# Determination of CP violating H-A mixing from $h_2 \to WW,\ ZZ$ decays in 2HDM: PLC and comparison with LHC and LC.


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ECFA Study
SUSY/Higgs working group meeting
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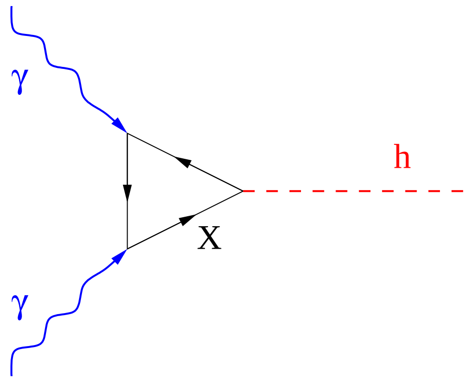
## Outline

- Higgs boson production and decays to $WW$ and $ZZ$ at PLC
  JHEP 0211 (2002) 034 [hep-ph/0207294]
- Weak CP violation in SM-like 2HDM (II) at PLC
  hep-ph/0307175; hep-ph/0403138
- Comparison with LHC and LC

# $\gamma\gamma \to \mathcal{H} \to WW,\ ZZ$

## Higgs boson production at the Photon Collider

Production cross section is proportional to the two-photon width



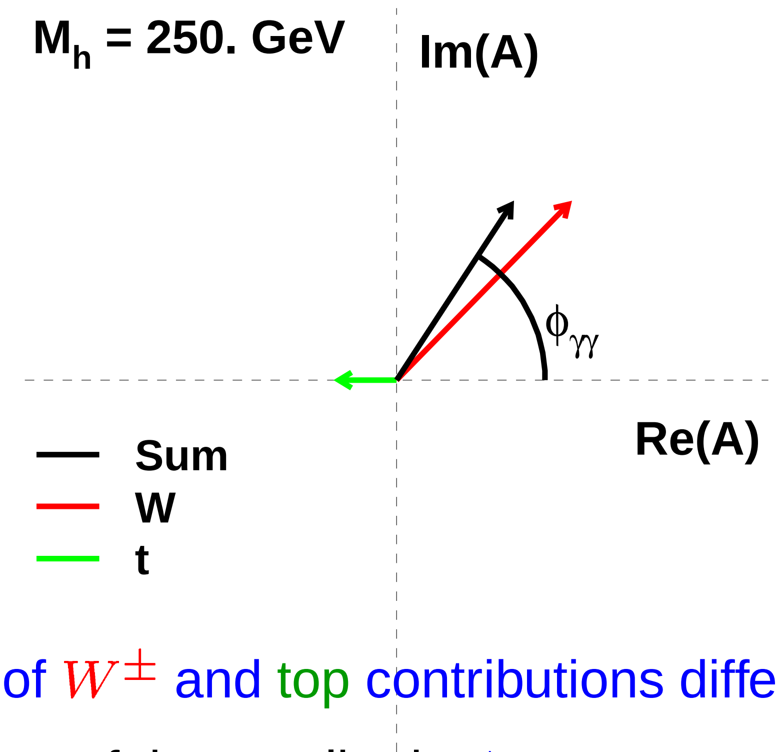

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\,\pi^3} \cdot |\mathcal{A}|^2$$

where:

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

two-photon amplitude

In SM, dominant contributions to two-photon amplitude $\mathcal{A}$ are due to $W^\pm$ and top loops.



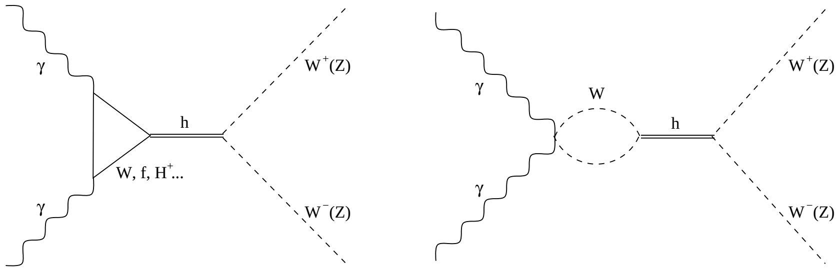

Phases of $W^\pm$ and top contributions differ !

The phase of the amplitude $\phi_{\gamma\gamma}$ depends on Higgs-boson couplings !

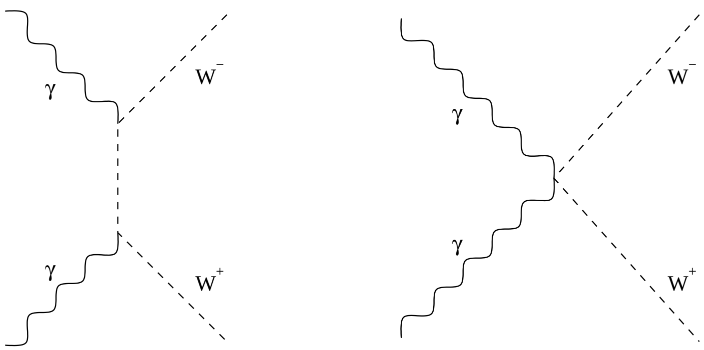
# $\gamma\gamma \to \mathcal{H} \to WW,\ ZZ$

We consider Higgs boson production and decays to $WW/ZZ$, for masses 200–350 GeV.

