

Associated projects to precision Monte Carlo projects

as seen from mine 43 years long perspective

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(A) I need to cover more than these 43 years. Stanislaw's achievements before 1981 were essential for that, and his projects will continue. Also monumental projects of Bryan Lynn, Robin Stuart, Dima Bardin, Wolfgang Hollik ... **Challenging call for me!**

(B) **Incomplete lists of** methodology domains, and projects:

1. (i) Phase space: symmetries (ii) matrix element preparation → factorizations (iii) program and development process design (iv) testing strategies (v) user interaction (vi) software tools (vii) partners and competitors
2. (i) FOWL (ii) GENRAP (iii) Mustraal (iv) Koralb (v) Lesko (vi) Tauola (vii) KoralZ, (viii) Lumlog (ix) Oldbab (x) Bh lumi (xi) Bhwide (xii) KKMC
3. Focus is on some of these points. Other, hopefully, will/were covered in other talks.

(C) No need to cover exponentiation, see yesterday B.F.L. Ward W. Placzek talks.

- (D) Developments took years → inevitable simplifications, biases in my talk, ... **apology**.

Main goals

- We want to confront measurements with field theory predictions.
- Agreements mean precision tests of theory and/or measurements of coupling constants masses etc. Disagreement point to NEW PHYSICS
- What is needed to perform such program in case of accelerator measurements? Especially in cases when precision is essential?
- I need to adress life effort of several people and only as starting point, because I want to point direction for the future work.
- Too many aspects too little time....

- Experiments (even pp) measure best directions of muons, then of electrons, then energies of muons, later of electrons. Jets are measured less precisely.
- From experimental side, one needs to adopt, acceptance details, often irregular and direction dependence. Detectors consist of rectangular (nearly rectangular) cells forming lattice or better say kind of 3 dimensional web. In this web there are dead zones (because of cables). Detector response in barrel and forward regions differ somewhat.
- Sometimes, parts of detectors are faulty, and this makes even more irregular shapes of acceptance domain.
- That, as we have seen in the past, does not bring big complications if precision requirements are not very high.
- Above essential preconditions , define what is needed.
- What one can learn from the the past.

- I will not cover details of the projects. Typically each one is involving many man-year efforts. Fortunately some of them are covered elsewhere.
- I will rely on achievements and LEP era observations, where in some cases precision better than 0.1 % in comparison of data with theory predictions was achieved. I will underline importance of efforts not directly for the program final projects but developed independently. However, more than often they needed adaptation and, often painful and complicated, interactions with users.
- Hopefully that experience will be useful for work on the future 0.01% precision regime of experiments such as at FCC. Precision at least one order of magnitude better than that at LEP.
- Precision predictions require managing **conflicting requirements**.
Most important are those from experiments, because they involve massive human and financial efforts. That is why, I have mentioned that at the start. Can phenomenology work ease in these burdens? Break no go limitations?
- But for high precision or for rare processes where background tails play important role, nothing is easy....

- Theoretical calculations, because of ultraviolet infinities, tend/must be organized around renormalization schemes. That is understandable, that is the way how to deal. That implies that usually mass corrections (thus phase-space details too) are added later, sometimes at lower perturbation level.
- What does it mean, what challenges and what solutions.
- Having theory and experimental things in one program is a target.
- However fitting functions (analytic or semi-analytic) with idealized acceptance, are essential, even now in ML world.
- Also intermediate detail level tools are helpful and I was advocating such solutions at the time.
- **Advantage:** For simplified acceptance with dressed leptons etc. mass corrections are less important and in general, higher order results are easier to get and incorporate
- **Disadvantage:** detector acceptance details have to be calculated/simulated separately.

- We have used such incomplete phase space solutions and it worked down to 0.5 % precision level well.
- First order simulations combined with correlated leading logs simulations of collinear photons OLDBAB+LUMLOG
- But finally at 0.3 % 0.1% 0.043% levels they gave way to more refined tools (but remained as essential tests Phys.Lett.B 253 (1991) 469):
- Simulations with all details of phase space and higher order induced kinematical configurations included, on one side, fitting functions on other.
- Simulation had to take care of configurations with explicit 3 bremsstrahlung photons even at LEP, for FCC this will be probably 5 photons.
- Such configurations are essential to understand effects due to detector cell structure, but their inclusion complicates installation of other theory effects. That points to important work domain.
- But at somewhat lower precision simplified phase space tools remain useful.

- **KandY** hep-ph/0104049: correlated simulations of 4-fermion final states with initial state exponentiation KORALW all tree diagrams, YFSWW for initial and final state radiation only double resonant diagrams for hard interaction.
- An idea: $(1 + A + B)^2 \rightarrow (1 + A)^2 + (1 + B)^2 - 1$ define A and B well
A- effects of all tree-level diagrams with respect to double resonant ones (initial state exclusive exponentiation of QED only)
B- effects of exclusive exponentiation for initial and final state QED effects but for hard interaction of double resonant diagrams only.
- That is essential step of work on Monte Carlos, and in many cases enough, even if it brings massive difficulties for the experimental users.
- **For future.** Necessary step for new processes like for 4 fermion, 6 fermion (or jets) final states (WW, ZZ ZH intermediate states). Solutions will be working at 0.5% level and will open gate to new applications as benchmarks.
- No compromise on phase space details. KandY was a step forward with respect to solutions like OLDBAB+LUMLOG, earlier Mustraal+YFS2.

- But let's look at 2 fermion production like $e^+e^- \rightarrow l\bar{l}$ or Bhabha scattering where high precision was achieved:
- Separation of SM into QED and hard interaction corrections: genuine weak, vacuum polarization, some strong interaction also New Physics. **First!**
- Eikonal parts of amplitudes $\beta_0 \times \int \dots$ plus corrections β_1, β_2 available perturbatively. YFS way of reordering of QED perturbation expansion. At the zeroth order kinematical configurations with arbitrary large number of photons and all over the phase space.
- Gauge invariant sectors: initial state - final state interference (or for Bhabha upper line, lower line and interference).
- Interference (real and virtual can be added at later steps by re-weighting (with bounded from above weights)) For interference also $\beta_0, \beta_1, \beta_2$
- Now to the bottom of generation foundations.

- Part of QED consisting of eikonal parts for initial and final state interaction can be solved to all orders and results represented as **functional** exponent. That means algorithm for complete phase space (number of photons as generation variable too) could be constructed on the bases of approximated, but known exactly and analytically amplitudes.
- Why it was possible: conformal symmetry of eikonal factors and phase space for massless photons added.
- That created basis of algorithm where initial state photons, invariant mass of intermediate state and final state ones could be generated independently, starting from independent photons and phase space limits adjusted because of scale symmetry.
- Minor difficulty: to match virtual corrections one has to have an algorithm to deal with photon candidates of energies below lower limit for generation. The lower limit of photons energy can be arbitrarily low, but should be the same for all photons. Fortunately for that regime eikonal part of amplitudes is enough. That is important for virtual corrections.

- Now with re-weighting we can go back with matrix elements:
- First add effect of QED: β_1, β_2 .
- That looks like trivial, but it is not, for ν_e in final state one has to add charged Higgs ghost contribution... Is it still QED? When emissions from charged W's...
- The cancellation of singularities require contributions to be organized before adding hard interactions in form of Form factors, otherwise gauge invariance would be ruined. That worked fabulously well at 0.1% precision level and CMS energies below 205 GeV. *but at 2012 GeV ;-)*
- Huge effort on genuine weak corrections was needed, even at one loop level. *First, star couplings, at the end electroweak form factors.*
- analytic and anti analytic constraints of field theory need to be preserved. Proven to work well at at 0.1% precision level, no compromises. Anti-analytic features, optical theorem, Cutkosky rules, broken only at $\mathcal{O}(\alpha^2) \sim 10^{-4}$.
- One needed this massive effort of revisiting all perturbation expansions its re-ordering, before Monte Carlo implementation.

- Even at LEP, precision level eikonal part of QED was needed to at least third order. Thanks to re-ordering of perturbation expansion one loop genuine weak effects were sufficient.
- For FCC that will probably mean two loop genuine weak plus third order QED and may me 5-th order for eikonal in its part?
- We have some hints how to start work for 0.01% precision level, see eg 2505.00272 but question is how to keep projects on-going, expertise to be passed to new contributors and let it be extended.
- Old style solutions like OLDBAB+LUMLOG or KORALZ(YFS2) +Mustraal offered gate to the framework of NLL NNLL picture of some ambiguities evaluation.
- But at the end observable dependent evaluation of ambiguities in numbers % has to be provided, only that is meaningful for measurement-theory comparisons..

- My intention is not to talk about internal elements of KKMC because this is supposed to be covered in other talk.
- Nonetheless I need to mention one essential step: from vector indices to spinor indices.
- KKMC works not only at spin amplitudes, that enables reduction of terms, because interferences can be calculated directly from squares of the sum of complex interfering contributions (true for real emissions).
- vector objects residing in feynman diagram (like k) are represented as external product of spinors. That is because of Kleiss-Stirling spin amplitude language.
- That was advantageous and reduced size of formulas a lot, enabled a lot of tests for partial results too.
- Not only, from spin amplitudes density matrices for tau pairs could be calculated. Safely and accurately from first principles, in presence of arbitrary number of photons.

- Surely, for precision level 0.01 % two loop electroweak corrections will be needed. Third order QED and possibly up to 5th order of dominant (eikonal parts) that means also configurations with 5 explicit photons.
- Two loops electroweak corrections need to have the form separated into QED+genuine weak. This to match with QED only higher orders.
- Two loop electroweak corrections will impose new pressures on how necessary higher order QCD/QED corrections, can be installed. This is also true about the part of non perturbative QCD effects taken from low energy $e^+e^- \rightarrow hadrons$ data.
- At the level of two electroweak loops, such h.o. QED QCD need to be added for s-channel and for t-channel exchanges in vertex corrections simultaneously.
- Then, what about complex masses schemes? Solutions proposed by R. Stuart and later by A. Denner, to preserve constraints of optical theorem Cutkosky rules need then to remain valid with the first offending terms at $\mathcal{O}(\alpha^3)$ level.

- At this precision level corrections of 4 fermion processes will be needed in full, that complicates patterns for bremsstrahlung, interference's and crude level generation. **Language of tangent spaces and CW-complexes** may be helpful to systematize matching of collinear/soft sub-spaces. That was the case in PHOTOS Monte Carlo. Stasze was working in that direction too...
- For s-channel t-channel processes simultaneously, use contact interaction and expansion with respect to contact interaction. It was helpful hep-ph/0406045 for ν_e and hopefully will be helpful in future too.
- Question of tests. **It is so easy** to make the code working 'nearly correctly'. Should be beasuse we had to do so many adaptations, automatic algebraic manipulations could not be used.

- Because most of the calculations can not be used as off shelf segments there is quite broad spectrum of necessary tests which sometimes coincide with phenomenological projects.
- Big pressure comes from the need to identify the QED part.
- Lots of new tests techniques: theoretical calculations to provide benchmarks, numerical results to evaluate reliability of physics parts.
- Long time projects. Software effort, physics input, algorithms development, tests. For computer software engineer perspective see PhD thesis of Tomasz Przedzinski 2203.11650 and Comput.Sci.Eng. 22 (2020) 4, 86-98
- **Man power and expertise of all sub domains. Survive? Or not?**
- **How to identify requested parts of amplitudes?** Lorentz group sub-groups and layers? Extended theories and their symmetries. There is hope, but long way to go, see some other talks...
- Subtracting is OK at first level, but at higher ones? Negative weights. Beware of detector granularities and details. → [Another talk on Monte Carlo design itself.](#)

For the future...

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Thanks for listening.