DESY 99–070
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hep-ph/9908433

ZFITTER v.6.21

A Semi-Analytical Program for Fermion Pair Production in e^+e^- Annihilation

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Abstract

We describe ZFITTER, a Fortran program based on a semi-analytical approach to fermion pair production in e^+e^- annihilation at a wide range of centre-of-mass energies, including the PETRA, TRISTAN, LEP1/SLC, and LEP2 energies. A flexible treatment of complete $\mathcal{O}(\alpha)$ QED corrections and of some higher order contributions is made possible with three calculational chains containing different realistic sets of restrictions in the photon phase space. Numerical integrations are at most one-dimensional. Complete $\mathcal{O}(\alpha)$ weak loop corrections supplemented by selected higher-order terms may be included. The program calculates Δr, the Z width, differential cross-sections, total cross-sections, integrated forward-backward asymmetries, left-right asymmetries, and for τ pair production also final-state polarization effects. Various interfaces allow fits to be performed with different sets of free parameters.

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Standard Model Calculations Using

the ZFITTER Package

(c) ZFITTER Instruments (v.6.21)	Run ZFITTER to Compute:	X-section, nb	30.3908499
		Asymmetry	Inf.

Process: e+e- -> q+q- (inclusive) at Collision Energy = 91.19 GeV

No cuts	sqrt(s'/s) Cut	Acol,Emin Cut
	Acceptance: from 0. to 180. degrees	
	sqrt(s'/s) > 0.1	Acol < 20. degrees
		Emin = 10. GeV

M_z	m_top	M_higgs	Dal5h	alpha_s
91.187 GeV	175. GeV	100. GeV	0.0280398091	0.118

Comments to Alexander OLCHEVSKI

to: LEP2 MC Workshop, $2f$-subgroup

from: ZFITTER team [a]

LEP2 ZFITTER updates

presented by D. Bardin, JINR, Dubna

October 12, 1999

[a] `ZFITTER`–team:

D. Bardin, P. Christova, M. Jack,

L. Kalinovskaya, A. Olshevsky,

S. Riemann and T. Riemann.

OUTLINE

- ZFITTER v.6.21 from 01/10/99
  CERN afs ~bardindy/public/ZF6_21
  - Includes:
    - all Zeuthen results with *realistic cuts*;
    - Arbuzov revision of ISPP-corrections;
    - update of `ZUATSM` – a routine for angular distribution;
    - some bug fixes (like Wynhoff's bug).
  - The description of version 6.21:
    DESY 99-070, August 1999;
  - A study of EW boxes at LEP2 energies with `ZUATSM`;
  - SM-calculator based on version 6.21;
- Status of implementation of $e^+e^- \to t\bar{t}$;
- Status for LEP2 and further plans.

σ_μ [nb] with $\theta_{\rm acol} < 10^\circ$					
$\theta_{\rm acc} = 0$	$M_Z - 3$	$M_Z - 1.8$	M_Z	$M_Z + 1.8$	$M_Z + 3$
TOPAZ0	0.21932	0.46287	1.44795	0.67725	0.39366
	0.21776	0.46083	1.44785	0.67894	0.39491
	–7.16	**–4.43**	**–0.07**	**+2.49**	**+3.17**
ZFITTER	0.21928	0.46284	1.44780	0.67721	0.39360
	0.21772	0.46082	1.44776	0.67898	0.39489
	–7.16	**–4.40**	**–0.03**	**+2.60**	**+3.27**

Table 1: *A comparison of cross-section predictions around the Z peak*

$A^\mu_{\rm FB}$ with $\theta_{\rm acol} < 10^\circ$					
$\theta_{\rm acc} = 0$	$M_Z - 3$	$M_Z - 1.8$	M_Z	$M_Z + 1.8$	$M_Z + 3$
TOPAZ0	–0.28450	–0.16914	0.00033	0.11512	0.16107
	–0.28158	–0.16665	0.00088	0.11385	0.15936
	+2.92	**+2.49**	**+0.55**	**–1.27**	**–1.71**
ZFITTER	–0.28497	–0.16936	0.00024	0.11496	0.16083
	–0.28222	–0.16710	0.00083	0.11392	0.15926
	+2.75	**+2.27**	**+0.60**	**–1.03**	**–1.56**

Table 2: *A comparison of predictions for forward-backward asymmetries around the Z peak*

TOPAZ0: from Tables 37 and 38 of: D.Bardin et al., hep-ph/9902452
ZFITTER v.6.11: see DESY 99-070;
new QED calculation for accolinearity cut: P. Christova et al., Phys. Lett. B456 (1999) 264
First row: without IFI, second row: with IFI, third row: relative effect of IFI in per mil
IFI = initial-final-state interference

