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

A. v. Manteuffel

M. Manitias, O. Nachtmann, F. Nagel,
M. Pospischil, A. Utermann

Universität Heidelberg,
Universität Zürich

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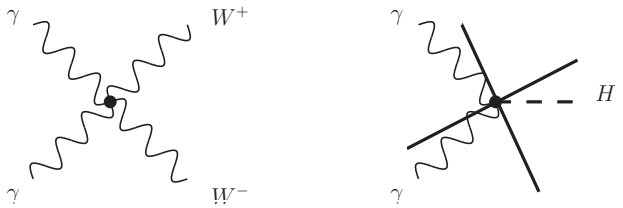
The Effective Lagrangian approach

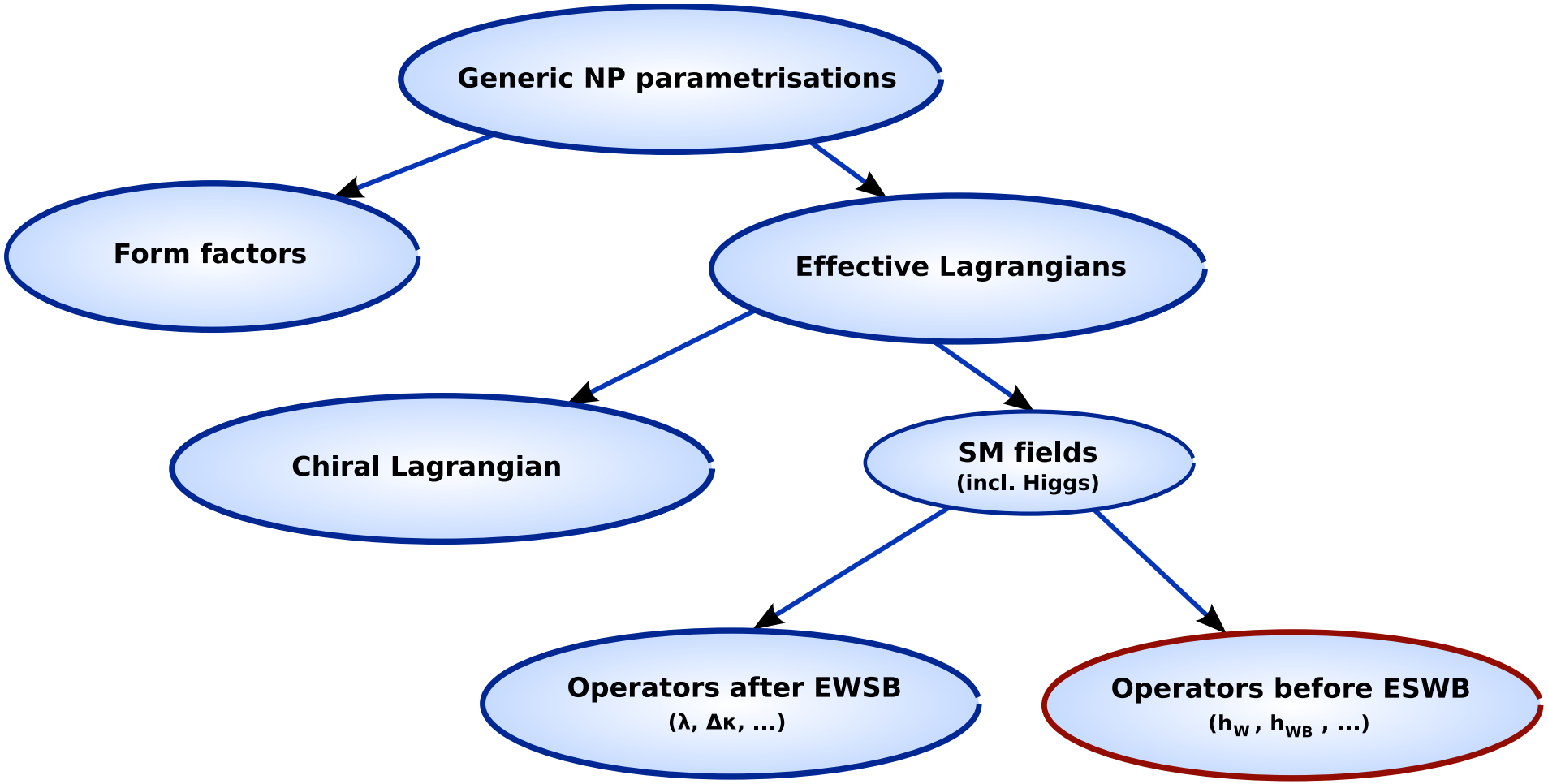
Standard Model:

- Standard Model (SM) γ, W, Z couplings fixed by: gauge invariance & renormalisability
- deviations $\Rightarrow$ signal for new physics (NP)



Generic NP parametrisation:

- assume $\Lambda_{NP} \gg v \approx 246$ GeV
- general effective anomalous couplings at low E
- discovery of deviations, exclusion of models
  $\Rightarrow$ *multi-purpose interface*: experiment $\leftrightarrow$ theory


Generic NP parametrisations
Form factors
Effective Lagrangians
Chiral Lagrangian
SM fields
(incl. Higgs)
Operators after EWSB
(λ, Δκ, ...)
Operators before ESWB
(h_W , h_{WB} , ...)

