EvtGen – Status and prospects

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JENNIFER workshop
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WARWICK
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Overview

- Introduction to EvtGen
- Status and recent developments

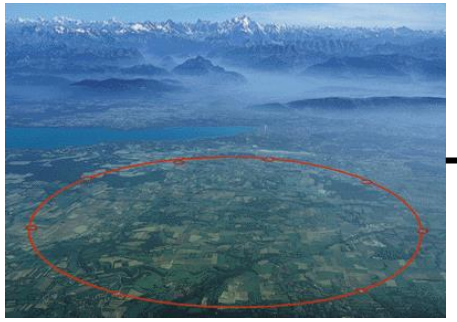
  $\Rightarrow$ Focus on new plugins for final-state radiation
- Future plans

Introduction

Simulation in high-energy physics

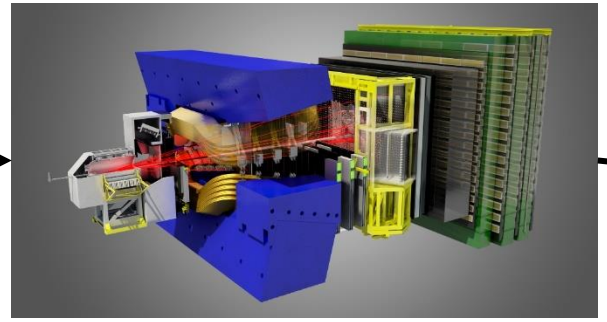
Essential since we interpret measurements by comparing simulation with collision data
⇒ Ideally, simulation should mirror data differing only by the knowledge of the “truth”

The world



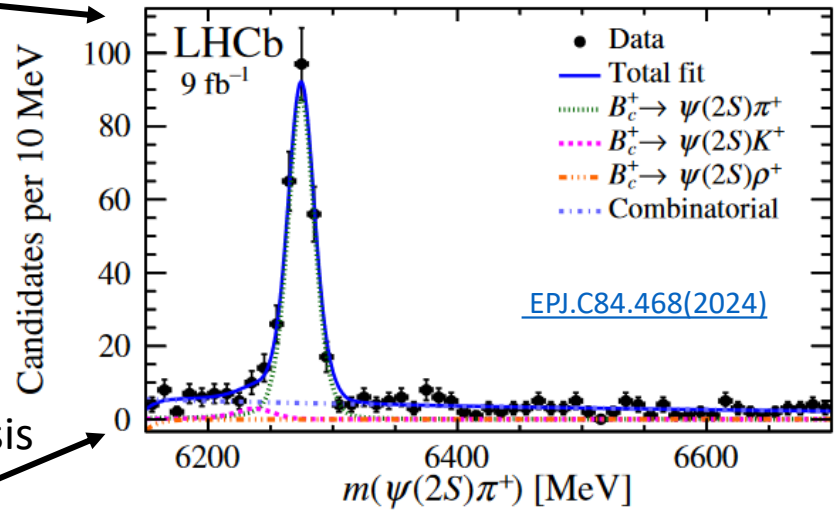
Collisions

Experiment



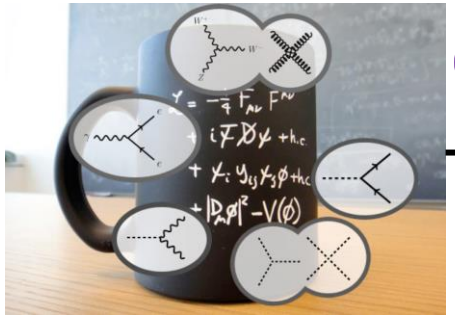
Analysis

Measurement



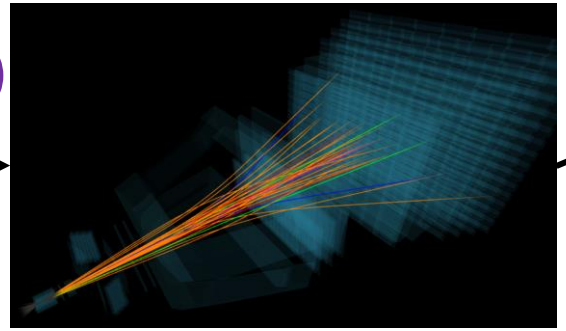
EPJ.C84.468(2024)

Theory



Event generators

Simulation

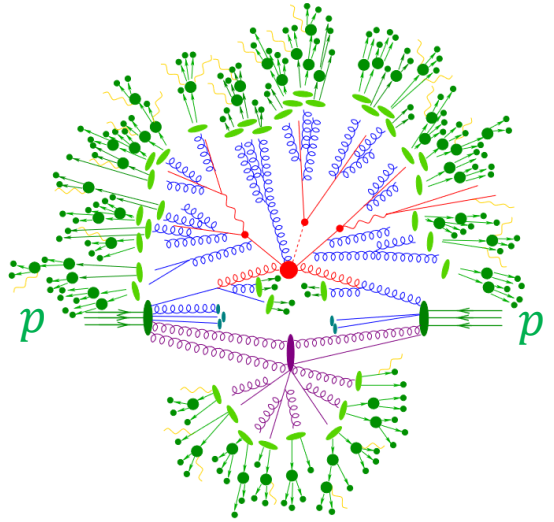


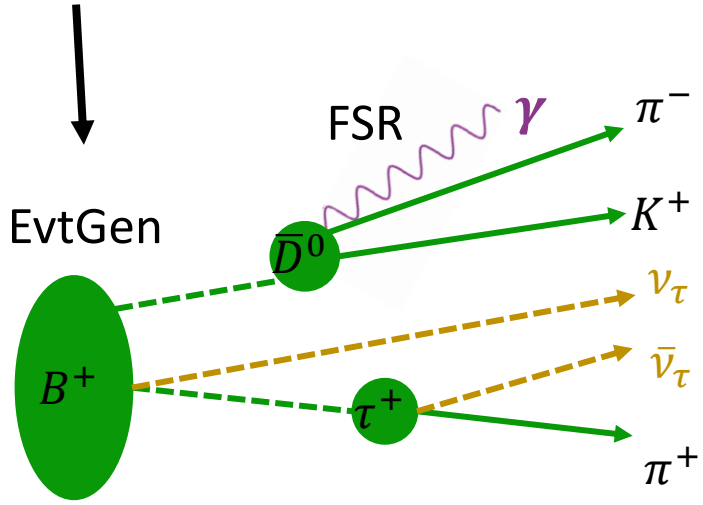
Analysis

The EvtGen generator

Simulation generator package specialised for decays of heavy particles containing b and c quarks.

