Electroweak radiative corrections and $\alpha_{EM}(m_z)$ determinations

Z. WAS

in collaboration with S. Jadach and B.F.L. Ward

IFJ-PAN, Kraków, Poland

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More material on http://jadach.web.cern.ch/ and http://wasm.web.cern.ch/wasm/

Role of $\alpha_{QED}(M_Z)$

Key input parameter for precision physics of FCC-ee.
Several observables such as total cross section or forward-backward asymmetries in $e^+e^- \to l^+l^-$ were proposed to measure $\alpha(M_Z)$ without use of low enery e^+e^- data.
Precise $\alpha(Q)$ (needed also for negative Q^2) mean good resummation (control) of loop diagrams.
It was dominant component of 0.04% systematic error for luminosity measurement at LEP.
At this moment there is plenty of time for improvements from:

- better measurements of $e^+e^- \to$ hadrons at low eneries
- Lattice QCD calculations.
- Direct measurement of $\alpha(Q)$ at FCC itself.

Important: what matter is not the size of the effect, but related systematic error. That is why I would be careful to estimate advantage of some observables before detailed studies.

Evil in details

It looks that discussion started before my talk:

Alain Blondel, yesterday: The point is to identify a measurement that can be done with great precision (e.g. a forward-backward asymmetry) and whose physics content is as sensitive as possible to $\alpha_(QED)(M_Z)$, but is such that the sensitivity to other inputs can be effectively constrained by other measurements....
....so Patrick has investigated the possibility of the lepton forward-backward asymmetry in the vicinity of the Z peak. It is found that this quantity at sqrt(s) = 88 and 95 GeV has large and opposite sensitivity to $\alpha_(QED)(M_Z)$ so that, either directly or as input to a global fit, it would constrain it at a level similar or better to the expected further measurements of hadronic cross-sections at low energies.

My duty, I guess, is to point: small effects but of sizable uncertainties.

Disclaimer

In the following I wanted to concentrate on the issue:

0.01 % theoretical precision tag for realistic observable(s)

From Patrick Janot talk: **0.001 %** to be targeted too!!

I will recall experience of our KKMC Monte Carlo program of LEP time. Also BHLUMI as possible example/starting point.

It took *decades* to prepare phenomenology frame for LEP. Some of the calculations are at use and improve, but some other may be lost. Needed are *stable devoted research groups*.

Precision of $\alpha_{QED}(M_Z)$ measurements

Useful, direct, measurement of $\alpha(M_Z), \alpha(Q)$ from cross section measurement an option for FCC-ee if calculations available.
Programs of LEP time upgrade-able, or just inspiration? Every factor of 2 in systematic error is paid by enormous effort, to be distributed among many people. We talk about factor 10-100.

- Precision range of $10^{-4} - 10^{-5}$ requires measured samples of $10^8 - 10^{10}$ events. To match technical tests and Monte Carlo programs will need to be numerically stable for samples at least 100 times larger!
- Granularity of the detectors to be taken into theoretical predictions!
- Detector response to final states with explicit multiple photons (at least 6?) and up to two extra pairs will need to be in simulation.
- Exclusive exponentiation of YFS type with extensions to complete 2-loops of EW sector and with pair emissions.
- All $(\frac{\alpha}{\pi})^2$ of complete electroweak calculations with separation of spin amplitudes into QED (QED-like) parts, vacuum polarization parts, genuine weak corrections.
- Specific programs: MC's for $e^+e^- \to e^+e^-$, $e^+e^- \to l^+l^-$, $e^+e^- \to 4f$, for fits, will have to use that. Migration from semi-analytical programs to MC weight techniques?

MC project useful for $\alpha_{QED}(M_Z)$ measurement. What is KKMC?

KKMC is the MC event generator for the process:

$\boxed{e^- e^+ \to f\bar{f} + n\gamma}$ $f = \mu, \tau, \nu, u, d, s, c, b,\ \ n = 0, 1, 2 ... \infty.$

Interfaced: TAUOLA+PHOTOS and electroweak library DIZET.

Published version 4.13 (FCC perspective: continuous improvements, checks with new compilers etc.):

- Comput.Phys.Commun. 130(2000) 360, hep-ph/9912214,
  F77 code description and user guide (manual).
- Phys. Rev. D63 (2001) 113009, hep-ph/0006359
  physics content, CEEX exponentiation of QED corrs.

