Measurement of the Higgs-boson couplings and CP properties from decays into WW and ZZ

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NŻK

Workshop of the Extended ECFA/DESY Study
Amsterdam, April 2003

Workshop of the ECFA Study
Montpellier, France, November 13, 2003

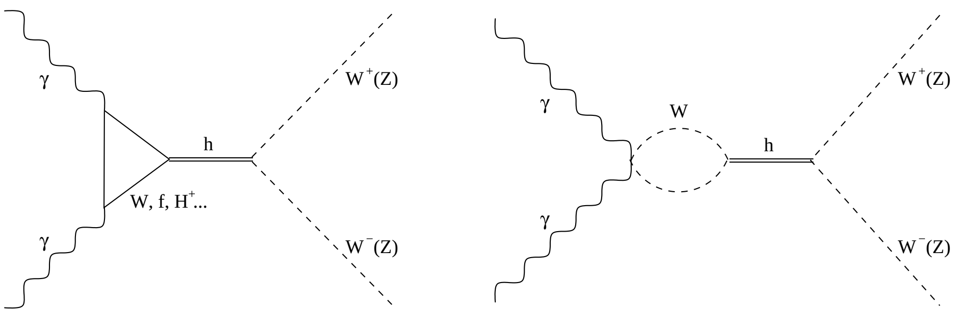
- $\gamma\gamma \rightarrow (h) \rightarrow W^+W^-, ZZ$
- SM Higgs results hep-ph/0207294
  measurement of $\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$
- 2HDM(II) results SM-like scenario B_h
- 2HDM(II) with CP violation
  measurement of $\tan\beta$ and H-A mixing
  hep-ph/0403138
- CP violation in generic model

results sent to EPS'2003: hep-ph/0307175

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

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 $\gamma\gamma \to W^+W^-$

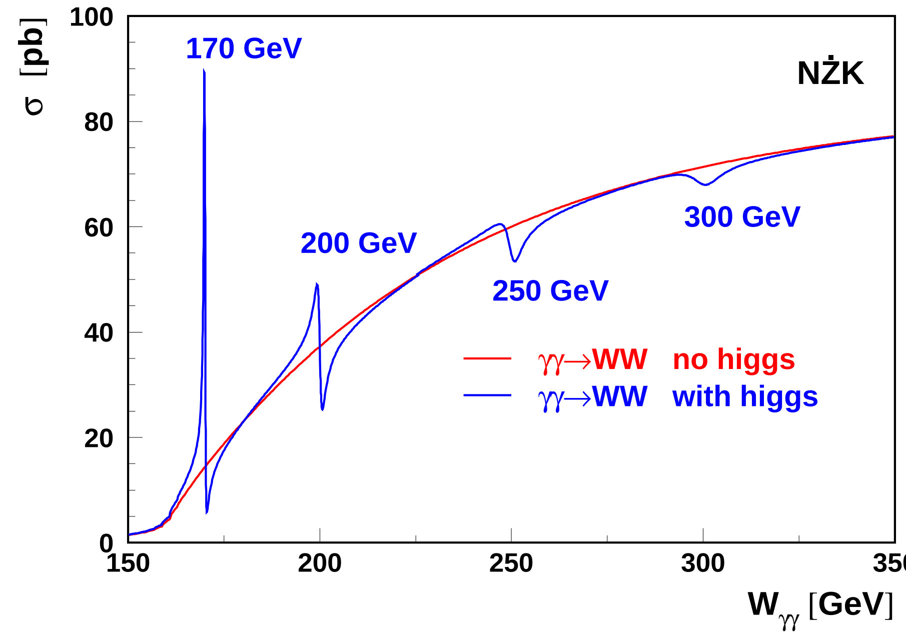
G.Belanger,F.Boudjema, Phys.Lett.B288(1992)210;
D.A.Morris, et al., Phys. Lett. B323(1994)421;
I.F.Ginzburg, I.P.Ivanov, Phys. Lett. B408(1997)325.

Interference

Resonant and direct amplitudes interfere

Large effects expected:

$J_z = 0$

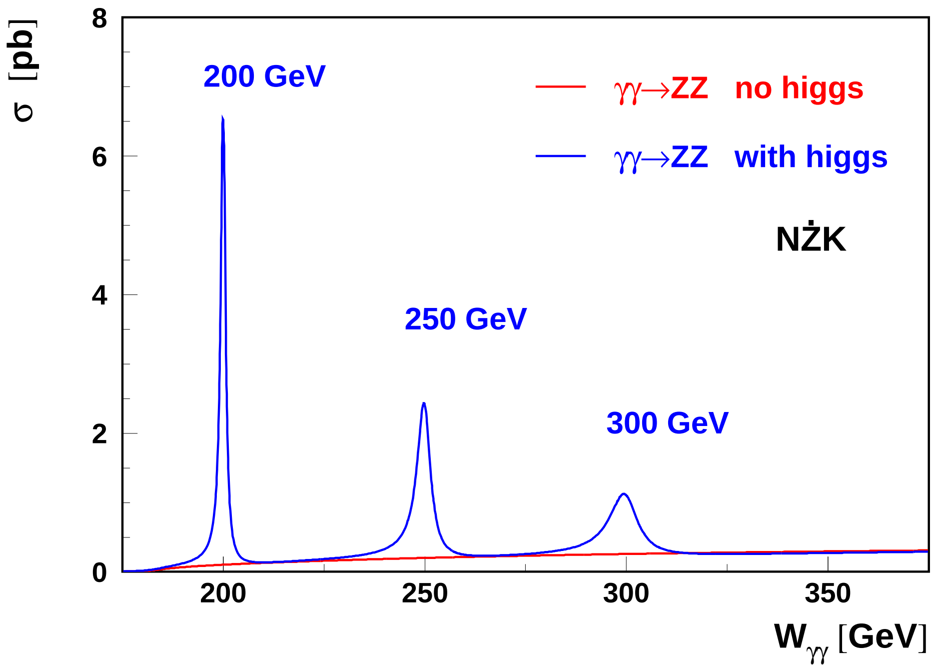


Destructive interference dominates above ~200 GeV

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

$\gamma\gamma \to ZZ$

Non-resonant background only at loop level



$\Rightarrow$ 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:

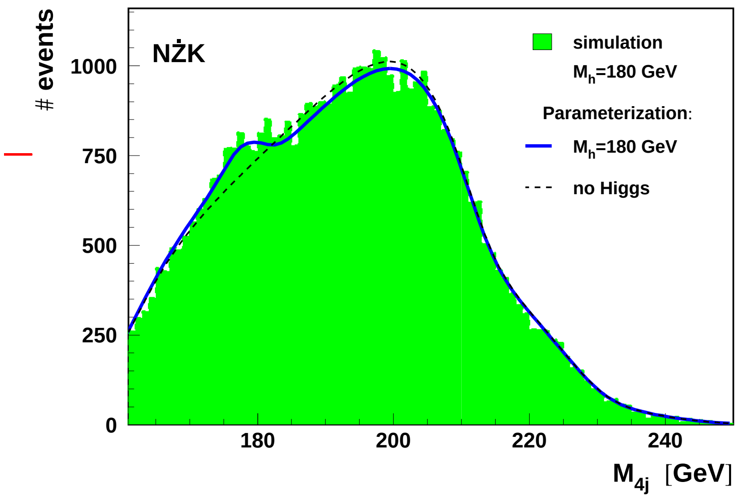
- Analytical luminosity Spectra **CompAZ**
- Cross section formula
  for signal + background + interf.
- Invariant mass resolution
  parametrized as a function of $W_{\gamma\gamma}$

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

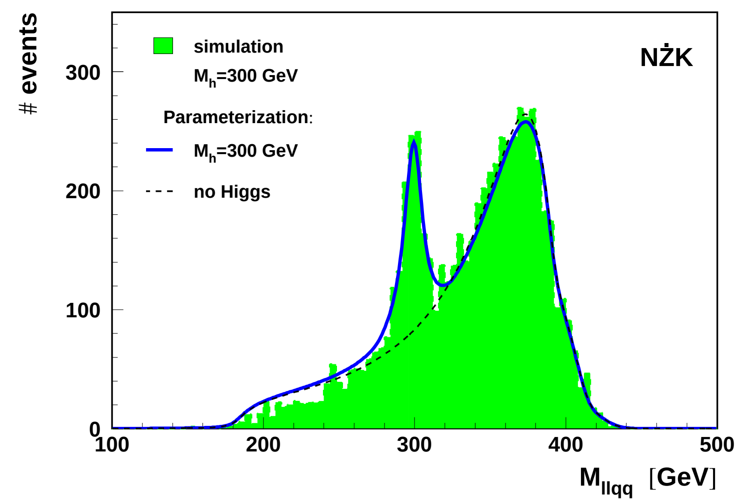
$\Rightarrow$ can be used for fast simulation and fitting

Comparison with full simulation:

W^+W^-



ZZ

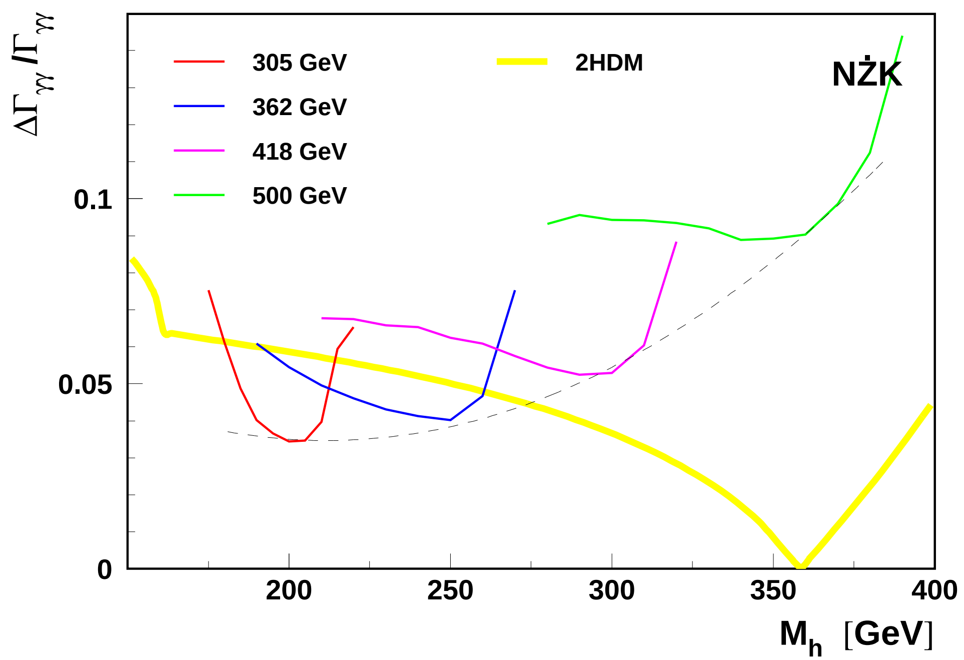


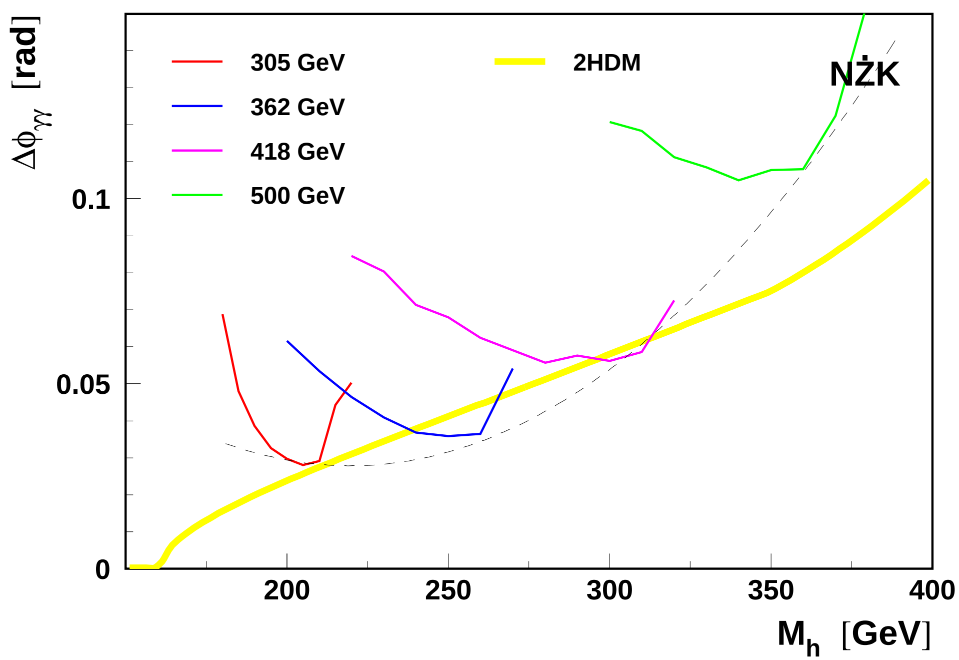
SM results

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

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_h

	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 $\tan\beta$.