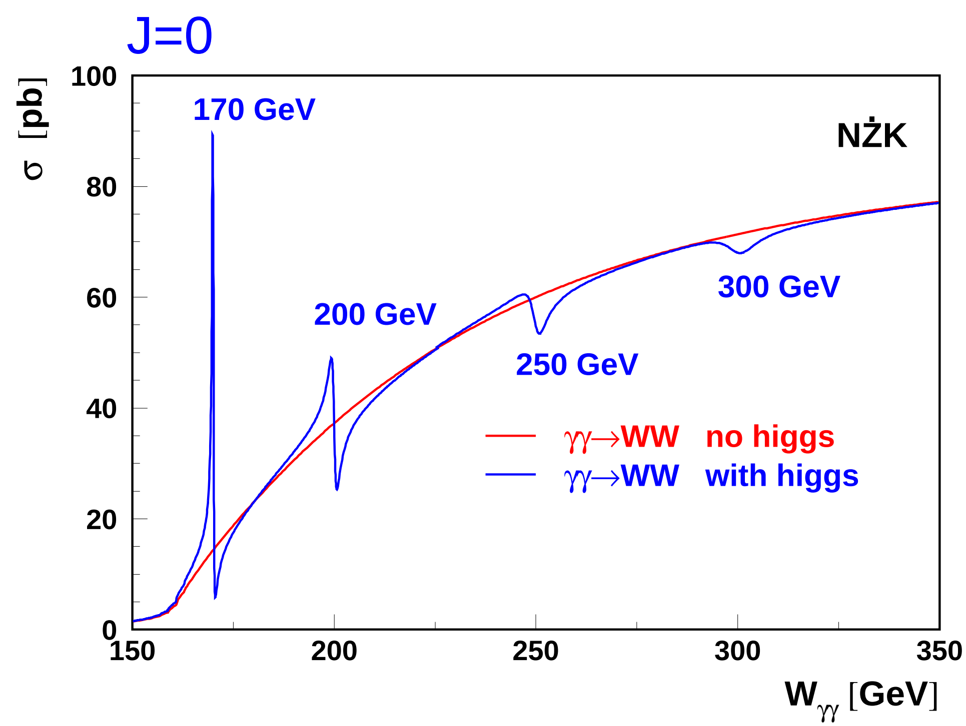
For resonant $\gamma\gamma \to h \to W^+W^-$ signal




there is a large non-resonant bg.




Large interference effects are expected in the considered mass range




Interference is sensitive to the phase of the two-gamma amplitude

# $\gamma\gamma \rightarrow \mathcal{H} \rightarrow WW,\ ZZ$

## Simulation

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

$\gamma\gamma \rightarrow W^+W^-,\ ZZ$ 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

## 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 $W_{\gamma\gamma}$

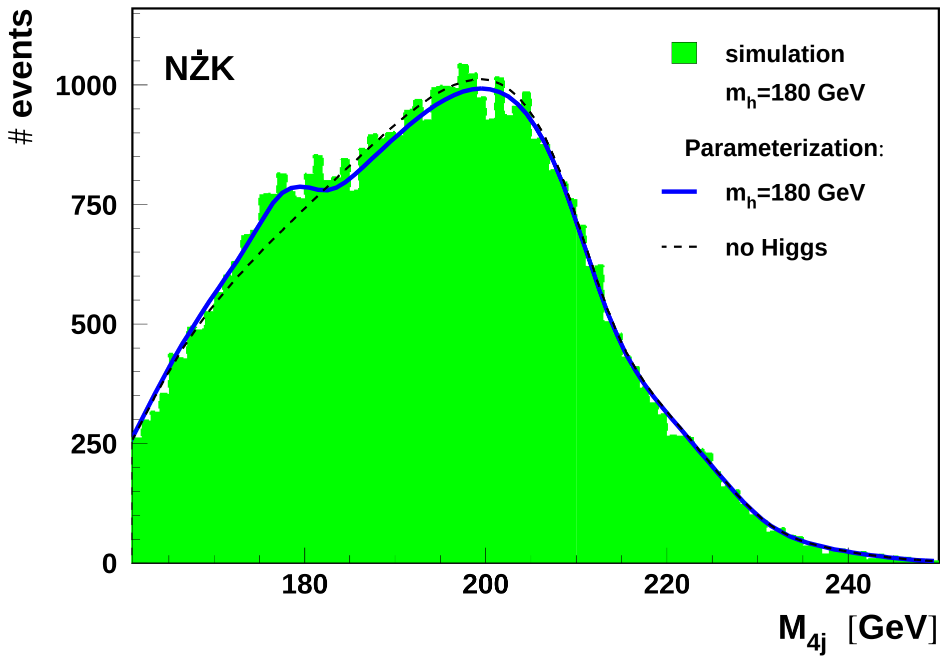
$\Rightarrow$ mass spectra can be calculated for any $\sqrt{s_{ee}}$ and $m_h$ without time-consuming MC simulation

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

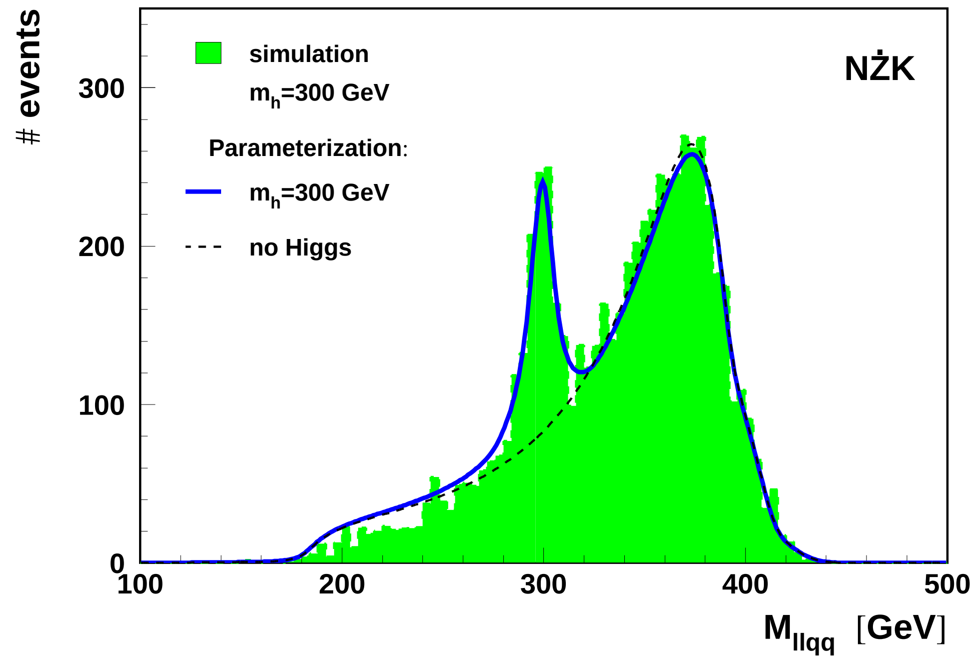
# $\gamma\gamma \to \mathcal{H} \to WW,\ ZZ$

