Tau Decays in Pythia 8

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Introduction

- why tau decays?
  - lepton universality
  - lepton flavor violation
  - tests of CPT violation
  - very light ($M_H \approx 10$ GeV) Higgs sensitivity
  - SM Higgs sensitivity ($M_H \approx 115$ GeV)
  - tool to determine Higg's spin
  - important product from SUSY decay chains
  - ...
- polarization (Herwig++, TAUOLA)
- decay (Herwig++, TAUOLA, PHOKHARA)

Channel	Percent	
one prong decays		
$\Rightarrow \nu_\tau h^- + h^0 \geq 1$	37%	**85%**
$\Rightarrow \nu_\tau l^- \bar{\nu}_l$	35%	
$\Rightarrow \nu_\tau h^-$	12%	
three prong decays		
$\Rightarrow \nu_\tau h^- h^- h^+$	10%	**15%**
$\Rightarrow \nu_\tau h^- h^- h^+ + h^0 \geq 1$	5%	
five prong decays	$<$ **1%**	

Polarization (Method I)

- Richardson. (2001). “Spin correlations in Monte Carlo Simulations”, *JHEP*. 11, p. 29.

1. calculate hard process momenta

$$\rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}_{\kappa_1\ \kappa_2;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\kappa'_1\ \kappa'_2;\lambda'_1\ldots\lambda'_n}\prod_{i=1,n}D_{\lambda_i\lambda'_i}$$

κ_i incoming particle helicity, λ_i outgoing particle helicity, ρ incoming particle spin density matrix, D outgoing particle decay matrix, $\mathcal{M}$ matrix element

$$D=\delta_{\lambda_i\lambda'_i},\ \rho=\frac{1}{2}\delta_{\kappa_i\kappa'_i}\ \text{(unpolarized)}$$

2. choose outgoing particle and calculate ρ

$$\rho_{\lambda_j\lambda'_j}=\frac{1}{N_\rho}\rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}_{\kappa_1\ \kappa_2;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\kappa'_1\ \kappa'_2;\lambda'_1\ldots\lambda'_n}\prod_{i\neq j}D_{\lambda_i\lambda'_i}$$

Polarization (Method I)

3. select decay mode and calculate decay momenta

$$\rho_{\lambda_0\lambda_0'}\mathcal{M}_{\lambda_0\ \lambda_1\ldots\lambda_n}\mathcal{M}^*_{\kappa_0';\lambda_1'\ldots\lambda_n'}\prod_{i=1,n}D_{\lambda_i\lambda_i'}$$

4. select decay particle and calculate ρ

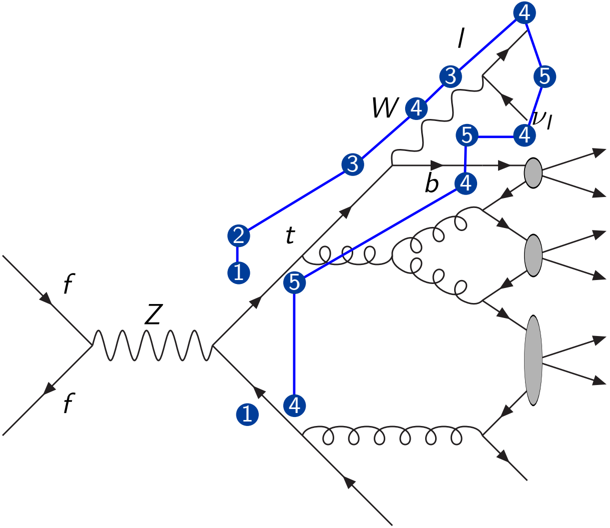
$$\rho_{\lambda_j\lambda_j'} = \frac{1}{N_{D_\rho}}\rho_{\lambda_0\lambda_0'}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\lambda_0';\lambda_1'\ldots\lambda_n'}\prod_{i\neq j}D_{\lambda_i\lambda_i'}$$

5. repeat steps 3 and 4 until decay chain complete and calculate decay matrix

$$D_{\lambda_0\lambda_0'} = \frac{1}{N_D}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\lambda_0';\lambda_1'\ldots\lambda_n'}\prod_{i=1,n}D_{\lambda_i\lambda_i'}$$

6. calculate next decay chain using decay matrix from step 5
7. continue until all products from hard process decayed

Polarization (Method I): $f\bar{f} \to Z \to t\bar{t}$



Polarization (Method II)

- Jadach, Kühn, and Wąz. (1990). "TAUOLA - a library of Monte Carlo programs to simulate decays of polarized τ leptons". *CPC*. 64, p. 275.
- look only at SM hard processes (tau's from Z and W)
- use a *polarimeter* vector to characterize polarization effects in tau decay products

1. create tau (or tau pair) from hard process with no polarization
2. decay the tau (or tau pair) without polarization
3. calculate polarimeter vectors from tau decays
4. calculate weight for event and accept or reject
5. if rejected, repeat from 1

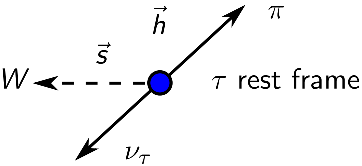
Polarization (Method II): $W(H^{\pm}) \rightarrow \tau \rightarrow \nu_\tau \pi$

- differential cross section of the general form

$$d\sigma = |A|^2(1 + a_\mu s_a^\mu + b_\mu s_b^\mu + c_{\mu\nu} s_a^\mu s_b^\mu)$$