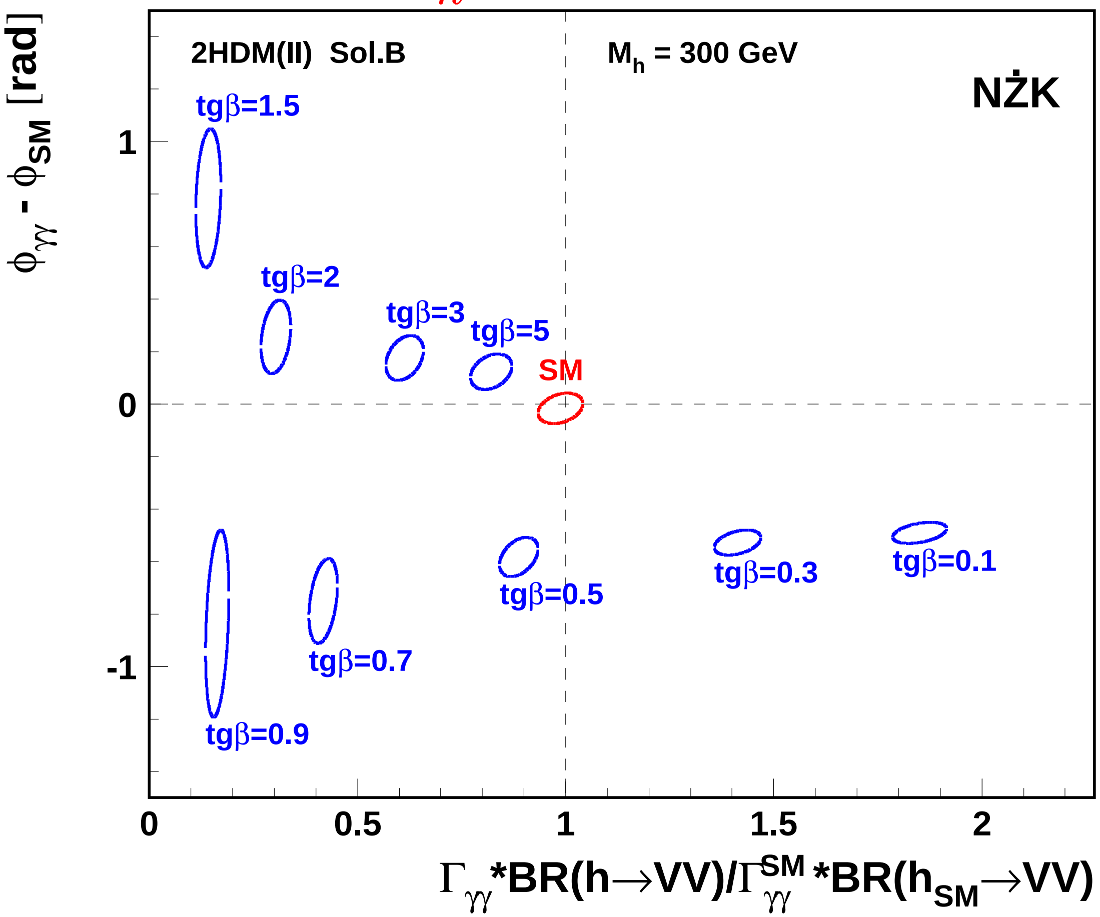
Can we extract $\tan\beta$ value from the measured W^+W^- and ZZ invariant mass distributions ?

SM-like 2HDM(II)

Light Higgs boson

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

M_h = 300 GeV



Measurement very sensitive to $\tan\beta$
$\Rightarrow$ precise determination possible.

Ambiguity resolved by the phase measurement (distinguishes between low $\tan\beta$ and large $\tan\beta$)

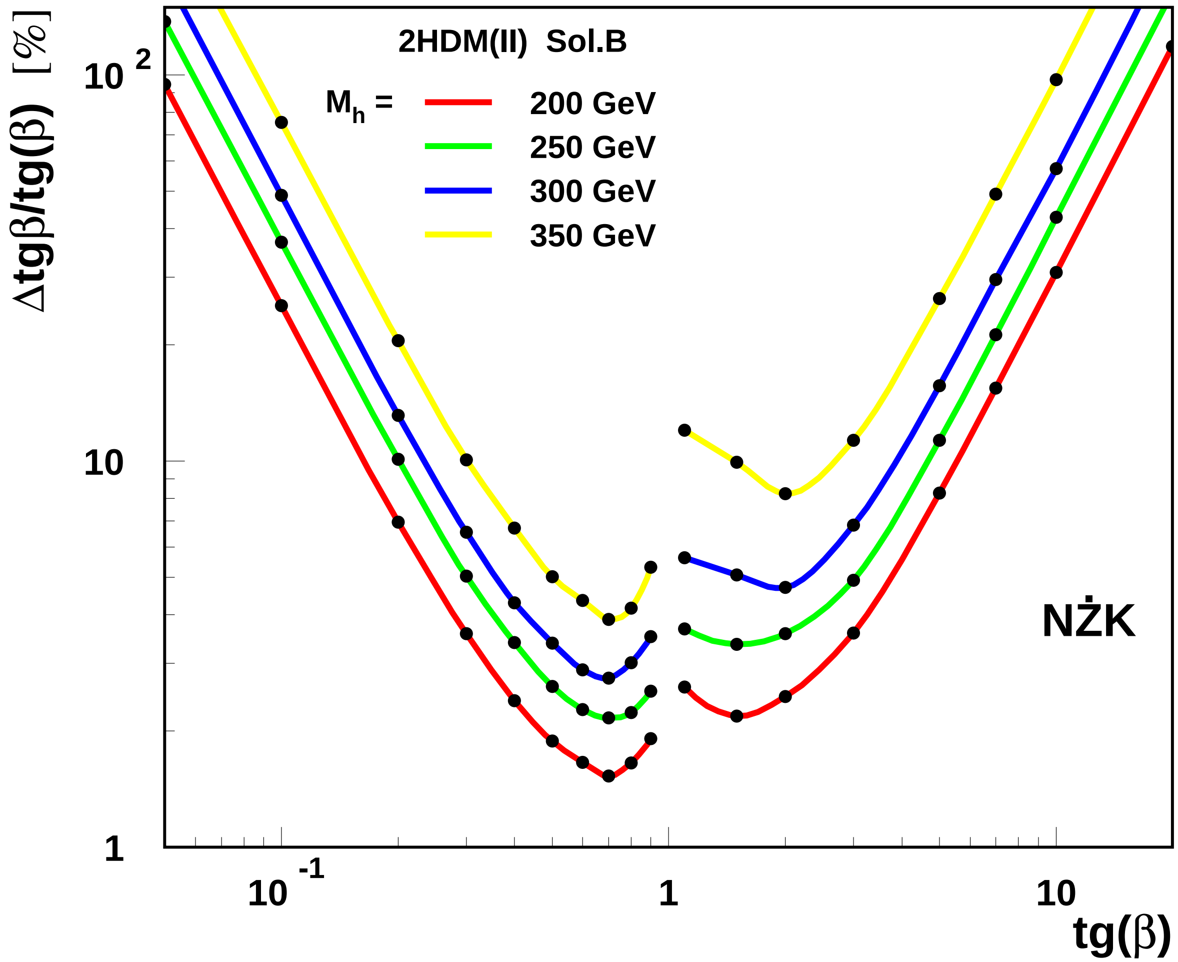
1σ contours for 1 year of PC running

statistical errors only M_{H+}=800 GeV

SM-like 2HDM(II)

Light Higgs boson

Expected statistical precision in $\tan\beta$ determination (1 PC year):



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	⇒ overall normalization relative normalization of WW and ZZ samples fixed
• energy scale	⇒ Higgs boson mass
• mass resolution	⇒ Higgs boson width
• luminosity spectra	⇒ spectra shape variations

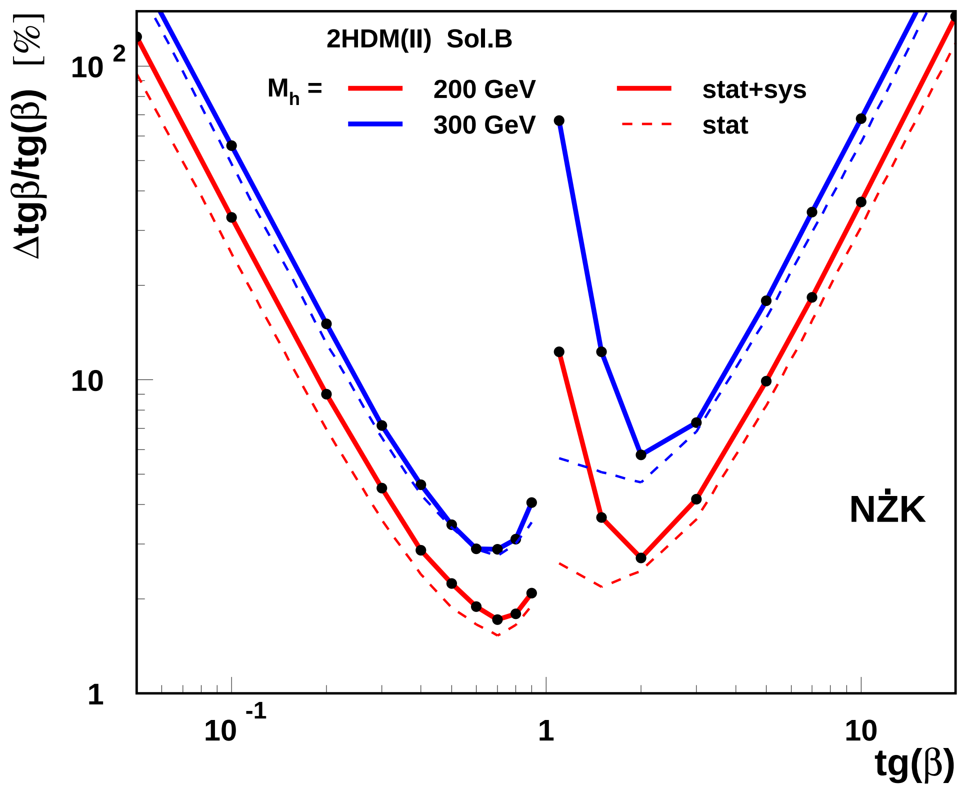
$$\frac{dL}{dW_{\gamma\gamma}} = \frac{dL^{CompAZ}}{dW_{\gamma\gamma}}(1 + A \cdot \sin \pi x + B \cdot \sin 2\pi x)$$

