Tau Decays in PYTHIA 8

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Overview

- sophisticated tau decays available in Pythia since 8.150
  - spin correlations
  - fully modeled hadronic currents
  - extensibility
- based on the work of Tauola [6] and Herwig++ [7]
- all known decays with $\mathcal{B} > 0.04\%$ available in upcoming Pythia 8.170

- helicity correlation
  - algorithm
  - example
- tau production
  - electroweak
  - Higgs
  - additional
- tau decay
  - two body
  - three body
  - four body
  - five body
  - six body
- implementation
  - interface
  - matrix elements

Pythia dev. 8.165
Herwig++ 2.6.2
Tauola 2.9 with Pythia 6

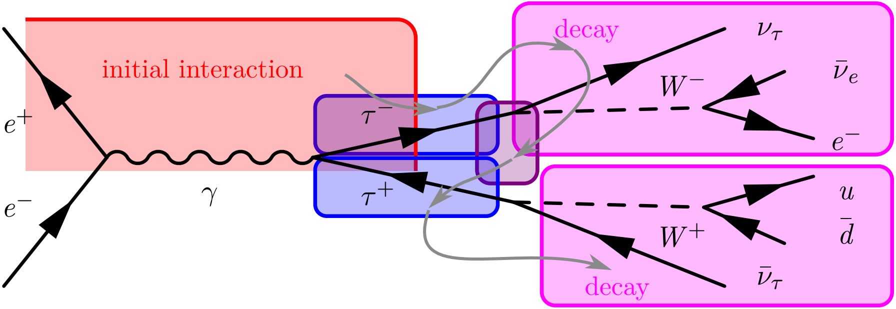
Algorithm

- based on algorithm by Collins [2] and Knowles [9] and expanded by Richardson [12]
- $D \equiv$ decay matrix for each particle, $D_{\text{initial}} = \mathbb{I}$
- $\mathcal{M} \equiv$ matrix element, $\rho \equiv$ density matrix

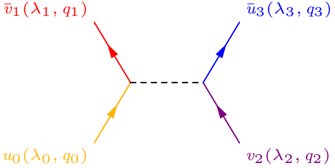
1. Calculate $\mathcal{M}$ for the initial interaction.
2. Find ρ for an outgoing particle using the interaction $\mathcal{M}$ and D's of the remaining outgoing particles.
3. Decay the particle using its $\mathcal{M}$, ρ, and the D's of its decay products.
4. Repeat 2 - 3 until all decay products are 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

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



Electroweak



- W boson

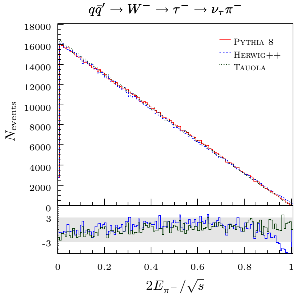
$$\mathcal{M}_W \propto \left(\bar{v}_1(1-\gamma_5)u_0\right)\left(\bar{u}_3(1-\gamma_5)v_2\right)$$

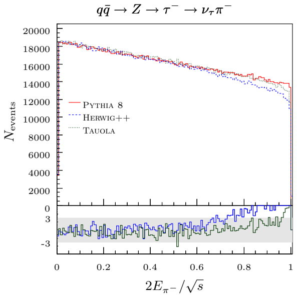
- Z boson

$$\mathcal{M}_Z = \frac{g_e^2}{16\cos^2\theta_W \sin^2\theta_w \left(s - m_Z^2 + i\frac{\Gamma_Z}{m_Z}\right)} \times \left(\bar{v}_1\gamma^\mu\left(c_V^0 - c_A^0\gamma^5\right)u_0\right) \times \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{m_Z^2}\right)\left(\bar{u}_3\gamma^\nu\left(c_V^2 - c_A^2\gamma^5\right)v_2\right)$$

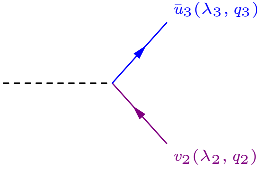
- photon

$$\mathcal{M}_\gamma = \frac{g_e^2 Q_0 Q_2}{s}\left(\bar{v}_1\gamma_\mu u_0\right)\left(\bar{u}_3\gamma^\mu v_2\right)$$





Higgs



- charged Higgs

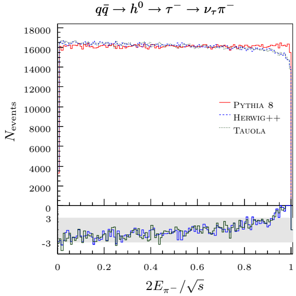
$$\mathcal{M}_{H^\pm} \propto \left(\frac{ig_w}{2\sqrt{2}m_W}\right) \bar{u}_3 \times \Big((m_1 \tan\beta + m_2 \cot\beta) \pm (m_1 \tan\beta - m_2 \cot\beta)\gamma^5\Big) v_2$$

