Simulations of the Higgs boson measurements at the PLC

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Outline

- Introduction
- SM Higgs boson production
- Heavy MSSM Higgs bosons
- CP properties of the Higgs boson
- PLC complementarity

Introduction

Simulations of the Higgs boson production at the PLC

Studies by P.Nieżurawski, A.F.Żarnecki, M.Krawczyk (NŻK) :

$\mathcal{H} \to b\bar{b}$ decay channel

- Standard Model
  "The SM Higgs boson production $\gamma\gamma \to h \to b\bar{b}$ at the photon collider at TESLA," Acta Phys. Polon. B **34** (2003) 177 [arXiv:hep-ph/0208234].
- MSSM
  "Extended analysis of the MSSM Higgs boson production at the photon collider," Proceedings of LCWS 2005 [arXiv:hep-ph/0507006];
  "LHC wedge at the PLC: Observability of $\gamma\gamma \to A, H \to b\bar{b}$," Acta Phys. Polon. B **37** (2006) 1187.

$\Rightarrow$ see also P. Nieżurawski, "Higgs-boson production at the photon collider at TESLA," arXiv:hep-ph/0503295 (PhD Thesis).

Introduction

Simulations of the Higgs boson production at the PLC

Studies by P.Nieżurawski, A.F.Żarnecki, M.Krawczyk (NŻK):

$\mathcal{H} \rightarrow WW/ZZ$ decay channels

- Standard Model

  "Study of the Higgs-boson decays into W+ W- and Z Z at the photon collider," JHEP **0211** (2002) 034 [arXiv:hep-ph/0207294].

- 2HDM

  "Determination of the Higgs-boson couplings and CP properties in the SM-like two Higgs doublet model," JHEP **0502** (2005) 041 [arXiv:hep-ph/0403138].

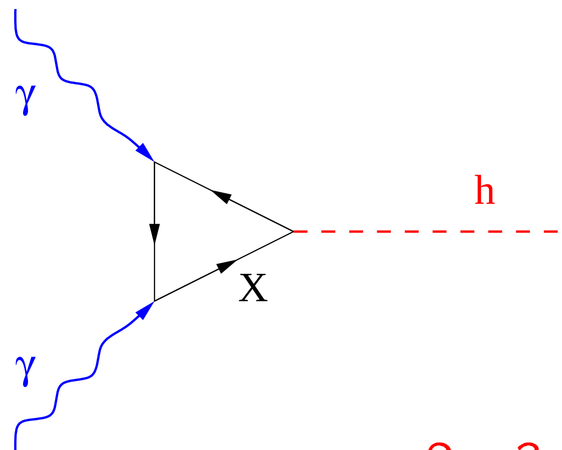
- Generic model

  "Model-independent determination of CP violation from angular distributions in Higgs boson decays to W W and Z Z at the Photon Collider," Acta Phys. Polon. B **36** (2005) 833 [arXiv:hep-ph/0410291].

$\gamma\gamma \to h$

Width

Two-photon width of the Higgs boson $\Gamma_{\gamma\gamma}$ is sensitive to all massive and charged particles in the loop:



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

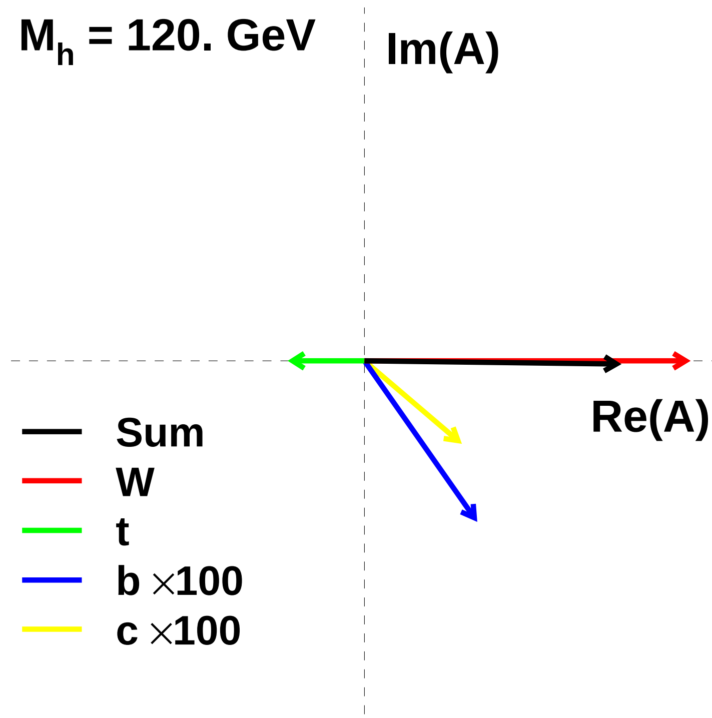
where:

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

two-photon amplitude

Amplitude

For Higgs boson mass $M_h < 2\ M_W$ amplitude $\mathcal{A}$ is real



contribution to $Im(\mathcal{A})$ from light fermions - very tiny

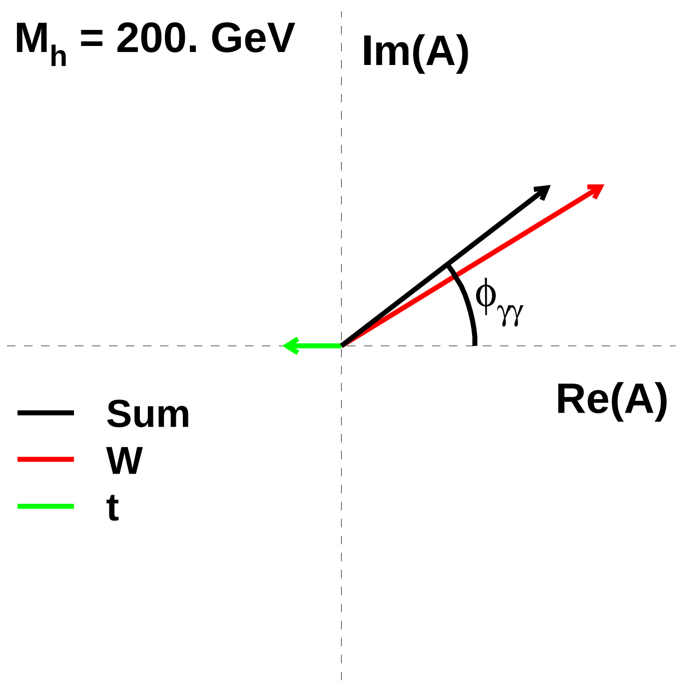
contribution from new heavy particles - real

$\gamma\gamma \rightarrow h$

Phase

However, for $M_h > 2\ M_W$

W contribution is complex



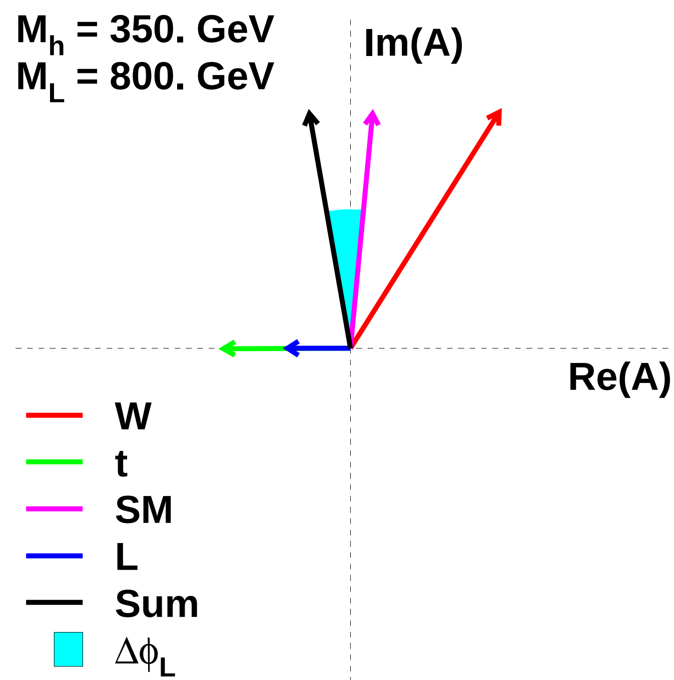
$\Rightarrow\ \mathcal{A} = |\mathcal{A}| \cdot e^{i\phi}$ phase $\phi_{\gamma\gamma} \neq 0$

$$\Gamma_{\gamma\gamma} \sim |\mathcal{A}|^2 = Im(\mathcal{A})^2 + Re(\mathcal{A})^2$$

New particles

Will contribute to both $\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$.

For new charged lepton:



for M_h ~350 GeV

$\Rightarrow$ amplitude mostly imaginary: $Re(\mathcal{A}) \sim 0$

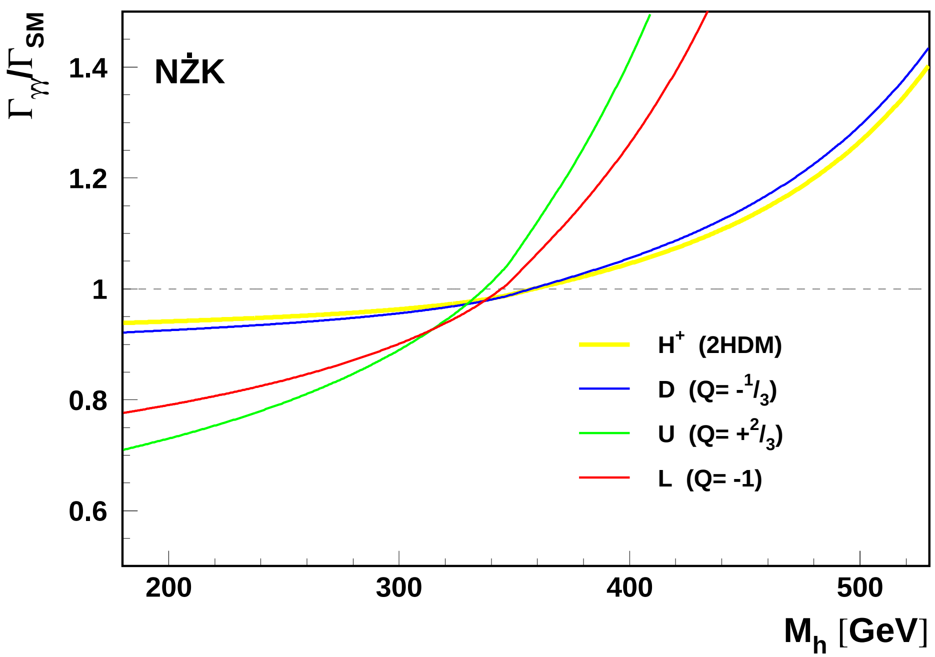
$\Rightarrow$ $\Gamma_{\gamma\gamma}$ little sensitive to new particles !

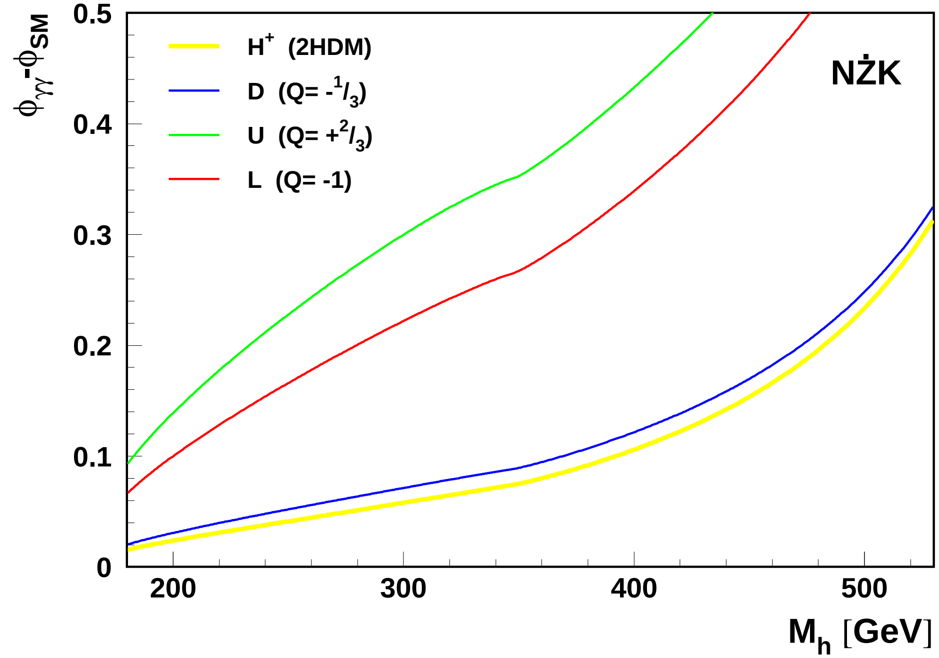
$\gamma\gamma \to h$

Expected deviations from SM

Contribution to $\Gamma_{\gamma\gamma}$ and $\phi_{\gamma\gamma}$ from new heavy charged particles with mass ~800 GeV
For SM with fourth-generation fermions and for SM-like 2HDM (II) type A
(additional contribution due to charged Higgs boson)

width hep-ph/0207294 phase





$\Rightarrow$ little effect on $\Gamma_{\gamma\gamma}$ for $M_h \sim$ 350 GeV

$\Rightarrow$ significant change in $\phi_{\gamma\gamma}$

Can we measure it !?

HUPD-9705

AJC-HEP-30

Measuring the two-photon decay width of Intermediate-mass Higgs at a photon-photon collider

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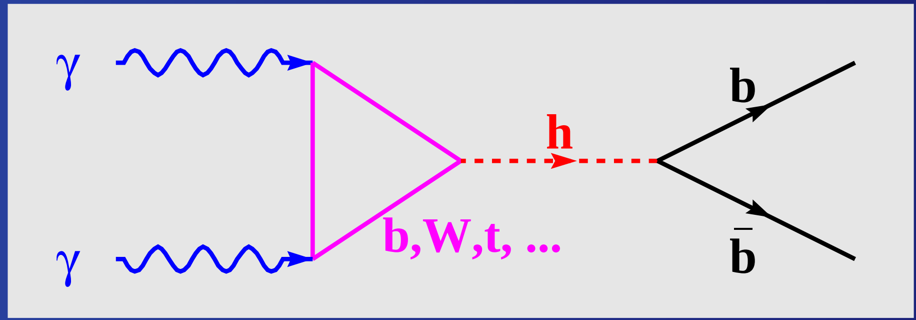
Abstract

Feasibility of a measurement of the partial decay width of the intermediate-mass Higgs boson into two photons at a photon-photon collider

$m_h \approx 120$ GeV

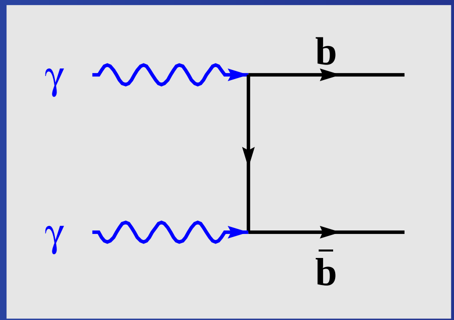
Process: $\gamma + \gamma \to h \to b + \bar{b}$

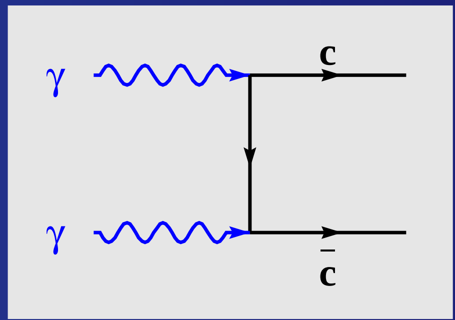
$$J_z = 0$$



"Hard" background:

- $\gamma + \gamma \to b + \bar{b}$
- $\gamma + \gamma \to c + \bar{c}$





$$\sigma \propto Q_q^4$$

$$\sigma^{LO}(|J_z| = 2) \gg \sigma^{LO}(J_z = 0)$$

Other background:

- Resolved photon(s) interactions $\gamma + \gamma \to X + Q + \bar{Q}$
- Overlaying events
  (high intensity of photon-beams in the low-energy part of the spectrum)

$\gamma\gamma \to$ ***higgs*** $\to b\bar{b}$

Analysis of precision $\sigma(\gamma\gamma \to$ *higgs* $\to b\bar{b})$ measurement includes:

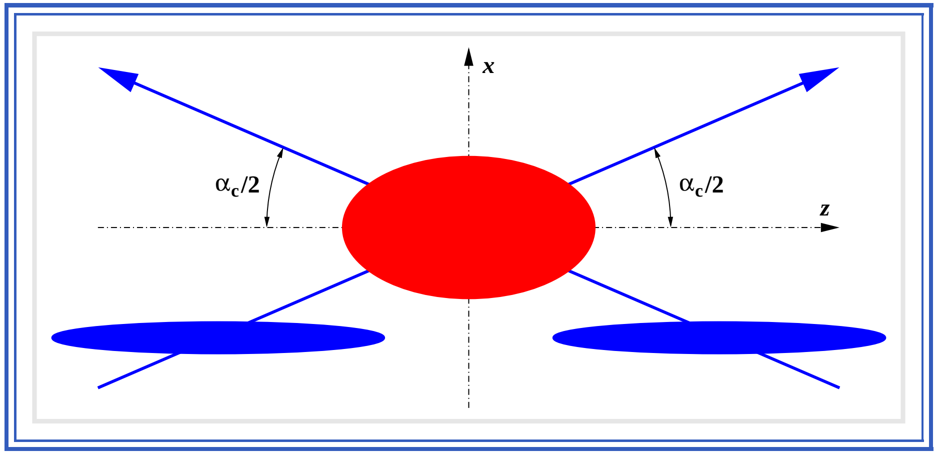
- realistic $\gamma\gamma$-spectra
- Background: NLO $Q\bar{Q}(g)$ (G. Jikia)
- overlaying events $\gamma\gamma \to$ *hadrons* (OE)
- Detector performance: SIMDET 4.01
- b-tagging (ZVTOP-B-Hadron-Tagger)
- Signal: HDECAY, PYTHIA (PS)

Special treatement:

- crossing angle
- primary vertex distribution
- $\gamma\gamma \to W^+W^-$ background

Crab-crossing of beams

$\alpha_c = 34$ mrad



	Bunch	Primary vertex
σ_x	140 nm	3.6 μm
σ_y	15 nm	11 nm
σ_z	0.3 mm	0.2 mm

$\gamma + \gamma \longrightarrow F + \bar{F}$

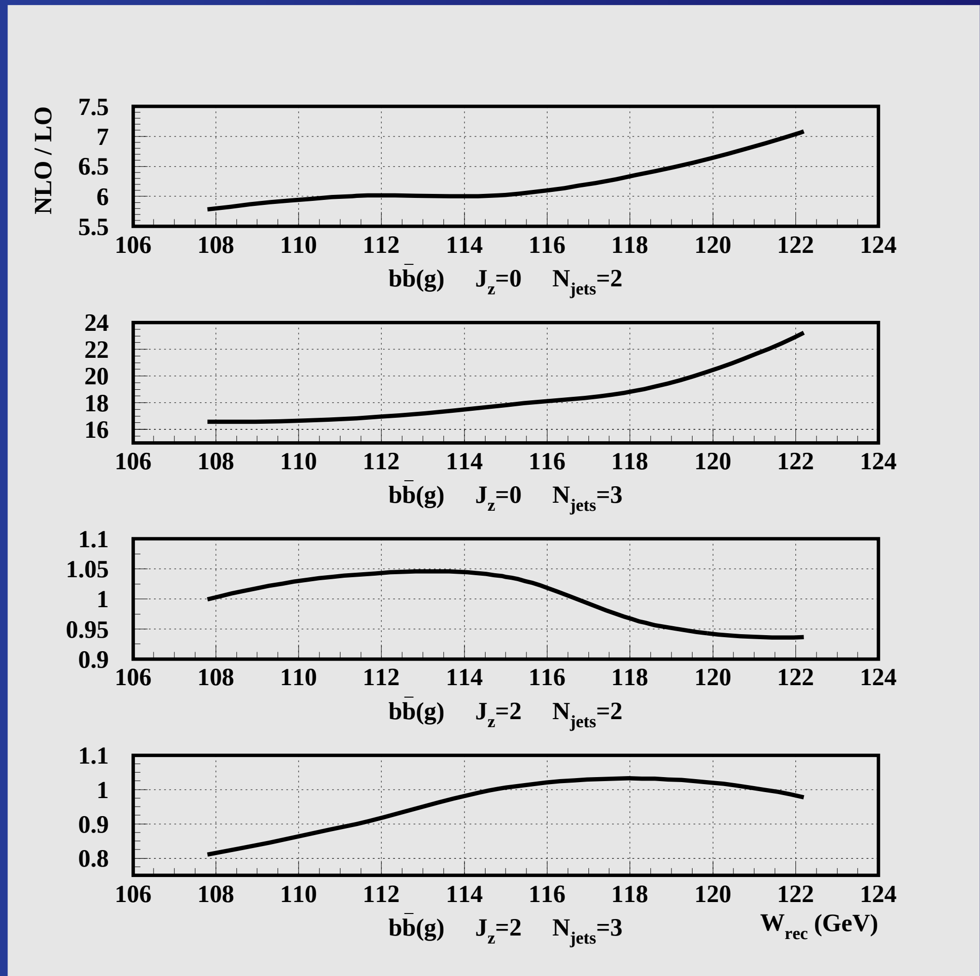
- NLO cross section for massless fermions

$$\Longrightarrow \sigma \propto \frac{\alpha^2 \alpha_s}{s}$$

$$\frac{d\sigma}{dE_g}(J_z = 2) \propto \frac{1}{E_g}$$

$$\sigma(J_z = 0) \propto E_g^3$$

- NLO cross section for massive fermions

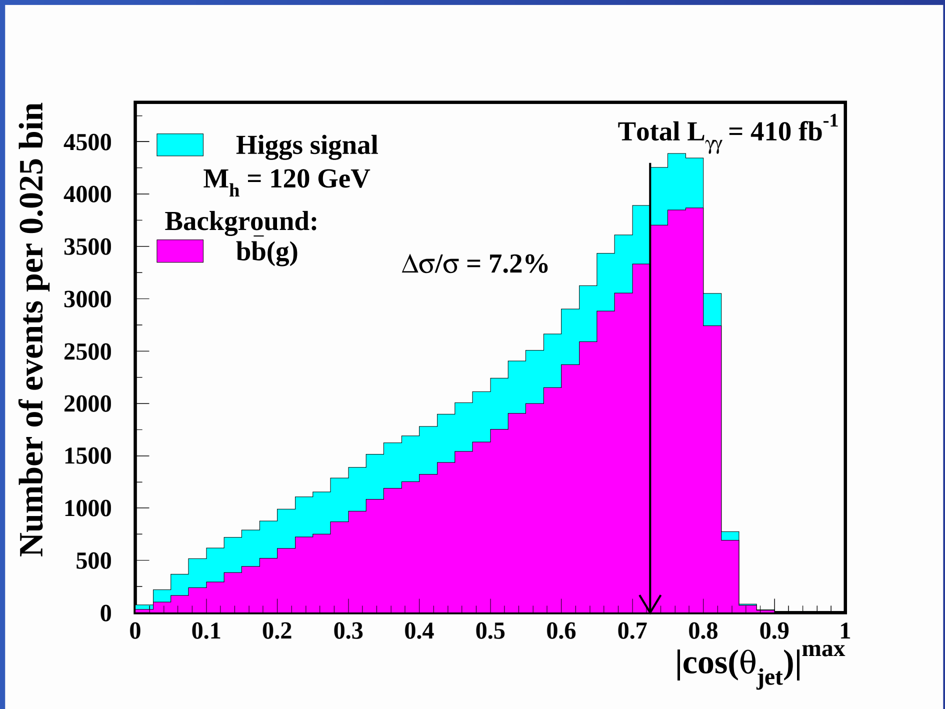


Cuts

Cuts optimized by minimizing:

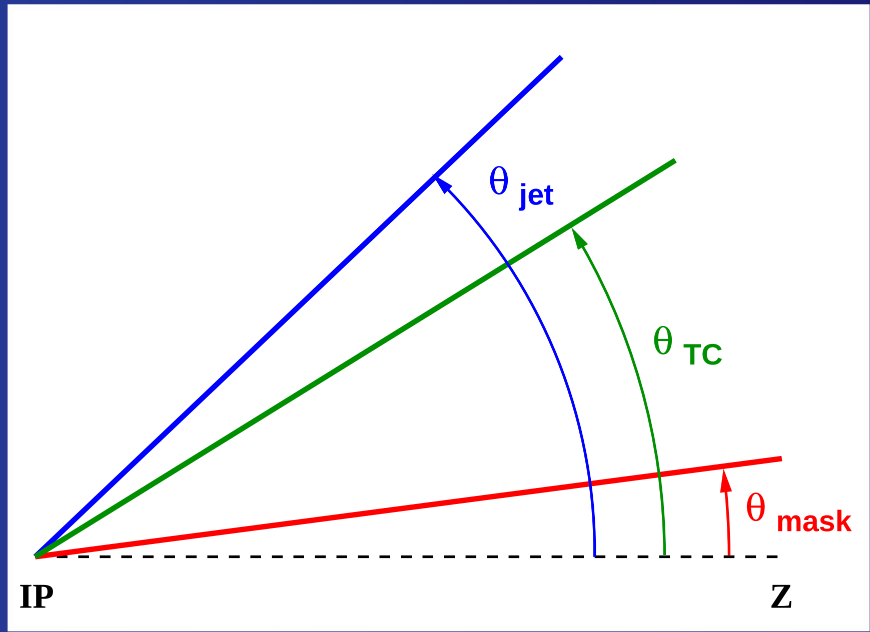
$$\frac{\Delta\sigma(\gamma\gamma \to h \to b\bar{b})}{\sigma(\gamma\gamma \to h \to b\bar{b})} = \frac{\sqrt{\mu_S + \mu_B}}{\mu_S},$$

For example:



Maximal value of $|\cos\theta_{jet}|$
over all jets in the event

All angular cuts



Detector mask
Particles on Pythia level: $\cos\theta_{mask} \approx 0.99$

OE suppression
Tracks & clusters: $\cos\theta_{TC} = 0.85$

$\gamma\gamma \to Q\bar{Q}(g)$ suppression
Jets: $|\cos\theta_{jet}|^{\max} = 0.725$

higgs-tagging at $M_h = 120$ GeV

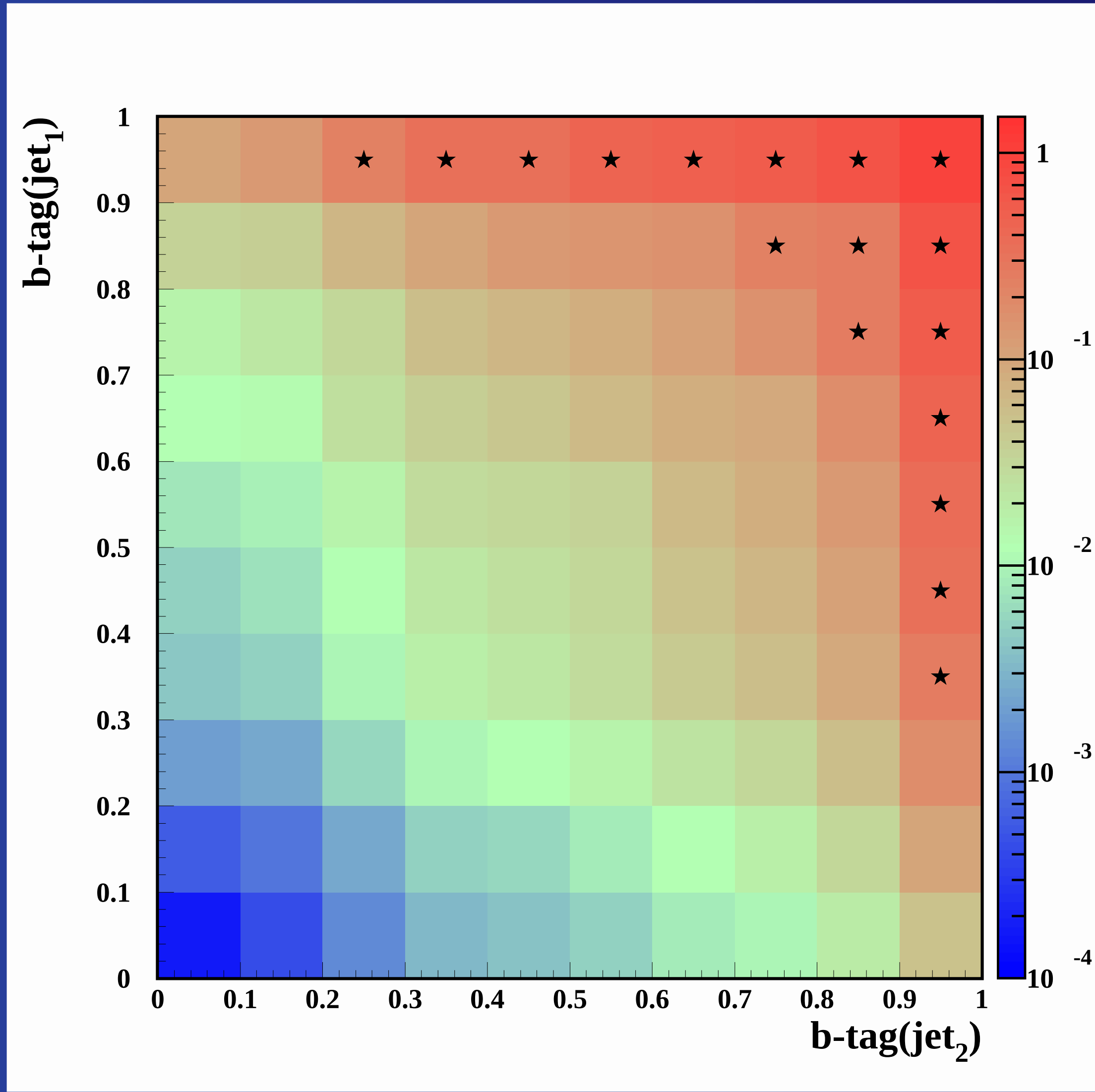
higgs-tagging: a cut on the ratio
of $\gamma\gamma \to h \to b\bar{b}$
to $\gamma\gamma \to b\bar{b}(g), c\bar{c}(g), q\bar{q}$ $(q = u, d, s)$
events

$\Rightarrow \varepsilon_h = 58\%$
$\varepsilon_{bb} = 50\%$
$\varepsilon_{cc} = 2.2\%$
$\varepsilon_{uds} = 0.16\%$

Without OE

$\Rightarrow \varepsilon_h = 71\%$
$\varepsilon_{bb} = 64\%$
$\varepsilon_{cc} = 2.9\%$
$\varepsilon_{uds} = 0.11\%$

Tighter cuts are needed
due to OE contribution



Reconstruction & Selection

Selection of $b\bar{b}$ events for $M_h = 120$ GeV:

- OE suppression: clusters & tracks with $|\cos\theta_i| > \cos\theta_{TC} = 0.85$ ignored
- $W_{rec} > 1.2\, W_{\gamma\gamma}^{\min}$

Jets: Durham algorithm, $y_{cut} = 0.02$

- $N_{jets} =$ 2, 3
- for each jet: $|\cos\theta_{jet}| < 0.725$
- $|P_z|/E < 0.1$

Rejection of W^+W^- events (for $M_h =$ 150, 160 GeV):

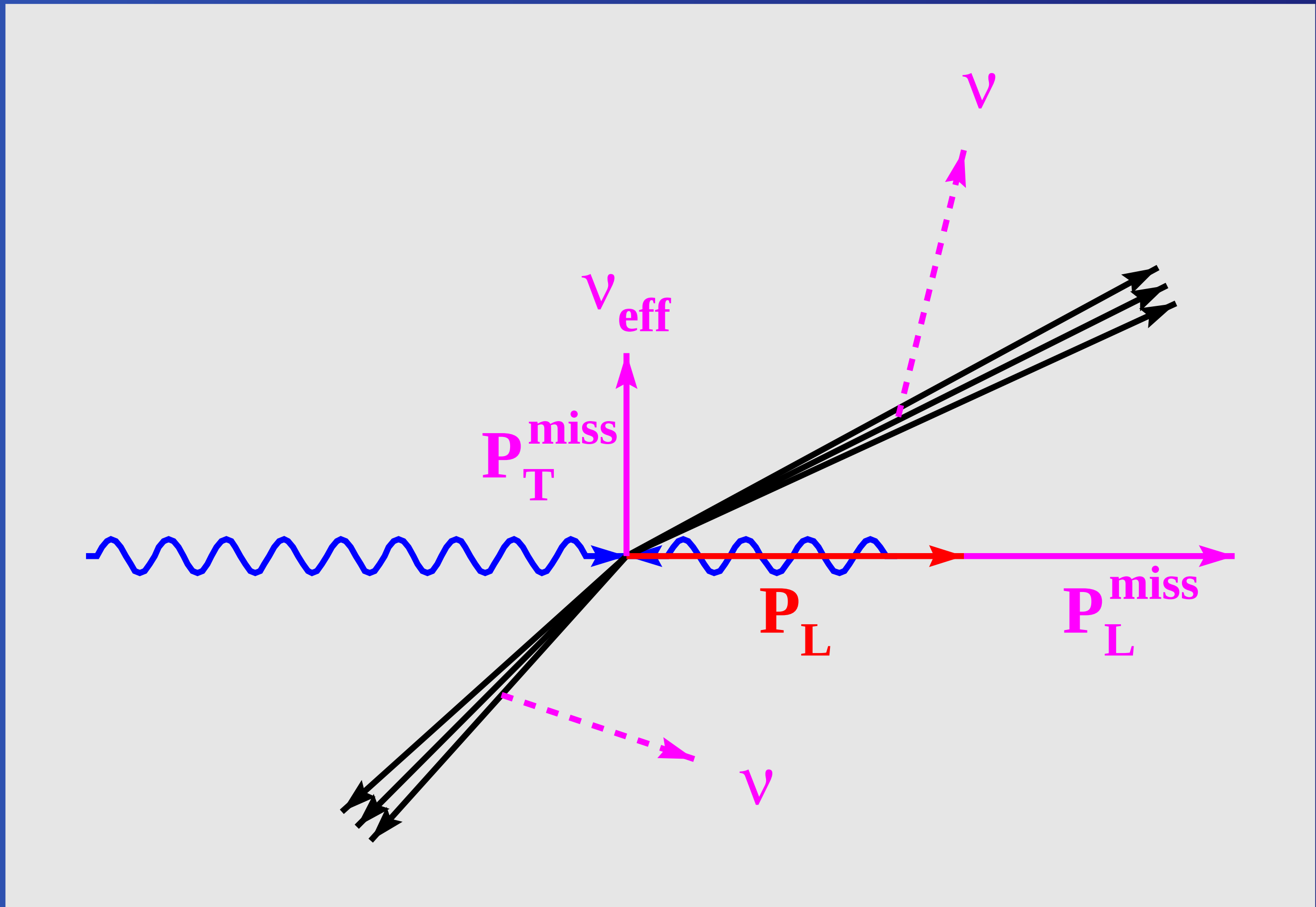
- for each jet: $M_{jet} < 70$ GeV
- energy below θ_{TC}: $E_{TC} < 90$ GeV
- for each jet: $N_{trk} \geq 4$

b-tagging: ZVTOP-B-HADRON-TAGGER (T. Kuhl)

Correction for crossing angle: jets boosted with $\beta = -\sin(\alpha_c/2)$

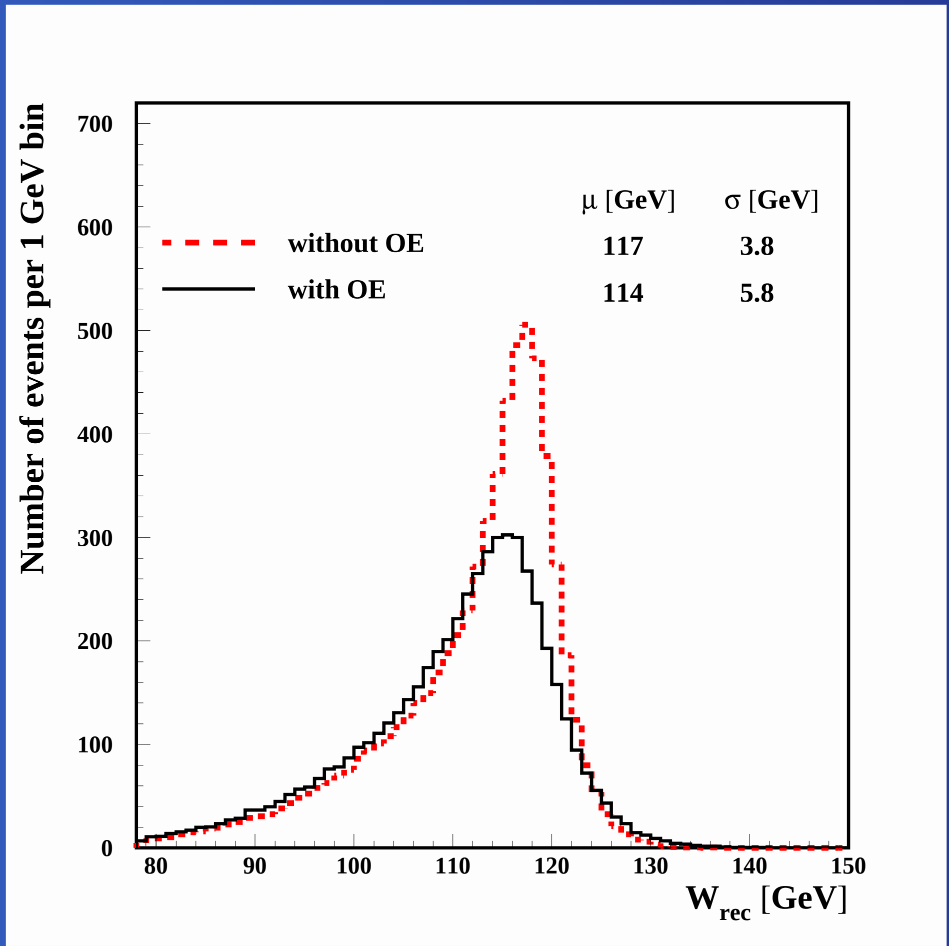
Missing P_T

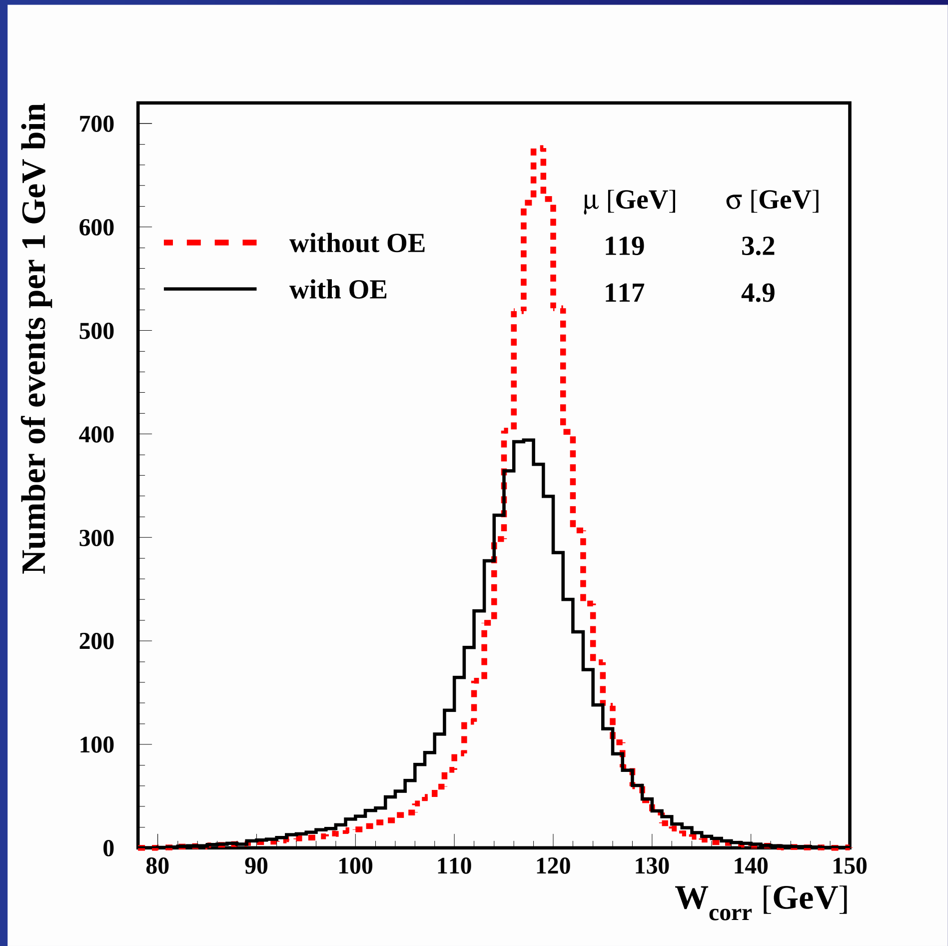
Neutrinos from semileptonic decays of D- and B-mesons.



$$W_{corr} \equiv \sqrt{W_{rec}^2 + 2P_T(E_{vis} + P_T)}$$

SM, $M_h = 120$ GeV





Without OE: 6450 events
With OE : 5530 events

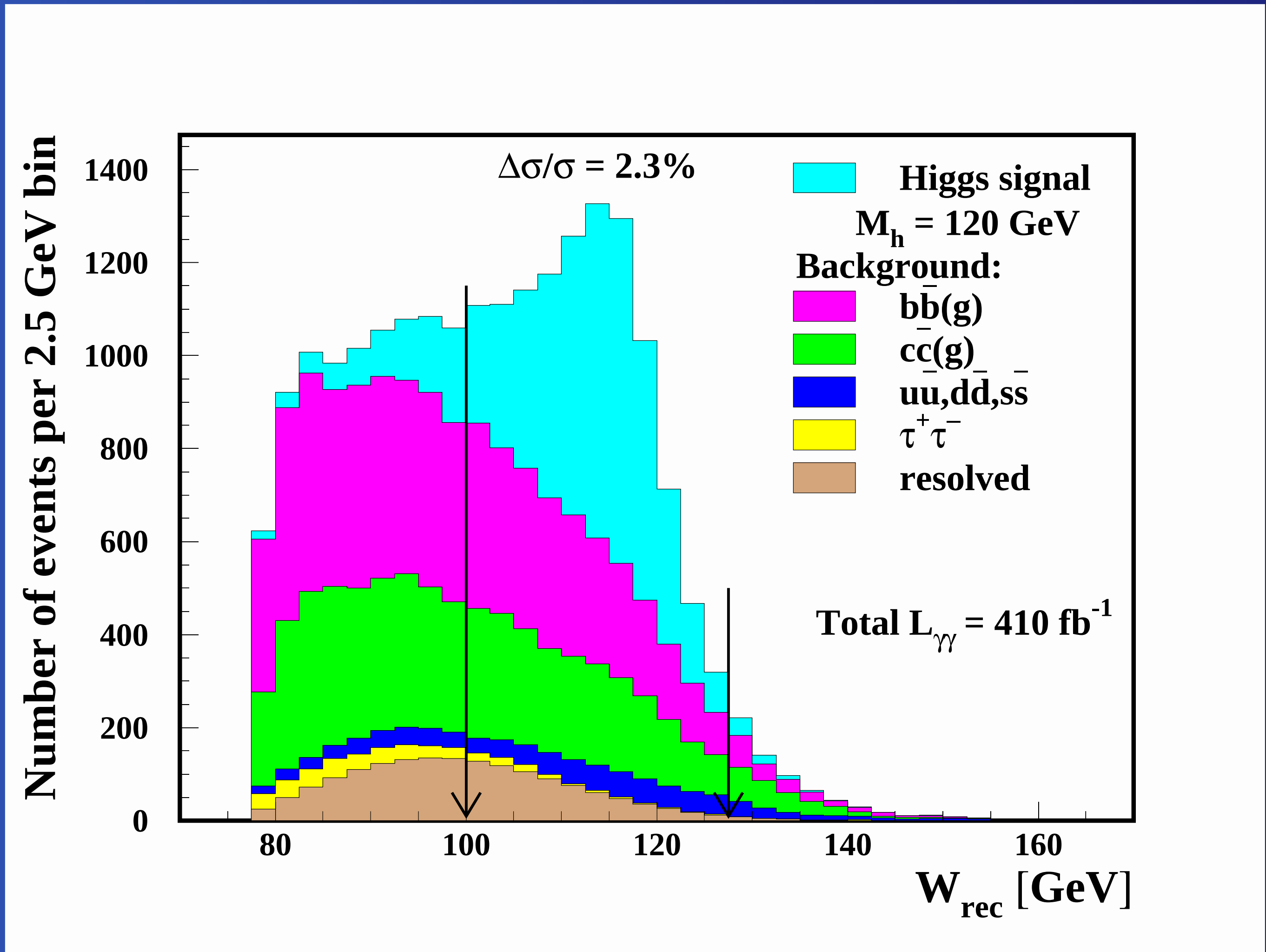
$W_{\rm corr} \equiv \sqrt{W_{rec}^2 + 2P_T(E + P_T)}$

Acta Phys. Pol. B34 177 2003, hep-ph/0208234

Gaussian fit from $\mu - 1.3\sigma$ to $\mu + 1.3\sigma$.

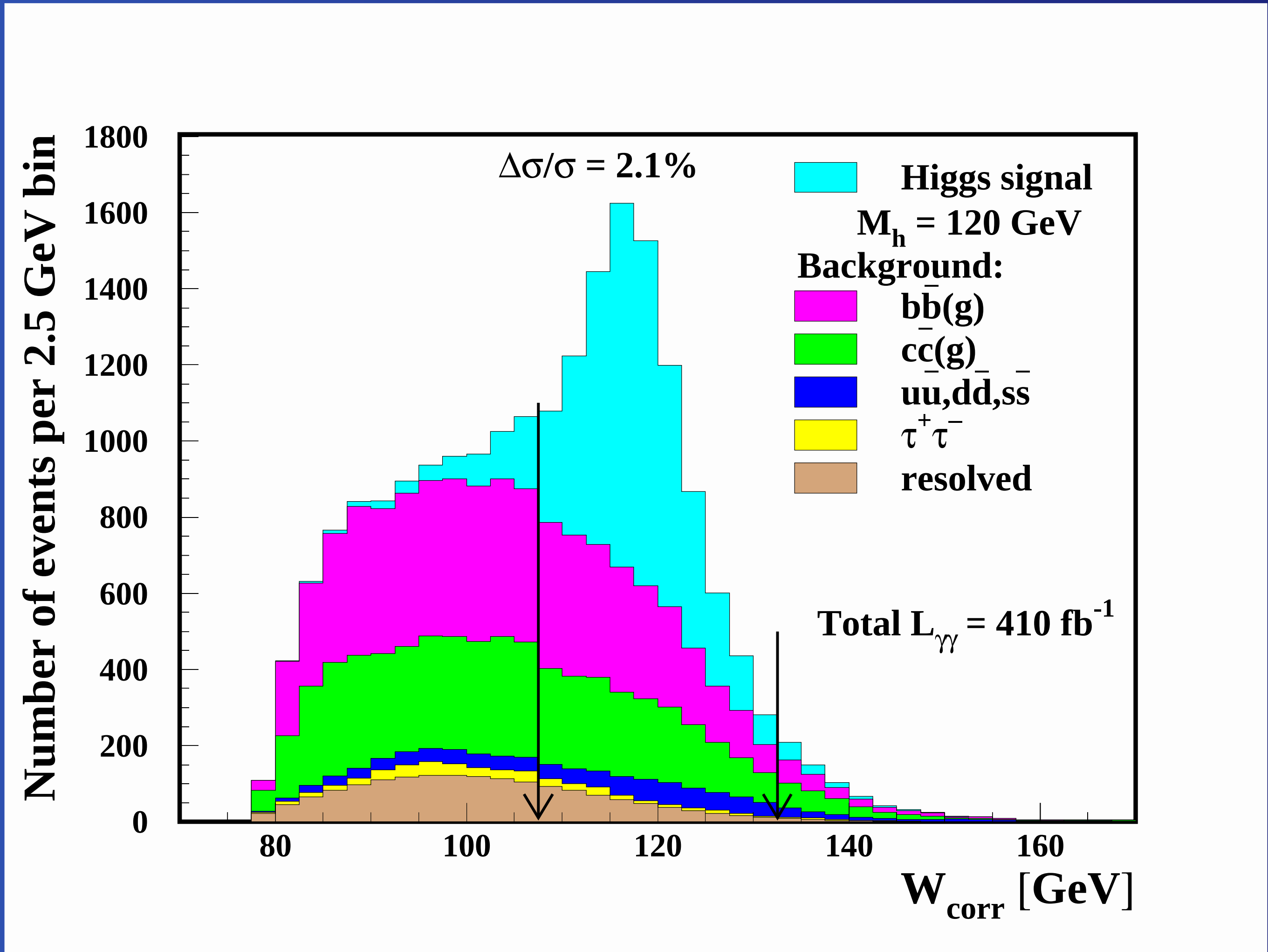
SM, $M_h = 120$ GeV

Final results

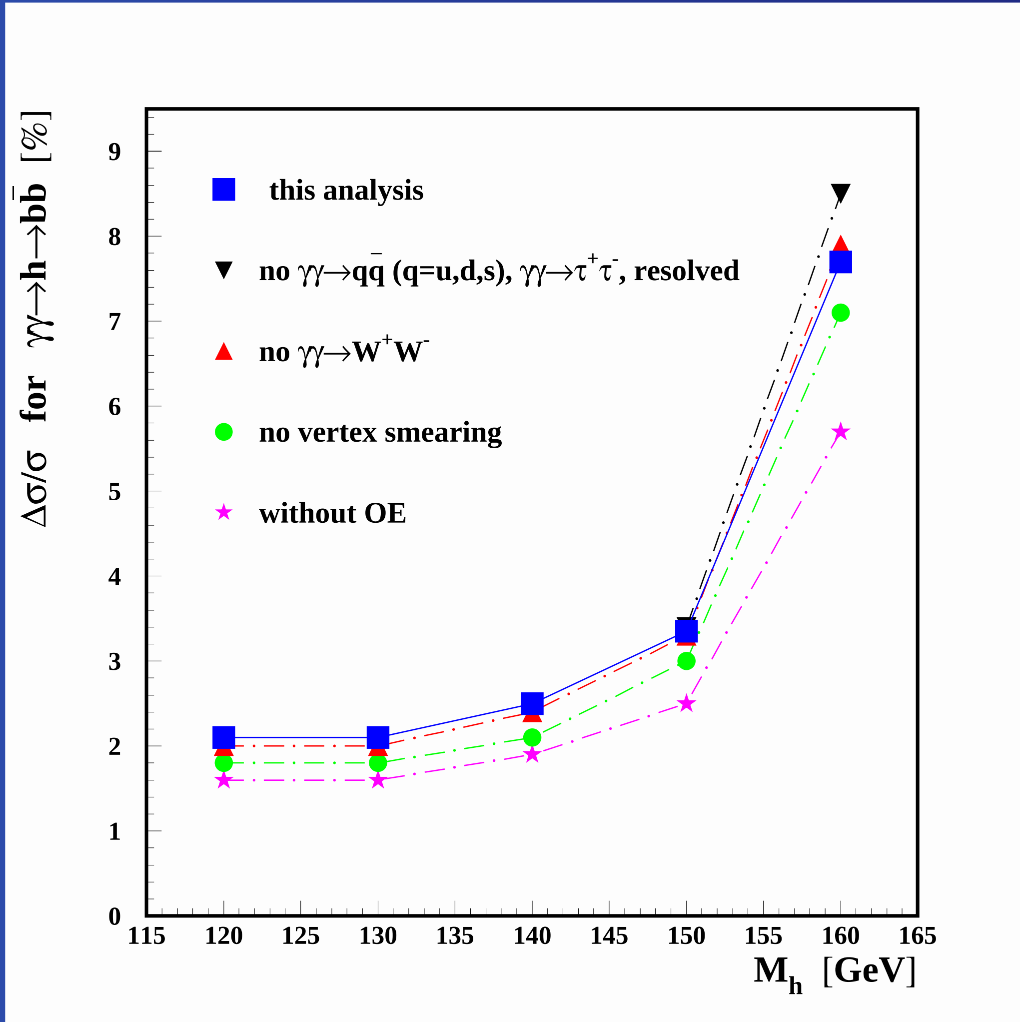


SM, $M_h = 120$ GeV

Final results



SM summary

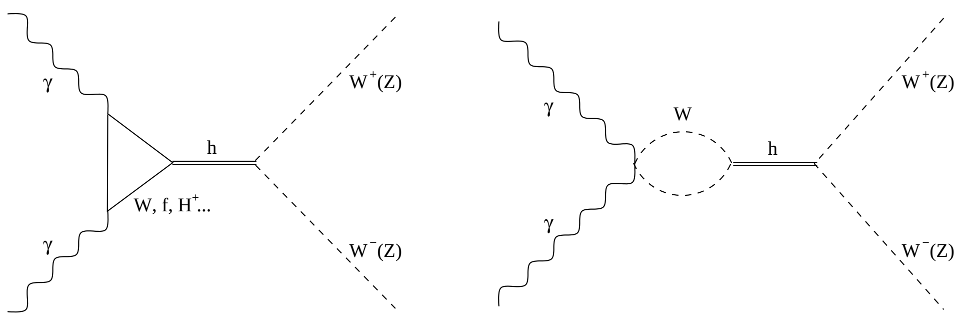


For $M_h = 150$, 160 GeV additional cuts to reduce $\gamma\gamma \to W^+W^-$.