"Workhorse" in data analysis of all four LEP collaborations.

At present it is used by Belle collaboration, for tests by LHC.

Important theoretical aspects: • separation of EW results into QED, line shape and genuine weak corrections, • reorganization of QED pert. expansion to all orders thanks to Yennie-Frautchi-Suura scheme, • exact MC parametrization of phase space for photons (conformal symmetry), • math. aspects of groups, subgroups and resulting layers for representations.

More KKMC versions available since 2000

http://jadach.web.cern.ch/jadach/KKindex.html

- Production Version 4.16, Oct. 2001, (KKMC-v.4.16d-export.tar.gz). Improved $\nu\bar{\nu}$ matrix elm. RRes module for $\gamma^* \to$ *narrow resonances* at LEP.
- Developement Version 4.19, Sept. 2002, (KKMC-v.4.19.b-export.tar.gz). C++ wrapper. Improved $\nu\bar{\nu}$ matrix element and RRes for low energy colliders. ISR with complete NLO corrs, as in Phys.Rev. D65(2002) 073030 by S.J., M.Melles, B.F.L.Ward and S.A. Yost. Collinear beamstrahlung for NLC/ILC.
- Developement Version 4.22, June 2013, (KKMC_v4_22.tgz). Tested $\mu^-\mu^+$ and $q\bar{q}$ beams (instead of e^-e^+) at fixed energy. Optionaly, collinear PDFs for $q\bar{q}$ beams instead of beamstrahlung, as a patch in the source code (temp. solution).
- The complete "algebraic" description of the NNLO formulas has been published in Phys.Rev. D73 (2006) 073001 (an extension of the work in Phys.Rev. D65 (2002) 073030), the code still not public. PHOKHARA MC is an alternative here for low energy colliders.

KKMC is special because:

- Resummed (exponentiated) multiphoton effects at the AMPLITUDE level (CEEX). $\sim$10 man-years of work in QED, use reorganization of QED perturbation expansion, thanks to Yennie-Frautchi-Suura work.
- QED rad. corrections up to third LO and NLO, both in the initial and final state plus (exponentiated) initial-final interference.
- Complete spin effects, including transverse correlations, for incoming beams and outgoing femions (needed for taus).

KKMC is useful in the LHC data analysis,

- Testing/calibrating for FSR in leptonic decays of Z/W, ϕ^*_η observables
- Studies/estimations of ISR-FSR interferences in $q\bar{q} \to Z \to l + \bar{l}$ data
- Electroweak+QCD corrections in the for Z production.cross section
- Spin correlations in $Z \to \tau^- \tau^+$

More on KKMC version 4.22 (2013)
Technical points, important for project continuity

- Old benchmarks, Table III in Pys.Rev. D 63 (2001) and more, are reproduced under SLC5 and SLC6, after adjustments of flags in makefile's and minor corrections in f77 code.
- Unpublished (public) v.4.16,4.19 include varying subset of extra subdirectories, not included in v4.13. Also not in v.4.22.
- System of original interrelated custom *Makefile*'s is renamed *Makefile* $\rightarrow$ *KKMakefile* and preserved.
- *Automake*/*Autotools* are introduced (*makefile.am* etc.).
  Hence KKMC is more platform independent
  and can be easily put under *kdevelop*3 or *eclipse*.
- Interface to C++ is provided. Main program (histogramming, etc) can be in C++, using optionally ROOT. (On request, or in v4.19)
- Scripts for running on PC-farms slightly upgraded and working.
- Old versions of PHOTOS and TAUOLA are straightforward to improve.