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

$\Rightarrow$ $\mathscr{L}_1$: none, $\mathscr{L}_2$: $\propto$80 operators $\ni$ 10 pure gauge/Higgs

Buchmüller, Wyler (1986)

- small number of couplings

Effective Lagrangian before EWSB

Gauge and gauge-Higgs anomalous couplings

- pure gauge and gauge-Higgs part: $\mathscr{L}_2 = \frac{1}{v^2} \sum h_i O_i$

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

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

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

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

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

- 10 dimensionless anomalous couplings h_i, where 4 ops. CP odd

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

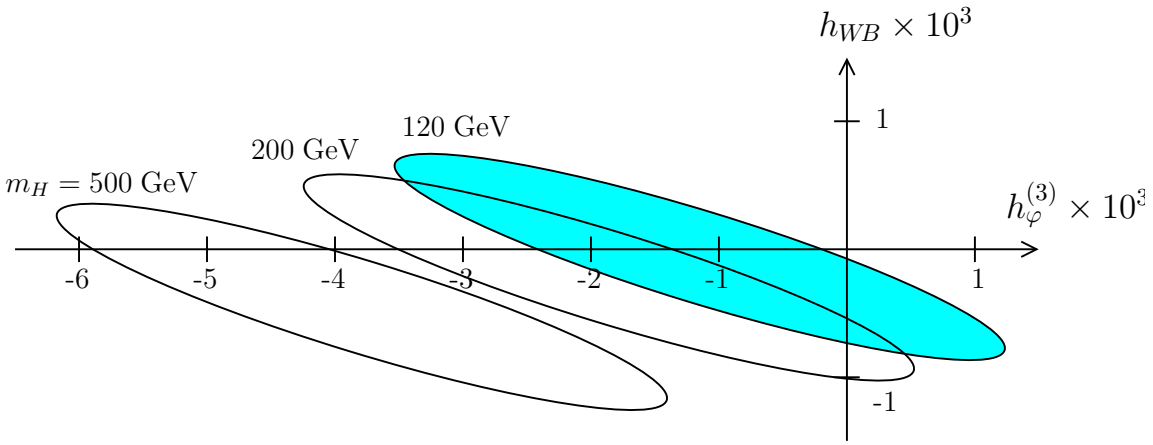
- EWSB: anomalous contrib. to kinetic and mass terms of gauge bosons
  - kinetic: $h_{\varphi W},\ h_{\varphi B},\ h_{WB}$
  - mass: $h^{(1)}_{\varphi},\ h^{(3)}_{\varphi}$

  $\Rightarrow$ physical $W^\pm,\ Z,\ \gamma$ modified wrt. SM
- Z decays sensitive to anom. couplings: $h^{(3)}_{\varphi},\ h_{WB}$ (scheme P_Z)
- approx. relations to $U(1)_{em}$ effect. Lagr.: $\lambda \propto h_W$, $\Delta\kappa \propto h_{WB}$, ...

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

		$s^2_{\rm eff}$, 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

Selected 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)

