Determination of CP violation

from $higgs \rightarrow WW,\ ZZ$ decays at PLC

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NŻK

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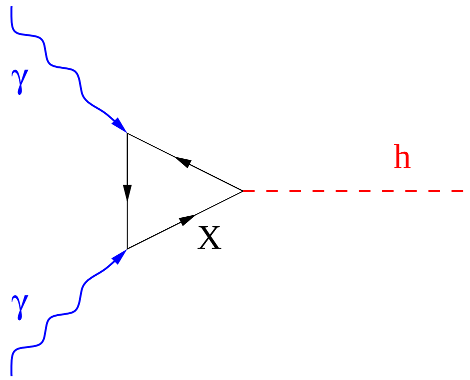
Outline

- Higgs boson production
  and decays to WW and ZZ at PLC
  JHEP 0211 (2002) 034 [hep-ph/0207294]
- Weak (indirect) CP violation in SM-like
  2HDM (II) at PLC
  hep-ph/0403138
  Comparison with LHC and LC
  hep-ph/0404024
- Direct CP violation in generic model
  update of hep-ph/0307175

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

Higgs boson production at the Photon Collider

Production cross section is proportional to the two-photon width



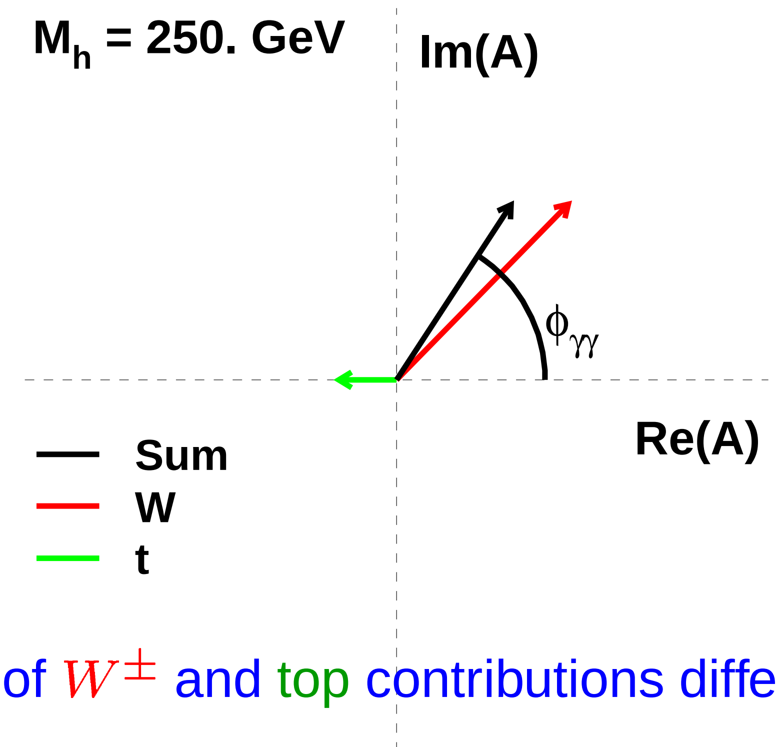
$$\Gamma(h \to \gamma\gamma) \;=\; \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\,\pi^3} \cdot |\mathcal{A}|^2$$

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.



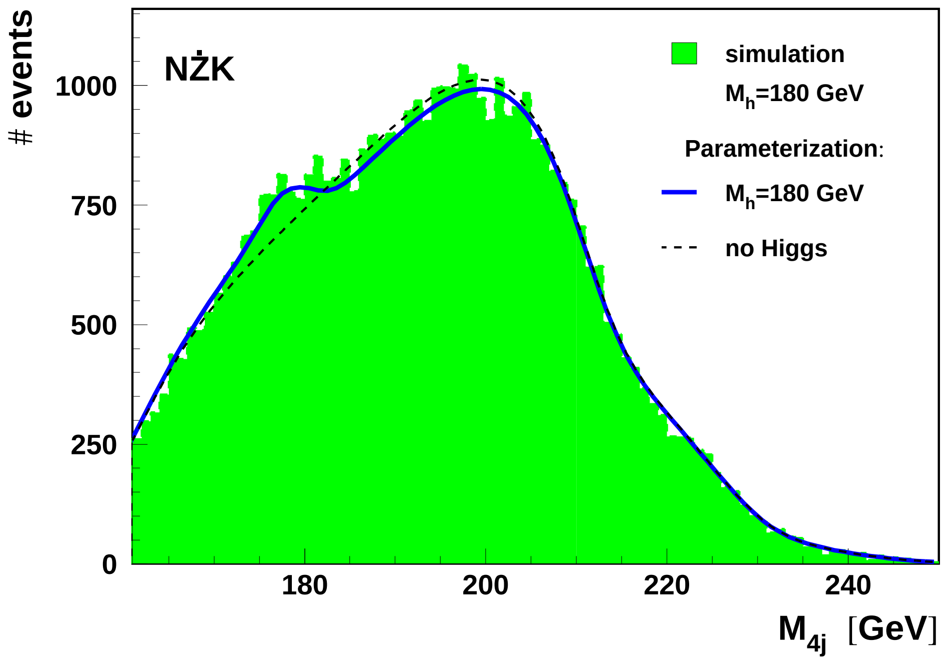
Phases of $W^\pm$ and top contributions differ !

Both $\Gamma_{\gamma\gamma}$ and the phase of the amplitude $\phi_{\gamma\gamma}$ depend on Higgs-boson couplings !

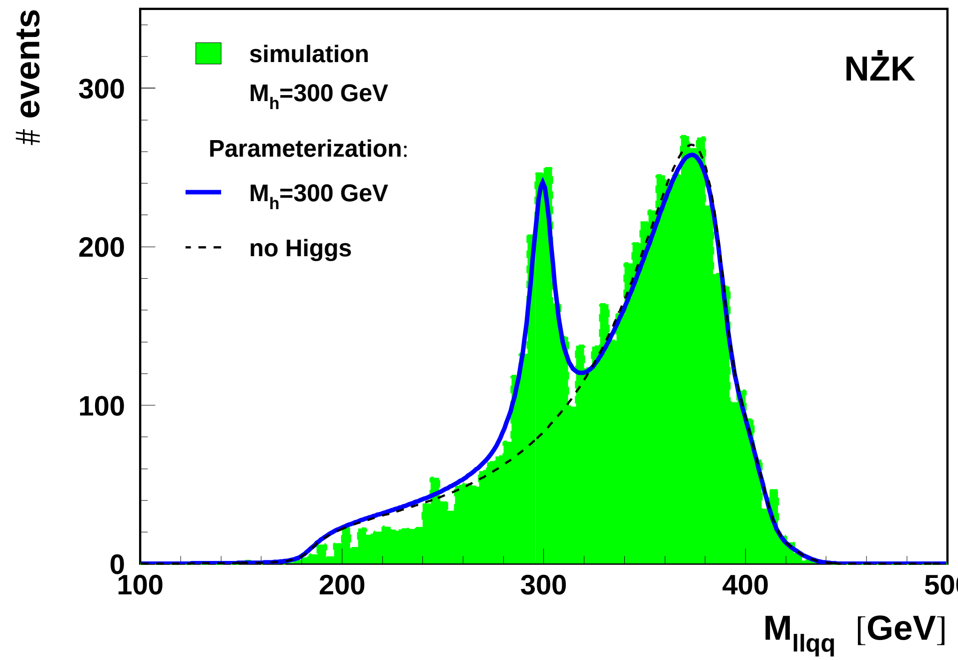
$\gamma\gamma \to \mathcal{H} \to WW,\ ZZ$

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.

W^+W^-



ZZ



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
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

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:

$$\begin{aligned}
\chi^{h_1}_X &\approx \chi^h_X \\
\chi^{h_2}_X &\approx \chi^H_X \cdot \cos\Phi_{HA} + \chi^A_X \cdot \sin\Phi_{HA} \\
\chi^{h_3}_X &\approx \chi^A_X \cdot \cos\Phi_{HA} - \chi^H_X \cdot \sin\Phi_{HA}
\end{aligned}$$

$\Rightarrow$ additional model parameter:

CP-violating mixing phase Φ_{HA}

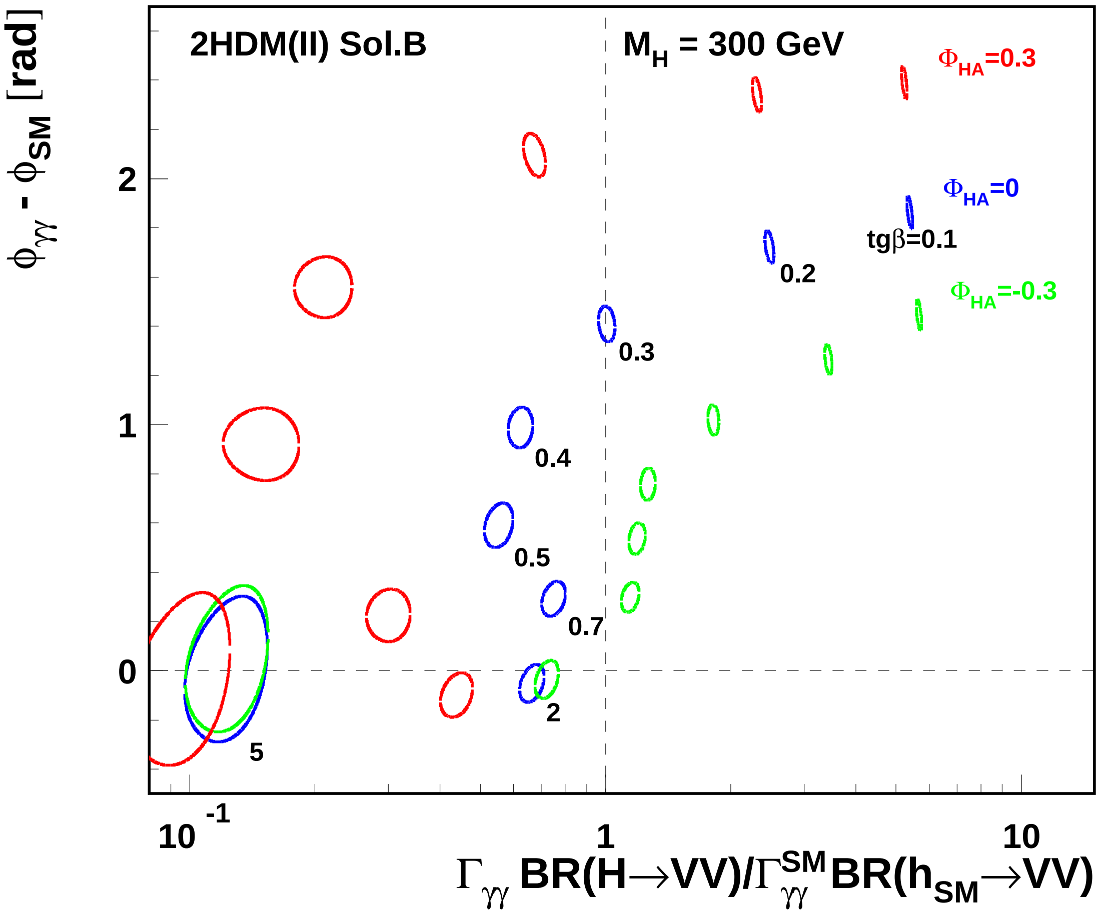
We consider h_2 production and decays

2HDM(II)

