Measurement of the Higgs-boson CP properties from decays into WW and ZZ at the Photon Collider

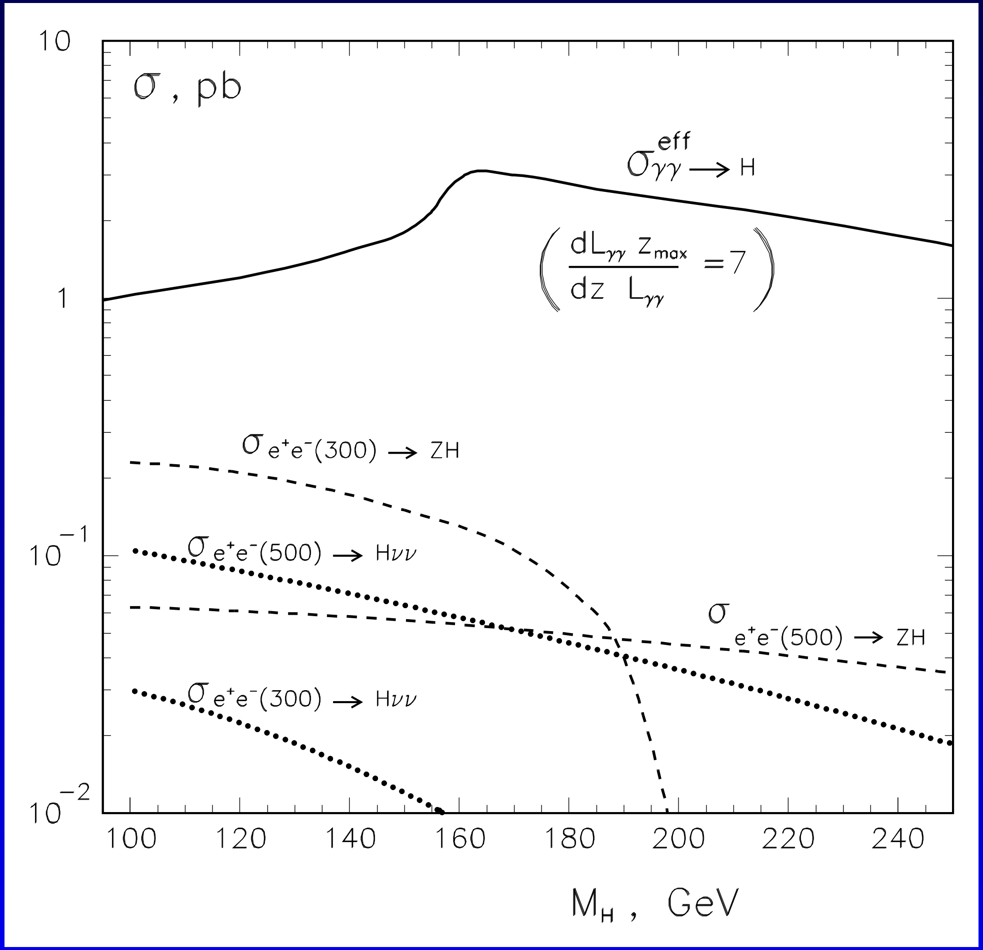
Higgs Physics at Future Colliders workshop
2004/2005

A.F.Żarnecki
09.03.2005

Introduction

Why do we need Photon Collider ?

Comparison of SM Higgs boson production cross sections:



$\gamma\gamma$ cross section order of magnitude higher

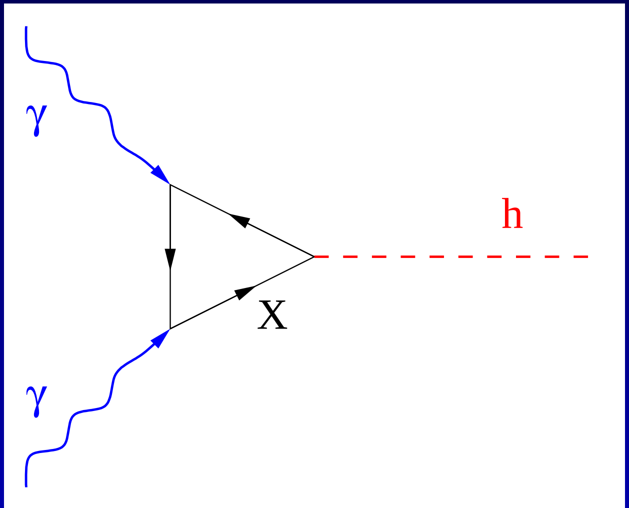
$$\sigma = \frac{1}{\mathcal{L}_{\gamma\gamma}} \frac{d\mathcal{L}^{J_z=0}_{\gamma\gamma}}{dW_{\gamma\gamma}} \cdot \frac{4\pi^2\,\Gamma_{\gamma\gamma}}{M_h^2}$$

expected $\gamma\gamma$ luminosity similar to e^+e^-

Higgs boson at PC

Two-photon width of the Higgs boson $\Gamma_{\gamma\gamma}$ is sensitive to all massive and charged particles in the loop:

$$\Gamma(h \to \gamma\gamma) \;=\; \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\,\pi^3} \cdot |\mathcal{A}|^2$$



where:

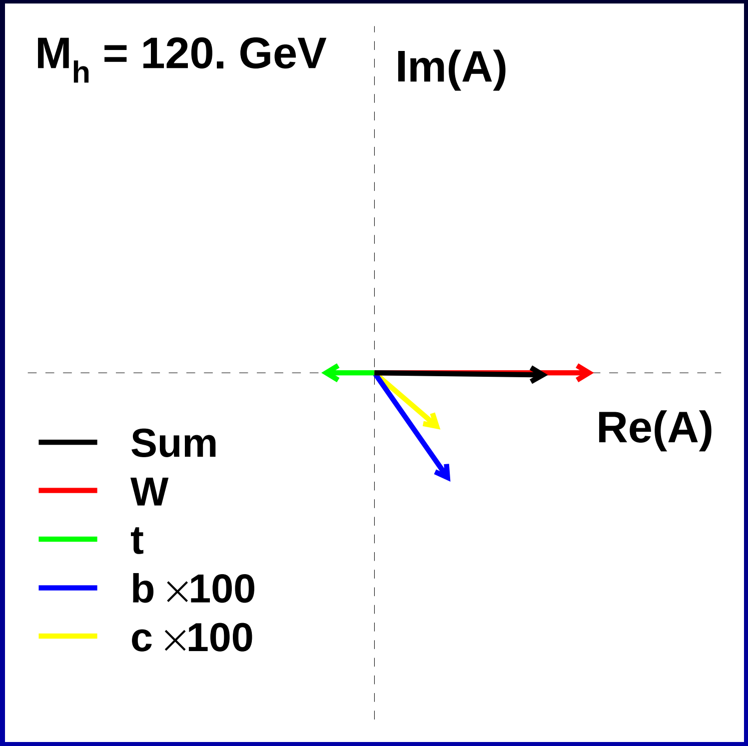
$$\mathcal{A} = A_W(M_W) + \sum_f N_c Q_f^2 A_f(M_f) + \ldots$$

two-photon amplitude

Phase

amplitude $\mathcal{A}$ is real

imaginary contribution from light fermions - very tiny



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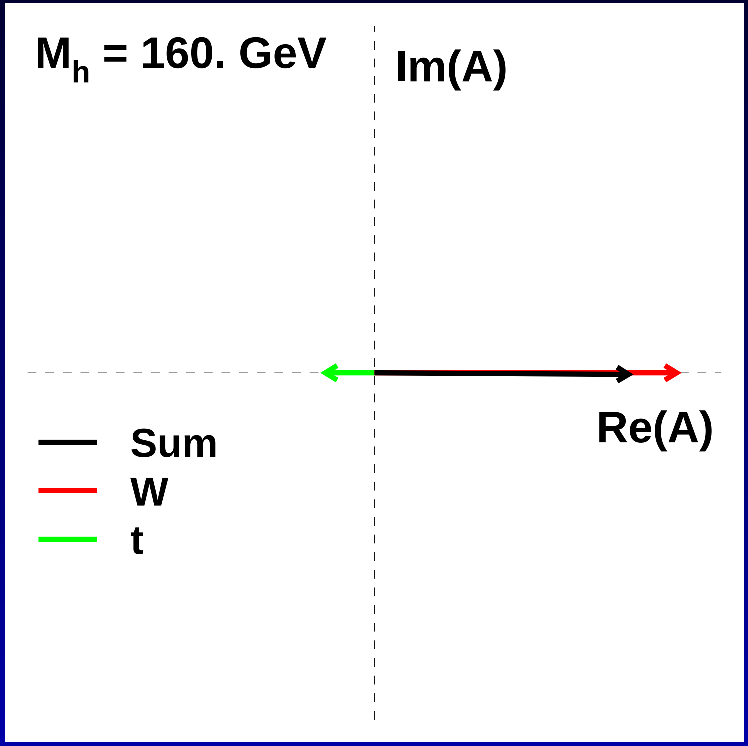
amplitude $\mathcal{A}$ is real