Comparison of parametrization with full simulation:

$W^+W^-$



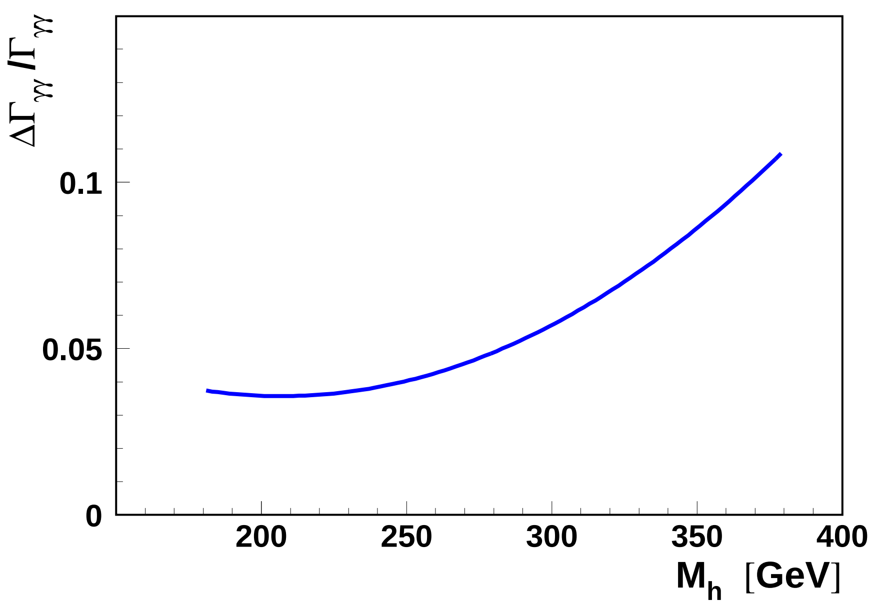

$ZZ$

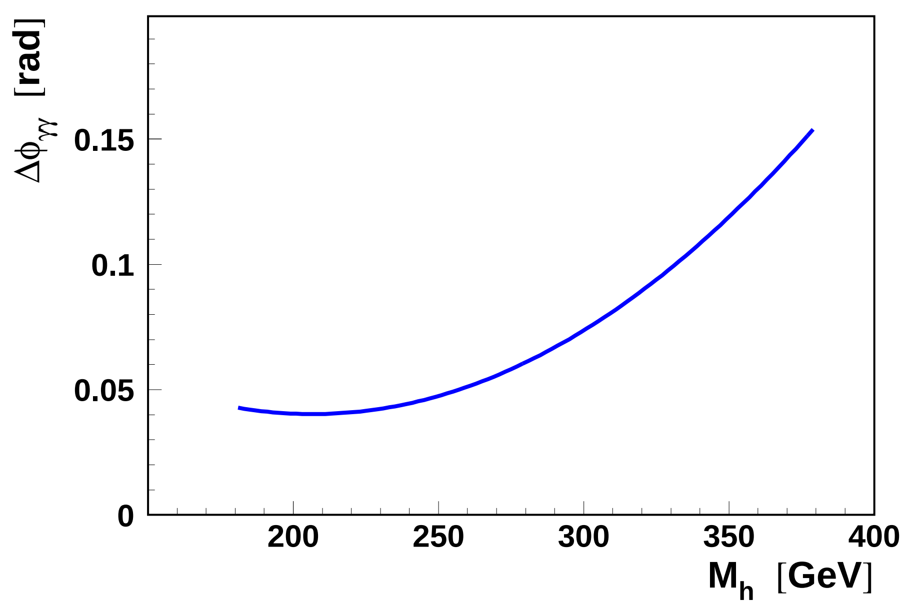


# $\gamma\gamma \rightarrow \mathcal{H} \rightarrow WW,\ ZZ$

From the simultaneous fit to the observed $W^+W^-$ and $ZZ$ mass spectra both the two-photon width $\Gamma_{\gamma\gamma}$ and phase $\phi_{\gamma\gamma}$ can be determined.

For SM: $\Gamma_{\gamma\gamma}$ with precision $\sim 4 - 9\%$ $\phi_{\gamma\gamma}$ with precision $40 - 120$ mrad




JHEP 0211 (2002) 034 [hep-ph/0207294]

A.F.Żarnecki, ECFA/DESY workshop, November 2002, Praha (including systematic uncertainties)

# 2HDM(II)

## SM-like 2HDM(II)

We consider SM-like **solution $B_h$**

Basic couplings, relative to SM:

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

| | $h$ | $H$ | $A$ |
|---|---|---|---|
| $\chi_u$ | $-1$ | $-\frac{1}{\tan\beta}$ | $-i\,\gamma_5\,\frac{1}{\tan\beta}$ |
| $\chi_d$ | $+1$ | $-\tan\beta$ | $-i\,\gamma_5\,\tan\beta$ |
| $\chi_V$ | $\cos(2\beta)$ | $-\sin(2\beta)$ | $0$ |

CP conserving model:

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

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

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

## CP violation

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

We consider weak CP violation through a small mixing between $H$ and $A$ states:

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

$\Rightarrow$ additional model parameter:

**CP-violating mixing phase $\Phi_{HA}$**

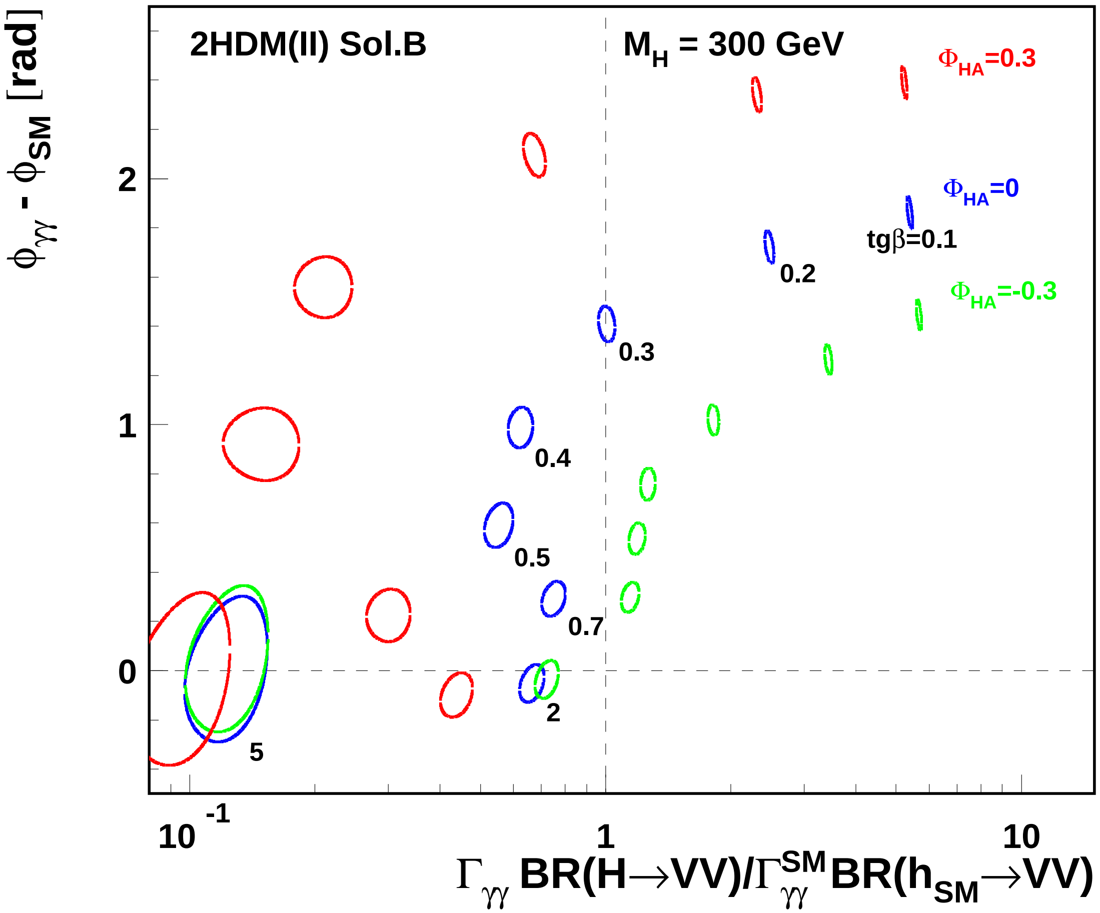
**We consider $h_2$ production and decays**

# 2HDM(II)

## Higgs boson $h_2$

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

$M_{h_2}$ = 300 GeV




$1\sigma$ contours for 1 year of PC running

statistical errors only

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

Expected precision at PLC:

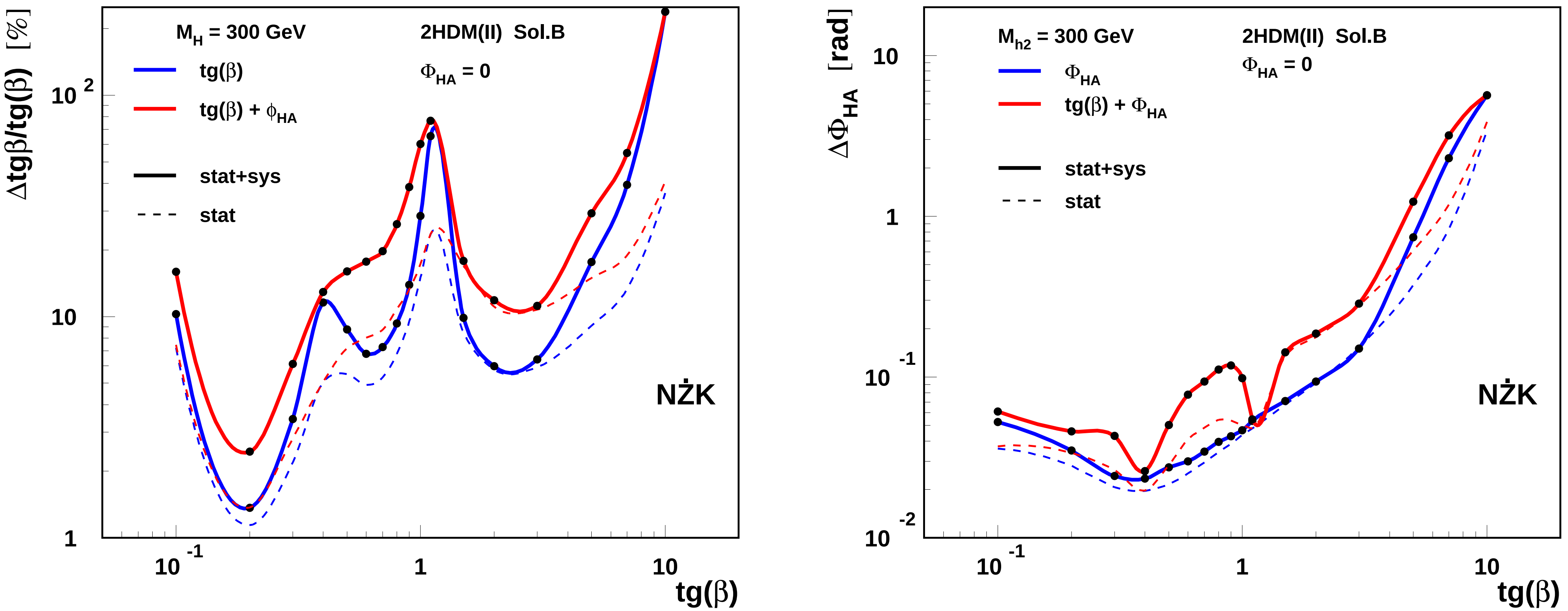
(for small mixing i.e. $\Phi_{HA} \sim 0$)

