Stefan Liebler

Off-shell effects and signal-background interference in $H \to VV$ at the (I)LC

Helmholtz-Alliance LC Forum

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Bonn - 30 April 2014

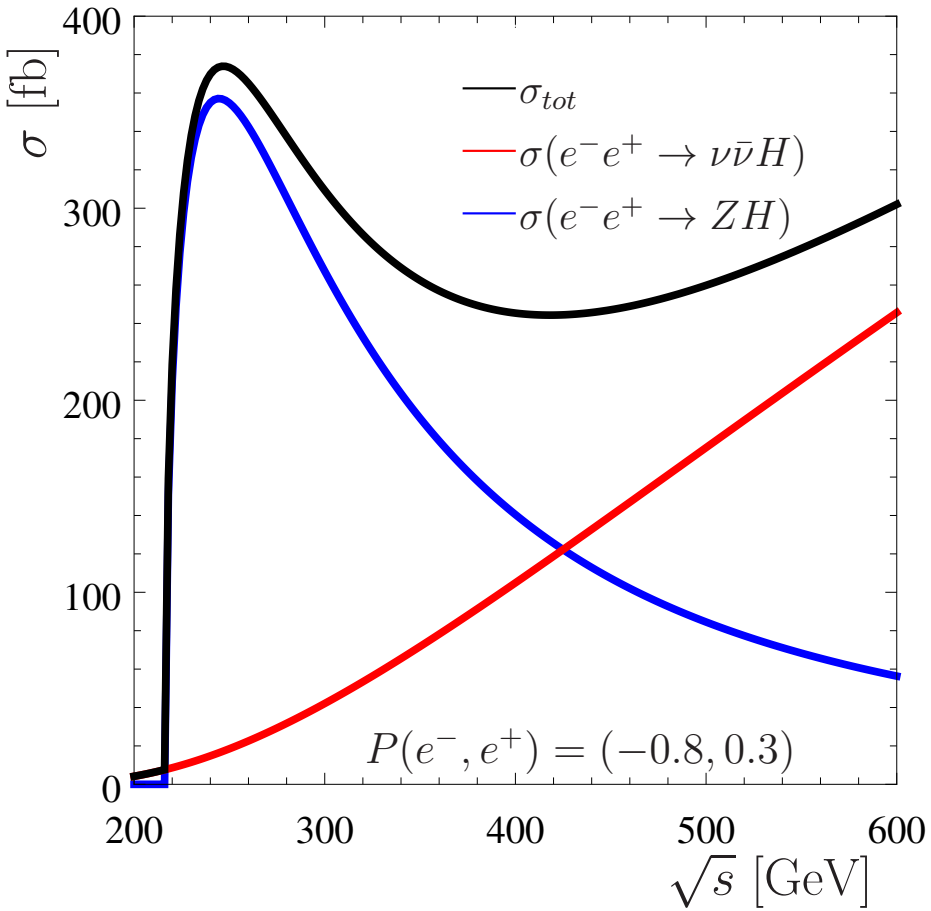
University of Hamburg

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

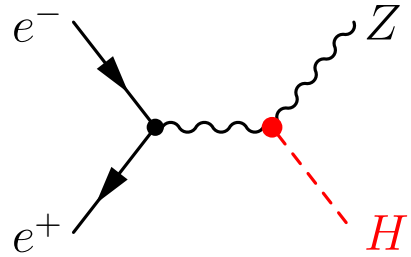
DESY

HELMHOLTZ GEMEINSCHAFT

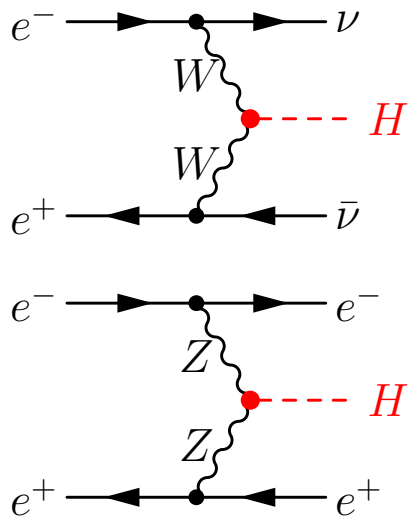
Main production mechanisms of the SM Higgs at the (I)LC:



Higgsstrahlung

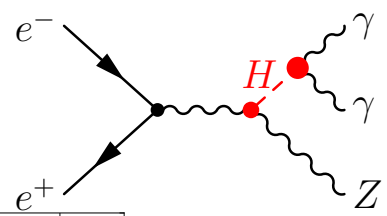


Vector boson fusion

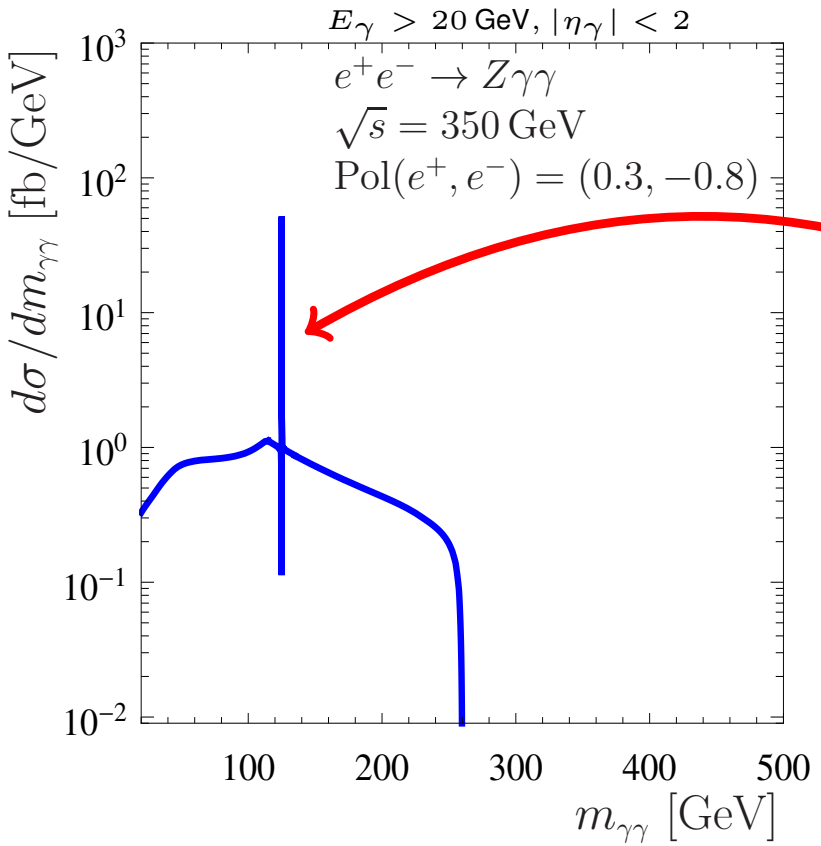


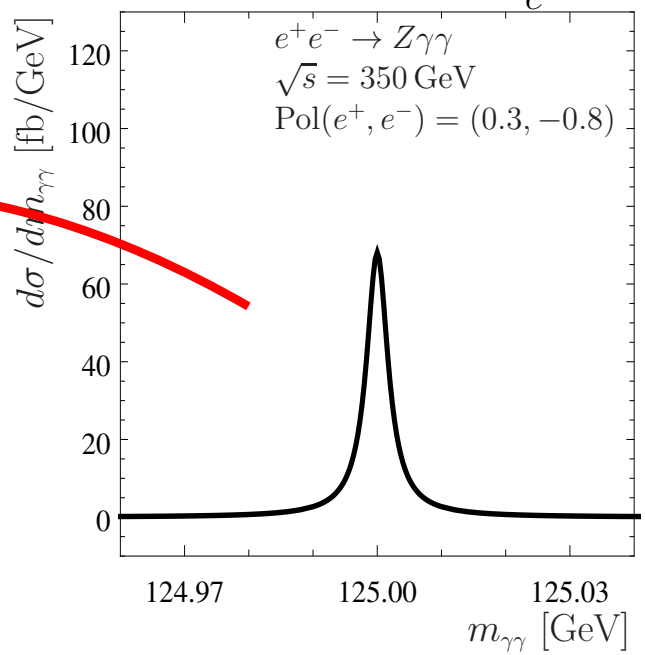
How to obtain information about the total Higgs width Γ_H?
$\to$ Measure the Breit-Wigner peak e.g. in $H \to \gamma\gamma$?

