# KORALZ/TAUOLA ambiguities as of LEP time.

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**I found preparation of the talk difficult:**

- **(1)** For KORALZ project evaluation of systematic ambiguities was and remain the central focus. KORALZ Monte Carlo for $e^+e^- \to \tau^+\tau^- n\gamma$ with $\tau$ decays included has long history:

Comput.Phys.Commun. 66 (1991) 276, ibid, 79 (1994) 503, 124 (2000) 233

- **(2)** Predecessors KORALB Comput.Phys.Commun. 36 (1985) 191 and Mustraal Comput.Phys.Commun. 29 (1983) 185 found place among testing tools.

- **(3)** Successor KKMC Comput.Phys.Commun. 130 (2000) 260 ibid. 260 (2021) 107734.

**change of name** - new technology: exponentiation at spin amplitudes level.

**Benefits** better control of spin effects, especially for the transverse degrees of freedom and in presence of high $p_T$ photons.

Convenient for center of mass energies above $Z$ peak: LEP2, FCC ...

Initial-Final state interference under full control.

- **(4)** "New" KKMC offered useful test test bed for KORALZ as well
- **(5)** All programs agree, where they should. Test may need to be repeated.
- **(6)** KORALZ last version from web page: https://wasm.web.cern.ch/f77.html,

search there for:

Official web page for the final versions of KORALB and KORALZ: Last version of KORALZ and KORALB. This distribution was frozen already before Sep 4 2000. In particular:

(A) Tauola included in this file is not up to date, it does not work for Linux, you need to superimpose it with the code constructed from TAUOLA-exp.tar.gz as above.

(B) Do not forget to change (by hand) "classical" compiler flags in all makefiles.

(C) In all demos and/or KORALB, KORALZ interfaces, replace initialization routines of Tauola with ones matching Tauola version you plan to use.

- **(7)** Even older versions, published in CPC, can be revived...

— If necessary, I can help all versions running.

— Configuration scripts are minimal, programs are in ANSI F77 :

— *no dependencies on external libraries*.

In Belle KKMC instead of KORALZ: $m_\tau / E_{beam}$ larger, thus transverse spin effects more important, as well as $\alpha_{QED}(s)$ dependence $\rightarrow$ distinct talk.

## My approach: guilty unless proven otherwise:

- General distributions, electroweak, ISR FSR
- Longitudinal spin correlations
- Transverse spin
- ISR-FSR interference
- decays of $\tau$'s
- Radiative corrections in decays
- Interfaces of $\tau$ decays, case when bremsstrahlung is present or not.
- Interface to collaboration software.

20 years ago I would be of better help.

**Now I may need to iterate, may answers only later ...**

$\rightarrow$ There is nothing like ambiguity tag for the Monte Carlo program

$\rightarrow$ One has to ask what observable one is interested in.

$\rightarrow$ Of course for many purposes ambiguities will be the same, but not always.

$\rightarrow$ Presence of cuts may result with damage of some cancellations for example.

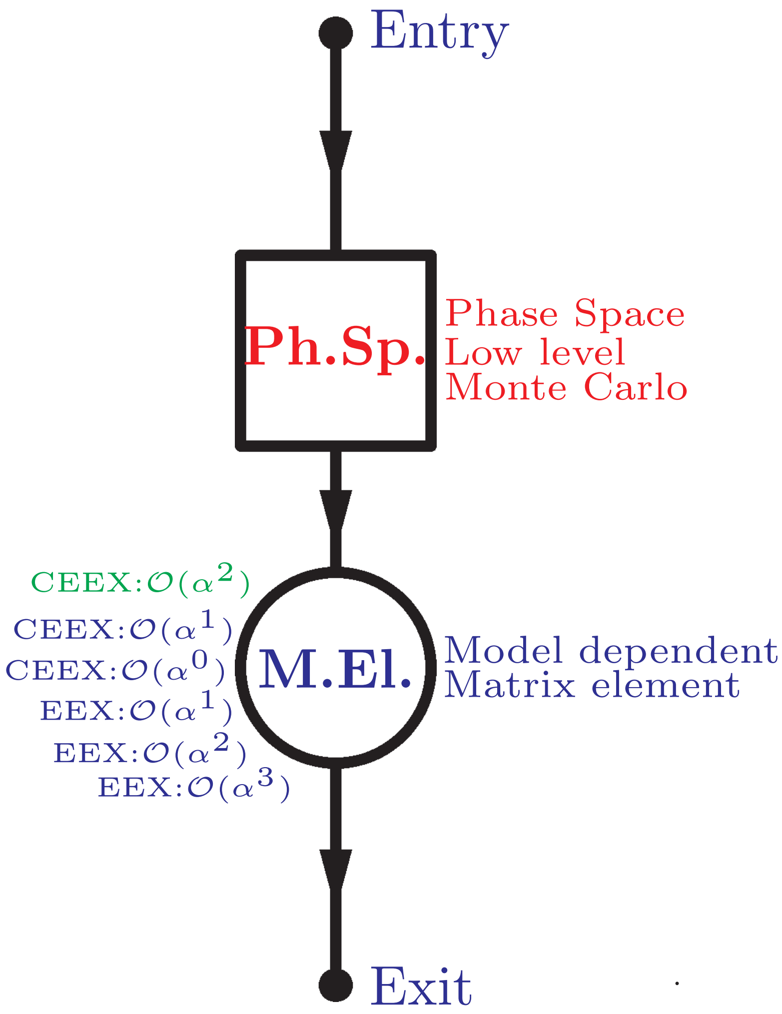
$\rightarrow$ This is the case of QED ISR-FSR bremsstrahlung interference

