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Overview of the Belle II Physics Generators

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Abstract

This note describes the event generators for Belle II as available in software release-00-05-00 and externals-00-05-09 with some updates for newer releases that are labeled as such. Cross section calculations for normalization are provided for beam energies around the $\Upsilon(4S)$ with some remarks for runs at the $\Upsilon(3S)$. Some recommendations for validation and integration in physics studies are also given. Future update event generator plans are described.

Contents

1. OVERVIEW

In this note the available event generators for Belle II, some generator–related tools, cross section calculations, and the validation strategy are discussed. The focus is on event generation for runs at the $\Upsilon(4S)$, but some remarks are given for the generation close to a narrow resonance like the $\Upsilon(3S)$. First estimations of the generator precision tags for precision QED generators are provided.

In the near future, the following generators will become available: `TEEGG` (small angle e^+e^- for tagged single photons or electrons) [7], `CRY` (cosmic ray showers) [8] and a yet nameless generic ISR generator for hadronic final states from the Novosibirsk group [9]. A new implementation of `KKMC` as outlined in [3] is planned. Beam parameters such as the mean beam energies, beam energy spread and also the vertex position will soon be provided by a "`BeamParameter`" class.

The externals-00-06-00 package uses `EvtGen` version 1.40 and `PYTHIA` version 8.209.

All generators are still to be thoroughly tested.

2. AVAILABLE EVENT GENERATORS

The event generators available in in the Belle II software framework are listed in turn below in alphabetical order.

- `AAFH` (see Sec. 4 4.1): Two–photon processes.
- `BABAYAGA.NLO` (see Sec. 4 4.2): e^+e^- (Bhabha, large angle), $\mu^+\mu^-$, $\gamma\gamma$.
- `BBBREM` [1]: Single bremsstrahlung in e^+e^- (Bhabha) scattering in the very forward direction.
- `BHWIDE` (see Sec. 4 4.3): e^+e^- (Bhabha, large angle).
- `EvtGen` (see Sec. 4 4.8): B, D, τ, etc. decay chains.
- `KKMC` (see Sec. 4 4.4): $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, $\nu\overline{\nu}$.
- `KORALW` (see Sec. 4 4.5): Radiative two–photon processes.
- `MadGraph/MadEvent` (see Sec. 4 4.6): Direct production of New Physics (NP).
- `PHOKHARA` (see Sec. 4 4.7): Selected exclusive low multiplicity final states with and without initial state radiation (ISR).

In addition to the aforementioned event generators, several secondary generators are used in the event generation that are listed below

- `TAUOLA` [2]: Tau decays, used by `EvtGen` and `KKMC` (older, internal version `TAUOLA-exp-11-10-2005`).

- PHOTOS [4]: Radiative corrections for decays, used by EvtGen and PYTHIA8-EvtGen as well as KKMC (older, internal version).
- PYTHIA8.205 [5, 6]: Quark fragmentation and inclusive decays, used by EvtGen and the Fragmentation module. (Since externals-00-06-00: PYTHIA8.209)

Standardized HepEvt or Les Houches event (LHE) format can be read by dedicated input modules in the basf2 framework. The generated events from all generators can be output in the HepEvt file format.

A single track cosmic muon generator based on the Belle generator by K. Toshio as well as a particle gun for single or multiple different particle per event are available.

3. CROSS SECTIONS

Fiducial cross sections for all main generators in basf2 are given in Table I. In addition to the normalization values, a rough estimate for observable cross sections within acceptance and some typical generator level cuts are given by the indented values.

The $\Upsilon(4S)$ cross section is the on peak cross section assuming a collision energy at the $\Upsilon(4S)$ nominal mass and includes NLO ISR corrections and a beam energy spread of 5 MeV [10]. In addition to the direct production of $\Upsilon(4S)$, there is a contribution of $\sim 0.1\,\mathrm{nb}$ from continuum $b\bar{b} \to B\bar{B}$ production that is not included in this value.

Physics process	Cross section [nb]	Cuts	Reference
$\Upsilon(4S)$	1.05 ± 0.10	-	[10]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta^*_{e's} < 170°$, $E^*_{e's} > 0.15$ GeV	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	e's (p >0.5GeV) in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta^*_{\gamma's} < 170°$, $E^*_{\gamma's} > 0.15$ GeV	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	γ's (p >0.5GeV) in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	μ's (p >0.5GeV) in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	μ's (p >0.5GeV) in CDC, ≥ 1 γ (E_γ >0.5GeV) in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	-
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV	AAFH
$e^+e^-e^+e^-$	1.1	≥ 2 tracks (p >0.5 GeV) in CDC	-
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV	AAFH
$e^+e^-\mu^+\mu^-$	1.0	≥ 2 tracks (p >0.5 GeV) in CDC	-

TABLE I: Total production cross section from various physics processes from collisions at $\sqrt{s} = 10.573\,\text{GeV}$ to be used for MC normalization.

