Anomalous couplings in $\gamma\gamma \to W^+W^-$ at LHC and ILC

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in collaboration with

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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

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 $\longleftarrow$ here
      - ★ 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

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

- 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

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

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

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

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

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

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

- 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

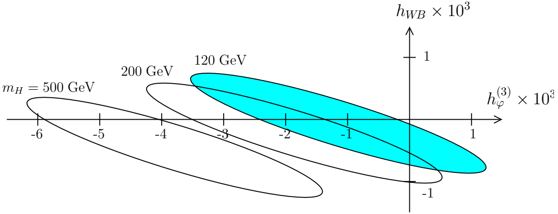
Spontaneous symmetry breaking

- Higgs field φ obtains VEV
- anomalous contrib. to kinetic and mass terms of gauge bosons:
  - kinetic term: $h_{\varphi W},\ h_{\varphi B},\ h_{WB}$
  - mass term: $h_{\varphi}^{(1)},\ h_{\varphi}^{(3)}$
- get physical $W^{\pm},\ Z,\ \gamma$ fields:
  - renormalisation of $W^{\pm}$
  - simultaneous diag. of kinetic and mass terms for $\gamma,\ Z$
- $\Rightarrow$ physical $W^{\pm},\ Z,\ \gamma$ modified wrt. SM
  - e.g.: Z decays sensitive to anom. couplings

Present limits

Nachtmann, Nagel, Pospischil

Present bounds on CP conserving couplings (P_Z)
from LEP1, LEP2, SLD, and Tevatron:



TGCs		
	h	δh
$h_{\tilde{W}}$	0.068	0.081
$h_{\tilde{W}B}$	0.033	0.084

		s^2_{eff}, Γ_Z, σ^0_{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

Processes at ILC and LHC

- $e^+e^- \to Z$ (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:

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

  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),
Piotrzkowski (2001),
Božović-Jelisavčić, Mönig, Šekarić (2002),
Bredenstein, Dittmaier, Roth (2004),
Mönig, Šekarić (2005),
Nachtmann, Nagel, Pospischil, Utermann (2005),
de Favereau de Jeneret, Lemaître, Liu, Ovyn, Pierzchała, Piotrzkowski, Rouby, Schul, Vander Donckt (in prep.),
...

see also other talks, in particular by:
D. Zeppenfeld, O. Eboli, T. Pierzchała, O. Kepka, and N. Schul

Layout

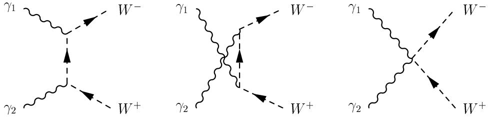
Feynman diagrams

Consider

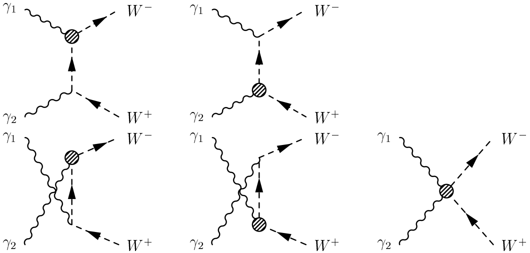
$$\gamma\gamma \to W^+W^- \to f\bar{f}\,f\bar{f}$$

in narrow-width-approximation.

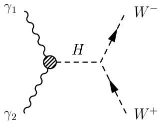
Production in SM:



via anom. gauge couplings:

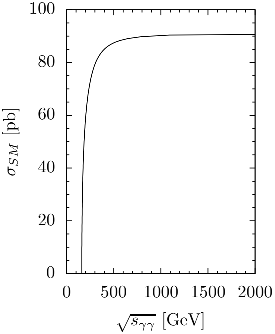


via anom. $\gamma\gamma H$ coupling:



Total cross section and energy dependencies

Standard Model:



High energy dependence of leading amplitudes:

$\mathcal{M}_i$	CP even				CP odd		
	SM	W	φW	WB	$\tilde{W}$	$\varphi\tilde{W}$	$\tilde{W}B$
LL	$1^{(*)}$	γ^{-2}	1	$\gamma^{2\,(\dagger)}$	γ^{-2}	1	$\gamma^{2\,(\dagger)}$
TL	γ^{-1}	γ^{-1}	0	γ	γ^{-1}	0	γ
TT	1	1	γ^{-2}	1	1	γ^{-2}	1

where $\gamma := \sqrt{s_{\gamma\gamma}}/(2m_W)$,
$(*)$: for $(\lambda_1 = -\lambda_2)$,
$(\dagger)$: for $(\lambda_1 = \lambda_2)$,

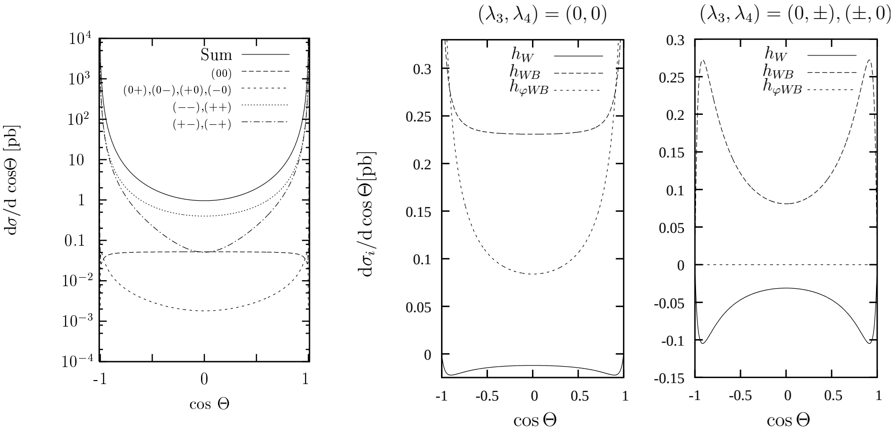
- up to γ^2 enhancements for anomalous amplitudes
- CP odd only at quadratic order

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

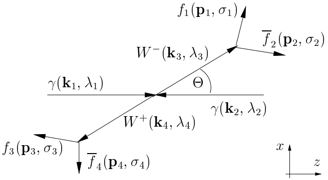
Nachtmann, Nagel, Pospischil, Utermann

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.



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:

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

- 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 $\left\langle \circ \right\rangle_0 = \frac{\int \mathrm{d}\phi S_0(\phi) \circ}{\int \mathrm{d}\phi S_0(\phi)}$
to get estimate of couplings

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

- covariance matrix for h_i computable without data

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

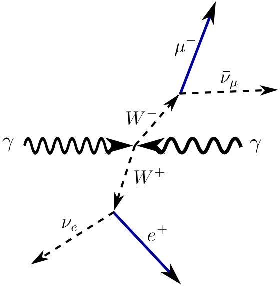
Choice of final states

- center-of-mass system not fixed in photon production
- loss of kinem. information $\Rightarrow$ treatable with opt. observ., but: lower sensitivies
- balance: signature, branching ratio, available information

type	signature	branching ratio	kinem. information
leptonic ($l = e, \mu$)	++	4/81	-
semi-leptonic ($l = e, \mu$)	+	24/81	+
hadronic	-	36/81	(++)

Leptonic final state:

- if CMS known: full reconstruction of final state
- if CMS unknown: no rec. possible



Choice of final states

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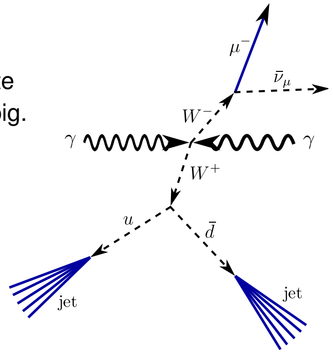
hadronic	-	36/81	(++)

Semi-leptonic final state:

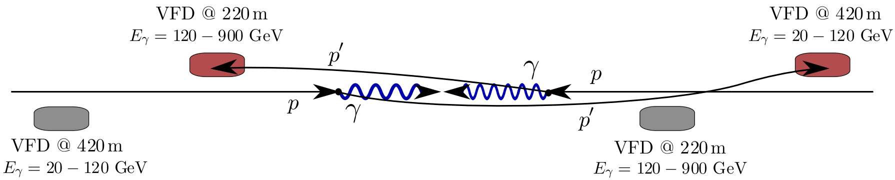
- if CMS known: full reconstruction of final state
- if CMS unknown: rec. up to 4-fold discr. ambig.
  - neutrino momentum unknown
  - transverse reconstruction unique
  - two-fold ambiguity for neutrino energy (for part of phase space)
  - two-fold jet ambiguity if q flavour ID missing

