Lowest-order predictions for the processes $\gamma\gamma \to 4f$ and $\gamma\gamma \to 4f + \gamma$[†]

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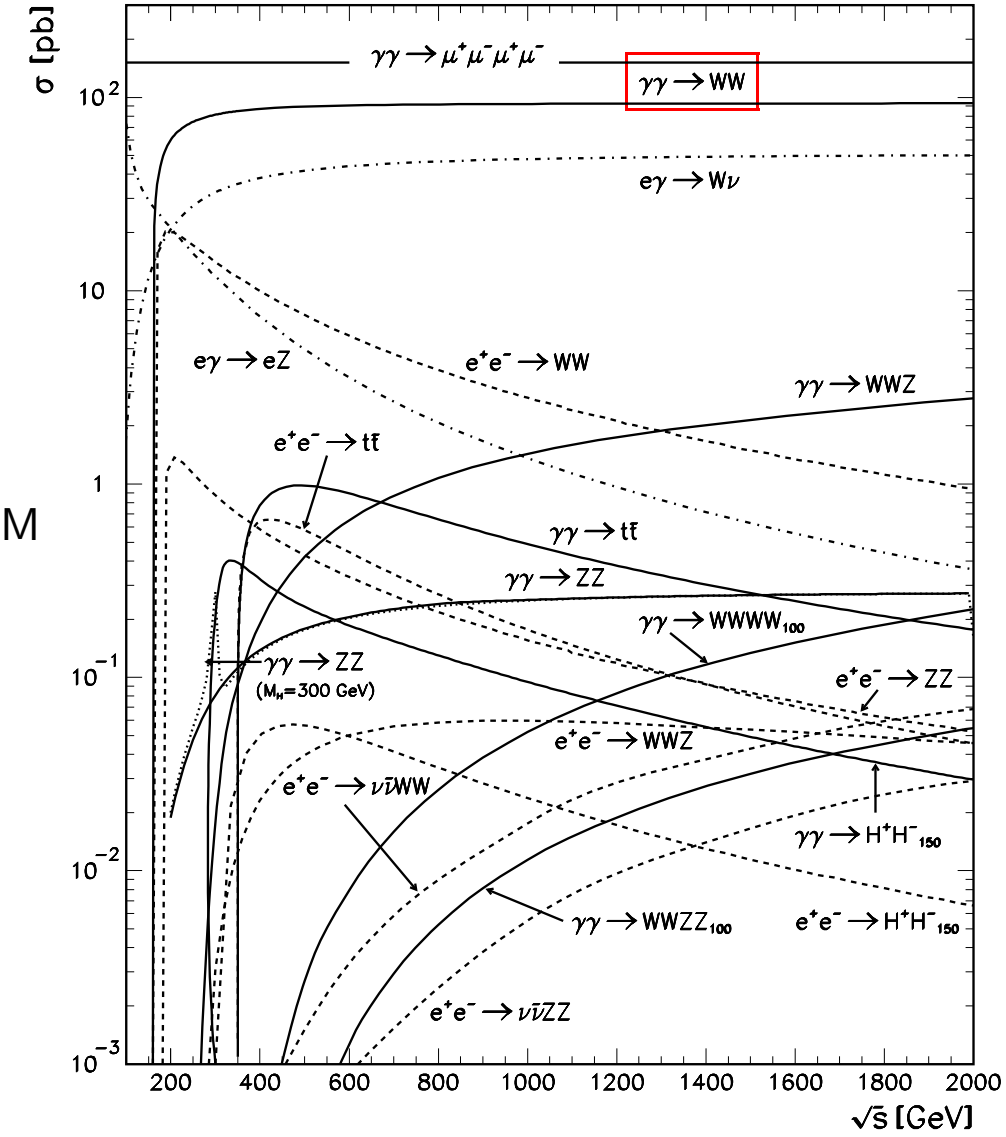
[†]based on the results of Eur. Phys. J. C **36** (2004) 341 (hep-ph/0405169)