Higgs boson h_2

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

M_{h_2} = 300 GeV



1σ 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. $\Phi_{HA} \sim 0$)

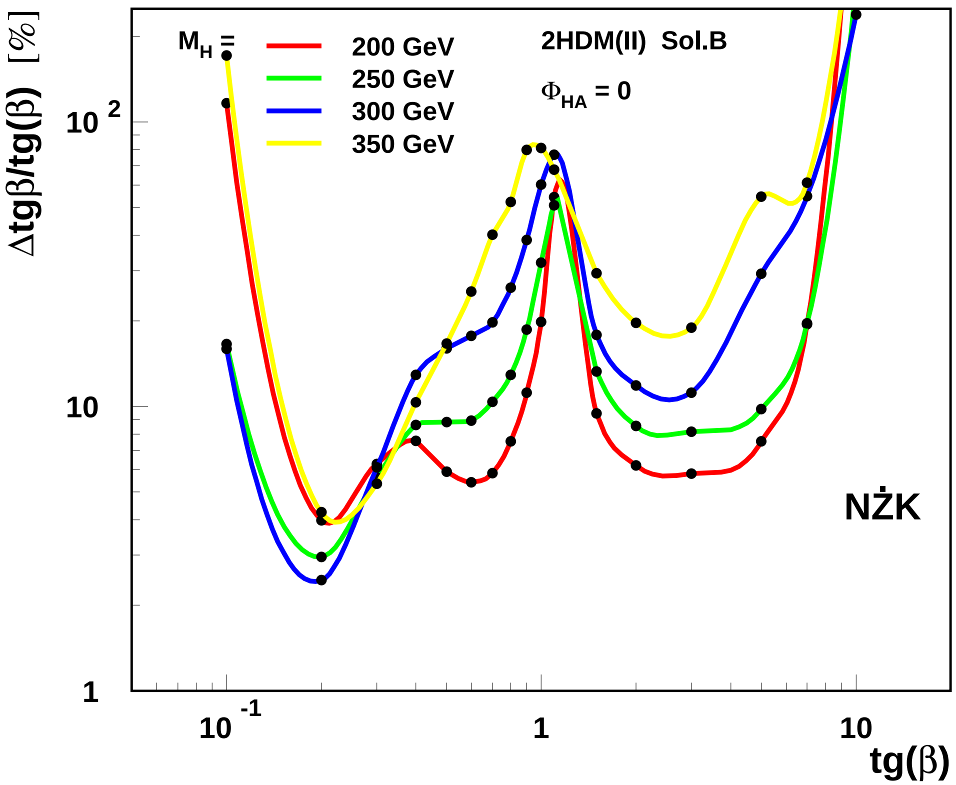
- $\sim$ 10 % for $\tan\beta$
- $\sim$ 100 mrad for Φ_{HA} (for low $\tan\beta$)

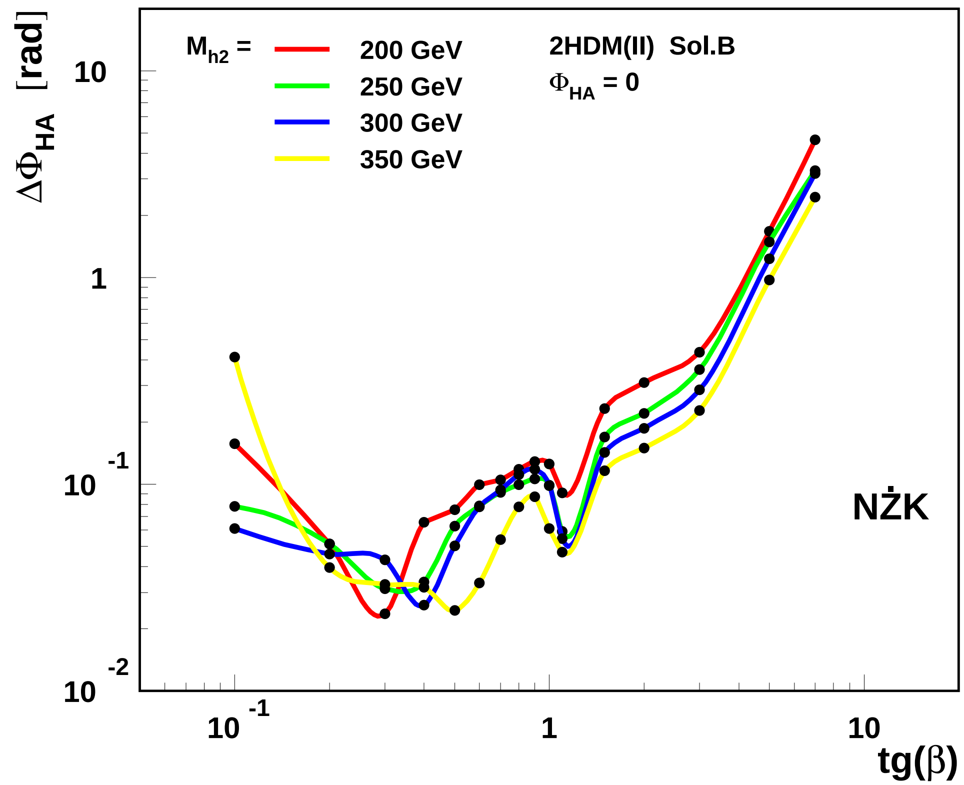
Higgs boson h_2

2HDM(II)

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

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



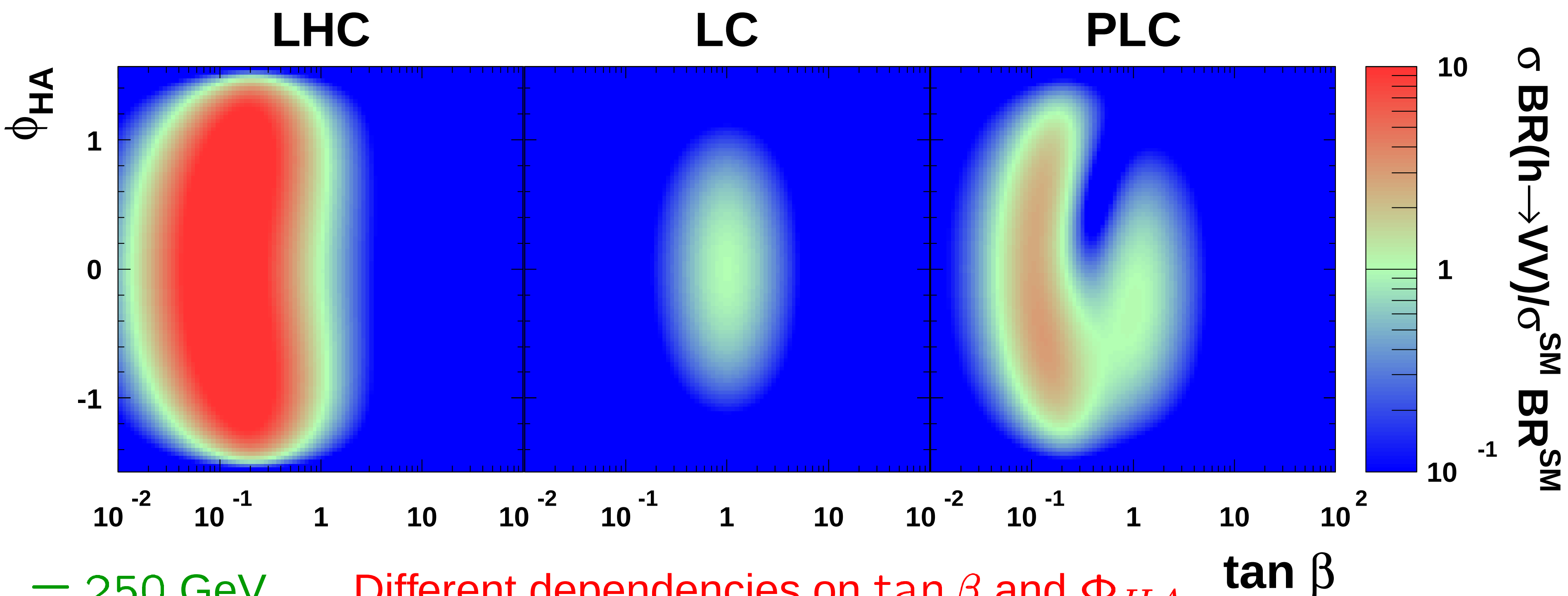


CP violating H–A mixing angle can be precisely measured, if $\tan\beta$ is not too large

Comparison with LHC and LC

Higgs boson h_2 (Solution 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 Φ_{HA}



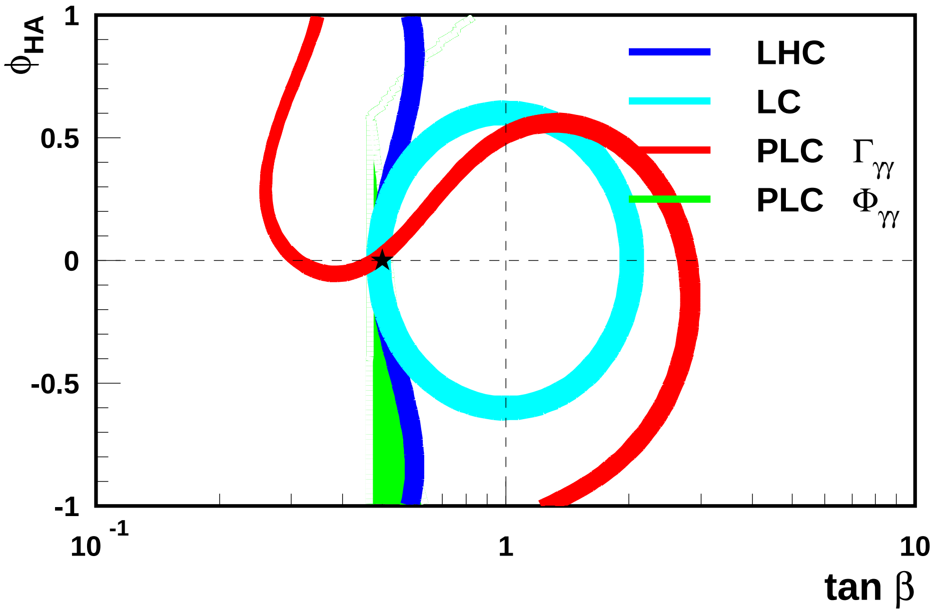
$M_{h_2} = 250$ GeV   Different dependencies on $\tan\beta$ and Φ_{HA}