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



Problem: $m_H = 125\,\text{GeV} \leftrightarrow \Gamma_H = 4.07\,\text{MeV}$





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

How to obtain information about the total Higgs width Γ_H?
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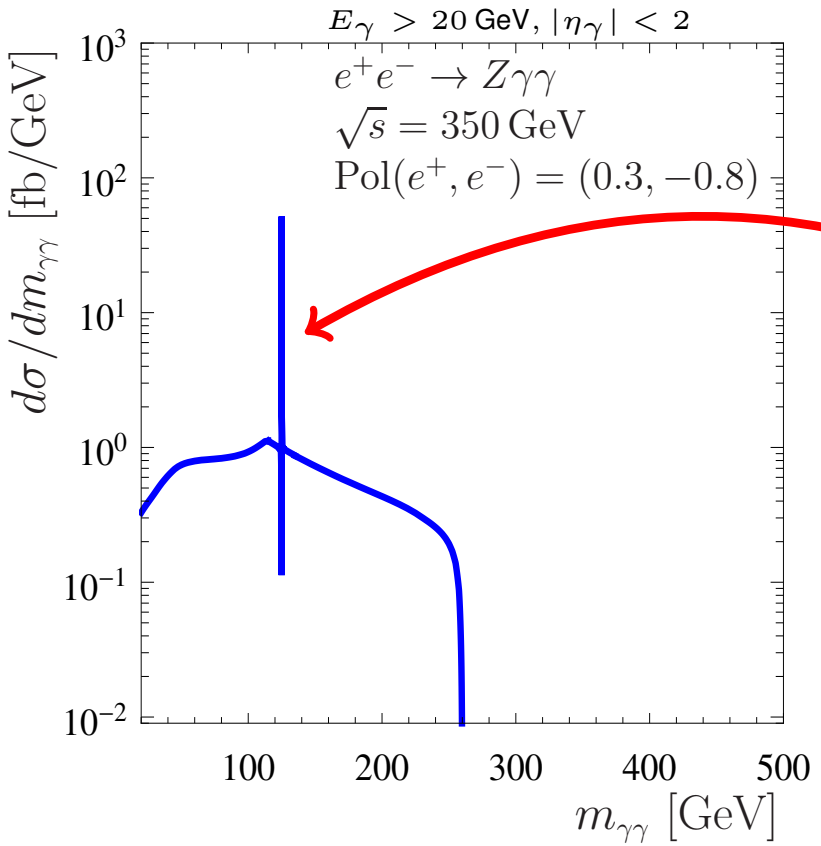
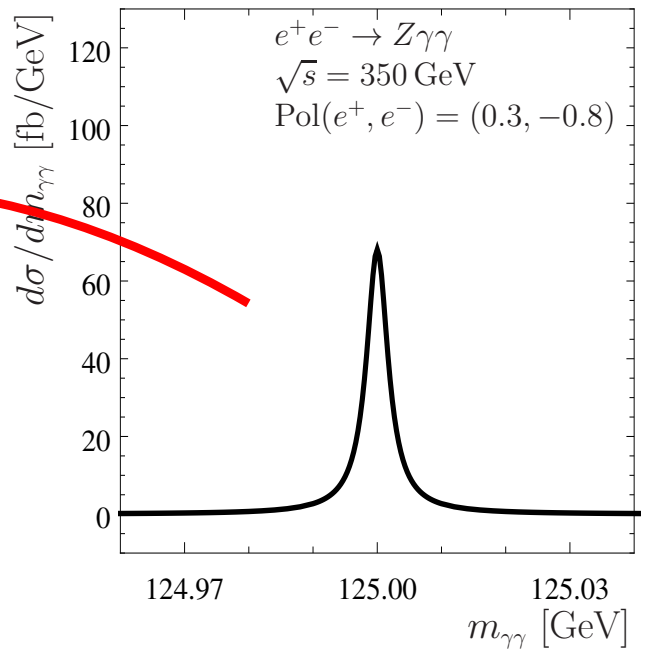
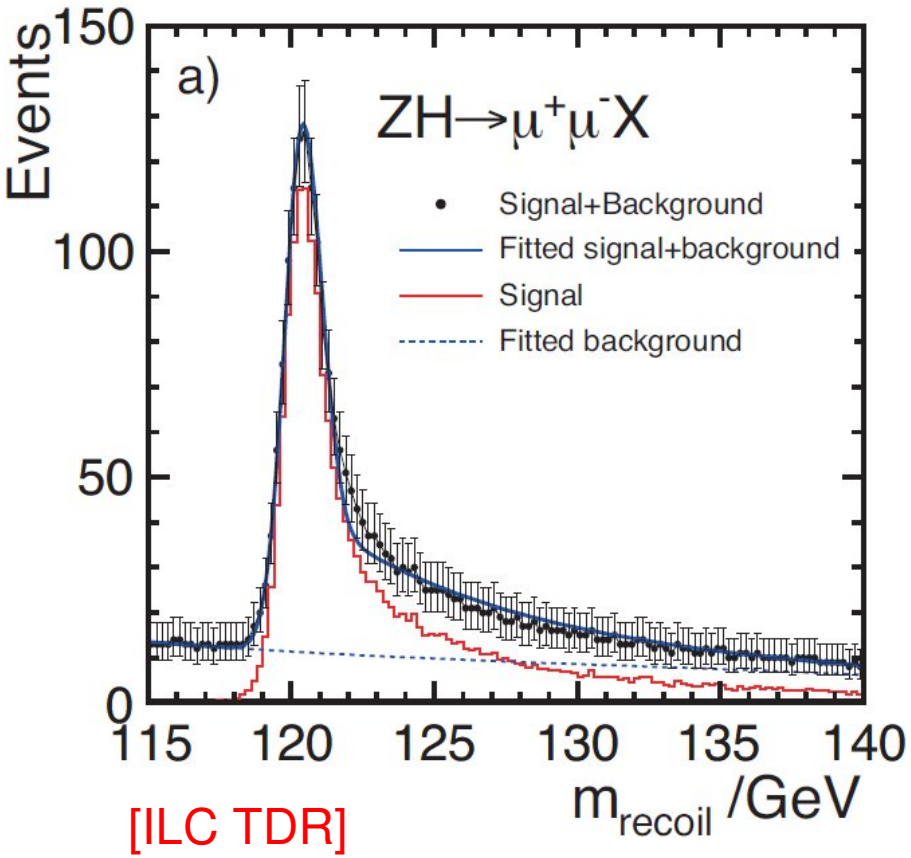
Problem: $m_H = 125\,\text{GeV} \leftrightarrow \Gamma_H = 4.07\,\text{MeV}$ $\quad \to \sigma^{Z\gamma\gamma}_{\text{ZWA}} = \sigma^{ZH}\,\frac{\Gamma_{H\to\gamma\gamma}}{\Gamma_H}$





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

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



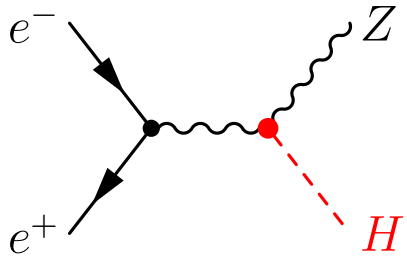
[ILC TDR]

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

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

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

Higgsstrahlung



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

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

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

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

Details: [1311.7155: Han, Liu, Sayre]

Two questions:
Is it possible to extract the total width from interference effects/off-shell contributions in $H \to VV$ (LHC inspired methods)?
Might off-shell contributions be problematic for the Z recoil method?

- 1. Quantification of contributions $m_{VV} > 2m_V$ 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]
[1307.4935; Caola, Melnikov: Constraining the Higgs boson width with ZZ production at the LHC]
Further elaboration of bounding the Higgs width in [1310.1397, 1311.3589, 1312.1628]
Application by CMS: [CMS-PAS-HIG-14-002]

- 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 of the mass peak shift in [1303.1397, 1305.3854]

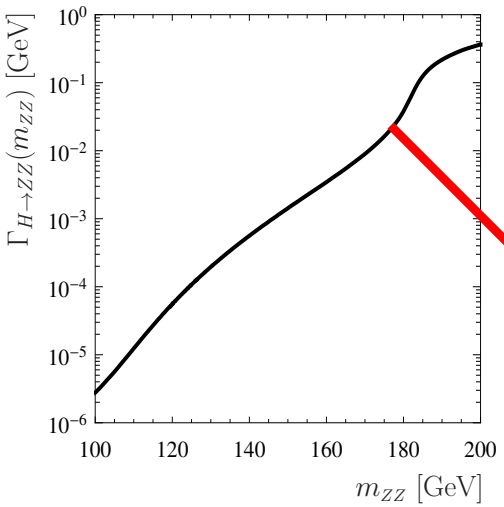
$\to$ Can also be investigated at the (I)LC!