Example collision simulated by PYTHIA8



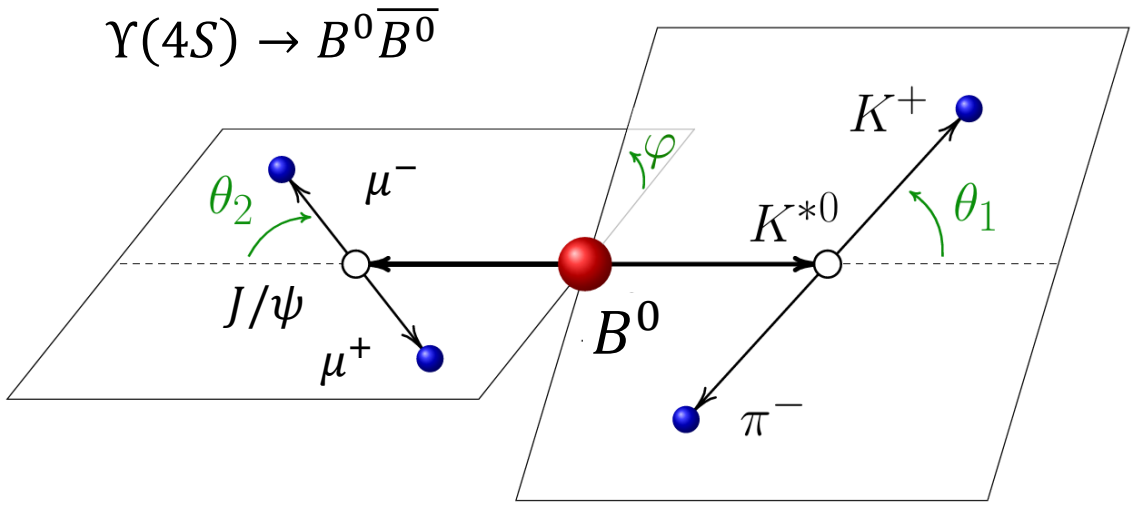


- Implements detailed decay dynamics based on theoretical models
- Originally developed for BaBar and CLEO by Anders Ryd and David Lange
- Used in multiple high-energy physics experiments:

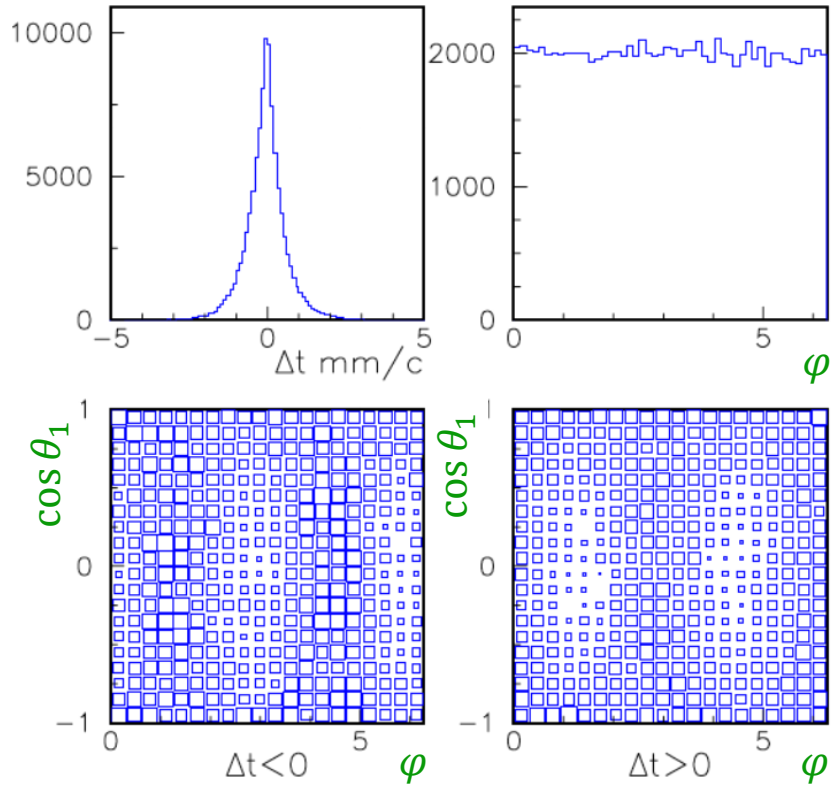
  ATLAS, Belle II, BES III, CMS, LHCb, …

Physics motivation

- Designed to handle complicated decay chains
- Account for dependencies between different observables

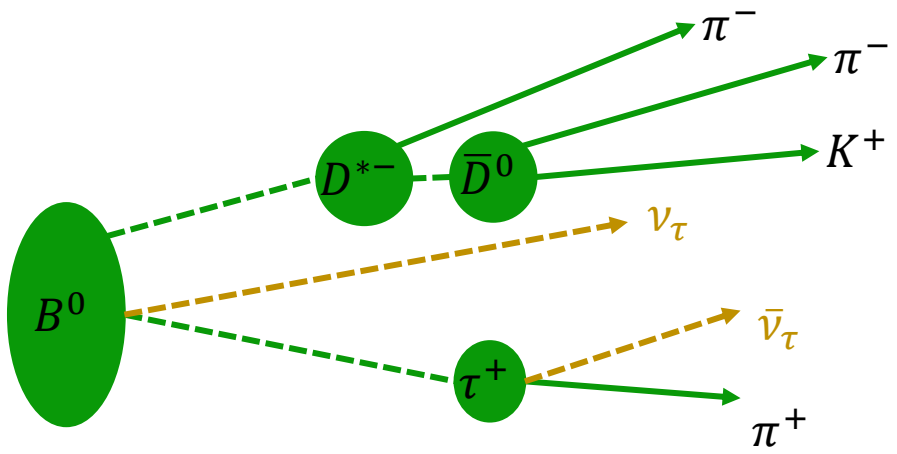


Example decay with CP violation and dependencies between decay time and angular observables.



Decay Chains

Decays of heavy-flavour particles often involve many sequential decays



Concept for a reusable generic tool

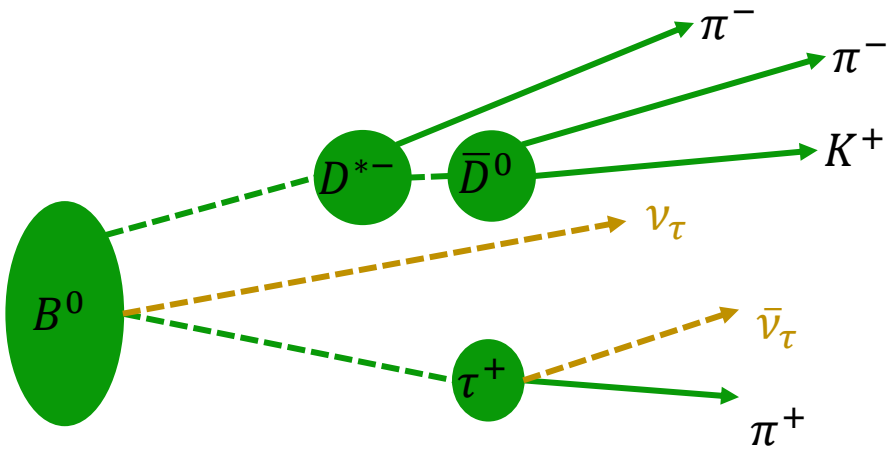
- Simulate correctly the **full decay chain** implementing only **individual nodes**