Phase

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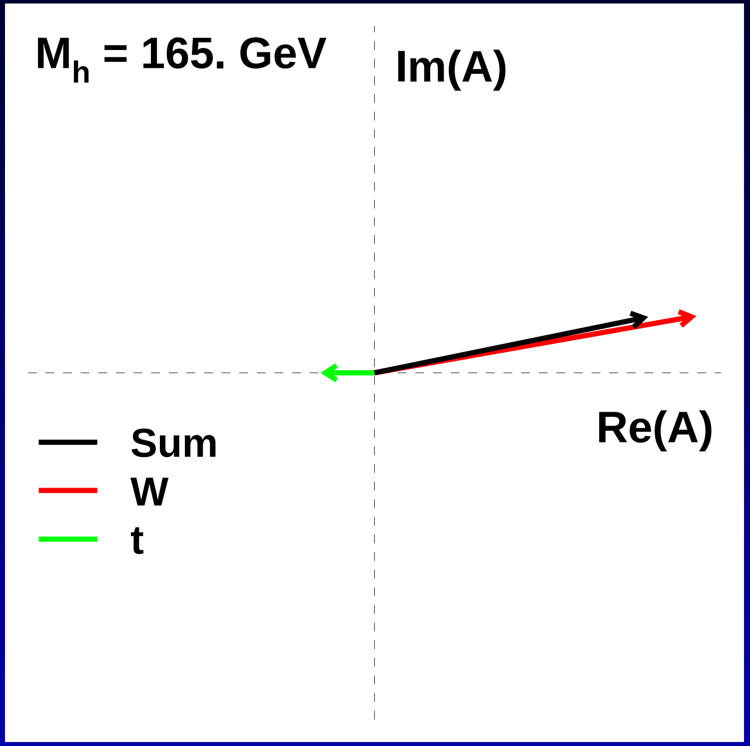
For $m_H > 2m_W$
W contribution is complex



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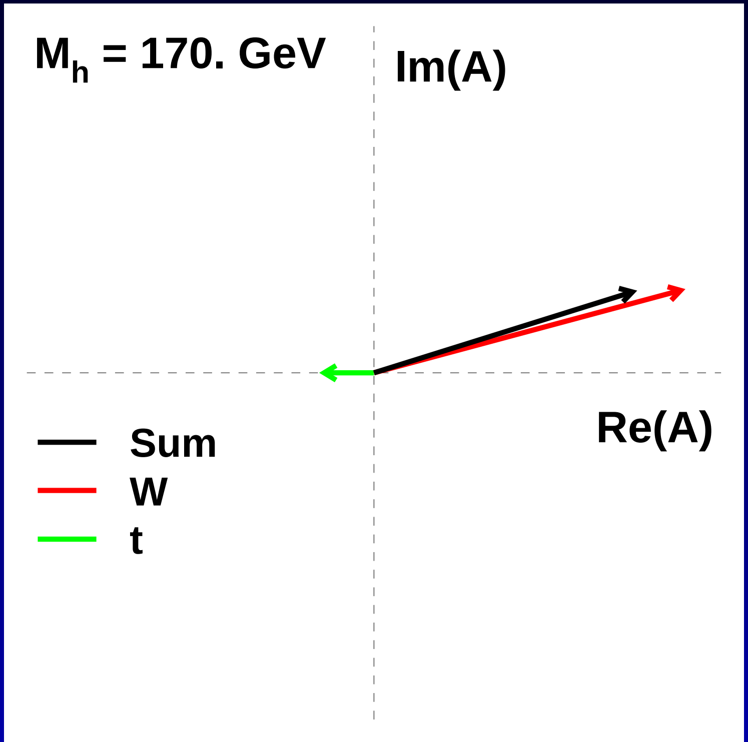

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For $m_H > 2m_W$
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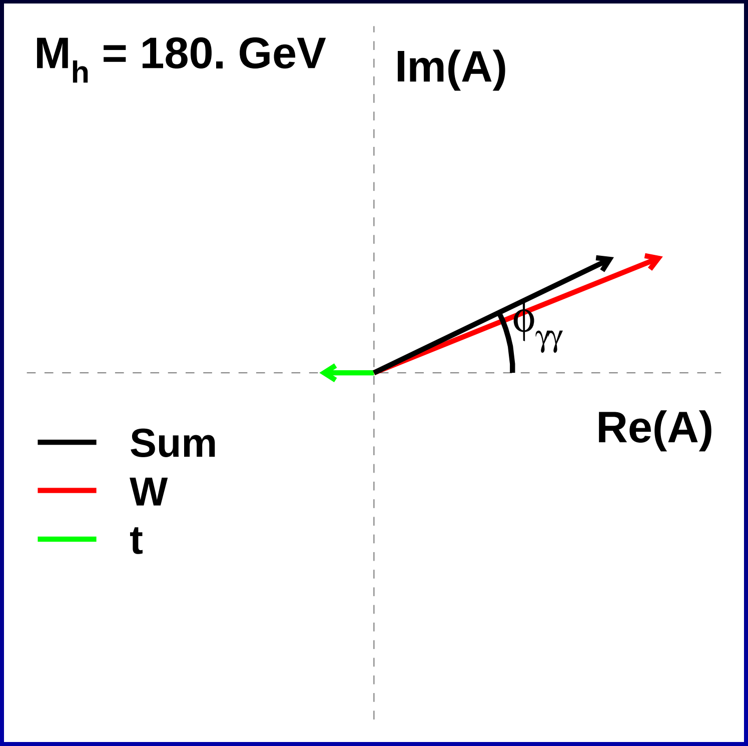
$\mathcal{A} = |\mathcal{A}| \cdot e^{i\phi}$ - phase $\phi_{\gamma\gamma} \neq 0$

$\Gamma_{\gamma\gamma} \sim Im(\mathcal{A})^2 + Re(\mathcal{A})^2$



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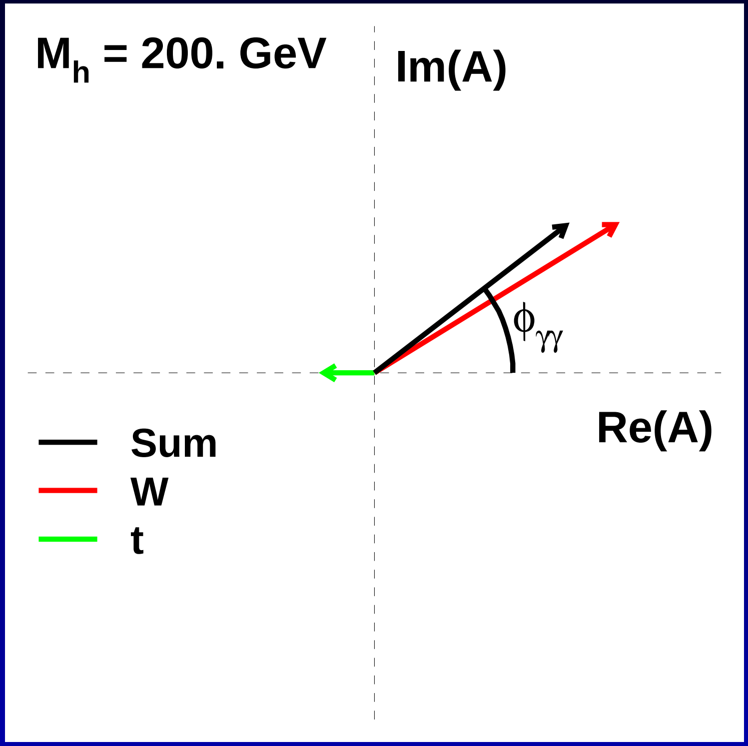

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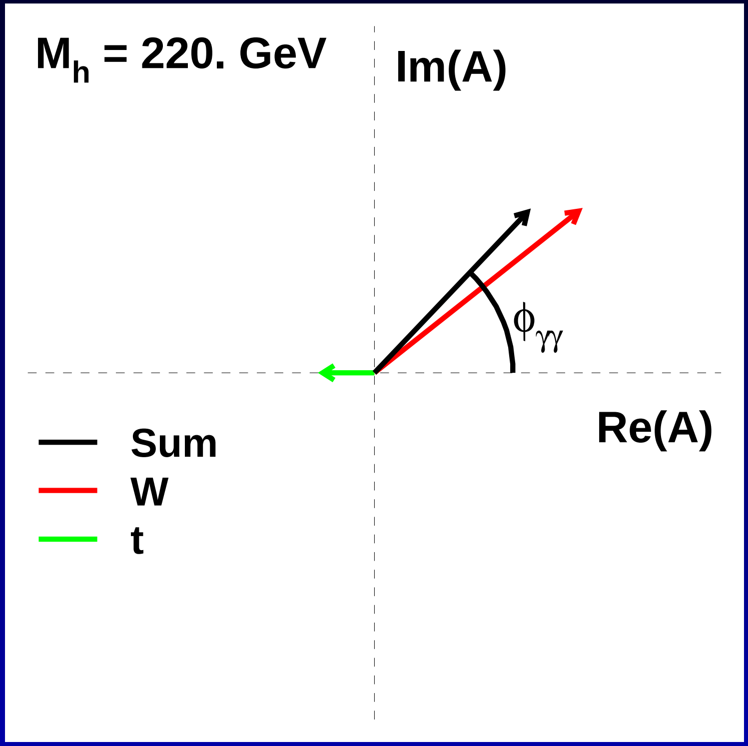

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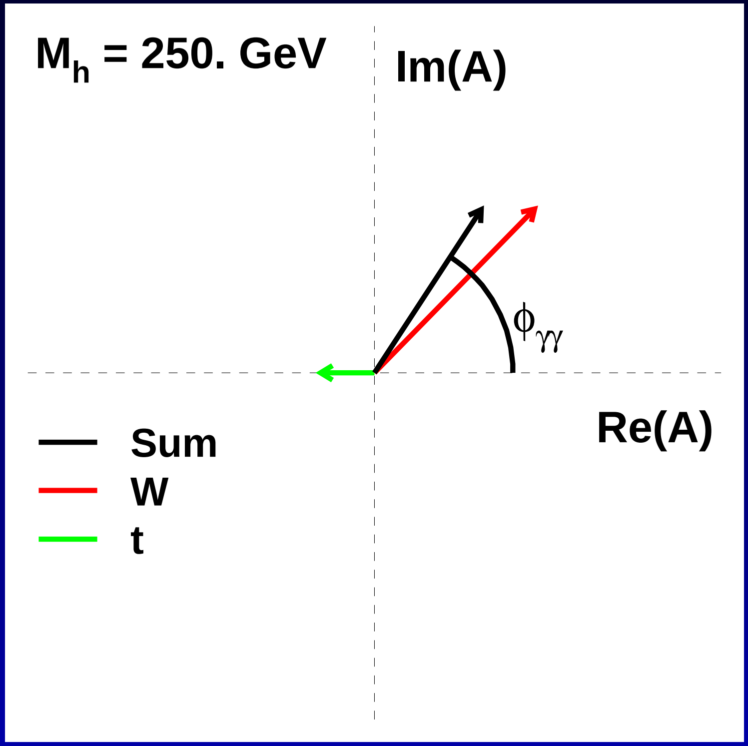

