Four-fermion production at the $\gamma\gamma$ Collider

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September 1,2004

based on Eur. Phys. J. C **36** (2004) 341 [arXiv:hep-ph/0405169]

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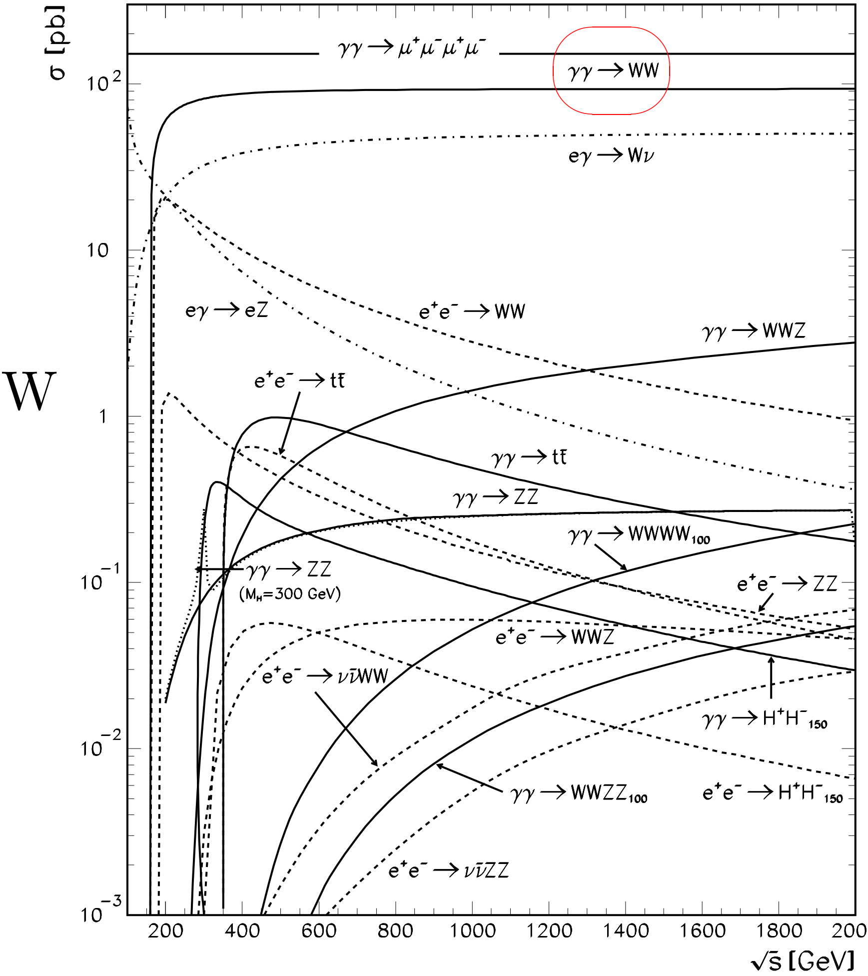
Motivation

$\gamma\gamma \to \mathrm{WW}$

- one of the largest cross sections
- contains gauge boson couplings
  $\gamma\mathrm{WW}$ and $\gamma\gamma\mathrm{WW}$
  (limits on anomalous couplings)
- if $M_{\mathrm{H}} \gtrsim 160\,\mathrm{GeV} \Rightarrow \gamma\gamma \to \mathrm{H} \to \mathrm{WW}$
- sensitive on extra dimensions

Baillargeon, et al. '95



Motivation

W bosons are unstable $\Rightarrow$ $\gamma\gamma \to \mathrm{WW} \to 4f$ (“W-pair signal diagrams”)

Experimental precision requires

- inclusion of single and non-resonant diagrams (“background diagrams”) in lowest order $\mathcal{O}(\Gamma_{\mathrm{W}}/M_{\mathrm{W}}), \mathcal{O}(\Gamma_{\mathrm{W}}/M_{\mathrm{W}})^2$
  $\Rightarrow$ $\gamma\gamma \to 4f$
- inclusion of radiative corrections $\mathcal{O}(\alpha)$

$\gamma\gamma \to 4f\gamma$:

Building block for real corrections to $\gamma\gamma \to \mathrm{WW} \to 4f$

Existing studies:

$\gamma\gamma \to 4f$: Moretti ’96; Baillargeon et al. ’97; Boos, Ohl ’97

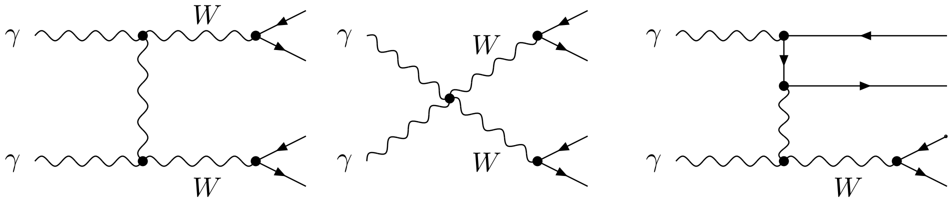
Amplitudes

- Helicity amplitudes
- Weyl-van der Waerden formalism
- fermion masses neglected