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

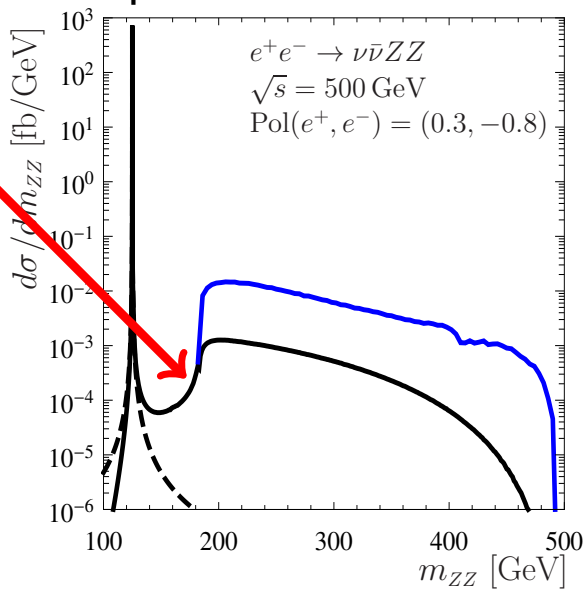
$$\left(\frac{d\sigma^{\nu\bar{\nu}ZZ}_{\text{ZWA}}}{dm_{ZZ}}\right) = \sigma^{\nu\bar{\nu}H}(m_H)\,\frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2}\,\frac{m_H\Gamma_{H\to ZZ}(m_H)}{\pi}$$

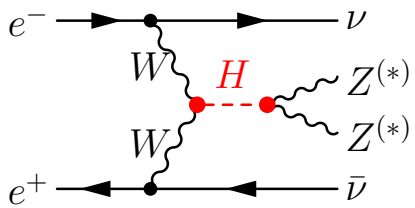
$$\left(\frac{d\sigma^{\nu\bar{\nu}ZZ}_{\text{off}}}{dm_{ZZ}}\right) = \sigma^{\nu\bar{\nu}H}(m_{ZZ})\,\frac{2m_{ZZ}}{(m_{ZZ}^2 - m_H^2)^2 + (m_H\Gamma_H)^2}\,\frac{m_{ZZ}\Gamma_{H\to ZZ}(m_{ZZ})}{\pi}$$