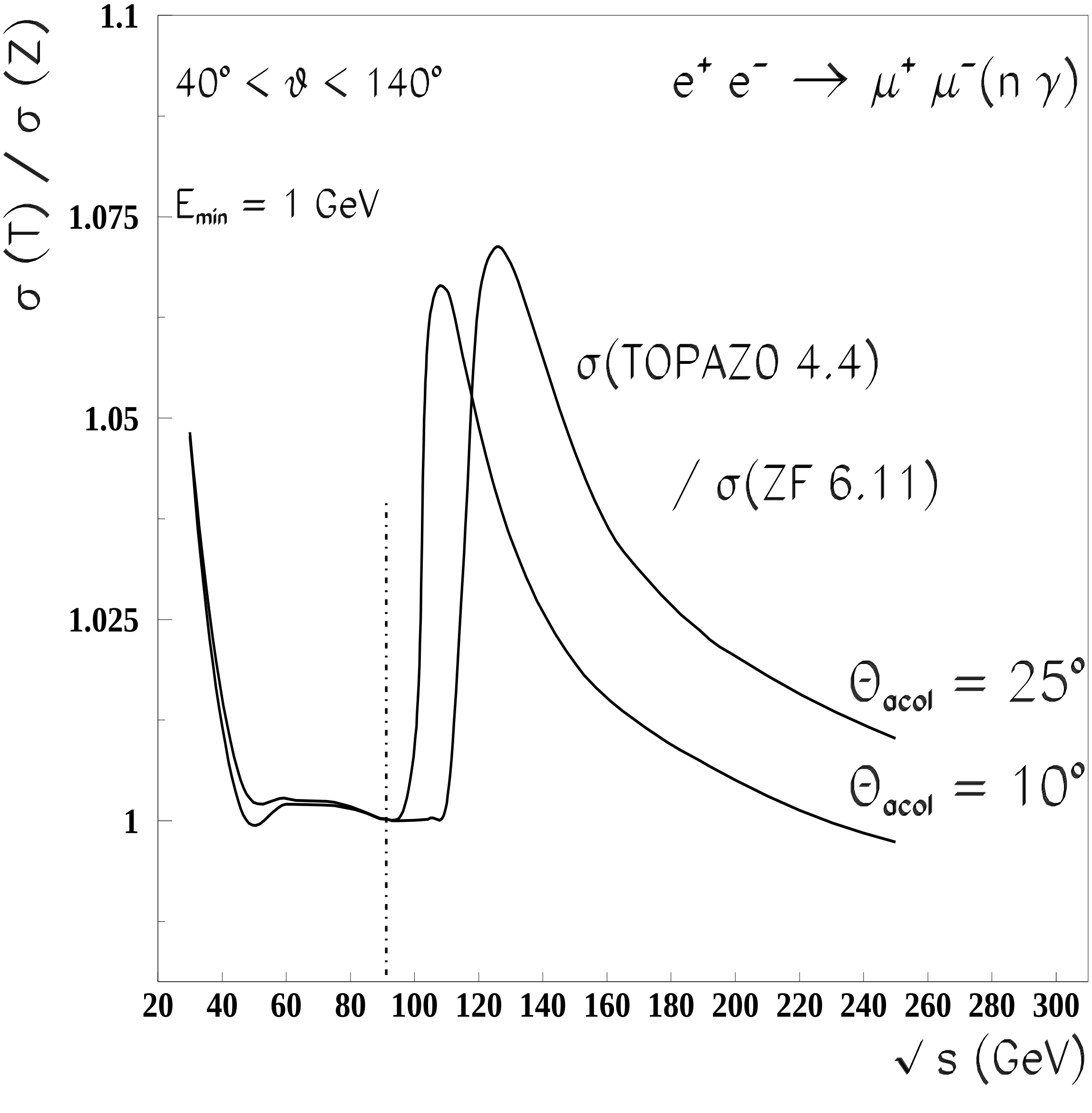

Figure 1: Muon-pair production cross-section ratios with $\theta_{\rm acol}^{\rm max} = 10^o, 25^o$ and $\theta_{\rm acc} = 40^o$; `TOPAZO v.4.4` versus `ZFITTER v.6.11`.

