Stefan Liebler

Off-shell effects and constraints on the total width at the Linear Collider and the LHC

LHC Physics discussion

Hamburg - 22 September 2014

University of Hamburg

Universität Hamburg
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DESY

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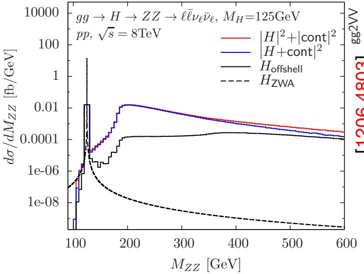
Aim: Insight in off-shell effects of Higgs bosons decays at LHC/ILC.

▷ First discussion: Off-shell contributions in $H \to VV^{(*)}$

[1206.4803; Kauer Passarino: Inadequacy of zero-width approximation for a light H boson signal]

[1305.2092, 1310.7011; Kauer: Interference effects for $H \to WW/ZZ \to l\bar{\nu}_l \bar{l} \nu_l$ searches in gluon fusion at the LHC]



[1206.4803]

▷ Idea: Access to the Higgs width Γ_H

[1307.4935; Caola Melnikov: Constraining the Higgs boson width with ZZ production at the LHC]

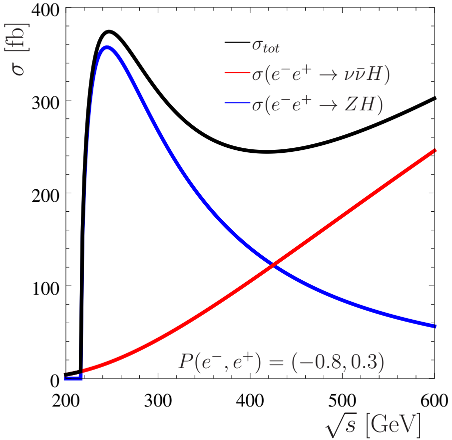
Further elaboration: [1311.3589, 1312.1628, 1408.1723; Campbell Ellis Williams]

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

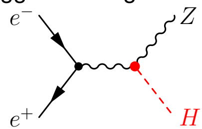
▷ Limitations of Higgs width constraint and opportunities:

[1310.1397, 1405.0285, 1405.1925, 1406.1757, 1406.6338]

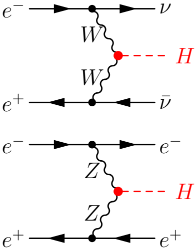
Main production mechanisms of the SM Higgs at the (I)LC:



Higgsstrahlung



Vector boson fusion



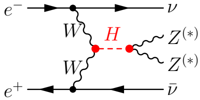
Discussion of off-shell contributions $m_{ZZ} > 2m_Z$ in $H \to ZZ^{(*)}$

Breit-Wigner improved ZWA

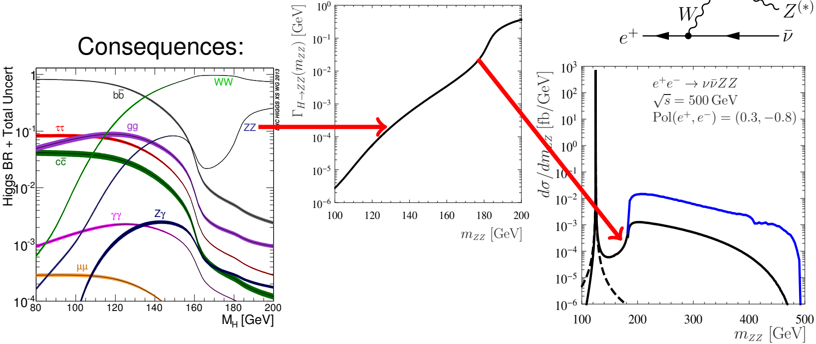
$$\left(\frac{d\sigma^{\nu\bar{\nu}ZZ}_{\text{ZWA}}}{dm_{ZZ}}\right) = \sigma^{\nu\bar{\nu}H}(m_H)\frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2}\frac{m_H\Gamma_{H\to ZZ^{(*)}}(m_H)}{\pi}$$