Comparison with LHC and LC

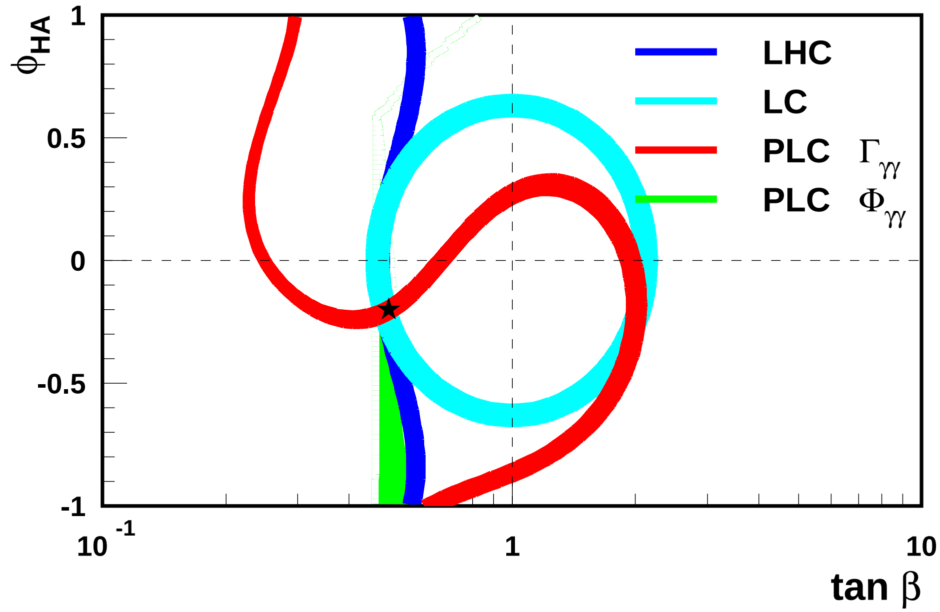
LHC $\oplus$ LC $\oplus$ PLC

Determination of $\tan\beta$ and the CP violating mixing angle Φ_{HA} (1σ contours) for 2HDM (II) solution B_h with CP violation ($M_{h_2} = 250$ GeV, $\tan\beta = 0.5$):

$\Phi_{HA} = 0$



$\Phi_{HA} = -0.2$



CP violating H–A mixing can be precisely measured in SM-like 2HDM (II) solution B_h.

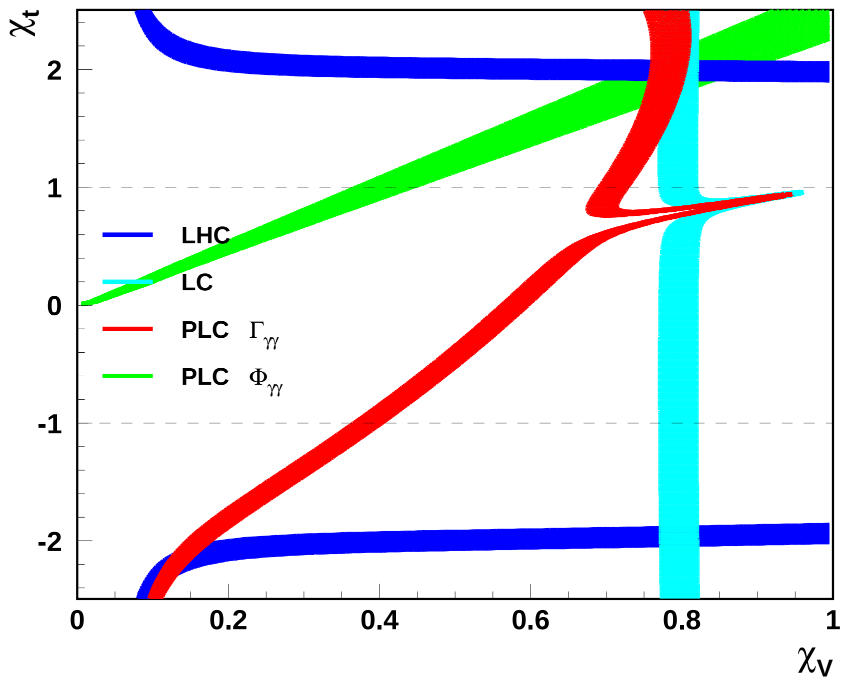
Can we distinguish between solution B_h with CP violation ($\tan\beta$ and Φ_{HA}) **from CP conserving 2HDM (II)** (also with two parameters: $\tan\beta$ and α) **?**

Comparison

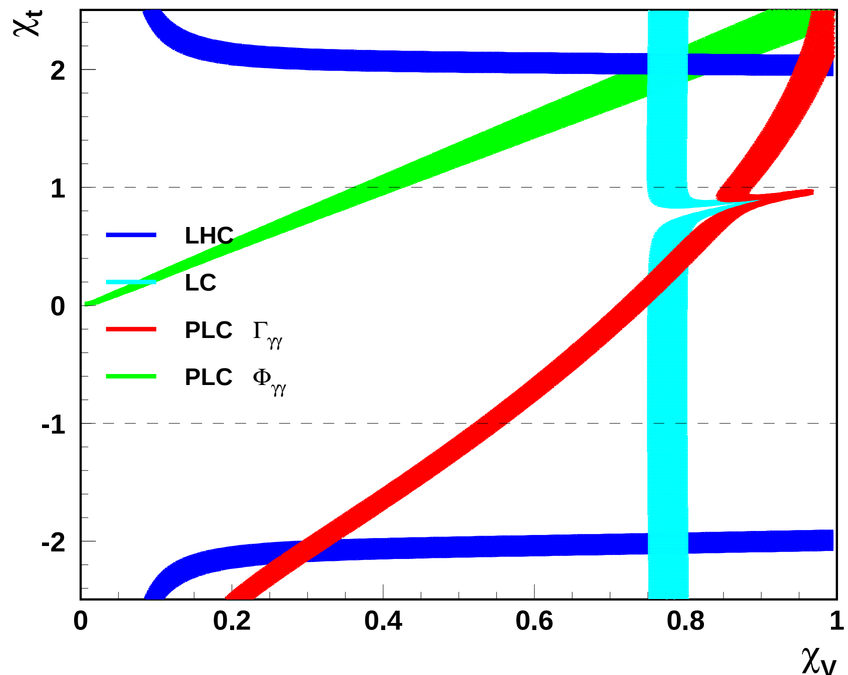
LHC $\oplus$ LC $\oplus$ PLC

2HDM (II) couplings determined (assuming CP conservation) at LHC, LC and 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 conserving 2HDM (II) can be excluded.

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

Generic model

Couplings

Model with a generic tensor couplings of a Higgs boson $\mathcal{H}$, to ZZ and W^+W^-:

$$g_{\mathcal{H}ZZ} = ig\frac{M_Z}{\cos\theta_W}\left(\lambda_H \cdot g^{\mu\nu} + \lambda_A \cdot \varepsilon^{\mu\nu\rho\sigma}\frac{(p_1+p_2)_\rho\,(p_1-p_2)_\sigma}{M_Z^2}\right)$$

$$g_{\mathcal{H}WW} = igM_W\left(\lambda_H \cdot g^{\mu\nu} + \lambda_A \cdot \varepsilon^{\mu\nu\rho\sigma}\frac{(p_1+p_2)_\rho\,(p_1-p_2)_\sigma}{M_W^2}\right)$$

with: $\lambda_H = \lambda \cdot \cos\Phi_{HA}$ $\quad \lambda_A = \lambda \cdot \sin\Phi_{HA}$

Standard Model (scalar) couplings are reproduced for $\Phi_{HA} = 0$ ($\lambda_H = 1$ and $\lambda_A = 0$).

Pseudoscalar Higgs boson corresponds to $\lambda_H = 0$ and $\Phi_{HA} = \frac{\pi}{2}$ $\lambda_A = 1$.

We consider small CP violation (small deviations from SM), i.e. $|\Phi_{HA}| \ll 1$

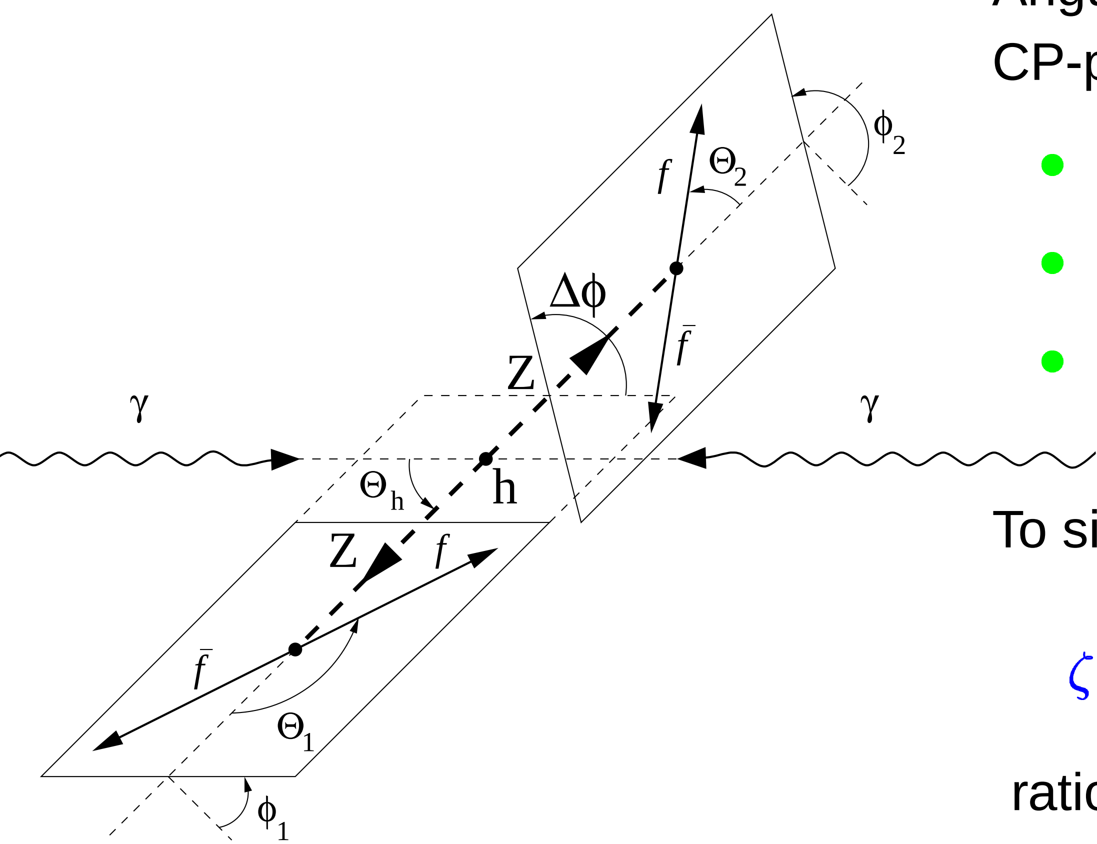
Model: S.Y. Choi, D.J. Miller, M.M. Mühlleitner and P.M. Zerwas, hep–ph/0210077;
D.J. Miller, S.Y. Choi, B. Eberle, M.M. Mühlleitner and P.M. Zerwas, Phys. Lett. B505 (2001) 149;
D.J. Miller, *Spin and Parity in the HZZ vertex*, ECFA/DESY meeting, Prague, November 2002.

Higgs CP from $\mathcal{H} \to \tau^+\tau^-$: K. Desch, A. Imhof, Z. Was, M. Worek, hep-ph/0307331;
K. Desch, Z. Was, M. Worek, Eur.Phys.J.C29 (2003) 491, hep-ph/0302046.

