TAUOLA and TAUSPINNER for physics with tau signatures at LHC

E. Richter-Was, Institute of Physics UJ

Tau decays

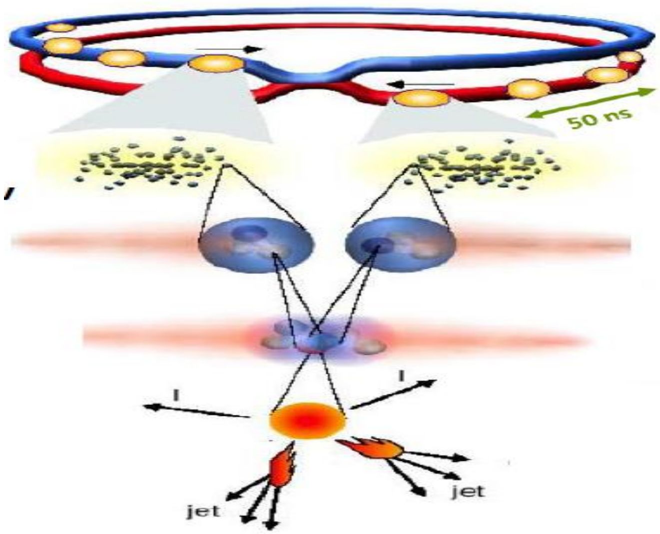
Tauola and TauSpinner

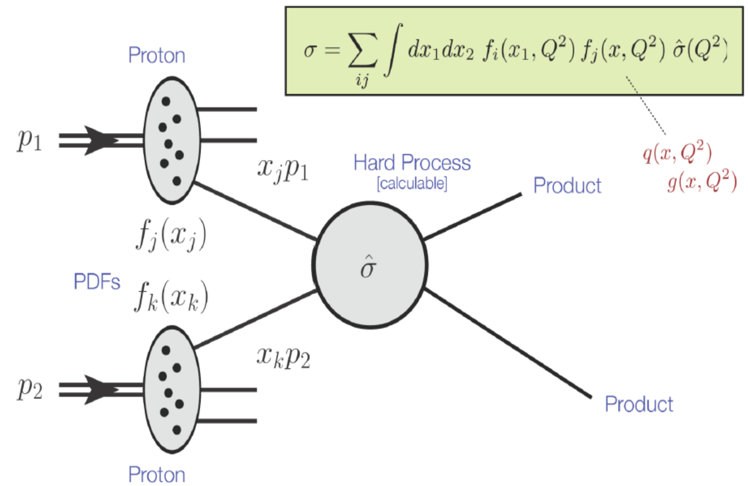
Algorithm of TauSpinner

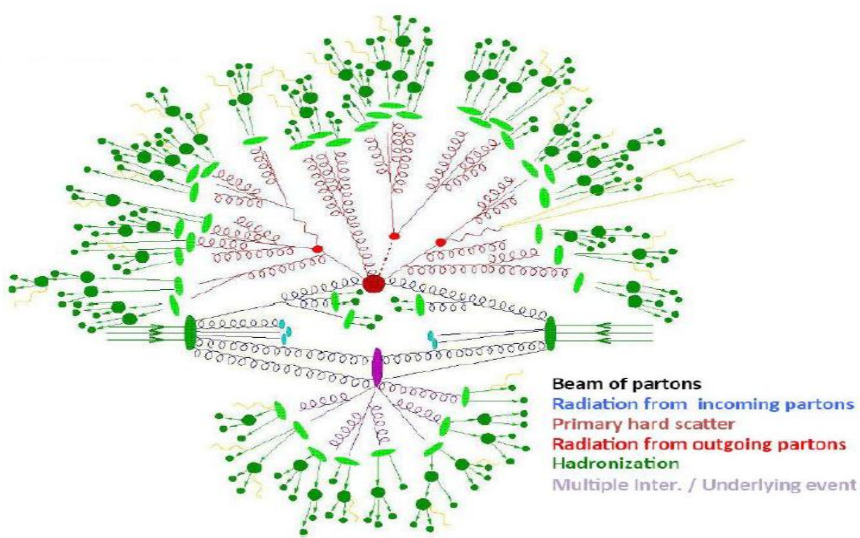
Examples

Other MC generators

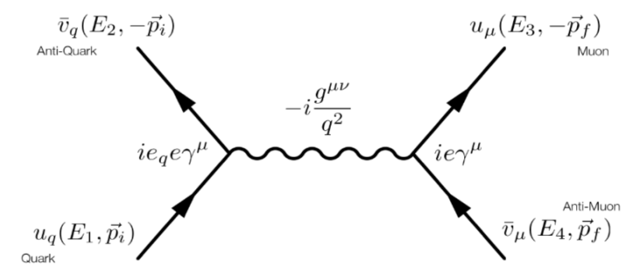
Proton-proton scattering at LHC







Hard process Z/γ*-> ττ



Averaging over initial spins

Summing over initial and final spins

$$\overline{|M_{fi}|^2} = \frac{1}{(2s_q+1)^2} \cdot \sum_{s_q, s_q'} \sum_{s_\mu, s_\mu'} |M_{fi}|^2$$

Monte Carlo packages

Tauola: decay library

package exists since 89 for τ 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 τ and its predecessors/neighbors. Several initializations of τ 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 Γ)**

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 τ-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)

Tau decays

Separation of τ-lepton production and decay is not a problem, $\Gamma_t/m_t << 1$.

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 τ data analysis.

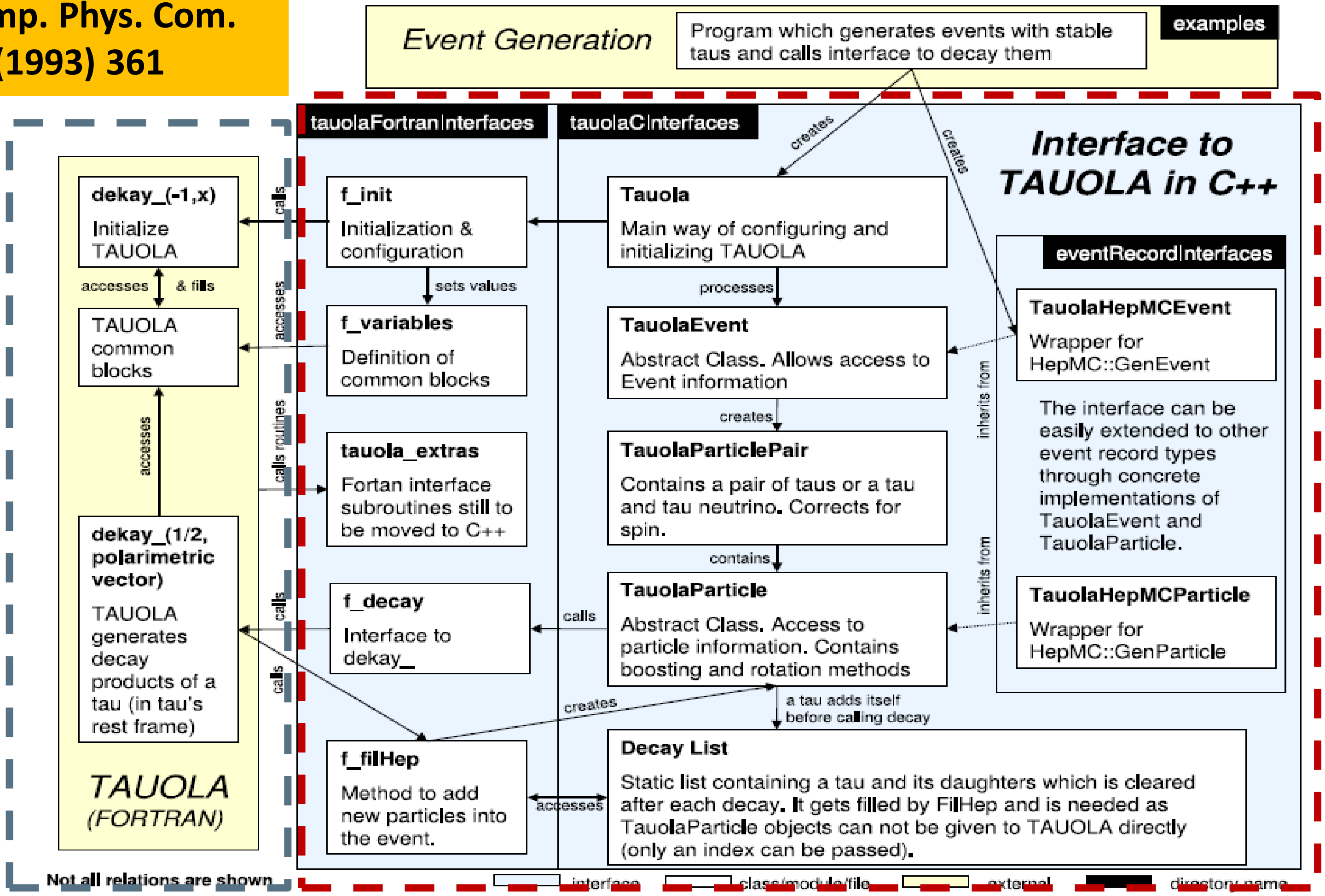
Why separating tau decays?

- Natural in the case of embedded τ's.
  - Embedded events: data events Z->$\mu\mu$, where muons are replaced by simulated tau decay; used to model Z->$\tau\tau$ background in H->$\tau\tau$ 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 τ 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



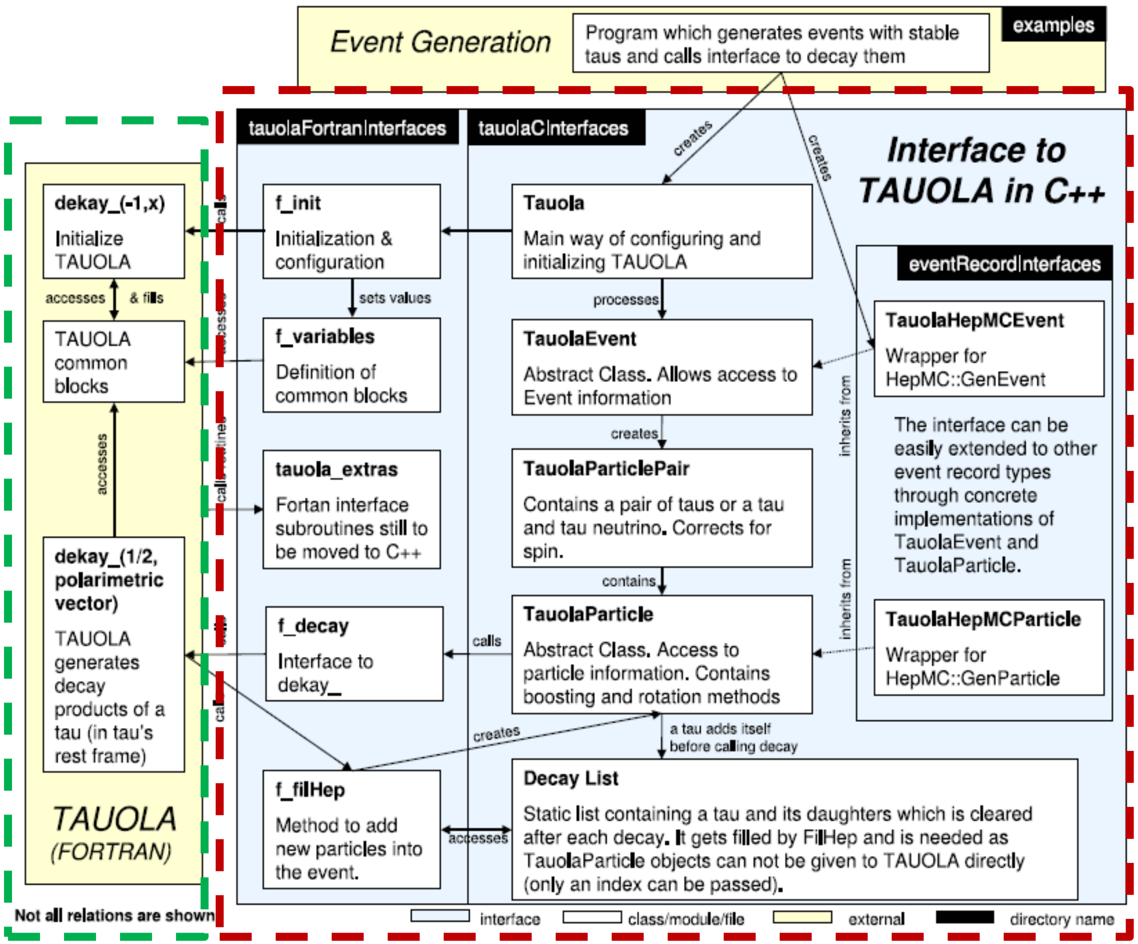
LHC interface

Tauola for LHC

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

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

Z. Czyczula et al.,
Eur. Phys. J. C72 (2012) 1988



Program which generate 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 wt:**
  - **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^{+-}, and MSSM A, H^{+-}.**

TaySpinner: basic formulas

Separation of τ-lepton production and decay is not a problem, $\Gamma_\tau/m_\tau << 1$.

For processes pp-> $\tau^+\tau^-$ X; τ-> $Y\nu$ cross-section reads

$$d\sigma = |\mathcal{M}|^2 d\Omega = \underbrace{|\mathcal{M}|^2}_{\text{Matrix element}} \underbrace{d\Omega_{prod}\, d\Omega_{\tau^+}\, d\Omega_{\tau^-}}_{\text{phase-space element}}$$

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

spin projection

This formalism is fine but because of 20 distinct decay modes we have over 400 distinct processes.

TauSpinner: basic formulas

Cross-section can be rewritten further, still exact formula

$$d\sigma = \Big(\sum_{\lambda_1\lambda_2} |\mathcal{M}^{prod}|^2\Big)\Big(\sum_{\lambda_1} |\mathcal{M}^{\tau^+}|^2\Big)\Big(\sum_{\lambda_2} |\mathcal{M}^{\tau^-}|^2\Big) wt_{spin}\, d\Omega_{prod}\, d\Omega_{\tau^+}\, d\Omega_{\tau^-}.$$

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

spin weight

polarimetric vectors

density matrix

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 τ leptons.

This is a core formula for TauSpinner algorithm.

Polarimetric vectors h_τ

Polarimetric vectors are calculated for each τ decay kinematics

$$h^i_{\tau^\pm} = \sum_{\lambda,\bar{\lambda}} \sigma^i_{\lambda,\bar{\lambda}} \mathcal{M}^{\tau^\pm}_{\lambda} \mathcal{M}^{\tau^\pm\,\dagger}_{\bar{\lambda}}$$

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

$$h^i_{\tau^\pm} = \frac{h^i_{\tau^\pm}}{h^t_{\tau^\pm}}.$$

Polarimetric vectors depends only on τ lepton decay mode.

Spin correlation matrix R_{ij}

Spin correlations matrix

production process

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

Also normalised to set its time component R_{00}=1.

R_{ij} is calculated from τ lepton production process.

The definition of R_{ij} is rather lengthy, see references

S. Jadach and Z. Was, *Acta Phys. Polon.* **B15** (1984) 1151, Erratum: **B16** (1985) 483.

S. Jadach, Z. Wąs, R. Decker, and J. H. Kü, *Comput. Phys. Commun.* **76** (1993) 361.

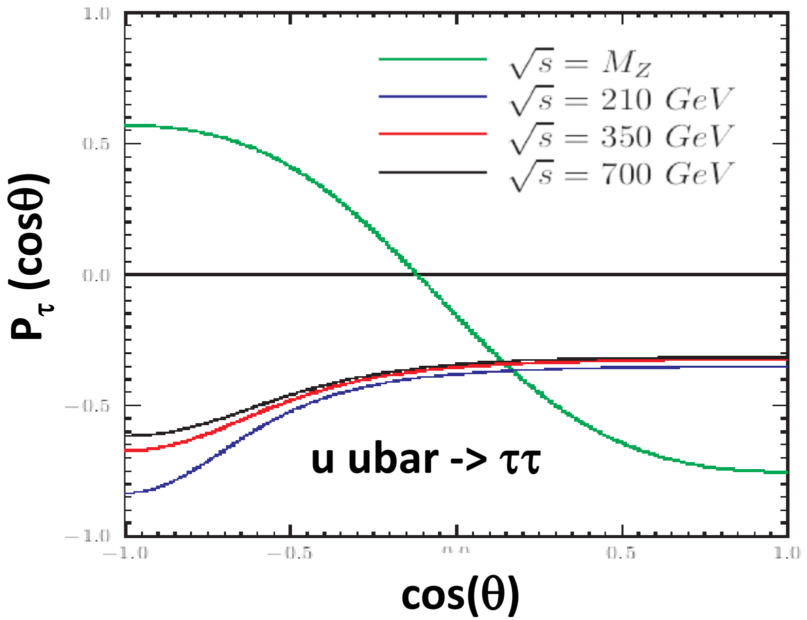
Example: Drell-Yan   qqbar -> Z/γ*-> ττ

Spin correlations matrix

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

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

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

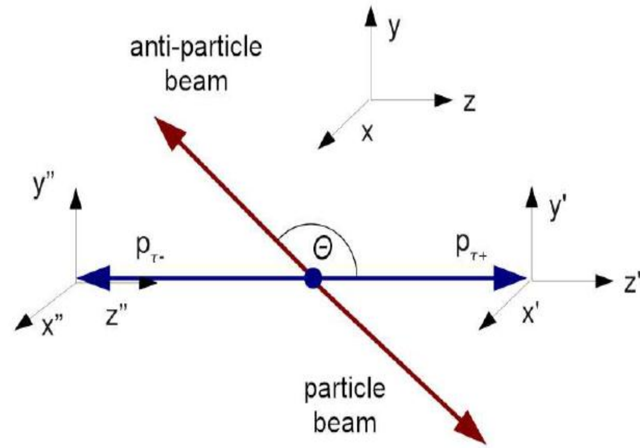


P_z (cosθ) calculated from Born 2->2 matrix elements.

Longitudinal tau polarisation is then defined as

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

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}

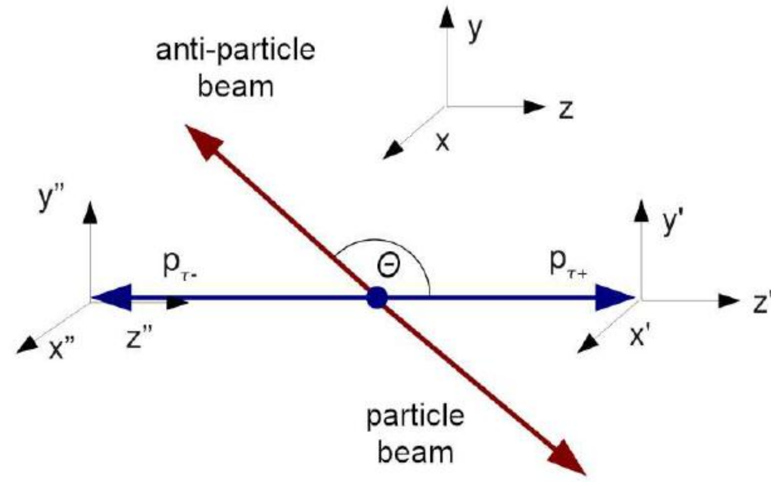
(B) Rest frame of tau lepton pairs with tau leptons along z-axis: for constacting polarimetric vectors hi, hj with R_{ij}.

(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)

More on spin weight

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.

Formula with parton-level amplitudes

We do not have at disposal matrix element for complete pp->ττX processes; factorisation theorem

$$d\sigma = \sum_{flavours} \int dx_1 dx_2 f(x_1,\ldots) f(x_2,\ldots) d\Omega^{parton\ level}_{prod}\ d\Omega_{\tau^+}\ d\Omega_{\tau^-}$$
$$\Big(\sum_{\lambda_1,\lambda_2} |\mathcal{M}^{prod}_{parton\ level}|^2\Big) \Big(\sum_{\lambda_1} |\mathcal{M}^{\tau^+}|^2\Big) \Big(\sum_{\lambda_2} |\mathcal{M}^{\tau^-}|^2\Big) wt_{spin}.$$

The Rij used in calculation of wt, is taken as an average (with PDFs and production matrix squared) over all flavour configurations

$$R_{ij} \quad \rightarrow \quad \Big[\sum_{flavours} f(x_1,\ldots) f(x_2,\ldots) \Big(\sum_{\lambda_1,\lambda_2} |\mathcal{M}^{prod}_{parton\ level}|^2\Big)\ R_{ij}\ \Big] /$$
$$\Big[\sum_{flavours} f(x_1,\ldots) f(x_2,\ldots) \Big(\sum_{\lambda_1,\lambda_2} |\mathcal{M}^{prod}_{parton\ level}|^2\Big)\ \Big].$$

More on spin weight

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

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

But iterative solutions like in HERWIG++ exists: treat decays of τ'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 τ samples.

(embedded sample: data Z->μμ event, where muon is replaced by simulated tau decay)

Introducing different physics model

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

$$d\sigma = \sum_{flavours} \int dx_1 dx_2 f(x_1,\ldots) f(x_2,\ldots) d\Omega_{prod}^{parton\ level}\, d\Omega_{\tau^+}\, d\Omega_{\tau^-}$$
$$\Big(\sum_{\lambda_1,\lambda_2} |\mathcal{M}_{parton\ level}^{prod}|^2\Big)\Big(\sum_{\lambda_1} |\mathcal{M}^{\tau^+}|^2\Big)\Big(\sum_{\lambda_2} |\mathcal{M}^{\tau^-}|^2\Big) wt_{spin} \boxed{WT.}$$

New model as correcting weight

Introducing different physics model

- **The weight WT factorizes into multiplicative components**

$$WT = wt_{prod} \; wt^{\tau^+}_{decay} wt^{\tau^-}_{decay} \underbrace{wt_{spin\,new} / wt_{spin\,old}}$$

eg. introducing polarisation

eg. new matrix element for production process

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

$$wt^{\tau^\pm}_{decay} = \frac{\sum_{spin} |\mathcal{M}^{\tau^\pm}_{new}|^2}{\sum_{spin} |\mathcal{M}^{\tau^\pm}_{old}|^2}$$

eg. introducing new parametrisation for hadronic current

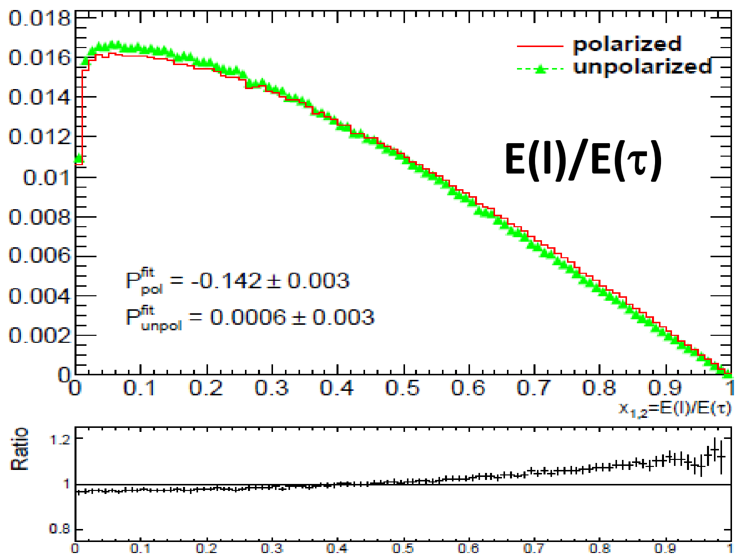
TauSpinner: longitudinal spin correlations

- **Spin effects can be added/modified into sample after τ decay. Polarised (red) sample is generated and green (unpolarised) is obtained with weight (1/wt). Case of pp→Z/γ*→ ττ**
- **Shown is also results of fits to analytical formulas.**

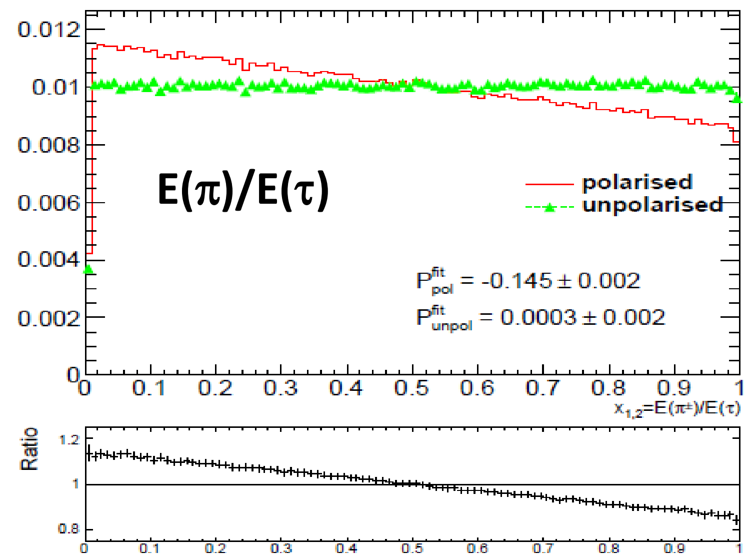
A. Kaczmarska et al., arXiv:1402.2068

τ -> l ν ν

τ -> π ν



(a) $\tau \to l \nu_l \nu_\tau$



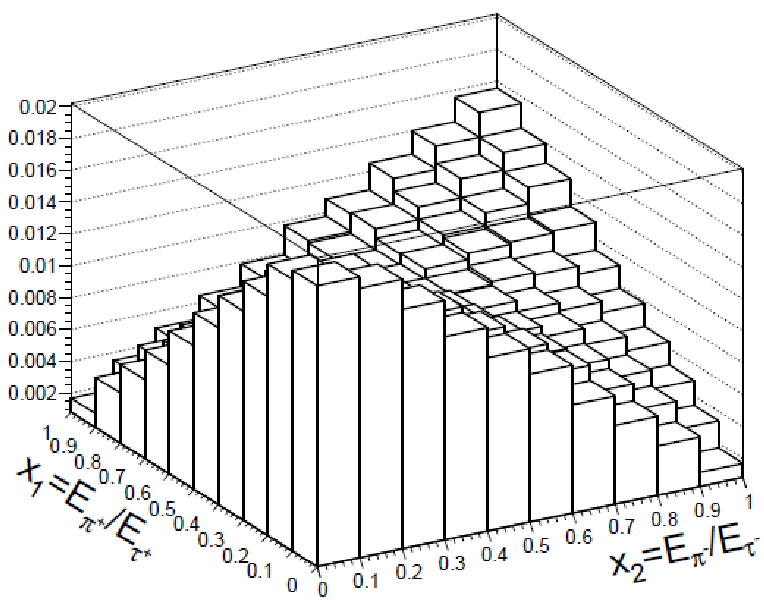
(b) $\tau \to \pi \nu_\tau$

TauSpinner: longitudinal spin correlations

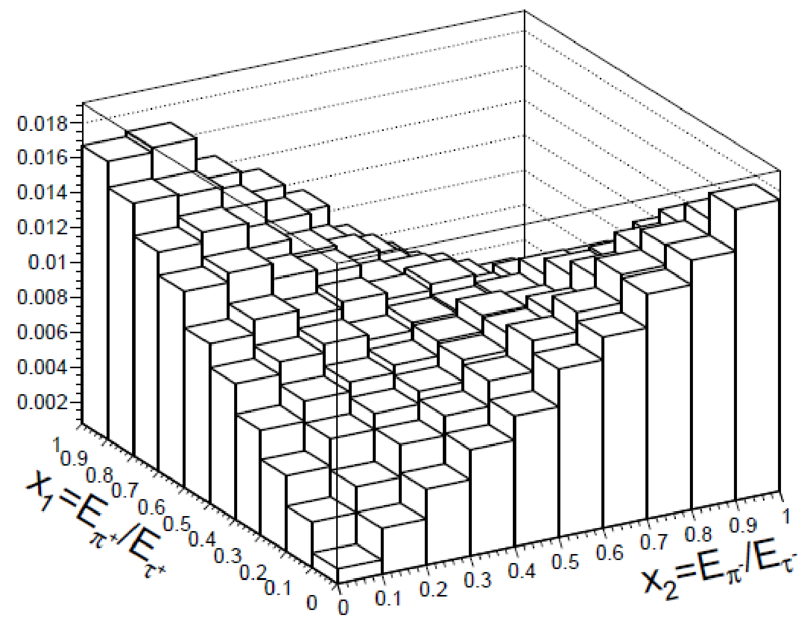
- **Allows to add/modify longitudinal spin correlations.**

A. Kaczmarska et al., arXiv:1402.2068

$Z \to \tau^+\tau^-;\ \tau^\pm \to \pi^\pm\nu_\tau$



$\Phi \to \tau^+\tau^-;\ \tau^\pm \to \pi^\pm\nu_\tau$



TauSpinner: EW loop corrections

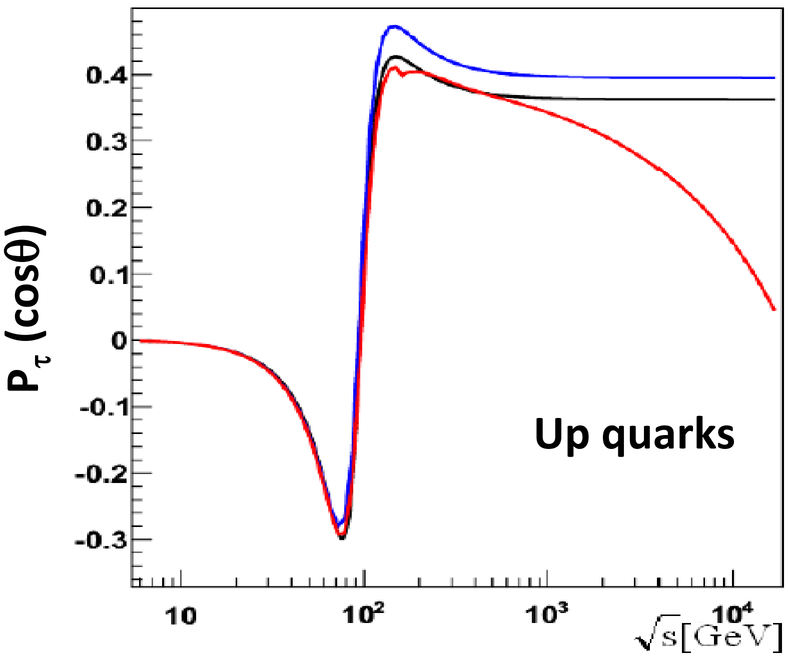
Allows to add EW loop corrections to q qbar -> Z/γ* -> $\tau\tau$ events, implemented as correcting weight.
EW loop corrections tabulated from SANC library.

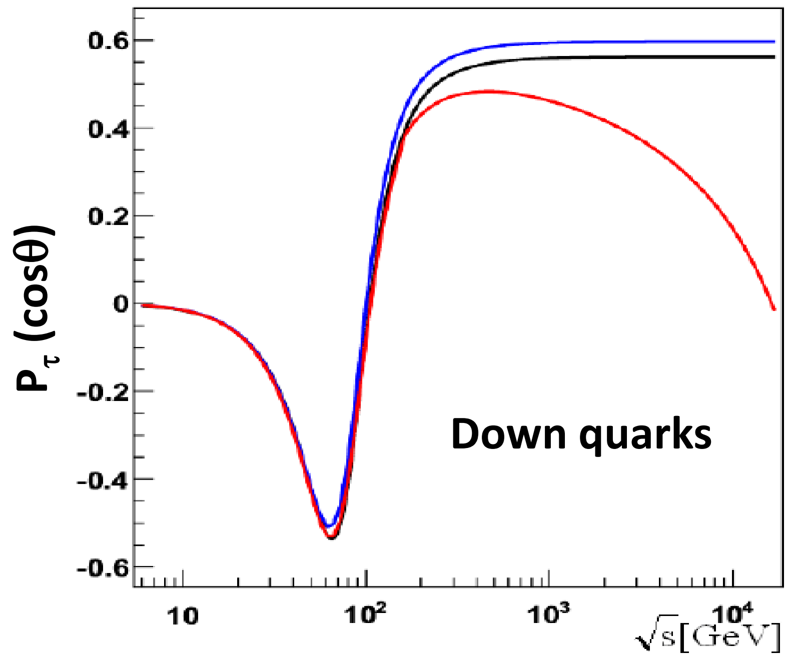
Born α scheme

Born effective

Born + EW loops+boxes

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





TauSpinner: using production weight

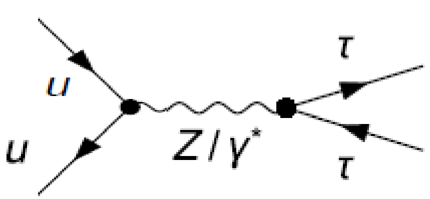
J. Kalinowski et al.,
Eur. Phys. J. C76 (2016) 540

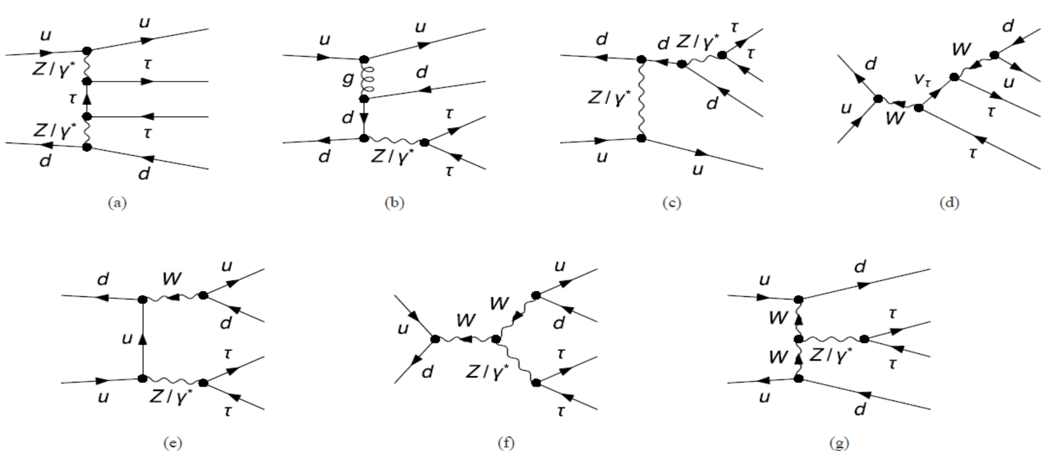
Simulating spin effects using different matrix elements. Calculate weight using 2->2 or 2->4 matrix element. Access systematics on predicted polarisation.

$$wt^{A\to B}_{prod} = \frac{\sum_{i,j,k,l} f_i^B(x_1) f_j^B(x_2) |M^B_{i,j,k,l}(p_1,p_2,p_3,p_4)|^2}{\sum_{i,j,k,l} f_i^A(x_1) f_j^A(x_2) |M^A_{i,j,k,l}(p_1,p_2,p_3,p_4)|^2}$$

B: 2 -> 4 process

A: 2 -> 2 process





TauSpinner: using production weight

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

J. Kalinowski et al.,
Eur. Phys. J. C76 (2016) 540

Tau lepton polarisation from Z decay, P_τ ,with different EW schemes

EW parameter (sensitive)	EW scheme	Polarisation $(2 \to 2)$	Polarisation $(2 \to 4)$
$\sin^2\theta_W = 0.222246$	EWSH=1	-0.2140 ± 0.0004	-0.2134 ± 0.0004
$\sin^2\theta_W = 0.231470$	EWSH=2	-0.1488 ± 0.0008	-0.1487 ± 0.0008
$\sin^2\theta_W = 0.222246$	EWSH=3	-0.2140 ± 0.0008	-0.2144 ± 0.0008
$\sin^2\theta_W = 0.231470$	EWSH=4	-0.1488 ± 0.0008	-0.1486 ± 0.0008

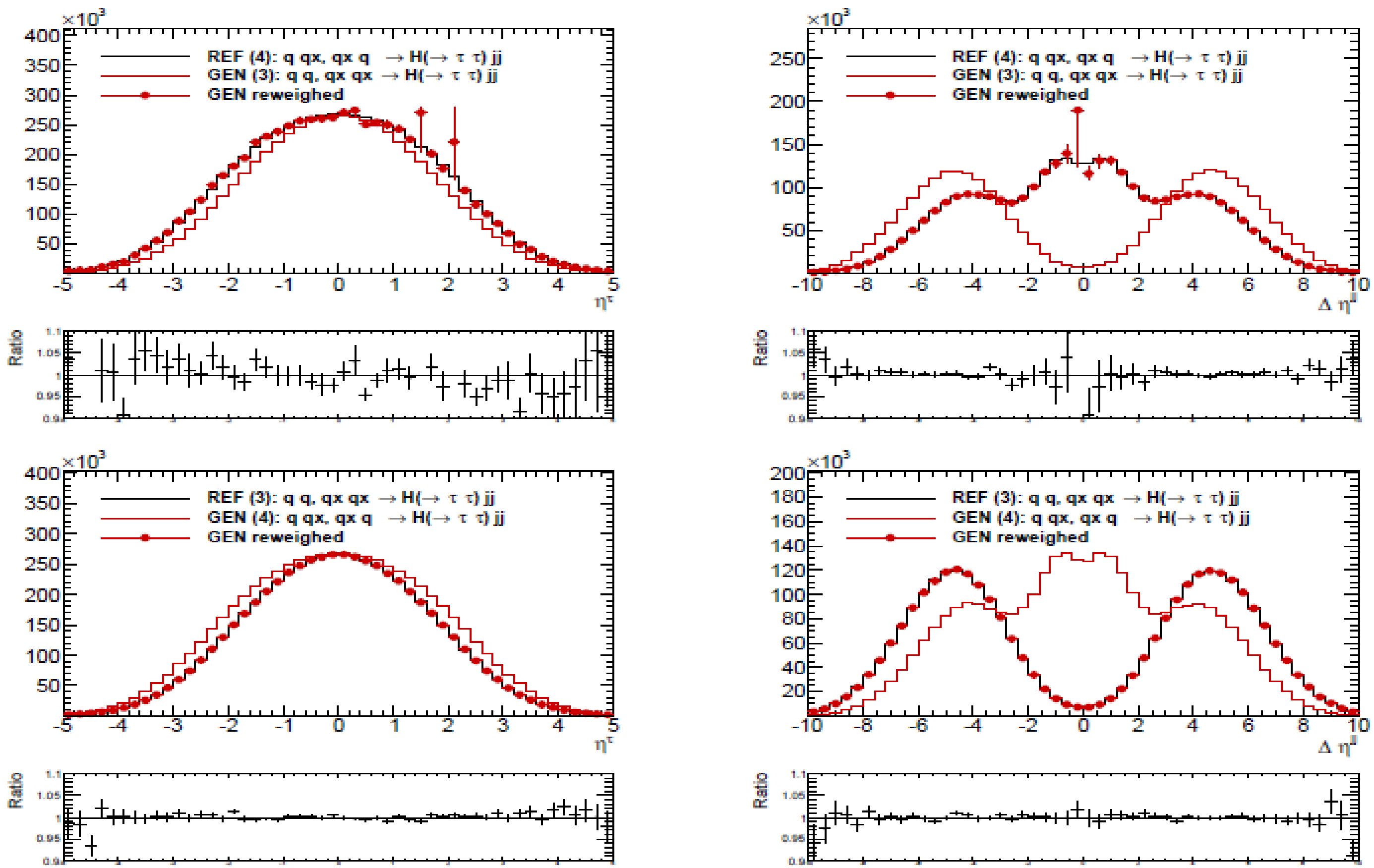
recommended

Type	EWSH=1 input: G_F, α_{QED}, m_Z	EWSH=2 input: $G_F, sin^2\theta_W, m_Z$	EWSH=3 input: G_F, m_W, m_Z	EWSH=4 input: $G_F, m_W, m_Z, \sin^2\theta_W^{eff}$
m_Z	91.1882 GeV	91.1882 GeV	91.1882 GeV	91.1882 GeV
m_W	80.4190	79.9407 GeV	80.4189 GeV	80.4189 GeV
$sin^2\theta_W$	0.222246	0.231470	0.222246	0.231470
$1/\alpha_{QED}$	132.5070	128.7538	132.5069	127.2272
G_F	$1.16639\ 10^{-5}\ GeV^{-2}$	$1.16639\ 10^{-5}\ GeV^{-2}$	$1.16639\ 10^{-5}\ GeV^{-2}$	$1.16639\ 10^{-5}\ GeV^{-2}$

TauSpinner: using production weight

Reweighting between different Higgs boson production subprocesses. ME are spin aware.

J. Kalinowski et al., arXiv:1604.00964



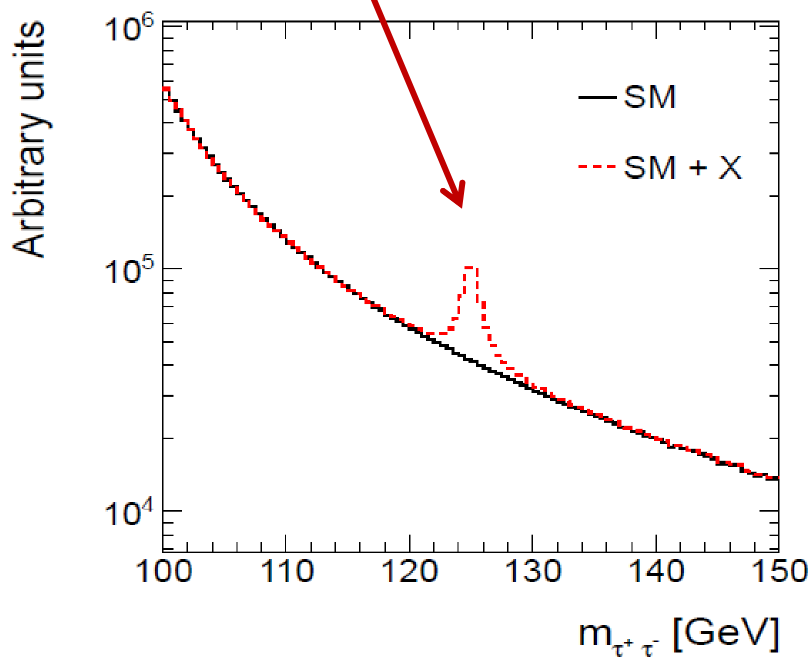
TauSpinner: using production weight

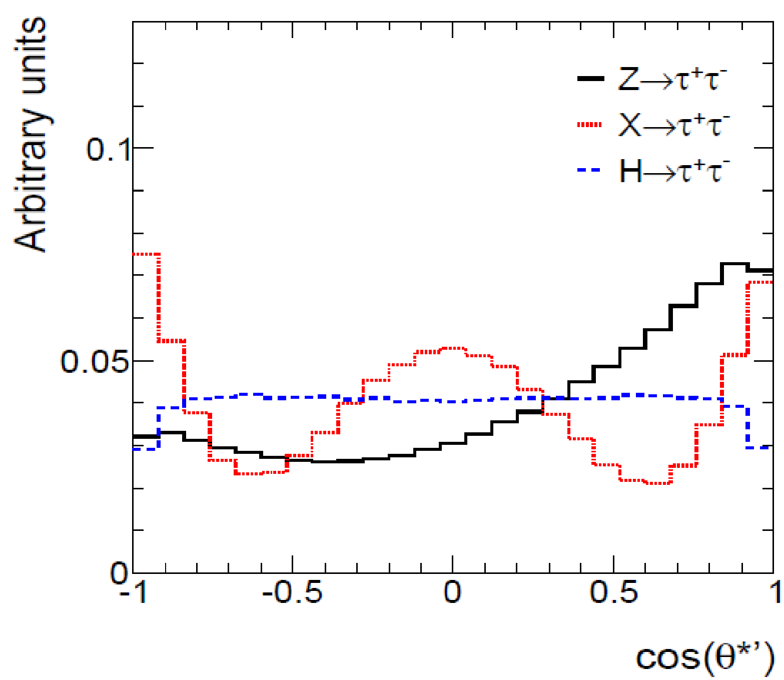
Example is implementing resonances with TauSpinner weights. Shown is invariant mass and $\cos\theta^*$ distribution for resonance production: $Z \to \tau\tau$, $X \to \tau\tau$, $H \to \tau\tau$

$$\left(\sum_{spin} |\mathcal{M}^{prod}|^2 \right)$$

Resonance spin = 2
(weight method)

S. Banerjee et al., Eur.J. C73 (2013) 2313



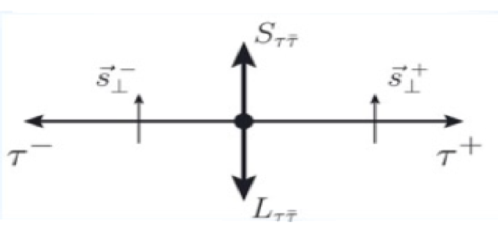


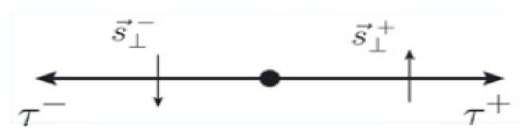
Higgs boson CP state

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

Angle between decay planes is best observable to measure this

scalar	pseudoscalar
h^0	A^0
CP-even (SM), $\phi_\tau = 0$	CP-odd, $\phi_\tau = \frac{\pi}{2}$
$\mathcal{L}_{h^0\tau\tau} = -g_\tau \cdot \bar{\tau}\tau h$	$\mathcal{L}_{A^0} = -g_\tau \cdot \bar{\tau} i \gamma_5 \tau h$
$J^{PC} = 0^{++}$	$J^{PC} = 0^{-+}$
$L_{\tau\bar{\tau}} = 1,\ S_{\tau\bar{\tau}} = 1$	$L_{\tau\bar{\tau}} = 0,\ S_{\tau\bar{\tau}} = 0$





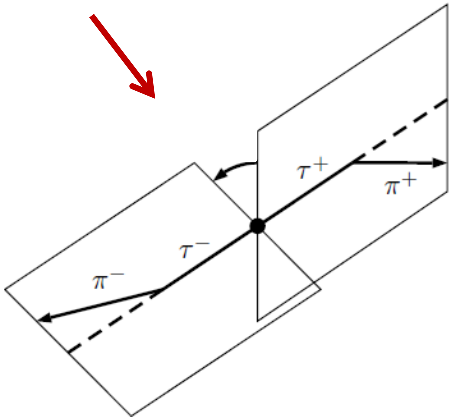
TauSpinner: transverse spin correlations

T. Przedzinski et al., Eur. Phys. J C74 (2014) 3177

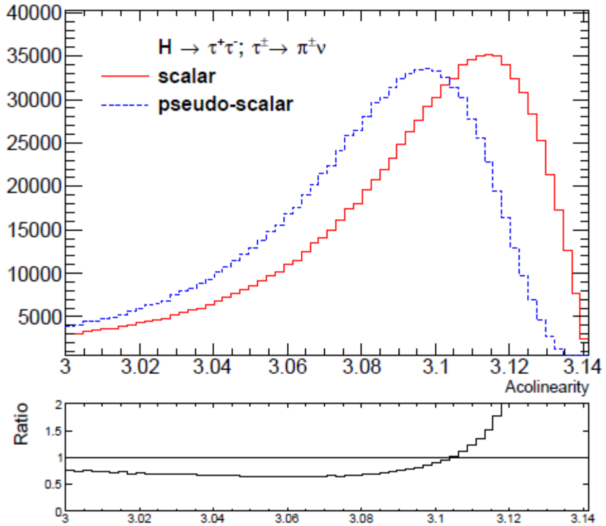
Allows to add transverse spin correlations to any mixture of scalar-pseudoscalar state;

Shown here CP sensitive observables;

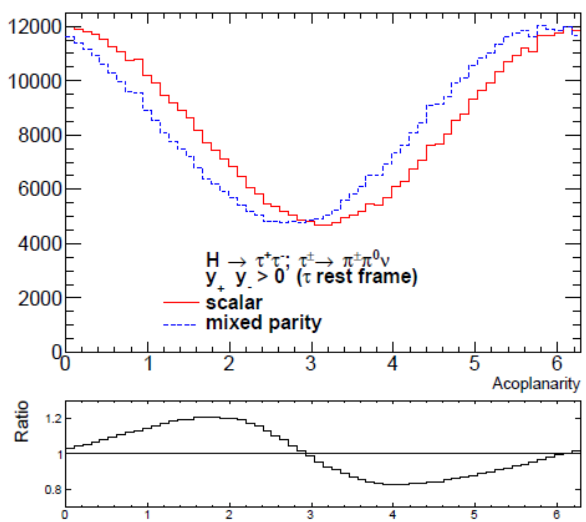
acoplanarity angle



acolinearity



acoplanarity



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

$$y_\rho^\pm = \frac{E^{\pi^\pm} - E^{\pi^0}}{E^{\pi^\pm} + E^{\pi^0}}$$

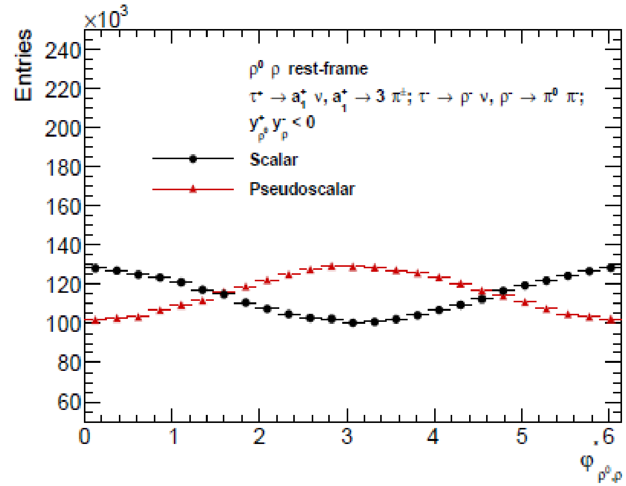
TauSpinner: transverse spin correlations

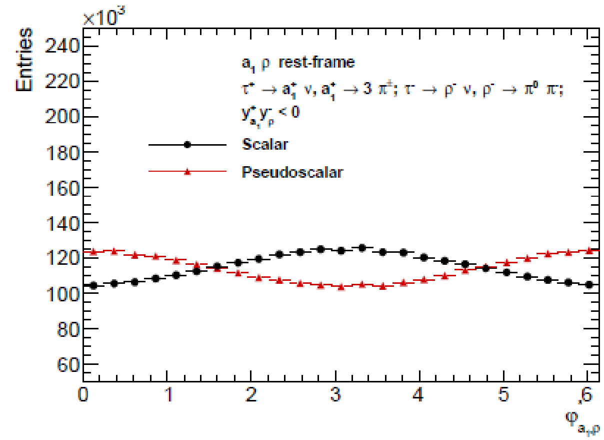
R. Jozefowicz et al., Phys. Rev. D94 (2016) 093001

Adding more decay modes to study Higgs CP

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

Decay mode	Cascade decay	τ BR.	Cumul. frac. $H \to \tau\tau$	Used
$\tau^\pm \to \rho^\pm \nu$	$\rho^\pm \to \pi^0\ \pi^\mp$	25.5%	6.5%	Yes
$\tau^\pm \to a_1^\pm \nu$	$a_1^\pm \to \rho^0 \pi^\mp$, $\rho^0 \to \pi^+\pi^-$	9.0%	11.9%	Yes
$\tau^\pm \to a_1^\pm \nu$	$a_1^\pm \to 2\pi^0\ \pi^\mp$	9.3%	19.2%	No





Adding $\tau^+ \to a_1^+\ \nu,\ a_1^+ \to 3\ \pi^\pm;\ \tau^- \to \rho^-\ \nu,\ \rho^- \to \pi^0\ \pi^-;$ 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

TauSpinner: transverse spin correlations

R. Jozefowicz et al., Phys. Rev. D94 (2016) 093001

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

Features/variables	Decay mode: $\rho^\pm - \rho^\mp$ $\rho^\pm \to \pi^0\, \pi^\pm$	Decay mode: $a_1^\pm - \rho^\mp$ $a_1^\pm \to \rho^0\pi^\pm,\ \rho^0 \to \pi^+\pi^-$ $\rho^\mp \to \pi^0\, \pi^\mp$	Decay mode: $a_1^\pm - a_1^\mp$ $a_1^\pm \to \rho^0\pi^\pm,\ \rho^0 \to \pi^+\pi^-$
$\varphi^*_{i,k}$	1	4	16
$\varphi^*_{i,k}$ and y_i, y_k	3	9	24
$\varphi^*_{i,k}$, 4-vectors	25	36	64
$\varphi^*_{i,k}$, y_i, y_k and m_i, m_k	5	13	30
$\varphi^*_{i,k}$, y_i, y_k, m_i, m_k and 4-vectors	29	45	78

y_i helps in separation into CP sensitive categories

$$y_\rho^\pm = \frac{E^{\pi^\pm} - E^{\pi^0}}{E^{\pi^\pm} + E^{\pi^0}} \qquad y_{\rho^0}^\pm = \frac{E^{\pi^+} - E^{\pi^-}}{E^{\pi^+} + E^{\pi^-}}, \quad y_{a_1}^\pm = \frac{E^{\rho^0} - E^{\pi^\pm}}{E^{\rho^0} + E^{\pi^\pm}} - \frac{m_{a_1}^2 - m_{\pi^\pm}^2 + m_{\rho^0}^2}{2m_{a_1}^2}$$

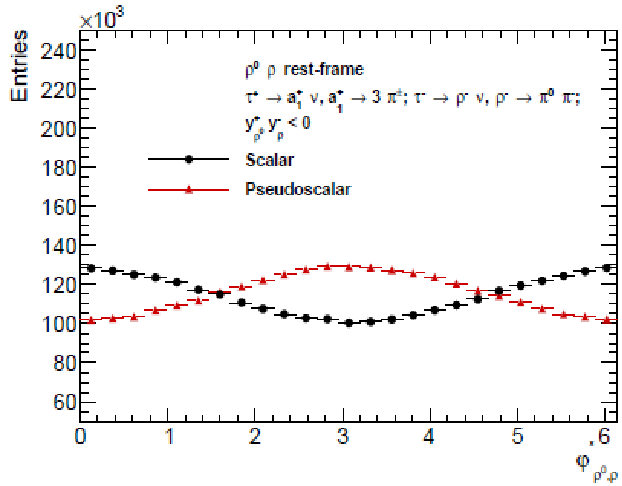
TauSpinner: transverse spin correlations

R. Jozefowicz et al., Phys. Rev. D94 (2016) 093001

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.

NN score

Features/variables	Decay mode: $a_1^\pm - \rho^\mp$ $a_1^\pm \to \rho^0\pi^\mp,\ \rho^0 \to \pi^+\pi^-$ $\rho^\mp \to \pi^0\ \pi^\mp$
True classification	0.782
$\varphi^*_{i,k}$	0.500
$\varphi^*_{i,k}$ and y_i, y_k	0.569
4-vectors	0.590
$\varphi^*_{i,k}$, 4-vectors	0.594
$\varphi^*_{i,k}$, y_i, y_k and m_i^2, m_k^2	0.578
$\varphi^*_{i,k}$, y_i, y_k, m_i^2, m_k^2 and 4-vectors	0.596



TauSpinner: transverse spin correlations

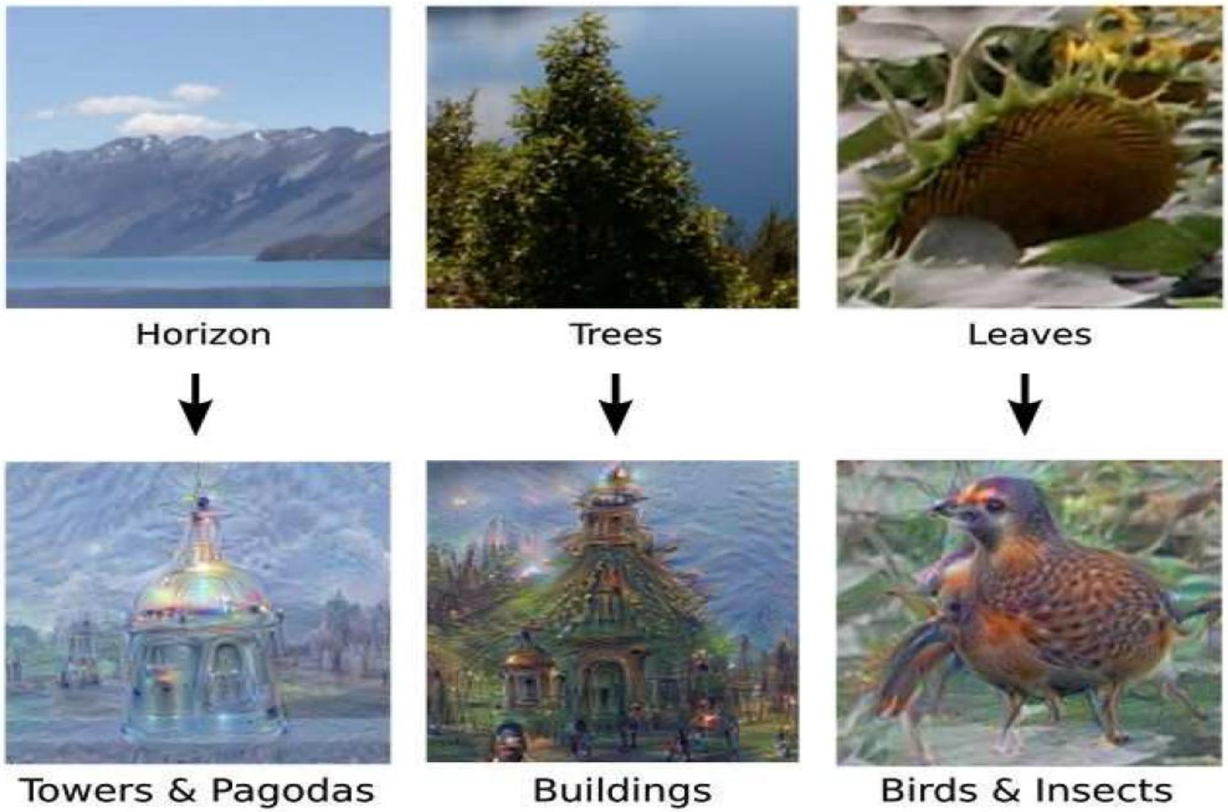
R. Jozefowicz et al., Phys. Rev. D94 (2016) 093001

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 III: Average probability p_i that a model predicts correctly event x_i to be of a type A (scalar), with training being performed for separation between type A and B (pseudo-scalar).

Features/variables	Decay mode: $\rho^\pm - \rho^\mp$ $\rho^\pm \to \pi^0\ \pi^\pm$	Decay mode: $a_1^\pm - \rho^\mp$ $a_1^\pm \to \rho^0\pi^\mp,\ \rho^0 \to \pi^+\pi^-$ $\rho^\mp \to \pi^0\ \pi^\mp$	Decay mode: $a_1^\pm - a_1^\mp$ $a_1^\pm \to \rho^0\pi^\pm,\ \rho^0 \to \pi^+\pi^-$
True classification	0.782	0.782	0.782
$\varphi^*_{i,k}$	0.500	0.500	0.500
$\varphi^*_{i,k}$ and y_i, y_k	0.624	0.569	0.536
4-vectors	0.638	0.590	0.557
$\varphi^*_{i,k}$, 4-vectors	0.638	0.594	0.573
$\varphi^*_{i,k}$, y_i, y_k and m_i^2, m_k^2	0.626	0.578	0.548
$\varphi^*_{i,k}$, y_i, y_k, m_i^2, m_k^2 and 4-vectors	0.639	0.596	0.573

Deep Neural Network classification



Artificial Neural Network have spurred remarkable recent progress in image classification and speech recongnition. But even though there are very useful tools based on well-known mathematical methods, we actually understand suprisingly little of why certain models work and others don't.
From http://googleresearch.blogspot.com/2015/06/inceptionism-going-deeper-into-neural.html

TauSpinner: transverse spin correlations

R. Jozefowicz et al., Phys. Rev. D94 (2016) 093001

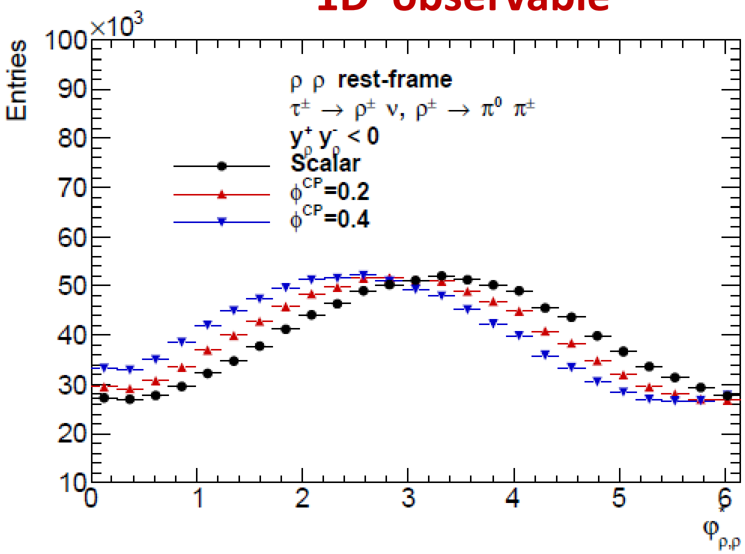
Preparing for fitting CP state mixing angle with NN approach

Deep NN classification score per event

TABLE IV: Average probability p_i that a model predicts correctly event x_i to be of a type A (scalar), with training being performed for separation between type A and B (CP-mix state) with mixing angle of ϕ^{CP} =0.2, 0.3, 0.4 respectively. Results are shown only for $\rho^{\pm} - \rho^{\mp}$ decay mode.

Features/variables	$\phi^{CP} = 0.2$	$\phi^{CP} = 0.3$	$\phi^{CP} = 0.4$
True classification	0.560	0.588	0.616
$\varphi^*_{i,k}$, y_i, y_k, m_i^2, m_k^2 and 4-vectors	0.526	0.540	0.553

1D observable



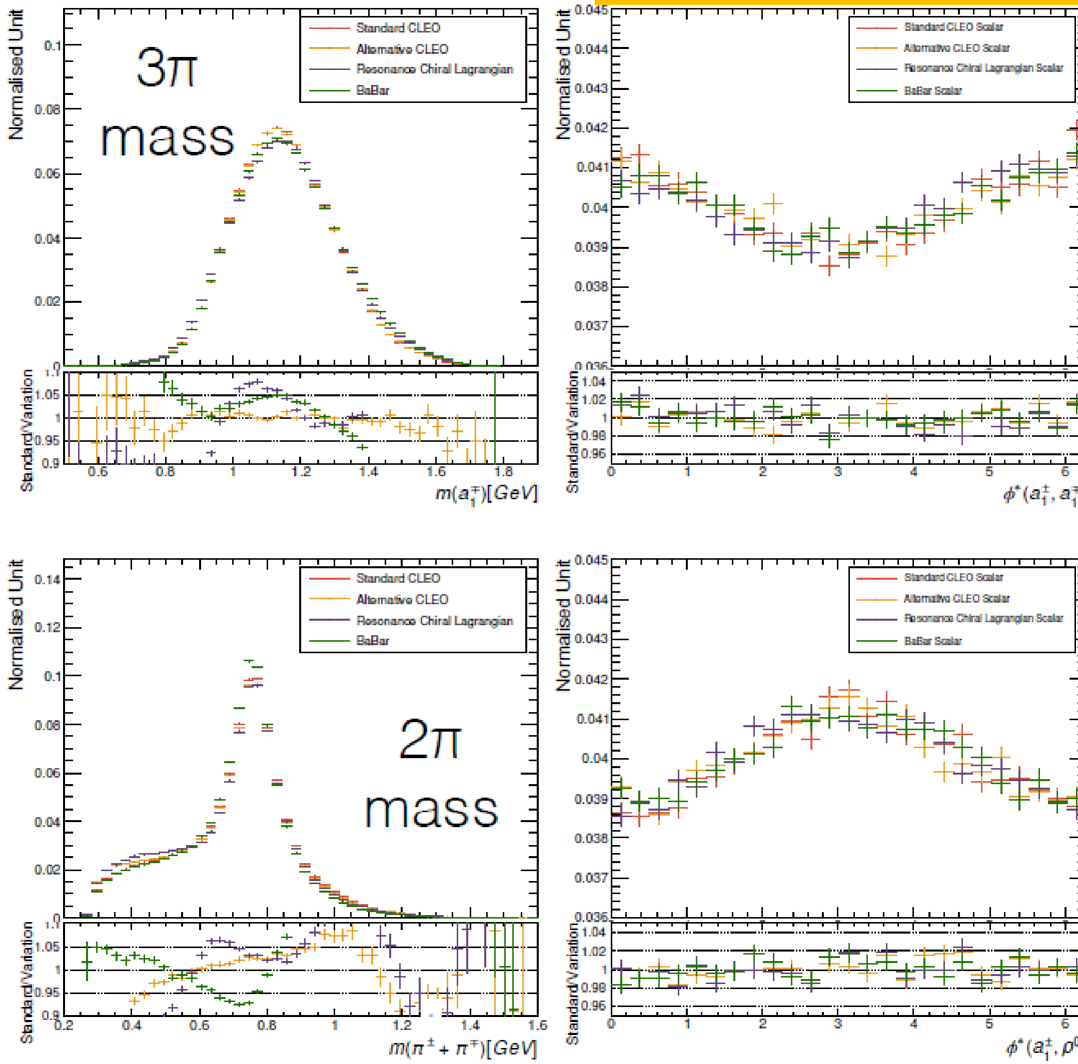
TauSpinner: systematics from hadronic currents

B. Le et al., in preparation

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)

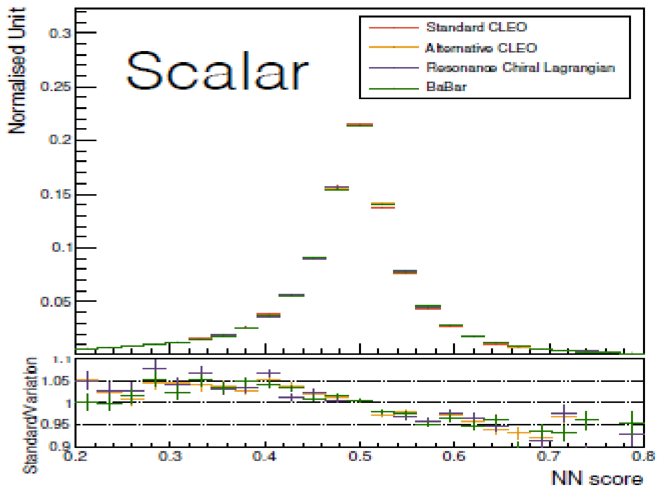


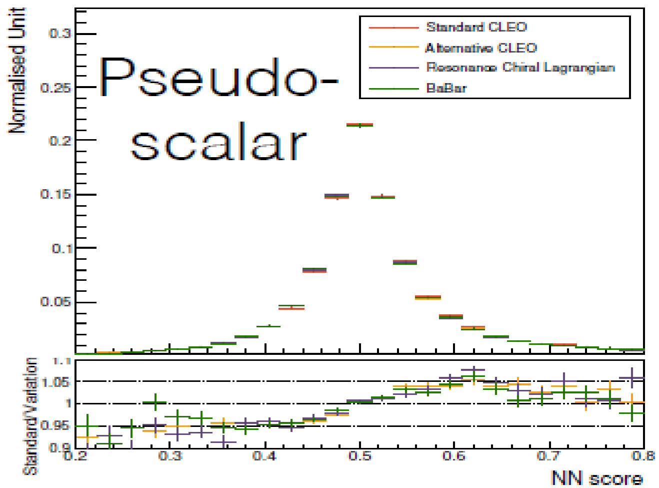
TauSpinner: systematics from hadronic currents

B. Le et al., in preparation

Variations in AUC score not significant, at 1% level.

		CLEO	RχL	Alt. CLEO	BaBar
ρ-a_1	φ^*, y	0.584	0.582	0.583	0.582
	φ^*, y, m	0.594	0.595	0.595	0.595
	φ^*, 4-vec	0.602	0.602	0.602	0.602
a_1-a_1	φ^*, y	0.541	0.538	0.537	0.536
	φ^*, y, m	0.552	0.550	0.550	0.549
	φ^*, 4-vec	0.571	0.566	0.567	0.568





Conclusions

Nowdays several tools available for simulating τ 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 σ story (slide 10).**
- **Be able to modify spin correlations, τ decay model or τ 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 τ's samples as for MC based samples.**

Towards precise physics with τ leptons

- Strategy for evaluating systematics error from τ-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 τ 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?

Tauola

Documentation: Comp.Phys.Comm 76 (1993) 361

http://tauolapp.web.cern.ch/tauolapp/

Recent updates on models used:

Phys. Rev D88(2013) 093012, Phys.Rev. D86 (2012) 113008

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.

Tauola++ Interface

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 τ 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.

TauSpinner

Documentation:

Eur. Phys. J C72 (2012) 1988, Eur.J. C73 (2013) 2313

More on polarisation and spin correlations: arXiv:1402.2068; arXiv:1406.1647

Code in C++:

With weights methods allows to introduce/modify spin correlations on already τ 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)

Tau2012 conference proc. arXiv:1211.6730v1

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)

website:http://www.mpipks-dresden.mpg.de/~laubrich/diplom.pdf

Code in C++: fully integrated with event generator

- Several τ – 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.

Herwig++

Documentation: arXiv:07101951v1

Code in C++: integrated with event generator

- **Full treatment of spin correlations: the modified version of Collins-Knowles algorithm (P. Richardson, arXiv:hep-ph/0110108)**
- **Extended comparison with generic TAUOLA library documented**

Prospects:

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