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Precision calculations for $\gamma\gamma \to$ WW $\to$ 4 fermions $(+\gamma)$

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Contents

1 Introduction

Four-fermion production at a future $\gamma\gamma$ collider:

- large $\gamma\gamma \to \mathrm{WW} \to 4f$ cross section: $\sigma_{\mathrm{total}} \to 80\,\mathrm{pb}$ at high energies
  $\hookrightarrow$ precision signal / background to new physics
- test of $\gamma\mathrm{WW}$ and $\gamma\gamma\mathrm{WW}$ couplings
- s-channel Higgs production $\gamma\gamma \to \mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$

Requirements from theory:

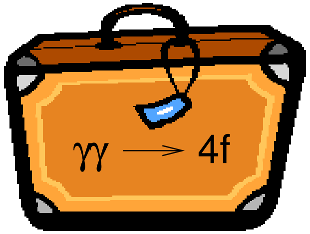
Predictions at %-level or better achieved by

- thorough description of decays of resonant gauge bosons
- inclusion of radiative corrections
- optional inclusion of non-standard gauge-boson couplings
- special improvements for Higgs production

Requirements neither fulfilled by multi-purpose Monte Carlo generators nor by previous dedicated analyses !

$\Rightarrow$ Motivation for constructing the dedicated event generator COFFER$\gamma\gamma$ to fill this gap

2 The Monte Carlo generator



Bredenstein, S.D., Roth '04–'05

Features of the generator COFFER$\gamma\gamma$

(COrrections to Four-FERmion production in $\gamma\gamma$ collisions)

- Complete lowest-order matrix elements
  - ◇ compact results in terms of Weyl–van-der-Waerden spinor products
  - ◇ massless fermions (mass effects restored in corrections)
  - ◇ loop-induced or effective $\gamma\gamma\mathrm{H}$ coupling
  - ◇ anomalous triple and quartic gauge-boson couplings
- Radiative corrections to $\gamma\gamma \to \mathrm{WW} \to 4f(+\gamma)$

  in "double-pole approximation" (DPA) similar to $\mathrm{e}^{+}\mathrm{e}^{-}$ case

  Aeppli, v.Oldenborgh, Wyler '93; Beenakker, Berends, Chapovsky '98
  Jadach et al. '99; Denner, S.D., Roth, Wackeroth '99
- Multi-channel Monte Carlo integration with adaptive weight optimization

  Berends, Kleiss, Pittau '94 Kleiss, Pittau '94
- Realistic γ beam spectrum, e.g., by COMPAZ Zarnecki '02

Note: all parts checked by a second independent Monte Carlo generator !

3 Selected lowest-order results

A semileptonic integrated cross section

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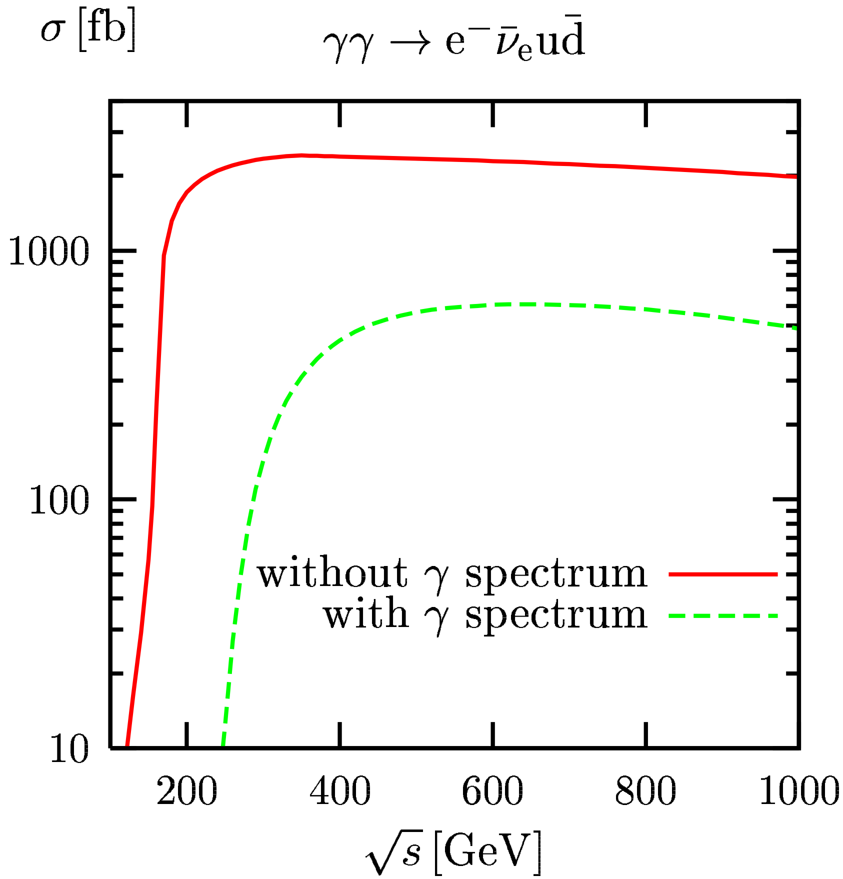
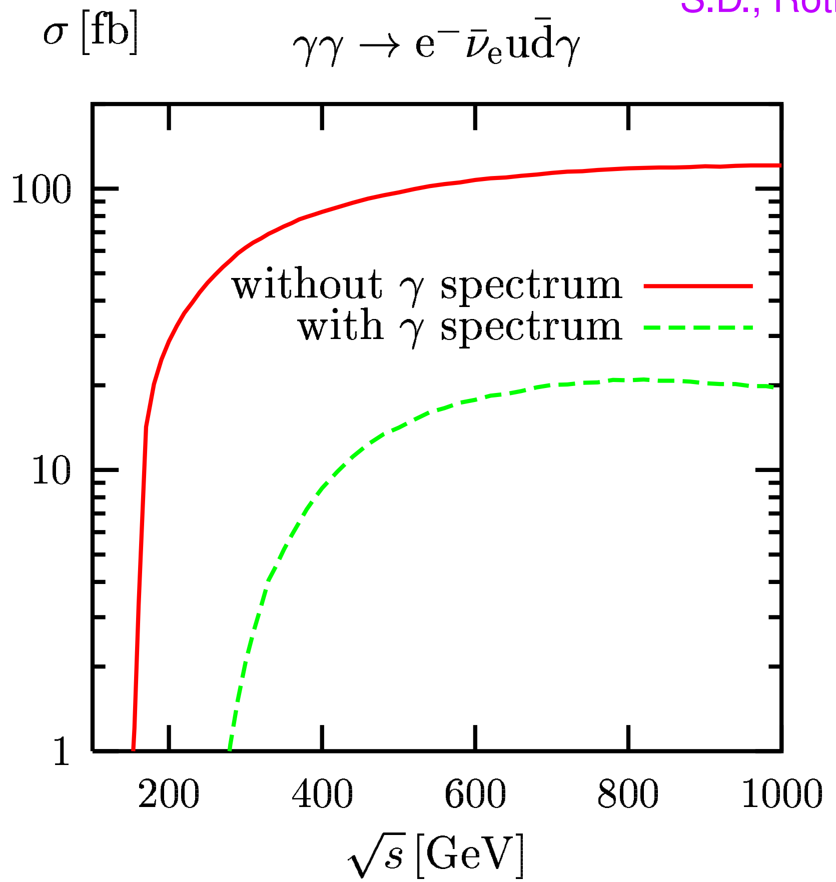