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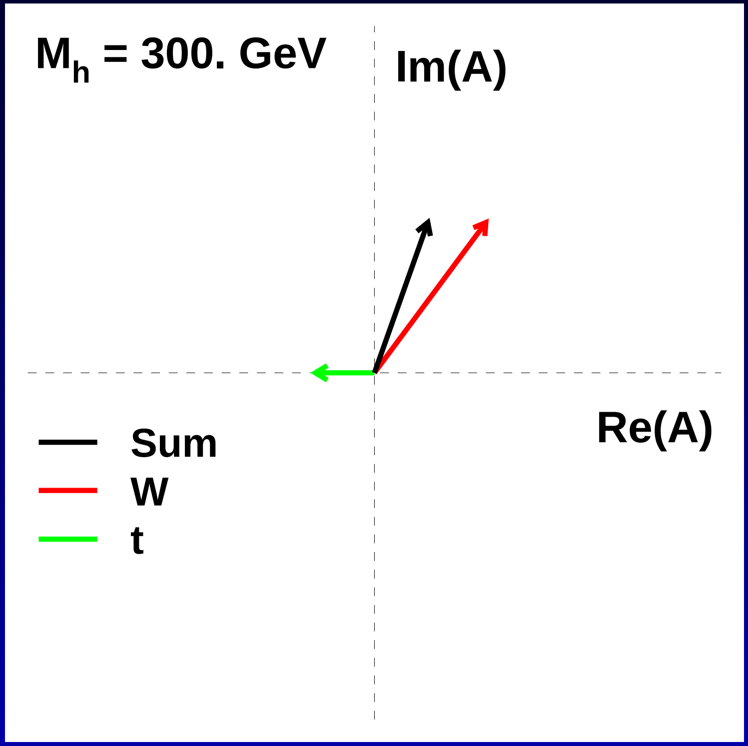

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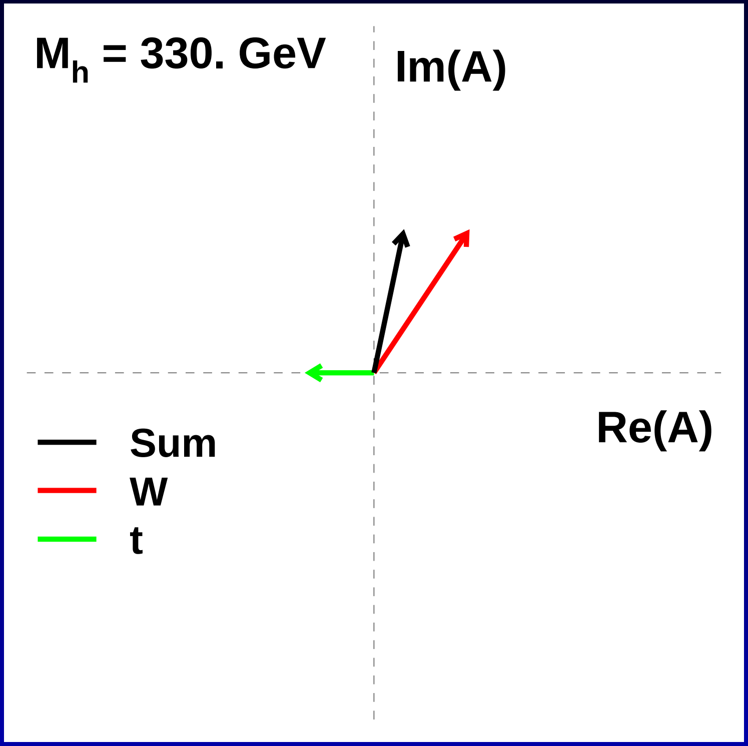

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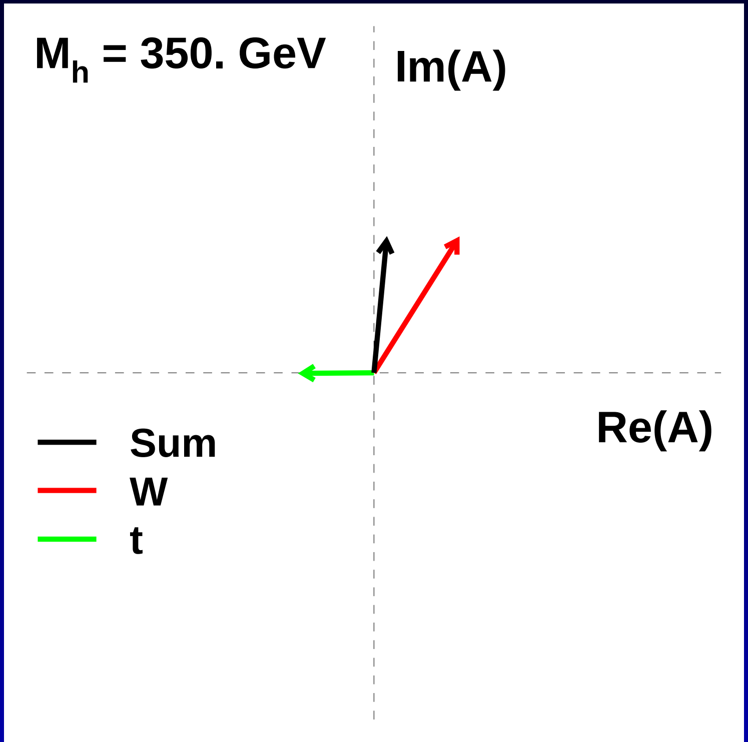

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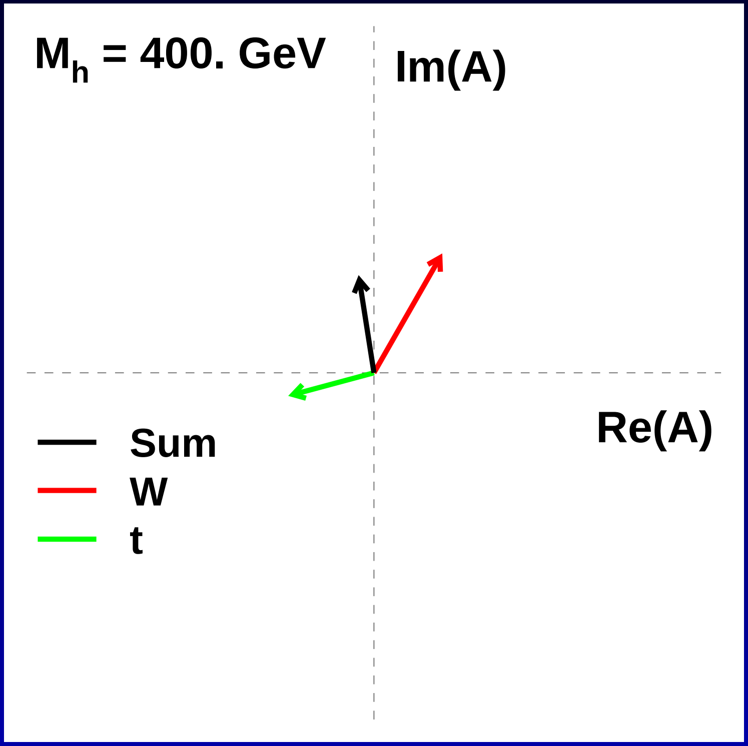

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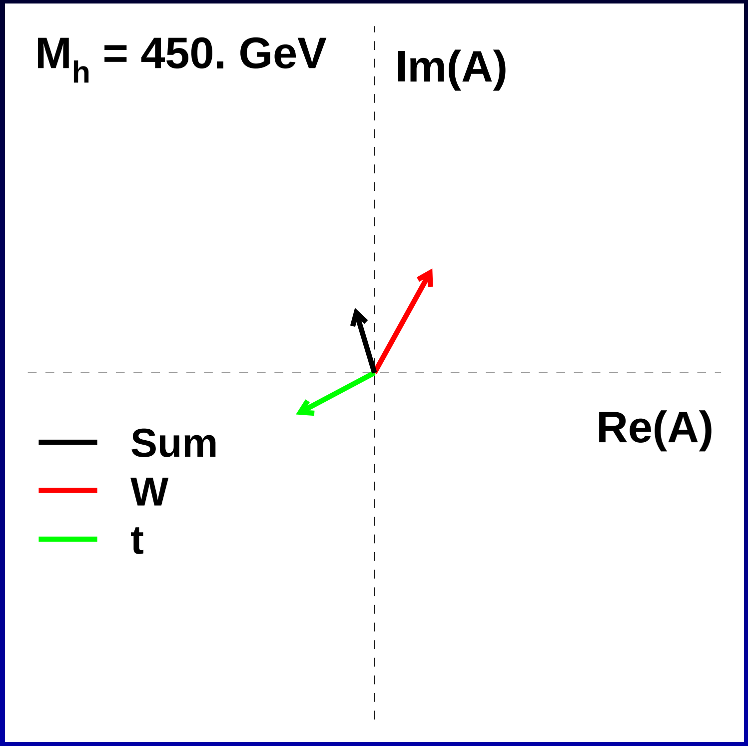