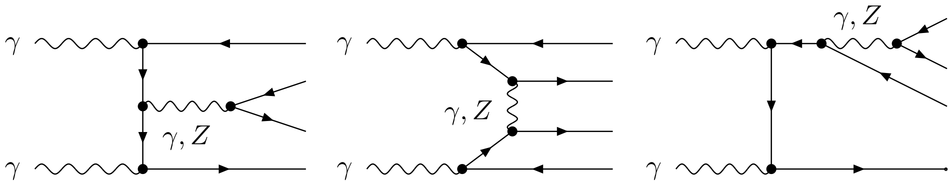
representative final states

final state	reaction type	$\gamma\gamma \to$
leptonic	CC	$\mathrm{e}^-\bar\nu_\mathrm{e}\nu_\mu\mu^+$
	NC(a)	$\mathrm{e}^-\mathrm{e}^+\nu_\mu\bar\nu_\mu$
		$\mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$
	NC(b)	$\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$
	CC/NC	$\mathrm{e}^-\mathrm{e}^+\nu_\mathrm{e}\bar\nu_\mathrm{e}$
semi-leptonic	CC(c)	$\mathrm{e}^-\bar\nu_\mathrm{e}\mathrm{u}\bar{\mathrm{d}}$
	NC(a)	$\nu_\mathrm{e}\bar\nu_\mathrm{e}\mathrm{u}\bar{\mathrm{u}}$
		$\nu_\mathrm{e}\bar\nu_\mathrm{e}\mathrm{d}\bar{\mathrm{d}}$
		$\mathrm{e}^-\mathrm{e}^+\mathrm{u}\bar{\mathrm{u}}$
		$\mathrm{e}^-\mathrm{e}^+\mathrm{d}\bar{\mathrm{d}}$
hadronic	CC	$\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}$
	NC(a)	$\mathrm{u}\bar{\mathrm{u}}\mathrm{c}\bar{\mathrm{c}}$
	NC(a)	$\mathrm{u}\bar{\mathrm{u}}\mathrm{s}\bar{\mathrm{s}}$
	NC(a)	$\mathrm{d}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{s}}$
	NC(b)	$\mathrm{u}\bar{\mathrm{u}}\mathrm{u}\bar{\mathrm{u}}$
	NC(b)	$\mathrm{d}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{d}}$
	CC/NC	$\mathrm{u}\bar{\mathrm{u}}\mathrm{d}\bar{\mathrm{d}}$

charged current (CC) (dominates)

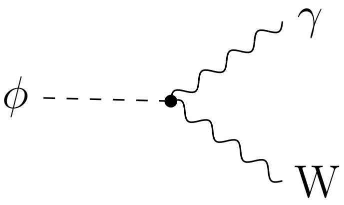


neutral current (NC)



gluon-exchange diagrams

Amplitudes

non-linear gauge: 

vanishes

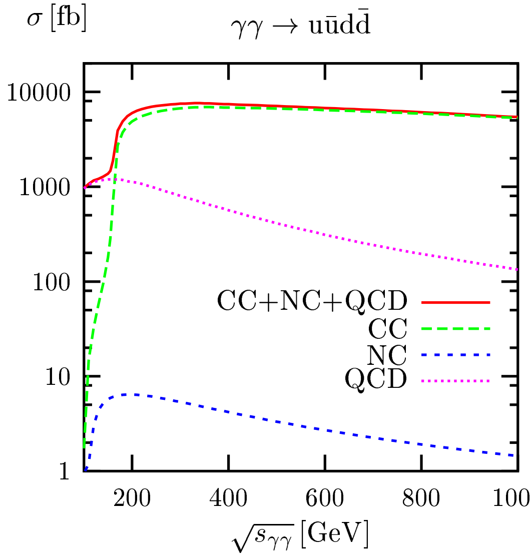
diagrams: 6 ($e^-e^+\nu_\mu\bar{\nu}_\mu$) to 588 ($u\bar{u}d\bar{d}+\gamma$)

