Model-independent analysis of the CP violation using angular distributions in the WW and ZZ decays of the Higgs boson at the Photon Collider.

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Outline

- Generic Higgs couplings to WW/ZZ
- Simulation and event selection
- Reconstruction of angular distributions
- Results (ICHEP'04 #12-0739)

ECFA Study meeting
Durham, September 1-4, 2004

Generic model

CP-even, CP-odd couplings

We consider 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: $\lambda_H = \lambda\cdot\cos\Phi_{CP}$ $\lambda_A = \lambda\cdot\sin\Phi_{CP}$

Standard Model scalar $\Rightarrow \Phi_{CP} = 0$ ($\lambda_H = 1$ and $\lambda_A = 0$).

Pseudoscalar Higgs boson $\Rightarrow \Phi_{CP} = \frac{\pi}{2}$ ($\lambda_H = 0$ and $\lambda_A = 1$).

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

The other generic CP-even coupling $\sim (p_1+p_2)^\mu(p_1+p_2)^\nu$
leads to the angular distributions similar to that of the SM scalar.

Generic model

Model description

S.Y. Choi, D.J. Miller, M.M. Mühlleitner and P.M. Zerwas, hep–ph/0210077;

D.J. Miller, et al., Phys. Lett. B505 (2001) 149;

D.J. Miller, ECFA/DESY meeting, Prague, November 2002.

Higgs CP from $\gamma\gamma \to \mathcal{H} \to t\bar{t}$:

E. Asakawa, K. Hagiwara, hep-ph/0305323.

LC studies:

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;

M.T. Dova, S. Ferrari, hep-ph/0406313.

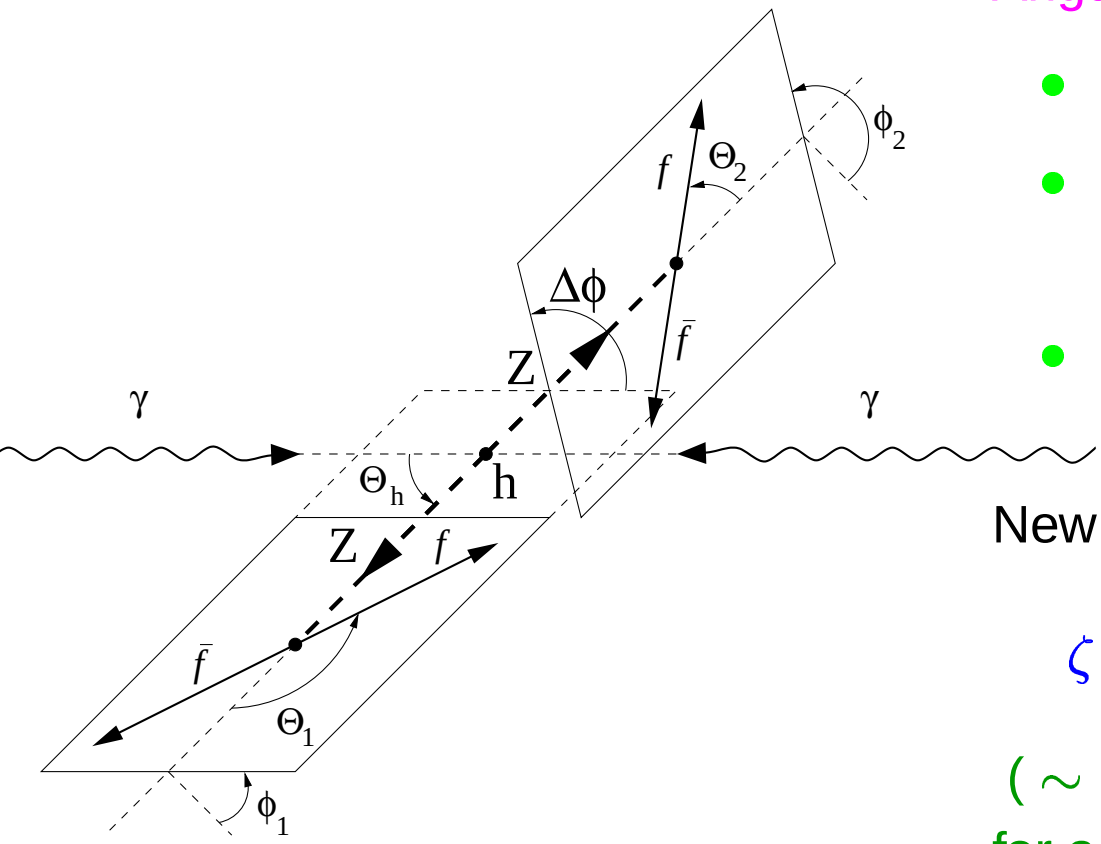
LHC study:

C.P. Buszello, et al., Eur. Phys. J. C32 (2004) 209;

C.P. Buszello, et al., hep-ph/0406181.

Generic model

Angles definition for ZZ decays (similar for WW)



Angular variables:

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

New variable:

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

($\sim$ ratio of the distributions expected for a scalar and a pseudoscalar higgs)

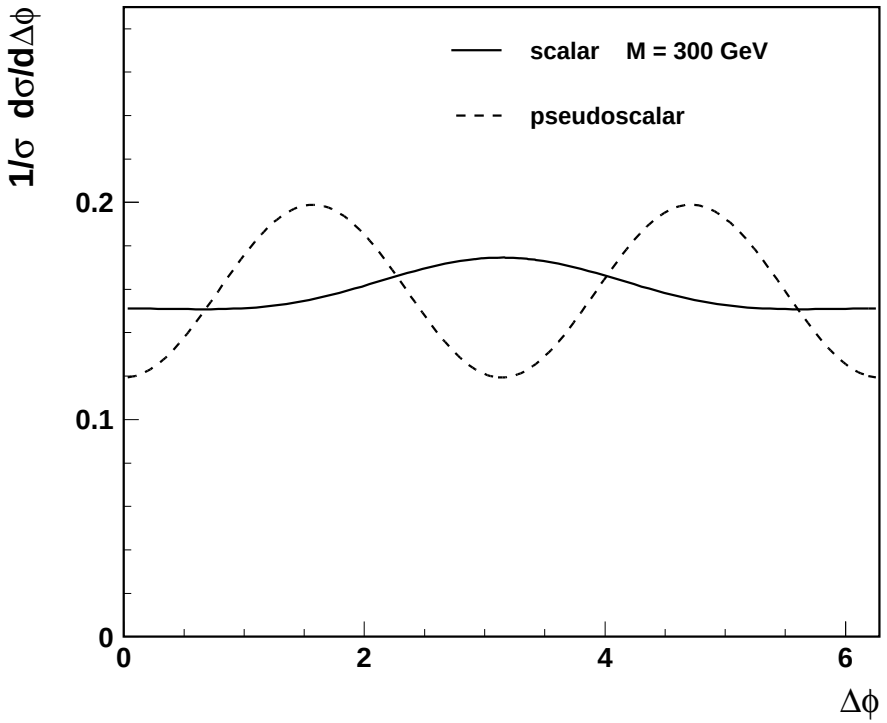
All angles are calculated in the rest frame of the decaying particle