Good agreement with WHIZARD / MADGRAPH for all final states !

Kilian '01 Stelzer, Long '94

Predictions with anomalous TGCs

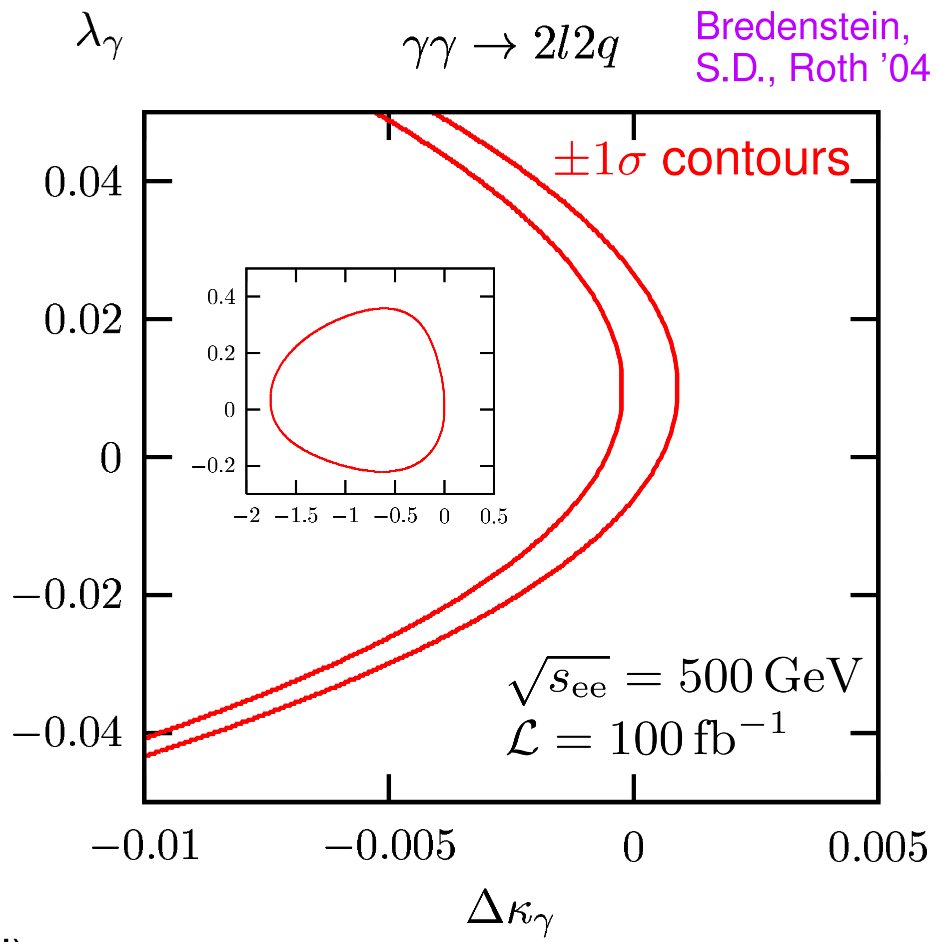
$$\delta\mathcal{L} = \mathrm{i}g_1 \frac{\alpha_{\mathrm{B}\phi}}{M_\mathrm{W}^2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) - \mathrm{i}g_2 \frac{\alpha_{\mathrm{W}\phi}}{M_\mathrm{W}^2}(D_\mu\Phi)^\dagger \boldsymbol{\sigma}\cdot\mathbf{W}^{\mu\nu}(D_\nu\Phi) - g_2\frac{\alpha_\mathrm{W}}{6M_\mathrm{W}^2}\mathbf{W}^\mu{}_\nu\cdot(\mathbf{W}^\nu{}_\rho\times\mat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

$\Delta\kappa_\gamma = \alpha_{\mathrm{W}\phi} + \alpha_{\mathrm{B}\phi}$

$\hookrightarrow$ anomalous $\gamma\mathrm{WW}$ coupling

$\lambda_\gamma = \alpha_\mathrm{W}$

$\hookrightarrow$ anomalous $\gamma\mathrm{WW}$ and $\gamma\gamma\mathrm{WW}$ couplings (elmg. gauge invariance!)