$\Rightarrow$ Use **decay amplitudes** instead of probabilities

$\Rightarrow$ Make use of **modular design** in C++ implementation

Decay amplitudes

- Use decay amplitudes to simulate **sequences** of decays
- Each node in the chain generated separately
  $\Rightarrow$ Must be associated with a **decay model**
- Decay models provide the amplitudes
- Framework handles bookkeeping to generate full decay chain



Workflow

Generate kinematics of B^0 according to phase space

Perform accept/reject based on

$$P_B = \sum_{\lambda_{D^*}\lambda_\tau} \left| A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau} \right|^2$$

Propagate the spin-state information to subsequent decays through spin-density matrix

Decay models

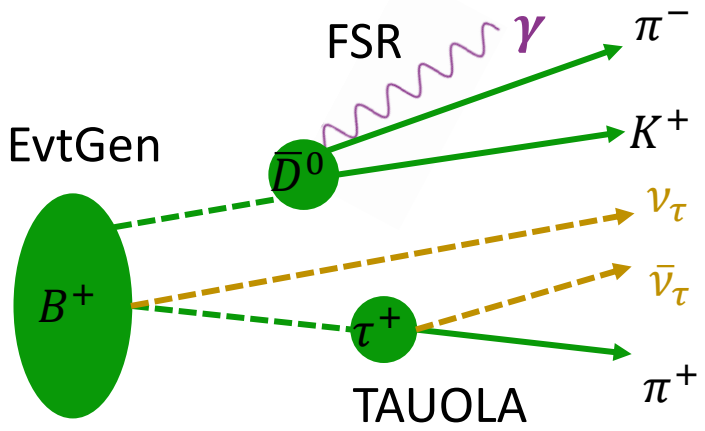
EvtGen contains about **130 decay models**

- **General purpose** models
  - Based on particle spin properties
  - Or specified helicity/partial wave amplitudes
- **Semileptonic** models with **form-factors**
- **Dalitz plot** decays (generic and specific Dalitz models)
- **Specific models** for electroweak penguins / radiative decays
  - For example $b \to s\ell\ell$, $b \to s\gamma$
- Many models have versions including $\boldsymbol{CP}$ **violation**

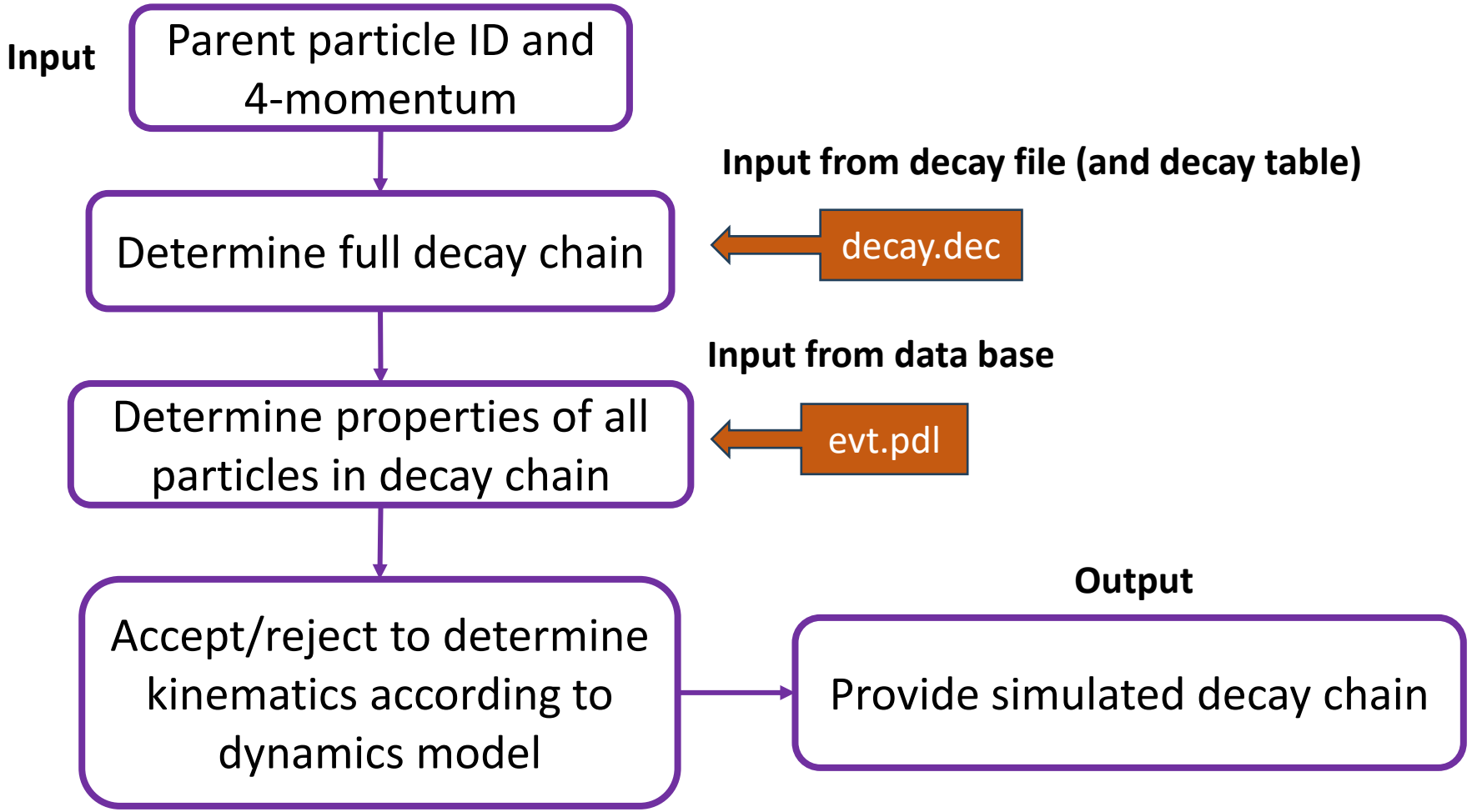
External dependencies

Interface with external packages for **additional features**

- HepMC for writing events in HepMC format (mandatory)
- Pythia8 for decays of generic quark configurations (optional)
- TAUOLA for decays of τ particles (optional)
- PHOTOS for final-state photon radiation (FSR) (optional)
- PHOTONS++ for final-state photon radiation (FSR) (optional)



EvtGen decay algorithm



Decay files and decay table

Decay files determine the decay chain

- Specify **decay modes** and their **branching fractions**
- Specify **decay models** and their **input parameters**
- Can be provided as text (.dec) or XML file

```
Decay B0sig
  0.90 J/psi K*0    SVV_HELAMP Hp pHp Hz pHz Hm pHm;
  0.10 Jpsi  K+ pi- PHSP;
Enddecay
```

EvtGen maintains a **generic decay table** (DECAY.dec) with properties of $\sim 10^4$ explicit decays

- Updated from PDG at intervals (nontrivial effort)
- When known branching fractions do not add up to 100%
  - $\Rightarrow$ Fill up remainder with generic quark configurations and pass to Pythia8
  - $\Rightarrow$ b-baryons rely more on Pythia8 than other particles