- of these, 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

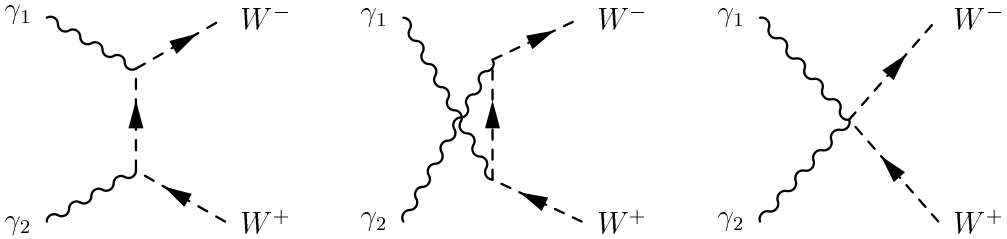
Feynman diagrams

Consider

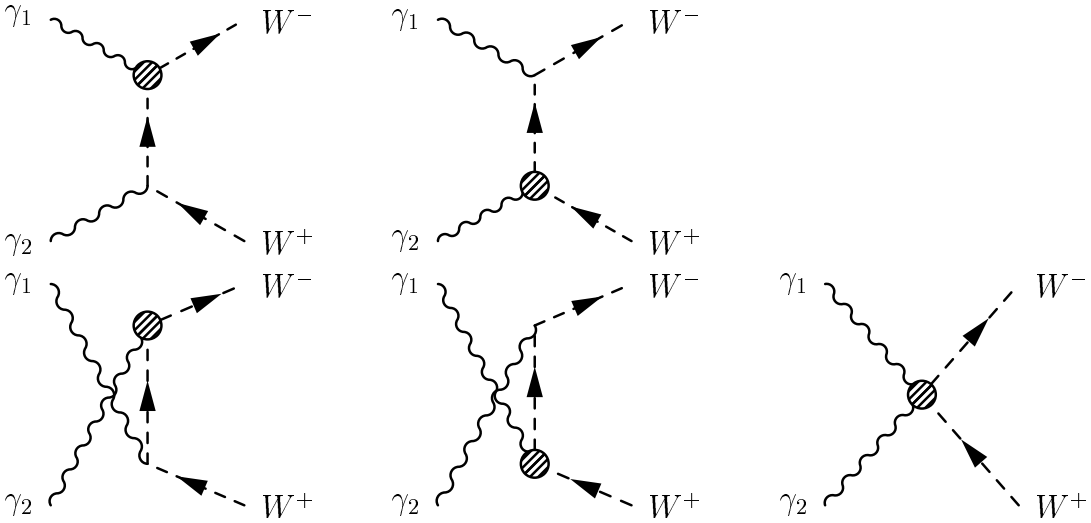
$$\gamma\gamma \to W^+W^- \to f\bar{f}\,f\bar{f}$$

in narrow-width-approximation.

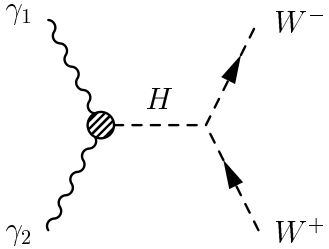
Production in SM:



via anom. gauge couplings:



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

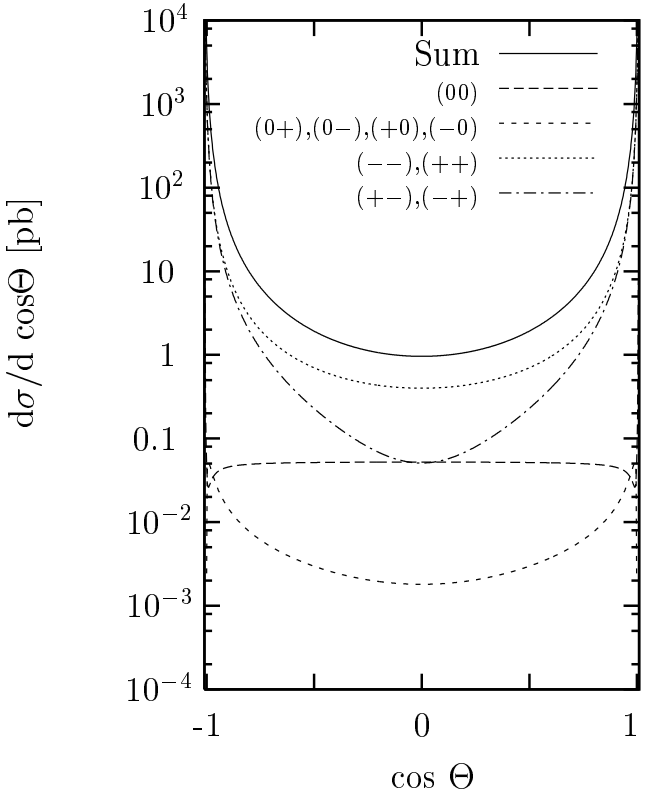


Disentanglement of anomalous contributions

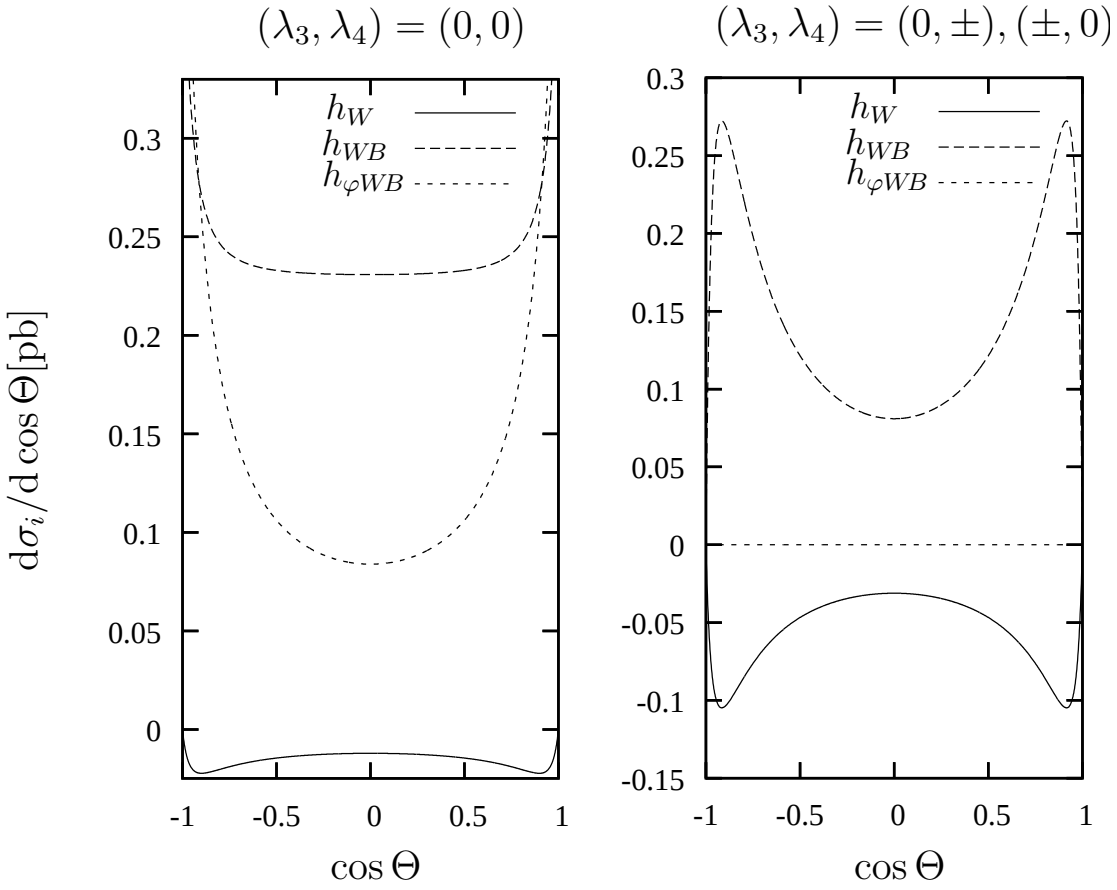
- specific γ-enhancements for anom. amplitudes, W pol. dependent
- more information via angular distributions, e.g.:

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

Standard Model:



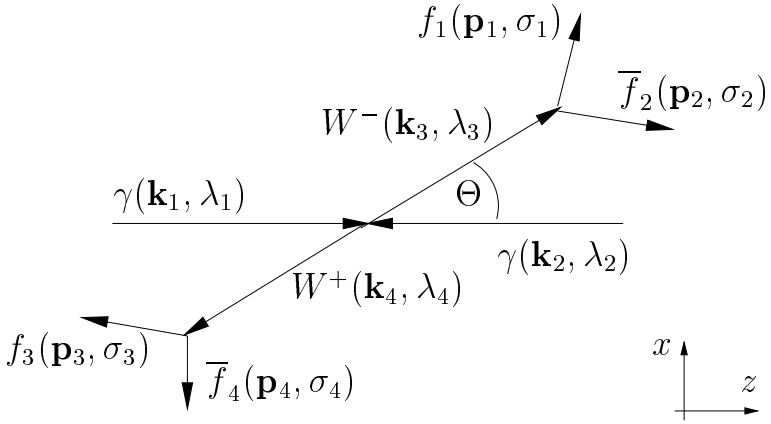
Anomalous CP even:



Optimal observables

How to measure anom. coupl. with best statistical accuracy ?

- full information: diff. cross section incl. W decays



- access via optimal observables *(Atwood & Soni, Davier et al., Diehl & Nachtmann)*
  - expand fully diff. cross section:

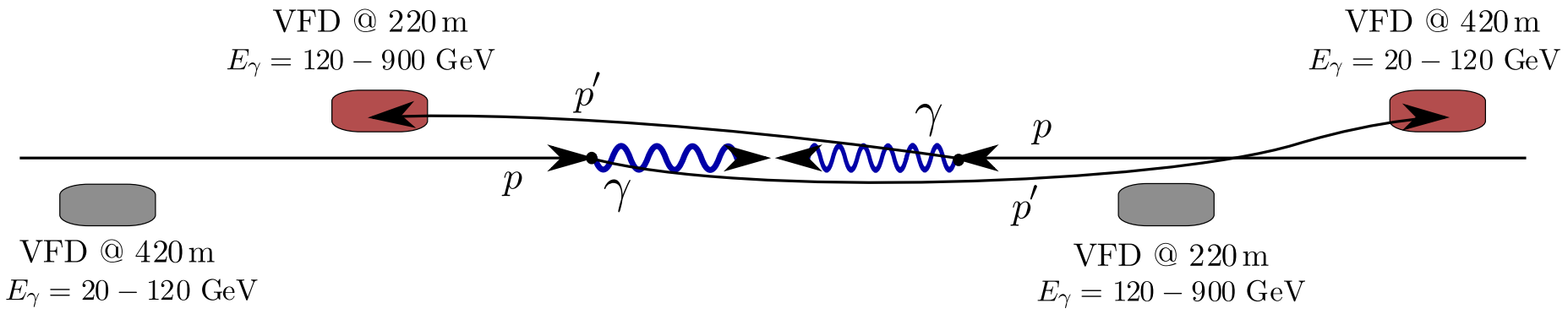
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} = S_0(\phi) + \sum_i h_i S_{1i}(\phi) + \mathcal{O}(h^2) \qquad \text{where} \quad \phi = \text{phase space variables}$$