Above result based on cross section only.

More stringent constraints will result from distributions!

(See also Tupper, Samuel '81; Choi, Schrempp '91; Yehudai '91; Božović-Jelisavčić, Mönig, Šekarić '02)

Predictions with anomalous QGCs

$$\delta\mathcal{L} = -\frac{e^2}{16\Lambda^2}\, a_0\, F^{\mu\nu}F_{\mu\nu}\overline{\mathbf{W}}_\alpha\overline{\mathbf{W}}^\alpha - \frac{e^2}{16\Lambda^2}\, a_c\, F^{\mu\alpha}F_{\mu\beta}\overline{\mathbf{W}}^\beta\overline{\mathbf{W}}_\alpha - \frac{e^2}{16\Lambda^2}\, \tilde{a}_0\, F^{\mu\nu}\tilde{F}_{\mu\nu}\overline{\mathbf{W}}_\alpha\overline{\mathbf{W}}^\alpha$$

$a_0, a_c, \tilde{a}_0$

$\hookrightarrow$ anomalous $\gamma\gamma WW$ and $\gamma\gamma ZZ$ couplings

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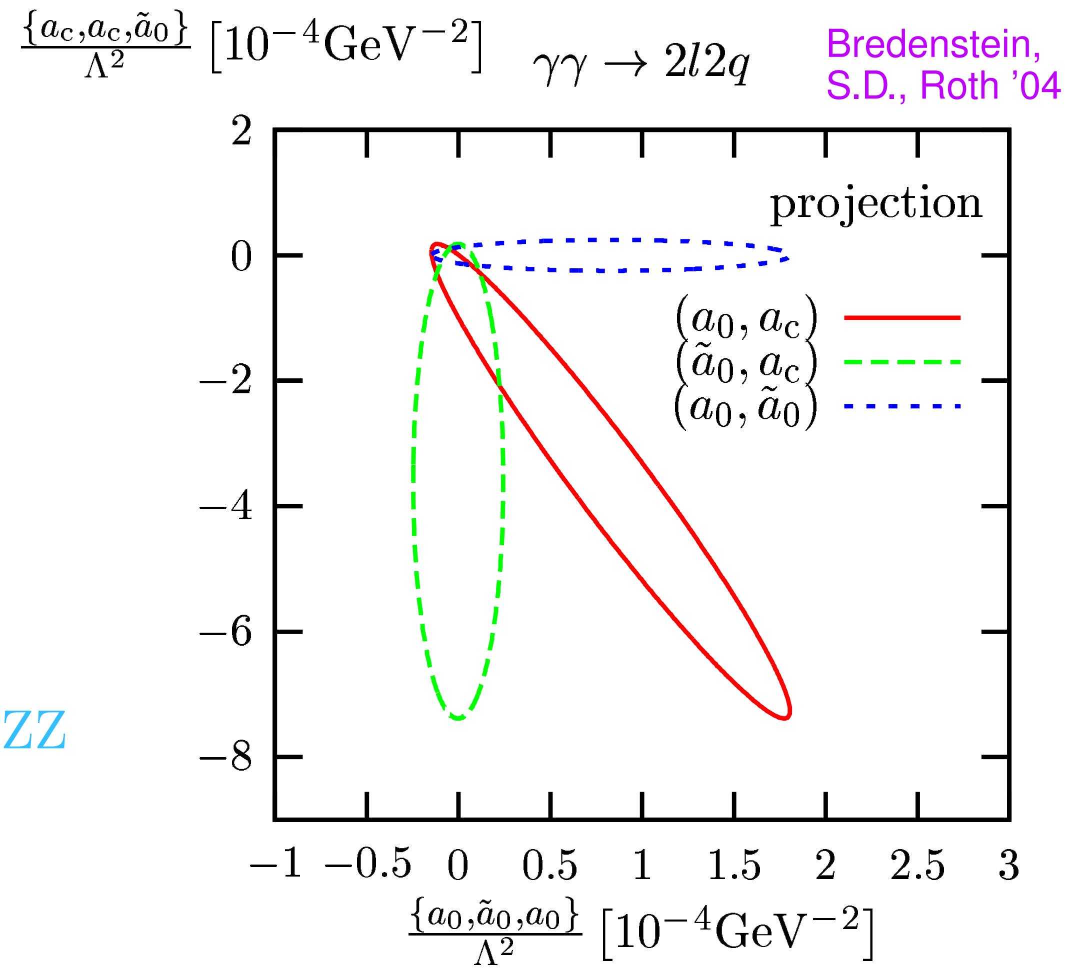
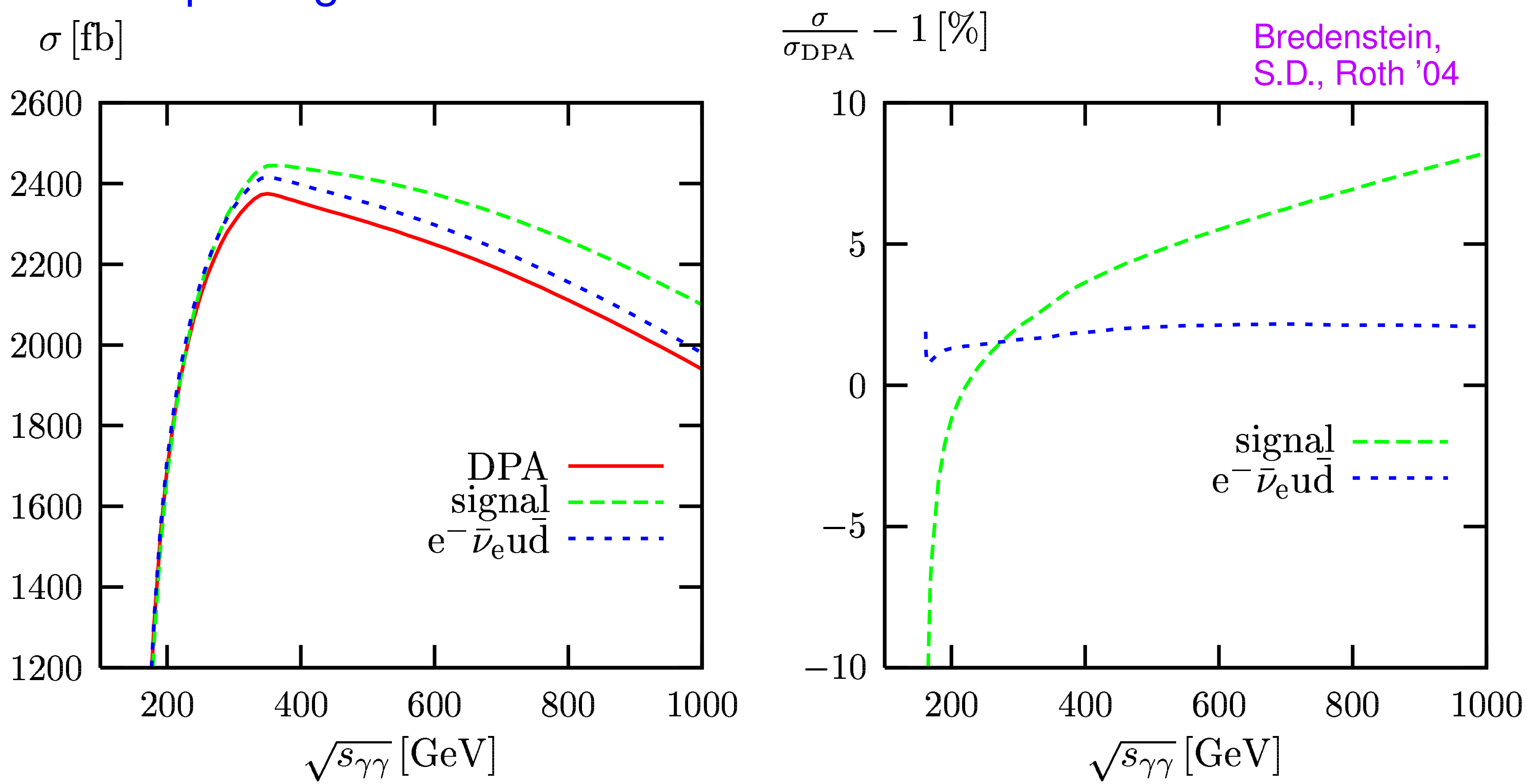