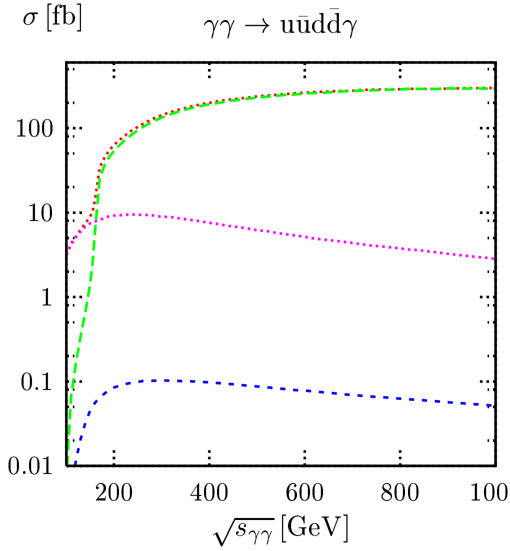
$\gamma\gamma\to 4f$: calculation with general
gauge spinor of γ, drops out in the end

use of discrete symmetries
$\to$ only 2 independent helicity ampl. for $\gamma\gamma\to 4f$

gluon diagrams similar to NC diagrams,
add colour structure

check against Madgraph (Stelzer, Long '94)





Phase-space integration

RacoonWW
Denner et al. ’01

Problem: rich peaking structure of integrand

“importance sampling” : more points near peaks

$$\int \underbrace{dx}_{\substack{\downarrow \\ \text{random numbers}}} f(x) = \int dx\, g(x) \frac{f(x)}{g(x)} = \int dy\, \underbrace{\frac{f(x(y))}{g(x(y))}}_{\text{„weight“} \sim \mathrm{const}}$$

$\int_0^x d\bar{x}\, g(\bar{x}) = y(x)$: „mapping“ → integrand flattened

many Feynman diagrams/propagators → “multi-channel”

one phase-space generator per diagram with appropriate „mapping“

Photon spectrum (CompAZ (Zarnecki ’02; Telnov ’95; Chen et al. ’95)):

$$\mathrm{d}\sigma = \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2\, f(x_1) f(x_2) \mathrm{d}\sigma(x_1 P_1, x_2 P_2)$$

“stratified sampling” + adaptive optimization

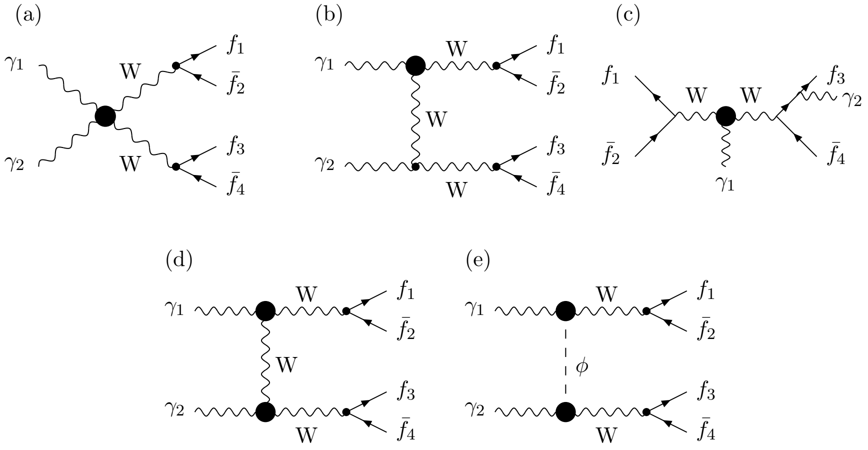
Comparison with Whizard&Madgraph (Kilian ’01; Stelzer, Long ’94) → good agreement

Anomalous triple couplings

Effective Lagrangian with dimension-6 operators

assumption: symmetries of SM are respected

$$\mathcal{L}_{\rm CC}^{\rm ATGC} = {\rm i}g_1 \frac{\alpha_{{\rm B}\phi}}{M_{\rm W}^2} (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) - {\rm i}g_2 \frac{\alpha_{{\rm W}\phi}}{M_{\rm W}^2} (D_\mu \Phi)^\dagger \boldsymbol{\sigma} \cdot \mathbf{W}^{\mu\nu} (D_\nu \Phi)$$
$$- g_2 \frac{\alpha_{\rm W}}{6M_{\rm W}^2} \mathbf{W}^\mu{}_\nu \cdot (\mathbf{W}^\nu{}_\rho \times \mathbf{W}^\rho{}_\mu),$$



→ $\gamma\mathrm{WW}$ (and related $\gamma\gamma\mathrm{WW}$)

coefficients are related to

$\Delta\kappa_\gamma$ and λ_γ (LEP2)

NC triple couplings ($\gamma\gamma\mathrm{Z}$,$\gamma\mathrm{ZZ}$):