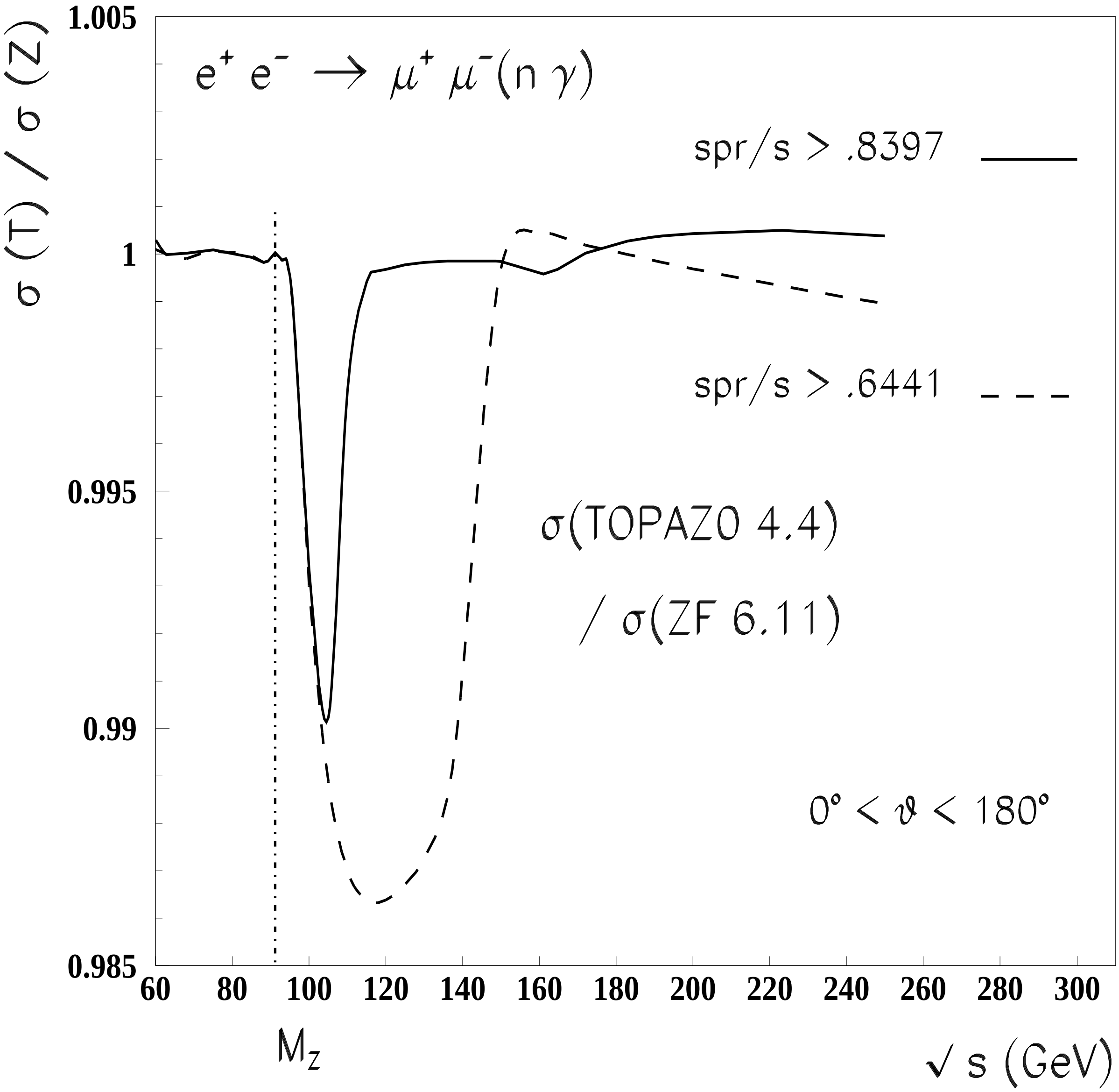

Figure 2: Comparison of predictions from `ZFITTER` `v.6.11` and `TOPAZO` `v.4.4` with s'-cut: Muon-pair production cross-section ratios. Flag setting: `ISPP=1`, `FINR=0`; further: `SIPP=S_PR`.

