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

Higgs Physics at Future Colliders workshop
2004/2005

A.F.Żarnecki
2 - III - 2005

2HDM(II)

SM-like 2HDM(II)

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:

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

$\Rightarrow$ additional model parameter:

CP-violating mixing phase

A General Model

What would happen if the 'Higgs' had a general spin?

General rules of helicity $\Rightarrow$

$$\langle Z(\lambda_Z) H(\lambda_H) | Z^*(m) \rangle = \frac{g_W M_Z}{\cos\theta_W} d^1_{m,\,\lambda_Z - \lambda_H}(\theta)\, \Gamma_{\lambda_Z \lambda_H}$$

"d functions" known and universal

reduced vertex independent of m

Assume (for this talk) that HHZ vertex is $\mathcal{CP}$-conserving

$$\Rightarrow \Gamma_{\lambda_Z \lambda_H} = n_H\, \Gamma_{-\lambda_Z\, -\lambda_H}$$

normality of H: $n_H \equiv (-1)^{\mathcal{J}} \mathcal{P}$

$\Rightarrow$ For odd normality: $\Gamma_{00} = 0$

But what are the Γ_{ij}'s?

Most general current:

$$\mathcal{J}_\mu = \frac{g_W M_Z}{\cos\theta_W} T_{\mu\alpha\beta_1\ldots\beta_\mathcal{J}}\,\varepsilon^*(Z)^\alpha\,\varepsilon^*(H)^{\beta_1\ldots\beta_\mathcal{J}}$$

Compare general tensor with helicity formalism

$\longrightarrow$ expressions for Γ_{ij}

Generally find:

$\diamondsuit$ Either Γ_{ij} zero

OR

$\diamondsuit$ for all $\mathcal{J}^\mathcal{P}$ except 0^+, Γ_{ij} contains a power of β at least as high as:

$$\boxed{\begin{array}{l}\Gamma_{ij} \sim \beta^{|\mathcal{J}-2|} \text{ for } n_H = + \\ \Gamma_{ij} \sim \beta^{|\mathcal{J}-1|} \text{ for } n_H = -\end{array}}$$

$\mathcal{J}^{\mathcal{P}}$	HZ^*Z Coupling	Helicity Amplitudes	Threshold
		Even Normality $n_H = +$	
0^+	$\boxed{a_1\, g^{\mu\nu} + a_2\, p^\mu p^\nu}$	$\mathcal{T}_{00} = (2a_1 (M_H^2 - M_*^2 - M_Z^2) + a_2 M_H^4 \beta^2)/(4M_* M_Z)$ $\mathcal{T}_{11} = -a_1$	1 1
1^-	$b_1 g^{\mu\nu} k^\beta + b_2 g^{\mu\beta} p^\nu$ $+ b_3 g^{\nu\beta} p^\mu + b_4 p^\mu p^\nu k^\beta$	$\mathcal{T}_{00} = \beta\, [-2b_1 (M_H^2 - M_*^2 - M_Z^2) - b_2 (M_H^2 - M_Z^2 + M_*^2)$ $+ b_3 (M_H^2 - M_*^2 + M_Z^2) - b_4 M_H^4 \beta^2] M_H/(4\, M_* M_Z)$ $\mathcal{T}_{01} = \beta\, b_3 M_H^2/(2M_*)$ $\mathcal{T}_{10} = -\beta\, b_2 M_H^2/(2M_Z)$ $\mathcal{T}_{11} = \beta\, b_1 M_H$	β β β β
2^+	$c_1\, (g^{\mu\beta_1} g^{\nu\beta_2} + g^{\mu\beta_2} g^{\nu\beta_1})$ $+ c_2\, g^{\mu\nu}\, k^{\beta_1} k^{\beta_2}$ $+ c_3\, (g^{\mu\beta_1} k^{\beta_2} + g^{\mu\beta_2} k^{\beta_1})\, p^\nu$ $+ c_4\, (g^{\nu\beta_1} k^{\beta_2} + g^{\nu\beta_2} k^{\beta_1})\, p^\mu$ $+ c_5\, p^\mu p^\nu k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{00} = \Big\{ -c_1\, (M_H^4 - (M_Z^2 - M_*^2)^2)/M_H^2$ $+ M_H^2 \beta^2 [c_2\, (M_H^2 - M_Z^2 - M_*^2) + c_3\, (M_H^2 - M_Z^2 + M_*^2)$ $- c_4\, (M_H^2 - M_*^2 + M_Z^2)] + \frac{1}{2} c_5\, M_H^6 \beta^4 \Big\}/(\sqrt{6} M_Z M_*)$ $\mathcal{T}_{01} = (-c_1 (M_H^2 - M_Z^2 + M_*^2) - c_4\, M_H^4 \beta^2)/(\sqrt{2} M_* M_H)$ $\mathcal{T}_{10} = (-c_1 (M_H^2 - M_*^2 + M_Z^2) + c_3\, M_H^4 \beta^2)/(\sqrt{2} M_Z M_H)$ $\mathcal{T}_{11} = -\sqrt{2/3}\, (c_1 + c_2 M_H^2 \beta^2)$ $\mathcal{T}_{1,-1} = -2\, c_1$	 1 1 1 1 1
		Odd Normality $n_H = -$	
0^-	$\boxed{a_1\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma}$	$\mathcal{T}_{00} = 0$ $\mathcal{T}_{11} = i\, \beta\, M_H^2\, a_1$	 β
1^+	$b_1\, \epsilon^{\mu\nu\beta\rho} p_\rho$ $+ b_2\, \epsilon^{\mu\nu\beta\rho} k_\rho$ $+ b_3\, (\epsilon^{\mu\beta\rho\sigma} p^\nu$ $+ \epsilon^{\nu\beta\rho\sigma} p^\mu)\, p_\rho k_\sigma$	$\mathcal{T}_{00} = 0$ $\mathcal{T}_{01} = i\, (b_1\, (M_Z^2 - M_H^2 - M_*^2) + b_2\, (M_H^2 - M_Z^2 - 3M_*^2)$ $+ b_3\, M_H^4 \beta^2)/(2M_*)$ $\mathcal{T}_{10} = i\, (b_1\, (M_*^2 - M_H^2 - M_Z^2) - b_2\, (M_H^2 - M_*^2 - 3M_Z^2)$ $+ b_3\, M_H^4 \beta^2)/(2M_Z)$ $\mathcal{T}_{11} = i\, (-b_1\, M_H^2 + b_2\, (M_Z^2 - M_*^2))/M_H$	 1 1 1
2^-	$c_1\, \epsilon^{\mu\nu\beta_1\rho} p_\rho k^{\beta_2}$ $+ c_2\, \epsilon^{\mu\nu\beta_1\rho} k_\rho k^{\beta_2}$ $+ c_3\, (\epsilon^{\mu\beta_1\rho\sigma} p^\nu$ $+ \epsilon^{\nu\beta_1\rho\sigma} p^\mu)\, k^{\beta_2} p_\rho k_\sigma$ $+ c_4\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma k^{\beta_1} k^{\beta_2}$ $+ \beta_1 \leftrightarrow \beta_2$	$\mathcal{T}_{00} = 0$ $\mathcal{T}_{01} = i\, \beta\, (c_1\, (M_H^2 + M_*^2 - M_Z^2) - c_2\, (M_H^2 - M_Z^2 - 3M_*^2)$ $- c_3 M_H^4 \beta^2) M_H/(\sqrt{2} M_*)$ $\mathcal{T}_{10} = i\, \beta\, (c_1\, (M_H^2 + M_Z^2 - M_*^2) + c_2\, (M_H^2 - M_*^2 - 3M_Z^2)$ $- c_3 M_H^4 \beta^2) M_H/(\sqrt{2} M_Z)$ $\mathcal{T}_{11} = i\, \beta\, 2\sqrt{2/3}\, (c_1\, M_H^2 + c_2\, (M_*^2 - M_Z^2) + c_4\, M_H^4 \beta^2)$ $\mathcal{T}_{1,-1} = 0$	 β β β

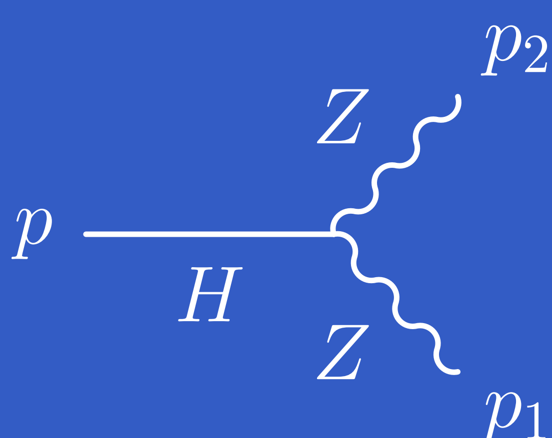
Model

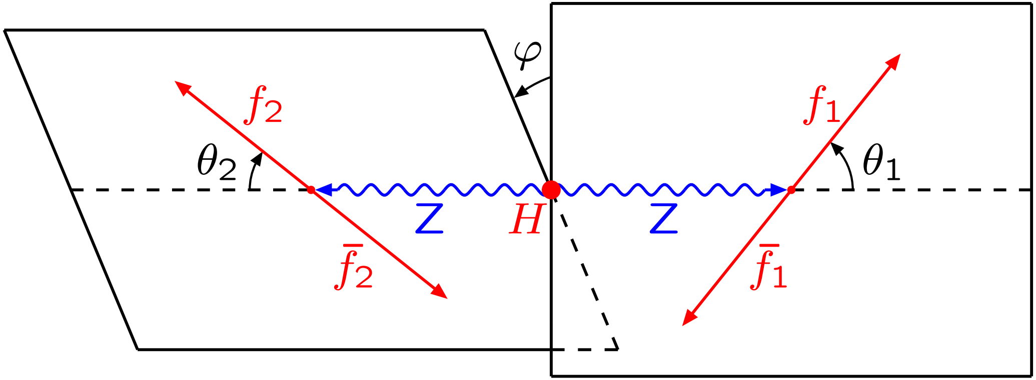
$$\mathcal{L} \approx X g^{\mu\nu} + Y \frac{p^\mu p^\nu}{M_H^2} + P \epsilon^{\mu\nu\rho\sigma} \frac{p_1^\rho p_2^\sigma}{M_H^2}$$

Standard model

CP-even

CP-odd





Particularly suited to

$$\begin{array}{ll} \gamma\gamma \to H \to ZZ & \text{TESLA} \\ gg \to H \to ZZ & \text{LHC} \end{array}$$