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

SM-like 2HDM(II)

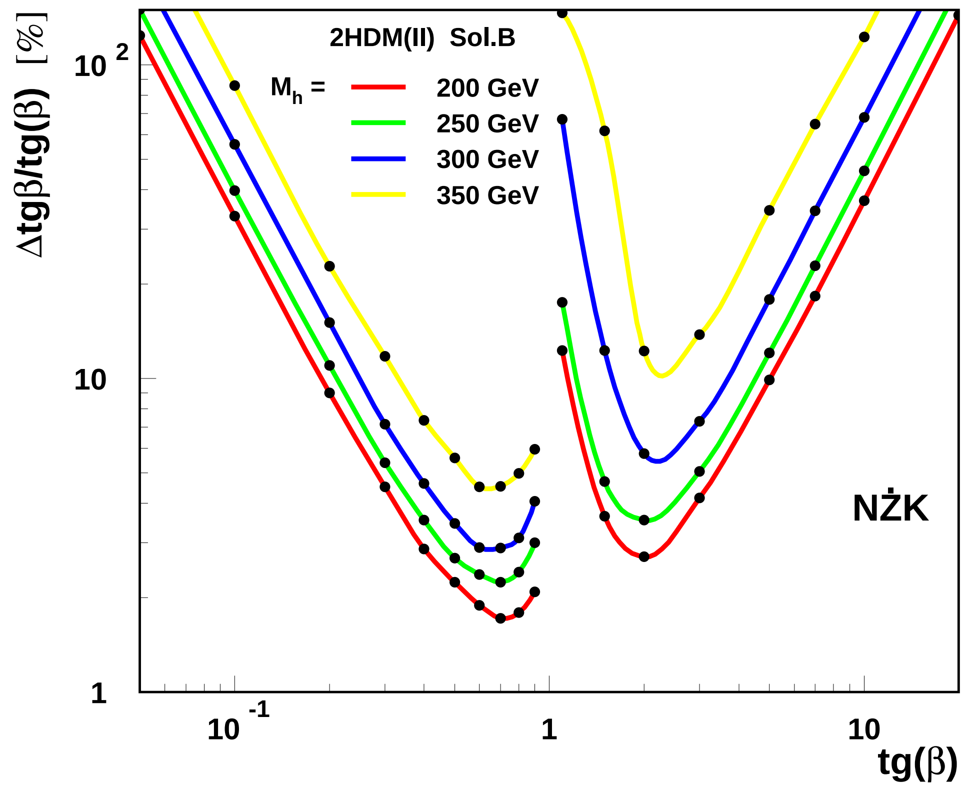
Light Higgs boson

Influence of systematic uncertainties for $M_h = 200$ GeV and $M_h = 300$ GeV



Expected precision in $\tan\beta$ determination

stat. + sys. errors



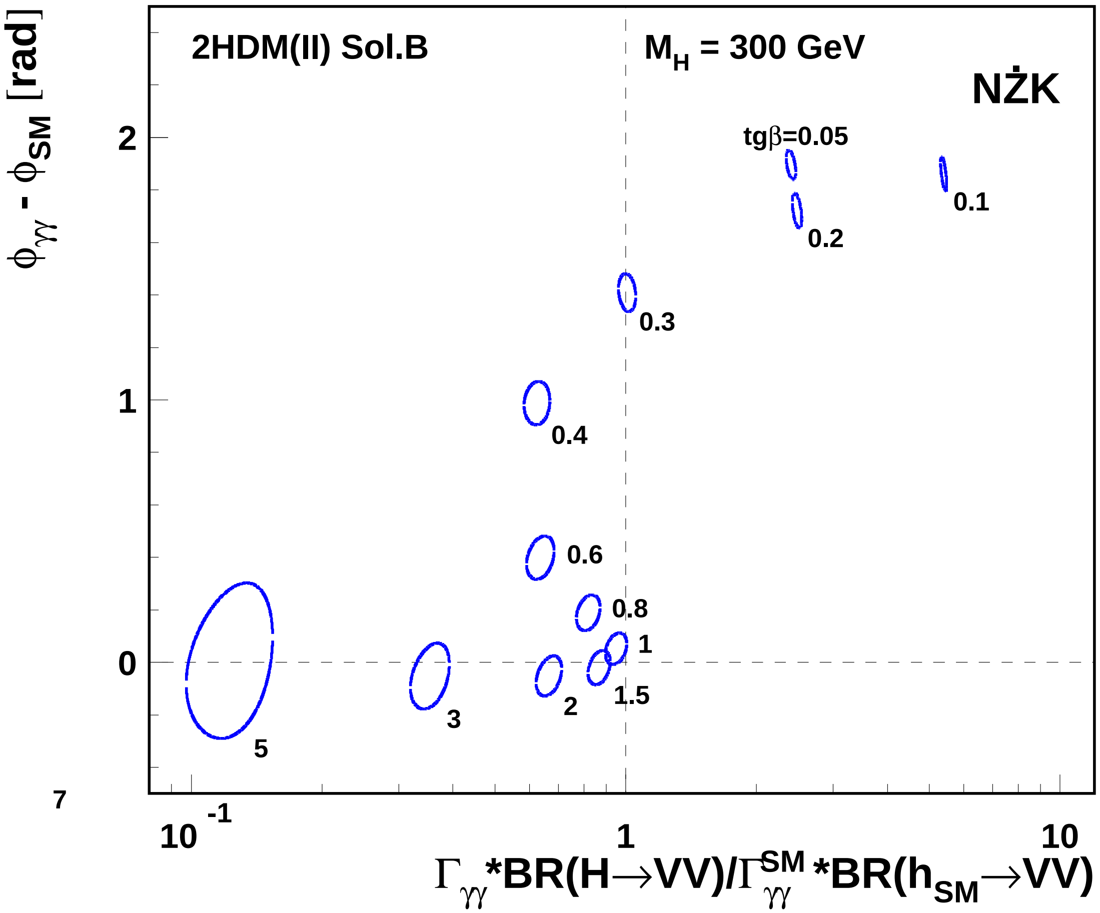
Large effects of systematic uncertainties for $\tan\beta \sim 1$.
For small and large $\tan\beta$ expected error increases by 10–30%.

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

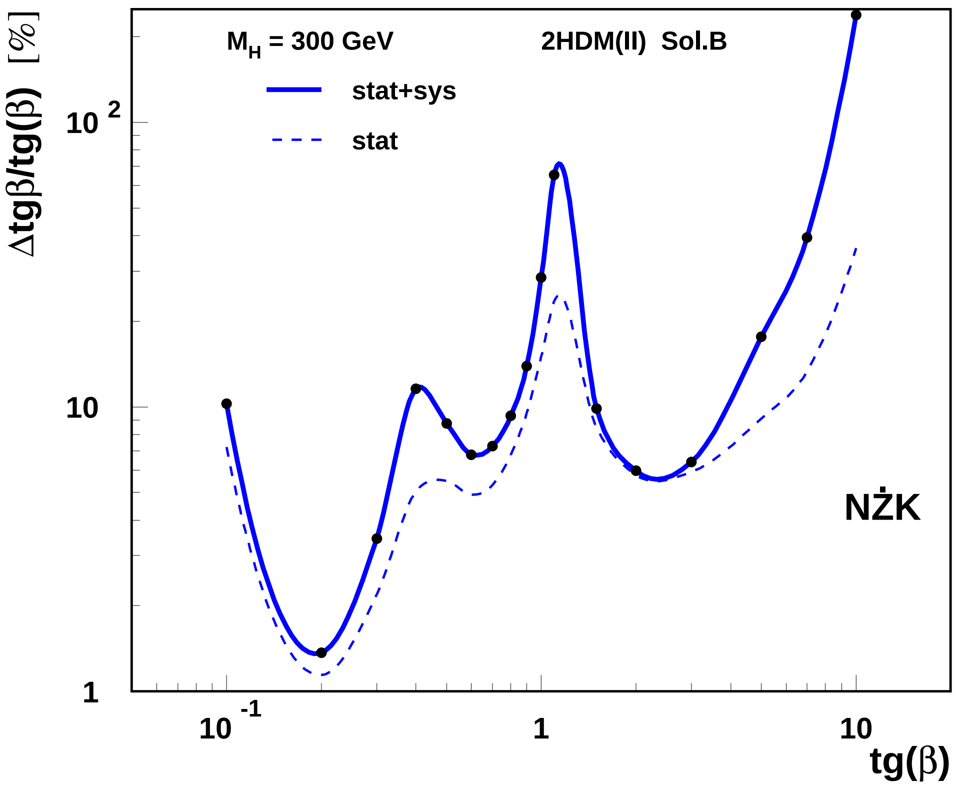
statistical errors only

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

SM-like 2HDM(II)

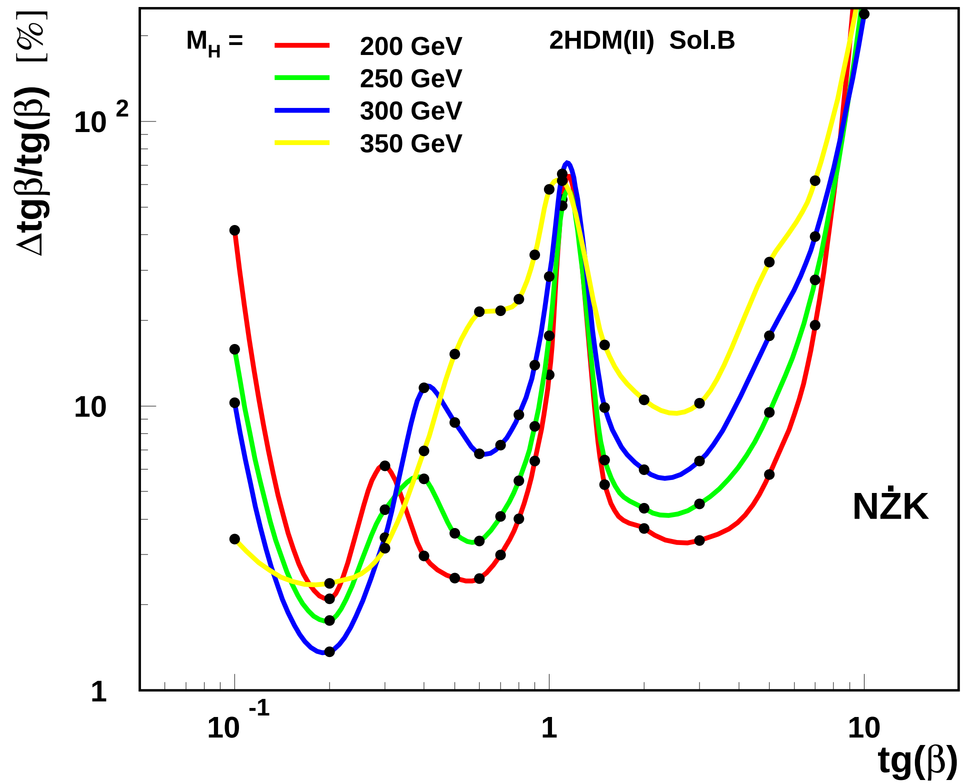
Heavy Higgs boson H

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 $|\Phi_{HA}| \ll 1$)

