Anomalous Couplings in $\gamma\gamma \to W^+W^-$

based on work by

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Outline

Layout

The Effective Lagrangian approach

Anomalous couplings:

- in Standard Model (SM) couplings of γ, W, Z fixed by: gauge invariance & renormalisability
- deviations $\Rightarrow$ signal for new physics
- *ILC* allows precise tests (see e.g. talks by G. Weiglein, J. Reuter)
- here: sensitivity at *ILC* $\gamma\gamma$ option via W^+W^- production

Generic descriptions of deviations from SM:

1. Form Factors
   - allow arbitrary complex couplings for vertices
   - very general, many parameters
   - process specific
2. Effective Lagrangians
   - add higher dimensional operators
   - real couplings
   - process independent

   (a) $\mathscr{L}_{eff}$ after EWSB
   - ★ moderate number of couplings for low dim. op.

   (b) $\mathscr{L}_{eff}$ before EWSB
   - ★ few couplings for low dim. op.

Effective Lagrangian before EWSB

- start from SM Lagrangian (incl. Higgs doublet φ)
- add all higher dim. operators which are
  - Lorentz-invariant
  - $SU(3) \times SU(2) \times U(1)$ invariant

$$\Rightarrow \quad \mathscr{L}_{eff} = \mathscr{L}_0 + \underbrace{\mathscr{L}_1}_{\text{dim 5 op.}} + \underbrace{\mathscr{L}_2}_{\text{dim 6 op.}} + \dots$$

- imposing
  - equation of motion
  - lepton and baryon number conservation

$\Rightarrow \quad \mathscr{L}_1$: none, $\mathscr{L}_2$: 80 operators

(Buchmüller, Wyler 1986)

Gauge and gauge-Higgs anomalous couplings

- pure gauge and gauge-Higgs part

$$\mathscr{L}_2 = \frac{1}{v^2}\Big(h_W O_W + h_{\tilde{W}} O_{\tilde{W}} + h_{\varphi W} O_{\varphi W} + h_{\varphi \tilde{W}} O_{\varphi \tilde{W}} + h_{\varphi B} O_{\varphi B} + h_{\varphi \tilde{B}} O_{\varphi \tilde{B}} + h_{WB} O_{WB} + h_{\tilde{W}B} O_{\tilde{W}B} + h_{\varphi}^{(1)} O_{\varphi}^{(1)} + h_{\varphi}^{(3)} O_{\varphi}^{(3)}\Big),$$

$$O_W = \epsilon_{ijk}\, W_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu}, \qquad O_{\tilde{W}} = \epsilon_{ijk}\, \tilde{W}_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu},$$

$$O_{\varphi W} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) W_{\mu\nu}^i W^{i\,\mu\nu}, \qquad O_{\varphi \tilde{W}} = \left(\varphi^\dagger \varphi\right) \tilde{W}_{\mu\nu}^i W^{i\,\mu\nu},$$

$$O_{\varphi B} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) B_{\mu\nu} B^{\mu\nu}, \qquad O_{\varphi \tilde{B}} = \left(\varphi^\dagger \varphi\right) \tilde{B}_{\mu\nu} B^{\mu\nu},$$

$$O_{WB} = \left(\varphi^\dagger \tau^i \varphi\right) W_{\mu\nu}^i B^{\mu\nu}, \qquad O_{\tilde{W}B} = \left(\varphi^\dagger \tau^i \varphi\right) \tilde{W}_{\mu\nu}^i B^{\mu\nu},$$

$$O_\varphi^{(1)} = \left(\varphi^\dagger \varphi\right) \left(\mathcal{D}_\mu \varphi\right)^\dagger \left(\mathcal{D}^\mu \varphi\right), \qquad O_\varphi^{(3)} = \left(\varphi^\dagger \mathcal{D}_\mu \varphi\right)^\dagger \left(\varphi^\dagger \mathcal{D}^\mu \varphi\right).$$

- 10 dimensionless anomalous couplings h_i with

$$h_i \sim \mathcal{O}\left(v^2/\Lambda^2\right),$$

  where $v = 246$ GeV, $\Lambda =$ new physics scale
- 4 anomalous couplings CP violating

Processes at the ILC

- $e^+e^- \to Z$ (Giga Z) highly sensitive to (P_Z):

$$h_{WB}, h_{\varphi}^{(3)}$$

- $e^+e^- \to W^+W^-$ sensitive to (P_W):

$$h_W,\ h_{WB},\ h_{\varphi}^{(3)},\ h_{\tilde{W}},\ h_{\tilde{W}B}$$

  (3 CP conserving, 2 CP violating)

- $\gamma\gamma \to W^+W^-$ sensitive to (P_W):

$$h_W,\ h_{WB},\ h_{\tilde{W}},\ h_{\tilde{W}B}, (s_1^2 h_{\varphi W} + c_1^2 h_{\varphi B}),\ (s_1^2 h_{\varphi \tilde{W}} + c_1^2 h_{\varphi \tilde{B}})$$

  (3 CP conserving, 3 CP violating)

- only $\gamma\gamma$ process allows direct measurement of:

$$h_{\varphi WB} \equiv s_1^2\, h_{\varphi W} + c_1^2\, h_{\varphi B}$$
$$h_{\varphi \tilde{W}\tilde{B}} \equiv s_1^2\, h_{\varphi \tilde{W}} + c_1^2\, h_{\varphi \tilde{B}}$$

  where $s_1^2 \equiv \frac{e^2}{4\sqrt{2}G_F m_W^2}, \quad c_1^2 \equiv 1 - s_1^2$

- all processes together: 7 out of 10 indep. couplings observable

Previous work

a lot of excellent work on anomalous couplings in $\gamma\gamma \to WW$ exists: e.g. (incomplete)
Tupper, Samuel (1981),
Choi, Schrempp (1991),
Yehudai (1991),
Bélanger, Boudjema (1992),
Herrero, Ruiz-Morales (1992),
Bélanger, Couture (1994),
Choi, Hagiwara, Baek (1996),
Baillargeon, Bélanger, Boudjema (1997),
Božović-Jelisavčić, Mönig, Šekarić (2002),
Bredenstein, Dittmaier, Roth (2004),
Mönig, Šekarić (2005),
Nachtmann, Nagel, Pospischil, Utermann (2005),
...

Layout

Feynman diagrams

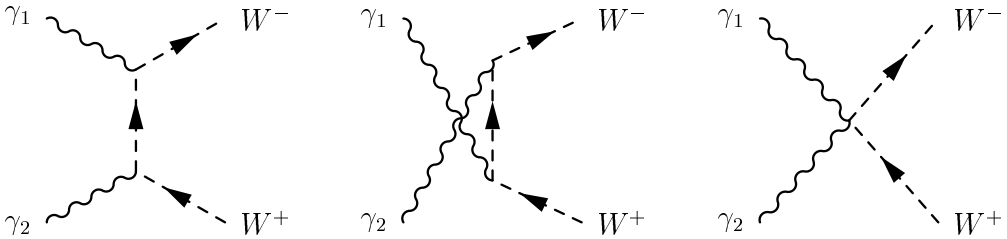
Nachtmann, Nagel, Pospischil, Utermann

Consider

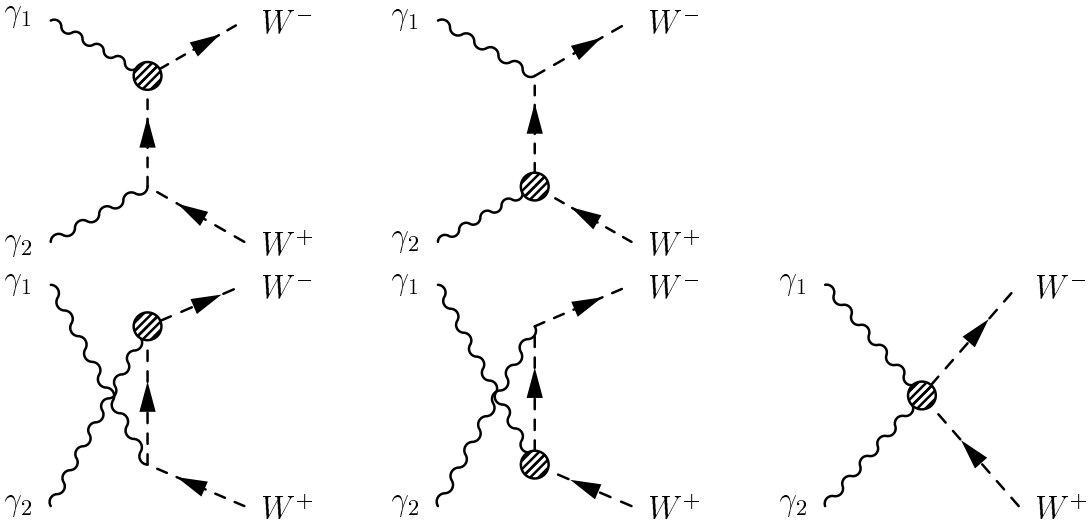
$$\gamma\gamma \to W^+W^- \to f\bar{f}\,f\bar{f}$$

in narrow-width-approximation.

