

# HNL Decays with PYTHIA 8

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NINTH 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
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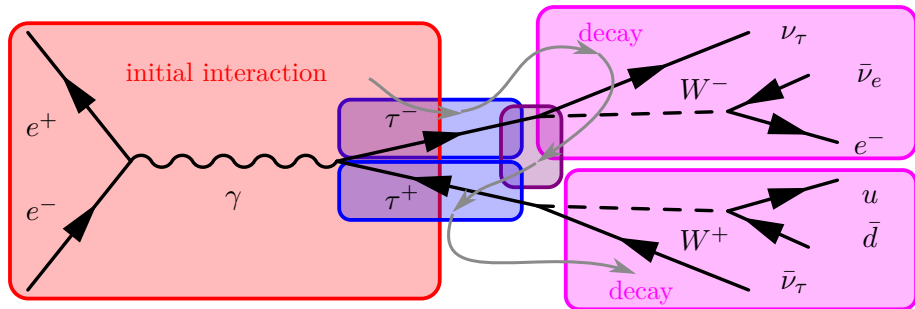
- helicity correlation
  - algorithm
  - example
- tau production
  - electroweak
  - Higgs
- tau decay
  - 2-6 body
- implementation
  - matrix elements
  - HNLs

# Algorithm

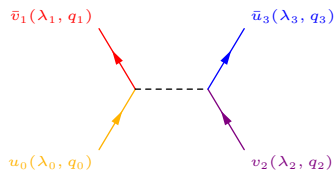
- based on algorithm by Collins and Knowles and expanded by Richardson
  - $D \equiv$  decay matrix for each particle,  $D_{\text{initial}} = \mathbb{I}$
  - $\mathcal{M} \equiv$  matrix element,  $\rho \equiv$  density matrix
- ① Calculate  $\mathcal{M}$  for the initial interaction.
  - ② Find  $\rho$  for an outgoing particle using the interaction  $\mathcal{M}$  and  $D$ 's of the remaining outgoing particles.
  - ③ Decay the particle using its  $\mathcal{M}$ ,  $\rho$ , 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  $\rho_{\lambda_j \lambda'_j}^j = \rho_{\kappa_1 \kappa'_1}^1 \rho_{\kappa_2 \kappa'_2}^2 \mathcal{M}_{\kappa_1 \kappa_2; \lambda_1 \dots \lambda_n} \mathcal{M}_{\kappa'_1 \kappa'_2; \lambda'_1 \dots \lambda'_n}^* \prod_{k \neq j} D_{\lambda_k \lambda'_k}^k$
- ③  $\mathcal{W}_{\text{decay}} = \rho_{\lambda_0 \lambda'_0} \mathcal{M}_{\lambda_0; \lambda_1 \dots \lambda_n} \mathcal{M}_{\lambda'_0; \lambda'_1 \dots \lambda'_n}^* \prod_{k=1, n} D_{\lambda_k \lambda'_k}^k$
- ⑤  $D_{\lambda_0 \lambda'_0} = \mathcal{M}_{\lambda_0; \lambda_1 \dots \lambda_n} \mathcal{M}_{\lambda'_0; \lambda'_1 \dots \lambda'_n}^* \prod_{l=1, n} D_{\lambda_l \lambda'_l}^l$



## Electroweak



- $W$  boson

$$\mathcal{M}_W \propto (\bar{\nu}_1(1-\gamma_5)u_0)(\bar{u}_3(1-\gamma_5)\nu_2)$$

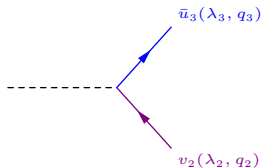
- $Z$  boson

$$\begin{aligned} \mathcal{M}_Z &= \frac{g_e^2}{16 \cos^2 \theta_W \sin^2 \theta_w \left( s - m_Z^2 + i \frac{\Gamma_Z}{m_Z} \right)} \\ &\times \left( \bar{\nu}_1 \gamma^\mu (c_V^0 - c_A^0 \gamma^5) u_0 \right) \\ &\times \left( g_{\mu\nu} - \frac{q_\mu q_\nu}{m_Z^2} \right) \left( \bar{u}_3 \gamma^\nu (c_V^2 - c_A^2 \gamma^5) \nu_2 \right) \end{aligned}$$

- photon

$$\mathcal{M}_\gamma = \frac{g_e^2 Q_0 Q_2}{s} (\bar{\nu}_1 \gamma_\mu u_0) (\bar{u}_3 \gamma^\mu \nu_2)$$

## Higgs



- $\mathcal{CP}$ -even Higgs

$$\mathcal{M}_{\text{even}} \propto \left( \frac{ig_w m_2}{2m_W} \right) \bar{u}_3 c_\Phi^2 v_2$$