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

Higgs signal

For $M_h > 2\ M_W$ (phase $\phi_{\gamma\gamma} \neq 0$) decays to W^+W^- dominate:



"resonant"

There is a large background from "direct", non-resonant production $\gamma\gamma \to W^+W^-$

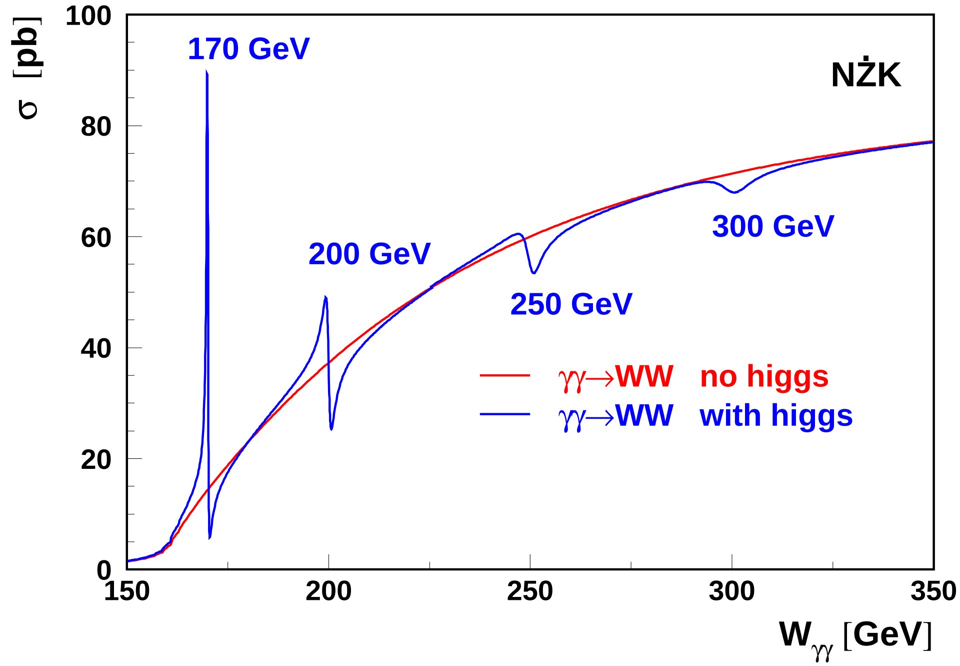
G.Belanger, F.Boudjema, Phys.Lett.B288 (1992) 210;
D.A.Morris, et al., Phys. Lett. B323 (1994) 421;
I.F.Ginzburg, I.P.Ivanov, Phys. Lett. B408 (1997) 325.

Interference

Resonant and direct amplitudes interfere

Large effects expected:

$J_z = 0$ hep-ph/0207294



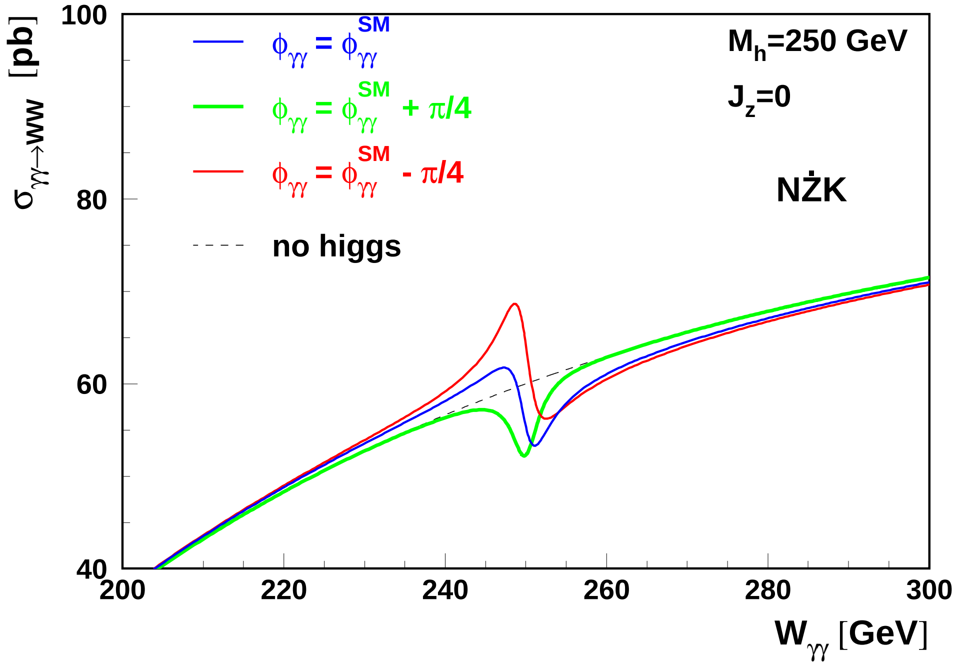
Destructive interference dominates above $\sim$ 200 GeV

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

Phase measurement

Interference term is sensitive to the phase $\phi_{\gamma\gamma}$ of the $\gamma\gamma \to h$ amplitude

$\sigma(\gamma\gamma \to W^+W^-)$ dependence on $\phi_{\gamma\gamma}$

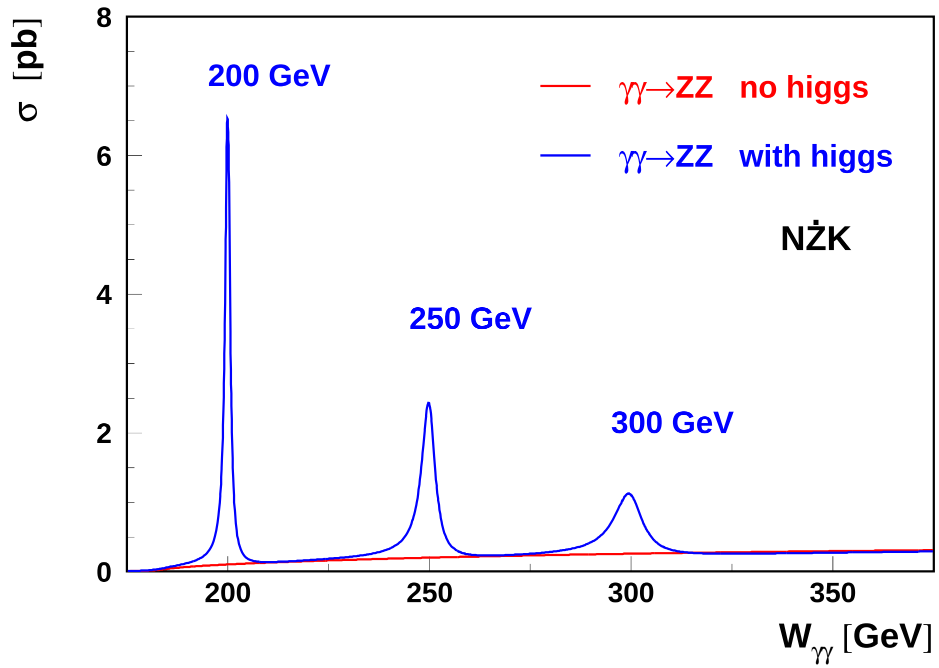


⇒ can be measured !

$\gamma\gamma \to ZZ$

Non-resonant background only at loop level

hep-ph/0207294



⇒ small interference effects

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

Analysis

Parametrization

“Measured” invariant mass distribution for selected W^+W^- and ZZ events is described by convolution of:

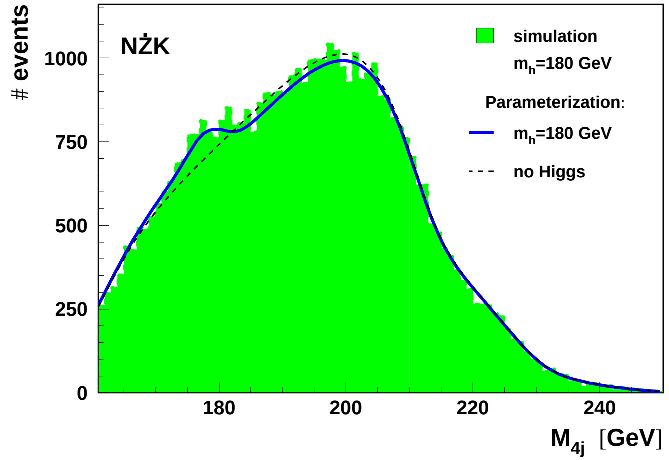
- Analytical luminosity Spectra **CompAZ**
- Cross section formula
  for signal + background + interf.
- Invariant mass resolution
  parametrized as a function of $W_{\gamma\gamma}$

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

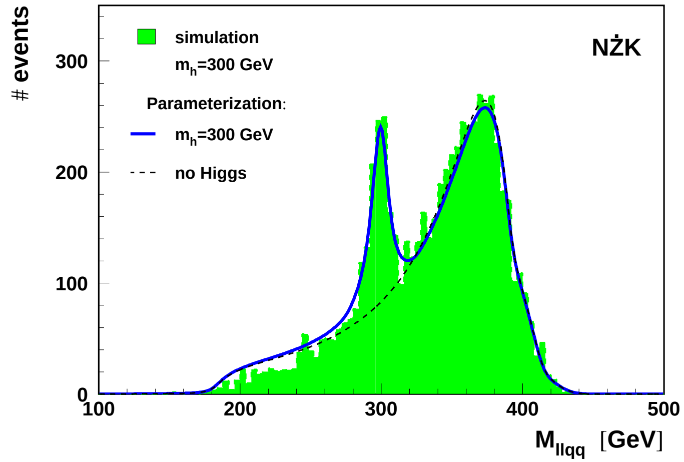
$\Rightarrow$ can be used for fast simulation and fitting

Comparison with full simulation:

W^+W^-



ZZ

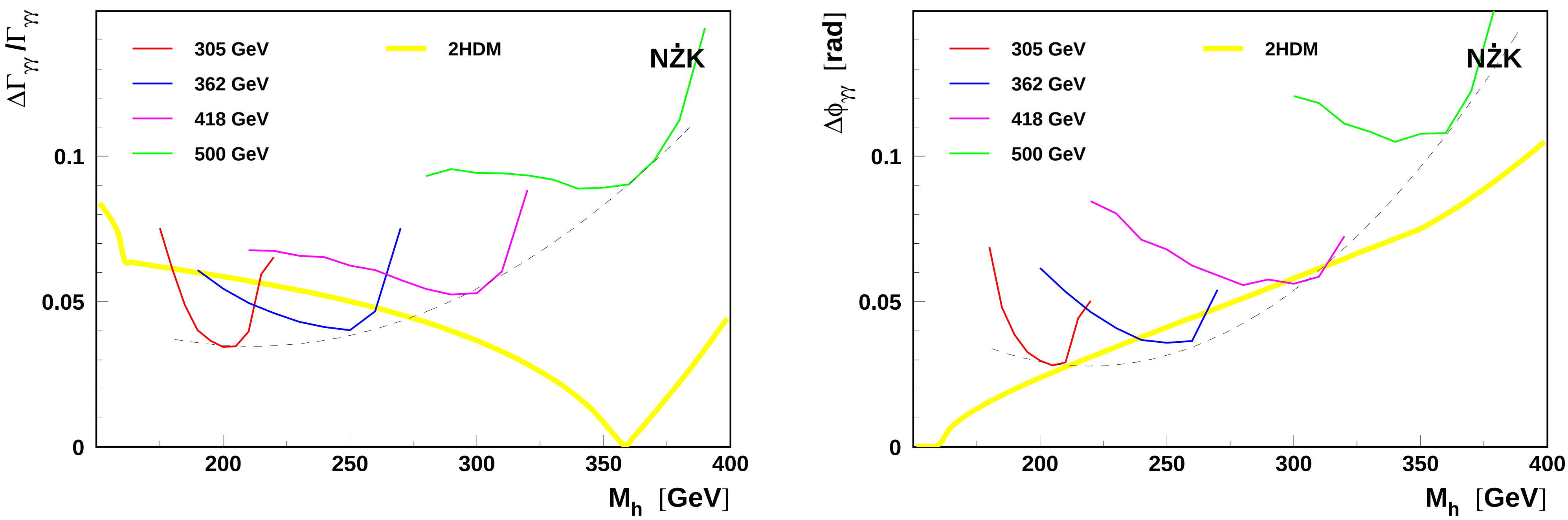


SM results

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 $\phi_{\gamma\gamma}$



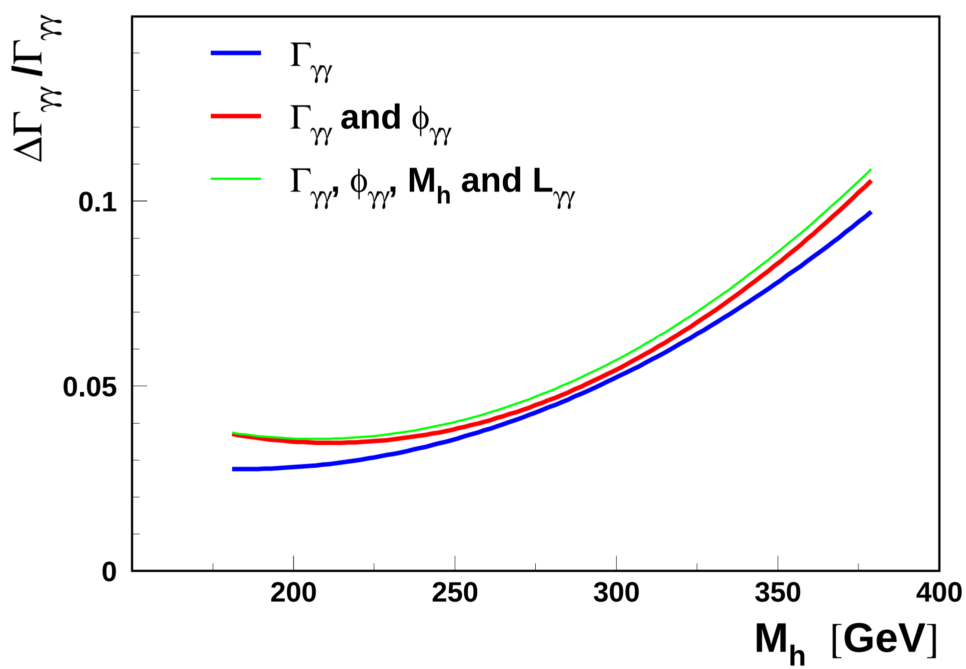
Phase measurement significantly improves our sensitivity to new heavy charged particles
e.g. heavy charged Higgs boson of the SM-like 2HDM(II) with $M_{H+} = 800$ GeV
at large Higgs boson masses

SM results

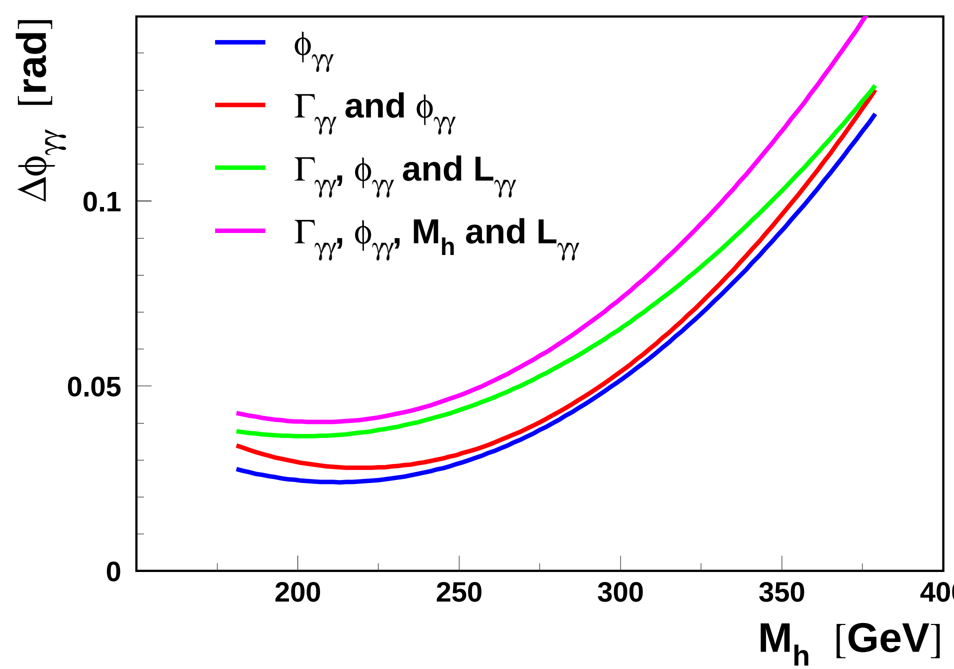
Systematic effects

Statistical precision for different choices of fit parameters:

$\Gamma_{\gamma\gamma}$



$\phi_{\gamma\gamma}$



Precize knowledge of M_h and luminosity not crucial
$\Rightarrow$ can be constrained by the data itself

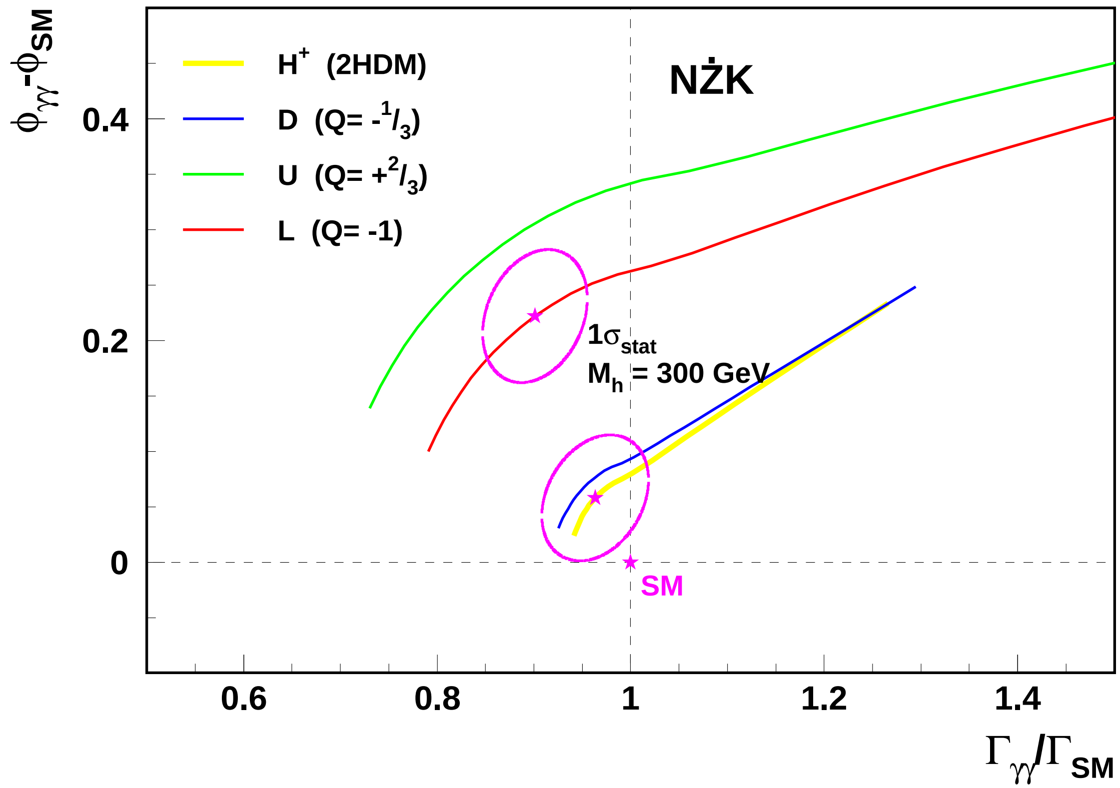
$\Rightarrow$ sensitive to M_h and luminosity uncertainty

SM results

Expected statistical error contours (1σ) in $\phi_{\gamma\gamma} - \Gamma_{\gamma\gamma}$, for $M_h = 300$ GeV:

4^{th} generation lepton
$M_L = 800$ GeV $\Rightarrow$

SM-like 2HDM (II) $\Rightarrow$
$M_{H+} = 800$ GeV

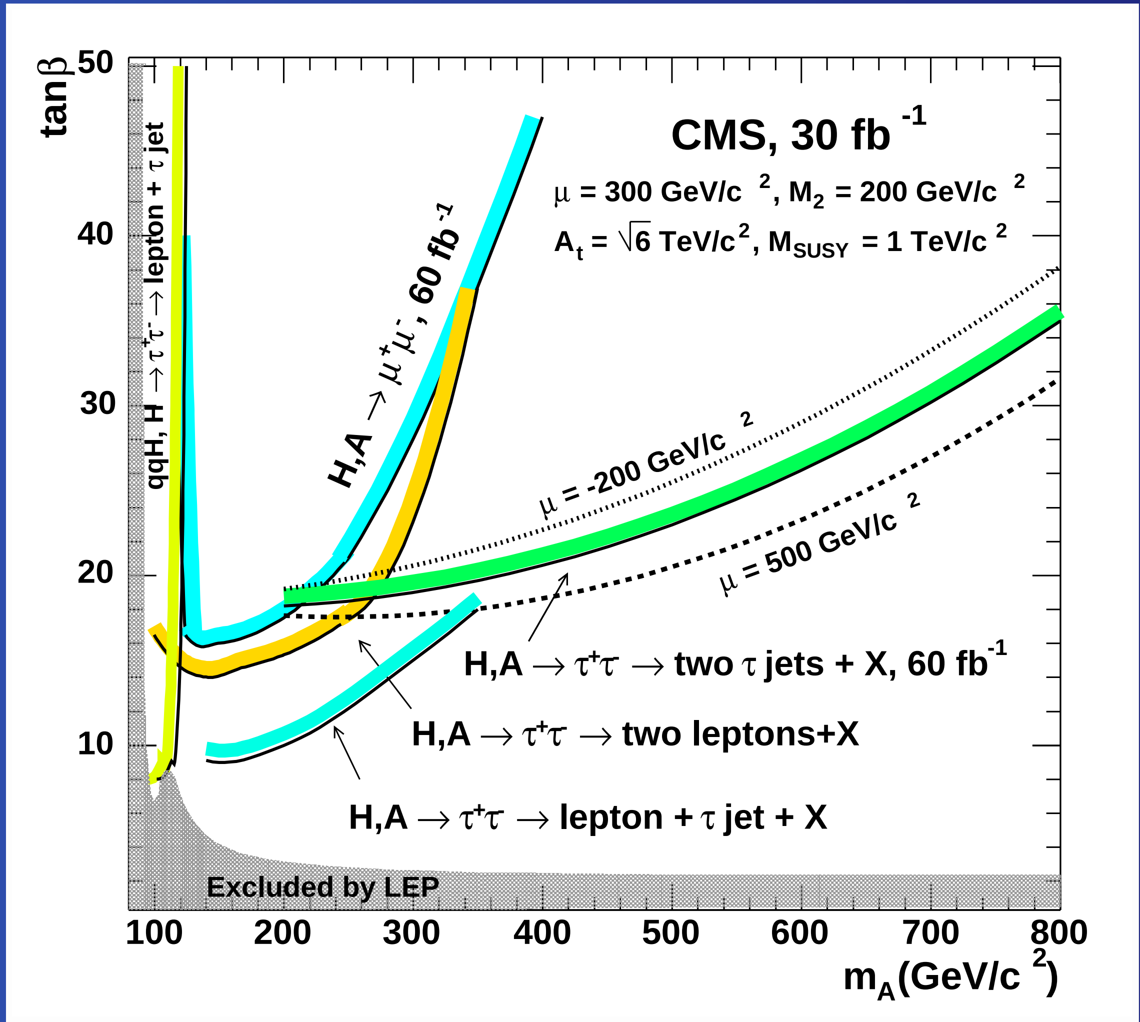


$\Rightarrow$ separation not possible without phase measurement !

Two parameter fit to W^+W^- and ZZ invariant mass distribution; one year of Photon Collider running.

