

DEVELOPMENTS OF `TauSpinner` PREPARED FOR PRODUCTION OF τ LEPTON PAIRS WITH HIGH p_T JETS FOR THE SPIN-2 CASE*

M. BAHMANI, Z. WAS

H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland

J. KALINOWSKI, W. KOTLARSKI

Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland

E. RICHTER-WAS

M. Smoluchowski Institute of Physics, Jagiellonian University
Łojasiewicza 11, 30-348 Kraków, Poland

(Received January 22, 2018)

In the recently published paper, a new version of `TauSpinner` tool ver. 2.0.0 has been presented. It introduces non-standard states and couplings in the case of spin-2 state (as an example), and study their effects in the vector-boson-fusion processes by exploiting the spin correlations of τ -lepton pair decay products in processes where final states include also two hard jets. The implementation is prepared as the external routine. Consistency tests of the implemented matrix elements, reweighting algorithm and numerical results for observables sensitive to τ polarization are presented.

DOI:10.5506/APhysPolBSupp.11.339

1. Introduction

Exploring final states with τ leptons has become very important by increasing data obtained by LHC experiments. The high mass of τ leptons provide a sensitive window to physics beyond the Standard Model. The `TauSpinner` package [1] (and references therein) is a tool that allows to modify the physics model of Monte Carlo generated samples containing τ leptons.

* Presented by M. Bahmani at the Final HiggsTools Meeting, Durham, UK, September 11–15, 2017.

This is obtained with the help of weights attributed to each event. The only information used is the kinematics of final state, therefore, it can be used both for data and Monte Carlo simulations. In a recent paper [2], an extended version of `TauSpinner` was presented which now includes hard processes featuring tree-level parton matrix elements for production of a τ -lepton pair and two jets. Let us recall results of this paper. The tool was prepared to be used for studying spin effects in processes of Standard Model and searches of new physics like in Ref. [3, 4], and in experimental applications for the Standard Model measurements [5–8]. In the present paper, we summarize how a user can apply the `TauSpinner` algorithm to chosen physics model. We take as a case study a non-standard spin-2 object coupled to SM particles. This work is documented in Ref. [2]. In the present paper, in Section 2, the physics model of process of spin-2 object is presented, Section 3 documents test of implemented matrix elements. In Section 4, we present spin-dependent characteristics and in the last section, a summary is presented.

2. Physics model of $2 \rightarrow 4$ process of spin-2 object

We consider a simplified model of a massive gauge singlet spin-2 object X coupled to the SM gauge bosons. We use this model as a case study to show how to prepare and test external matrix element to be used by `TauSpinner` algorithm.

Connecting to our previous study [9], dedicated to study of the Drell–Yan-like production of τ s through a hypothetical spin-2 object X , now we focus on the X production in the VBF topology $pp \rightarrow jjX$ followed by $X \rightarrow \tau^+\tau^-$ decay.

We start by extending the Lagrangian of Ref. [9] by a set of gauge invariant dimension 5 operators, coupling the field X to gauge boson field strength tensors B , W and G as

$$\mathcal{L} \ni \frac{1}{F} X_{\mu\nu} \left(g_{XBB} B^{\mu\rho} B_{\rho}^{\nu} + g_{XWW} W^{\mu\rho} W_{\rho}^{\nu} + g_{Xgg} G^{\mu\rho} G_{\rho}^{\nu} \right), \quad (1)$$

where group indices are implicitly summed over (where appropriate). For keeping the coupling constants dimensionless, the parameter F is introduced and set to 1 TeV. Note that on the origin of the state X , we do not claim it is connected to gravity. Hence, we do not couple it to the entire energy momentum tensor and couplings g_X are kept as free parameters. In this work, we focus on technical aspects of incorporating the couplings of X to the EW gauge bosons. Relevant diagram topologies are shown in Fig. 1: for the VBF process (Fig. 1, left) and the X -strahlung process (Fig. 1, right). The squared matrix elements of this model are generated by using

MadGraph5, employing the spin-2 support of the HELAS library [10]. This is done with commands which can be found in Ref. [2].