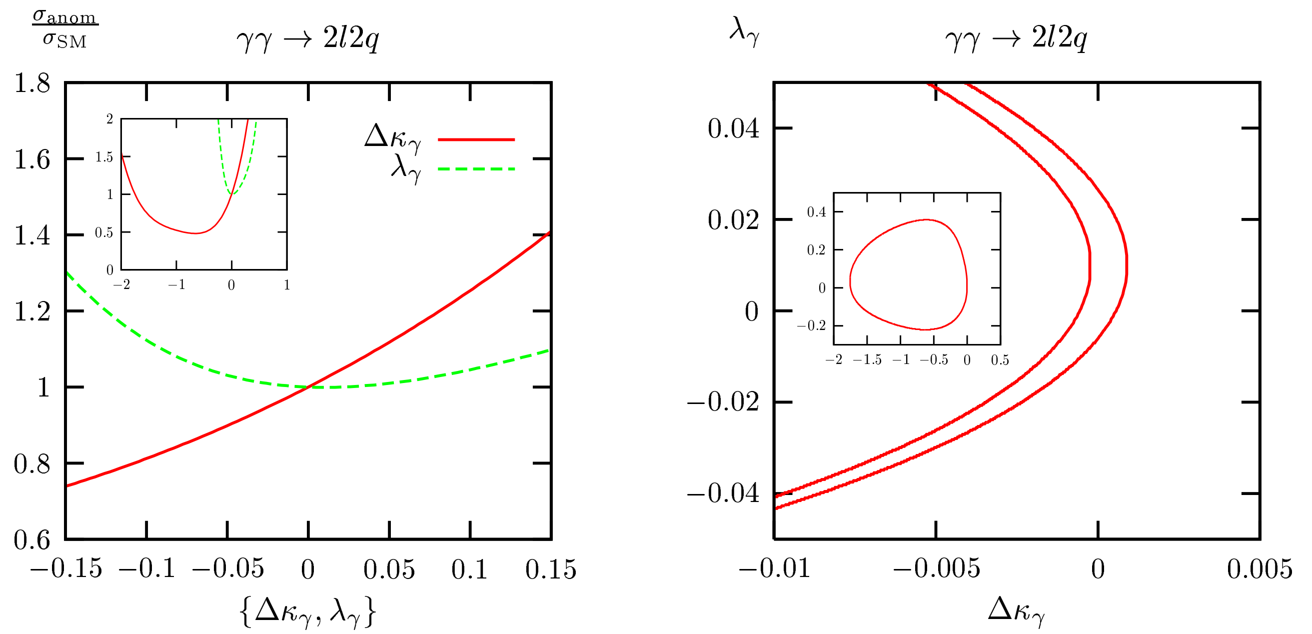
$\mathcal{O}(a_{\rm NC} \cdot (\Gamma_{\rm W}/M_{\rm W})^2)$

are suppressed and thus neglected

Anomalous triple couplings

$\gamma\gamma \to 4f$ all semi-leptonic final states photon spectrum included

$\sqrt{s_{ee}} = 500\,\mathrm{GeV}$ $\int Ldt = 100\,\mathrm{fb}^{-1}$ $\chi^2 = 1$ $\chi^2 \equiv \frac{(N(a_i) - N_{\mathrm{SM}})^2}{N_{\mathrm{SM}}}$



$\longrightarrow$ large interference with SM amplitude

expected limits comparable to e^+e^--mode (see also Baillargeon et al. '97; Bozovic-Jelisavcic et al. '02)

full study requires consideration of distributions

Anomalous quartic couplings

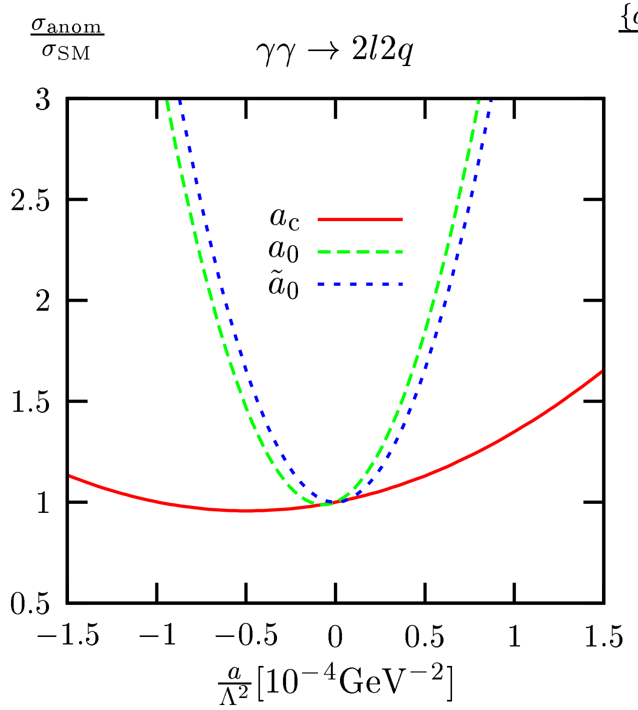
Assumption: CP, $\mathrm{U}(1)_{\mathrm{em}}$, $\mathrm{SU}(2)_{\mathrm{cust}}$