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

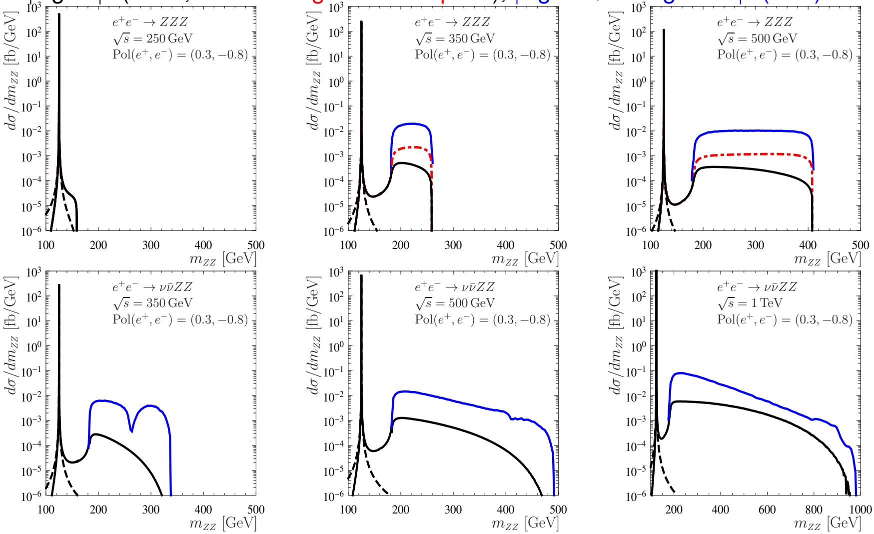
Second equation describes $e^+e^- \to \nu\bar{\nu}ZZ^{(*)}$ at LO!



Consequences:

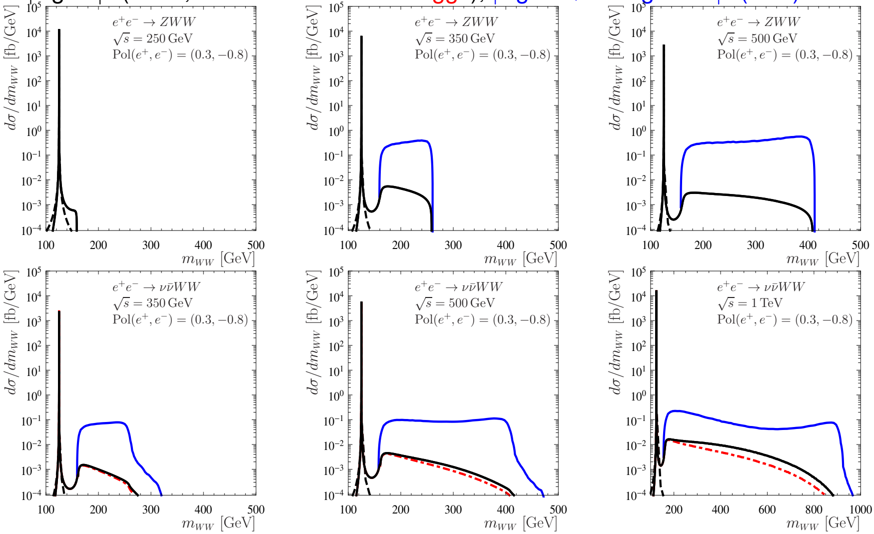


Quantification for $H \to ZZ^{(*)}$ as function of $\sqrt{s}$:
$|\text{signal}|^2$ (black, red - average over ZZ pairs), $|\text{signal} + \text{background}|^2$ (blue)



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: 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 %

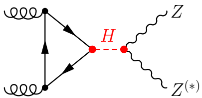
$\sqrt{s}$	$\sigma^{ZWW}_{\text{off}}$	$\Delta^{ZWW}_{\text{off}}$	$\sigma^{\nu\bar{\nu}WW}_{\text{off}}$	$\Delta^{\nu\bar{\nu}WW}_{\text{off}}$
250 GeV	76.3 fb	0.03 %	3.98(3.99) fb	0.13(0.12) %
350 GeV	41.4 fb	0.92 %	15.5(15.5) fb	0.49(0.43) %
500 GeV	18.6 fb	2.61 %	38.1(38.1) fb	1.21(0.96) %
1 TeV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

Comments:
- Δ_{off} independent of the polarisation.
- Important: On-shell XS strongly dependent on Higgs mass, off-shell not!

