KKMCee/BHLUMI/BHWIDE MC generators: status and prospects

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What is KKMC?

KKMC is the MC event generator for the process:

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

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

Interfaced with TAUOLA+PHOTOS
and with electroweak library DIZET.
Published version $\boxed{4.13}$ (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.

(Replacement of earlier MC's KORALZ and KORALB.)
(Not aplicable for $e^- e^+ \to e^- e^+$)

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).

Moreover it features:

- 1-st order electroweak corrections
- screening of the initial-final state interference for narrow Z resonance (following Frascati prescription)
- hadronization for quark pairs
- initial machine beam spread

Older KKMC versions 2000-2017

http://nz42.ifj.edu.pl/user/jadach/main http://192.245.169.66:8000/FCCeeMC/wiki/kkmc

KKMC for fermion pair production at electron-positron colliders

- 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). With C++ wrappers. 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 with $\mu^-\mu+$ and $q\bar{q}$ beams (instead of e^-e^+) at fixed energy. Optionally, collinear PDFs for $q\bar{q}$ beams instead of beamstrahlung, as a patch in the source code (temp. solution).

More on KKMC version 4.22 (2013)
Technical points

- 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* → *KKMakefile* and preserved.
- *Atomake*/*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.

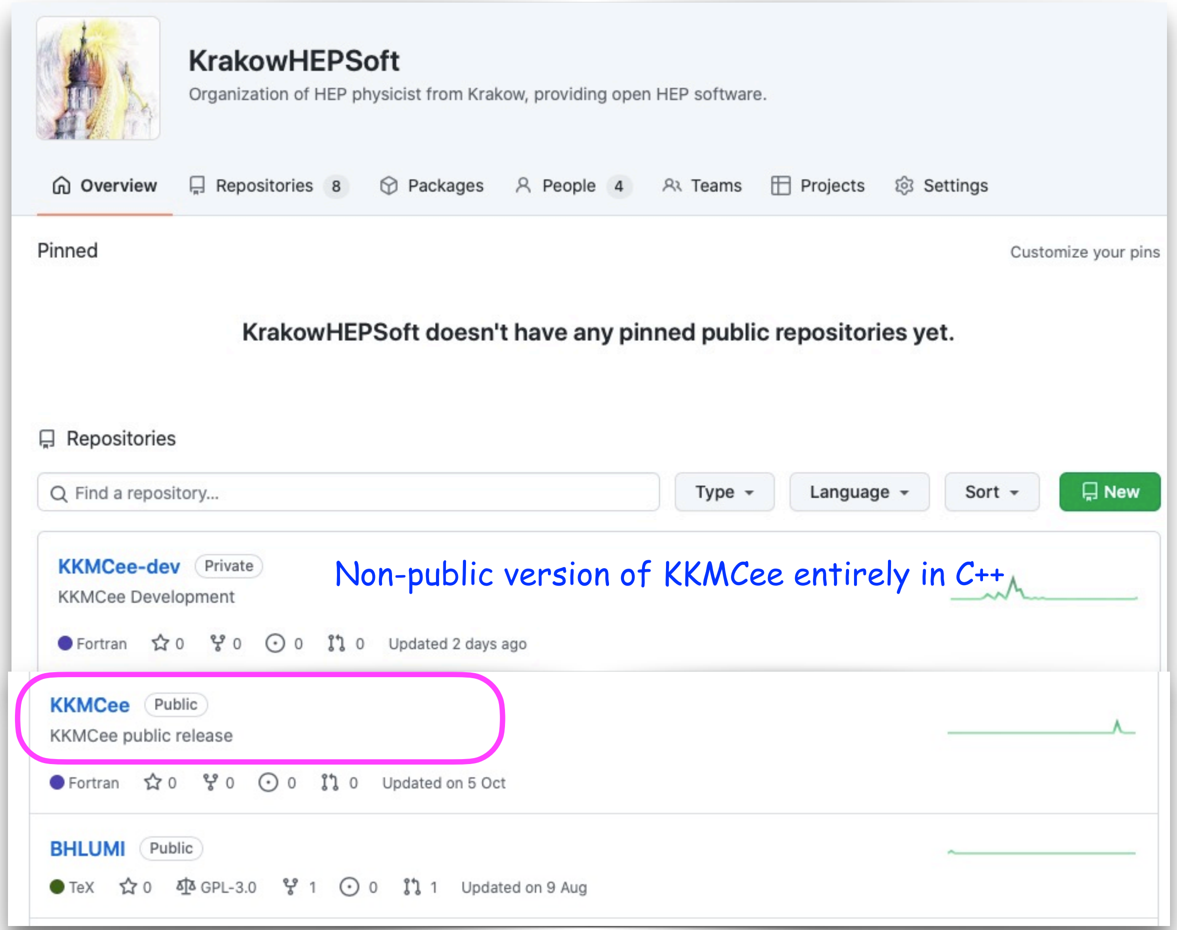
- First version [4.24] of the **KKMCee development branch**.