Higgs CP from $\mathcal{H} \to t\bar{t}$: E. Asakawa, K. Hagiwara, hep-ph/0305323.

Generic model

Angular distributions



Angular variables used in the analysis of higgs CP-properties:

- higgs decay angle angle Θ_h
- polar angles Θ_1 and Θ_2
- angle between two Z/W decay planes, $\Delta\phi = \phi_2 - \phi_1$

To simplify the analysis, we introduce

$$\zeta = \frac{\sin^2\Theta_1 \cdot \sin^2\Theta_2}{(1+\cos^2\Theta_1)\cdot(1+\cos^2\Theta_2)}$$

ratio of the distributions expected for a scalar and a pseudoscalar higgs (for $M_h \gg M_Z$).

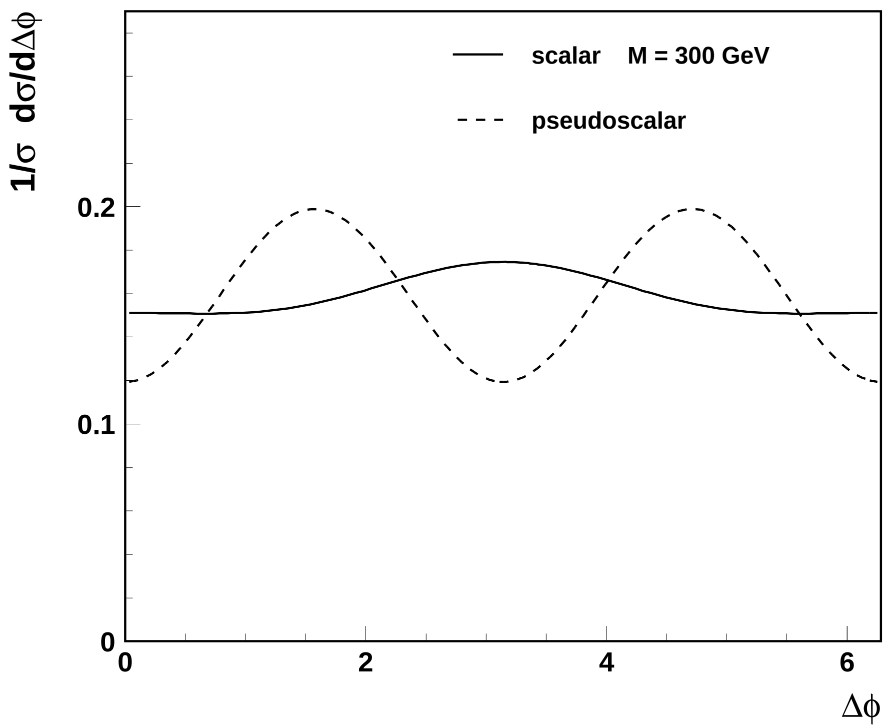
All polar angles are calculated in the rest frame of the decaying particle.

Generic model

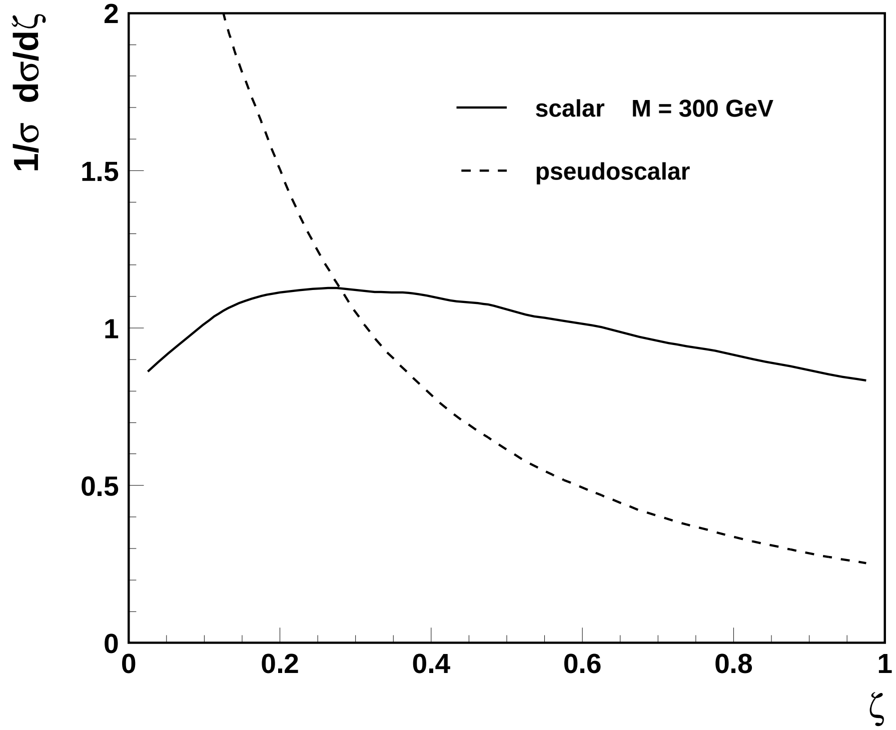
Angular distributions

Normalized angular distributions expected for scalar and pseudoscalar higgs,
for $\mathcal{H} \rightarrow ZZ \rightarrow l^+l^-jj$ $\quad M_{\mathcal{H}} = 300$ GeV.

$\Delta\phi$



ζ

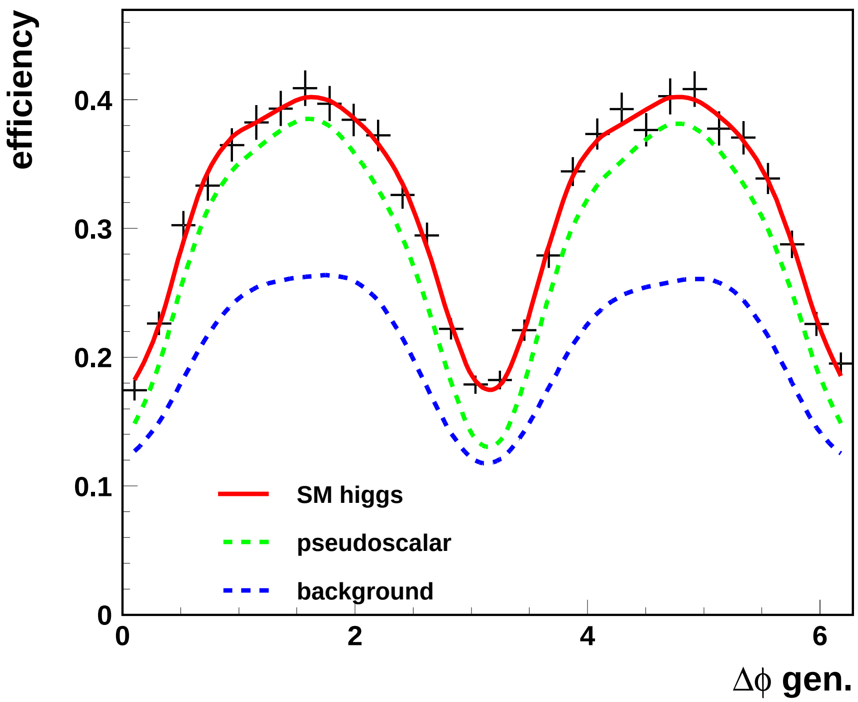


Both distributions clearly distinguish between decays of scalar and pseudoscalar higgs.

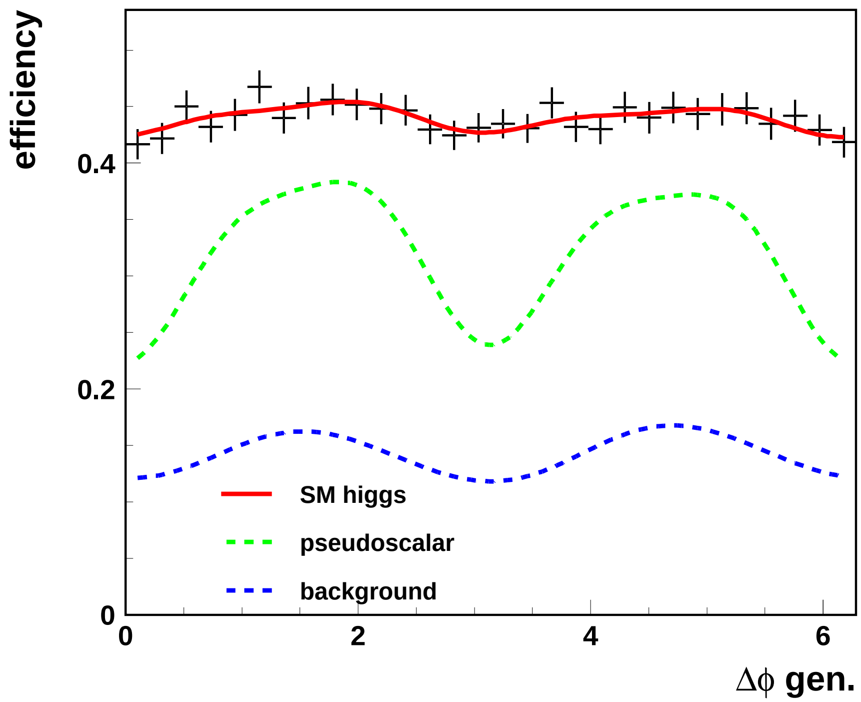
Generic model

Nonuniformity of selection efficiency in $\Delta\phi$ largest for small m_h

m_h = 200 GeV, $\sqrt{s_{ee}}$=305 GeV



m_h = 300 GeV, $\sqrt{s_{ee}}$=418 GeV



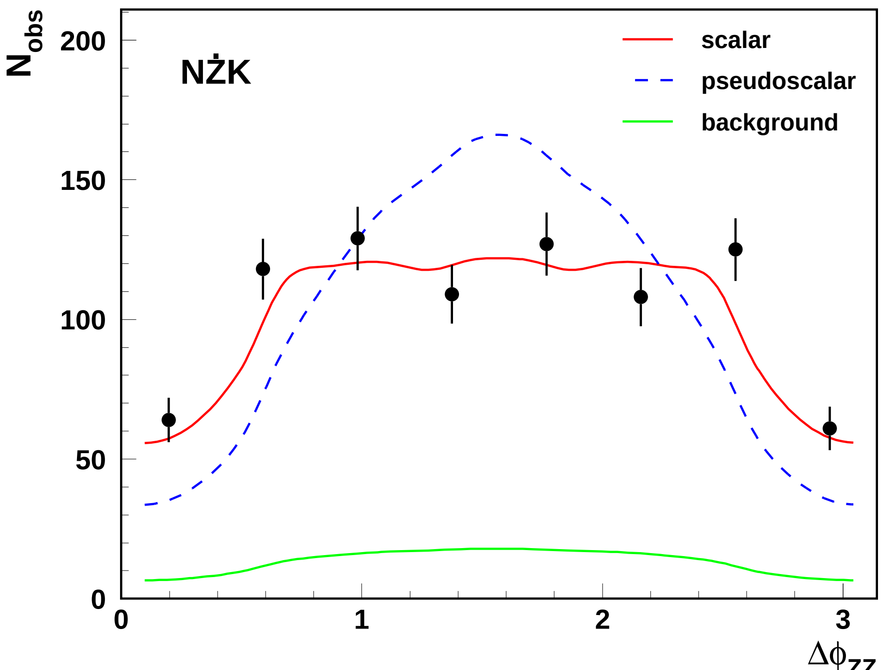
Effect much stronger for background events and pseudoscalar higgs