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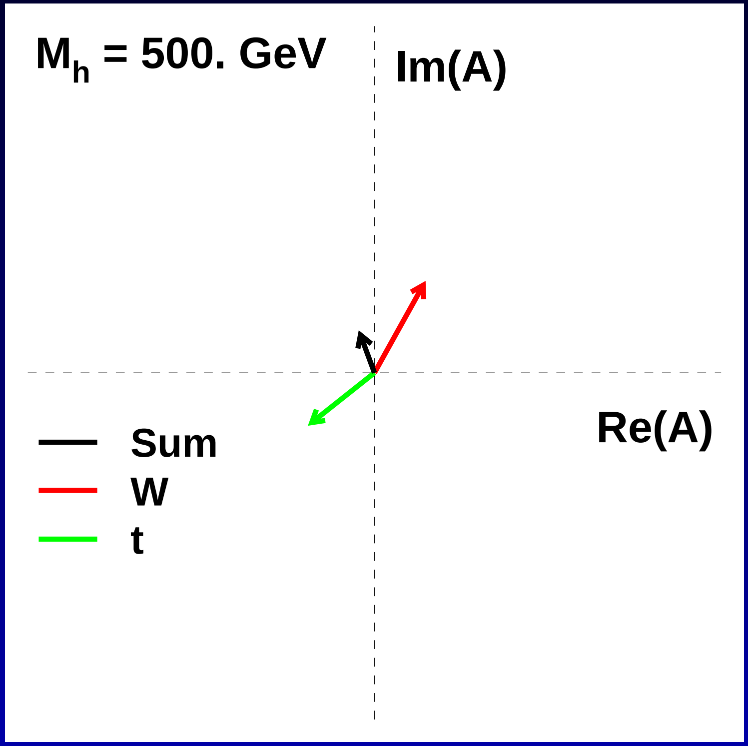
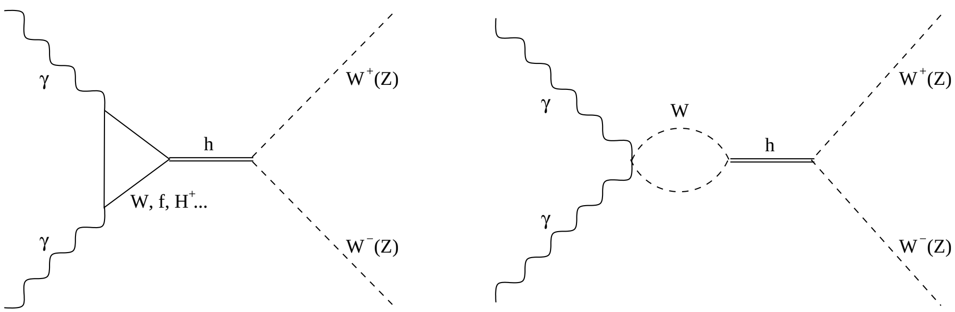


$\gamma\gamma \to (h) \to W^+W^-, ZZ$

Higgs production and decay

For $M_h > 2M_W$, $h \to W^+W^-$ dominate:



"resonant"

There is a large background from "direct", non-resonant production $\gamma\gamma \to W^+W^-$

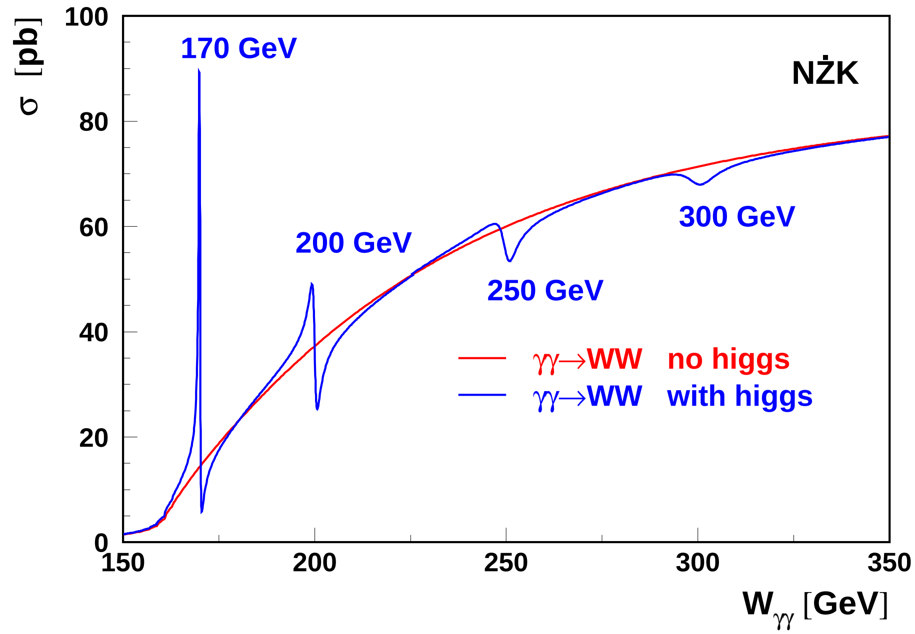
G.Belanger,F.Boudjema, Phys.Lett.B288(1992)210;
D.A.Morris, et al., Phys. Lett. B323(1994)421;
I.F.Ginzburg, I.P.Ivanov, Phys. Lett. B408(1997)325.

Interference

Resonant and direct amplitudes interfere

Large effects expected:

$J_z = 0$

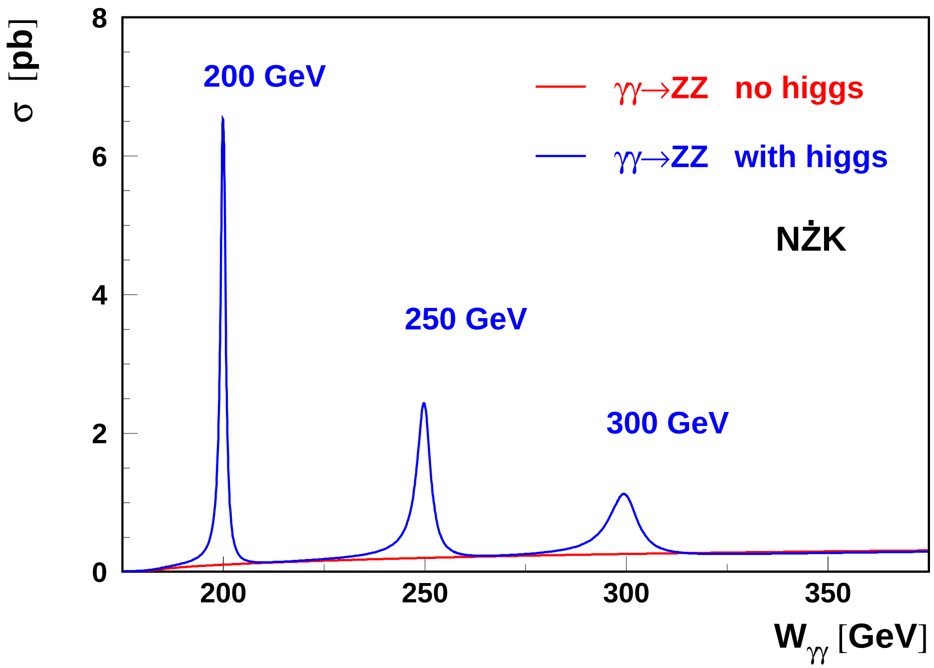


Destructive interference dominates above $\sim$200 GeV

$\gamma\gamma \to (h) \to W^+W^-, ZZ$

$\gamma\gamma \to ZZ$

Non-resonant background only at loop level



⇒ small interference effects

G.J.Gounaris et al., Eur. Phys. J. C13 (2000) 79.

Simulation

$\gamma\gamma$ spectra from **CompAZ** hep-ex/0207021

$\gamma\gamma \to W^+W^-, ZZ$ events generated with PYTHIA 6.152

events reweighted to take into account:

- beam polarization
- Higgs production and interference

detector simulation with SIMDET v. 3.01

total $\gamma\gamma$ luminosity: 600 – 1000 fb^{-1}

High $W_{\gamma\gamma}$ peak: 75 – 115 fb^{-1}

for $\sqrt{s_{ee}}$ = 305 – 500 GeV

$\gamma\gamma \to (h) \to W^+W^-, ZZ$

Parametrization

"Measured" invariant mass distribution
for selected W^+W^- and ZZ events
is described by convolution of:

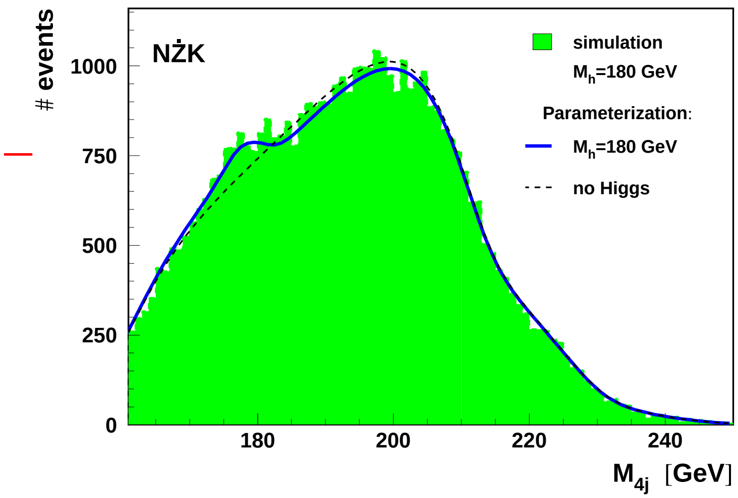
- Analytical luminosity Spectra **CompAZ**
- Cross section formula
  for signal + background + interf.
- Invariant mass resolution
  parametrized as a function of $W_{\gamma\gamma}$