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

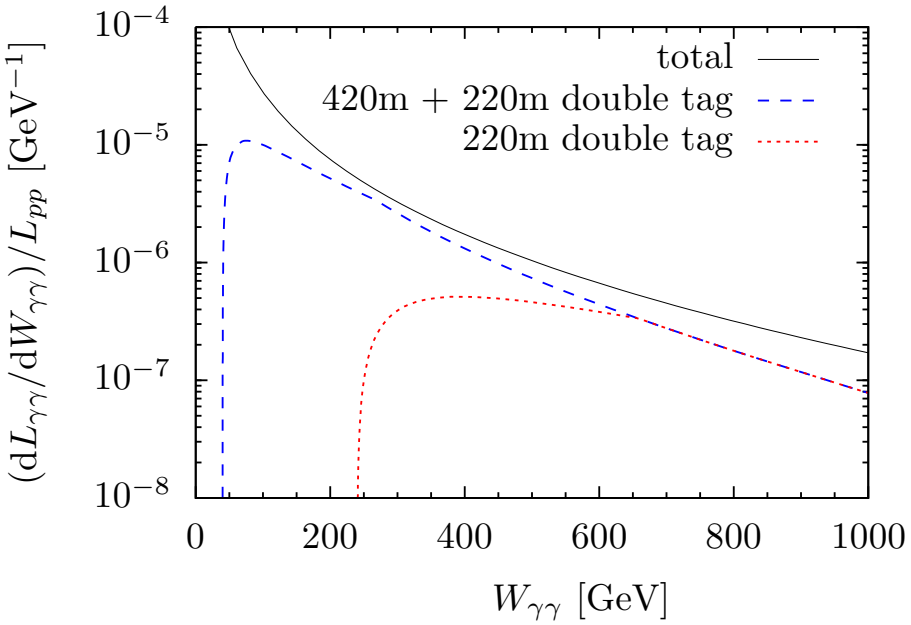
$$\mathcal{O}_i \equiv \frac{S_{1i}(\phi)}{S_0(\phi)}$$

- access to $\mathcal{O}(h)$ contrib. for all h_i (total cross section $\mathcal{O}(h^2)$ for CP odd)

Elastic photon production at the LHC



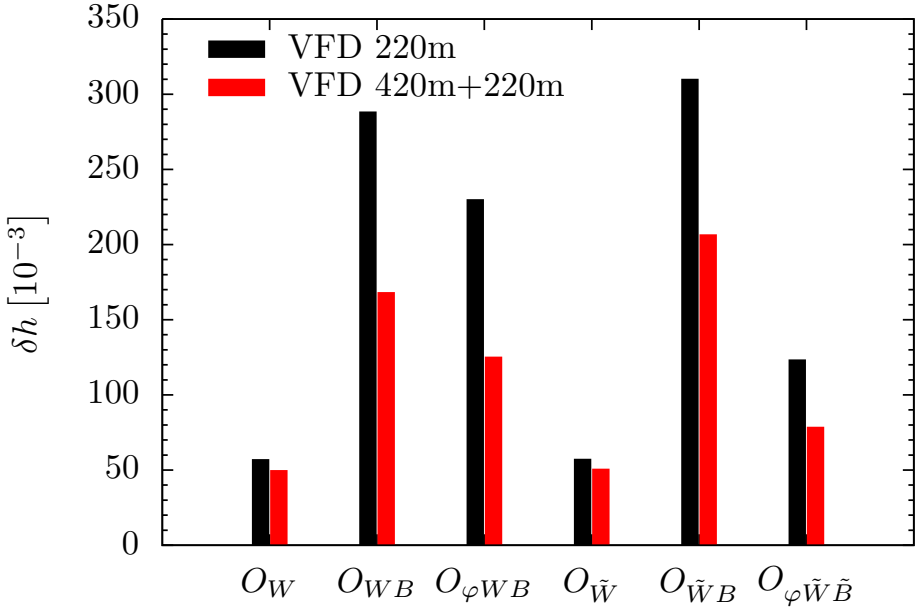
- almost real photons
  by elastic radiation off p
- tagging by very forward dectectors (VFD):
  120 GeV $\leq E_\gamma \leq$ 900 GeV (@220m)
  20 GeV $\leq E_\gamma \leq$ 900 GeV (@220m+420m)
- $\gamma\gamma$ CMS known via double tag
- $\mathrm{d}\sigma_{pp} \approx \mathrm{d}\sigma_{\gamma\gamma}\,\mathrm{d}N_1\,\mathrm{d}N_2$ (EPA)