Generic model

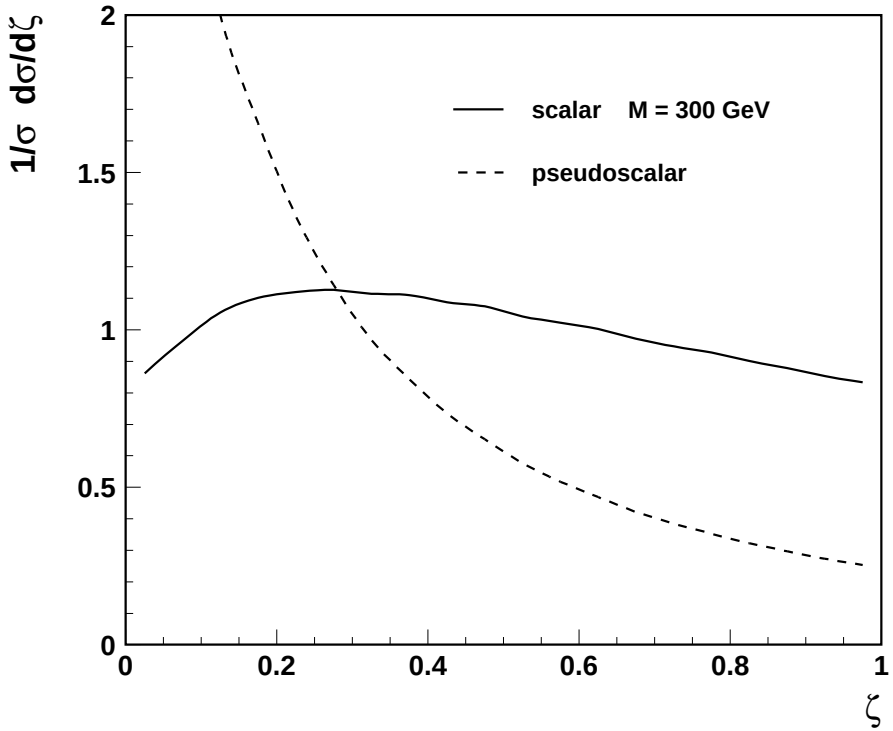
Angular distributions for $\mathcal{H} \to ZZ \to l^+l^-jj$

$\Delta\phi$ and ζ distributions expected for scalar and pseudoscalar higgs, $M_{\mathcal{H}} = 300$ GeV.

$\Delta\phi$



ζ



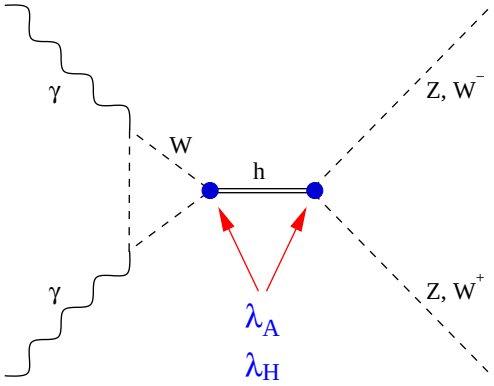
Both $\Delta\phi$ and ζ distributions clearly distinguish between scalar and pseudoscalar higgs.

Model-independent analysis

Old: model-dependent

EPS'2003 and Montpellier results

hep-ph/0307175



Generic couplings to W/Z

both in production (W loop) and decay.

Couplings to fermions as in SM

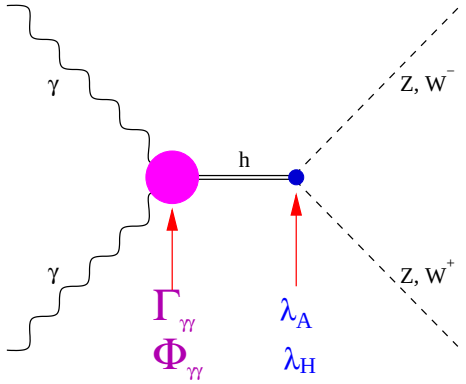
No other "new physics"

(eg. loops with heavy particles)

⇒ results not model-independent

New approach

LCWS'2004 and ICHEP'04



Generic couplings to W/Z in decay

Generic production vertex:

no constraints on $\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$

⇒ **model independent analysis**

Only assumption:

deviations from SM are not large

$\Gamma_{\gamma\gamma} \approx \Gamma_{\gamma\gamma}^{SM}$, $\Phi_{\gamma\gamma} \approx \Phi_{\gamma\gamma}^{SM}$, $BR_{h\to VV} \approx BR^{SM}$

Simulation

$\gamma\gamma$ spectra from **CompAZ**,
$\sqrt{s_{ee}} = 270 - 500$ GeV

higgs events generated with PYTHIA 6.214

$\gamma\gamma \to h \to ZZ \to e^+e^-q\bar{q}\ /\ \mu^+\mu^-q\bar{q}$

$\gamma\gamma \to h \to WW \to q\bar{q}\,q\bar{q}$

m_h = 170 – 350 GeV

PYTHIA properly simulates all angular distributions for SM higgs

"pseudoscalar" higgs

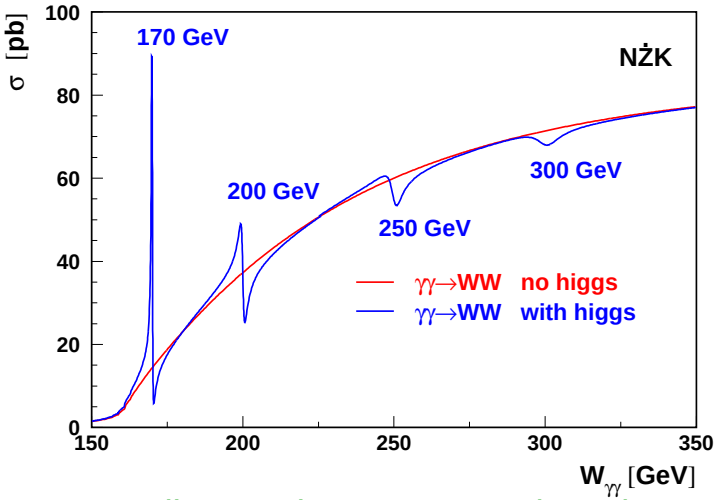
$\Rightarrow$ reweighting of angular distributions
(σ and BR assumed same as for h)