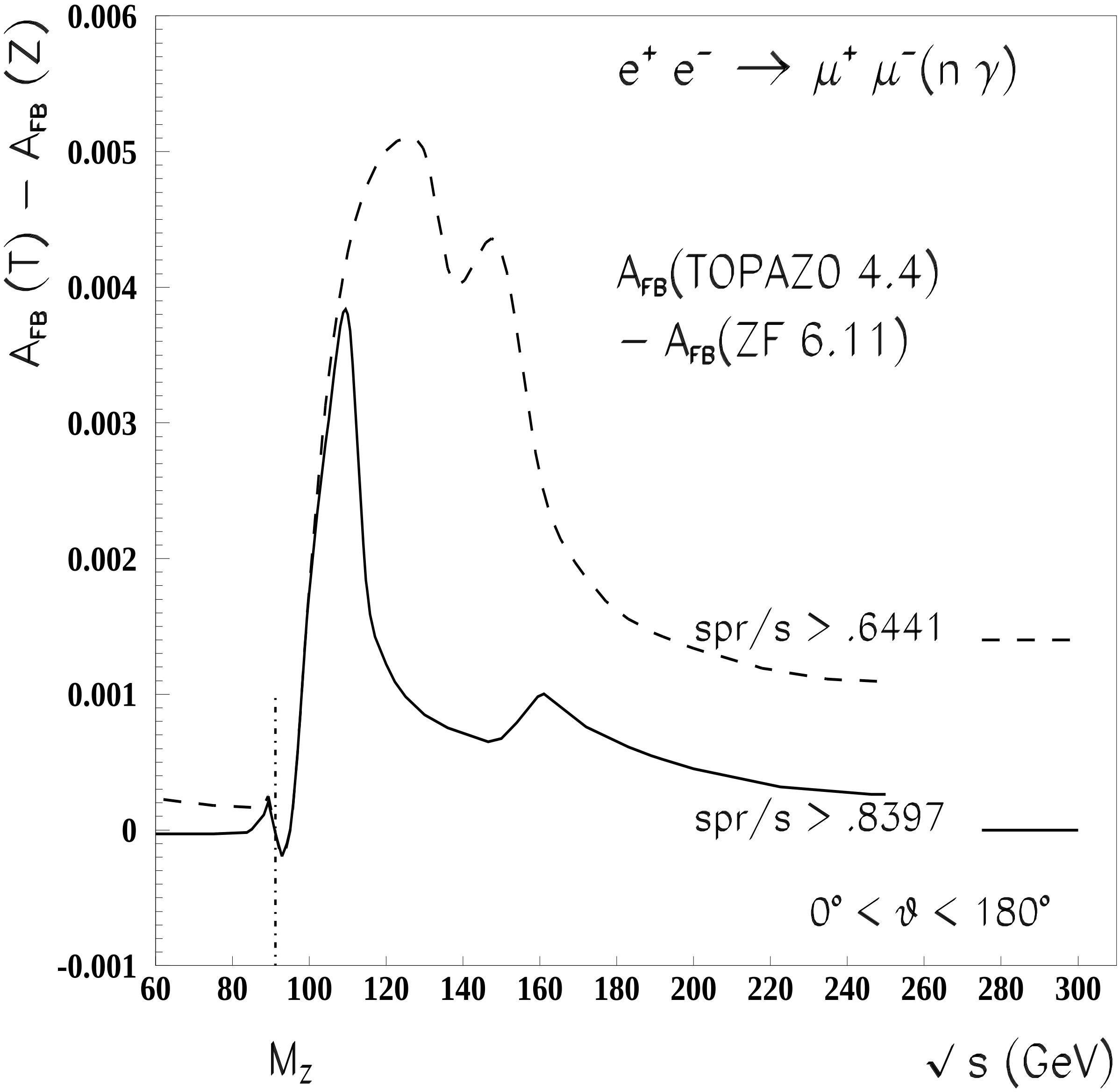

Figure 3: Comparison of predictions from `ZFITTER v.6.11` and `TOPAZO v.4.4` with s'-cut: Muon-pair production forward-backward asymmetry differences. Flag setting: `ISPP=1, FINR=0`; further: `SIPP=S_PR`.

Pair corrections to electron-positron annihilation at LEP

- The complete $O(\alpha^2)$ result for leptonic pairs:
  [1] F.A. Berends *et al.*, Nucl. Phys. B 88'.

- The complete $O(\alpha^2)$ result for hadronic pairs:
  [2] B.A. Kniehl *et al.*, Phys. Lett. B 88'.

The ISR pair radiation is accounted as:

$$\mathrm{d}\sigma^{\mathrm{pair}} = \int\limits_{z_{\min}}^{1} \mathrm{d}z \tilde{\sigma}(zs) H(z)$$

† The convergence of perturbative series for pairs is worse than for photons. Higher orders are strictly required.

† The LLA approximation is not good enough at Z-peak: the particular structure of subleading RC gives about 1/2 at $O(\alpha^2)$ level.

- Simultaneous exponentiation of photonic and pair radiation:
  [3] S. Jadach, *et al.*, Phys. Lett. B 92'.