$\rightarrow$ **Anyway, one has to check:**

- Technical precision
- Statistical precision
- Physics precision

# General distributions, electroweak, ISR FSR

Textbook principle "matrix element × full phase space" useful




- Always used exact phase-space Monte Carlo module producing "raw events": in KORALZ, TAUOLA, PHOTOS.
- Library of models for provides input for "model weight"
- **Useful for any application, not only $\tau$ production/decay.**
- Lots on test for that. Technical precision validated down to fraction of permille.
- Lots of reproducible tests. Analytic or with other programs.
- Can be reproduced, but major effort to restart.

## Formalism for $\tau^+\tau^-$

- Because narrow $\tau$ width approximation can be obviously used for phase space, cross-section for the process $f\bar{f} \to \tau^+\tau^- Y; \tau^+ \to X^+\bar{\nu}; \tau^- \to \nu\nu$ reads:

$$d\sigma = \sum_{spin} |\mathcal{M}|^2 d\Omega = \sum_{spin} |\mathcal{M}|^2 d\Omega_{prod}\; d\Omega_{\tau^+}\; d\Omega_{\tau^-}$$

- This formalism is fine, but, e.g. for 20 $\tau$ decay channels we would have 400 distinct processes. Also picture of production and decay are mixed.

- Below only $\tau$ spin indices are explicitly written:

$$\mathcal{M} = \sum_{\lambda_1\lambda_2=1}^{2} \mathcal{M}^{prod}_{\lambda_1\lambda_2}\; \mathcal{M}^{\tau^+}_{\lambda_1} \mathcal{M}^{\tau^-}_{\lambda_2}$$

- Cross section can be rewritten into **core formula of spin algorithms**

$$d\sigma = \Big(\sum_{spin} |\mathcal{M}^{prod}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^+}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^-}|^2\Big) wt\; d\Omega_{prod}\; d\Omega_{\tau^+}\; d\Omega_{\tau^-}$$

- where

$$wt = \Big( \sum_{i,j=0,3} R_{ij} h^i h^j \Big)$$

$$R_{00} = 1, \quad < wt >= 1, \quad 0 \leq wt \leq 4.$$

$R_{ij}$ can be calculated from $\mathcal{M}_{\lambda_1 \lambda_2}$ by contraction with Pauli $\sigma^i$ matrices and similarly $h^i$, $h^j$ respectively from $\mathcal{M}^{\tau^+}$ and $\mathcal{M}^{\tau^-}$.

- Bell inequalities tell us that it is impossible to rewrite $wt$ in the following form

$$wt \neq \Big( \sum_{i,j=0,3} R^A_i h^i \Big) \Big( \sum_{i,j=0,3} R^B_j h^j \Big)$$

that means it is impossible to generate first $\tau^+$ and $\tau^-$ first in some given ' quantum state' and later perform separately decays of $\tau^+$ and $\tau^-$

- It can be done only if approximations are used !!!

- May be reasonable in e.g. ultra-relativistic regime, Approximation used in KORALZ.

# Longitudinal spin correlations

- Exact algorithm for spin were used, also for frames.
- But matrix $R_{ij}$ only longitudinal part was taken.
- Ambiguities of results were tested in many ways, see eg. Eberhard:1989ve P. H. Eberhard, B. van Eijk, J. Fuster, S. Jadach, A. M. Lutz, E. Richter-Was, P. Rosselet, O. Schneider and Z. Was, "THE tau POLARIZATION MEASUREMENT AT LEP," CERN-EP-89-129.
- Unless you are sensitive to transverse parts of $\tau$ decay products (with respect to $\tau$ decays. This is correct.
- But it was checked further.