MSSM Study: LHC wedge

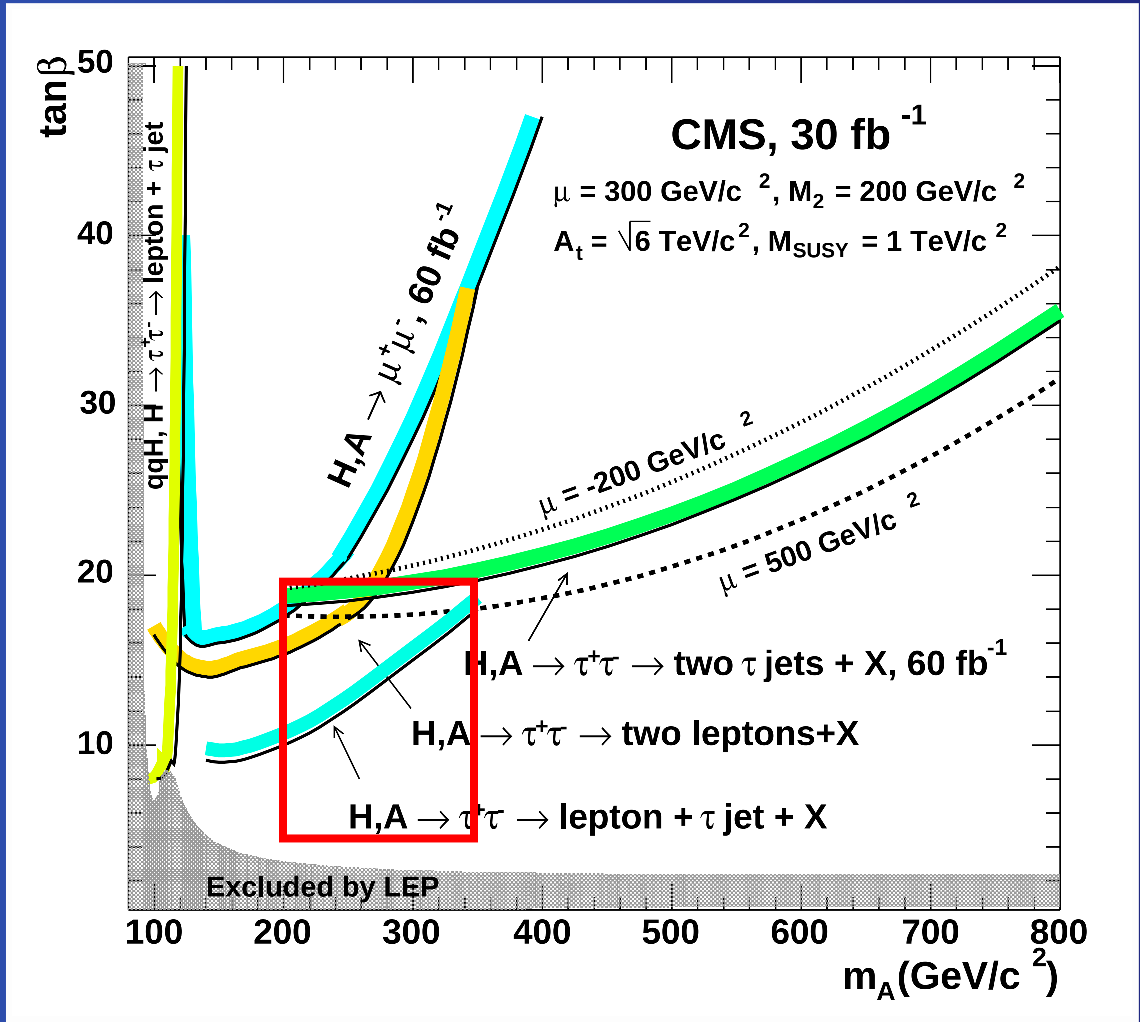
LHC wedge: only one light SM-like higgs boson h can be seen



Photon Collider offers unique possibility for precise H/A studies

Choice of MSSM parameters

LHC wedge



From: CMS NOTE 2003/033
(the same results as in newer CMS CR 2004/058)

Choice of MSSM parameters

We consider following MSSM parameter sets:

Symbol	μ [GeV]	M_2 [GeV]	$A_{\tilde{f}}$ [GeV]	$M_{\tilde{f}}$ [GeV]
I	200	200	1500	1000
II	-150	200	1500	1000
III	-200	200	1500	1000
IV	300	200	2450	1000

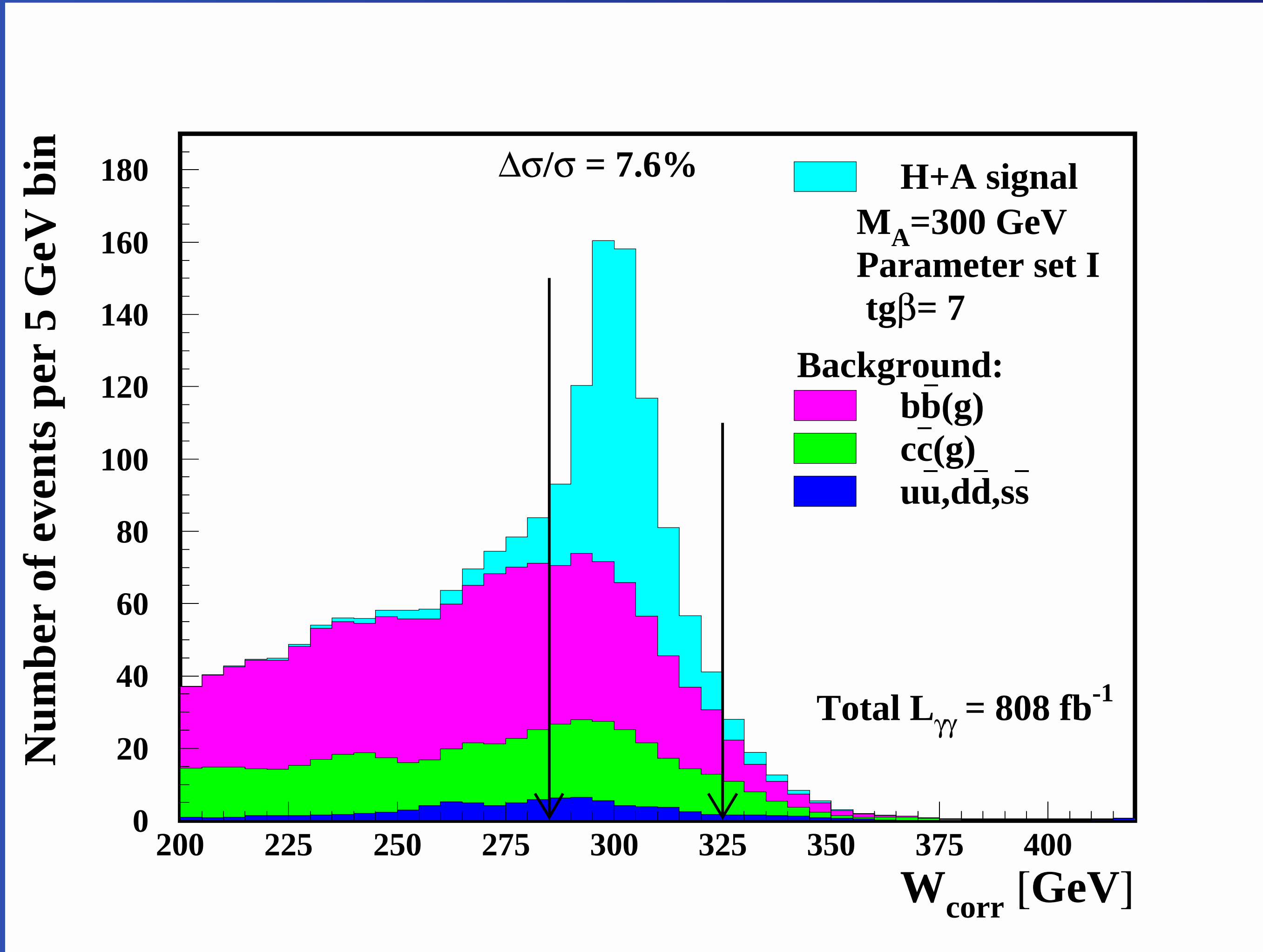
I and III – as in M. Mühlleitner *et al.* but we take higher $A_{\tilde{f}}$ to have M_h above limit

II – an intermediate scenario

IV – as in CMS NOTE 2003/033

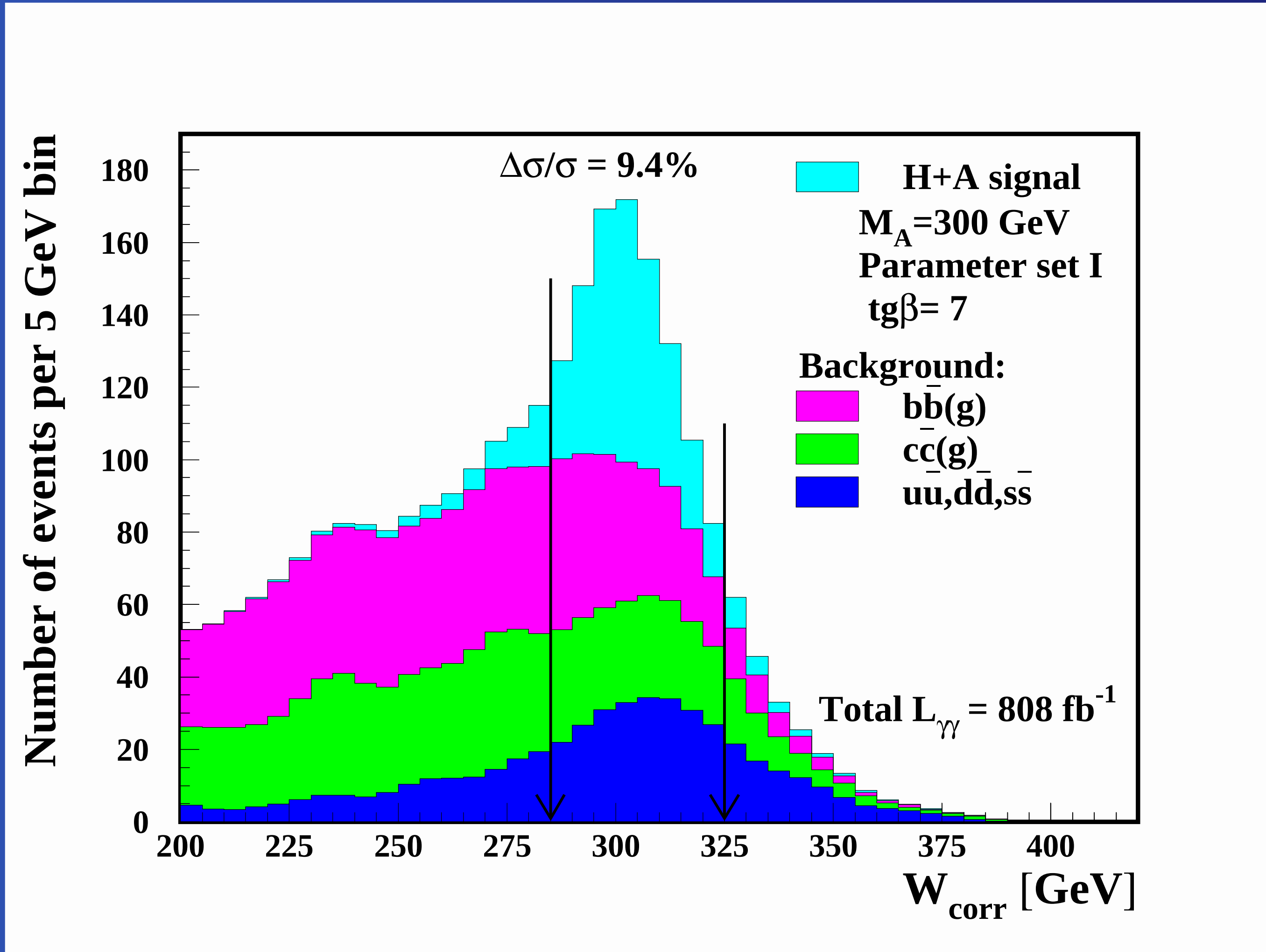
$M_A = 300$ GeV

Without OE, without $\gamma\gamma \to W^+W^-$



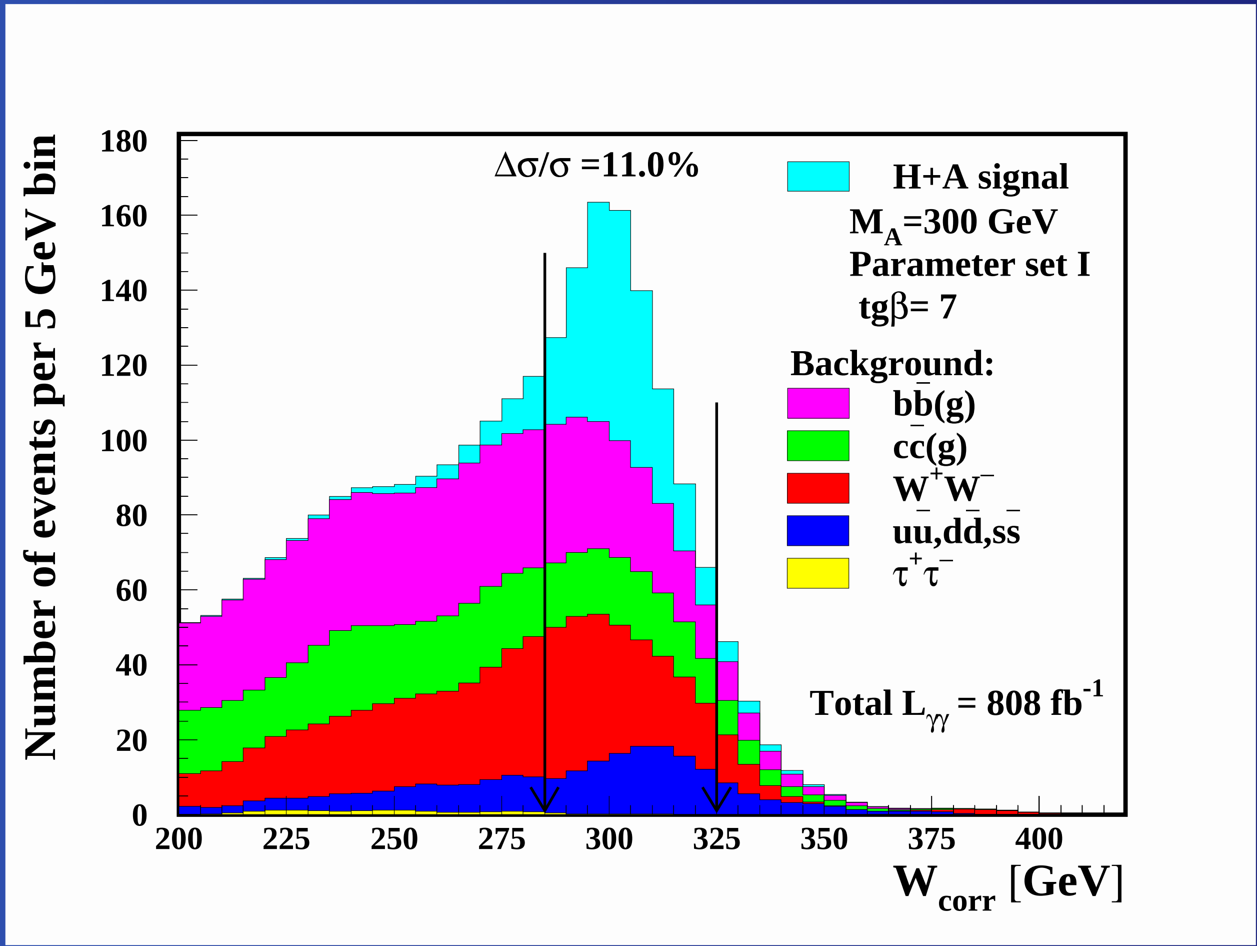
$M_A = 300$ GeV

With OE, without $\gamma\gamma \to W^+W^-$



$M_A = 300$ GeV

Final results

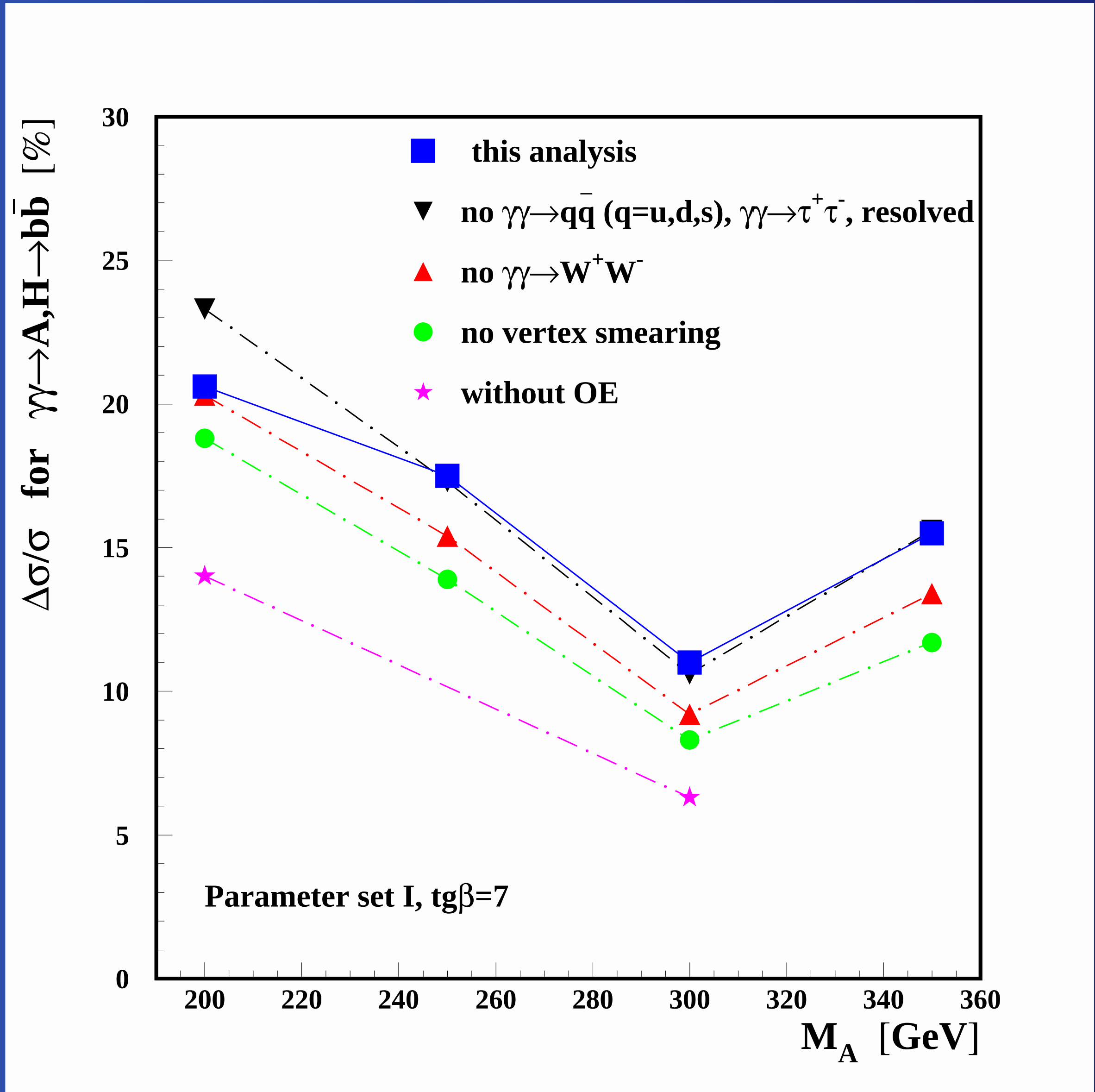


$\gamma\gamma \rightarrow hadrons$ (resolved) as a separate contribution – ineffi cient generation

$\Rightarrow$ we estimate number of events in the mass window

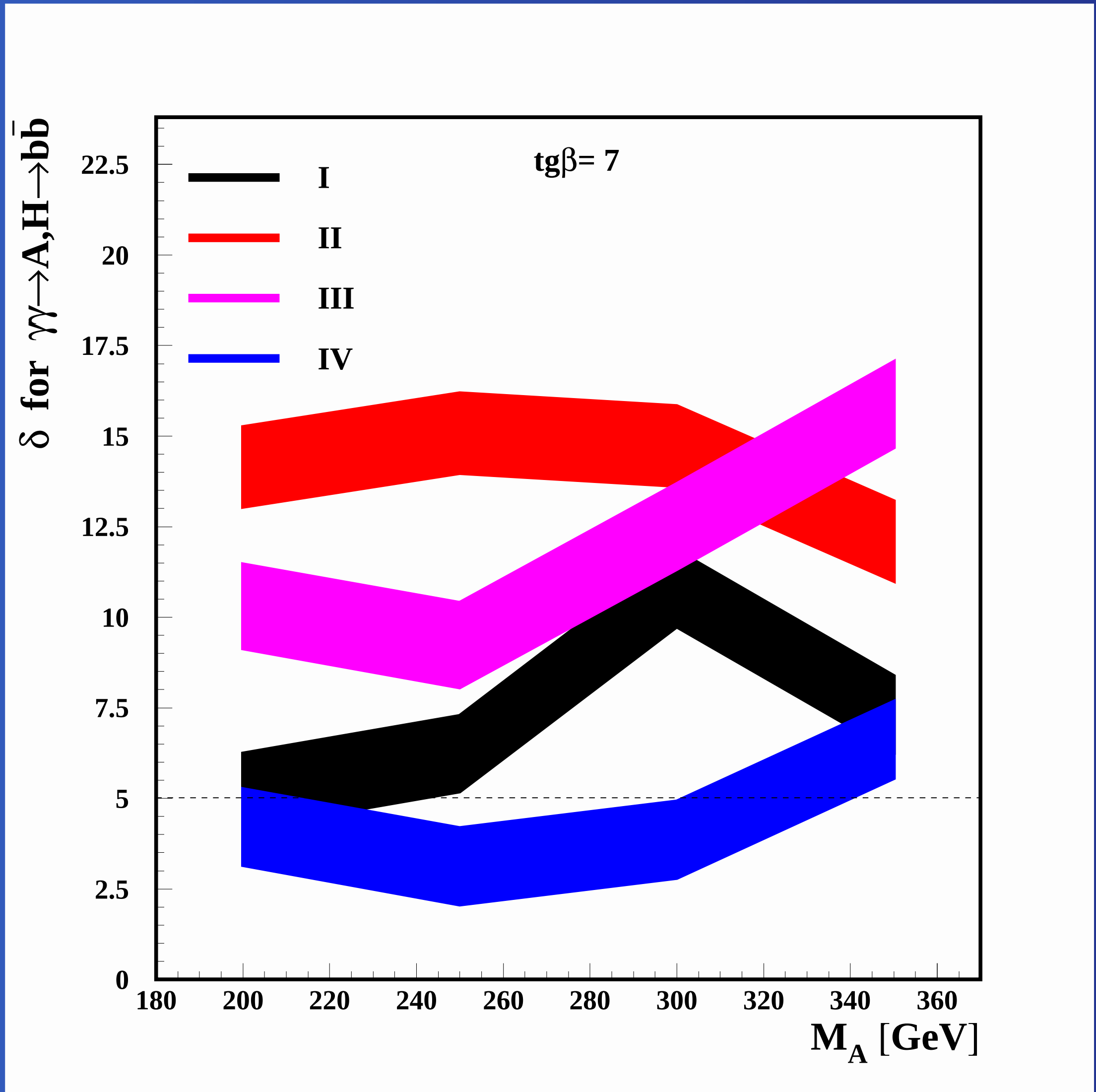
$\gamma\gamma \rightarrow q\bar{q}$ $(q\!=\!u,d,s)$ (unpolarized cross sec.) is overestimated
but compensates the lack of *resolved* contribution

MSSM summary



Photon Collider reach

Significance for $\gamma\gamma \to A, H \to b\bar{b}$



Symbol	μ [GeV]	$A_{\tilde{f}}$ [GeV]
I	200	1500
II	-150	1500
III	-200	1500
IV	300	2450

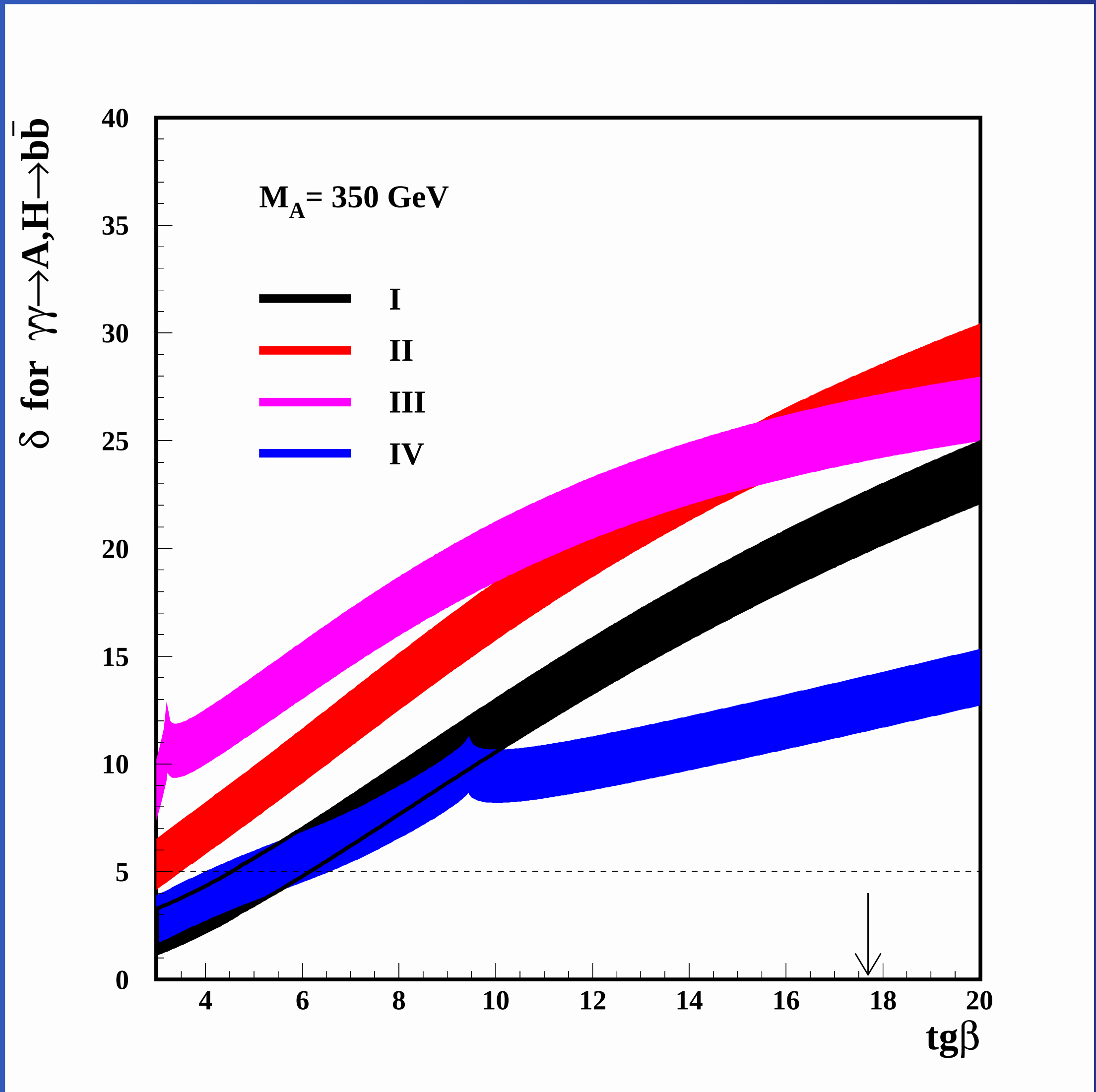
Significance

$$\delta = \frac{\mu_S}{\sqrt{\mu_B}} \pm \sqrt{1 + \frac{\mu_S}{\mu_B}}$$

The band widths indicate the level of possible statistical fluctuations

Photon Collider reach

Significance for $\gamma\gamma \to A, H \to b\bar{b}$



Symbol	μ [GeV]	$A_{\tilde{f}}$ [GeV]
I	200	1500
II	-150	1500
III	-200	1500
IV	300	2450

Significance

$$\delta = \frac{\mu_S}{\sqrt{\mu_B}} \pm \sqrt{1 + \frac{\mu_S}{\mu_B}}$$

The band widths indicate the level of possible statistical fluctuations

Arrow – lower limit of the LHC discovery region.

MKSZ: Results

Cross sections of $\gamma\gamma \to A, H \to b\bar{b}$ and $\gamma\gamma \to b\bar{b}$ processes

M. Mühlleitner, M. Krämer, M. Spira,
P. Zerwas, Phys. Lett. B 508 (2001) 311.

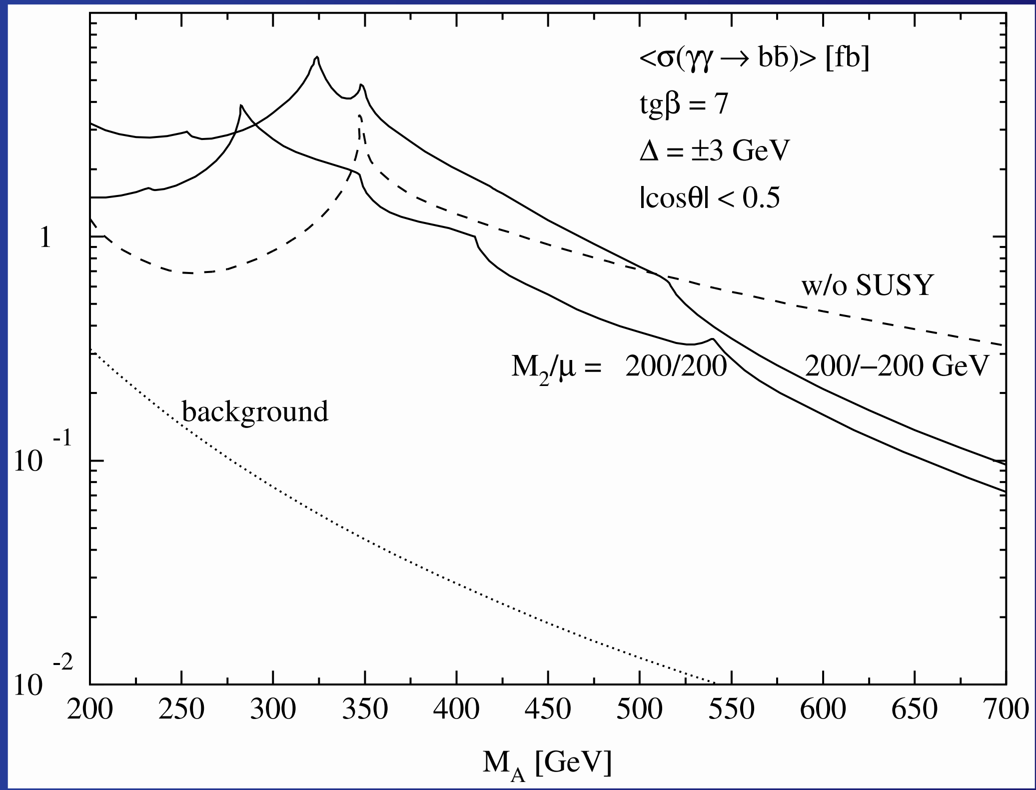
Considered MSSM parameter sets

μ [GeV]	M_2 [GeV]	$A_{\tilde{f}}$ [GeV]
200	200	0
-200	200	0

Also the limit of vanishing SUSY-particle contributions considered.