- New calculation: the third order corrections as convolution of the pair radiator $H(z)$ with the photonic radiator, the fourth order is estimated in LLA:
  [4] A.B. Arbuzov, `hep-ph/9907500`

Results for LEP1

$$\delta = 10^3 \ \frac{\sigma_{\rm RC}^{\rm pairs,\gamma} - \sigma_{\rm RC}^{\gamma}}{\sigma_{\rm RC}^{\gamma}} \ , \qquad z_{\rm min} = 0.04$$

$\boldsymbol{E}_{\rm cm}$	ZF(−1)	ZF(1)	[1] + [2]	[3] + [2]	[4]
88.1867	−2.23	−2.38	−3.22	−2.28	−2.23
89.3867	−2.51	−2.58	−3.61	−2.46	−2.50
89.3867	−2.51	−2.58	−3.61	−2.46	−2.50
91.1867	−2.49	−2.52	−3.44	−2.52	−2.47
92.9867	−0.69	−0.45	−0.43	−0.93	−0.99
94.1867	+0.78	+1.77	+1.36	+0.27	+0.08

Note agreement between two last columns. These agree very well with `TOPAZO v.4.4` from April '99.

Results for LEP2

$\boldsymbol{E}_{\rm cm}$	ZF(−1)	ZF(1)	[1] + [2]	[3] + [2]	[4]
189	11.26	62.58	34.70	13.09	34.90
without singlet pairs in [1] and [4]					
189	11.26	62.58	14.12	13.09	15.51

Note, we obtain 15.19 instead of 13.09 for [3] + [2], if we treat the hadronic pairs there in the same way as in [4].

The LLA formula for singlet pair contribution to H [1]:

$$H^S(z) = \left(\frac{\alpha}{\pi}\right)^2 \ln\frac{s}{m_e^2}\left[\frac{1}{2}(1+z)\ln z + \frac{1}{3z} + \frac{1}{4} - \frac{z}{4} - \frac{z^2}{3}\right]$$

The term with z in denominator is responsible for the large correction. Note, that the kernel cross section is also proportional to $1/z$.

$E_{\mathrm{mc}} = 189$ GeV, different values for $z_{\min}$

$z_{\min}$	ZF(−1)	ZF(1)	[1] + [2]	[3] + [2]	[4]
0.01	11.35	63.29	44.30	13.16	44.42
0.1	11.21	62.08	33.08	13.04	33.31
0.3	2.64	3.77	4.26	2.60	4.03
0.7	−0.31	−0.56	−0.60	−0.80	−0.69
0.9	−2.28	−2.05	−2.74	−2.37	−2.27

Note jump in numbers between 0.1 and 0.3, which is due to singlet pairs if radiative return is allowed.

EW boxes (WW and ZZ) are vanishingly small at Z peak. They are very important at higher energies, already at LEP2.

`ZFITTER` has three options `BOXD=0,1,2`

- `BOXD=0`, boxes are ignored.
- `BOXD=1`, boxes are calculated as additive separate contribution to the cross-section. numerically integrated over the angle.

  If one convolutes with ISR only an IBA part without boxes and adds boxes without convolution, then an apparent violation of gauge invariance is introduced.
- `BOXD=2`, box contributions are added to every EW four form factor. This is the only gauge invariant treatment, however, this may be achieved only via differential in the scattering angle interface `ZUATSM`, since boxes are angular dependent.

A study of convolution of EW boxes was done with `ZUATSM`. Its results are shown in following 5 Tables.

Columns:

- C1 – `ZUTHSM`, NO EW-boxes
- C2 – `ZUATSM`, followed by numerical integration over the angle: $-0.999999 \le \cos\theta \le +0.999999$
- C3 – `ZUTHSM` with EW-boxes as additive separate contribution to the cross-section
- C4 – `ZUATSM` with EW-boxes via EWFF, followed by numerical integration

Relative *Deviations* for cross-sections in per mill
and absolute *Differences* for the asymmetry in 10^{-3} are shown.

DD-Setup	NO EW BOXES		WITH EW BOXES	
	C1	C2	additive C3	via EWFF C4
$\sigma_\mu(M_Z), nb$	2.0033	2.0033	2.0033	2.0033
Deviations per mill		C2/C1-1 -0.015	C3/C1-1 -0.006	C4/C1-1 -0.015
			C3/C4-1 0.009	
A^μ_{FB}	0.01741	0.01741	0.01741	0.01741
Differences 10^{-3}		C2-C1 0.000	C3-C1 -0.005	C4-C1 0.000
			C3-C4 0.005	
$\sigma_\mu(120), pb$	11.725	11.725	11.713	11.713
per mill		-0.015	-0.989	-1.026
			0.037	
A^μ_{FB}	0.73608	0.73607	0.73527	0.73526
10^{-3}		-0.004	0.803	-0.812
			-0.008	
$\sigma_\mu(189), pb$	3.3923	3.3922	3.3759	3.3759
per mill		-0.015	-4.828	-4.813
			0.015	
A^μ_{FB}	0.56783	0.56782	0.56532	0.56527
10^{-3}		-0.003	-2.504	-2.559
			-0.055	

