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Single- and multi-photon events with missing energy

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based on Nucl. Phys. B541 (1999) 31

Physics Motivations

The events with single photon production plus missing energy have been used at LEP1 for the determination of the number of light neutrino species as an alternative method to the "invisible width".

At LEP2, single photon production plus missing energy, together with two photon production plus missing energy, are important channels for the search of New Physics.

- Supersymmetry searches

  $e^+e^- \to \tilde{\chi}_1\tilde{\chi}_1\gamma$
  $e^+e^- \to \tilde{G}\tilde{G}\gamma$
  $e^+e^- \to \tilde{\chi}_1\tilde{\chi}_1\gamma\gamma$
  $e^+e^- \to \tilde{G}\tilde{G}\gamma\gamma$
  $\ldots$

  See for instance
  S. Ambrosanio et al
  Nucl. Phys. B478 (1996) 46; Phys. Rev. D56 (1997) 1761; Phys. Rev. D54 (1996) 5395
  J.L. Lopez, D.V. Nanopoulos and A. Zichichi
  Phys. Rev. Lett. 77 (1996) 5168; Phys. Rev. D55 (1997) 5813
  A. Brignole, F. Feruglio and F. Zwirner
  hep-ph/9711516, Nucl. Phys. B516 (1998) 13)

- Anomalous couplings $WW\gamma$

  The single photon channel can be used as a complementary channel with respect to $e^+e^- \to W^+W^- \to 4f$ for the determination of the trilinear coupling, without contamination from WWZ vertex.

The main Standard Model backgrounds come from the processes

- $e^+e^- \to \gamma\nu\bar{\nu}$
- $e^+e^- \to \gamma\gamma\nu\bar{\nu}$

A theoretical prediction for these processes with an accuracy of the order of 1% would be desirable.

$$e^+e^- \rightarrow \gamma\nu\bar{\nu}$$

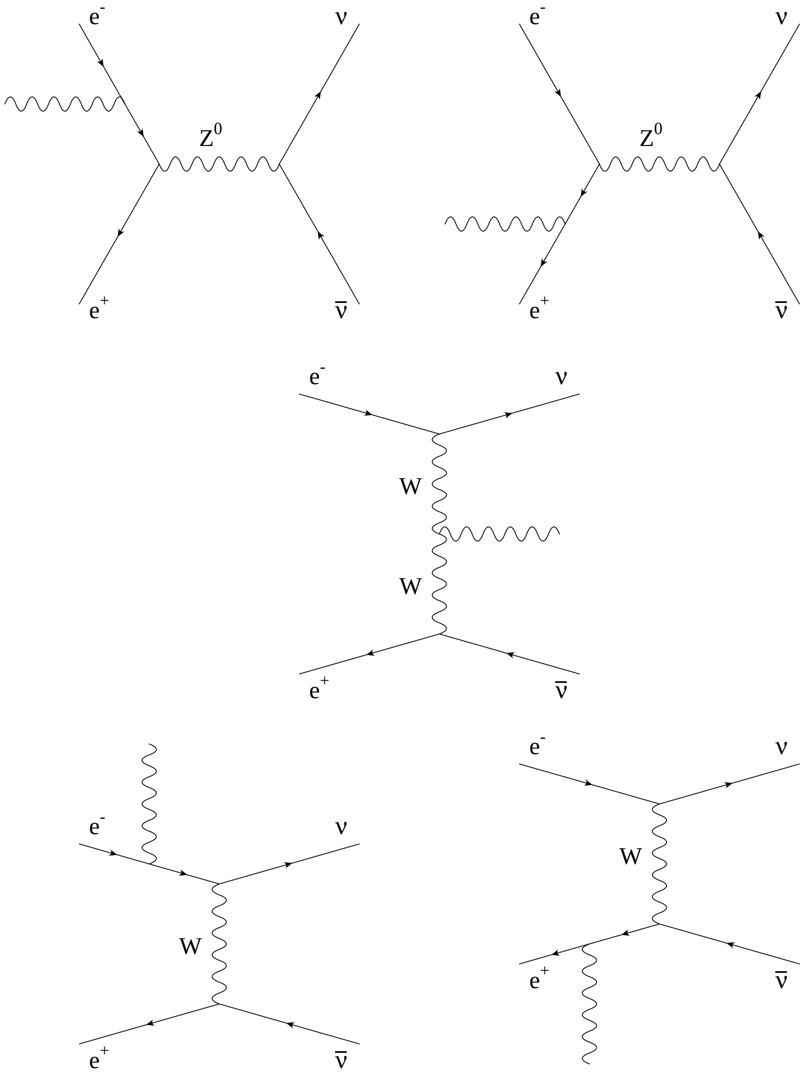

Figure 1: The tree-level Feynman diagrams for $e^+e^- \rightarrow \gamma\nu\bar{\nu}$.

Existing calculations and programs

$e^+e^- \to \gamma\nu\bar{\nu}$:

- approximate calculation of $e^+e^- \to \gamma\nu\bar{\nu}$ cross section using parton shower (`PYTHIA`) or YFS approach (`KORALZ`), dressing the invisible cross section with one external photon and including also higher-order QED effects

  T. Sjöstrand
  Comput. Phys. Commun. 79 (1994) 503, CERN-TH.7112/93
  S. Jadach, B. F. L.Ward and Z. Wąs
  Comput. Phys. Commun. 79 (1994) 503
  A. Jachołkowska, J. Kalinowski and Z. Wąs
  CERN-TH/98-55, Eur. Phys. J. C6 (1999) 485

- complete lowest-order calculation plus exact $\mathcal{O}(\alpha)$ photonic corrections and dominant weak effects to Z-exchange diagrams

  F.A. Berends et al.
  Nucl. Phys. B301 (1988) 583

  The complete matrix element is implemented in the event generator `MMM` in association with ISR

  R. Miquel, C. Mana and M. Martinez
  Z. Phys. C48 (1990) 309

- The Monte Carlo program `NUNUGPV` (old version) includes the treatment of ISR with p_T/p_L effects