3.1. Status flags and mother–daughter relations

All particles produced by any generator of the basf2 framework are assigned the flag 'c_PrimaryParticle'. This flag is unambiguous and must only be set by an event generator.

If a generator stores initial beam particles e^+ and e^-, they get the flag 'c_InitialParticle'. If a generator stores virtual particles such as the exchanged boson (γ, Z^0, $W^\pm$), the particle is flagged 'c_VirtualParticle'. Note that the PDG–code of this virtual particle must not be used to distinguish between the interaction types but is purely a convention of the specific generator: E.g. KKMC always uses the PDG code of a Z^0 for the exchanged boson. In addition, it is not defined if a generator stores the initial or intermediate virtual particle(s) at all.

Most of the QED generators include interference effects of ISR and FSR. This makes it fundamentally impossible to distinguish between ISR and FSR photons: These photons are assigned both the 'c_IsISR' and 'c_IsFSR' flags and the mother of these photons is assigned based on the convention of the respective generator and is not related to the nature of ISR or FSR emission. Usually these photons are daughters of the first final state particle in the event listing. At the moment, the assignment of the 'c_IsFSR' flag is unambiguous only for QED FSR photons generated by the TimeShower algorithm of PYTHIA8.2 when used within the Fragmentation module.

In the future, photons produced by PHOTOS via EvtGen will be flagged 'c_IsPHOTOSPhoton'. For the QED generators it is planned to assign either 'c_IsISR' or 'c_IsFSR' flags if the user switches off interference contributions.

BABAYAGA.NLO and PHOKHARA9.1b also include the interference of resonance and continuum contributions which makes it fundamentally impossible to distinguish between the mother of the emitted final state particles. In this case, the intermediate resonance will not appear in the list of generated MC particles.

3.2. Generator Filter

While some generators allow basic selection cuts on the generated final state four vectors, applications for so called generator filters exist.

The 'GeneratorPreselection' module is aiming at reducing the output of large cross section QED generators before feeding them into the detector simulation. Apart from some NNLO generation modes, the time required to generate one event is much faster than the time required to run the full detector simulation. This generator selection is typically based on the requirement that at least one track above a certain transverse momentum (p_T) threshold, points into the CDC acceptance or at least one photon above a certain energy (E) threshold, points into the ECL acceptance. The preselection parameters can be changed via module parameters, an example is given in generators/examples/AafhGenerationWithPreselection.py.

Another approach is used to simulate specific families of decay modes using a single generic $B\bar{B}$ EvtGen decay file (decay.dec) using so-called "generator skims". The respective scripts and instructions can be found under analysis/physics/GeneratorSkimScripts. They have been used to prepare $B-$tag, rare-B, charmless (semi-)leptonic B, radiative B, and dileptonic B decay samples without the need to produced dedicated decay files. This approach allows for maintenance of only one nominal, master decay file.

3.3. QED at narrow resonances

Unlike the wide $\Upsilon(4S)$, the narrow lower mass resonances such as the $\Upsilon(3S)$ require serious modifications to the phase–space sampling, the vacuum polarization corrections and a re–evaluation of the theoretical uncertainties of QED precision generators. At the moment no precision generator included in basf2 includes the necessary modifications. While the phase–space sampling is mainly a technical issue, the vacuum polarization correction and interference of the resonances with continuum require modifications of the underlying physics that will be addressed in the future.

4. EVENT GENERATOR DESCRIPTIONS

In the following, the respective generators are described briefly, including known limitations and validation plans.

4.1. AAFH

The FORTRAN–based AAFH generator [11, 12] is used to simulate the four fermion final states $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^-e^+e^-$. It includes all leading–order QED diagrams (i.e. photon exchange only) and their interference, but no higher order QED corrections. The leading order calculation is exact and includes final state mass kinematics. The 36 (12) diagrams for $e^+e^- \to e^+e^-e^+e^-$ ($e^+e^- \to e^+e^-\mu^+\mu^-$) are divided into four different sub–generators (named A–D in the generator) according to multi-peripheral (A), bremsstrahlung (B, t–channel), conversion (C) and annihilation (D, s–channel) (see Fig. 1).

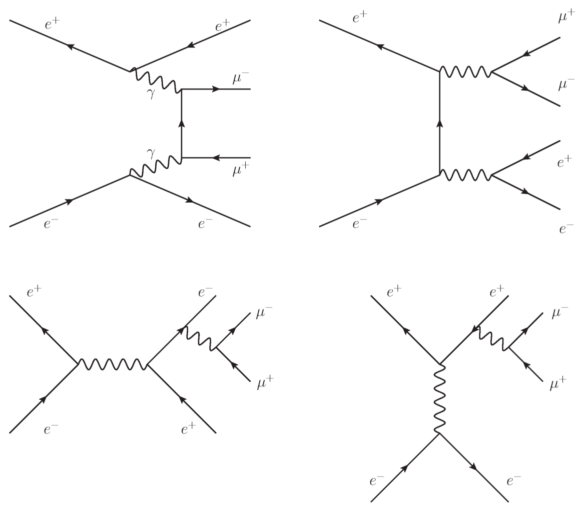


FIG. 1: Feynman diagrams for the two–photon muon pair production: Multi-peripheral (top left), conversion (top right), annihilation in the s–channel (bottom left) and bremsstrahlung in the t–channel (bottom right).

