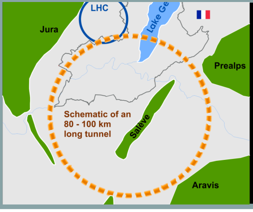


Monte Carlos for TeraZ

Stanisław Jadach

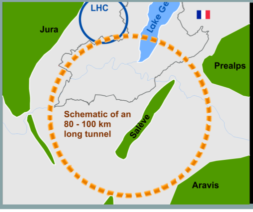
3-rd FCC Physics and Experiments Workshop , CERN

January 14-th, 2020

*This work is partly supported by the Polish National Science Center grant 2016/23/B/ST2/03927 and the CERN FCC Design Study Programme.

The above talk at the Software Workshop October 2019 talk has focussed on the technical matters and LEP legacy MCs like KKMC, BHLUMI, BHWIDE.

Here I focus on specification of the future ultimate MC(s) for TeraZ, needed for FCC-ee TeraZ tremendous precision, up to factor 100 better than at LEP, which will replace LEP legacy MCs.



A few statements from ESSP input #101

European Strategy Update

Input to the European Particle Physics Strategy Update 2018-2020

arXiv:1901.02648

1 November 2018 to 19 December 2018
Europe/Zurich timezone

Janusz Gluza (University of Silesia)
Alain Blondel (Universite de Genev...)
Patrick Janot (CERN)
Staszek Jadach (Polish Academy of S...)
Tord Riemann
Sven Heinemeyer (CSIC (Madrid, ES))
Ayres Freitas (University of Pittsbur...)

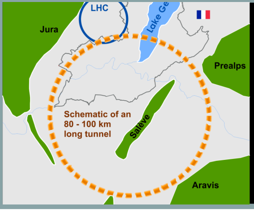
Overview
Guidelines
Submit Input

Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders

FCC-ee, a circular collider with extremely high statistics and high energy resolution, will provide the possibility to test the Standard Model with its fine quantum electroweak effects **with a precision far beyond the current state of the art.** Significant future theory effort will be needed for both for parametric and theoretical calculational errors to match the experimental accuracy of FCC-ee physics program. **No potential showstoppers are foreseen** [1, 2]. It will be important

FCC-ee: the first stage of the most powerful high energy discovery tool. The FCC-ee will provide a set of ground-breaking measurements of a large number of new-physics sensitive observables, with improvement by one to two orders of magnitude in experimental precision. **This will require the corresponding improvement in calculation ability with respect to the present baseline of perturbative Quantum Field Theory (pQFT).** An im-

For extracting the interesting physics from data in form of EWPOs **it will be mandatory to develop a library of new Monte Carlo (MC) event generators** implementing both QED and EW/QCD higher order effects. They will have to be developed for all processes at FCC-ee in all four stages, Tera-Z, WW, HZ and $t\bar{t}$. Well tested legacy MC programs of the LEP era can be used for benchmarking purposes, but the development of new event generation techniques and programs, should be done in parallel with a campaign of advances in the theoretical physics calculation methods.



Ultimate TeraMC for TeraZ

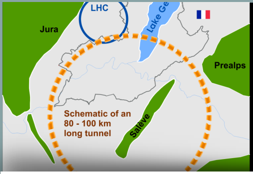
Data at LEP near Z resonance for 2-fermion processes
$e^+e^- \to f\bar{f} + n\gamma, \quad f = e, \mu, \tau, u, d, c, s, b, \quad \tau \to X, \;\; q\bar{q} \to jets \to hadrons$
were analysed using a handful of MC event generators:
KKMC (earlier KORALZ), BHWIDE and BHLUMI (+ non-MC ZFITTER, TOPAZ0)
MCs for $e^+e^- \to 4f$ were playing only minor role near Z peak.

For FCC-ee it is not clear yet whether for $e^+e^- \to 2f$ process
it will be more handy to have a few separate MCs or just one.

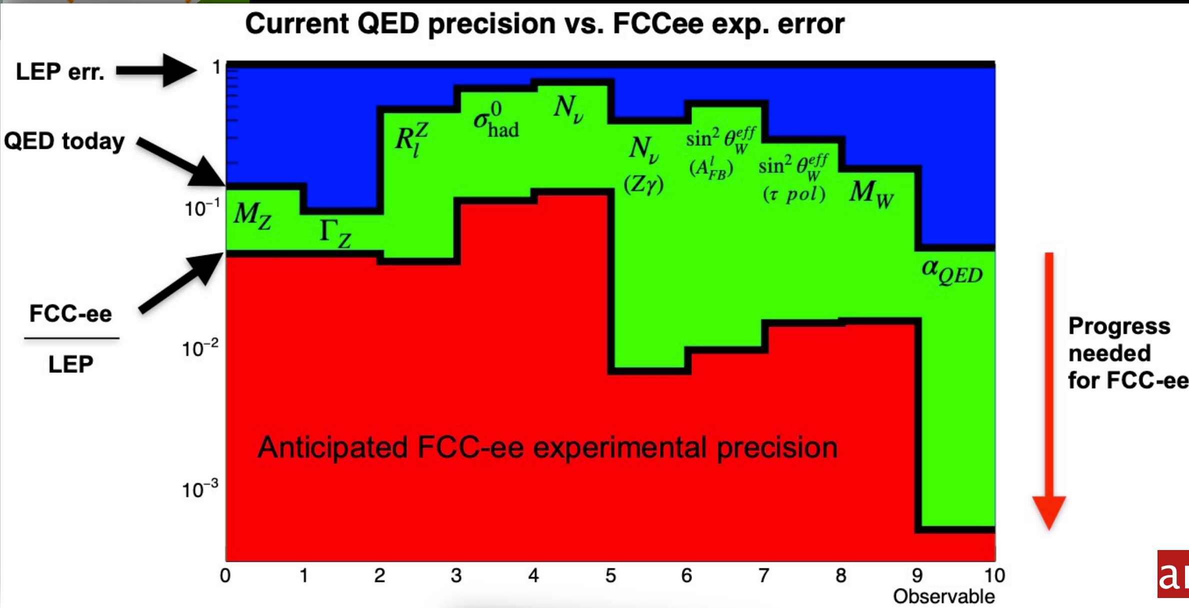
In the following I shall try to define specification of the MC(s),
which would match TeraZ experimental precision, hence we assume temporarily
that it will be just single ultimate MC for TeraZ, **TeraMC** in short.

Specification of TeraMC will be determined going
observable-wise as much as subprocess-wise.

At least in the initial phase, one will probably start with the upgrade
of KKMC, BHWIDE and BHLUMI but most likely later on
a completely new code, or better two, will have to be developed.



QED is the biggest numerically



The present precision of QED theoretical predictions would severely limit the analysis of precise measurements at FCC-ee.

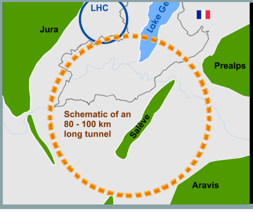
To properly confront the data with theoretical predictions of similar accuracy demands a huge progress in precision calculations!

Needed factor 6-200 improvement with respect to LEP.

arXiv:1903.09895 (Jadach&Skrzypek)

EW pseudo-observables EWPOs

Observable EWPO	Source LEP	Err.{QED} LEP	Stat[Syst] FCC-ee	LEP / FCC-ee	main development to be done
M_Z [MeV]	Z linesh.	2.1{0.3}	0.005[0.1]	$3\times3^{\star}$	light fermion pairs
Γ_Z [MeV]	Z linesh.	2.1{0.2}	0.008[0.1]	$2\times3^{\star}$	fermion pairs
σ^0_{had} [pb]	σ^0_{had}	37{25}	0.1[4.0]	$6\times3^{\star}$	better lumi MC
$R_l^Z\times10^3$	$\sigma(M_Z)$	25{12}	0.06[1.0]	$12\times3^{\star\star}$	better FSR
$N_\nu\times10^3$	$\sigma(M_Z)$	8{6}	0.005[1.0]	$6\times3^{\star\star}$	CEEX in lumi MC
$N_\nu\times10^3$	$Z\gamma$	150{60}	0.8[< 1]	$60\times3^{\star\star}$	$\mathcal{O}(\alpha^2)$ for $Z\gamma$
$\sin^2\theta_W^{eff}\times10^5$	$A_{FB}^{lept.}$	53{28}	0.3[0.5]	$55\times3^{\star\star}$	h.o. and EWPOs
$\sin^2\theta_W^{eff}\times10^5$	$\langle\mathcal{P}_\tau\rangle$,$A_{FB}^{pol,\tau}$	41{12}	0.6[< 0.6]	$20\times3^{\star\star}$	better τ decay MC
M_W [MeV]	mass rec.	33{6}	0.3[?.?]	$20\times3^{\star\star}$	$\mathcal{O}(\alpha)$, FSR_{exp}
M_W [MeV]	threshold	200{30}	0.5[0.3]	$100\times3^{\star\star\star}$	$\mathcal{O}(\alpha^2)$ at thresh.
$A_{FB,\mu}^{M_Z\pm3.5\mathrm{GeV}}\times10^5$	$\frac{d\sigma}{d\cos\theta}$	2000{100}	1.0[0.3]	$100\times3^{\star\star\star}$	improved IFI



QED ME for TeraMC

Precision of QED calculations is advancing
neither order-by-order (rows) nor LO-NLO-NNLO (columns) but somehow in between.

How to follow this trend in the MC matrix element?

How to combine that with genuine EW corrections which are going rather order-by-order?

Eur. Phys. J. C (2019) 79:756 — Page 3 of 24 — 756

Fig. 1 The parameter γ_{nr} of Eq. (2.1) characterizing the size of the QED corrections

Single mass logs $L = 2\frac{\alpha}{\pi}\ln\frac{s}{m_e^2}$ are shown, while double Sudakov logs are resumed to infinite order.

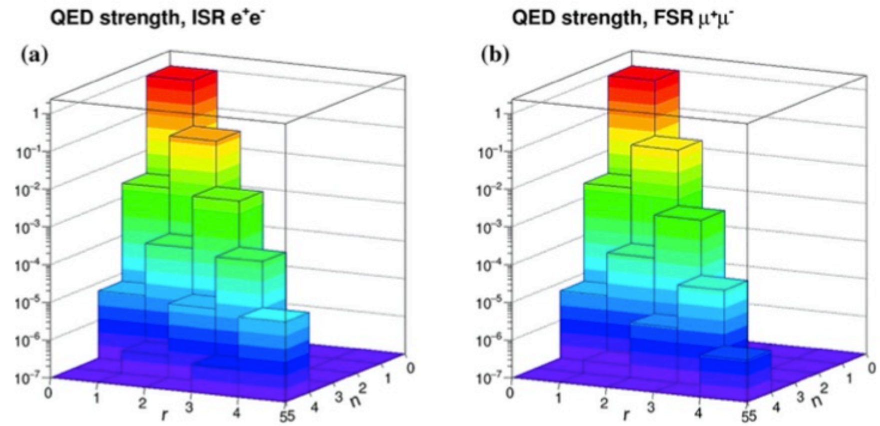


Fig. 2 QED perturbative leading and subleading corrections. Rows represent corrections in consecutive perturbative orders – the first row is the Born contribution. The first column represents the leading logarithmic (LO) approximation and the second column depicts the next-to-leading (NLO) approximation. In the figure, terms selected for the same precision level are limited with the help of an additional line

(a) 0.6% PETRA/PEP early LEP

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
⋮	⋮	⋮		

(b) 0.03% LEP KKMC

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
⋮	⋮	⋮		

EEX only — CEEX

(c) 0.001% FCC-ee

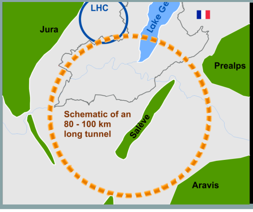
1				
αL	α			
α^2L^2	α^2L	α^2		
α^3L^3	α^3L^2	α^3L	α^3	
α^4L^4	α^4L^3	α^4L^2	α^4L^1	α^4
α^5L^5	⋮	⋮	⋮	

arXiv:1903.09895

Z.Phys. C56 (1992) 285
M. Jezabek
(inclusive)

arXiv:1911.12040,
arXiv:1909.03886,
S. Frixione et.al.
(inclusive)

arXiv:1911.05029
Blumlein & DeFreitas
(inclusive)



Types of QED matrix element 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, SHERPA?

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

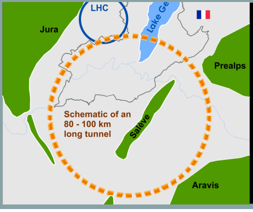
Examples:
YFS2, YFS3 in KORALZ
YFS3WW, BHWIDE

CEEX

Best suited for TeraMC

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



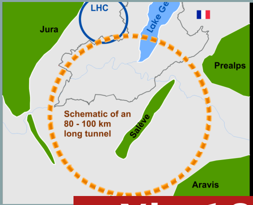
TeraMC as a precision calculation tool including h.o. EW corrections

- KKMC with CEEX $\mathcal{O}(\alpha^2)$ QED matrix element and $\mathcal{O}(\alpha^1)$ EW corrections can be treated as a prototype of **TeraMC**
- As shown on next slide KKMC was already used for high precision 0.001% studies on the FCCee physics, using routinely 10^{10} event samples.
- Event generation takes 50-100 hours on the 100-processor farm (no hadronization)

- A notorious problem with the use of MC as a precision calculation tool is that changing input parameters may require new MC run, which takes long CPU time.
- This could be the problem preventing us of the TeraMC in the construction/extraction of EW pseudo-observables from FCCee data

- The solution is however well known: TeraMC must be armed with the functionality of recalculating its M.E. due to changed value of the input parameters.
- Using the above capability and the technique of MC weight differences, one could corrects results of long CPU time run with very short time additional run, simply because input parameter variation will be permille level.

- The above goes well with the ongoing effort of parametrising/interpolating multi-loop EW corrections in terms of input parameters and kinematical variables, because they also are very costly in terms of CPU time!



Recent high precision FCCee-related studies using KKMC

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

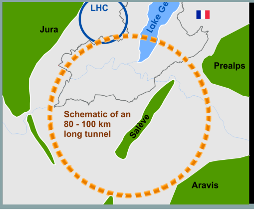
arXiv:1912.02067

Improved Bhabha cross section at LEP and the number of light neutrino species

Patrick Janot, Stanisław Jadach

(Submitted on 4 Dec 2019)

In e^+e^- collisions, the integrated luminosity is generally measured from the rate of low-angle Bhabha interactions $e^+e^- \to e^+e^-$. In the published LEP results, the inferred theoretical uncertainty of $\pm 0.061\%$ on the predicted rate is significantly larger than the reported experimental uncertainties. We present an updated and more accurate prediction of the Bhabha cross section in this letter, which is found to reduce the Bhabha cross section by about 0.064%, and its uncertainty to $\pm 0.037\%$. When accounted for, these changes modify the number of light neutrino species (and its accuracy), as determined from the LEP measurement of the hadronic cross section at the Z peak.



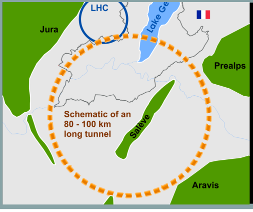
Selected issues on TeraMC

- TeraMC as a precision calculation tool including h.o. EW corrections

- Separating and/or recombining non-soft pure EW correction and QED resummed soft part, at any perturbative order

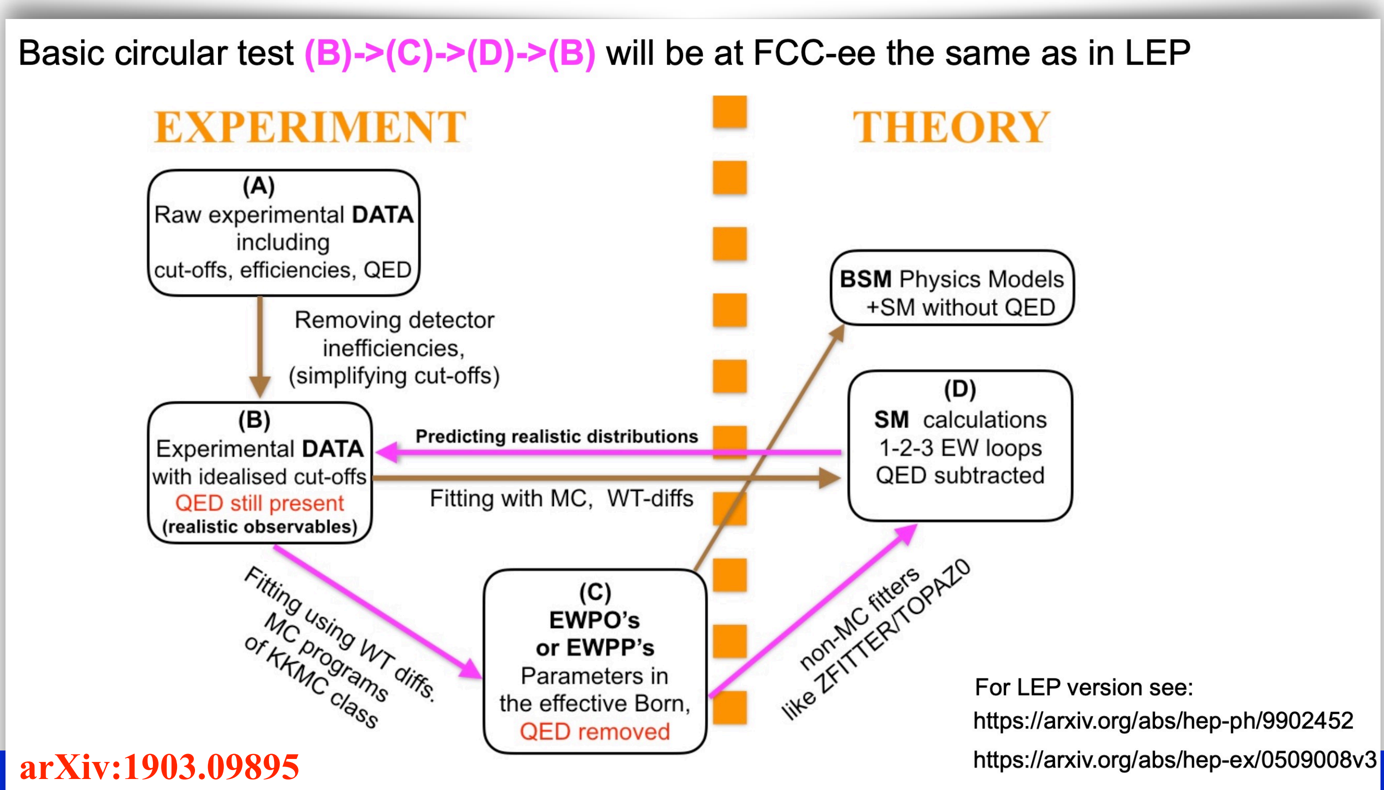
- New bigger role of MC in defining and constructing of EWPOs (EWPPs)

- Requirements for **TeraMC** matrix element specific for certain TeraZ observables

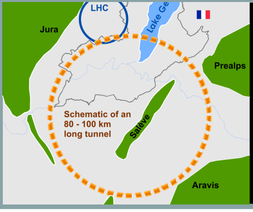


New bigger role of TeraMC in defining/constructing EWPOs

- It was pointed out on many occasions that the scheme of Electroweak Pseudo-Observables (EWPOs) successfully used to encapsulate LEP data extracted from cross sections and asymmetries near Z resonance may not survive at the two order higher higher experimental precision at FCC-ee TeraZ experiments.
- In **arXiv:1903.09895** Eur.Phys.J. C79 (2019) 756 and **arXiv:1905.05078** a possible generalisation of the LEP scheme was proposed in which bigger role would be played by the MC (TeraMC) in removing QED effects and parametrising data.
- One could also keep in mind that at the extremely high precision of FCCee it will be necessary to remove from data not only QED effects but also the $\mathcal{O}(\alpha^1)$ EW corrections, or their well defined leading part.



Main difference with LEP is Monte Carlo use in steps (B)->(C) and (B)->(D) instead of progs like ZFITTER/TOPAZ0



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-resumed to infinite and non-soft QED typically up to $\mathcal{O}(\alpha^2)$, while EW corrections up to $\mathcal{O}(\alpha^1)$.

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

- Is there any systematic and practical scheme of calculating the two classes of 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.
  Monte Carlo implementation is the key part of this methodology!

- Next slide offers a little bit insight into this methodology.

- Important: Never everuse Bloch-Nordsieck method of killing IR singularities in the EW+QED multi-loop integrals!
  Simply because MC with resummations already did that!

CEEX QED+EW matrix element for TeraMC

In the CEEX *factorization scheme*, the cross-section for the process

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

with complete perturbative corrections up to $\mathcal{O}(\alpha^r)$ and soft photon resummation reads as follows:

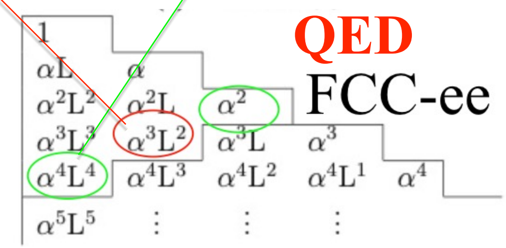
$$\sigma^{(r)} = \sum_{n=0}^{\infty} \frac{1}{n!} \int d\tau_n(p_1 + p_2;\ p_3, p_4,\ k_1, \ldots, k_n)\ e^{2\alpha \Re B_4(p_a,\ldots,p_d)} \frac{1}{4} \sum_{\text{spin}} \left| \mathfrak{M}_n^{(r)}(p, k_1, k_2, \ldots k_n) \right|^2, \quad \text{(C.120)}$$

where the virtual form factor B_4 is factorized (exponentiated) and real emission factors $\mathfrak{s}$ are also factorized out:[6]

KKMC/CEEX ⟵

$$\mathfrak{M}_n^{(r)}(p, k_1, k_2, k_3, \ldots, k_n) = \prod_{s=1}^{n} \mathfrak{s}(k_s) \left\{ \hat{\beta}_0^{(r)}(p) + \sum_{j=1}^{n} \frac{\hat{\beta}_1^{(r)}(p, k_j)}{\mathfrak{s}(k_j)} + \sum_{j_1<j_2} \frac{\hat{\beta}_2^{(r)}(p, k_{j_1}, k_{j_2})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})} + \sum_{j_1<j_2<j_3} \frac{\beta_3^{(r)}(k_{j_1}, k_{j_2}, k_{j_3})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})\mathfrak{s}(k_{j_3})} + \sum_{j_1<j_2<\ldots<j_r} \frac{\beta_r^{(r)}(k_{j_1}, k_{j_2}, \ldots, k_{j_r})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})\ldots\mathfrak{s}(k_{j_r})} + \ldots \right\} \quad \text{(C.121)}$$

$\mathcal{O}(\alpha^3)$ $\mathcal{O}(\alpha^r)$



QED
FCC-ee

such that the subtracted amplitudes $\hat{\beta}_j^{(r)}$ are IR-finite. Resummation, that is spin summing or averaging of the squared amplitudes and the phase space integration $\int d\tau_n$, is performed numerically in a separate Monte Carlo module of the KKMC, independent from the other part of the KKMC where spin amplitudes $\mathfrak{M}_n^{(r)}(p, k_1, k_2, k_3, \ldots, k_n)$ are constructed and evaluated. The S-matrix methodology of Eqs. (C.111)–(C.116) is relevant for the $2 \to 2$ Born-like object $\hat{\beta}_0^{(r)}$. In the $\mathcal{O}(\alpha^2)$ $(r = 2)$ implementation of KKMC, this object reads:

$$\hat{\beta}_0^{(2)}(p) = \mathfrak{M}_0^{(2)}(p) = \left[e^{-\alpha B_4(p)} \mathcal{M}_0^{(2)}(p) \right] \Big|_{\mathcal{O}(\alpha^2)}, \quad \text{(C.122)}$$

where $\mathcal{M}_0^{(2)}(p)$ represents Born spin amplitudes corrected up to two loops, derived directly from Feynman diagrams. In practice, the non-soft parts of the QED corrections are complete in $\hat{\beta}_0^{(2)}(p)$ up to two loops, while the EW corrections are taken from DIZET 6.21 [32] (i.e., they are at 1+1/2 loops), exactly according to the prescription shown in Eq. (C.124); see also Eqs. (21)–(24) in Ref. [34]. This implementation of the EW corrections in KKMC can easily be modified to be compatible with the S-matrix approach, following the prescription of Eqs. (C.125)–(C.129)).

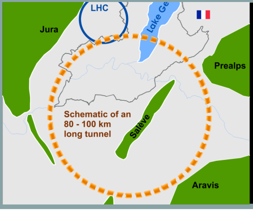
$\mathcal{O}(\alpha^2)$ 2-loop and 1-loop **EW** cor.

Concerning the EW corrections to the $2 \to 3$ process, they would enter into

$$\hat{\beta}_1^{(2)}(p, k_1) = \mathfrak{M}_1^{(2)}(p, k_1) - \hat{\beta}_0^{(1)}(p)\mathfrak{s}(p, k_1), \qquad \mathfrak{M}_1^{(2)}(p, k_1) = \left[e^{-\alpha B_4(p)} \mathcal{M}_1^{(2)}(p, k_1) \right] \Big|_{\mathcal{O}(\alpha^2)}. \quad \text{(C.123)}$$

IMPORTANT! The existing EW $\mathcal{O}(\alpha^2)$ calculations for $e^+e^- \to f\bar{f}$ are only for *inclusive* quantities. Special effort needed for realistic exclusive distributions and MC.

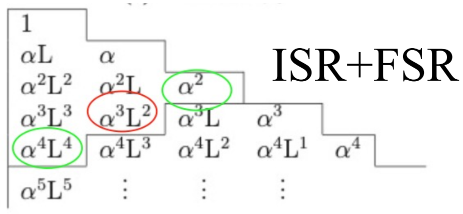
In the KKMC implementation, one-loop complete QED corrections are included in $\hat{\beta}_1^{(2)}$, mandatory for the completeness of the $\mathcal{O}(\alpha^2)$ QED,[7] neglecting the one-loop EW part. For the future FCC-ee applications, it will also be necessary to include one-loop (five-point) EW corrections, see the discussion in Subsection C.2.8. However, it should be stressed that, in order to be useful in the CEEX scheme, they will have to be properly subtracted at the amplitude level, instead of combined with real emission for the differential cross-sections à la Bloch–Nordsieck.



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

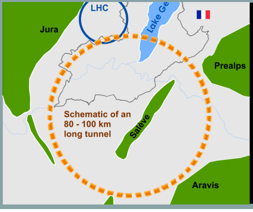
- ✦ Upon removal of QED effects, hadronic $\sigma_h^0 = \sigma_h(M_Z)$ will serve as an input for neutrino counting (invisible Z width) and for very precise $\alpha_S(M_Z)$ determination from $R_l = \sigma_h^0/\sigma_l^0$
- ✦ For $\sigma_h(s)$ acceptance rate is almost 100%, cut-off dependent acceptance 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….

- O 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).
- O 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.



Specification of TeraMC for Charge asymmetry $A^{\mu}_{FB} \to \sin^2\theta^{eff}_W,\ \alpha_{QED}(M_Z)$

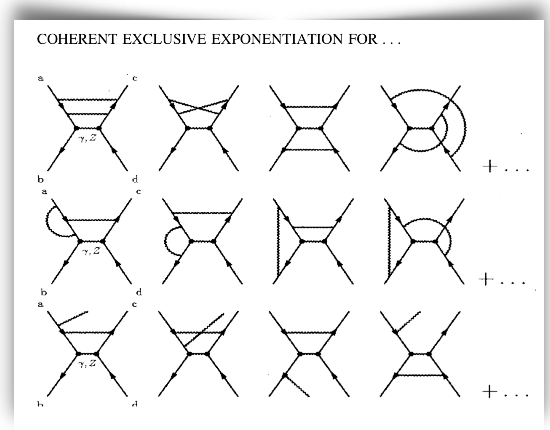
- Muon charge asymmetry at TeraZ with $\delta A^{\mu}_{FB}(M_Z) \simeq 10^{-5}$ will provide $\delta \sin^2\theta^{eff}_W \simeq 0.5 \cdot 10^{-5}$ and $\Delta A^{\mu}_{FB} = A^{\mu}_{FB}(M_Z + 3.5\text{GeV}) - A^{\mu}_{FB}(M_Z - 3.5\text{GeV})$, will hopefully provide $\delta\alpha_{QED}(M_Z) \simeq 10^{-5}$. See arXiv:1903.09895.

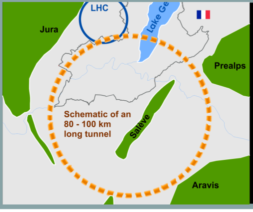
- IFI contribution $A^{\mu,IFI}_{FB}(M_Z) \simeq 50 \cdot 10^{-5}$ was negligible at LEP. Here 2-digits precision required!

- However, in arXiv:1801.08611 (SJ&S.Yost), thanks to power of CEEX/KKMC soft photon resummation (with Frascati improvements) much bigger IFI contribution $[\Delta A^{\mu}_{FB}]_{IFI} \simeq 1\,\%$ was shown to be controlled at the $\sim 10 \cdot 10^{-5}$ level!

- It looks that another factor 10 improvement in IFI requires inclusion of missing non-soft contributions from $\mathcal{O}(\alpha^2)$ penta-box diagrams. Can German Rodrigo provide us with that?

- For extraction of $\sin^2\theta^{eff}_W$ with $0.5 \cdot 10^{-5}$ precision, the inclusion of the remaining $\mathcal{O}(\alpha^2)$ EW corrections and of QED beyond $\mathcal{O}(\alpha^2)$ may also be necessary (because of experimental cut-offs dependence!).





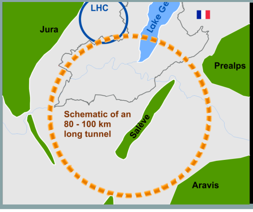
Specification of TeraMC for Neutrino counting

- Invisible Z decay rate parametrised in terms of N_ν can be deduced from:
  (I) peak hadronic σ_h^0,
  (II) radiative return absolute $\sigma(e^+e^- \to X\gamma)$,
  (III) ratio $\sigma(X\gamma)/\sigma(\mu^+\mu^-\gamma)$.
- All three methods rely strongly on comparison of data with MC.

- For (I) present result based on LEP data is N_ν =2.9975±0.0074,
  [arXiv:1912.02067, Janot&Jadach]
  and depends heavily on the MC for luminosity using low angle Bhabha. See next slides.

- According to [arXiv:1903.09895, Jadach&Skrzypek],
  at FCCee experiments all three methods will yield $\delta N_\nu \simeq 0.001$.

- **TeraMC** to be used effectively for (I) and (II) at $\sqrt{s} = 125,\ 161\mathrm{GeV}$ (parasitic to H and WW),
  provided its matrix element is upgraded to $\mathcal{O}(\alpha^2)$ for EW corrections
  and well beyond $\mathcal{O}(\alpha^2)$ for the QED part.
  This is because of the effective loss of one perturbative order for $f\bar{f}\gamma$ final state.



Specification of TeraMC for small and large angle Bhabha process

- Small angle Bhabha data were analysed using BHLUMI and large angle Bhabha data using BHWIDE.

The Path to 0.01% Theoretical Luminosity Precision for the FCC-ee

S. Jadach, W. Płaczek, M. Skrzypek, B.F.L. Ward, S.A. Yost

arXiv:1812.01004

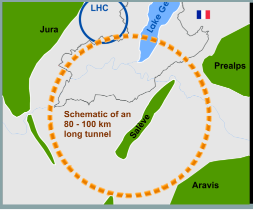
(Submitted on 3 Dec 2018)

The current status of the theoretical precision for the Bhabha luminometry is critically reviewed and pathways are outlined to the requirement targeted by the FCC-ee precision studies. Various components of the pertinent error budget are discussed in detail -- starting from the context of the LEP experiments, through their current updates, up to prospects of their improvements for the sake of the FCC-ee. It is argued that with an appropriate upgrade of the Monte Carlo event generator BHLUMI and/or other similar MC programs calculating QED effects in the low angle Bhabha process, the total theoretical error of 0.01% for the FCC-ee luminometry can be reached. A new study of the Z and s-channel γ exchanges within the angular range of the FCC-ee luminometer using the BHWIDE Monte Carlo was instrumental in obtaining the above result. Possible ways of BHLUMI upgrade are also discussed.

- In ref. arXiv:1812.01004 upgrade of BHLUMI with $\mathcal{O}(\alpha^2)$ CEEX matrix element for FCCee was outlined.
  It would help to reduce theory uncertainty of luminosity measurement form present 0.037% below FCCee experimental precision $\simeq 0.010\,\%$. (Talk of Bennie Ward).

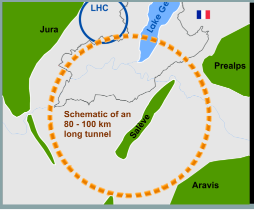
- However, due to twice wider angular range of FCC luminometer than at LEP and bigger contribution of Z_s and γ_t, it makes probably sense to implement within a single **TeraMC** both sub-processes together.

- Nevertheless, upgrade of BHLUMI and/or BHWIDE makes sense as an intermediate step.



Innovation fronts

- 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 problem 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 there but implementation nontrivial.
- Subtraction of IR part from (gauge invariant) sets of multi-loop diagrams at the loop integrand level (can German Rodrigo do it?)
- Fitting EWPOs to data using high statistics “MC templates”, wight differences, machine learning etc.
- Effective methods of parametrising virtual (loop) correction to be used in the matrix element in the MC generators.

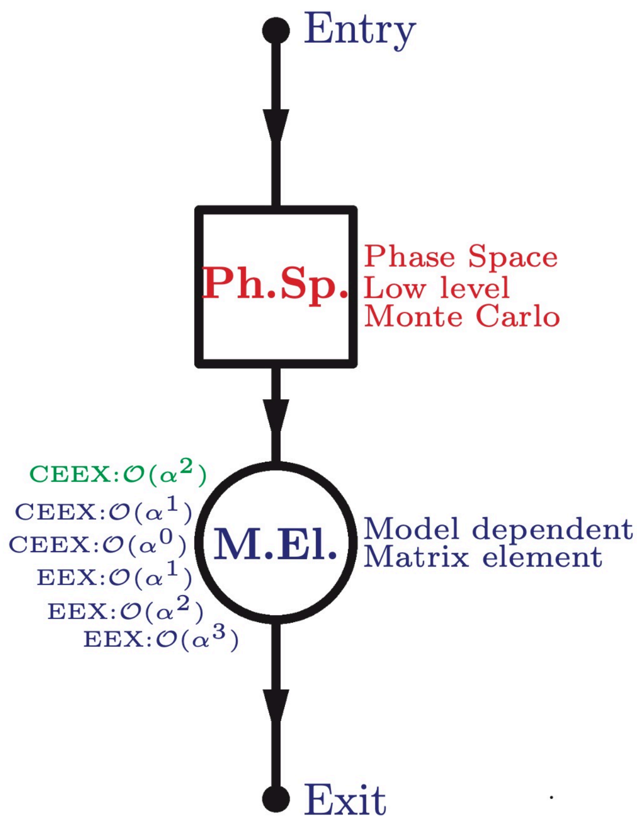


Strategy issues

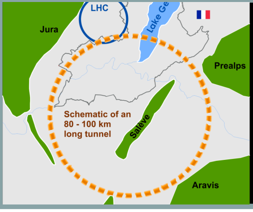
- One should avoid "monopoly" of a single MC for a given process/observable.
  The best would be (at least) two MCs of similar high quality developed *independently* by two groups of authors.
  Example of duo-poly:) YFSWW3 + RACOONWW,
  Examples of monopoly:(KKMC, BHLUMI, BHWIDE
- Upgrade of LEP legacy MCs is 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 single or small subset of observables/processes is *optimal* approach.
- LEP experience shows that developing 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.

Example of Matrix Element organisation in KKMC

Textbook principle "matrix element × full phase space" for technical and physics uncertainties

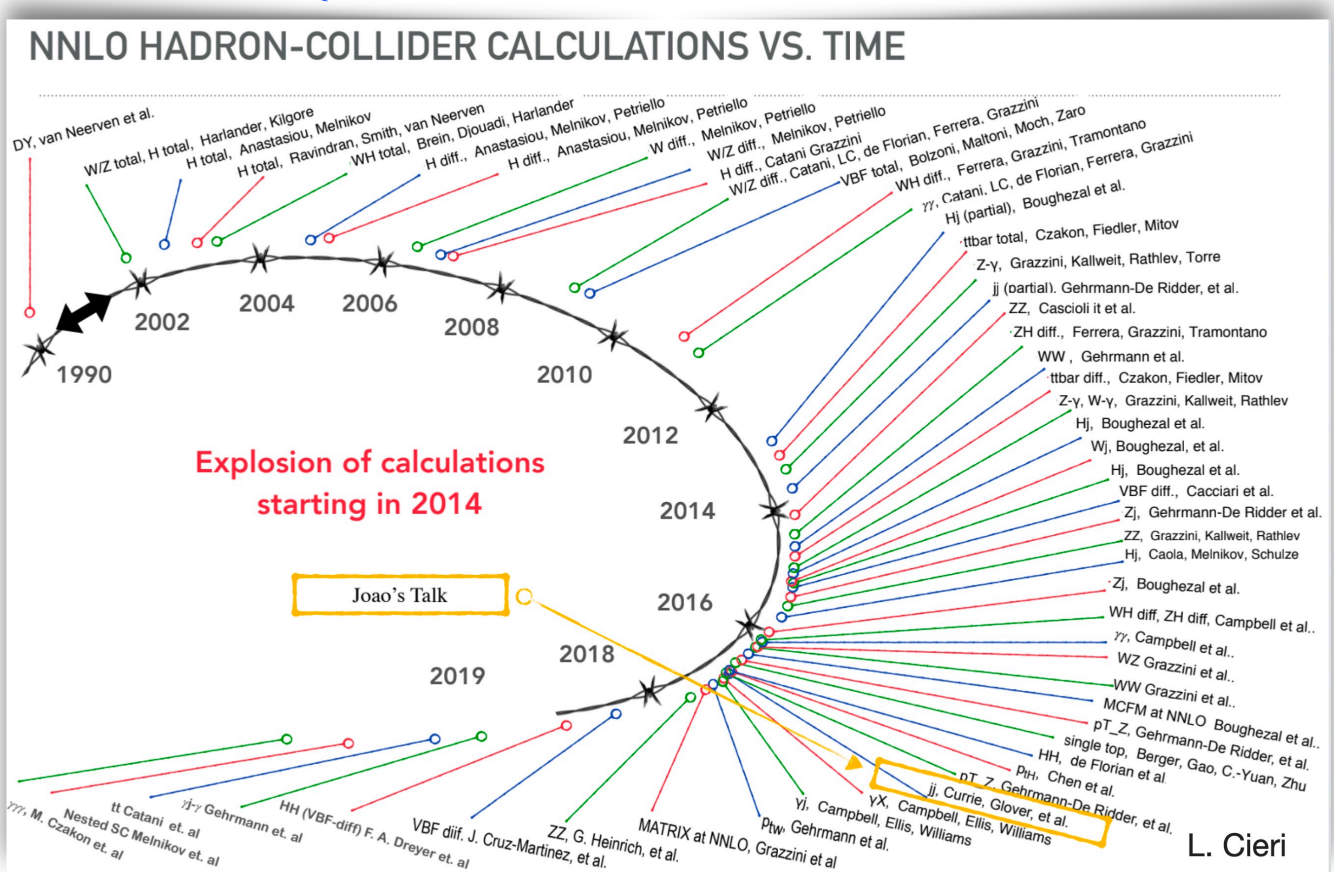


- Phase-space Monte Carlo simulator is a module producing "raw events" (including importance sampling for possible intermediate resonances/singularities)
- Library of Matrix Elements; input for "model weight"; independent module
- "model weight"-s may differ by implemented variant of electroweak form-factors (see later).
- Correlated samples techniques. Variants used for the difference semi-analytical vs. Monte Carlo simulation. Beware: relation of crude level phase-space and semianalytical integration variables, Phys. Rev. D41 (1990) 1425.
- **Useful for fit arrangements!**

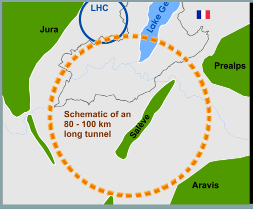


Strategy issues

- LHC has seen **huge progress** in QCD perturbative calculations and in the QCD parton shower MC development.
- Can one profit from that for the QED+EW calculations and MCs ???



- So far it has happened only in a very limited way.



Summary

- **LEP era has seen development of the precision MC event generators tailored for just one scattering process.**

- **Much better MC generators for precision physics at FCCee will have to be developed in the future**

- **Legacy MCs will help, but at the precision two orders higher, developing new much better innovative projects is mandatory.**

Many thanks to my usual collaborators M. Skrzypek, Z. Wąs, Bennie Ward, W. Płaczek for discussions, help and encouragement!!!

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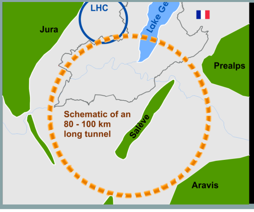
*This work is partly supported by the Polish National Science Center grant 2016/23/B/ST2/03927 and the CERN FCC Design Study Programme.


LHC
Jura
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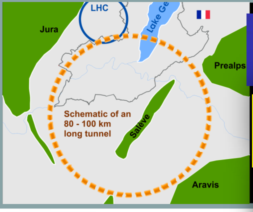
Schematic of an
80 - 100 km
long tunnel
Aravis

Reserve



More KKMC versions available since 2000

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

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) tested/run under Centos7 and Ubuntu16

What is KKMC?

KKMC is the MC event generator for the process:

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

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

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.

(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

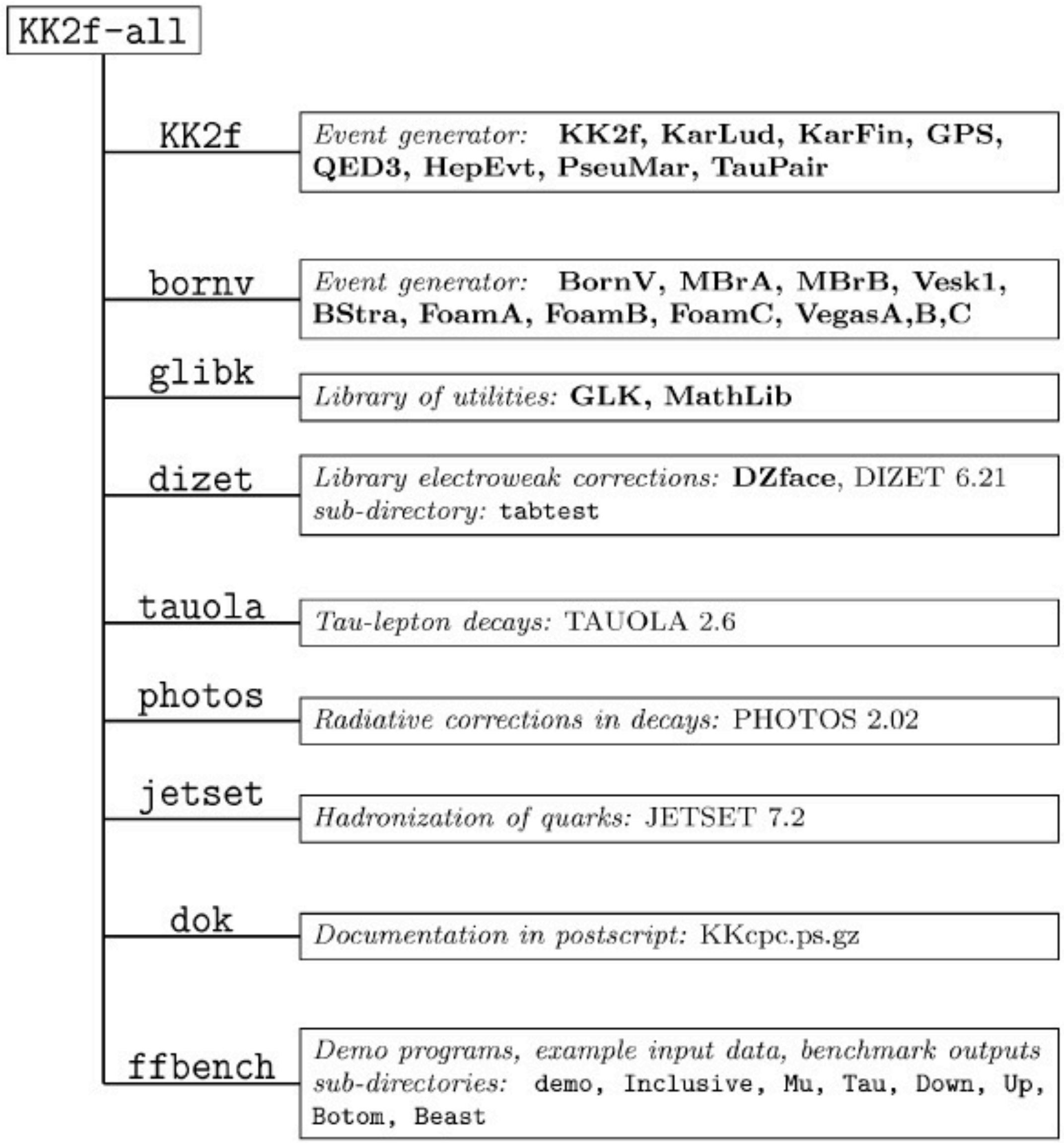
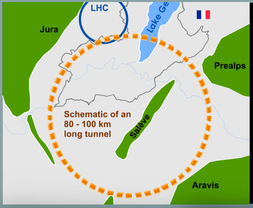


Fig. 1. Topography of the distribution directory.



TAUOLA is an important part of KKMC

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

Search
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CommonTools
FccGenerators
- Bhabha
- Higgsline
- Kkmc
- Tauola

FCC web page
FCC-ee (TLEP) web page
FCC-hh (FHC) old twiki
FCC-eh (LHeC) web page

Web Left Bar

TWiki > FCC Web > CommonTools > FccGenerators (2017-05-03, MarcinChrzaszcz)

Edit Attach PDF

Welcome to LEP/TLEP/FCCee repository of the MC generators

Low Angle Bhabha BHLUMI (by S.Jadach, W.Placzek, E.Richter-Was, B.F.L.Ward and Z.Was)

source code, documentation, talks

Fermion pair production: KKMC (by S.Jadach, et. al)

source code, documentation, talks

Tau lepton decays: TAUOLA (by M.Chrzaszcz, T. Przedzinski, Z. Was, J. Zaremba)

source code, documentation, talks

TAUOLA source code:

* Source code of TAUOLA for FCCee TAUOLA-FORTRAN-03-05-2017.tar.gz

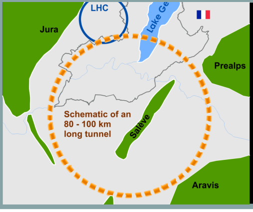
Documentation (papers):

- https://arxiv.org/abs/1609.04617

PHOTOS is inside

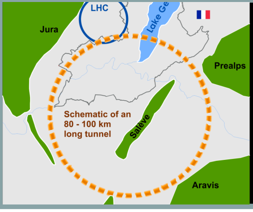
Attachments

I	Attachment	History	Action	Size	Date	Who
	TAUOLA-FORTRAN-03-05-2017.tar.gz	r1	manage	9914.1 K	2017-05-03 - 23:09	MarcinChrzaszcz



Ongoing developments in KKMC

- Provisions for recalculating matrix element with modified EW parameters like $\alpha_{QED}(M_Z)$ for example. (For fitting SM parameters using MC.) Soon.
- Upgrade of DIZET electroweak library, hadronic VP routine, more steering parameters for manipulating EW corrections. Soon.
- Upgrade of TAUOLA library. To early?
- Cleanup and posting on the web next improved version, also with enriched C++ interface. Soon?



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

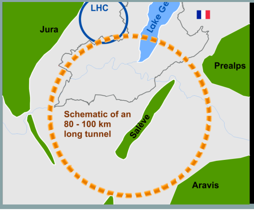
Documentation (papers):

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

Talks on low angle Bhabha and BHLUMI are HERE

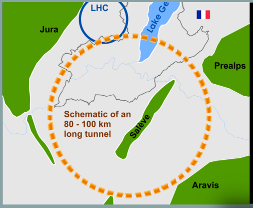
▶ **Attachments**

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



BHLUMI Monte Carlo
Ongoing development

- Adding two more routines, with more precise recent calculations of the hadronic vacuum polarisation.
- Upper level (main program and analysis) in C++,
  similarly as in KKMC with wrappers, ROOT histogramming etc.
- Programming event selection as in FCCee lumi detector.
- Preparing baseline for implementing new ***second order*** QED matrix element in the CEEX style in C++.
- NB. there are several versions of BHLUMI with beamstrahlung developed by within the ILC community.



Monte Carlos for WW production

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

Homepage of **Wieslaw Placzek**

CERN, TH-Division
CH-1211 Geneva 23
Switzerland
tel. (+41) (22) (76) 74146
E-mail: Wieslaw.Placzek@uj.edu.pl.

Home Institute:
Department of Applied Computing Methods
Marian Smoluchowski Institute of Physics
Jagiellonian University
ul. Lojasiewicza 11, 30-348 Krakow
POLAND

Monte Carlo programs:

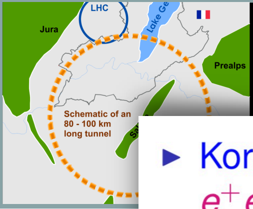
- **LESKO-E & FRANEQ**: For Deep Inelastic Neutral Current Scattering at HERA (not updated since January 1993).
- **BHWIDE**: For Large-Angle Bhabha Scattering.
- **KoralW**: For 4-Fermion Production in Electron-Positron Collisions.
- **YFSWW**: For W-Pair Production and Decay in Electron-Positron Collisions.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



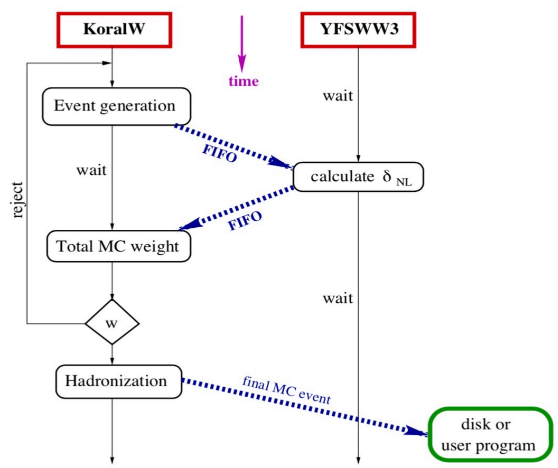
Monte Carlos for WW production

- KoralW Monte Carlo contains complete process $e^+e^- \rightarrow 4fermions$ at the Born level. Radiation: multiphoton ISR YFS-type
- YFSWW3 Monte Carlo generates signal process $e^+e^- \rightarrow W^+W^- \rightarrow 4fermions$ with up to $\mathcal{O}(\alpha)$ electroweak corrs. in production of W^+W^-. It includes multiphotonic radiation from the production part in the YFS framework.
- KandY = KoralW⊕YFSWW3 combined 4-fermion and $\mathcal{O}(\alpha)$ WW
- KandY: is precision 0.02% at FCCee feasible ????

Merge of KoralW and YFSWW3 = KandY

Possible because the underlying photonic distribution is the same YFS-ISR in both codes. All other photonic effects are included as weights. So are the $\mathcal{O}(\alpha)$ EW corrs.

Concurent realization of $\sigma_{K/Y}$ with "named pipes"



Works effectively as a single MC event generator