Pythia 8: Simulating Tau Decays

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τ2014

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 [6] and Herwig++ [7]
- all known decays with $\mathcal{B} > 0.04\%$ available
- documentation available in online manual, arXiv:1211.6730, and arXiv:1401.4902

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

Pythia 8.170
Herwig++ 2.6.2
Tauola 2.9 with Pythia 6

History I

- 8.150: 20 April 2011
  - The description of tau lepton decays has been significantly enhanced, to include helicity information related to the production process and hadronic currents fitted to data. A complete writeup is in preparation, while a summary can be found in [Ilt12]. A new flag is introduced to revert to the old behavior, for cross-checks, see Particle Decays. The new tau decay machinery is on by default.
- 8.153: 10 August 2011
  - New possibility to force the tau polarization.
  - Bug fix in handling of tau decays, where setting of decay vertices could write outside memory. Thanks to Steven Schramm.
- 8.157: 10 November 2011
  - Bug fix in the machinery for the user to force the setting of tau polarization.
- 8.160: 23 January 2012
  - Remove warning message when tau polarization is set by hand.

History II

- 8.165: 8 May 2012
  - For a tau lepton in an external process, by default the SPINUP number in the Les Houches Accord now is interpreted as giving the tau helicity, and is used for its decay.
  - A tau coming from a W now defaults to being purely lefthanded when neither of the existing matrix elements apply.
- 8.170: 21 September 2012
  - The tau decay machinery has been further augmented with matrix elements and form factors for a variety of decay modes, such that all modes with a branching ratio above 0.1% are fully modeled. Several new classes and methods have been added to this end, Also, a tau pair coming from a Z^0 decay is now handled by assuming the Z^0 to be unpolarized when neither of the existing matrix elements apply. Taus coming from B-baryons are handed as for B-mesons.
  - When a tau pair comes from a massless photon, in dipole shower evolution, for the decay description the mother photon is reassigned to have the sum of the tau momenta.

History III

- 8.175: 18 February 2013
  - The sophisticated tau decay machinery has been expanded so that it can also handle production of taus in hypothetical lepton-number-violating processes, such as $H^0 \to \tau^+\mu^-$.
  - Branching ratios for most light hadrons, and the tau lepton, have been updated to agree with the 2012 Review of Particle Physics [Ber12], by Anil Pratap Singh.
- 8.180: 20 September 2013
  - Introduced new mode LesHouches:setLifetime so that the lifetime information in Les Houches input can be replaced by the standard PYTHIA selection procedure. By default this is applied to tau leptons, since some matrix-element generators do not set this lifetime. Thanks to James Monk and Thorsten Kuhl.
  - Bug fix in the tau decay description for decay chains like $H^0 \to A^0 A^0 \to 4\tau$, caused by an erroneous assignment of the number of spin states. Thanks to Brock Tweedie.

Helicity Correlation

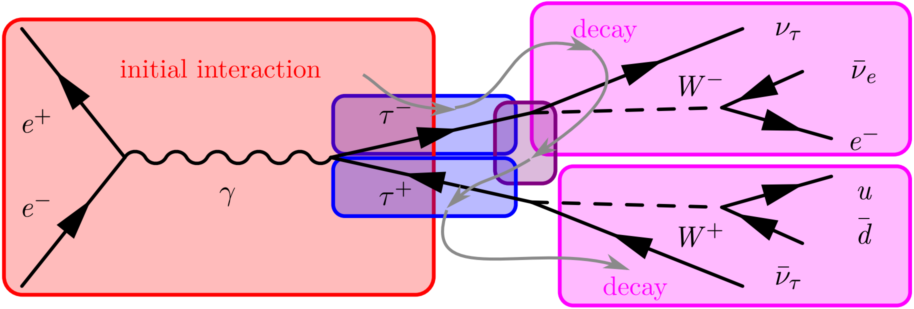
Algorithm

- 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.