due to different $\cos\theta_{j,l}$ distribution

Generic model

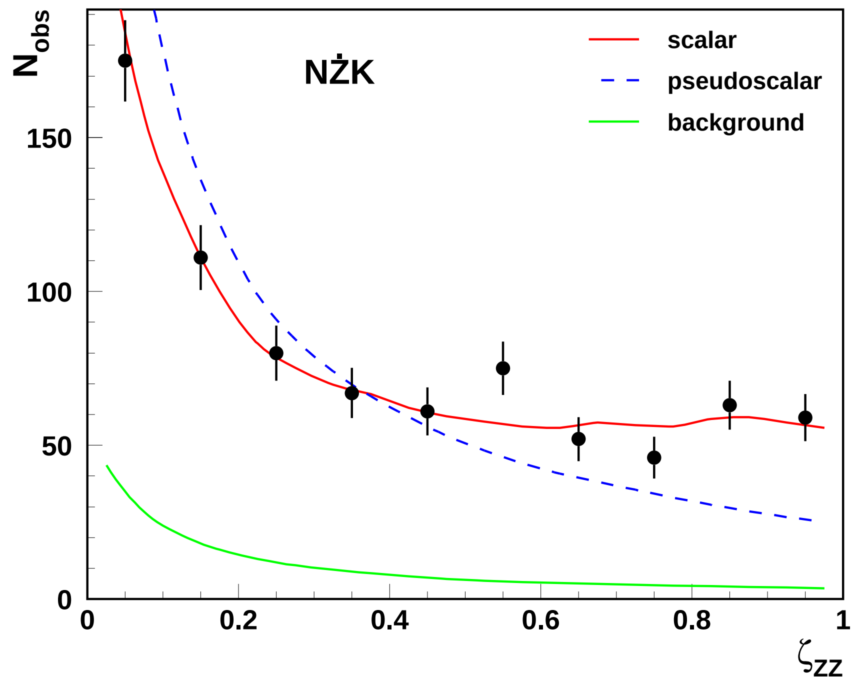
Measured $\Delta\phi$ and ζ distributions for $h \to ZZ \to q\bar{q}\, l^+ l^-$ m_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ ~675 reconstructed SM higgs events expected + 145 ZZ background events

Measured $\Delta\phi_{ZZ}$ distribution:



$q \leftrightarrow \bar{q}$ ambiguity $\Rightarrow 0 \leq \Delta\phi \leq \pi$

Measured ζ_{ZZ} distribution:



pseudoscalar normalized to the same number of events

Generic model

Sensitivity

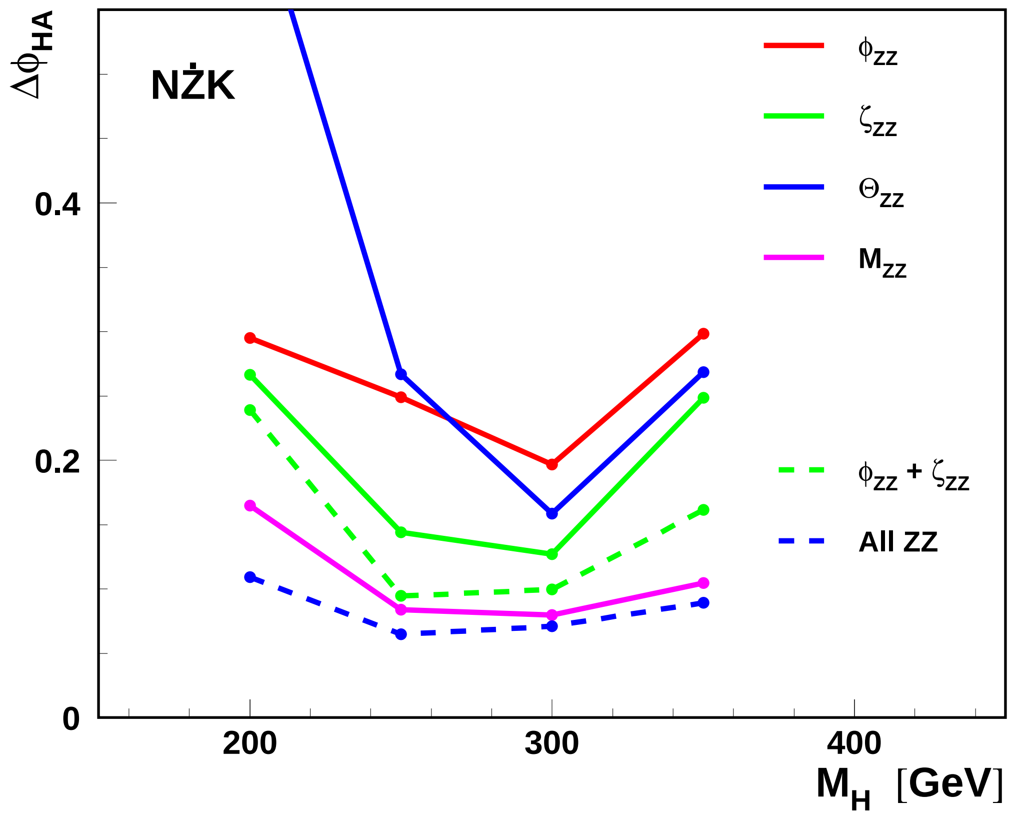
Statistical error on Φ_{HA}
from fits to different distributions $\Rightarrow$

Fits of two parameters:

Φ_{HA} + normalization

We assume here:

$$\Gamma_{\gamma\gamma} = \Gamma_{\gamma\gamma}^{SM}$$
$$\phi_{\gamma\gamma} = \phi_{\gamma\gamma}^{SM}$$
$$\lambda = \lambda^{SM} \equiv 1$$



In the general case We can not assume that $\Gamma_{\gamma\gamma}$, $\phi_{\gamma\gamma}$ and λ are the same as in the SM
$\Rightarrow$ fit all distributions simultaneously to constrain all parameters

Generic model

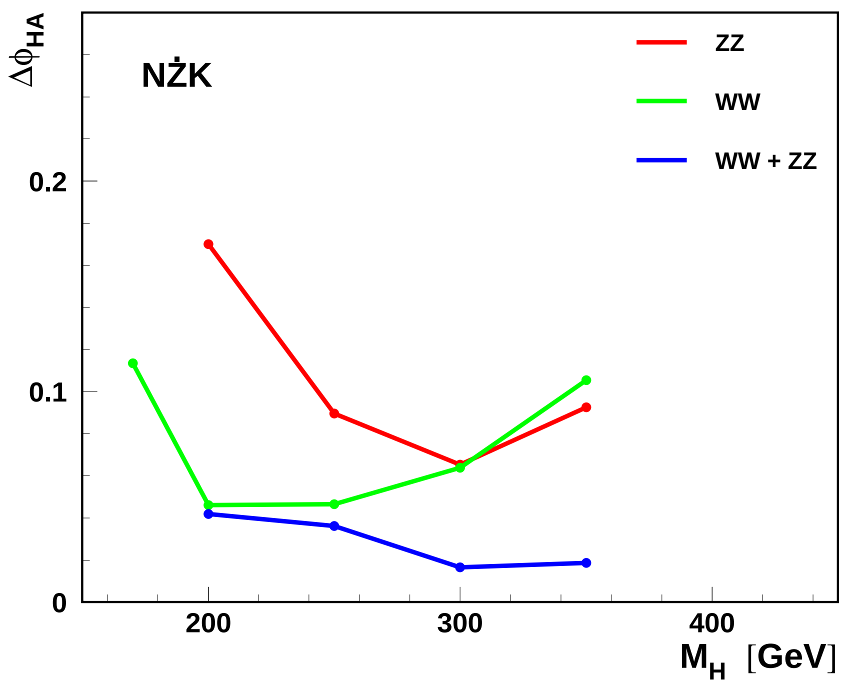
Results

Combined measurement for W^+W^- and ZZ decay channels

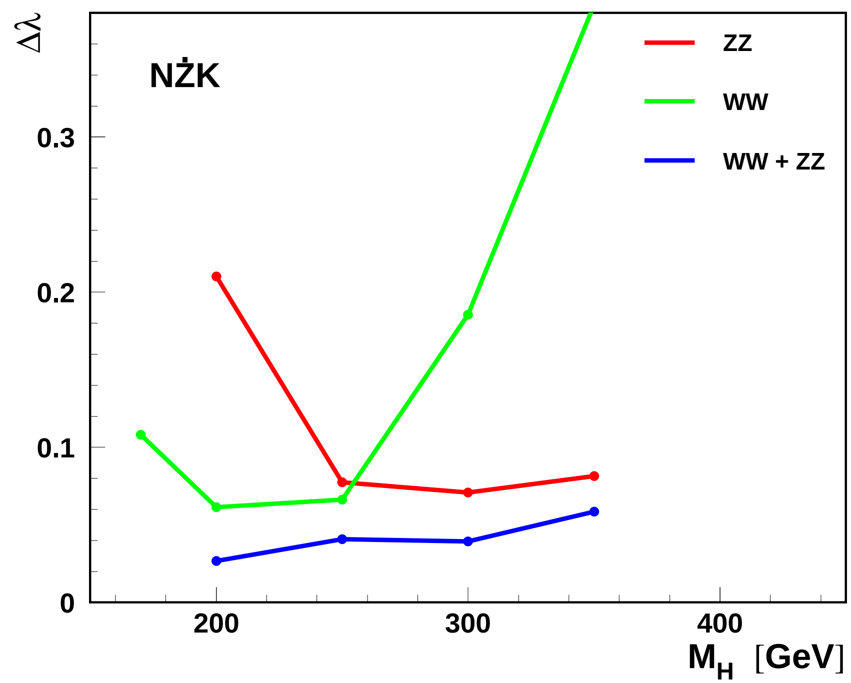
from simultaneously fit of $\Gamma_{\gamma\gamma}$, $\phi_{\gamma\gamma}$, λ and Φ_{HA} to all considered distributions

Measurement error for Higgs-boson couplings to vector bosons:

CP phase Φ_{HA}



Value λ



assuming SM-like couplings: $\lambda = 1$, $\Phi_{HA} = 0$

$W^+W^- \Rightarrow$ higher statistics, but huge background $\Rightarrow$ large systematic uncertainties

Summary

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

Mass range $200 < M_{\mathcal{H}} < 350$ GeV considered.

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

Φ_{HA} with precision $\Delta\Phi_{HA} \leq 0.1$ rad, for $\tan\beta < 1$

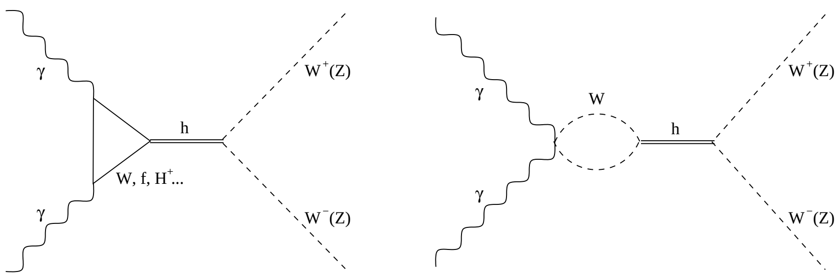
In general case, combined analysis of LHC, LC and PLC measurements is needed to establish weak CP violation.