Results for $M_A =$ 200-700 GeV
and for $\tan\beta = 7$

Results for $M_A =$ 200-700 GeV



Average cross sections in the invariant mass window ± 3 GeV.
$M_A =$ 300 GeV, $\mu =$ 200 GeV $\Rightarrow S/B \approx 36$

Summary of comparison

JADE | *Sterman–Weinberg*

MKSZ: σ_i —*Compton*→ 2j+3j: S/B=12
2j: S/B=19 → 2j: S/B=36

agreement at 5–30%

NŻK: σ_i —*CompAZ*→ 2j+3j: S/B=6
2j: S/B=7

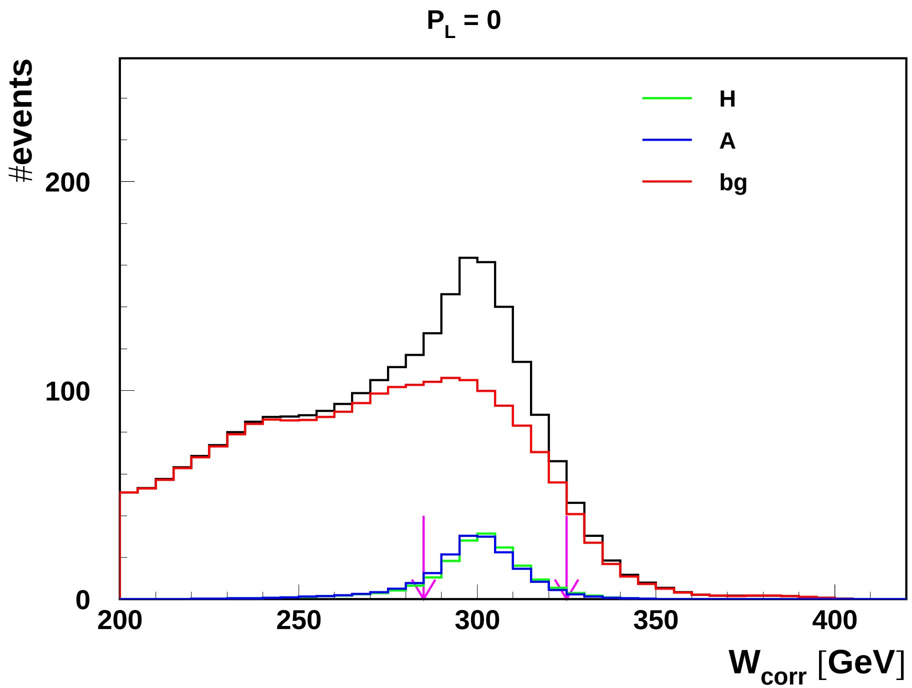
More detailed description: hep-ph/0612369

Higgs CP properties

MSSM results

Results for $M_A = 300$ GeV

Circular laser polarization, $P_C = 100\%$



We can not distinguish between H and A

$\Rightarrow$ measurement of

$$\sigma_{tot} \;=\; \sigma_H + \sigma_A$$

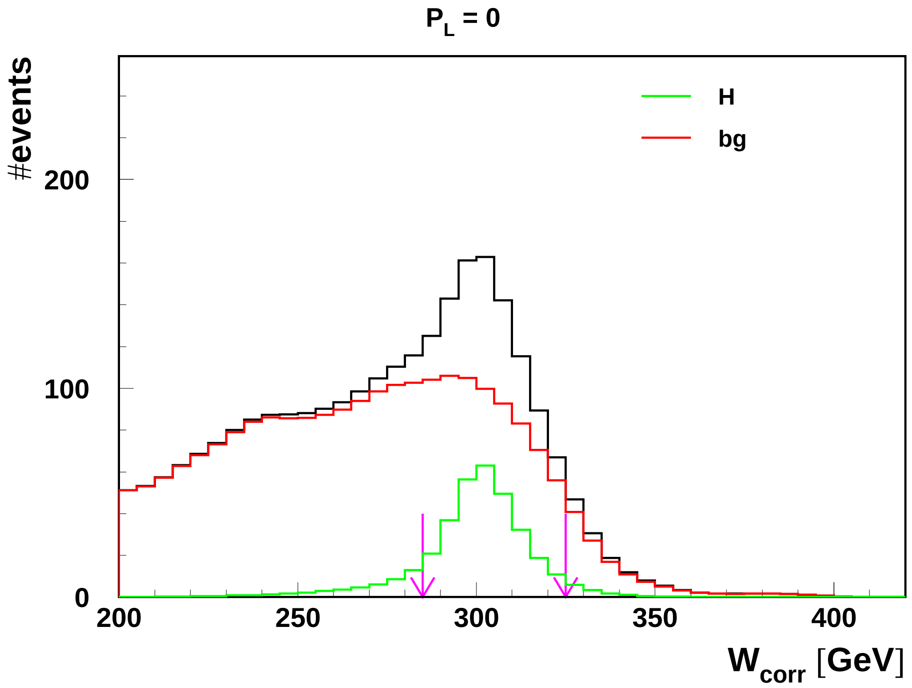
Corrected invariant mass distributions

Higgs CP properties

MSSM results

Results for $M_A = 300$ GeV

Circular laser polarization, $P_C = 100\%$



Corrected invariant mass distributions

We can not distinguish between H and A

$\Rightarrow$ measurement of

$$\sigma_{tot} \;=\; \sigma_H + \sigma_A$$

$\Rightarrow$ Need for linear photon polarization

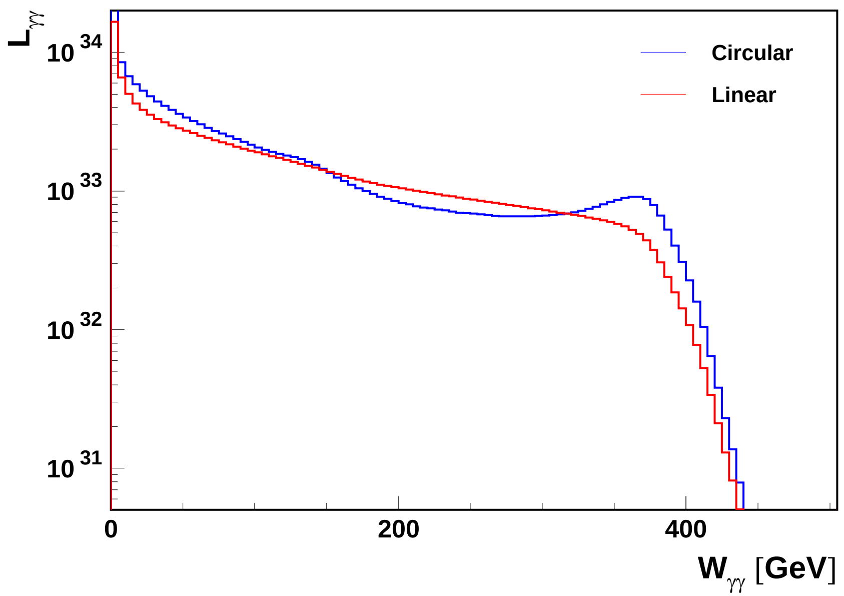
New results

with all backgrounds included!

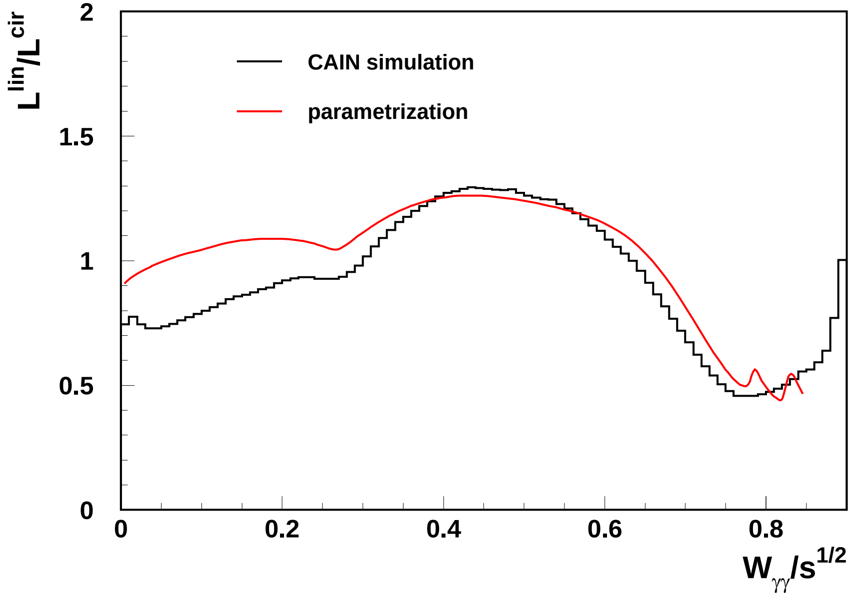
Linear polarization

CAIN simulation

$\gamma\gamma$ luminosity spectra for circular and linear laser beam polarization



Ratio of $\gamma\gamma$ luminosities

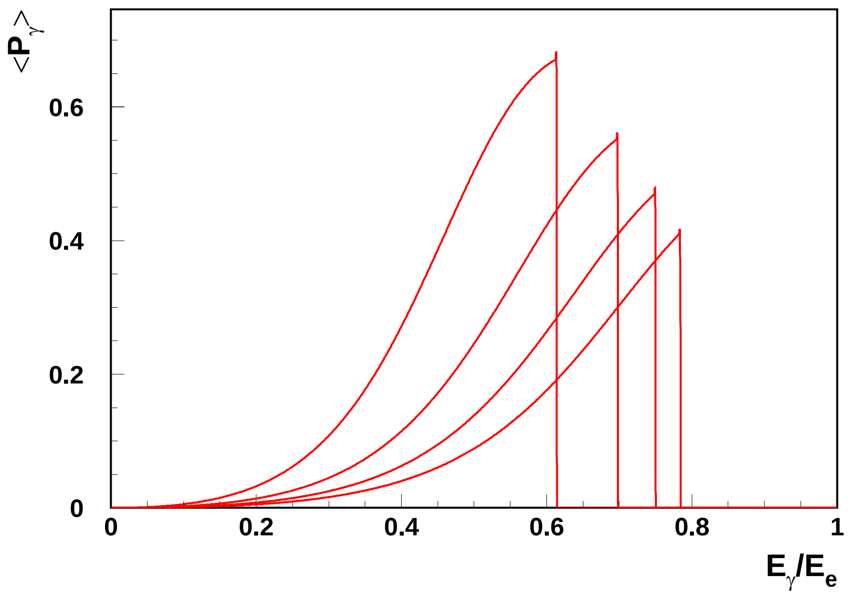


CompAZ gives proper description of the spectra modification

Linear polarization

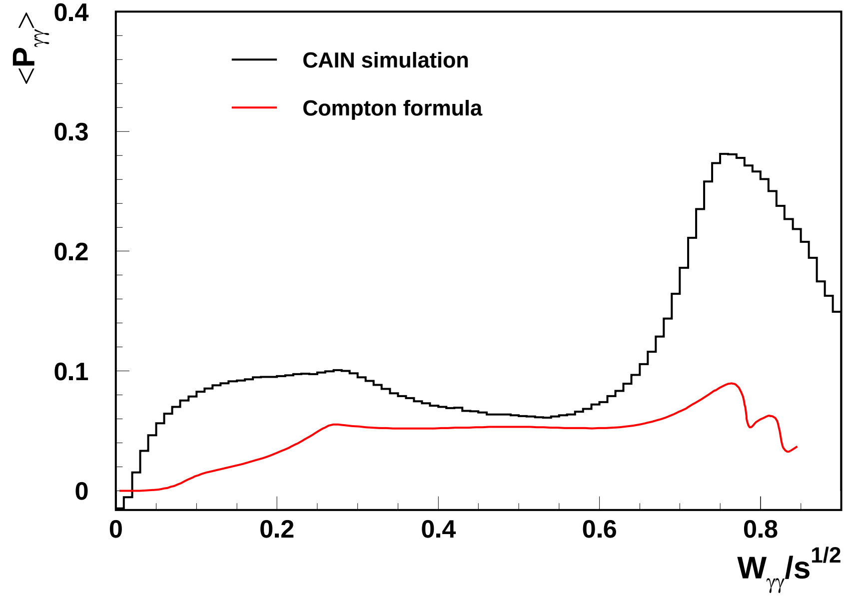
CAIN simulation

Expected photon polarization from LO Compton process



for E_e = 100, 150, 200 and 250 GeV

$\gamma\gamma$ polarization from CAIN for 250 GeV



CompAZ fails to describe polarization !

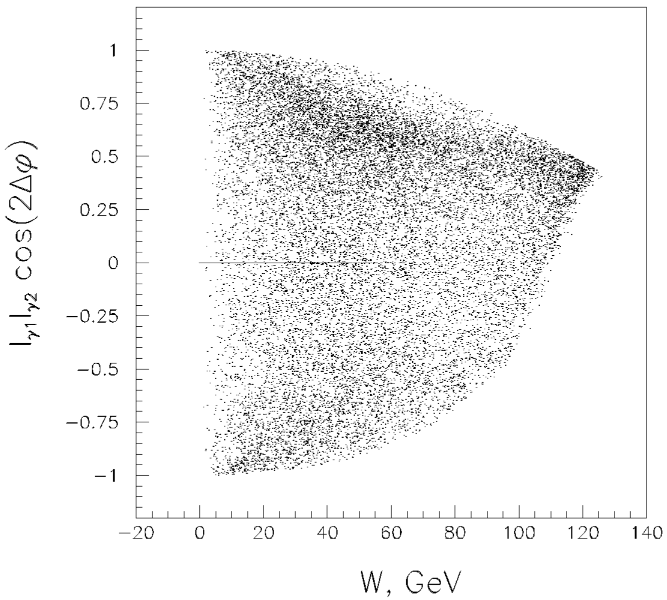
Linear polarization

Angular correlations

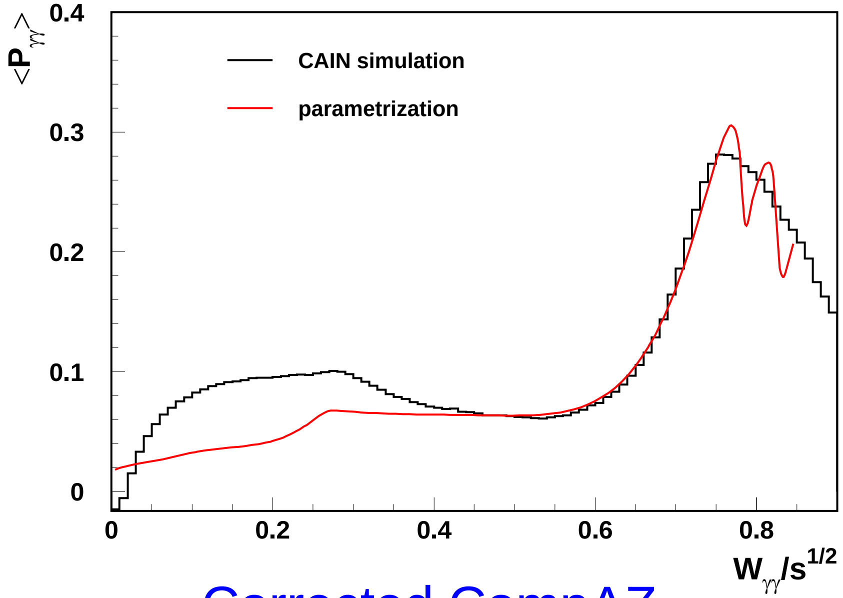
As pointed out by V.Telnov ("Nontrivial effects in linear polarization at photon colliders", ECFA workshop, Montepellier, November 2003) there are large correlations between photon polarization and scattering direction. In collision of two very thin beams:

$$\langle P_{\gamma_1} P_{\gamma_2} \rangle \gg \langle P_{\gamma_1} \rangle \cdot \langle P_{\gamma_2} \rangle$$

V.Telnov



Average $\gamma\gamma$ polarization from CAIN

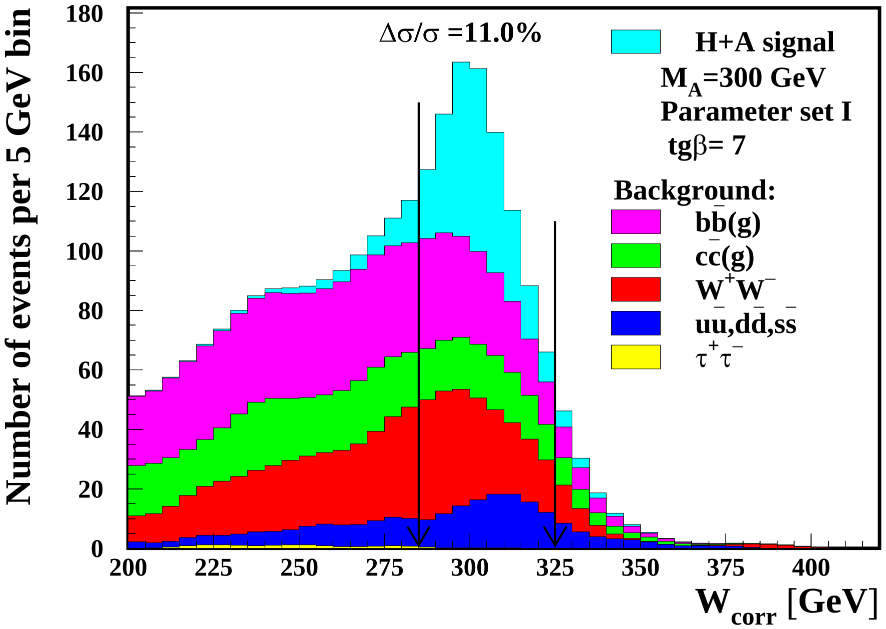


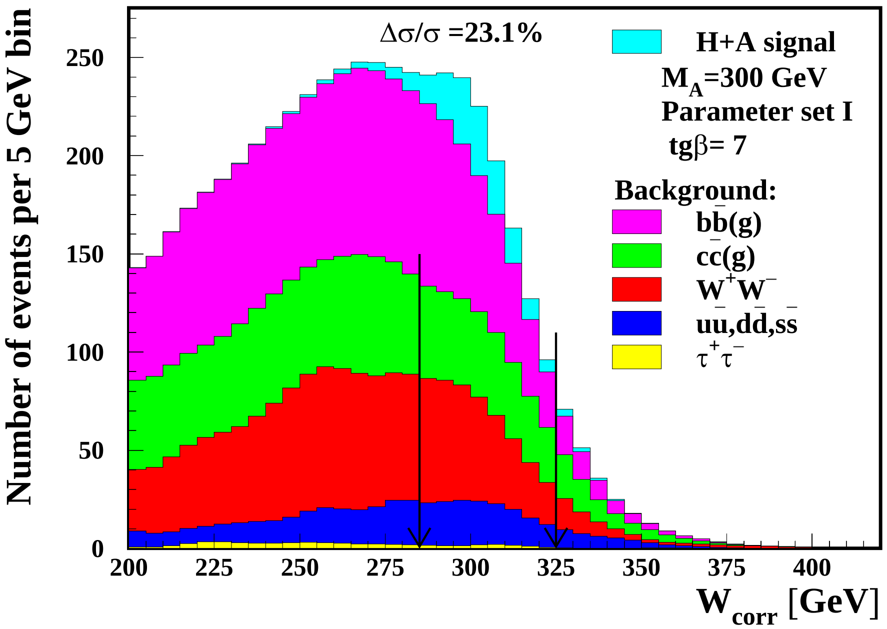
Corrected CompAZ

Results

$M_A = 300$ GeV

Linear laser polarization, $P_L = 100\%$





Lower luminosity at M_A, lower $J_z = 0$ contribution $\Rightarrow$ signal down by 40%

Higher $J_z = 2$ contribution $\Rightarrow$ no background suppression $\Rightarrow$ background up by 90%

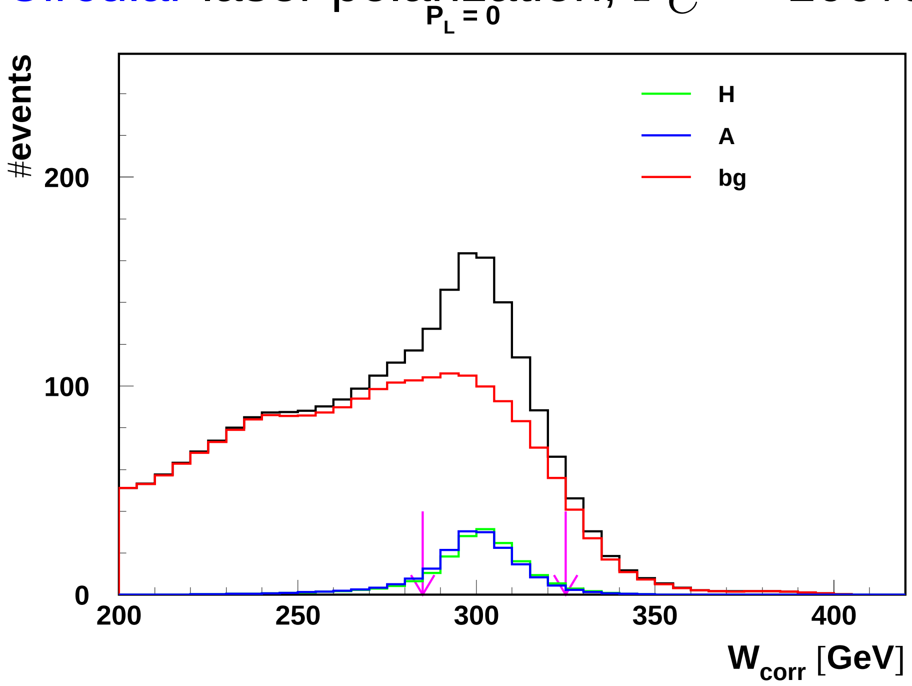
Selection cuts differ !!!

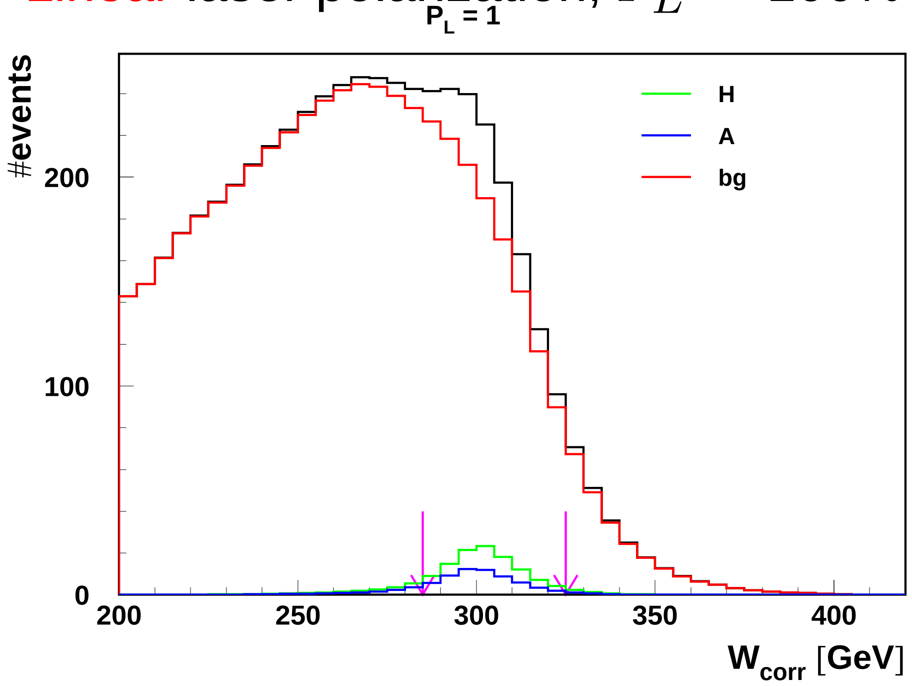
Results

$M_A = 300$ GeV

Measurements start to be sensitive to the Higgs boson(s) CP properties.