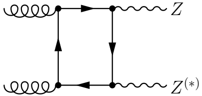
Relevant processes at the LHC: Have in mind $Z/Z^{(*)} \to l^+l^-/\nu\bar{\nu}$!

ggF:

S:



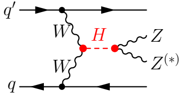
B:



$+ \ldots$

VBF:

S:



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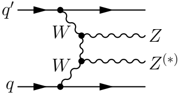
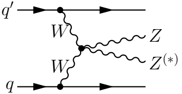


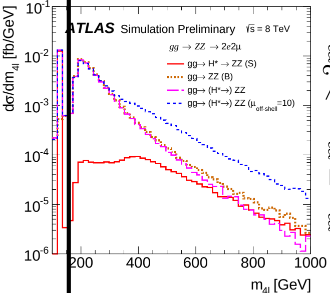
$+$



$+ \ldots$

$HZZ^{(*)}: |S|^2$ | $H^{(*)}ZZ: |S|^2 + |B|^2 + 2\text{Re}(SB)$

$m_{4l} = m_{ZZ} < 2m_Z$



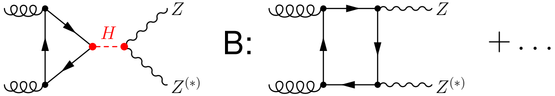
$m_{4l} = m_{ZZ} > 2m_Z$

[ATLAS-CONF-2014-042]

Relevant processes at the LHC: Have in mind $Z/Z^{(*)} \to l^+l^-/\nu\bar{\nu}$!

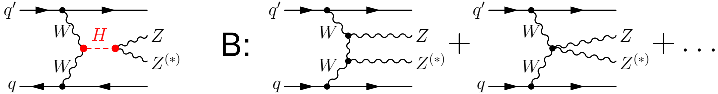
ggF:

S: B: $+\ldots$



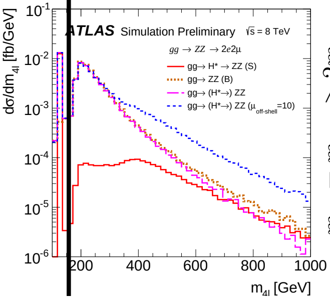
VBF:

S: B: $+$ $+\ldots$

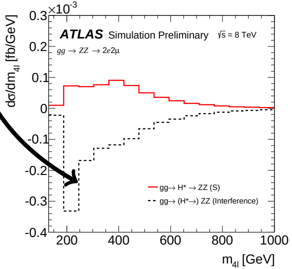


$HZZ^{(*)}$: $|S|^2$ | $H^{(*)}ZZ$: $|S|^2 + |B|^2 + 2\text{Re}(SB)$

$m_{4l} = m_{ZZ} < 2m_Z$



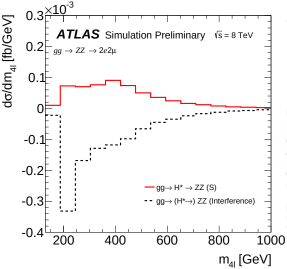
$m_{4l} = m_{ZZ} > 2m_Z$



[ATLAS-CONF-2014-042]

Theoretical issues:

▷ Interference $I = 2\text{Re}(SB)$ is negative at LHC!
I restores unitarity in $W_L W_L \to W_L W_L$!
$\to$ Negative I affects sensitivity to Γ_H!



[ATLAS-CONF-2014-042]

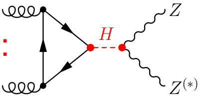
▷ Precision for gluon fusion:
S: known at NNLO QCD as fct. of $m_{ZZ} = m_{4l}$
B: known at LO QCD!

ATLAS: Unkown K-factor

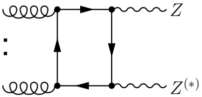
$$R_H^B = \frac{K(gg \to ZZ)}{K(gg \to H^{(*)} \to ZZ)}$$

without m_{ZZ} dependence!