# Transverse spin

- Tests of longitudinal spin only approximation were performed within ALEPH
- I have contributed also, with special version of `KORALB`
- It was published in: Phys.Lett.B 351 (1995) 562-568
- Transverse spin correlations were measured: R. Barate *et al.* [ALEPH], "Measurement of the transverse spin correlations in the decay Z $\longrightarrow$ tau+ tau-," Phys. Lett. B **405** (1997), 191-201 doi:10.1016/S0370-2693(97)00664-3

# ISR-FSR interference



In KORALZ Initial-Final state QED interference was not included

Smallness of the effect was studied.

The physics origin is $Z$ lifetime separating $Z$ production from decay.

Phys.Lett.B 219 (1989) 103-106

Phys.Lett.B 465 (1999) 254

For further tests KKMC can be used.

# Formalism for semi-leptonic decays at 0.2% precision level

- Matrix element used in TAUOLA for semi-leptonic decay of $\tau$ with $P$ momentum and spin $s$. (Phase-space parametrization exact).

$$\tau(P,s) \to \nu_\tau(N) X$$
$$\mathcal{M} = \frac{G}{\sqrt{2}} \bar{u}(N)\gamma^\mu(v + a\gamma_5)u(P)J_\mu$$

- $J_\mu$ – the current, depends on the momenta of all hadrons ($h_\mu = H_\mu/H_t$)

$$|\mathcal{M}|^2 = G^2 \frac{v^2+a^2}{2}(\omega + H_\mu s^\mu)$$
$$\omega = P^\mu(\Pi_\mu - \gamma_{va}\Pi^5_\mu)$$
$$H_\mu = \frac{1}{M}(M^2\delta^\nu_\mu - P_\mu P^\nu)(\Pi^5_\nu - \gamma_{va}\Pi_\nu)$$
$$\Pi_\mu = 2[(J^* \cdot N)J_\mu + (J \cdot N)J^*_\mu - (J^* \cdot J)N_\mu]$$
$$\Pi^{5\mu} = 2\,\mathrm{Im}\,\epsilon^{\mu\nu\rho\sigma} J^*_\nu J_\rho N_\sigma$$
$$\gamma_{va} = -\frac{2va}{v^2+a^2}$$
$$\hat{\omega} = 2\frac{v^2-a^2}{v^2+a^2} m_\nu M(J^* \cdot J)$$
$$\hat{H}^\mu = -2\frac{v^2-a^2}{v^2+a^2} m_\nu\,\mathrm{Im}\,\epsilon^{\mu\nu\rho\sigma} J^*_\nu J_\rho P_\sigma$$

# decays of $\tau$'s

- Hadronic currents have to fulfill Lorentz invariance.
- In $\tau^\pm \to \rho^\pm \to \pi^\pm\pi^0\nu$ channel fits are straightforward: $Q = m(\pi^\pm\pi^0)$ to be fitted with $J^\mu = (p_{\pi^\pm} - p_{\pi^0})^\mu F_V(Q^2) + (p_{\pi^\pm} + p_{\pi^0})^\mu F_S(Q^2)$. Because $F_S \simeq 0$, single real $F_V(Q^2)$ remain for fit.
- For 3-scalar channels: 4 complex functions each of 3 variables to fit. Role of theoretical assumptions (oversimplifications?) is essential. Agreement on 1-dim distribution is just a consistency check. $J^\mu = J_1^\mu + J_2^\mu +_4^\mu +J_5^\mu$.
- **No go for model independent measurements? Not necessarily.** Use of all dimensions for data distributions: invariant masses $Q^2$, $s_1$, $s_2$ as arguments of form-factors. Angular asymmetries help to separate currents: scalar $J_4^\mu \sim Q^\mu = (p_1 + p_2 + p_3)^\mu$, vector $J_1^\mu \sim (p_1 - p_3)^\mu|_{\perp Q}$ and $J_2^\mu \sim (p_2 - p_3)^\mu|_{\perp Q}$ and finally pseudo-vector $J_5^\mu \sim \epsilon(\mu, p_1, p_2, p_3)$.
- Model independent methods, if: (i) enough data, (ii) absolute precision, (iii) no background, (iv) full detector coverage of decay phase-space helpful. We need that for orthogonality of fitted functions. ML techniques instead?
- It is a challenge but worth a try.

  So far, multidimensional distributions within collaborations only

# decays of $\tau$'s



- Three versions of $\tau$ decay hadronic currents parametrisations of that time remain available: `Aleph`, `Cleo`, `CPC`
- Internally within ALEPH (Cleo, BaBar, Belle,...)further variants were available.
- but this about quantities being measured, not about Monte Carlo

# Radiative corrections in decays

PHOTOS Monte Carlo for radiative corrections in decays was developed starting from the phenomenology requirements of $\tau$ decays.

Later it gained large popularity and as a consequence lots of tests were performed.

It was used for radiative corrections in all $\tau$ decays, except leptonic ones, where explicit matrix element based solution was prepared for TAUOLA.

Nothing essential for ambiguities has changed since Photos Monte Carlo became available with the option of up to two hard photons:
Comput.Phys.Commun. 79 (1994) 291

Program was validated with much larger $\tau$ data samples of Belle 2 and BaBar.

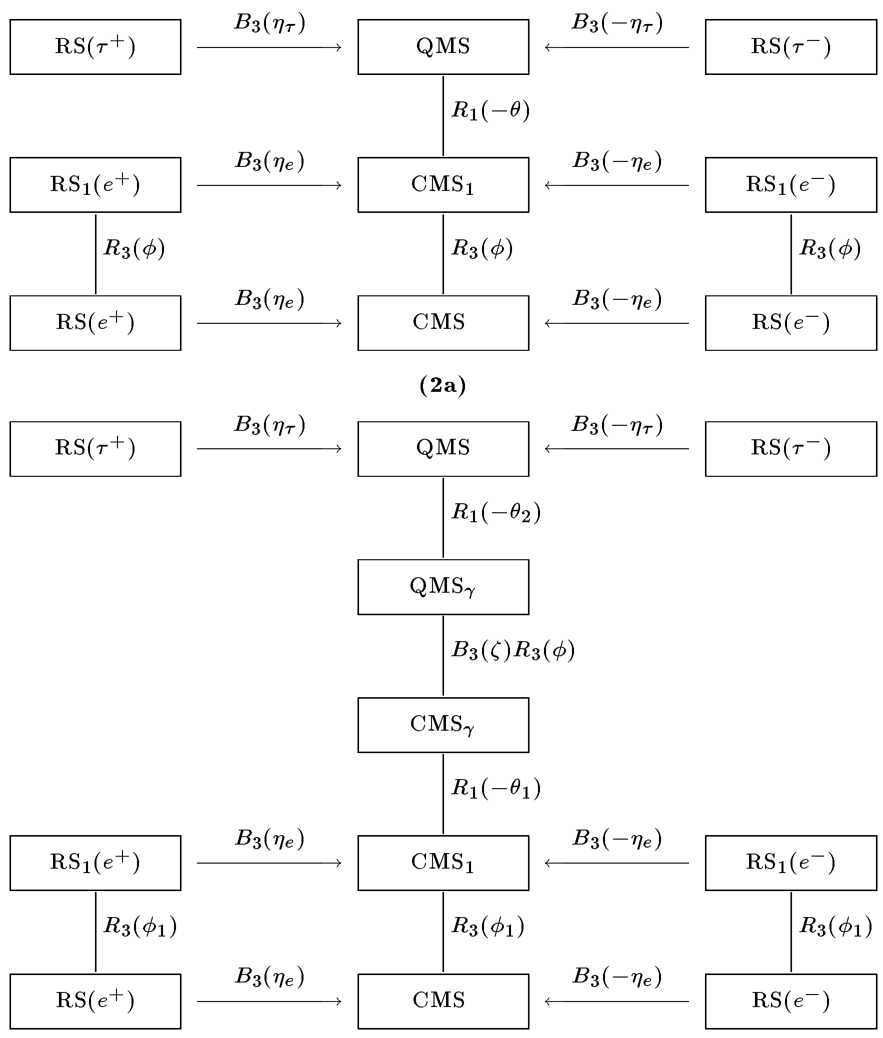
The initialization which was used at LEP data is still available, through up to date versions of Photos as well. Its performance can be easily checked.

That mode of operation is important for modern tests with second order matrix elements. In practice it was for $Z \to \mu^+\mu^-\gamma\gamma$ but it will be enlarged one day.

# Interface of $\tau$ decays – bremstrahlung present or not. 

**Spin ref. frames; production, decay. QED pheno. optimized, as in `KORALB`, similar `KORALZ`.**

**Figure 2**




**(2b)**

# Interface of $\tau$ decays – bremstrahlung present or not. 

- Important feature of QED: spin carried by bremsstrahlung photons tend to zero.
- Photon helicity sums up with its orbital momentum to zero.
- That is why `Photos` could be designed and that is why we can have accelerator beam polarization.
- That property of Lorentz group, more fundamental than QED, was essential in design for tree of reference frames.

# Interface to collaboration software.



Programs were carefully installed in ALEPH.

I had was involved in some checked, but as non-member of ALEPH not in every aspect.

# Summary.



- I am not sure if any work is needed, however ...
- ... if not, I am looking forward for details, what may need to be re-checked.
- I hope I will be able to help in reasonable time.
- But not in all details I will be as fluent as years ago.
- **IMPORTANT: programs of that time are archived, so one can also look for their correctness.**