# Observables with $\tau$ Leptons at LHC and LC Structure of Event Records and Monte Carlo Algorithms

Z. Wąs (Cracow, INP & CERN)

G. Bower (SLAC), C. Biscarat (Fermilab), K. Desch (Hamburg U.), A. Imhof (DESY),

B. Kersevan (Lubliana), T. Pierzchała (Silesia U.) and M. Worek (Cracow, INP)

## Points:

- Physics elements taken from KORALB, KORALZ etc. by S. Jadach et al.
- CP-parity sensitive observable at LC in $H/A^0 \to \tau^+\tau^-$ decay channel.
- Problems of the deterministic event records.
- Summary and Outlook.

## *Main References*


- T. Pierzchala, E. Richter-Was, Z. Was and M. Worek, Acta Phys. Polon. B **32** (2001) 1277
- Z. Was and M. Worek, Acta Phys. Polon. B **33** (2002) 1875
- G. R. Bower, T. Pierzchala, Z. Was and M. Worek, Phys. Lett. B **543** (2002) 227
- K. Desch, Z. Was and M. Worek, Eur. Phys. J. C **29** (2003) 491
- K. Desch, A. Imhof, Z. Was and M. Worek, "Probing the CP nature of the Higgs boson at linear colliders with tau spin correlations: The case of mixed scalar pseudoscalar couplings," arXiv:hep-ph/0307331.
- P. Golonka, B. Kersevan, T. Pierzchala, E. Richter-Was, Z. Was, M. Worek "The tauola-photos-F environment for the TAUOLA and PHOTOS packages", CERN-TH/2003-287.

**Any LC programme must include Higgs boson parity measurement**

1. There are many possibilities for the measurement.
2. There are many scenarios of Higgs mechanism: SM, MSSM, ...
3. We will concentrate on the measurement using $H \to \tau^+\tau^-$ decay; i.e. the measurement of Higgs boson couplings to fermions.
4. This measurement is to a laSrge degree production independent.
5. It offers good example for software architecture as well:
   (a) Hard production process
   (b) Bremsstrahlung
   (c) Primary, secondary, 3-rd, (4-th) levels of decays, $\to$ density matrices
   (d) detecor and accelerator effects.
   (e) For high precision points (a) (b) and density matrix of (c) must go together $\to$ troubles for architecture.
6. MC simulation is a must.

## $\tau$ Production And Decay Process In Our MC's

- The cross section for the process

$$e^+(p_1)e^-(p_2) \to \tau^+(q_1,s_1)\tau^-(q_2,s_2)$$

$$d\sigma = |A|^2 \; wt \; dLips(p_1+p_2;q_1,q_2); \quad wt = (1+R_{\mu\nu}s_1^\mu s_2^\nu)$$

- The partial width for the $\tau^\pm$ decay is given by

$$\tau^+(q_1) \to \bar{\nu}_\tau(k_1)\nu_e(k_2)e^-(k_3)$$

$$d\Gamma_e = \frac{1}{2M}|\bar{\mathcal{M}}|^2(1+h_{1\mu}s_1^\mu)dLips(q_1;k_1,k_2,k_3)$$

$$\tau^-(q_2) \to \nu_\tau(k_1^{'})\bar{\nu}_e(k_2^{'})e^+(k_3^{'})$$

$$d\Gamma_e = \frac{1}{2M}|\bar{\mathcal{M}}^{'}|^2(1+h_{2\mu}s_2^\mu)dLips(q_2;k_1^{'},k_2^{'},k_3^{'})$$

- The cross section for the combined production and decay process

$$d\sigma = |A|^2|\bar{\mathcal{M}}|^2|\bar{\mathcal{M}}^{'}|^2(1+R_{\mu\nu}h_1^\mu h_2^\nu)$$

$$dLips(p_1+p_2;q_1,q_2)dLips(q_1;k_1,k_2,k_3)dLips(q_2;k_1^{'},k_2^{'},k_3^{'})$$

- Semi separation only, note the non-trivial spin correlations, Bell inequalities !

## Density matrix

Only transverse spin correlations between $\tau^+$ and $\tau^-$ are different for scalar and pseudoscalar Higgs

- The correlations can not be measured directly
- One need to measure distributions of $\tau$ decay products
- Precisely their transverse (to $\tau$ direction in Higgs boson rest frame) momenta
- Most sensitive to spin is $\tau^\pm \to \pi^\pm \nu$
- The largest branching ratio (25 % ) has $\tau^\pm \to \pi^\pm \pi^0 \nu$

## Classic approach

We take the most sensitive to spin $\tau^\pm \to \pi^\pm \nu$ decay channels and we look at $\pi^+\pi^-$ acollinearity in **Higgs boson rest-frame**.

In reality it is difficult at LC to reconstruct Higgs boson rest-frame precisely enough, because of beamstrahlung and uncertainties in reconstruction of jets (from Z decay).

## Phenomenology Of General Case

- Decay probability for the mixed scalar–pseudoscalar case, formalism Kramer et al, see also Grzadkowsi 1995.

$$\Gamma(h_{mix} \to \tau^+\tau^-) \sim 1 - s_{\|}^{\tau^+} s_{\|}^{\tau^-} + s_{\perp}^{\tau^+} R(2\phi)\, s_{\perp}^{\tau^-}$$

- $R(2\phi) -$ operator for the rotation by angle $2\phi$ around the $\|$ direction.

$$R_{11} = R_{22} = \cos 2\phi \qquad R_{12} = -R_{21} = \sin 2\phi$$

- Pure scalar case is reproduced for $\phi = 0$.
- For $\phi = \pi/2$ we reproduce the pure pseudoscalar case.

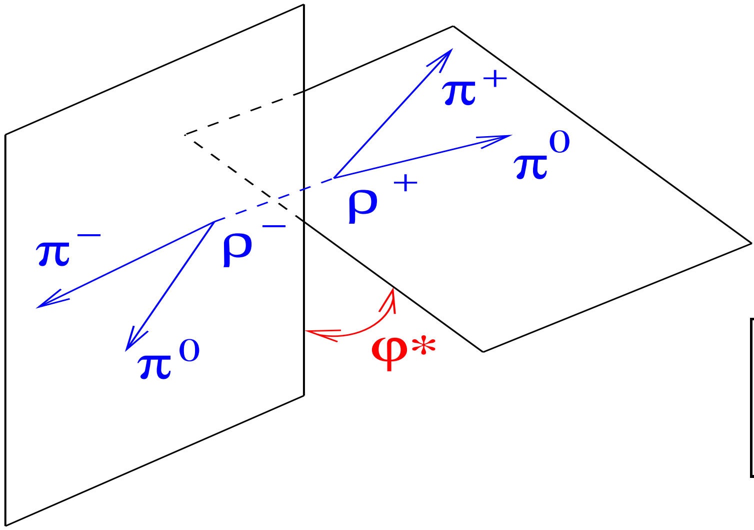
## General Elements Of Observable

- Case of $\tau \to \rho\nu_\tau$ decay, $\mathcal{BR}(\tau \to \rho\nu_\tau) = 25\%$
- The polarimeter vector is given by the formula where $q$ for $\pi^\pm - \pi^0$, $N$ for $\nu_\tau$.

$$h^i = \mathcal{N}\Big(2(q\cdot N)q^i - q^2 N^i\Big)$$

$$q\cdot N = (E_{\pi^\pm} - E_{\pi^0})m_\tau$$

- Acoplanarity of $\rho^+$ and $\rho^-$ decay prod. (in $\rho^+\rho^-$ r.f.) and events separation.




$y_1 y_2 > 0$ ; $y_1 y_2 < 0$ (in $\tau^\pm$ r.f.'s)

$$y_1 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}\ ; \qquad y_2 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}}.$$

## Replacement $\tau$ Rest Frame

- Take just laboratory frame instead of $\tau^{\pm}$ r.f.'s.
- Better (but by invisible amount) replacement $\tau$ rest frames.
  - In the restframe of $\rho^+\rho^-$ pair define $\tau^{\pm}$ momenta along direction of $\rho^{\pm}$,
  - For $\tau^{\pm}$ energies take half of the Higgs boson mass.
  - Boost replacement $\tau^{\pm}$ momenta to the lab frame.
- Many more, equally "good" options checked. Problem is that we can not determine direction of $\nu_\tau$ because of Beamstrahlung.
- The only exception is if we use measurement of direction for $\tau$ impact parameter (with $25^o$ error). It gives not much better way to determine $\tau$ rest-frame but distinct, we can take only those events where the two methods will match.

