MC codes for FCC-ee

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QED = main challenge in Precision Measurements

In the yesterday talk by John Ellis on Physics at FCC-ee QED corrections were cited as the main challenge in 5 out of 9 possible FCC-ee precision measurements.

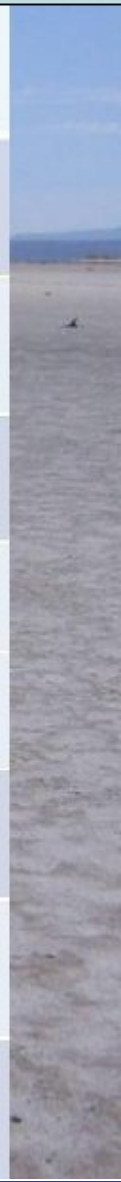
In fact they are critical in 6 them:
M_Z, Γ_Z, R_l, $N_\nu \in \sigma(M_Z)$, $N_\nu \in \nu\bar{\nu}\gamma$, M_W.

The other 3 ones are: R_b, A_{LR}, M_t

QED = main challenge in Prec. Measur. in FCC-ee

ossible FCC-ee Precision Measurements

Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_z (keV)	Input	91187500 ±2100	Z Line shape scan	5 keV	<100 keV	E_cal	QED corrections
Γ_z (keV)	Δρ (T) (no Δα!)	2495200 ±2300	Z Line shape scan	8 keV	<100 keV	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	<0.001	Statistics	QED corrections
N_ν	PMNS Unitarity sterile ν's	2.984 ±0.008	Z Peak	0.00008	<0.004		Bhabha scat.
N_ν	PMNS Unitarity sterile ν's	2.92 ±0.05	(γ+Z_inv) (γ+Z→ ℓℓ)	0.001 (161 GeV)	<0.001	Statistics	
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003	<0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	Δρ, ε_3, Δα (T, S)	0.1514 ±0.0022	Z peak, polarized	0.000015	<0.000015	4 bunch scheme, > 2exp	Design experiment
M_W MeV/c2	Δρ, ε_3, ε_2, Δα (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV	<0.5 MeV	E_cal & Statistics	QED corections