From combined measurement of angular correlations in the W^+W^- and ZZ decays CP violation in the higgs couplings to vector bosons can be determined to about 10%.

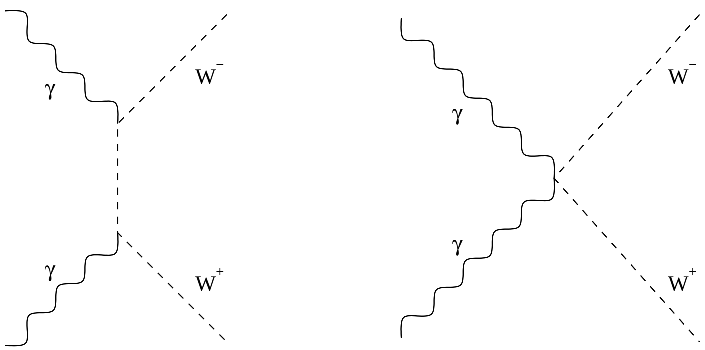
$\gamma\gamma \to \mathcal{H} \to WW,\ ZZ$

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

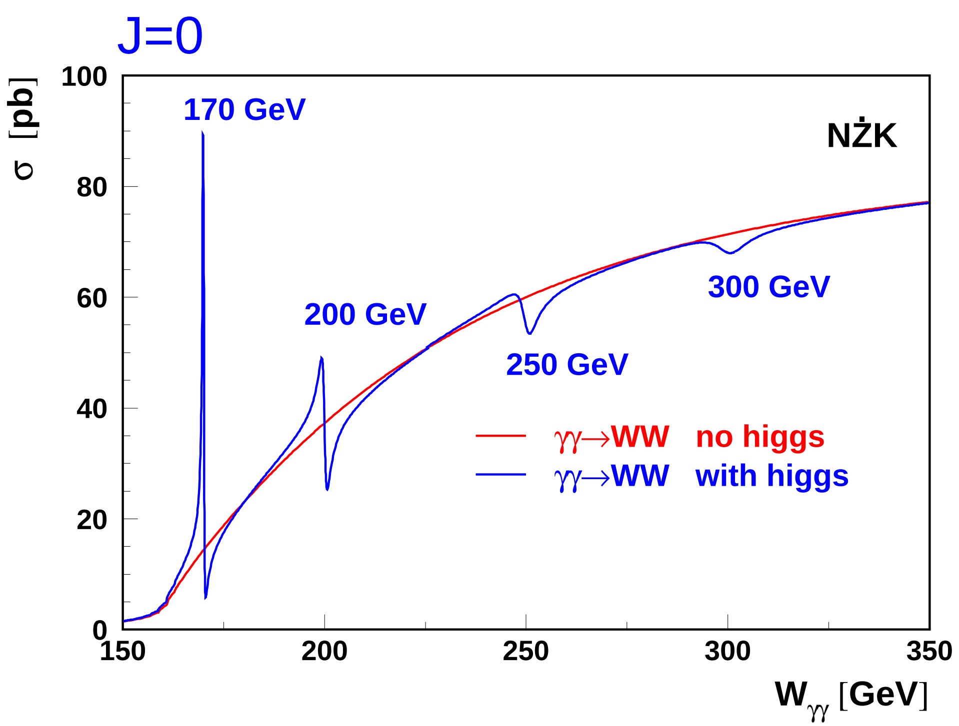
For resonant $\gamma\gamma \to h \to W^+W^-$ signal



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

2HDM(II)

Systematic uncertainties

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

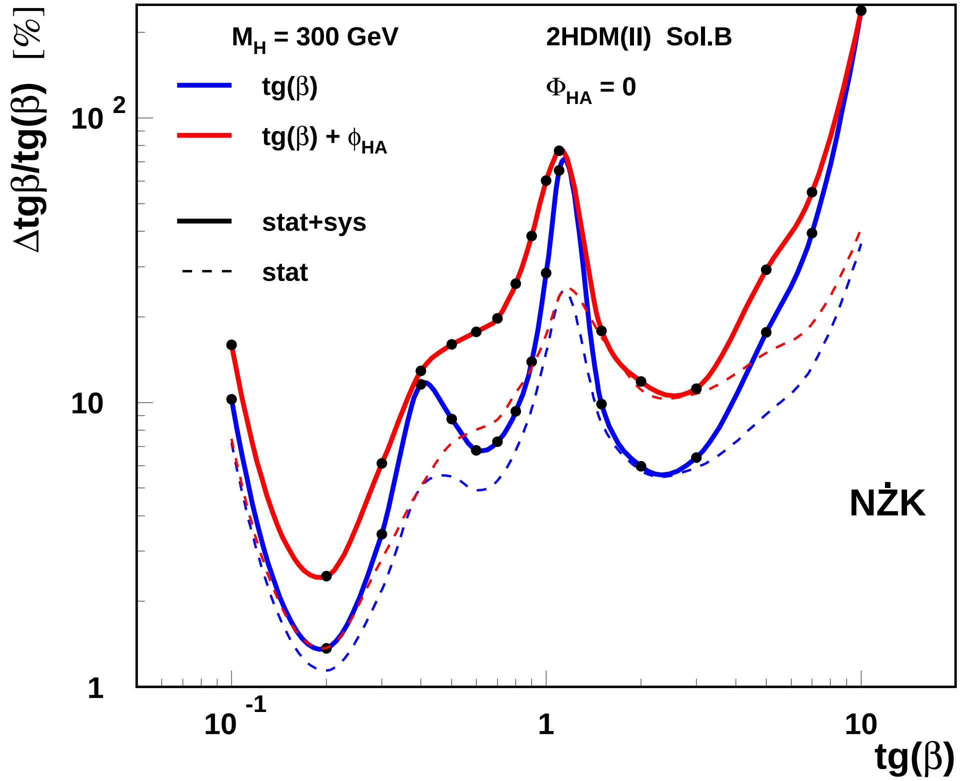
Uncertainties:		Parameters:
• luminosity	$\Rightarrow$	overall normalization relative normalization of WW and ZZ samples fixed
• energy scale • Higgs boson mass	} $\Rightarrow$	Higgs boson mass
• mass resolution • Higgs boson width	} $\Rightarrow$	Higgs boson width
• luminosity spectra	$\Rightarrow$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

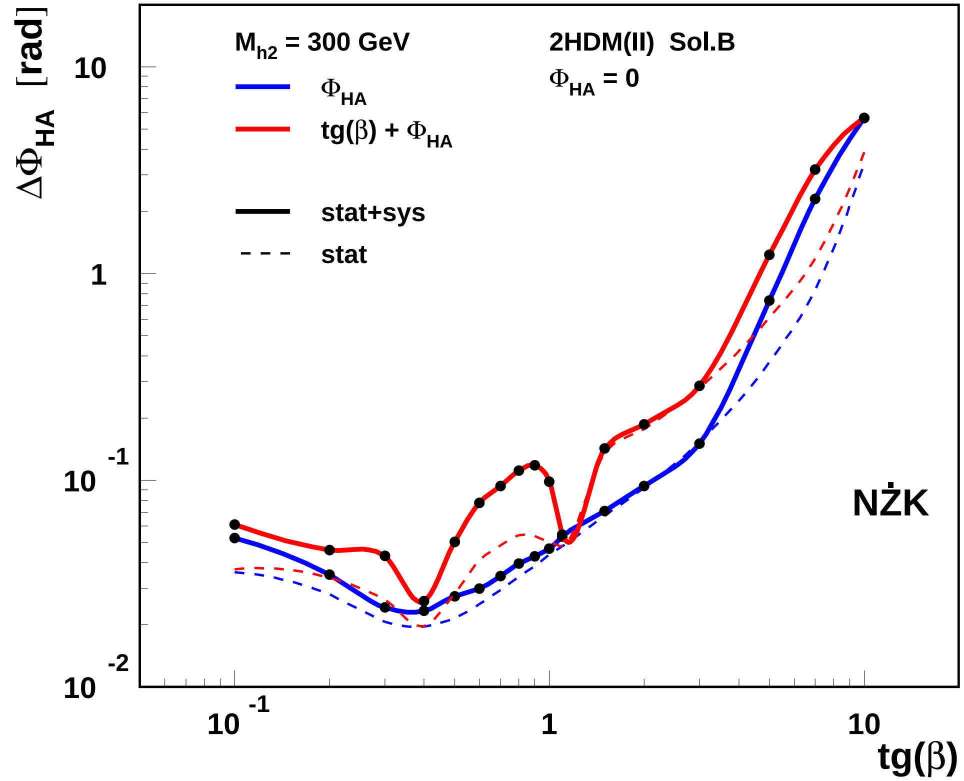
$$\frac{dL}{dW_{\gamma\gamma}} = \frac{dL^{CompAZ}}{dW_{\gamma\gamma}}(1 + A \cdot \sin \pi x + B \cdot \sin 2\pi x) \qquad x = \frac{W_{\gamma\gamma} - W_{min}}{W_{max} - W_{min}}$$

2HDM(II)

Higgs boson h_2

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



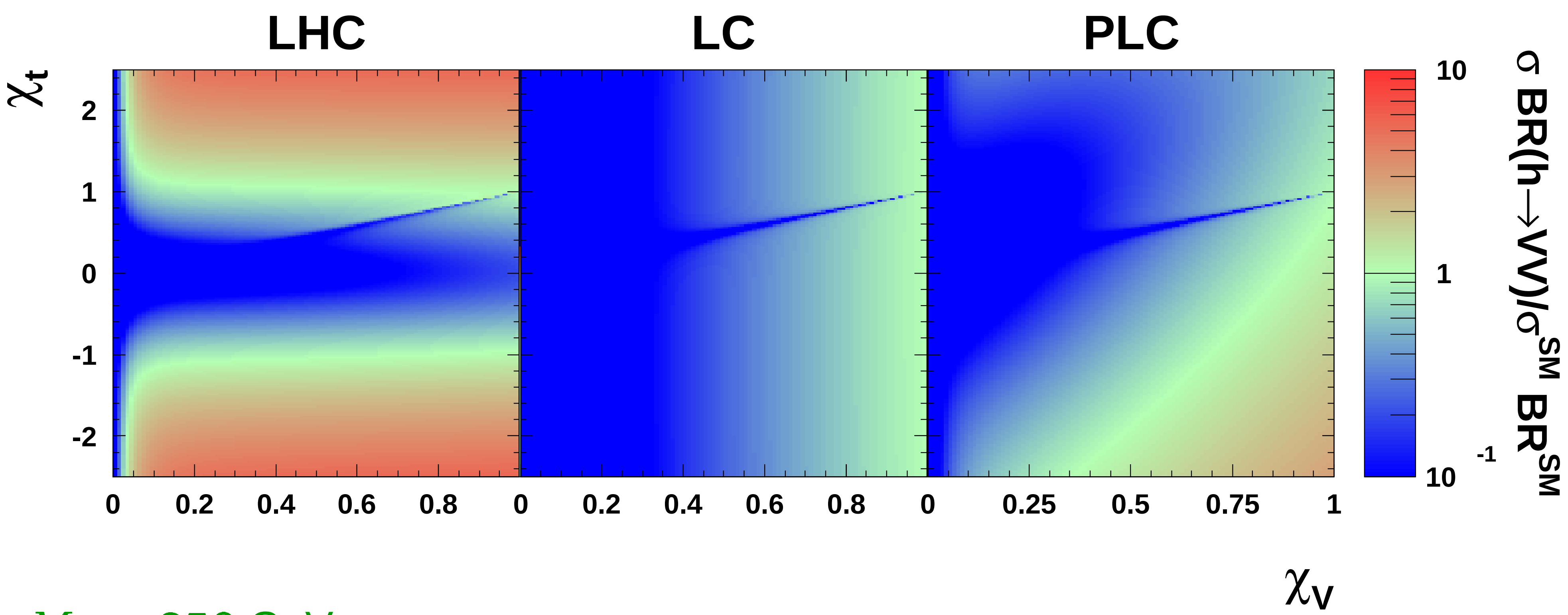


Correlation between $\tan\beta$ and Φ_{HA} increases expected measurement errors

Comparison with LHC and LC

CP conserving 2HDM (II)