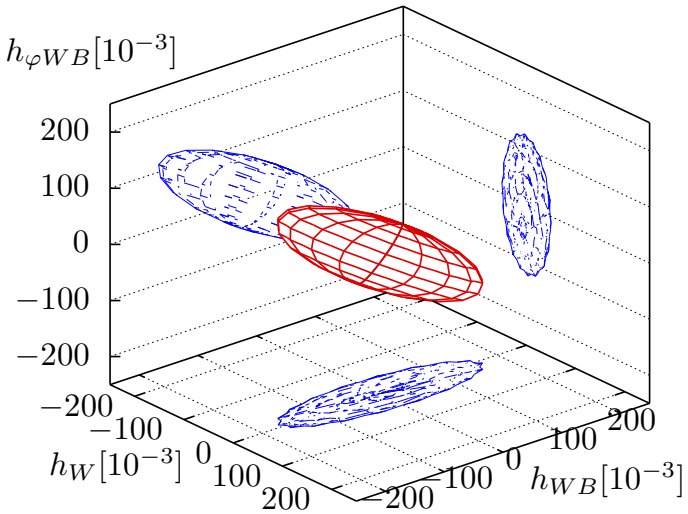


Results: Sensitivities at the LHC

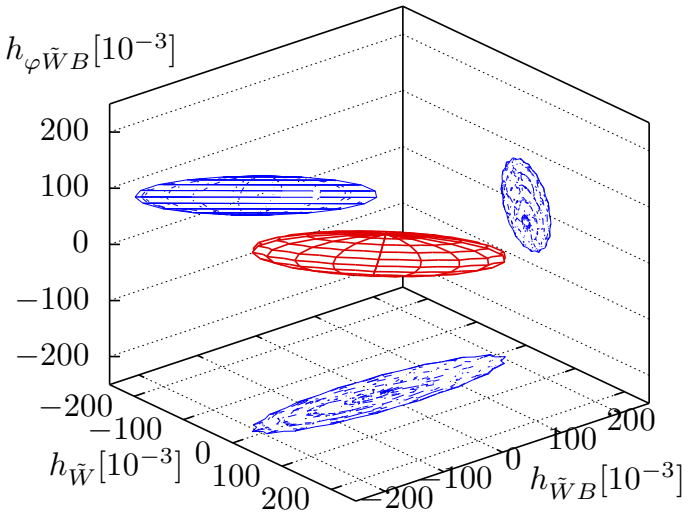
preliminary

- leptonic channels
- $\int L_{pp} = 30$ fb^{-1}
- both charged leptons: $|\eta| \leq 2.5$, $p_T \geq 10$ GeV
- $m_{Higgs} = 120$ GeV
- CP even-odd corr. vanish





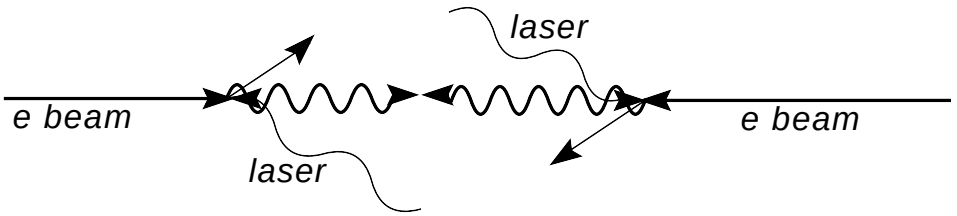
CP even (VFD 420m+220m)



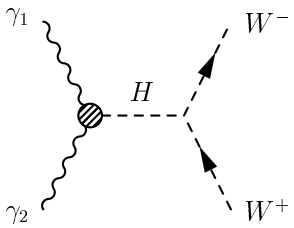
CP odd (VFD 420m+220m)