Introduction

Motivation for $\gamma\gamma \to 4f(+\gamma)$

- One of the largest cross sections
  $\gamma\gamma \to \mathrm{WW} \to 4f$ is precision observable
  $\Rightarrow$ Radiative corrections important!
  (Possibility for detector calibration?)
- Triple- and quartic-gauge-boson couplings
  $\Rightarrow$ Precision test of the gauge sector of the SM
  $\gamma\gamma \to \mathrm{WW}$ sensitive to γWW, $\gamma\gamma WW$
  $\mathrm{e^+e^-} \to \mathrm{WW}$ sensitive to γWW, ZWW
- Loop-induced Higgs production $\gamma\gamma \to \mathrm{H}$,
  (similar to $\mathrm{gg} \to \mathrm{H}$ at the LHC)
  $\Rightarrow$ One of the most important Higgs-production channels

Baillargeon, et al.'95



Theoretical status

Existing numerical studies for $\gamma\gamma \to 4f$

- Moretti'97
- Boos,Ohl'97
- Baillargeon,Bélanger,Boudjema'97

$\Rightarrow$ Monochromatic photon beams, only leptonic and semi-leptonic final states

Multi-purpose event generators

- GRACE — Ishikawa et al.'92
- PHEGAS & HELAC — Papadopoulos,Kanaki'00
- WHIZARD & MADGRAPH/O'MEGA — Kilian'01; Stelzer,Long'94; Moretti et al.'01

Dedicated Monte Carlo generator for $\gamma\gamma \to 4f(+\gamma)$

- Bredenstein,Dittmaier,M.R.'04 $\Longrightarrow$ this work
  - Detailed numerical study for lowest-order processes $\gamma\gamma \to 4f$ and $\gamma\gamma \to 4f + \gamma$
  - First step in the calculation of radiative corrections for $\gamma\gamma \to \mathrm{WW} \to 4f$

Details of the calculation

Features of the calculation

- Monte Carlo event generator for $\gamma\gamma \to 4f$ and $\gamma\gamma \to 4f + \gamma$
- All $4f(+\gamma)$ final states, full lowest-order amplitudes (including gluon-exchange diagrams)
- All fermions massless
- Multi-channel integration technique with adaptive optimization
- Realistic photon spectrum implemented in the parameterization of CompAZ

Zarnecki'02;Telnov'95;
Chen et al.'95

Main complications for $\gamma\gamma \to 4f(+\gamma)$

- Fast evaluation of diagrams with complicated structure due to 2(3) external photon lines

  Number of diagrams: 6(24) $\nu_e\bar{\nu}_e u\bar{u}(\gamma)$
  (unitary gauge, no gluons) ⋮
  71(468) $u\bar{u}d\bar{d}(\gamma)$

- Rich peaking structure
  $\Rightarrow$ many different channels (=8-dim. phase space), one channel for each diagram
- Stable numerical convolution over the photon spectra
- Gauge invariance in presence of unstable particles

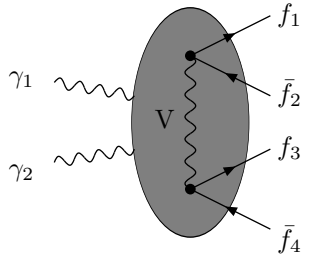
Generic calculation of amplitudes

- Analytic part: helicity amplitudes for generic diagrams

  Evaluation with Weyl–van der Waerden spinors and use of discrete symmetries

  $\gamma\gamma \longrightarrow 4f$: 2 compact functions for 1 generic diagram, for all final states and polarizations

  $\gamma\gamma \longrightarrow 4f\gamma$: Fortran code for each generic diagram generated by a Mathematica program



- Combinatorics: field insertions for generic diagrams

  Permutations of external fermions and insertions of internal fermion and boson fields

- Square amplitude: squared diagrams and interferences

  Fermi signs and colour algebra (for gluon-exchange diagrams)

Simplification from non-linear gauge fixing

$$\mathcal{L}_{\mathrm{fix,W}} = -\left|\partial^\mu W^+_\mu - \mathrm{i}M_\mathrm{W}\phi^+ + \mathrm{i}e(A^\mu - \frac{c_\mathrm{W}}{s_\mathrm{W}}Z^\mu)W^+_\mu\right|^2.$$

$\Rightarrow$ No $\gamma\phi W$ coupling and simplified VWW, γVWW vertices ($V = \gamma, Z$)

Introduction of decay widths

Optional: constant, step, running width, complex-mass scheme

$\Rightarrow$ Important for controlling gauge invariance

- Gauge invariant complex-mass scheme: replace everywhere Denner,Dittmaier,M.R.,Wackeroth'99

$$M^2_{\mathrm{W/Z}} \to M^2_{\mathrm{W/Z}} - \mathrm{i}\Gamma_{\mathrm{W/Z}} M_{\mathrm{W/Z}} \qquad \text{as well as} \qquad \cos^2\theta_{\mathrm{w}} \to \frac{M^2_{\mathrm{W}} - \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}}{M^2_{\mathrm{Z}} - \mathrm{i}\Gamma_{\mathrm{Z}} M_{\mathrm{Z}}}.$$