$\Rightarrow$ mass spectra can be calculated for any $\sqrt{s_{ee}}$ and m_h without time-consuming MC simulation

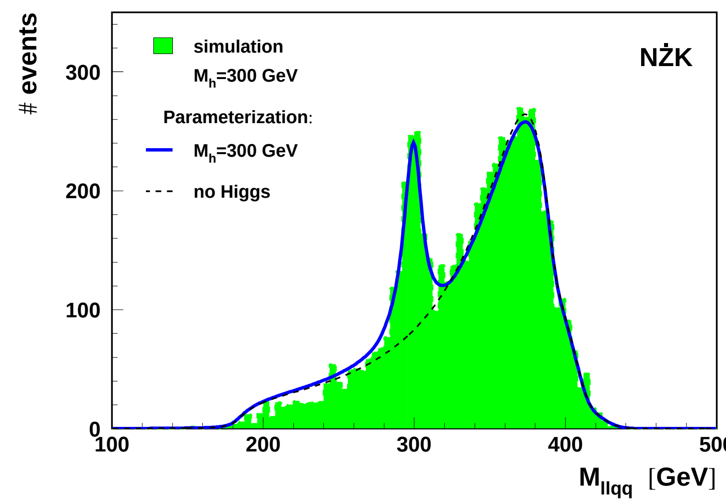
$\Rightarrow$ can be used for fast simulation and fitting

Comparison with full simulation:

W^+W^-



ZZ

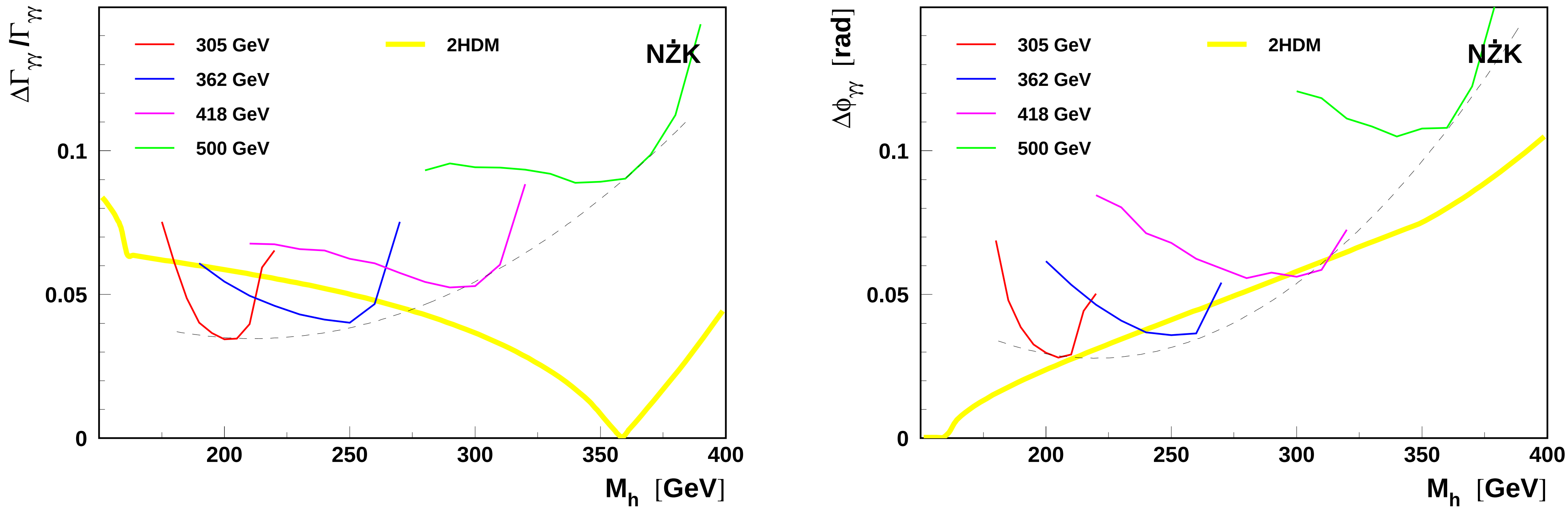


SM results

Two parameter fit to W^+W^- and ZZ invariant mass distribution

Expected statistical precision, assuming SM branching ratios (1 PC year):

$\Gamma_{\gamma\gamma}$ hep-ph/0207294 $\phi_{\gamma\gamma}$



Phase measurement significantly improves our sensitivity to new heavy charged particles
e.g. heavy charged Higgs boson of the SM-like 2HDM(II) with $M_{H+} = 800$ GeV
at large Higgs boson masses

CP conserving 2HDM (II)

Higgs boson couplings

Scalar Higgs bosons h and H with basic couplings (relative to SM):

$$\chi_x = g_{\mathcal{H}xx}/g^{SM}_{\mathcal{H}xx} \qquad \mathcal{H} = h, H, A$$

	h	H	A
χ_u	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-i\,\gamma_5\,\frac{1}{\tan\beta}$
χ_d	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-i\,\gamma_5\,\tan\beta$
χ_V	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0

For charged Higgs boson couplings (loop contribution to $\Gamma_{\gamma\gamma}$) we set

$$M_{H^\pm} = 800\,GeV \qquad \mu = 0$$

Higgs couplings are related by "patter relation"

$$(\chi_V - \chi_d)(\chi_u - \chi_V) + \chi_V^2 = 1$$

I. F. Ginzburg, M. Krawczyk and P. Osland, hep-ph/0101331

Instead of angles α and β use couplings χ_V and χ_u to parametrize cross sections

$$0 \leq \chi_V \leq 1$$

If we neglect H decays to h and A (small) cross sections and BRs calculated for H are also valid for h

2HDM(II)

SM-like 2HDM(II)

Solution A

For light Higgs boson h:

$$\chi_u = \chi_d = \chi_V \;=\; 1$$

χ_i - couplings normalized to SM couplings

All couplings are the same as in SM.

$\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$ affected only by the H^+ loop

For heavy Higgs bosons H and A:

$$\chi_V \;\equiv\; 0$$

No decays to W^+W^- and ZZ ...

I. F. Ginzburg, M. Krawczyk and P. Osland,
Nucl. Instrum. Meth. A472:149, 2001
hep-ph/0101331; hep-ph/0101208.

Solution B (extended)

	h	H	A
χ_u	-1	$-\frac{1}{\tan\beta}$	$-i\,\gamma_5\,\frac{1}{\tan\beta}$
χ_d	$+1$	$-\tan\beta$	$-i\,\gamma_5\,\tan\beta$
χ_V	$\cos(2\beta)$	$-\sin(2\beta)$	0

$\tan\beta \to 0 \;\Rightarrow$ sol. B_u

$\tan\beta \to \infty \Rightarrow$ sol. B_d

Higgs production ($\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$)
and decays depend on $\tan\beta$.

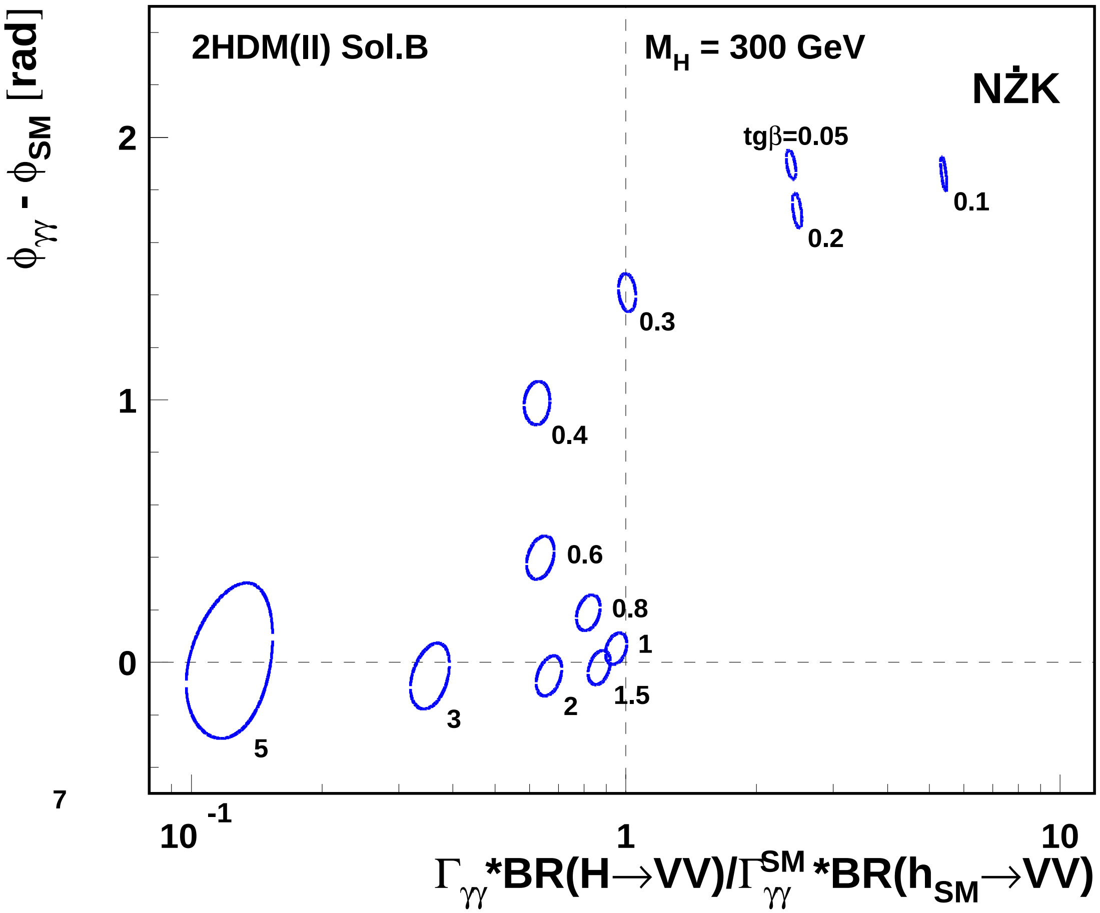
Can we extract $\tan\beta$ value from the measured W^+W^- and ZZ invariant mass distributions ?