More on KKMC version 4.22 (2013)
Table III in Pys.Rev. D 63 (2001) reproduced

$v_{\rm max}$	$\mathcal{KK}$sem Refer.	$\mathcal{O}(\alpha^3)_{\rm EEX3}$	$\mathcal{O}(\alpha^2)_{\rm CEEX}$ intOFF	$\mathcal{O}(\alpha^2)_{\rm CEEX}$
	$\sigma(v_{\rm max})$ [pb]			
0.01	1.6712 ± 0.0000	1.6736 ± 0.0018	1.6738 ± 0.0018	1.7727 ± 0.0021
0.10	2.5198 ± 0.0000	2.5205 ± 0.0020	2.5210 ± 0.0020	2.6009 ± 0.0024
0.30	3.0616 ± 0.0000	3.0626 ± 0.0022	3.0634 ± 0.0022	3.1243 ± 0.0026
0.50	3.3747 ± 0.0000	3.3745 ± 0.0022	3.3761 ± 0.0022	3.4254 ± 0.0026
0.70	3.7223 ± 0.0000	3.7214 ± 0.0022	3.7249 ± 0.0022	3.7648 ± 0.0027
0.90	7.1430 ± 0.0000	7.1284 ± 0.0022	7.1530 ± 0.0022	7.1821 ± 0.0026
0.99	7.6136 ± 0.0000	7.5974 ± 0.0021	7.6278 ± 0.0021	7.6567 ± 0.0026
	$A_{\rm FB}(v_{\rm max})$			
0.01	0.5654 ± 0.0000	0.5661 ± 0.0012	0.5661 ± 0.0012	0.6121 ± 0.0014
0.10	0.5664 ± 0.0000	0.5667 ± 0.0009	0.5667 ± 0.0009	0.5931 ± 0.0011
0.30	0.5692 ± 0.0000	0.5694 ± 0.0008	0.5693 ± 0.0008	0.5864 ± 0.0010
0.50	0.5744 ± 0.0000	0.5744 ± 0.0008	0.5743 ± 0.0008	0.5870 ± 0.0009
0.70	0.5863 ± 0.0000	0.5858 ± 0.0007	0.5857 ± 0.0007	0.5953 ± 0.0008
0.90	0.3105 ± 0.0000	0.3107 ± 0.0004	0.3100 ± 0.0004	0.3176 ± 0.0004
0.99	0.2851 ± 0.0000	0.2856 ± 0.0003	0.2848 ± 0.0003	0.2918 ± 0.0004

Energy cut-off study of total cross section σ and charge asymmetry $A_{\rm FB}$ for annihilation process $e^-e^+ \to \mu^-\mu^+$, at $\sqrt{s}$ =189GeV.
Energy cut: $v < v_{\rm max}$, $v = 1 - M^2_{f\bar{f}}/s$.
From http://arxiv.org/abs/arXiv:1307.4037

Pair emissions

KKMC was developed with 0.1% precision tag in mind.

Every factor of 2 improvement will be a challenge and we need to get to at least 0.01 % precision level.

One of such necessary elements is extra lepton pair emissions from final startes. It became available with the help of PHOTOS C++ version http://photospp.web.cern.ch/photospp/

Pair emissions are not ready for precision simulation now; offer an option for detector response studies.

Pair emissions are closely related to loop corrections (i.e. to $\alpha_{QED}(Q)$) What about corrections from initial-final state interference of soft pair emissions to A_{FB} at 10^{-5} precision level?

WARNING: According to LEP2 workshops KKMC was providing the best calculation of the QED initial-final interference contribution to charge asymmetry A_{FB} in muon pair production for any energy near Z mass and higher. It is of order 1-2% off Z peak (Γ/M_Z suppression is only at at the peak) and has to be mastered very precisely.

All four LEP experiments used KKMC for estimating INI-FIN QED interference.