  G. Montagna, O. Nicrosini, F.P. and L. Trentadue
  Nucl. Phys. B452 (1995) 161
  G. Montagna, O. Nicrosini and F.P.
  Comput. Phys. Commun. 98 (1996) 206

  It is based on the formula

$$\sigma(s) = \int dx_1\, dx_2\, dc_\gamma^{(1)}\, dc_\gamma^{(2)}\, dE_\gamma\, dc_\gamma\, \tilde{D}(x_1, c_\gamma^{(1)}; s)\tilde{D}(x_2, c_\gamma^{(2)}; s) \frac{d\sigma}{dE_\gamma dc_\gamma}\Theta(\text{cuts}), \quad (1)$$

where $d\sigma/dE_\gamma dc_\gamma$ is the simple differential spectrum on the energy and angle of the photon has been obtained, neglecting the terms with at least three propagators obtained in

F.A. Berends et al.
Nucl. Phys. B301 (1988) 583

$\tilde{D}(x, c_\gamma; s)$ is a proper combination of the QED collinear SF $D(x; s)$ with an angular factor inspired by the leading behaviour $1/(p \cdot k)$

`NUNUGPV` has been upgraded in several aspects, see the following

$e^+e^- \to \gamma\gamma\nu\bar{\nu}$:

- approximate calculations by using `PYTHIA` (parton-shower) and `KORALZ` (YFS method)
- automatic packages, such as `GRACE` and `CompHEP`, are used by experiments to calculate the cross section and generate events. For ISR `GRACE` implements both collinear SFs and PS; `CompHEP` uses collinear SFs

GRACE, MINAMI-TATEYA group
KEK Report 92-19
CompHEP, E. Boos et al
hep-ph/9503280

- `NUNUGPV`: Exact matrix element convoluted with p_T dependent SFs

Improvements of NUNUGPV

To match the requirements from LEP experimentalists, the generator NUNUGPV has been upgraded in several respects

- exact matrix element for $e^+e^- \to \gamma\nu\bar{\nu}$ calculated by means of helicity amplitude techniques, including the possibility of anomalous $WW\gamma$ couplings Δk_γ and λ_γ
- exact matrix element for $e^+e^- \to \gamma\nu\bar{\nu}$ for massive neutrino belonging to a fourth generation with standard couplings
- exact matrix element for $e^+e^- \to \gamma\gamma\nu\bar{\nu}$ calculated by means of the algorithm ALPHA

F. Caravaglios and M. Moretti
Phys. Lett. B358 (1995) 332

- improved treatment of ISR with p_t/p_L in order to estimate the effects due to the overlapping of IS pre-emission photons with the observed ones:

$$\sigma^{1\gamma}_{QED} = \int dx_1 dx_2 \int_{|c_\gamma| \geq c^m_\gamma} dc^{(1)}_\gamma dc^{(1)}_\gamma \, \tilde{D}(x_1, c^{(1)}_\gamma; s) \tilde{D}(x_2, c^{(2)}_\gamma; s) \left(d\sigma^{1\gamma} + d\sigma^{2\gamma} + d\sigma^{3\gamma} \right)$$
$$\sigma^{2\gamma}_{QED} = \int dx_1 dx_2 \int_{|c_\gamma| \geq c^m_\gamma} dc^{(1)}_\gamma dc^{(1)}_\gamma \, \tilde{D}(x_1, c^{(1)}_\gamma; s) \tilde{D}(x_2, c^{(2)}_\gamma; s) \left(d\sigma^{2\gamma} + d\sigma^{3\gamma} \right)$$

to be confronted with

$$\sigma^{1\gamma}_{coll} = \int dx_1 dx_2 \, D(x_1; s) D(x_2; s) \, d\sigma^{1\gamma}$$
$$\sigma^{2\gamma}_{coll} = \int dx_1 dx_2 \, D(x_1; s) D(x_2; s) \, d\sigma^{2\gamma}$$

- exact matrix element for $e^+e^- \to \gamma\gamma\gamma\nu\bar{\nu}$ calculated by means of ALPHA (first calculation in the literature)

The code **NUNUGPV** has been updated to include the exact matrix element for $e^+e^- \to \gamma\nu\bar{\nu}$ calculated by means of helicity amplitude techniques, with a tree body phase space numerical integration. The differences can become sizeable (of the order of several %) when a cut on the missing mass $\not{M}$ is imposed.

