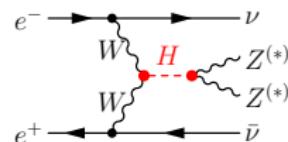


Discussion of off-shell contributions $m_{ZZ} > 2m_Z$ in $H \rightarrow ZZ^{(*)}$
 Breit-Wigner improved ZWA

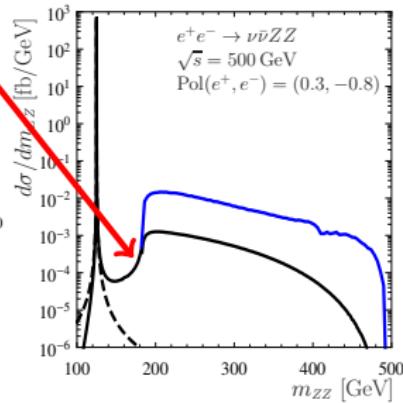
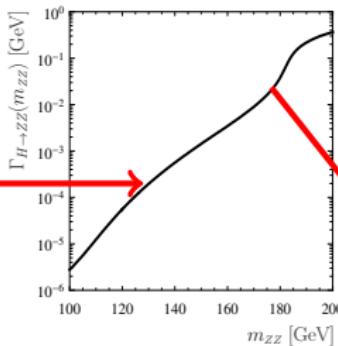
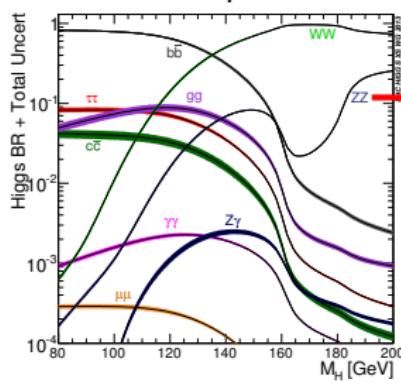
$$\left(\frac{d\sigma_{ZWA}^{\nu\bar{\nu}ZZ}}{dm_{ZZ}} \right) = \sigma^{\nu\bar{\nu}H}(m_H) \frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2} \frac{m_H\Gamma_{H \rightarrow ZZ^{(*)}}(m_H)}{\pi}$$

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

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

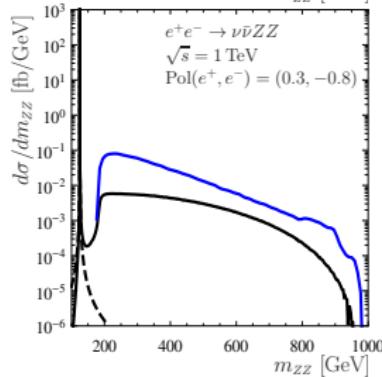
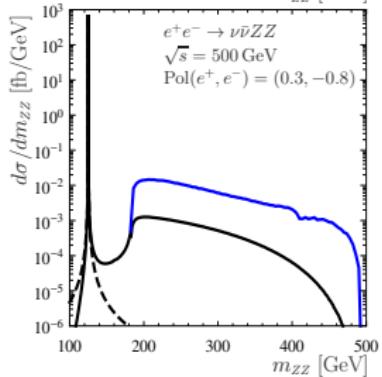
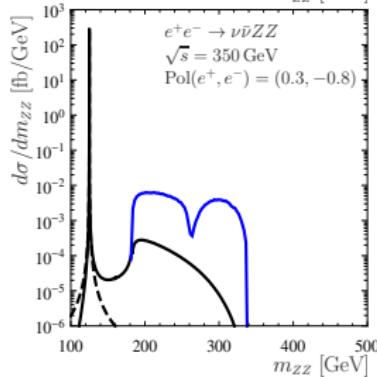
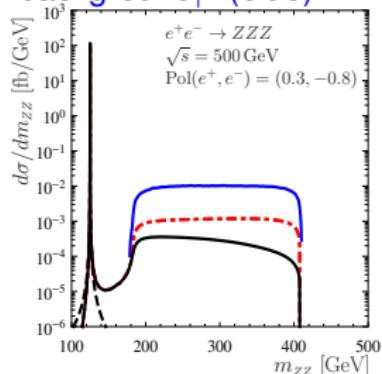
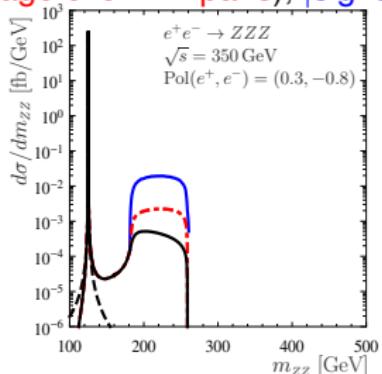
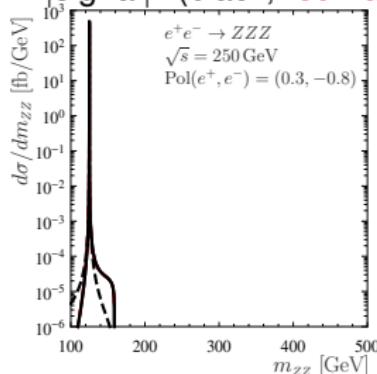