Pair emission

```
This example contains files and instructions on attaching Photos++ to KKMC v4.16d,
easily adaptable to other KKMC versions.
                         =========================
                           PHOTOS, Version:  3.58
                           Released at:  2/3/15
                         =========================

                    Photos QED corrections in Particle Decays

           Monte Carlo Program - by E. Barberio, B. van Eijk and Z. Was
           From version 2.09   - by P. Golonka and Z. Was
           From version 3.00   - by N. Davidson, T. Przedzinski and Z. Was
 EVENT BEFORE Photos++ PROCESSING:

INFO from PHOTOS:
PhotosHEPEVTEvent

P:( 0)   11  3|  0.0000e+0  0.0000e+0  1.0000e+2  1.0000e+2|  5.1100e-4|M: -1 -1|D:  2  4
P:( 1)  -11  3|  0.0000e+0  0.0000e+0 -1.0000e+2  1.0000e+2|  5.1100e-4|M: -1 -1|D:  2  4
P:( 2)   23  2| -2.3929e-2  3.5715e-2 -9.9410e+1  1.0059e+2|  1.5352e+1|M:  0  1|D:  5  6
P:( 3)   22  1|  2.3120e-2 -2.7186e-2  9.9379e+1  9.9379e+1|  0.0000e+0|M:  0  1|D: -1 -1
P:( 4)   22  1|  8.0862e-4 -8.5288e-3  3.0802e-2  3.1971e-2|  0.0000e+0|M:  0  1|D: -1 -1
P:( 5)   15  2|  7.2460e-1 -1.3170e+0 -9.7575e+1  9.7603e+1|  1.7770e+0|M:  2  2|D:  7  8
P:( 6)  -15  2| -7.4853e-1  1.3527e+0 -1.8353e+0  2.9860e+0|  1.7770e+0|M:  2  2|D: 11 12
P:( 7)   16  1|  1.0911e+0 -5.8632e-1 -4.6120e+1  4.6137e+1|  9.9998e-3|M:  5  5|D: -1 -1
P:( 8) -213  2| -3.6653e-1 -7.3072e-1 -5.1455e+1  5.1466e+1|  6.9034e-1|M:  5  5|D:  9 10
P:( 9) -211  1| -3.2170e-1 -3.6679e-2 -1.4112e+1  1.4116e+1|  1.3957e-1|M:  8  8|D: -1 -1
P:(10)  111  1| -4.4830e-2 -6.9404e-1 -3.7343e+1  3.7350e+1|  1.3496e-1|M:  8  8|D: -1 -1
P:(11)  -16  1| -2.8502e-1 -1.8574e-1  1.9563e-1  3.9257e-1|  9.9949e-3|M:  6  6|D: -1 -1
P:(12)  211  1| -4.6351e-1  1.5385e+0 -2.0309e+0  2.5935e+0|  1.3957e-1|M:  6  6|D: -1 -1
```

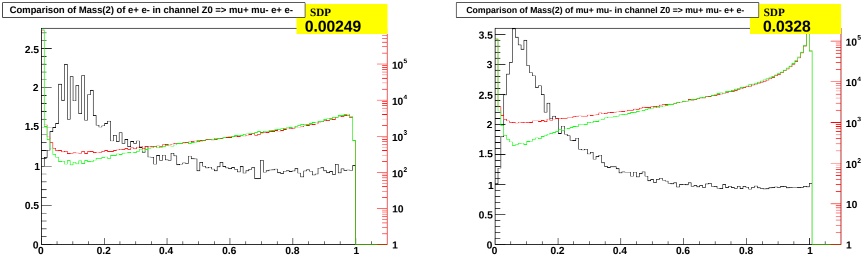
```
 EVENT AFTER Photos++ PROCESSING:
INFO from PHOTOS:
PhotosHEPEVTEvent
P:( 0)   11  3|  0.0000e+0  0.0000e+0  1.0000e+2  1.0000e+2|  5.1100e-4|M: -1 -1|D:  2  4
P:( 1)  -11  3|  0.0000e+0  0.0000e+0 -1.0000e+2  1.0000e+2|  5.1100e-4|M: -1 -1|D:  2  4
P:( 2)   23  2| -2.3929e-2  3.5715e-2 -9.9410e+1  1.0059e+2|  1.5352e+1|M:  0  1|D:  5  8
P:( 3)   22  1|  2.3120e-2 -2.7186e-2  9.9379e+1  9.9379e+1|  0.0000e+0|M:  0  1|D: -1 -1
P:( 4)   22  1|  8.0862e-4 -8.5288e-3  3.0802e-2  3.1971e-2|  0.0000e+0|M:  0  1|D: -1 -1
P:( 5)   15  2|  7.2412e-1 -1.3162e+0 -9.7512e+1  9.7540e+1|  1.7770e+0|M:  2 -1|D:  9 10
P:( 6)  -15  2| -7.2159e-1  1.3580e+0 -1.8401e+0  2.9848e+0|  1.7770e+0|M:  2 -1|D: 13 14
P:( 7)   11  1| -9.3541e-3 -2.0009e-3 -2.1191e-2  2.3256e-2|  5.1100e-4|M:  2 -1|D: -1 -1
P:( 8)  -11  1| -1.7109e-2 -4.1491e-3 -3.6517e-2  4.0542e-2|  5.1100e-4|M:  2 -1|D: -1 -1
P:( 9)   16  1|  1.0909e+0 -5.8590e-1 -4.6091e+1  4.6107e+1|  9.9998e-3|M:  5 -1|D: -1 -1
P:(10) -213  2| -3.6678e-1 -7.3026e-1 -5.1422e+1  5.1433e+1|  6.9034e-1|M:  5 -1|D:  9 10
P:(11) -211  1| -3.2170e-1 -3.6679e-2 -1.4112e+1  1.4116e+1|  1.3957e-1|M:  8 -1|D: -1 -1
P:(12)  111  1| -4.4830e-2 -6.9404e-1 -3.7343e+1  3.7350e+1|  1.3496e-1|M:  8  8|D: -1 -1
P:(13)  -16  1| -2.7704e-1 -1.8577e-1  1.9630e-1  3.8716e-1|  9.9949e-3|M:  6 -1|D: -1 -1
P:(14)  211  1| -4.4455e-1  1.5438e+0 -2.0364e+0  2.5976e+0|  1.3957e-1|M:  6  6|D: -1 -1

 Photos++ test: successfully added at least 1 particle. Exiting.
make[1]: Leaving directory '/tmp/KK-all/ffbench/Tau'
```