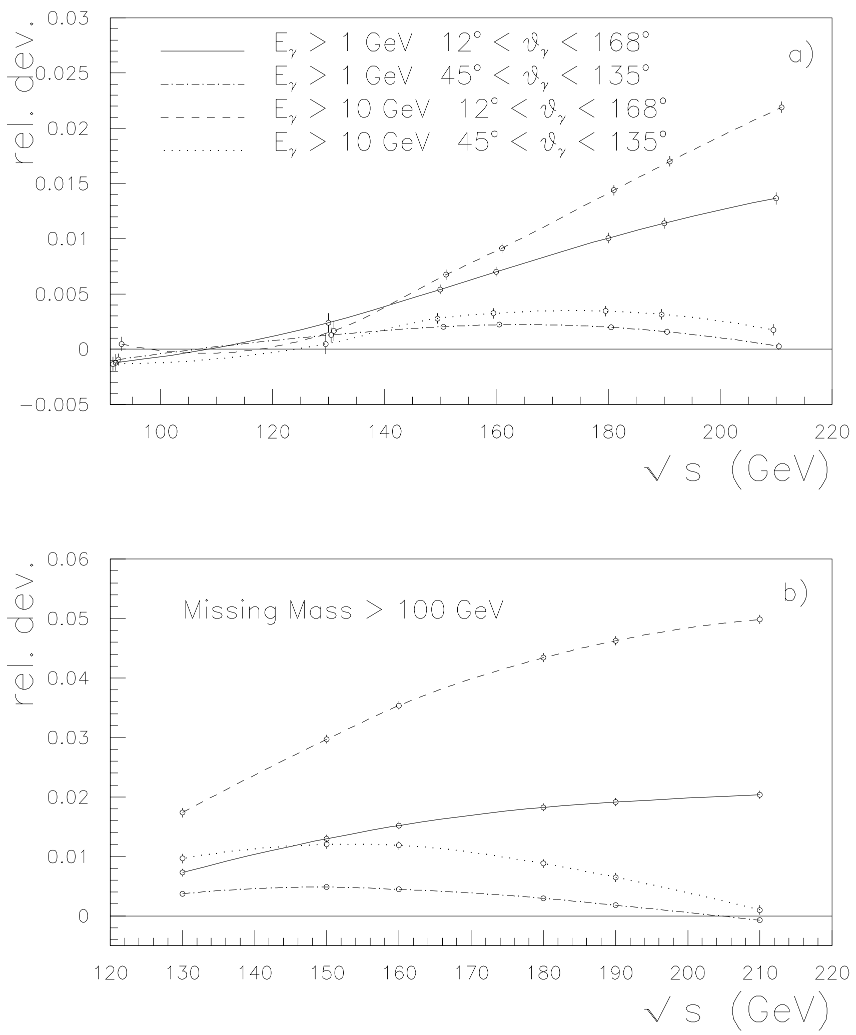

Figure 2: The relative deviation between $\sigma(e^+e^- \to \gamma\nu\bar{\nu})$ calculated with the exact matrix element and the approximated one implemented in the old version of NUNUGPV.

Conclusions

- careful treatment of lowest-order cross section and ISR effects at LEP2 necessary for a sensible experimental analysis

- evaluation of potentially dangerous QED effects due to "overlapping" photons at the level of several %, both for single-photon and double-photon events, depending on the experimental event selection

- the present theoretical accuracy is estimated at the $\mathcal{O}(1\%)$ level

- lowering the theoretical accuracy well below $\mathcal{O}(1\%)$ requires the calculation of unknown exact $\mathcal{O}(\alpha)$ electroweak corrections

- first calculation of $e^+e^- \to \gamma\gamma\gamma\nu\bar{\nu}$ events rate

- improved version of `NUNUGPV` released both for single- and multi-photon events with missing energy. It is now under test by the LEP Collaborations

Thanks to S. Arcelli, J. Busenitz, P. Checchia, A. De Min, P. Krieger, C. Matteuzzi, P. Molnar, D. Ruschmeier, G. Wilson for many useful discussions and suggestions

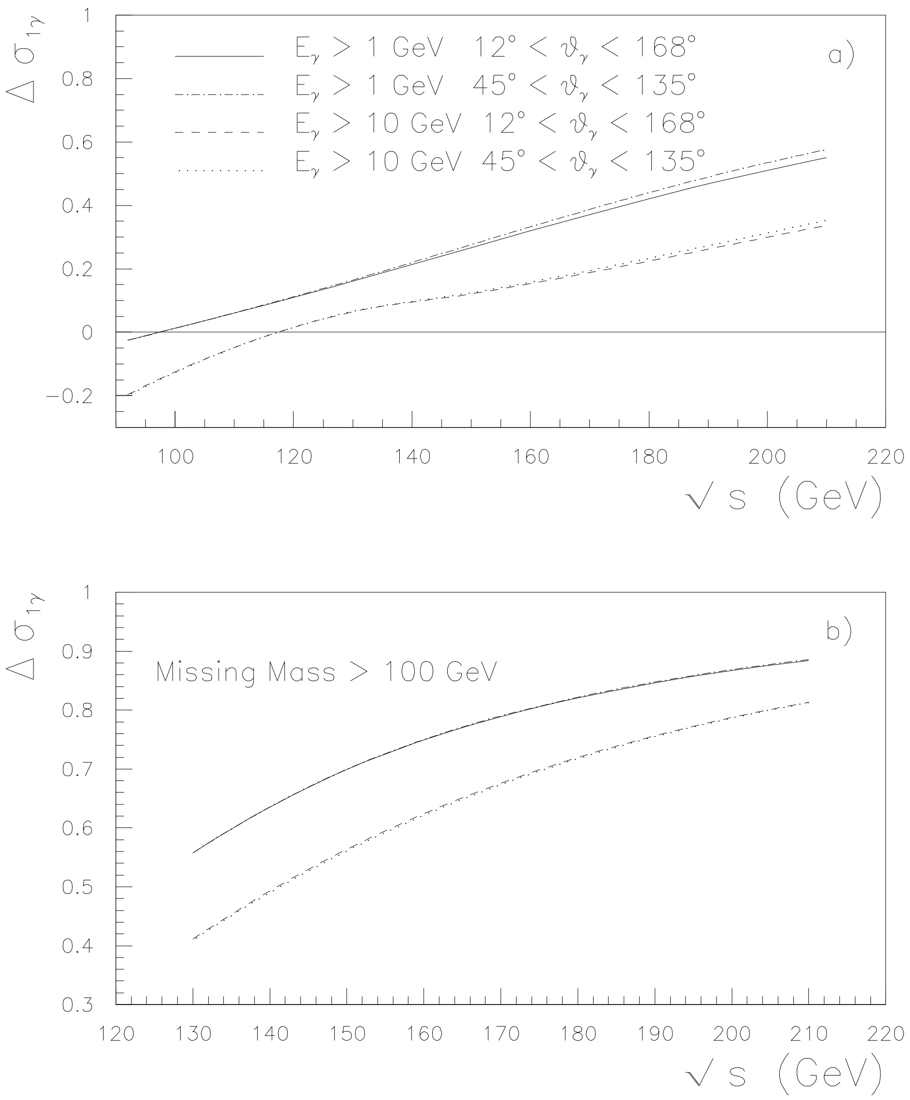

Figure 3: The relative size of the W-exchange diagrams with respect to the total cross section of the signature $\nu\bar{\nu}\gamma$, for different experimental cuts. The quantity $\Delta\sigma_{1\gamma}$ is defined as: $\Delta\sigma_{1\gamma} = 1 - 3\sigma(\nu_\mu\bar{\nu}_\mu\gamma)/\sigma(\nu\bar{\nu}\gamma)$. In Fig. 3a the four lines correspond to the cuts on the photon energy and angle specified in the plot; Fig. 3b is the same as Fig. 3a, with an additional cut on the missing mass of the event.

