Studies on spin effect in τ production and decay at LHC with TauSpinner program

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12-15 April 2016 U.Granada

Outline

1. HiggsTools
   - ESR 18 status
2. Introduction
   - Study of τ spin correlations in Z$\rightarrow \tau\tau$ and H$\rightarrow \tau\tau$
   - τ transverse spin effects,observable for CP test
3. Tauola interface and `Tauspinner`
   - Tauola++ Interface
   - `TauSpinner` program
   - Result from analysis at 13 TeV pp Scattering
4. Outlook

ESR 18: Marzieh Bahmani

- Joined the Higgstools program from September 2015
- Project title: Search for extended scenarios of electroweak symmetry breaking with the ATLAS experiment at LHC (WP2) with the supervision of Dr Pawel Bruckman and Professor Jan Kalinowski

ESR 18: Marzieh Bahmani

- Collaboration with Professor Elzbieta Richter-Was from Jagiellonian University, getting familiar with `TauSpinner` algorithm for $2 \rightarrow 2$ processes.
- Joined ATLAS experiment at CERN LHC Started the "Qualification task" in Feb 2016
  - Project title :Validation of tau decay simulation in different generators and maintenance of tau Monte Carlo tools:
    - Validate Sherpa2.2 vs. Powheg+Pythia8 in MC15 for Run II data analysis

- In 1971, Four years before the discovery of the τ lepton, It was predicted that if the lepton is heavy enough to decay to quarks there is a correlation between its decay products, hence its helicity would be accessible through the kinematics of its decay products, due to the maximal parity violation in the weak decay of the heavy lepton. [1]

DECAY CORRELATIONS OF HEAVY LEPTONS IN $e^+ + e^- \to \ell^+ + \ell^-$ *

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ABSTRACT

Assuming leptons heavier than muons exist in nature we consider their decay modes and the correlations between the decay products of ℓ^+ and ℓ^- in the colliding beam experiment: $e^+ + e^- \to \ell^+ + \ell^-$. Far above the threshold, the helicities of ℓ^+ and ℓ^- tend to be opposite to each other and near the threshold the directions of spins of ℓ^+ and ℓ^- like to be parallel to each other and the sum of the two spins likes to be either parallel or antiparallel to the direction of the

The properties of τ lepton

- τ mass$\sim$ 1.77 Gev, τ life time $=(290.6\ \pm 1.0)\times\ 10^{-15}$ second
  pp$\rightarrow\tau\tau$, $\tau\rightarrow$X, $\tau\rightarrow$Y

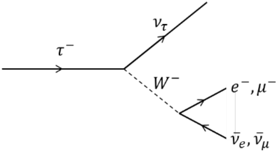
$$d\sigma \quad = \quad |\mathbf{M}|^2 d\Omega_{prod} d\Omega_{\tau^+} d\Omega_{\tau^-} \tag{1}$$

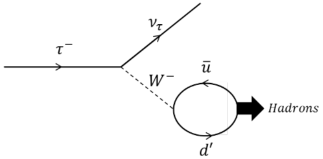
- Because of its narrow width,τ decays can be factorized from its production process.

$$\mathbf{M} \quad = \quad \Sigma^2_{\lambda_1,\lambda_2} \mathbf{M}^{prod}_{\lambda_1,\lambda_2} \mathbf{M}^{\tau^+}_{\lambda_1} \mathbf{M}^{\tau^-}_{\lambda_2} \tag{2}$$

λ is the helicity of τ

- τ lepton can decay to up- and down-quarks or leptons,Therefore two types of decay modes: hadronic and leptonic.





The properties of τ lepton

- The τ lepton can decay to pseudo-scalar, vector or axial-vector mesons that are either Cabibbo-favoured (π^-,ρ^-,a^-) or Cabibbo-suppressed (K^-,K^{*-},K_l^-)
- Leptonic decays have a total branching fraction of 35 percent and the hadronic decays have a total branching fraction of 65 percent.

Decay Modes	Branching fraction [%]
$e^-\bar{\nu}_e\nu_\tau$	17.82 ± 0.04
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.39 ± 0.04
$\pi^-\nu_\tau$	10.91 ± 0.07
$K^-\nu_\tau$	0.696 ± 0.023
$\rho^-\nu_\tau$	25.94 ± 0.09
$K^{*-}\nu_\tau$	0.429 ± 0.015
$h^-2\pi^0\nu_\tau$	10.85 ± 0.11
$h^- \geq 3\pi^0\nu_\tau$	1.34 ± 0.07
$h^-h^+h^-\nu_\tau$	9.80 ± 0.07
$h^-h^+h^- \geq 1\pi^0\nu_\tau$	5.38 ± 0.07

Figure: $h^\pm$ stands for $\pi^\pm$ or $K^\pm$

The importance of τ lepton

- In search for new physics τ lepton can be used for separation of signal from background.
- Parity violating Z boson decays to fermions: Left handed fermions are favoured (and right handed anti-fermions), inducing τ polarisation and hence spin correlations between decay products.
- Polarization of the τ lepton can be measured through the kinematics of its decay products
- Spin correlations depend on the natures of decaying resonance (scalar, pseudoscalar, vector) Higgs is a scalar, and Yukawa coupling does not distinguish handedness, therefore τ leptons originating from Higgs decay is unpolarized, Z boson is a vector and its decay products are polarized, hence **Polarization can be used as an extra separator between the Higgs and the Z.**

τ lepton polarization

- The longitudinal polarization of τ^- in the decay of resonance (Z,H) is the asymmetry between the number of right-handed and left-handed τ^- in ultra relativistic limit.

$$P_\tau = \frac{N_R - N_L}{N_R + N_L} = \frac{\sigma_\tau(\lambda = 1) - \sigma_\tau(\lambda = -1)}{\sigma_\tau(\lambda = 1) + \sigma_\tau(\lambda = -1)}$$

here λ is helicity state.
At the Z pole the integrated polarization will be:

$$\langle P_\tau \rangle = -\frac{2\bar{g}_V^\tau \bar{g}_A^\tau}{\bar{g}_V^{\tau\,2} + \bar{g}_A^{\tau\,2}} = -\mathcal{A}_\tau$$

$$\langle P_\tau \rangle \approx -2\frac{\bar{g}_A^\tau}{\bar{g}_V^\tau} = -2\left(1 - 4\sin^2_{eff}\theta_W\right)$$

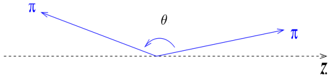
- The polarization is therefore a measure of effective mixing angle, The so called chiral coupling asymmetry A_τ was measured very precisely at LEP experiment from which the effective weak mixing angle $sin^2\theta_{eff} = 0.23147 \pm 0.00057$ was derived. [2]

τ transverse spin effects, observables for CP test

- The transverse spin effects in τ pairs can be helpful to distinguish between the scalar and pseudoscalar natures of the spin zero particle.
- The spin density matrix for the two τs resulting from the decay of the state which is a mixture of scalar/pseudoscalar is given by:

$$\Gamma(H/A^0 \to \tau^+\tau^-) \sim 1 - s_{\parallel}^{\tau^+} s_{\parallel}^{\tau^-} \pm s_{\perp}^{\tau^+} s_{\perp}^{\tau^-}$$

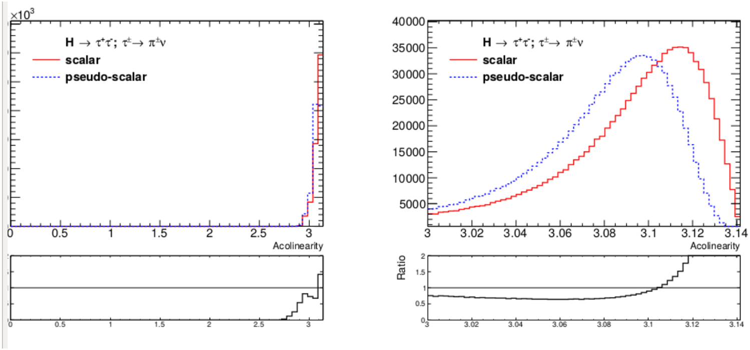
[5]



- The transverse spin correlations, carry information on Higgs parity which can be translated into observables such as acollinearity in H$\to \tau^+\tau^-$,$\tau^\pm \to \pi^\pm \nu$ decay chain in the rest frame of H.

$$\theta_{acollinearity} = cos^{-1}\left(\frac{\vec{p}_{\pi^+} . \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+}||\vec{p}_{\pi^-}|}\right) \quad (3)$$

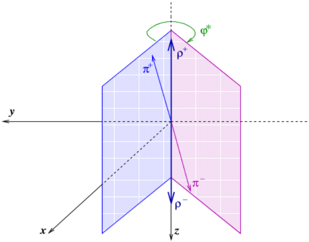
Observables for CP test



The acollinearity distributions of the $\pi^+\pi^-$ in H$\to \tau^+\tau^-$,$\tau^\pm \to \pi^\pm\nu$ decays.

Observables for CP test

- For the H$\to \tau^+\tau^-$, $\tau^\pm \to \rho^\pm\nu$, $\rho^\pm \to \pi^\pm\pi^0$ decay chain using the $\rho^+\rho^-$ rest frame which has the advantage that it can be constructed only from directly visible decay products.
- One-dimensional angular distribution of the acoplanarity angle between $\pi^+\pi^0$ and $\pi^-\pi^0$ decay planes in the $\rho^+\rho^-$ pair rest frame was proposed as CP sensitive observable.

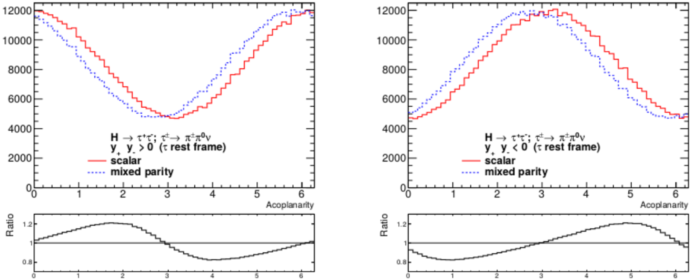


e.g. for the decay
$\tau^\pm \to \rho^\pm \bar{\nu_\tau}(\nu_\tau)$
$\to \pi^\pm\pi^0$
one has:
$\mathbf{n}_\pm = \mathbf{p}_{\pi^\pm} \times \mathbf{p}_{\pi^0}$

$$cos\varphi^* = \frac{\mathbf{n}_+ \cdot \mathbf{n}_-}{|\mathbf{n}_+||\mathbf{n}_-|}$$

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

Observables for CP test

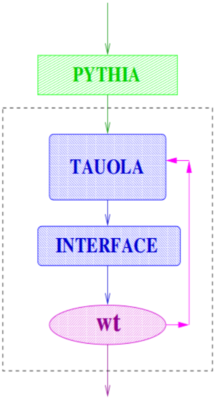


[4]

Tauola++ Interface

- Tauola is a MC Generator dedicated to generating tau-lepton decays
- The algorithm is organized in two steps:
  - first step:
    -$\tau^+\tau^-$ lepton pairs are generated
    -$\tau^\pm$ leptons decays in their respective frames
    ,assuming no spin effect
  - second step
    -spin weight is calculated and rejection is preformed
    -accepted events model complete spin correlations.

[6]

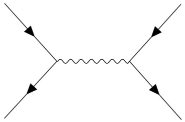


TauSpinner program

- The TauSpinner is a program associated with Tauola++, enabling calculation of weights for events previously generated or constructed by other means.
- The events must feature kinematics of τ lepton production and decay products, but information on partons from which intermediate resonance decaying to the τs was produced is assumed to be unknown, and therefore is not used.
- The algorithm calculates for each event, from this information alone, spin weight corresponding to a presumed PDF configuration and matrix element for the hard process

TauSpinner program

- TauSpinner algorithm assume that τ pairs is produced in $2 \rightarrow 2$ processes, it calculates weight for any given intermediate state for example scalar or vector.



- The weight calculated WT can be separated into multiplicative components:

$$
\begin{aligned}
WT &= wt_{\sigma_{prod}} wt_{\Gamma_{decay}}^{\tau^+} wt_{\Gamma_{decay}}^{\tau^-} wt_{spin} \\
wt_{spin} &= R_{i,j} h^i_{\tau^+} h^j_{\tau^-}.
\end{aligned}
$$

- R_{ij} is a matrix describing the full spin correlation between the two τs and individual spin states of them. h_i and h_j are components of the two τs polarimetric vectors.

TauSpinner program

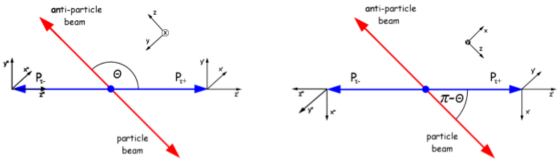


Figure: Tauola and Tauspinner frame

The complete density matrix for a scalar neutral Higgs boson H^0

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

For a pseudoscalar neutral Higgs boson A^0

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

A mixed $A^0/H^0 \to \tau^+\tau^-$

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{(\beta cos\phi)^2 - sin\phi^2}{(\beta cos\phi)^2 + sin\phi^2} & -\frac{2\beta cos\phi sin\phi}{(\beta cos\phi)^2 + sin\phi^2} & 0 \\ 0 & \frac{2\beta cos\phi sin\phi}{(\beta cos\phi)^2 + sin\phi^2} & \frac{(\beta cos\phi)^2 - sin\phi^2}{(\beta cos\phi)^2 + sin\phi^2} & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \qquad \beta = \sqrt{1 - (\frac{2M_\tau}{M_{A^0/H^0}})^2}$$

ϕ is the scalar-pseudoscalar mixing angle.

In the case of $Z/\gamma \to \tau^+\tau^-$

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

where P_Z is calculated from the square of the matrix elements of the Born-level 2→2 process $f\bar{f} \to \tau^+\tau^-$

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

TauSpinner Program

- With the wt_{spin} weight one can evaluate on event-by-event basis spin effects transmitted from the production to the decay of τ leptons
- The event weight is always larger than zero. It can be used at the analysis level for:
  - Simulating τ spin effects:in a sample generated without spin effects,It takes values between (0,2)but in a case of $Z/\gamma^* \rightarrow \tau\tau$ (0,4).
  - Removing τ spin effects,from a sample generated with spin effects. The event weight equals 1/WT,it is greater than zero with no upper limit.
  - Reverting τ spin effects,in a sample generated with certain longitudinal tau polarization (and/or correlations) to the different one, It is greater than zero without an upper limit.

Analysis of $\sqrt{s}$=13 TeV pp sample

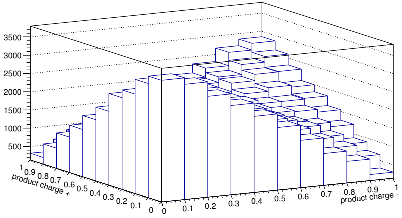
- The samples generated with Pythia8 Monte Carlo with the center of mass energy of 13 TeV, each containing 20M events which stored in HepMC format.
- The decays of τ leptons are generated with Tauola++ initialized with standard options.
- The samples are generated including spin effects (polarisation and correlations)

Analysis of $\sqrt{s}$=13 TeV pp sample

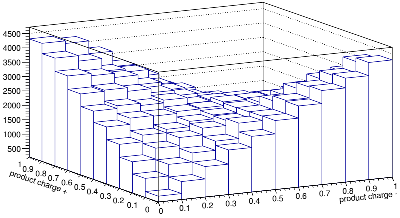
- First sample: $Z \to \tau^+\tau-$
- The spin effects strongly depend on the virtuality of the Z/γ^* intermediate state. Events were generated explicitly requiring virtuality of Z/γ^* within 88-94 GeV window.
- second sample: $\phi \to \tau^+\tau-$ with $M_\phi = M_Z$

Observable sensitive to longitudinal polarization

In $\tau^{\pm} \rightarrow \pi^{\pm}\nu$ decay chain.



(a) $E_{\pi^{\pm}}/E_{\tau^{\pm}}$ in $Z \rightarrow \tau\tau$



(b) $E_{\pi^{\pm}}/E_{\tau^{\pm}}$ in $\phi \rightarrow \tau\tau$

Observable sensitive to longitudinal polarization

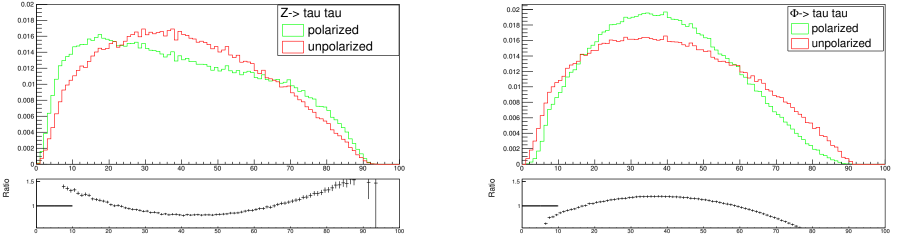


Figure: Visible invariant mass distribution of τ pairs decay to $\pi^{\pm}\nu$

Analysed event samples, observable sensitive to longitudinal polarization

fit parameter = -0.1316 $\pm$ 0.00057 calculated with semi-analytical formulae: [3]

$$1 + P \times (2x - 1) \tag{4}$$

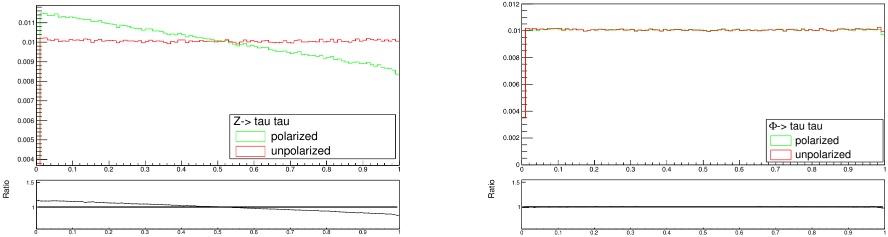
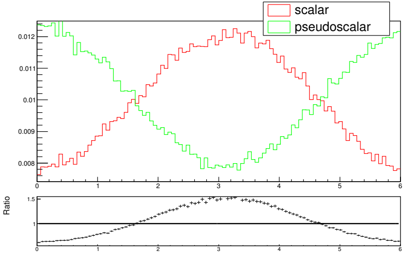


Figure: The spectra of visible energy in τ pairs decay to $\pi^{\pm}\nu$

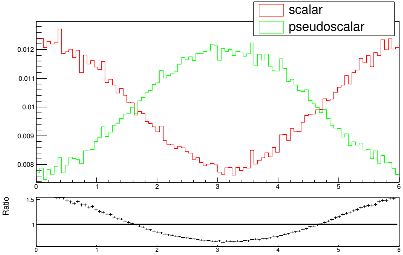
CP test observable sensitive to transverse polarization

For observing the sensitivity of transverse spin correlation one needs to split into fast-fast, fast-slow and slow slow configurations. Acoplanarity for ϕ sample in the rest frame of ρ pairs, $\phi \to \tau^+\tau^-$, $\tau^\pm \to \rho^\pm\nu$, $\rho^\pm \to \pi^\pm\pi^0$ decay chain.

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



(a) $y_1.y_2 < 0$



(b) $y_1.y_2 > 0$

CP test observables

for mixed parity case spin correlation matrix has non-diagonal components parametrised by mixing angle:

setHiggsParametersTR($-cos(2\phi)$,$cos(2\phi)$,$-sin(2\phi)$,$-sin(2\phi)$)

and $\phi = 0.2$

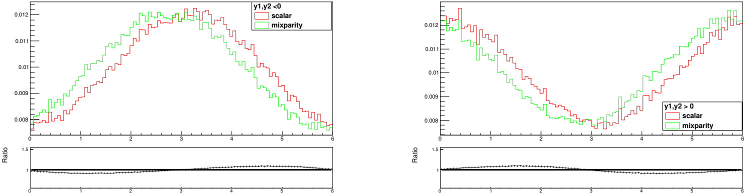


Figure: **the acoplanarity distribution** $H \to \tau^+\tau^-.\tau^\pm \to \pi^\pm\pi^0\nu$

For Z the effect is averaging out if no experimental selection applied.

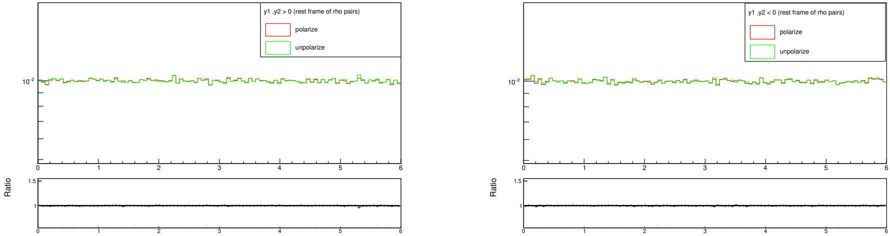


Figure: Acoplanarity for Z sample

CP test observable

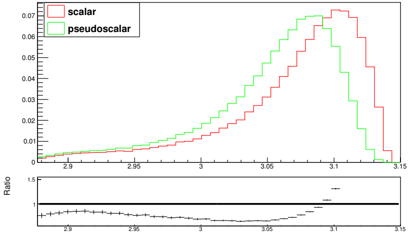


Figure: The acollinearity of $\pi^{\pm}$ in $H \to \tau^+\tau^-$,$\tau^{\pm} \to \pi^{\pm}\nu$ decay. The acollinearity range is zoomed to show its endpoint region

Outlook

- Continue collaboration with Professor E.Richter-Was(UJ): Installation and validation of `TauSpinner` algorithm for $2 \rightarrow 4$ processes in the framework of the ATLAS experiment. Using `TauSpinner` algorithm including $2 \rightarrow 4$ processes for validation of `TauSpinner` algorithm including $2 \rightarrow 2$ processes.
- Secondment at Warsaw University with Professor Jan Kalinowski(fall 2016): Training on theoretical aspects and tools.
- Secondment at CERN (May 2016):
  - Training on experimental software tools used for simulation and data analysis
  - Optimisation of observables for vector boson scattering processes in ATLAS experiment.
  - Optimisation of selection of charged Higgs signal in its decay to tau leptons, background estimation for the charged Higgs search in ATLAS.
- Completing the qualification procedure (Feb 2017).

For Further Reading I

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