Consequences:



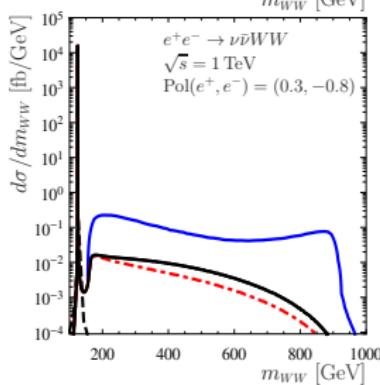
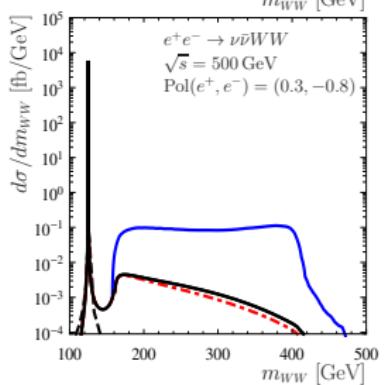
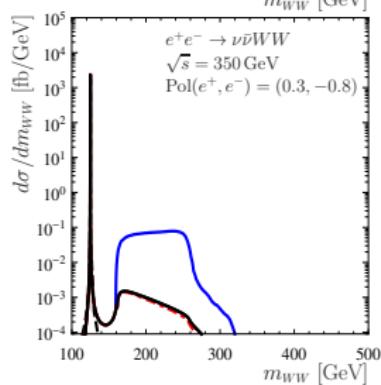
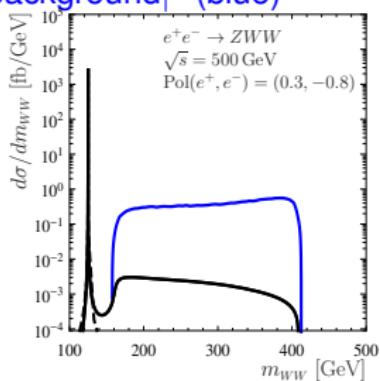
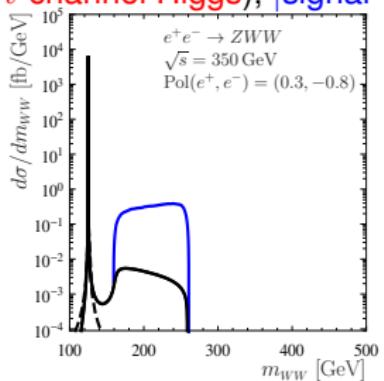
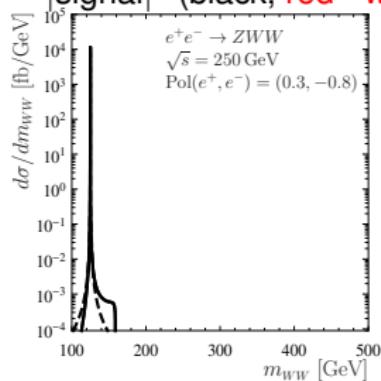
Quantification for $H \rightarrow ZZ^{(*)}$ as function of \sqrt{s} :

$|\text{signal}|^2$ (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 to the total signal cross section: $\text{Pol}(e^+, e^-) = (0.3, -0.8)$

