Phase-space generation improvements for Belle II and LHC-b τ decay generation

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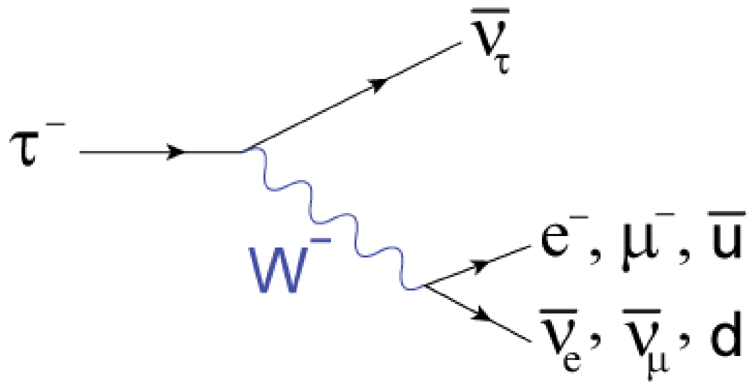
Introduction

- τ lepton has multiple decay channels, buth leptonic and hdronic.
- Many more are expected, but not yet detected due to very low branching ratios predicted by theory.
- Searches aimed at those rare channels may expose New Physics phenomena.
- Lepton Flavour Violating τ dacays are of intrest for many physicists.
- Phase-space generation improvements described in this presentation are meant to facilitate models for rare decays.



Event generation in TAUOLA

τ decay is simulated from the phase space Jacobian (J) and the matrix element ($\mathcal{M}$) being separate blocks. The decay width is obtained using the canonical calculation:

$$d\Gamma = W * \prod_{i}^{N} dx_i, \tag{1}$$

where $\{x_i\}$ denote set of random numbers and weight:

$$W = \frac{|\mathcal{M}|^2 * J}{2M_\tau}, \tag{2}$$

where M_τ is the τ lepton mass.

If weight is bigger than the random number multiplied by the maximum weight, event is accepted, otherwise it is rejected.

Phase-space generator structure

Phase-spaces are usually parametrized using Lorentz invariant quantities and angles of outgoing particles. In `TAUOLA`, the square of the invariant masses of systems of particles with descending number of decay products are used as the Lorentz invariant quantities.

If no significant features are expected in the invariant mass squared s, the relevant coordinate of phase space is translated into a random number in [0,1] range using:

$$s = s_{min} + (s_{max} - s_{min}) \cdot x. \tag{3}$$

Let us call this Eq. a flat type coordinate presampler.

If the matrix element contains a resonance in the variable s, we introduce a change of variable:

$$\begin{aligned} \alpha_{min} &= \arctan \frac{s_{min} - M_R^2}{\Gamma_R M_R}, \\ \alpha_{max} &= \arctan \frac{s_{max} - M_R^2}{\Gamma_R M_R}, \\ \alpha &= \alpha_{min} + (\alpha_{max} - \alpha_{min}) \cdot x, \\ s &= M_R^2 + \Gamma_R M_R \tan \alpha, \end{aligned} \tag{4}$$

where M_R and Γ_R are parameters describing the resonance present in the matrix element. Let us call this Eq. a resonant type phase-space presampler.

Phase-space generator structure

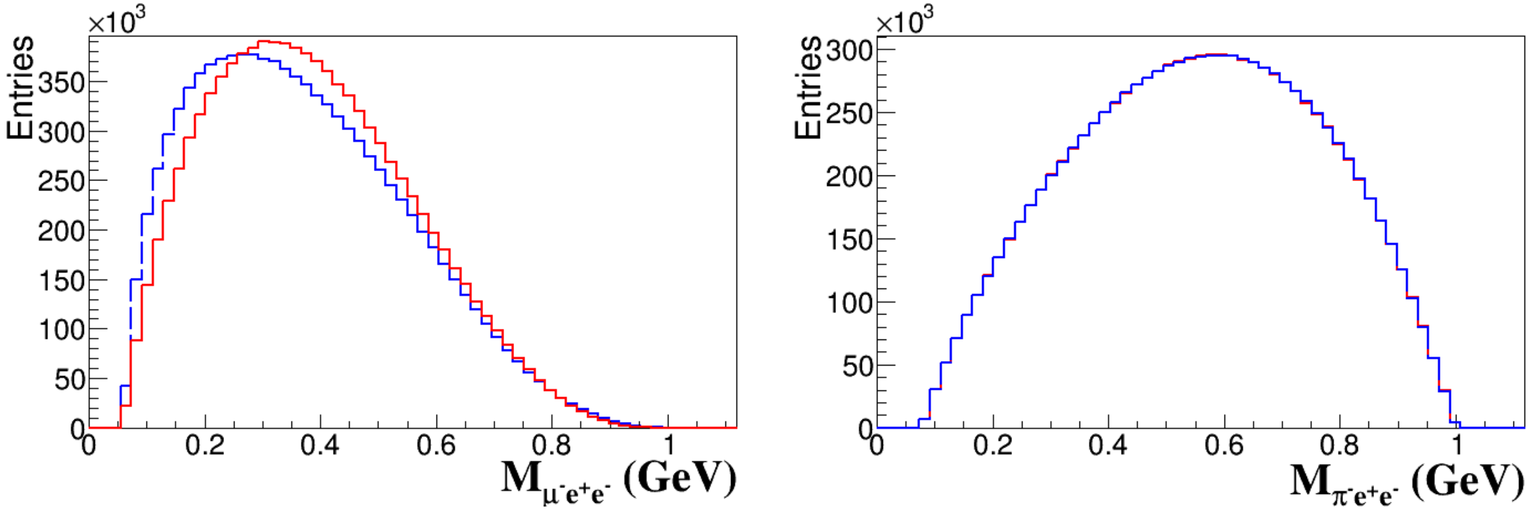
Whenever a change of variable is performed, the Jacobian of a such change enters into the phase space formula. In our case we have multiple channels in presampler, which with necessitates multiple change of variables. This can be taken into account by introducing harmonically averaged Jacobian (J_{total}) from n different channels in the presampler:

$$\frac{1}{J_{total}} = \sum_{i=1}^{n} \frac{P_i}{J_i}, \tag{5}$$

where P_i is the probability of the i^{th} presampler channel, and J_i is the Jacobian corresponding to change of variable performed for the i^{th} channel.

Phase-space generator structure

- Let us recall that: "the square of the invariant masses of systems of particles with descending number of decay products are used as the Lorentz invariant quantities".
- Above statement implies that inside Monte Carlo proper order of particles has to be maintained.
- Presampler parameters have to be set accordingly to features of matrix elemet used for generation.
- As long as parameters are within reasonable range of model prediction they affect only efficiency of generation.



New phase-space enchancement

- Modern experiments like Belle II and LHC-b alow us to better investigate phenomena like rare τ decays.
- An example of such rare dacay is $\tau^- \to \bar{\nu}_\mu \mu^- e^- e^+ \nu_\tau$, which also is a source of background for LFV decays.
- Facilitating models for such decays requires making sure that Monte Carlo generator can handle structures like:

$$\mathcal{M} = \frac{1}{k^2}, \tag{6}$$

where $k = P_{e^-} + P_{e^+}$.

New phase-space enchancement

Facilitating models for decay channels like $\tau^- \to \bar{\nu}_\mu \mu^- e^- e^+ \nu_\tau$ boils down to making sure that proper phase-space enchancements are present. In this case it required adding and proper parametrization of resonant type phase-space presampler in the mass of e^+e^-, that is in the mass of pair of particles in the final state for tau decays into 5 particles.

Presampler param.	Presampler performance			
Probability	Efficiency	over-weighted	width [GeV]	relative error
0.0	0.0005	48%	$0.13784 \cdot 10^{-2}$	0.00204682
0.2	0.036	0	$0.13747 \cdot 10^{-2}$	0.00014140
0.4	0.066	0	$0.13742 \cdot 10^{-2}$	0.00012545
0.6	0.099	0	$0.13744 \cdot 10^{-2}$	0.00011399
0.8	0.132	0	$0.13741 \cdot 10^{-2}$	0.00010129

Table 1: Probability of new phase space channel and resulting efficiency of generation for $\tau^- \to \bar{\nu}_\mu \mu^- e^- e^+ \nu_\tau$. M$= 1/\mathrm{k}^2$.

Decay mode	theoretical BR	Monte Carlo BR	experimental BR
$\tau^- \to \bar{\nu}_\mu \mu^- e^- e^+ \nu_\tau$	$(4.21 \pm 0.01) \times 10^{-5}$	$(1.538 \pm 0.0005) \times 10^{-5}$	$<3.2 \times 10^{-5}$ (at 90% C.L.)
$\tau^- \to \bar{\nu}_e e^- e^- e^+ \nu_\tau$	$(1.984 \pm 0.004) \times 10^{-5}$	$(2.871 \pm 0.0004) \times 10^{-5}$	$2.7^{+1.5+0.4+0.1}_{-1.1-0.4-0.3} 10^{-5}$

Table 2: Comparison of branching ratios obtained from MC implementation our model with theoretical prediction (A. Flores-Tlalpa, G. Lopez Castro, and P. Roig. Five-body leptonic decays of muon and tau leptons. JHEP, 04:185, 2016.) and experimental results from the CLEO experiment (M. S. Alam et al. Tau decays into three charged leptons and two neutrinos. Phys. Rev. Lett., 76:2637–2641, 1996.).

Summary

- New phase-space enchancements were added to facilitate rare decay channels.
- Echnancements were tested with physical model implemented into Monte Carlo providing good agreement with other predictions.
- Complete results of the work are collected in: S. Antropov, S. Banerjee, Z. Was and J. Zaremba, "TAUOLA update for decay channels with e^+e^- pairs in the final state," arXiv:1912.11376 [hep-ph].