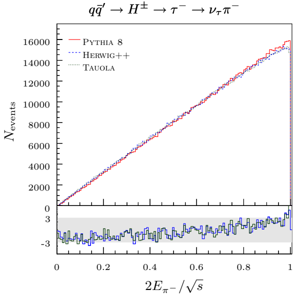
- $\mathcal{CP}$-even Higgs

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

- $\mathcal{CP}$-odd Higgs

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



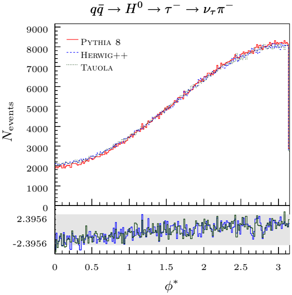


Higgs (ϕ^*)

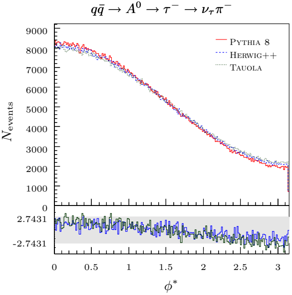
$$\vec{n}_- \equiv \frac{\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}}{\left|\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}\right|} \qquad \vec{n}_+ \equiv \frac{\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}}{\left|\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}\right|}$$

$$\cos(\phi^*) \equiv \vec{n}_- \cdot \vec{n}_+$$

$\mathcal{CP}$-even Higgs

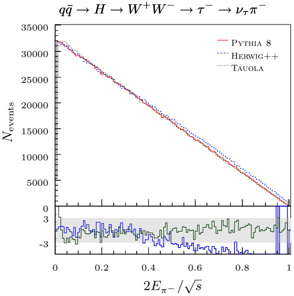


$\mathcal{CP}$-odd Higgs

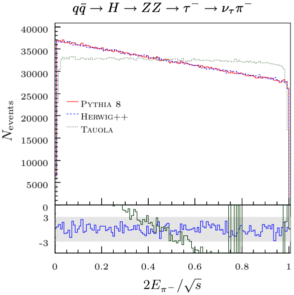


Additional

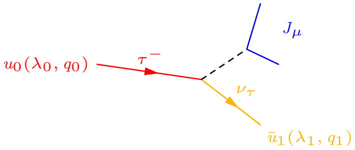
- $B/D \to X + \tau\nu$
  $\mathcal{M}_W$ with incoming B/D and outgoing X
- unknown W
  assume $\mathcal{P}_\tau \sim -1$
  i.e. $H \to W^+W^-$



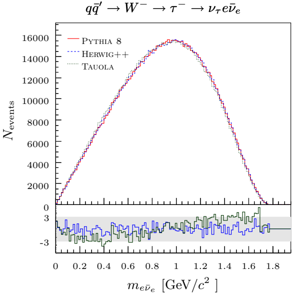
- $B/D \to \tau\nu$
  $\mathcal{M}_W$ with half B/D momentum per quark
- unknown Z
  assume unpolarized Z decay
  i.e. $H \to ZZ$

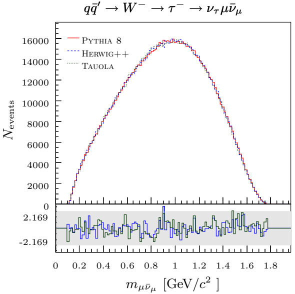


General Form



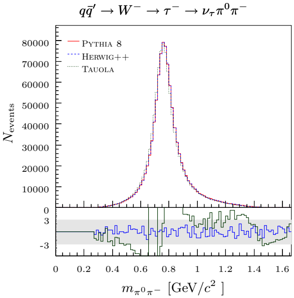
- $\mathcal{M} = \frac{g_w^2}{8m_W^2} L_\mu J^\mu$
- $L_\mu = \bar{u}_1 \gamma_\mu (1 - \gamma 5) u_0$
- J_μ dependent upon the decay
  - charged lepton and neutrino $J_\mu = \bar{u}_{\ell^-} \gamma^\mu (1 - \gamma^5) v_{\bar{\nu}_\ell}$
  - single hadron $J_\mu = f q_{h^-}$

