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

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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 precision of FCC-ee phenomenology:

$\frac{\delta\alpha}{\alpha} \sim 3.6 \cdot 10^{-9}$	$\frac{\delta G_\mu}{G_\mu} \sim 8.6 \cdot 10^{-6}$
$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 1.6 \leftrightarrow 6.8 \cdot 10^{-4}$	$\frac{\delta M_Z}{M_Z} \sim 2.4 \cdot 10^{-5}$

Clear: better control of $\alpha(M_Z)$ is needed for precision physics.
In fact what is needed is precision of $\alpha(Q)$;
It was this uncertainty contributing dominantly to 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: how programs are going to use the input.
Resummations, Monte Carlo impementations, fitting programs.

Disclaimer

In the following I want to concentrate on the issue:

0.01 % theoretical precision tag for realistic observable(s)

- I will not review existing programs and calculations, for reference see for example *Oct 28 meeting*: https://indico.cern.ch/event/337673/other-view?view=standard
  or talks of the present meeting.
- I will not review phenomenology possibilites, it is also presented elsewhere

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

TH lumi precision: $\sim 4 \cdot 10^{-4}$, similar to $\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 1.6 \leftrightarrow 6.8 \cdot 10^{-4}$

Hint: useful, direct, measurement of $\alpha(M_Z), \alpha(Q)$ from cross section measurement may be an option for FCC-ee.

Programs of LEP time useful, or better to start from scratch?

In either case LEP experience can be helpful.

At this moment it seems that there is plenty of time for improvements.
However every factor of 2 in systematic error is paid by enormous effort.
Which need to be distributed among many people.

It took decades to prepare phenomenology frame for LEP.

- perturbative calculations of fixed higher orders, results from lattice QCD.
- Separation of results into QED (QED-like) parts, vacuum polarization parts, genuine weak corrections.
- Resummation techniques, such as exclusive exponentiation, or introduction of effective Z width.
- Specific programs: MC's for $e^+e^- \to e^+e^-$, $e^+e^- \to l\bar{l}$, for fits, for electroweak corrections, vac. pol. etc.

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

KKMC is the MC event generator for the process:

$$\boxed{e^- e^+ \rightarrow f\bar{f} + n\gamma}$$

$f = \mu, \tau, \nu, u, d, s, c, b, \quad n = 0, 1, 2 \ldots \infty.$

Interfaced with TAUOLA+PHOTOS
and with electroweak library DIZET.
Published version 4.13 (to be cited):

- 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 extensively by Belle collaboration, also test for LHC
(FCC perspective: continuous improvements, checks with new compilers etc.)

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.

Hidden treasures in KKMC
Can be useful for LHC?

KKMC is special because:

- Resummed (exponentiated) multiphoton effects at the AMPLITUDE level (CEEX). $\sim$10 man-years of work in QED.
- 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 $q\bar{q} \rightarrow Z \rightarrow l + \bar{l}$ data
- Electroweak+QCD corrections in the for Z production.cross section
- Spin correlations in $Z \rightarrow \tau^- \tau^+$

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.
- Still only old versions of PHOTOS and TAUOLA, straightforward to improve.

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

$v_{\max}$	$\mathcal{KK}$sem Refer.	$\mathcal{O}(\alpha^3)_{\rm EEX3}$	$\mathcal{O}(\alpha^2)_{\rm CEEX}$ intOFF	$\mathcal{O}(\alpha^2)_{\rm CEEX}$
	$\sigma(v_{\max})$ [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
	$A_{\rm FB}(v_{\max})$			
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: $v < v_{\max}$, $v = 1 - M_{f\bar{f}}^2/s$.
From http://arxiv.org/abs/arXiv:1307.4037

More on KKMC version 4.22 (2013)
Physics extensions, 1st step: lepton beams

Lepton beams $\neq e^{\pm}$, for instance $\mu^-\mu^+$, $q\bar{q}$, etc.