Numerical integration

- Multi-channel Monte Carlo integration Berends,Daverveldt,Kleiss'85 Hilgart,Kleiss,Le Diberder'93

  A channel corresponds to each diagram, importance sampling for all propagators (6–468 different channels)

- Adaptive weight optimization Kleiss,Pittau '94

- Phase-space generators similar to RacoonWW and Lusifer Denner,Dittmaier,M.R.,Wackeroth'00,'01 Dittmaier,M.R.'02

  Compact phase-space generator for each generic diagram

- Standard cut already taken into account in event generation: invariant-mass cuts, energy cuts, angular cuts

  $\Rightarrow$ Important for the numerical stability and efficiency

Implementation of the photon spectra

$$\mathrm{d}\sigma = \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \, f_\gamma(x_1) f_\gamma(x_2) \, \mathrm{d}\sigma_{\gamma\gamma}(x_1 P_1, x_2 P_2).$$

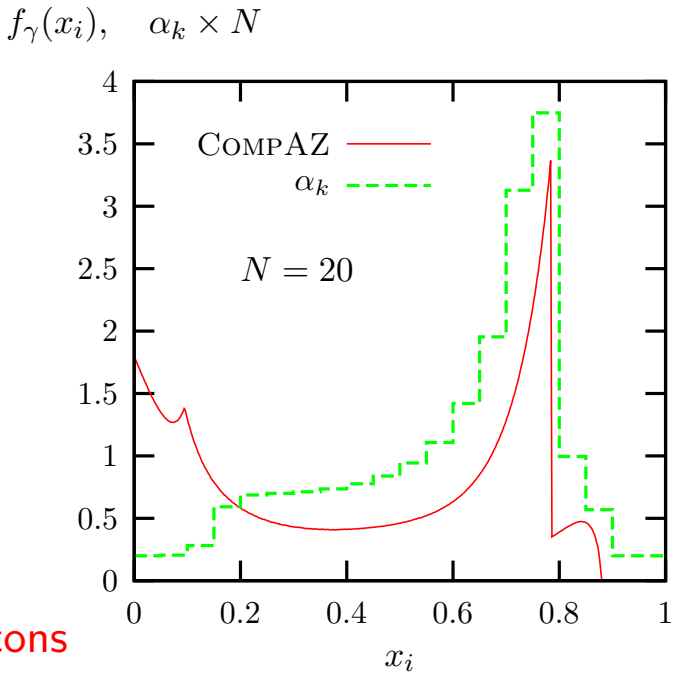
- Importance sampling in numerical integration over the photon spectra $f_\gamma(x)$

  Method:

  - decompose x-range in N equal bins ($N = 500$)
  - choose a bin with probability α_k
  - divide weight by α_k $\quad (\sum_k \alpha_k = 1)$

  Choose $\alpha_k \propto$ cross section in bin i

  Polarization of the laser beam: -1
  Polarization of the electron beam: $+0.85$



- Photon spectra determine the polarization of the incoming photons

Process	σ_{4f}[fb]	$\sigma_{4f\gamma}$[fb]
$\gamma\gamma \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\mathrm{u}\bar{\mathrm{d}}(\gamma)$	565.05(33)	14.216(27)
$\gamma\gamma \to \nu_\mathrm{e}\mathrm{e}^+\mathrm{d}\bar{\mathrm{u}}(\gamma)$	558.39(32)	15.459(30)

$\Rightarrow$ Cross sections for CP-equivalent final states are not equal!