Above result based on cross section only ($\sqrt{s_{ee}} = 500\,\text{GeV}$, $\mathcal{L} = 100\,\text{fb}^{-1}$).

More stringent constraints will result from distributions!

(See also Bélanger, Boudjema '92; Marfin, Mossolov, Shishkina '03)

"Naive W-pair signal" versus DPA in lowest order



- "signal" = sum of diagrams with two resonant W bosons
  $\hookrightarrow$ non-gauge-invariant result, approximation out of control
- "DPA" = "signal" with on-shell-projected residue
  $\hookrightarrow$ gauge-invariant result with accuracy of $\mathcal{O}(\Gamma_W/M_W) = 1$–$3\%$

(See also M. Moretti '96; Boos, Ohl '97; Baillargeon, Bélanger, Boudjema '97)

4 Radiative corrections

Strategy essentially follows approach of RACOONWW Denner, S.D., Roth, Wackeroth '99–'01

Lowest-order predictions

$\hookrightarrow$ full matrix elements for $\gamma\gamma \to 4f$

Radiative corrections to $\gamma\gamma \to \mathrm{WW} \to 4f$

- Real photonic corrections

  $\hookrightarrow$ full matrix elements for $\gamma\gamma \to 4f + \gamma$

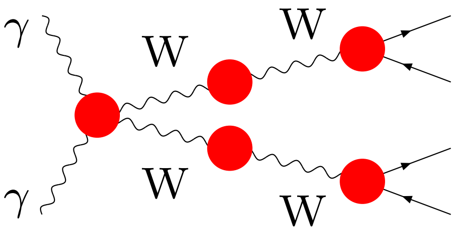
- Virtual corrections in DPA

  ◇ factorizable contributions

  $\hookrightarrow$ results for on-shell W's as building blocks:

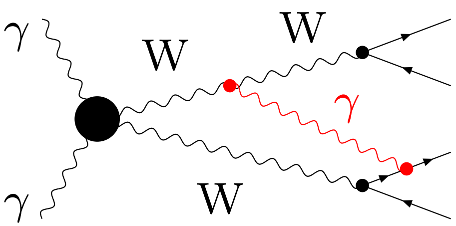
  – $\gamma\gamma \to \mathrm{WW}$ Denner, S.D., Schuster '94,'95; Jikia '96

  – $\mathrm{W} \to f\bar{f}'$ Bardin, S. Riemann, T. Riemann '86 Jegerlehner '86; Denner, Sack '90