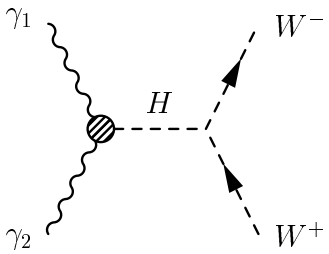
Production in SM:



via anom. gauge couplings:



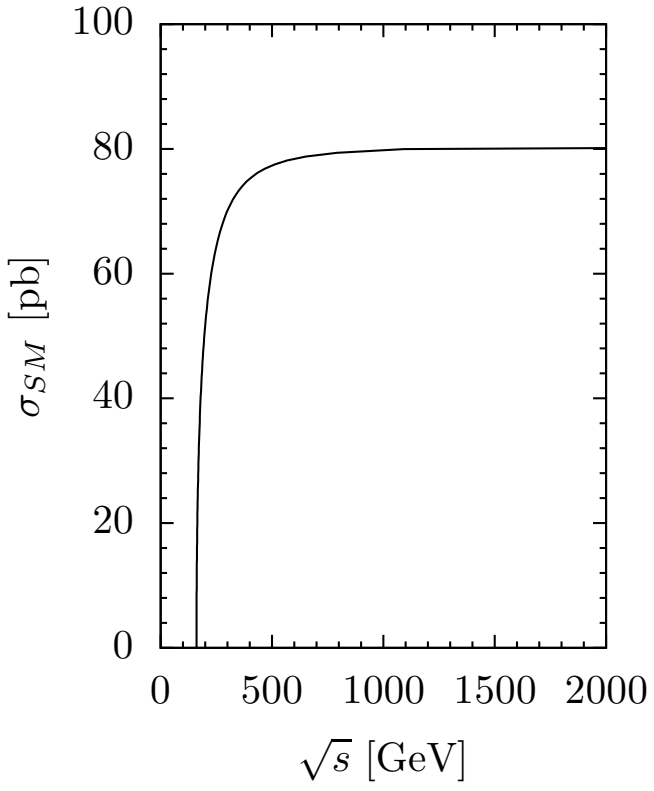
via anom. $\gamma\gamma H$ coupling:



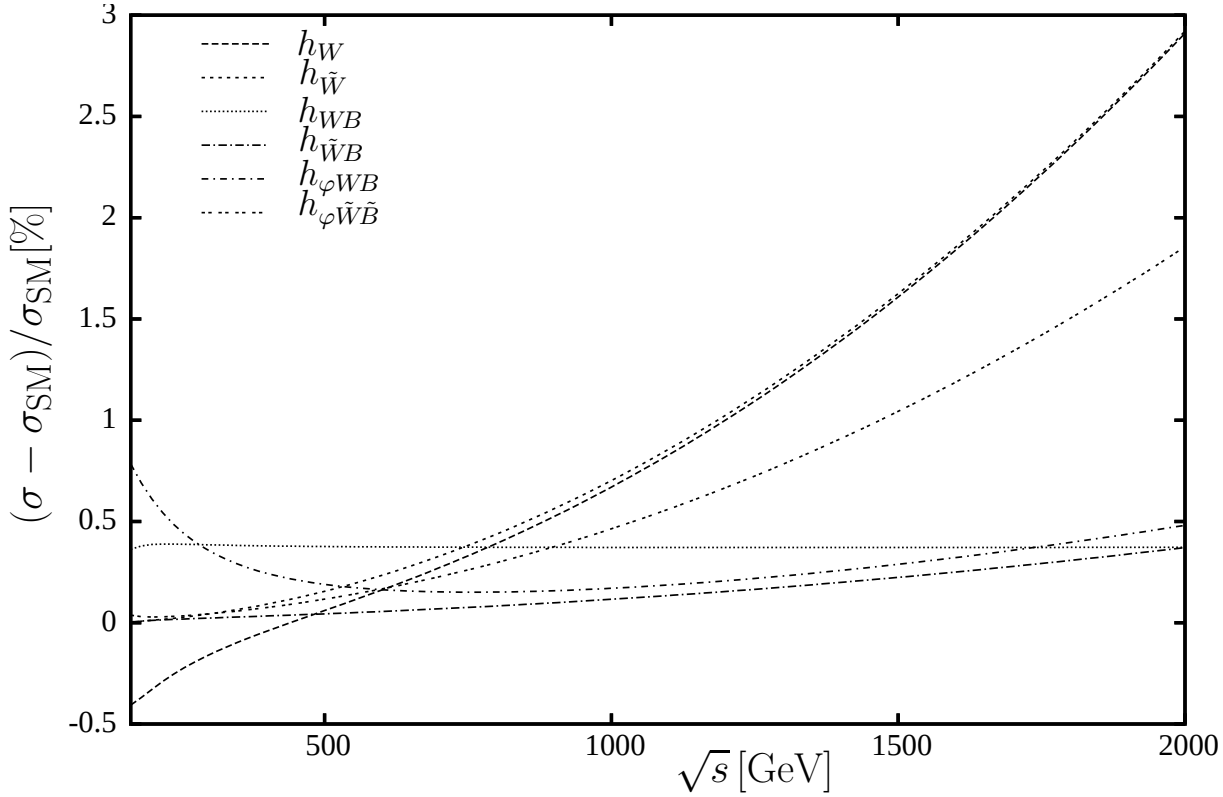
Total cross section

Nachtmann, Nagel, Pospischil, Utermann

Standard Model:



Deviations through anom. couplings:



(plot for $h_{WB} = 10^{-3}$, other $h_i = 10^{-2}$)

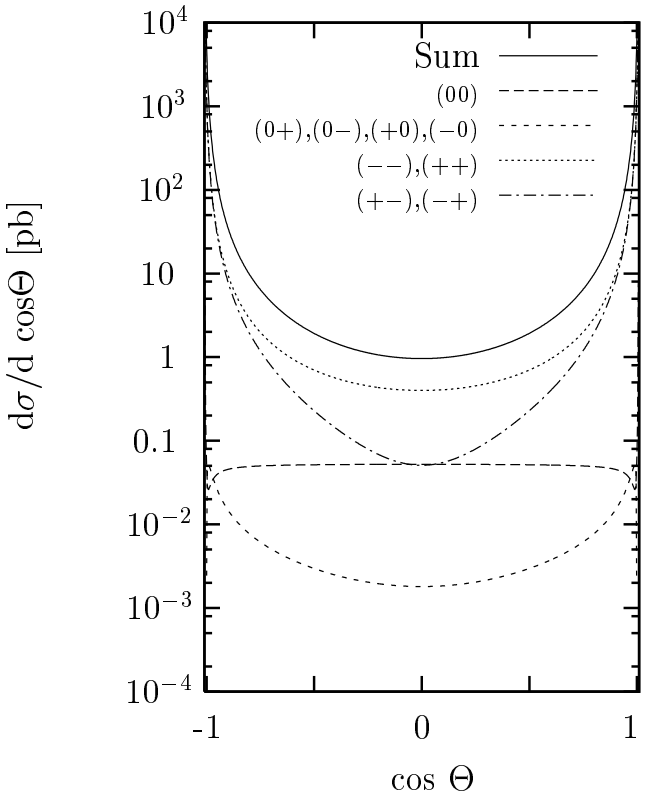
- up to γ^2 enhancements for anomalous ME
- CP odd only at quadratic order