AAFH is designed to study untagged events covering the full angular range for all four fermions, the leading order divergency is controlled using a cut on the minimum invariant secondary fermion pair mass $W_{min} > 2m_{secondary}$, with typically $W_{min} = 0.5\,\mathrm{GeV}$ for the primary application of the generator. The parameter $m_{secondary}$ is the mass of the secondary pair particle and must be set by the user. The multi-peripheral diagram (A), characterized by small angle primary electron pair emission and low invariant mass secondary pair, accounts for almost the entire total cross section of 18.9 nb ($e^+e^- \to e^+e^-\mu^+\mu^-$, $W_{min} > 0.5\,\mathrm{GeV}$) and 40.8 nb ($e^+e^- \to e^+e^-e^+e^-$, $W_{min} > 0.5\,\mathrm{GeV}$). Radiative corrections to the total cross section and also for most untagged differential distributions are small (a few percent at most, usually below 1 %) at $\sqrt{s} = 10.58\,\mathrm{GeV}$ [13]. (Anti–)Tagged event selections (i.e. (anti–)tagging the primary electron, positron or both of them) for differential cross section measurements may be subject to significantly larger radiative corrections.

Since radiative corrections for the untagged case are very small, the exact LO `AAFH` approach is the first choice for untagged analysis to avoid possible issues with e.g. mass divergencies in higher order generators. If four fermion processes are background for the two fermion process ($ee \to \gamma/Z \to f\bar{f}$), the latter are typically selected using more or less hard cuts on the secondary pair invariant mass, where the conversion diagram is the dominant contribution and can be understood as real pair emission correction to the fermion pair production.

Belle used a modified version of `AAFH`, called `AAFHB`, to include the beam energy spread and final state fragmentation for $e^+e^-q\bar{q}$ final states. Beam energy spread was included approximately by applying a random Gaussian smearing of the boost to the lab system, while the event kinematics itself were calculated at the mean center of mass energy. If `AAFHB` was used to generate $e^+e^-q\bar{q}$ final states, the quarks were passed to `JETSET7.3` with some JETSET parameters directly set in the subroutine LUNINI (`lunini73.F`). Note that the so called direct production as implemented in `AAFH` usually is not the dominant two–photon contribution to hadronic final states, but is rather vector meson dominance and resolved photon processes not included in `AAFH`.

Gaussian beam energy spread is currently not included in the basf2 implementation and for hadronic final states a slightly modified version of the existing `Fragmentation` module should be used.

In oder to reduce the load for subsequent simulation steps, a preselection cut after generation requiring at least one true charged track with $p_T \gtrsim 0.5\,\mathrm{GeV}$ or two true charged tracks with $p_T \gtrsim 0.1\,\mathrm{GeV}$ pointing into the tracking detectors should be considered since `AAFH` does not support such cuts at generator level on single particle basis. These selections reduce the effective cross section by a factor of 20 to 40.

4.2. `BABAYAGA.NLO`

The FORTRAN–based generator `BABAYAGA.NLO`, is the default generator to simulate large angle e^+e^- (Bhabha) and exclusive photon $\gamma\gamma$ final states [14, 15, 16, 17, 18] at and above the $\Upsilon(4S)$. Is is possible to simulate the $\mu^+\mu^-$ final state as well. `BABAYAGA.NLO` generates multi–photon initial state radiation (ISR), final state radiation (FSR) and the interference of initial and final state radiation (IFI) based on the matching of exact NLO corrections with a Parton Shower algorithm. Z exchange and $\gamma - Z$ interference are included at LO. Narrow resonances and vacuum polarization corrections are included but no other electroweak corrections.

For the e^+e^- final state a minimum cut of about 5° for both outgoing e^+ and e^- is necessary. It is important to note that when generating small angle events, the user should check if the number of overweighted events and/or the fraction of the corresponding cross section is acceptable for the desired precision. A weight monitoring histogram is provided if the respective module option is set.

The theoretical precision of the generator is about 0.1 % (0.5 %) for e^+e^- and $\gamma\gamma$ ($\mu\mu$) final states for both cross section and inclusive differential distributions within the detector acceptance for for beam energies at and above the $\Upsilon(4S)$, including uncertainties due to vacuum polarization. Gaussian beam energy spread is currently not included. `BABAYAGA.NLO` should not be used as primary generator for electroweak precision studies due to the absence of electroweak corrections and missing exponentiation of the QED IFI.