Mainly the problem of transfering properly mass of beam leptons.

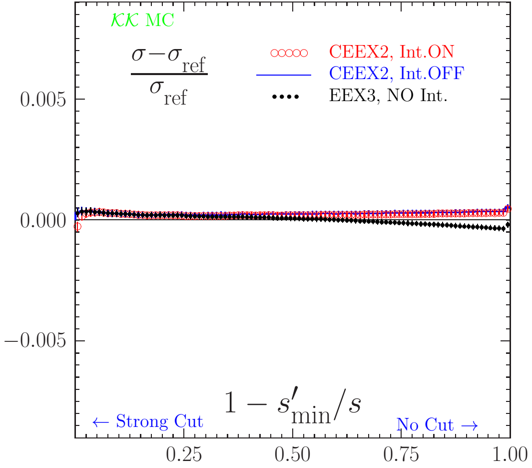
A few corrections, et voilá! $\boxed{\mu^-\mu^+ \rightarrow e^-e^+}$ at 189GeV.

$v_{\max}$	$\mathcal{KK}$sem Refer.	$\mathcal{O}(\alpha^3)_{\rm EEX3}$	$\mathcal{O}(\alpha^2)_{\rm CEEX}$ intOFF	$\mathcal{O}(\alpha^2)_{\rm CEEX}$
	$\sigma(v_{\max})$ [pb]			
0.01	1.6703 ± 0.0000	1.6716 ± 0.0040	1.6718 ± 0.0040	1.7721 ± 0.0048
0.10	2.5076 ± 0.0000	2.5119 ± 0.0046	2.5123 ± 0.0046	2.5946 ± 0.0055
0.30	3.0153 ± 0.0000	3.0192 ± 0.0048	3.0203 ± 0.0048	3.0813 ± 0.0057
0.50	3.2808 ± 0.0000	3.2839 ± 0.0049	3.2867 ± 0.0049	3.3348 ± 0.0058
0.70	3.5252 ± 0.0000	3.5277 ± 0.0049	3.5338 ± 0.0049	3.5712 ± 0.0059
0.90	5.4288 ± 0.0000	5.3946 ± 0.0047	5.4412 ± 0.0047	5.4699 ± 0.0057
0.99	5.7248 ± 0.0000	5.6824 ± 0.0046	5.7414 ± 0.0046	5.7697 ± 0.0057
	$A_{\rm FB}(v_{\max})$			
0.01	0.5654 ± 0.0000	0.5664 ± 0.0028	0.5664 ± 0.0028	0.6132 ± 0.0032
0.10	0.5659 ± 0.0000	0.5666 ± 0.0021	0.5666 ± 0.0021	0.5934 ± 0.0025
0.30	0.5675 ± 0.0000	0.5684 ± 0.0019	0.5684 ± 0.0019	0.5855 ± 0.0022
0.50	0.5705 ± 0.0000	0.5710 ± 0.0018	0.5710 ± 0.0018	0.5835 ± 0.0021
0.70	0.5774 ± 0.0000	0.5776 ± 0.0017	0.5777 ± 0.0017	0.5870 ± 0.0020
0.90	0.3844 ± 0.0000	0.3873 ± 0.0011	0.3848 ± 0.0011	0.3921 ± 0.0012
0.99	0.3613 ± 0.0000	0.3652 ± 0.0010	0.3622 ± 0.0010	0.3683 ± 0.0012

Quark beams at fixed energy, for LHC, for continuity.

Mainly the problem of transfering properly weak isospin of beams.

$u\bar{u} \to e^- e^+ + n\gamma$ at $\sqrt{s} = M_Z$. Again KKMC vs. KKsem.



More on KKMC version 4.22 (2013)
Physics extensions, 3rd step: PDFs for quark beam

Quark beams at energies varying according to PDFs. From FCC-ee perspective it is important that program may go over evolution during LHC precision era. Also compatibility with FCC-pp applications.