SM-like 2HDM(II)

Heavy Higgs boson H

Two-photon width and phase measurement for different $\tan\beta$ $\chi_V = -\sin 2\beta$

M_H = 300 GeV



$\Gamma_{\gamma\gamma}$ enhancement for $\tan\beta < 1$ due to top contribution ($\chi_u = -\frac{1}{\tan\beta}$)

1σ contours for 1 year of PC running

statistical errors only

M_h=120 GeV, M_{H+}=800 GeV

SM-like 2HDM(II)

Light Higgs boson

Influence of systematic uncertainties on the $\tan\beta$ determination
is estimated by adding additional free parameters to the fit:

Uncertainties:	Parameters:
• luminosity	$\Rightarrow$ overall normalization relative normalization of WW and ZZ samples fixed
• energy scale	$\Rightarrow$ Higgs boson mass
• mass resolution	$\Rightarrow$ Higgs boson width
• luminosity spectra	$\Rightarrow$ spectra shape variations

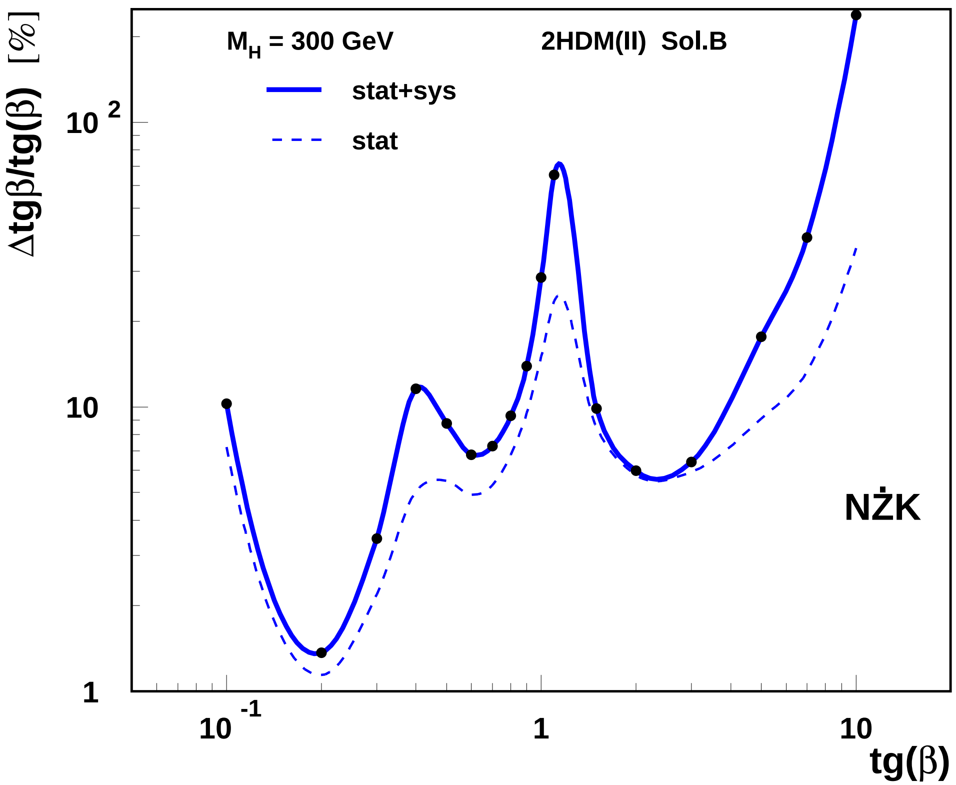
$$\frac{dL}{dW_{\gamma\gamma}} = \frac{dL^{CompAZ}}{dW_{\gamma\gamma}}(1 + A \cdot \sin \pi x + B \cdot \sin 2\pi x)$$

$$x = \frac{W_{\gamma\gamma} - W_{min}}{W_{max} - W_{min}}$$

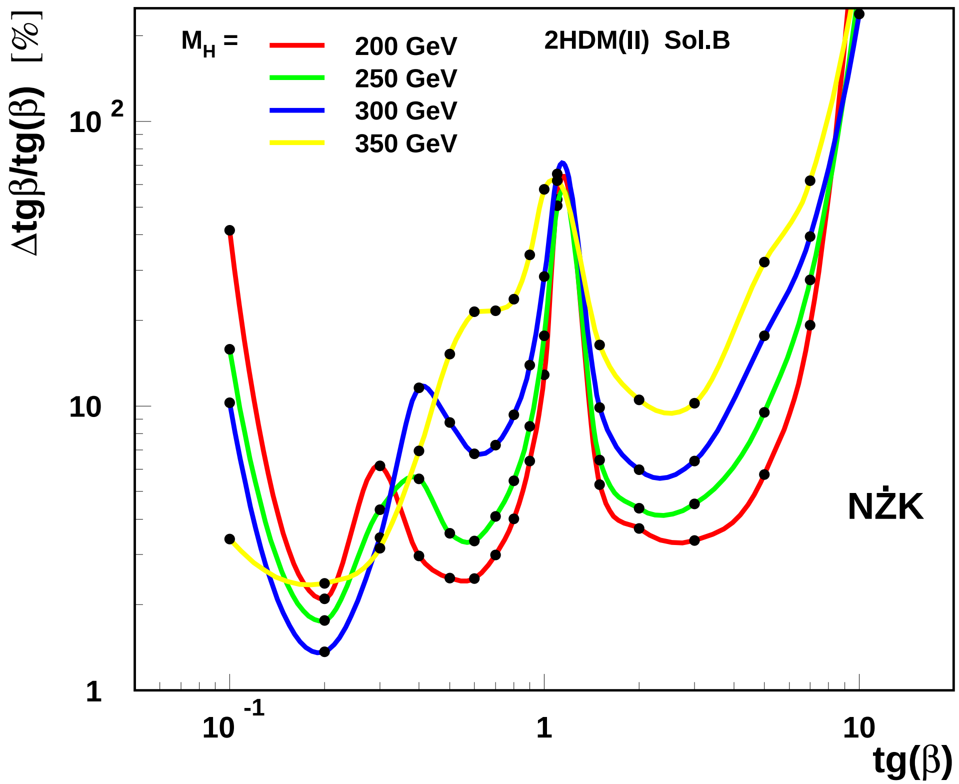
SM-like 2HDM(II)

Heavy Higgs boson H

Influence of systematic uncertainties for $M_H = 300$ GeV



Expected precision in $\tan\beta$ determination stat. + sys. errors



Large effects of systematic uncertainties

2HDM(II) with CP violation

General Two Higgs Doublet Model

Mass eigenstates of the neutral Higgs-bosons h_1, h_2 and h_3 do not need to match CP eigenstates h, H and A.

We consider SM-like 2HDM(II) with CP violation

through a small mixing between H and A states

Couplings relative to SM: (assuming $|\Phi_{HA}| \ll 1$)

$$\begin{aligned}
\chi_X^{h_1} &\approx \chi_X^{h} \\
\chi_X^{h_2} &\approx \chi_X^{H} \cdot \cos\Phi_{HA} + \chi_X^{A} \cdot \sin\Phi_{HA} \\
\chi_X^{h_3} &\approx \chi_X^{A} \cdot \cos\Phi_{HA} - \chi_X^{H} \cdot \sin\Phi_{HA}
\end{aligned}$$

$X = u,\ d$ or V; $\quad V = W$ or Z

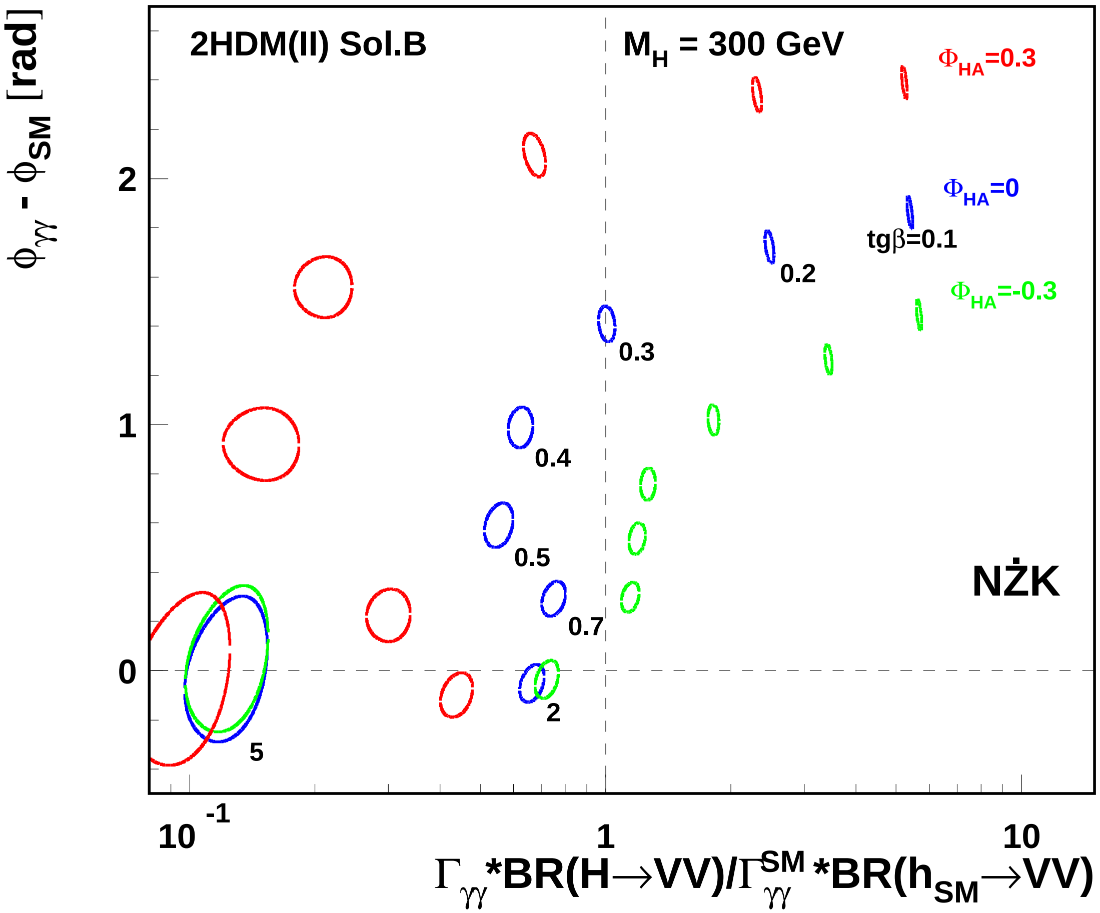
$\Rightarrow$ additional model parameter: **CP-violating mixing phase** Φ_{HA}