♢ Again use helicity methods:

$$\langle Z(\lambda_1) Z(\lambda_2) | H_{\mathcal{J}}(m) \rangle = \frac{g_W M_Z}{\cos\theta_W} \mathcal{T}_{\lambda_1\lambda_2} \, d^{\mathcal{J}}_{m,\, \lambda_1-\lambda_2}(\Theta) \, \mathrm{e}^{-i(m-\lambda_1+\lambda_2)\,\Phi}$$

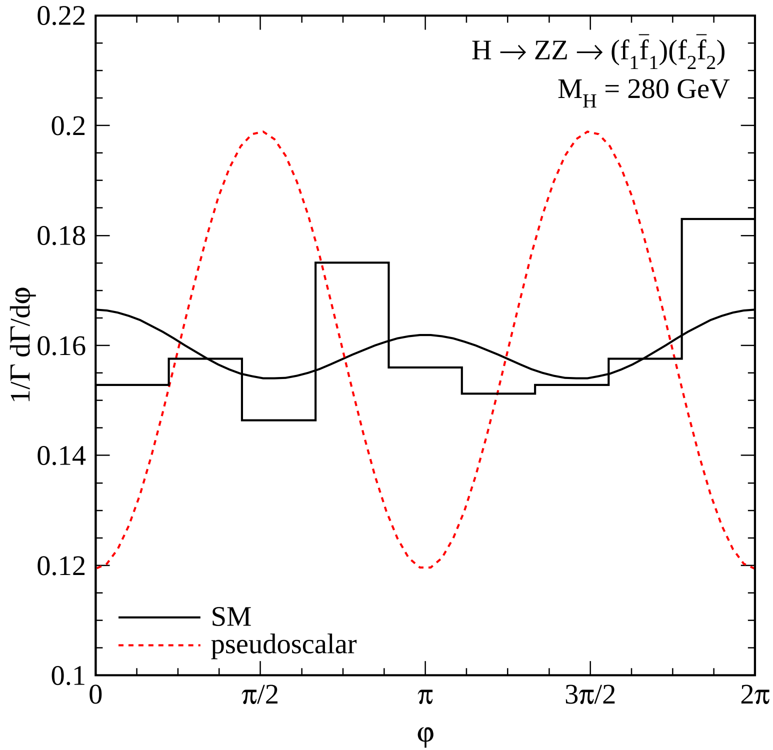


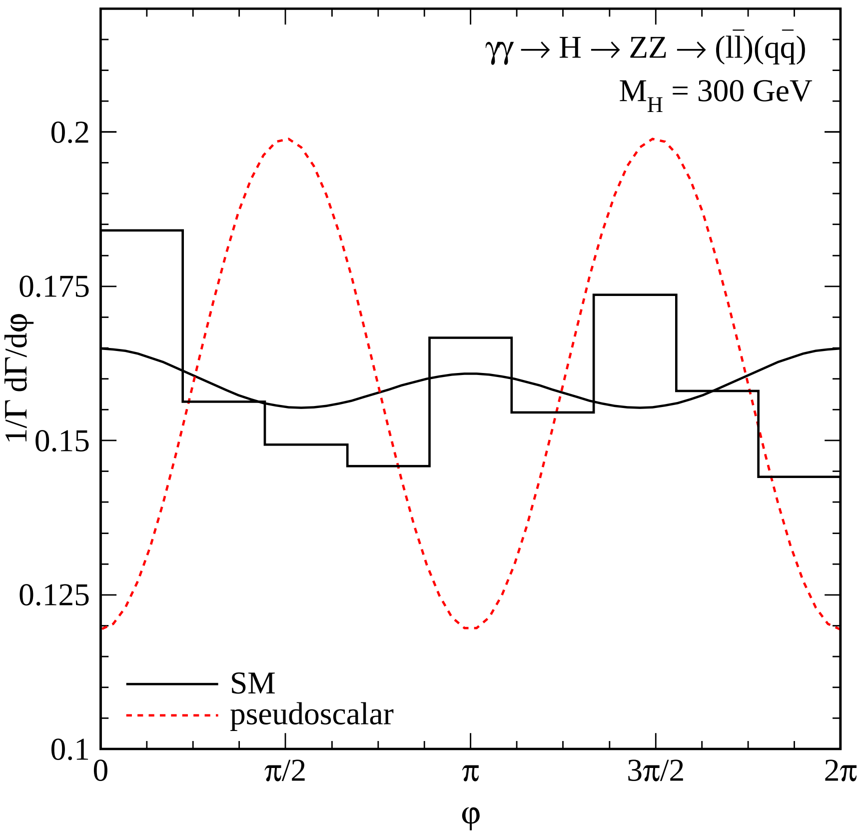
Figure 2: *The azimuthal distributions, $d\Gamma/d\varphi$, for the Standard Model Higgs boson and a pseudoscalar boson, with a Higgs mass of* 280 *GeV. The histogram for the Standard Model shows the expected result from* 900 *signal events corresponding to an integrated luminosity of* $\int \mathcal{L}\, dt = 300\,\mathrm{fb}^{-1}$ *at LHC [with efficiencies and cuts included according to the experimental simulation Ref.[10]]. The curves show the exact theoretical dependences for the scalar and pseudoscalar, appropriately normalised.*

Also, azimuthal distributions different:

$$\frac{d\sigma}{d\varphi} \sim A + \eta_1\eta_2 B \cos\varphi + \frac{1}{4} n_H |T_{11}|^2 \cos 2\varphi$$

zero for 0^-

eg. at TESLA $\gamma\gamma$ collider (825 signal events per year)
[Nieżurawski, Żarnecki, Krawczyk hep-ph/0207294]



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:

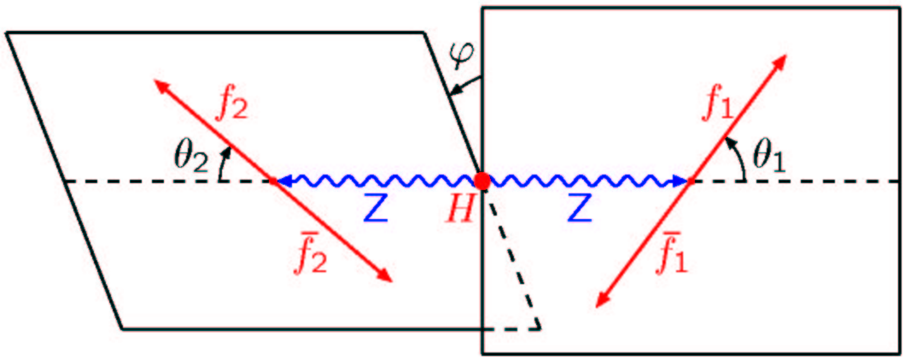
K. Desch, A. Imhof, Z. Was, M. Worek, hep-ph/0307331;
K. Desch, Z. Was, M. Worek, Eur.Phys.J.C29 (2003) 491, hep-ph/0302046;
M.T. Dova, S. Ferrari, hep-ph/0406313.

LHC study:

C.P. Buszello, et al., Eur. Phys. J. C32 (2004) 209;
C.P. Buszello, et al., hep-ph/0406181.

Introduction

Angular distributions



5 angles:

- polar angle θ_Z for $h \to ZZ$ decay
- polar angle θ_l for $Z \to l^- l^+$ decay
- polar angle θ_j for $Z \to q\bar{q}$ decay
- azimuthal angles between higgs and Z decay planes: ϕ_l and ϕ_j

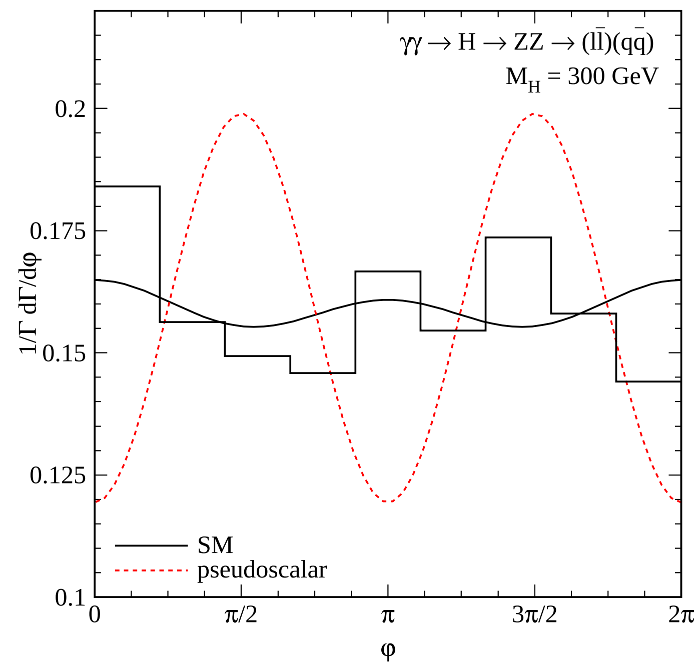
angle between two planes: $\Delta\phi = \phi_j - \phi_l$

S.Y.Choi, D.J.Miller, M.M.Muhlleitner, P.M. Zerwas, Phys.Lett.B553(2003)61, hep-ph/0210077

D.J.Miller, Prague, November 2002:

Measurement of angular distributions

$\Rightarrow$ higgs spin and parity



$\Rightarrow$ **Can PC measure this ?!**

Introduction

Simulation

$\gamma\gamma$ spectra from **CompAZ**,

$\sqrt{s_{ee}} =$ 270 – 500 GeV

higgs events generated with PYTHIA 6.214

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

$\gamma\gamma \rightarrow h \rightarrow WW \rightarrow q\bar{q}\; q\bar{q}$

m_h = 170 – 350 GeV

PYTHIA properly simulates all angular distributions for SM higgs

“pseudoscalar” higgs

$\Rightarrow$ reweighting of angular distributions

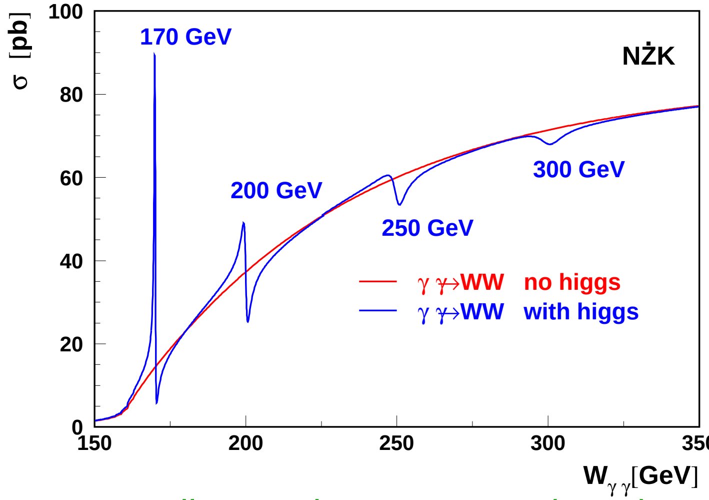
(σ and BR assumed same as for h)

angular distributions for background

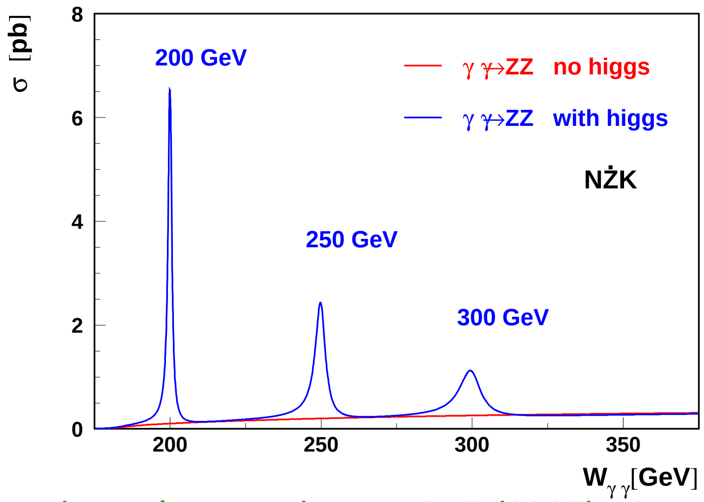
$\Rightarrow$ PYTHIA + reweighting

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.