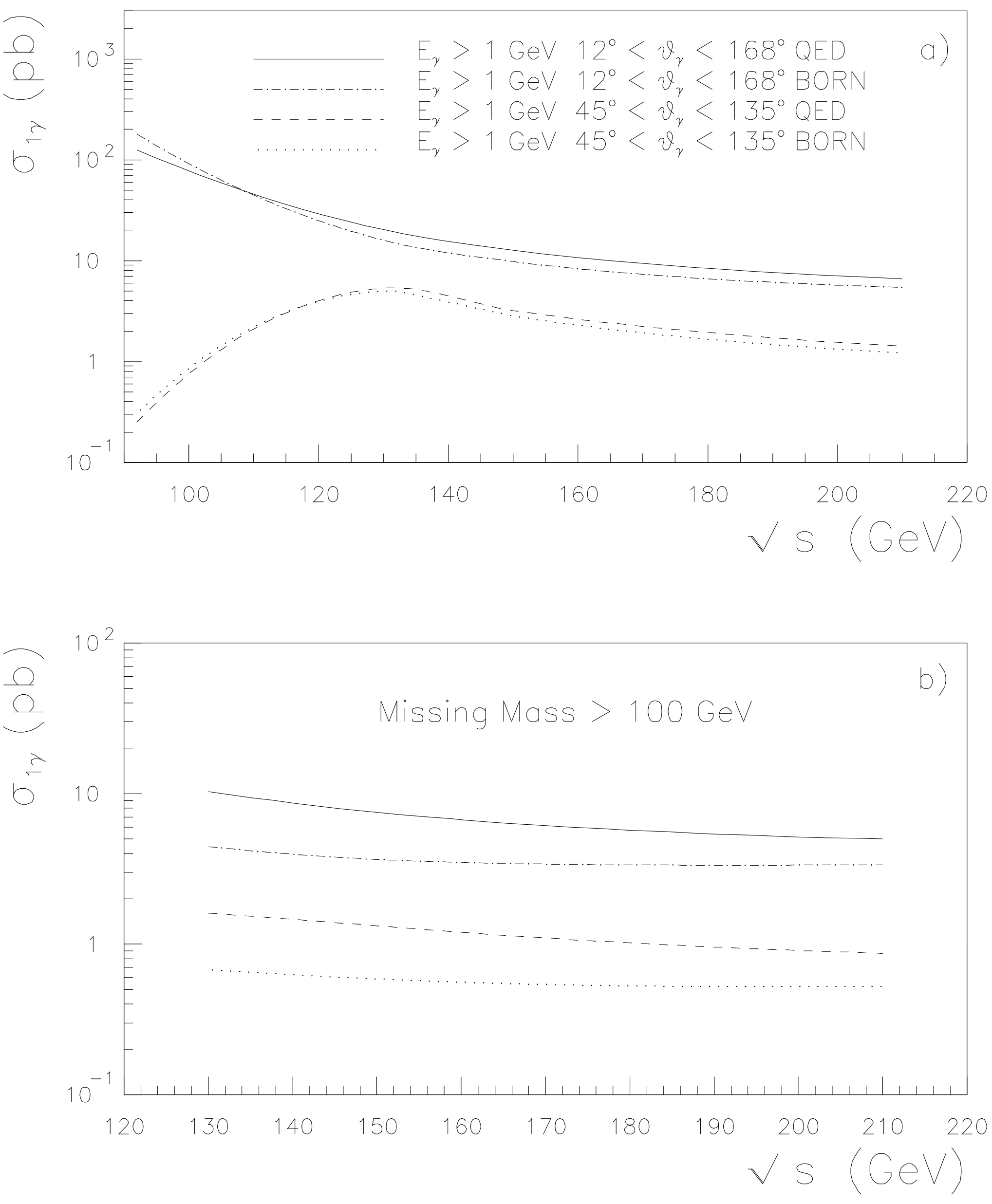

Figure 4: The tree level cross section for $\gamma\nu\bar{\nu}$ is compared to the QED corrected one for two different set-up.