Distributions

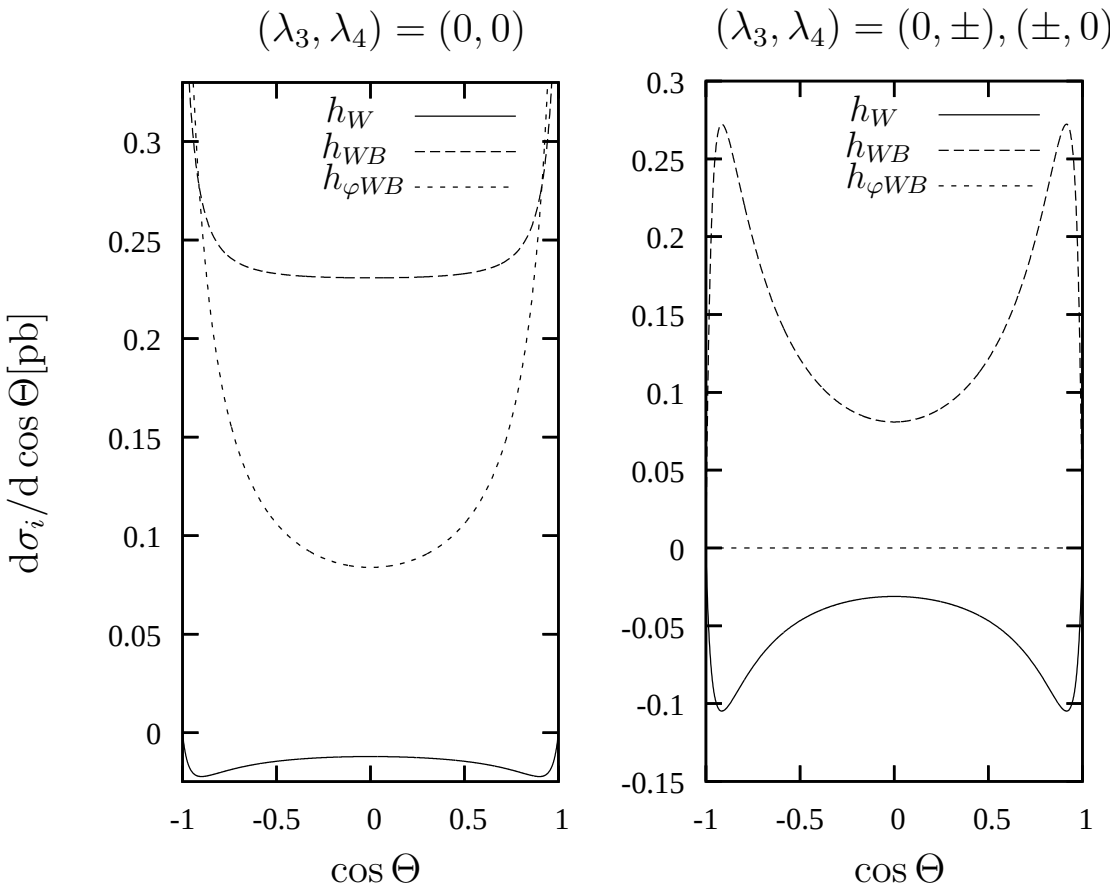
Nachtmann, Nagel, Pospischil, Utermann

diff. cross section: $$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\Theta} = \frac{\mathrm{d}\sigma_{SM}}{\mathrm{d}\cos\Theta} + \sum_i h_i \frac{\mathrm{d}\sigma_i}{\mathrm{d}\cos\Theta} + \mathcal{O}(h^2)$$

Standard Model:



Anomalous CP even:



- no CP odd in linear order

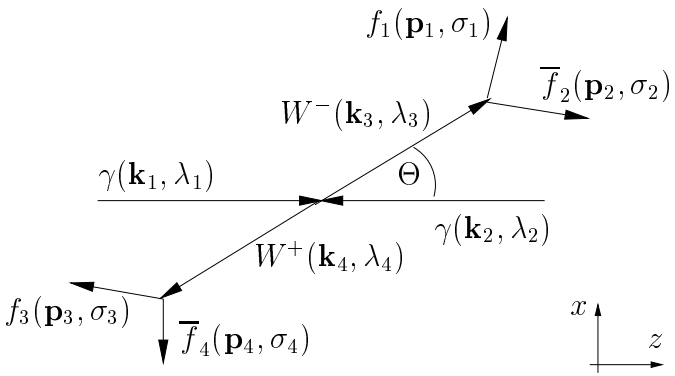
Inclusion of decay information

Nachtmann, Nagel, Pospischil, Utermann

Full information: diff. cross section incl. W decays

$$S(\phi) \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\Theta\,\mathrm{d}\cos\vartheta\,\mathrm{d}\varphi\,\mathrm{d}\cos\bar{\vartheta}\,\mathrm{d}\bar{\varphi}}$$
$$= \frac{3^2\beta}{2^{11}\pi^3 s} B_{12} B_{34} \mathcal{P}^{\lambda_3\lambda_4}_{\lambda_3'\lambda_4'} \mathcal{D}^{\lambda_3}_{\lambda_3'} \bar{\mathcal{D}}^{\lambda_4}_{\lambda_4'}$$

where $\phi =$ phase space variables



$\Rightarrow$ access to $\mathcal{O}(h)$ contrib. for all h_i.

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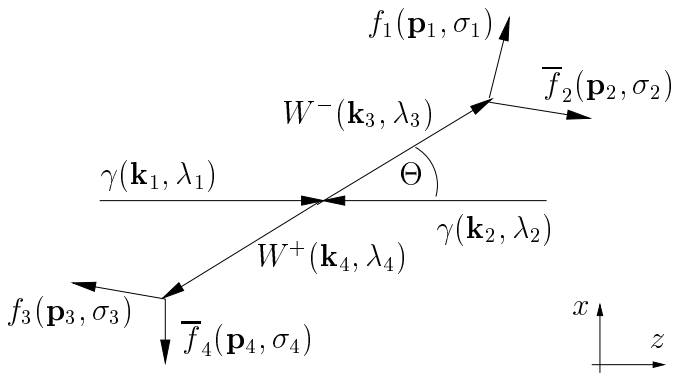


$\Rightarrow$ access to $\mathcal{O}(h)$ contrib. for all h_i.

No CP odd contributions $\mathcal{O}(h)$ after phase space integration:

- expand diff. cross section in h_i: $\mathrm{d}\sigma/\mathrm{d}\phi = S_0(\phi) + \sum_i h_i S_{1i}(\phi) + \mathcal{O}(h^2)$
- linear coefficient = interference term

$$S_i(\phi) \propto \sum_{\lambda_3,\lambda_4,\lambda_3',\lambda_4'} 2\,\mathrm{Re}\,\mathcal{M}_{SM}(\lambda_3,\lambda_4)\mathcal{M}_i^*(\lambda_3',\lambda_4')\mathcal{D}^{\lambda_3}_{\lambda_3'}\bar{\mathcal{D}}^{\lambda_4}_{\lambda_4'}$$

- for CP parity $\pi_i = \pm 1$ of $\mathcal{O}_i$ we have

$$\mathcal{M}_i^* = \pi_i \mathcal{M}_i, \qquad (\mathcal{D}^{\lambda}_{\lambda'}(\cos\vartheta,\varphi))^* = \mathcal{D}^{\lambda}_{\lambda'}(\cos\vartheta,-\varphi)$$

$\Rightarrow$ CP mixed expressions vanish after $\varphi, \bar{\varphi}$ integration

Optimal observables

Atwood & Soni, Davier et al., Diehl & Nachtmann

How to measure anom. coupl. with best statistical accuracy ? $\Rightarrow$ optimal observables

- expand diff. cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} = S_0(\phi) + \sum_i h_i S_{1i}(\phi) + \mathcal{O}(h^2) \qquad \text{where} \quad \begin{array}{l} h_i = \text{anomalous couplings} \\ \phi = \text{phase space variables} \end{array}$$

- statist. optimal observables for small h_i (wo/ rate info):

$$\mathcal{O}_i \equiv \frac{S_{1i}(\phi)}{S_0(\phi)}$$

- measure ϕ_k for each event $k = 1, \ldots, N$, evaluate:

$$\bar{\mathcal{O}}_i = \frac{1}{N} \sum_k \mathcal{O}_i(\phi_k)$$

  and calculate $c_{ij} \equiv \left\langle \, (\mathcal{O}_i - \langle \mathcal{O}_i \rangle_0)\,(\mathcal{O}_j - \langle \mathcal{O}_j \rangle_0) \, \right\rangle_0$ with $\langle \circ \rangle_0 = \frac{\int \mathrm{d}\phi S_0(\phi)\,\circ}{\int \mathrm{d}\phi S_0(\phi)}$
  to get estimate of couplings

$$h_i = \sum_j c_{ij}^{-1} \, \left(\bar{\mathcal{O}}_j - \langle \mathcal{O} \rangle_0\right)$$

- covariance matrix for h_i computable without data

$$V(h) = \frac{1}{N} c_{ij}^{-1}$$

Layout

Parameters

Choices and assumptions:

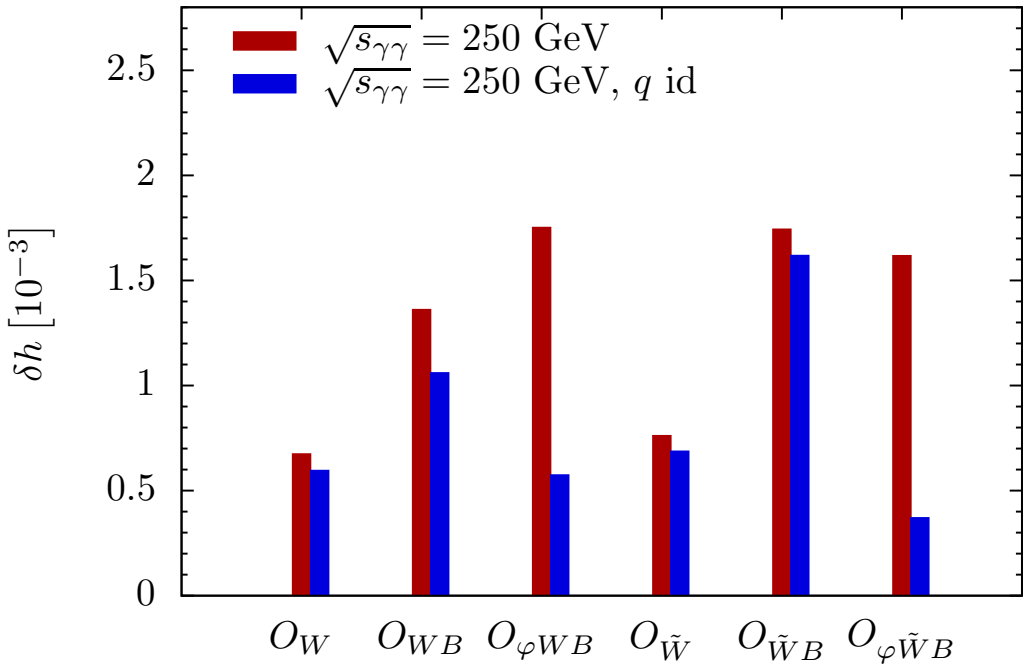
- semileptonic channels with $l = e^+, \mu^+, e^-, \mu^-$
- no q flavour id $\Rightarrow$ two-fold jet ambiguity
- $m_{Higgs} = 120$ GeV
- $\int L_{ee} = 500$ fb^{-1}