D-Setup	NO EW BOXES		WITH EW BOXES	
M^2=0.01s	C1	C2	additive C3	via EWFF C4
$\sigma_\mu(M_Z)$,nb	2.0066	2.0066	2.0066	2.0066
Deviations per mill		C2/C1-1 -0.002	C3/C1-1 -0.006	C4/C1-1 -0.002
			C3/C4-1 0.004	
A^μ_{FB}	0.01738	0.01738	0.01738	0.01738
Differences 10^{-3}		C2-C1 0.000	C3-C1 -0.005	C4-C1 0.000
			C3-C4 0.005	
$\sigma_\mu(120)$,pb	11.744	11.744	11.732	11.732
per mill		0.002	-0.988	-1.011
			-0.023	
A^μ_{FB}	0.73479	0.73479	0.73399	0.73398
10^{-3}		0.000	-0.803	-0.813
			-0.010	
$\sigma_\mu(189)$,pb	3.3977	3.3977	3.3814	3.3815
per mill		-0.002	-4.821	-4.793
			0.028	
A^μ_{FB}	0.56683	0.56683	0.56433	0.56427
10^{-3}		0.000	-2.505	-2.567
			-0.062	

CA3-Setup	NO EW BOXES		WITH EW BOXES	
s'=0.01 s	C1	C2	additive C3	via EWFF C4
$\sigma_\mu(M_Z), nb$	1.4795	1.4795	1.4795	1.4795
Deviations per mill		C2/C1-1 -0.029	C3/C1-1 -0.008	C4/C1-1 -0.029
			C3/C4-1 -0.021	
$A^\mu_{FB} \cdot 10^3$	-0.30578	-0.27845	-0.31232	-0.27845
Difference		C2-C1 0.027	C3-C1 -0.007	C4-C1 0.027
			C3-C4 0.034	
$\sigma_\mu(120), pb$	30.741	30.738	30.730	30.711
per mill		-0.105	-0.377	-0.990
			-0.613	
A^μ_{FB}	0.29719	0.29723	0.29672	0.29574
10^{-3}		0.045	-0.472	-1.444
			-0.972	
$\sigma_\mu(189), pb$	7.6847	7.6832	7.6683	7.6380
per mill		-0.189	-2.131	-6.075
			-3.952	
A^μ_{FB}	0.28725	0.28729	0.28555	0.28120
10^{-3}		0.036	-1.702	-6.054
			-4.352	

CA3-Setup	NO EW BOXES		WITH EW BOXES	
Acol= 25^o	C1	C2	additive C3	via EWFF C4
$\sigma_\mu(M_Z), nb$	1.4660	1.4659	1.4660	1.4659
Deviations per mill		C2/C1-1 -0.026	C3/C1-1 -0.008	C4/C1-1 -0.026
			C3/C4-1 -0.018	
$A^\mu_{FB} \cdot 10^3$	-0.42572	-0.42399	-0.43233	-0.42399
Difference		C2-C1 0.002	C3-C1 -0.007	C4-C1 0.002
			C3-C4 0.008	
$\sigma_\mu(120), pb$	20.771	20.770	20.760	20.738
per mill		-0.048	-0.558	-1.605
			-1.047	
A^μ_{FB}	0.46111	0.46112	0.46050	0.45969
10^{-3}		0.010	-0.607	-1.424
			-0.817	
$\sigma_\mu(180), pb$	3.6119	3.6114	3.5955	3.5883
per mill		-0.135	-4.535	-6.538
			-2.013	
A^μ_{FB}	0.55533	0.55539	0.55292	0.55225
10^{-3}		0.059	-2.408	-3.085
			-0.677	

CA3-Setup	NO EW BOXES		WITH EW BOXES	
s'=0.6441 s	C1	C2	additive C3	via EWFF C4
$\sigma_\mu(M_Z), nb$	1.4264	1.4264	1.4264	1.4264
Deviations per mill		C2/C1-1 -0.025	C3/C1-1 -0.008	C4/C1-1 -0.025
			C3/C4-1 -0.017	
$A^\mu_{FB} \cdot 10^3$	-0.13233	-0.13246	-0.13912	-0.13246
Difference		C2-C1 0.000	C3-C1 -0.007	C4-C1 0.000
			C3-C4 0.007	
$\sigma_\mu(120), pb$	12.453	12.453	12.442	12.440
per mill		-0.018	-0.931	-1.077
			-0.145	
A^μ_{FB}	0.71489	0.71489	0.71412	0.71396
10^{-3}		-0.004	-0.776	-0.931
			-0.155	
$\sigma_\mu(189), pb$	31.709	31.708	31.545	31.554
per mill		-0.025	-5.166	-4.896
			0.271	
A^μ_{FB}	0.57224	0.57224	0.56958	0.56966
10^{-3}		-0.004	-2.657	-2.586
			-0.071	