  ⇒ reconstruction possible up to 4-fold discrete ambiguity



Layout

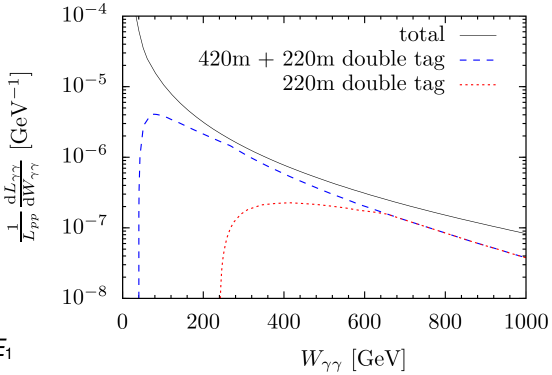
High energy photon production at the LHC



Budnev, Ginzburg, Meledin, Serbo

- almost real photons by elastic radiation off p
- tagging: large rap. gaps or very forward dectectors (VFD)
- $\mathrm{d}\sigma_{pp} \approx \mathrm{d}\sigma_{\gamma\gamma}\,\mathrm{d}N_1\,\mathrm{d}N_2$ (EPA)
- def. photon luminosity $L_{\gamma\gamma}$ (Q^2 integrated), then:

$$\sigma_{pp} = \int \sigma_{\gamma\gamma}(W_{\gamma\gamma}, E_1) \times \frac{1}{L_{pp}} \frac{\partial^2 L_{\gamma\gamma}(W_{\gamma\gamma}, E_1)}{\partial W_{\gamma\gamma}\,\partial E_1}\,\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}E_1$$



Parameters, cuts and covariance matrix features

Choices and assumptions:

- fully leptonic decays $\Rightarrow$ clean signature
- double tag for both $p \Rightarrow$ full reconstr. of final state
- $m_{Higgs} = 120$ GeV

Cuts:

- both charged leptons: $|\eta| \leq 2.5$
- both charged leptons: $p_T \geq 10$ GeV
- both photons:
  - 120 GeV $\leq E_\gamma \leq$ 900 GeV for "VFD 220m", or
  - 20 GeV $\leq E_\gamma \leq$ 900 GeV for "VFD 220m + 420m"

Covariance matrix:

- CP even - CP odd correlations vanish

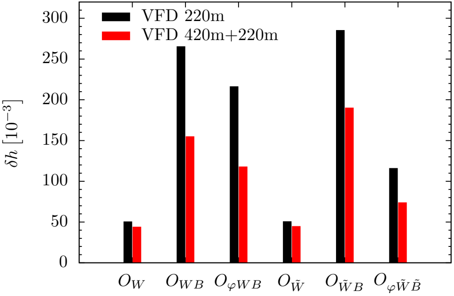
Results: Sensitivities at the LHC

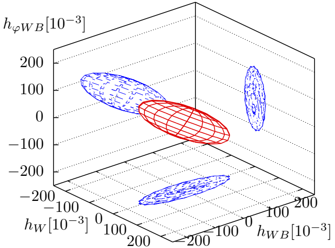
elastic spectrum, leptonic channels, double tag VFD

preliminary

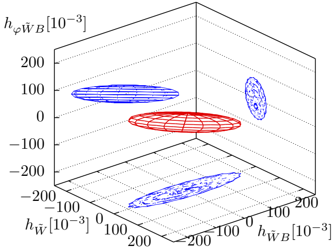
$\int L_{pp} = 30$ fb^{-1},

accept. events = 26 (VFD 220m), 94 (VFD 420m+220m)





CP even (VFD 420m+220m)



CP odd (VFD 420m+220m)

Results: Sensitivities at the LHC
elastic spectrum, comparison of channels

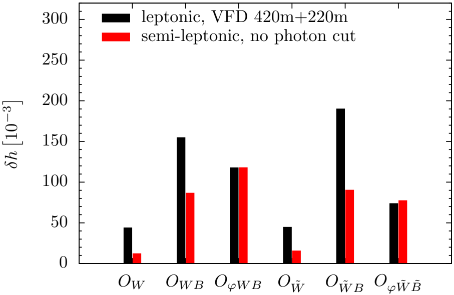
preliminary

- semi-leptonic measurements more difficult (background)
- but:
  - VFD tagging not crucial for reconstruction of final state
  - gain color factor 3 in event rate
- interesting (at low lumi) ?