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

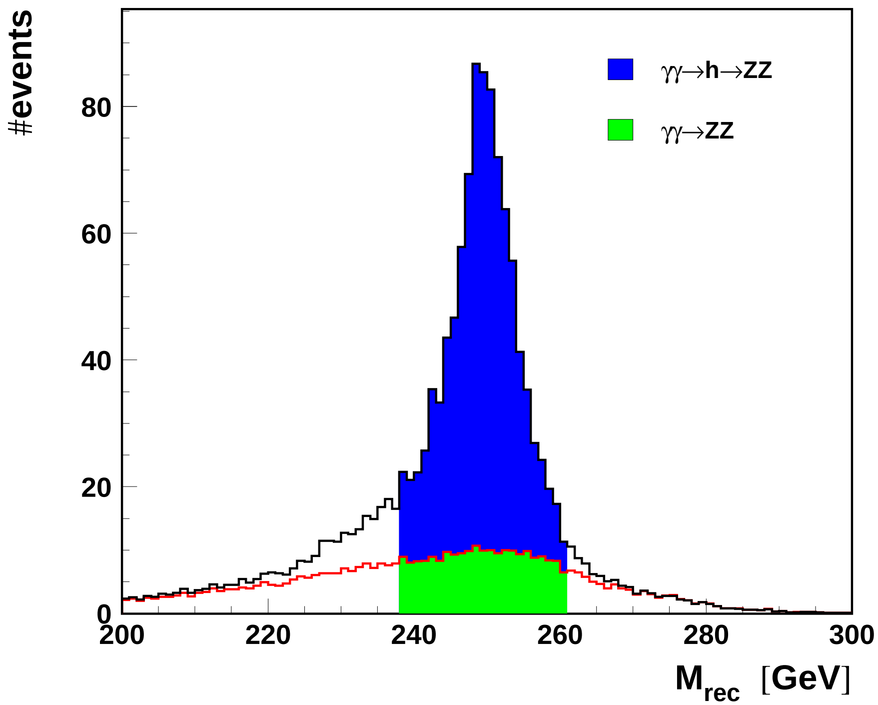


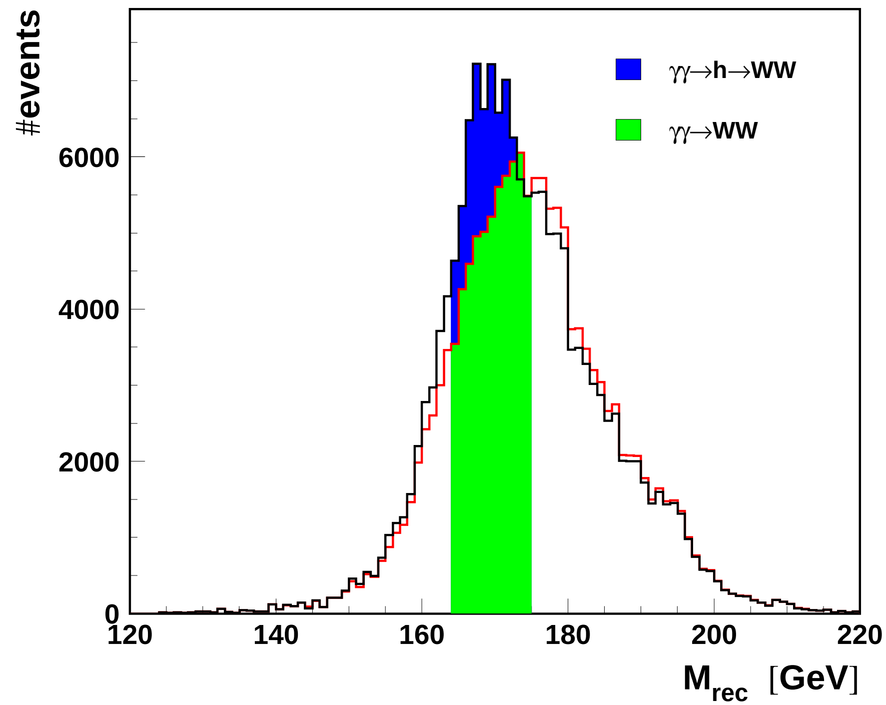
$M_h = 250$ GeV

Generic model

Invariant mass cut optimized for background rejection

$h \to ZZ \to q\bar{q}\, l^+ l^-$ m_h=250 GeV: $h \to WW \to q\bar{q}q\bar{q}$ m_h=170 GeV:





SM higgs selection efficiency ∼40%

(for $ZZ \to q\bar{q}\, l^+ l^-$ events, $l = \mu, e$)

$\times BR(ZZ \to q\bar{q}\, l^+ l^-) \approx$ 9.4%

SM higgs selection efficiency ∼30%

(for $WW \to q\bar{q}q\bar{q}$ events)

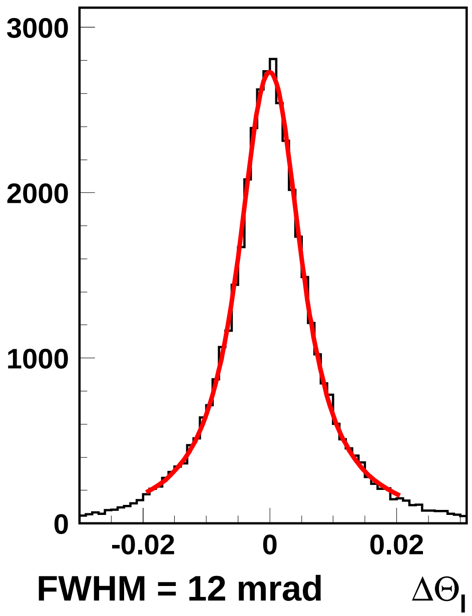
$\times BR(WW \to q\bar{q}q\bar{q}) \approx$ 46.9%

Generic model

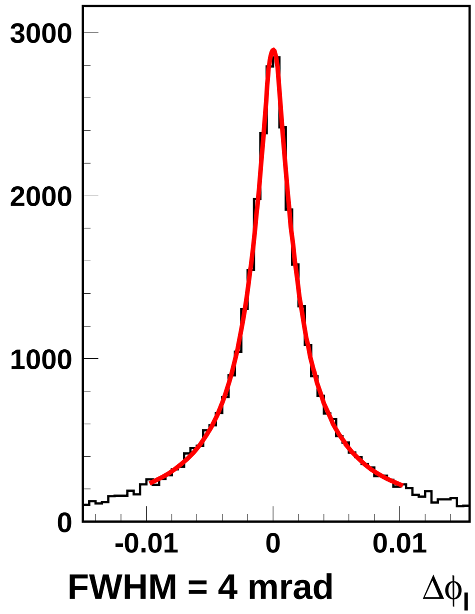
Expected accuracy of decay angles measurement:

$Z \rightarrow l^+ l^-$

polar angle θ_l

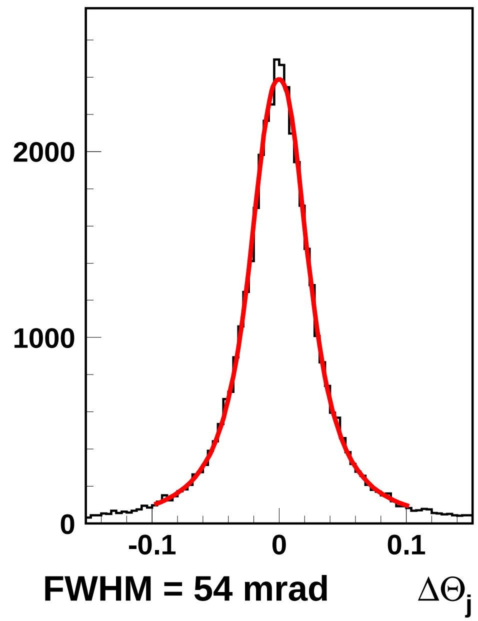


azimuthal angle ϕ_l

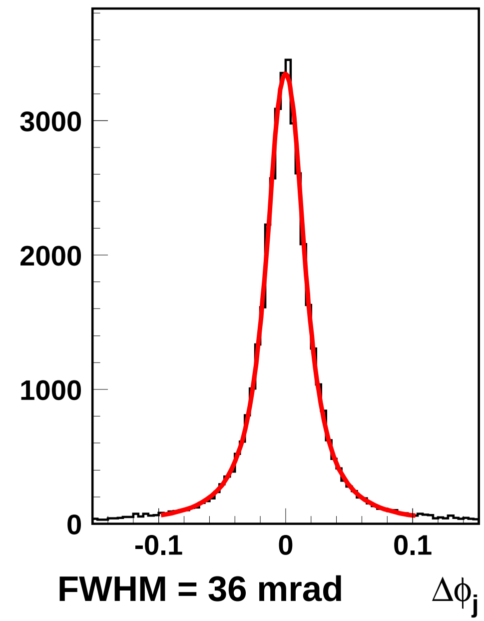


$Z/W \rightarrow q\bar{q}$

polar angle θ_q



azimuthal angle ϕ_q



$\sim$ same for $\Delta\phi$

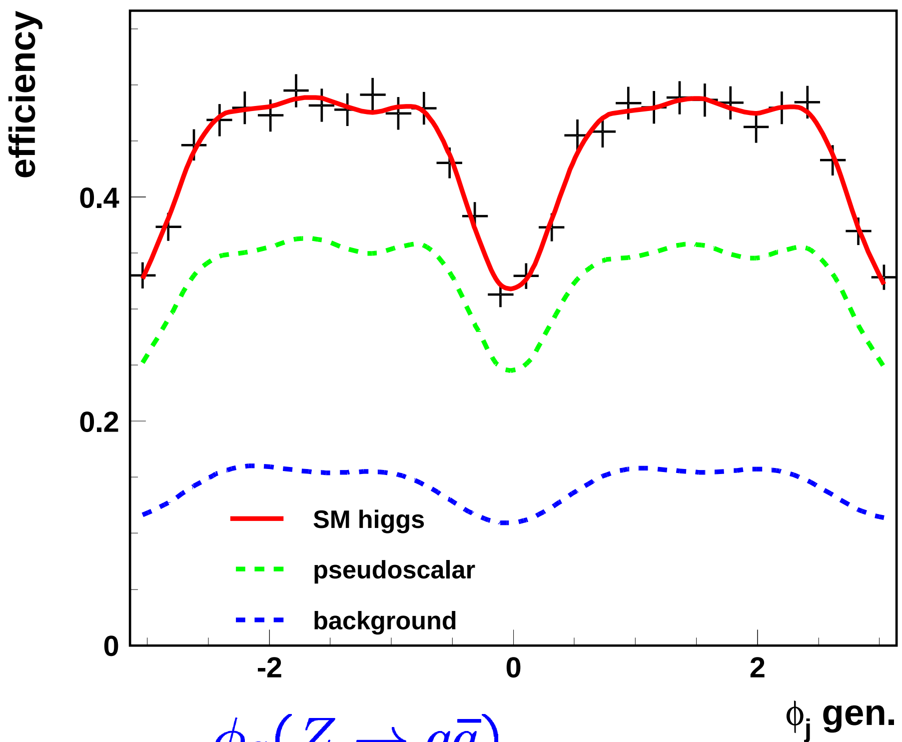
All angles can be measured with high accuracy