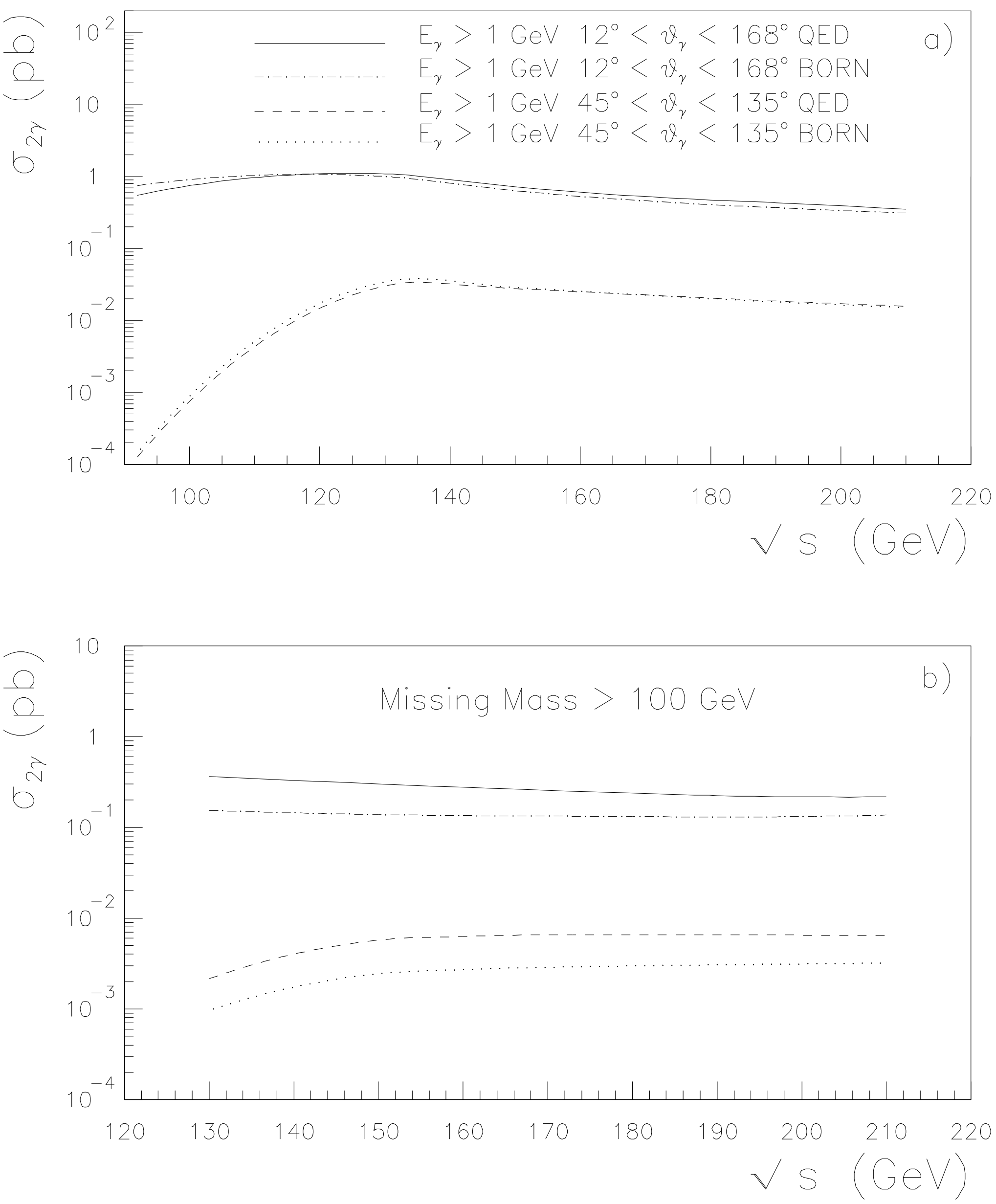

Figure 5: The tree level cross section for $\gamma\gamma\nu\bar{\nu}$ is compared to the QED corrected one for two different set-up.

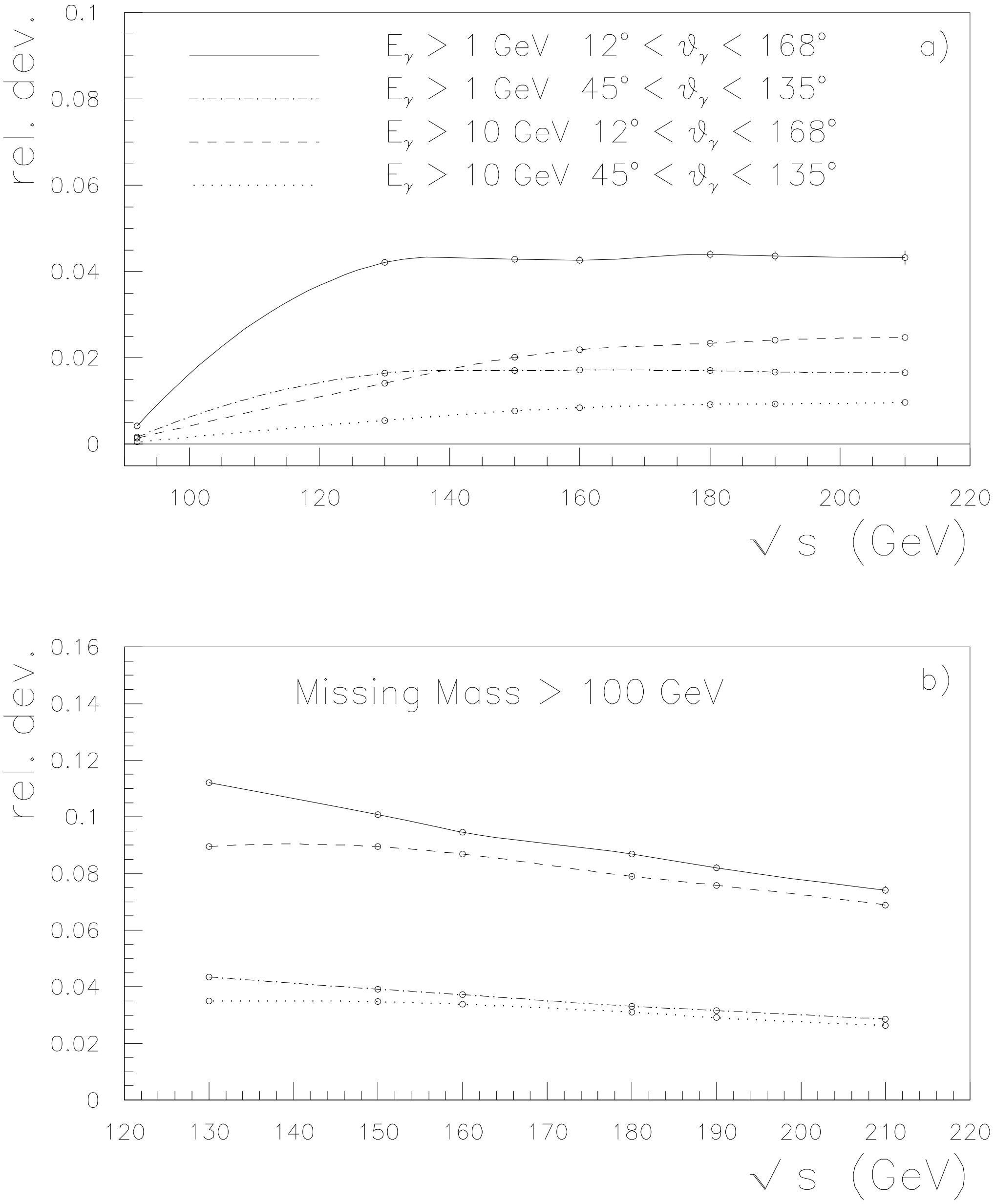

Figure 6: The relative deviation $(\sigma^{1\gamma}_{coll} - \sigma^{1\gamma}_{QED})/\sigma^{1\gamma}_{coll}$ is shown.