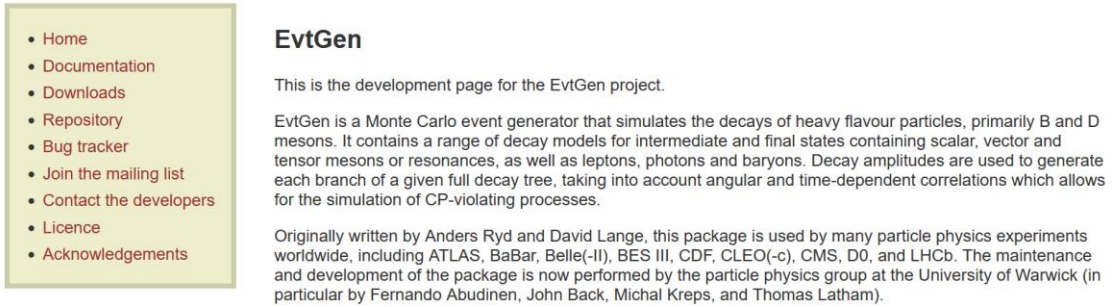
Status and recent developments

EvtGen status

- Developed in the 90's, stable over past 10 years
- Changes mostly additions of new models by different collaborators
- Maintained at Warwick since 2012 following merge of various experiment's forks by Anders Ryd
- Recently worked on **source-code modernisation** with help of research software engineers (RSEs) at Warwick

⇒ Main goal of recent campaign: **enable thread safety**

https://evtgen.hepforge.org



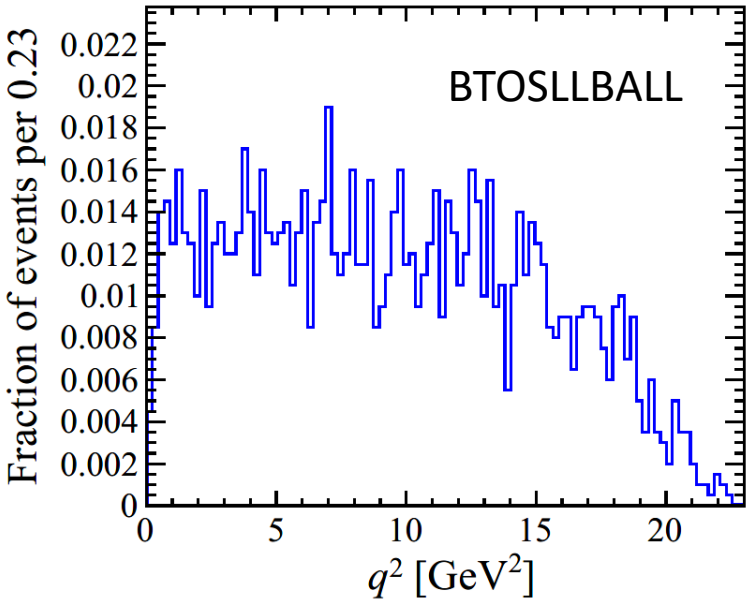
Mirror at https://gitlab.cern.ch/evtgen/evtgen
with continuous integration tests

Validation

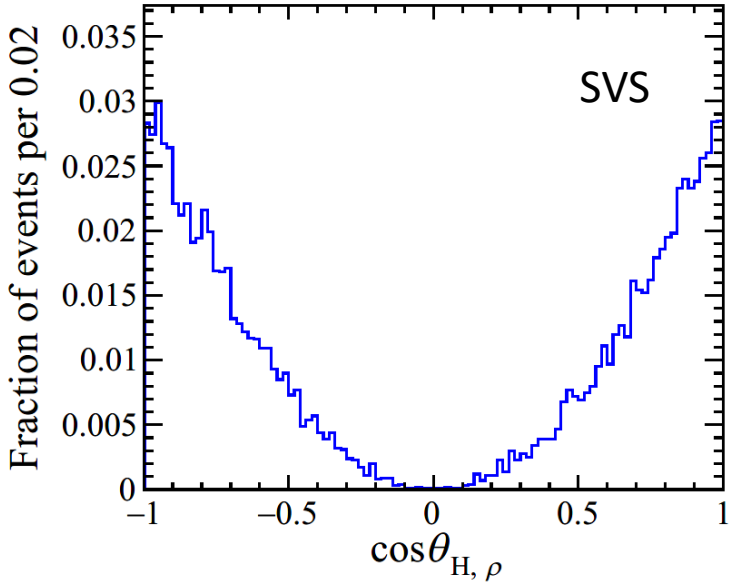
Simulation needs testing and validation after changes to ensure invariance of the physics models

- Implemented **testing framework** with common testing module and JSON configuration files
- Migrated all previous tests (covered only 40% of models) and added new ones to framework
- Tests cover all models and external generators
- Helped uncover and fix bugs
- Used for **continuous integration** in GitLab
- Available for users to facilitate testing models

$B^+ \to K^+\mu^+\mu^-$



$B^+ \to \bar{D}^0\rho^+(\to \pi^+\pi^0)$



Implementation of multithreading

With help of research-software engineers:
Heather Ratcliffe, Chris Brady

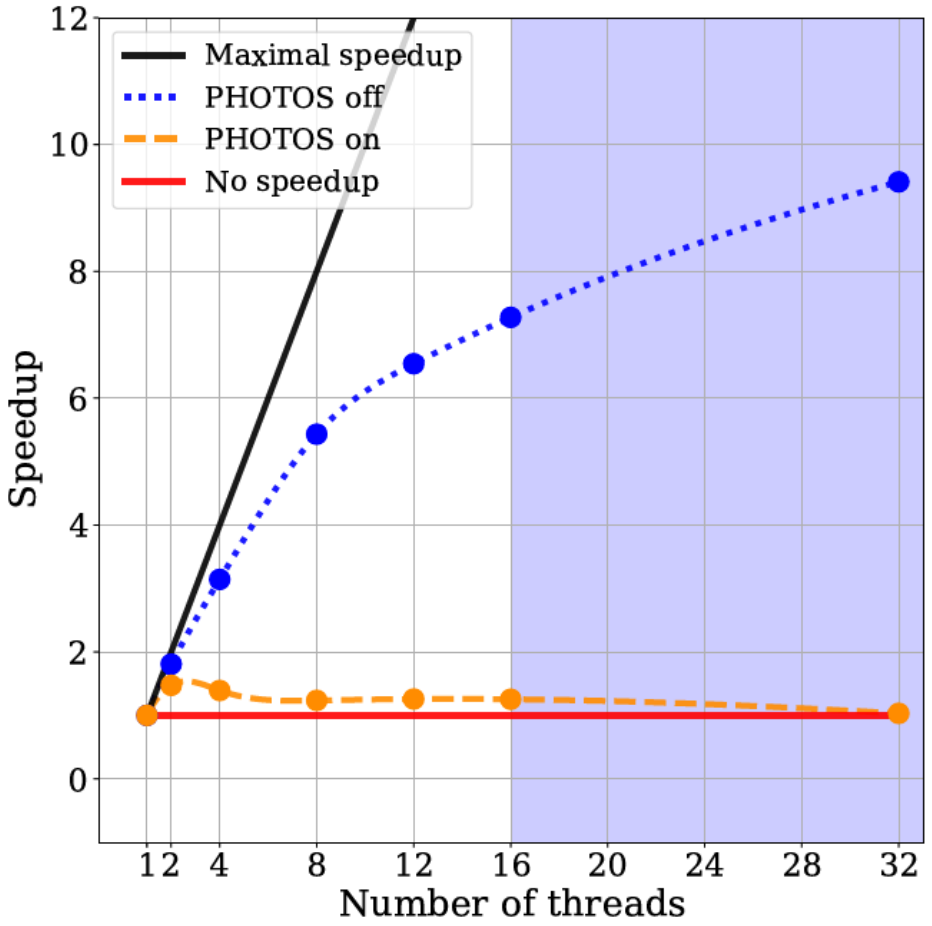
Challenges

- Internal: structural limitations
  - Global instance of random number generator
  - Global instance of particle properties and decay table
- External: limitations from dependences (look for alternatives) on TAUOLA and PHOTOS