It is currently not recommended to use `BABAYAGA.NLO` for beam energies close to the narrow resonances $\Upsilon(1/2/3S)$ for the $\mu^+\mu^-$ and e^+e^- final states since the time-like vacuum polarization corrections and narrow resonances are not modelled with sufficient precision. A version that works close to and at narrow resonances is currently being developed (see Section 3 3.3) and will be available within basf2 soon. This version will also include gaussian beam energy spread and finer user control over the final state cuts. `BHWIDE` is an alternative generator for the e^+e^- final state with comparable precision at and above the $\Upsilon(4S)$. The 'DarkPhoton' model of `BABAYAGA.NLO` is currently not available in basf2.

4.3. `BHWIDE`

The FORTRAN–based generator `BHWIDE 1.05`, is an alternative generator to simulate large angle e^+e^- (Bhabha) final states [29] at and above the $\Upsilon(4S)$. `BHWIDE` generates multi–photon initial state radiation (ISR), final state radiation (FSR) and the interference of initial and final state radiation (IFI) based on Yennie–Frautschi–Suura exponentiation (YFS) and exact NLO matrix elements. Z exchange and $\gamma - Z$ interference are included and different options for electroweak corrections are available. Narrow resonances and their interference with continuum are not included. Time-like vacuum polarization corrections (s–channel) are approximated using the space-like $\Delta\alpha(-t)$.

A minimum cut of about 1° for both outgoing e^+ and e^- is necessary. When generating small angle events, the user should check if the number of overweighted events and/or the fraction of the corresponding cross section is acceptable for the desired precision.

The theoretical precision of the generator is about $0.1\,\%$ for both cross section and inclusive differential distributions within the detector acceptance for for beam energies at and above the $\Upsilon(4S)$, including uncertainties due to vacuum polarization. Gaussian beam energy spread is not included.

It is not recommended to use `BHWIDE` for beam energies close to the narrow resonances $\Upsilon(1/2/3S)$ since the time-like vacuum polarization corrections and narrow resonances are not modelled with sufficient precision. `BABAYAGA.NLO` is an alternative generator for the e^+e^- final state with comparable precision at and above the $\Upsilon(4S)$. It is not planned to develop the existing `BHWIDE` implementation and it is recommended to use `BABAYAGA.NLO` for physics studies.

4.4. `KKMC`

The FORTRAN–based generator `KKMC`, sometimes also called `KK2f` or `KK`, is the default generator to simulate the two fermion final states $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu^+\nu^-$ and $q\bar{q}$ [19, 20] for beam energies at and above the $\Upsilon(4S)$. The currently implemented version is based on the Belle implementation of KKMC4.19 including a modified interface for tau decays. KKMC generates multi–photon initial state radiation (ISR), final state radiation (FSR) and the interference of initial and final state radiation (IFI). These QED corrections are complete NLO for ISR, IFI and FSR and almost complete NNLO for ISR and FSR within the framework of exclusive coherent exponentiation (CEEX) based on Yennie–Frautschi–Suura exclusive exponentiation (YFS/EEX). τ decays are handled by TAUOLA-exp-11-10-2005, taking into account spin polarization effects and transverse spin correlations in τ decays as in KORALB. The hadronic currents for $\tau \to 4\pi$ are taken from CMD–2 ('binp'), all other from CLEO ('cleo').

Electroweak corrections within KKMC are implemented using the DIZET6.21 library of the ZFITTER project [22, 23]. The DIZET6.21 routine REPI for the calculation of the timelike real part of the electromagnetic coupling $\alpha_{QED}(s)$ has been replaced as described in [21] and is used by default via the internal flag IHVP=4. The electroweak corrections are complete one–loop with some higher order extensions. The (numerically small) beyond one–loop electroweak corrections rely partially on approximations valid close to or above the Z–pole only and are potentially invalid at Belle II energies.

The Belle II default KKMC does not include resonances [41] and it is not possible to generated the e^+e^- (and the $t\bar{t}$) final state. Gaussian beam energy spread is included and no generator level cuts apart from a usual soft photon cutoff are applied.

Unlike at Belle, the production of $q\bar{q}$ pairs is performed using KKMC ($e^-e^- \to q\bar{q}$), PYTHIA8.2 ($q\bar{q} \to$ hadrons) and EvtGen (decays of unstable hadrons). In contrast to lepton pairs production, IFI (KeyINT=0) and FSR (KeyFSR=0 and KeyQSR=0) are switched off for quark pair production. The QCD FSR emission of gluons is included in the cross section calculation using overall normalization factors (KeyQCD=1) via DIZET6.21 [26], whereas the relative separation into configurations with or without photons and gluons is subsequently handled by the parton shower generator of PYTHIA8.2. Soft QED FSR radiation from hadrons is included via PHOTOS called from EvtGen.