Circular laser polarization, $P_C = 100\%$ | Linear laser polarization, $P_L = 100\%$





$f \approx 0.5$

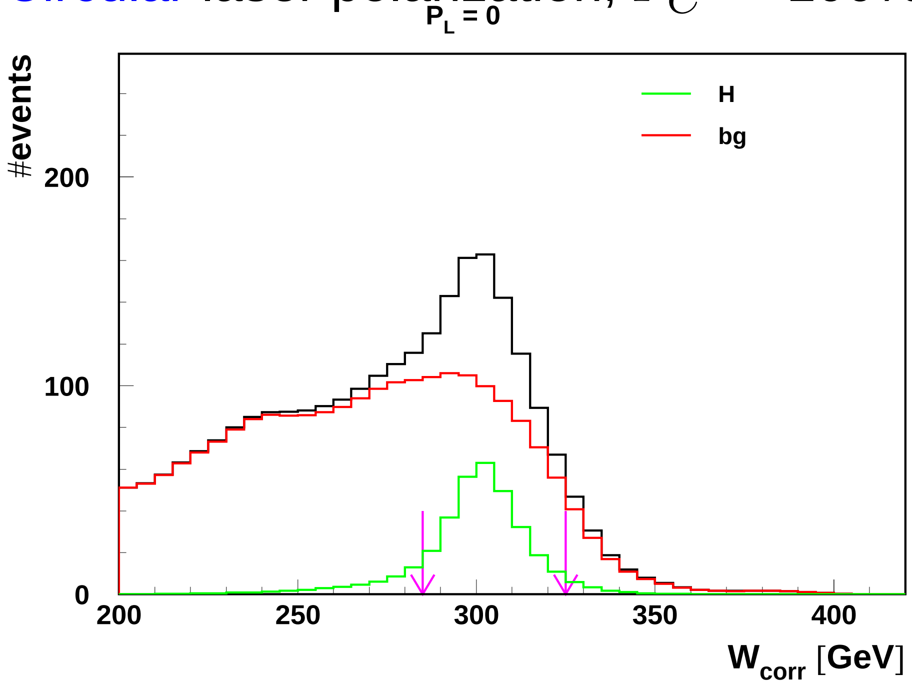
$\sigma_H = f \cdot \sigma_\circ, \quad \sigma_A = (1-f) \cdot \sigma_\circ$ where $\sigma_\circ \equiv \sigma_{H+A}(P_L = 0)$

Results

$M_A = 300$ GeV

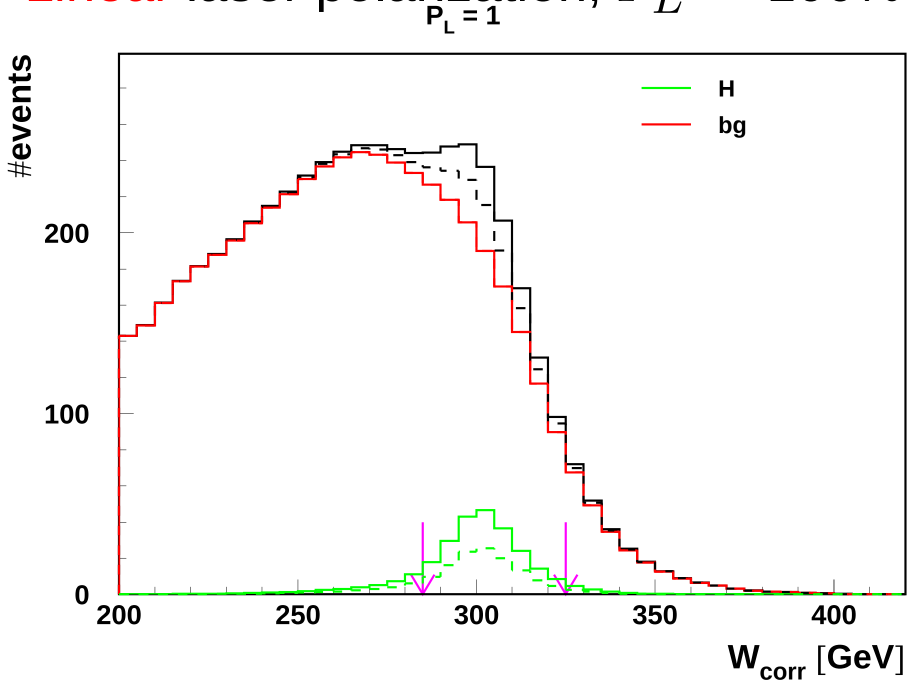
Measurements start to be sensitive to the Higgs boson(s) CP properties.

Circular laser polarization, $P_C = 100\%$



$f = 1$

Linear laser polarization, $P_L = 100\%$



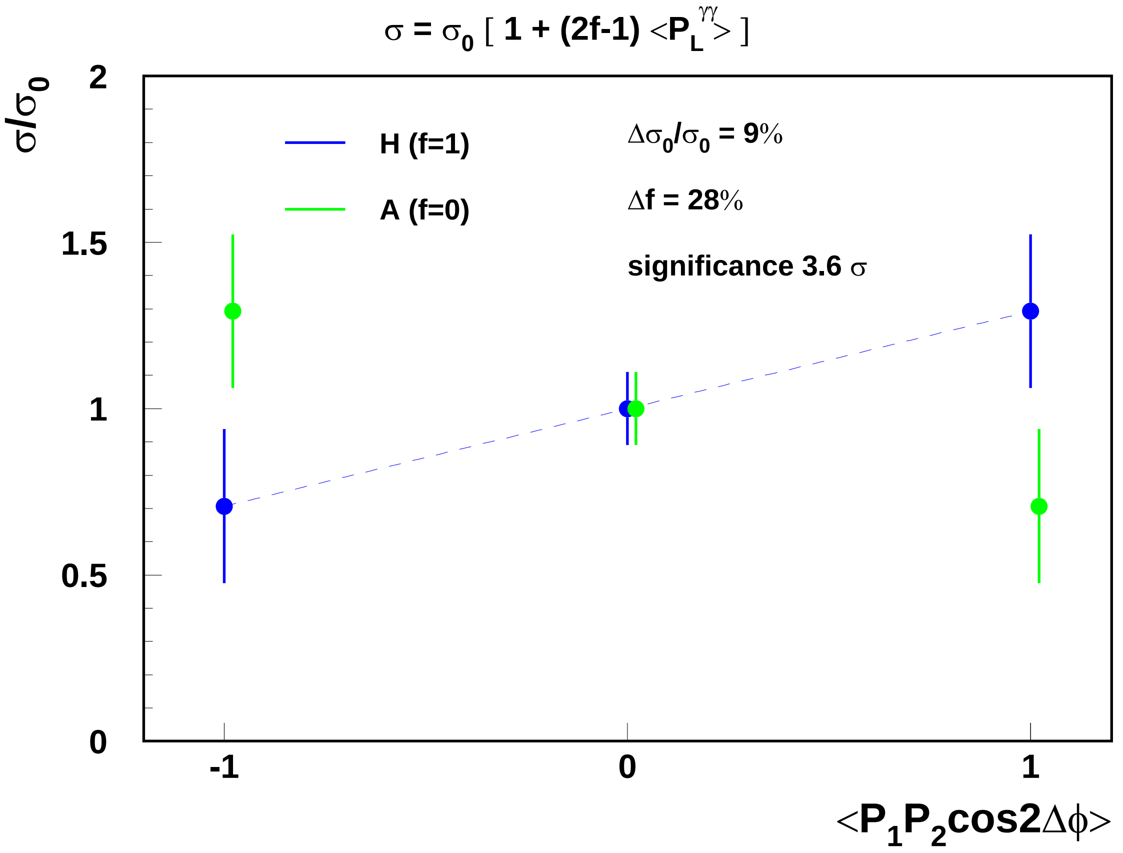
parallel (solid), perpendicular (dashed)

$\sigma_H = f \cdot \sigma_\circ, \qquad \sigma_A = (1-f) \cdot \sigma_\circ$ where $\sigma_\circ \equiv \sigma_{H+A}(P_L = 0)$

Results

$M_A = 300$ GeV

Results expected after 3×1 years of PLC running



$\sigma_\circ$ corresponding to MSSM parameter set I

Higgs CP

Generic model

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

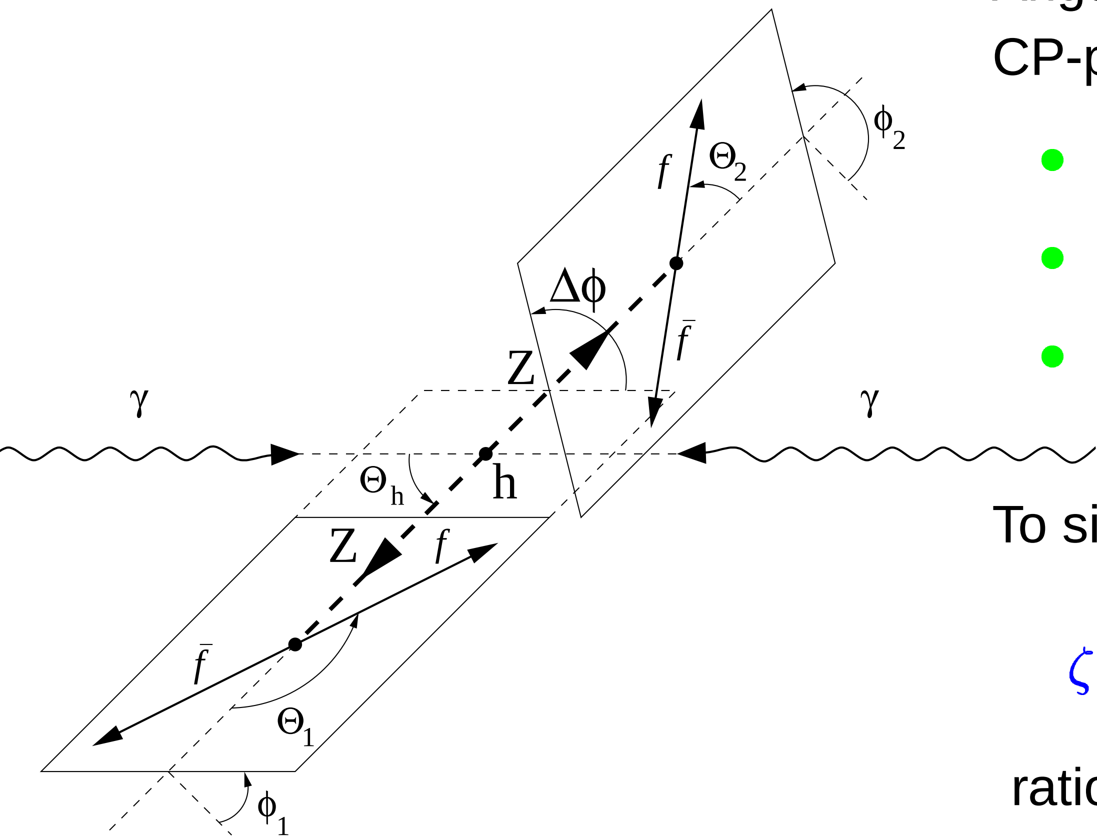
Model: S.Y. Choi, D.J. Miller, M.M. Mühlleitner and P.M. Zerwas, hep–ph/0210077;
D.J. Miller, S.Y. Choi, B. Eberle, M.M. Mühlleitner and P.M. Zerwas, Phys. Lett. B505 (2001) 149;
D.J. Miller, *Spin and Parity in the HZZ vertex*, ECFA/DESY meeting, Prague, November 2002.

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 $M_h \gg M_Z$).

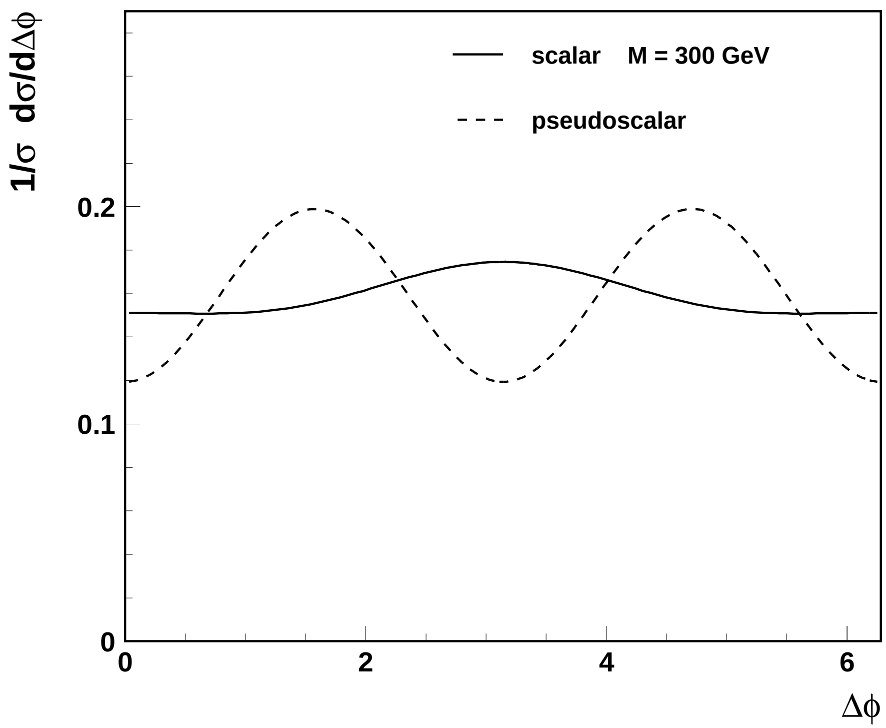
All polar angles are calculated in the rest frame of the decaying particle.

Generic model

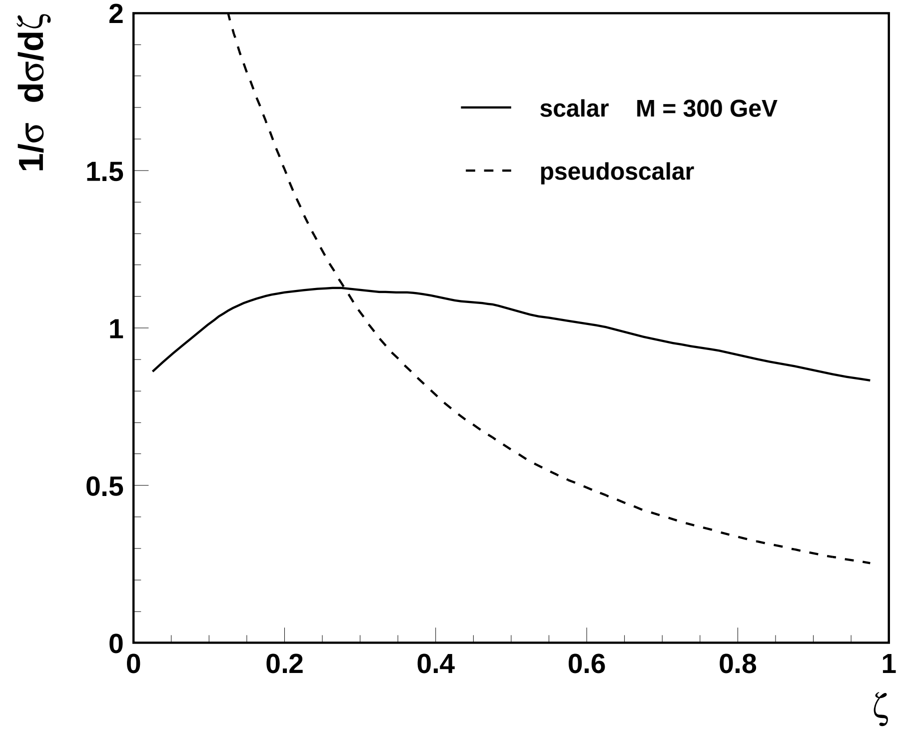
Angular distributions

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

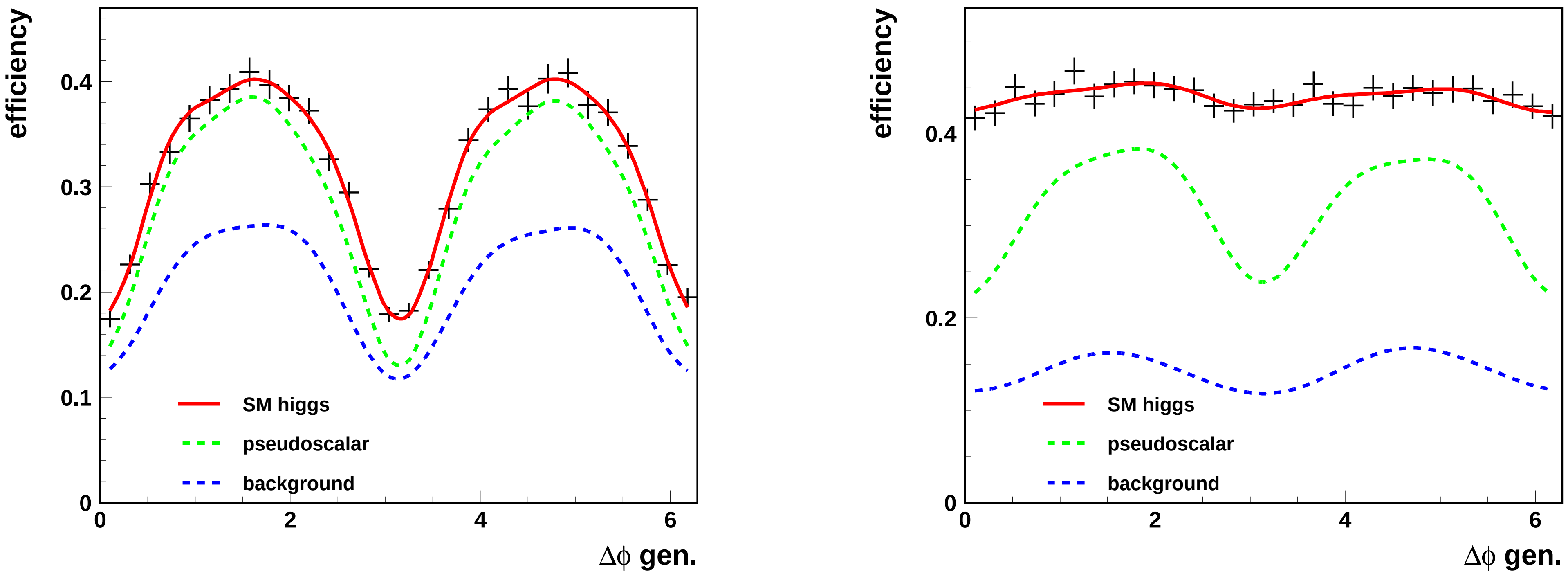


Both distributions clearly distinguish between decays of scalar and pseudoscalar higgs.

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

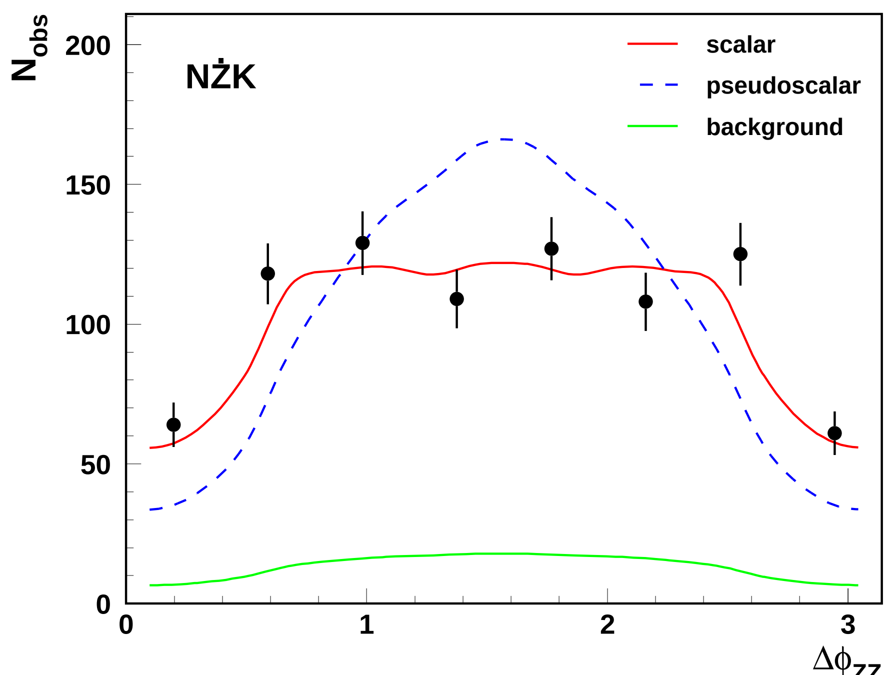


Effect much stronger for background events and pseudoscalar higgs
due to different $\cos\theta_{j,l}$ distribution

Generic model

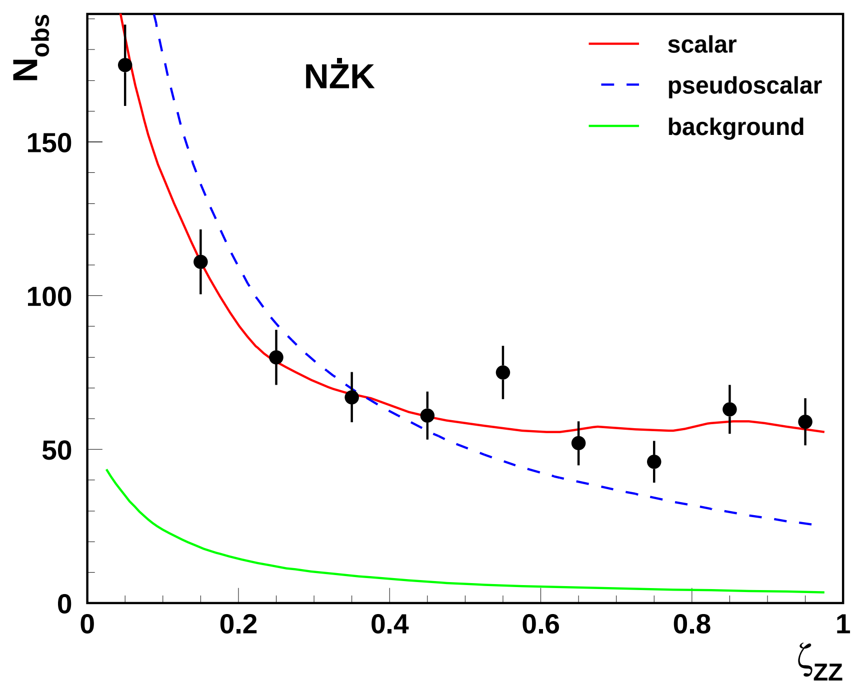
Measured $\Delta\phi$ and ζ distributions for $h \to ZZ \to q\bar{q}\, l^+ l^-$ m_h = 200 GeV
after 1 year of PC running at $\sqrt{s_{ee}}$=305 GeV, $\mathcal{L} = 610\ fb^{-1}$
$\Rightarrow$ ~675 reconstructed SM higgs events expected + 145 ZZ background events

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



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

Measured ζ_{ZZ} distribution:

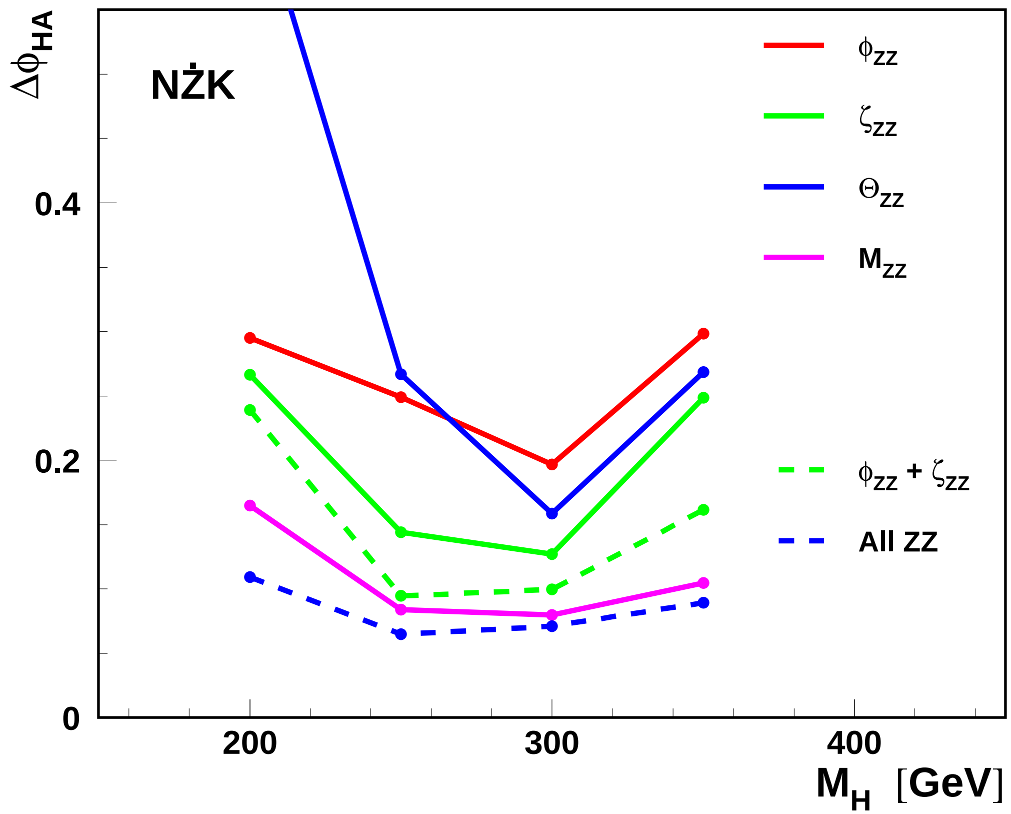


pseudoscalar normalized to the same number of events

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

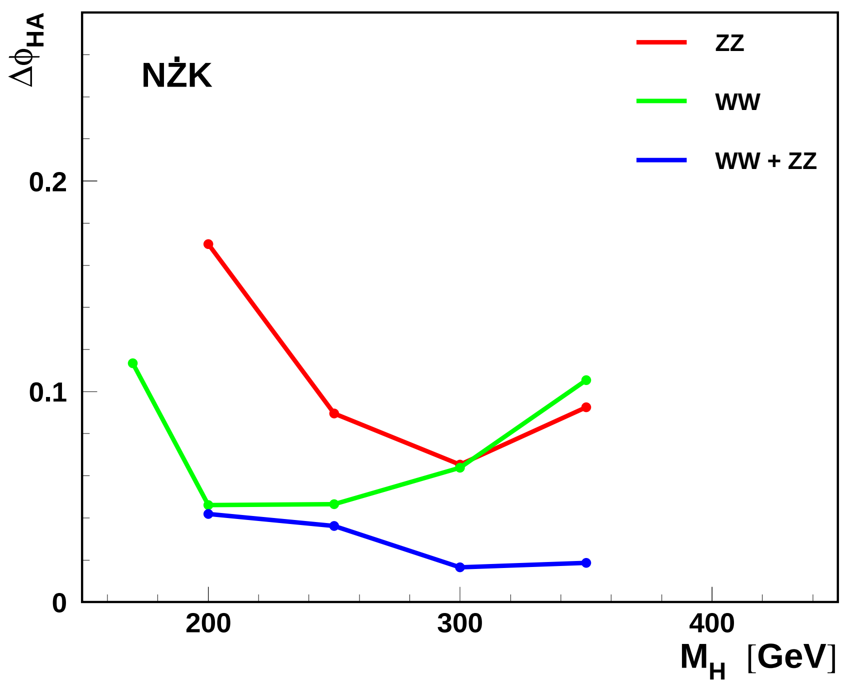
Results

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

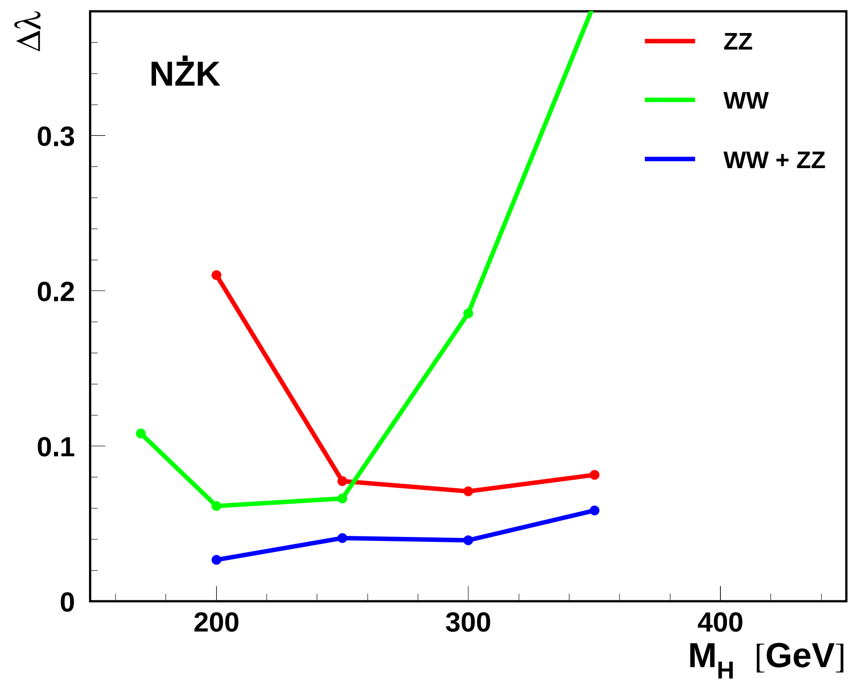
from simultaneously fit of $\Gamma_{\gamma\gamma}$, $\phi_{\gamma\gamma}$, λ and Φ_{HA} to all considered distributions