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

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

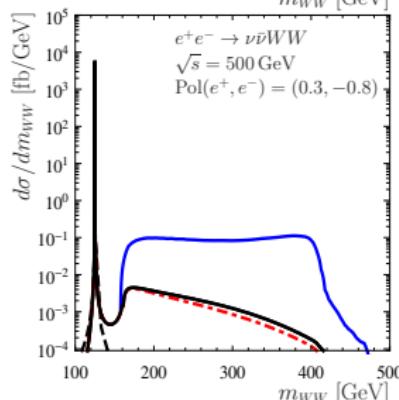
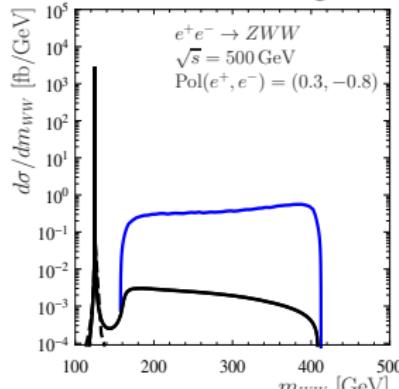
\sqrt{s}	$\sigma_{\text{off}}^{ZZZ}$	$\Delta_{\text{off}}^{ZZZ}$	$\sigma_{\text{off}}^{\nu\bar{\nu}ZZ}$	$\Delta_{\text{off}}^{\nu\bar{\nu}ZZ}$
250 GeV	3.12(3.12) fb	0.03(0.03) %	0.490 fb	0.12 %
350 GeV	1.71(1.82) fb	1.82(7.77) %	1.91 fb	0.88 %
500 GeV	0.802(0.981) fb	7.20(24.1) %	4.78 fb	2.96 %
1 TeV	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.
- ▷ For $H \rightarrow ZZ \rightarrow 4l$ off-shell contributions accessible by m_{4l} .
- ↔ For $H \rightarrow WW \rightarrow 2l2\nu$ 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 $\text{Pol}(e^+, e^-) = (0.3, -0.8)$:

\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) %

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

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

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

- ▷ They are needed for and allow to test unitarity in $WW \rightarrow WW!$
- ▷ 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. $e^+e^- \rightarrow \nu\bar{\nu} + 4\text{ jets}$: [\[1309.7038, Contino Grojean et al.\]](#)

- ▷ They can test anomalous HVV couplings and 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:

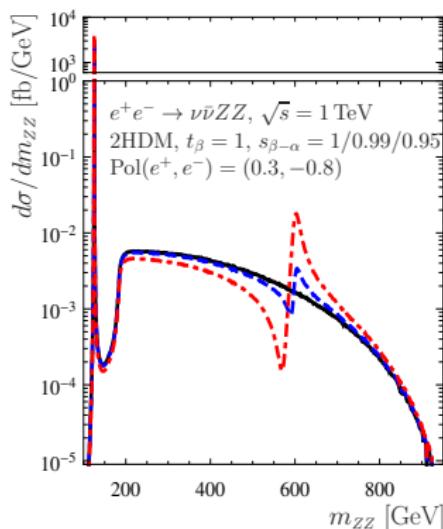
- ▷ light and heavy Higgs h and H (with Higgs mixing angle α)
- ▷ pseudoscalar A .

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

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



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

$$\frac{d\sigma_S^{ZZ}}{dm_{ZZ}} = \sigma^{ZH}(m_{ZZ}) \frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H \Gamma_H)^2} \frac{m_{ZZ} \Gamma_{H \rightarrow ZZ}(m_{ZZ})}{\pi}$$

$$m_{ZZ} \approx m_H : \int dm_{ZZ} : \quad \sigma_S^{ZZ} = \sigma^{ZH}(m_H) \frac{\Gamma_{H \rightarrow ZZ}(m_H)}{\Gamma_H} \propto \frac{g_{HVV}^{OS,4}}{\Gamma_H}$$

$$m_{ZZ} \gg m_H : \frac{d\sigma_S^{ZZ}}{dm_{ZZ}} = \sigma^{ZH}(m_{ZZ}) \frac{2m_{ZZ}^2 \Gamma_{H \rightarrow ZZ}(m_{ZZ})}{\pi(m_{ZZ}^2 - m_H^2)^2} \propto g_{HVV}^4(m_{ZZ})$$

If g^{OS} and $g(m_{ZZ})$ are related $(*)$ you can extract the width Γ_H !