Photon collider at the ILC

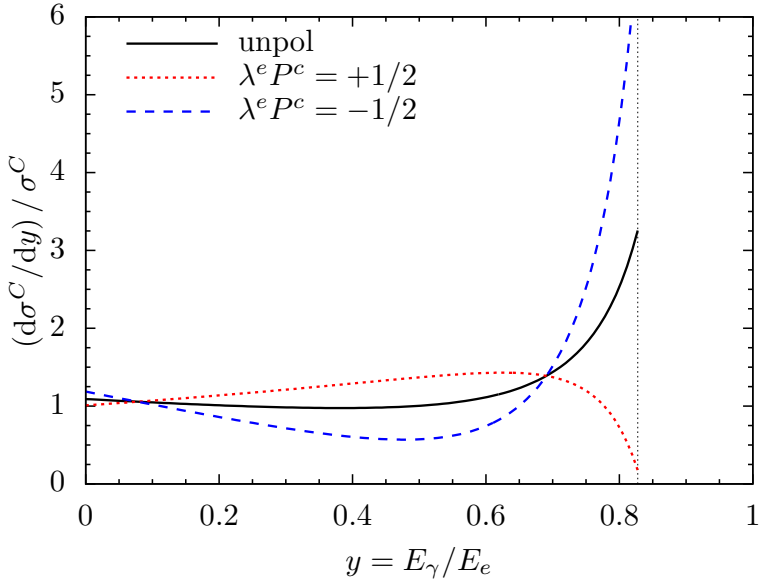
Photons via Compton backscattering of laser on *e* beam



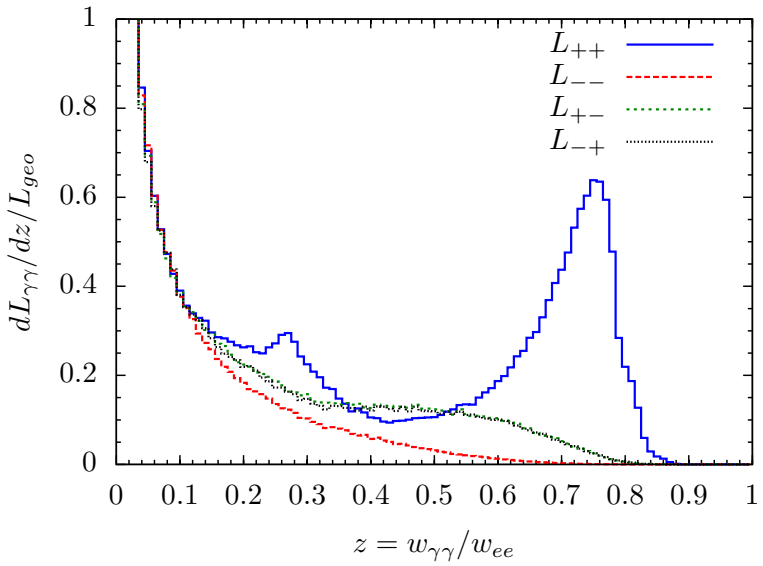
- high lumi for hard photons
- higher energies through polarisation
- $\gamma\gamma$ CMS statistically distrib.
- beyond LO: multiple scatt., nonlin., ...
- here: energy / polarisation distrib. helps to disentangle contrib. e.g. $|J_z| = 2$ "switches off" Higgs prod.



norm. single γ spectrum (LO):



norm. $\gamma\gamma$ luminosity spectrum (sim.):