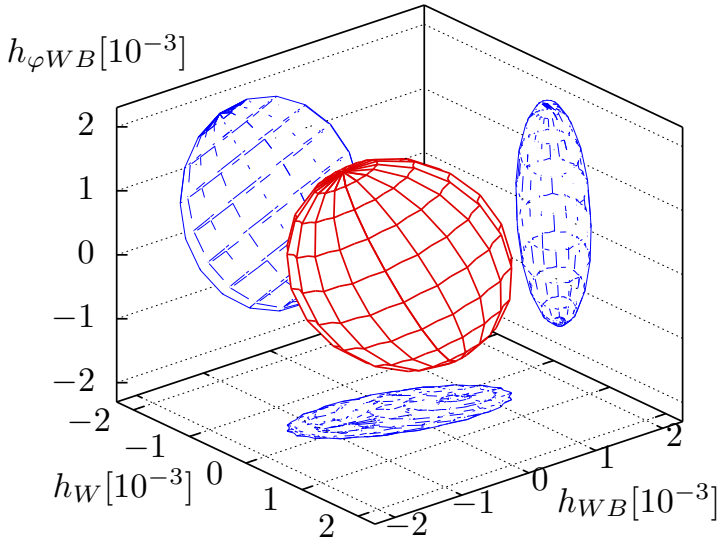
Note:

- CP even - CP odd correlations vanish

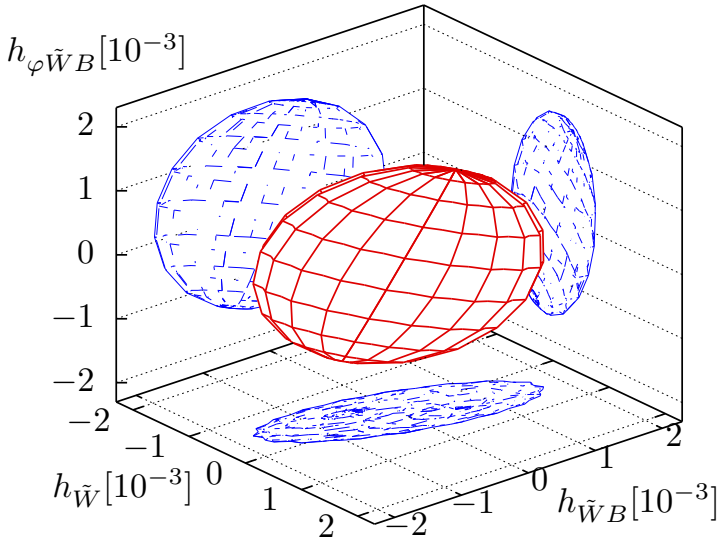
Results: Sensitivity at fixed $\gamma\gamma$ energy

preliminary





CP even (no q id)

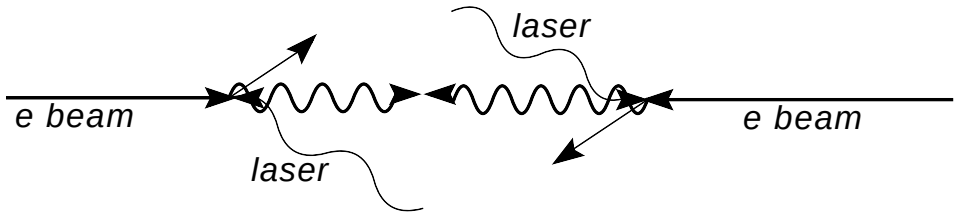


CP odd (no q id)

Unpolarised Compton spectrum

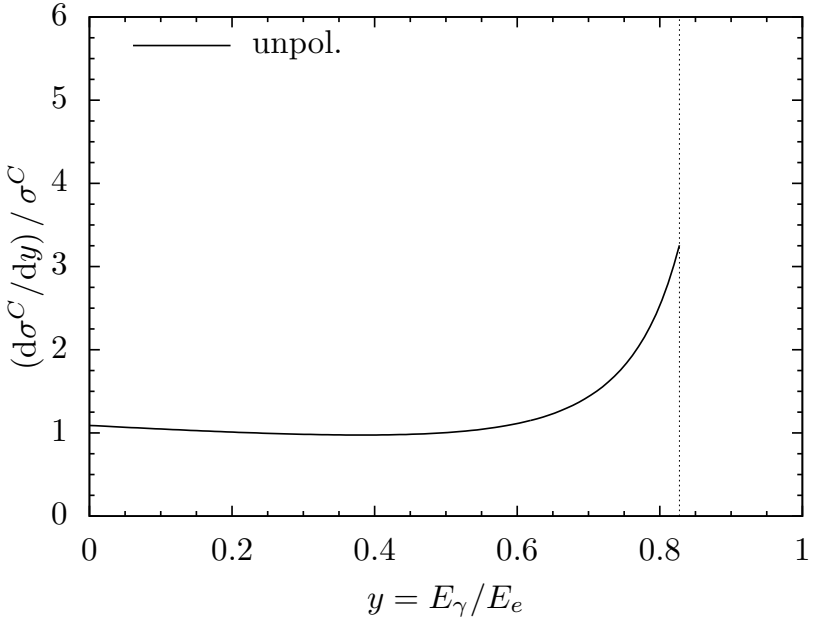
Ginzburg, Kotkin, Panfil, Serbo, Telnov

Photons via Compton backscattering of laser on *e* beam

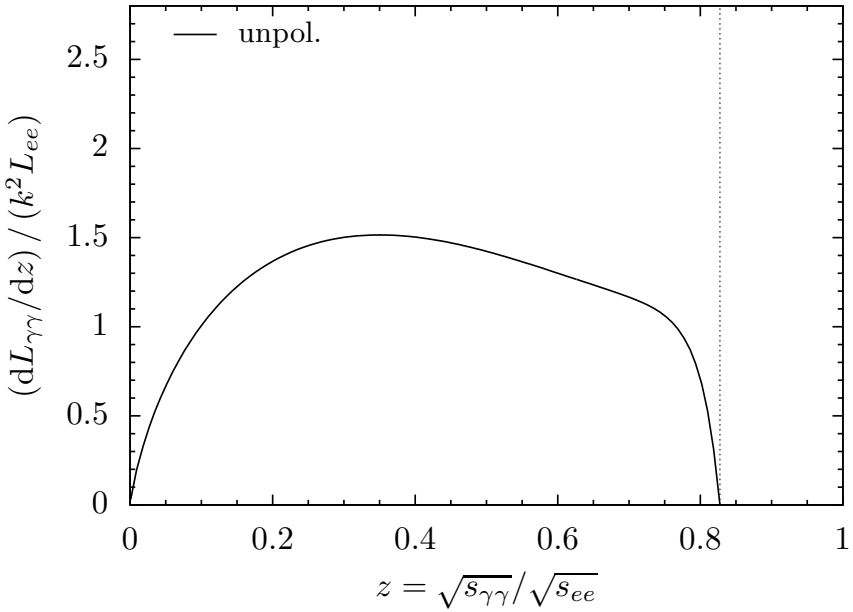


- use simple Compton formula
- $\sqrt{s_{ee}} = 500$ GeV
- hard $\gamma\gamma$ CMS statistically distrib.
- more realistic: nonlinear effects + multiple scattering

norm. single γ spectrum:



norm. $\gamma\gamma$ luminosity spectrum:



Neutrino ambiguity

neutrino momentum unknown, reconstruction not unique:

- transversal momentum unique
- two-fold ambiguity for neutrino energy (for part of phase space)
- $\times$ two-fold jet ambiguity (as before)

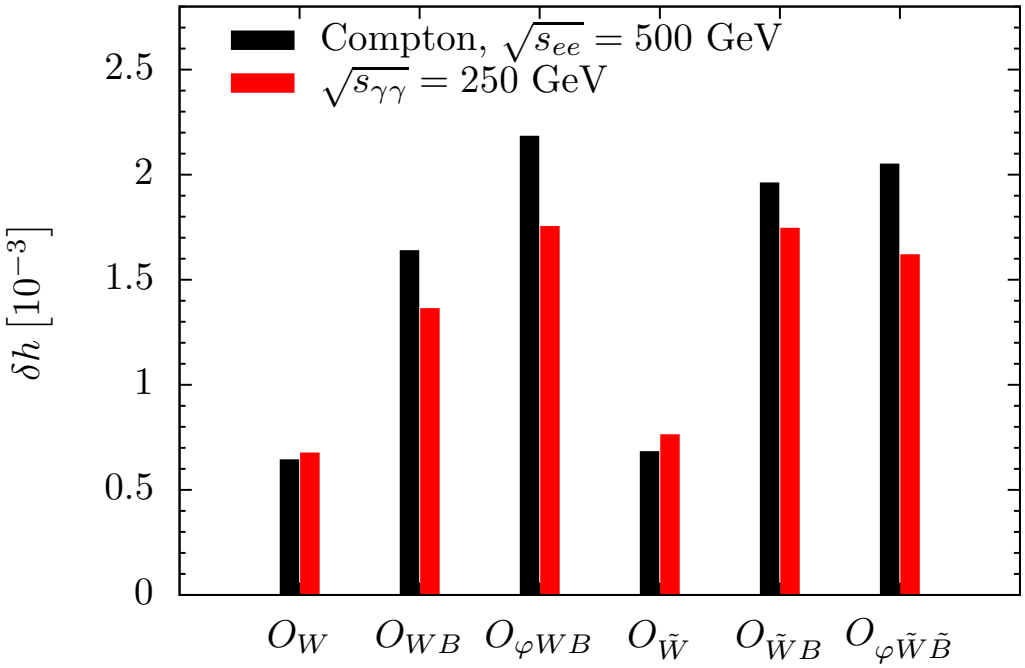
for calculation of covariance matrix:

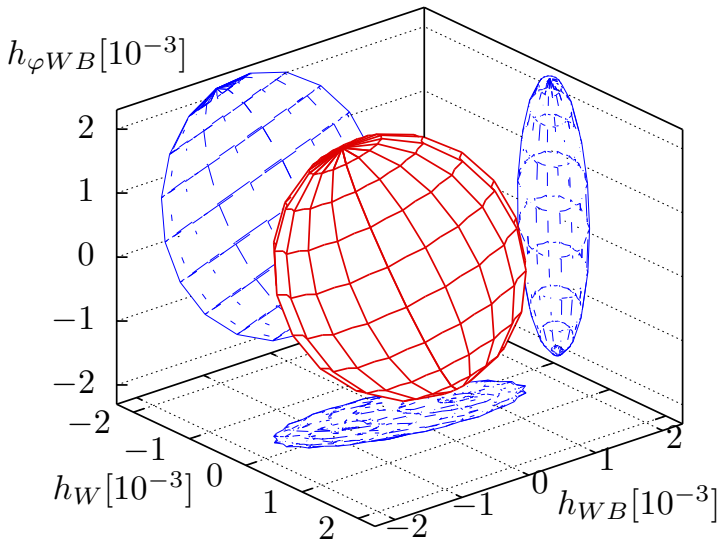
- use Jacobi-weighted sums over experim. equivalent states
- integrate sums over unique phase space

general discussion of opt. observ. in presence of ambiguities:
Nachtmann, Nagel, Pospischil

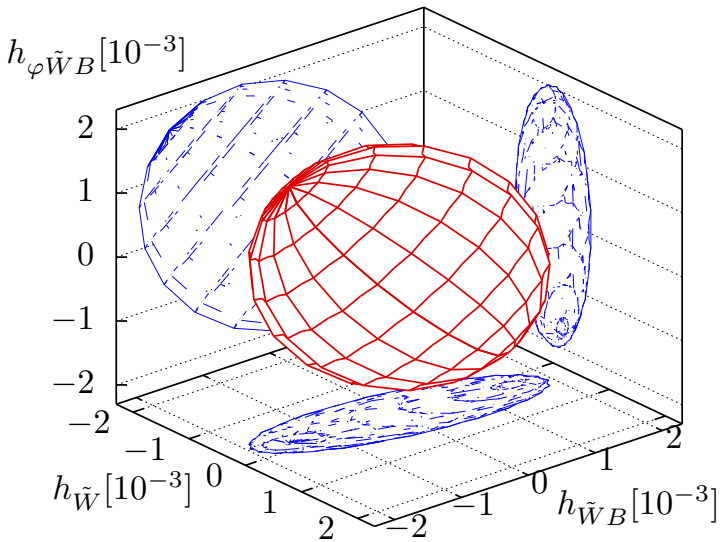
Results: Sensitivity with Compton spectrum

preliminary





CP even (Compton)



CP odd (Compton)

Layout

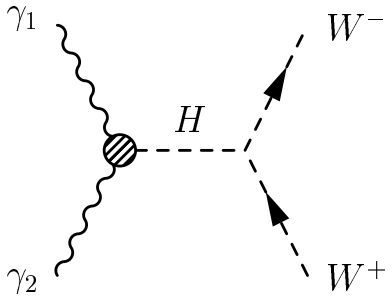
Possible improvements

Expect higher accuracies from

- higher energies
- polarised $\gamma\gamma$ initial state

Polarisation ($\sim$ more information) disentangles different contributions:

- increased differences in angular distributions
- even "switch off terms" completely:
  e.g.: no Higgs production for $\lambda_1 = -\lambda_2$, that is $|J_z| = 2$



High energies through polarisation

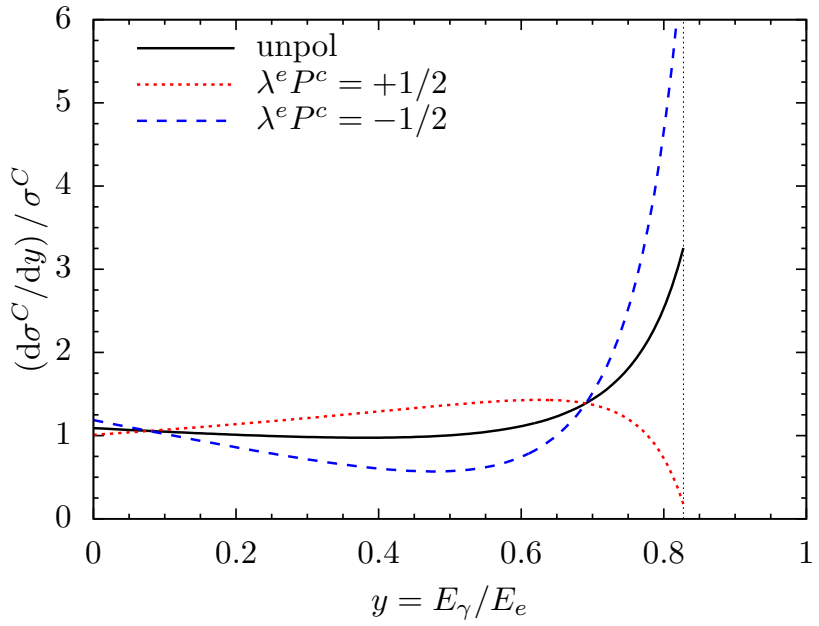
Notation:

- λ^e = mean e helicity
- P^C = circular laser polarisation
- k = conversion efficiency

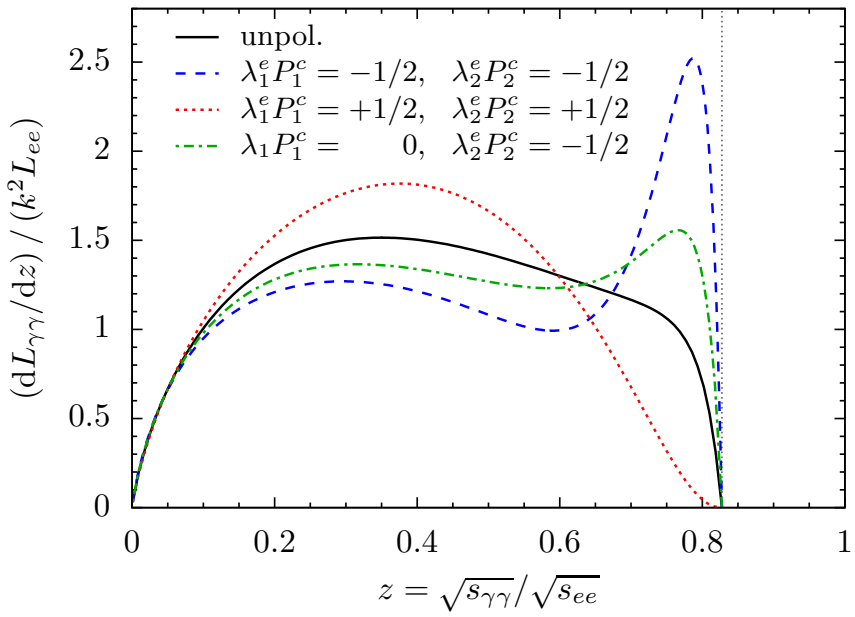
Polarisation of e and laser gives

- significant change in spectral distributions
- enhanced high energy peak for opposite mean helicities ($\lambda^e P^C = -1/2$)

norm. single γ spectrum:

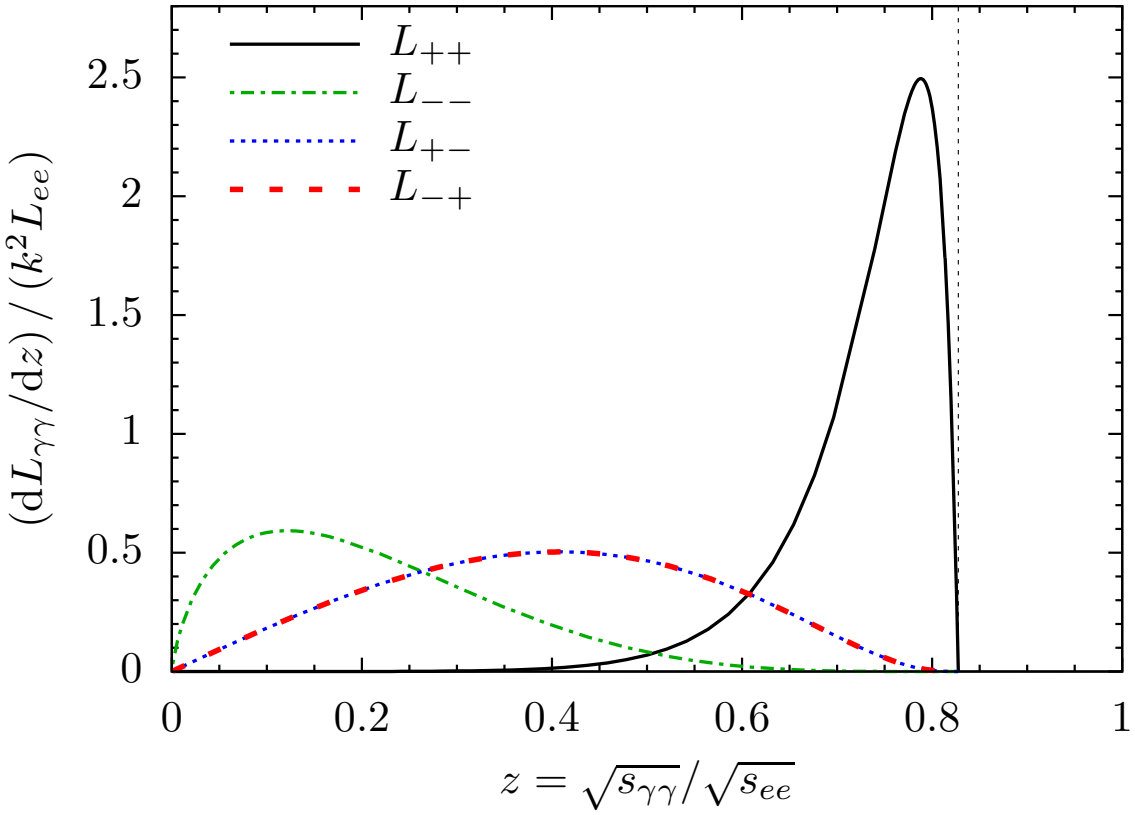


norm. $\gamma\gamma$ spectral luminosity:



Effective polarisation of hard $\gamma\gamma$

Norm. luminosity spectra for different helicities for choice $\lambda_1^e = \lambda_2^e = 1/2$, $P_1^C = P_2^C = -1$:

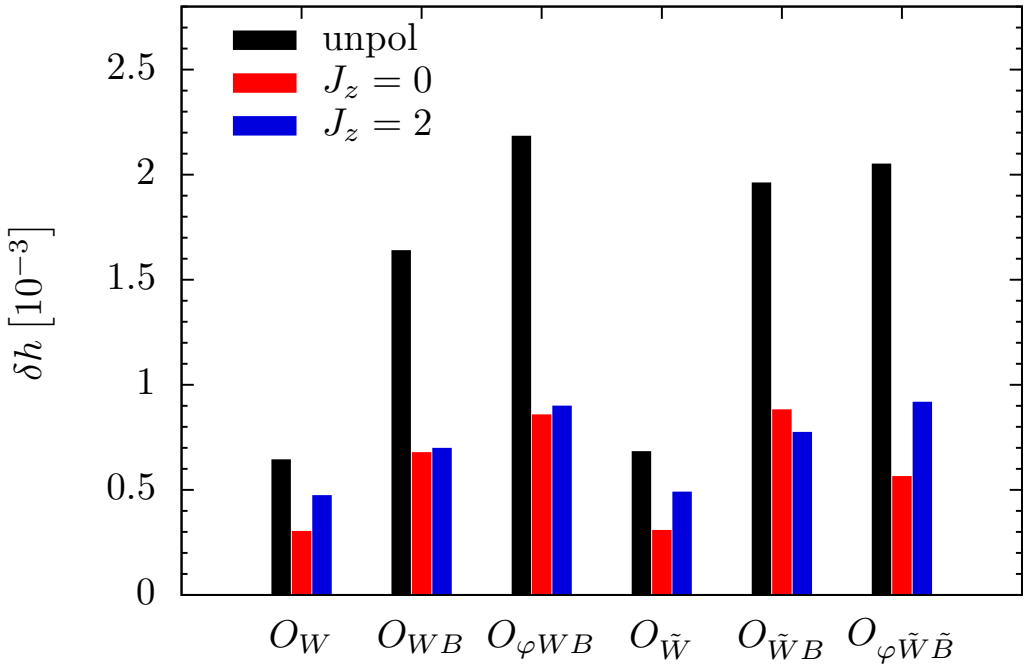


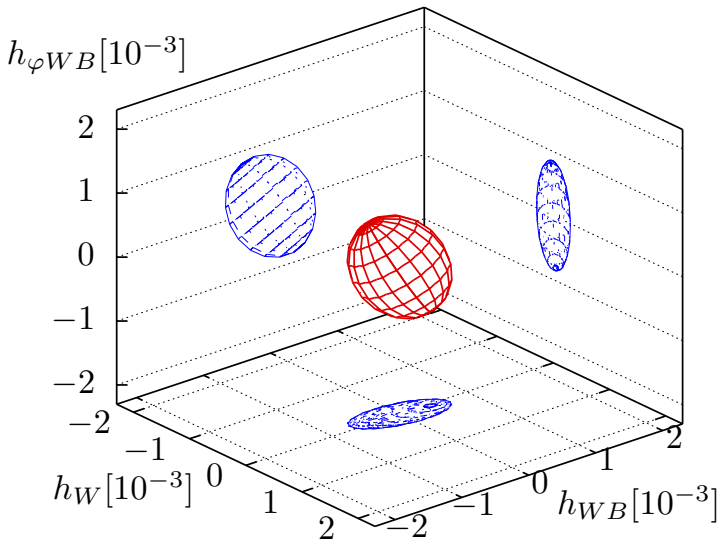
Polarisation of resulting hard $\gamma\gamma$:

- only slight average polarisation
- but: considerable separation in energy
- high energy enhancement provided by $\lambda^e P^C = -1/2$
- still free choice: signs of λ_i^e
  $\Rightarrow$ adjust signs to select high energy peak for specific helicities

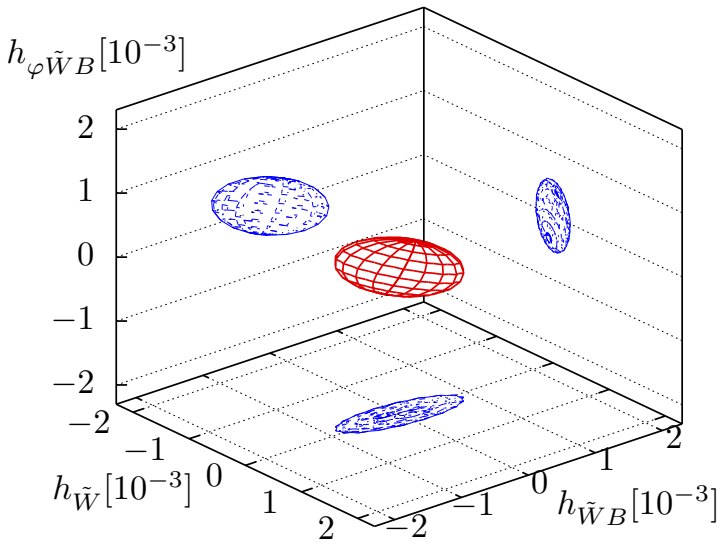
Results: Sensitivity with polarisation

preliminary





CP even ($J_z = 0$)



CP odd ($J_z = 0$)

Comparison to e^+e^-

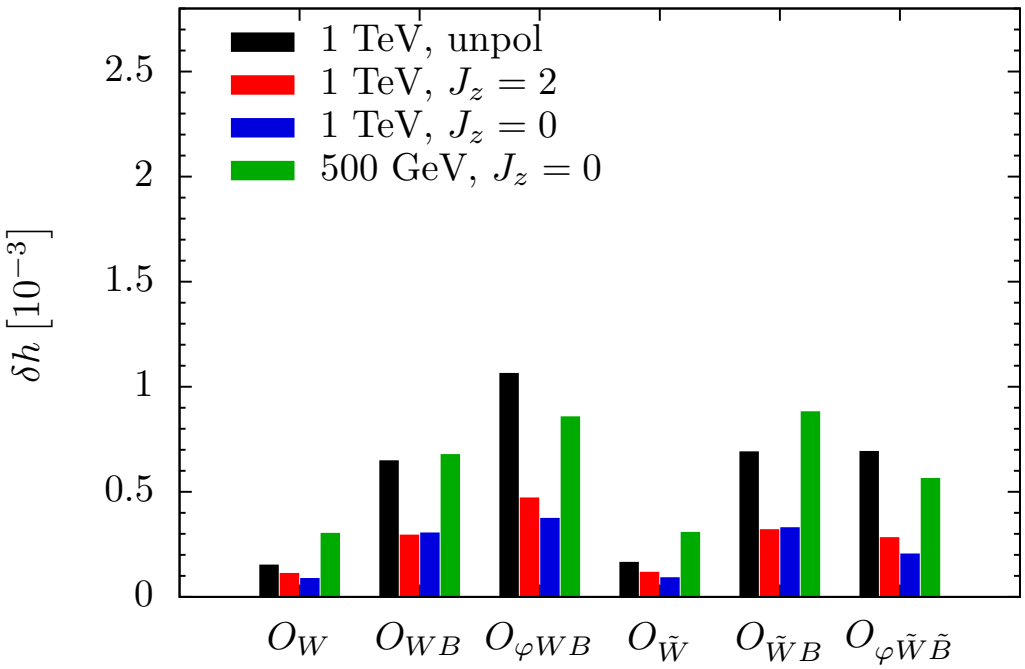
	LEP & SLD (*)	$ee \to WW$ (*)	$\gamma\gamma \to WW$ unpolarised	$\gamma\gamma \to WW$ $J_z = 0$
	$h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$
measurable CP conserving couplings:				
h_W	-69 ± 39	0.3	0.6	0.3
h_{WB}	-0.06 ± 0.79	0.3	1.6	0.7
$h_{\varphi WB}$	$\times$	$\times$	2.2	0.9
$h_\varphi^{(3)}$	-1.15 ± 2.39	36.4	$\times$	$\times$
measurable CP violating couplings:				
$h_{\tilde{W}}$	68 ± 81	0.3	0.7	0.3
$h_{\tilde{W}B}$	33 ± 84	2.2	2.0	0.9
$h_{\varphi\tilde{W}\tilde{B}}$	$\times$	$\times$	2.0	0.6