If you get an upper bound on g , you get an upper bound on Γ_H !

There is one more thing:

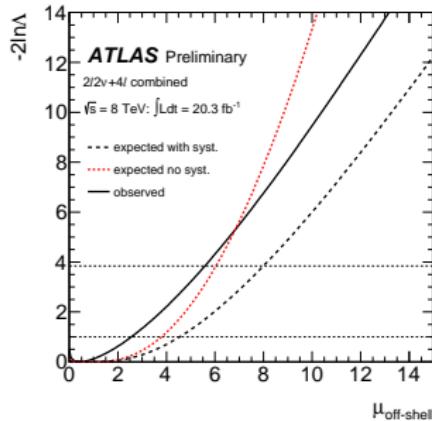
Experiments measure the “signal strength”. It yields:

$$\sigma_S^{ZZ} = \mu \sigma_{SM}^{ZZ}, \quad \frac{d\sigma_S^{ZZ}}{dm_{ZZ}} = \mu(m_{ZZ}) \frac{d\sigma_{SM}^{ZZ}}{dm_{ZZ}} \quad \xrightarrow{(*)} \quad \mu(m_{ZZ}) \sim \mu \frac{\Gamma_H}{\Gamma_H^{SM}} =: \mu r$$

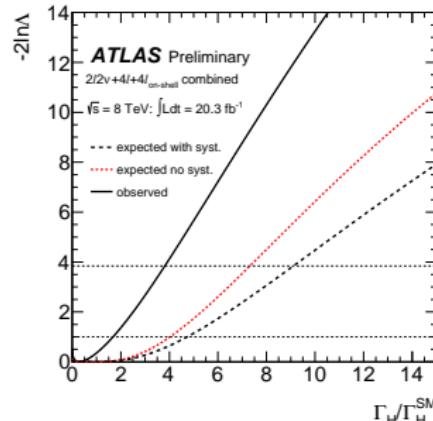
Application of the method by ATLAS and CMS (only $H \rightarrow ZZ \rightarrow 4l/2l2\nu$):

Bound on $\mu(m_{ZZ}) = \mu_{\text{off-shell}}$

Bound on $r = \Gamma_H/\Gamma_H^{\text{SM}}$



Bound ATLAS: $\mu_{\text{off-shell}} < 5.6 - 9.0$



Bound ATLAS: $r < 4.8 - 7.7$

Bound CMS: $r < 5.4$

[CMS-PAS-HIG-14-002, 1405.3455]

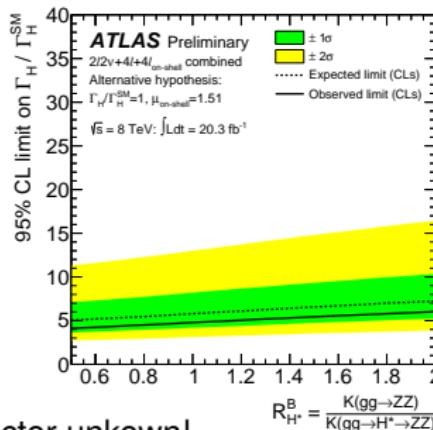
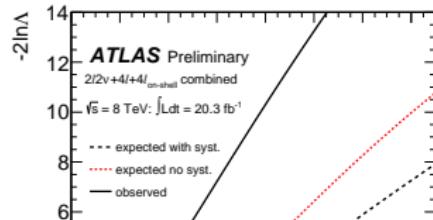
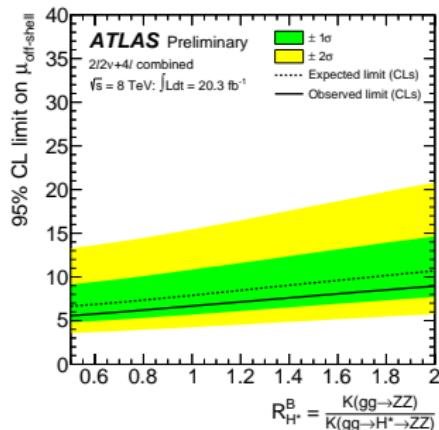
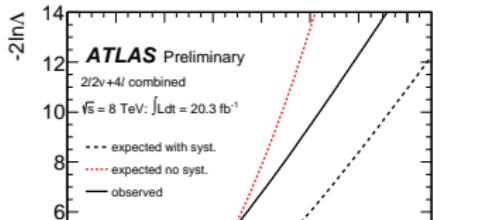
[ATLAS-CONF-2014-042]