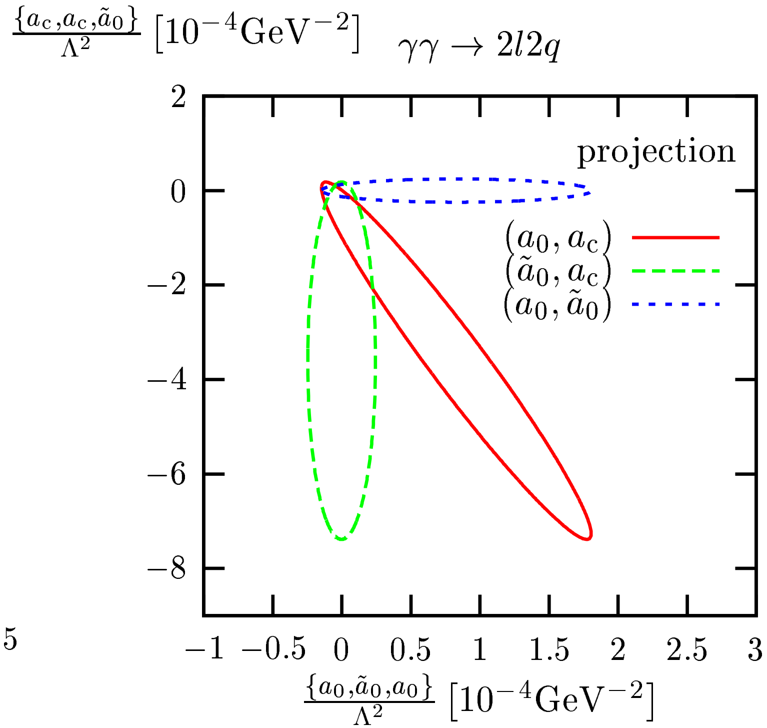
Bélanger, Boudjema '92; Abu Leil, Stirling '95;
Stirling, Werthenbach '00; Denner et al. '01

$$\mathcal{L}_{\mathrm{anom}} = -\frac{e^2}{16\Lambda^2}\left(a_0\, F^{\mu\nu}F_{\mu\nu}\overline{\mathbf{W}}_\alpha\overline{\mathbf{W}}^\alpha + a_c\, F^{\mu\alpha}F_{\mu\beta}\overline{\mathbf{W}}^\beta\overline{\mathbf{W}}_\alpha + \tilde{a}_0\, F^{\mu\nu}\tilde{F}_{\mu\nu}\overline{\mathbf{W}}_\alpha\overline{\mathbf{W}}^\alpha\right)$$

$$\overline{\mathbf{W}}_\mu=(\overline{W}^1_\mu,\overline{W}^2_\mu,\overline{W}^3_\mu)=\left(\frac{1}{\sqrt{2}}(W^+ + W^-)_\mu,\frac{\mathrm{i}}{\sqrt{2}}(W^+ - W^-)_\mu,\frac{1}{\mathrm{c_w}}Z_\mu\right)$$

$\rightarrow$ $\gamma\gamma\mathrm{WW}$ and $\gamma\gamma\mathrm{ZZ}$



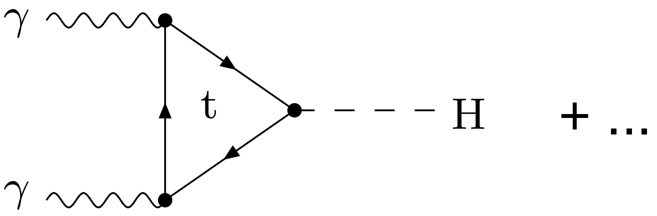


better than in

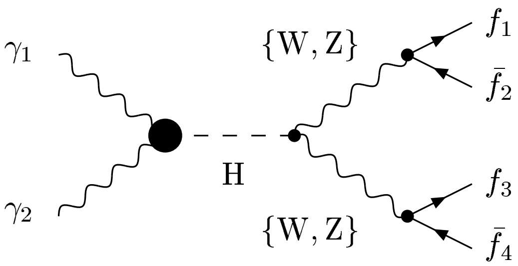
$\mathrm{e^+e^-} \longrightarrow 4f\gamma$

