Monte Carlo Simulations of Long-lived Particles

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Introduction and Outline

Beyond Standard Model scenarios often involve particles with significantly longer lifetimes compared to the particles in the Standard Model.

Reliable Monte Carlo tools for simulation of processes involving such long-lived particles (LLPs) are essential for BSM searches.

A fully accurate simulation of LLPs can be problematic due to various numerical instabilities.

Introduction and Outline

Topics that will be discussed:

1. solutions to numerical instabilities in general
2. custom event generator for a well-motivated specific process
3. possible implementations and interface to a well-established Monte Carlo software

For more physics, see the talk by M. Nemevšek!

Monte Carlo: General Framework

Simulation of signal and background involves several steps, in our case:

1. model definition (FeynRules)
2. event generation (MadGraph, custom generator)
3. hadronization (Pythia)
4. detector simulation (Delphes)
5. analysis, cuts (MadAnalysis, other custom tools)

Numerical Difficulties

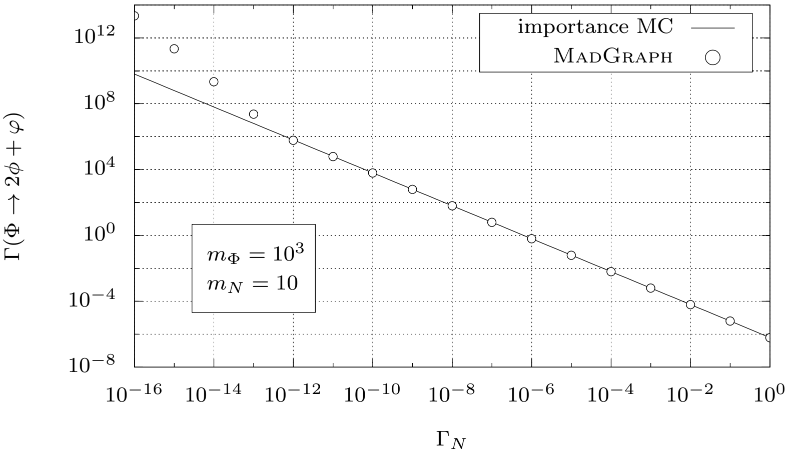
Problems to consider in simulations involving long-lived particles:

1. numerical instabilities in the presence of very narrow resonances; general (adaptive) integrators may not be able to probe the narrow peaks
2. possible numerical difficulties in propagators when (nearly) on-shell [(cancellation of p^2 and m^2) $\sim m\Gamma$]:

$$|\mathcal{M}|^2 \supset \frac{1}{(p^2 - m^2)^2 + m^2\Gamma^2}$$

The Narrow Width Problem

Simple test with scalars: $\Phi \to \phi N, N \to \phi\varphi$:



Solutions to Numerical Problems

Excellent software already exists, e. g. MadGraph + MadSpin (separating production from decay, preserving spin correlations). Relies on the narrow width approximation (with great success).

Note that the narrow width approximation may not be applicable even when narrow resonances are present.[1] ⇒ Full simulation sometimes unavoidable.

A general approach to solve all numerical difficulties (or at least the most problematic ones) can be the useful alternative.

[1] Berdine, Kauer, Rainwater, PRL 99 (2007) 111601

Solutions to Numerical Problems

A systematic way to treat the various peaking structures in the amplitudes is already developed (e. g. EXCALIBUR[2,3] event generator for four-fermion processes at LEP).

In case of multiple peaks, use a basis of functions (MADEVENT[4]):

$$f = \sum_i f_i \qquad f_i = \frac{|\mathcal{M}_i|^2}{\sum_j |\mathcal{M}_j|^2} |\mathcal{M}_{\text{tot}}|^2 \qquad \mathcal{M}_{\text{tot}} = \sum_i \mathcal{M}_i$$

In general, each f_i has a different peaking structure.

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[2] Berends, Kleiss, Pittau, NPB424 (1994) 308
[3] Berends, Kleiss, Pittau, Comput. Phys. Commun. 85 (1995) 437
[4] Maltoni, Stelzer, JHEP 0302 (2003) 027

General Procedure

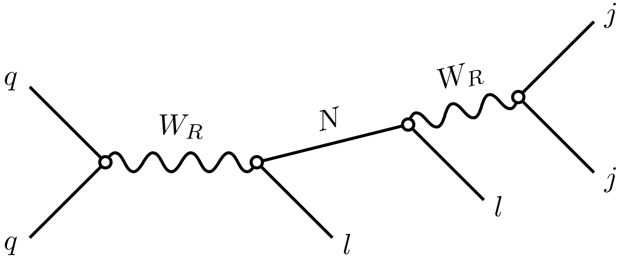
Procedure:

1. decompose the phase space in a suitable way (reflecting the toplogy of diagrams)
2. choose the appropriate integration variables (use p^2 of the propagators as the integration variables)
3. sample the integration variables according to the suitable distributions
4. evaluate the amplitudes

Point 2 solves the cancellation problem in the propagators. Minor technical complication: use p^2 for evaluation of the chosen diagram (basis function f_i), calculate from external momenta for other diagrams.