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

CP conserving 2HDM (II)

Higgs boson couplings

Scalar Higgs bosons h and H
with 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	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-i\,\gamma_5\,\frac{1}{\tan\beta}$
χ_d	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-i\,\gamma_5\,\tan\beta$
χ_V	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0

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

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

Higgs couplings are related by
"patter relation"

$$(\chi_V - \chi_d)(\chi_u - \chi_V) + \chi_V^2 \;=\; 1$$

I. F. Ginzburg, M. Krawczyk and P. Osland,
hep-ph/0101331

Instead of angles α and β use couplings χ_V and χ_u to parametrize cross sections

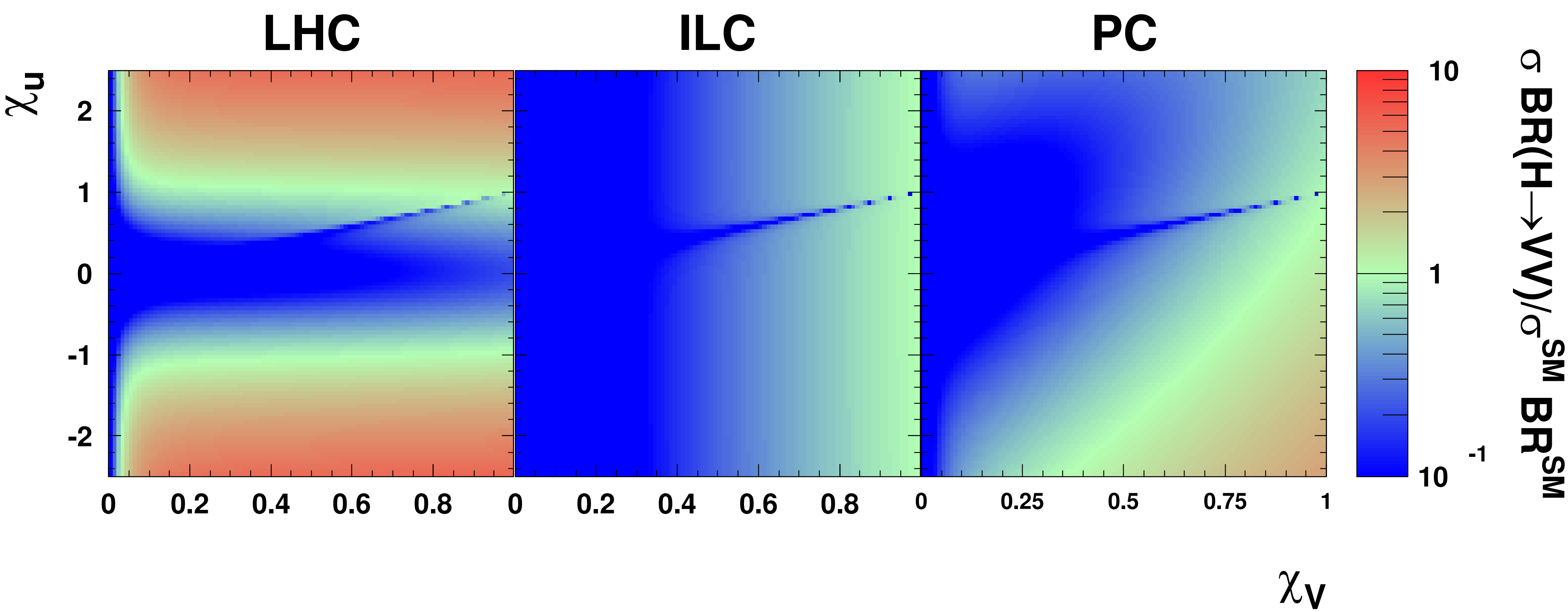
$$0 \;\leq\; \chi_V \;\leq\; 1$$

If we neglect H decays to h and A (small) cross sections and BRs calculated for H are also valid for h

LHC $\oplus$ ILC $\oplus$ PC

Measurements at LHC, ILC and Photon Collider are complementary, being sensitive to different combinations of Higgs-boson couplings

Cross sections $\times$ BR relative to SM $\qquad M_H = 250 GeV$



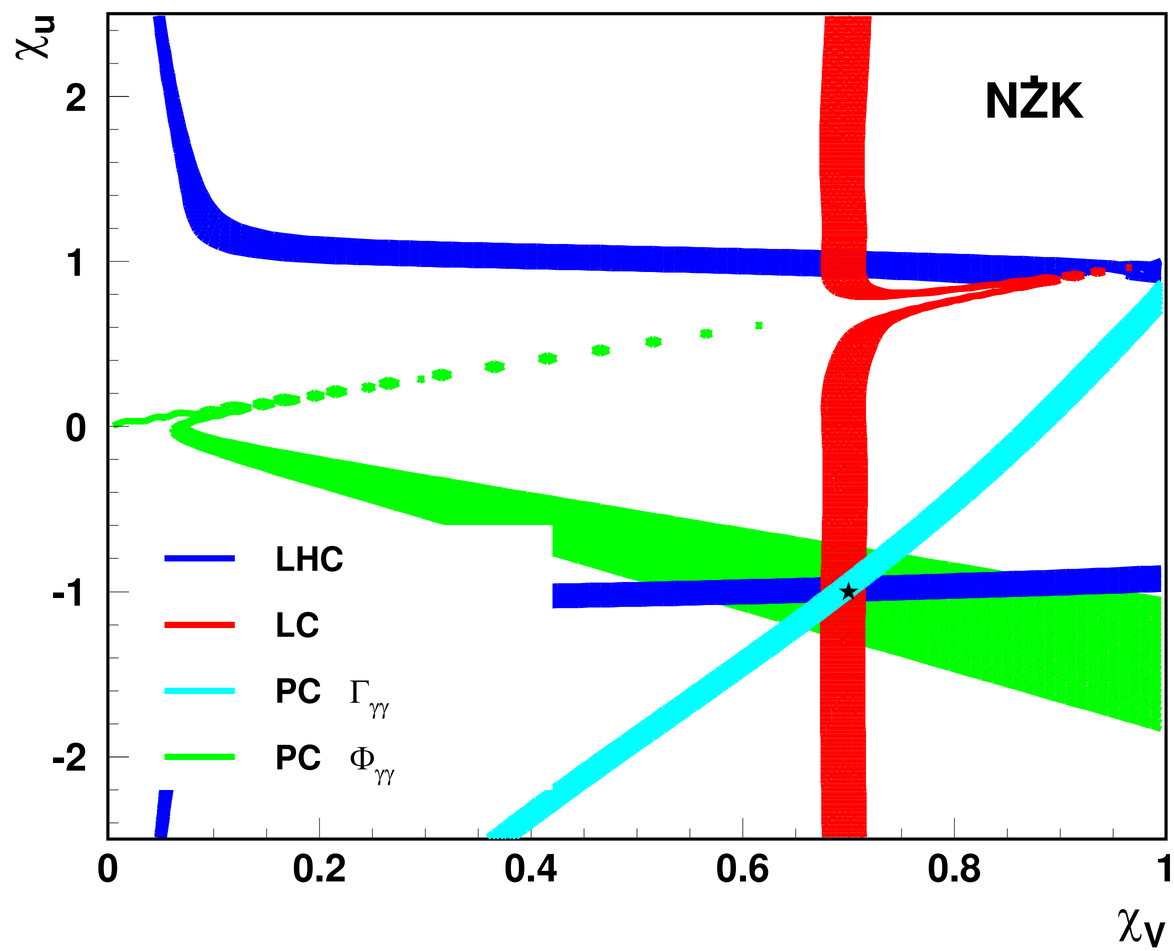
LHC $\oplus$ ILC $\oplus$ PC

Allowed coupling values (1 σ) from cross section measurements at LHC, ILC and PC, and the phase measurement at PC.

Consistency of all these measurements verifies the coupling structure of the model

statistical errors only

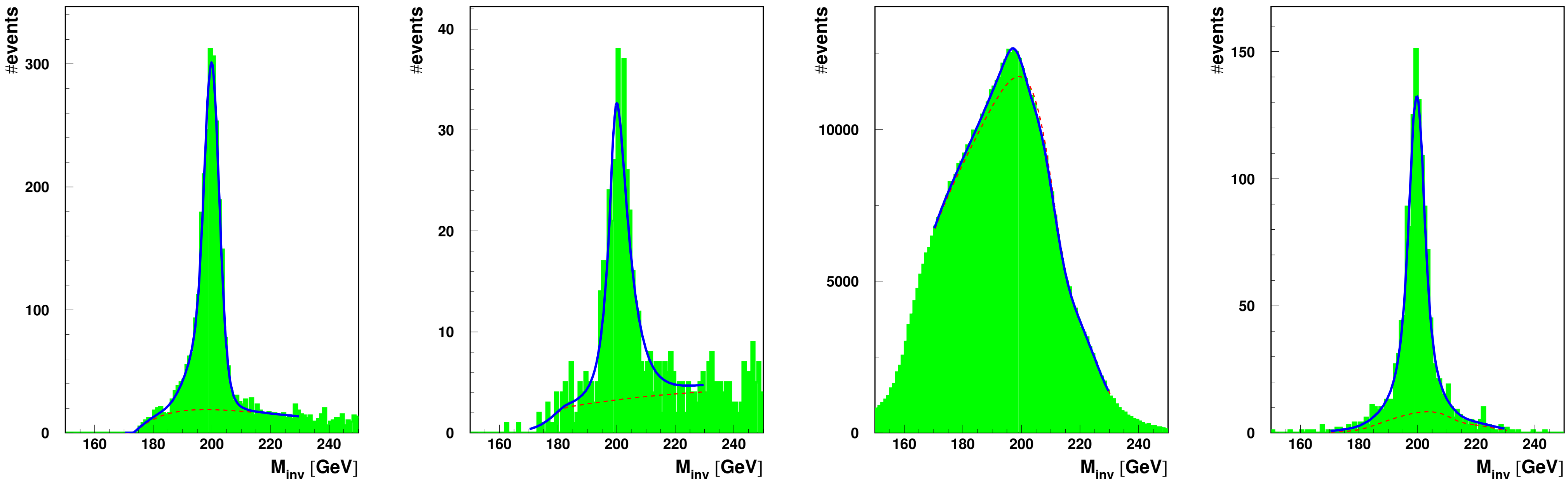
$\chi_V = 0.7$ $\chi_u = -1$ $M_H = 250$ GeV



LHC $\oplus$ ILC $\oplus$ PC

Combined fit to the expected invariant mass distributions:

LHC | ILC | PC $H \to WW$ | PC $H \to ZZ$



12 parameter fit: • χ_V • χ_u • M_H • Φ_{HA}

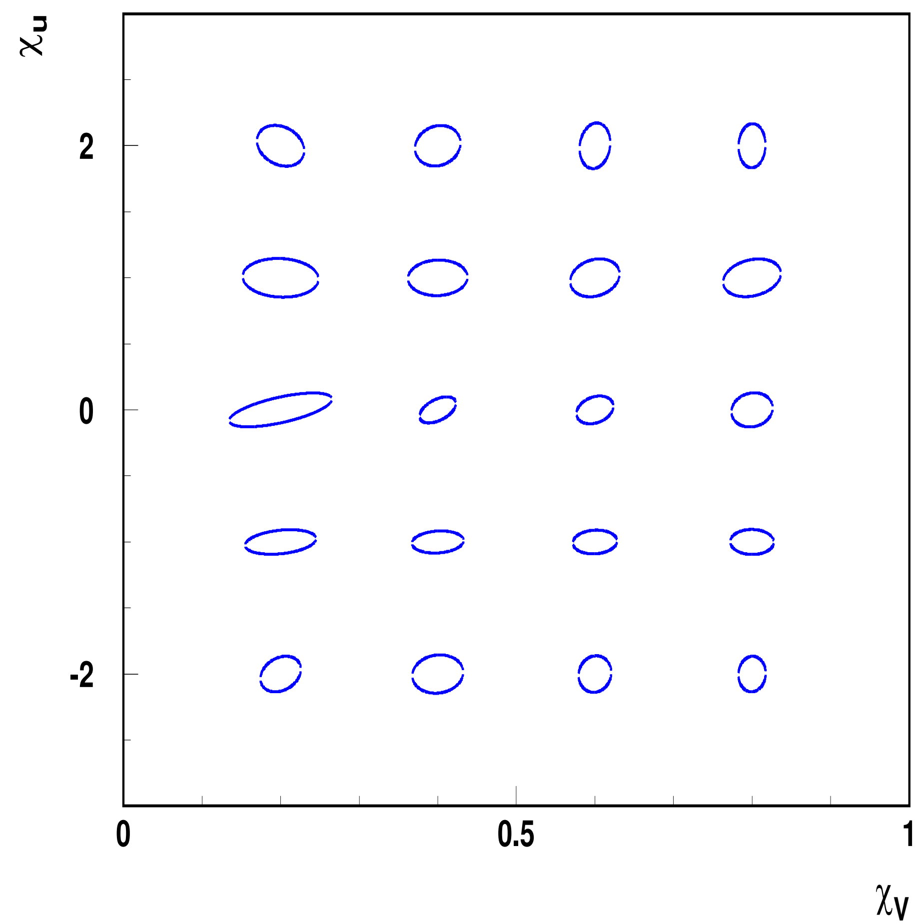
+ 8 normalization and $\gamma\gamma$-spectra shape parameters (systematic uncertainties)

LHC $\oplus$ ILC $\oplus$ PC

Simultaneous fit to LHC, ILC and PC (W^+W^- and ZZ) invariant mass distributions

1σ (stat.+sys.) contours

H couplings to vector bosons (χ_V) and up fermions (χ_u) for $M_H = 250$ GeV



$\langle \Delta\chi_V \rangle$ = 0.03

$\langle \Delta\chi_u \rangle$ = 0.13

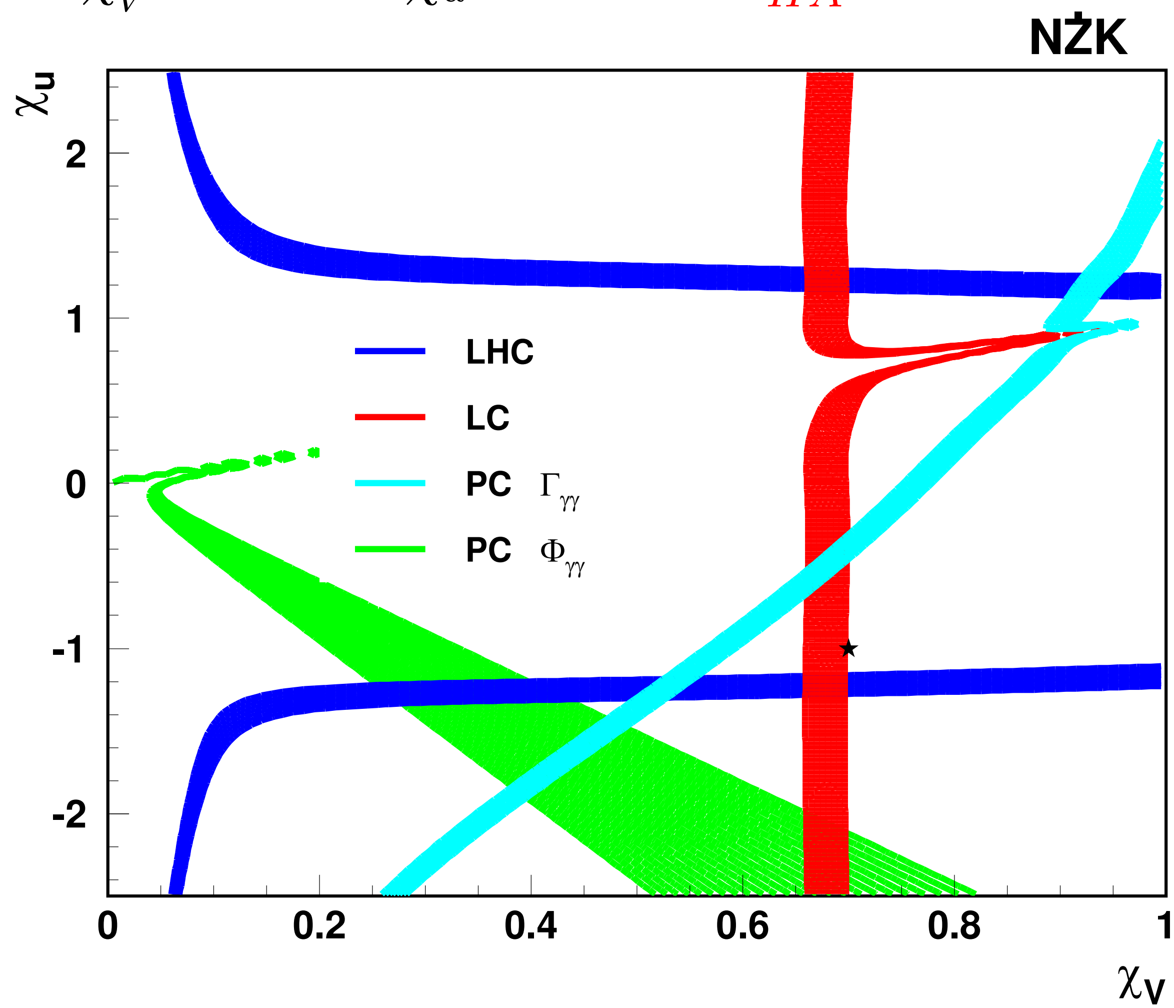
LHC $\oplus$ ILC $\oplus$ PC

Allowed coupling values from cross section measurements at LHC, ILC and PC, and the phase measurement at PC.

Measurements compared assuming CP-conserving 2HDM(II) not consistent
$\Rightarrow$ “new physics”:

- different coupling structure (eg. CP violation)
- existence of new heavy particles contributing to Γ_{gg} and $\Gamma_{\gamma\gamma}$

$\chi_V = 0.7 \quad \chi_u = -1 \quad \Phi_{HA} = -0.2$



Summary

Very precise measurement of light SM Higgs boson production

For heavy SM Higgs boson phase measurement opens a new window for "new physics" searches

Higgs coupling determination possible from WW/ZZ decay measurements - complementary to LHC and ILC

Heavy MSSM Higgs bosons measurements in LHC wedge possible

Angular distribution allow to probe CP violation in Higgs couplings

Measurements with linear beam polarization very difficult - only qualitative determination of Higgs CP

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 $\tan\beta$.

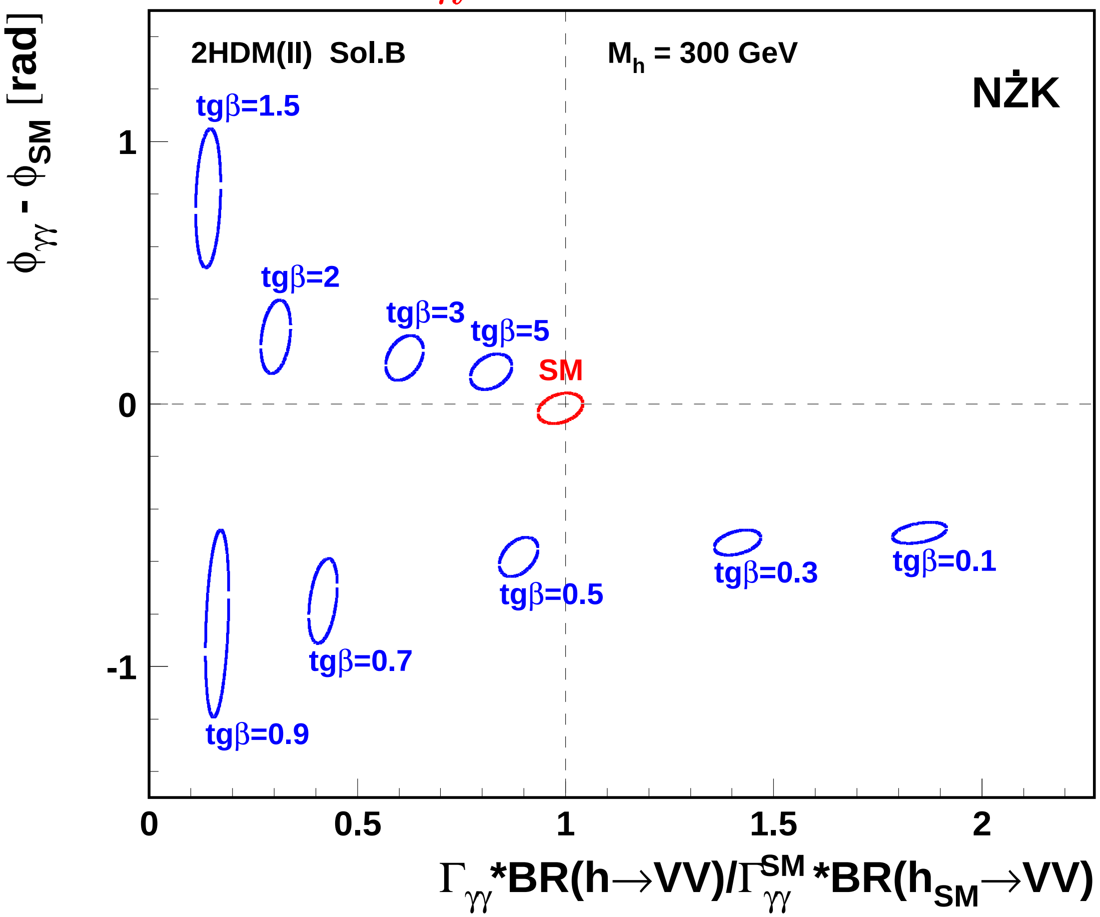
Can we extract $\tan\beta$ value
from the measured W^+W^- and ZZ
invariant mass distributions ?

SM-like 2HDM(II)

Light Higgs boson h

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

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

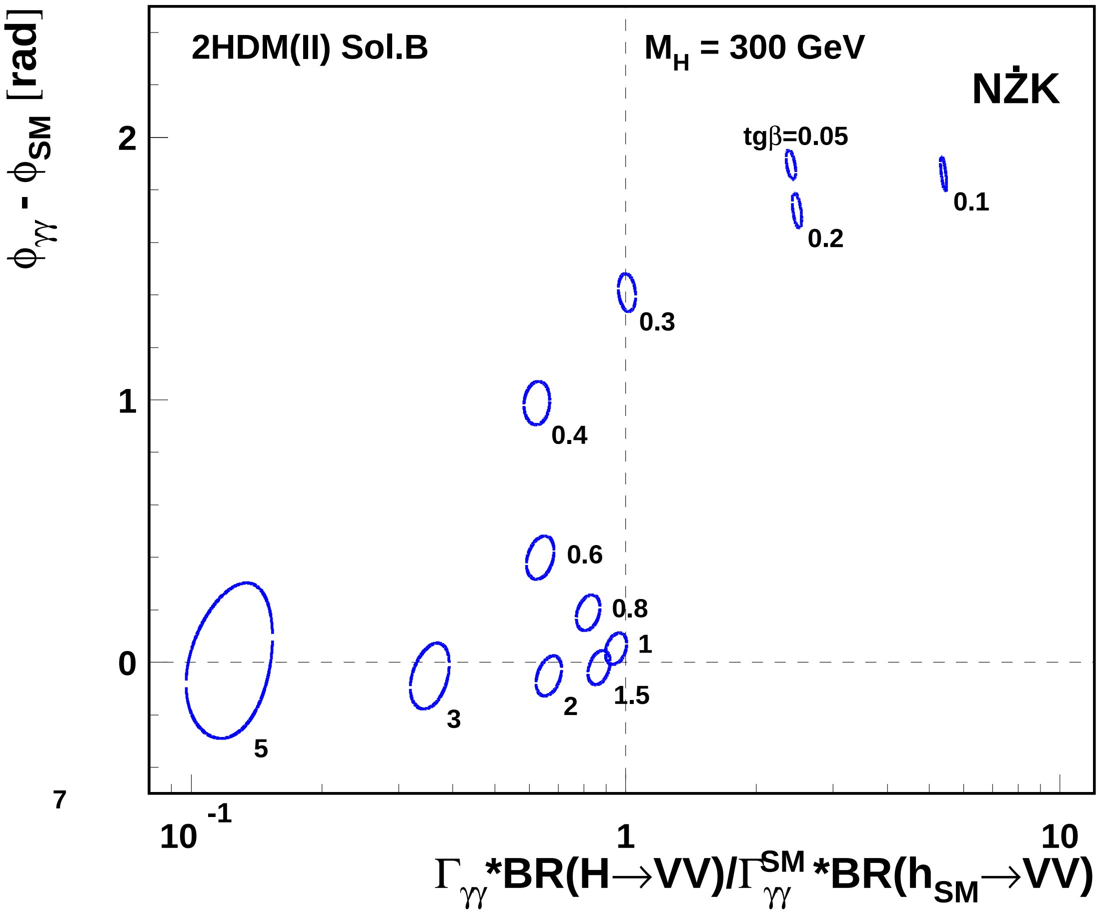
statistical errors only M_{H+}=800 GeV

SM-like 2HDM(II)