Main problem in the code: variable $\sqrt{s}$ from one MC event to another.

Luckily already solved for beamstrahlung.

Test for $\boxed{u\bar{u} \to e^- e^+ + n\gamma}$ at $\sqrt{s} = M_Z$.

KKMC vs. KKsem not available:(
Only kinematics was tested, see event printout next slide.

More on KKMC version 4.22 (2013)
Physics extensions, 3rd step: PDFs for quark beam

```
**************************************************************************
*                          KK Monte Carlo                                *
*             Version       4.22            May 2013                     *
*    7000.00000000                  CMS energy average        CMSene   a1 *
*       0.00000000                  Beam energy spread        DelEne   a2 *
*              100                  Max. photon mult.         npmax    a3 *
*                0                  wt-ed or wt=1 evts.       KeyWgt   a4 *
*                1                  ISR switch                KeyISR   a4 *
*                1                  FSR switch                KeyFSR   a5 *
*                2                  ISR/FSR interferenc       KeyINT   a6 *
*                1                  New exponentiation        KeyGPS   a7 *
*                0                  Hadroniz.  switch         KeyHad   a7 *
*       0.20000000                  Hadroniz. min. mass       HadMin   a9 *
*       1.00000000                  Maximum weight            WTmax   a10 *
*              100                  Max. photon mult.         npmax   a11 *
*                2                  Beam ident                KFini   a12 *
*       0.03500000                  Manimum phot. ener.       Ene     a13 *
*  0.10000000E-59                   Phot.mass, IR regul       MasPho  a14 *
*    1.2500000                      Phot. mult. enhanc.       Xenph   a15 *
*       0.00000000                     PolBeam1(1)            Pol1x   a17 *
*       0.00000000                     PolBeam1(2)            Pol1y   a18 *
*       0.00000000                     PolBeam1(3)            Pol1z   a19 *
*       0.00000000                     PolBeam2(1)            Pol2x   a20 *
*       0.00000000                     PolBeam2(2)            Pol2y   a21 *
*       0.00000000                     PolBeam2(3)            Pol2z   a22 *
**************************************************************************
```

Event listing (summary)

I	particle/jet	KS	KF	orig	p_x	p_y	p_z	E	m
1	!u!	21	2	0	0.000	0.000	22.668	22.668	0.005
2	!ubar!	21	-2	0	0.000	0.000	-245.458	245.458	0.005
3	(Z0)	11	23	1	23.016	18.370	-80.068	115.249	77.487
4	gamma	1	22	1	-30.989	-6.132	-128.905	132.719	0.000
5	gamma	1	22	1	0.000	0.000	0.031	0.031	0.000
6	gamma	1	22	1	7.973	-12.238	-13.848	20.127	0.000
7	gamma	1	22	1	0.000	0.000	3477.332	3477.332	0.000
8	gamma	1	22	1	0.000	0.000	-3254.542	3254.542	0.000
9	tau-	1	15	3	-24.701	21.657	-20.217	38.613	1.777
10	tau+	1	-15	3	47.716	-3.287	-59.851	76.635	1.777
		sum:	0.00		0.000	0.000	0.000	7000.000	7000.000