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

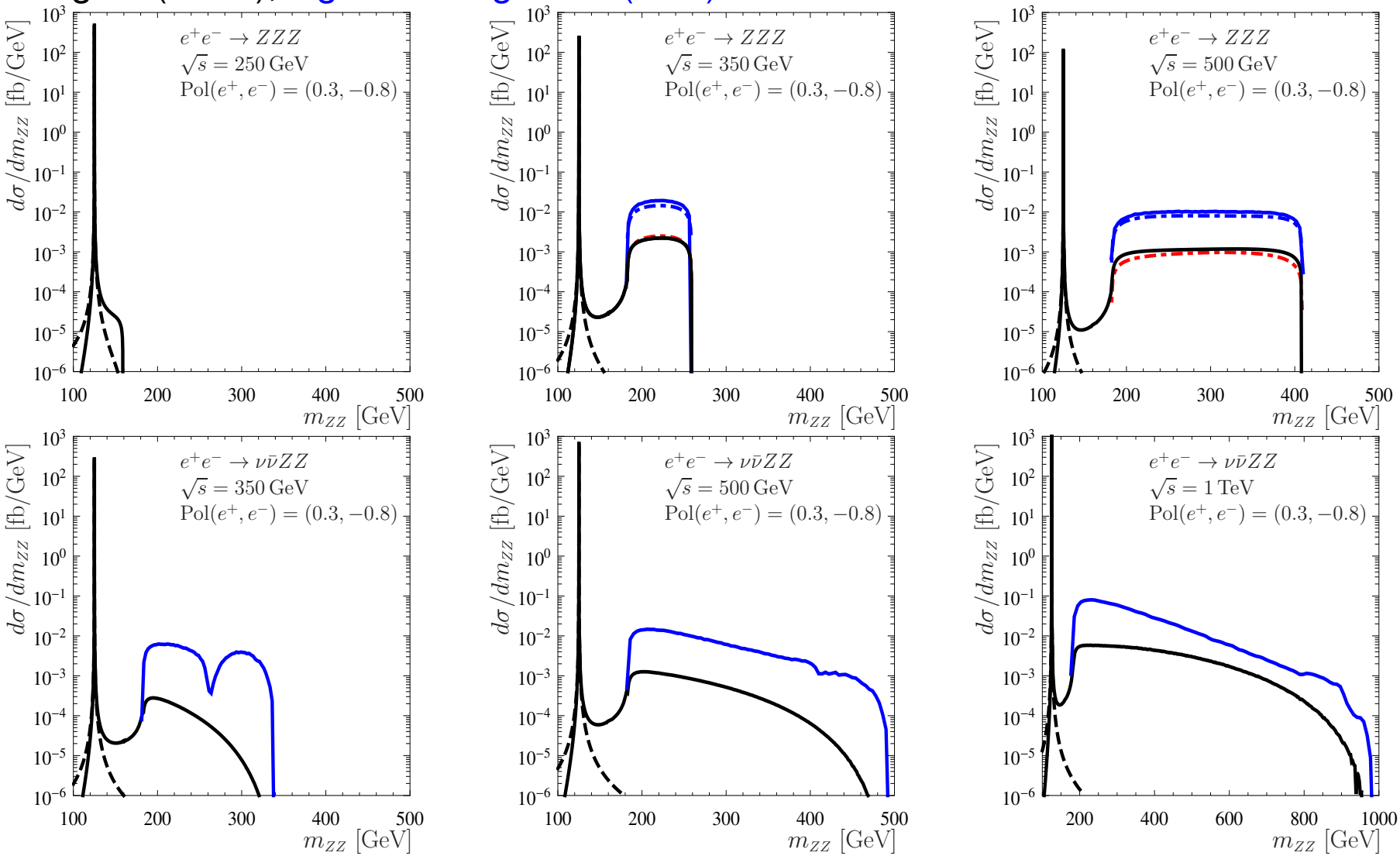


Consequences:





Quantification for the two production processes for different $\sqrt{s}$:
signal (black), signal+background (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

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

$\sqrt{s}$	$\sigma^{ZZZ}_{\text{off}}(0, \sqrt{s} - m_Z)$	$\Delta^{ZZZ}_{\text{off}}$	$\sigma^{\nu\bar{\nu}ZZ}_{\text{off}}(0, \sqrt{s})$	$\Delta^{\nu\bar{\nu}ZZ}_{\text{off}}$
250 GeV	3.12 fb	0.03 %	0.490 fb	0.12 %
300 GeV	2.40 fb	1.83 %	1.12 fb	0.40 %
350 GeV	1.82 fb	7.77 %	1.91 fb	0.88 %
500 GeV	0.981 fb	24.1 %	4.78 fb	2.96 %
1 TeV	0.341 fb	50.9 %	15.0 fb	13.0 %

Comments:

- Δ_{off} independent of the polarisation.
- For $H \to ZZ \to 4l$ off-shell contributions accessible by m_{4l}.

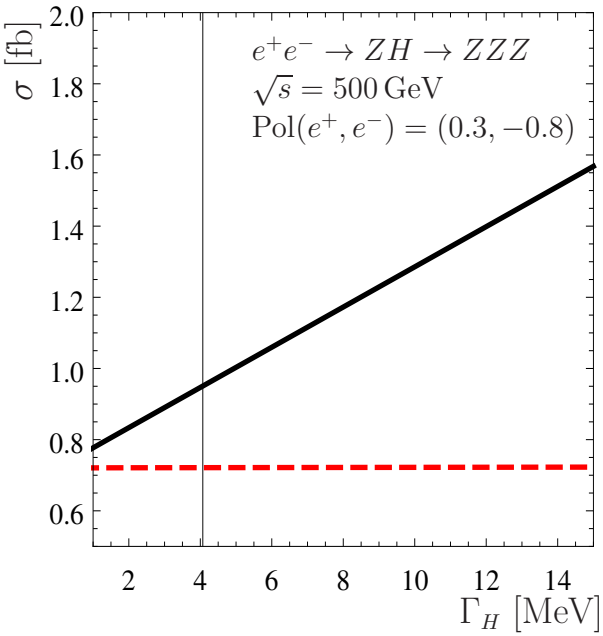
$\leftrightarrow$ For $H \to WW \to 2l2\nu$ not directly accessible! $\leftrightarrow$ Z recoil method!

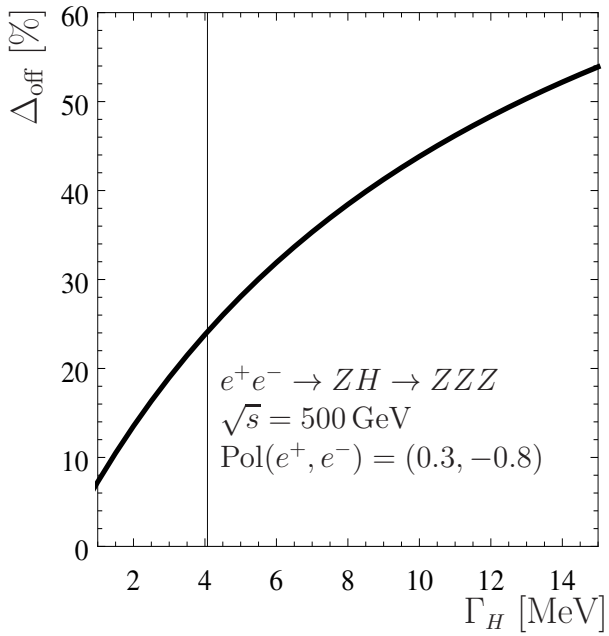
- Very important: High precision in Higgs mass measurement!

