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Spin polarization and the Einstein–Podolsky–Rosen paradox in the Monte Carlo event records *

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Abstract

In the future high energy physics experiments, the question of properly matching the phenomenological programs that describe different parts of the physics processes (such as hard scattering, hadronization, decay of resonances, detector response, etc.) is very important. In the past, FORTAN common blocks filled with lists of objects (particles, strings, clusters, etc.) of defined properties, origins and descendants were in use. Similar structures are now envisaged, for future programs, to be written in languages such as C++ or Java. From the physics point of view such an approach is not correct, since this kind of data structures impose certain approximations on the physics content. In the present paper, we will explore their limits, using examples from the physics of W 's, τ 's and the Higgs boson, still to be discovered.

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At present, intensive studies are being performed to design future software architectures for experiments on proton proton colliders, such as the Tevatron [1] or the LHC [2,3] and high energy e^+e^- linear colliders such as JLC [4], NLC [5] or TESLA [6].

One of the important ingredients in such designs is the data structure for storing the Monte Carlo events. It is generally accepted that the data structures based on objects such as particles, clusters, strings, etc. with properties such as tracks, momenta, colour, spin, mass, etc. and on the relations explaining the origins and descendants of the objects is the most convenient one. This is the case at present [7], and it is also envisaged for the future, see [8]. At the same time such a picture is in conflict with the basic principles of quantum mechanics. Einstein–Rosen–Podolsky paradox is an example of such phenomena. A general problem is that the quantum state of a multiparticle system cannot (at least in principle) be represented as a statistical combination of the states defined by the products of the pure quantum states of the individual particles. It is thus of the utmost importance to examine whether the approximation enforced by the data structure is purely academic, or if it rather represents a real difficulty, which may affect the interpretation of the future data.

It would not be a serious problem if the predictions of the Standard Model used in the interpretation of the future data could be provided by a single program, black box, without any need of analysing its parts. Then anything that would be measured beyond the prediction of such a hypothetical Monte Carlo program¹ would be interpreted as “new physics”. Agreement, on the other hand, would constitute confirmation of the Standard Model, as it is understood at present (and proper functioning of the detector as well).

Because of the complexity of the problem, Monte Carlo predictions need to be dealt with by programs describing: the action of the detector and of the analysis, on the experimental side, and various effects, such as those from hard processes, hadronization, decay of resonances, etc., on the theoretical side. Every part is inevitably calculated with some approximation and, as a consequence, some systematic errors affect these predictions.

In the following, we will omit these complex issues from the discussion. We will limit ourselves to the question of spin effects, more precisely to the consequences of approximations used in combining production and decays of the intermediate states. As examples we will use effects in the production of pairs of τ -leptons and W -bosons².

I advocate here that spin effects are non-treatable in the scheme where properties are attributed to individual particles only, in spite of the fact that it is the very method we used in KORALZ [9] – the program widely used at LEP for the simulation of τ -lepton pair production and decay, including spin and QED bremsstrahlung effects. As described in ref. [9] the algorithm of spin generation for any individual event was consisting of the following steps:

1. An event consisting of a pair of τ leptons, bremsstrahlung photons, etc., was gener-

¹As experimental data are always obtained with imperfect detectors, cuts, inefficiencies, etc. theoretical predictions must be convoluted with the experimental effects. Monte Carlo simulation techniques are the only tools, for the time being, able to complete the task.

²For the sake of convenience, I will use as examples theoretical calculations I was involved in myself.

ated.

2. Helicity states for both τ^+ and τ^- were generated. At this point, an approximation with respect to quantum mechanics was introduced.
3. Information on these helicity states, including the definition of quantization frames, i.e. the relation between τ 's rest frame and laboratory frame, was then transmitted to TAUOLA [10–12], the package for the generation of τ -lepton decays.
4. Finally TAUOLA performed decays of 100% polarized τ 's, and the event in the HEPEVT common block was completed. It was not considered necessary to store the information about spin degrees of freedom; however, it proved convenient, for applications that rely on the approximate spin picture.

At LEP, in (nearly) all cases, such an approach was sufficient. Thanks to the ultrarelativistic nature of τ -leptons $(m_\tau m_Z)^2 \ll 1$, missing effects were in most cases negligible. Let us note, however, that it was *not always* the case. Thanks to the excellent performance of the LEP detectors it was necessary to revisit the complete spin effects [13] and indeed the effects turned out to be measurable [14, 15]. Even more important was the case of complete spin effects in the measurement of the τ -lepton lifetime, using the method of impact parameter sum (see e.g. [16]). In that case, terms missing in KORALZ were not at all suppressed by the mass factors. Fortunately we could recall the solution of KORALB [17, 18], which was always serving as a *backup solution* for the spin treatment in KORALZ. KORALB relies on the full spin density matrix, but includes first order bremsstrahlung corrections only; it also misses electroweak corrections, necessary in high precision studies of LEP.

We conclude that the solution for the spin treatment of τ leptons at LEP was optimal. On one side, a convenient picture of particles with properties, origins and descendants could be used and, on the other, a complete full spin solution was available, if necessary.

Let us now turn to another example of the spin effect, this time in the process, which can be a source of a background. Let us consider a semi-realistic observable of invariant mass distribution for pairs of s -flavoured jets, and its background from the four-jet process in the e^+e^- annihilation into four quarks ($c\bar{c}s\bar{s}$ jets) at the 350 GeV centre-of-mass energy, with the veto cut on c -jets forcing them into directions close to the beam pipe. We will not discuss details of the study, which is presented in ref. [19]. We will simply recall some numerical results from that paper. In fig. 1, thin line represents the result of the complete CC-43³ matrix element. Not only the expected peak of Z -boson is clearly visible, but there is another one, at high energies as well. If we reduce the matrix element to the simple case of CC-03, where the double resonant WW -pair production is kept only (thick line), the Z resonance disappears, but the second peak remains visible. In fig. 2 we investigate the origin of the second peak even further. We compare the CC-03 (distribution identical to that in the previous figure) with the case when transverse spin correlations are switched

³At the Born level there are in total **43** diagrams for the charge current mediated $e^+e^- \rightarrow c\bar{c}s\bar{s}$ process. This number is reduced to **3** if only the doubly W -resonant diagrams are taken.

off. The difference is enormous. Not only is the peak at high energies reduced by a factor of 4, but also a huge shoulder of the distribution forms at lower invariant masses. There is no question, if an observable like ours was used in a search for new particles, that the lack of proper spin effects in the code simulating the background could lead to difficulties in data analysis and even to the temporary “discovery” of non-existing resonance for small experimental samples.

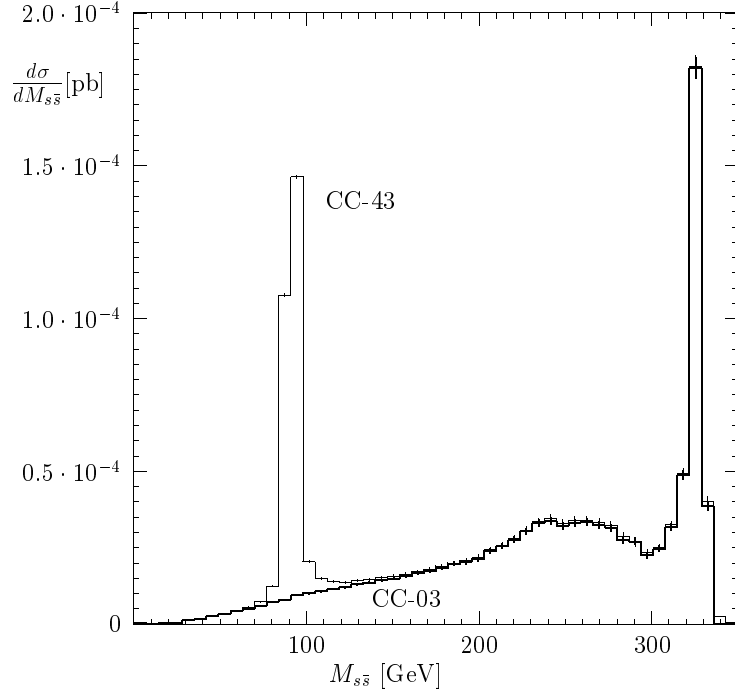


Figure 1: The $d\sigma dM_{s\bar{s}}$ differential distribution of the invariant mass of the “visible” $s\bar{s}$ jet pair. Veto cut on $c\bar{c}$ jets is applied. The centre-of-mass energy is 350 GeV. Matrix element of type CC-03 (thick line) and type CC-43 (thin line). For details, see the text and ref. [19].

Is this example really worrisome? Probably not. At the future high energy experiments, data will be collected in sufficient quantities, all Monte Carlo programs will use the matrix elements for the combined production *and* decay of the W -pairs with no approximations. Already now the physics of the W -pair production is well established and the separation between production and decay is neither necessary (all its decay channels can be described by the same matrix element) nor convenient; effects due to the structure of the W propagator make the separation into production and decay complicated.

Let us now turn to another example of the spin implementation algorithm. It is taken from ref. [20]. The algorithm, essentially that of KORALZ, was adopted to work with any Monte Carlo program providing the production of τ -leptons. If the generated events are

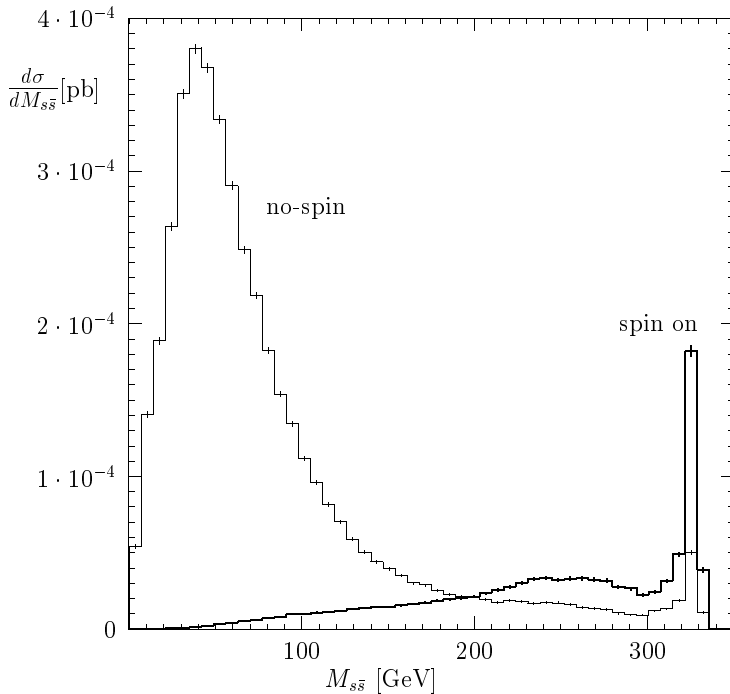


Figure 2: The $d\sigma/dM_{s\bar{s}}$ differential distribution of the invariant mass of the “visible” $s\bar{s}$ jet pair. Veto cut on $c\bar{c}$ jets is applied. The centre-of-mass energy is 350 GeV. Matrix element of type CC-03: no spin correlation (thin line), of type CC-03: with spin correlations switched on (thick line). For details, see the text and ref. [19].

stored in the format of a HEPEVT common block, then the algorithm consisting of the following basic steps can be used:

1. Search for τ -leptons in a HEPEVT common block (filled by any MC program).
2. Check what the origin of τ -lepton is: Z, γ, W, h, H^\pm or eventually, $2 \rightarrow 2$ -body process such as: $e^+e^-, (u\bar{u}), (d\bar{d}) \rightarrow \tau^+\tau^-$.
3. For the $2 \rightarrow 2$ -body process of τ -pair production, it is sometimes possible to calculate the τ polarization as a function of the invariant mass of the τ -lepton pair and angle between the directions of τ -leptons and incoming effective beams (in the rest frame of τ -pair).
4. If in addition to the τ -leptons, photons or partons (gluons, quarks, etc.) are stored in HEPEVT common block, one needs to define the “effective incoming beams”.
5. From such an information one can generate τ helicity states and define the relation between the τ rest frame and the laboratory frame.
6. The τ decay is generated with the help of a program such as TAUOLA.

7. Finally the entire event stored in a `HEPEVT` common block is appended with the τ 's decay products.
8. Optionally the final-state bremsstrahlung (emission from τ -leptons) can be generated using `PHOTOS` [21, 22].

As we can see in figs. 3 and 4, all leading spin effects are nicely reproduced by the above set of programs. A more complete discussion can be found in ref. [20].

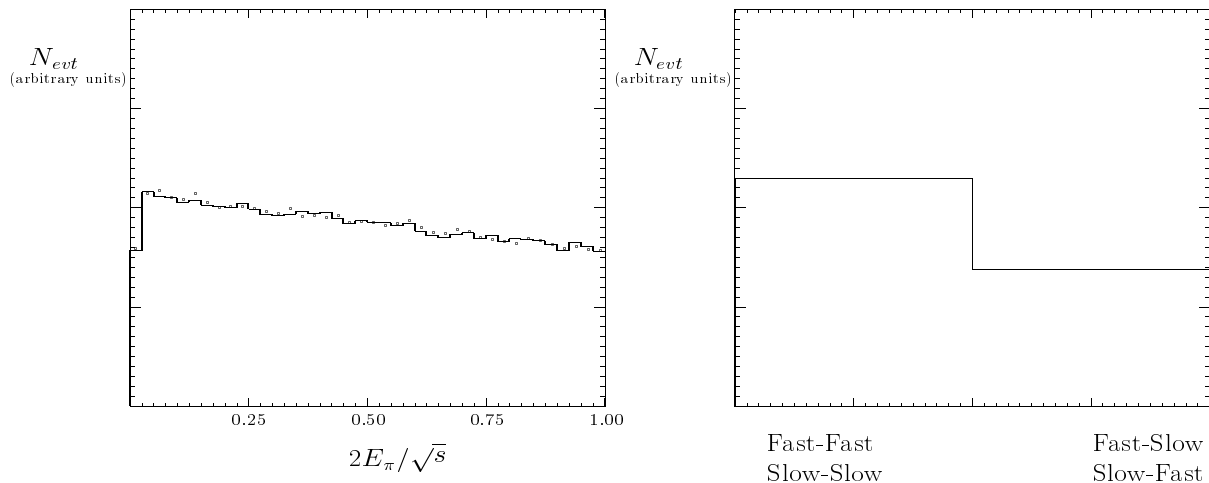


Figure 3: Basic properties of the spin effects in the case of τ -leptons produced from Z/γ intermediate state. The effects of τ polarization are in the left-hand side plot. We can see the slope of the π^{\pm} energy slopes calculated in the Z boson rest frame. The effects of the spin correlations are in the right-hand side plot. See ref. [20] for details.

The Monte Carlo `PHOTOS`, is another example of a program that uses a `HEPEVT` common block as a data structure. Its role is to generate, whenever suitable, bremsstrahlung photons in the decays of particles, resonances or sometimes from other intermediate charged states. The program was developed starting from the careful downgrading of the matrix element `MUSTRAAL` Monte Carlo [23], more precisely its part describing the decay of a Z to a pair of leptons. Then, the algorithm was extended to work for the decay of “any” particle or resonance. By construction it is limited to leading logarithmic (ll) approximation with proper soft-photon angular distributions only. Thanks to comparisons with codes based on matrix elements, `PHOTOS` was checked to performed better than ll in the following cases: $\tau \rightarrow e\nu\bar{\nu}\gamma$, $\tau \rightarrow \pi\nu\gamma$, $Z \rightarrow \mu^+\mu^-\gamma(\gamma)$, $gg \rightarrow t\bar{t}\gamma(\gamma)$.

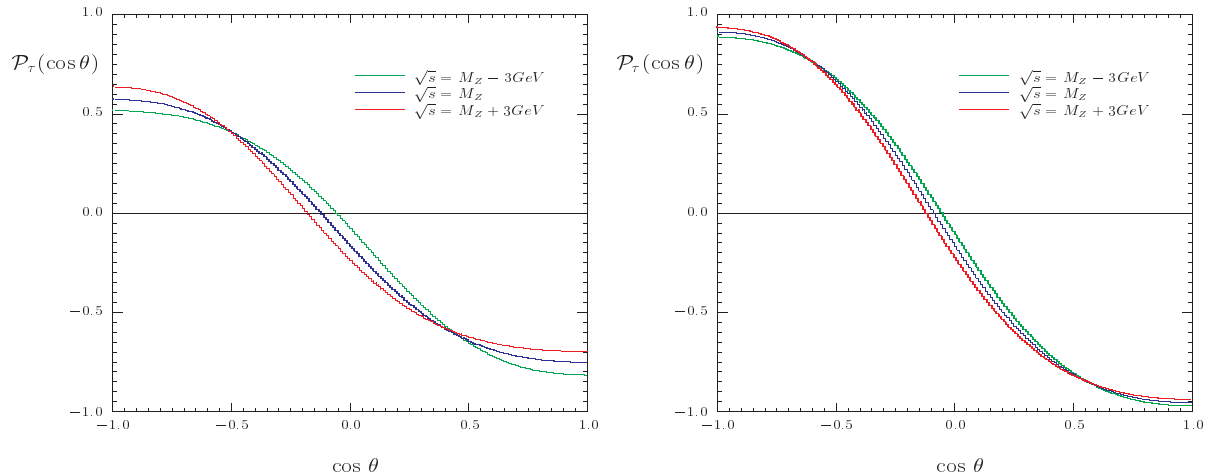


Figure 4: Angular dependence of the τ polarization produced through Z/γ intermediate state at energies close to the Z mass from u flavour (left side) and d flavour (right side). See ref. [20] for details.

In the special case of a hypothetical (scalar or pseudoscalar) Higgs boson decay $h \rightarrow \tau^+\tau^-$, it is possible to define the full spin density matrix for the pair of τ -leptons, independently of the Higgs boson production mechanism. The previously discussed algorithm of the spin implementation was extended (ref. [24]) to include the full spin effects in that case. As we can see in fig. 5, the program reproduces the effects of the Higgs parity correctly for the $\pi^+\pi^-$ acollinearity calculated in the rest frame of the Higgs boson and decay chain $h \rightarrow \tau^+\tau^-; \tau^\pm \rightarrow \pi^\pm\nu_\tau$ [25]. When some detector smearings are introduced, see fig. 6, the effect becomes less visible. In this example, the Higgs-strahlung production mechanism at 350 GeV centre-of-mass energy was generated with the help of PYTHIA [26]; see ref. [24] for details of the study.

Summary

We can conclude that, in none of the discussed cases was it necessary to store spin degrees of freedom in the event records. In fact, storing such information in an approximate way as an attribute of particles would not lead to the correct solutions anyway. The general principle was shown of how to construct an interface that can calculate the relevant multiparticle density matrix from the kinematical information stored in the event record. A backup solution was always necessary.

Another solution relies on algorithms where decays and productions of some interme-

mediate states are embodied in the monolithic program individually tailored to the process. This is a good approach in cases such as production and decay of $(\tau\tau)$ (WW) (ZZ) intermediate states. It may be reasonable as well for the case of $t\bar{t}$ production and decay, even though at least 6-body final states will have to be generated in single steps. Such a solution may pose problems if production and decay of pairs of *new* particles carrying spin will be discovered, especially if a multitude of decay channels, each described by a distinct model, would have to be combined.

We think that non-factorizability of the spin density matrices into properties of individual particles is important, and should be borne in mind in the discussions of future standards for event records, and redesigned software for high energy physics.

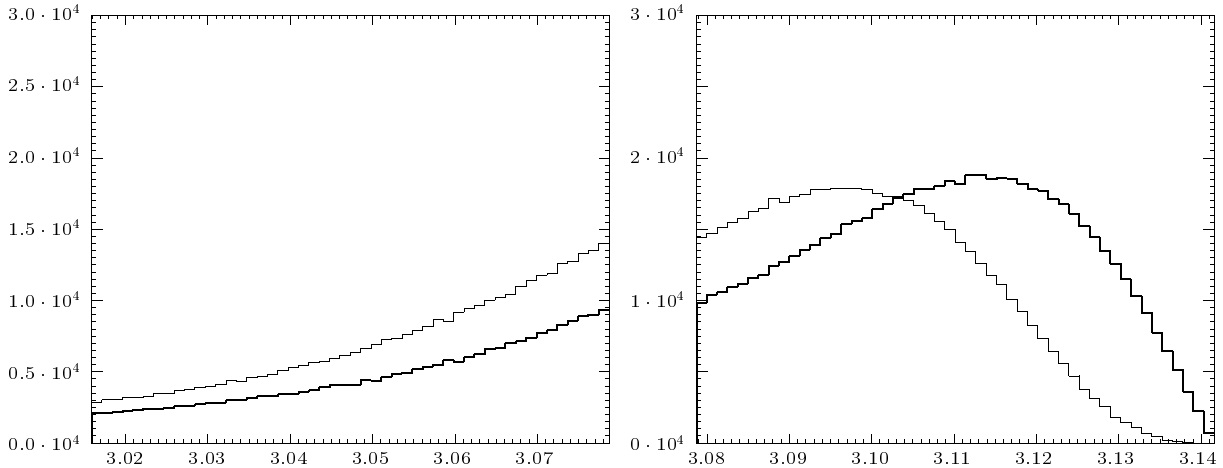


Figure 5: The $\pi^+\pi^-$ acollinearity distribution (angle δ^*) in the Higgs boson rest frame. Parts of the distribution close to the end of the spectrum; $\delta^* \sim \pi$ are shown. The thick line denotes the case of the scalar Higgs boson and the thin line the pseudoscalar one.

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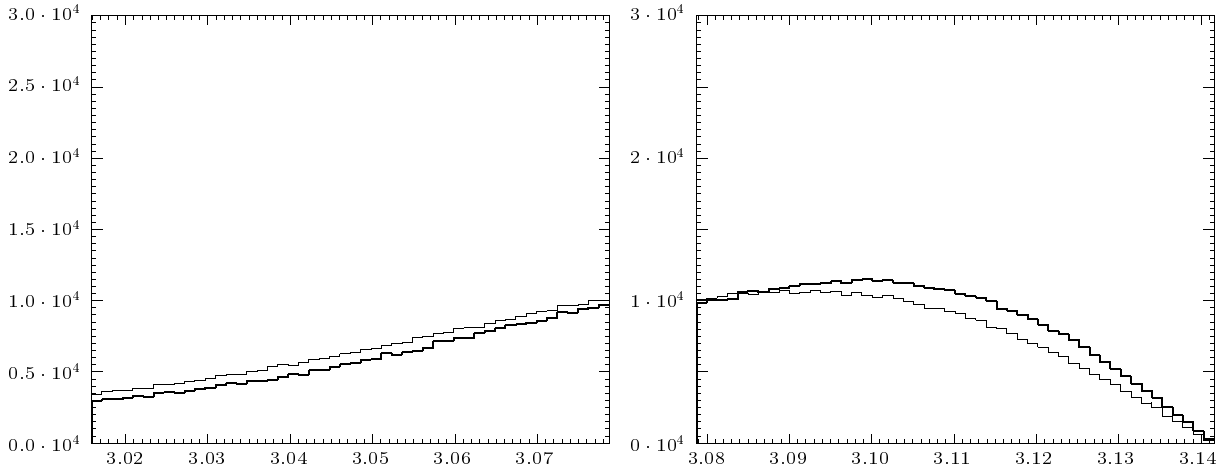


Figure 6: The $\pi^+\pi^-$ acollinearity distribution (angle δ^*) in the scalar Higgs boson reconstructed rest frame. Parts of the distribution close to the end of the spectrum; $\delta^* \sim \pi$ are shown. The thick line denotes the case when all spin effects are included, while only longitudinal spin correlations are taken for the thin line.

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