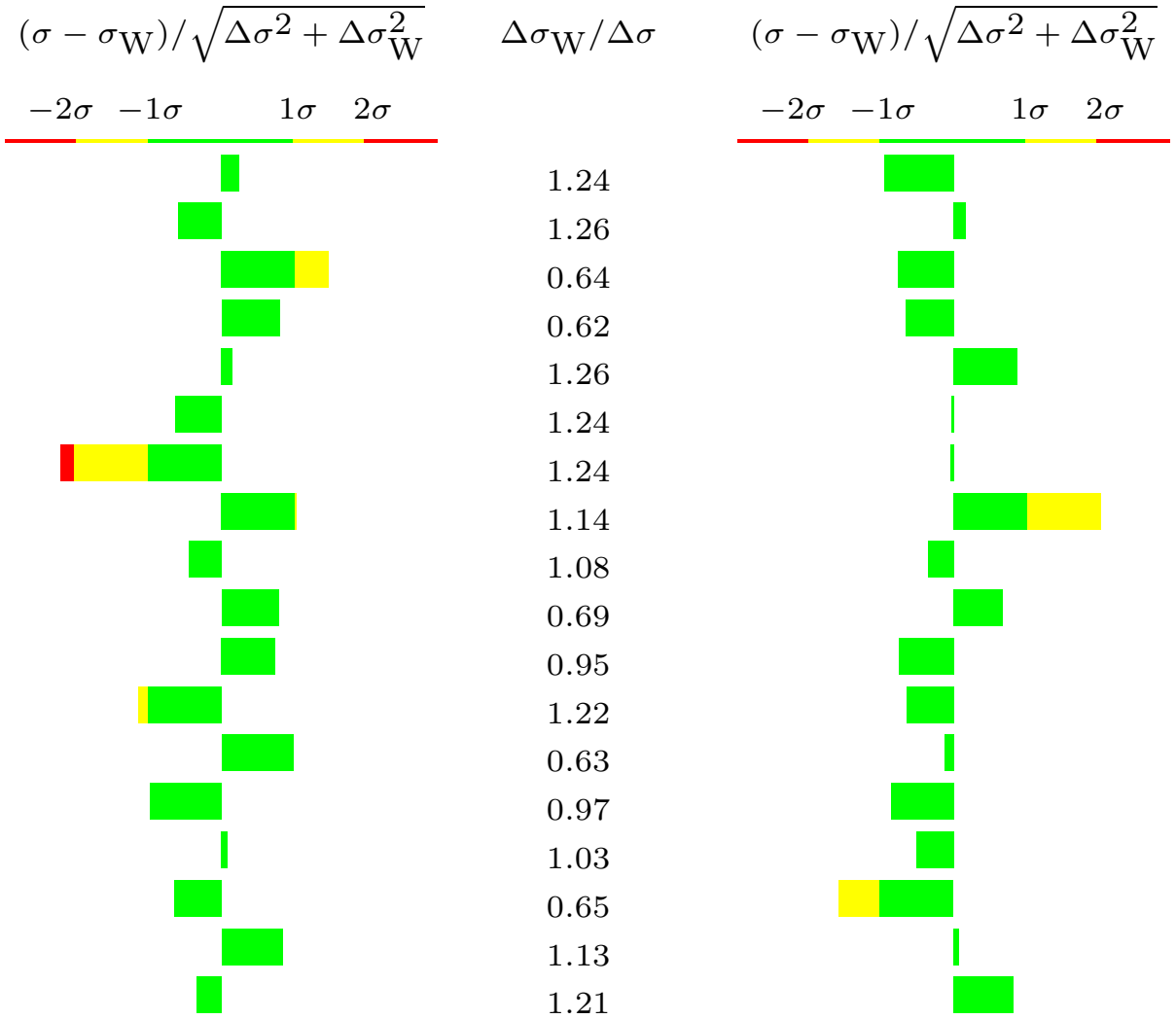
Comparison with MADGRAPH & WHIZARD

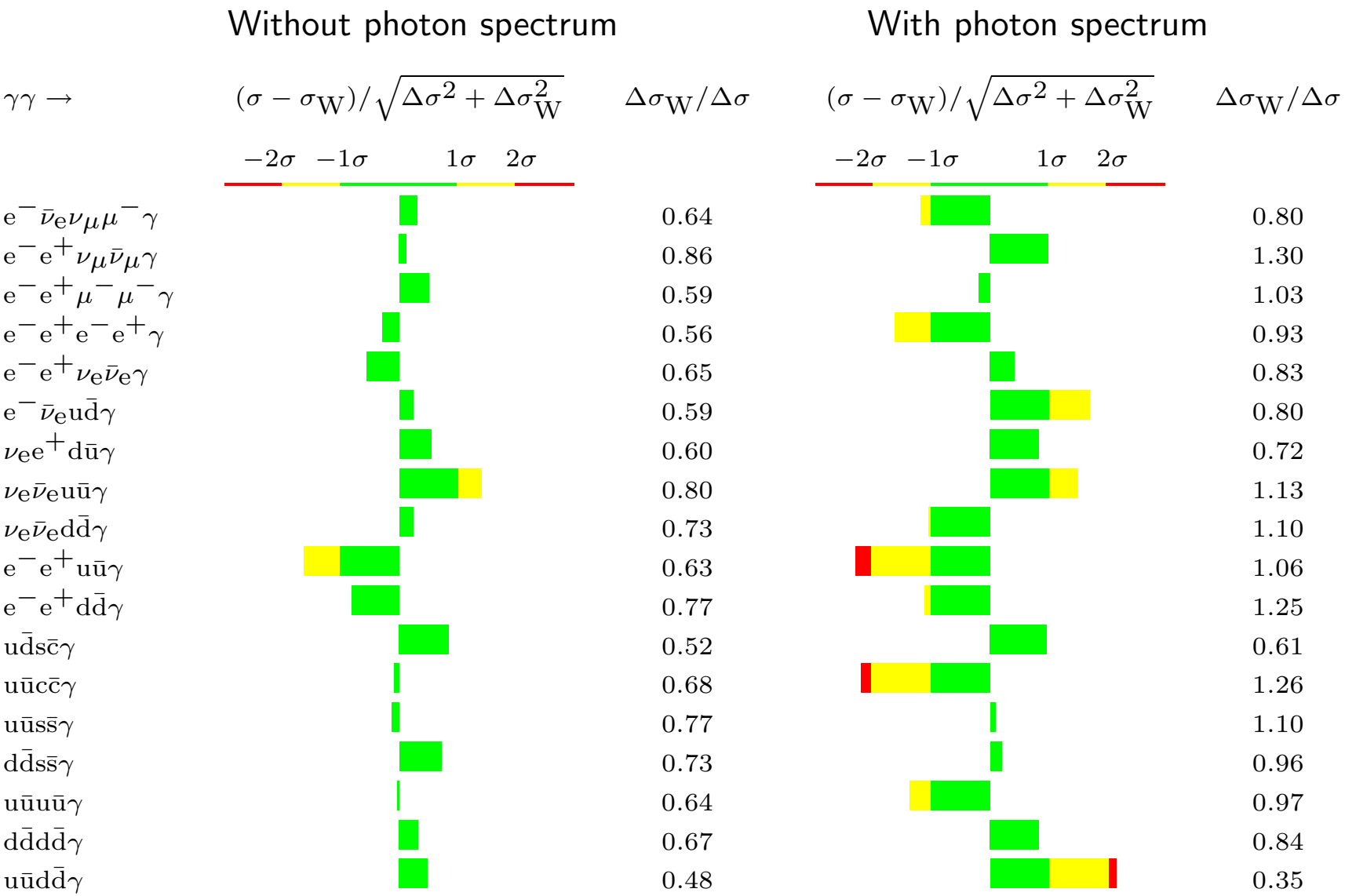
Outcome of comparison with MADGRAPH & WHIZARD:

- Very good agreement between our results and the results of MADGRAPH & WHIZARD
- Statistical errors are comparable
- MADGRAPH & WHIZARD up to 10 times slower for complicated neutral-current processes