Cont.

```
                           Event listing (summary)
    I particle/jet KS      KF  orig    p_x      p_y      p_z       E        m
    1 !u!          21       2    0    0.000    0.000  271.908  271.908    0.005
    2 !ubar!       21      -2    0    0.000    0.000   -6.542    6.542    0.005
    3 (Z0)         11      23    1    0.047    1.133  244.401  257.454   80.928
    4 gamma         1      22    1   -0.047   -1.133   20.965   20.996    0.000
    5 gamma         1      22    1    0.000    0.000 3228.092 3228.092    0.000
    6 gamma         1      22    1    0.000    0.000-3493.458 3493.458    0.000
    7 mu-           1      13    3    0.601   14.537    2.005   14.687    0.106
    8 mu+           1     -13    3   -0.554  -13.404  242.396  242.767    0.106
                 sum:  0.00           0.000    0.000    0.000 7000.000 7000.000
                           Event listing (summary)

    I particle/jet KS      KF  orig    p_x      p_y      p_z       E        m
    1 !u!          21       2    0    0.000    0.000 1816.851 1816.851    0.005
    2 !ubar!       21      -2    0    0.000    0.000   -1.137    1.137    0.005
    3 (Z0)         11      23    1    0.011    0.003 1810.259 1812.532   90.760
    4 gamma         1      22    1   -0.012   -0.002    5.371    5.371    0.000
    5 gamma         1      22    1    0.000    0.000 1683.149 1683.149    0.000
    6 gamma         1      22    1    0.000    0.000-3498.863 3498.863    0.000
    7 mu-           1      13    3   12.468  -25.466 1612.743 1612.992    0.106
    8 mu+           1     -13    3  -12.457   25.469  197.516  199.540    0.106
                 sum:  0.00          -0.001    0.001   -0.084 6999.916 6999.916

*************************************************************************
*                        KK2f_Finalize  printouts                       *
*    7000.00000000                  cms energy total         cmsene     a0 *
*             5000                  total no of events       nevgen     a1 *
*               ** principal info on x-section **                       *
*     233.95163953  +- 1.04896414   xs_tot MC R-units        xsmc       a1 *
*       0.41468908                  xs_tot    picob.         xSecPb     a3 *
*       0.00185933                  error     picob.         xErrPb     a4 *
*       0.00448368                  relative error           erel       a5 *
*       0.82048782                  WTsup, largest WT        WTsup     a10 *
*                       ** some auxiliary info **                       *
*       0.00219522                  xs_born   picobarns       xborn     a11 *
*       0.73760000                  Raw phot. multipl.                 === *
*       5.00000000                  Highest phot. mult.                === *
*                         End of KK2f  Finalize                         *
*************************************************************************
```

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.
Recently it became available with the help of PHOTOS C++ version http://photospp.web.cern.ch/photospp/, which is now 100% in C++ but has an interface to HEPEVT of F77 as well, thus can work with KKMC as well.

Pair emissions are not ready for precision simulation, but offer an option for detector response studies. Improvements will come over the next months.

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
```

Pair emissions, cont.

```
 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'
```

Possible extensions for LHC use.

Could one include/improve QCD correction for the incoming beams? Yes, for example classic NLO corrs, Powheg style etc.

In this case the upper level of KKMC would be replaced by C++ code, which is already in place in some simple form.

The extension to $q\bar{q} \to W \to l + \nu$ is thinkable, but would require update of the QED matrix element (also new EW corrs.)

NB. t-channel W exchange with h.o. QED is already there for $\nu\bar{\nu}$ chanel and could be exploited as a starting point.

The bottom line:

The existing KKMC can be exploited for LHC and for Belle applications, ensuring that it is living project !!!

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.
• This requires effort of many peoples (groups) of distinct interest and over many years. It is not going to be easy.
• But it may be done. Note that BHLUMI precision tag of 0.04 % for LEP luminosity observables was reached years ago.

Summary, cont.

• For KKMC QED component, path for improvements toward 0.01 % precision is clear. It requires effort, also in training of new people. No unexpected difficulties?
• Electroweak correctionsup to two loops and in a form suitable for separation into: QED, line shape and genuine weak parts more difficult. We keep scientific links e.g. with people of former DIZET team having this challenge in mind.
• QED part need to be separated, because its higher orders have to be resummed in an exclusive manner.
• If $\alpha_{QED}(M_Z)$ (and consequently $\alpha_{QED}(Q)$) is to be obtained from direct measurements at high energies then it may simplify theoretical tasks. Less complications of dispersion relations resulting from use of low energy $e^+e^- \to hadrons$ data.
• Semi-analytical calculations for tests and fitting programs (like ZFITTER) will be needed.
• All this look challenging, but do-able.