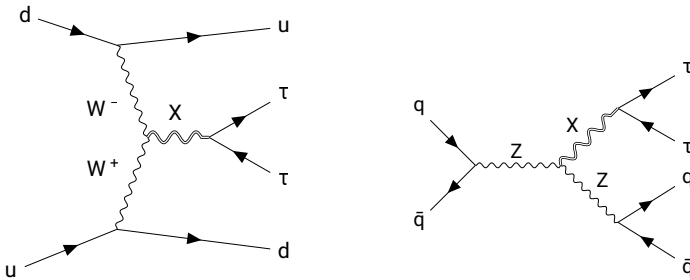


Fig. 1. Topologies of Feynman diagrams for X production through its coupling to gauge bosons. Similar diagrams, with different combinations of W^{\pm} s, Z s, photons and quark flavours also exist.

For numerical tests, we restrict ourselves setting $g_{XBB} = g_{Xgg} = 0$, though we emphasize that the matrix element, coded as an example for user, contains all of couplings.

2.1. Integrating matrix-element code into TauSpinner example

The matrix element code is based on automatically produced FORTRAN subroutines by MadGraph5¹ package, similarly as it has been done for processes of the Standard Model [1]. In the spin-2 case, they have been also manually modified and adapted for avoiding name clashes. Moreover, as a consequence of the fact that C++ user function for the spin-2 matrix element calls FORTRAN code created by MadGraph5, we cannot profit from namespace functionality of C++ as a natural solution to this problem and, therefore, some subroutine names changes were necessary. The corresponding code is stored in the directory TauSpinner/examples/example-VBF/SPIN2/ME.

The generated codes for the individual sub-processes are grouped together into subroutines, depending on the flavour of initial-state partons, and named accordingly. For example, SUBROUTINE DSX_S2(P, I3, I4, H1, H2, ANS) encompasses the X production processes initiated by the $d\bar{s}$ partons. We follow our previous convention [1], where symbol X in the subroutine or internal function name after the letter U, D, S or C means that the corresponding parton is an antiquark, *i.e.* UXCX corresponds to processes initiated by $\bar{u}\bar{c}$ partons, while GUX to processes initiated² by $g\bar{u}$. The S2 stands explicitly for the production of spin-2 X state. The input variables are: real matrix P(0:3,6) for four-momenta of incoming and outgoing particles, integers

¹ Version MG5_aMC_v2.4.3.

² X in this context should not be confused with the spin-2 field X .

I3,I4 for the Particle Data Group (PDG) identifiers for final-state parton flavours and integers H1,H2 for the outgoing τ helicity states. A number of modifications have been done, before integrating these subroutines into the `TauSpinner` program which is documented in Ref. [2].

In practice, the `TauSpinner` reweighting algorithm is expected to be used in regions of the phase-space where kinematic distributions of the original and new physics models are not massively different.

3. Tests of implementation of external matrix elements

Once the user-provided external matrix elements are prepared, numerical tests are necessary to test proper implementation into the `TauSpinner` environment. A single event with fixed kinematic configuration at the parton level has been chosen to check the consistency of the implemented codes generated with `MadGraph5` and modified as explained in previous section. For that event, the matrix elements squared have been calculated for all possible helicity and parton flavour configurations, using the code implemented as user example. By comparison of results with the numerical values obtained directly from `MadGraph5`, we have confirmed the agreement on the level of at least 6 significant digits.

Further tests of the internal consistency of external matrix element implementation have been explored for the reweighting procedure by comparing a number of kinematic distributions obtained directly or reweighted with $w_{\text{prod}}^{H \rightarrow X}$ which is the ratio due to the matrix element used in the generation of the sample for process (H) and the matrix elements corresponding to a new physics model (X) [1] from series of 10 M events generated by `MadGraph5` for Higgs boson and X particle. Samples were generated for pp collisions at 13 TeV using `CTEQ6L1` PDFs. The mass of both X particle and Higgs boson was set to 125 GeV and the width to 5.75 MeV. One can see in Fig. 2 that the weight distributions without selection contain a long tail extending to high weights, which would indicate a problem with reweighting in regions of the phase-space where the ratio of the matrix element with respect of the one of the original sample is too large in comparison to the typical event. Therefore, on the generated events, the following selections were applied: $m_{jj\tau\tau}$ ³ < 1500 GeV, $p_{\text{T}}^{\tau\tau}$ ⁴ < 600 GeV and m_{jj} < 800 GeV (loose selection) for eliminating excessive weight regions of the phase-space, or eliminating also $Z \rightarrow jj$ or $W \rightarrow jj$ resonance peaks $100 < m_{jj}$ ⁵ < 800 GeV (tight selection).

³ Invariant mass of outgoing particles.

⁴ Transverse momentum of τ s.

⁵ Invariant mass of jets.

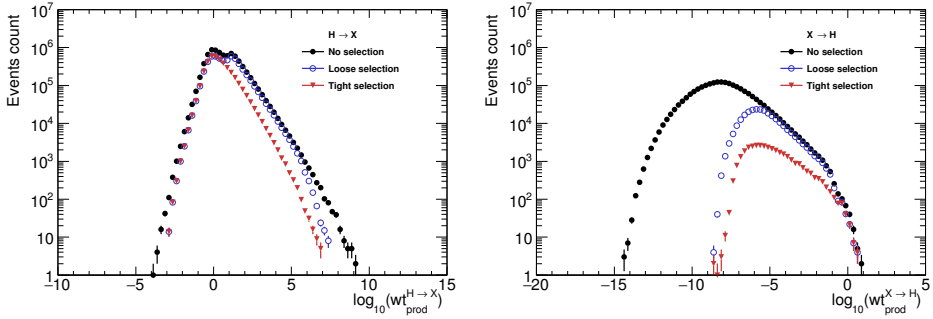


Fig. 2. Weight distribution for H sample reweighted to X (left panel) and for the X sample reweighted to H (right panel).

The tests were performed on a set of kinematic distributions: pseudorapidity of outgoing parton j , rapidity of $\tau\tau$ and jj systems, invariant mass of $\tau\tau$ system, pseudorapidity of $\tau\tau$ system, opening angle between jets, opening angle between τ s, angle between incoming parton and outgoing parton in the rest frame of jets, and angle between resonance and outgoing parton in the rest frame of jets.

For all these variables, plots can be found on the web page [11]. Here, in Fig. 3 and Fig. 4, we show only plots for: the difference of jet's rapidities $\Delta\eta^{jj}$, the invariant mass of the jet pair m^{jj} . In each plot, the distribution Ref, for the reference process, is shown as a black histogram, while the red histogram (in B&W gray histogram) is the original distribution of generated events which is reweighted using TauSpinner weight to obtain the distribution represented by the red points (in B&W gray points) with error bars. For

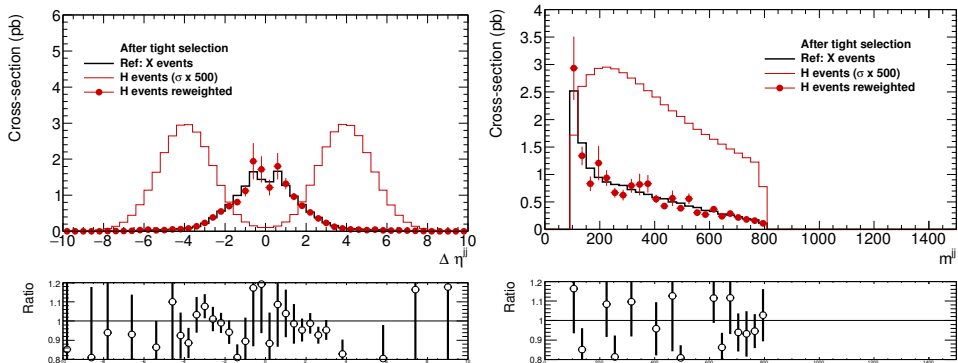


Fig. 3. The H sample reweighted to the X and compared with the X sample for the difference of jets rapidities $\Delta\eta^{jj}$ (left panel) and the invariant mass of the jet pair m^{jj} (right panel).

the test to be successful, the red points should follow the black histogram; the ratio of Ref and reweighted distributions is shown in the bottom panel of each figure.

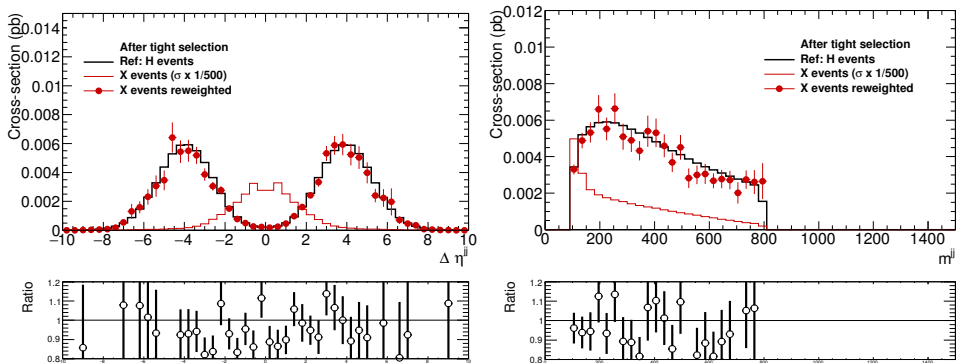


Fig. 4. The X sample reweighted to the H and compared with the H sample.

The reweighted distributions follow the Ref histograms, in both Figs. 3 and 4. For reweighting of X to H (see Fig. 4), the distributions show larger statistical errors than in the case of H to X reweighting (Fig. 3). This is simply because tight selection cuts leave only 1.7% of X events due to eliminating configurations with small m_{jj} . The tests validating reweighting algorithm are completed with the ones monitoring overall normalizations (integrated cross sections).

4. Spin-dependent characteristics

In the previous sections, we were discussing observables relying on the kinematics of final states consisting of four momenta of τ leptons and accompanying two jets. If we include the τ decay products, the phase-space dimensionality will increase substantially, making the analysis much more difficult, especially when the dependence on selection cuts is taken into account. In this section, we will present a few spin-dependent results obtained for the H and X samples within the tight selection cuts. By using TAUOLA++ [12], these samples are supplemented with τ decays in the simplest possible mode $\tau^\pm \rightarrow \pi^\pm \nu$ with no spin effects included. With the help of TauSpinner weights, the spin effects calculated according to the production and decay kinematics (see Refs. [13, 14]) are introduced. The spin weight histograms for the H and X samples in Fig. 5 show the comparison of spin weights calculated using the matrix element for X productions as described in Ref. [9], that is featuring effective Born $2 \rightarrow 2$ kinematic (open red circles), and using a new way in which amplitudes featuring two jet kinematics are taken into account (full blue circle points). In both cases, the same X - $\tau\tau$ couplings

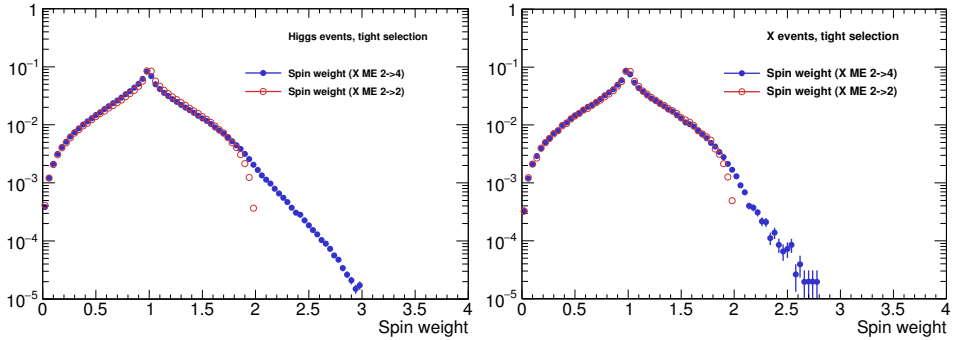


Fig. 5. Spin weight histograms, normalized to unity, obtained from X matrix elements for H sample (left plot) and X sample (right plot).

were used. As expected (see Eq. (8) from Ref. [13]), for the $2 \rightarrow 2$ case, the range of spin weights is limited to $[0, 2]$ since in this process there are no couplings which could lead to individual τ polarization. In the $2 \rightarrow 4$ case, the spin weight distribution exhibits a tail which extends beyond 2 and covers most of the allowed $[0, 4]$ range. This is due to, *e.g.*, the presence of the subprocess $W^+W^- \rightarrow X \rightarrow \tau^+\tau^-$ in which W s radiated off quarks are polarized which has impact on τ polarization. The tail above 2, although not so much pronounced, will manifest itself in the distribution of τ decay products. The τ polarization can originate from the X production via VBF process, which is asymmetric over the phase-space regions. To show the polarization effects, we have to sort out events according to the τ polarization; otherwise, the effects will average out. In the proton, there are more u -type quarks than d -type, therefore, the X particle produced in the VBF preferentially will follow the direction of W^+ which is right-handed and imparts its polarization on X bosons. One can then expect that τ lepton from X decay will have polarization dependent on τ direction with respect to the X flight direction correlated with its spin polarization. Thus, it is suggestive to sort events according to positive and negative value of $C = Y_X \cdot (p_z^{\tau^-} - p_z^{\tau^+})$, where Y_X denotes the τ -lepton pair rapidity and $p_z^{\tau^-}$, $p_z^{\tau^+}$ are the z components of τ^\pm four-momenta. In Fig. 6, events with positive and negative C are plotted separately. We observe that spin weights, calculated with the X production amplitude, when applied to the H sample lead to a larger spin effect, than when applied to the X sample. In the second case, the spin effect is barely visible. The results indicates that even within tight selection, there is a sizable difference between events of X and H production, which is reflected in τ polarization effects greater for the H sample than for X sample, even though the same $pp \rightarrow \tau\tau jj$ matrix elements featuring intermediate X are used in both cases.

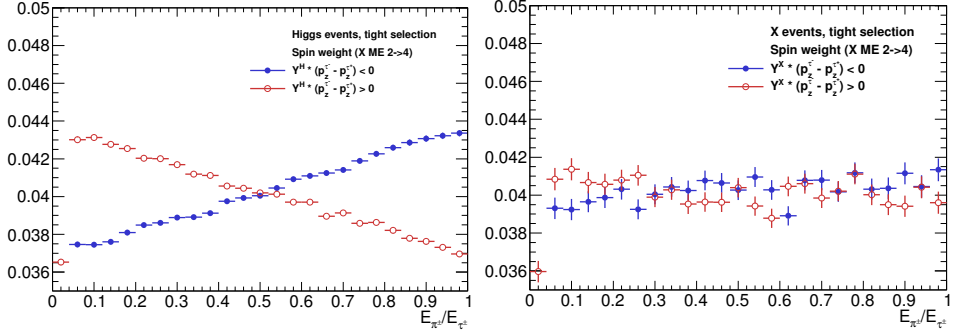


Fig. 6. (Color online) Histograms of $E_{\pi^{\pm}}/E_{\tau^{\pm}}$ spectra, normalized to unity, for the H sample (left panel) and for the X sample (right panel). In all cases $2 \rightarrow 4$ matrix elements of X exchange are used to implement spin effects. Open circle (red) points (in B&W gray) are for additional cut $Y_X \cdot (p_{Z^-} - p_{Z^+}) > 0$ and the full circle (blue) points for $Y_X \cdot (p_{Z^-} - p_{Z^+}) < 0$.

The reason might be that such small spin effect present in Fig. 6 for the X case is a consequence of substantial contribution from other than VBF channel in our samples, thus pointing out that our cuts may need to be refined. However, because of the weight distribution, as seen in the right plot of Fig. 5, such a refinement is unlikely to be found within our tight selection, since the tail of events with spin weight exceeding 2 is very small.

Nonetheless, τ polarization may offer (minor) help in exclusion of X hypothesis, even in the case when $X\tau\tau$ couplings are insensitive to parity.

5. Summary

We have recalled results of [2] which demonstrate how the new matrix elements for the production of τ -lepton pair accompanied with two jets in pp collisions can be used in **TauSpinner** environment to reweight events. For that purpose, the new physics matrix element for spin-2 X particle was implemented as a user example.

We have provided numerical tests of the algorithm, demonstrating that starting from the H sample (or X sample), the other one can be obtained by applying event-by-event weight calculated from the implemented matrix elements. We have chosen $\tau^{\pm} \rightarrow \pi^{\pm}\nu$ decay mode as a spin analyser, to indicate effects sensitive to the τ -lepton polarization. Spin effects originate from the X production vertex and are embedded in complexity of the multi-body phase space. They turn out to be rather small for our choice of the $X\tau\tau$ couplings. Nevertheless, they may turn useful in falsifying physics hypotheses alternative to Higgs production and decay processes.

The work has been supported in part from funds of the National Science Centre, Poland (NCN) under decisions UMO-2014/15/B/ST2/00049, by PLGrid Infrastructure of the Academic Computer Centre CYFRONET AGH in Kraków, Poland (where majority of numerical calculations were performed) and by HARMONIA project under contract UMO-2015/18/M/ST2/00518 (2016–2019). M.B., J.K., E.R.W. and Z.W. were supported in part by the Research Executive Agency (REA) of the European Union under the Grant Agreement PITNGA2012316704 (HiggsTools). W.K. was supported in part by the German DFG grant STO 876/4-1. J.K. thanks the CERN Theoretical Physics Department for hospitality during the final stage of this work.

REFERENCES

- [1] J. Kalinowski, W. Kotlarski, E. Richter-Was, Z. Was, *Eur. Phys. J. C* **76**, 540 (2016) [arXiv:1604.00964 [hep-ph]]; See also M. Bahmani *et al.*, *Acta Phys. Pol. B* **48**, 903 (2017).
- [2] M. Bahmani *et al.*, *Eur. Phys. J. C* **78**, 10 (2018) [arXiv:1708.03671 [hep-ph]].
- [3] G. Aad *et al.* [ATLAS Collaboration], *J. High Energy Phys.* **1411**, 056 (2014) [arXiv:1409.6064 [hep-ex]].
- [4] CMS Collaboration, Search for Additional Neutral Higgs Bosons Decaying to a Pair of tau Leptons in pp Collisions at $\sqrt{s} = 7$ and 8 TeV, CMS-PAS-HIG-14-029.
- [5] G. Aad *et al.* [ATLAS Collaboration], *Eur. Phys. J. C* **72**, 2062 (2012) [arXiv:1204.6720 [hep-ex]].
- [6] G. Aad *et al.* [ATLAS Collaboration], *J. High Energy Phys.* **1504**, 117 (2015) [arXiv:1501.04943 [hep-ex]].
- [7] CMS Collaboration, Model Independent Search for Higgs Boson Pair Production in the $b\bar{b}\tau^+\tau^-$ Final State, CMS-PAS-HIG-15-013.
- [8] V. Cherepanov, Measurement of the Polarization of tau-leptons Produced in Z Decays at CMS and Determination of the Effective Weak Mixing Angle, Ph.D. Thesis, Aachen, Tech. Hochsch., 2016.
- [9] S. Banerjee *et al.*, *Eur. Phys. J. C* **73**, 2313 (2013) [arXiv:1212.2873 [hep-ph]].
- [10] K. Hagiwara, J. Kanzaki, Q. Li, K. Mawatari, *Eur. Phys. J. C* **56**, 435 (2008) [arXiv:0805.2554 [hep-ph]].
- [11] M. Bahmani *et al.*, see <http://wasm.web.cern.ch/wasm/MadgraphIni.txt> and <http://wasm.web.cern.ch/wasm/MonitoringPlots.pdf> available from <http://wasm.web.cern.ch/wasm/newprojects.html>
- [12] N. Davidson *et al.*, *Comput. Phys. Commun.* **183**, 821 (2012) [arXiv:1002.0543 [hep-ph]].
- [13] Z. Czyczula, T. Przedzinski, Z. Was, *Eur. Phys. J. C* **72**, 1988 (2012) [arXiv:1201.0117 [hep-ph]].
- [14] A. Kaczmarska *et al.*, *Acta Phys. Pol. B* **45**, 1921 (2014) [arXiv:1402.2068 [hep-ph]].