- $\sim$ 10 % for $\tan\beta$
- $\sim$ 100 mrad for $\Phi_{HA}$ (for low $\tan\beta$)

# 2HDM(II)

## Higgs boson $h_2$

Influence of systematic uncertainties on $\tan\beta$ and $\Phi_{HA}$ measurement



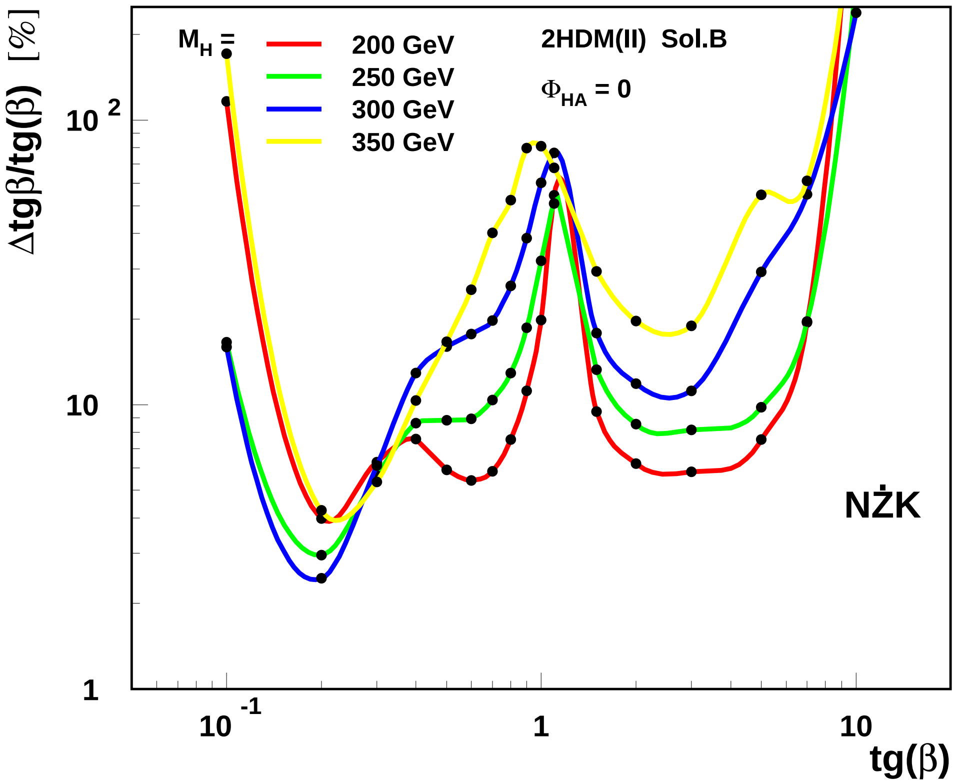

Correlation between $\tan\beta$ and $\Phi_{HA}$ increases expected measurement errors

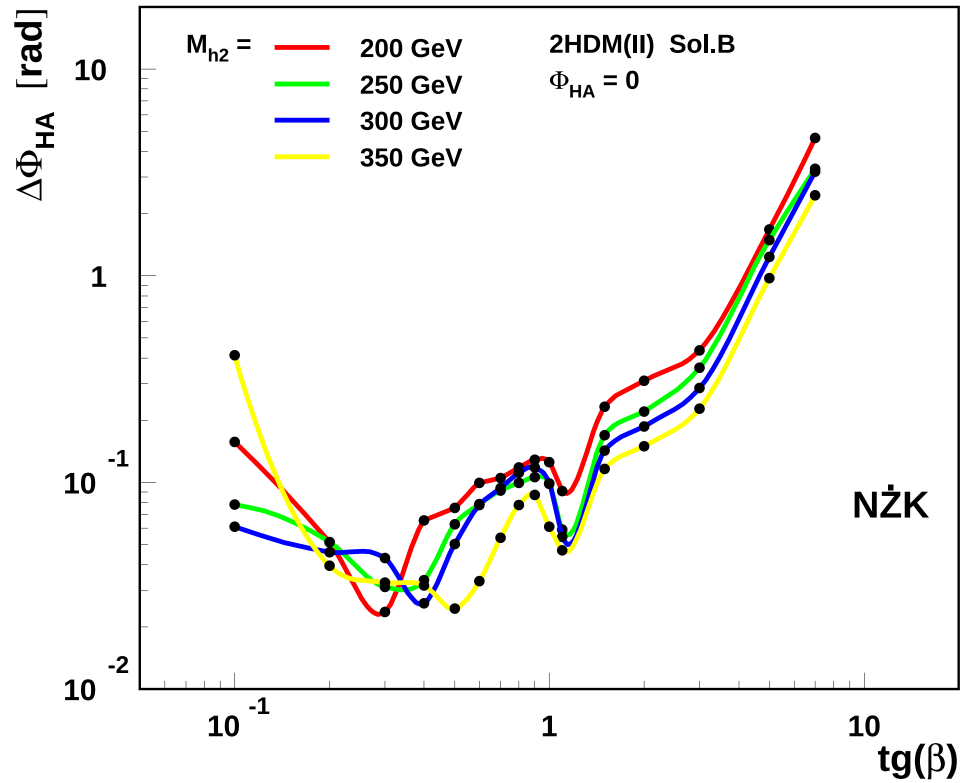
# 2HDM(II)

## Higgs boson $h_2$

Solution $B_h$ (with CP violation) $\Rightarrow$ two free parameters ($\tan\beta$ and $\Phi_{HA}$)

Expected precision in $\tan\beta$ and $\Phi_{HA}$ determination at PLC (stat.+sys. errors)