Application of the method by ATLAS and CMS (only $H \rightarrow ZZ \rightarrow 4l/2l2\nu$):

Bound on $\mu(m_{ZZ}) = \mu_{\text{off-shell}}$

$\xrightarrow{(*)}$

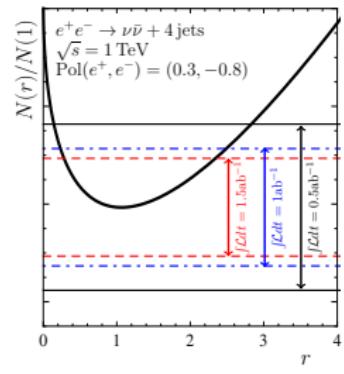
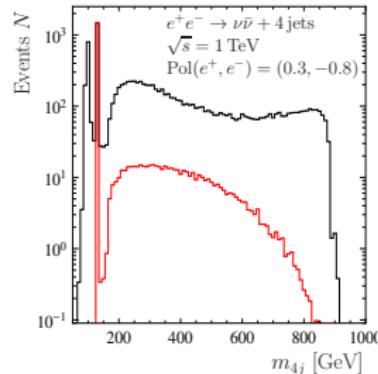
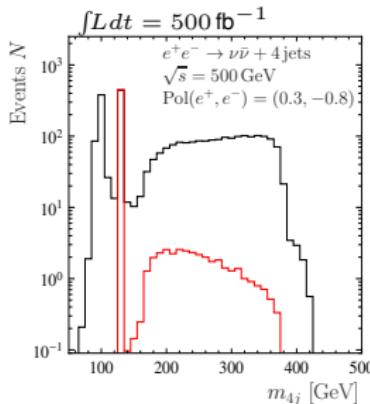
Bound on $r = \Gamma_H/\Gamma_H^{\text{SM}}$



K-factor unknown!