The theoretical precision of the generator for lepton pairs is better than 0.5 % for both cross section and inclusive differential distributions within the detector acceptance for for beam energies at and above the $\Upsilon(4S)$, including uncertainties due to vacuum polarization [25]. Exclusive observables involving explicit photon selections are subject to larger theoretical uncertainties. The theoretical precision for the muon pair asymmetry is currently under study and must not be taken from LEP or LEP2 studies since the QED asymmetry is different in the absence of the intermediate Z–resonance. For $q\bar{q}$ final states a larger, but not yet quantified, uncertainty arises from currently ignored threshhold effects of the QCD normalization factors and the question of wether QED FSR is emitted from quarks or hadrons [24].

It is not recommended to use KKMC for beam energies close to the narrow resonances $\Upsilon(1/2/3S)$ since the time-like vacuum polarization corrections and narrow resonances are not modelled with sufficient precision. KKMC provides a powerful tool to evaluate the theoretical precision by using internal alternative weights for the different orders of QED exponentiation as well as for virtual pair emissions that will be made available in a future update of the basf2 implementation. BABAYAGA.NLO and PHOKHARA are alternative generators for the $\mu^+\mu^-$ final state with comparable precision, EvtGen is an alternative generator for the $q\bar{q}$ final state but at much lower precision ignoring ISR. Note that the current implementation of KKMC is using an own version of TAUOLA and PHOTOS for the $\tau^+\tau^-$ final state.

4.5. KORALW

Description follows soon.

4.6. MadGraph/MadEvent

MadGraph5_aMCNLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computation of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis [30].

Within basf2 it is currently used to generate unweighted events based on the 'darkphoton' model provided by R. Essig. An example python script to generate, unpack and convert the LHE output to basf2 ROOT format are provided in generators/madgraph/examples.

4.7. PHOKHARA9.1b

The FORTRAN–based PHOKHARA9.1b generator [27, 28] is used to simulate currently eleven leptonic and hadronic final states both with and without photon emission, called radiative return (with photons) and scan mode (include no photon emission), respectively. The available final states are $\mu^+\mu^-$, $\pi^+\pi^-$, $2\pi^0\pi^+\pi^-$, $2\pi^+2\pi^-$, $p\bar{p}$, $n\bar{n}$, K^+K^-, $K^0\bar{K}^0$, $\pi^+\pi^-\pi^0$, $\Lambda(\to \pi^-p)\bar{\Lambda}(\to \pi^+\bar{p})$ and $\eta\pi^+\pi^-$.

If PHOKHARA9.1b is used in the radiative return mode (internal flag 'ph0=0'), the PHOKHARA9.1b 'Born level' corresponds to one photon emission and ISR corrections corrections are available at LO or NLO. For the scan mode (internal flag 'ph0=1') the PHOKHARA9.1b 'Born level' corresponds to no photon emission and ISR corrections corrections are available at NLO or NNLO. FSR corrections are available for the radiative return mode only with the exception of $p\bar{p}$ where FSR corrections must be switched on to include a multiplicative Coulomb factor also in scan mode. IFI is included in the radiative return mode if the ISR corrections are LO. For $\mu^+\mu^-$, $\pi^+\pi^-$ and K^+K^- NLO ISR and FSR with the simultaneous emission of one ISR and one FSR photon are available and for the $\mu^+\mu^-$ final state in radiative return mode, the full NLO corrections including IFI are available. Z exchange and $\gamma - Z$ interference are not included.

Wide resonances are always included, the narrow resonances J/Ψ and $\Psi(2S)$ can be included one at a time. The narrow resonances $\Upsilon(1/2/3S)$ are not included at the moment. Vacuum polarization corrections are included using either hadr5 or HLMNT (version 1.3, no narrow resonances) but no other electroweak corrections. Different choices for the the pion form factor, the kaon form factor and nucleon form factors as well as different models for radiative ϕ–decays are available.

It is currently not recommended to use `BABAYAGA.NLO` for beam energies close to the narrow resonances $\Upsilon(1/2/3S)$ since the time-like vacuum polarization corrections and narrow resonances are not modelled with sufficient precision. For the $\mu^+\mu^-$ final state, when running with complete NNLO corrections there might be problems with negative weights in the generation of unweighted events for high energies, in which case `PHOKHARA9.1b` can not be used. `BABAYAGA.NLO` and `KKMC` are alternative generators for the $\mu^+\mu^-$ final state with comparable precision for the radiative return mode.