angular distributions for background

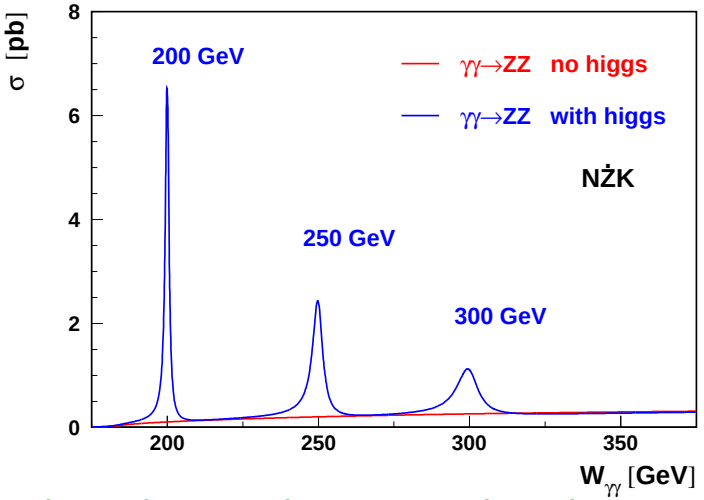
$\Rightarrow$ PYTHIA + reweighting

detector simulation with SIMDET v. 3.01

Cross sections for $J_Z = 0$:



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.



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

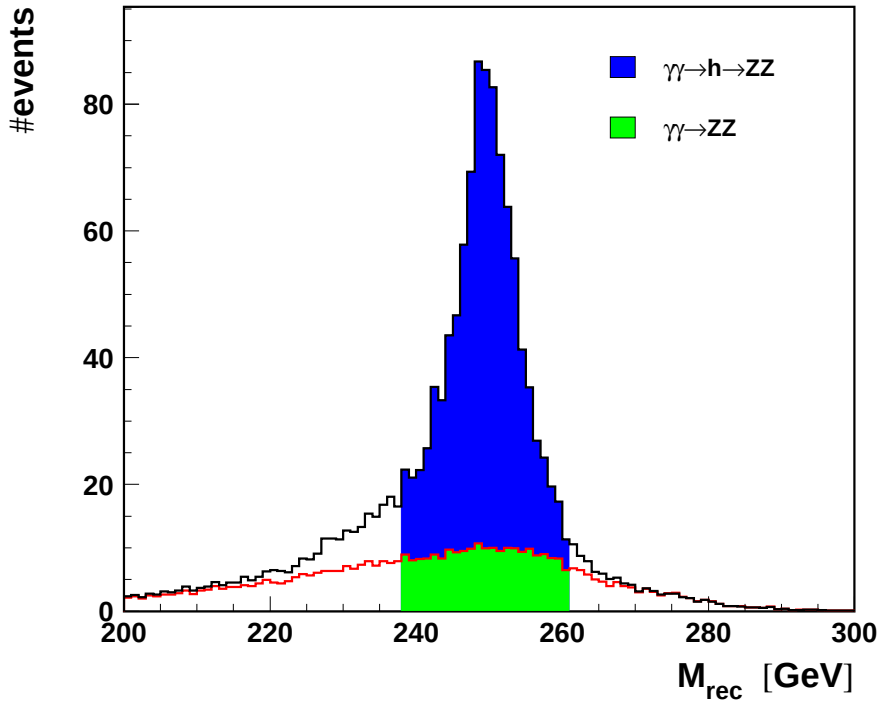
Event selection

$h \to ZZ \to llqq$ events

- balanced transverse momentum:
  $$P_T/E_T < 0.1$$
- 2 leptons ($e^{\pm}$ or $\mu^{\pm}$) + 2 hadronic jets
- cut on lepton and jet angle
  $$\cos\theta_l < 0.98, \quad \cos\theta_{jet} < 0.95$$
- leptons and jets reconstruct into two Z° with probability $P_Z > 0.001$
  based on reconstructed invariant mass
- invariant mass cut
  optimized for background rejection

P. Nieżurawski, A.F. Żarnecki, M. Krawczyk,
JHEP 0211 (2002) 034 [hep-ph/0207294]

Invariant mass cut for M_h=250 GeV:



Selection efficiency for SM higgs ∼40%
for $h \to ZZ \to q\bar{q}\, l^+l^-$ events, $l = \mu, e$

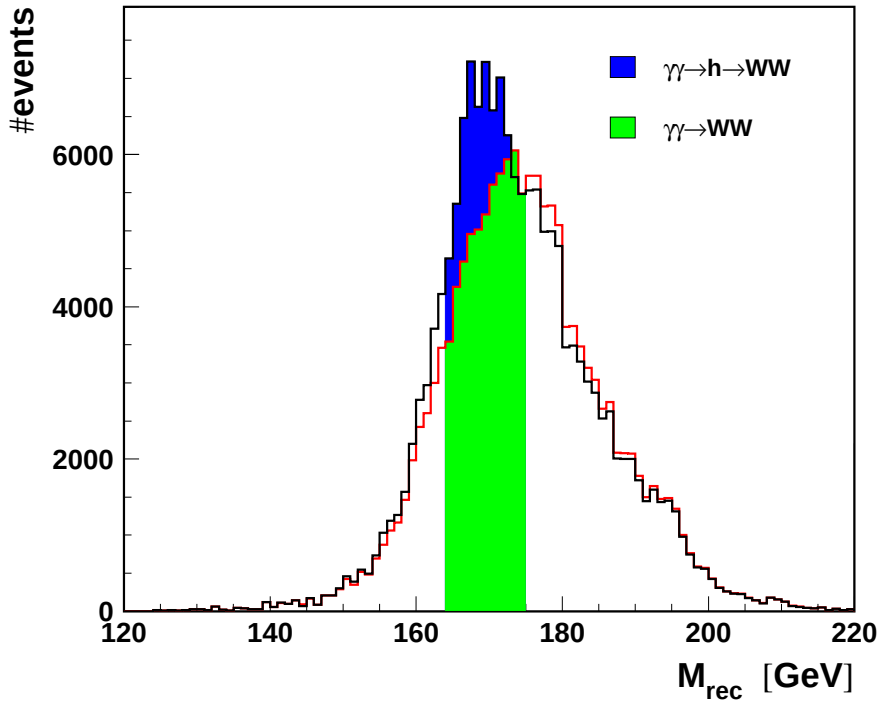
$$BR(ZZ \to q\bar{q}\, l^+l^-) \approx 9.4\%$$

Event selection

$h \to WW \to 4j$ events

- balanced transverse momentum:
  $$P_T/E_T < 0.1$$
- 4 hadronic jets
- cut jet angle
  $$\cos\theta_{jet} < 0.95$$
- jets reconstruct into two $W^{\pm}$
  with probability $P_W > 0.001$
  based on reconstructed invariant mass
- invariant mass and
  higgs decay angle cuts
  optimized for background rejection

Invariant mass cut for M_h=170 GeV:



Selection efficiency for SM higgs ∼30%
for $h \to WW \to q\bar{q}q\bar{q}$ events