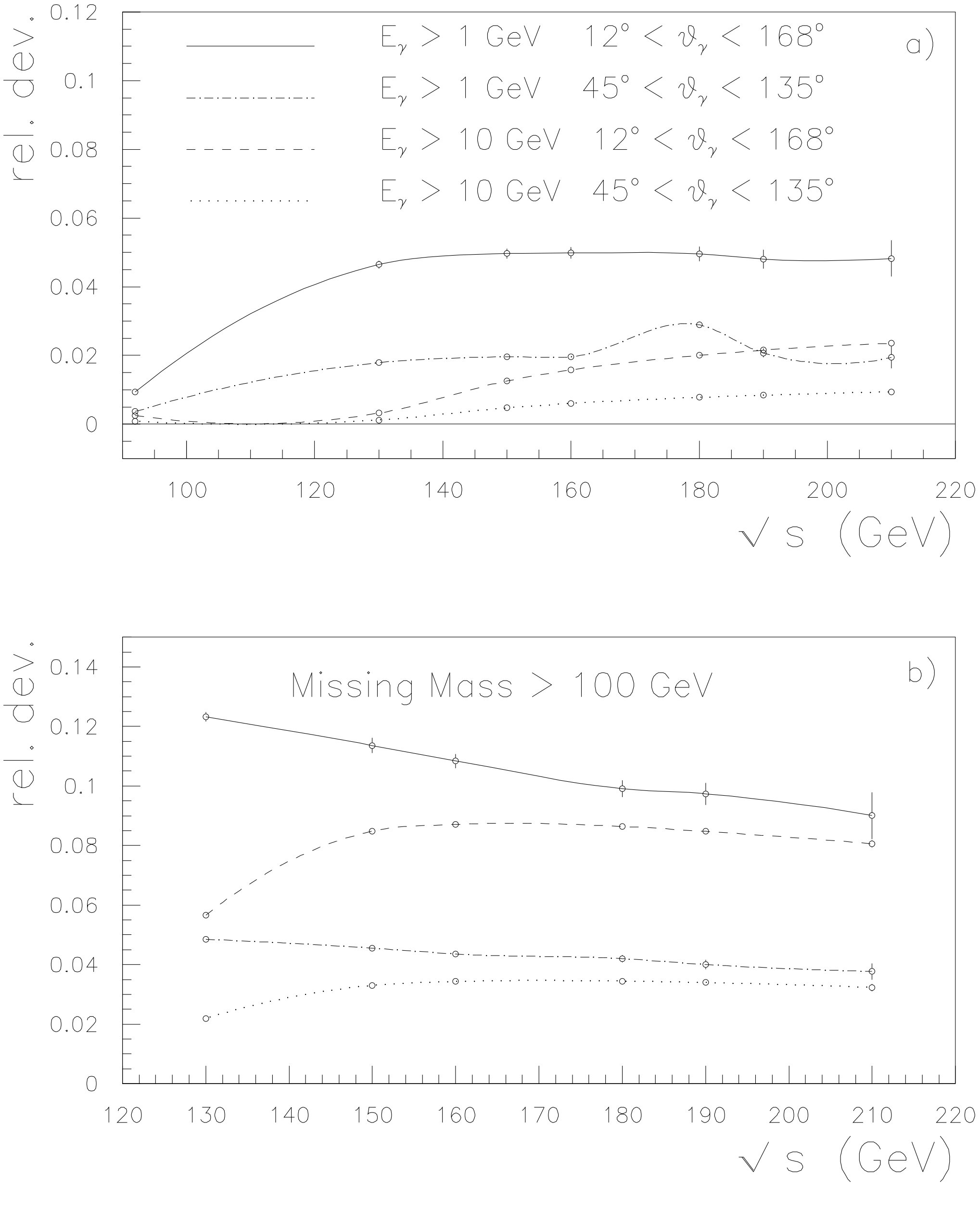

Figure 7: The relative deviation $(\sigma^{2\gamma}_{coll} - \sigma^{2\gamma}_{QED})/\sigma^{2\gamma}_{coll}$ is shown.

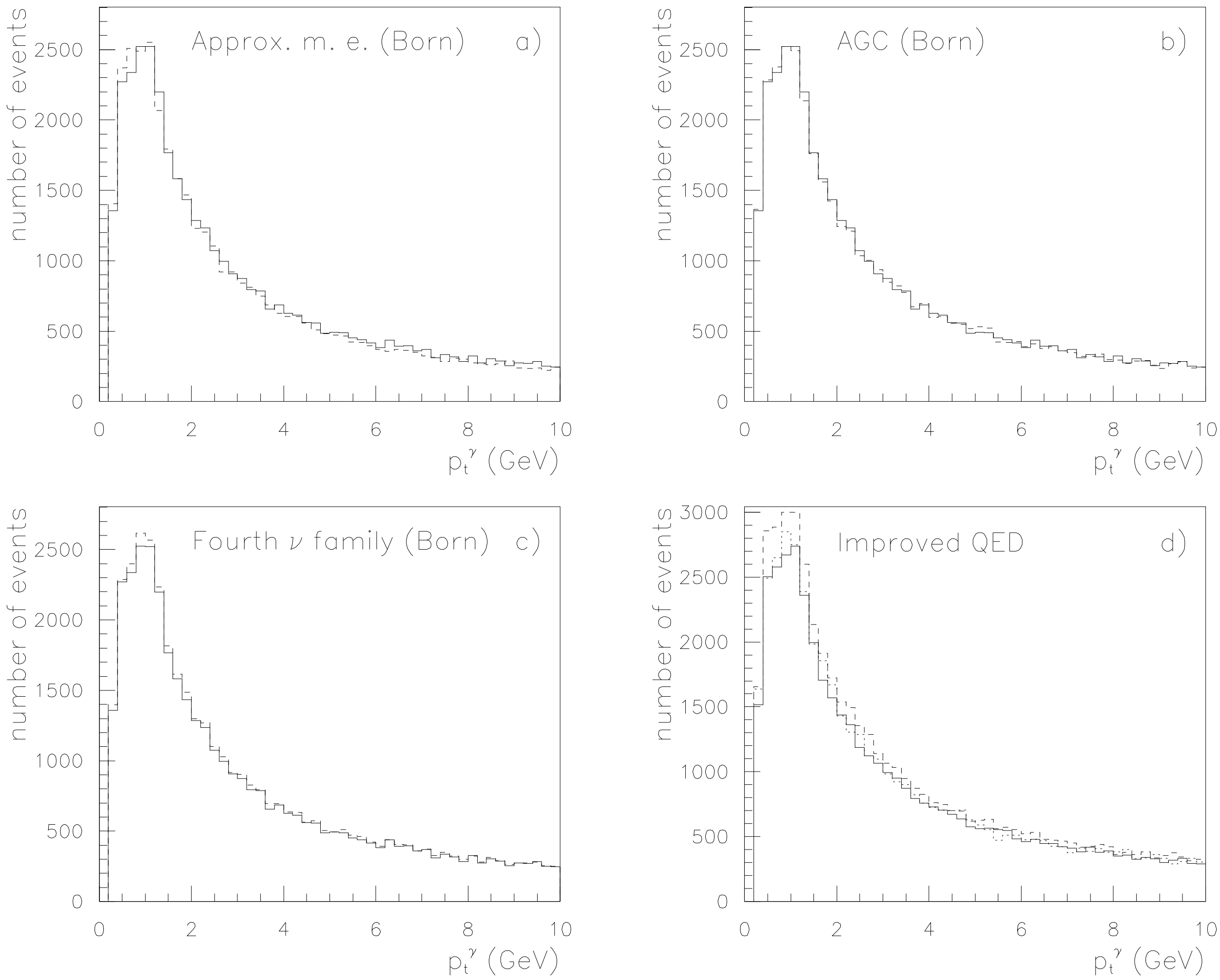

Figure 8: "Soft" p_t^γ distribution for the leading photon of the process $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$ at $\sqrt{s} = 190$ GeV. The cuts on the observed photons are $E_\gamma > 1$ GeV and $12^\circ < \vartheta_\gamma < 168^\circ$. Exact tree-level calculation (solid line) versus: approximate analytic spectrum of eq. 1 (dashed line) (Fig. 8a), exact SM calculation plus anomalous couplings contribution (dashed line) (Fig. 8b), exact SM calculation plus massive ($m_\nu = 50$ GeV) fourth family neutrinos (dashed line) (Fig. 8c). In Fig. 8d ISR correction is implemented according to the new treatment of **NUNUGPV** (solid line), via collinear SFs (dashed line) and via SFs with p_t/p_L effects as in the previous version of NUNUGPV (dotted line).