S:



B:



Less problematic for VBF!

▷ Other issues:
Dominant background $q\bar{q} \to ZZ$ known at NNLO QCD
(Interference of $WW \to 2l2\nu$ and $ZZ \to 2l2\nu$ known)
For OS high precision in m_H: $m_H \pm 200\,$MeV $\to \Gamma_{H\to ZZ/WW} \sim$ BR $\sim \pm 2.5\%$

How can the width be determined from off-shell contributions (LHC example)?

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

$$m_{ZZ} \approx m_H : \int dm_{ZZ} : \quad \sigma_S^{ZZ} = \sigma^H(m_H) \frac{\Gamma_{H\to ZZ}(m_H)}{\Gamma_H} \propto \frac{g_{Hgg}^{\text{OS},2} g_{HVV}^{\text{OS},2}}{\Gamma_H}$$

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

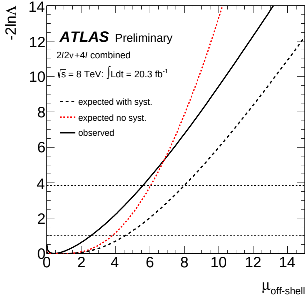
If g^{OS} and $g(m_{ZZ})$ are related $^{(*)}$ you can extract the width Γ_H!
If you get an upper bound on g, you get an upper bound on Γ_H!

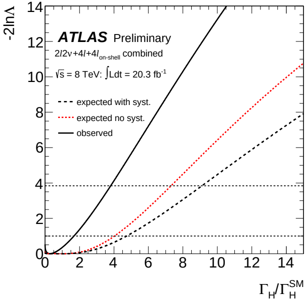
There is one more thing:
Experiments measure the “signal strength”. It yields:

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

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

Bound on $\mu(m_{ZZ}) = \mu_{\text{off-shell}}$ $\overset{(*)}{\Longrightarrow}$ Bound on $r = \Gamma_H/\Gamma_H^{SM}$





[ATLAS-CONF-2014-042]

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

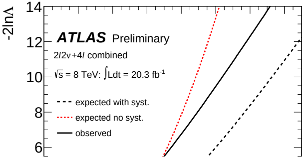
Bound ATLAS: $r < 4.8 - 7.7$

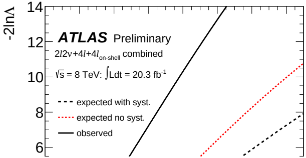
Bound CMS: $r < 5.4$

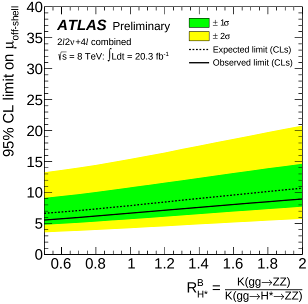
[CMS-PAS-HIG-14-002, 1405.3455]

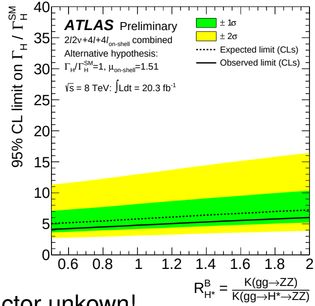
Application of the method by ATLAS and CMS (only $H \to ZZ \to 4l/2l2\nu$):

Bound on $\mu(m_{ZZ}) = \mu_{\text{off-shell}}$ $\overset{(*)}{\Longrightarrow}$ Bound on $r = \Gamma_H/\Gamma_H^{SM}$









[ATLAS-CONF-2014-042]

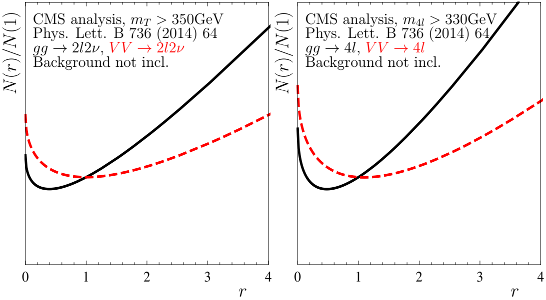
K-factor unkown!