Effective Higgs coupling

In the SM through radiative corrections

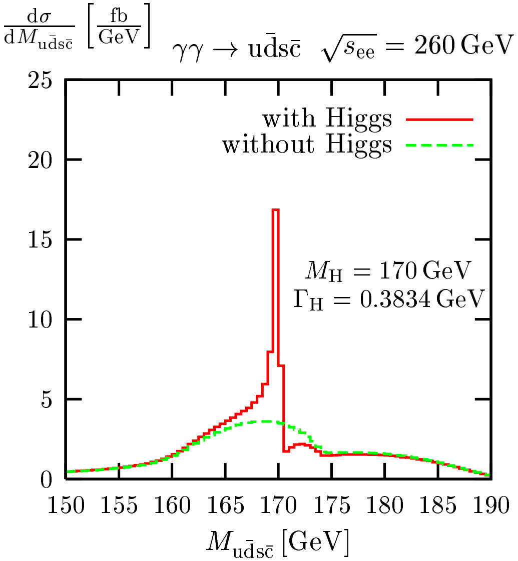


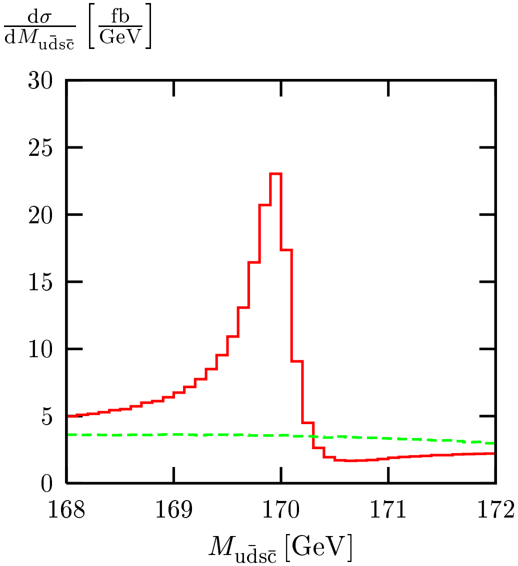
$$\mathcal{L}_{\gamma\gamma\mathrm{H}} = -\frac{g_{\gamma\gamma\mathrm{H}}}{4} F^{\mu\nu} F_{\mu\nu} \frac{H}{v}$$



$$\gamma\gamma \to \mathrm{H} \to \mathrm{WW} \to \mathrm{u\bar{d}s\bar{c}}$$

$g_{\gamma\gamma\mathrm{H}}$: SM value   incl. photon spectrum





Finite gauge-boson width

fixed width: $P_V(p^2) = \frac{1}{p^2 - M^2 + iM\Gamma}$ $U(1), \cancel{SU(2)}$

step width: $P_V(p^2) = \frac{1}{p^2 - M^2 + iM\Gamma\theta(p^2)}$ $\cancel{U(1)}, \cancel{SU(2)}$

running width: $P_V(p^2) = \frac{1}{p^2 - M^2 + iM\Gamma\frac{p^2}{M^2}\theta(p^2)}$ $\cancel{U(1)}, \cancel{SU(2)}$

complex mass scheme: $M^2 \to M^2 - iM\Gamma$ (e.g. in $\cos\theta_W = \frac{M_W}{M_Z}$) gauge invariant

Denner et al. '99

For $\gamma\gamma \to 4f(\gamma)$ (massless fermions and non-linear gauge)

fixed width equivalent to complex mass scheme

$\sigma(\gamma\gamma \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\mu\mu^+\gamma)$					
$\sqrt{s_{\gamma\gamma}}$ [GeV]	500	800	1000	2000	10000
fixed width	39.230(45)	47.740(73)	49.781(91)	43.98(18)	4.32(23)
step width	39.253(45)	47.781(73)	49.881(96)	44.01(18)	4.31(24)
running width	39.251(49)	47.781(74)	49.898(95)	44.48(22)	10.83(28)
complex mass	39.221(45)	47.730(73)	49.770(91)	43.97(18)	4.31(23)

Double-pole approximation

Naive W-pair signal:

only diagrams with two resonant

W propagators (not gauge invariant)

not sufficient

DPA = signal + “on-shell projection”

gauge invariant

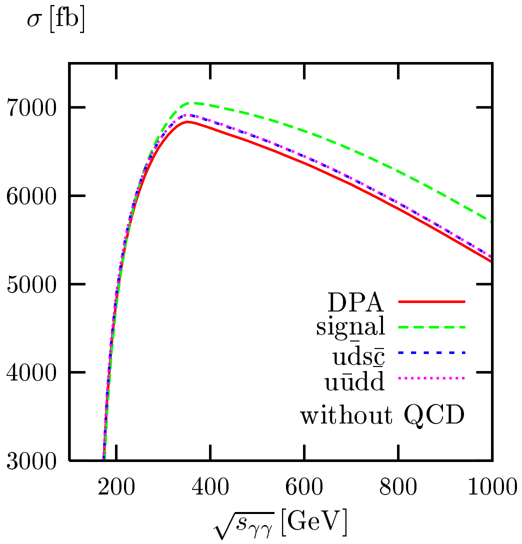
ambiguity of $\mathcal{O}(\Gamma_{\mathrm{W}}/M_{\mathrm{W}})$

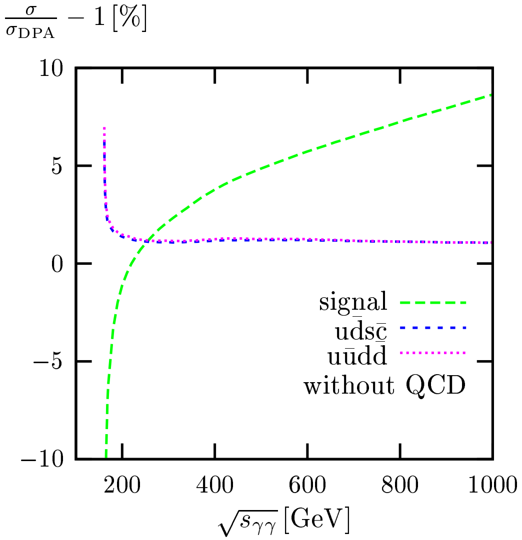
accuracy of 1–3%

breakdown at WW threshold

$\longrightarrow$ promising approach:

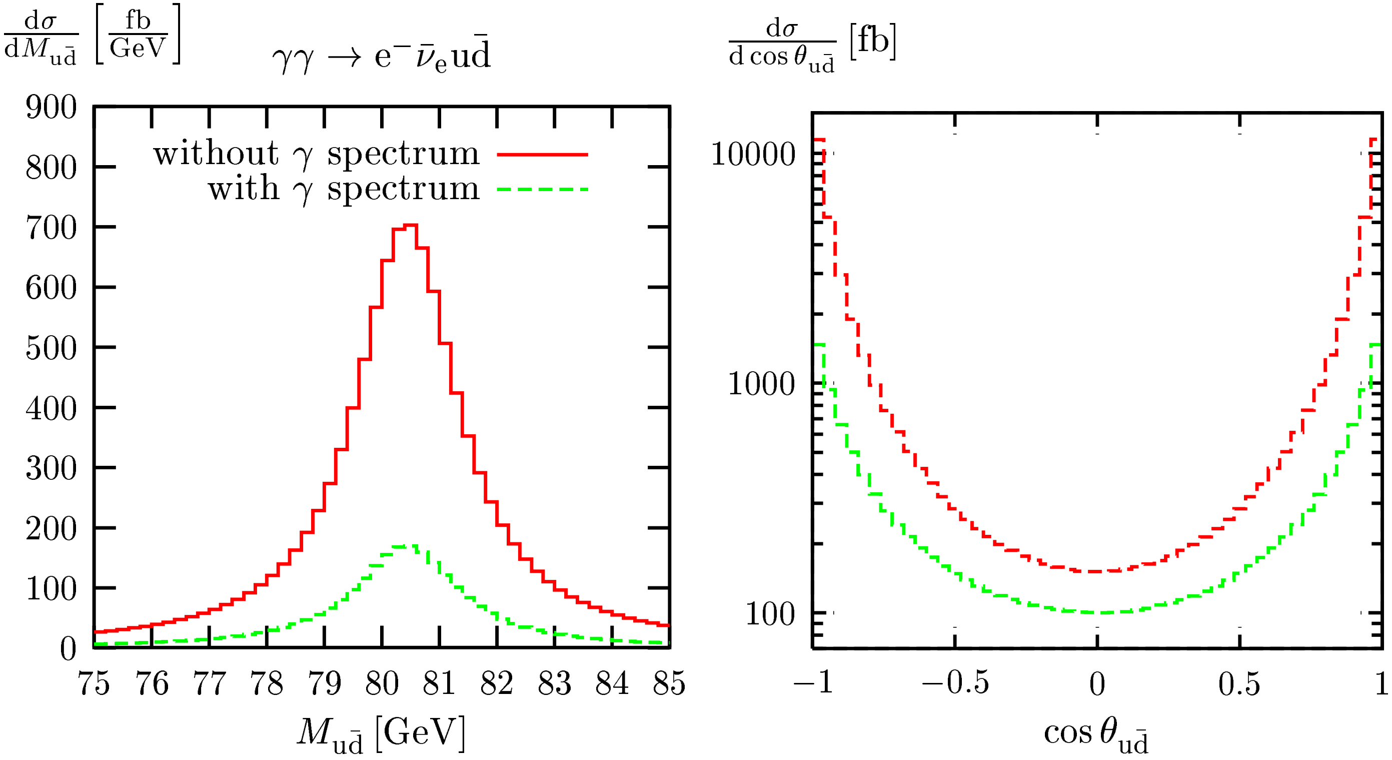
radiative corrections in DPA





Distributions

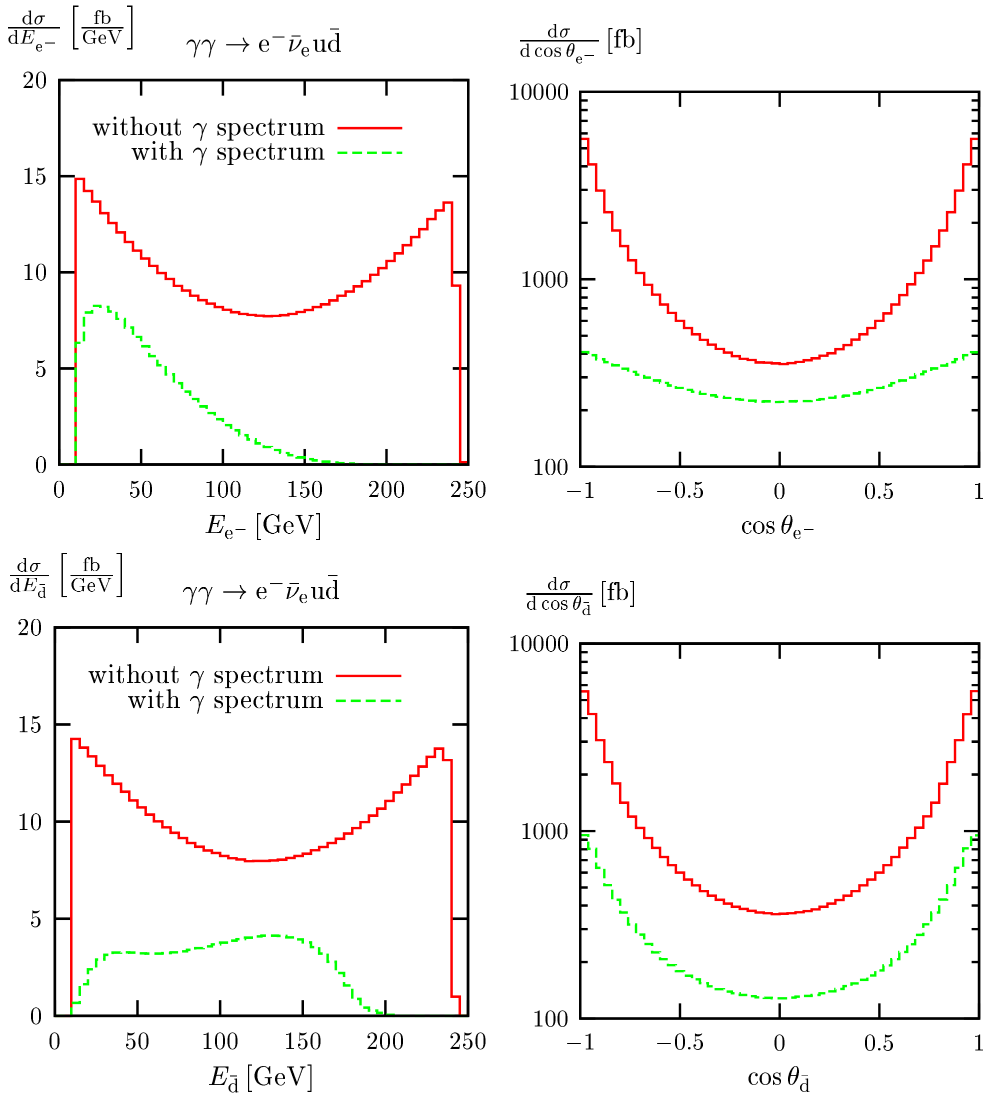
Invariant mass and production angle of the W^+ boson in $\gamma\gamma \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\mathrm{u}\bar{\mathrm{d}}$



Distributions

Energy and production angle of e^- and $\bar{\mathrm{d}}$ in $\gamma\gamma \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\mathrm{u}\bar{\mathrm{d}}$

Convolution over photon spectrum changes energy and angular distributions due to the effective polarisation of the $\gamma\gamma$ system



Summary

- Relevance of $\gamma\gamma \to \mathrm{WW}$ due to its high cross section
- Calculation of Born amplitudes for $\gamma\gamma \to 4f$ and $\gamma\gamma \to 4f\gamma$
- Monte Carlo generator with multi-channel Monte Carlo integration
- Inclusion of a realistic photon spectrum
- Anomalous couplings, Higgs resonance
- Double-pole approximation is a promising approach for radiative corrections (cf. RacoonWW), work in progress