Pair emission, numerical tests, examples:
with KORALW matrix element generator for 4f final states

KORALW, is kept updated for modern compilers and new conditions by M. Skrzypek. For our purpose it is adjusted to run for final states of four fermions (red line), essentally only from Z decay. We run at $\sqrt{s} = M_Z$, and epsilon Z width to suppress initial state pair emission diagrams. Black line is the ratio, green line is from PHOTOS run on 2 fermion final states.

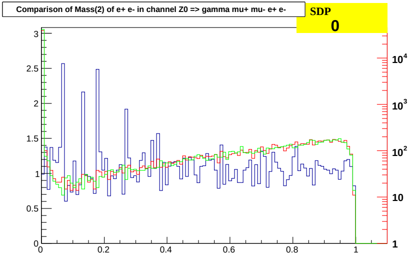
$$Z \to e^+ e^- \mu^+ \mu^-$$



Pair emission, numerical tests, examples:
PHOTOS algorithm downgraded, pairs always 'after' γ-s

This is to demonstrate that pair emissions can be used with KKMC already now (green line). Black line is the ratio. The red line, reference is when emissions are properly matched with photon emissions. No statistically significant differences for 100 Mevts are seen.

$$Z \to e^+e^-\mu^+\mu^-\gamma$$



Summary

• KKMC alive, useful for on-going experiments, but has to find **new contributors** within next 10 years, if is to remain available for later decenies!

• Precison tag improvement 0.1 $\to$ 0.01 % is a challenge, but may be feasible. Precision tag of 0.001 % will require far more basic redesign.

• This requires effort of many peoples (groups) of distinct interest and over many years.

• But it may be done. Note that BHLUMI (program for $e^+e^- \to e^+e^-$) precision tag of 0.04 % for LEP luminosity observables was reached years ago. It is also the project with continuing support.

Summary, cont.

- For KKMC; QED component, path toward 0.01 % precision is challenging but clear.
- Electroweak corrections to two loops suitable for separation into: QED, line shape and genuine weak parts.
- QED part need to be separated, because its higher orders have to be resummed in an exclusive manner. The same is true for line-shape corrections.
- If $\alpha_{QED}(M_Z)$ (also $\alpha_{QED}(Q)$ with $Q^2 < 0$) is to be obtained from direct measurements at high energies then there is less of dispersion relations from use of low energy $e^+e^- \to hadrons$. Less discussion of untarity etc.
- With precision gain will become less obvious. All parameters of Standard Model will be result of global fits.
- Semi-analytical calculations (like ZFITTER) for tests/fits.
- All this look challenging, but do-able.

The 0.001 % precision level is uncharted land ...
Main problem: man-power 2020-2030.