Sensitivity for low Γ_H: The $r = \Gamma_H/\Gamma_H^{SM}$ dependence is as follows (if $(*)$):

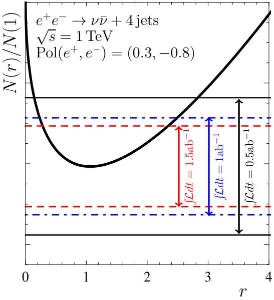
$$N(r) \propto |B|^2 + \sqrt{\mu r}\,2\mathrm{Re}(SB) + \mu r|S|^2$$

Since the interference is negative, the sensitivity on r around 1 is limited:

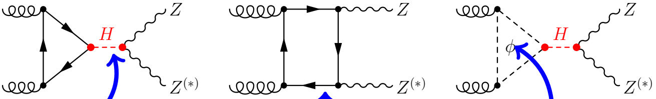
LHC



ILC



Limitation of the Higgs width determination:
As pointed out a relation between g^{OS} and $g(m_{ZZ})$ is needed.
If $\Gamma_H > \Gamma_H^{SM}$, then new physics contributions to Higgs decays are needed.
They in turn alter $g(m_{ZZ})$ with a possible threshold at a specific m_{ZZ} value.



Higher dimensional operators

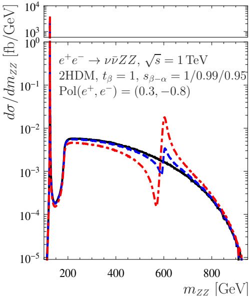
v-like quarks

New particles

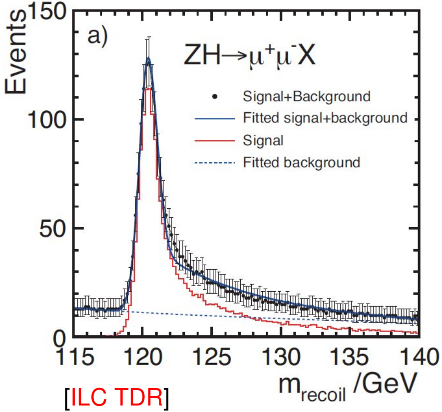
[1405.0285: Englert Spannowsky]

Opportunities (apart from measuring Γ_H):
- ▷ Test unitarity (indirectly)/anomalous g_{HVV}
- ▷ Look for new physics
- ▷ Test extended Higgs sectors
- ▷ Test higher dimensional operators

and thus composite Higgs scenarios
[hep-ph/0301097, 1309.7038, 1310.1397, 1405.1925, 1406.1757, 1406.6338]



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



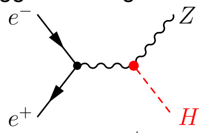
[ILC TDR]

$250\,\text{fb}^{-1}$@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:
$\text{BR}_{H\to X} = (\sigma_P \text{BR}_{H\to X})/\sigma_P$

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

Details: [1311.7155: Han, Liu, Sayre]

Conclusions:

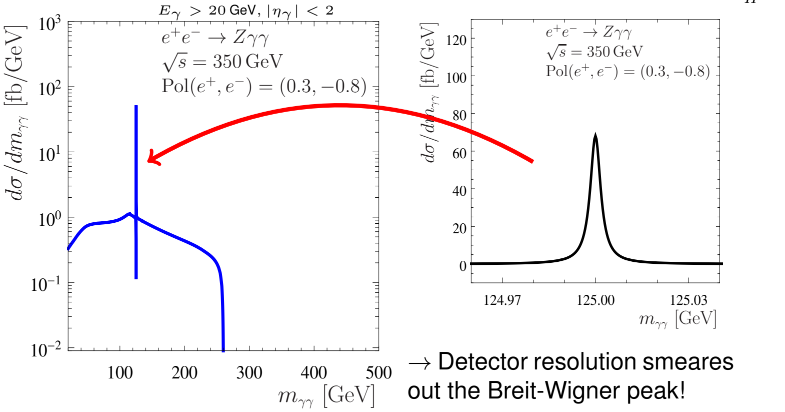
- Off-shell contributions in $H \to VV^{(*)}$ with $V \in \{W, Z\}$ are large at the LHC and the ILC.
  Dependent on the assumptions, they can be used to test unitarity, new physics, higher dimensional operators, extended Higgs sectors or to set a bound on Γ_H. The latter case has a limited sensitivity around $\Gamma_H \sim \Gamma_H^{SM}$.
  Current bounds by ATLAS and CMS: $\Gamma_H < (4-8)\Gamma_H^{SM}$.
- The Higgs width can be well-measured at the ILC using the Z recoil in $e^+e^- \to ZH$.
- 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?
$\rightarrow$ Measure the Breit-Wigner peak e.g. in $H \rightarrow \gamma\gamma$?