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

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

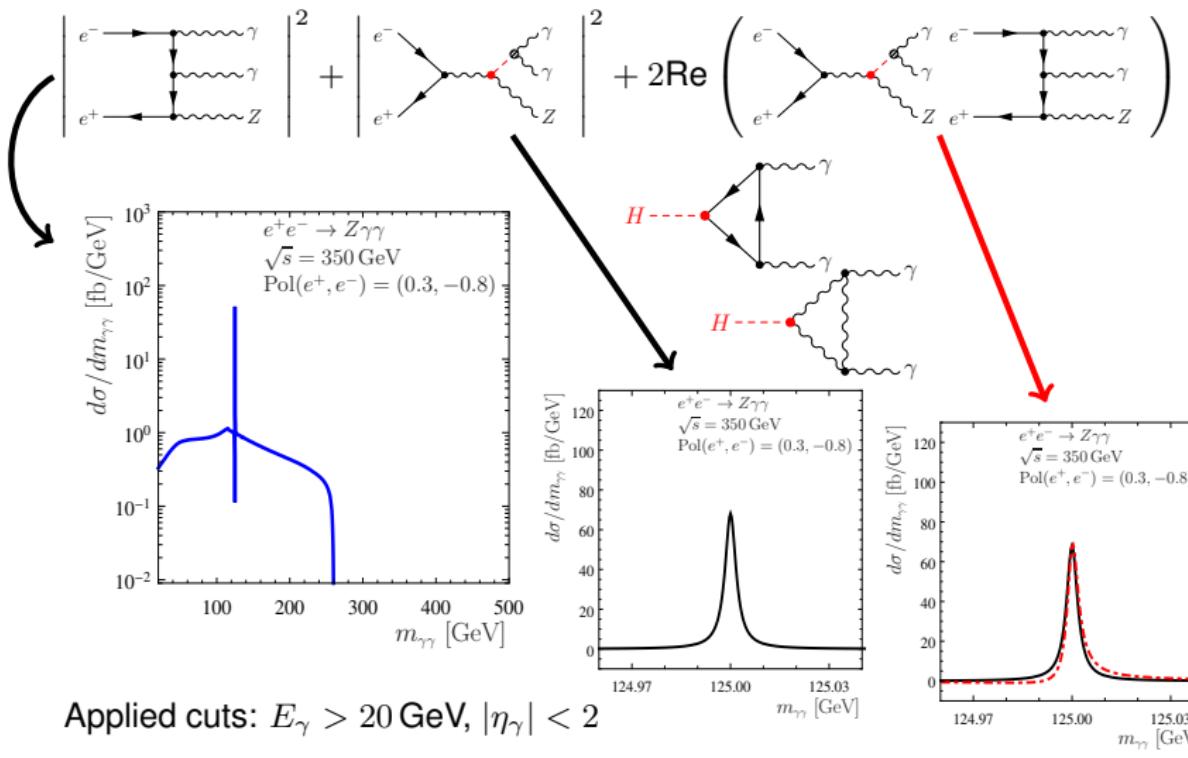


Rescaling couplings and the width (assuming pure SM!!!):

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

\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
 (same@LHC)!
 In contrast to LHC:
 Pure tree-level processes!

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


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

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

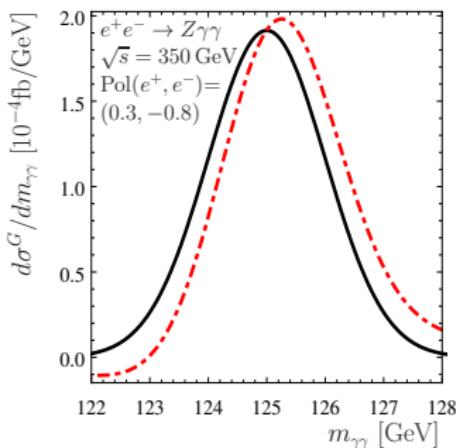
$$\frac{d\sigma^{int}}{dm_{\gamma\gamma}} = \frac{(m_{\gamma\gamma}^2 - m_H^2)R + m_H \Gamma_H I}{(m_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \rightarrow \sigma^{int} = \frac{\pi I}{2m_H}$$

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

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

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

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

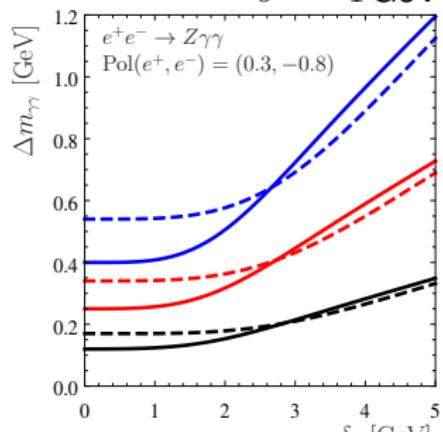


Mimic the method of peak extraction:

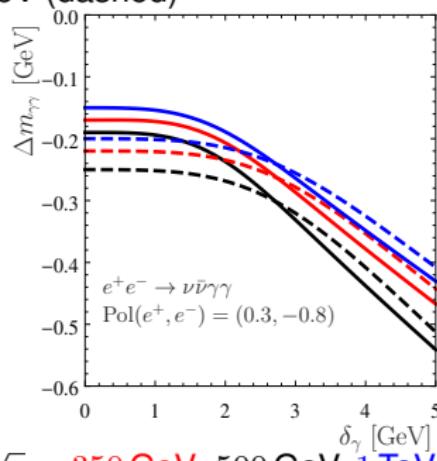
$$\langle m_{\gamma\gamma} \rangle_{\delta, X} = \frac{1}{N} \int_{m_p - \delta}^{m_p + \delta} dm_{\gamma\gamma} m_{\gamma\gamma} \frac{d\sigma_X^G}{dm_{\gamma\gamma}} \rightarrow \Delta m_{\gamma\gamma} = \langle m_{\gamma\gamma} \rangle_{\delta_\gamma, S+I} - \langle m_{\gamma\gamma} \rangle_{\delta_\gamma,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