- charged Higgs

$$\begin{aligned} \mathcal{M}_{H^\pm} &\propto \left( \frac{ig_w}{2\sqrt{2}m_W} \right) \bar{u}_3 \\ &\times \left( (m_1 \tan \beta + m_2 \cot \beta) \right. \\ &\left. \pm (m_1 \tan \beta - m_2 \cot \beta) \gamma^5 \right) v_2 \end{aligned}$$

- $\mathcal{CP}$ -odd Higgs

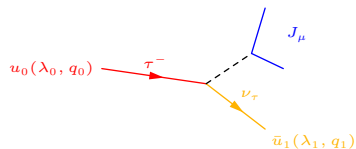
$$\mathcal{M}_{\text{odd}} \propto - \left( \frac{g_w m_2}{2m_W} \right) \bar{u}_3 c_\Phi^2 \gamma^5 v_2$$

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

# General Form



- $\mathcal{M} = \frac{g_w^2}{8m_W^2} L_\mu J^\mu$
- $L_\mu = \bar{u}_1 \gamma_\mu (1 - \gamma^5) u_0$
- $J_\mu$  dependent upon the decay
  - charged lepton and neutrino
 
$$J_\mu = \bar{u}_\ell - \gamma^\mu (1 - \gamma^5) v_{\bar{\nu}_\ell}$$
  - single hadron
 
$$J_\mu = f q_{h^-}$$

## Decay Summary

decay	$\mathcal{M}$	decay	$\mathcal{M}$
$\tau^- \rightarrow \nu_\tau \pi^-$	1521	$\tau^- \rightarrow \nu_\tau K^0 \pi^- K^0$	1542
$\tau^- \rightarrow \nu_\tau K^-$	1521	$\tau^- \rightarrow \nu_\tau K_S^0 \pi^- K_L^0$	1542
$\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e$	1531	$\tau^- \rightarrow \nu_\tau K^- \pi^0 K_L^0$	1542
$\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu$	1531	$\tau^- \rightarrow \nu_\tau \pi^0 \pi^0 K^-$	1542, 1543
$\tau^- \rightarrow \nu_\tau \pi^0 \pi^-$	1532	$\tau^- \rightarrow \nu_\tau K^- \pi^- \pi^+$	1542, 1543
$\tau^- \rightarrow \nu_\tau K^0 K^-$	1532	$\tau^- \rightarrow \nu_\tau \pi^- \bar{K}^0 \pi^0$	1542, 1543
$\tau^- \rightarrow \nu_\tau \eta K^-$	1532	$\tau^- \rightarrow \nu_\tau \pi^- \pi^0 \eta$	1543
$\tau^- \rightarrow \nu_\tau \pi^- \bar{K}^0$	1533	$\tau^- \rightarrow \nu_\tau \gamma \pi^0 \pi^-$	1544
$\tau^- \rightarrow \nu_\tau \pi^0 K^-$	1533	$\tau^- \rightarrow \nu_\tau \pi^0 \pi^- \pi^- \pi^+$	1551
$\tau^- \rightarrow \nu_\tau \pi^0 \pi^0 \pi^-$	1541, 1543	$\tau^- \rightarrow \nu_\tau \pi^0 \pi^0 \pi^0 \pi^-$	1551
$\tau^- \rightarrow \nu_\tau \pi^- \pi^- \pi^+$	1541, 1543	$\tau^- \rightarrow \nu_\tau \pi^0 \pi^0 \pi^- \pi^- \pi^+$	1561
$\tau^- \rightarrow \nu_\tau K^- \pi^- K^+$	1542, 1543	$\tau^- \rightarrow \nu_\tau \pi^0 \pi^0 \pi^0 \pi^-$	1561
$\tau^- \rightarrow \nu_\tau K^0 \pi^- \bar{K}^0$	1542, 1543	$\tau^- \rightarrow \nu_\tau \pi^- \pi^- \pi^- \pi^+ \pi^+$	1561
$\tau^- \rightarrow \nu_\tau K_S^0 \pi^- K_S^0$	1542		

# 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
- tau decay mechanism implemented in `TauDecays.cc`

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

$$\Downarrow$$

$$\mathcal{M} = \sum_{\mu} p_1.\text{waveBar}(\lambda_1) * \text{GammaMatrix}(\mu) * (1 - \text{GammaMatrix}(5)) * p_0.\text{wave}(\lambda_0) * \text{GammaMatrix}(4)(\mu, \mu) * \text{Wave4}(q_2)(\mu)$$

# HNLs

- <https://gitlab.com/hnls/pythia>
- no validation yet
- $D$  and  $B$  production
- CC leptonic and single pseudo-scalar decays
  
- dynamic maximum finding for additional channels
- full helicity decay treatment of heavy meson decays
- recursive helicity decay structure
- include charged/neutral current interference in leptonic channel