Process $e^+e^- \to t\bar{t}$

Massive SM calculations (*Beenakker, Hollik, 1991*)

Massive MSSM calculations (*Hollik et al., 1998*)

New calculation of EWFF in R_ξ-gauge
(*DB, L.Kalinovskaya, G.Nanava*)

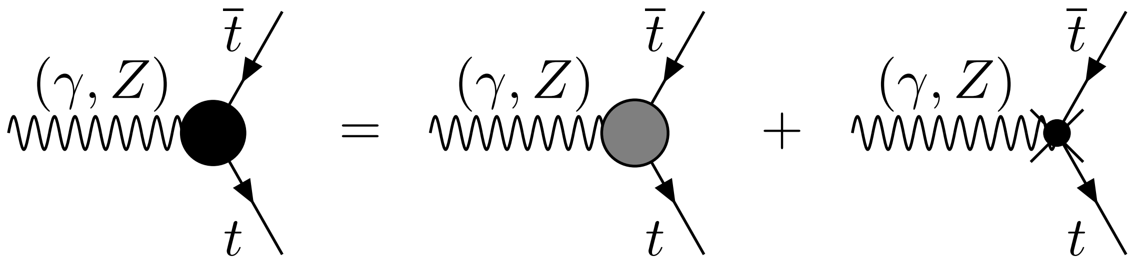

Figure 4: *Off-shell $Zt\bar{t}$ and $\gamma t\bar{t}$ vertices*

General structure of vertex in the LQD-basis,

$$V_\mu^{Zt\bar{t}} = (2\pi)^4 \, i \, \frac{g^3}{16\,\pi^2} \Big[i\gamma_\mu \left(1+\gamma_5\right) F_{\scriptscriptstyle L}(s) + i\gamma_\mu F_{\scriptscriptstyle Q}(s) + \left(p_t - p_{\bar{t}}\right)_\mu F_{\scriptscriptstyle D}(s) \Big]$$

Every form factor

$$F_{\scriptscriptstyle I}(s) = F_{\scriptscriptstyle I}^1(s) + F_{\scriptscriptstyle I}^{\rm add}\left(s, \xi_{\scriptscriptstyle A}, \xi_{\scriptscriptstyle Z}, \xi\right)$$

$I = L, Q, D$; $\xi_{\scriptscriptstyle A}, \xi_{\scriptscriptstyle Z}, \xi$ are parameters of gauge transformations and $F_{\scriptscriptstyle I}^1(s)$ represent the answers in t'Hooft–Feynman gauge.

Box diagrams

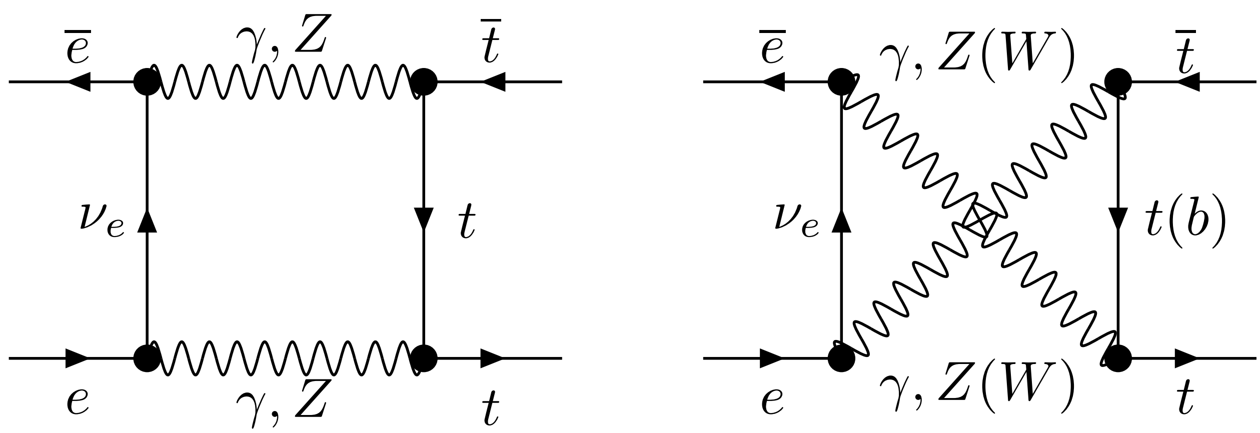

Figure 5: *The WW boxes*

Have the Born-like structure in massless limit:

$$\mathcal{A}_Z^{OLA} = \sim \Big\{\gamma_\mu(1+\gamma_5)\otimes\gamma_\mu(1+\gamma_5)F_{LL}(s,t)$$
$$+\gamma_\mu\otimes\gamma_\mu(1+\gamma_5)F_{QL}(s,t)$$
$$+\gamma_\mu(1+\gamma_5)\otimes\gamma_\mu F_{LQ}(s,t)$$
$$+\gamma_\mu\otimes\gamma_\mu F_{QQ}(s,t)\Big\}$$

Now new structure appear, e.g. for WW box:

$$\gamma_\mu\left(1+\gamma_5\right)\otimes I\big(p_t - p_{\bar{t}}\big)_\mu$$

$$\gamma_\mu\left(1+\gamma_5\right)\otimes \gamma_5\big(p_t - p_{\bar{t}}\big)_\mu$$

$$\gamma_\mu\left(1+\gamma_5\right)\otimes \not{p}_e\gamma_\mu\left(1+\gamma_5\right)$$

$$\gamma_\mu\left(1+\gamma_5\right)\otimes \not{p}_e\gamma_\mu\left(1-\gamma_5\right)$$

Result is rather cumbersome but still *analytically presentable.*

Status for LEP2 and further plans

- Implementation of LLA $\mathcal{O}\left(\alpha^2 L^2\right)$ ISPP corrections for A_{FB} (A. Arbuzov);
- Exponentiation of IFI corrections;
- `ZFITTER`–`GENTLE` merger as outlined in **PP-Manifesto** *by Giampiero Passarino* from 07/09/1999:
  - FSPP-final state pairs: soft and virtual;
  - Examination of contributions of $4f$ processes of simple topologies, `NC08/NC32`, to $2f$ observables in variables Q^2 and q^2 (primary and secondary pair invariant masses) using `GENTLE`;
- A continuation of comparison between `TOPAZ0` and `ZFITTER` is welcome;
- Critical revision of `ZFITTER` theoretical precision at LEP2 energies: $\sim 2 \div 3 \cdot 10^{-3}$ seem to be within a reach, $\sim 10^{-3}$ tough.

For LEP2 energies still more work is needed!

TOPAZ0

ZFITTER 6.06

$E_{CM} = 189$ GeV

```
                    WITHOUT IFI   WITH IFI
----------------------------------------------
          | XS(MU)(PB)= 7.6553    7.6819   T
          |             7.6414    7.6682   Z
          |            +0.18%    +0.18%    T/Z
M^2/s=0.01|            -----------------------
          | A_FB(MU)  = 0.28478   0.28933  T
          |             0.28171   0.28560  Z
          |             0.00307   0.00373  T-Z
----------------------------------------------
          | XS(MU)(PB)= 7.1766    7.2037   T
          |             7.1672    7.1946   Z
          |            +0.13%    +0.13%    T/Z
M^2/s=0.1 |            -----------------------
          | A_FB(MU)  = 0.30597   0.31099  T
          |             0.30360   0.30813  Z
          |             0.00237   0.00286  T-Z
----------------------------------------------
```

```
            | XS(MU)(PB)= [illegible] [illegible] T
            |             3.7193    3.7502   Z
            |            +0.09%    +0.09%    T/Z
 M^2/s=0.3  |            ------------------------
            | A_FB(MU)  = 0.57404   0.58306  T
            |             0.57393   0.58237  Z
            |             0.00011   0.00069  T-Z
-----------------------------------------------
            | XS(MU)(PB)= 3.3749    3.4181   T
            |             3.3708    3.4141   Z
            |            +0.12%    +0.12%    T/Z
 M^2/s=0.5  |            ------------------------
            | A_FB(MU)  = 0.57184   0.58385  T
            |             0.57166   0.58339  Z
            |             0.00018   0.00046  T-Z
-----------------------------------------------
            | XS(MU)(PB)= 3.0602    3.1200   T
            |             3.0580    3.1177   Z
            |            +0.07%    +0.07%    T/Z
 M^2/s=0.7  |            ------------------------
            | A_FB(MU)  = 0.56920   0.58647  T
            |             0.56888   0.58602  Z
            |             0.00032   0.00045  T-Z
-----------------------------------------------
```