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

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



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

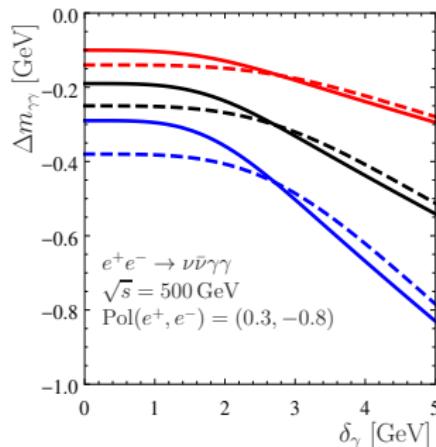
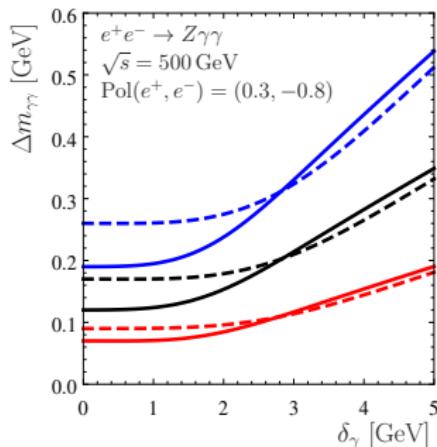


$\sqrt{s} = 350 \text{ GeV}, 500 \text{ GeV}, 1 \text{ TeV}$

Higgs width dependence?

Perform similar rescaling of the couplings $g_{HZZ}, g_{HW\bar{W}}, g_{HA\bar{A}}$ and the width Γ_H to keep σ_{ZWA} constant.

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



Further studies: Perform analysis with detector simulation?!

Conclusions:

- ▷ Off-shell contributions in $H \rightarrow VV^{(*)}$ 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 $e^+e^- \rightarrow ZH$ at 250 GeV, which is safe from off-shell contributions.
- ▷ Signal-background interference in $H \rightarrow \gamma\gamma$ 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.

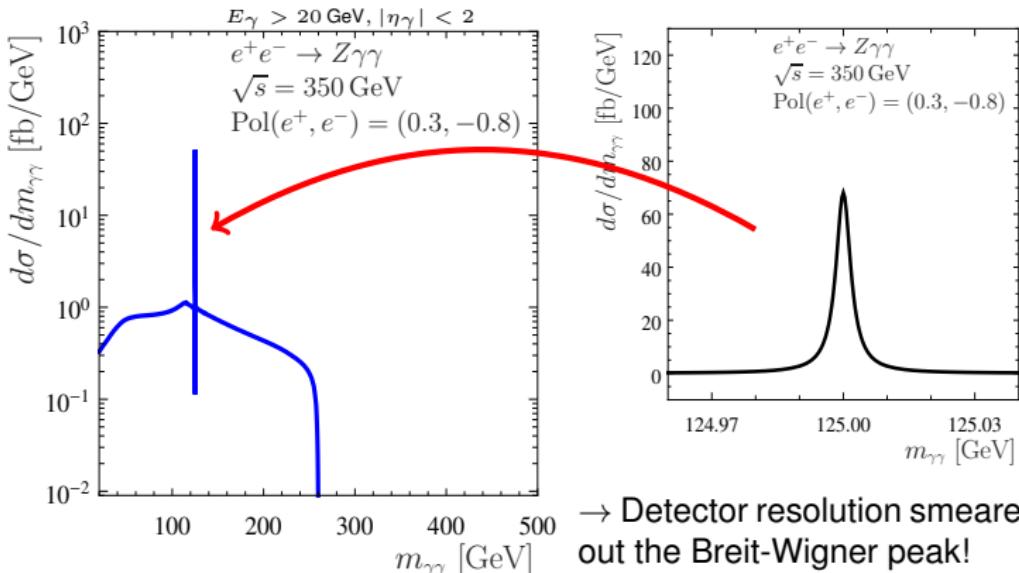
Thank you for your attention!

How to obtain information about the total Higgs width Γ_H ?