Preliminary solution

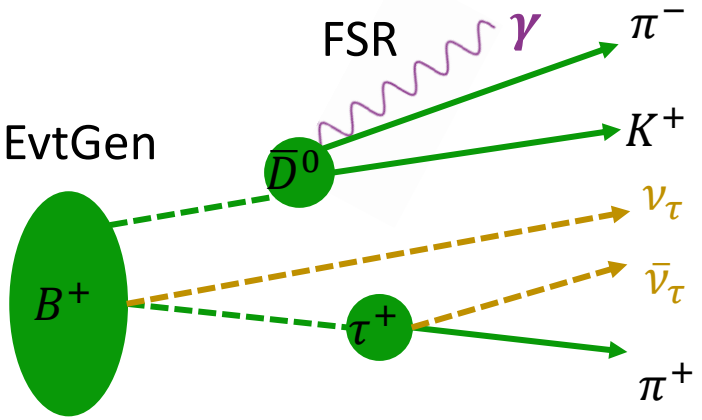
- Static objects made constant or thread-local
- Global singleton objects made thread-local
- Serialized (mutexed) calls to PHOTOS and TAUOLA

⇒ Performance limited by external dependencies



Final-state radiation in EvtGen

- EvtGen relies on external specialised generators to add QED FSR corrections
- Generators generally treat the effect of FSR as a multiplicative correction to the decay rate



$$d\Gamma^{\text{radiative}} = d\Gamma^{\text{Born}}\, f(\Phi)\, d\Phi$$

Φ: Phase-space of photons

```
Decay D0sig
  0.0390   K-   pi+   PHOTOS PHSP;
Enddecay
CDecay anti-D0sig
```

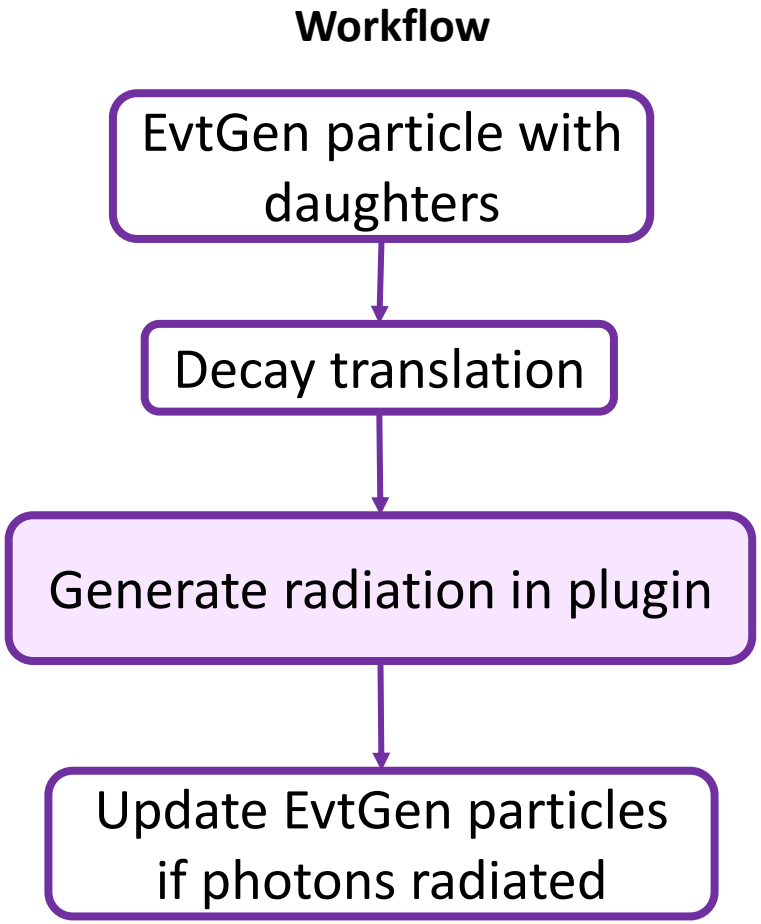
- Generators add photons (accept/reject) based on $f(\Phi)$
- Default generator is PHOTOS
- Recently included Sherpa's PHOTONS++ as alternative
- Currently developing Vincia (inside Pythia8) as alternative

PHOTOS flag deprecated with FSR flag in EvtGen r3.X.X

Interfaces between EvtGen and Plugins

- Each decay-chain node translated
  - Into intermediate HepMC events (for PHOTOS)
  - Directly into Sherpa or Pythia objects (for Photons and Vincia)
- EvtGen random number propagated (full seed control)
- PHOTOS and Sherpa's PHOTONS++ not thread-safe yet ⇒ **mutex**
  - Need to mutex also HepMC translation (for PHOTOS)