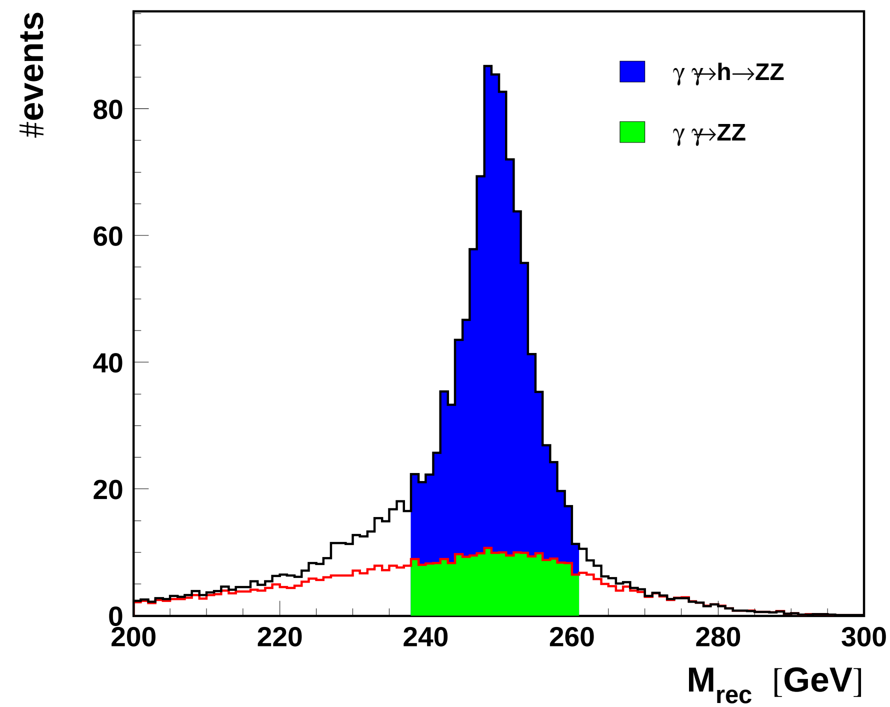
Selection

$h \to ZZ \to lljj$ event selection

- 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,
Study of the Higgs-boson decays into W^+W^- and ZZ at the Photon Collider
JHEP 0211 (2002) 034 [hep-ph/0207294]

Invariant mass cut for m_h=250 GeV:



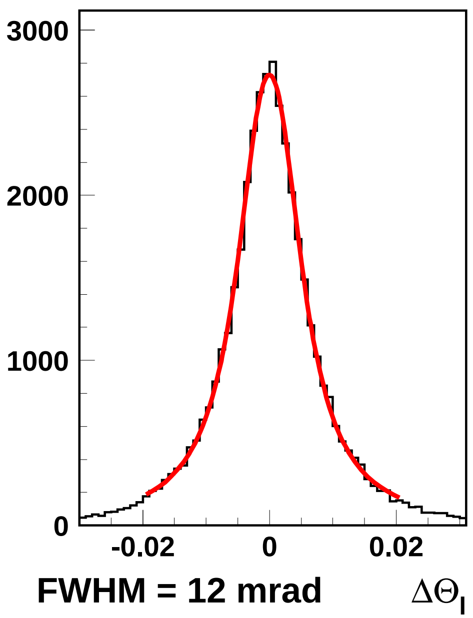
SM higgs selection efficiency ~40%
(for $ZZ \to q\bar{q}\, l^+l^-$ events, $l = \mu, e$)
$\times BR(ZZ \to q\bar{q}\, l^+l^-) \approx 9.4\%$

Resolution

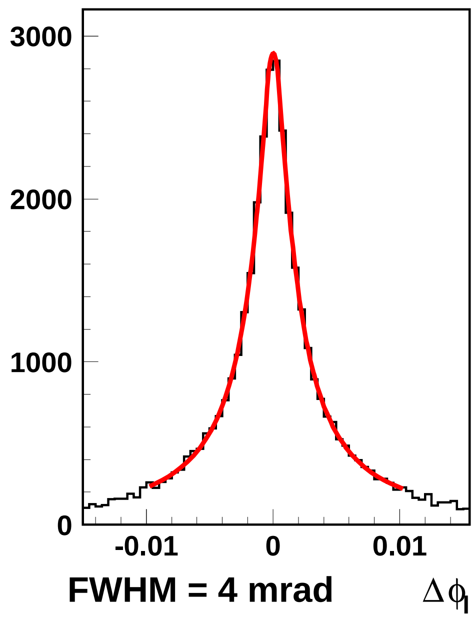
Expected accuracy of decay angles measurement:

$Z \rightarrow l^+ l^-$

polar angle θ_l

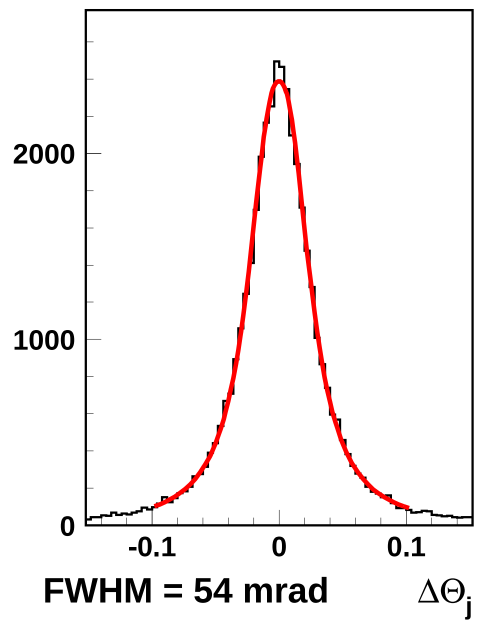


azimuthal angle ϕ_l

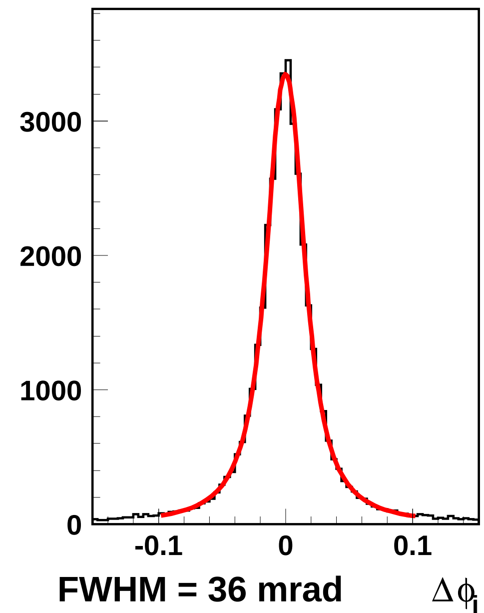


$Z \rightarrow q\bar{q}$

polar angle θ_q



azimuthal angle ϕ_q



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

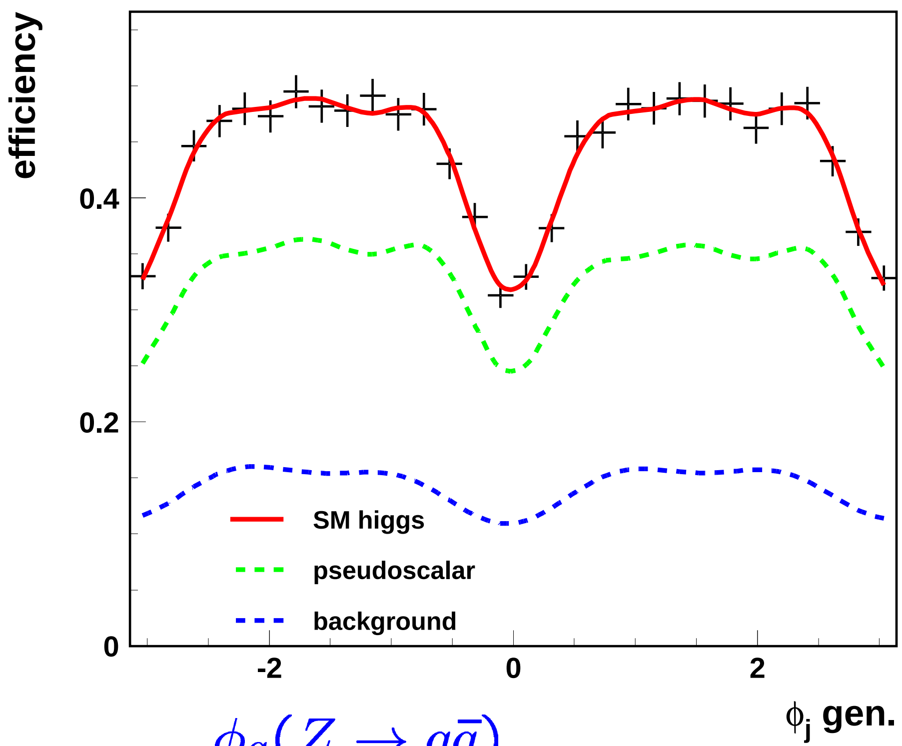
All angles can be measured with high accuracy