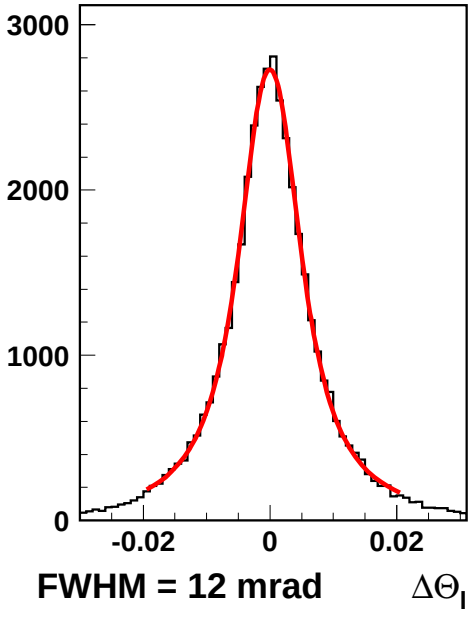
$$BR(WW \to q\bar{q}q\bar{q}) \approx 46.9\%$$

Angle reconstruction

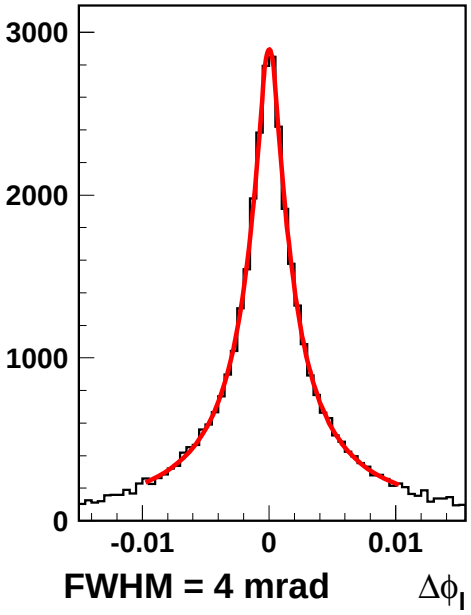
Expected accuracy of decay angles measurement:

$Z \to l^+ l^-$

polar angle θ_l

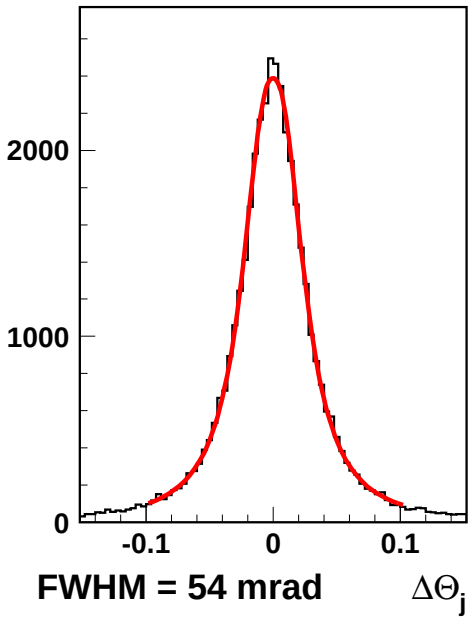


azimuthal angle ϕ_l

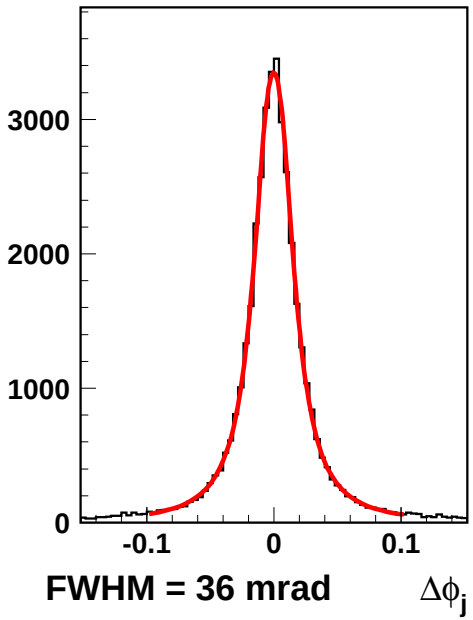


$Z/W \to q\bar{q}$

polar angle θ_q



azimuthal angle ϕ_q



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

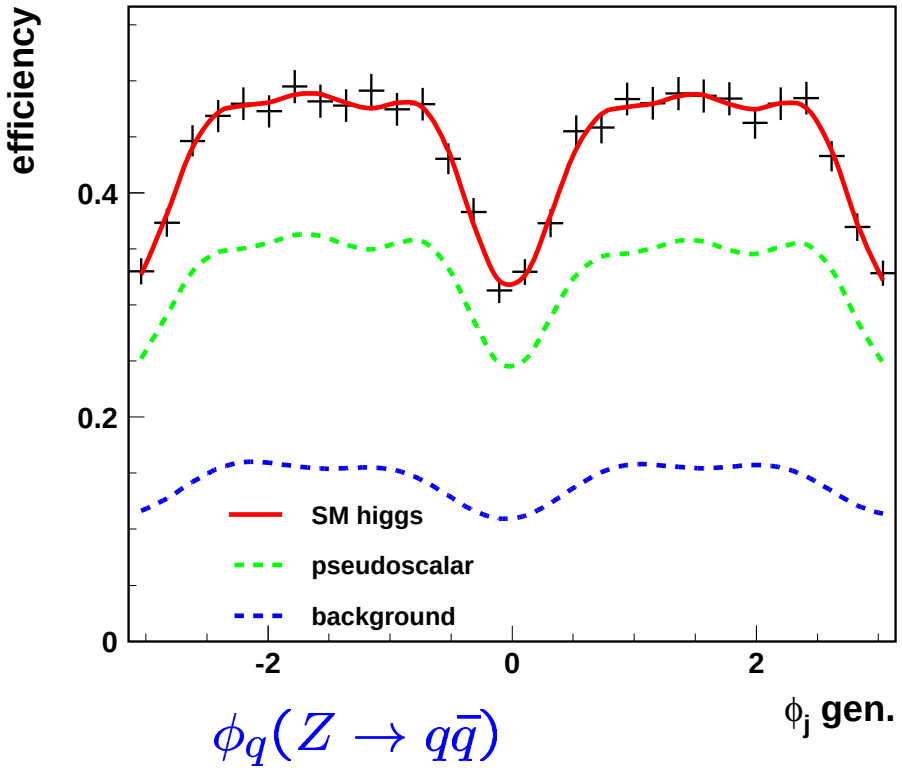
All angles can be measured with high accuracy