Review (for Sherpa) by Marek Schönherr and Frank Krauss

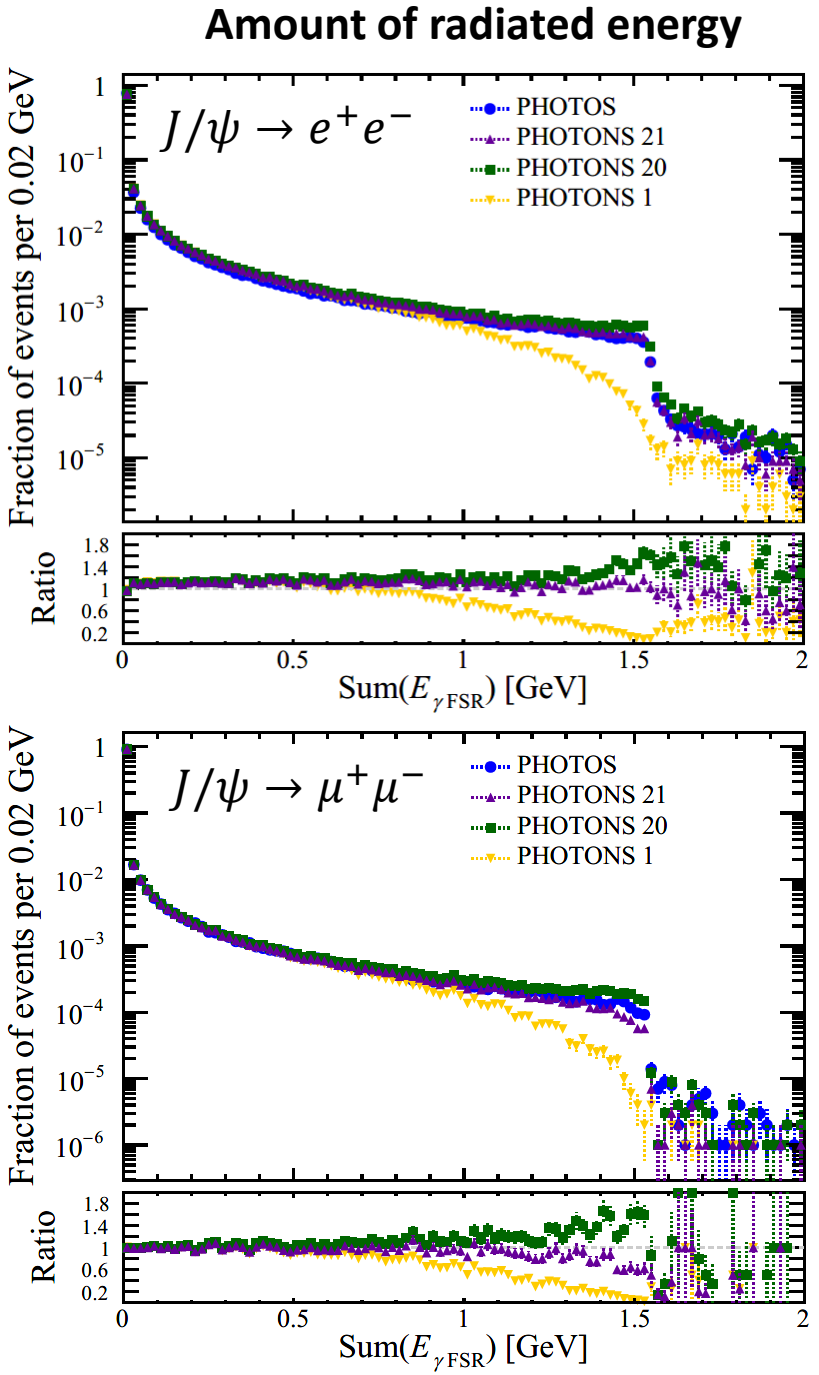


Sherpa's PHOTONS++ for FSR

- PHOTONS++ in Sherpa can simulate emission of soft photons based on YFS approximation (mode 1)
- If switched on also hard photons based on collinear approximation (mode 2)
  - Approx. matrix-element corrections (mode 20) or
  - Exact matrix-element corrections (mode 21)
- With mode 1: fewer hard photons compared to PHOTOS (PHOTOS has matrix-element corrections implemented)
- With mode 2: generally good agreement with PHOTOS

⇒ Implemented switches for systematic studies

New in EvtGen R03-00-00-beta1!



Vincia QED shower for FSR

- Vincia parton shower evolution based on Antenna approximation (can be interleaved)
- Recently adapted to radiate off hadrons (previously supporting only leptons)
- Matrix-element corrections (MECs) in progress

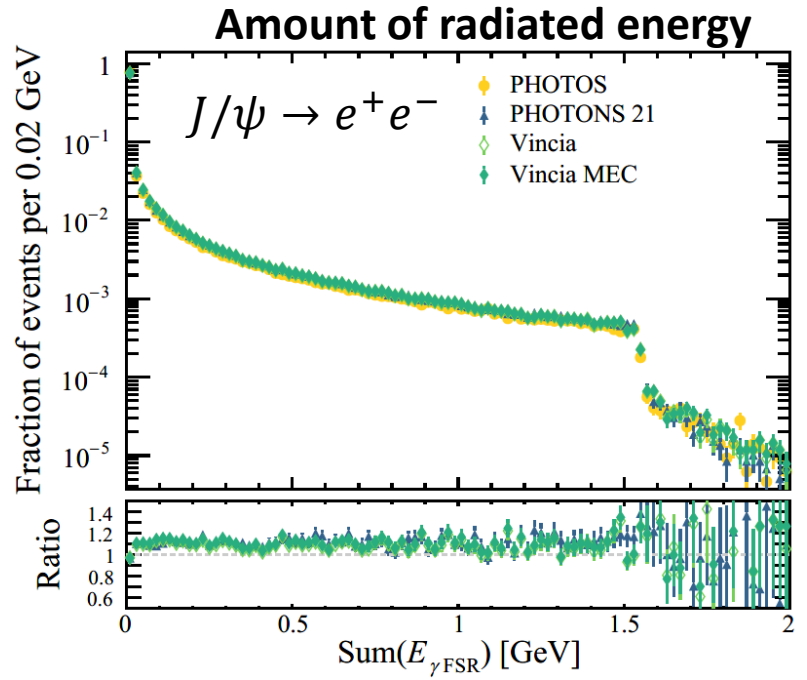
⇒ Currently implementing and validating

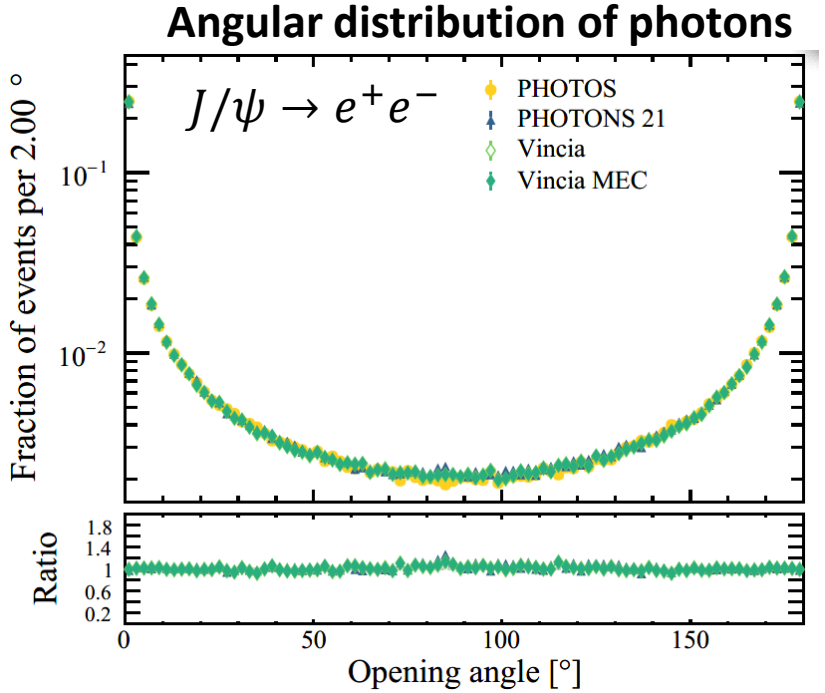
⇒ Preliminary results look promising

Technical aspects

- Vincia is embedded in Pythia8
- Algorithm implementation enables thread safety
- Developed EvtGen ↔ Vincia interface based on existing dependency with Pythia8

⇒ To be added to release (once in Pythia8 release)





Comparisons between FSR plugins

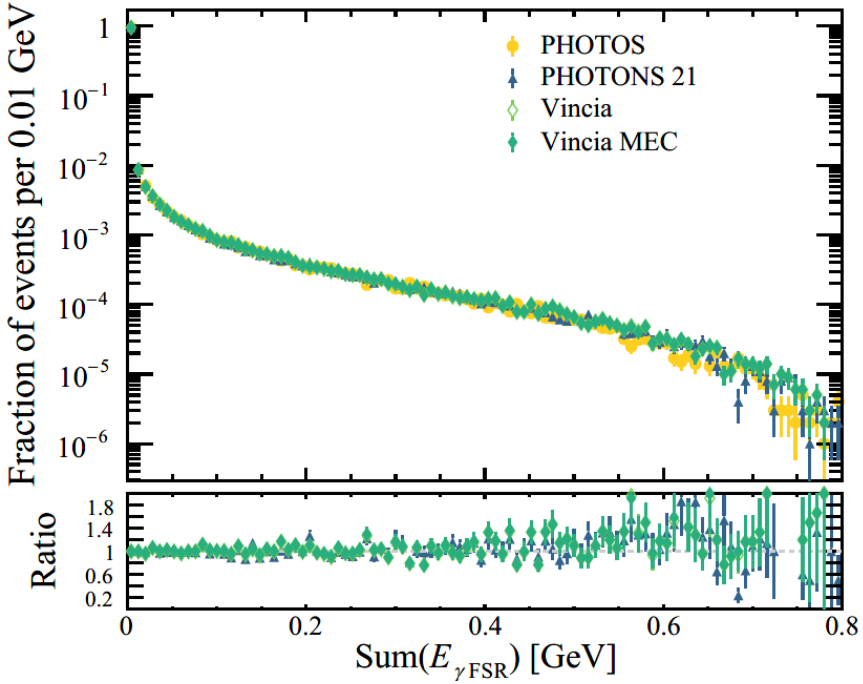
Many studies ongoing for various modes and matrix element corrections

Example $D^0 \to K^-\pi^+$

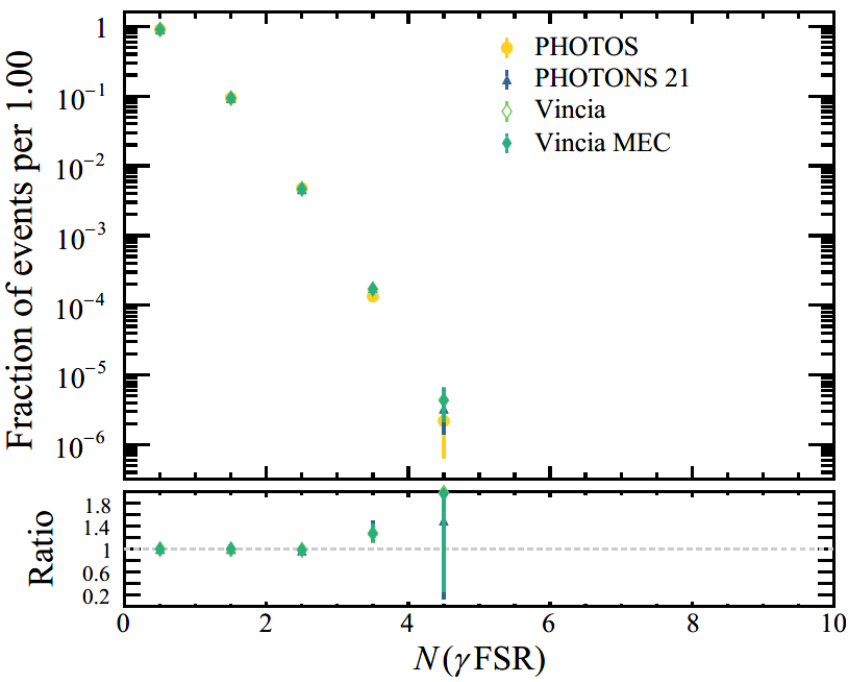
See HFLAV Sec 11.3

$$\mathcal{B}(D^0 \to K^-\pi^+) = (3.999 \pm 0.006_{\text{stat.}} \pm 0.031_{\text{syst.}} \pm 0.032_{\text{FSR}})\,\%$$