Keung-Senjanović Event Generator

Using these techniques, we developed a custom event generator (KSEG) for the Keung-Senjanović process[5].



Some important features of KS process:

- Majorana neutrino, lepton number violation
- *displaced vertices*: $\Gamma_N \sim \left(\frac{M_W}{M_R}\right)^4 m_N^5 \Rightarrow$ possibly long-lived N

[5] Keung, Senjanović, PRL **50** (1983) 1427

Keung-Senjanović Event Generator

KSEG does the following:

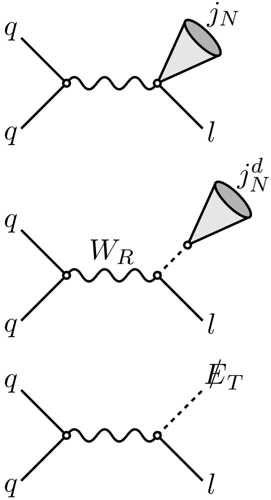
- calculates the W_R and N widths
- calculates the cross section for a given set of processes
- produces unweighted events and outputs them to an LHE file

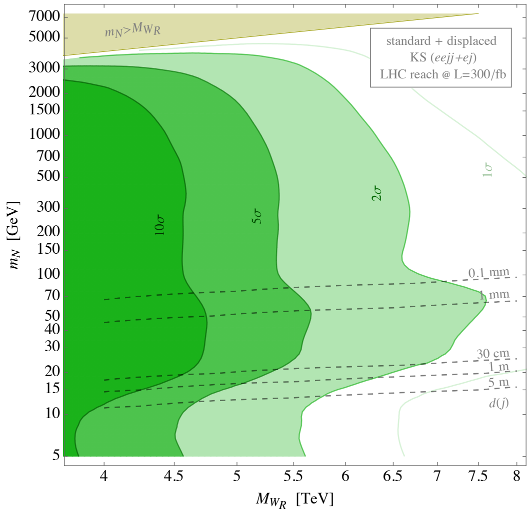
The process itself is hard-coded, but the model parameters are adjustable. Relevant parameter space of the left-right model is smoothly covered.

Model file, event generator and modified DELPHES and MADANALYSIS sources can be found on the web:

https://sites.google.com/site/leftrighthep

KS Sensitivity Plot





Roadmap for the Future Developments

There is a possibility to implement the above procedures for any process:

- use the standalone output of MadGraph to evaluate the amplitudes (great interface to the UFO model format)

Some difficulties:

- MadGraph routines for amplitude evaluation need to be modified to address the cancellations in the propagators
- diagram topologies are not clear from the output, making the automation of phase space decomposition difficult

This procedure is tested on some simple examples (along with the neccessary modifications), but it's too early to make any definite conclusions.

Roadmap for the Future Developments

Potential drawbacks:

- computationally expensive
- importance sampling (used to remove the peaks in the amplitude) is not optimal in general (undersamples the tails of the peaks)

The performance can be greatly improved by a sophisticated random number sampling. A self-adapting FOAM algorithm[6] shows promising results by greatly increasing the unweighting efficiency.

[6] Jadach, Comput. Phys. Commun. 152 (2003) 55

Summary

- a general procedure for addressing the numerical inefficiencies in simulations involving long-lived particles was presented
- custom event generator for a specific process was used as a realistic example
- possible implementations and interface to a well-established Monte Carlo software was also discussed