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

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

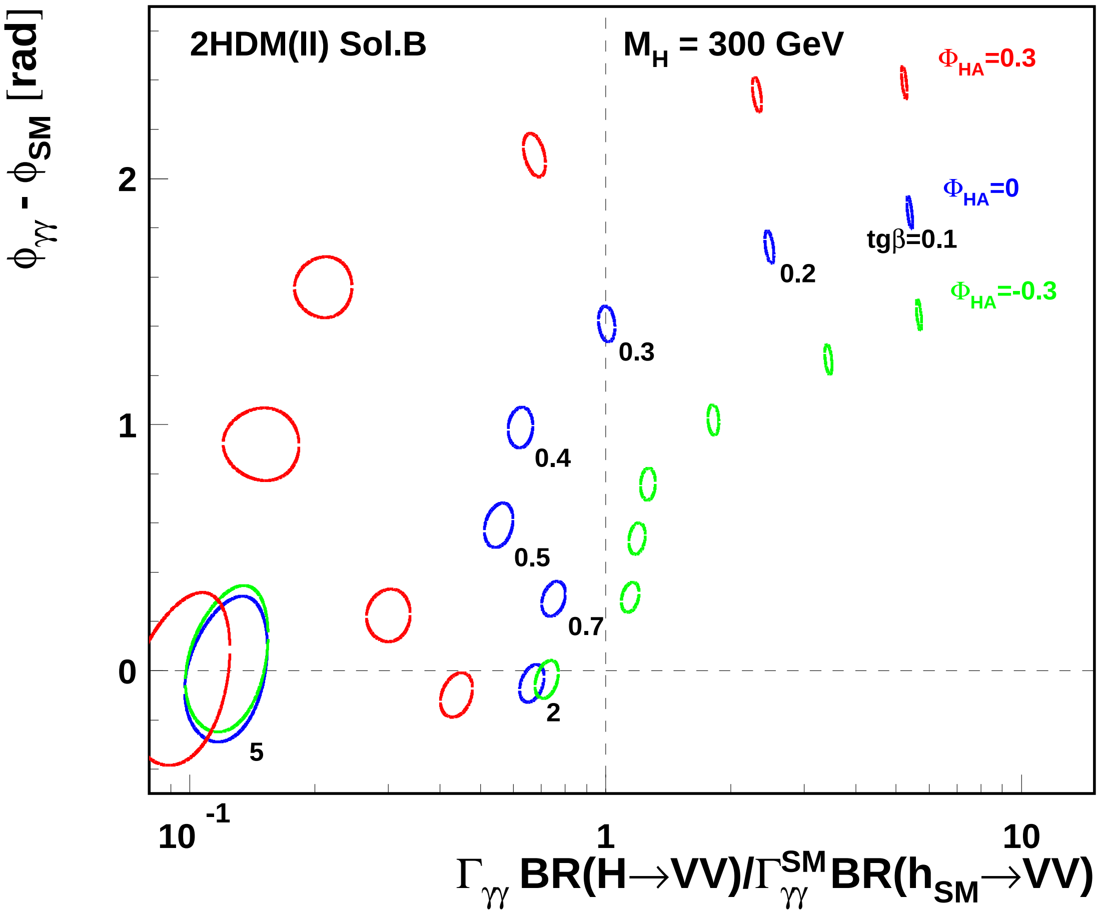
$\Rightarrow$ additional model parameter: **CP-violating mixing phase** Φ_{HA}

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

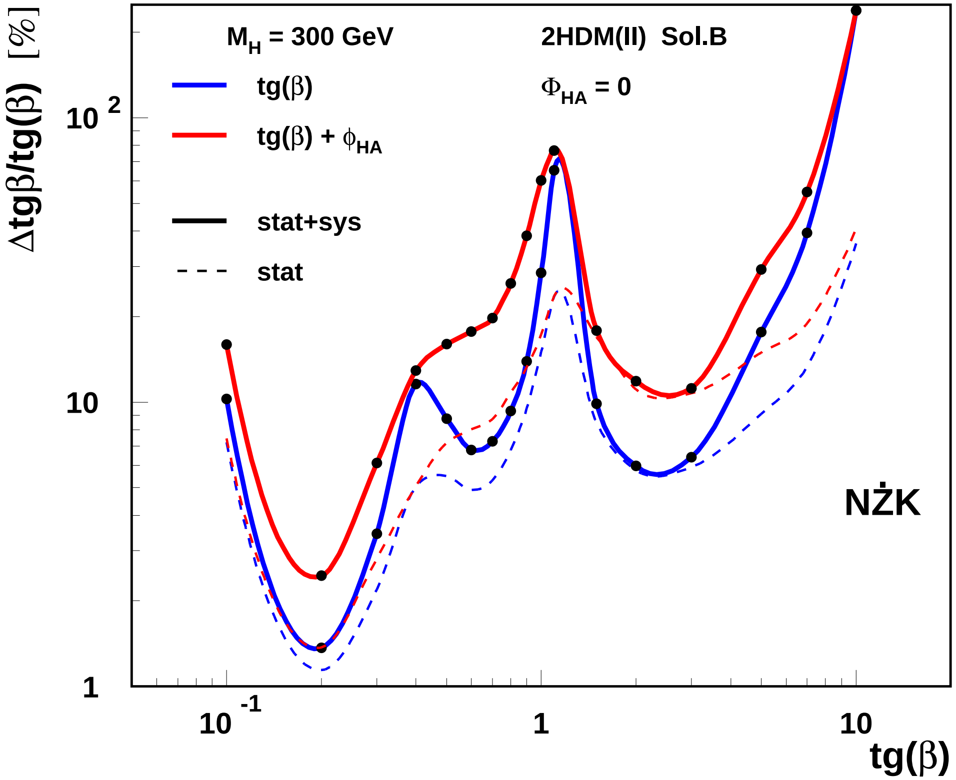
statistical errors only

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

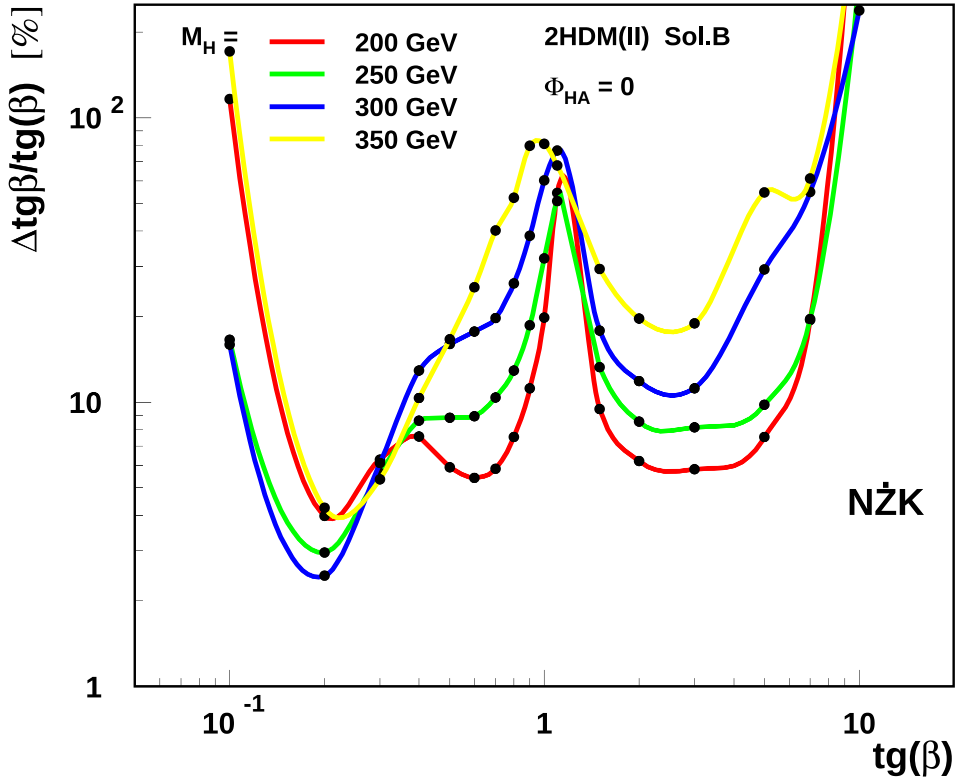
2HDM(II) with CP violation

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

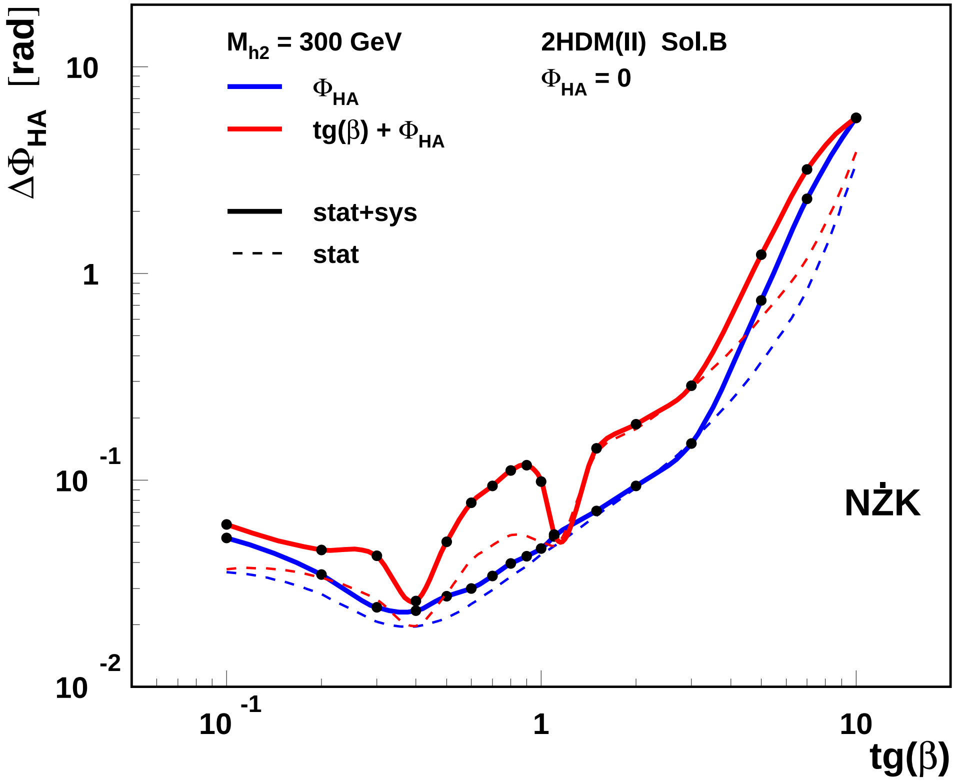


Possible CP violation increases expected $\tan\beta$ measurement errors

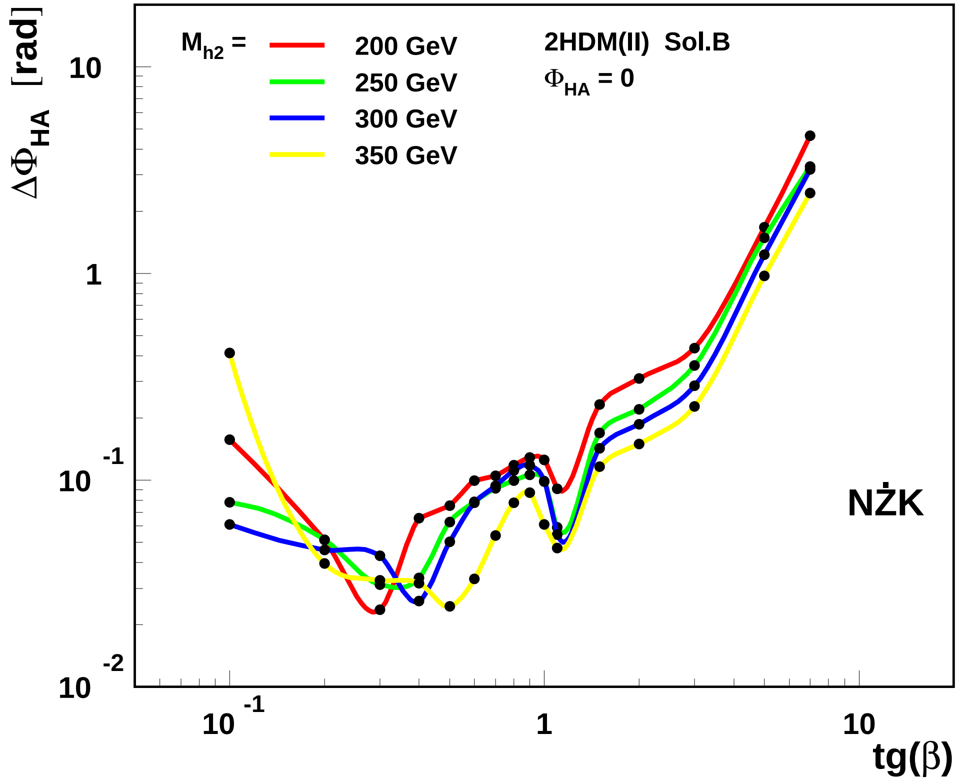
2HDM(II) with CP violation

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



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

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.