Beamstrahlung implementation for FCCee/ILC/CLIC is now improved, simplified and better debugged. Temporary insertions in the source code for quark beams are removed (kept and developed further in KKMChh branch, to be published).

Version 4.24 (2017) was tested/run under Centos7 and Ubuntu16

Up to date KKMCee F77 version available on GITHUB

The current PUBLIC version in F77:
https://github.com/KrakowHEPSoft/KKMCee
https://github.com/KrakowHEPSoft/KKMCee/releases/tag/v4.32.01



BHLUMI Monte Carlo

The same source code on two wiki webpages

http://192.245.169.66:8000/FCCeeMC/wiki/bhlumi

FCC hh ee he MC

logged in as jadach | Logout | Preferences | Help/Guide

Wiki | Timeline | Roadmap | View Tickets | New Ticket | Search

wiki: bhlumi

Start Page | Ind

Last modified

BHLUMI 4.0x source code:

- Source code of the linux version: bhlp-4.x-linux.tar.gz (2.5MB)
- Original CPC version: bhlp-4.04-export.tar.gz WARNING! will not compile under modern systems

How to compile and run simple examples: HERE

Documentation (papers):

- program description and user manual, Phys. Commun. 102 (1997)
- more papers in the attachments

Talks on low angle Bhabha and BHLUMI are HERE

Attachments

https://twiki.cern.ch/twiki/bin/view/FCC/Bhabha

BHWIDE and other Monte Carlos for electron colliders

http://placzek.web.cern.ch/placzek/

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Monte Carlo programs:

- **LESKO-E & FRANEQ**: For Deep Inelastic Neutral Current Scattering at HERA (not updated since January 1993).
- **BHWIDE**: For Large-Angle Bhabha Scattering.
- **KoralW**: For 4-Fermion Production in Electron-Positron Collisions.
- **YFSWW**: For W-Pair Production and Decay in Electron-Positron Collisions.
- **YFSZZ**: For Z-Pair Production and Decay in Electron-Positron Collisions.
- **WINHAC**: For Single W-Boson Production in Hadron Collisions.

KoralW – source code

Available from: **/afs/cern.ch/user/s/skrzypek/public/**

- koralw-1.51.3-export.tgz
  – last version published in CPC
- koralw-1.53.3-export.30sep02.tgz
  – last version, as used at LEP2, with t-channel ISR
- koralw-1.53.3-linux-export.tar.gz
  – last version, adapted for Linux
- koralw-1.53.3-QuadPrec-export.tar.gz
  – last version upgraded to quadruple precision i.e. stable in small angles for e^+e^- in final state

Instructions in README and RELEASE.NOTES files
Simple demo: goto demo.14x directory and execute:
make KWdemoCC03 or make KWdemoGRCall

Ongoing developments in KKMCee

- Upgrade of DIZET electroweak library, new hadronic VP routine, more steering parameters for EW corrections. Done.