  ◇ non-factorizable contributions

  $\hookrightarrow$ adapt known results for $\mathrm{e}^+\mathrm{e}^-$ annihilation Beenakker, Berends, Chapovsky '97; Denner, S.D., Roth '97



- Combination of real and virtual corrections

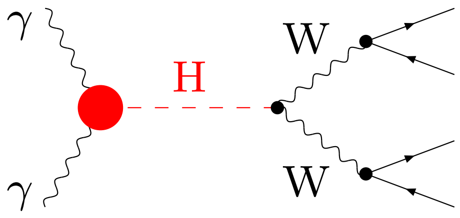
  $\hookrightarrow$ two methods: slicing and dipole subtraction S.D. '99; Roth '00

More details about the corrections:

- Higgs resonance:

  interference term $2\,\mathrm{Re}\{\mathcal{M}_{\mathrm{Higgs}}\mathcal{M}_0^*\}$
  with Born matrix element $\mathcal{M}_0$ insufficient

  $\hookrightarrow$ inclusion of $|\mathcal{M}_{\mathrm{Higgs}}|^2$
  (with gauge-invariant residue at $s = M_{\mathrm{H}}^2$)



- WW threshold region: DPA becomes unreliable

  $\hookrightarrow$ use "improved Born approximation" for $\sqrt{s_{\gamma\gamma}} < 170\,\mathrm{GeV}$
  (based on Coulomb singularity, Higgs resonance, and effective couplings)

- Final-state mass singularities versus photon recombination:

  ◇ phase-space cuts on "bare" momenta p_f of charged fermions f yield large corrections $\propto \alpha \ln m_f$

  $\hookrightarrow$ generalized dipole subtraction applied

  ◇ photon recombination:

  $$\min\{\angle(f,\gamma)\} < \theta_{\mathrm{rec}} = 5^\circ \quad \Rightarrow \quad p_f \to p_f + k_\gamma,\; k_\gamma \to 0$$

  $\hookrightarrow$ inclusiveness ensures cancellation of mass singularities $\propto \alpha \ln m_f$
  (KLN theorem)

$\mathcal{O}(\alpha)$-corrected integrated cross section for $\gamma\gamma \to \nu_e e^+ d\bar{u}$:

cuts: $E_{l/q} > 10\,\text{GeV},\ \theta(l/q,\text{beam}) > 5°,\ \theta(l,q) > 5°,\ m(q,q') > 10\,\text{GeV}$

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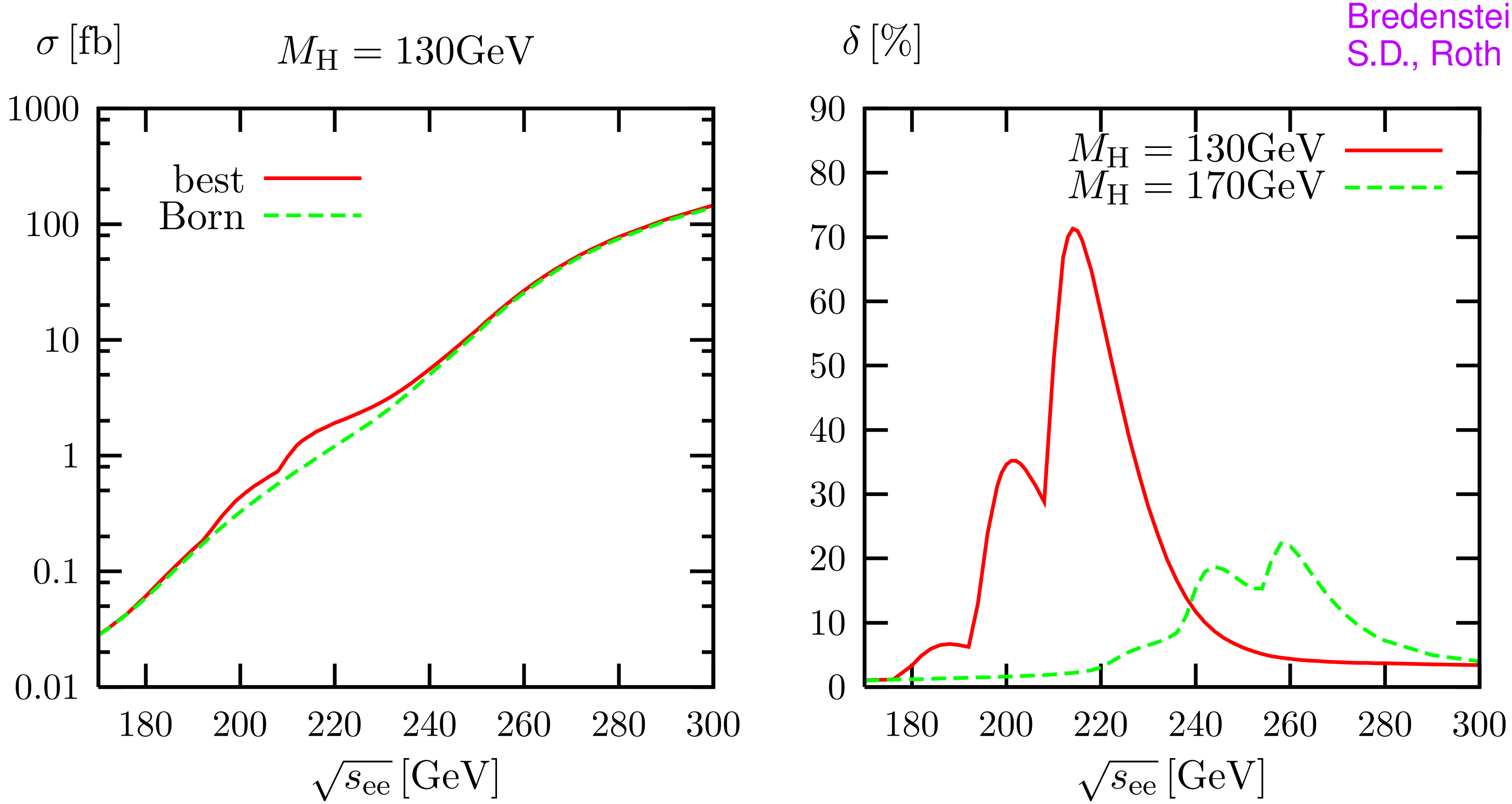