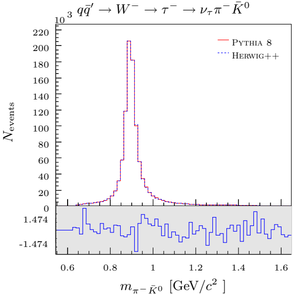




Three Body

- three models
- leptonic current
  - $\tau^- \to \nu_\tau e^- \bar{\nu}_e$
  - $\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$
- *Kühn and Santamaria* [10]
  - $\tau^- \to \nu_\tau \pi^0 \pi^-$
  - $\tau^- \to \nu_\tau K^0 K^-$
  - $\tau^- \to \nu_\tau \eta K^-$
- *Finkemeier and Mirkes* [5]
  - $\tau^- \to \nu_\tau \pi^- \bar{K}^0$
  - $\tau^- \to \nu_\tau \pi^0 K^-$



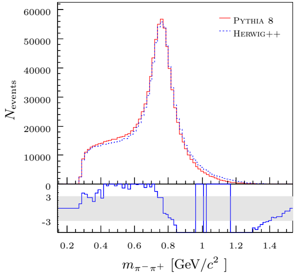


Four Body

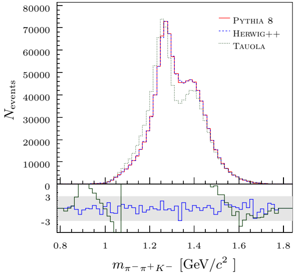
- four models
- *CLEO model* [13]
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^-$
  - $\tau^- \to \nu_\tau \pi^- \pi^- \pi^+$
- *Finkemeier and Mirkes* [4]
  - $\tau^- \to \nu_\tau K^- \pi^- K^+$
  - $\tau^- \to \nu_\tau K^0 \pi^- \bar{K}^0$
  - $\tau^- \to \nu_\tau K^0_S \pi^- K^0_S$
  - $\tau^- \to \nu_\tau K^0_L \pi^- K^0_L$
  - $\tau^- \to \nu_\tau K^0_S \pi^- K^0_L$
  - $\tau^- \to \nu_\tau K^- \pi^0 K^0$
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 K^-$
  - $\tau^- \to \nu_\tau K^- \pi^- \pi^+$
  - $\tau^- \to \nu_\tau \pi^- \bar{K}^0 \pi^0$
- *Decker, Mirkes, et al.* [3]
  - $\tau^- \to \nu_\tau \pi^- \pi^- \pi^+$
  - $\tau^- \to \nu_\tau \pi^0 \pi^- \pi^-$
  - $\tau^- \to \nu_\tau K^- \pi^- K^+$
  - $\tau^- \to \nu_\tau K^0 \pi^- \bar{K}^0$
  - $\tau^- \to \nu_\tau K^- \pi^0 K^0$
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 K^-$
  - $\tau^- \to \nu_\tau K^- \pi^- \pi^+$
  - $\tau^- \to \nu_\tau \pi^- \bar{K}^0 \pi^0$
  - $\tau^- \to \nu_\tau \pi^- \pi^0 \eta$
- *Jadach, Was, et al.* [8]
  - $\tau^- \to \nu_\tau \gamma \pi^0 \pi^-$

Four Body

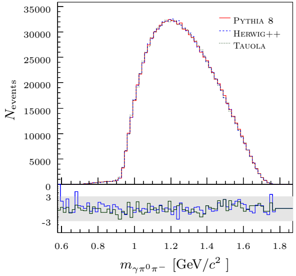
$q\bar{q}' \to W^- \to \tau^- \to \nu_\tau \pi^- \pi^- \pi^+$



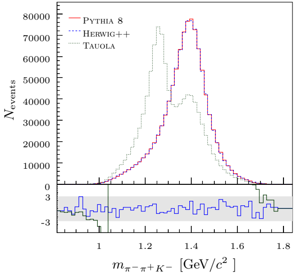
$q\bar{q}' \to W^- \to \tau^- \to \nu_\tau \pi^- \pi^+ K^-$



$q\bar{q}' \to W^- \to \tau^- \to \nu_\tau \gamma \pi^0 \pi^-$

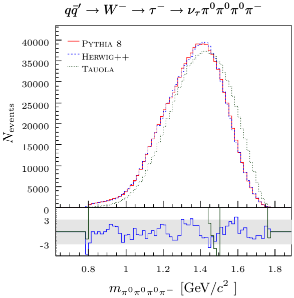


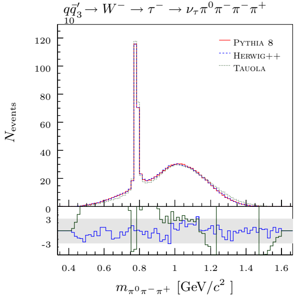
$q\bar{q}' \to W^- \to \tau^- \to \nu_\tau \pi^- \pi^+ K^-$