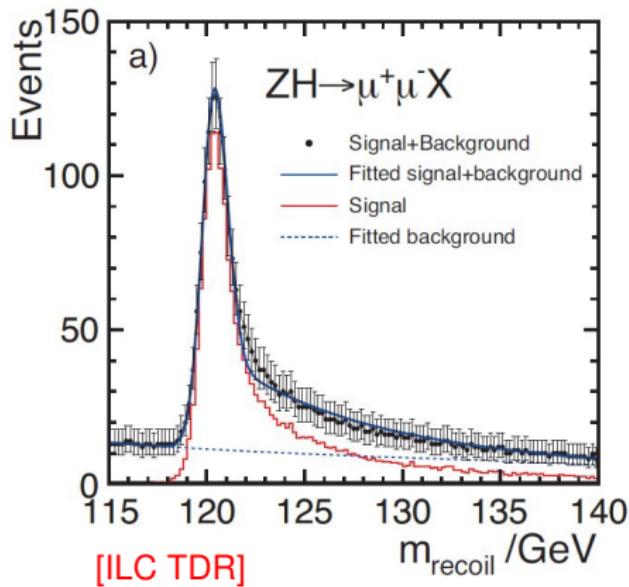
→ Measure the Breit-Wigner peak e.g. in $H \rightarrow \gamma\gamma$?

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

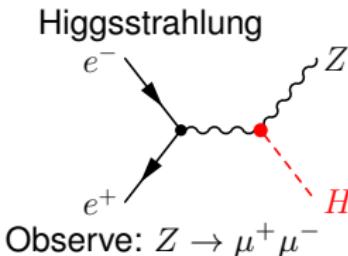
Problem: $m_H = 125 \text{ GeV} \leftrightarrow \Gamma_H = 4.07 \text{ MeV}$ $\rightarrow \sigma_{\text{ZWA}}^{Z\gamma\gamma} = \sigma^{ZH} \frac{\Gamma_{H \rightarrow \gamma\gamma}}{\Gamma_H}$



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



250 fb^{-1} @ 250 GeV
 $\Delta \sigma_P / \sigma_P = 2.5\%$
 $\Delta m_H = 30 \text{ MeV}$



Reconstruct:

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

(needs defined initial state)

Obtain absolute BR:

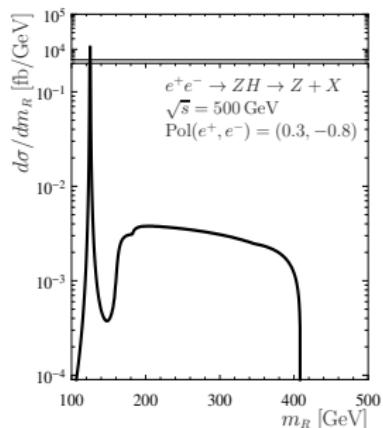
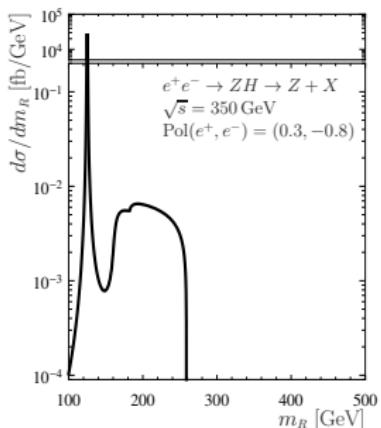
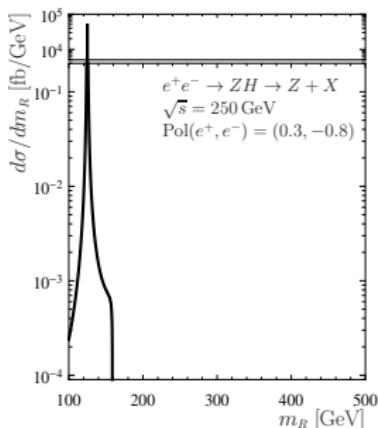
$$\text{BR}(H \rightarrow X) = (\sigma_P \text{BR}_X) / \sigma_P$$

Reconstruct (example):

$$\begin{aligned} \Gamma_H &\propto \Gamma(H \rightarrow ZZ) / \text{BR}(H \rightarrow ZZ) \\ &\propto g_{HZZ}^2 / \text{BR}(H \rightarrow Z) \end{aligned}$$

Details: [1311.7155: Han, Liu, Sayre]

Off-shell contributions in the Z recoil method:



Recoil mass:

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

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