Multichannel MC

Kleiss, Pittau, Comput. Phys. Commun. 83 (1994) 141

Solution is the multichannel Monte Carlo, where

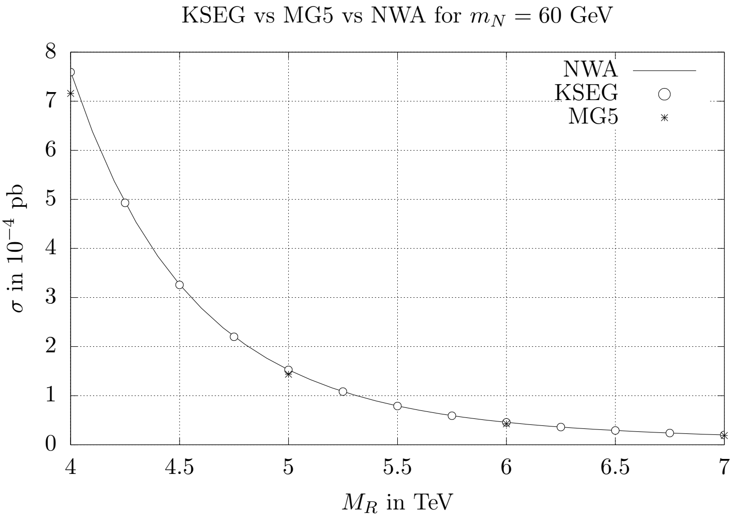
$$g(\vec{x}) = \sum_{i=1}^{n} \alpha_i \, g_i(\vec{x}), \quad \int \mathrm{d}\vec{x} \, g_i(\vec{x}) = 1, \quad \sum_{i=1}^{n} \alpha_i = 1$$

$g_i(\vec{x})$ – one peaking structure,
α_i – weight (probability) for a channel.

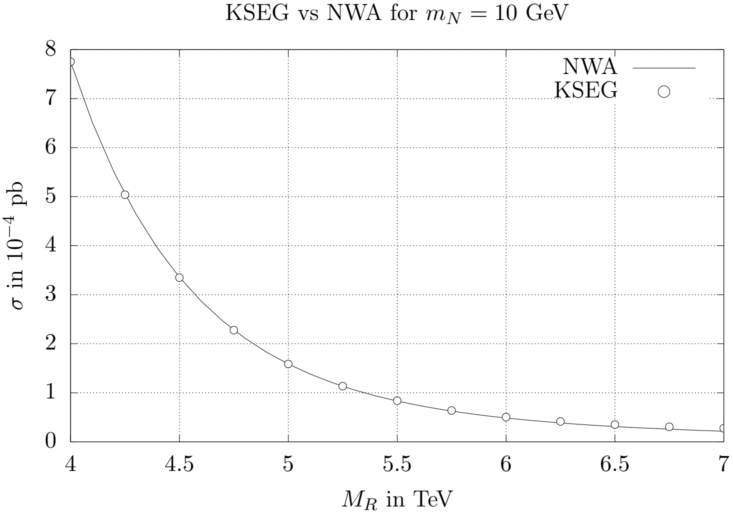
Weights can be optimized during the integration:

$$\alpha_i^{\mathrm{new}} \propto \alpha_i \sqrt{W_i(\alpha)} \qquad W_i(\alpha) = \left\langle \frac{g_i(\vec{x})}{g(\vec{x})} w(\vec{x})^2 \right\rangle$$

MadGraph vs KSEG

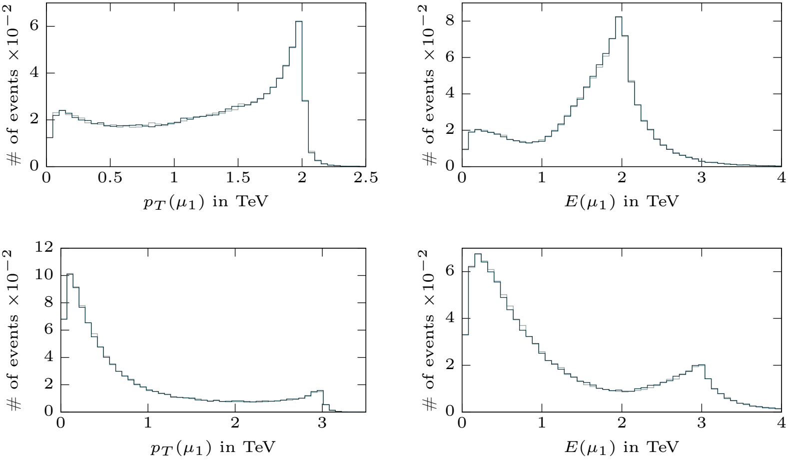


MadGraph vs KSEG



MadGraph vs KSEG

Transverse momentum and energy distributions (KSEG & MG5) of the prompt muon for $m_N = 80$ GeV and $M_R = 4$ TeV (upper panel) and $M_R = 6$ TeV (lower panel):



MadGraph vs KSEG

Invariant mass of the muons and jets for $m_N = 80$ GeV and $M_R = 4$ TeV (left) and $M_R = 6$ TeV (right):