The Monte Carlo Program KKMC , for the Lepton or Quark Pair Production at LEP/SLC Energies—Updates of electroweak calculations

A. Arbuzov (Dubna, JINR), S. Jadach (Cracow, INP), Z. Wąs (Cracow, INP), B.F.L. Ward (Baylor U., Waco), S.A. Yost (Citadel Military Coll.) (Jul 15, 2020)

Published in: *Comput.Phys.Commun.* 260 (2021) 107734 • e-Print: 2007.07964 [hep-ph]

- Upgrade of TAUOLA library. Done.

TAUOLA of τ lepton decays—framework for hadronic currents, matrix elements and anomalous decays

M. Chrzaszcz (Cracow, INP and Zurich U.), T. Przedzinski (Jagiellonian U.), Z. Was (Cracow, INP), J. Zaremba (Cracow, INP) (Sep 15, 2016)

Published in: *Comput.Phys.Commun.* 232 (2018) 220-236 • e-Print: 1609.04617 [hep-ph]

- Cleanup and posting on GUTHUB actual F77 version, new LHE interface, DIZET, TAUOLA, Beam Energy Spread, etc. Done. https://github.com/KrakowHEPSoft/KKMCee

- Translation of KKMCee into C++. 80% done. Completed for $\mu^+\mu^-$ final state.

- New upgraded CEEX matrix element with non-soft corrections beyond $\mathcal{O}(\alpha^2)$. Planning.

- Provisions for recalculating matrix element with modified input EW parameters like $\alpha_{QED}(M_Z)$ for example. (For fitting EWPOs using MC.) Started.

A few technical points

- In F77 version (on GitHub) we use two makefile systems:
  the older one "custom" and the new one using *autotools*.

- In the c++ version the only makefile system is *autotools* based.

- MC generator object in the c++ version will feature full persistency based on ROOT. ROOT is used for Lorentz vectors and transformations.

- F77 code will remain for DIZET and TAUOLA for some time.
  For TAUOLA status and plans see talk by Z. Wąs.

- DIZET communicates with c++ through disk files only.
  The versions of DIZET 6.21, 6.42, 6.45 are included.

- BHLUMI is already 50% translated into c++.
  It will be probably merged with KKMCee.

- KKMChh for $pp \to f\bar{f} + X,\ f = e, \mu, \tau$ process written in c++ is ready for use and already well tested. To be published soon.

How KKMCee compares with other QED schemes in MC programs

Order-by-order approach (OLDBIS, MUSTRAL, KORALZ) disfavoured, soft photon resummation mandatory, collinear resumm. recommended.

Collinear resummation of mass logs

Strictly collinear PDFs (kT=0)

1. LO formulas available analytically at any higher order
2. Convenient and useful only for very inclusive observables like σ_{tot}. For A_{FB} already problematic.
3. Matching with NLO hard process possible but messy.
4. Soft limit only in inclusive form.

Examples: LUMLOG, ALIBABA, SABSPV, RACOONWW, ZFITTER, TOPAZ0, KKsem, KKfoam, WHIZARD

Parton shower (finite kT)

1. Well developed for QCD but little used in QED
2. Problems the same as in QCD: lack of NLO evolution, factorisation scheme dependence, kinks, gaps in angular distributions in the soft limit, messy algorithms of matching with NLO hard proc., hopeless beyond NLO, approximate LIPS…
3. In principle resummation of coll. mass logs to infinite order is there, but in practice not easy (needs backward evolution etc.)

Examples: BABAYAGA

Soft photon resummation YFS-style

1. Correct soft photon limit for *n* real or virtual photons
2. Exact Lorentz invariant Phase Space (LIPS)
3. Well defined scheme of including higher order non-soft real and virtual corrections at any order
4. Resummation of collinear logs truncated to finite order, non-singlet transitions out of scope

EEX

1. Differential sections
2. YFS 1961 based
3. Simpler algebraically in some cases

Examples:
YFS2, YFS3 in KORALZ
YFS3WW, BHWIDE,
KKMC, SHERPA

CEEX

1. Amplitudes
2. Generalised, YFS-inspired
3. Better suited for spin polarised charged emitters
4. Well suited for narrow resonances like Z, W
5. Automatically accounts for interferences
6. Easy separating/combining QED and pure EW corrs.

Examples: KKMC

CEEX = Coherent Exclusive EXponentiation

Consider process $\mathrm{e}^-(p_a) + \mathrm{e}^+(p_b) \to \mathrm{f}(p_c) + \bar{\mathrm{f}}(p_d) + \gamma(k_1), \dots, \gamma(k_n)$

Master formula covering the entire multi photon phase space (no approximations):

$$\sigma^{(r)} = \sum_{n=0}^{\infty} \frac{1}{n!} \int d\tau_n(p_1 + p_2;\ p_3, p_4,\ k_1, \dots, k_n)\ \mathrm{e}^{2\alpha \Re B_4(p_a, \dots, p_d)} \frac{1}{4} \sum_{\rm spin} \left| \mathfrak{M}_n^{(r)}(p, k_1, k_2, \dots k_n) \right|^2,$$

Infrared (IR) cancellations occur between

S. Jadach, B. F. L. Ward, Z. Was, Coherent exclusive exponentiation for precision Monte Carlo calculations, Phys. Rev. D63 (2001) 113009 (2001). arXiv:hep-ph/0006359, doi:10.1103/PhysRevD.63.113009.

Spin amplitudes:

$$\mathfrak{M}_n^{(r)}(p, k_1, k_2, k_3, \dots, k_n) = \prod_{s=1}^{n} \mathfrak{s}(k_s) \left\{ \hat{\beta}_0^{(r)}(p) + \sum_{j=1}^{n} \frac{\hat{\beta}_1^{(r)}(p, k_j)}{\mathfrak{s}(k_j)} + \sum_{j_1 < j_2} \frac{\hat{\beta}_2^{(r)}(p, k_{j_1}, k_{j_2})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})} + \cdots \right\},$$

All $\hat{\beta}_k^{(r)}$ functions are IR finite

Summary

- KKMCee legacy F77 code is alive and is available.
- KKMCee in C++ is already there,
  to be completed, documented and published.
- Public GitHub repository with the F77 code off KKMC available.
  Extensive documentation is available.
  Two other web pages contain older versions.
- The ultimate future KKMCee version for the precision physics at FCCee to be developed starting from actual C++ version.
- BHLUMI and BHWIDE are available,
  it is now translated into C++, will also get CEEX matrix element.
- BHWIDE to be incorporated into KKMC?

Many thanks to my collaborators: Z. Wąs, B.F.L. Ward, S. Yost, M. Skrzypek,
A. Siodmok, M. Chrząszcz for help and encouragement!

Reserve

Separating and/or recombining non-soft pure EW correction and QED part

- QED corrections are bigger, hence they have to be calculated at the 1-2 orders higher level than pure EW corrections. For instance at LEP era QED corrections were soft-resummed to infinite and non-soft QED typically up to $\mathcal{O}(\alpha^2)$, while EW corrections up to $\mathcal{O}(\alpha^1)$.

- In TeraZ/GigaZ era non-soft QED corrections will have to be calculated to $\mathcal{O}(\alpha^4)_{LO}$, while non-soft EW corrections up to $\mathcal{O}(\alpha^2)$.

- Is there any systematic and practical scheme of calculating QED and EW corrections separately and recombining them without violating gauge invariance, IR cancellations etc.?

- The CEEX matrix elements of KKMC offers good workable example of such a scheme, which can be easily extended to higher orders. See next slide…
  Monte Carlo implementation is the key part of this methodology!

- *Advice for loop calculators:*
  Never ever use Bloch-Nordsieck method of killing IR singularities in the EW+QED multi-loop integrals!!! (Subtract IR as early as possible!)
  Simply because MC with resummations already did that!

Recent studies using KKMCee

arXiv:1801.08611

QED Interference in Charge Asymmetry Near the Z Resonance at Future Electron-Positron Colliders

Stanislaw Jadach, Scott Yost

(Submitted on 25 Jan 2018 (v1), last revised 16 Jul 2019 (this version, v4))

The measurement of the charge asymmetry $A_{FB}(e^-e^+ \to \mu^-\mu^+)$ will play an important role at the high-luminosity circular electron-positron collider FCCee considered for construction at CERN. In particular, near the Z resonance, $\sqrt{s} \simeq M_Z \pm 3.5$ GeV, A_{FB} will provide a very precise value of the pure electromagnetic coupling constant $\alpha_{QED}(M_Z)$, which is vitally important for overall tests of the Standard Model. For this purpose, A_{FB} will be measured at the FCCee with an experimental error better than $\delta A_{FB} \simeq 3 \cdot 10^{-5}$, at least a factor 100 more precisely than at past LEP experiments! The important question is whether the effect of interference between photon emission in the initial and final state can be removed from the A_{FB} data at the same precision level using

arXiv:1908.06338

Precision measurement of the Z boson to electron neutrino coupling at the future circular colliders

R. Aleksan, S. Jadach

(Submitted on 17 Aug 2019)

At the high luminosity electron-positron circular colliders like FCC-ee in CERN and CEPC in China it will possible to measure very precisely $e^+e^- \to Z\gamma$ process with subsequent Z decay into particles invisible in the detector, that is into three neutrina of the Standard Model and possibly into other weakly coupled neutral particles. Apart from the measurement of the total invisible width (which is not the main subject of this work) this process may be used as a source of Z coupling to electron neutrino -- known very poorly. This is possible due to the presence of the t-channel W exchange in the $e^+e^- \to \nu_e\bar{\nu}_e\gamma$ channel which deforms slightly spectrum of the photon. We are going

Innovation fronts in QED/EW precision calculations

- Better Monte Carlo algorithm for phase space with very hard photons. Phase space generation in KKMC for extremely hard photos is inefficient.
- Novel ideas for better incorporation of the collinear resummation within soft photon resummation, especially at the amplitude level (CEEX), main problems are loops.
- Alternative methods of calculating spin amplitudes in CEEX, instead of Kleiss-Stirling, for massive particles?
- Soft photon emission resummation from unstable charged particles like W boson. Outline is already there (arxiv.org/1906.09071 by S.J and M.Skrzypek) but implementation is nontrivial.
- Subtraction of IR part from (gauge invariant) sets of multi-loop diagrams at the loop integrand level.
- Fitting EWPOs to data using high statistics "MC templates", weight differences, machine learning etc.
- Effective methods of parametrising the virtual (loop) correction to be used in the matrix element in the MC generators.

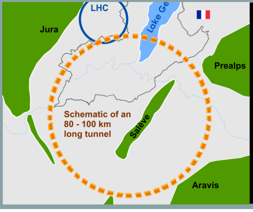
Strategy issues

- One should avoid the "monopoly" of a single MC for a given process/observable.
  The best would be (at least) two MCs of similar high quality developed *independently* by two groups of authors.
  Example of duo-poly:) YFSWW3 + RACOONWW,
  Examples of monopoly:(KKMC, BHLUMI, BHWIDE)
- Upgrade of LEP legacy MCs is a good but limited strategy. For factor 50-150 improvement in precision one needs new *innovative* projects.
- The division of MCs into "general purpose" class covering hundreds of processes, background, BSM, good for fast simulation of the detectors and "high precision" MCs specialising for a single or small subset of observables/processes is the *optimal* approach.
- LEP experience shows that developing a good quality MC costs many years of hard work and bright ideas. It should be planned well *in advance*.
  LEP was lucky that this activity has started already in the beginning of 80-ties.