photon spectrum from CompAZ

$\hookrightarrow$ determines shape of Higgs resonance as function of e^-e^- CM energy $\sqrt{s_{ee}}$

$\mathcal{O}(\alpha)$-corrected integrated cross section for $\gamma\gamma \to \nu_e e^+ d\bar{u}$:

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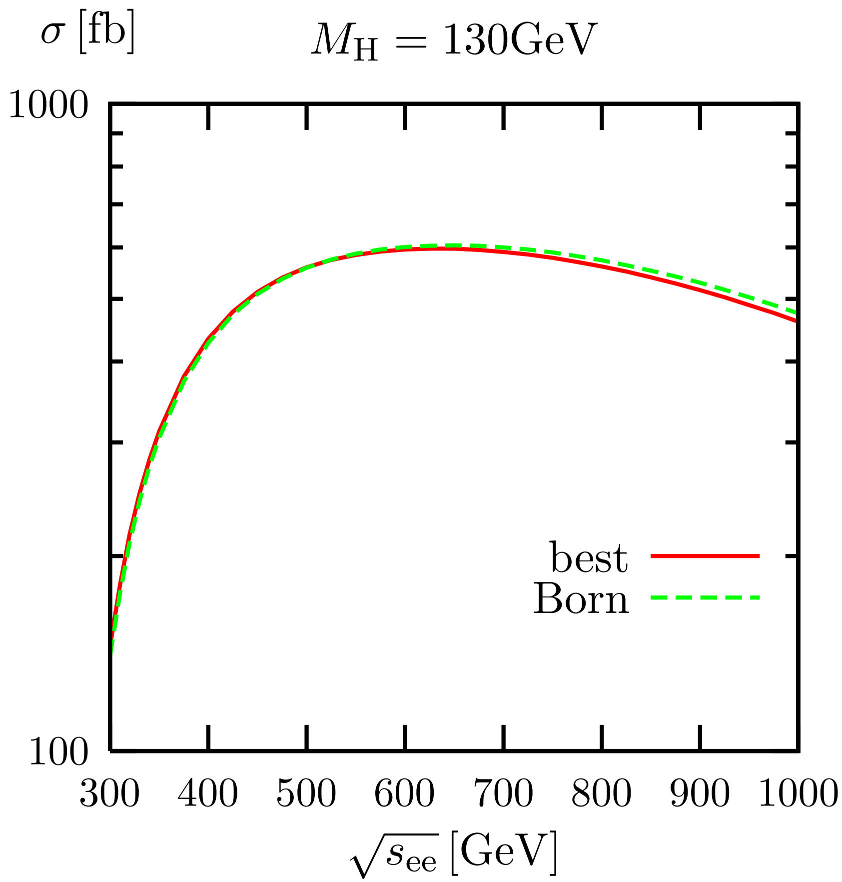
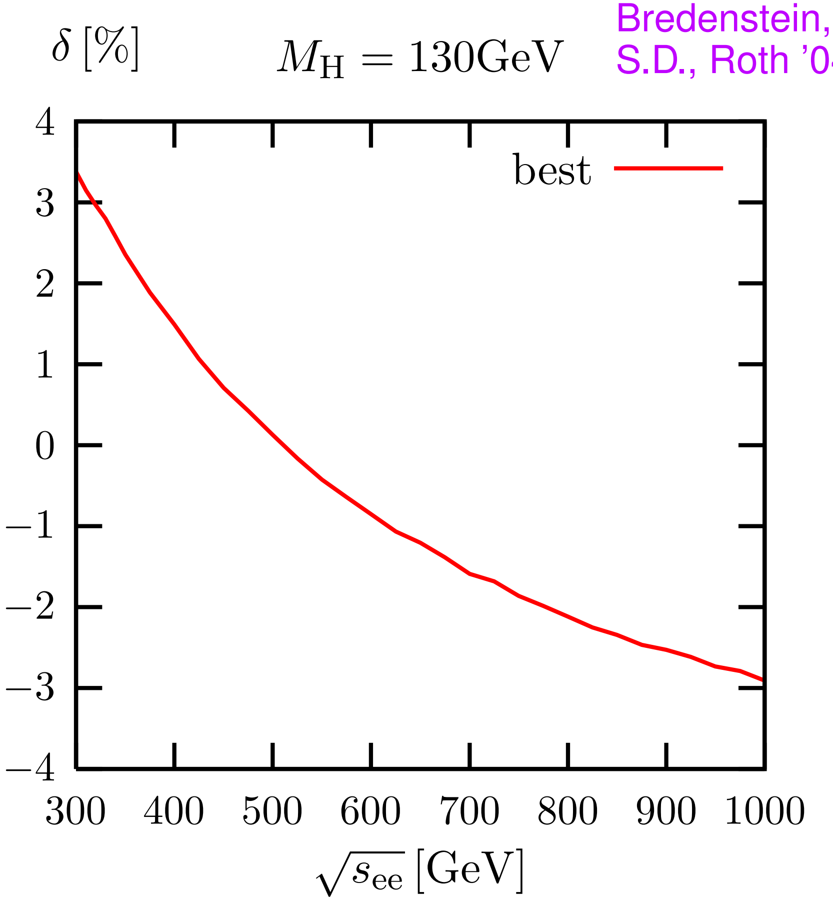