4.8. `EvtGen` Decay Generators

`EvtGen` is a MC generator originally developed for BaBar and CLEO, and used within Belle. It was originally designed for the simulation of the physics of B and D decays. Over the years the package grew more robust with added functionality until the development ceased in the early 2000s. The package then forked with each experiment adapting and modifying bits and pieces of the code for their purposes. The last overhaul happened in 2008 when Anders and Ryd merged several forks into one release, however this did not include the updates from the Belle collaboration. The Belle II collaboration now works closely with the `EvtGen` development team (they are largely based in LHCb), to jointly develop the `EvtGen` package.

An event generator which adequately captures the physics of beauty events must be able to account for cascade decays involving multiple vertices. Given that the angular distributions of final-state decay products often carry information on underlying physics, the package must also be able to handle a wide range of spin configurations. Quantum effects such as CP-violation and mixing play a significant role and must also be captured by the generator.

Firstly, the formalism of spin density matrices is included in the code. This facilitates the inclusion of spin effects into the simulation, and consequently allows the user to study the distribution of the decay angles of the final states.

Secondly, the input data for each decay process is passed to the code as a complex amplitude as opposed to the usual case where probabilities are used directly. In cases where a number of complex amplitudes are invoked for the same process, these are added before the decay probabilities are calculated and consequently the interference terms, which are of significant importance in many B-physics studies, are included. Such terms are lost in a conventional "probability-based" generator. The complex amplitudes are encoded as C++ classes which are referred to as models. All these models inherit from a single base class, in which is included a range of tools for the construction and manipulation of the amplitudes.

The package also uses a novel nodal decay algorithm, where each decay step is treated independently. This feature addresses the problem of the cascade decays which typify B-physics events. In a conventional MC generator kinematics for the whole chain would be generated at once, and the accept-reject decision applied on the result. Apart from the difficulty in calculating the maximum probability for the whole process, this method is in-efficient as a rejection leads to the whole chain being regenerated from scratch. The node-wise method of EvtGen avoids this, by generating kinematics for each step separately. This approach leads to increasingly complex spin density matrices being attached to the amplitudes for each node, but the computation time required to calculate these is very much less than that which would be needed to continually re-generate kinematics for the whole decay tree.

EvtGen is controlled by means of a decay table (DECAY.DEC), which lists all possible decay processes, their branching ratios and the model (amplitude) which is to be used to decay them. A user decay table can be written to over-ride the default table and thereby close off unwanted processes.

EvtGen is used to decay leptons and hadrons in the following decay categories.

- Scalar, Vector and Tensor decays.
- Semileptonic decays
- Leptonic decays
- Dalitz (3-body), two-body, and multi-body decays
- Baryonic decays
- Radiative and electroweak $B \to X_s[\gamma, \ell\ell]$ decays
- Other decays (typically require special matrix element calculations)

As stated above, some generators will also simulate CP violation. The current version used in the Belle II external library is R01-04-00, which is the latest release.

EvtGen can be configured to employ external generators, such as PYTHIA8.2 (for inclusive decays), and PHOTOS (for radiative corrections).

The long list of EvtGen decay generators and their test status are given on https://belle2.cc.kek.jp/~twiki/bin/view/Software/GeneratorsValidation. The plan is to systematically review each decay model, and possible flavour transitions for any decay distribution issues. It should not be expected that the core EvtGen development team can validate the myriad of modes where Belle II will be uniquely sensitive. Belle discovered many issues with the generators for the lifetime of the experiment, and therefore a cross check of EvtGen models is essential. There are two categories where EvtGen must be studied further in the context of Belle II: Decay Generators, and Branching fractions. In the next section we discuss tools and methods for finding and mitigating bugs before data taking.

1. Decay Generators

Typical issues discovered in the lifetime of the Belle experiment are listed below. Some or all of these issues have been corrected in more recent versions of EvtGen.

- $B \to D_s^{(*,**)}\ell\nu$: The hard-coded internal weighting maximal parameter in the ISGW2 decay model was not set for B_s decays. This resulted in a phase space decay of the W, i.e. a flat lepton helicity distribution.

- Radiative decays of $B*$, B_s^*, D_s^*, D^*, ρ, ω, ϕ, $b1$, K^*: Only one helicity state of the photon was produced, due to a bug in `EvtSpinDensity`. This affected all decays generated with `VSP_PWAVE`. A similar problem was found in the BSTD model, where one spin state was incorrectly neglected.

- $B \to X_s\ell\ell$: A bug was recently found in the BTOSLLBALL generator in `EvtGen` v1.3.0. Form factors calculated by Ball and Zwicky were used, which lead to an unphysically large photon pole around $q^2 = 0$.

- $B \to a_1\pi$ with the `STS` generator: The angle between the a_1 decay plane and the bachelor flight direction was found to be vastly different between data and MC.

- Many modes use simplistic generators such as `PHSP` due to the absence of either form factor information, or due to the lack of an implementation into an existing generator that requires hard coded weights, e.g. $\chi_{c2} \to \gamma J/\psi$.