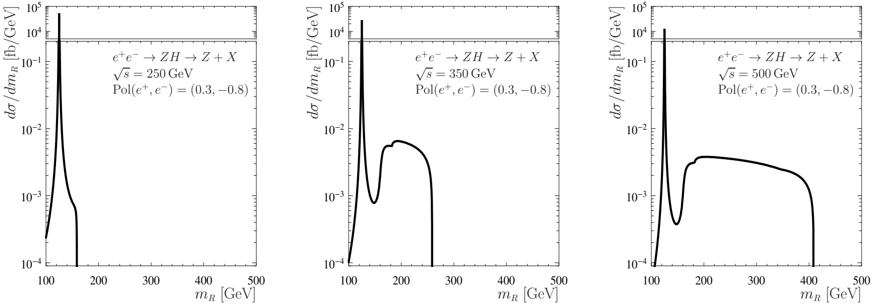
$$\frac{d\sigma^{Z\gamma\gamma}_{\mathrm{ZWA}}}{dm_{\gamma\gamma}} = \sigma^{ZH}(m_H)\frac{2m_{\gamma\gamma}}{(m^2_{\gamma\gamma}-m^2_H)^2+m^2_H\Gamma^2_H}\frac{m_H\Gamma_{H\rightarrow\gamma\gamma}(m_H)}{\pi}$$

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



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

Off-shell contributions in the Z recoil method:

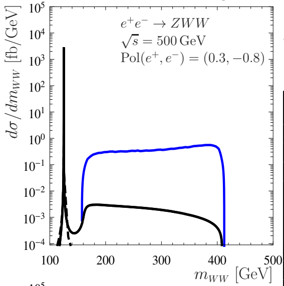


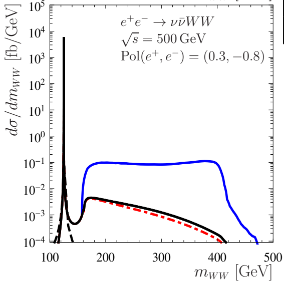
Recoil mass:

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

$\sqrt{s}$	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:





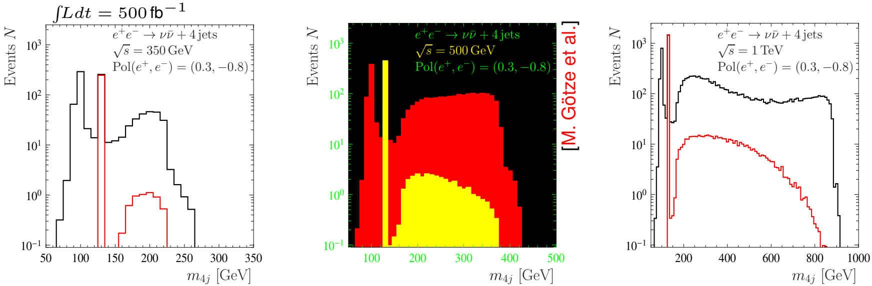
Inclusive cross sections for $m_{VV} > 130\,$GeV for Pol$(e^+, e^-) = (0.3, -0.8)$:

$\sqrt{s}$	$\sigma_{\text{all}}^{ZZZ}$	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 $WW \to WW$!

Bounding the Higgs width using e.g. $e^+e^- \to \nu\bar{\nu} + 4\,\text{jets}$:
`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!!!):

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

$\sqrt{s}$	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!