Without photon spectrum

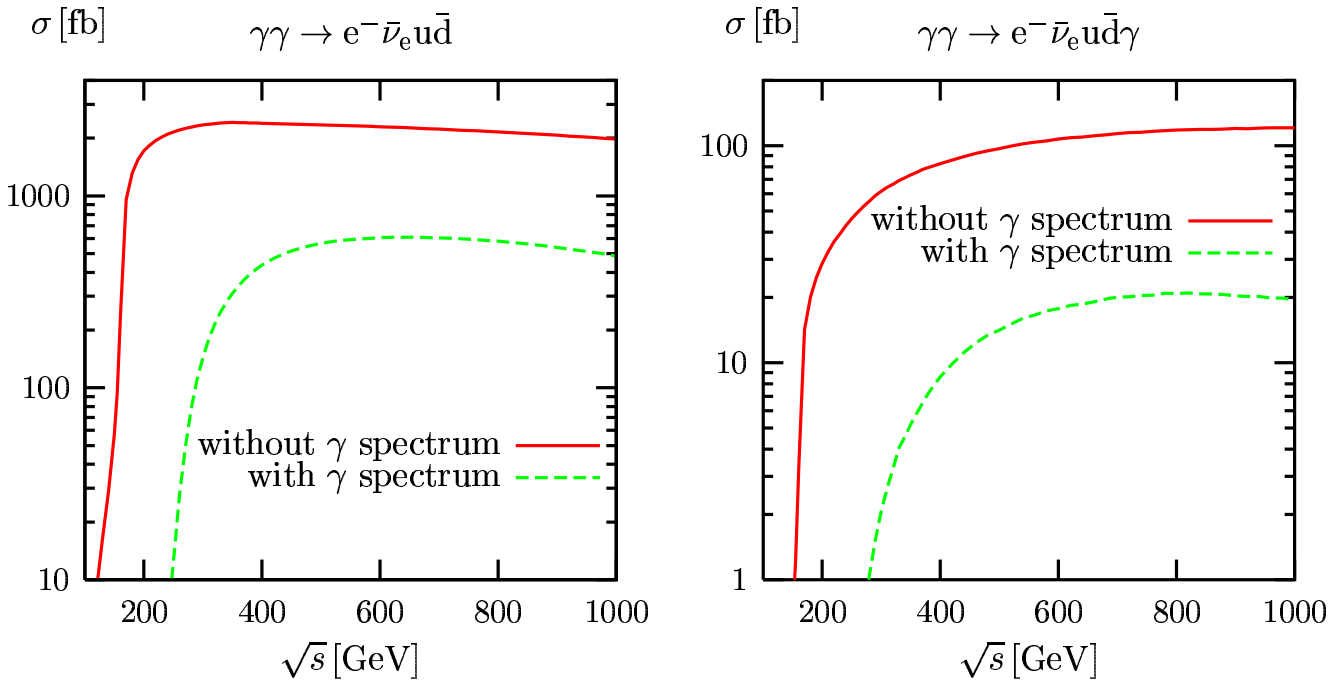
With photon spectrum




Without photon spectrum
With photon spectrum
$\gamma\gamma \to$
$(\sigma - \sigma_W)/\sqrt{\Delta\sigma^2 + \Delta\sigma_W^2}$
$\Delta\sigma_W/\Delta\sigma$
-2σ -1σ 1σ 2σ
$e^-\bar{\nu}_e\nu_\mu\mu^-\gamma$ 0.64 0.80
$e^-e^+\nu_\mu\bar{\nu}_\mu\gamma$ 0.86 1.30
$e^-e^+\mu^-\mu^-\gamma$ 0.59 1.03
$e^-e^+e^-e^+\gamma$ 0.56 0.93
$e^-e^+\nu_e\bar{\nu}_e\gamma$ 0.65 0.83
$e^-\bar{\nu}_e u\bar{d}\gamma$ 0.59 0.80
$\nu_e e^+ d\bar{u}\gamma$ 0.60 0.72
$\nu_e\bar{\nu}_e u\bar{u}\gamma$ 0.80 1.13
$\nu_e\bar{\nu}_e d\bar{d}\gamma$ 0.73 1.10
$e^-e^+u\bar{u}\gamma$ 0.63 1.06
$e^-e^+d\bar{d}\gamma$ 0.77 1.25
$u\bar{d}s\bar{c}\gamma$ 0.52 0.61
$u\bar{u}c\bar{c}\gamma$ 0.68 1.26
$u\bar{u}s\bar{s}\gamma$ 0.77 1.10
$d\bar{d}s\bar{s}\gamma$ 0.73 0.96
$u\bar{u}u\bar{u}\gamma$ 0.64 0.97
$d\bar{d}d\bar{d}\gamma$ 0.67 0.84
$u\bar{u}d\bar{d}\gamma$ 0.48 0.35

Integrated cross section

γ spectrum included, cuts applied



- W-pair threshold $\sqrt{s} \gtrsim 160\,\mathrm{GeV}$ clearly visible
- γ spectrum reduces the cross section and shifts the threshold to higher energies
- Cross section decreases for high energies because of cuts
  Remark: $\sigma_{\mathrm{tot}}(\gamma\gamma \to \mathrm{WW}) \to$ const., $\sqrt{s} \to \infty$.