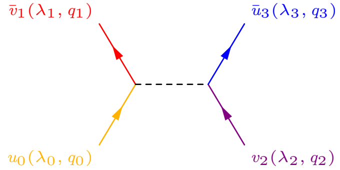
Example

- 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 $\mathcal{W}_{\text{decay}} = \rho_{\lambda_0 \lambda'_0} \mathcal{M}_{\lambda_0; \lambda_1 \ldots \lambda_n} \mathcal{M}^{*}_{\lambda'_0; \lambda'_1 \ldots \lambda'_n} \prod_{k=1,n} D^{k}_{\lambda_k \lambda'_k}$
- ❺ $D_{\lambda_0 \lambda'_0} = \mathcal{M}_{\lambda_0; \lambda_1 \ldots \lambda_n} \mathcal{M}^{*}_{\lambda'_0; \lambda'_1 \ldots \lambda'_n} \prod_{l=1,n} D^{l}_{\lambda_l \lambda'_l}$



Tau Production

Electroweak



- W boson

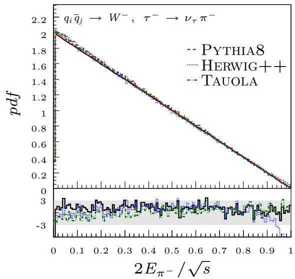
$$\mathcal{M}_W \propto \left(\bar{v}_1(1-\gamma_5)u_0\right)\left(\bar{u}_3(1-\gamma_5)v_2\right)$$

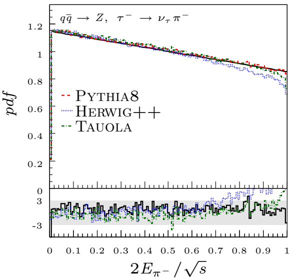
- Z boson

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

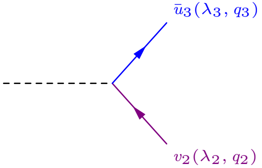
- photon

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





Higgs



- $\mathcal{CP}$-even Higgs

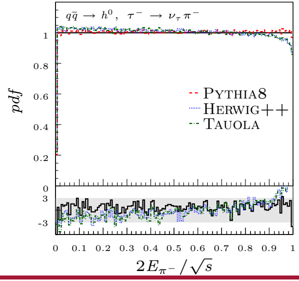
  $\mathcal{M}_{\text{even}} \propto \left(\frac{i g_w m_2}{2 m_W}\right) \bar{u}_3 c_\Phi^2 v_2$

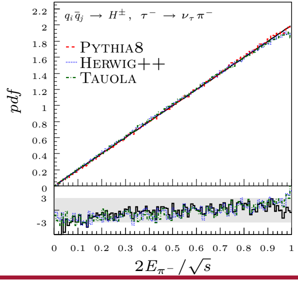
- charged Higgs

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

- $\mathcal{CP}$-odd Higgs

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





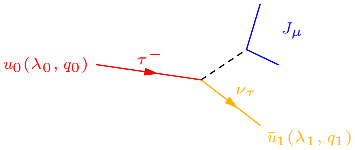
Production Summary

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

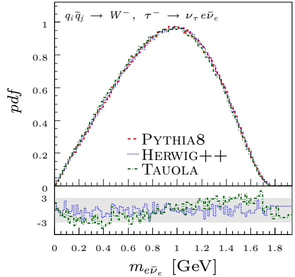
production	$\mathcal{M}$
$f\bar{f} \to \gamma \to f\bar{f}$	`TwoFermions2Gamma2TwoFermions`
$f\bar{f} \to Z \to f\bar{f}$	`TwoFermions2Z2TwoFermions`
$f\bar{f} \to \gamma^*/Z \to f\bar{f}$	`TwoFermions2GammaZ2TwoFermions`
$f\bar{f}' \to W \to f\bar{f}'$	`TwoFermions2W2TwoFermions`
$Z \to f\bar{f}$	`Z2TwoFermions`
$W \to f\bar{f}$	`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`