Shape described by Breit-Wigner distribution

Acceptance

Selection efficiency as a function of the azimuthal angle ϕ_q

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

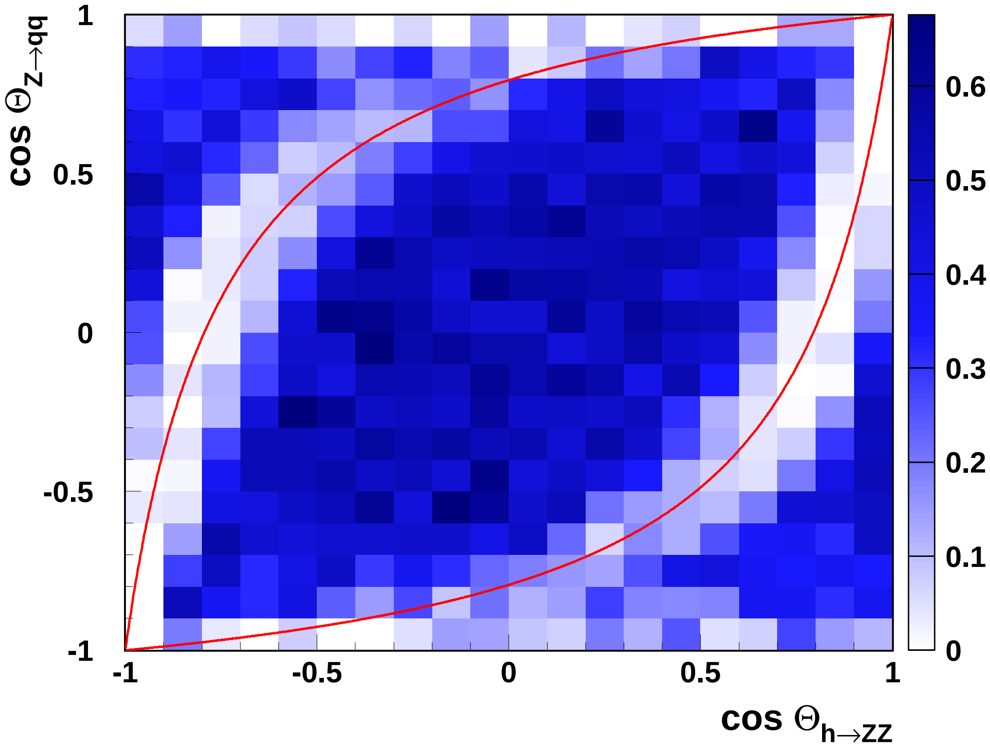


$\phi_q(Z \to q\bar{q})$

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 $\phi_j \approx 0$:

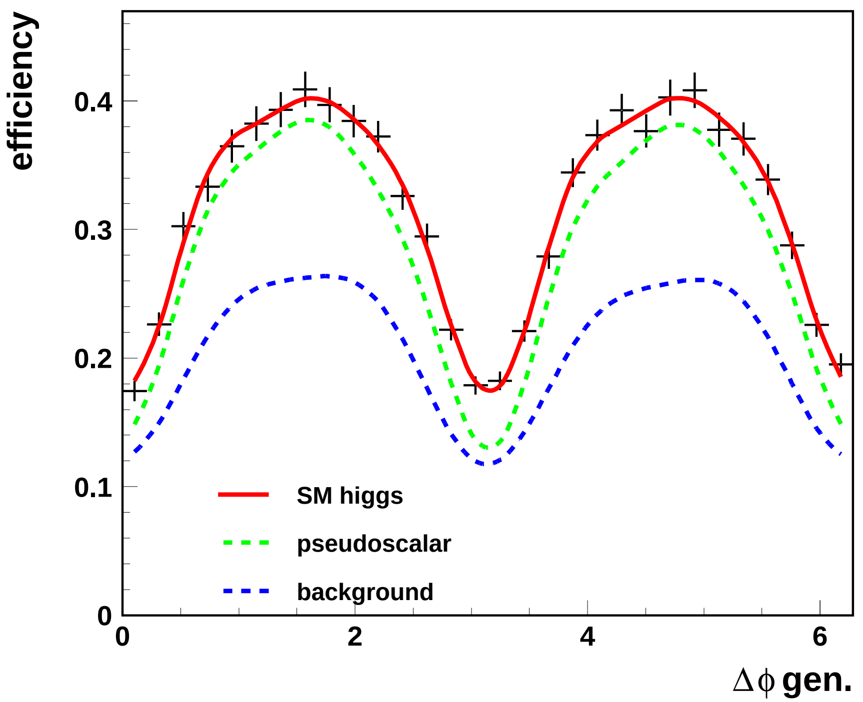


red lines: $\cos\theta_j^{LAB} = \pm\cos\theta_Z^{LAB}$

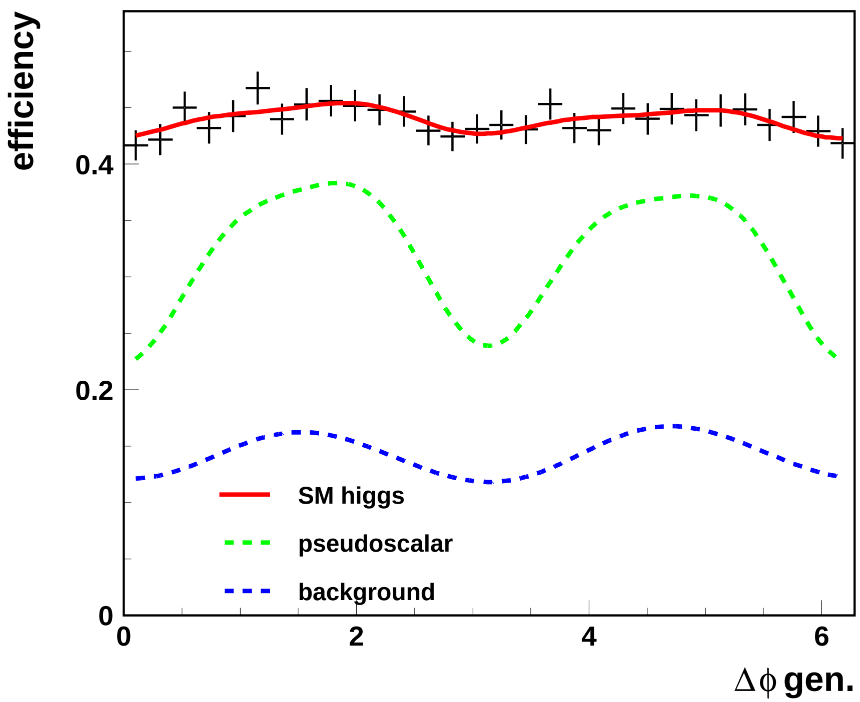
Acceptance

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



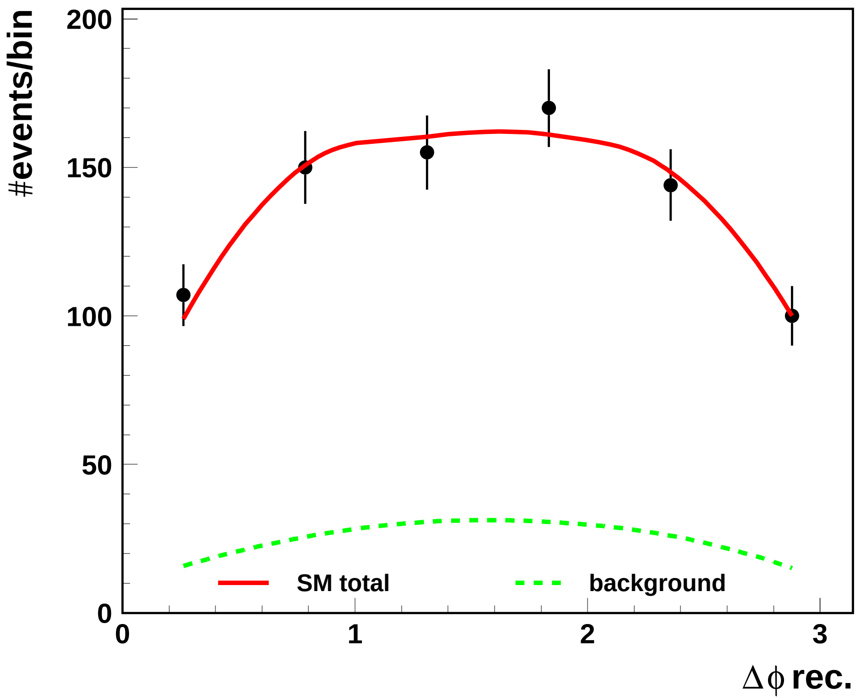
Effect much stronger for background events and pseudoscalar higgs

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

Results

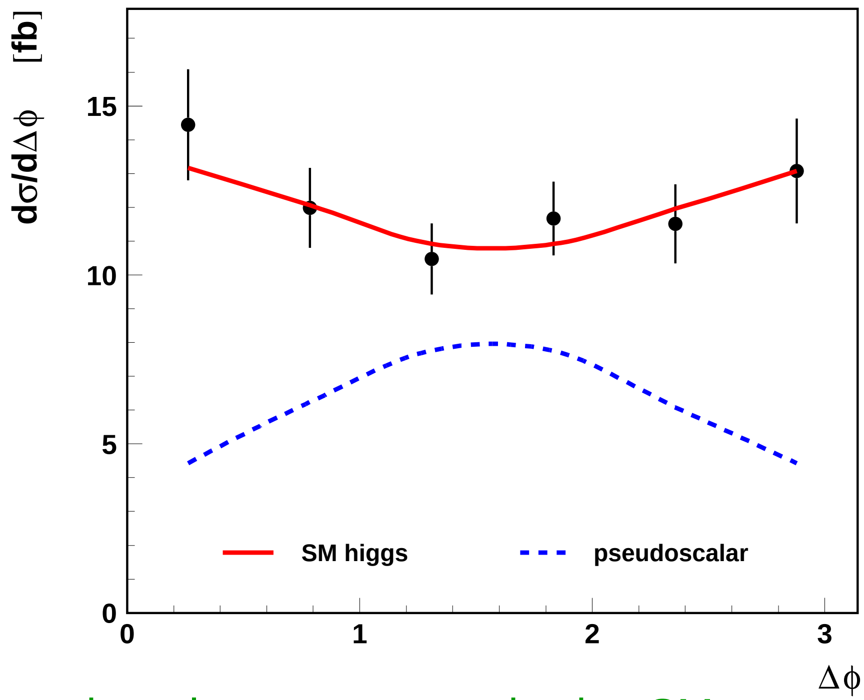
Measured $\Delta\phi$ distribution for m_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ ~675 reconstructed SM higgs events expected + 145 ZZ background events

Measured distribution:



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

Extracted $\frac{d\sigma}{d\Delta\phi} \times BR(h \to ZZ)$



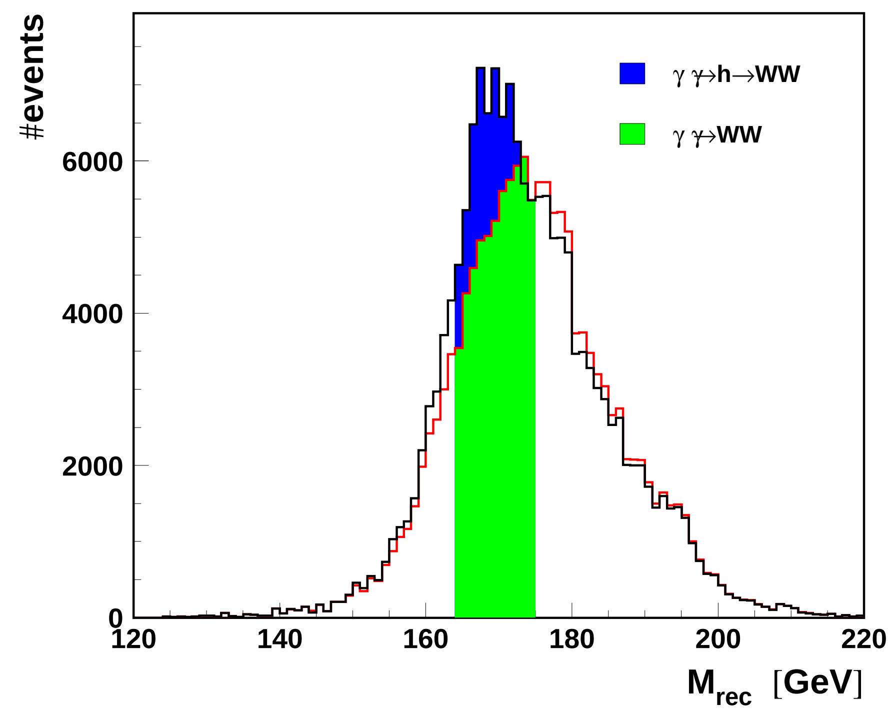
pseudoscalar reconstructed using SM acceptance

Selection

$h \to WW \to 4j$ event selection

- 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:



SM higgs selection efficiency ∼30%
(for $WW \to q\bar{q}q\bar{q}$ events)
$\times BR(WW \to q\bar{q}q\bar{q}) \approx 46.9\%$

Results

m_h = 200 GeV

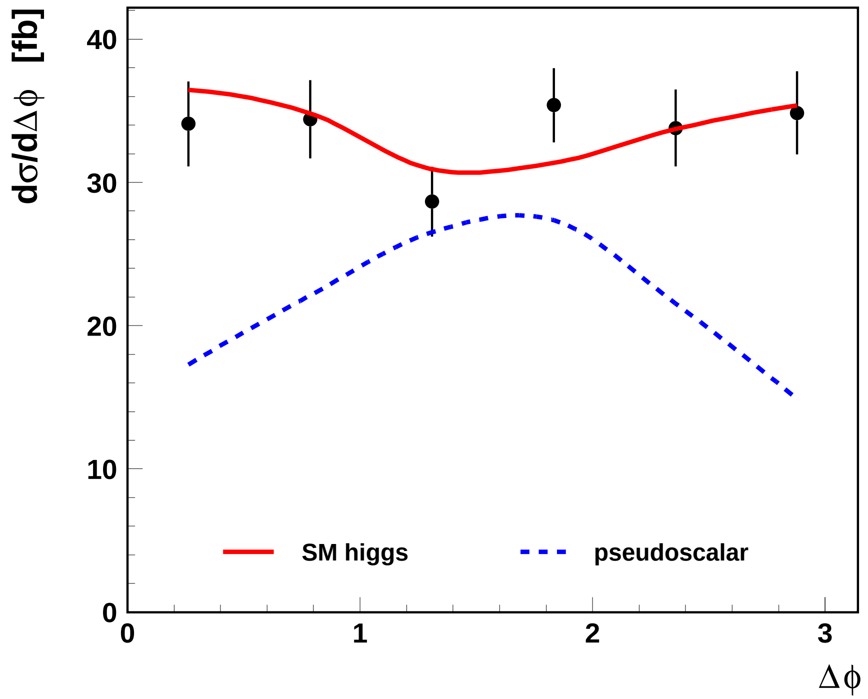
$\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$

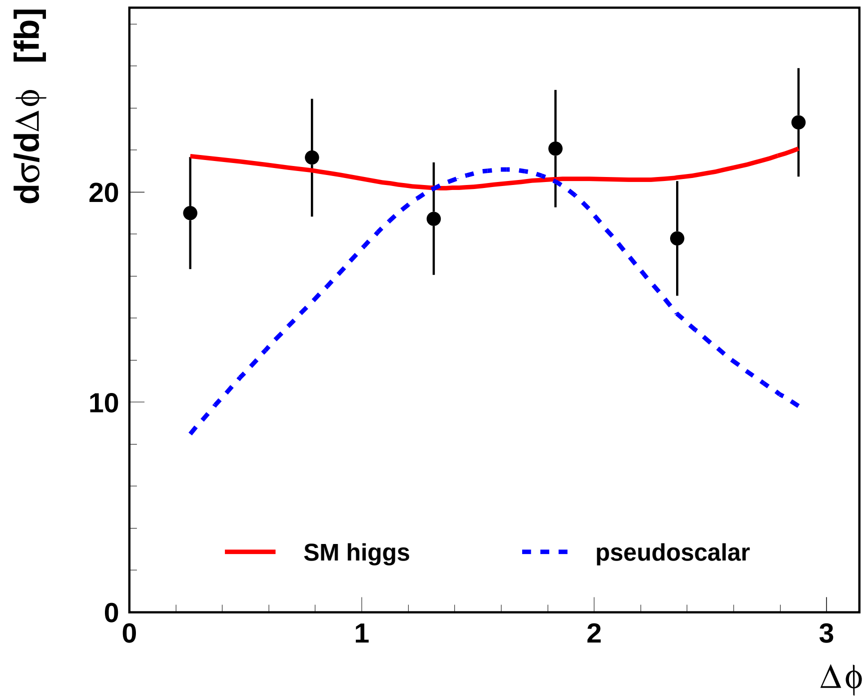
$\sim$8 000 SM higgs + 173 000 WW events

m_h = 250 GeV

$\sqrt{s_{ee}}$=362 GeV, $\mathcal{L} = 720\ fb^{-1}$

$\sim$5 500 SM higgs + 189 000 WW events





Large background contribution subtracted $\Rightarrow$ systematic effects can be very important !

Generic model

Couplings

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

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

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

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

Pseudoscalar Higgs boson corresponds to $\lambda_H = 0$ and $\lambda_A = 1$.

We consider small CP violation (deviations from SM), i.e. $\lambda_H \sim 1$, $|\lambda_A| \ll 1$

$\mathcal{H}$ couplings to fermions assumed to be the same as in the Standard Model.

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.

Model

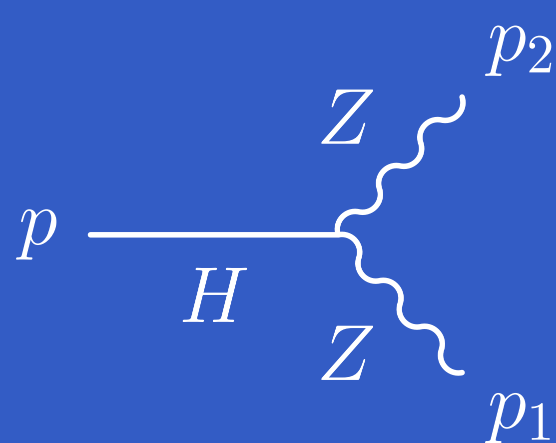
Neglected

$$\mathcal{L} \approx X g^{\mu\nu} + Y \frac{p^\mu p^\nu}{M_H^2} + P \epsilon^{\mu\nu\rho\sigma} \frac{p_1^\rho p_2^\sigma}{M_H^2}$$