Comparison between different width schemes

$\sigma(\gamma\gamma \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\mu\mu^-)$

$\sqrt{s_{\gamma\gamma}}\,[\mathrm{GeV}]$	500	800	1000	2000	10000
fixed width	826.40(21)	788.35(21)	746.94(21)	500.70(20)	31.745(68)
step width	827.45(22)	789.34(21)	748.17(23)	501.41(21)	31.746(68)
running width	827.43(23)	789.29(21)	748.11(23)	501.32(21)	31.715(68)
complex mass	826.23(21)	788.18(21)	746.78(21)	500.59(20)	31.738(68)

$\sigma(\gamma\gamma \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\mu\mu^-\gamma)$

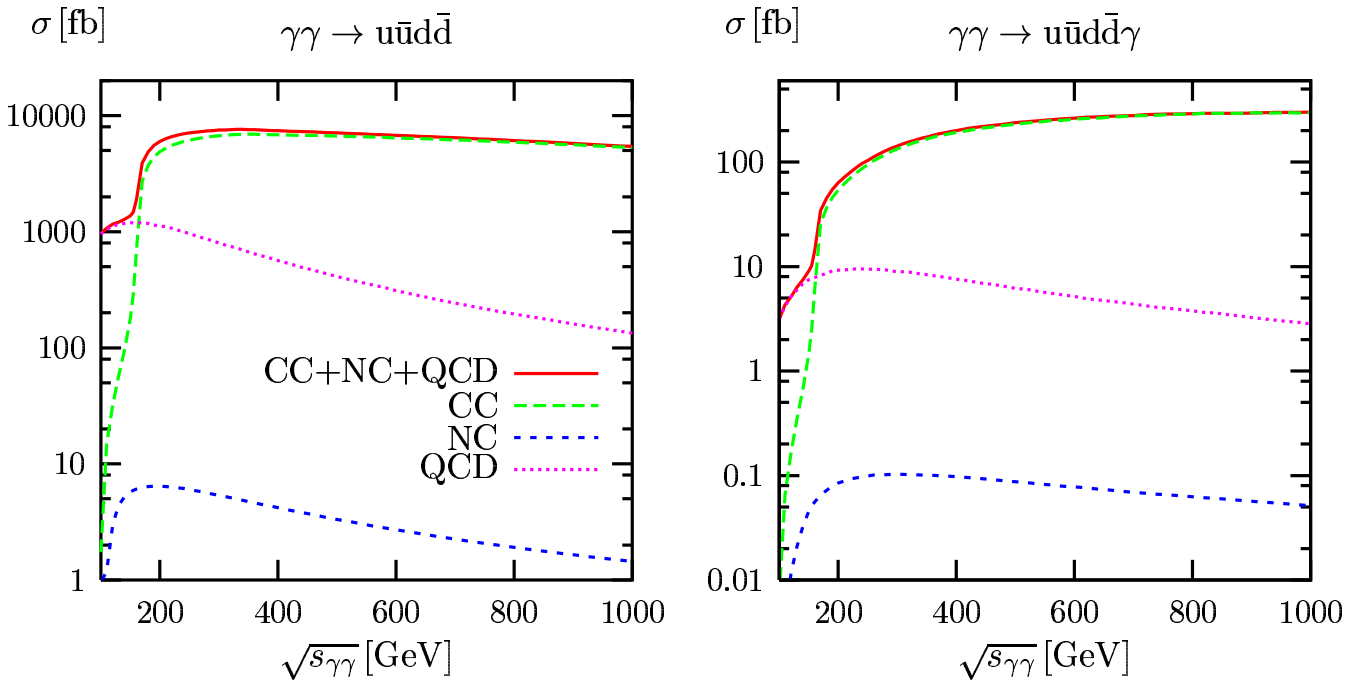
$\sqrt{s_{\gamma\gamma}}\,[\mathrm{GeV}]$	500	800	1000	2000	10000
fixed width	39.230(45)	47.740(73)	49.781(91)	43.98(18)	4.32(23)
step width	39.253(45)	47.781(73)	49.881(96)	44.01(18)	4.31(24)
running width	39.251(49)	47.781(74)	49.898(95)	44.48(22)	10.83(28)
complex mass	39.221(45)	47.730(73)	49.770(91)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

$\Rightarrow$ Running width scheme yields wrong results from $\gamma\gamma \to 4f + \gamma$ at $1\,\mathrm{TeV}$

$\Rightarrow$ Fixed with, step width, and gauge-invariant complex-mass scheme agree within $\mathcal{O}(\Gamma_\mathrm{W}/M_\mathrm{W}) \approx 2\%$.