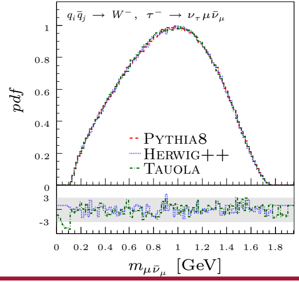
Tau Decay

General Form



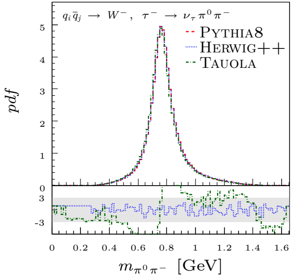
- $\mathcal{M} = \frac{g_w^2}{8m_W^2} L_\mu J^\mu$
- $L_\mu = \bar{u}_1 \gamma_\mu (1 - \gamma 5) u_0$
- J_μ dependent upon the decay
  - charged lepton and neutrino $J_\mu = \bar{u}_{\ell^-} \gamma^\mu (1 - \gamma^5) v_{\bar{\nu}_\ell}$
  - single hadron $J_\mu = f q_{h^-}$

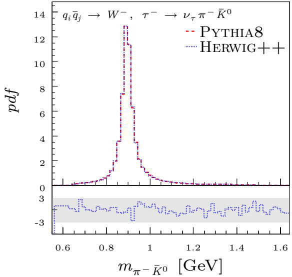




Three Body

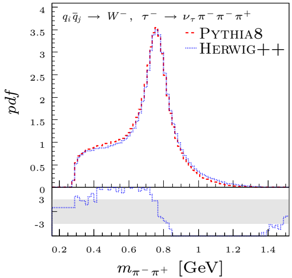
- three models
- leptonic current
  - $\tau^- \to \nu_\tau e^- \bar{\nu}_e$
  - $\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$
- *Kühn and Santamaria* [10]
  - $\tau^- \to \nu_\tau \pi^0 \pi^-$
  - $\tau^- \to \nu_\tau K^0 K^-$
  - $\tau^- \to \nu_\tau \eta K^-$
- *Finkemeier and Mirkes* [5]
  - $\tau^- \to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

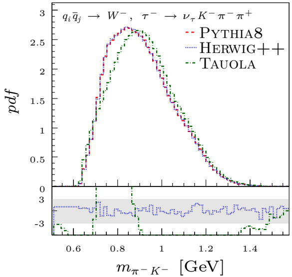




Four Body I

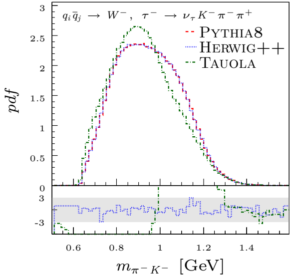
- four models
- *CLEO model* [13]
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^-$
  - $\tau^- \to \nu_\tau \pi^- \pi^- \pi^+$
- *Finkemeier and Mirkes* [4]
  - $\tau^- \to \nu_\tau K^- \pi^- K^+$
  - $\tau^- \to \nu_\tau K^0 \pi^- \bar{K}^0$
  - $\tau^- \to \nu_\tau K^0_S \pi^- K^0_S$
  - $\tau^- \to \nu_\tau K^0_L \pi^- K^0_L$
  - $\tau^- \to \nu_\tau K^0_S \pi^- K^0_L$
  - $\tau^- \to \nu_\tau K^- \pi^0 K^0$
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 K^-$
  - $\tau^- \to \nu_\tau K^- \pi^- \pi^+$
  - $\tau^- \to \nu_\tau \pi^- \bar{K}^0 \pi^0$

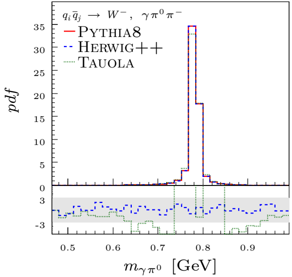




Four Body II

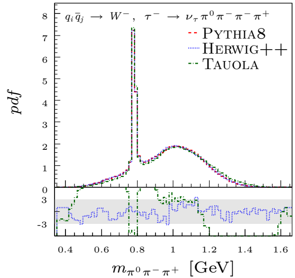
- *Decker, Mirkes, et al.* [3]
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^-$
  - $\tau^- \to \nu_\tau \pi^- \pi^- \pi^+$
  - $\tau^- \to \nu_\tau K^- \pi^- K^+$
  - $\tau^- \to \nu_\tau K^0 \pi^- \bar{K}^0$
  - $\tau^- \to \nu_\tau K^- \pi^0 K^0$
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 K^-$
  - $\tau^- \to \nu_\tau K^- \pi^- \pi^+$
  - $\tau^- \to \nu_\tau \pi^- \bar{K}^0 \pi^0$
  - $\tau^- \to \nu_\tau \pi^- \pi^0 \eta$
- *Jadach, Wąs, et al.* [8]
  - $\tau^- \to \nu_\tau \gamma \pi^0 \pi^-$