Shape described by Breit-Wigner distribution

Generic model

Selection efficiency as a function of the azimuthal angle ϕ_q

m_h = 300 GeV, $\sqrt{s_{ee}}$=418 GeV

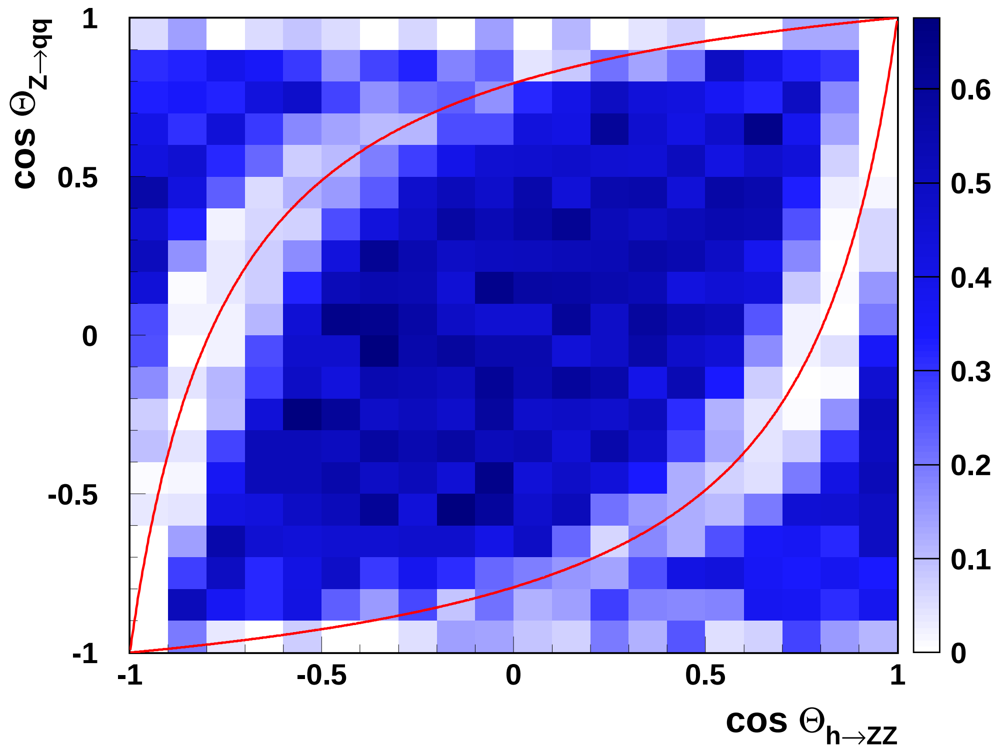


$\phi_q(Z \to q\bar{q})$

similar pattern observed for $Z \to l^- l^+$

Acceptance losses for $\phi = 0, \pi, \ldots$ are due to the jet/lepton going in the beam direction

Selection efficiency for $\phi_j \approx 0$:

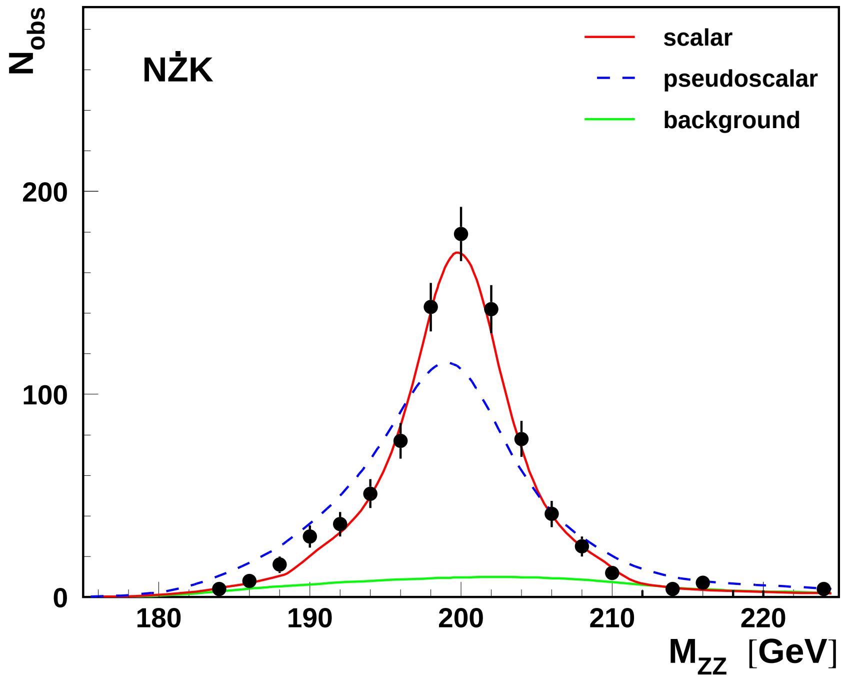


red lines: $\cos\theta_j^{LAB} = \pm\cos\theta_Z^{LAB}$

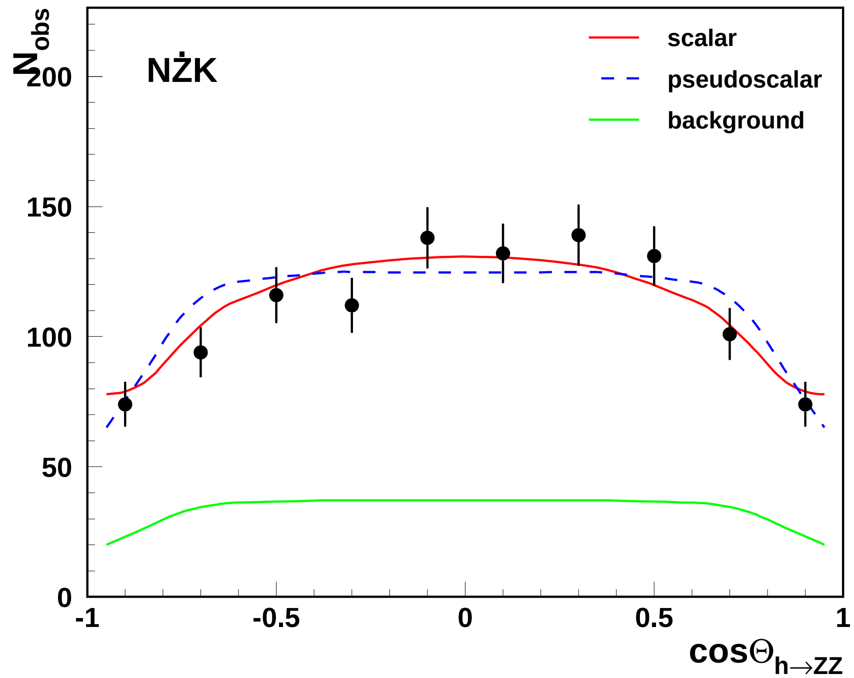
Generic model

Measured M_{ZZ} and Θ_h distributions for $h \to ZZ \to q\bar{q}\,l^+l^-$ m_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$

Measured M_{ZZ} distribution:



Measured Θ_h distribution:



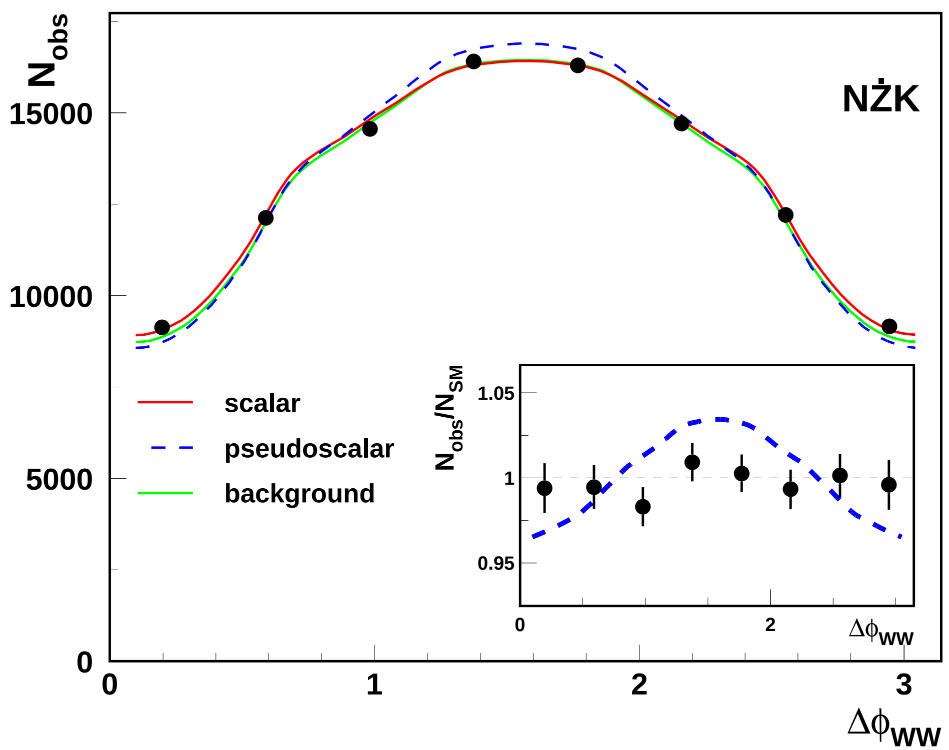
pseudoscalar normalized to the same number of events

Sensitive to CP violation mainly due to interference with SM background.

Generic model

Measured $\Delta\phi$ and ζ distributions for $h \to WW \to q\bar{q}\, l^+ l^-$ m_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ ~8000 reconstructed SM higgs events expected + ~ 170 000 background events

Measured $\Delta\phi_{WW}$ distribution:



Measured ζ_{WW} distribution: