.

Status of Electroweak Corrections to Top Pair Production $e^+e^- \to \bar{t}t\ (\gamma)$

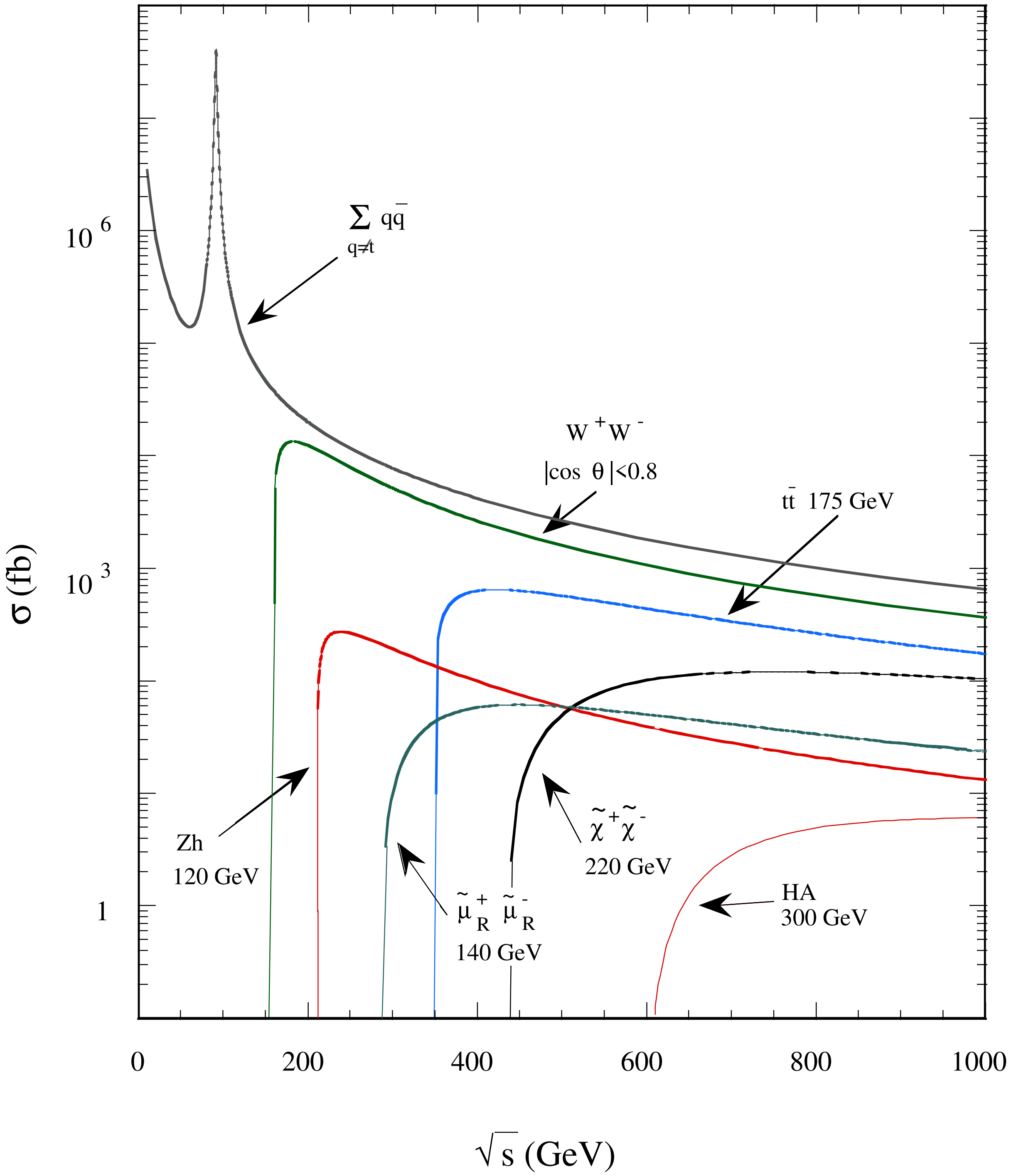
Tord Riemann, DESY Zeuthen

Contributed to Session C: Precision Electroweak Physics,
in collaboration with

Jochem Fleischer, Arnd Leike, Anja Werthenbach

- Introduction
- DIANA etc.
- topfit
- Numerical Results
- Conclusions

Cross-sections at TESLA - from TDR (2001)



For $\sigma_T \sim$ 0.5 pbarn at $\sqrt{s} = 500$ GeV
and a luminosity of $\mathcal{L} \sim 300$/fbarn,
we may expect about 10^5 top pairs.

Why study EWRC to $e^+e^- \to \bar{t}t$?

Building Block for Experimental Analysis

$\longrightarrow$ susy and other new physics

$\longrightarrow$ QCD + higher order calculations

$\longrightarrow$ 4-, 5- or 6-fermion production

Numerical Checking of Available Codes

Status of March 2001:

- Fujimoto,Shimizu (1988): **SM, QED**
- Hollik,Hahn et al. (1991-1999): **SM, MSSM**
- Bardin et al. (2000): **SM**

Nontrivial Testing for Complicated Calculations

We were exploring a tool for a semi-automated calculation of Feynman diagams – DIANA – and wanted to start with something familiar to us

See also talk of Anja Werthenbach in LOOPVEREIN session

For Nogueira's qgraph see:

ftp://gtae2.ist.utl.pt/pub/qgraf/

Its output: a list of diagrams, described in a combinatorial fashion.

DIANA – a DIAgramANAlyser

For DIANA (M. Tentyukov, J. Fleischer) see:

http://www.physik.uni-bielefeld.de/~tentukov/diana.html

What does the program do?

- DIANA reads qgraf output.
  Analyzes the diagrams and produces graphical representation of them.
- Is interpreter of a special text manipulating language (TM).
  Executes the TM-program to insert explicit expressions for the vertices, propagators etc.
  The TM-program produces input text for FORM.

See also http://www-zeuthen.desy.de/~alorca/

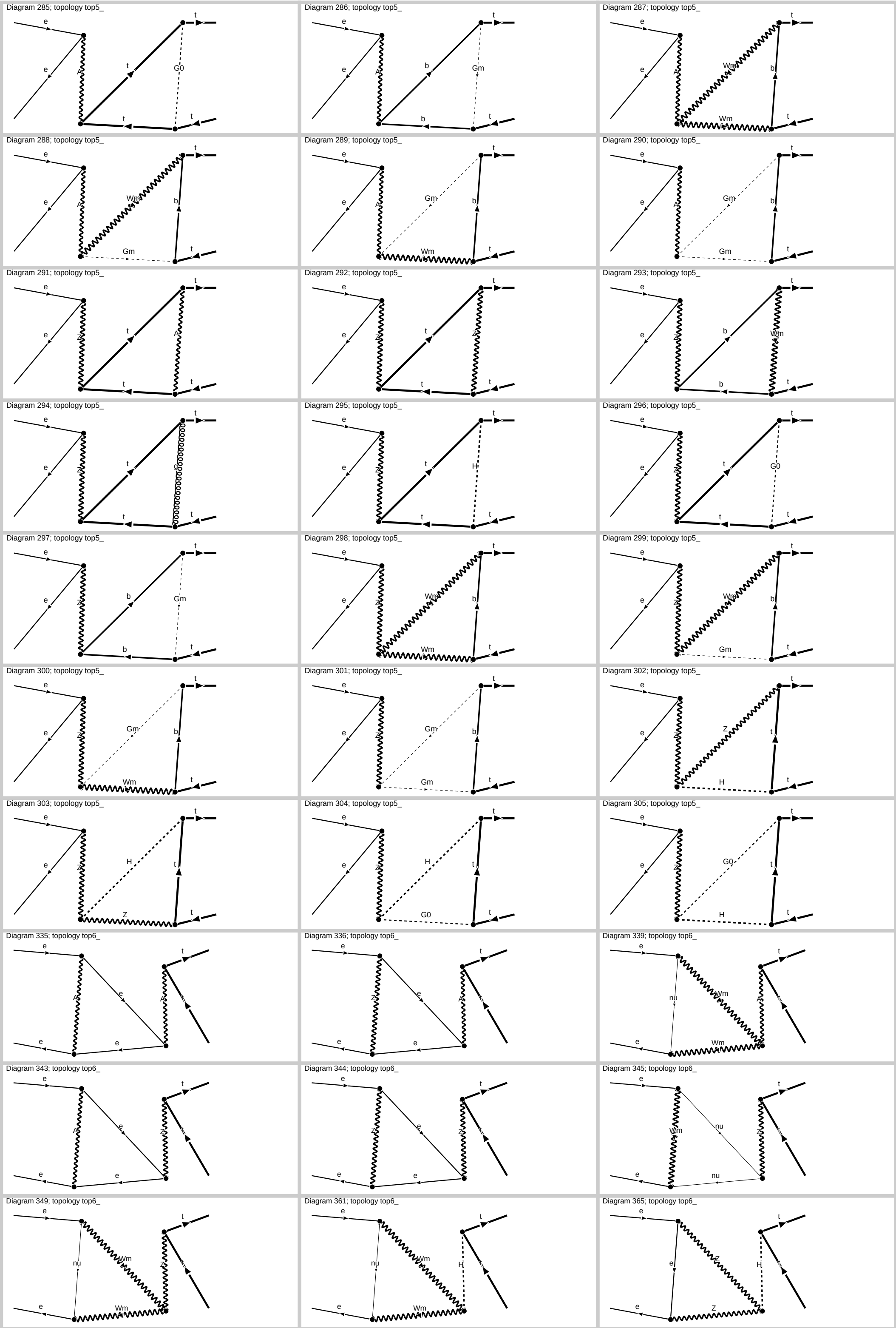
From here DIANA 2.24 is now downloadable for linux systems, together with a simple example how to use it.

We are creating a new home page
DESY Zeuthen "Loops'n Legs" Home Page
for a more systematic sampling of loop calculational tools.

DIANA: file = create.OneLoop

```
SET _processname        = OneLoop
SET _qgrafname          = "qgraf2"
SET _TOPOLOGYEDITORNAME = tedi
==========================================================
\Begin(model,Standard.model)        \End(model)

\excludevertex(E,e,H;E,e,G0;NU,e,Gp;E,nu,Gm)
==========================================================
\Begin(process)

  ingoing  e(; p1),E(; p4);
  outgoing t(;-p2),T(;-p3);

     loops = 1;                       \End(process)
==========================================================
\Begin(topology,topol.Born)          \End(topology)
==========================================================
\Begin(qgrafoptions)  options=onepi;  \End(qgrafoptions)
==========================================================
\Begin(output) .........

   g Rq =\integrand();                \End(output)
```

DIANA OneLoop_page5.ps



5

DIANA OneLoopInfo1037.ps

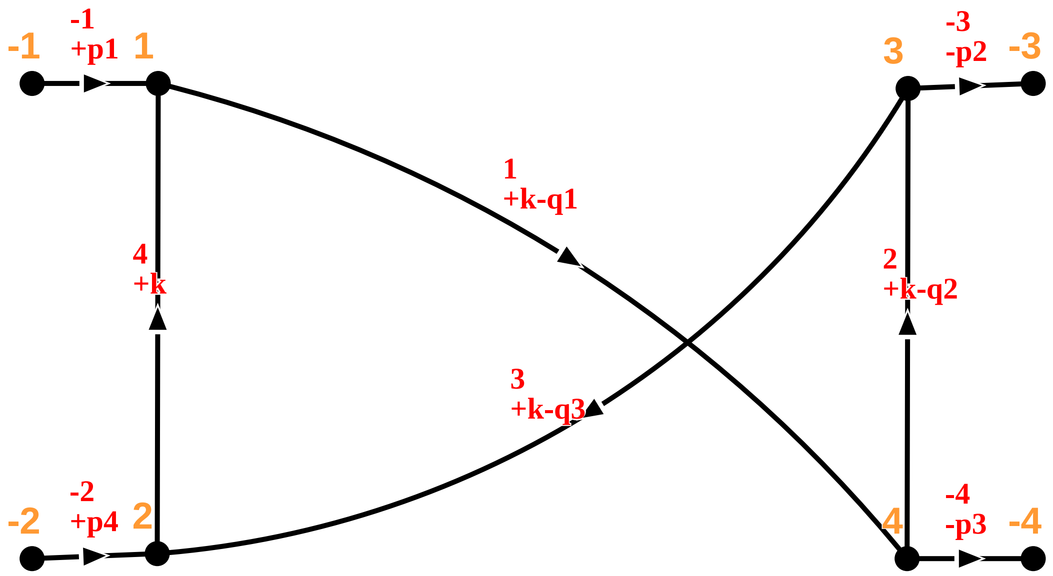
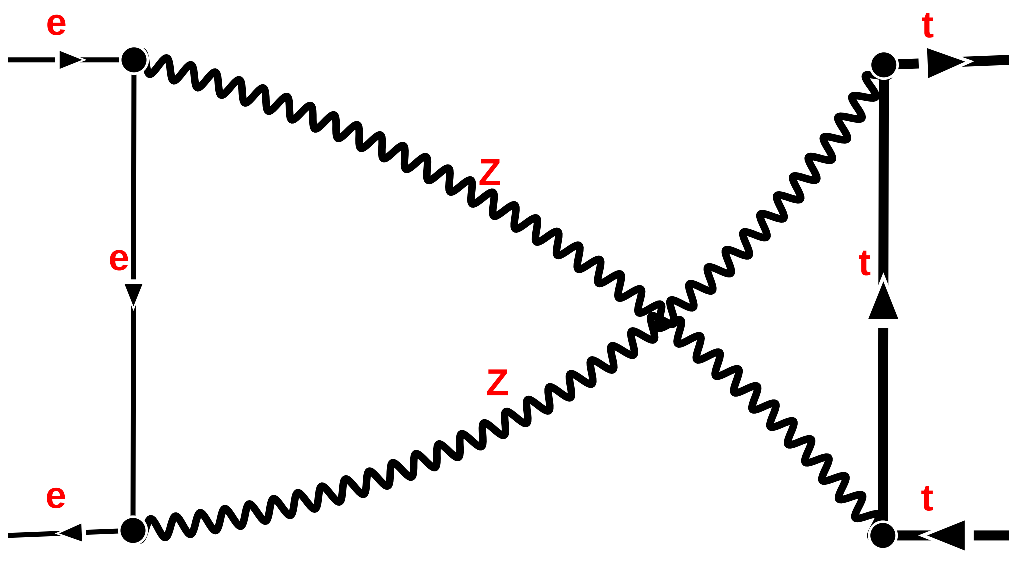


Diagram 1037 topology top15_ (unique top15_) momentaset 1 (of 1)



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DIANA: file = manipulateBorn.log

```
   FORM version 2.3 Apr 24 1997

Born1 loaded
Born2 loaded
               g bornA=Born1;
               g bornZ=Born2;

   id c^-2*c1^-1 = c^-2/denZ;
   id      c1^-1 =    1/denA;

   .......

   print;
   .end

  bornA = 4 *
         gamma(1,mu1)*gamma(2,mu1)*i_*e^2
       * denA^-1    * ( Qe*Qt );

  bornZ =
         gamma(1,mu1)*gamma(2,mu1)*i_*e^2*s^-2*c^-2
       * denZ^-1
       * ( GVe*GVt - GVe*GAt - GVt*GAe + GAe*GAt )

      +  ..........
```

Additional Amplitudes from virtual corrections

Additional 12 structures appear:

$$
\begin{aligned}
{M_2}^{H_t,h_e} &= [\bar{u}_t(-p_2)\not{p}_4\omega_\pm v_t(-p_3)] \times [\bar{v}_e(p_4)\not{p}_2\omega_{\pm'}u_e(p_1)] \\
{M_3}^{H_t,h_e} &= [\bar{u}_t(-p_2)1\omega_\pm v_t(-p_3)] \times [\bar{v}_e(p_4)\not{p}_2\omega_{\pm'}u_e(p_1)] \\
{M_4}^{H_t,h_e} &= [\bar{u}_t(-p_2)\gamma^\mu\not{p}_4\omega_\pm v_t(-p_3)] \times [\bar{v}_e(p_4)\gamma_\mu\not{p}_2\omega_{\pm'}u_e(p_1)]
\end{aligned}
$$

For $m_e = 0$, but $m_{top} \neq 0$ only 6 amplitudes out of 16 are independent.

For $m_e = 0$ *and* $m_{top} = 0$, the 4 Born amplitudes remain.

Our form factors and the effective mixing angle

The Born matrix element:

$$M_1^{Born} = \bar{u}_t\gamma^{\mu}[2\omega_- - 4|Q_t|\sin^2\theta_W]v_t \times \bar{v}_e\gamma_{\mu}[2\omega_- - 4|Q_e|\sin^2\theta_W]u_e$$

with

$$\omega_{\pm} = \frac{1\pm\gamma_5}{2}, 1 = \omega_- + \omega_+$$

The general structure M_1 has 4 form factors:

$$\begin{aligned} M_1 &= 4\rho\gamma^{\mu}\omega_- \otimes \gamma^{\mu}\omega_- \\ &- 8\rho\sin^2\theta_W|Q_e|\kappa_e\gamma^{\mu}\omega_- \otimes \gamma^{\mu}(\omega_- + \omega_+) \\ &- 8\rho\sin^2\theta_W|Q_t|\kappa_t\gamma^{\mu}(\omega_- + \omega_+) \otimes \gamma^{\mu}\omega_- \\ &+ 16\rho\sin^4\theta_W|Q_e||Q_t|\kappa_{et}\gamma^{\mu}(\omega_- + \omega_+) \otimes \gamma^{\mu}(\omega_- + \omega_+) \end{aligned}$$

Or in another notation:

$$M_1 = F_1^{--}\gamma^{\mu}\omega_- \otimes \gamma^{\mu}\omega_- + F_1^{-+}\gamma^{\mu}\omega_- \otimes \gamma^{\mu}\omega_+ + F_1^{+-}\gamma^{\mu}\omega_+ \otimes \gamma^{\mu}\omega_- + F_1^{++}\gamma^{\mu}\omega_+ \otimes \gamma^{\mu}\omega_+$$

Relation of commonly used form factor sets:

$$\begin{aligned}
\rho &= \frac{1}{4}[F_1^{--} - 2F_1^{-+} - 2F_1^{+-} - F_1^{++}] \\
\kappa_t &= -\frac{1}{4\rho\sin^2\theta_W|Q_t|}F_1^{+-} \\
\kappa_e &= -\frac{1}{4\rho\sin^2\theta_W|Q_e|}F_1^{-+} \\
\kappa_{et} &= \frac{1}{16\rho\sin^4\theta_W|Q_t||Q_e|}F_1^{++}
\end{aligned}$$

The Fortran program topfit

Authors: J. Fleischer A.Leike T. Riemann A. Werthenbach

Features of v.0.91 (06 March 2002):

– Exactly one-loop

– SM weak loops and/or pure QED

– Input: $\alpha_{qed}(0)$, all masses

– u, c, t, ν: full weak + QED, μ, τ, d, s, b: presently only QED

Typical results from a calculation:

– six weak form factors

– $\frac{d\sigma}{d\cos\theta}, \sigma_T, A_{FB}$ with hard bremsstrahlung (some simple cuts)

– $\frac{d\sigma}{d\cos\theta}, \sigma_T, A_{FB}$ without photonic diagrams for use in a Monte Carlo

Special: Two independent calculations
using either package FF or package LoopTools
with dim.reg. for IR-divergency or finite photon mass

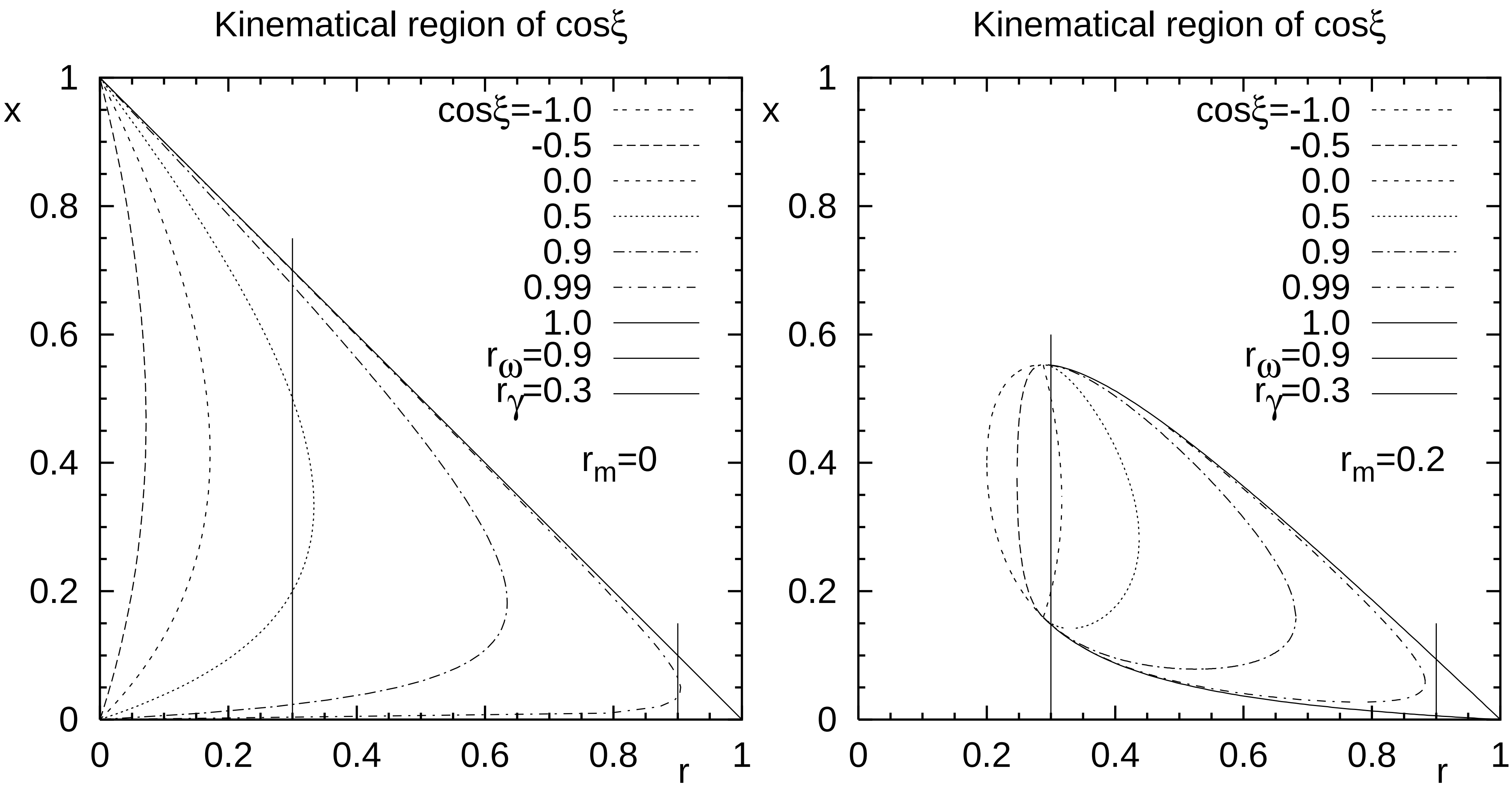
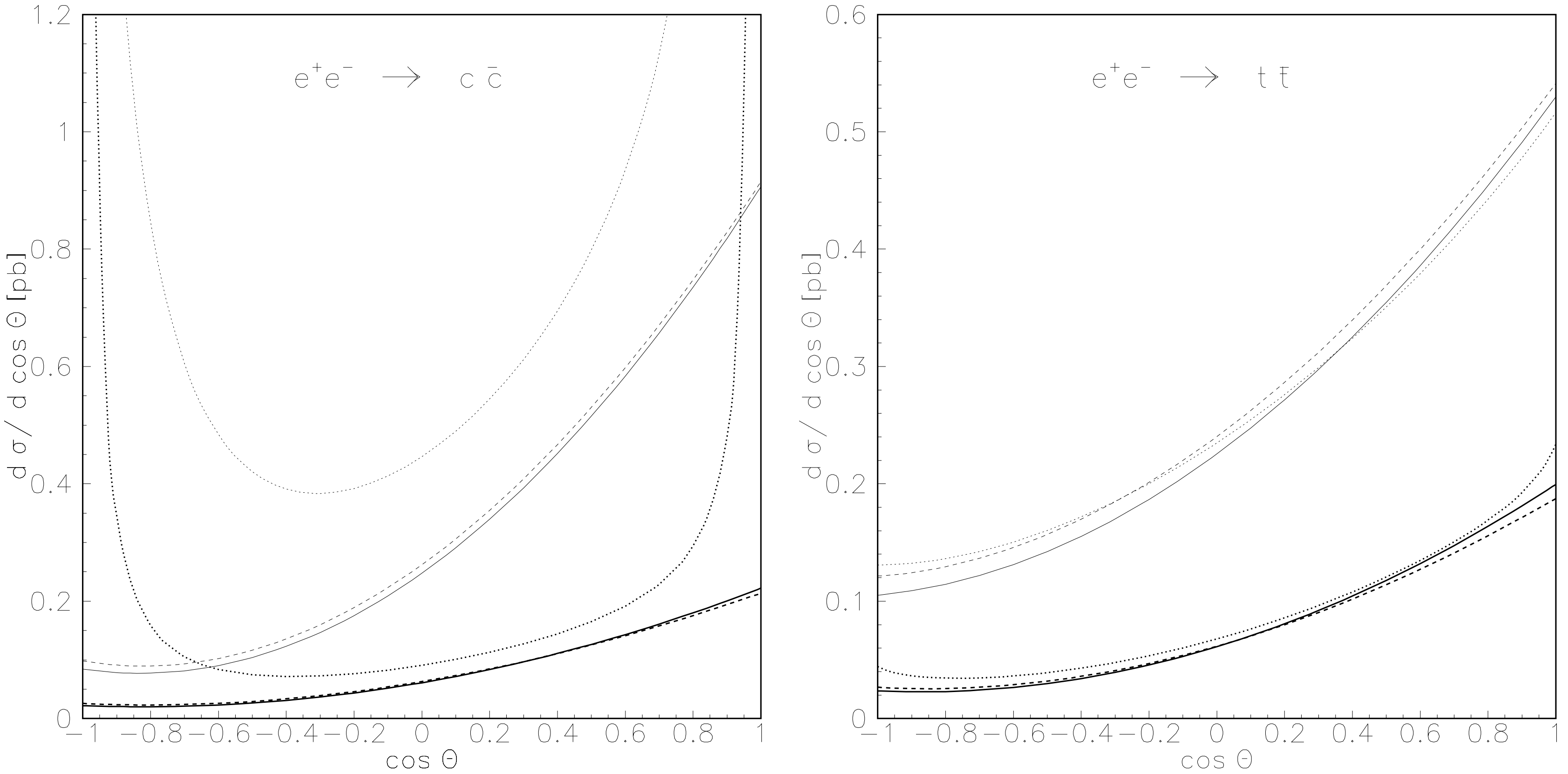


Figure 6: Phase space with acollinearity cut R_ξ; $v_2 := V_2/s \equiv x$.

a. $R_m = 4m_t^2/s = 0$ b. $R_m = 4m_t^2/s = 0.2$

topfit: charm pairs versus top pairs

$\frac{d\sigma}{dcos\theta}$ for $e^+ + e^- \to c + \bar{c} + \gamma$ and $e^+ + e^- \to t + \bar{t} + \gamma$ at TESLA



Solid: Born   Dashed: weak   Dotted: SM = weak + QED (no cut)

Thin lines: $\sqrt{s} = 500$ GeV, thick lines: $\sqrt{s} = 1000$ GeV.

Numerical Results Based on

J. Fleischer, T. Riemann, A. Werthenbach

and

T. Hahn, W. Hollik, C. Schappacher

Complete Electroweak One-loop Corrections to Top-pair Production at TESLA - a Comparison

hep-ph/0202109

(weak corrections, topfit compared to Feynarts)

J. Fleischer, A. Leike, T. Riemann, A. Werthenbach

and

J. Fujimoto, T. Ishikawa, Y. Shimizu

One-loop Corrections to the Process $e^+e^- \to t\bar{t}$ Including Hard Bremsstrahlung

hep-ph/0203220

(also hard bremsstrahlung, topfit compared to Grace)

Top-quark Pair-production Cross section

Conventions for comparison with Karlsruhe team T. Hahn, Ch. Schappacher and W. Hollik:

$$
\begin{aligned}
\Gamma_Z &= 0 \\
\alpha = \frac{e^2}{4\,\pi} &= 1/137.03599976 \\
E_\gamma^{\max} &= \sqrt{s}/10 \\
M_w &= 80.4514958 \text{ GeV} \\
M_z &= 91.1867 \text{ GeV} \\
M_h &= 120 \text{ GeV} \\
m_e &= 0.00051099907 \text{ GeV} \\
m_t &= 173.8 \text{ GeV} \\
m_b &= 4.7 \text{ GeV} \\
m_\mu &= 0.105658389 \text{ GeV} \\
m_u &= 0.062 \text{ GeV} \\
m_d &= 0.083 \text{ GeV} \\
m_\tau &= 1.77705 \text{ GeV} \\
m_c &= 1.5 \text{ GeV} \\
m_s &= 0.215 \text{ GeV}
\end{aligned}
$$

Top pair production: Feynarts and topfit

$\sqrt{s} = 500$ GeV: $e^+ + e^- \to \bar{t} + t$ at TESLA

$\cos\theta$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{Born}}$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{QED}}$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{weak}}$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{SM}}$
-0.9	0.1088 3919 4075	0.09866 4253	0.1242 59037 1	0.1140 8410
	0.1088 3919 4075	0.09866 4253	0.1242 59037 6	0.1140 8410
-0.5	0.1422 7506 9392	0.1285 0790	0.1568 48371 9	0.1430 8121
	0.1422 7506 9392	0.1285 0790	0.1568 48371 8	0.1430 8121
0.	0.2254 7046 4032	0.2023 9167	0.2402 6680 4	0.2171 8801
	0.2254 7046 4033	0.2023 9167	0.2402 6680 3	0.2171 8801
0.5	0.3546 6647 0331	0.3151 1724	0.3688 8650 7	0.3293 3727
	0.3546 6647 0332	0.3151 1723	0.3688 8650 5	0.3293 3727
0.9	0.4911 4371 5766	0.4307 1437	0.5033 3751 2	0.4429 0817
	0.4911 4371 5767	0.4307 1437	0.5033 3750 8	0.4429 0816

Agreement confirms accuracy of electroweak calculations of two groups (06 March, 2002):
upper line: Feynarts, lower line: topfit

Top pair production: topfit and Grace, angular distribution

$\cos\theta$	$\omega/\sqrt{s}$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{Born}}$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{QED}}$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{SM}}$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{tot}}$
-0.9	T : 0.1	0.108839194075	+0.098664253	+0.11408410	0.13144
	T : 0.00001	0.108839194075	−0.017474702	−0.002054858	0.13229
	G : 0.00001	0.108839194076		−0.002054859	0.13206(12)
-0.5	T : 0.1	0.142275069392	+0.12850790	+0.14308121	0.15973
	T : 0.00001	0.142275069392	−0.029702340	−0.015129038	0.16029
	G : 0.00001	0.142275069393		−0.015129039	0.16013(13)
$+0.0$	T : 0.1	0.225470464033	+0.20239167	+0.21718801	0.23638
	T : 0.00001	0.225470464033	−0.058010508	−0.043214169	0.23476
	G : 0.00001	0.225470464033		−0.043214168	0.23513(14)
$+0.5$	T : 0.1	0.354666470332	+0.31511723	+0.32933727	0.35651
	T : 0.00001	0.354666470332	−0.109721291	−0.095501257	0.35062
	G : 0.00001	0.354666470332		−0.095501252	0.35104(17)
$+0.9$	T : 0.1	0.491143715767	+0.43071437	+0.44290816	0.48796
	T : 0.00001	0.491143715767	−0.179672655	−0.16747886	0.47768
	G : 0.00001	0.491143715767		−0.16747886	0.47709(21)

Various differential cross sections. The upper and lower numbers correspond to the `topfit` (T) and GRACE (G) approach, respectively, $\sqrt{s} = 500$ GeV.

Top pair production: topfit and Grace

$\sqrt{s}$	$\sigma^0_{\rm tot}$	$A^0_{\rm FB}$	$\sigma_{\rm SM,tot}$	$\sigma_{\rm SM,FB}$	$\sigma_{\rm tot}$	$A_{\rm FB}$
500	T : 0.5122744	0.4146039	−0.1198972	−0.0855551	0.526337	0.362929
	G : 0.5122751	0.4146042	−0.1198973		0.526371	0.363140
1000	T : 0.1559185	0.5641706	−0.0683693	−0.0522582	0.171916	0.488869
	G : 0.1559187	0.5641710	−0.0683695		0.171931	0.488872

Total cross sections (in pbarn) and forward-backward asymmetries.

$\sigma^0_{\rm tot}$ – Born
$\sigma_{\rm SM,tot}$ – elastic (with soft photons)
$\sigma_{\rm tot}$ – also hard photons, $\omega/\sqrt{s} = 0.00001$.

Summary

Hopefully everybody may be happy now with the numerical status reached for the weak corrections to $e^+e^- \to t\bar{t}$.

For hard photons: do better.

We gathered some experience using DIANA and FORM and FF and LoopTools for a complex calculation.

We are collecting some sample programs for everybodies use.

It is very important to make sure that what we do today may be re-animated in 10 or 20 years when a Linear Collider might start working.

Let us hope that then people will have yet linux and Fortran and CD format iso 9660 etc.

Comment from Woody Allen

The project is the first one explaining

Everything You Always Wanted to Know About Loops

Of course I feel little interest

in the

physical and theoretical motivation

of this study

if any at all.