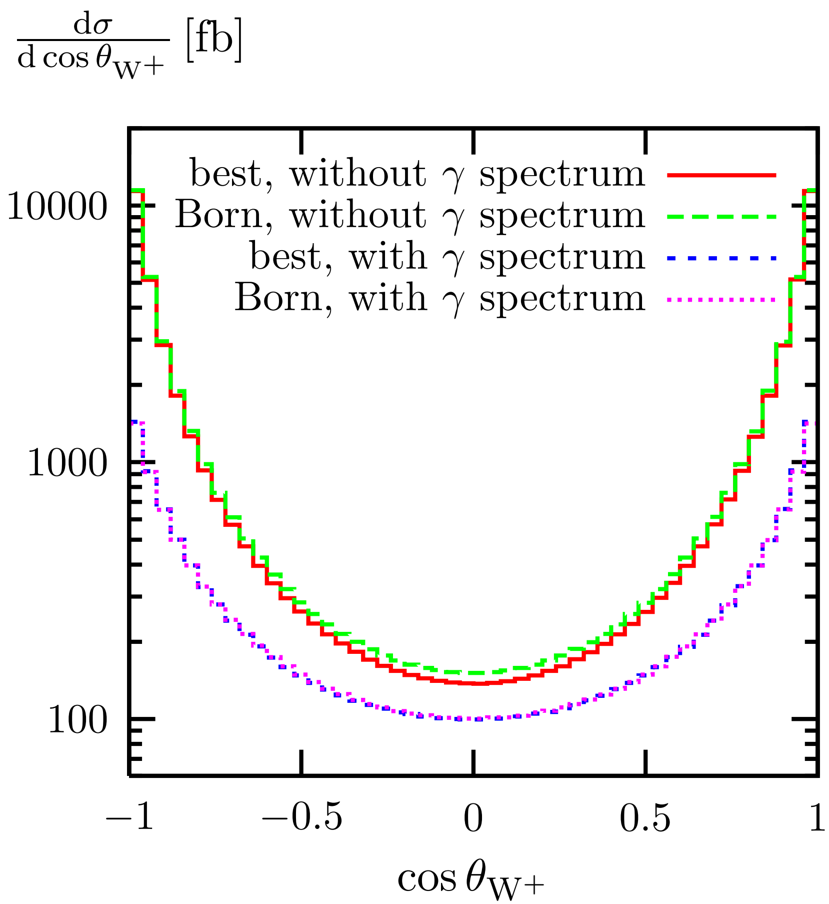


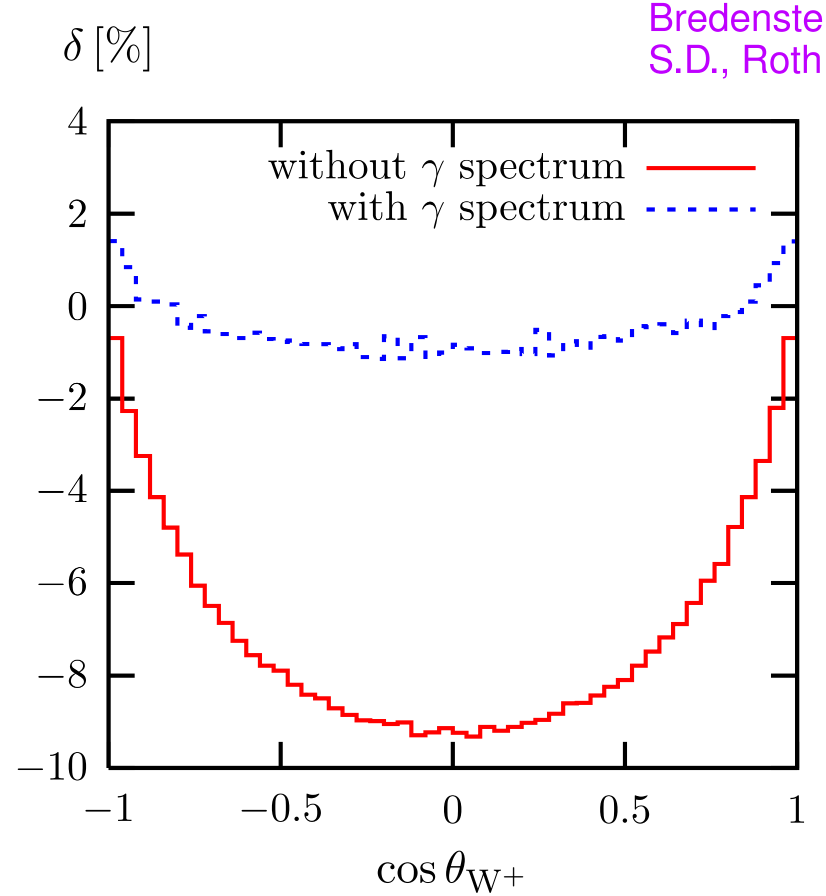
$\mathcal{O}(\alpha)$ corrections $\sim$ $\mathcal{O}(3\%)$ off Higgs resonance

$\mathcal{O}(\alpha)$-corrected W-production angle distribution for $\gamma\gamma \to \nu_e e^+ d\bar{u}$:

$\sqrt{s} = 500\,\text{GeV}$

Bredenstein, S.D., Roth '04–'05





pronounced forward-backward peaking behaviour,

but moderate corrections after convolution with photon spectrum

$\hookrightarrow$ only small distortion of distribution by corrections

$\mathcal{O}(\alpha)$-corrected W invariant-mass distribution for $\gamma\gamma \to \nu_e e^+ d\bar{u}$:

$\sqrt{s} = 500\,\mathrm{GeV}$, photon recombination applied !

