TAUOLA and TAUSPINNER for physics with tau signatures at LHC

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Tau decays
Tauola and TauSpinner
Algorithm of TauSpinner
Examples
Other MC generators
Proton-proton scattering at LHC

Hard process $Z/\gamma^* \rightarrow \tau\tau$

\[ |M_{fi}|^2 = \frac{1}{(2s_q + 1)^2} \cdot \sum_{s_q} \sum_{s_\mu} |M_{fi}|^2 \]
Monte Carlo packages

**Tauola**: decay library

package exists since 89 for \(\tau\) decay alone, arrangements for fits to low energy data developed and installed in low energy experiments softwares. The „after-burn” library. Uses information on already generated \(\tau\) and its predecessors/neighbors. Several initializations of \(\tau\) decay matrix elements available for studies of systematics errors (CLEO, Belle, Babar). Phase-space optimised for narrow intermediate resonances: important for studies of technical correctness for current instalations (tests with analytical formulas for \(\Gamma\))

**Tauola++ Interface**: The „after-burn” interface prepared for LHC.

**TauSpinner**: next level of „after-burn”, acts on events with already decayed taus to add/modify spin effects.

**Sherpa, Pythia8, Herwig++**: MC event generators

Now equipped with their own \(\tau\)-decay generation, integrated with production processes including spin correlations; in some cases better models than in Tauola, but tools for tests with low energy data are nonexisting (or are not public)
Separation of $\tau$-lepton production and decay is not a problem, $\Gamma_\tau/m_\tau \ll 1$.

More than 20 distinct decay modes; well known and implemented in MC since years (first version of Tauola in 1989).

- Do not scale with energy, so low-energy experimental results valid at LHC as well; no evolution like for PDF’s
- Leptonic channels described by perturbative formulas (including QED radiation)
- Hadronic decays more difficult, several phenomenological (theoretical) models on the market for different channels; subject of adjusting parametrisations with the data: CLEO, LEP, Belle, Babar
  - Usually best parametrisations are not a public code; issues of unfolded multi-dimensional distributions
  - Often specific to a given experimental analysis; however improvement of particular mode may deteriorate e.g. average charge energy taken over all decay modes.

Question of systematic error requires combined effort of low energy hadronic modeling and low energy $\tau$ data analysis.
Why separating tau decays?

- Natural in the case of embedded $\tau$’s.
  - Embedded events: data events $Z\rightarrow\mu\mu$, where muons are replaced by simulated tau decay; used to model $Z\rightarrow\tau\tau$ background in $H\rightarrow\tau\tau$ analysis
  - Tau decays and spin correlations calculated from final state kinematics, no “history entries” for production process, etc.

- For studying sensitive observables, eg. Higgs CP state, it may be useful to consider $\tau$ decays not as a part of hard-process but as a part of “detection” method.

- Convenience of weight methods for studies on multitude of new physics models.
 Tauola for LHC

N. Davidson et al., Comp. Phys. Com. 183 (2012) 821

S. Jadach et al., Comp. Phys. Com. 76 (1993) 361

E. Richter-Was
Tau Workshop, Mexico, May 2017

Decay List
Static list containing a tau and its daughters which is cleared after each decay. It gets filled by FillHep and is needed as TauolaParticle objects can not be given to TAUOLA directly (only an index can be passed).

LHC interface

Not all relations are shown

Event Generation
Program which generates events with stable taus and calls interface to decay them

TAUOLA in C++

TAUOLA (FORTRAN)

N. Davidson et al., Comp. Phys. Com. 183 (2012) 821

S. Jadach et al., Comp. Phys. Com. 76 (1993) 361

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Tauola for LHC

S. Jadach et al., Comp. Phys. Com. 76 (1993) 361

N. Davidson et al., Comp. Phys. Com. 183 (2012) 821


Program which generates events with decayed taus

TauSpinner
TauSpinner

Package for introducing/modifying spin effects in already generated + decayed taus MC sample or data events with method of event weights.

- Component of the Tauola distribution tarball.
- For calculating event weight $w_t$:
  - Only final state particles used to reconstruct complete event kinematics; special algorithms prepared for handling this.
  - Tauola library used for calculating polarimetric vectors of the decaying taus.
  - Implemented tree level ME for selected processes for spin correlations and polarisation.
- Allows to remove/introduce both longitudinal and transverse spin correlations for taus from resonance decays: $Z, Z+2j, H, W^{\pm},$ and MSSM $A, H^{\pm}$. 
Separation of $\tau$-lepton production and decay is not a problem, $\Gamma_\tau/m_\tau \ll 1$.
For processes $pp \rightarrow \tau^+\tau^- X; \tau \rightarrow Y\nu$ cross-section reads

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

Matrix element phase-space element

$$M = \sum_{\lambda_1 \lambda_2 = 1}^2 M_{\lambda_1 \lambda_2}^{prod} M_{\lambda_1}^{\tau^+} M_{\lambda_2}^{\tau^-}. \quad (\lambda = 1, 2)$$

spin projection

This formalism is fine but because of 20 distinct decay modes we have over 400 distinct processes.
Cross-section can be rewritten further, still exact formula

\[
d\sigma = \left( \sum_{\lambda_1 \lambda_2} |M^{prod}|^2 \right) \left( \sum_{\lambda_1} |M^{\tau^+}|^2 \right) \left( \sum_{\lambda_2} |M^{\tau^-}|^2 \right) wt_{spin} \ d\Omega_{prod} \ d\Omega_{\tau^+} \ d\Omega_{\tau^-}.
\]

\[
wt_{spin} = \sum_{i,j=t,x,y,z} R_{i,j} h_i^{\tau^+} h_j^{\tau^-},
\]

Useful properties:  \( < wt_{spin} > = 1 \), \( 0 < wt_{spin} < 4 \)

Spin weight contains information of all spin effects transmitted from the production to the decay of \( \tau \) leptons.

This is a core formula for TauSpinner algorithm.
Polarimetric vectors are calculated for each $\tau$ decay kinematics

$$h_{\tau}^{i} = \sum_{\lambda, \bar{\lambda}} \sigma_{\lambda, \bar{\lambda}}^{i} M_{\lambda}^{\tau \pm} M_{\bar{\lambda}}^{\tau \pm}$$

where $\sigma_{\lambda, \bar{\lambda}}^{i}$ stands for Pauli matrices, and then normalised further to set their time component to 1, taking

$$h_{\tau}^{i} = \frac{h_{\tau}^{i}}{h_{\tau}^{\pm}}.$$

Polarimetric vectors depends only on $\tau$ lepton decay mode.
Spin correlation matrix $R_{ij}$

Spin correlations matrix

$$R_{ij} = \sum_{\lambda_1, \bar{\lambda}_1 \lambda_2, \bar{\lambda}_2} \sigma^i_{\lambda_1, \bar{\lambda}_1} \sigma^j_{\lambda_2, \bar{\lambda}_2} M_{\lambda_1 \lambda_2}^{\text{prod}} M_{\bar{\lambda}_1 \bar{\lambda}_2}^{\text{prod} \dagger}$$

Also normalised to set its time component $R_{00}=1$. $R_{ij}$ is calculated from $\tau$ lepton production process. The definition of $R_{ij}$ is rather lengthy, see references

Spin correlations matrix

\[ R = \begin{pmatrix} 1 & 0 & 0 & 2P_z(\cos \theta) - 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 2P_z(\cos \theta) - 1 & 0 & 0 & 1 \end{pmatrix} \]

\[ P_z(s, \theta) = \frac{d\sigma(s,\theta,+,+)}{d\Omega} + \frac{d\sigma(s,\theta,-,-)}{d\Omega} \]

\[ P_z(\cos \theta) \text{ calculated from Born 2->2 matrix elements.} \]

Longitudinal tau polarisation is then defined as

\[ P_\tau = R_{zt} = 2P_z(\cos \theta) - 1. \]

T. Pierzhchala et al., hep-ph/0101311

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Frames used use in TauSpinner

Several frames used for calculating components of the basic formula

(A) Rest frame of tau lepton pairs with incoming partons along $z$-axis: for calculating production matrix element and $R_{ij}$

(B) Rest frame of tau lepton pairs with tau leptons along $z$-axis: for constactiong polarimetric vectors $h_i$, $h_j$ with $R_{ij}$.

(C1, C2) Rest frames of individual tau leptons with boost direction to tau-pair rest frame along $z$-axis.

(D1, D2) Rest frames of individual tau leptons with neutrino along $z$-axis. For calculating polarimetric vectors which are boosted/rotated back to (B)
Relative orientation of all axises for all these frames is essential if we want to control transverse spin correlations

- Configuration of hard process: flavors and 4-momenta of incoming quarks and outgoing tau’s (ν)
- Algorithm for spin correlations has no approximations
- Density matrix may include EW corrections
- Helicity states are attributed at the end and then approximation is used.
We do not have at disposal matrix element for complete pp-$\to\tau\tau X$ processes; factorisation theorem

\[ d\sigma = \sum_{\text{flavours}} \int dx_1 dx_2 f(x_1, \ldots) f(x_2, \ldots) d\Omega_{\text{prod}}^{\text{parton level}} d\Omega_{\tau^+} d\Omega_{\tau^-} \]

\[ \left( \sum_{\lambda_1, \lambda_2} |M_{\text{prod}}^{\text{parton level}}|^2 \right) \left( \sum_{\lambda_1} |M^{\tau^+}|^2 \right) \left( \sum_{\lambda_2} |M^{\tau^-}|^2 \right) w_{t_{\text{spin}}}. \]

The $R_{ij}$ used in calculation of $w_t$, is taken as an average (with PDFs and production matrix squared) over all flavour configurations

\[ R_{ij} \rightarrow \left[ \sum_{\text{flavours}} f(x_1, \ldots) f(x_2, \ldots) \left( \sum_{\lambda_1, \lambda_2} |M_{\text{prod}}^{\text{parton level}}|^2 \right) R_{ij} \right] / \]

\[ \left[ \sum_{\text{flavours}} f(x_1, \ldots) f(x_2, \ldots) \left( \sum_{\lambda_1, \lambda_2} |M_{\text{prod}}^{\text{parton level}}|^2 \right) \right]. \]
More on spin weight

Bell inequalities tells us that we cannot factorise further $wt$ into form

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

But iterative solutions like in HERWIG++ exists: treat decays of $\tau'$s in an ordered way.

Spin weight $wt$ can be calculated after event generation is completed and detector simulated. It can be also calculated for embedded $\tau$ samples.

(embedded sample: data $Z \to \mu\mu$ event, where muon is replaced by simulated tau decay)
To introduce modification due to different spin effects, modified production process or decay model in the generated sample and without re-generation of events one can use the weight $WT$, ratio of cross-section at each point in the phase-space.

The modified cross-section takes then the form

$$d\sigma = \sum_{\text{flavours}} \int dx_1 dx_2 f(x_1, \ldots) f(x_2, \ldots) d\Omega_{\text{prod level}}^{\text{parton}} d\Omega_{\tau^+} d\Omega_{\tau^-} \left( \sum_{\lambda_1, \lambda_2} |M_{\text{prod level}}^{\text{parton}}|^2 \right) \left( \sum_{\lambda_1} |M^{\tau^+}|^2 \right) \left( \sum_{\lambda_2} |M^{\tau^-}|^2 \right) \text{wt}_{\text{spin}}^{WT}.$$
The weight $WT$ factorizes into multiplicative components.

\[ WT = wt_{prod} \cdot wt_{\tau^+} \cdot wt_{\tau^-} \cdot \frac{wt_{spin \ new}}{wt_{spin \ old}} \]

- $wt_{prod}$
  \[ wt_{prod} = \frac{\sum_{flavours} f(x_1, \ldots) f(x_2, \ldots) \left( \sum_{spin} |M_{parton \ level}^{prod}|^2 \right)_{new}}{\sum_{flavours} f(x_1, \ldots) f(x_2, \ldots) \left( \sum_{spin} |M_{parton \ level}^{prod}|^2 \right)_{old}} \]

- $wt_{\tau^\pm}$
  \[ wt_{\tau^\pm} = \frac{\sum_{spin} |M_{new}^{\tau^\pm}|^2}{\sum_{spin} |M_{old}^{\tau^\pm}|^2} \]

- eg. new matrix element for production process
- eg. introducing polarisation
- eg. introducing new parametrisation for hadronic current
Spin effects can be added/modified into sample after $\tau$ decay. Polarised (red) sample is generated and green (unpolarised) is obtained with weight $1/\text{wt}$. Case of $pp\rightarrow Z/\gamma^*\rightarrow \tau\tau$

Shown is also results of fits to analytical formulas.

A. Kaczmarska et al., arXiv:1402.2068
TauSpinner: longitudinal spin correlations

- Allows to add/modify longitudinal spin correlations.

A. Kaczmarska et al., arXiv:1402.2068

\[ Z \rightarrow \tau^+\tau^-; \tau^\pm \rightarrow \pi^\pm \nu_\tau \]

\[ \Phi \rightarrow \tau^+\tau^-; \tau^\pm \rightarrow \pi^\pm \nu_\tau \]
**TauSpinner: EW loop corrections**

Allows to add EW loop corrections to $q \bar{q} \rightarrow Z/\gamma^* \rightarrow \tau\tau$ events, implemented as correcting weight.

EW loop corrections tabulated from SANC library.

- **Born $\alpha$ scheme**
- **Born effective**
- **Born + EW loops+boxes**

N. Davidson et al., Comp. Phys. Com. 183 (2012) 821-843

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**Plots:**

- **Up quarks**
  - $P_\tau (\cos \theta)$ vs $\sqrt{s} [\text{GeV}]$

- **Down quarks**
  - $P_\tau (\cos \theta)$ vs $\sqrt{s} [\text{GeV}]$

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E. Richter-Was
Tau Workshop, Mexico, May 2017
Simulating spin effects using different matrix elements. Calculate weight using 2->2 or 2->4 matrix element. Access systematics on predicted polarisation.

\[ w_{A \to B}^{prod} = \frac{\sum_{i,j,k,l} f_i^B(x_1) f_j^B(x_2) |M_{i,j,k,l}^B| p_1, p_2, p_3, p_4|^2}{\sum_{i,j,k,l} f_i^A(x_1) f_j^A(x_2) |M_{i,j,k,l}^A| p_1, p_2, p_3, p_4|^2} \]

A: 2 -> 2 process

B: 2 -> 4 process
Simulating spin effects using different matrix elements. Calculate weight using 2->2 or 2->4 matrix element. Access systematics on predicted polarisation.

Tau lepton polarisation from Z decay, $P_\tau$, with different EW schemes

<table>
<thead>
<tr>
<th>EW parameter (sensitive)</th>
<th>EW scheme</th>
<th>Polarisation (2→2)</th>
<th>Polarisation (2→4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_W = 0.222246$</td>
<td>EWSH=1</td>
<td>$-0.2140 \pm 0.0004$</td>
<td>$-0.2134 \pm 0.0004$</td>
</tr>
<tr>
<td>$\sin^2 \theta_W = 0.231470$</td>
<td>EWSH=2</td>
<td>$-0.1488 \pm 0.0008$</td>
<td>$-0.1487 \pm 0.0008$</td>
</tr>
<tr>
<td>$\sin^2 \theta_W = 0.222246$</td>
<td>EWSH=3</td>
<td>$-0.2140 \pm 0.0008$</td>
<td>$-0.2144 \pm 0.0008$</td>
</tr>
<tr>
<td>$\sin^2 \theta_W = 0.231470$</td>
<td>EWSH=4</td>
<td>$-0.1488 \pm 0.0008$</td>
<td>$-0.1486 \pm 0.0008$</td>
</tr>
</tbody>
</table>

Recommended


E. Richter-Was

Tau Workshop, Mexico, May 2017
Reweighting between different Higgs boson production subprocesses. ME are spin aware.

J. Kalinowski et al., arXiv:1604.00964
Example is implementing resonances with TauSpinner weights. Shown is invariant mass and $\cos\theta^*$ distribution for resonance production: $Z \rightarrow \tau\tau$, $X \rightarrow \tau\tau$, $H \rightarrow \tau\tau$

Resonance spin = 2
(weight method)

Higgs boson CP state

Higgs boson CP state is encoded in the tau-tau transverse spin correlations

Angle between decay planes is best observable to measure this

**scalar**

\[ h^0 \]

CP-even (SM), \( \phi_\tau = 0 \)

\[ \mathcal{L}_{h^0\tau\bar{\tau}} = -g_\tau \cdot \bar{\tau}\tau h \]

\( J^{PC} = 0^{++} \)

\( L_{\tau\bar{\tau}} = 1, \ S_{\tau\bar{\tau}} = 1 \)

**pseudoscalar**

\[ A^0 \]

CP-odd, \( \phi_\tau = \frac{\pi}{2} \)

\[ \mathcal{L}_{A^0} = -g_\tau \cdot \bar{\tau}i\gamma_5\tau h \]

\( J^{PC} = 0^{-+} \)

\( L_{\tau\bar{\tau}} = 0, \ S_{\tau\bar{\tau}} = 0 \)
Allows to add **transverse spin correlations** to any mixture of scalar-pseudoscalar state; 
Shown here CP sensitive observables;

**Acoplanarity** alone brings no sensitivity; one must split into categories using

\[ y_\rho^\pm = \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}} \]
Adding more decay modes to study Higgs CP


Adding \( \tau^+ \rightarrow a_1^+ \nu, a_1^+ \rightarrow 3 \pi^\pm; \tau^+ \rightarrow \rho^- \nu, \rho^- \rightarrow \pi^0 \pi^-; \)
mode increases available statistics for analysis by factor 2. Cascade decays: more combinations of decay planes.
Calls for multi-variate methods to access CP state

TABLE I: Branching ratios of the \( \tau \) lepton decay modes [22], and resulting cumulated fraction of \( H \rightarrow \tau \tau \) events available for parity analysis.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Cascade decay</th>
<th>( \tau ) BR.</th>
<th>Cumul. frac.</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^\pm \rightarrow \rho^\pm \nu )</td>
<td>( \rho^\pm \rightarrow \pi^0 \pi^\pm )</td>
<td>25.5%</td>
<td>6.5%</td>
<td>Yes</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow a_1^\pm \nu )</td>
<td>( a_1^\pm \rightarrow \rho^0 \pi^\mp ), ( \rho^0 \rightarrow \pi^+ \pi^- )</td>
<td>9.0%</td>
<td>11.9%</td>
<td>Yes</td>
</tr>
<tr>
<td>( \tau^\pm \rightarrow a_1^\pm \nu )</td>
<td>( a_1^\pm \rightarrow 2\pi^0 \pi^\mp )</td>
<td>9.3%</td>
<td>19.2%</td>
<td>No</td>
</tr>
</tbody>
</table>
TauSpinner: transverse spin correlations

Use Deep Neural Network for classification; allows to explore non-linear correlations between variables.

Calculate features in frames, which removed trivial rotation symmetries, so NN does not have to learn them.

**TABLE II:** Dimensionality of the features which may be used in each discussed configuration of the decay modes.

<table>
<thead>
<tr>
<th>Features/variables</th>
<th>Decay mode: $\rho^{\pm} - \rho^{\mp}$</th>
<th>Decay mode: $a_1^{\pm} - \rho^{\mp}$</th>
<th>Decay mode: $a_1^{\pm} - a_1^{\mp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varphi_{i,k}$</td>
<td>1</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>$\varphi_{i,k}$ and $y_i, y_k$</td>
<td>3</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td>$\varphi_{i,k}$, 4-vectors</td>
<td>25</td>
<td>36</td>
<td>64</td>
</tr>
<tr>
<td>$\varphi_{i,k}$, $y_i, y_k$ and $m_i, m_k$</td>
<td>5</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>$\varphi_{i,k}$, $y_i, y_k$, $m_i, m_k$ and 4-vectors</td>
<td>29</td>
<td>45</td>
<td>78</td>
</tr>
</tbody>
</table>

$y_i$ helps in separation into CP sensitive categories

$$y_{\rho}^{\pm} = \frac{E_{\pi^{\pm}} - E_{\pi^0}}{E_{\pi^{\pm}} + E_{\pi^0}}$$  
$$y_{\rho^0}^{\pm} = \frac{E_{\pi^0} - E_{\pi^\pm}}{E_{\rho^0} + E_{\pi^\pm}}$$  
$$y_{a_1}^{\pm} = \frac{E_{\rho^0} - E_{\pi^\pm}}{E_{\rho^0} + E_{\pi^\pm}} - \frac{m_{a_1}^2 - m_{\pi^\pm}^2 + m_{\rho^0}^2}{2m_{a_1}^2}$$
Transverse spin correlations added as weight calculated with TauSpinner. This allows to analyse statistically correlated samples. Shown results for scalar/pseudoscalar classification score per event.

<table>
<thead>
<tr>
<th>Features/variables</th>
<th>Decay mode: $a_1^\pm \rightarrow \rho^\mp$, $a_1^\pm \rightarrow \rho^0 \pi^\mp$, $\rho^0 \rightarrow \pi^+ \pi^-$, $\rho^\mp \rightarrow \pi^0 \pi^\mp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>True classification</td>
<td>$\varphi_{i,k}$</td>
</tr>
<tr>
<td></td>
<td>$\varphi_{i,k}$ and $y_i, y_k$</td>
</tr>
<tr>
<td>4-vectors</td>
<td>$\varphi_{i,k}$, 4-vectors</td>
</tr>
<tr>
<td></td>
<td>$\varphi_{i,k}$, $y_i, y_k$ and $m_i^2, m_k^2$</td>
</tr>
<tr>
<td></td>
<td>$\varphi_{i,k}$, $y_i, y_k$, $m_i^2, m_k^2$ and 4-vectors</td>
</tr>
<tr>
<td>NN score</td>
<td>0.782</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
</tr>
<tr>
<td></td>
<td>0.569</td>
</tr>
<tr>
<td></td>
<td>0.590</td>
</tr>
<tr>
<td></td>
<td>0.594</td>
</tr>
<tr>
<td></td>
<td>0.578</td>
</tr>
<tr>
<td></td>
<td>0.596</td>
</tr>
</tbody>
</table>

![Graph showing NN score for different classifications](image)
Transverse spin correlations added as weight calculated with TauSpinner. This allows to analyse statistically correlated samples. Shown results for scalar/pseudoscalar classification score per event.

<table>
<thead>
<tr>
<th>Features/variables</th>
<th>Decay mode: $\rho^\pm - \rho^\mp$</th>
<th>Decay mode: $a_1^\pm - \rho^\mp$</th>
<th>Decay mode: $a_1^\pm - a_1^\mp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>True classification</td>
<td>0.782</td>
<td>0.782</td>
<td>0.782</td>
</tr>
<tr>
<td>$\varphi_{i,k}$</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
</tr>
<tr>
<td>$\varphi_{i,k}$ and $y_i, y_k$</td>
<td>0.624</td>
<td>0.569</td>
<td>0.536</td>
</tr>
<tr>
<td>4-vectors</td>
<td>0.638</td>
<td>0.590</td>
<td>0.557</td>
</tr>
<tr>
<td>$\varphi_{i,k}$; 4-vectors</td>
<td>0.638</td>
<td>0.594</td>
<td>0.573</td>
</tr>
<tr>
<td>$\varphi_{i,k}$; $y_i, y_k$ and $m_i^2, m_k^2$</td>
<td>0.626</td>
<td>0.578</td>
<td>0.548</td>
</tr>
<tr>
<td>$\varphi_{i,k}$; $y_i, y_k$, $m_i^2$, $m_k^2$ and 4-vectors</td>
<td>0.639</td>
<td>0.596</td>
<td>0.573</td>
</tr>
</tbody>
</table>
Artificial Neural Network have spurred remarkable recent progress in image classification and speech recognition. But even though there are very useful tools based on well-known mathematical methods, we actually understand surprisingly little of why certain models work and others don’t. From [http://googleresearch.blogspot.com/2015/06/inceptionism-going-deeper-into-neural.html](http://googleresearch.blogspot.com/2015/06/inceptionism-going-deeper-into-neural.html)
Preparation for fitting CP state mixing angle with NN approach

Deep NN classification score per event

<table>
<thead>
<tr>
<th>Features/variables</th>
<th>$\phi^{CP} = 0.2$</th>
<th>$\phi^{CP} = 0.3$</th>
<th>$\phi^{CP} = 0.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>True classification</td>
<td>0.560</td>
<td>0.588</td>
<td>0.616</td>
</tr>
<tr>
<td>$\varphi^*, y_i, y_k, m_i^2, m_k^2$</td>
<td>0.526</td>
<td>0.540</td>
<td>0.553</td>
</tr>
</tbody>
</table>

1D observable

- $\rho^0 \to \pi^0 \pi^0$ rest-frame
- $\gamma' \gamma' < 0$
- $\rho^0$, Scalar
- $\phi^{CP} = 0.2$
- $\phi^{CP} = 0.4$
Modelling of tau decays dependent on parameterisation of vector currents. Variations are evaluated as systematics.

Available parameterisations:
- CLEO - Standard in Tauola
- Resonance Chiral Lagrangian
- Alternative CLEO current (never fully published by collaboration)
- BaBar (also not published)
Variations in AUC score not significant, at 1% level.

<table>
<thead>
<tr>
<th></th>
<th>CLEO</th>
<th>(R_{\chi}L)</th>
<th>Alt. CLEO</th>
<th>BaBar</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho-a_1)</td>
<td>(\varphi^*, y)</td>
<td>0.584</td>
<td>0.582</td>
<td>0.583</td>
</tr>
<tr>
<td></td>
<td>(\varphi^*, y, m)</td>
<td>0.594</td>
<td>0.595</td>
<td>0.595</td>
</tr>
<tr>
<td></td>
<td>(\varphi^*, 4\text{-vec})</td>
<td>0.602</td>
<td>0.602</td>
<td>0.602</td>
</tr>
<tr>
<td>(a_1-a_1)</td>
<td>(\varphi^*, y)</td>
<td>0.541</td>
<td>0.538</td>
<td>0.537</td>
</tr>
<tr>
<td></td>
<td>(\varphi^*, y, m)</td>
<td>0.552</td>
<td>0.550</td>
<td>0.550</td>
</tr>
<tr>
<td></td>
<td>(\varphi^*, 4\text{-vec})</td>
<td>0.571</td>
<td>0.566</td>
<td>0.567</td>
</tr>
</tbody>
</table>

B. Le et al., in preparation

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E. Richter-Was

Tau Workshop, Mexico, May 2017
Nowadays several tools available for simulating $\tau$ decays:

- Stand-alone library: **Tauola** *(Tauola++ interface, TauSpinner)*
- Integrated with event generators: **Pythia8**, **Herwig++**, **Sherpa**

Each tool provides solution for controlling longitudinal and transverse spin correlations and QED bremsstrahlung.

Each tool implements often more than one model for a given decay chain.

**Precision tau physics with Run II data:**

- Use more than one generator to study systematics.
- Be able to use low energy data for studying systematics. Comparisons of different theoretical models is good but counter examples are known, see the $\sigma$ story (slide 10).
- Be able to modify spin correlations, $\tau$ decay model or $\tau$ production process on already simulated events with weight method important to gain flexibility and save CPU /disc space need.
- Have equally matured solutions for embedded $\tau$’s samples as for MC based samples.
Strategy for evaluating systematics error from $\tau$-lepton simulation depends on the answers to following questions:

- Do we want to use same parameterizations in all generators, to avoid problem with differences in acceptances etc.? Or do we want flexibility to study different models for our systematics?

- Do we want to use $\tau$ production and decay integrated in the physics generator? No need to control technical interfaces then but as consequence no profits from potential better flexibility (eg. studying systematics with weights correcting models)?

- Do we want systematic error on decay simulation based on comparison of different theoretical models or on confrontation with data from Belle and Babar?
Recent updates on models used:

Code in fortran:
natural consequence of serving both low (Belle, Babar) and high energy (LHC) experiments. Interfaces in C++ (see next page)

Prospects:
Better control of systematic error: fits with low energy experimental data with use of weighted events or semianalitical formulas for unfolded invariant masses distributions.
**Documentation:** Comp. Phys. Com. 183 (2012) 821-843
http://tauolapp.web.cern.ch/tauolapp/

**Code in C++:**
serves as interface to HepMC event record and upstream MC generators
BUT as well:
With weights methods allows to introduce spin correlations density matrix into already generated $\tau$ decays (also when information not provided in HepMC event record). Allows to remove/modify such correlations. Very handy to study systematic effects on already simulated sample.

**Prospects:**
Adaptation to new versions of event record.
Evaluation of systematics errors related to spin weights: analysis of matrix elements and PFD’s syst.
Documentation:

Code in C++:
With weights methods allows to introduce/modify spin correlations on already \( \tau \) decayed events.
Do not require information from the event record.

Prospects:
VBF processes: ME calculated for \( qq \rightarrow \tau \tau \) jet jet
Pythia8

Documentation: arXiv:1401.4902 (PhD theses)

Code in C++: fully integrated with MC generator
- Spin correlations: The modified version of Collins-Knowledges algorithm (arXiv:0110108); similar to the one implemented in Herwig++.
- Radiative QED corrections: implemented
- Comparison with generic TAUOLA library documented.

Prospects:
Current implementation stable but still being actively developed with improvements such as new models and parameters setting.
Sherpa

**Documentation:** T. Laubrich diploma theses (2006)


**Code in C++:** fully integrated with event generator

- Several $\tau$ – lepton decay models; 38 decay channels
- Extended comparison with experimental data or generic TAUOLA library documented.
- **Spin correlation:** algorithm fully implemented
  - leptonic tau decays, you can use the full matrix element (optionally in the narrow-width approximation) and automatically have all correlations
  - for all types of tau decays implemented tau decay "after burner" (Sec. 8 of the documentation) after producing $pp \rightarrow \tau\tau$ on shell, which preserves spin correlations by passing spin density matrices back and forth a la hep-ph/0110108 case. One can also choose to disable spin correlations for testing purposes
- **Radiative QED corrections:** in leptonic decays: implemented through the YFS formalism, in the leptonic decays with exact $O(\alpha)$ corrections.

**Prospects:**

Code mature and stable, planned adding more decay channels but not with high priority.
Documentation: arXiv:07101951v1

Code in C++: integrated with event generator

- Extended comparison with generic TAUOLA library documented

Prospects:

Code mature and stable, planned adding more decay channels but not with high priority.