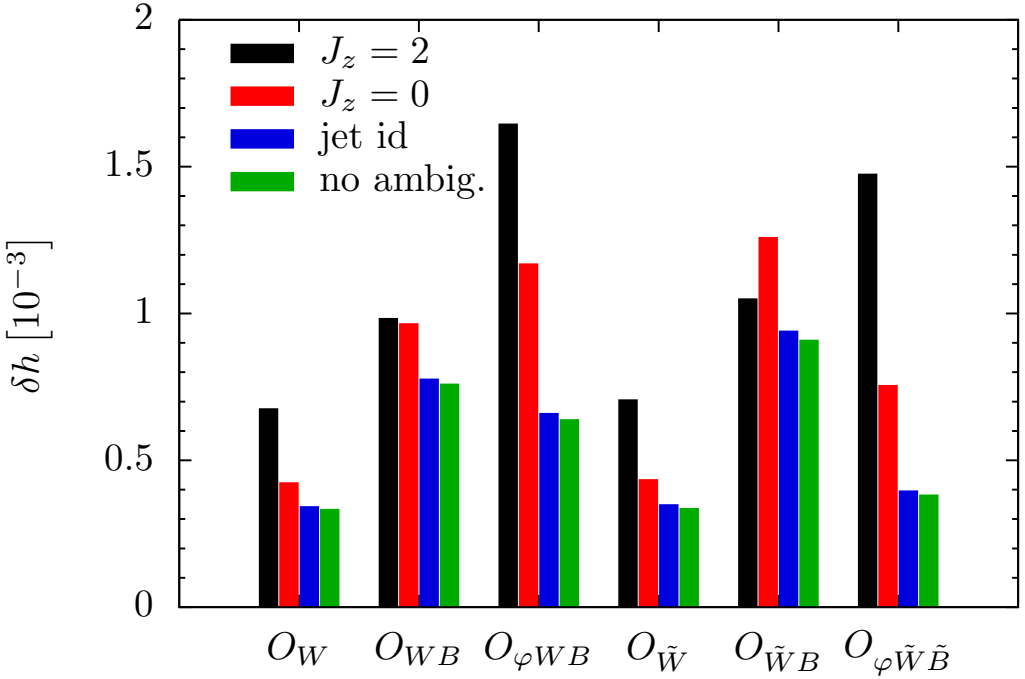
simulation by Telnov

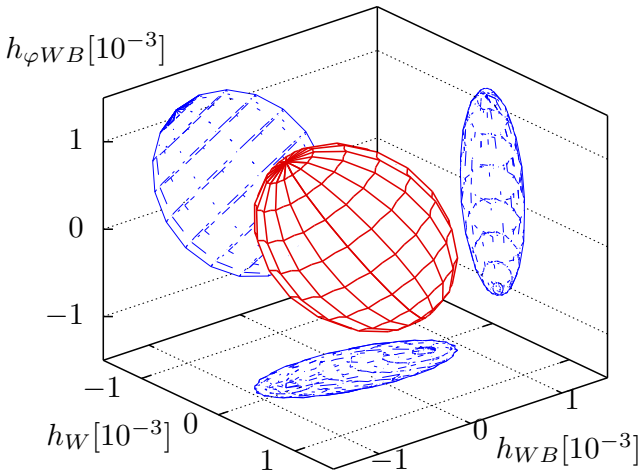
Results: Sensitivities at the ILC

semi-leptonic channels

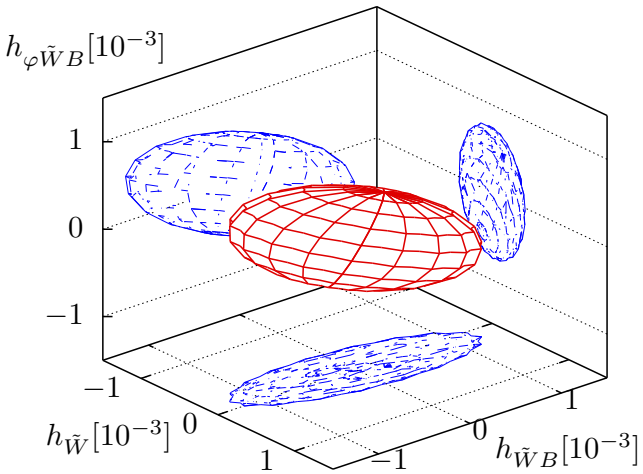
preliminary

- semi-leptonic, no jet id
  $\Rightarrow$ ambiguities (ν, jet)
- $\int L_{ee} = 500\ \text{fb}^{-1}$;
- $m_{Higgs} = 120$ GeV
- cuts on observed fermions:
  - energy ≥ 10 GeV
  - angle wrt. beam $\geq 10°$
  - angle betw. ferm. $\geq 25°$





CP even ($J_z = 0$)



CP odd ($J_z = 0$)

Comparison of sensitivities

preliminary

	present	LHC estimates	ILC estimates	
	LEP, SLD, Tevatron *(*)*	$\gamma\gamma \to WW$ elast., lept., $\int L = 30 fb^{-1}$	$ee \to WW$ *(*)* sl, $\int L = 500 fb^{-1}$	$\gamma\gamma \to WW$ sl, $J_z = 0$, $\int L = 500 fb^{-1}$
	$h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$	$\delta h_i\,[10^{-3}]$
measurable CP conserving couplings:				
h_W	-69 ± 39	50	0.3	0.4
h_{WB}	-0.06 ± 0.79	170	0.3	1.0
$h_{\varphi WB}$	$\times$	130	$\times$	1.2
$h_\varphi^{(3)}$	-1.15 ± 2.39	$\times$	36	$\times$
measurable CP violating couplings:				
$h_{\tilde{W}}$	68 ± 81	50	0.3	0.4
$h_{\tilde{W}B}$	33 ± 84	210	2.2	1.3
$h_{\varphi\tilde{W}\tilde{B}}$	$\times$	80	$\times$	0.8

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

Gauge symmetric effective Lagrangian approach:

- generic NP parametrisation
- 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

Normalised distributions for $\gamma\gamma \to WW$:

- access to 2 new anom. Higgs couplings (not in $ee \to WW$)
- allows important cross checks with ee data
- LHC (elastic γ production): $\delta h \approx \mathcal{O}(10^{-1})$
- ILC (photon collider mode): $\delta h \approx \mathcal{O}(10^{-3})$