2HDM(II) with CP violation

Higgs boson h_2

Two-photon width and phase measurement for different $\tan\beta$ $\Phi_{HA} = 0$

M_{h_2} = 300 GeV



Low $\tan\beta$

$\Rightarrow$ large effects due to H-A mixing

Large $\tan\beta$

$\Rightarrow$ little sensitivity to Φ_{HA}

1σ contours for 1 year of PC running

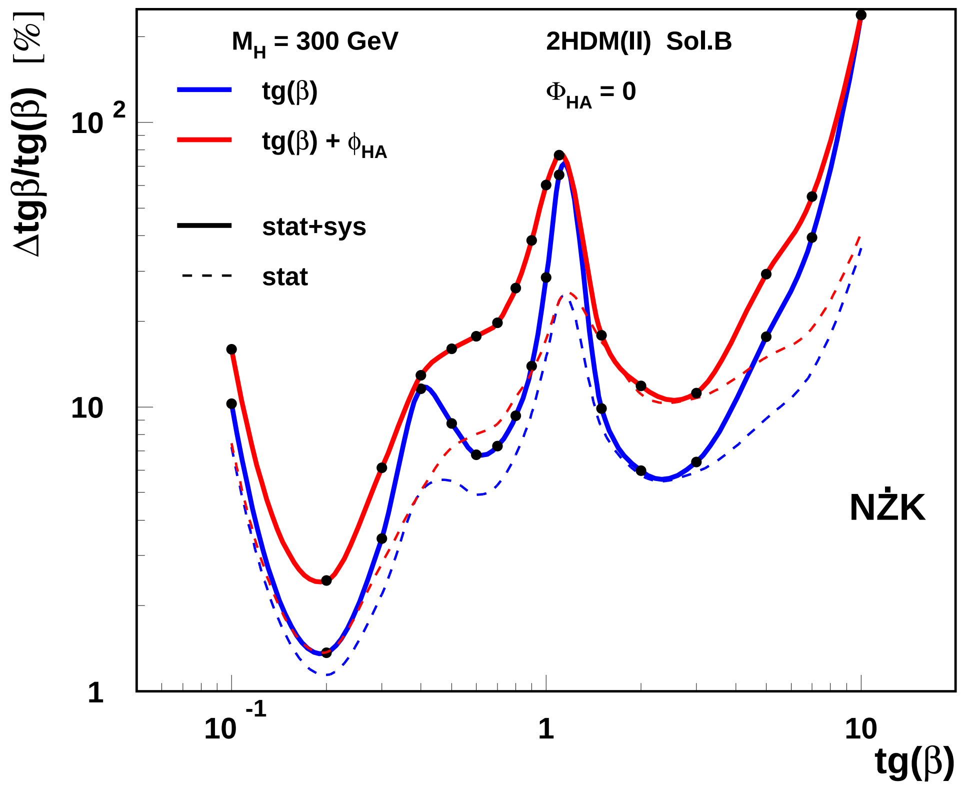
statistical errors only

M_h=120 GeV, M_{H+}=800 GeV

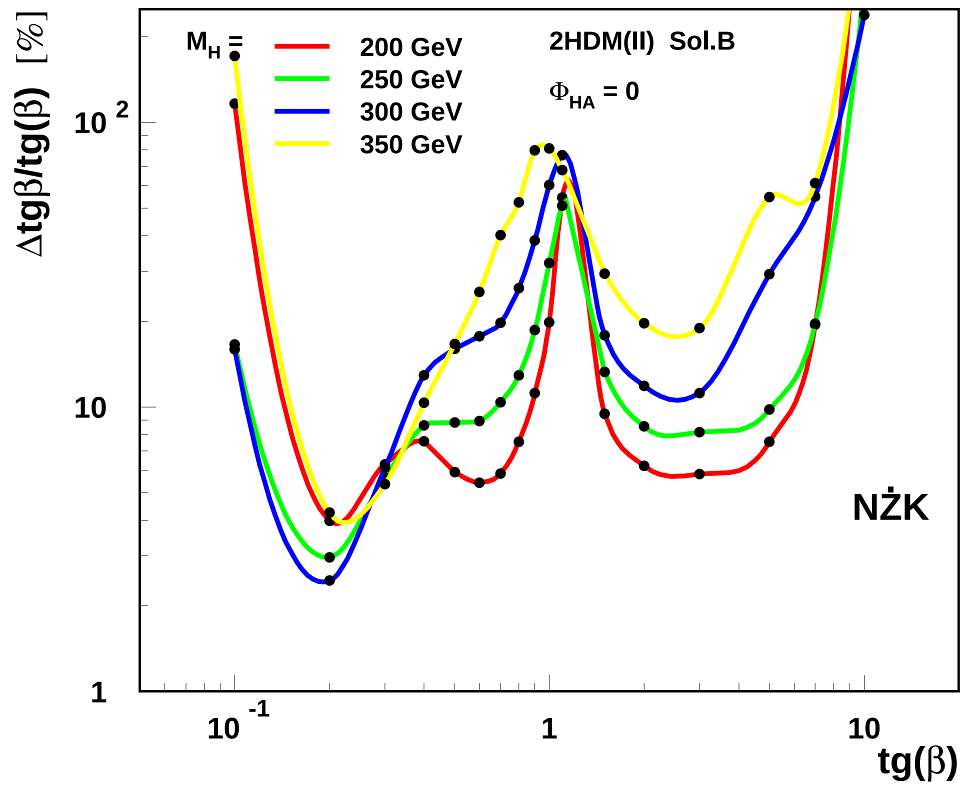
2HDM(II) with CP violation

Higgs boson h_2

Influence of phase and systematics in $\tan\beta$ determination ($M_H = 300$ GeV)



Expected precision in $\tan\beta$ determination
stat. + sys. errors from $\tan\beta$ and Φ_{HA} fit

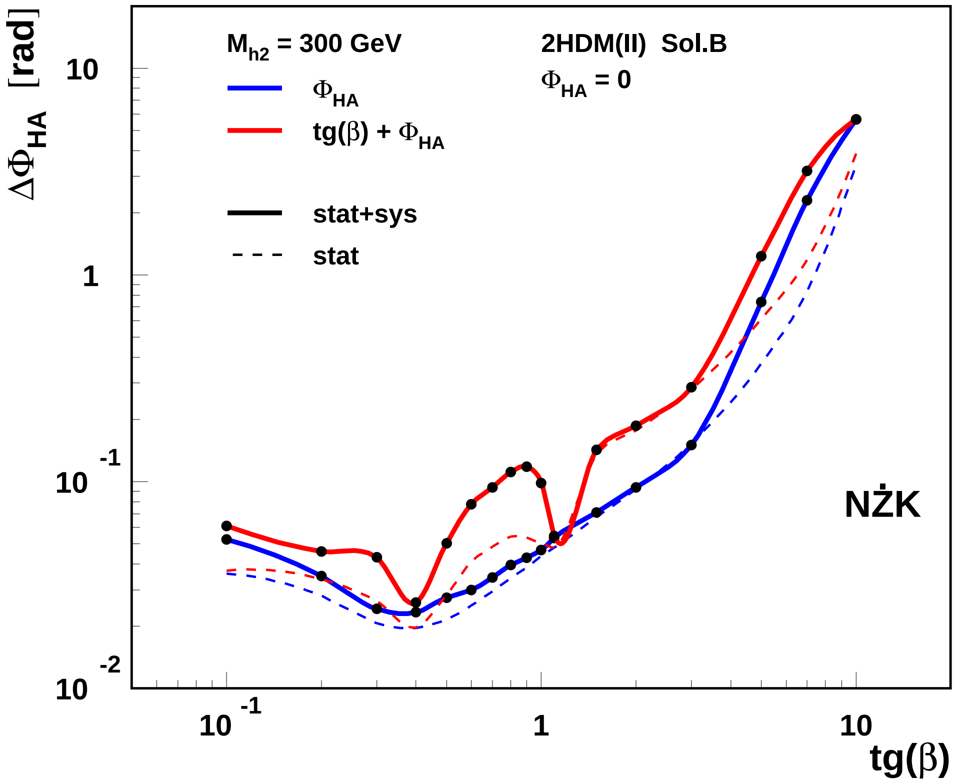


Possible CP violation increases expected $\tan\beta$ measurement errors

2HDM(II) with CP violation

Higgs boson h_2

Influence of $\tan\beta$ and systematics in Φ_{HA} measurement ($M_H = 300$ GeV, $\Phi_{HA} = 0$)