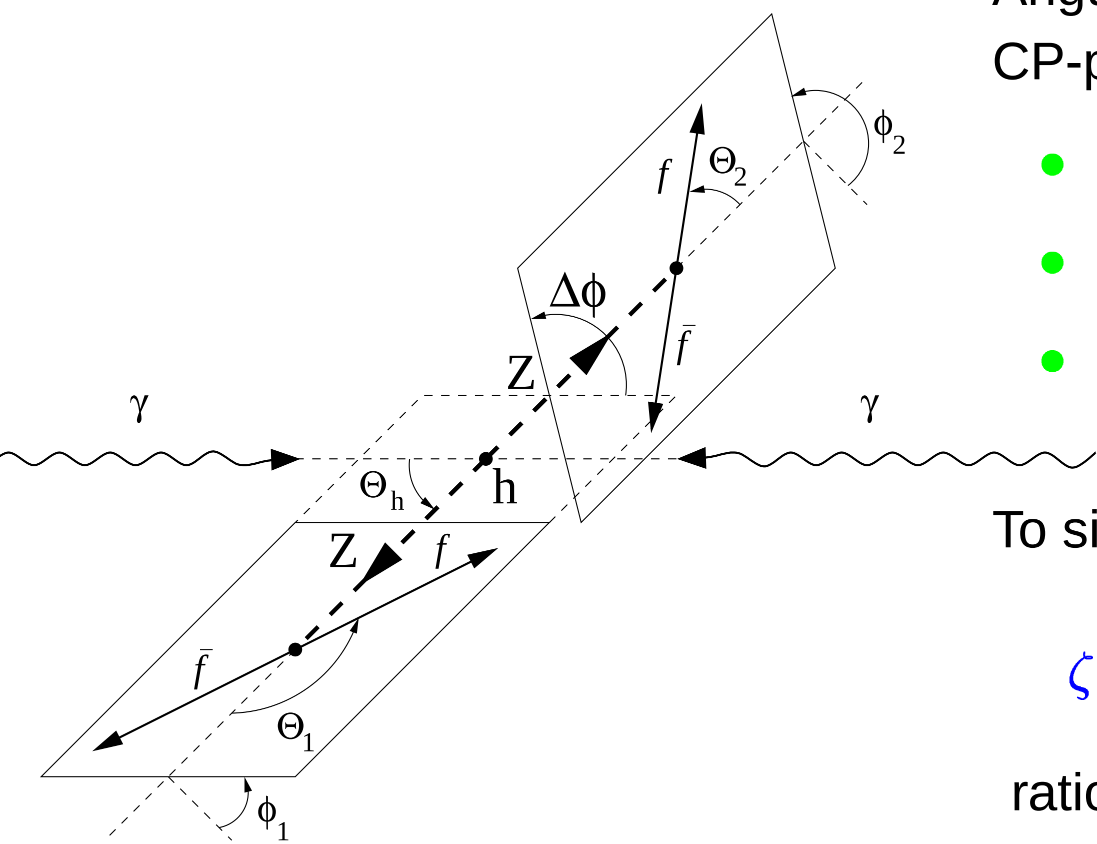
Model: S.Y. Choi, D.J. Miller, M.M. Mühlleitner and P.M. Zerwas, hep–ph/0210077;
D.J. Miller, S.Y. Choi, B. Eberle, M.M. Mühlleitner and P.M. Zerwas, Phys. Lett. B505 (2001) 149;
D.J. Miller, *Spin and Parity in the HZZ vertex*, ECFA/DESY meeting, Prague, November 2002.

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.

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 $M_h \gg M_Z$).

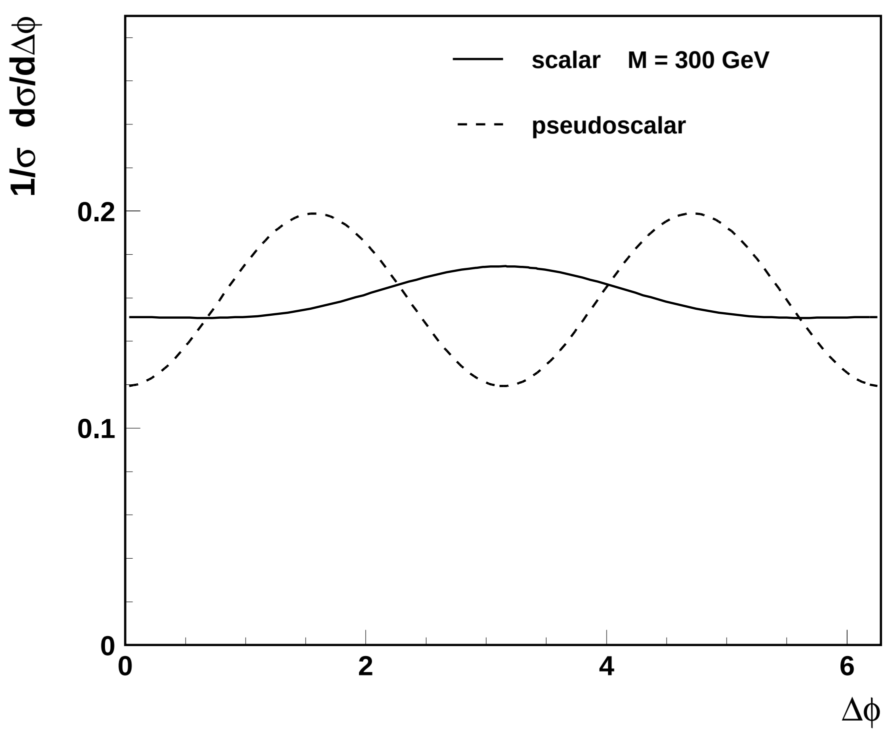
All polar angles are calculated in the rest frame of the decaying particle.

Generic model

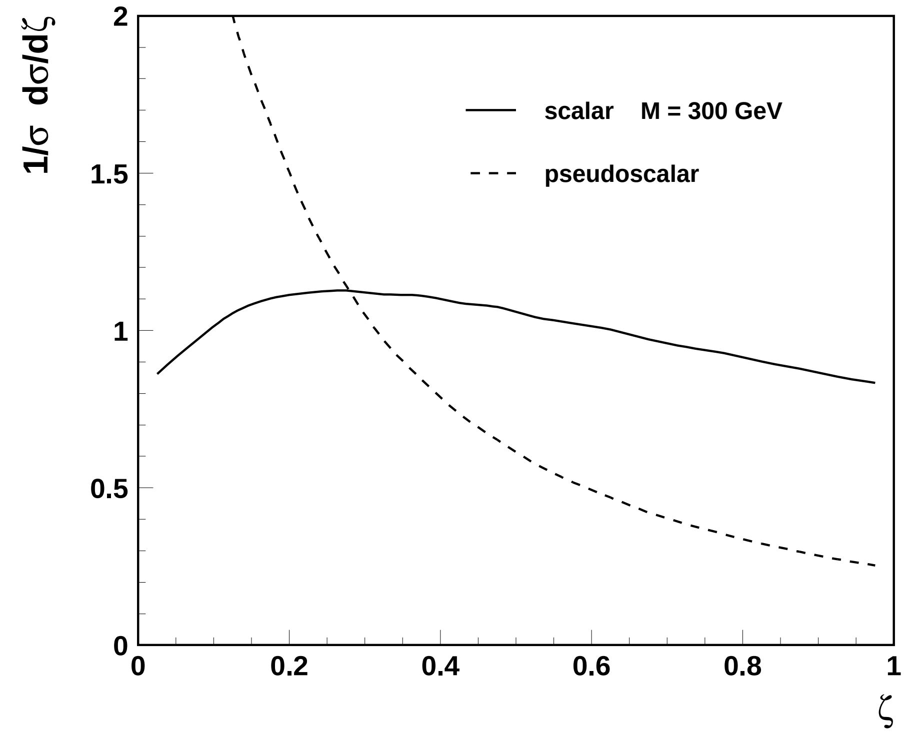
Angular distributions

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

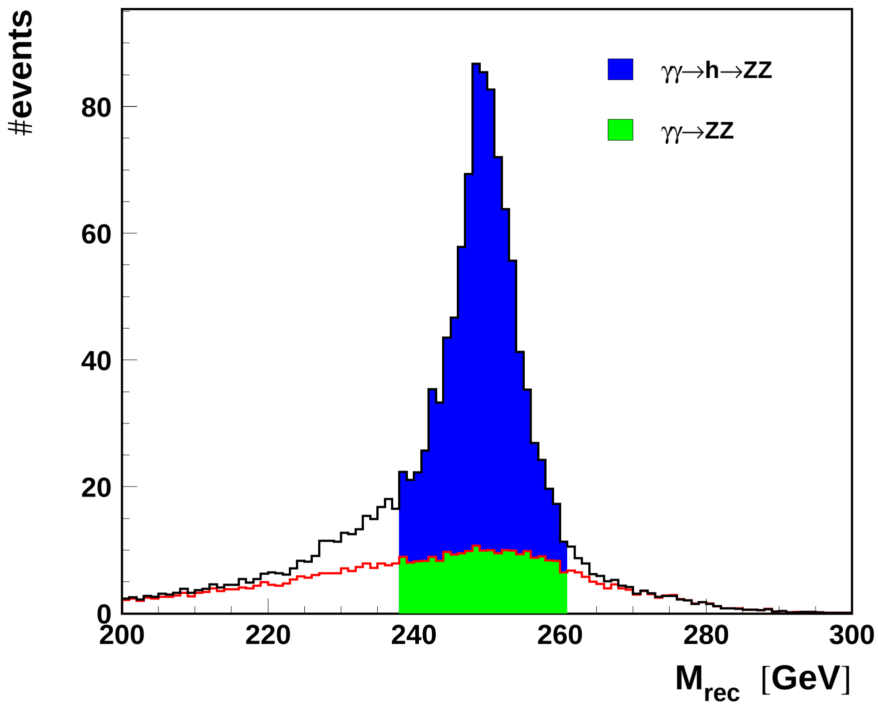


Both distributions clearly distinguish between decays of scalar and pseudoscalar higgs.