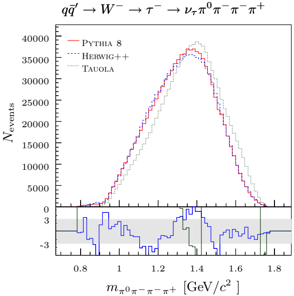


Five Body

- one model
- *Novosibirsk* [1]
    - $\tau^- \to \nu_\tau \pi^0 \pi^- \pi^- \pi^+$
    - $\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^0 \pi^-$

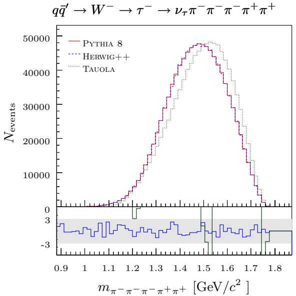


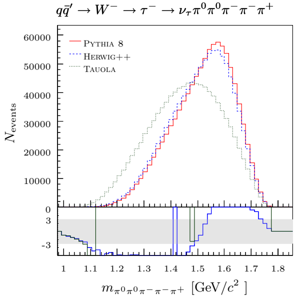


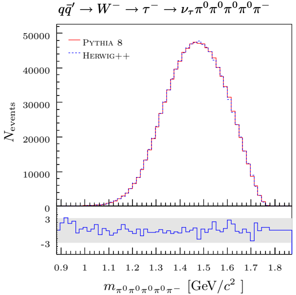


Six Body

- one model
- *Kühn and Was* [11]
  - $\tau^- \longrightarrow \nu_\tau \pi^0 \pi^0 \pi^- \pi^- \pi^+$
  - $\tau^- \longrightarrow \nu_\tau \pi^0 \pi^0 \pi^0 \pi^0 \pi^-$
  - $\tau^- \longrightarrow \nu_\tau \pi^- \pi^- \pi^- \pi^+ \pi^+$







Interface

- interface available under Particle Decays of the PYTHIA 8 manual

ParticleDecays:sophisticatedTau (`default = 1`; `minimum = 0`; `maximum = 3`)
Choice of tau decay model.
0 : old decay model, with isotropic decays. When reading LHEF files, the SPINUP digit will be ignored.
1 : sophisticated decays where tau polarization is calculated from the tau production mechanism. When reading LHEF files, the SPINUP digit will be used.
2 : sophisticated decays as above, but additionally tau polarization is set to `ParticleDecaus:tauPolarization` `ParticleDecays:tauMother`. When reading LHEF files, this overrides the SPINUP digit.
3 : sophisticated decays where tau polarization is set to `ParticleDecaus:tauPolarization` for all tau decays. this overrides the SPINUP digit.

Note: options 2 and 3, to force a specific tau polarization, only affect the decay of the tau. The angular distribution of the production, is not modified by these options. If you want, e.g., a righthanded W, or a SUSY decay chain, the kinematics should corresponding cross section class(es), supplemented by the resonance decay one(s). The options here could then still be used polarization at the tau decay stage.

ParticleDecays:tauPolarization [0] (`default = 0`; `minimum =  1.`; `maximum = 1.`
Polarization of the *tau* when mode *2* or *3* of `ParticleDecays:sophisticatedTau` is selected.

ParticleDecays:tauMother [0] (`default = 0`; `minimum = 0`)
Mother of the *tau* for forced polarization when mode *2* of `ParticleDecays:sophisticatedTau` is selected. You should give the positive identity code; to the extent an antiparticle exists it will automatically obtain the inverse polarization.

Matrix Elements

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

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

$$\Downarrow$$

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

Production Summary

- provide polarization for all taus
- provide polarization from taus from a specific mother
- read polarization from LHEF files
- use included polarization mechanisms

production	$\mathcal{M}$
$f\bar{f} \to \gamma \to f\bar{f}$	`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`
$H^{\mathcal{CP}-\text{even}} \to f\bar{f}$	`HiggsEven2TwoFermions`
$H^{\mathcal{CP}-\text{odd}} \to f\bar{f}$	`HiggsOdd2TwoFermions`
$H^{\pm} \to f\bar{f}'$	`HiggsCharged2TwoFermions`

Decay Summary

- switch between models with `15:meMode = X`

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

Remarks

- polarization of taus available in PYTHIA
- fully modeled taus in PYTHIA
  - 99.7% of all known tau decays modeled
  - all known decays with $\mathcal{B} > 0.04\%$ modeled
- easy-to-use (hopefully) and extensible interface
- hope to see new models implemented soon!
- thanks to Lund University and MCNet for funding this project
- thanks to the PYTHIA team for their dedicated help

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Performance

Herwig++ ≡ HERWIG++ Pythia 8p ≡ PYTHIA Pythia 6 ≡ TAUOLA