3 more anomalous couplings unaccessible by these methods:

$h_\varphi^{(1)}, h'_{\varphi WB}, h'_{\varphi\tilde{W}\tilde{B}}$

(*) Nachtmann, Nagel, Pospischil

Results: Sensitivity at 1 TeV



integrated luminosities:

- at $\sqrt{s_{ee}} = 500$ GeV: $L_{ee} = 500$ fb^{-1}
- at $\sqrt{s_{ee}} = 1$ TeV: $L_{ee} = 1000$ fb^{-1}

Summary

Effective Lagrangian approach:

- parametrisation of deviations from SM by new high energy physics
- process independent
- 10 anomalous gauge / gauge-Higgs couplings (6 CP cons., 4 CP viol.)

$e^+e^- \to WW$ at the ILC:

- norm. distributions: 5 anom. coupl.
- accuracies $\mathcal{O}(10^{-3})$ for anom. coupl.

Electroweak precision observables (Giga-Z) at the ILC:

- best for 2 of above 5 anom. coupl.

$\gamma\gamma \to WW$ at the ILC:

- norm. distributions: 2 more anom. coupl.
- accuracies $\mathcal{O}(10^{-3})$ for anom. coupl.
- polarisation may reduce errors by a factor of 2

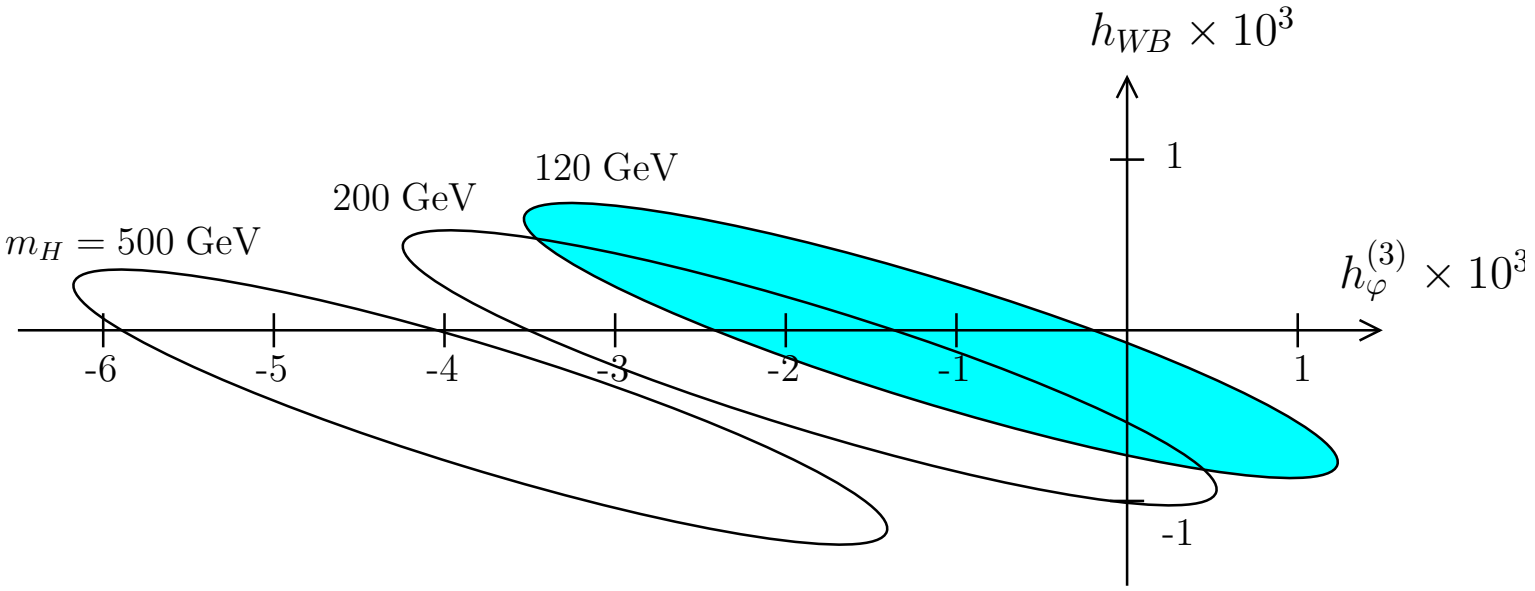
Supplementary Slides

- Details for present limits
- Heavy Higgs
- Separation Cuts
- Polarised photons at fixed energy

Present limits: CP conserving

Nachtmann, Nagel, Pospischil

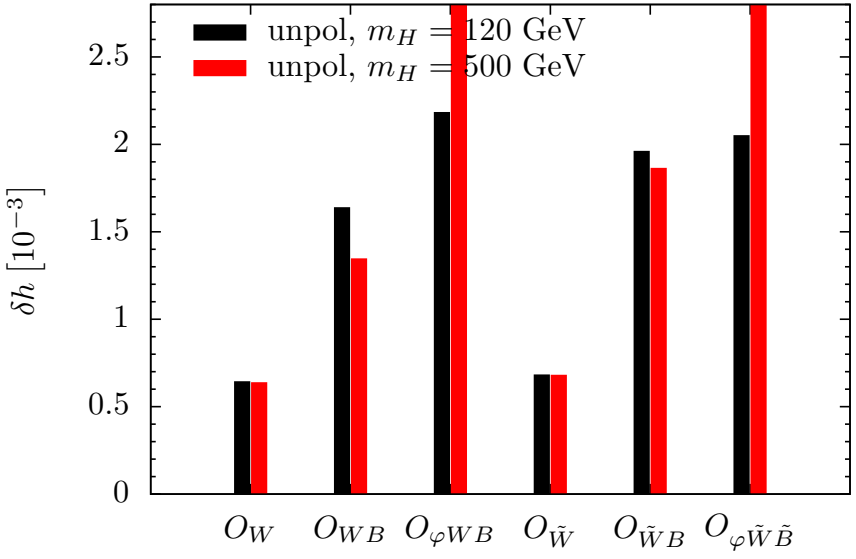
Present bounds on CP conserving couplings from LEP1, LEP2, SLD, Γ_W, M_W (P_Z):