Efficient methods of calculating higher order QED

General advice:

- Always use soft photon resummation to infinite order
- Resum big mass logarithms LO first, then NLO and NNLO
- Never ever use Bloch-Nordsieck! See below…
- Integrate one the entire multi photon phase space exactly using Monte Carlo method
- Resum $\alpha^n \ln^n(\Gamma/M)$ for narrow resonances
- Avoid using collinear structure functions (PDFs) integrated over kT



“DO and DONT” list in precision QED

- Do exponentiate (soft photon resummation)
- Do implement phase phase multi-photon in the Monte Carlo, experimental cutoffs will be (almost) never mastered analytically
- Dont add real photon emission to loop corrections a’la Bloch-Nordsieck (MC does it for you) but instead subtract well known IR terms
- Do keep finite masses of charged particles
- Do separate pure QED (IR) and pure EW parts at the early stage of calculations at the amplitude level

- Dont go order-by order but take care of non-soft leading mass logs first:

(a) 0.6%

1				
αL	α			
α^2L^2	α^2L	α^2		
α^3L^3	α^3L^2	α^3L	α^3	
α^4L^4	α^4L^3	α^4L^2	α^4L^1	α^4
$\vdots$	$\vdots$	$\vdots$		

(b) 0.03%

1				
αL	α			
α^2L^2	α^2L	α^2		
α^3L^3	α^3L^2	α^3L	α^3	
α^4L^4	α^4L^3	α^4L^2	α^4L^1	α^4
$\vdots$	$\vdots$	$\vdots$		

(c) 0.001%

1				
αL	α			
α^2L^2	α^2L	α^2		
α^3L^3	α^3L^2	α^3L	α^3	
α^4L^4	α^4L^3	α^4L^2	α^4L^1	α^4
α^5L^5	$\vdots$	$\vdots$	$\vdots$	

Figure 2: QED perturbative leading and subleading corrections. Rows represent corrections in consecutive perturbative orders – the first row is the Born contribution. The first column represents the leading logarithmic (LO) approximation and the second column depicts the next-to-leading (NLO) approximation. In the figure, terms selected for the same precision level (a) $6 \cdot 10^{-3}$ (b) $3 \cdot 10^{-4}$ and (c) $1 \cdot 10^{-5}$ are limited with the help of an additional line.

Specification of the MC for TeraZ
Total cross section $q\bar{q}$ and l^+l^-

✦ Upon removal of QED effects, hadronic $\sigma_h^0 = \sigma_h(M_Z)$ will serve as an input for neutrino counting (invisible Z width) and for very precise $\alpha_S(M_Z)$ determination from $R_l = \sigma_h^0/\sigma_l^0$

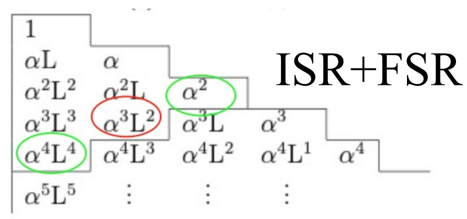
✦ For $\sigma_h(s)$ acceptance rate is almost 100%, cut-off dependent acceptance corrections negligible.

✦ Small and known $\mathcal{O}(\alpha^1)$ IFI corrections easily accountable, inclusive FSR handled analytically.

✦ *Initial state QED radiation (ISR) treatment of LEP seems almost sufficient,* non-MC programs might be able to cope with QED ISR, as in LEP. But no cut-offs….

○ For leptonic cross section $\sigma_l(s)$ acceptance correction will be sizeable, a few %, hence *the use of the MC will be mandatory* (non-MC program unable to cope).

○ One order better QED ISR and FSR mat. elem. (beyond KKMC) mandatory at 0.001% precision:



Recommendations:

✦ The inclusion of $\mathcal{O}(\alpha^1)$ EW corrections sufficient in both cases??

✦ Improved production of additional light fermion pairs necessary.

✦ IFI up to $\mathcal{O}(\alpha^1)$ probably enough? With soft photon resummation, of course.