$\int L_{pp} = 30$ fb^{-1};

accept. events =
94 lept. (VFD 420m+220m),
538 semi-lept. (no photon cut);

jet cuts as for $l^{\pm}$



But this means for $\int L_{pp} = 1$ fb^{-1}:

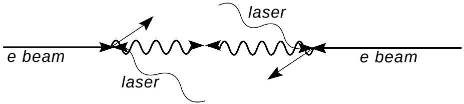
- only 18 semi-lept. events
- sensitiv. worse by factor of 5.5 wrt. fig.

Layout

Unpolarised Compton spectrum

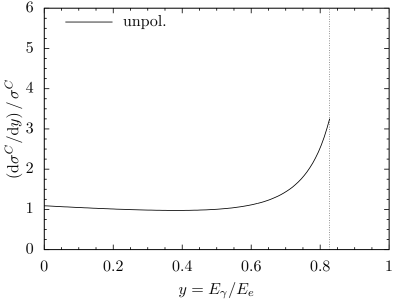
Ginzburg, Kotkin, Panfil, Serbo, Telnov

Photons via Compton backscattering of laser on e beam

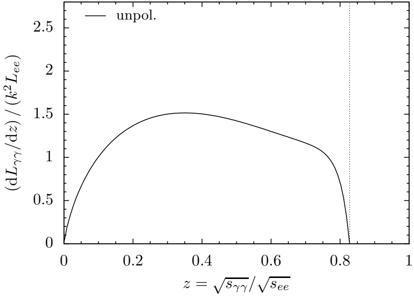


- use simple Compton formula
- $\sqrt{s_{ee}} = 500$ GeV
- hard $\gamma\gamma$ CMS statistically distrib.
- more realistic: nonlinear effects + multiple scattering

norm. single γ spectrum:



norm. $\gamma\gamma$ luminosity spectrum:



Parameters, cuts and covariance matrix features

Parameters and cuts:

- semi-leptonic, no jet id $\Rightarrow$ discrete ambiguities in reconstr.
- $m_{Higgs} = 120$ GeV
- cuts on observed fermions:
  - fermion energy ≥ 10 GeV
  - fermion angle wrt. beam $\geq 10^\circ$
  - angle betw. fermions $\geq 25^\circ$

Covariance matrix:

- CP even - CP odd correlations vanish
- calculation in presence of ambiguities:
  - use Jacobi-weighted sums over experim. equivalent states
  - integrate sums over unique phase space

(general discussion: *Nachtmann, Nagel, Pospischil*)

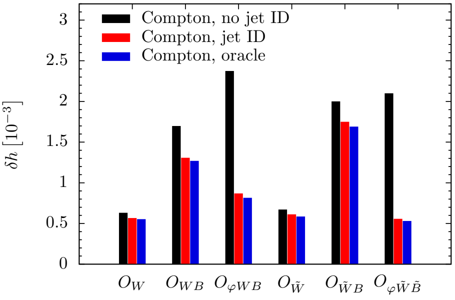
Results: Sensitivities at the ILC

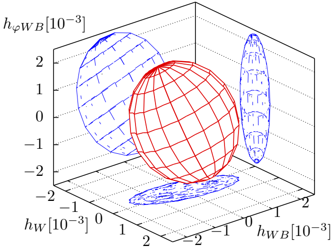
unpolarised Compton spectrum, semi-leptonic channels

preliminary

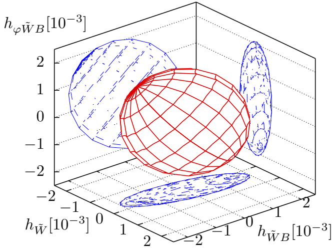
$\int L_{ee} = 500\ \text{fb}^{-1}$;

accept. events = $2.25 \cdot 10^6$





CP even (Compton, no jet id)