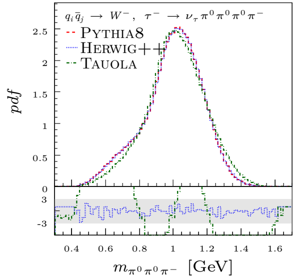




Five Body

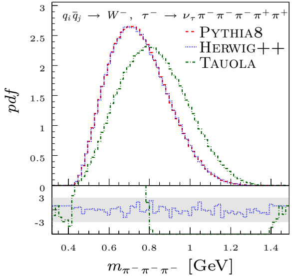
- one model
- *Novosibirsk* [1]
  - $\tau^- \to \nu_\tau \pi^0 \pi^- \pi^- \pi^+$
  - $\tau^- \to \nu_\tau \pi^0 \pi^0 \pi^0 \pi^-$

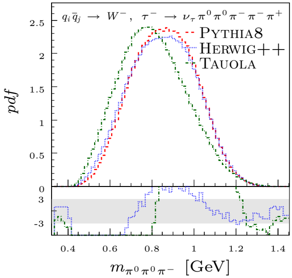


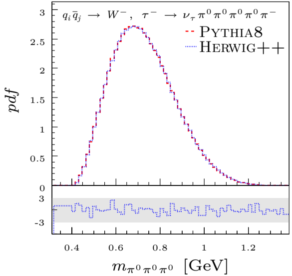


Six Body

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







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
$\tau^- \to \nu_\tau K^0_S \pi^- K^0_S$	1542

decay	$\mathcal{M}$
$\tau^- \to \nu_\tau K^0_L \pi^- K^0_L$	1542
$\tau^- \to \nu_\tau K^0_S \pi^- K^0_L$	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

Implementation

Interface

- interface available under Particle Decays of the PYTHIA 8 manual

`mode` **ParticleDecays:sophisticatedTau** (`default = 1`; `minimum = 0`; `maximum = 3`)
Choice of *tau* decay model.
`option 0` : old decay model, with isotropic decays. When reading LHEF files, the SPINUP digit will be ignored.
`option 1` : sophisticated decays where *tau* polarization is calculated from the *tau* production mechanism. When reading LHEF files, the SPINUP digit will be used.
`option 2` : sophisticated decays as above, but additionally *tau* polarization is set to `ParticleDecaus:tauPolarization` for *tau*s produced from `ParticleDecays:tauMother`. When reading LHEF files, this overrides the SPINUP digit.
`option 3` : sophisticated decays where *tau* polarization is set to `ParticleDecaus:tauPolarization` for all *tau* decays. When reading LHEF files, 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 *tau* itself, given by its production, is not modified by these options. If you want, e.g., a righthanded *W*, or a SUSY decay chain, the kinematics should be handled by the corresponding cross section class(es), supplemented by the resonance decay one(s). The options here could then still be used to ensure the correct polarization at the *tau* decay stage.

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

`mode` **ParticleDecays:tauMother** (`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 `HelicityMatrixElements.cc`
- only hadronic current needs to be implemented for new models
- tau decay mechanism implemented in `TauDecays.cc`

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

$$\Downarrow$$

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

Outlook

- tau decays in PYTHIA for over two years
  - extensive validation and usage
- PYTHIA 8.2 on the horizon
  - internal changes (primarily invisible to users)
  - updated LHAPDF and LHEF interfaces
  - new matching schemes
  - further documentation
- additional Higgs functionality (per request)
  - production of taus from $\mathcal{CP}$-mixed Higgs
  - weight/re-weighting of events
  - $\tau\tau$ or 4ℓ final states
- new models
- runtime adjustable parameters
- feedback and suggestions are appreciated!

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