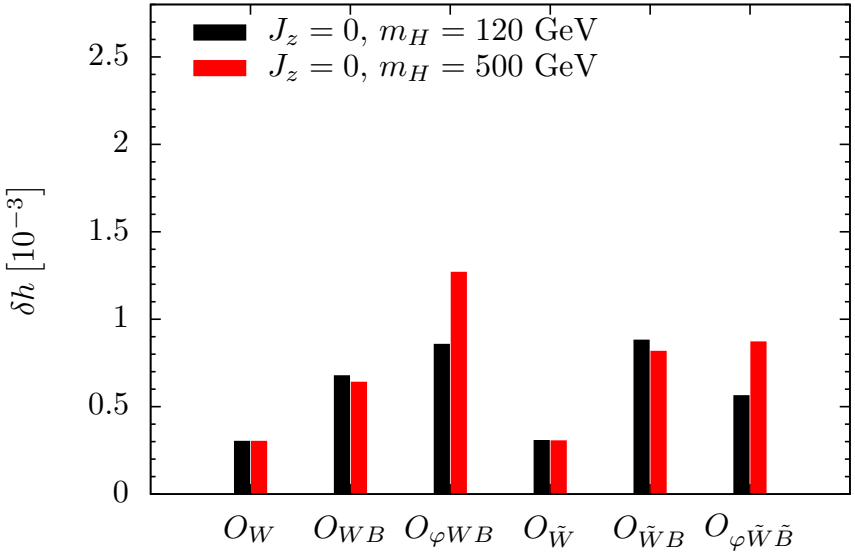


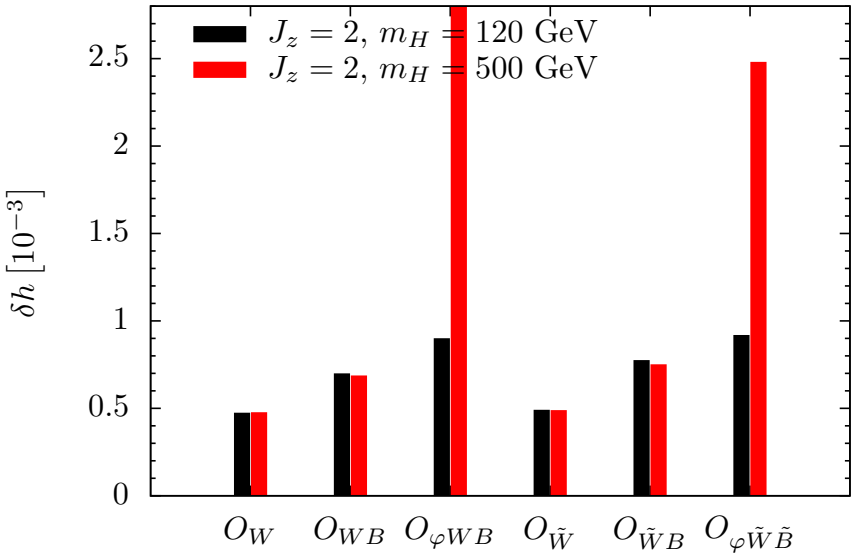
		$s^2_{\rm eff}$, Γ_Z, $\sigma^0_{\rm had}$, R^0_ℓ, m_W, Γ_W, TGCs						
m_H		120 GeV	200 GeV	500 GeV	$\delta h \times 10^3$			
h_W	$\times 10^3$	-62.4	-62.5	-62.8	36.3	1	-0.007	0.008
h_{WB}	$\times 10^3$	-0.06	-0.22	-0.45	0.79		1	-0.88
$h_\varphi^{(3)}$	$\times 10^3$	-1.15	-1.86	-3.79	2.39			1

Heavy Higgs

preliminary

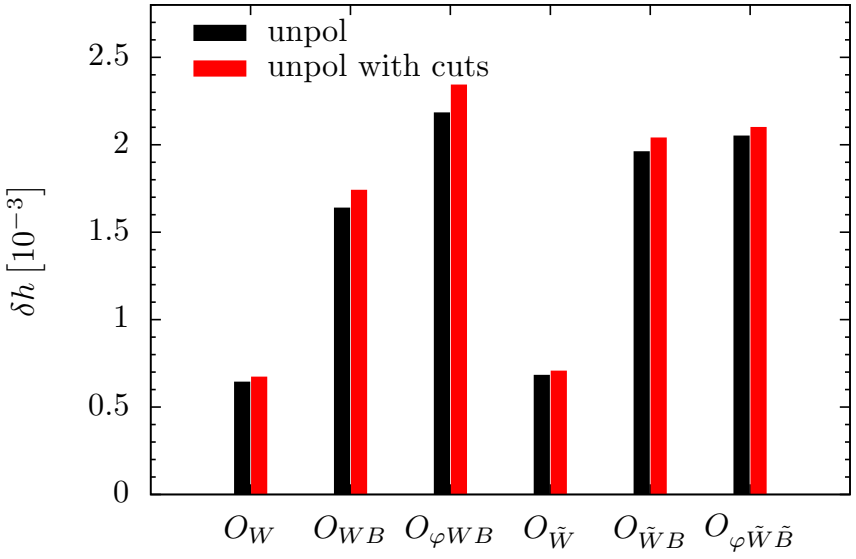


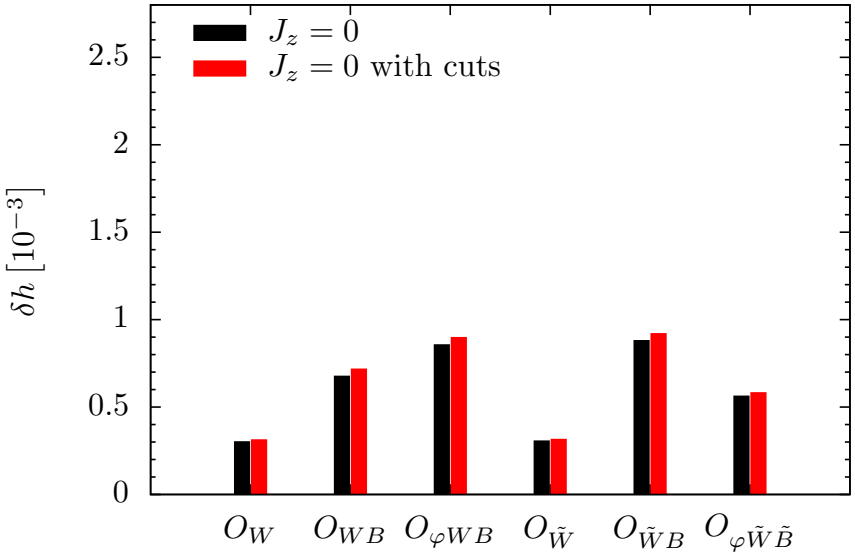


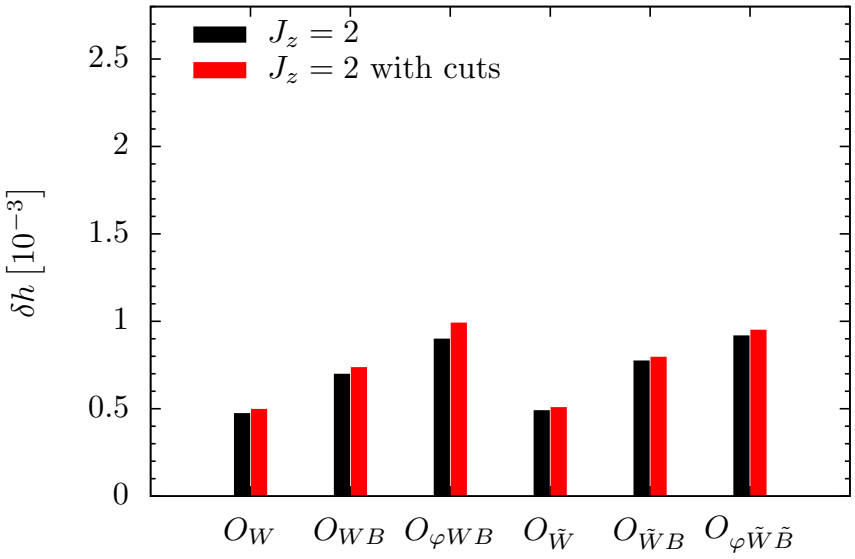


Separation cuts

preliminary





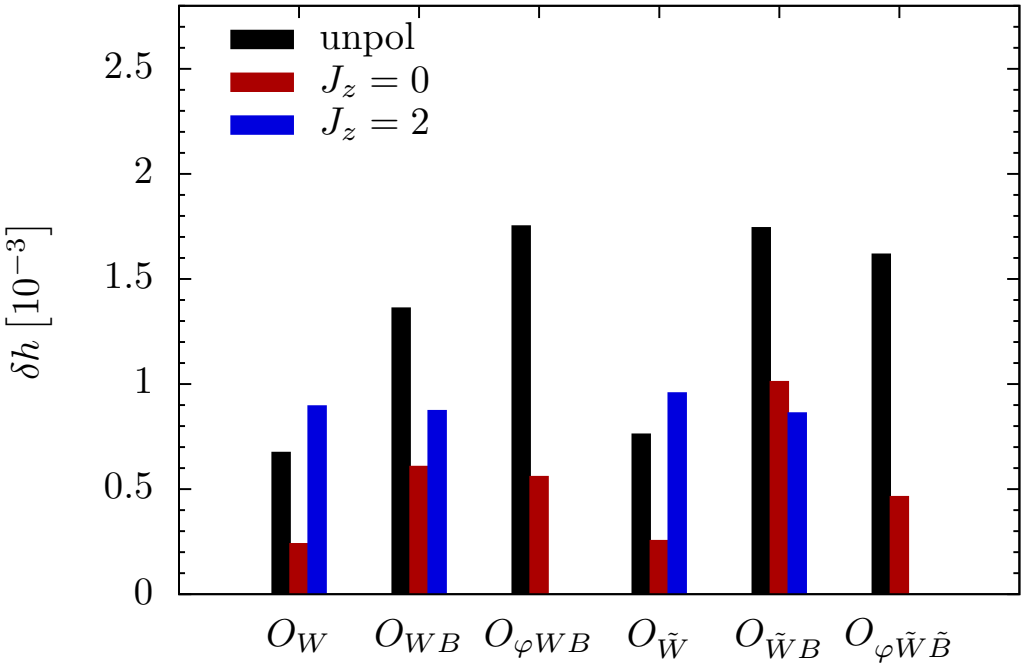


Separation cuts on observed fermions:

- fermion energy > 10 GeV
- fermion angle w.r.t. beam $> 10°$
- angle betw. obs. fermions $> 25°$

Polarised photons at fixed energy

preliminary



- $\sqrt{s_{\gamma\gamma}} = 250$ GeV
- no sensitivity on $h_{\varphi WB}, h_{\varphi\tilde{W}\tilde{B}}$ for $J_z = 2$