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

**Can we distinguish this case from CP conserving 2HDM (II) ?** (with $\tan\beta$ and $\alpha$)

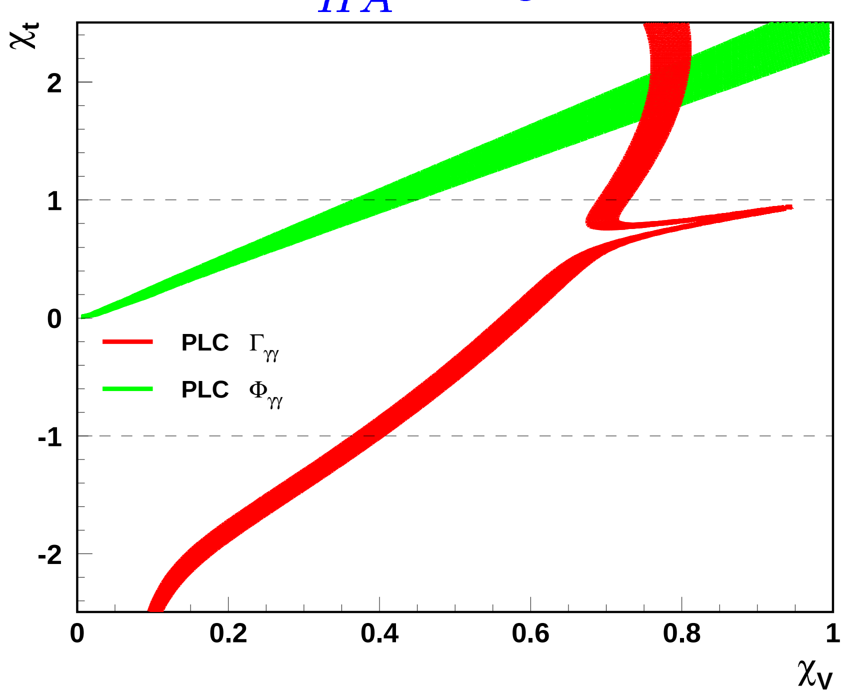
# 2HDM (II)

## CP or not CP

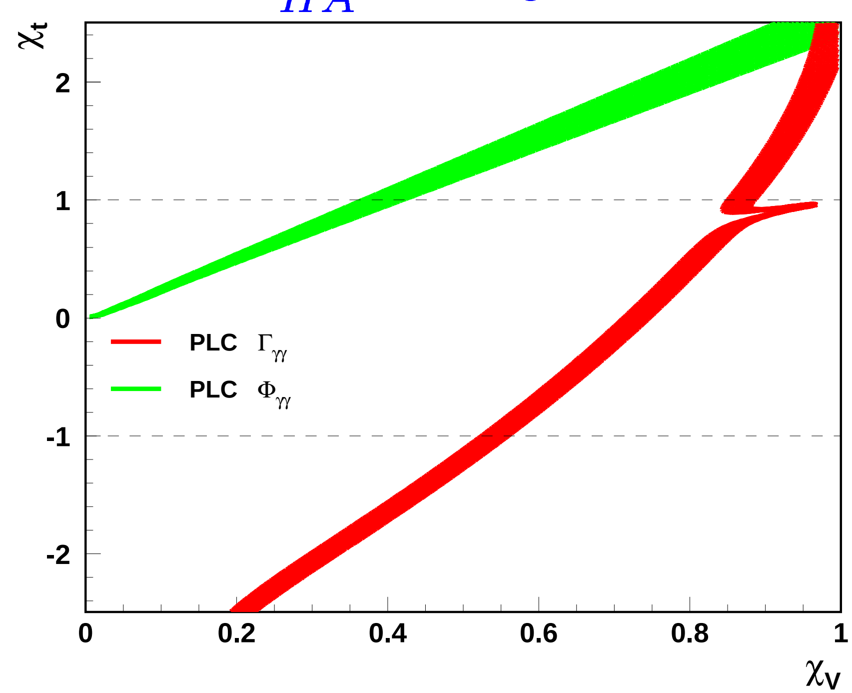
**Can we distinguish between solution $B_h$ with CP violation** ($\tan\beta$ and $\Phi_{HA}$)
**from CP conserving 2HDM (II)** (also with two parameters: $\tan\beta$ and $\alpha$) **?**

2HDM (II) couplings determined (assuming CP conservation) at PLC
for $h_2$ (solution $B_h$) with $M_{h_2} = 250$ GeV and $\tan\beta = 0.5$