- simple weight for $W \rightarrow \tau$ (assuming left-handed τ), $s^2 = 0$, $s \cdot q = -1$

$$w = 1 + s^\mu h_\mu$$

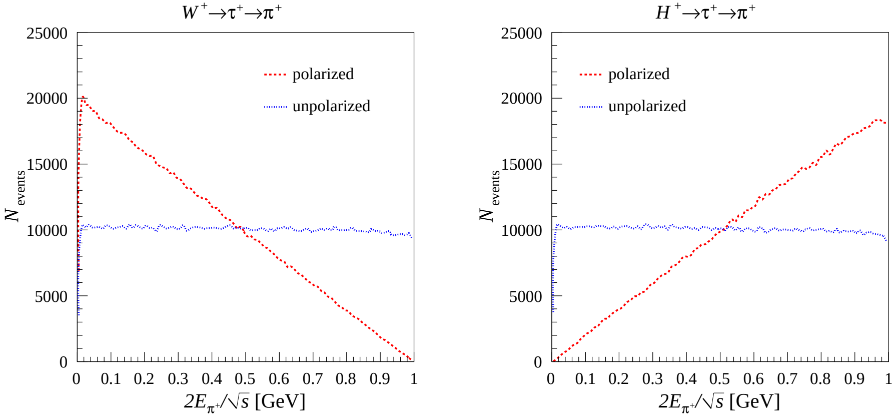


- polarimeter unit vector in pion direction, spin vector unit vector in direction of W boost for $\tau \rightarrow \nu_\tau \pi^{\pm}$

$$s^\mu = (0, 0, 0, -1),\ \ h_\mu = (0, sin\theta \cos\phi, \sin\theta \sin\phi, \cos\theta)$$

- $w = 1 - \cos\theta$ (for $H^{\pm}$ $w = 1 + cos\theta$)
- $w_{max} = 2$

Polarization (Method II): $W(H^{\pm}) \longrightarrow \tau \longrightarrow \nu_\tau \pi$



Polarization (Method II): $Z \to \tau\tau \to X$

$$w = \frac{1}{R_{00}} \sum_{a=0,3} \sum_{b=0,3} R_{ab} h_a h_b, \;\; w_{max} = 2$$

$$R = R^s + R^b + R^a + R^Z$$

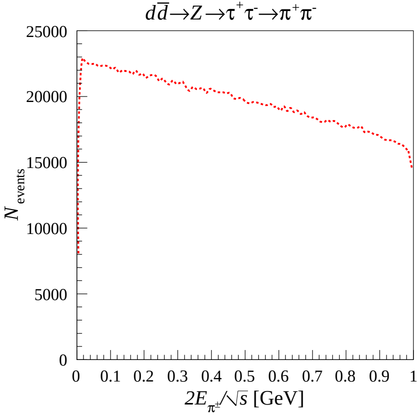
- R^s from soft and virtual photon corrections, R^b and R^a from $\mathcal{O}(\alpha^3)$ contributions, and R^z from Z contribution

$$R^z = \frac{2Z}{q_f q_\tau} \begin{bmatrix} v_f v_\tau (1+\cos^2\theta) + a_f a_\tau 2\cos\theta & 0 & 0 & v_f a_\tau (1+\cos^2\theta) + a_f v_\tau 2\cos\theta \\ 0 & v_f v_\tau \sin^2\theta & 0 & 0 \\ 0 & 0 & -v_f v_\tau \sin^2\theta & 0 \\ v_f a_\tau (1+\cos^2\theta) + a_f v_\tau 2\cos\theta & 0 & 0 & v_f v_\tau (1+\cos^2\theta) + a_f a_\tau 2\cos\theta \end{bmatrix}$$

  $Z = 1/(1 - m_Z^2/s)$, θ defined in rest frame of Z, v and a axial and vector couplings to the Z for fermion f

- for on-shell Z, R^Z dominates and other terms can be ignored

Polarization (Method II): $Z \to \tau\tau \to X$



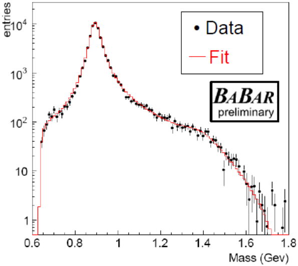
Decay Channels

- most decays not as simple as $\tau \to \nu_\tau \pi^\pm$ or leptonic decays
- need to use spectral functions

$$f(m) \propto \frac{1}{s}\left(1 - \frac{s}{m_\tau^2}\right)\left(1 + \frac{2s}{m_\tau^2}\right) P \left(P^2|F_V|^2 + \frac{3(m_K^2 - m_\pi^2)^2}{4s(1+\frac{s}{m_\tau^2})|F_s|^2}\right)$$

$$F_V = \frac{1}{1+\beta+\gamma+\cdots}\left(BW_{K^1}(s) + BW_{K^2}(s) + \cdots\right)$$

- example: $\tau \to \nu_\tau K_s^0 \pi^\pm$ (Adametz. 2010. "Studies of hadronic tau states". *TAU 2010*.)
- $K^*(892)$, $K^*(1410)$, $K^*(800)$



Current Status

- new class added to Pythia 8 handle τ decays, used by Pythia decayer class
- second polarization method implemented for W, $H^{\pm}$, and Z decays in Pythia 8
  - Z decays only for on-shell Z
  - Z decays not entirely correct, all polarization effects in τ^{+} decays, implementation issue
- decay channels (and polarimeters) implemented for $\tau \to \nu_\tau \pi^{\pm}$ and $\tau \to \nu_\tau \nu_l l$
- testing platform written to compare results from Pythia 8, Herwig++, and TAUOLA (with Pythia6)
  - C++ wrapper for TAUOLA integrated with ROOT Pythia 6 wrapper
  - Pythia 6, Pythia 8, and Herwig++ modules written to write to common format

Road Map

- investigate implementing first method
- determine how extensive the changes to Pythia 8 internal structure
- start to incorporate more (and trickier) decay channels
- fully validate decay channels and polarization effects