Expected precision in Φ_{HA} determination
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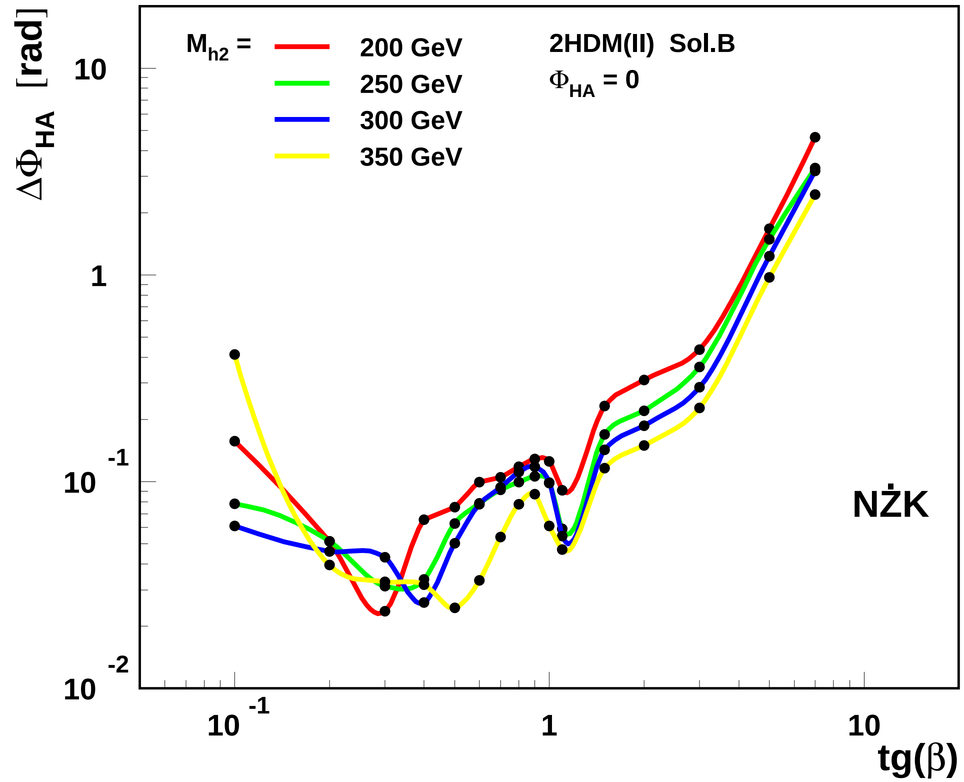


CP violating H–A mixing can be precisely measured if $\tan\beta$ is not too large

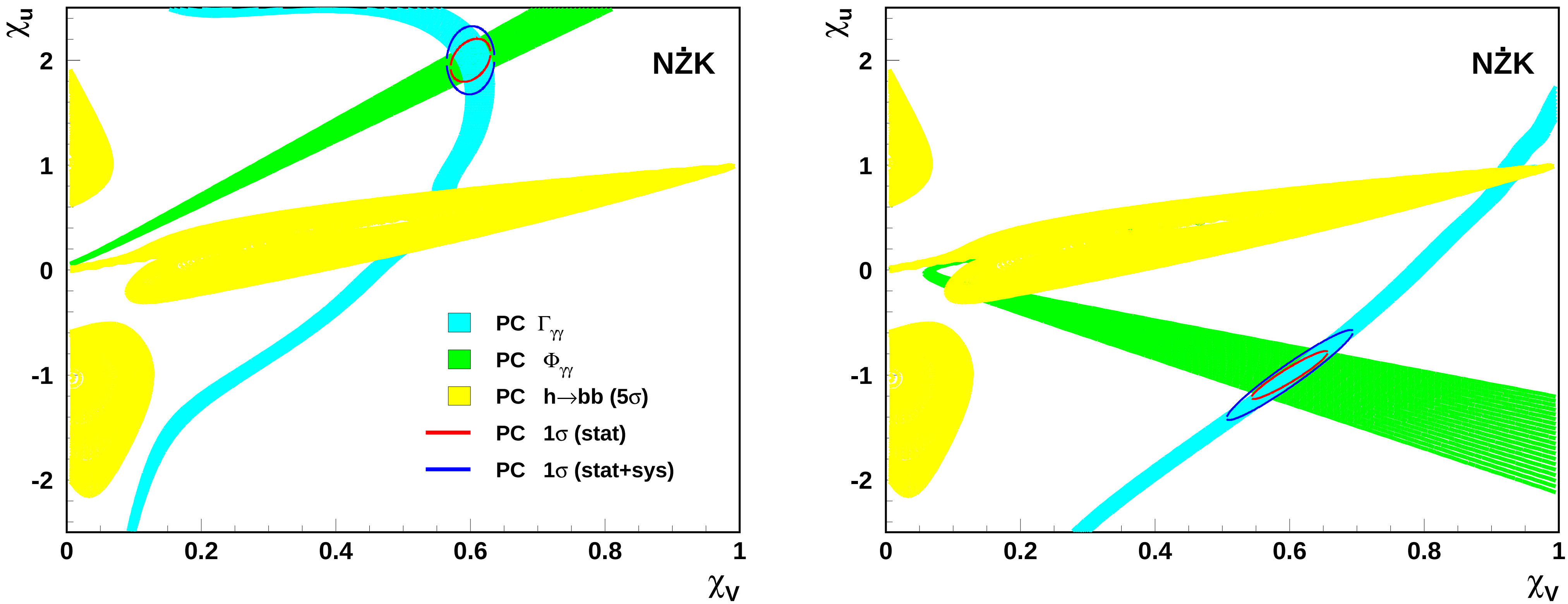
Photon Collider

Combined fit to W^+W^- and ZZ invariant mass distributions $\Rightarrow$ $\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$

$\Rightarrow$ couplings to both vector bosons (χ_V) and up fermions (χ_u) can be determined

1σ contours for 1 year of PC running, $M_H = 250$ GeV

$\chi_V = 0.7$ $\chi_u = 1.5$ $\chi_V = 0.7$ $\chi_u = -1$

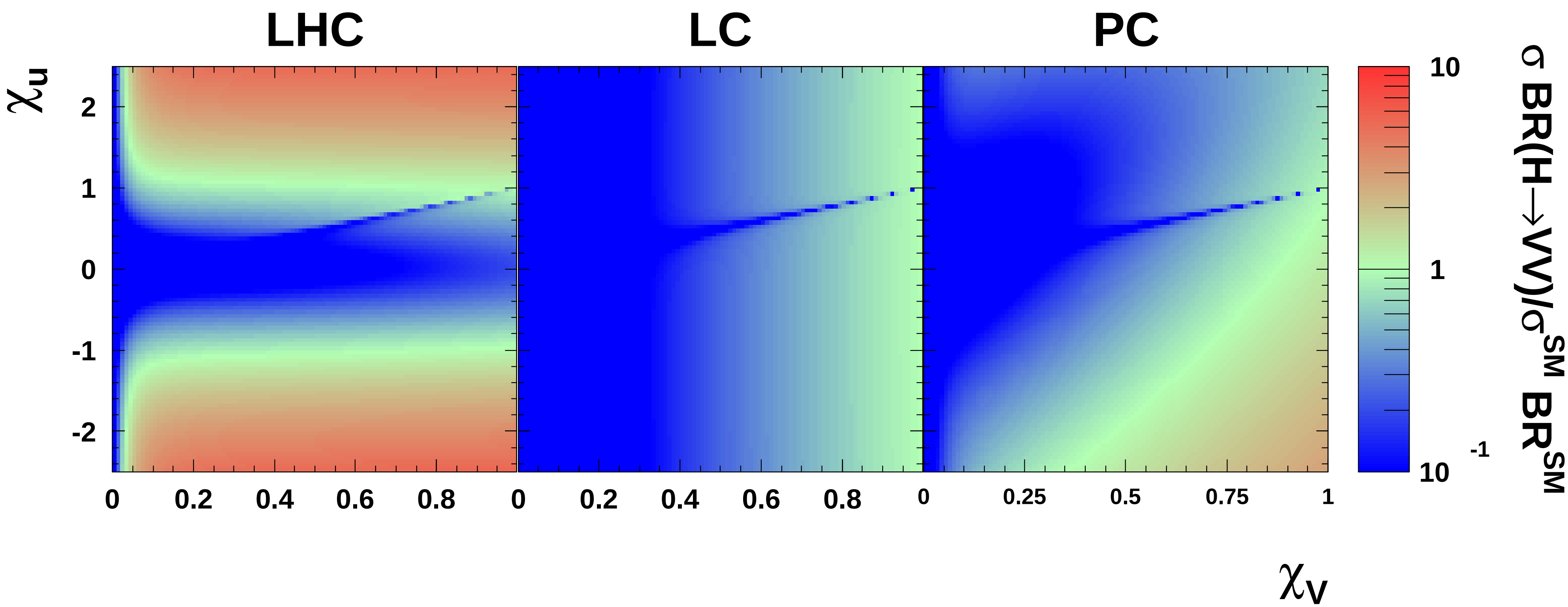


Systematic uncertainties affect mainly $\phi_{\gamma\gamma}$ measurement !

LHC ⊕ LC ⊕ PC

Measurements at LHC, LC and Photon Collider are complementary, being sensitive to different combinations of Higgs-boson couplings

Cross sections × BR relative to SM $\quad M_H = 250 GeV$



LHC ⊕ LC ⊕ PC

Allowed coupling values from cross section measurements at LHC, LC and PC, and the phase measurement at PC.

Inconsistency would indicate "new physics":

- different coupling structure or
- existence of new heavy particles contributing to Γ_{gg} and $\Gamma_{\gamma\gamma}$

Results for 2HDM (II) with weak CP violation: