HNL Decays with Pythia 8

Philip Ilten

University of CINCINNATI

November 10, 2021

Tenth workshop of the LLP Community

Overview

- sophisticated tau decays available in Pythia 8.150 and above
  - spin correlations
  - fully modeled hadronic currents
  - handles LHEF SPINUP digit
- based on the work of Tauola and Herwig++
- all known decays with $\mathcal{B} > 0.04\%$ available
- documentation available in online manual, arXiv:1211.6730, and arXiv:1401.4902
- use same framework for HNLs

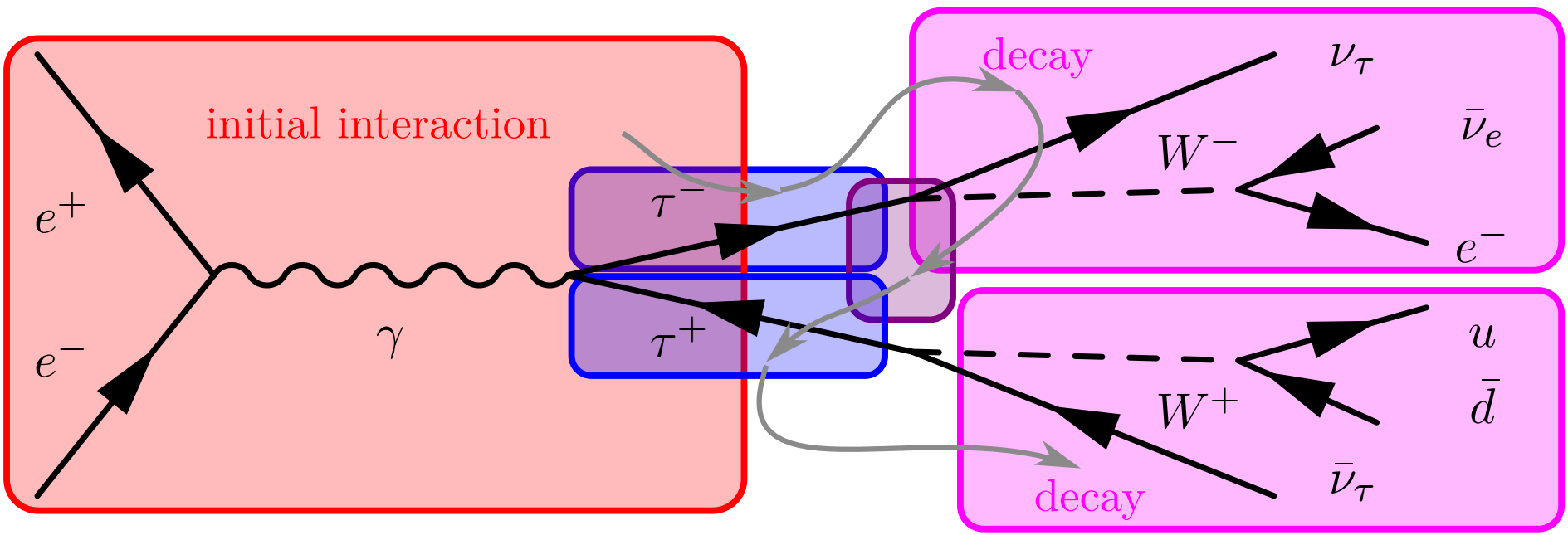
Algorithm

- based on algorithm by Collins and Knowles and expanded by Richardson
- $D \equiv$ decay matrix for each particle, $D_{\text{initial}} = \mathbb{I}$
- $\mathcal{M} \equiv$ matrix element, $\rho \equiv$ density matrix

1. Calculate $\mathcal{M}$ for the initial interaction.
2. Find ρ for an outgoing particle using the interaction $\mathcal{M}$ and D's of the remaining outgoing particles.
3. Decay the particle using its $\mathcal{M}$, ρ, and the D's of its decay products.
4. Repeat 2 - 3 until all decay products are stable.
5. Calculate D for the particle.
6. Go up a decay and perform 2 - 5 on the undecayed particles.
7. Repeat 2 - 6 until all particles are decayed.

Example

2. $\rho^{j}_{\lambda_j\lambda'_j} = \rho^{1}_{\kappa_1\kappa'_1}\rho^{2}_{\kappa_2\kappa'_2}\mathcal{M}_{\kappa_1\kappa_2;\lambda_1\ldots\lambda_n}\mathcal{M}^{*}_{\kappa'_1\kappa'_2;\lambda'_1\ldots\lambda'_n}\prod_{k\neq j} D^{k}_{\lambda_k\lambda'_k}$
3. $\mathcal{W}_{\text{decay}} = \rho_{\lambda_0\lambda'_0}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^{*}_{\lambda'_0;\lambda'_1\ldots\lambda'_n}\prod_{k=1,n} D^{k}_{\lambda_k\lambda'_k}$
5. $D_{\lambda_0\lambda'_0} = \mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^{*}_{\lambda'_0;\lambda'_1\ldots\lambda'_n}\prod_{l=1,n} D^{l}_{\lambda_l\lambda'_l}$