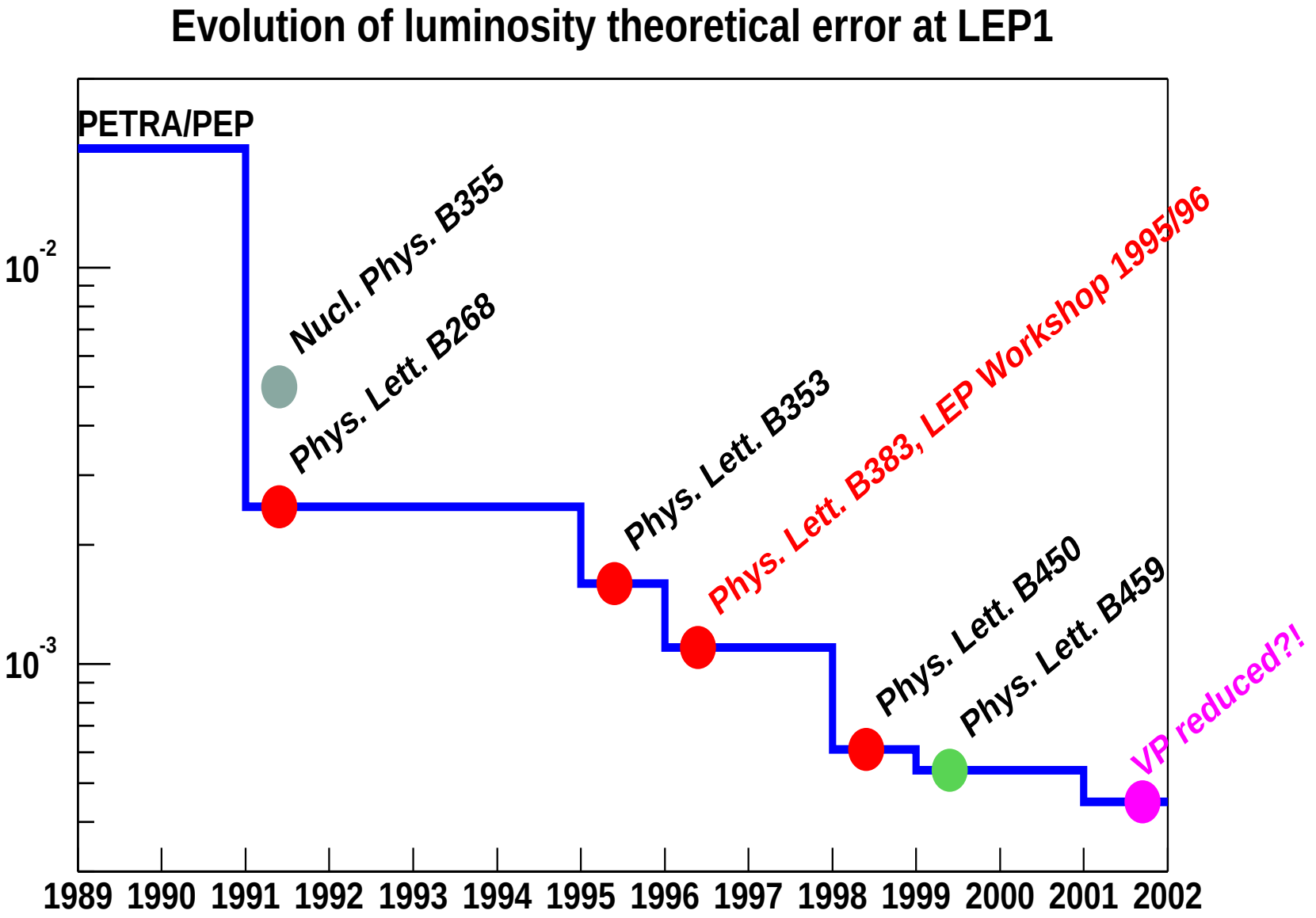


Lesson from LEP. Three golden rules

From LEP experience we know that
for the successful mastering of the QED correction effects
three criteria has to be met SIMULTANEOUSLY:

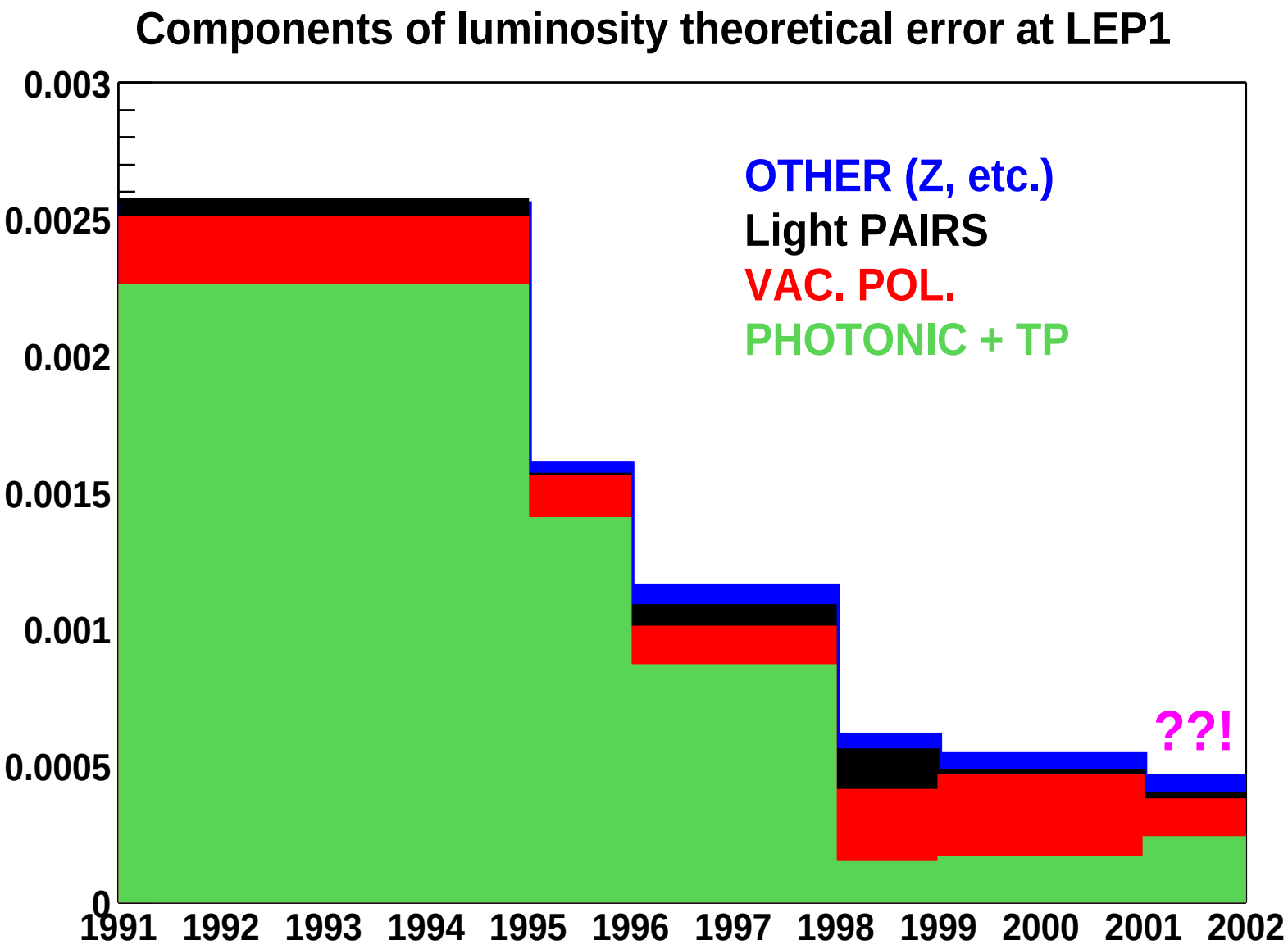
1. **Resummation of soft photons, collinear mass logarithms to ∞ order,**
   AND exploit RGE, (Γ/M) and (t/s), suppressions etc.
2. **Inclusion of the SELECTED higher order Feynman diagrams,**
3. **Monte Carlo event generator implementation**

The example of QED Precision time evolution in the project where 3 golden rules are followed



Not only photonic corrs.! Watch out for Vac.Pol.!

Room of improvement by factor 2-4 exists but... (TP=Technical Precision)



Progress after LEP?

My personal impressions on the progress in QED corr. calculations after LEP:

- **Enormous progress in last 12 years, in the methods for h.o. calculations of multiloop and multileg calculations, for ILC and LHC processes!!!**
- **Unfortunately, they are often not in a form suitable for matching with the QED soft/collinear resummation.**
- **In the MC codes for the QED corrs. for FCC-ee, essentially, there is (almost) nothing new/better than at the end of the LEP era**
- **Let's make catalogue of these codes, as they could be used for various studies and should serve as a starting point for the future developments.**
- **It is easy for me, as they come mostly from my own Krakow group:))**

LEP MC programs from Krakow group
with the important US component: B.F.L Ward, S.Yost!

Contact persons will tell you where to look for source code which compiles under modern Linux:

- **KKMC** for $e^-e^+ \to f\bar{f} + n\gamma$,
  $f = \mu, \tau, \nu, u, d, s, c, b, \quad n = 0, 1, 2 \ldots \infty$
  contact: S. Jadach, stanislaw.jadach@cern.ch
- **TAUOLA** for τ decays and **PHOTOS** for extra photons emission $\in$ KKMC and other programs, including LHC!
  contact: Z. Wąs, zbigniew.was@cern.ch
- **BHLUMI** for small angle $e^-e^+ \to e^-e^+$
  contact: S. Jadach, stanislaw.jadach@cern.ch
- **BHWIDE** for large angle $e^-e^+ \to e^-e^+$
  contact: W. Płaczek, wieslaw.placzek@uj.edu.pl
- **KORALW** for $e^-e^+ \to 4f$, **YFSWW** $e^-e^+ \to W^-W^+ \to 4f$
  contact: M. Skrzypek, maciej.skrzypek@ifj.edu.pl
- **YFSZZ** for $e^-e^+ \to ZZ \to 4f$
  contact: W. Płaczek, wieslaw.placzek@uj.edu.pl

More on KKMC

Due to limited time,
let me say a few more words on KKMC,
finishing with small example
of new study on QED uncertainty estimate
in $\boxed{N_\nu \in \nu\bar{\nu}\gamma}$ using KKMC.

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 interfaced 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 applicable for $e^- e^+ \to e^- e^+$)

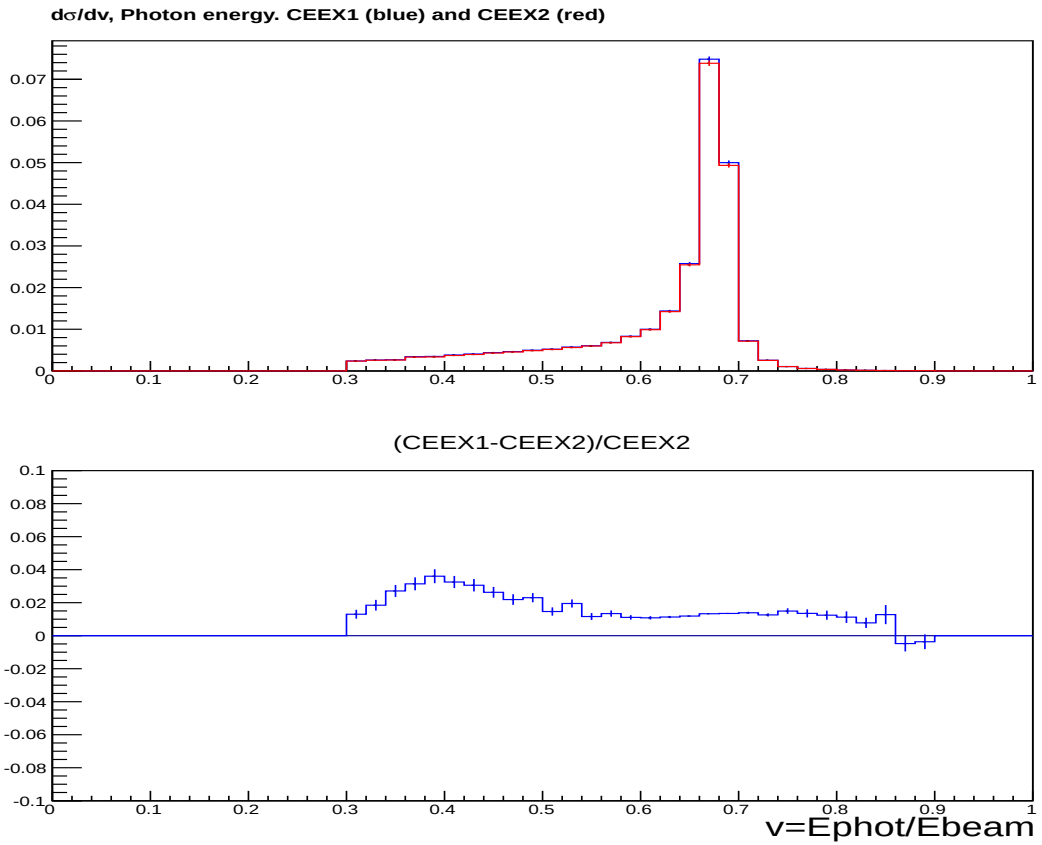
More KKMC versions available since 2000

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). 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).
- The complete "algebraic" description of the QED 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.

H.O. QED corrs. estimate in $e^- e^+ \to \nu + \bar{\nu} + \gamma$, for N_ν measurement

Study using KKMC: CEEX2 versus CEEX1



Min. photon angle $\Theta_{\text{min}} = 15^o$,
Min. photon energy $x_\gamma = 0.3, \quad E_\gamma > x_\gamma E_{beam}$,
Min. phot. transv. mom. $x_T = 0.3, \quad k_\gamma^T > x_\gamma E_{beam}$,
Only one photon within the above restrictions.
CEEX1= Born +soft photon resum., CEEX2= 1st ord. +soft photon resum.
$\sim$ 2% effect is seen!

Sorry about omissions due to limeted time/scope!

For example I would tell you more about:

- Other usefull MC codes from LEP era and some of the extedend for NLC/ILC like for $ee \to 4f\gamma$ RacoonWW by S.Dittmaier and A.Denner, WPHACT by A.Bellestrero, WHIZARD by T. Ohl, for Bhabha process SABSPV by O.Nicrosini et.al.
- Two-loop Electroweak corrections by several groups
- KORALW version in quadri-precision under newest Linux gcc by M. Skrzypek
- unpublished scheme of photon resummations near WW threshold by myself
- and more...:)

Conclusions

- MC codes from LEP era are still defining the state of art for QED correction FCC-ee.
- Most of legacy codes are maintained under present compilers/systems.
- One may contact their main authors for more info.
- Certain things in the were done better than needed for LEP, and may be useful for FCCee.

APPENDIX

Main features of KKMC

KKMC includes some features which were "overkill" for LEP, which can be exploited for FCCee:

- Resummed (exponentiated) multiphoton effects at the amplitude level.
  About 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 QED interferences.
- Most sophisticated M.E. for $e^+e^- \to \nu + \bar{\nu} + 2\gamma$, with t-channel W exchange,
- Complete spin effects, longitudinal+transverse(!) correlations, for incoming beams and outgoing femions, mandatory for taus.
- Interface to external library of Electroweak corrections
- beamstrahlung and more...

More on KKMC version 4.22 (2013)
Technical points

- Old benchmarks, Table III in Phys.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.