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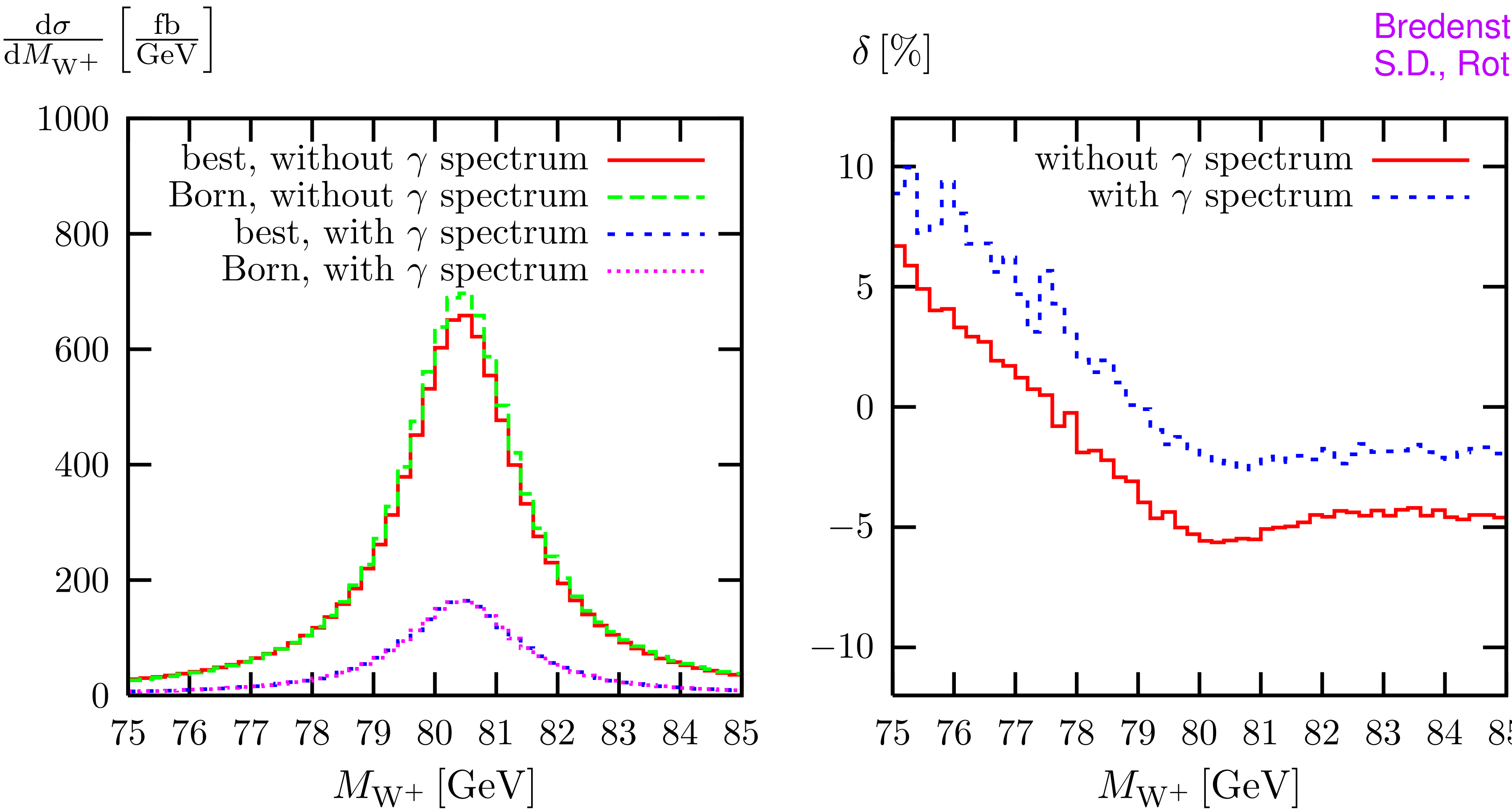


important corrections to W-line shape

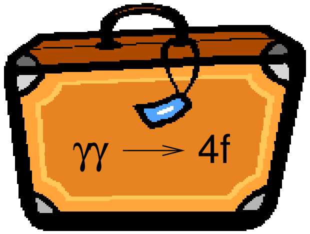
with and without convolution over photon spectrum

5 Conclusions

Four-fermion production among most interesting processes at $\gamma\gamma$ collider

- large $\gamma\gamma \to \mathrm{WW} \to 4f$ cross section
  $\hookrightarrow$ precision signal / background to new physics
- test of $\gamma\mathrm{WW}$ and $\gamma\gamma\mathrm{WW}$ couplings
- s-channel Higgs production

New event generator COFFER$\gamma\gamma$



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- lowest-order predictions for all $\gamma\gamma \to 4f$ and $4f+\gamma$ processes with light f
- loop-induced or effective $\gamma\gamma\mathrm{H}$ coupling for Higgs production
- anomalous triple and quartic gauge-boson couplings
- radiative corrections to $\gamma\gamma \to \mathrm{WW} \to 4f(+\gamma)$ in DPA

$\hookrightarrow$ Code well tested and ready to use ! (available from authors upon request)