Contributions to the cross section

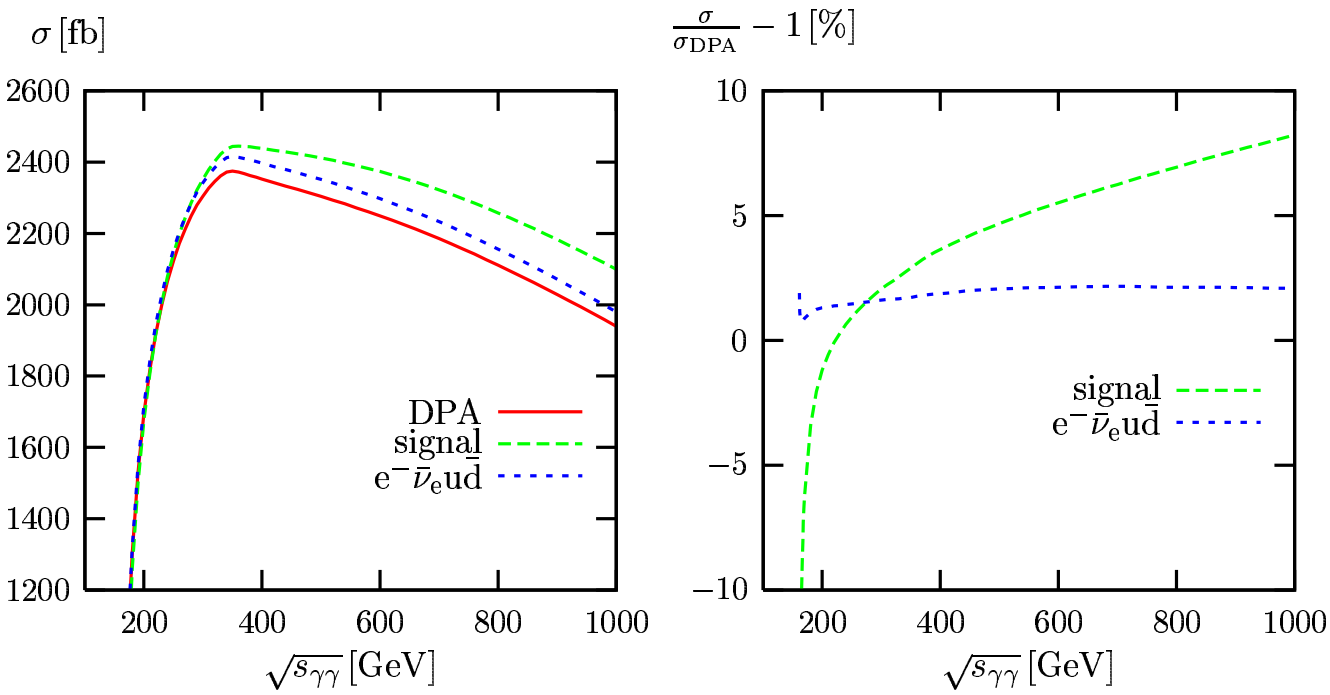
No γ spectrum included, cuts applied



- By far largest contribution from W-pair production (CC diagrams)
- Gluon-exchange contributions 1–2 orders of magnitude smaller
- NC diagrams negligible for CC processes

Signal diagrams versus double-pole approximation

No γ spectrum included, cuts applied



- Gauge-variant signal diagrams show large deviations of 5–10% for $\sqrt{s} = 0.5$–$1\,\mathrm{TeV}$
- Double-pole approximation (DPA) agrees within $\mathcal{O}(\Gamma_W/M_W) = 1$–$3\%$

$\Rightarrow$ Double-pole approximation is a promising approach to include radiative corrections into the theoretical predictions

Summary and outlook

Features of the calculation:

- Lowest-order prediction for all processes $\gamma\gamma \longrightarrow 4f$ and $\gamma\gamma \longrightarrow 4f + \gamma$ (including gluon-exchange diagrams)
- Monte Carlo generator available upon request
- Photon beam spectrum in the parametrization of CompAZ implemented
- Non-standard triple- and quartic-gauge-boson couplings and an effective $\gamma\gamma H$ coupling can be optional included.

$\Longrightarrow$ see talk of A. Bredenstein

Final aim of the calculation:

Calculation of the $\mathcal{O}(\alpha)$ corrections in double-pole approximation (similar to RacoonWW)