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

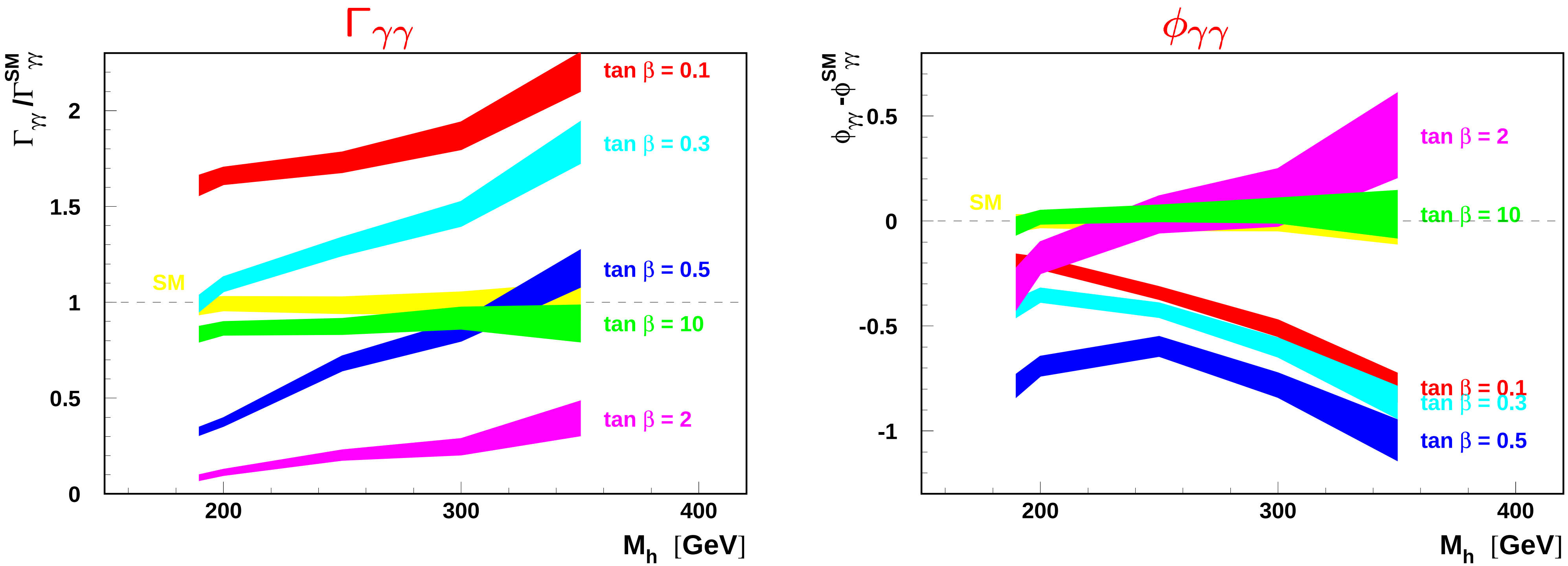
M_h=120 GeV, M_{H+}=800 GeV

2HDM(II)

Solution B SM-like

Two-photon width and phase measurement for different M_h

band width indicates statistical measurement error



Measurement of both phase and width can help to test Higgs sector structure

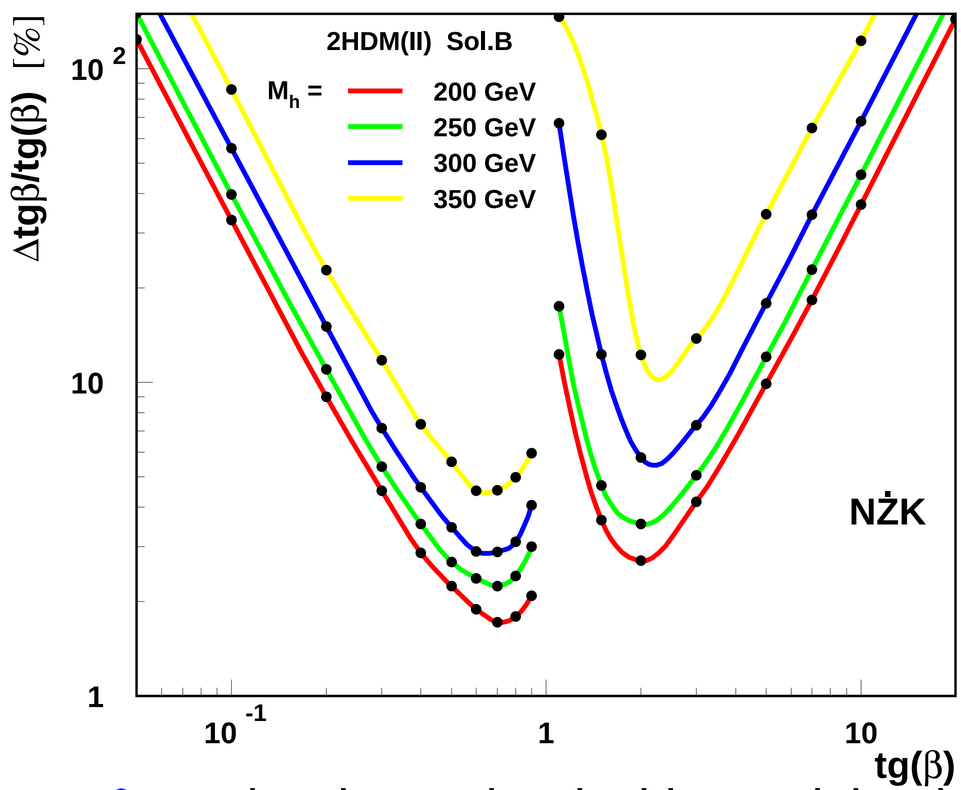
e.g. distinguish between large and small $\tan\beta$

SM-like 2HDM(II)

Light Higgs boson h

Expected precision in $\tan\beta$ determination

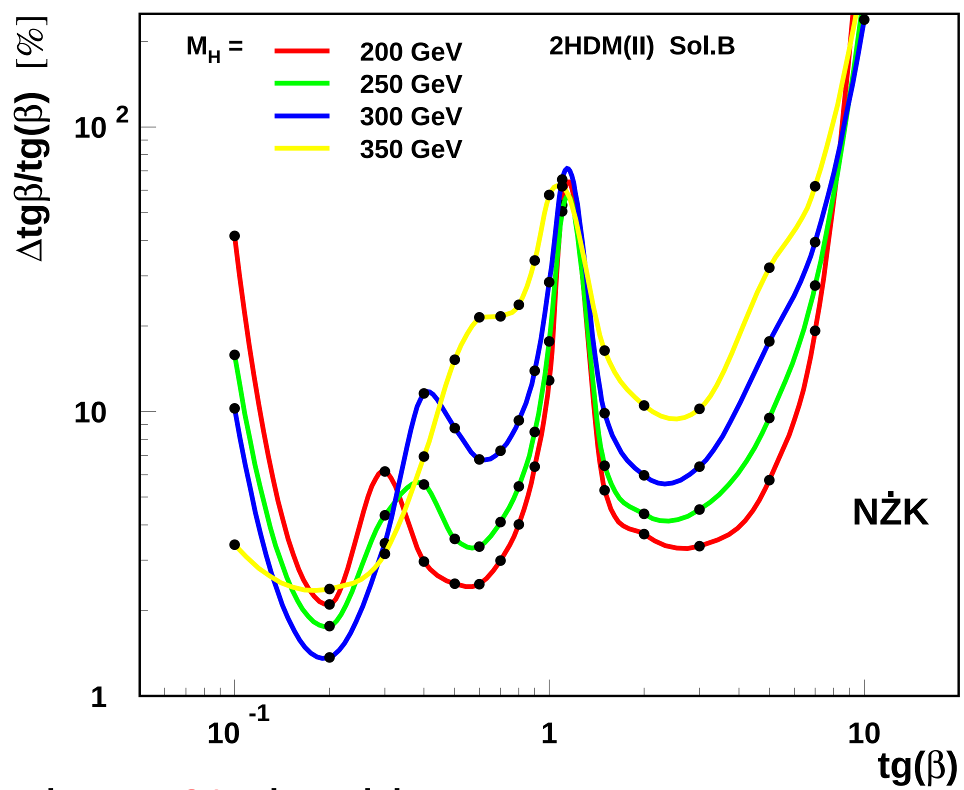
stat. + sys. errors



Heavy Higgs boson H

Expected precision in $\tan\beta$ determination

stat. + sys. errors



$\tan\beta$ can be determined with precision better than 10% in wide parameter range

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:

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

$\Rightarrow$ additional model parameter:

CP-violating mixing phase Φ_{HA}

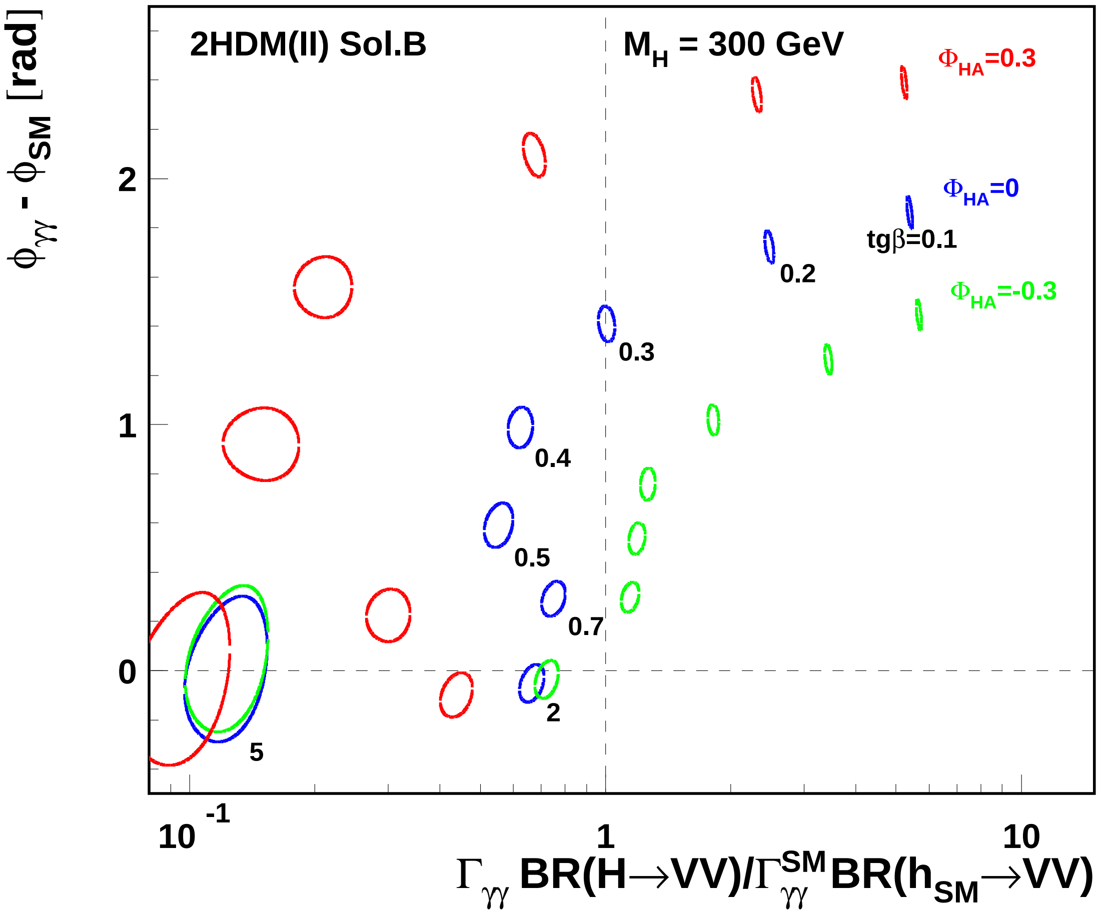
We consider h_2 production and decays

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. $\Phi_{HA} \sim 0$)

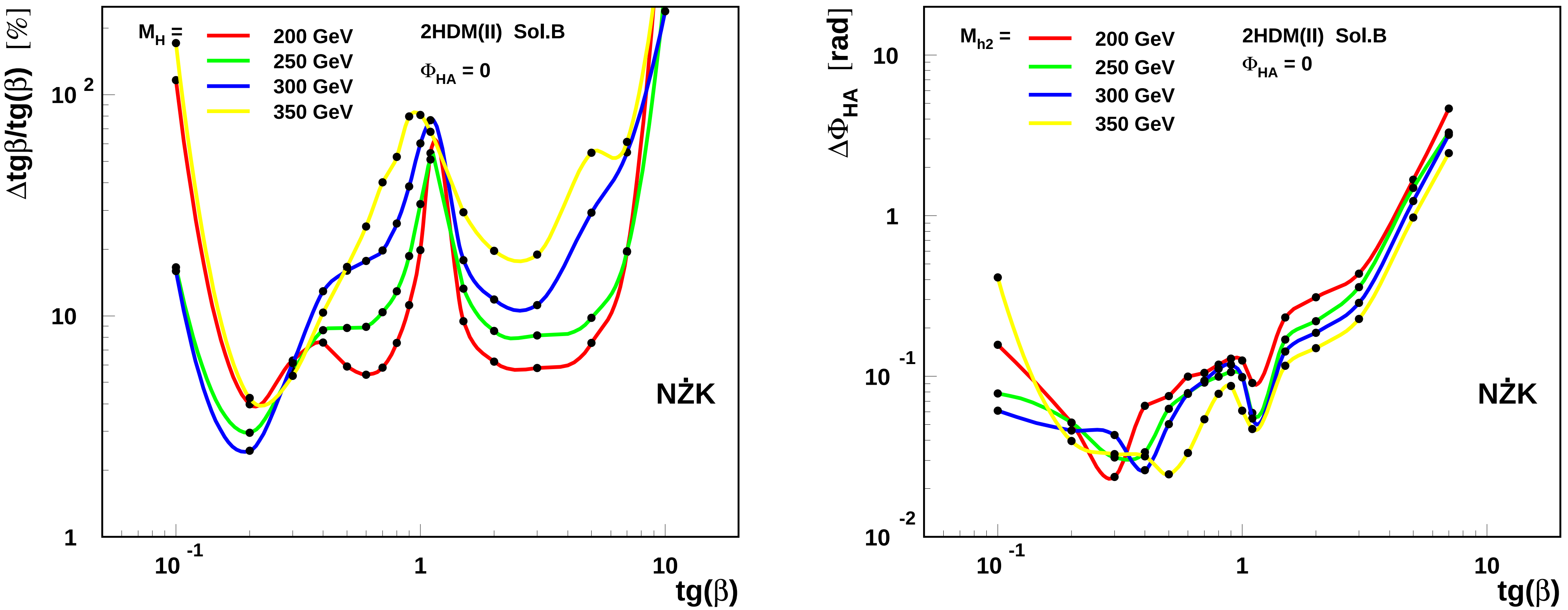
- $\sim$ 10 % for $\tan\beta$
- $\sim$ 100 mrad for Φ_{HA}
  (for low $\tan\beta$)

2HDM(II)

Higgs boson h_2

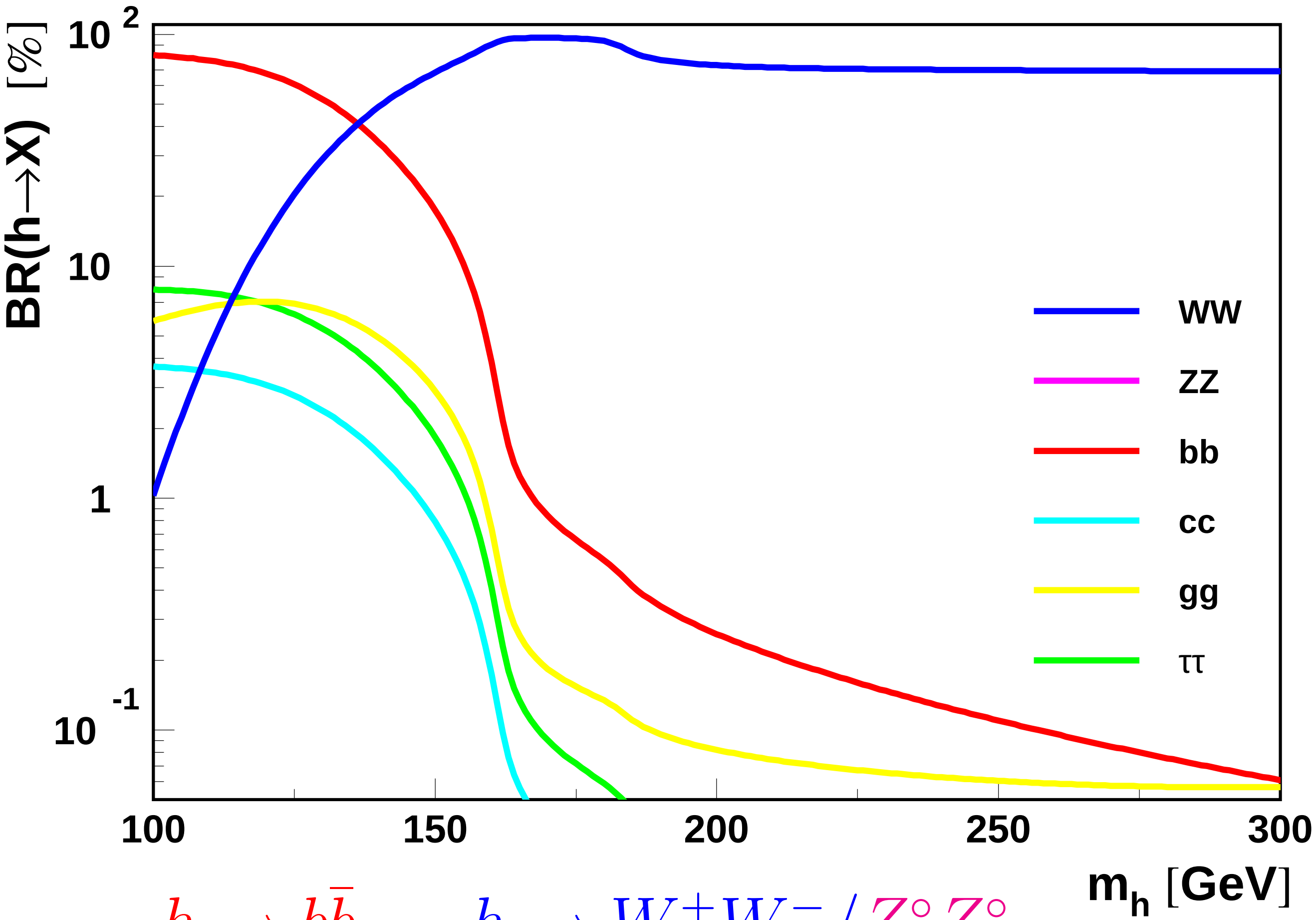
Solution B_h (with CP violation) $\Rightarrow$ two free parameters ($\tan\beta$ and Φ_{HA})

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

Higgs decays



$h \rightarrow b\bar{b}$ $h \rightarrow W^+W^-/Z^\circ Z^\circ$

Analysis

Event selection

W^+W^-

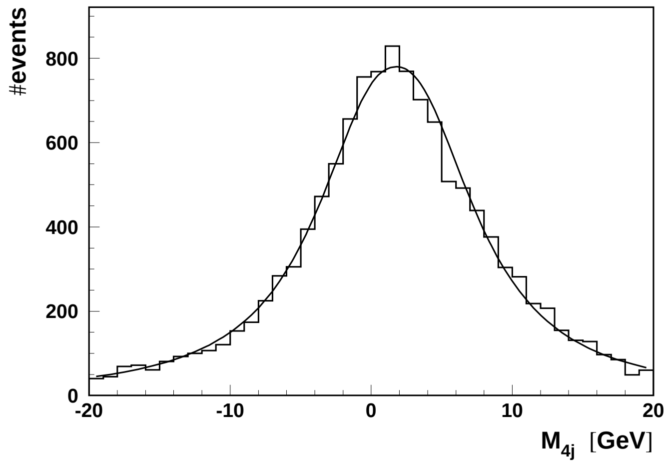
- balanced transverse momentum:
  $P_T/E_T < 0.1$
- 4 hadronic jets reconstructed
  (Durham algorithm)
- cut on jet angle $\cos\theta_{jet} < 0.95$
  to preserve good mass resolution
- two $W^\pm$ can be reconstructed
  with probability $P_W > 0.001$

ZZ

- balanced transverse momentum:
  $P_T/E_T < 0.1$
- 2 leptons ($e^\pm$ or $\mu^\pm$) + 2 hadronic jets
  too large background in 4-jet channel
- cut on lepton and jet angle $\cos\theta_{l,jet} < 0.95$
- leptons and jets reconstruct into two Z°
  with probability $P_Z > 0.001$

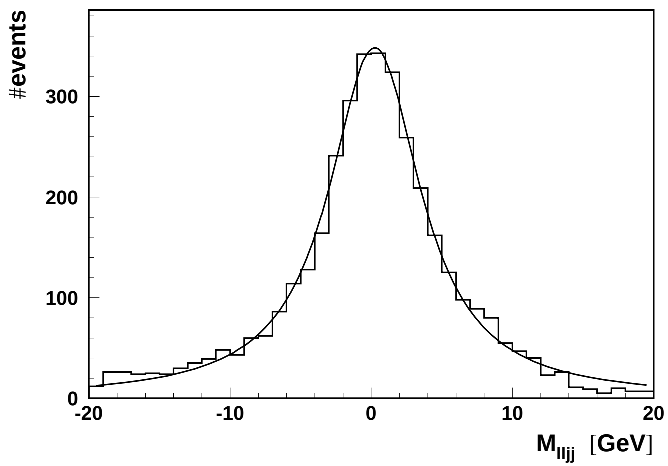
Mass resolution

$\gamma\gamma \to W^+W^- \to$ 4 jets



$\Gamma \sim$ 6.5 – 13 GeV

$\gamma\gamma \to ZZ \to l^+l^-$ + 2 jets



$\Gamma \sim$ 5.5 – 7.5 GeV

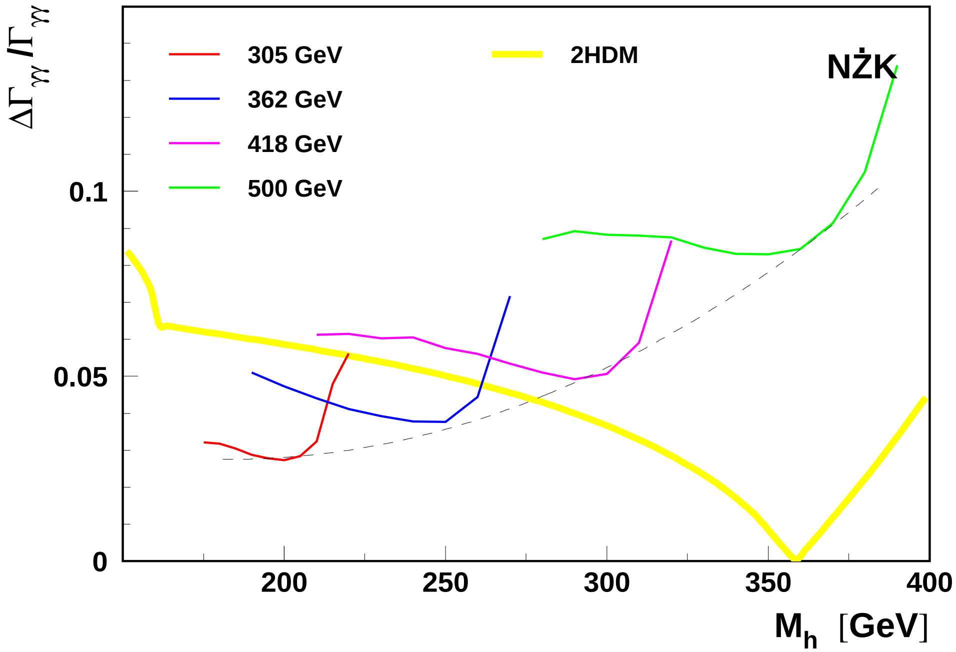
for $W_{\gamma\gamma}$=200–400 GeV

SM results

$\Gamma_{\gamma\gamma}$ measurement

One parameter fit to invariant mass distribution for W^+W^- and ZZ events

$\Rightarrow$ Average statistical precision (1 PC year):



assuming SM branching ratios

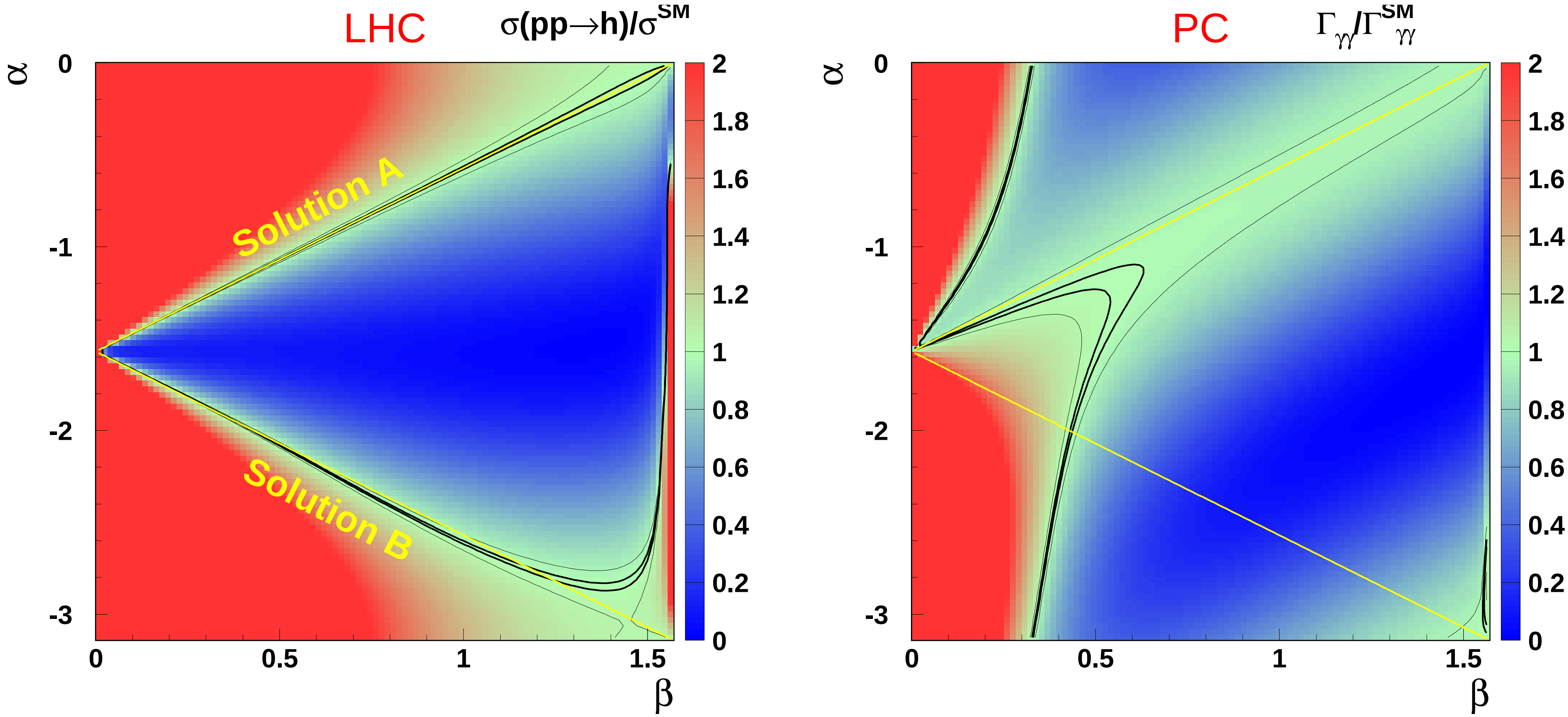
Sensitive to possible "new physics" only up to $M_h \sim 280$ GeV

For higher Higgs masses $\Gamma_{\gamma\gamma}$ is little sensitive to contribution of new heavy charged particles !

"new physics" modeled by SM-like 2HDM (II) with $M_{H^+} = 800$ GeV

2HDM(II)

Higgs production cross section compared to SM M_h=300 GeV



black contours: ± 1 and ± 5% deviations $\Rightarrow$ significant effects in solution B