Shape described by Breit-Wigner distribution

Acceptance - ϕ_q

Selection efficiency as a function of the azimuthal angle ϕ_q

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

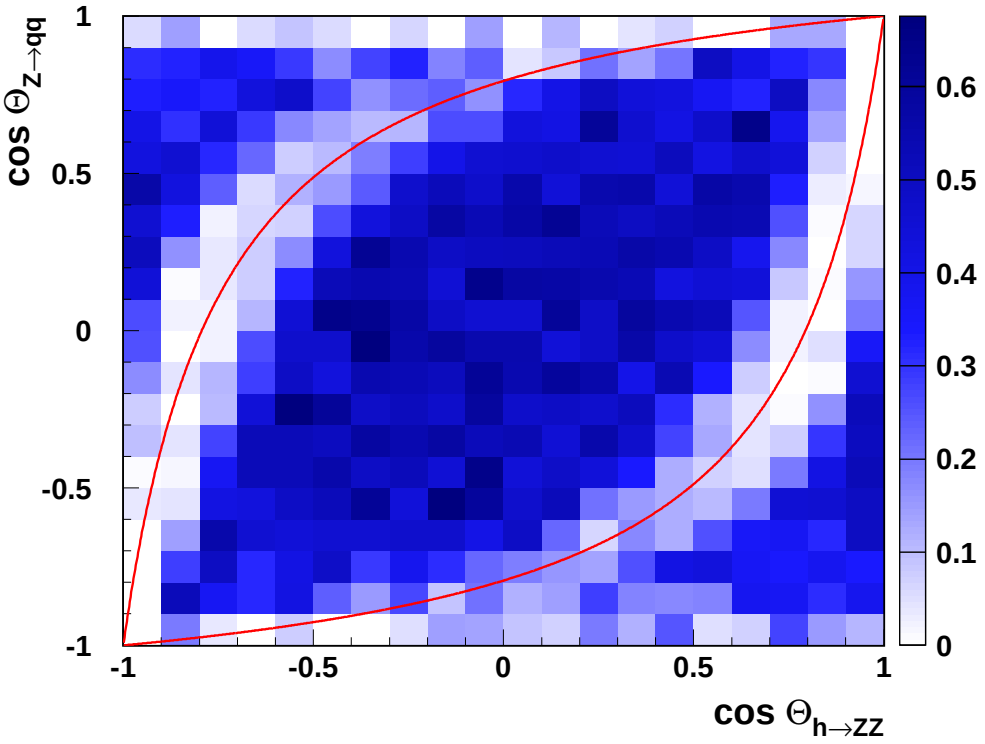


$\phi_q(Z \to q\bar{q})$

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 $\phi_j \approx 0$:

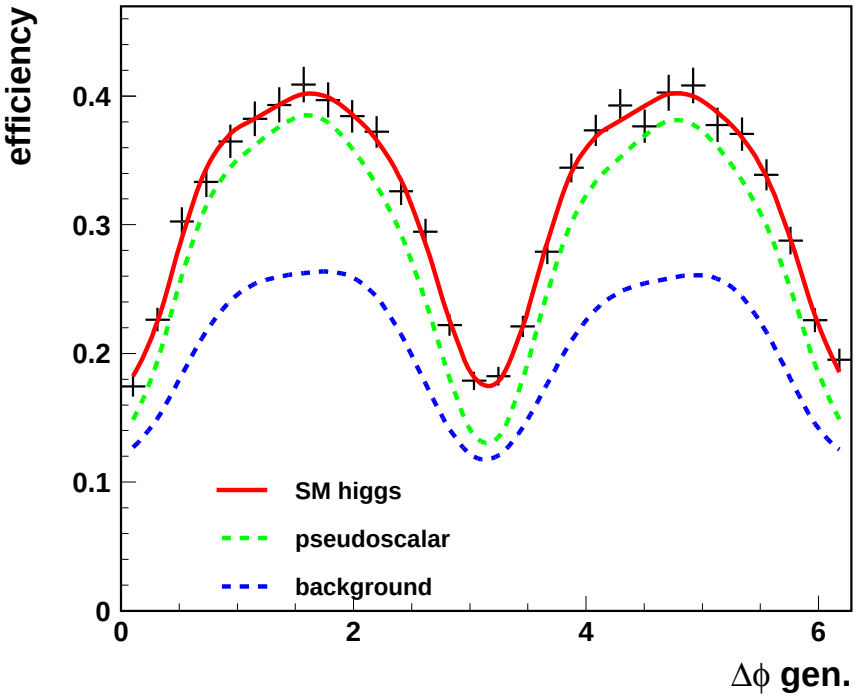


red lines: $\cos\theta_j^{LAB} = \pm\cos\theta_Z^{LAB}$

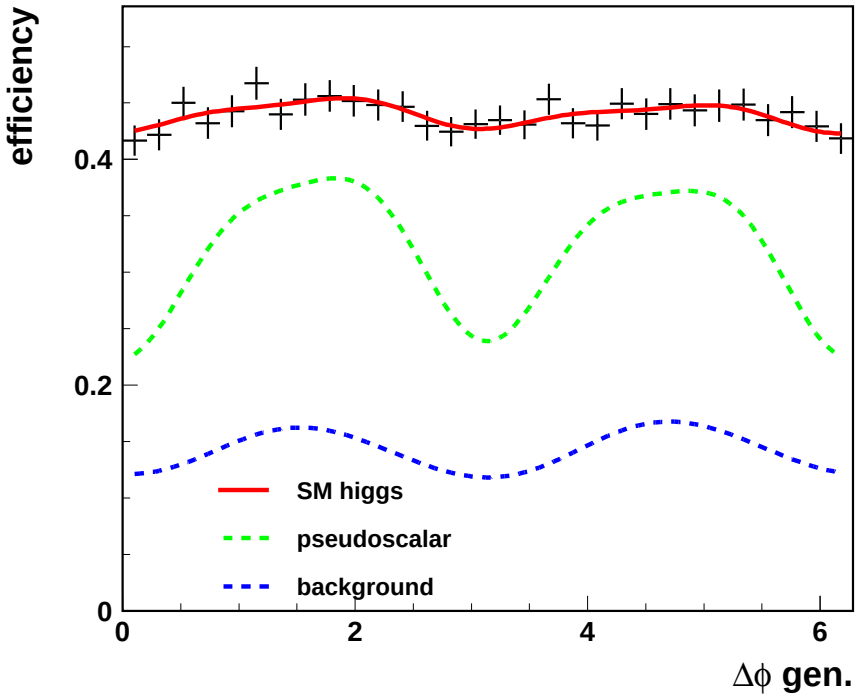
Acceptance - $\Delta\phi_{ZZ}$

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

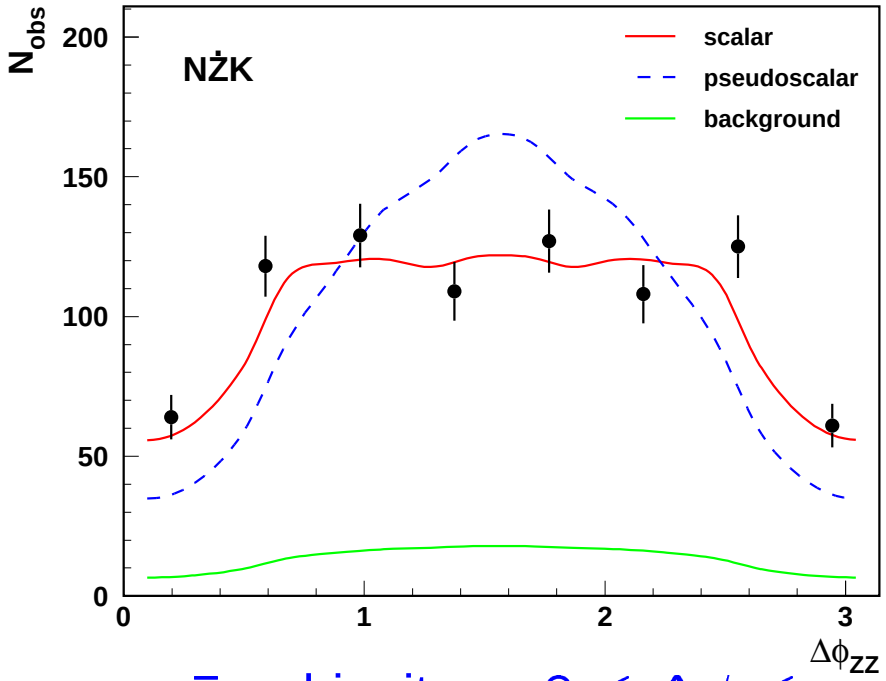


Effect much stronger for background events and pseudoscalar higgs due to different $\cos\theta_{j,l}$ distribution

Results for ZZ

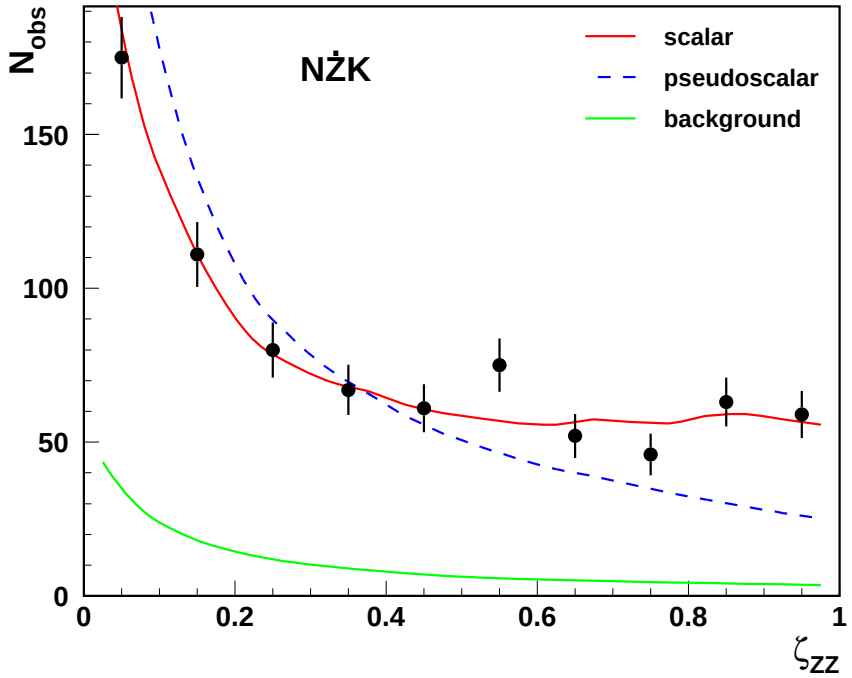
Measured $\Delta\phi$ and ζ distributions for $h \to ZZ \to q\bar{q}\, l^+l^-$ M_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ ~675 reconstructed SM higgs events expected + 145 ZZ background events

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



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

Measured ζ_{ZZ} distribution:

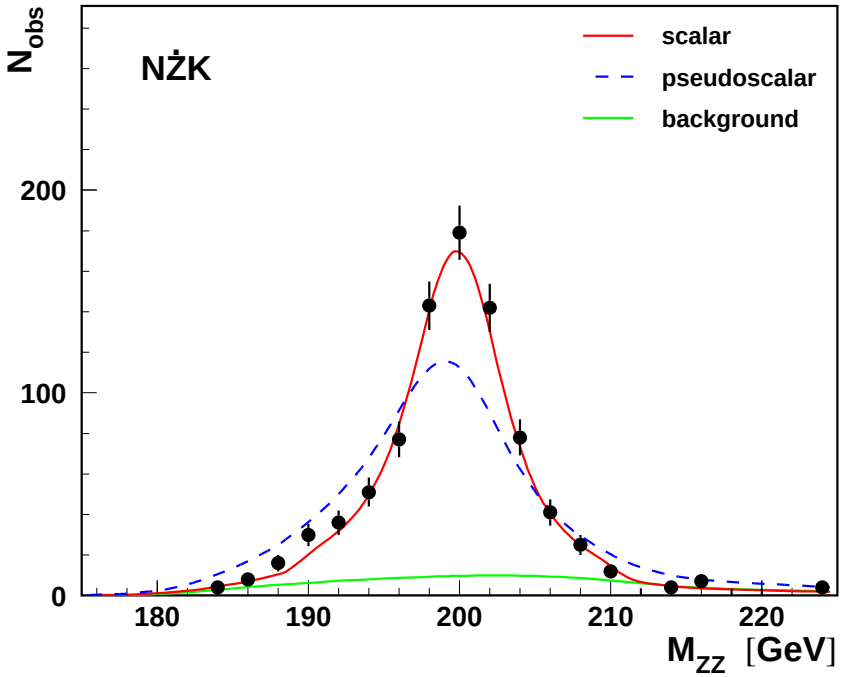


pseudoscalar normalized to the same number of events

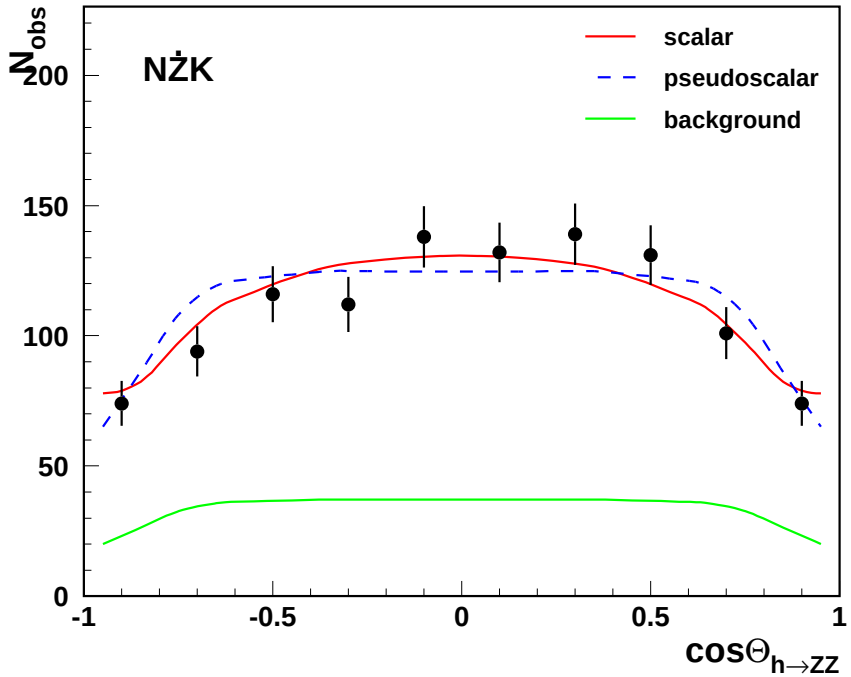
Results for ZZ

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:



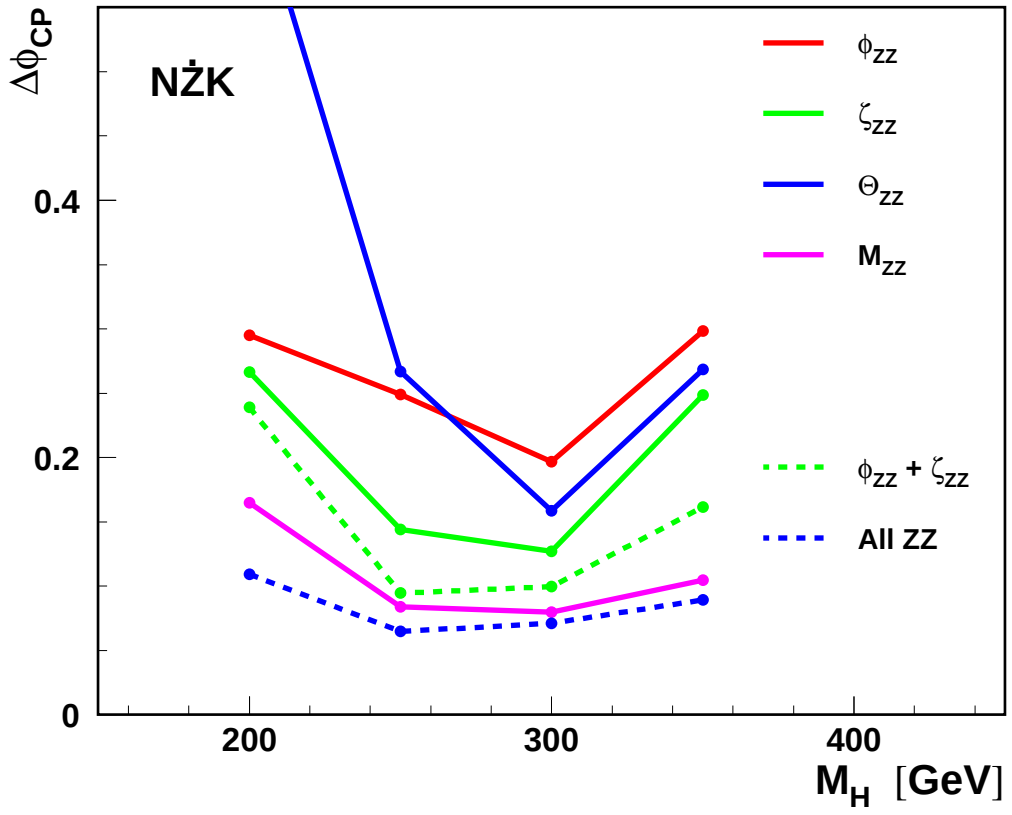
pseudoscalar normalized to the same number of events

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

Results for ZZ

Sensitivity

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



Two parameter fits:

Φ_{CP} + normalization

We assume here:

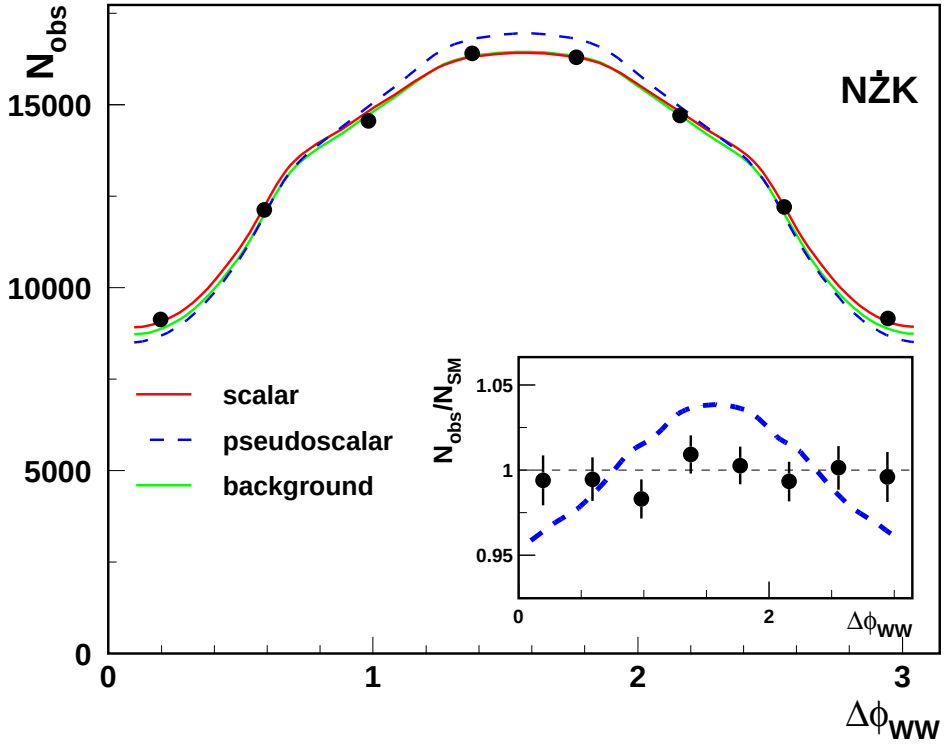
$$\begin{aligned} \Gamma_{\gamma\gamma} &= \Gamma_{\gamma\gamma}^{SM} \\ \phi_{\gamma\gamma} &= \phi_{\gamma\gamma}^{SM} \\ \lambda &= \lambda^{SM} \equiv 1 \end{aligned}$$

For final results we do 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

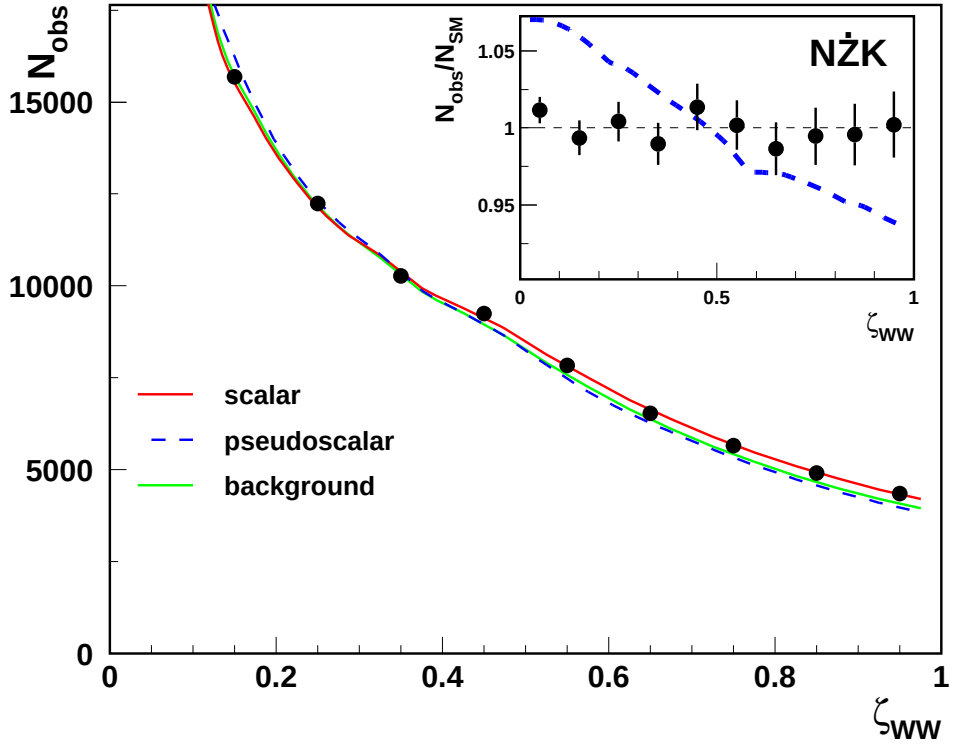
Results for WW

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, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ $\sim$8000 reconstructed SM higgs events expected + $\sim$ 170 000 background events

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



Measured ζ_{WW} distribution:



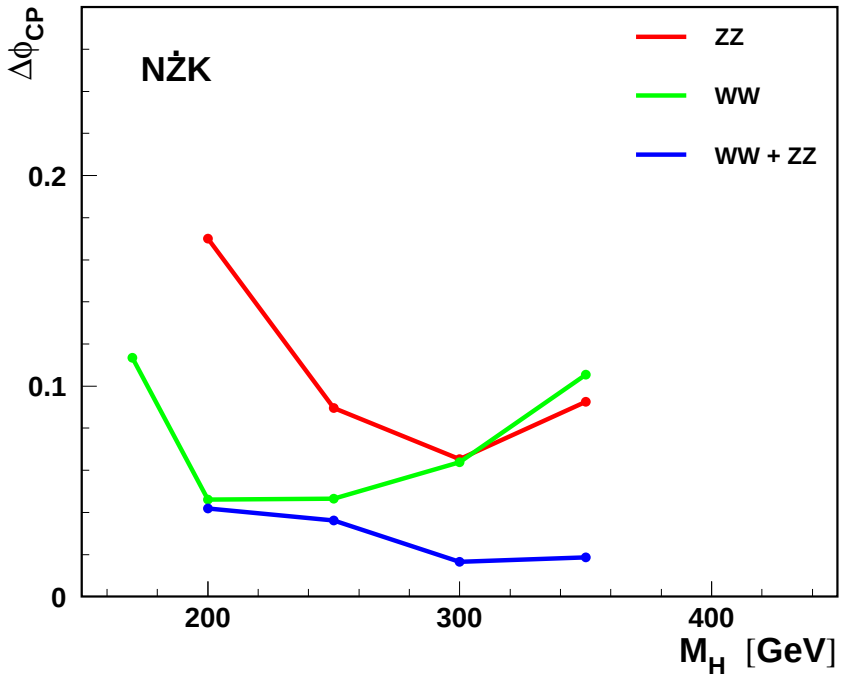
Results - WW & ZZ

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

simultaneously fit of $\Gamma_{\gamma\gamma}$, $\phi_{\gamma\gamma}$, λ and Φ_{CP} (+ normalization factors) to all distributions

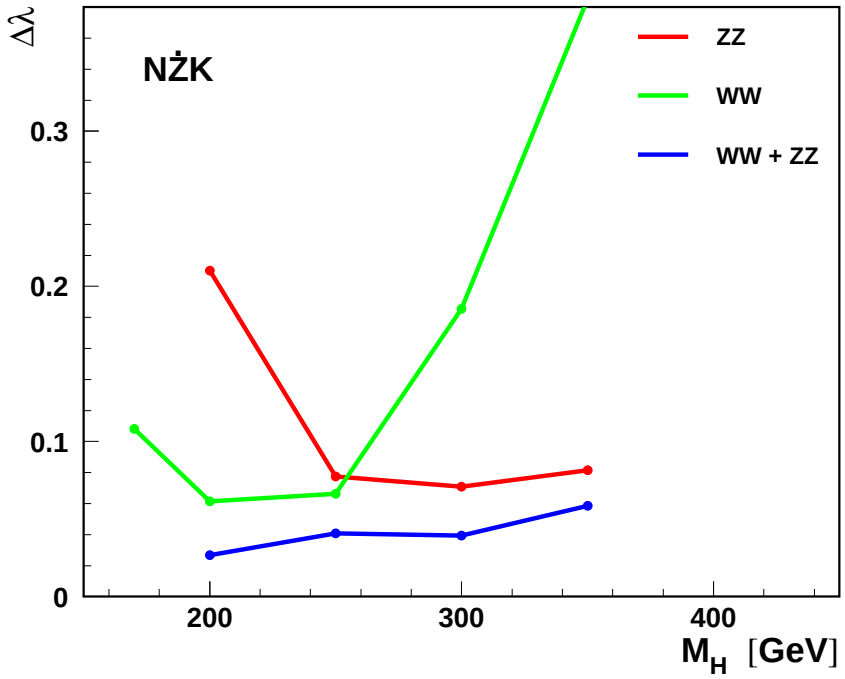
Measurement error for one year of Photon Collider running:

CP phase Φ_{CP}



$\Delta\Phi_{CP} \leq 50$ mrad

Coupling λ



$\Delta\lambda \leq 6\%$ assuming $\lambda \approx 1$, $\Phi_{CP} \approx 0$

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

Summary

Higgs-boson production at the the Photon Collider at TESLA studied for masses between 200 and 350 GeV, using realistic luminosity spectra and detector simulation.

New, **model-independen**t analysis, for generic tensor couplings of a Higgs boson to ZZ and W^+W^-

Measurement of various angular distributions of the W^+W^- and ZZ-decay products, and of the invariant mass distributions considered.

The angle describing a CP violation in the Higgs-boson couplings to vector bosons can be determined with accuracy of about 50 mrad.

ICHEP'2004 abstract 12-0739