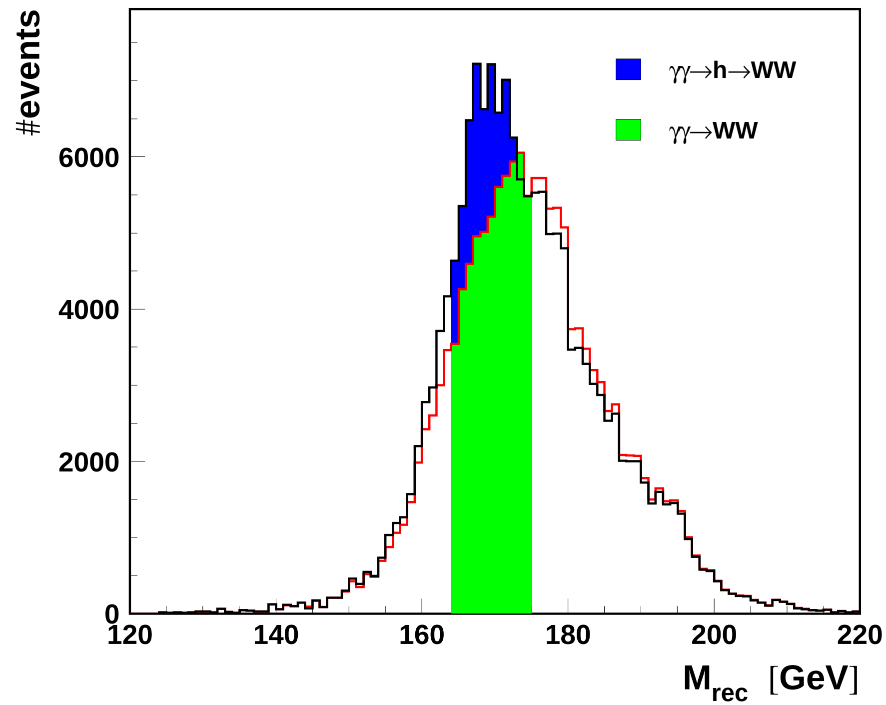
Selection

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

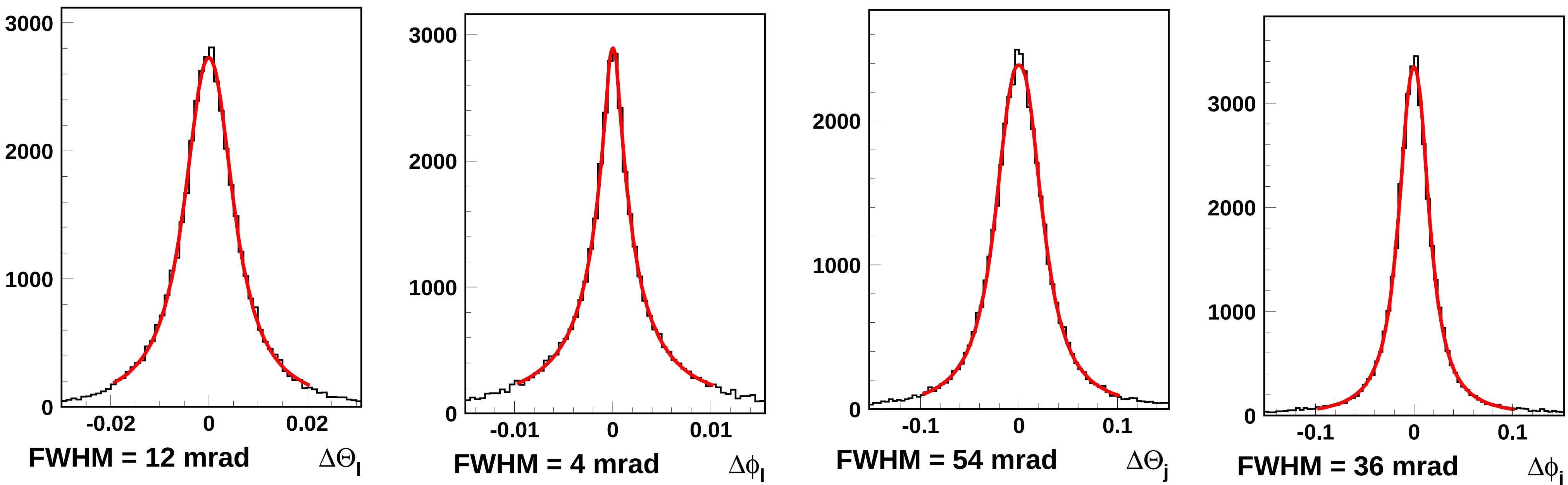
SM higgs selection efficiency ∼30%
(for $WW \to q\bar{q}q\bar{q}$ events)
$\times BR(WW \to q\bar{q}q\bar{q}) \approx 46.9\%$

Resolution

Expected accuracy of decay angles measurement:

$Z \rightarrow l^+ l^-$ — $Z/W \rightarrow q\bar{q}$

polar angle θ_l — azimuthal angle ϕ_l — polar angle θ_q — azimuthal angle ϕ_q



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

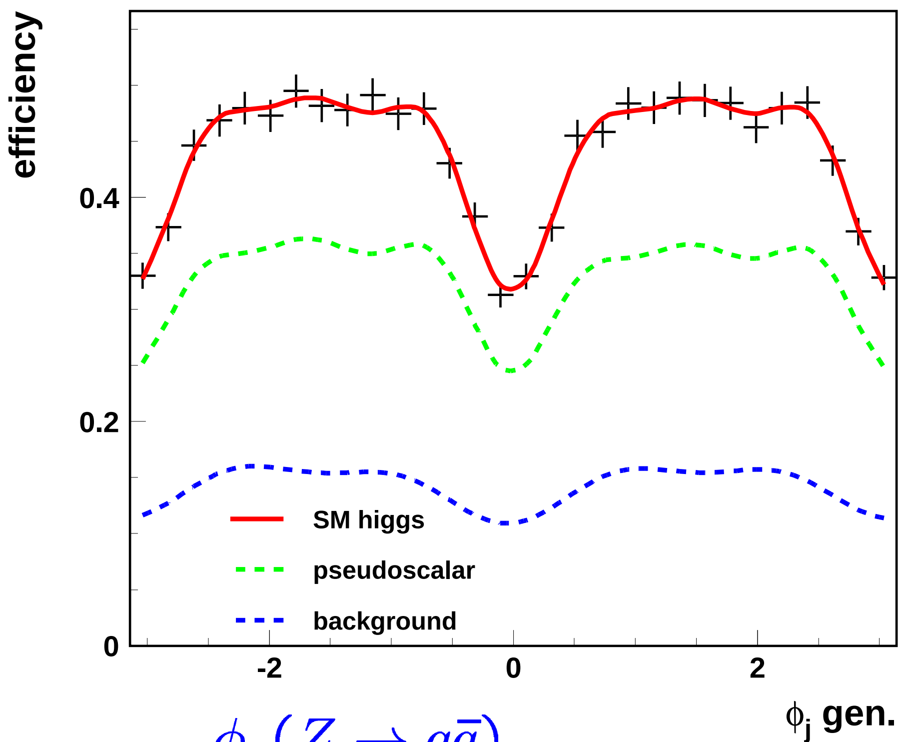
All angles can be measured with high accuracy

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

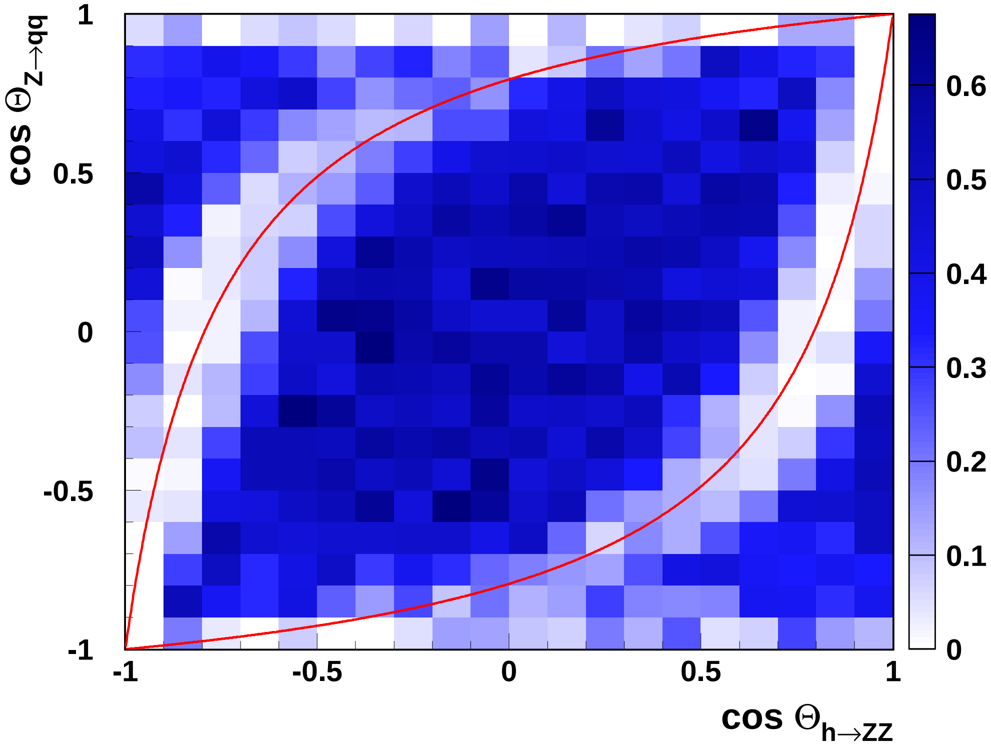


$\phi_q(Z \to q\bar{q})$

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 $\phi_j \approx 0$:

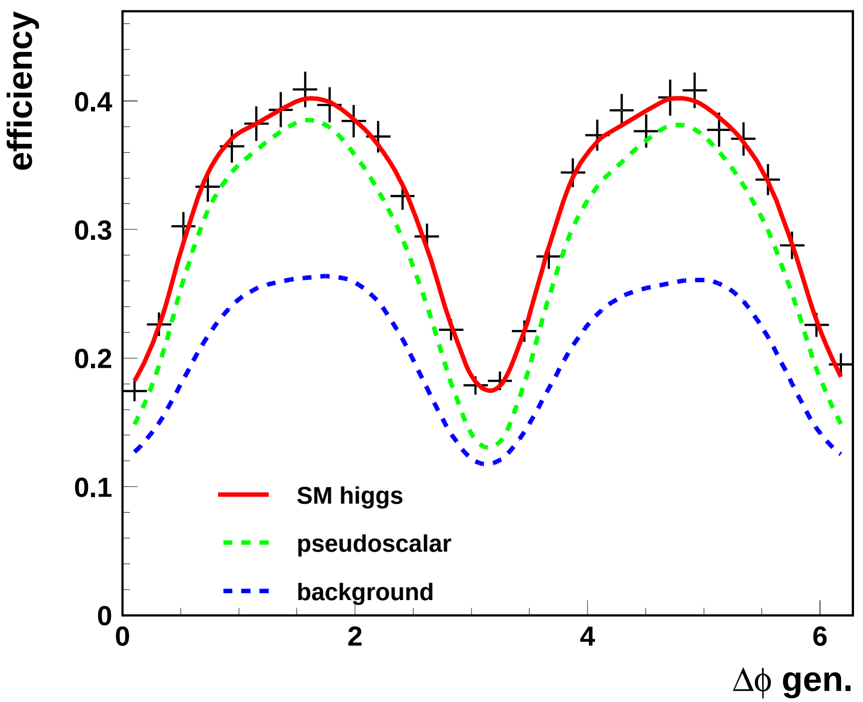


red lines: $\cos\theta_j^{LAB} = \pm\cos\theta_Z^{LAB}$

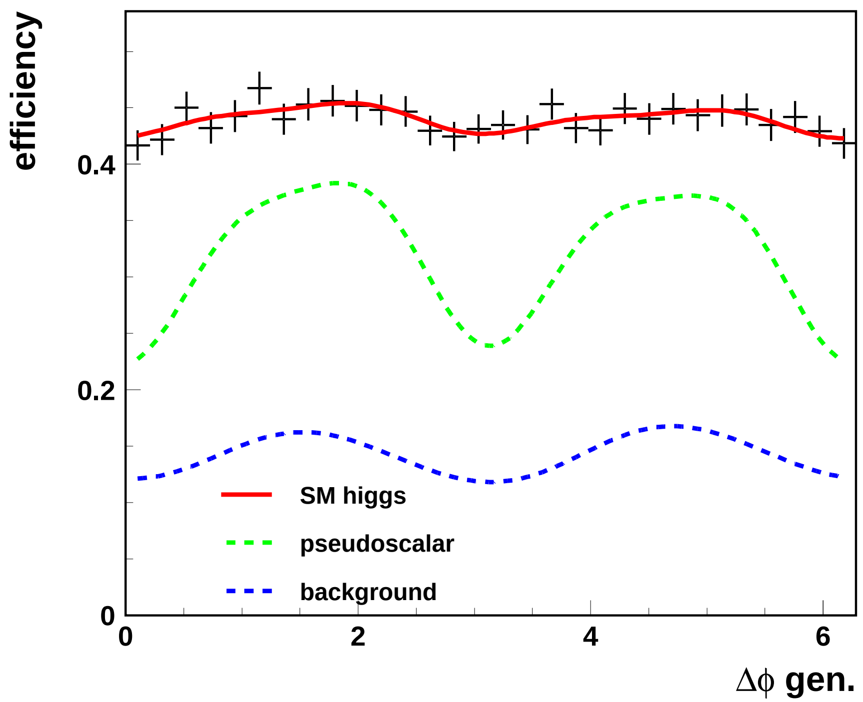
Acceptance

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



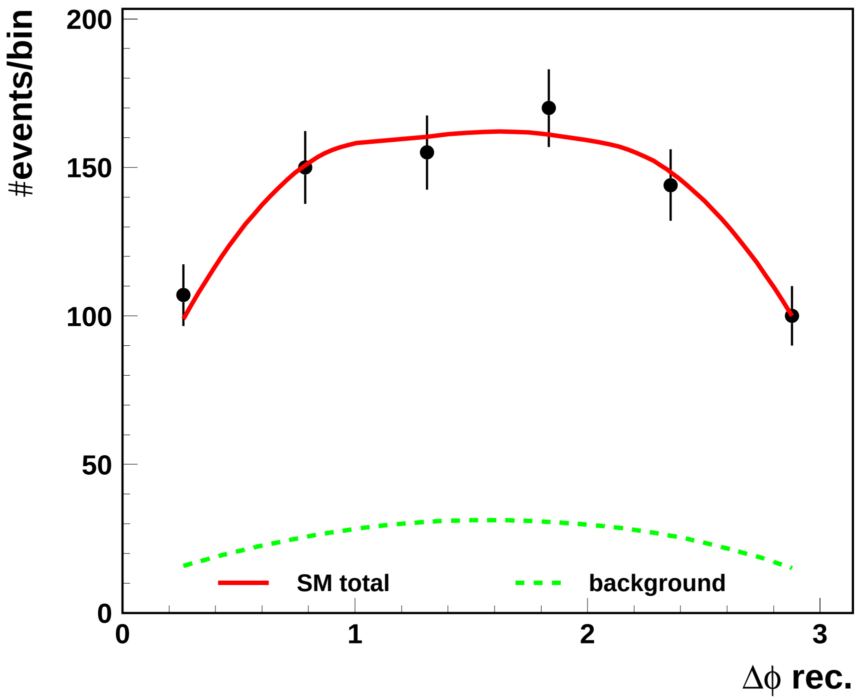
Effect much stronger for background events and pseudoscalar higgs

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

Results

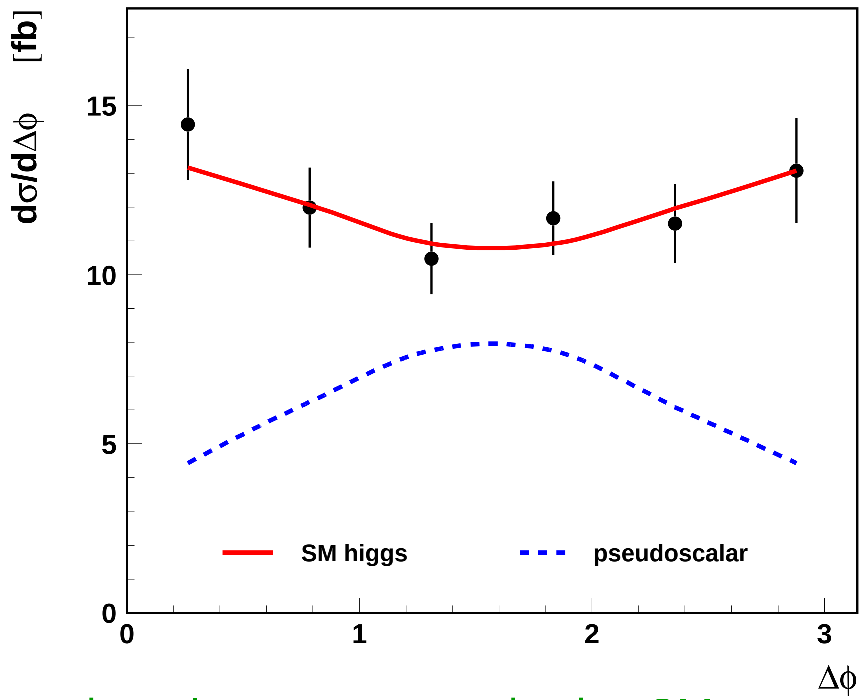
Measured $\Delta\phi$ distribution for $h \rightarrow ZZ \rightarrow q\bar{q}\, l^+ l^-$ m_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ ~675 reconstructed SM higgs events expected + 145 ZZ background events

Measured distribution:



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

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

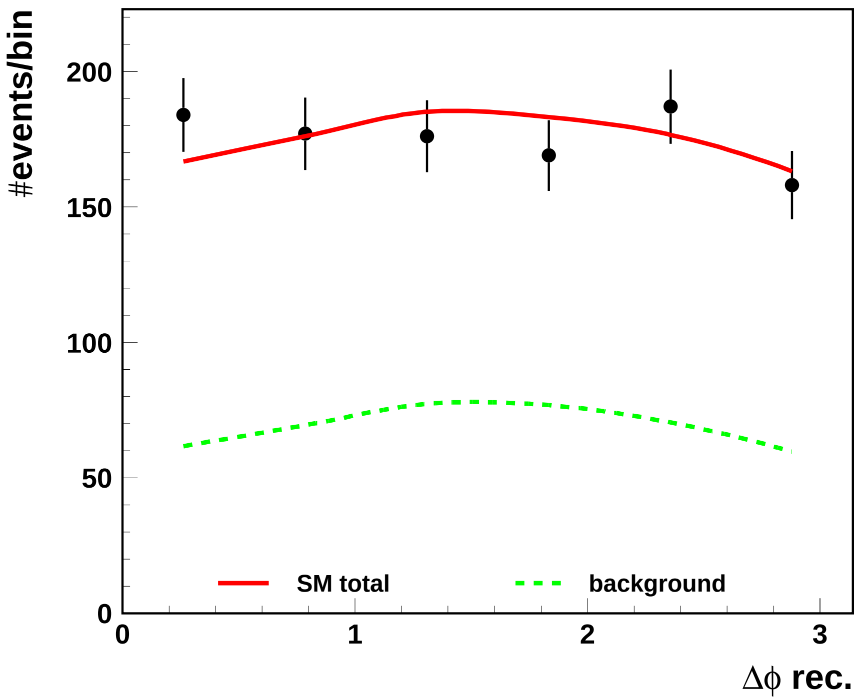


pseudoscalar reconstructed using SM acceptance

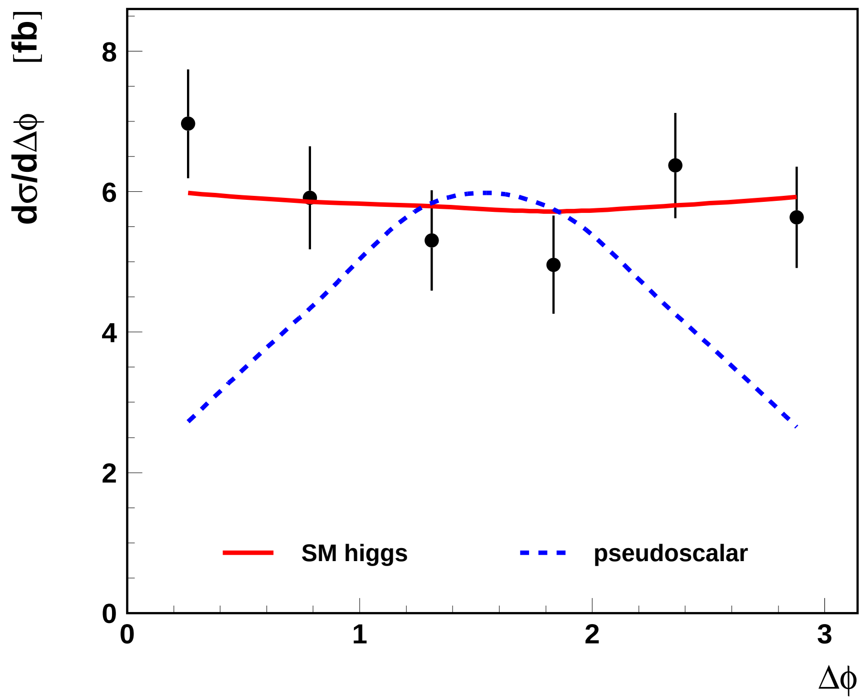
Results

Measured $\Delta\phi$ distribution for $h \to ZZ \to q\bar{q}\, l^+ l^-$ m_h = 300 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=418 GeV, $\mathcal{L} = 830\ fb^{-1}$
$\Rightarrow$ ~635 reconstructed SM higgs events expected + 415 ZZ background events

Measured distribution:



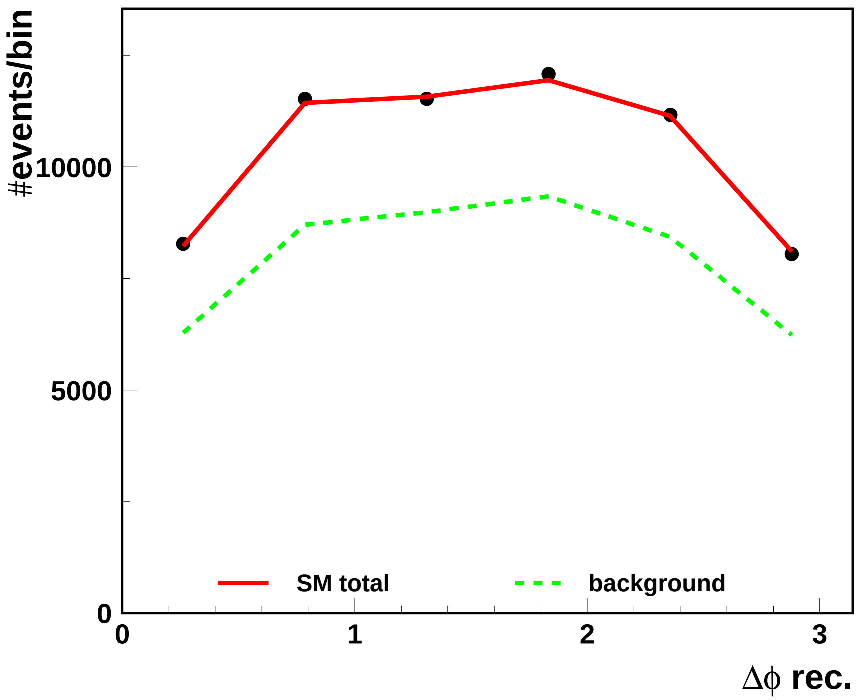
Extracted $\frac{d\sigma}{d\Delta\phi} \times BR(h \to ZZ)$