## *Mixed Scalar–Pseudoscalar Coupling Of* $h\tau\tau$

- *Both scalar and pseudoscalar couplings of the Higgs to* $\tau\tau$ *allowed.*
- *Measurement of the pseudoscalar admixture in the* $h\tau\tau$ *coupling to* $\mathcal{SM}$ *Higgs.*
- *Spin weight and general Higgs boson Yukawa coupling to the* $\tau$ *lepton.*

$$wt = \frac{1}{4}\left(1 + \sum_{ij=1}^{3} R_{ij} h^i h^j\right)$$

$$\bar{\tau}(a + ib\gamma_5)\tau$$

- *Non-zero components of spin correlation matrix* $R_{ij}$

$$R_{33} = -1 \qquad R_{11} = R_{22} = \frac{a^2\beta^2 - b^2}{a^2\beta^2 + b^2} \qquad R_{12} = -R_{21} = \frac{2ab\beta}{a^2\beta^2 + b^2}$$

- $\beta = \sqrt{1 - \frac{4m_\tau^2}{m_H^2}}$

## *Spin Weight For Mixed Scalar–Pseudoscalar Case*

- *Higgs boson Yukawa coupling expresed with the help of the scalar–pseudoscalar mixing angle* $\phi$

$$\bar{\tau} N (\cos\phi + i \sin\phi \gamma_5)\tau$$

- *Components of the spin density matrix*

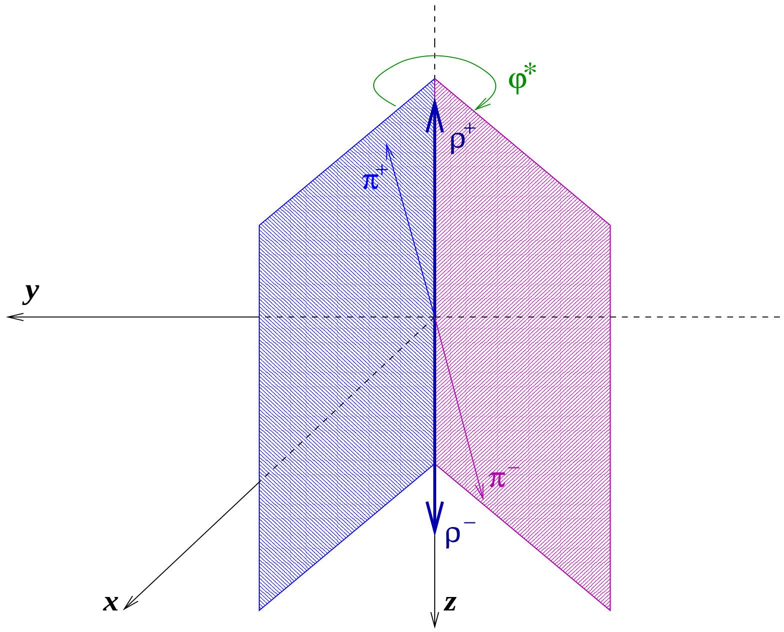
$$R_{11} = R_{22} = \frac{\cos\phi^2 \;\beta^2 - \sin\phi^2}{\cos\phi^2 \;\beta^2 + \sin\phi^2} \qquad R_{12} = -R_{21} = \frac{2\cos\phi \sin\phi \;\beta}{\cos\phi^2 \;\beta^2 + \sin\phi^2}$$

- *In the obvious limit* $\beta \to 1$ *– the components of the density matrix coincide with matrix for rotation by an angle* $-2\phi$ *around* $z$ *axis:*

$$R_{11} = R_{22} = \cos 2\phi \qquad R_{12} = -R_{21} = \sin 2\phi$$

## Observable For Mixed Scalar–Pseudoscalar Case

- *For mixing angle $\phi$, transverse component of $\tau^+$ spin polarization vector is correlated with the one of $\tau^-$ rotated by angle $2\phi$.*
- *Acoplanarity $0 < \varphi^* < 2\pi$ is of physical interest, not just $\arccos \mathbf{n}_- \cdot \mathbf{n}_+$.*
- *Distinguish between the two cases $0 < \varphi^* < \pi$ and $2\pi - \varphi^*$*
- *If no separation made the parity effect would wash itself out.*



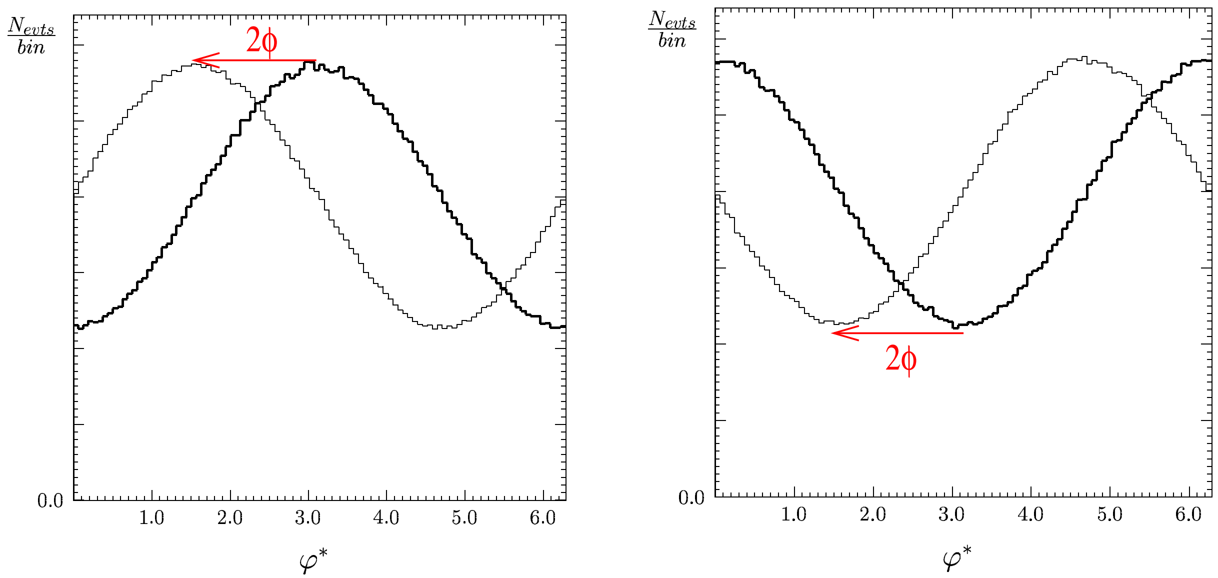

*Normal to planes:* $\mathbf{n}_\pm = \mathbf{p}_{\pi^\pm} \times \mathbf{p}_{\pi^0}$

*Find the sign of* $\mathbf{p}_{\pi^-} \cdot \mathbf{n}_+$

*Negative* $0 < \varphi^* < \pi$

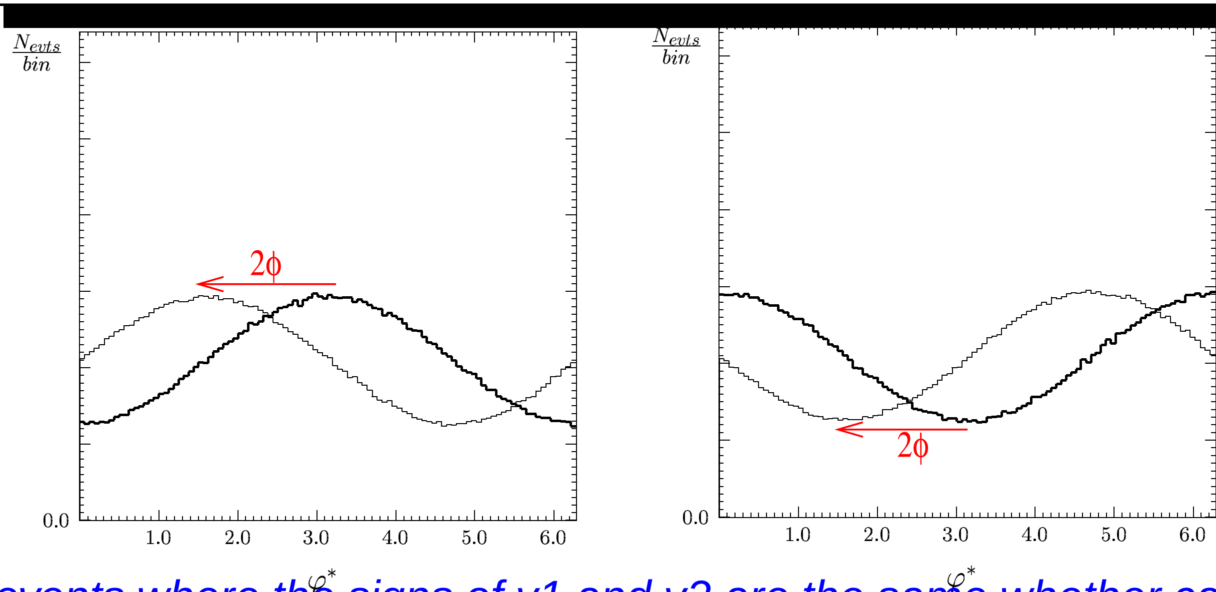
*Otherwise* $2\pi - \varphi^*$

## Results For Mixed Scalar–Pseudoscalar Case




- *The acoplanarity distribution in the rest frame of the* $\rho^+\rho^-$ *pair.*
- *Generator level* $\tau^\pm$ *rest frames are used.*
- *The thick line corresponds to a scalar Higgs boson, the thin line to a mixed one.*
- *The left figure contains events with* $y_1 y_2 > 0$, *the right one is for* $y_1 y_2 < 0$.

## Results For Mixed Scalar–Pseudoscalar Case




- *Only events where the signs of y1 and y2 are the same whether calculated using the method without or with the help of the $\tau$ impact parameter.*
- *Detector-like set-up is included (SIMDET that is TESLA, but with assumptions like for SLAC LC proposal results are similar, ATLAS detector should be OK).*
- *The thick line corresponds to a scalar Higgs boson, the thin line to a mixed one.*

*Precision on $\phi \sim 6^\circ$, for $1ab^{-1}$ and 350 GeV CMS.*

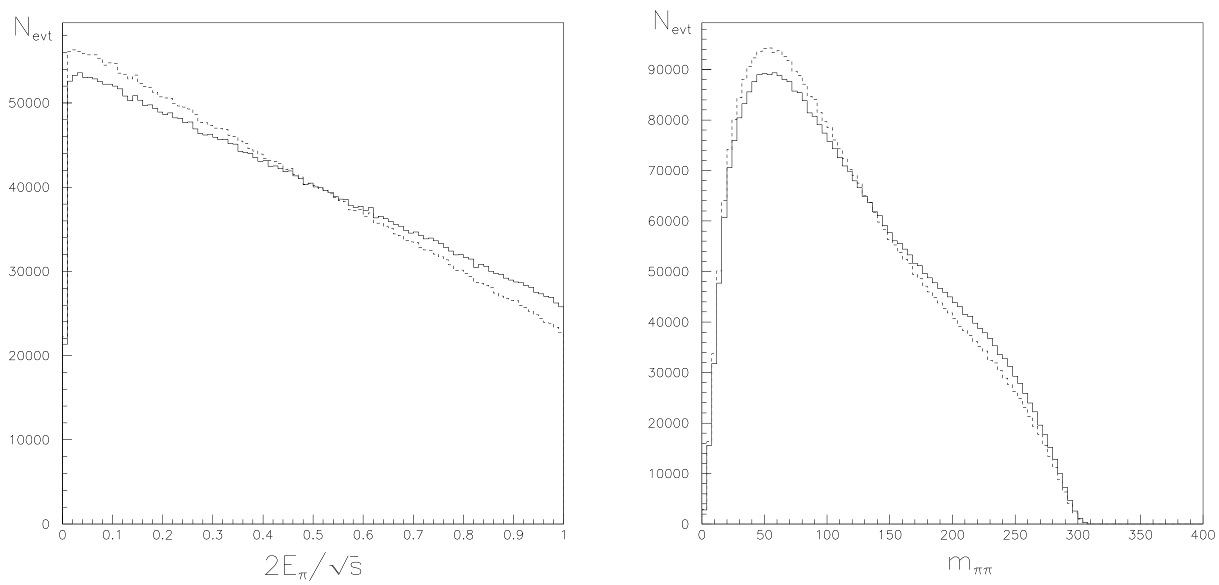
## Some Comments

- *Extended standard universal interface of the TAUOLA with the complete spin effects for $\tau$ leptons originating from the spin zero particle is available.*
- *Interface works with any Monte Carlo generator providing Higgs boson production, and subsequent decay into a pair of $\tau$ leptons.*
- *Promising method for the measurement of the Higgs boson parity using decay chain $H/A^0 \to \tau^+\tau^- \to \rho^+\bar{\nu}_\tau\rho^-\nu_\tau \to \pi^+\pi^0\bar{\nu}_\tau\pi^-\pi^0\nu_\tau$.*
- *The $\rho^+\rho^-$ decay products' acoplanarity distribution clearly distinguish the different parity states $-$ measurable using typical properties of a future detector at an $e^+e^-$ linear collider.*
- *This technique is both model independent and independent of the Higgs production mechanism. Depends only on good measurements of the Higgs decay products.*

## *Systematic Errors*

- *There was very little done into that direction*
- *But case is 'nearly' the same as $Z$ decay at LEP. Necessary studies will need to repeat those done for LEP era MC's: KORALZ KKMC*
- *Even though there is plenty of time to LC era, let us provide hint that we DO think about systematics.*
- *Example will be for LHC and for simulation of $Z \to \tau\tau$ background in Higgs boson searches.*
- *This also to ilustrate that arrangement of the software can work in that case as well.*

## Plots Indicating Size Of Systematic Error LHC Case

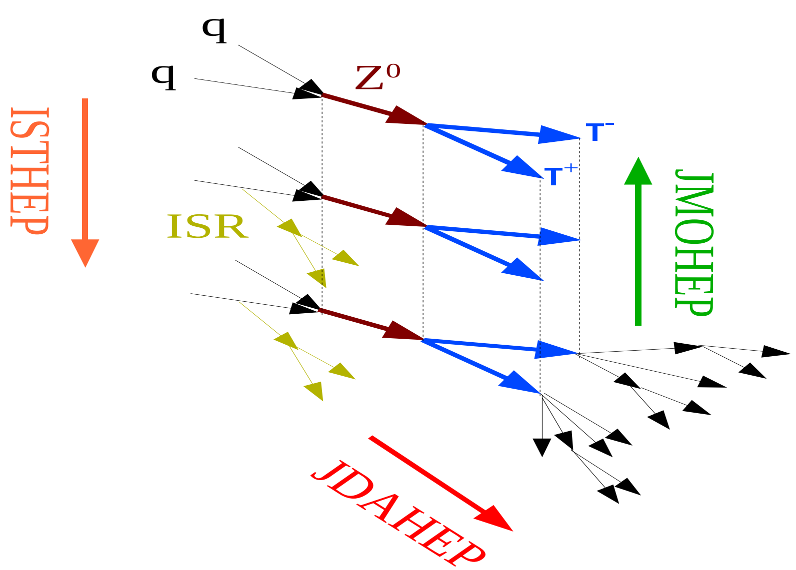



- *In case of LHC simulations it is ambiguous how to reconstruct kinematic of effective $2 \to 2$ hard process used in calulation of spin correlations.*
- *Two options lead to results which are somewhat different, pointing to systematic error.*
- *This must be carefully studied before high precision measurements at LHC (or LC) are to publish their data.*

## *Architecture*

- *To obtain the results special architecture of the software was developed:*
- *Production of Higgs in* $e^+e^- \to ZH$ *with* $H \to \tau^+\tau^-$ *from* `PYTHIA`.
- *Can be HERWIG and/or* $pp \to$ *H + X...*
- `TAUOLA` *universal interface was used for calculation of spin state. Impossible to use spin states of individual* $\tau$*'s !!!*
- `TAUOLA` *for* $\tau$ *decays*
- *Bremsstrahlung in H/A/Z/*$\gamma^*/\tau$ *decays is straighforward to control with the help of* `PHOTOS` *Monte Carlo.*
- *Other systematic errors due to genuine electroweak and QCD interactions were not studied at all so far.*
- *all segments communicate via* `EVENT RECORD` *only.*

## Problems With Event Record




1. Hard process
2. with shower
3. after hadronization
4. Event record overloaded with physics beyond design → gramar problems.
5. Here we have basically $LL$ phenomenology only.

## This Is Physics Not F77!

Similar problems are in any use of full scale Monte Carlos, lots of complaints at MC4LHC workshop, `HEPEVTrepair` utility (C. Biscarat and ZW) being probed in D0.

Design of event structure WITH some grammar requirements AND WITHOUT neglecting possible physics is needed NOW to avoid large problems later.

## Final comments

**This Is Physics Not F77!**

- *Similar problems are for event record filled by HERWIG*
- *In case when hard process is provided by the third party and fourth party is dealing with decays of something, difficulties acumulate.*
- *Non local spin- color-correlations are obstacle; I have shown how use of only kinematical information from main generator can help to overcome.*
- *Do we still need to care?*
- *Lots of arguments for yes, but also some for no.*
- *The problem is that at low precision the answer is no ...*
- *... and turn to yes when NLO corrections have to be included in full.*
- *When is this point? Do we have to worry? For LHC? For GLC?*
- *What is the solution? Black Box Monte Carlo providing all in one?*