CP odd (Compton, no jet id)

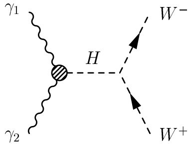
Possible improvements

Expect higher accuracies from

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

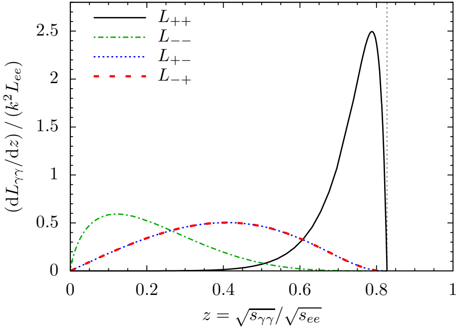
Polarisation ($\sim$ more information) disentangles different contributions:

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



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 hard $\gamma\gamma$:

- high energy enhancement
- polarisation strongly energy dependent
  (multiple scattering destroys pol. at lower energies)

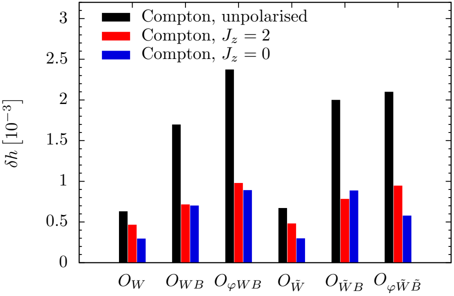
Results: Sensitivities at the ILC

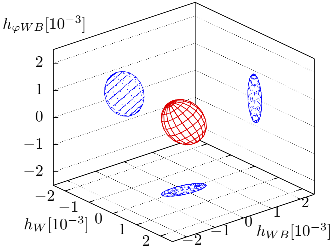
polarised Compton spectrum, semi-leptonic channels

preliminary

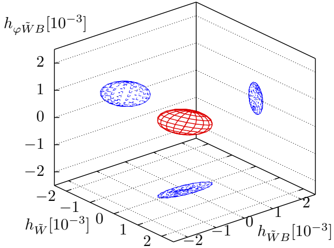
$\int L_{ee} = 500\ \text{fb}^{-1}$;

accept. events =
$2.25 \cdot 10^6$ (unpol),
$2.29 \cdot 10^6$ ($J_z = 2$),
$2.61 \cdot 10^6$ ($J_z = 0$)





CP even ($J_z = 0$)



CP odd ($J_z = 0$)

Comparison of sensitivities

preliminary

	present	LHC estimates	ILC estimates		
	LEP, SLD, Tevatron *(*)*	$\gamma\gamma \to WW$ leptonic	$ee \to WW$ *(*)*	$\gamma\gamma \to WW$ unpolarised	$\gamma\gamma \to WW$ $J_z = 0$
	$h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$

measurable CP conserving couplings:

h_W	-69 ± 39	44	0.3	0.6	0.3
h_{WB}	-0.06 ± 0.79	155	0.3	1.7	0.7
$h_{\varphi WB}$	$\times$	118	$\times$	2.4	0.9
$h_\varphi^{(3)}$	-1.15 ± 2.39	$\times$	36.4	$\times$	$\times$

measurable CP violating couplings:

$h_{\tilde{W}}$	68 ± 81	45	0.3	0.7	0.3
$h_{\tilde{W}B}$	33 ± 84	190	2.2	2.0	0.9
$h_{\varphi\tilde{W}\tilde{B}}$	$\times$	74	$\times$	2.1	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

- best for $h_{WB}, h_\varphi^{(3)}$: Giga Z

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.)
- LEP, SLD & Tevatron restrict 5 of them
- substantial improvements by $ee \to WW$, Giga-Z at ILC

Norm. distrib. for $\gamma\gamma \to WW$:

- access to 2 new anom. Higgs couplings (not in $ee \to WW$)
- sensitive to 6 anom. couplings
- allows important cross checks with *ee* data
- LHC:
  first access to 2 new anom. Higgs coupl.,
  supplements existing data with $\delta h \approx \mathcal{O}(10^{-1})$
- ILC:
  sensitivies $\delta h \approx \mathcal{O}(10^{-3})$,
  approx. factor 2 better with polarisation