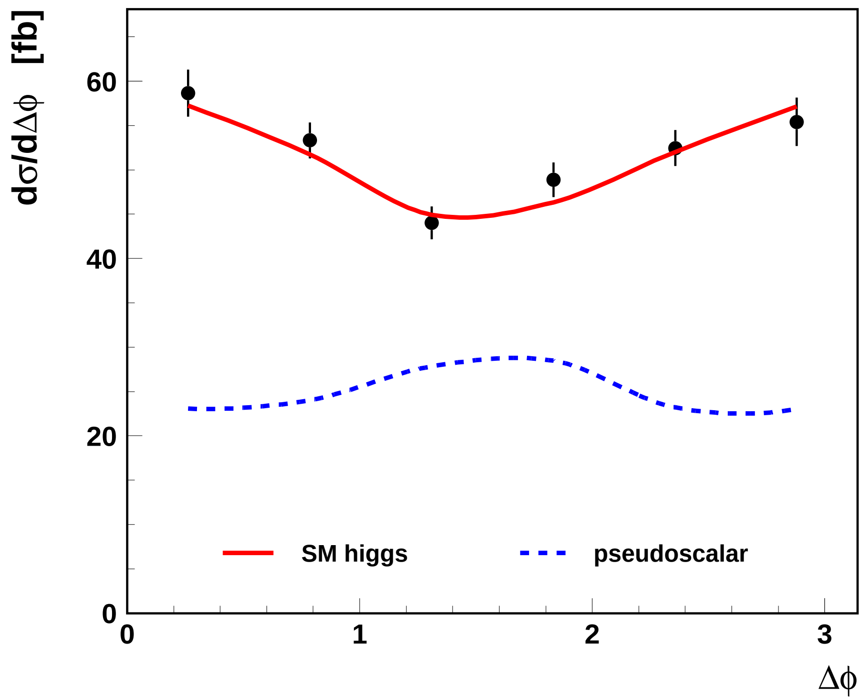
Results

Measured $\Delta\phi$ distribution for $h \to WW \to q\bar{q}q\bar{q}$ m_h = 170 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=270 GeV, $\mathcal{L} = 540\ fb^{-1}$
$\Rightarrow$ $\sim$14 400 reconstructed SM higgs events expected + 48 000 WW background events

Measured distribution:



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

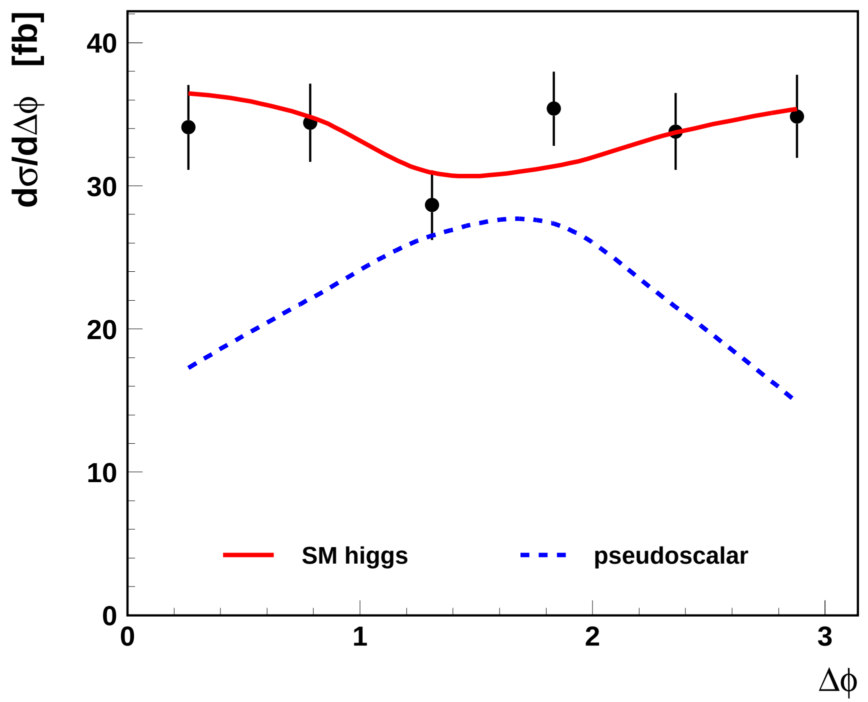


Results

m_h = 200 GeV

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

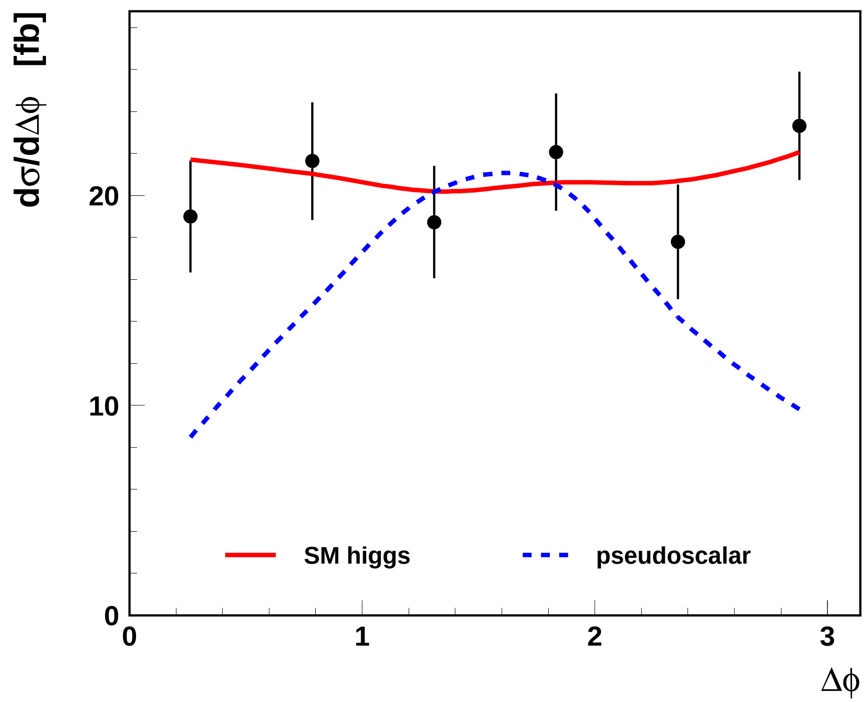
~8 000 SM higgs + 173 000 WW events



m_h = 250 GeV

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

~5 500 SM higgs + 189 000 WW events



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

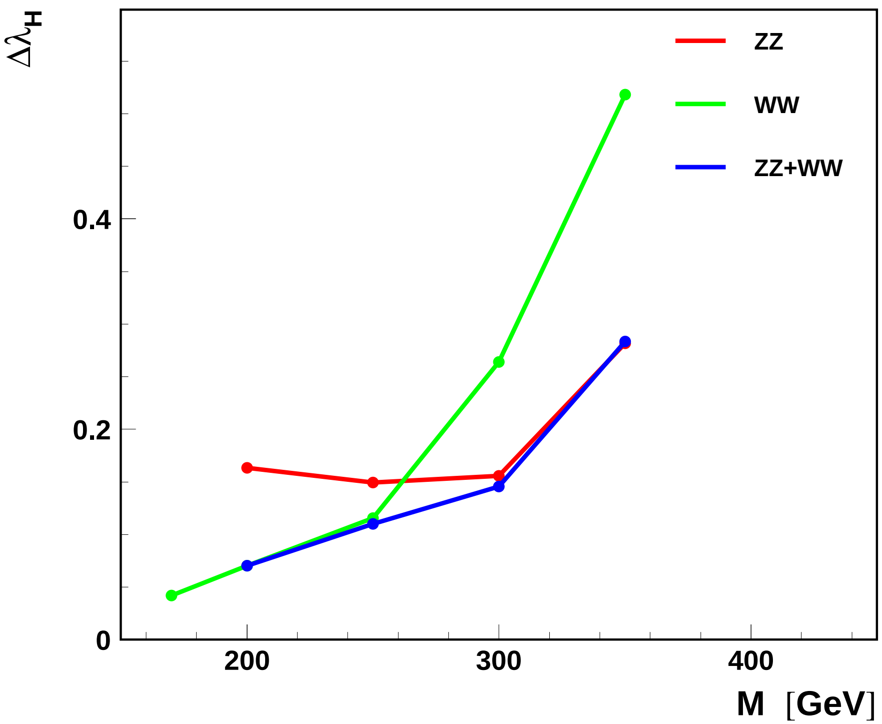
Results

Preliminary **EPS'2003**

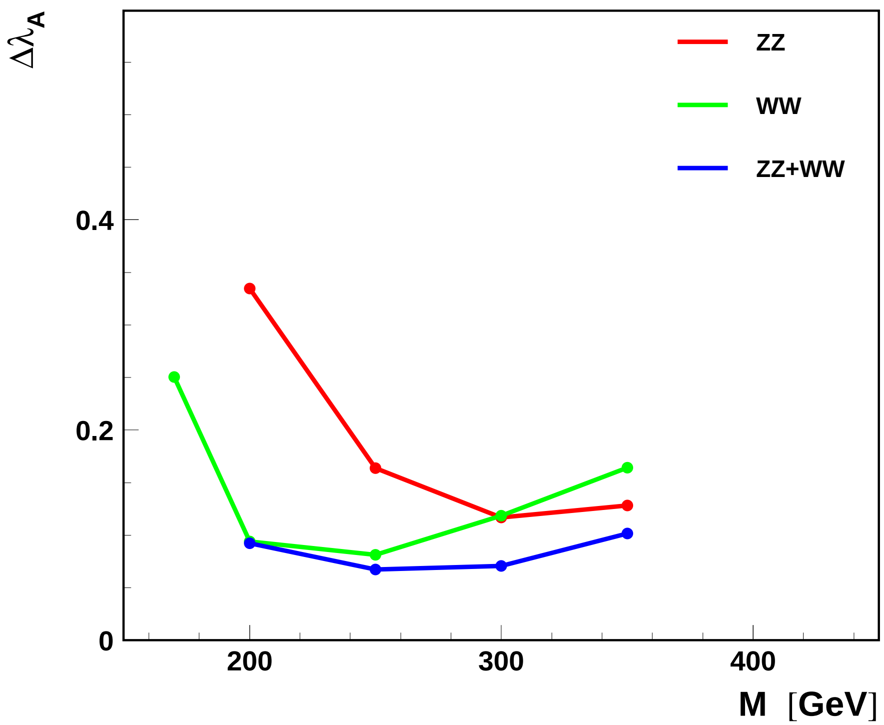
Combined measurement of angular correlations in the W^+W^- and ZZ-decay products

Measurement error for Higgs-boson couplings to vector bosons:

scalar



pseudoscalar



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

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.

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

Strong dependence on Higgs boson couplings is expected for SM-like 2HDM (II) sol. B_h

Both h and H boson decays can be used for precise determination of $\tan\beta$.

Precision better than 10% is obtained in wide parameter range.

CP violating H–A mixing phase Φ_{HA} can be measured with precision $\Delta\Phi_{HA} \leq 0.1$ rad, for $\tan\beta < 1$

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%.