$\Phi_{HA} = 0$




$\Phi_{HA} = -0.2$



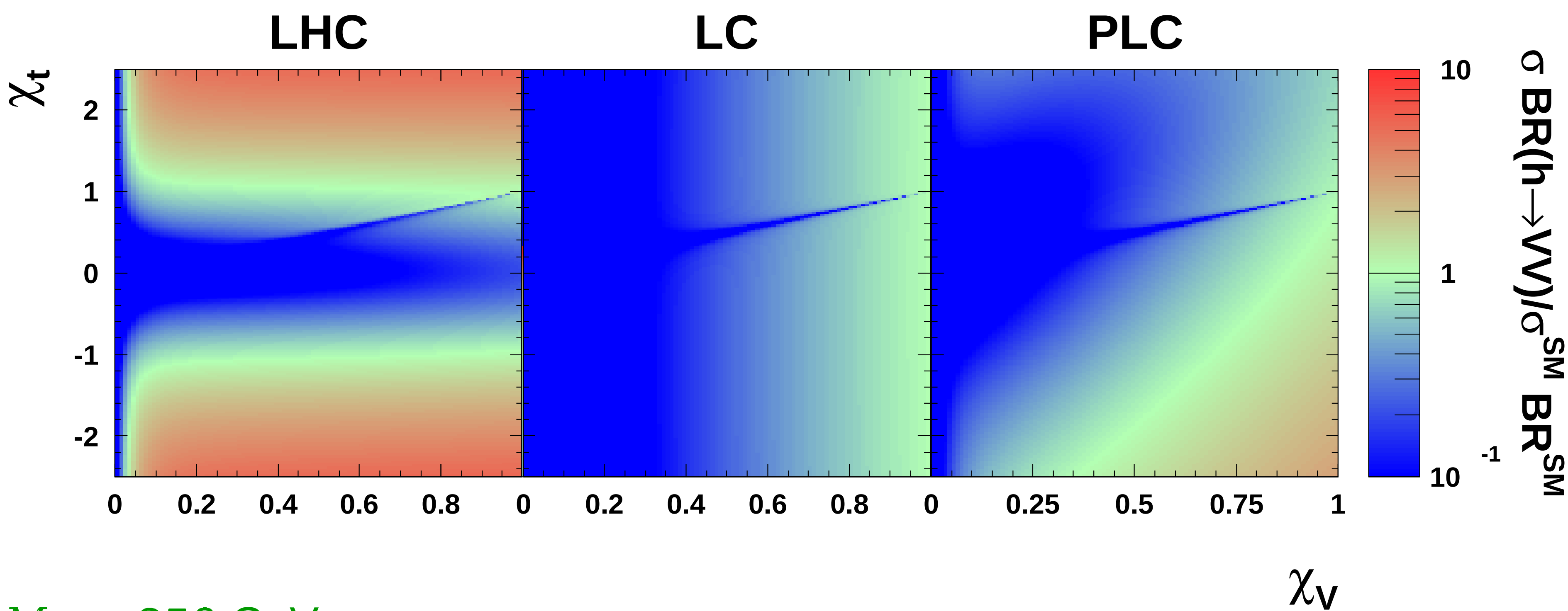

⇒ CP violation can “mimic” more general 2HDM (II)

# Comparison

## CP conserving 2HDM (II)

Can we profit from independent measurements at LHC and LC ?

Expected Higgs-boson $h$ production rates times $W^+W^-/ZZ$ branching ratios, relative to SM predictions, as a function of basic relative couplings:



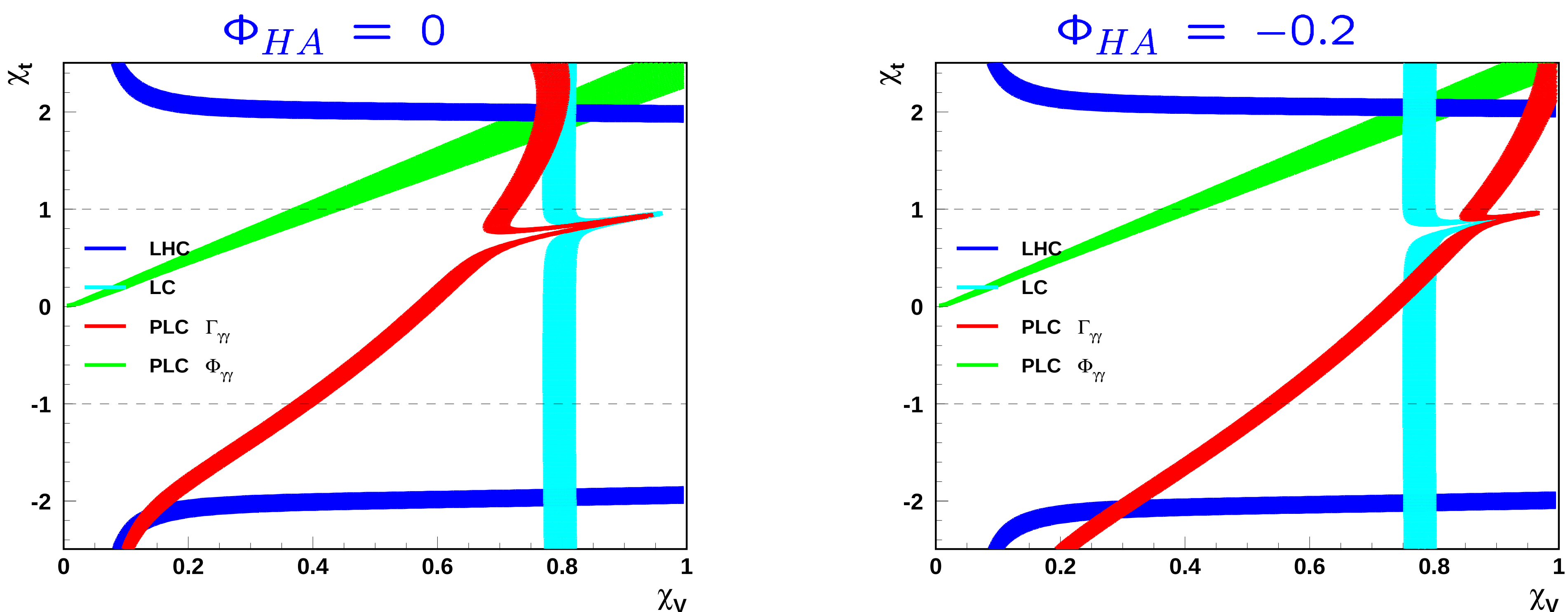

$M_h = 250$ GeV

# Comparison

## LHC $\oplus$ LC $\oplus$ PLC

Only from combined analysis of LHC, LC and PLC measurements we can establish CP violation in 2HDM (II)

Relative Higgs boson couplings determined from LHC, LC and PLC:

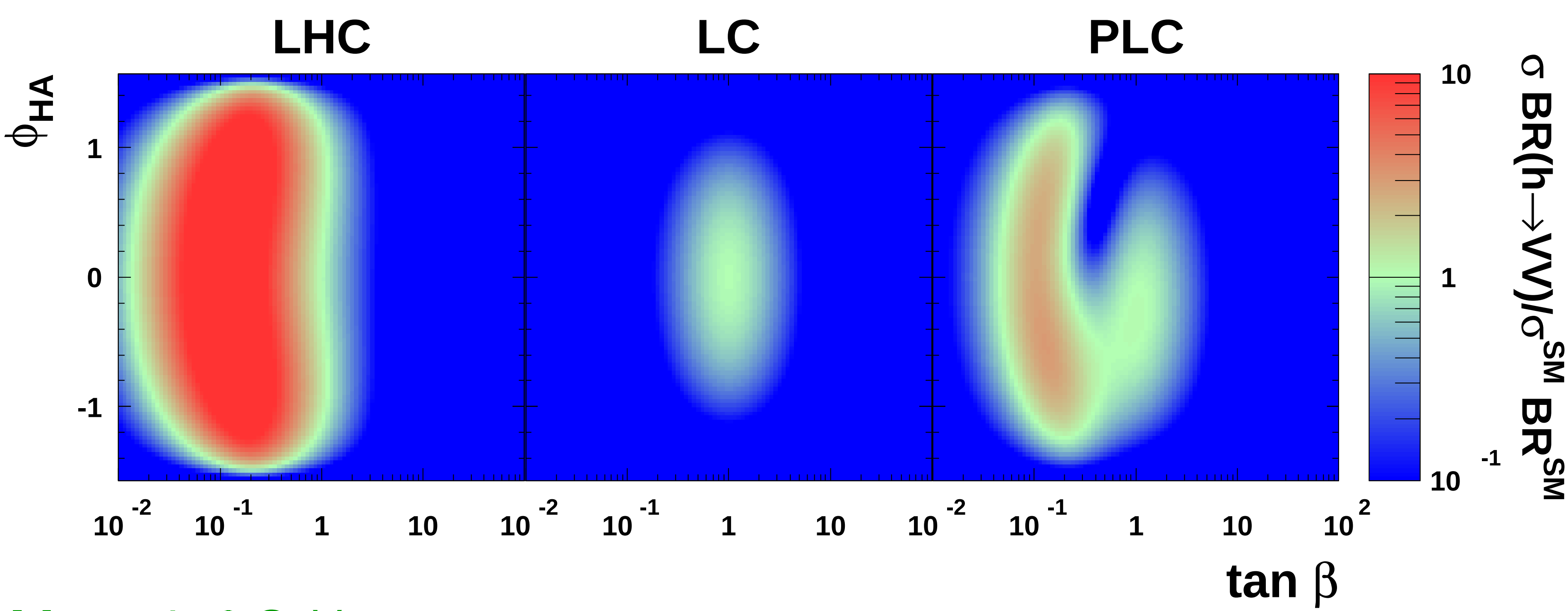



CP conserving 2HDM (II) can be excluded.

# Comparison

## 2HDM (II) sol. $B_h$ (with weak CP violation)

Expected Higgs-boson production rates times $W^+W^-/ZZ$ branching ratios, relative to SM predictions, as a function of $\tan\beta$ and the CP violating mixing angle $\Phi_{HA}$



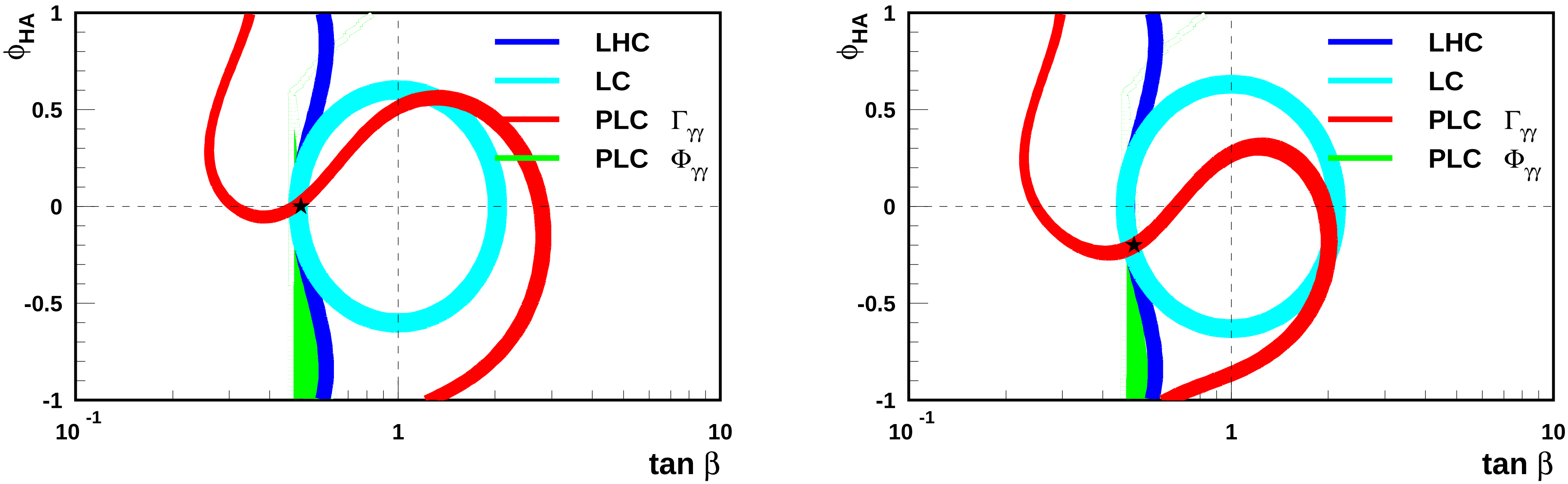

$M_{h_2} = 250$ GeV

# Comparison

## LHC ⊕ LC ⊕ PLC

Determination of $\tan\beta$ and the CP violating mixing angle $\Phi_{HA}$ for 2HDM (II) solution $B_h$ with CP violation ($M_{h_2} = 250$ GeV, $\tan\beta = 0.5$):

$\Phi_{HA} = 0$ $\qquad\qquad$ $\Phi_{HA} = -0.2$



# Summary

Using $W^+W^-$ and $ZZ$ final states both the partial width $\Gamma_{\gamma\gamma}$ and the phase of the $\mathcal{H} \to \gamma\gamma$ amplitude $\phi_{\gamma\gamma}$ can be measured at the Photon Linear Collider.

Both $\tan\beta$ and the CP violating H–A mixing phase $\Phi_{HA}$ can be measured at PLC, assuming solution $B_h$ of 2HDM (II).

In general case, combined analysis of LHC, LC and PLC measurements is needed to establish weak CP violation.