Standard model

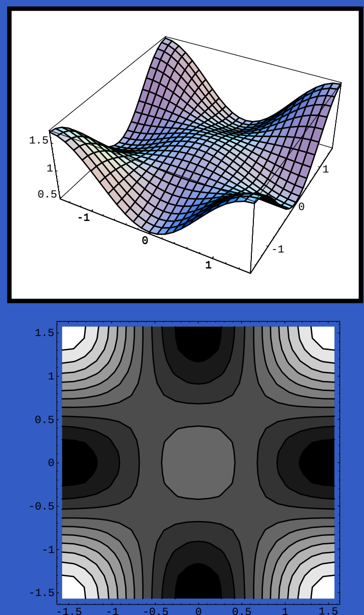
CP-even

CP-odd

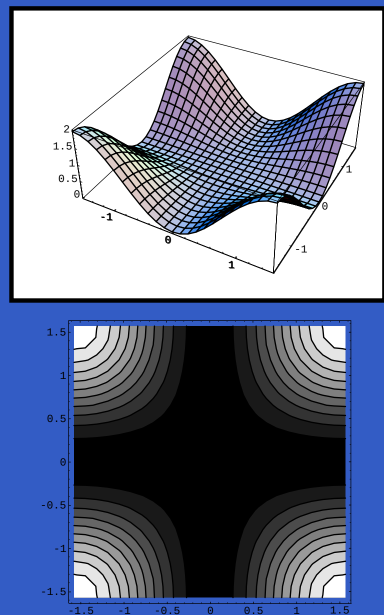


Polar angle distributions $M_h = 130$

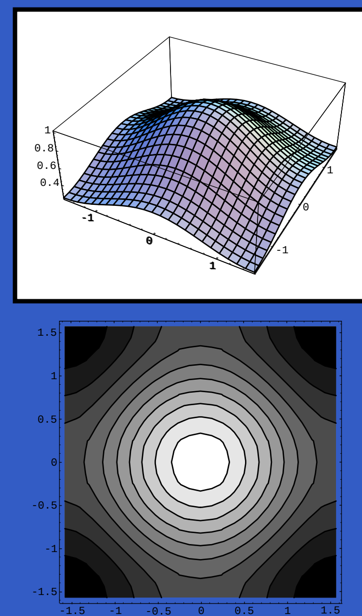
$X = 1$



$Y = 1$

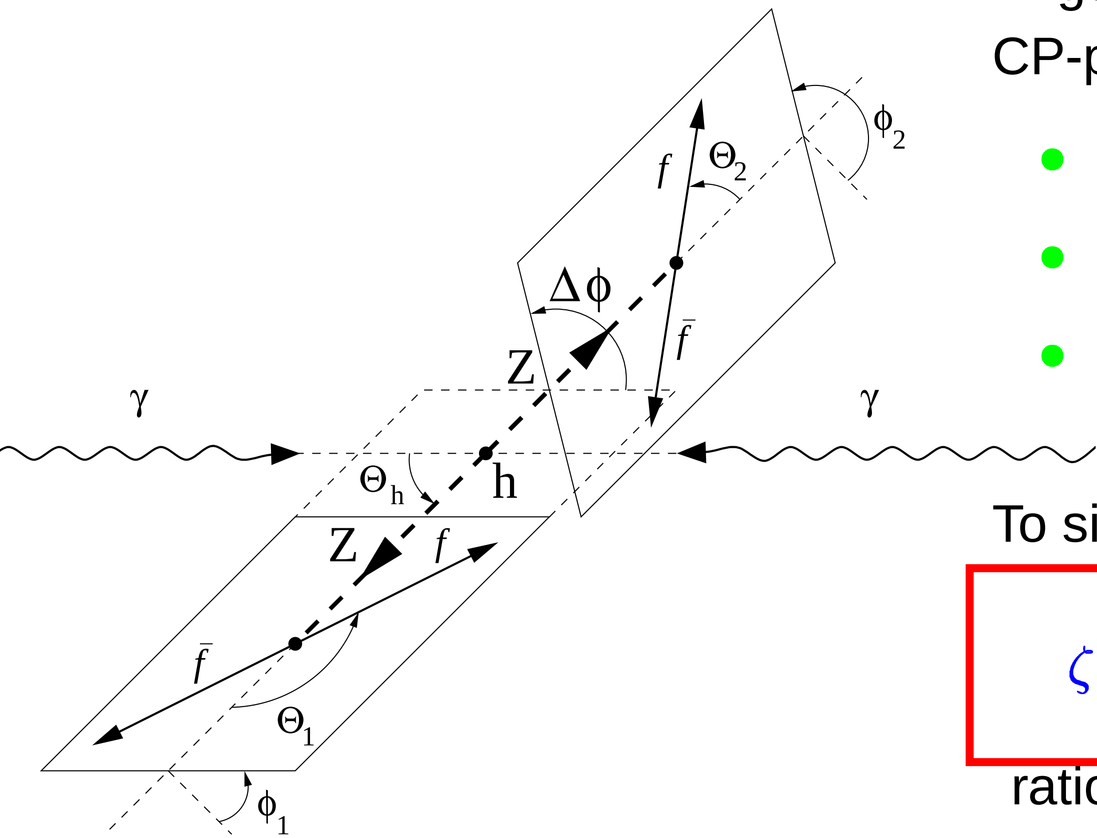


$P = 1$



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

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

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

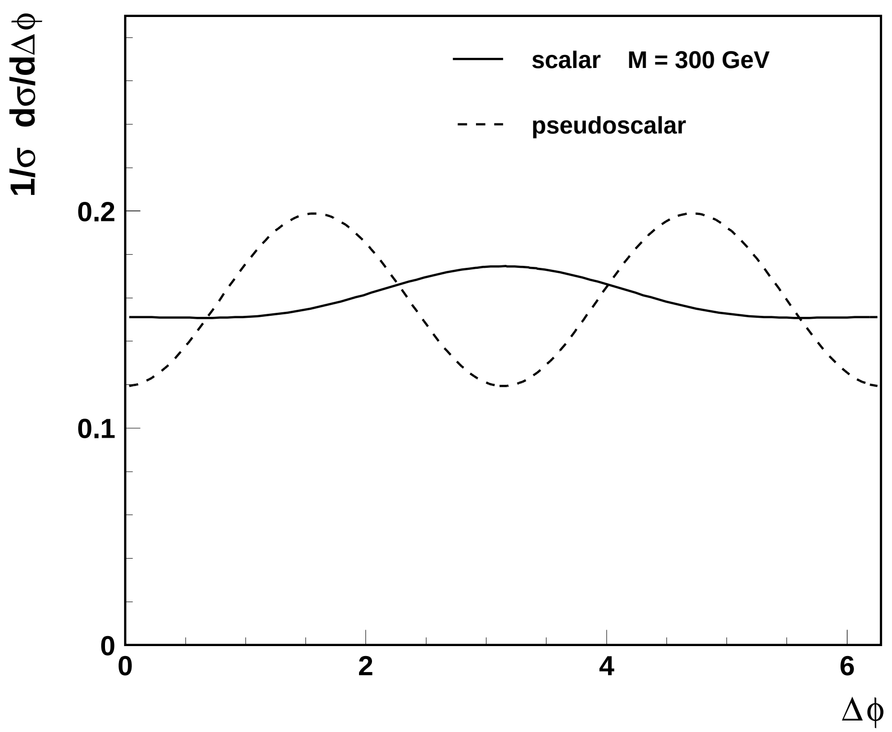
All polar angles are calculated in the rest frame of the decaying particle.

Generic model

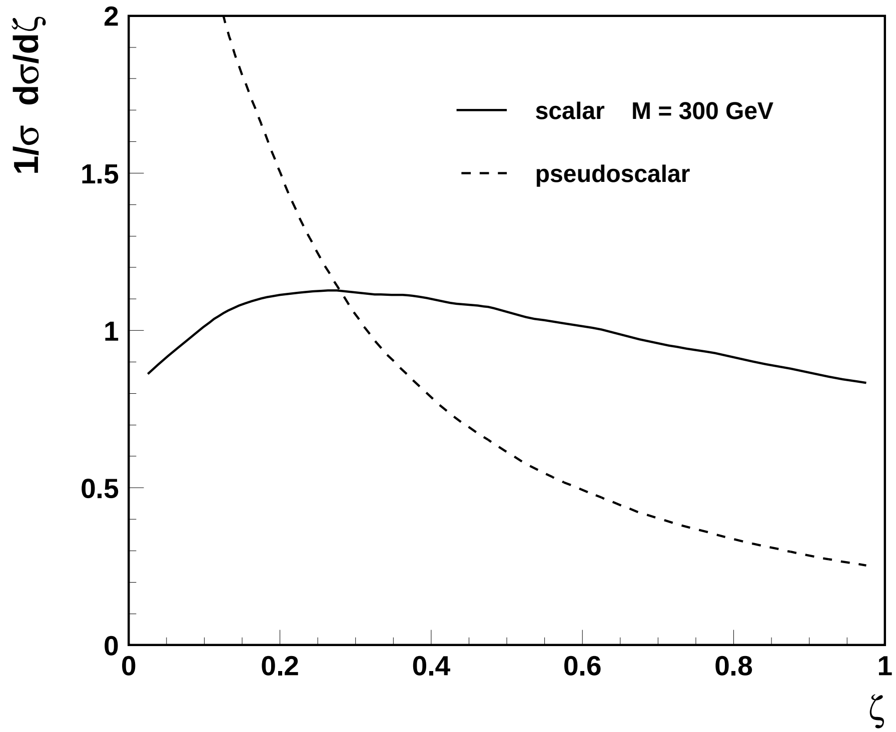
Angular distributions

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

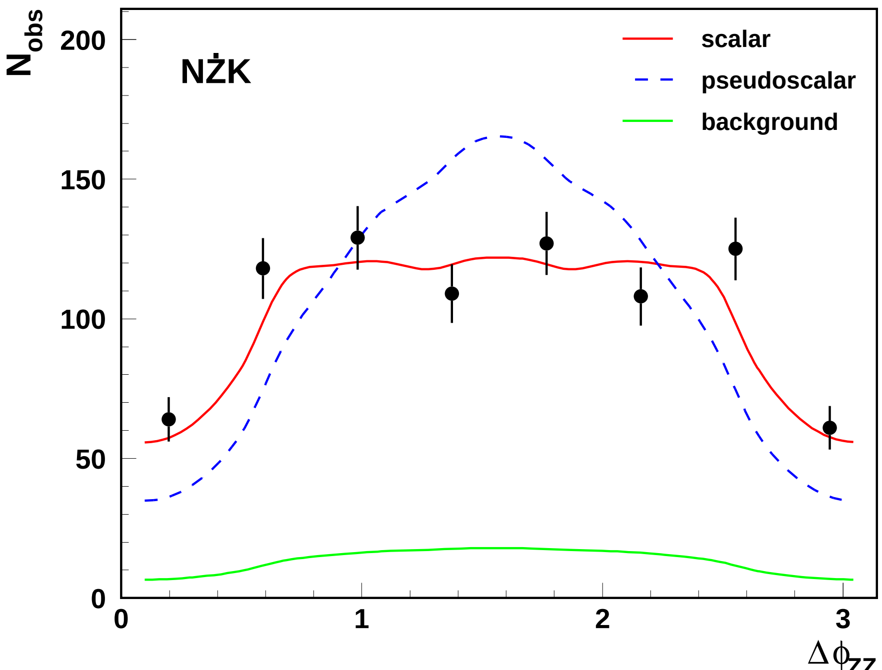


Both distributions clearly distinguish between decays of scalar and pseudoscalar higgs.

Results for ZZ

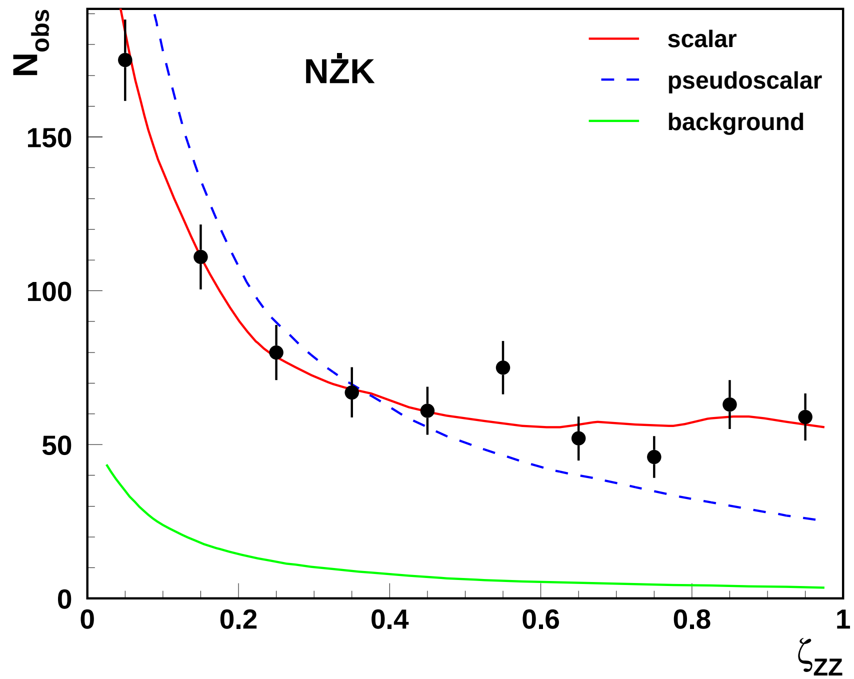
Measured $\Delta\phi$ and ζ distributions for $h \rightarrow ZZ \rightarrow q\bar{q}\, l^+ l^-$ M_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ ~675 reconstructed SM higgs events expected + 145 ZZ background events

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



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

Measured ζ_{ZZ} distribution:

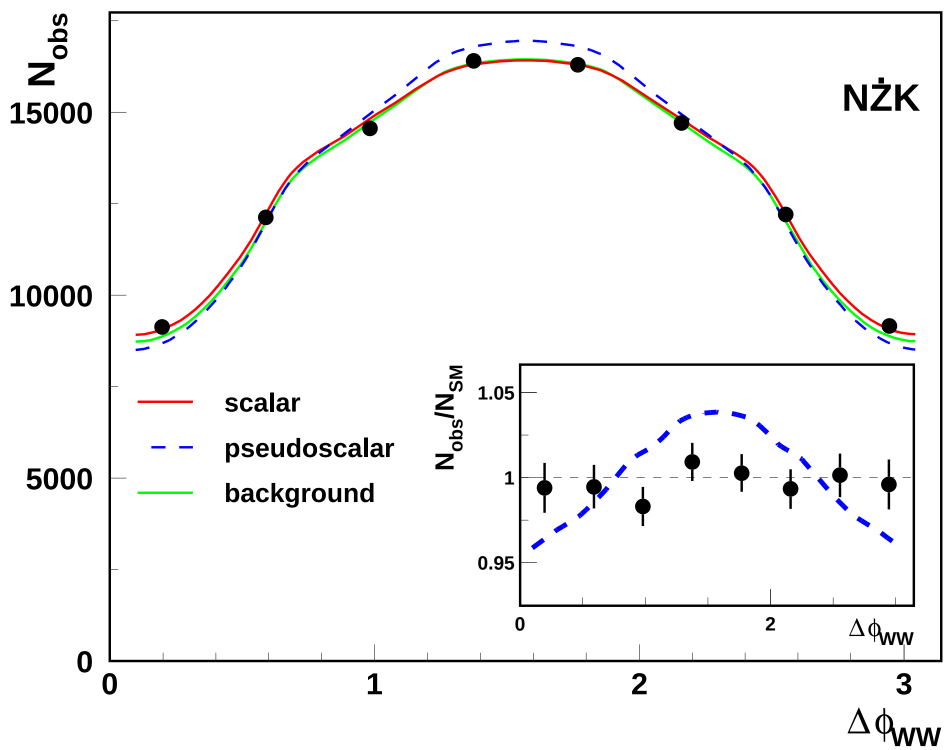


pseudoscalar normalized to the same number of events

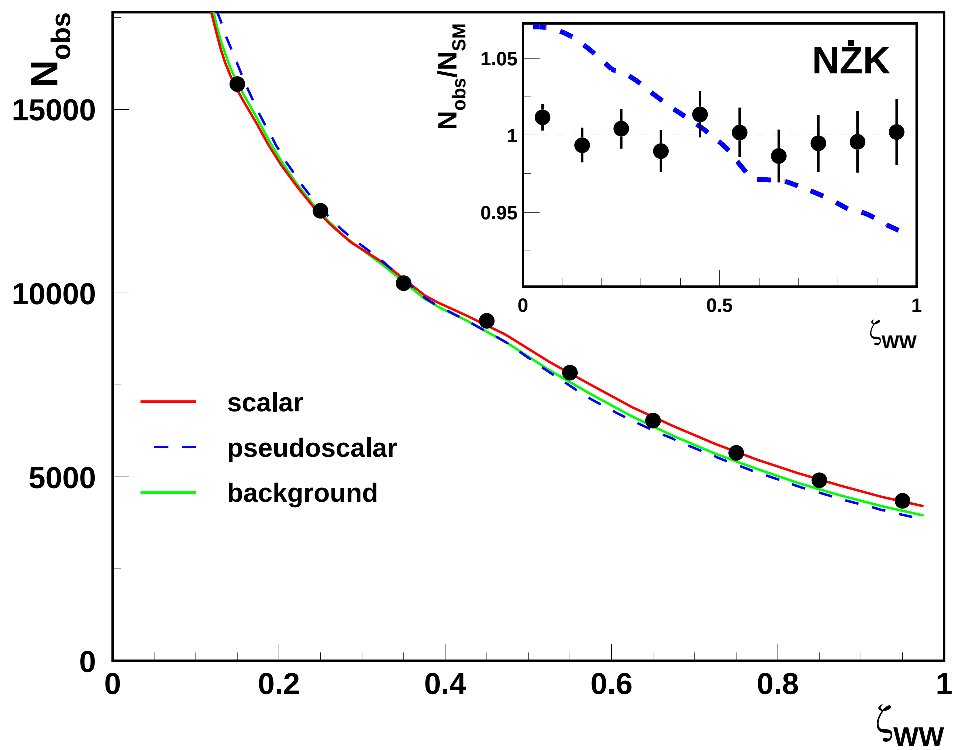
Results for WW

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

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



Measured ζ_{WW} distribution:



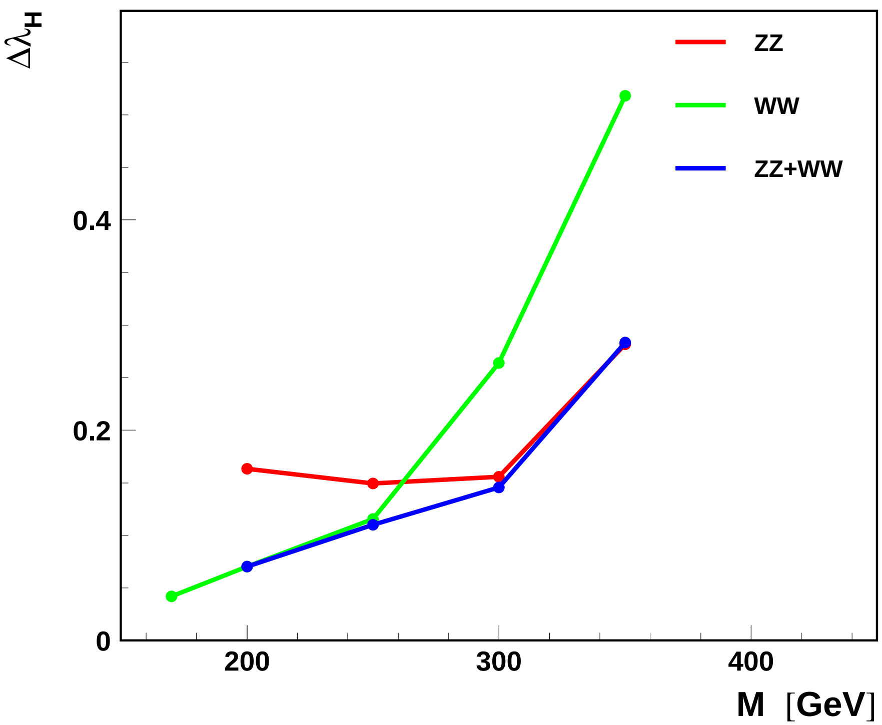
Generic model

Preliminary EPS'2003

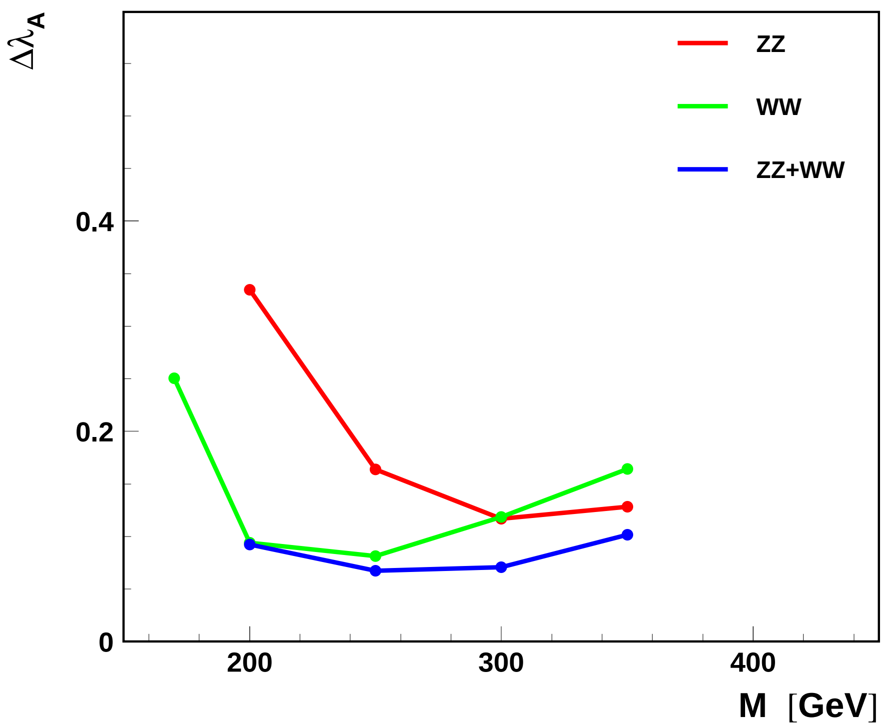
Combined measurement of angular correlations in the W^+W^- and ZZ-decay products

Measurement error for Higgs-boson couplings to vector bosons:

scalar



pseudoscalar



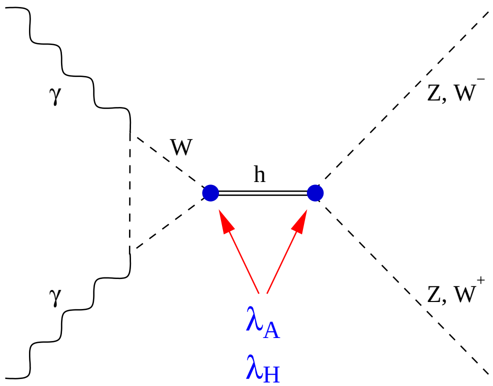
assuming SM-like couplings: $\lambda_H = 1$ $\lambda_A = 0$

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

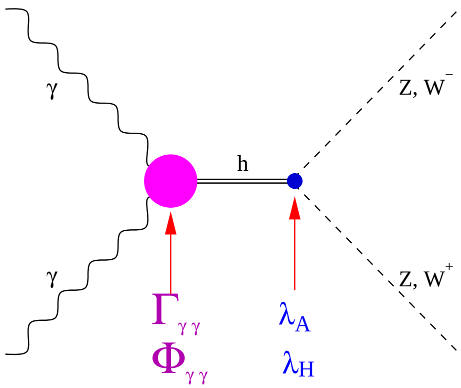
No other “new physics”

(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:

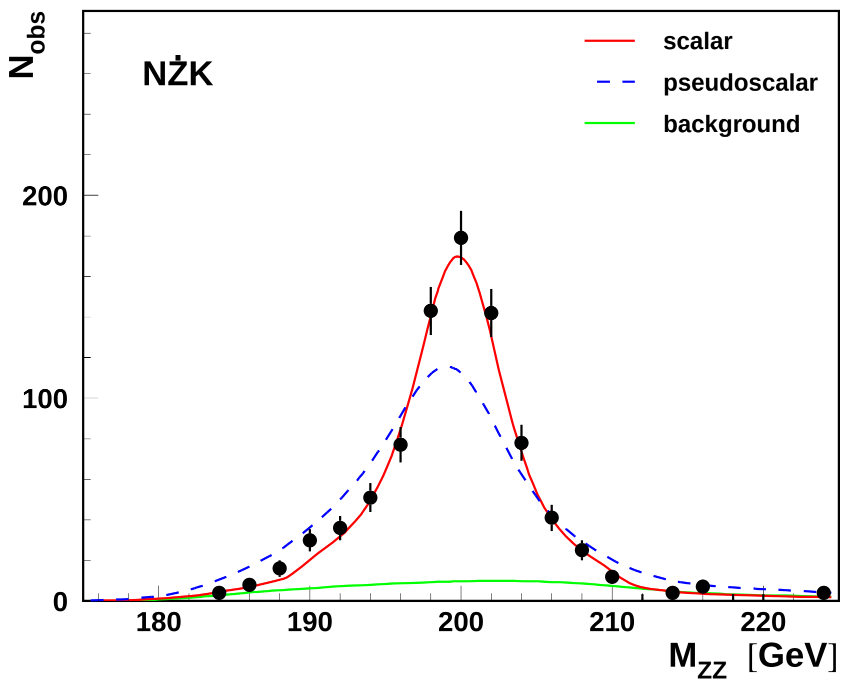
deviations from SM are not large

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

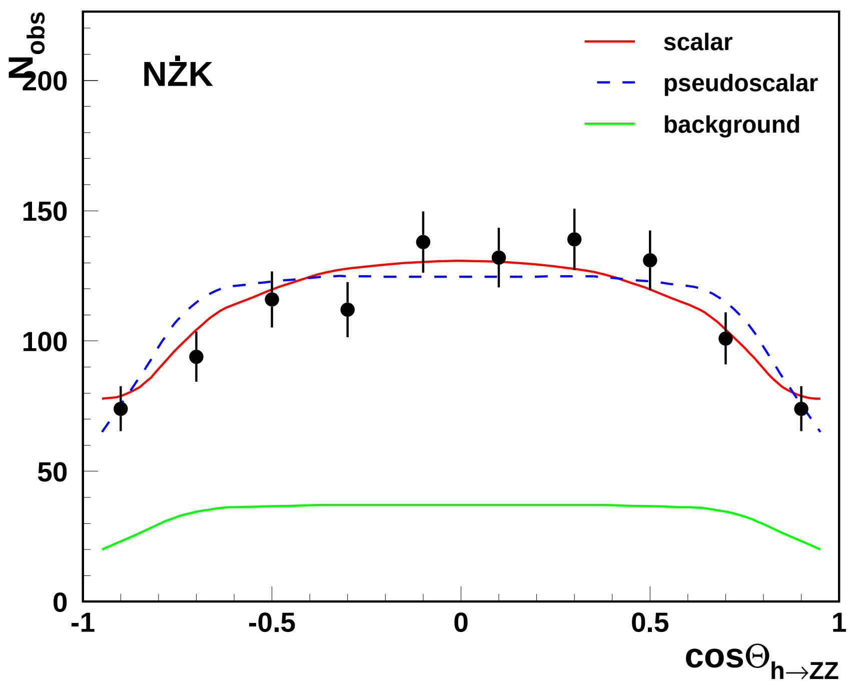
Results for ZZ

Measured M_{ZZ} and Θ_h distributions for $h \rightarrow ZZ \rightarrow q\bar{q}\, l^+ l^-$ 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:



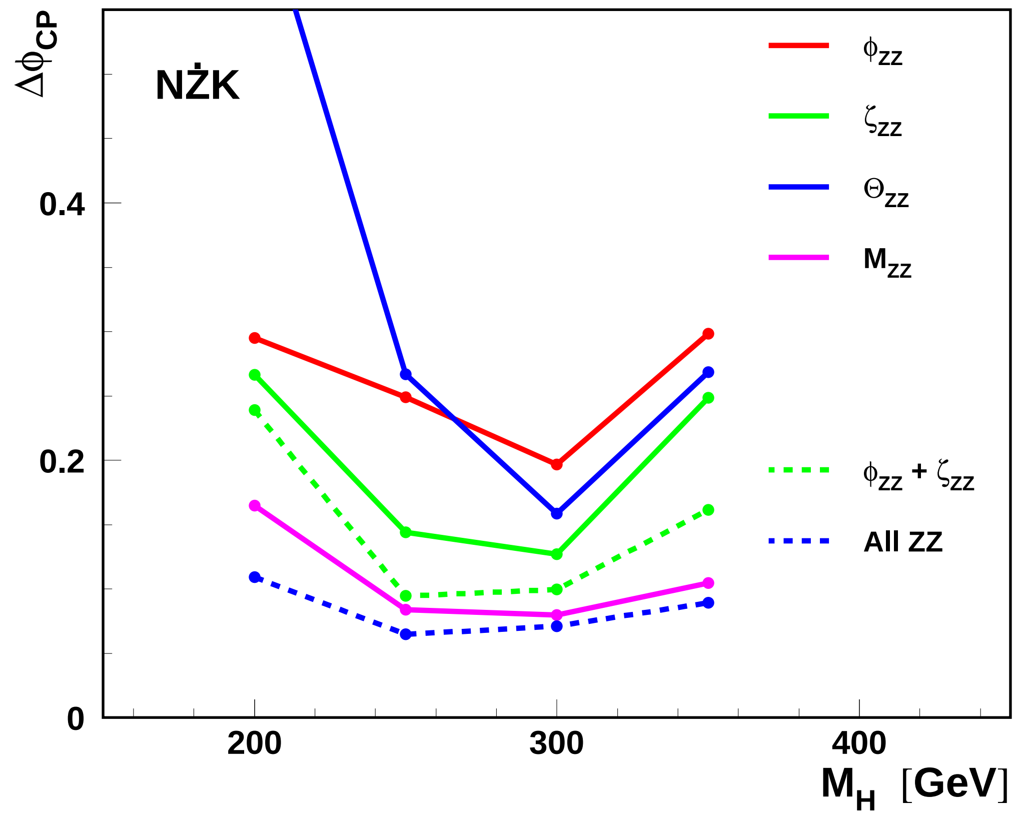
pseudoscalar normalized to the same number of events

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:

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

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

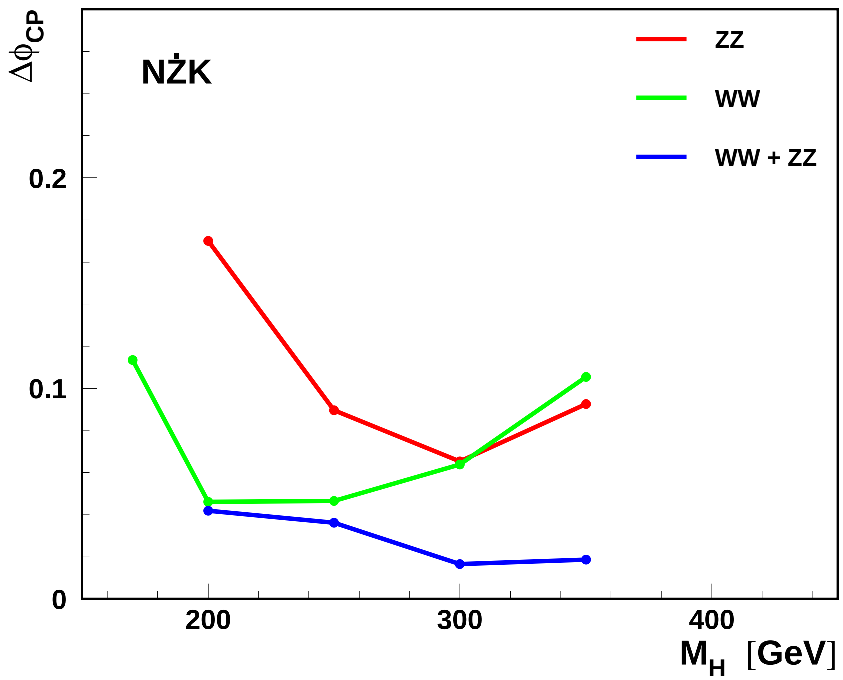
Results - WW & ZZ

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

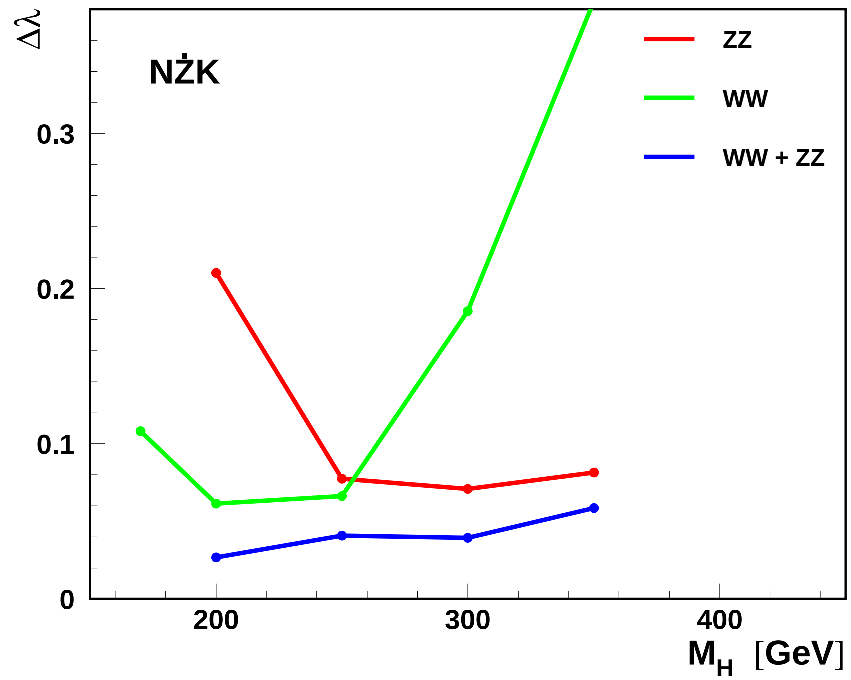
simultaneously fit of $\Gamma_{\gamma\gamma}$, $\phi_{\gamma\gamma}$, λ and Φ_{CP} (+ normalization factors) to all distributions

Measurement error for one year of Photon Collider running:

CP phase Φ_{CP}



Coupling λ



$\Delta\Phi_{CP} \leq$ 50 mrad $\quad$ $\Delta\lambda \leq$ 6% $\quad$ 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.