Some aspects of spin in physics MC – experience from PHOTOS, TAUOLA and TAUOLA universal interface

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Main Topics:

- **QM versus ’reasonable’ picture and legacy of LEP for spin and TAUOLA**
- **Worrisome example.**
- **PHOTOS, universal generator for Bremsstrahlung in decays.**
- **Four “standards” of event records which are physics enforced**
- **General solutions and specific solutions used for TAUOLA and PHOTOS**
- **Transparencies from Matrix element session; discusion on spin correlations.**

These and related slides/programs can be found from http://home.cern.ch/wasm

Quantum Mechanics

and
'reasonable' picture

- We all know that QM mechanics is nasty, Bell inequalities, non factorizable quantum states etc.
- We believe however that in practical cases HEP physics is free of these complications
- Let us ivestigate how it was at LEP and τ-pair production and decay.
- $\frac{m_\tau}{\sqrt{s}} \simeq 0.01$ thus comparable to detector granularity
- that is why complete spin effects could be often ignored
- Let me show some basic facts first.

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

- Because narrow τ 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 because of over 20 τ decay channels we have over 400 distinct processes. Also picture of production and decay are mixed.

- but (only τ spin indices are explicitely written):

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

- Formula for the cross section can be re-written

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

- where

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

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

R_{ij} can be calculated from $\mathcal{M}_{\lambda_1 \lambda_2}$
and h^i, h^j respectively from $\mathcal{M}^{\tau^+}$ and $\mathcal{M}^{\tau^-}$.

- Bell inequalities tell us that it is impossible to re-write wt in the following form

$$wt \ne \Big(\sum_{i,j=0,3} R_i^A h^i \Big) \Big(\sum_{i,j=0,3} R_j^B h^j \Big)$$

that means it is impossible to generate first τ^+ and τ^- first in some given ‘ quantum state’ and later perform separatelly decays of τ^+ and τ^-

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

- May be often reasonable, but nonetheless approximations.

Approximate spin generation

Example of reasonable approximation: KORALZ at LEP

S. Jadach, B.F.L. Ward, Z. Was Comput. Phys. Commun. 79 (1994) 503

- Generates first pair of τ leptons
- Generates helicity states of both τ^+ and τ^- i.e. approximation is used
- Provides helicty states and relation between τ's restframe and LAB to TAUOLA
- TAUOLA performs decay of 100 % polarized τ's.
- This solution worked in all cases, except τ-lifetime measurement with impact parameter difference method and simulations for direct measurement of transverse spin correlations
- In all other cases correlations of transverse (with respect to $\tau^\pm$ dirrections) components of $\tau^\pm$ decay products momenta could be neglected
- Backup solution was however always at hand.

LEP τ spin legacy

- Practically in all cases approximate spin generation like in KORALZ was enough
- In special cases backup solution was nonetheless necessary, but was easy to use
- But, $\frac{m_\tau}{\sqrt{s}} \simeq 0.01$ is rather small

Spin generation avoided

Matrix elements for combined production and decay

- All effects can be included
- In particular effects of interfering backgrounds
- Finite widths, etc.
- Sometimes it may be difficult to develop physical intuition
- If many channels for decays, then number of processes grows very fast.
- Matrix element always best for control of precision, especially for prcesses with W's, Z's and t's etc.

Exact spin generation

Example: KORALB and KKMC

S. Jadach, Z. Was Comput. Phys. Commun. 64 (1991) 267

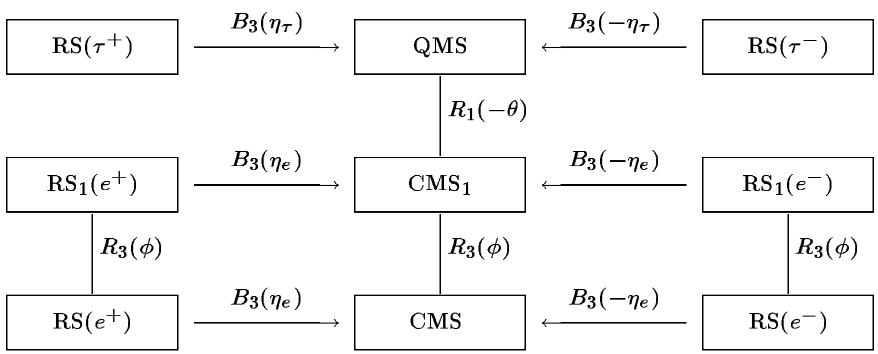
S. Jadach, B. F. L. Ward, Z. Was Comput. Phys. Commun. 130 (2000) 260

- Generate first pair of τ leptons, no polarization
- Calculate density matrix for the two-τ (plus photon(s))quantum state
- TAUOLA performs decay of unpolarized τ's.
- Spin weight is calculated from production and decay variables.

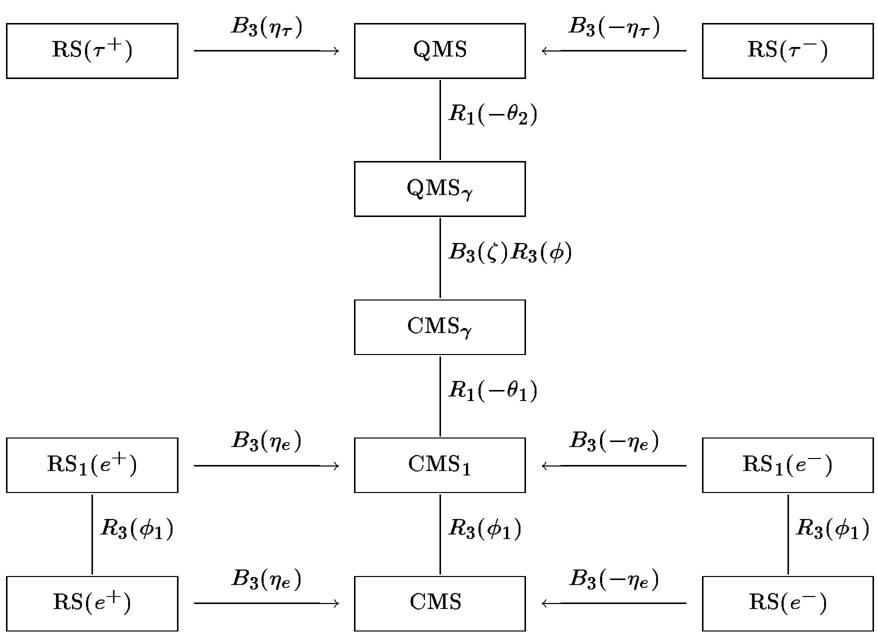
- Complete spin effects are introduced by rejection.
- in KORALB density matrix for $2 \rightarrow 2$ and $2 \rightarrow 3$ processes was used.
- in KKMC more universal solution suitable to any process $2 \rightarrow 2 + n$ was applied. KKMC method is friendly for applications with automatic generation of spin amplitudes. It uses universal definition of quatization frames.
- Slightly different solution is used in HERWIG
- and in software of BaBar.

Tree of KORALB boosts, used in spin quantization

Figure 2



(2a)



(2b)

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Case of KKMC

- In case of KKMC it turned out to be impracticable because of m any possibilities, multiphoton emissions.
- gains in simplicity of formulas are also rather small
- nuisances because of fermion quantization frames depending on *photon* momenta would be sizable.

Global Positioning of Spin, GPS scheme

- For calculation of spin amplitudes we use modified scheme of Kleiss-Stirling
- Spinors for every fermion e or τ is defined with the help of two 4-vectors, defined in the lab frame:
- massles $\zeta_\uparrow = (1,0,0,1)$ and spacelike $\eta = (0,1,0,0)$
- Then, for each fermion, z axis of its quantization frame is pointing along $\vec{\zeta}_\uparrow$ (as seen in its rest-frame).
- Place the x-axis in the plane defined by the z-axis from the previous point and the vector $\vec{\eta}$, in the same half-plane as $\vec{\eta}$.
- With the y-axis complete the right-handed system of coordinates.
- For details see S. Jadach, B.F.L. Ward, Z. Was Eur. Phys.J. **C22** (2001)423.

Tree of KORALB/KKMC spin comparison

```
++++++++++++++++++++++++++++++++ Born spin amplitudes +++++++++++++++++++++++++++++++++++
     { 1 1 1 1}  { 1 1-1 1}  { 1 1 1-1}  { 1 1-1-1}
     { 1-1 1 1}  { 1-1-1 1}  { 1-1 1-1}  { 1-1-1-1}
     {-1 1 1 1}  {-1 1-1 1}  {-1 1 1-1}  {-1 1-1-1}
     {-1-1 1 1}  {-1-1-1 1}  {-1-1 1-1}  {-1-1-1-1}
[   .000000    .000000] [   .000000    .000000] [   .000000    .000000] [   .000000    .000000]
[   .000000  -.042470] [  -.426444  -.355310] [  -.264620  -.355310] [   .000000    .042470]
[   .000000   .042470] [  -.264620   .355310] [  -.426444   .355310] [   .000000  -.042470]
[   .000000    .000000] [   .000000    .000000] [   .000000    .000000] [   .000000    .000000]
#################################### R-matrix GPS fram ##################################
[  1.000000    .000000] [   .000000    .000000] [   .000000    .000000] [   .000000    .000000]
[   .000000    .000000] [   .934245    .000000] [   .226379    .000000] [   .118825    .000000]
[   .000000    .000000] [  -.226379    .000000] [   .948448    .000000] [  -.027059    .000000]
[   .000000    .000000] [   .118825    .000000] [   .027059    .000000] [  -.985797    .000000]
#################################### R-matrix JacWick  ##################################
[  1.000000    .000000] [   .000000    .000000] [   .000000    .000000] [   .000000    .000000]
[   .000000    .000000] [   .975295    .000000] [   .000000    .000000] [  -.012863    .000000]
[   .000000    .000000] [   .000000    .000000] [   .968598    .000000] [   .000000    .000000]
[   .000000    .000000] [   .012863    .000000] [   .000000    .000000] [  -.993302    .000000]
*******************   R analytical     *******************
[    1.000000000000] [     .000000000000] [     .000000000000] [     .000000000000]
[     .000000000000] [     .975295402620] [     .000000000000] [    -.012863411954]
[     .000000000000] [     .000000000000] [     .968597565592] [     .000000000000]
[     .000000000000] [     .012863411954] [     .000000000000] [    -.993302162971]
*******************   R Difference     *******************
[     .000000000000] [     .000000000000] [     .000000000000] [     .000000000000]
[     .000000000000] [     .000000000000] [     .000000000000] [     .000000000000]
[     .000000000000] [     .000000000000] [     .000000000000] [     .000000000000]
[     .000000000000] [     .000000000000] [     .000000000000] [     .000000000000]
```

Spin density matrix in 3 coventions from 2 programs published 1984 and 2000

- We have found that even with our own programs, the best is to define relations between decayiong particle quantization frames (taken from different frameworks), with the help of laboratory frame.
- After all boost from rest frame to laboratory frame (and back) is at most simple rotation.

But it was LEP and high precision, let us now turn to:

CRAZY BACKGROUND

Aim:

- Observable that produces unexpected peaks out of background:
- Starting point: $s\bar{s}$ state in $e^+e^- \to s\bar{s}c\bar{c}$ at 350 GeV ($c\bar{c}$ lost in the beam pipe).
- This is not realistic observable, but in principle realizable experimentally.
- Let us look at it with:

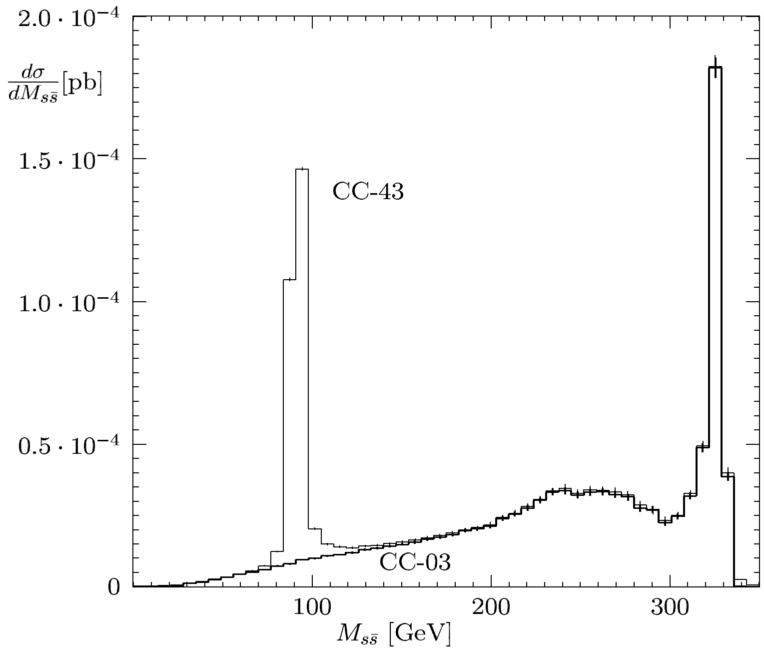
(i) full ME.,

(ii) CC03: WW prodction and decay

(iii) CC03 no transverse spin correlations.

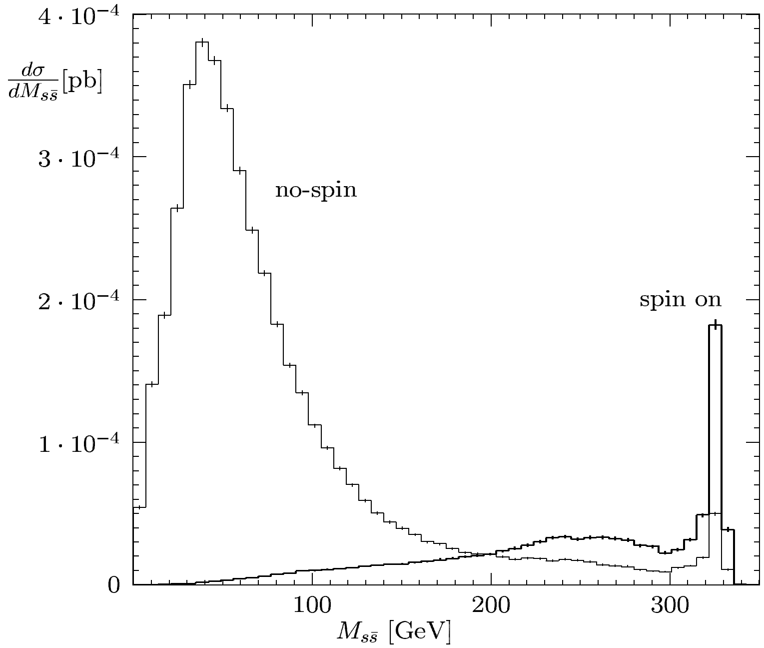
Worrisome example

What is the origin of the second peak?



Worrisome example

These crazy spin Correlations !!



Spin correlations are needed in full.

This second peak has showed up due to full spin correlations deeply related to Einstein-Rosen-Podolsky paradox. That means no hope for generating pair of W each in definite spin state first and later decay.

But anyway ...

1. W's are not narrow resonances
2. Full matrix elements for production and decay combined are available
3. All W decay channels are basically identical
4. Interfering background diagrams need to be taken into account
5. In real life nobody will separate production and decay, generators for $2 \to 6$ processes will do the job!
6. Similar case is with t physics.
7. No need for spin in event record.

Final call:

Who cares about full spin degrees of freedom in data structure?

Nobody cares:

Unless:

- One believes that there might be some heavy spiny new particles, rich in physics, produced in pairs at LC.
- This may not at present justify introduction of multi-particle density matrices into event records,
- but nonetheless calls for some thought toward backup solution.
- Experience of τ-physics may be useful.
- Experience with TopRex
- Density matrix formalism is also good for building intuition.
- Tools can be easily modified by the users.

PHOTOS MOnte Carlo for QED in decays

- the algorithm is based on the ‘no spin approach’
- bremsstrahlung photons have internal spin **1** but it is produced with non-pointlike interaction p-wave, thus there is orbital angular momentum as well.
- Total spin effect of the photon is thus **zero**
- At least in leading log and infrared limits,
- spin effects beyond that are of the order $\lambda\frac{\alpha}{\pi}$, where coefficient λ is typically significantly smaller than 1.

No problems for spin (at this level)

Presented on thursday,

Spin: where from, and how

- The most convenient solution is to have production and decay amplitudes combined in one single module. No room for ambiguities convention mismatches etc,
- also no room for intuition build-up.
- The most convenient for description is taylored solution:
- Main generator calls decay package and 'decay' with appropriate spin state, density matrix (for one or multiparticle quantum state) defined.
- Sometimes density matrix can be recalculated from kinematical information provided by main generator.
- See talk by Malgorzata Worek **now**.
- In reality you have many practical difficulties: 3 standards of HEPEVT in PYTHIA and another one from HERWIG. See talk by Borut Kersevan **just after**.
- You will have these difficulties in C++ as well, they are physics driven.
- External matrix element implementations into Pythia and Herwig only complicate the stuff.