Production Summary

- internally calculate polarization
- read polarization from LHEF SPINUP
- force given polarization for taus produced from specific mother
- force given polarization for all taus

production	$\mathcal{M}$
$\gamma\gamma \to f\bar{f}$	`HMETwoGammas2TwoFermions`
$f\bar{f} \to \gamma \to f\bar{f}$	`TwoFermions2Gamma2TwoFermions`
$f\bar{f} \to Z \to f\bar{f}$	`TwoFermions2Z2TwoFermions`
$f\bar{f} \to \gamma^*/Z \to f\bar{f}$	`TwoFermions2GammaZ2TwoFermions`
$f\bar{f}' \to W \to f\bar{f}'$	`TwoFermions2W2TwoFermions`
$Z \to f\bar{f}$	`Z2TwoFermions`
$W \to f\bar{f}$	`TwoFermions2W2TwoFermions`
$B/D \to f\bar{f}' + X$	`TwoFermions2W2TwoFermions`
$H^{\mathcal{CP}-\text{even}} \to f\bar{f}$	`Higgs2TwoFermions`
$H^{\mathcal{CP}-\text{odd}} \to f\bar{f}$	`Higgs2TwoFermions`
$H^{\pm} \to f\bar{f}'$	`Higgs2TwoFermions`

Decay Summary

decay	$\mathcal{M}$
$\tau^- \to \nu_\tau \pi^-$	1521
$\tau^- \to \nu_\tau K^-$	1521
$\tau^- \to \nu_\tau e^- \bar{\nu}_e$	1531
$\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$	1531
$\tau^- \to \nu_\tau \pi^0 \pi^-$	1532
$\tau^- \to \nu_\tau K^0 K^-$	1532
$\tau^- \to \nu_\tau \eta K^-$	1532
$\tau^- \to \nu_\tau \pi^- \bar{K}^0$	1533
$\tau^- \to \nu_\tau \pi^0 K^-$	1533
$\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^-$	1541, 1543
$\tau^- \to \nu_\tau \pi^- \pi^- \pi^+$	1541, 1543
$\tau^- \to \nu_\tau K^- \pi^- K^+$	1542, 1543
$\tau^- \to \nu_\tau K^0 \pi^- \bar{K}^0$	1542, 1543
$\tau^- \to \nu_\tau K_S^0 \pi^- K_S^0$	1542

decay	$\mathcal{M}$
$\tau^- \to \nu_\tau K_L^0 \pi^- K_L^0$	1542
$\tau^- \to \nu_\tau K_S^0 \pi^- K_L^0$	1542
$\tau^- \to \nu_\tau K^- \pi^0 K^0$	1542
$\tau^- \to \nu_\tau \pi^0 \pi^0 K^-$	1542, 1543
$\tau^- \to \nu_\tau K^- \pi^- \pi^+$	1542, 1543
$\tau^- \to \nu_\tau \pi^- \bar{K}^0 \pi^0$	1542, 1543
$\tau^- \to \nu_\tau \pi^- \pi^0 \eta$	1543
$\tau^- \to \nu_\tau \gamma \pi^0 \pi^-$	1544
$\tau^- \to \nu_\tau \pi^0 \pi^- \pi^- \pi^+$	1551
$\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^0 \pi^-$	1551
$\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^- \pi^- \pi^+$	1561
$\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^0 \pi^0 \pi^-$	1561
$\tau^- \to \nu_\tau \pi^- \pi^- \pi^- \pi^+ \pi^+$	1561

Matrix Elements

- helicity classes and representation (Weyl basis) implemented in `HelicityBasics.cc`
- helicity matrix elements (production and decay) implemented in `HelicityMatrixElements.cc`
- only hadronic current needs to be implemented for new models
- decay mechanism implemented in `HelicityDecays.cc`

$$\mathcal{M} = \bar{u}_1 \gamma_\mu (1 - \gamma_5) u_0 {q_2}^\mu$$

$$\Downarrow$$

$$\begin{aligned}\mathcal{M} = \sum_\mu \; & p_1\texttt{.waveBar}(\lambda_1)*\texttt{GammaMatrix}(\mu) \\ & *(1 - \texttt{GammaMatrix}(5)) * p_0\texttt{.wave}(\lambda_0) \\ & *\texttt{GammaMatrix}(4)(\mu,\mu) * \texttt{Wave4}(q_2)(\mu)\end{aligned}$$

HNLs

- `https://gitlab.com/hnls/pythia`
- some validation, but not extensive
- relevant hard process, D, and B production
- most relevant HNL decays available

- include charged/neutral current interference in leptonic channel
- recursive helicity decay structure for $\ell \to N$ or $N \to \tau\tau$