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

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

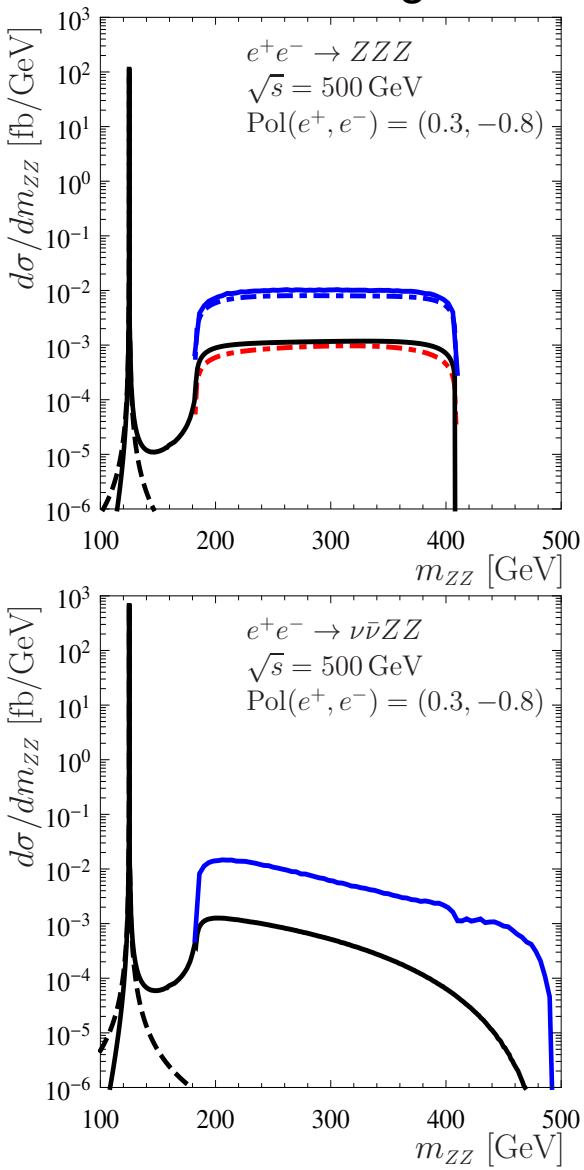
Rescaling $g'_{HZZ} = \xi g_{HZZ}$, $\Gamma'_H = \xi^4 \Gamma_H$ does not change $\sigma^{ZZZ}_{\text{ZWA}}$!
$\to$ Vary Γ_H (in reasonable interval!) and leave σ_{ZWA} constant!
$\to$ Off-shell contributions $\propto g^4_{HZZ} \to \Delta_{\text{off}}$ changes!.





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

Comment on the background:



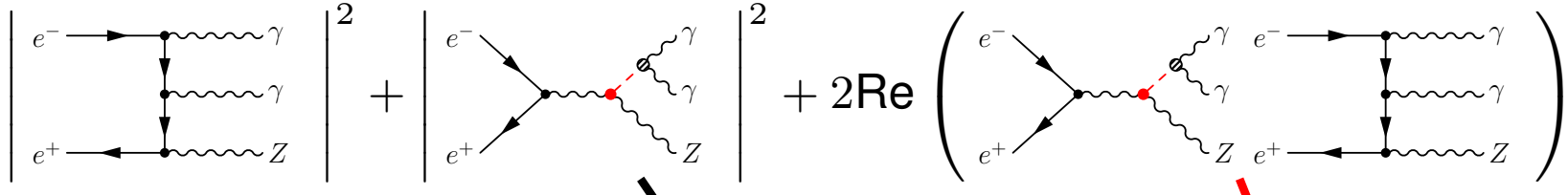
Inclusive cross sections for $m_{ZZ} > 130\,\text{GeV}$ for $\text{Pol}(e^+, e^-) = (0.3, -0.8)$:

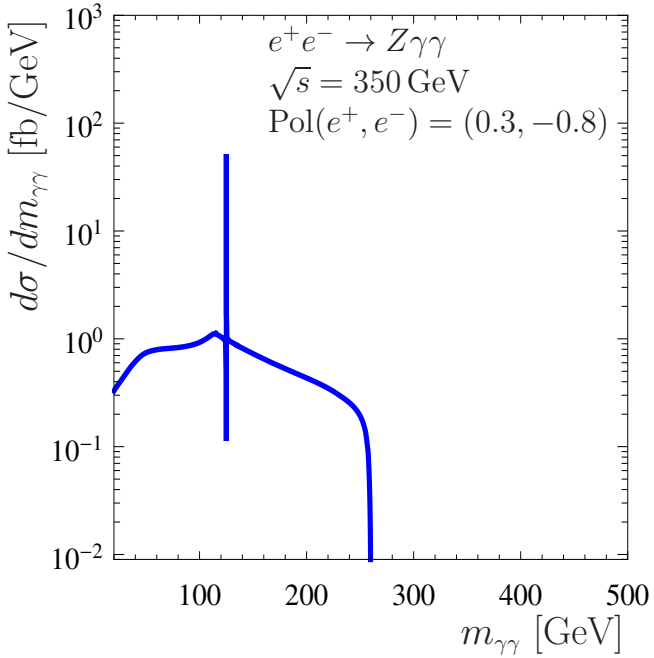
$\sqrt{s}$	$\sigma_{\text{all}}^{ZZZ}$	Δ_{SB}^{ZZZ}	$\sigma_{\text{all}}^{\nu\bar{\nu}ZZ}$	$\Delta_{\text{SB}}^{\nu\bar{\nu}ZZ}$
250 GeV	− − −	− − −	0.32 fb	0.18 %
300 GeV	0.34 fb	12.9 %	0.33 fb	1.36 %
350 GeV	1.19 fb	11.9 %	0.54 fb	3.07 %
500 GeV	2.06 fb	11.6 %	1.72 fb	8.20 %
1 TeV	1.71 fb	10.2 %	15.9 fb	12.2 %

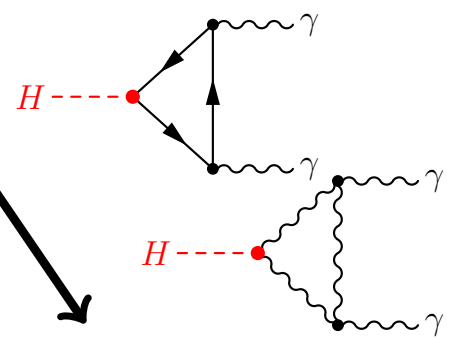
$\Delta_{\text{SB}} \leftrightarrow$ Signal/Background in off-shell region.