- Particle properties such as masses and widths are configured in `Evt.pdl`. This must be kept up to date, particularly in light of new particle discoveries in the bottomonium and charmonium sectors. There is also a mass cut-off parameter in the case of broad resonances.

2. Branching fractions and `Decay.dec`

The configuration of the branching fractions in `EvtGen` is a monumental task, with approximately 10^4 lines of decay configurations in the `DECAY.DEC` file. We currently perform all updates to `DECAY.DEC` in conjunction with the `EvtGen` developer team. In general, branching fractions are updated using a tool that compares the PDG values for all measured branching fractions with those configured by `EvtGen`. While this works well at first order, it can lead to double counting in the case of intermediate resonances. A new tool was recently developed in Belle II to analyse potential overlaps due to intermediate resonances [39]. It should be noted that many branching fractions are simply unknown, and therefore it is pertinent to review all branching fraction settings for any inconsistencies or to include sensible theoretical constraints.

3. Signal decay files

Signal `EvtGen` decay files are to be stored in the basf2 package `software/decayfiles`. Instructions for configuring decay files can be found on the `EvtGen` pages. The decay files must include adequate header information to state the purpose the files. A decay file sanity checker has been provided under `software/decayfiles/scripts`: it parses and checks the correctness of the decay file and the header information.

4.9. Continuum generation

Unlike at Belle, the production of $q\bar{q}$ pairs is not performed using `EvtGen`, mainly due to the missing ISR radiation in the recent `EvtGen` continuum model.

The continuum generation is performed in two steps: The hard process $e^+e^- \to q\bar{q}(\gamma)$ is generated using `KKMC` (see Sec. 4 4.4) and then the $q\bar{q}$ final state is fragmented using `PYTHIA8.2`. The decays of all hadrons produced during the fragmentation are performed using `EvtGen` called by `PYTHIA8.2`, which guarantees the same decay models for continuum background and signal MC. Due to a memory problem caused by double initialization of `TAUOLA` (once by `KKMC` and once by `EvtGen`), the continuum production must be split into two basf2 jobs.

The relative fractions of u, d, s and c contributions are given in Table I. Note that the $u/d/s$ fraction 4/1/1 is almost independent of higher order corrections or quark mass effects, whereas the uds/c fraction depends on the details of the (massive) charm threshold modelling.

At the moment `PYTHIA8.2` is not tuned to Belle data. It will need to be separately tuned for modelling inclusive decays in quark continuum samples, and in heavy meson decays. This is largely due to the cocktail–like nature of heavy meson decay modelling, i.e. they are a sum of exclusive and inclusive components. The plan is to use the `Professor` framework for this task [40] with the use of Belle data and constraints from published measurements.

There will be some issues to deal with in such an implementation. Belle found several limitations to its implementation of `PYTHIA`:

- Momentum distributions of inclusive quantities such as D momenta are difficult to get right.
- The generation of charmless semileptonic decays appears to violate isospin symmetry, i.e. the ratio of $\pi^+\pi^- : \pi^0\pi^0$.
- The multiplicity of final states in MC is often lower for B decays than in data, i.e. such as in the $B \to X_s\gamma$ sum-of-exclusives measurement.
- The abundance of η mesons is much lower in MC than in data, as shown in $B \to X_s\gamma$ inclusive analyses.
- The production angular distribution of Λ_c is flat and therefore unphysical.

5. VALIDATION

5.1. Tests

Validation of the generators used for Belle II is an program to undertake prior to large scale MC production for the data taking period. The types of validation are described in turn below.

- *Process generators.* Analyse kinematic spectra of the daughters of the initial interaction, such as momenta and opening angles, as well as final state particle multiplicity. Check for radiative corrections, and decay angles. Check thresholds used in generator production match the expected angular and energy thresholds.

- *Generator comparison.* Tests of generators that produce the same types of events as a cross-check (even if some are at different precision), e.g. `BABAYAGA.NLO` and `BHWIDE`.

- `EvtGen` *decay models.* Analyse kinematic spectra, particularly differentiating between $B \to PV$, $B \to VV$, $B \to V\ell\nu$ etc.. In general distributions must be consistent with the quantum numbers of the particle involved in the transition, and therefore show accurate polarisation amplitude information. Decay angles (or polarisations) are therefore key observables.

- *Decay file branching fractions.* Compare the exclusive modes with the PDG. Check both the decay files and the Evtgen output files, which may differ due to normalisation of the BFs. The difficult part is where exclusive resonant and inclusive non-resonant modes overlap.

- `PYTHIA8.2` *hadronisation in* $e^+e^- \to$ *continuum.* Analyse kinematic spectra, final state multiplicities in each flavour. Compare to Belle simulation.

- `PYTHIA8.2` *hadronisation in heavy meson decays,* B *and* Υ. Analyse kinematic spectra of prompt daughters and final state multiplicities in each flavour. Compare to Belle and theoretical expectations where available.

