Need of precision tools for ILC electroweak physics

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Outline

Introduction

- Certainly:
  it is not easy to argue that complicated calculations for Linear Collider physics are urgently needed,
- But:
  In view of time-scales and of available knowledges/experiences,
  one (i.e. we theorists) should work on that
- I will restrict myself to few remarks on fermion-pair production in the Standard Model

Two issues, two energy scales

Two related issues

- wide-angle scattering $e^+e^- \to \bar{f}f$, where f includes also electrons (Bhabha scattering)
- small angle Bhabha scattering $e^+e^- \to e^+e^-$

Two principally different energy ranges

- Giga$Z$ option with $\sqrt{s} = M_Z$
- true high-energy option, $\sqrt{s} = 0.5\mathrm{TeV} \cdots 3\mathrm{TeV} \cdots$

Assume the needed accuracy might be:
At $\sqrt{s} = M_Z$: about 0.1 % for 2f-production, about 0.01 % for forward Bhabha scattering
At $\sqrt{s} = O(\mathrm{TeV}$: about 1 % for 2$f$-production, about 0.1 % for forward Bhabha scattering
Please correct me if needed

$- >$ It would be nice to have a solid reference for all that.

What do we have?

For low energy scattering – at meson factories – there is a nice, comprehensive review:
"Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data", Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies Collaboration [[1, Actis:2010gg]]

ZFITTER, blueband-plot and all that

Evaluation of true cross-sections in different scenarios + fitting scenarios:
http://zfitter.desy.de/

GFITTER and all that

Modern tool for global fits to pseudo observables, includes also some New Physics

Table 2:
The differential Bhabha cross section in nbarn as function of the scattering angle and the cms-energy.
$M_Z = 91.16\ GeV$, $m_t = 150\ GeV$, $M_H = 100\ GeV$.
Upper rows: DZ, lower rows: H.
δ_m: *largest relative deviation in per mille.*

$\sqrt{s}$ (GeV) / θ	60	89	91.16	93	200
15°	129.6 129.6	65.11 65.11	57.93 57.93	49.00 49.00	11.82 11.82
45°	1.451 1.451	1.376 1.377	1.755 1.756	.4833 .4837	11.67 11.68
60°	.4303 .4305	.6124 .6129	1.125 1.126	.2697 .2699	.03075 .03077
75°	.1717 .1718	.3627 .3630	.8718 .8720	.2232 .2233	.01072 .01072
90°	.08873 .08876	.2768 .2769	.7790 .7787	.2088 .2087	.004862 .004855
105°	.05917 .05918	.2690 .2690	.8082 .8074	.2157 .2157	.002858 .002853
120°	.04906 .04906	.3053 .3051	.9323 .9309	.2429 .2426	.002077 .002074
135°	.04671 .04672	.3626 .3624	1.111 1.109	.2838 .2833	.001743 .001742
165°	.04839 .04839	.4638 .4635	1.425 1.422	.3590 .3584	.001539 .001540
δ_m	0.6	0.8	1.8	2.0	1.7

Bhabha scattering
Bardin,Hollik,T.R., Z.PhysikC49(1991)485

The 1991 result is yet the state of the art in e.g. the programs ZFITTER and BHWIDE.

Now, such calculations of O(1000) diagrams are better than to 10 digits.

Results: Numerical comparison in all $f\bar{f}$

Bhabha $e^- e^+ \to e^- e^+ \ (\gamma)$ **at LC:** $\sqrt{s} = 500$ GeV, $E_{\max}(\gamma_{\text{soft}}) = \frac{\sqrt{s}}{10}$

$\cos\theta$	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\text{Born}}$ (pb)	$\left[\frac{d\sigma}{d\cos\theta}\right]_{\mathcal{O}(\alpha^3)=\text{Born+QED+weak+soft}}$	Group
−0.9999	0.21482 70434 05632 5	0.14889 12125 78083 7	aITALC
−0.9999	0.21482 70434 05632 6	0.14889 12189 28404 0	*FeynArts*
−0.9	0.21699 88288 10920 5	0.19344 50785 26863 6	aITALC
−0.9	0.21699 88288 10920 0	0.19344 50785 26862 2	*FeynArts*
−0.9	0.21699 88288 41513 1	0.19344 50785 62637 9	$m_e = 0$
+0.0	0.59814 23072 50330 3	0.54667 71794 69423 1	aITALC
+0.0	0.59814 23072 50329 4	0.54667 71794 69421 8	*FeynArts*
+0.0	0.59814 23072 88584 4	0.54667 71794 99961 4	$m_e = 0$
+0.9	0.18916 03223 32270 6 · 10^3	0.17292 83490 66507 2 · 10^3	aITALC
+0.9	0.18916 03223 32270 6 · 10^3	0.17292 83490 66508 0 · 10^3	*FeynArts*
+0.9	0.18916 03223 31848 5 · 10^3	0.17292 83490 61347 4 · 10^3	$m_e = 0$
+0.9999	0.20842 90676 46142 9 · 10^9	0.19140 17861 11341 6 · 10^9	aITALC
+0.9999	0.20842 90676 46436 4 · 10^9	0.19140 17861 11979 0 · 10^9	*FeynArts*

Great independent agreement up to 14 digits! : limit in double precision

Previous agreement with *FeynArts*: 11 digits hep-ph/0307132, **SANC: 10 digits** hep-ph/0207156

Thanks to T. Hahn, numbers supplied with *FeynArts* + *FormCalc* + *LoopTools*

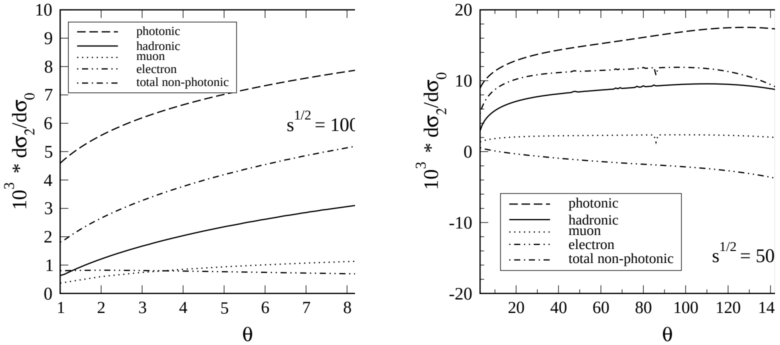
Some recent numerical results – Penin, Bonciani et al., Actis, Gluza, TR et al. and others

We will now discuss the numerical net effects arising from the $N_f = 2$ vertex plus box diagrams (i.e. excluding the pure running coupling effects):

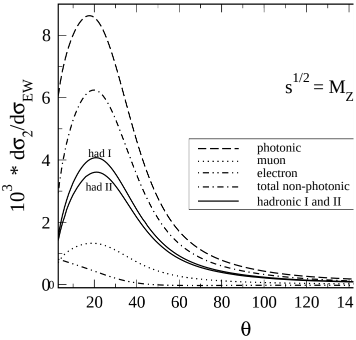
$$\frac{d\sigma_2}{d\Omega} = \frac{d\overline{\sigma}}{d\Omega} + \frac{d\sigma_v}{d\Omega},$$

with $d\overline{\sigma}/d\Omega$ from NNLO boxes and 'partners'. The expression for the irreducible vertex term $d\sigma_v/d\Omega$ derives directly from [2, 3]. The $d\sigma_2/d\Omega$ is normalized to the pure photonic Bhabha Born cross section $d\sigma_0/d\Omega$:

$$\frac{d\sigma_0}{d\Omega} = \frac{\alpha^2}{s}\left(\frac{s}{t} + 1 + \frac{t}{s}\right)^2.$$



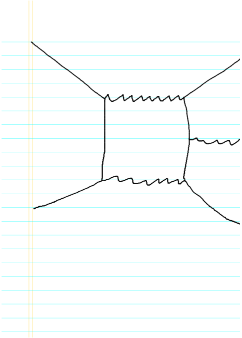
Two-loop vertex and box corrections $d\sigma_2$ to Bhabha scattering in units of $10^{-3} d\sigma_0$ at ILC energies of $\sqrt{s} = 100$ GeV (GigaZ option) and $\sqrt{s} = 500$ GeV. [[4, Actis:2007fs]] [[5, Actis:2008br]]



Two-loop corrections to Bhabha scattering at $\sqrt{s} = M_Z$, normalized to the effective weak Born cross section.

What is in the air if work is invested?

Radiative loop corrections



Among the non-leading NNLO corrections are the so-called radiative loop corrections, interfering with lowest order bremsstrahlung.

The main problems arise from the pentagon diagrams.

Tools for tensor reduction of 5-point functions to scalar boxes, vertices, self-energies:

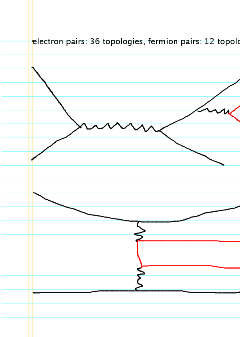
Czakon, Kajda, Gluza, Riemann, ambre.m, hexagon.m, MB.m

Pair corrections

M. Czakon, J. Gluza, T.R., M. Worek

Thanks to M. Worek's engagement, there are first results for event generation of Bhabha scattering with additional unresolved electron or muon pairs at $\sqrt{s} = 1.02, 10, 91$ GeV.
No cuts on the unresolved particles, but acceptance cuts on electron energy E_{min}, production angles $\theta_{\pm}$, acollinearity $\xi_{\max}$.

All particles are massive and observed, so there are no true singularities.



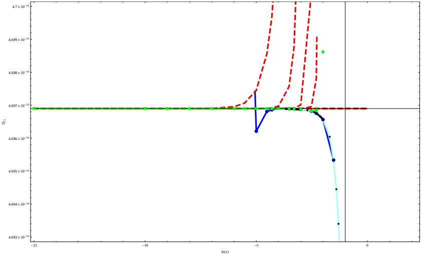
- At low energies, logarithms are not enhanced at all
- There are diagrams with quite different kinematics
- then, realistic cuts play a crucial role
- $\longrightarrow$ use HELAC-PHEGAS, Kanaki/Papadopulos/Worek/Cafarella webpage http://helac-phegas.web.cern.ch/helac-phegas/

What deserves hard work?

- True electroweak two-loop corrections for 2-fermion production at arbitrary energies (see: Passarino et al.)

What else we are doing?

Only for interested specialists



unplublished calculation of a 4-point tensor component at vanishing Gram determinant

J. Fleischer, TR, see also:

"Some variations of the reduction of one-loop Feynman tensor integrals", Contrib. to ACAT2010, e-Print: arXiv:1006.0679 [hep-ph]

Summary

- A lot of corrections are known, due to more recent work:
  – Hollik, Weiglein, Czakon, Freitas, Awramik et al.: electroweak two-loop corrections at the Z peak
  – v.d.Bij, Penin, Bonciani, Remiddi, Actis, Czakon, Gluza, T.R., Kuehn et al.: virtual QED NNLO corrections
- There is a lot of theoretical work to be done in order to have the basis for physics studies
- Some pieces are not so difficult, e.g. QED fermion pair emission corrections for Bhabha scattering (NNLO) and loop-by-loop corrections
- Others are technically available but have to be implemented by people who understand what they are doing, e.g. electroweak two-loop corrections at the Z peak
- If at high energies true electroweak twoloop corrections are needed: this might be really difficult

References I

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- B. Kniehl, M. Krawczyk, J. Kühn, and R. Stuart, *Hadronic contributions to o (alpha**2) radiative corrections in e+ e- annihilation*, *Phys. Lett.* **B209** (1988) 337.
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- S. Actis, M. Czakon, J. Gluza, and T. Riemann, *Virtual Hadronic and Leptonic Contributions to Bhabha Scattering*, *Phys. Rev. Lett.* **100** (2008) 131602, [arXiv:0711.3847].
- S. Actis, M. Czakon, J. Gluza, and T. Riemann, *Virtual hadronic and heavy-fermion O*(α^2) *corrections to Bhabha scattering*, *Phys. Rev.* **D78** (2008) 085019, [arXiv:0807.4691].