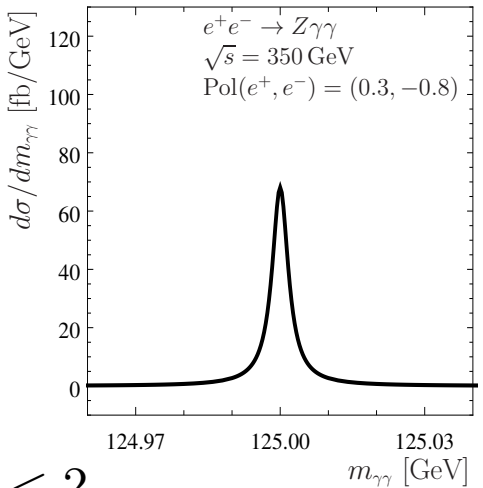
Further studies:
Needs simulation
with leptonic/hadronic final states!

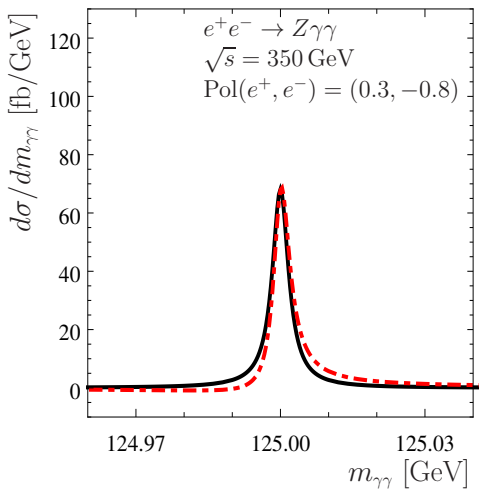
2. Interferometry with the background in $H \to \gamma\gamma$











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

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

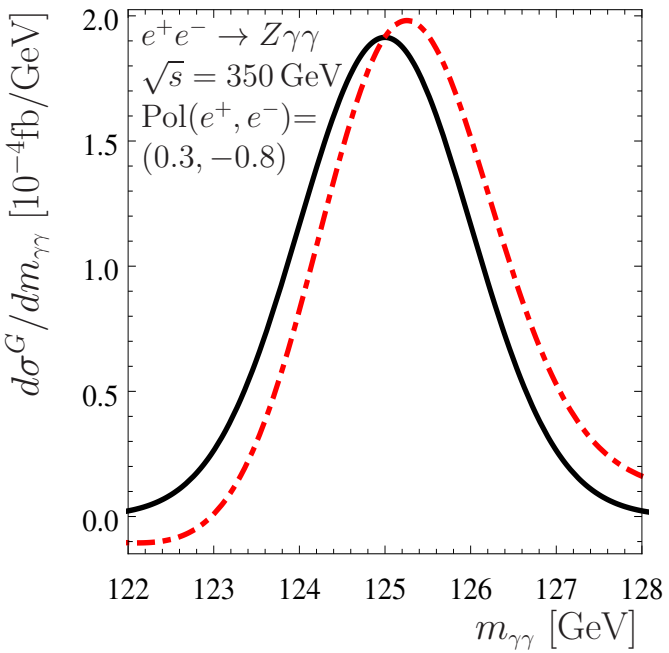
$$\frac{d\sigma^{sig}}{dm_{\gamma\gamma}} = \frac{S}{(m^2_{\gamma\gamma} - m^2_H)^2 + m^2_H\Gamma^2_H} \to \sigma^{sig} = \frac{\pi S}{2m^2_H\Gamma_H}$$
$$\frac{d\sigma^{int}}{dm_{\gamma\gamma}} = \frac{(m^2_{\gamma\gamma} - m^2_H)R + m_H\Gamma_H I}{(m^2_{\gamma\gamma} - m^2_H)^2 + m^2_H\Gamma^2_H} \to \sigma^{int} = \frac{\pi I}{2m_H}$$

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).

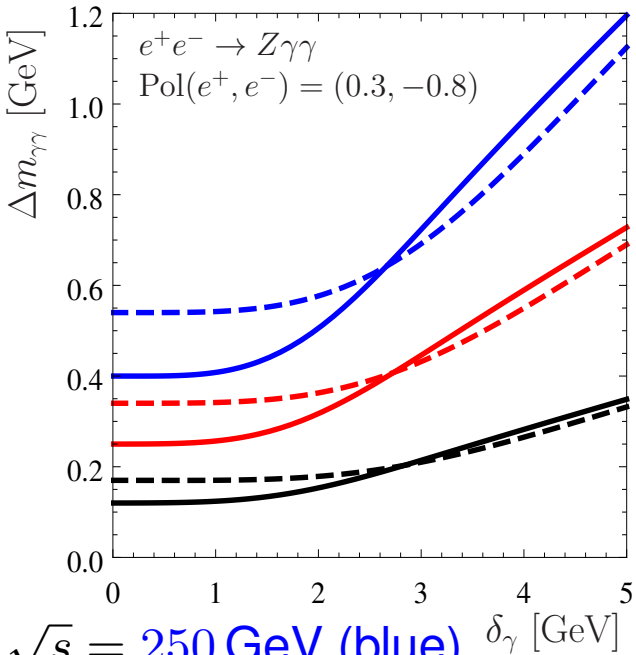


Mimic the method of peak extraction:

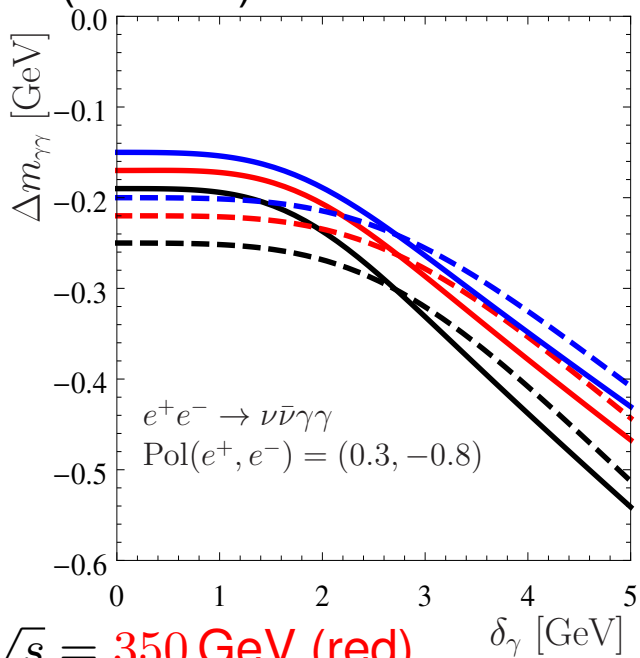
$$\langle m_{\gamma\gamma}\rangle_{\delta,X} = \frac{1}{N}\int_{m_p-\delta}^{m_p+\delta} dm_{\gamma\gamma}\, m_{\gamma\gamma}\,\frac{d\sigma_X^G}{dm_{\gamma\gamma}} \quad \to \Delta m_{\gamma\gamma} = \langle m_{\gamma\gamma}\rangle_{\delta_\gamma,S+I} - \langle m_{\gamma\gamma}\rangle_{\delta_\gamma,S}$$

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

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



$\sqrt{s} = 250\,\text{GeV}$ (blue), $350\,\text{GeV}$ (red), $500\,\text{GeV}$ (black)



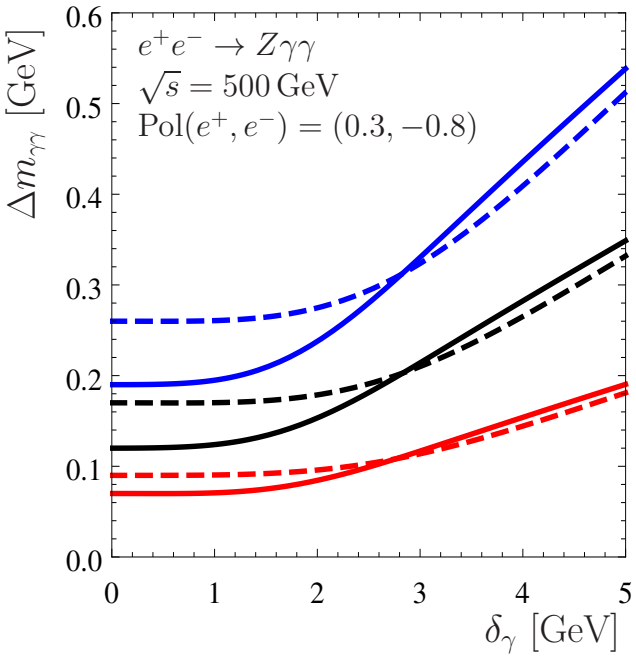
$\sqrt{s} = 350\,\text{GeV}$ (red), $500\,\text{GeV}$ (black), $1000\,\text{GeV}$ (blue)

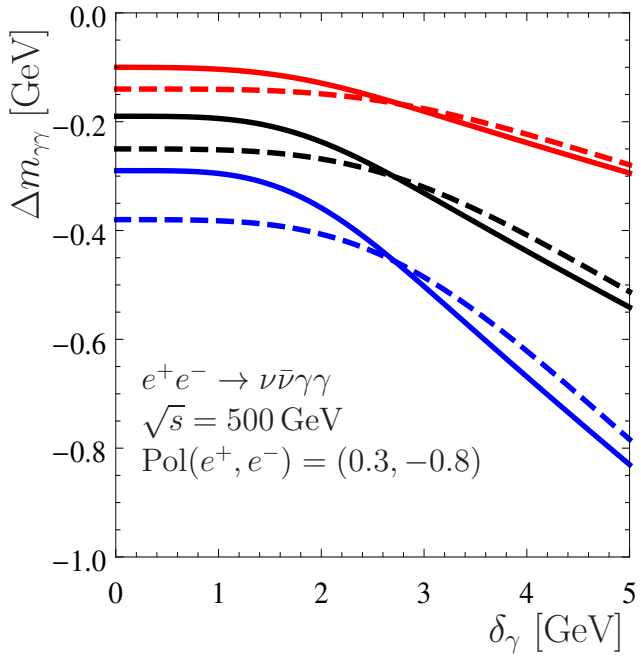
Higgs width dependence?

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

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

$\Gamma_H = 1\,\mathrm{MeV}$ (red), $4.07\,\mathrm{MeV}$ (black), $15\,\mathrm{MeV}$ (blue)





Further studies: Perform analysis with detector simulation?!

Conclusions:

- LC offers unique possibility to measure Higgs width through Z recoil measurements in $e^+e^- \to ZH$ at $250\,\text{GeV}$.
  For larger $\sqrt{s}$ be aware of off-shell contributions $m_{VV} > 2m_V$
  in $H \to ZZ/WW$!
- Recently discussed ideas to measure/bound Higgs width at LHC through
  - interferometry with background in $H \to \gamma\gamma$
  - off-shell contributions $m_{VV} > 2m_V$ in $H \to ZZ/WW$
  can be used at the (I)LC as well!
- For all purposes a well determined Higgs mass is necessary.

Simulation with fermionic/hadronic final states on order!
If you are interested, let me know!

Thank you for your attention!