- *Radiative corrections.* These may be tested by comparing matrix element calculations from MadGraph with the expectations of PHOTOS.

5.2. Tools

The above tests are typically not unique to specific modes. Therefore it is possible to prepare generic tools to prepare validation distributions and summary statistics. In this way all generators and models can be systematically tested.

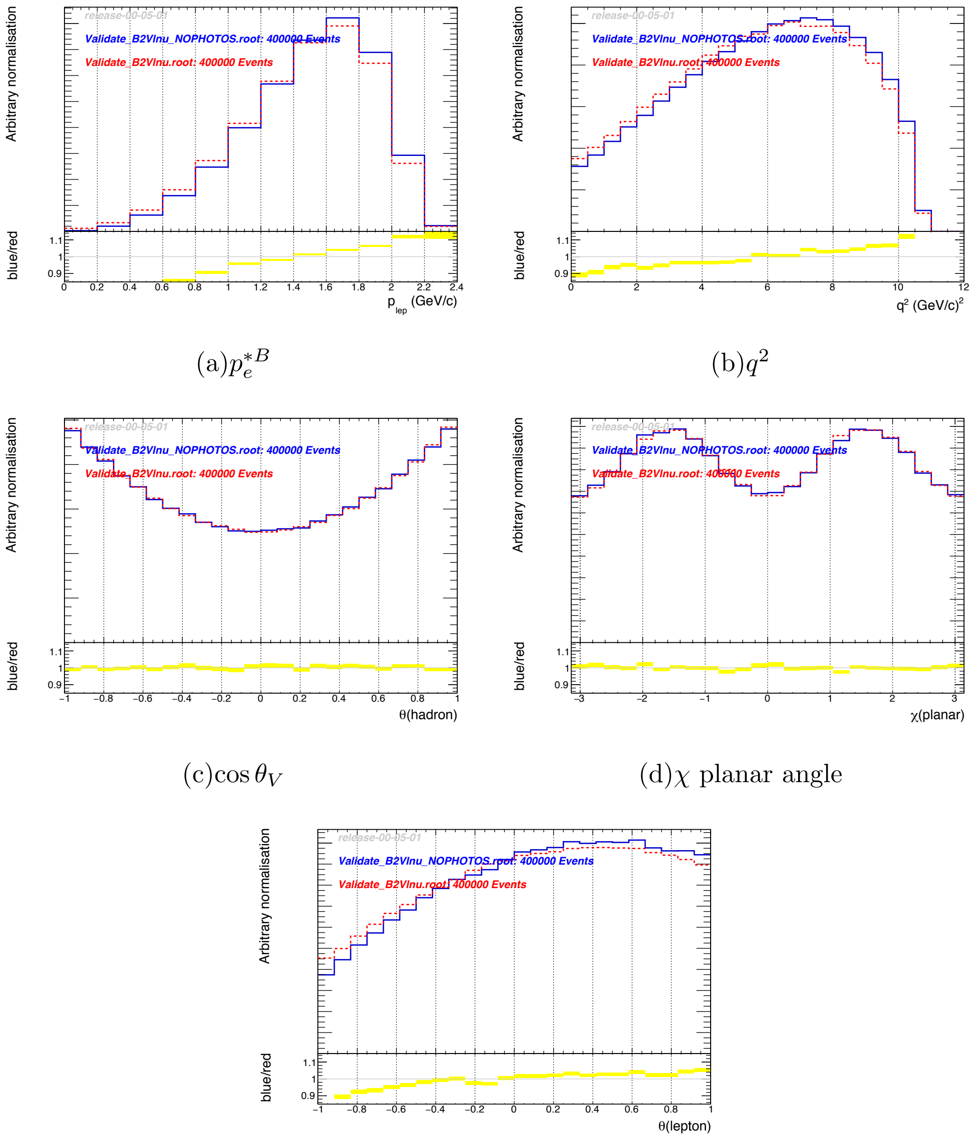
An example validation package has been prepared based on existing analysis tools, to check kinematics and regression in distributions between releases. The method is found under `software/decayfiles/validation`, and described as follows:

- MCDecayFinder: finds the decay mode of interest and builds a particle list for steering.

- NtupleMaker makes various kinematics ntuple tools for particles, and more can be added to study specific decay topologies. The tools are dedicated to study helicity distributions, 3-body, 4-body decay angles, momenta etc. The full list of available tools are found under `software/analysis/NtupleTools/src`.

- Analyse in ROOT or pyROOT, and save the results to a regression directory.

An example test is shown in Fig. 2.



(a)p_e^{*B} (b)q^2

(c)$\cos\theta_V$ (d)χ planar angle

(e)$\cos\theta_\ell$

FIG. 2: Results of an example generator study of the decay $B \to D^* e\nu$ for release-00-05-01. A comparison with and without PHOTOS is shown. All decay angles accurately reproduce theoretical expectations.

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