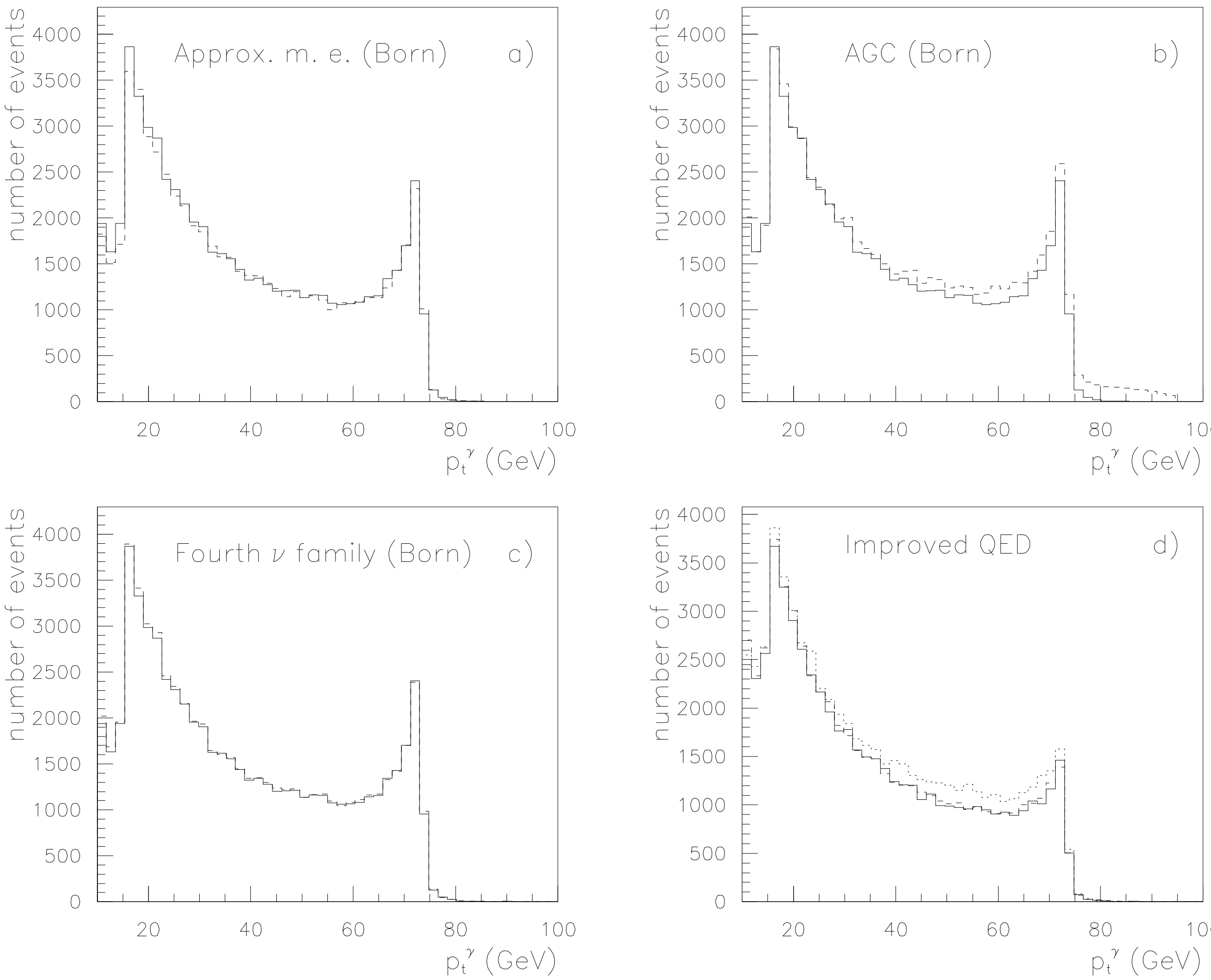

Figure 9: The same as Fig. 8, in the "hard" p_t^γ region.

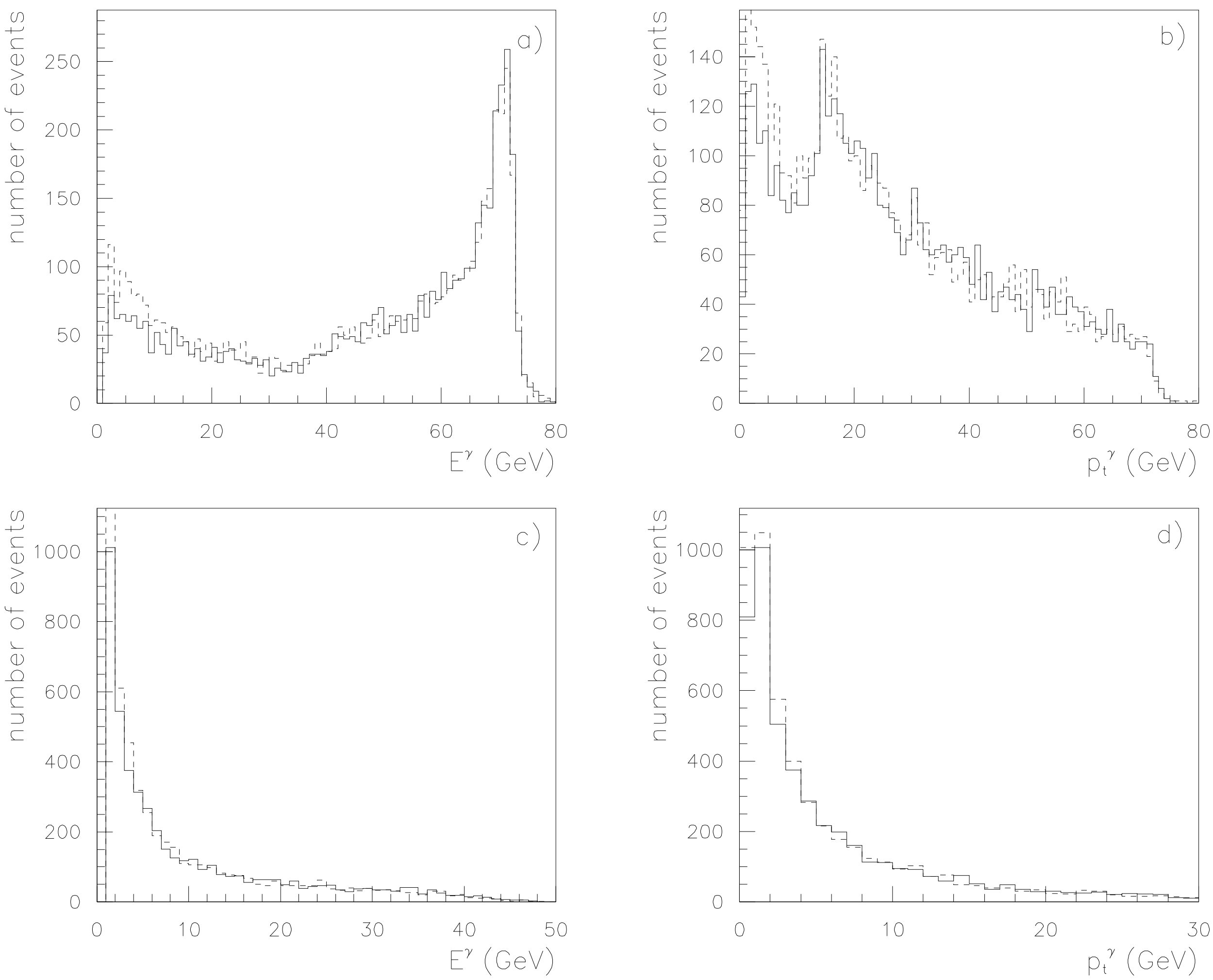

Figure 10: E_γ and p_t^γ distributions for the leading (Figs. 10a-10b) and next-to-leading photon (Figs. 10c-10d) of the process $e^+e^- \to \nu\bar{\nu}\gamma\gamma(\gamma)$ at $\sqrt{s} = 190$ GeV. The cuts on the observed photons are $E_\gamma > 1$ GeV and $12^\circ < \vartheta_\gamma < 168^\circ$. ISR correction is implemented according to the improved treatment (solid line) and via collinear SFs (dashed line).