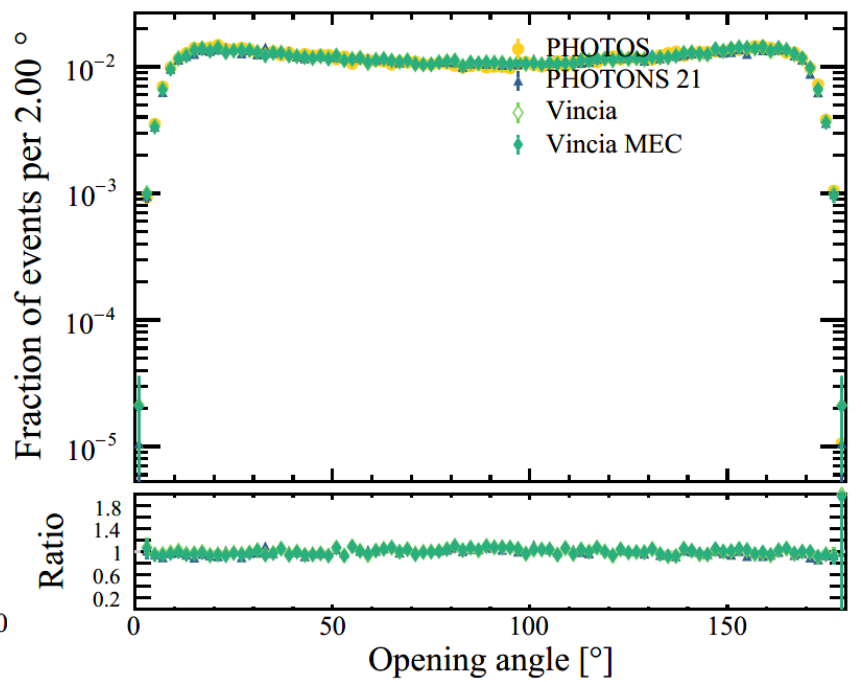
Amount of radiated energy



Number of photons



Angular distribution of photons

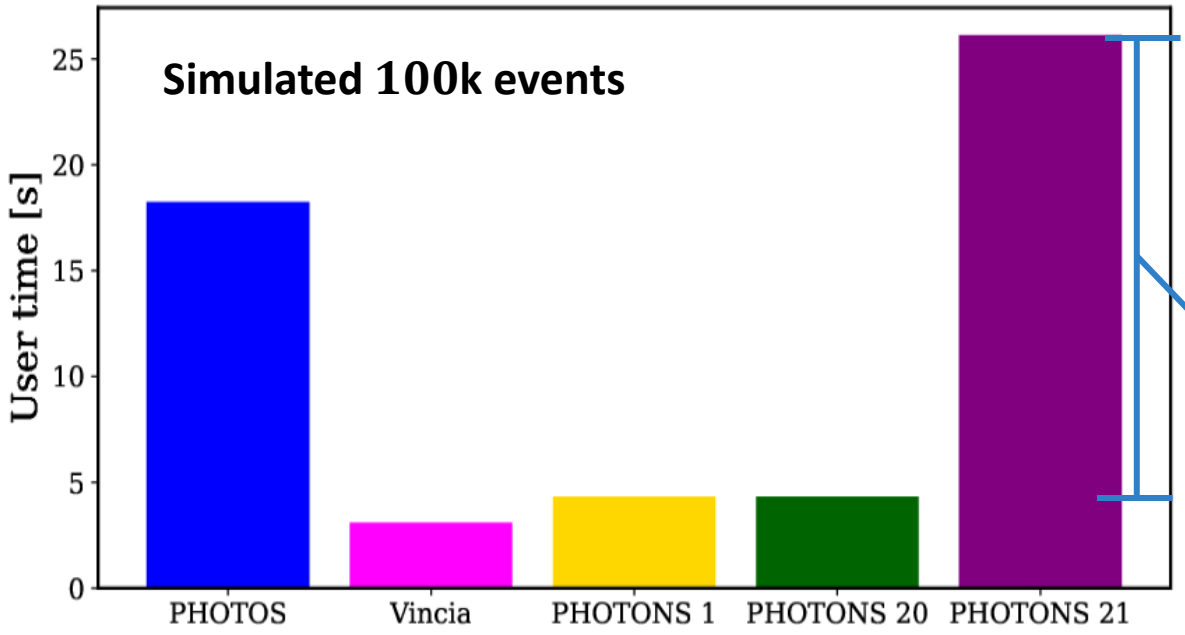


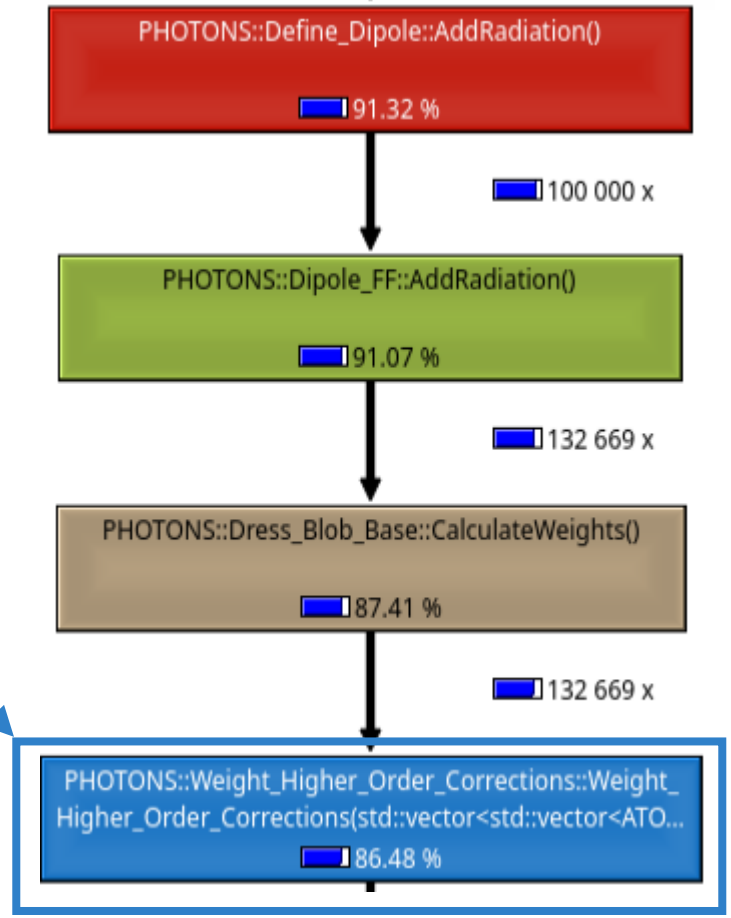
⇒ Good agreement among generators for sensitive case

A word on timing

- Compare simulation time using $J/\psi \to e^+e^-$ decay as benchmark

⇒ Collinear singularities enhanced due to small electron mass





⇒ Largest consumption by exact matrix-element calculation

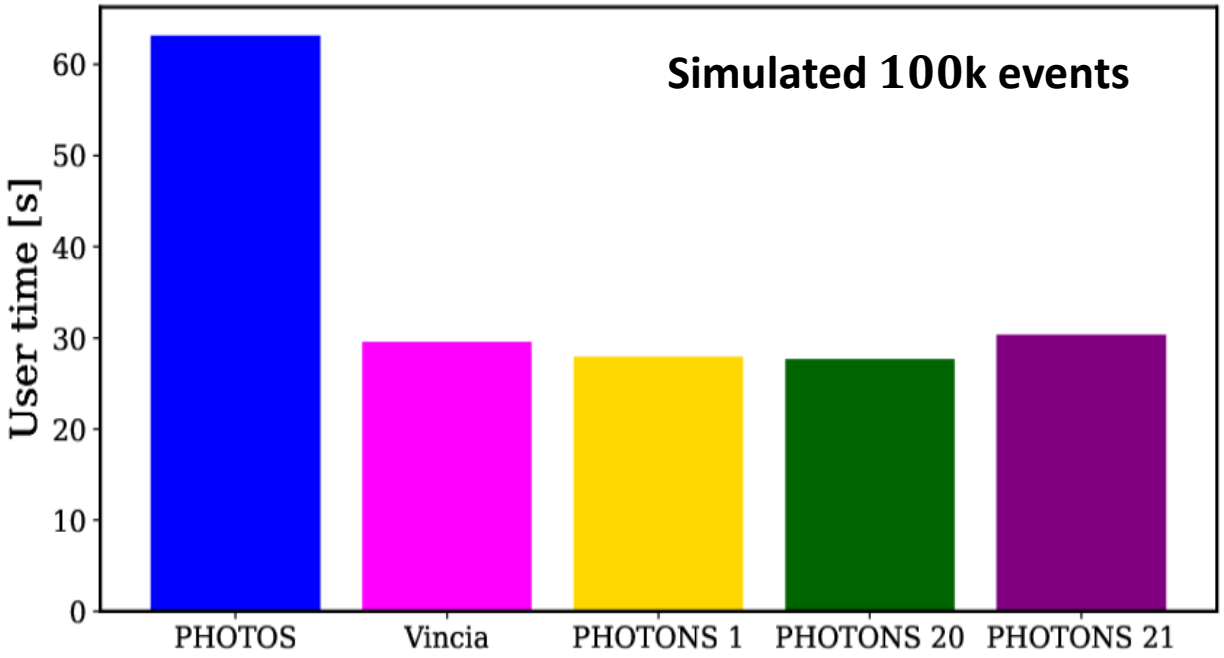
⇒ Good precision/time trade-off for option 20 (will use as default)

⇒ Potential speedup using Vincia or PHOTONS by about factor 4

Another word on timing

- Compare simulation time when simulating generic $\Upsilon(4S) \rightarrow B\bar{B}$

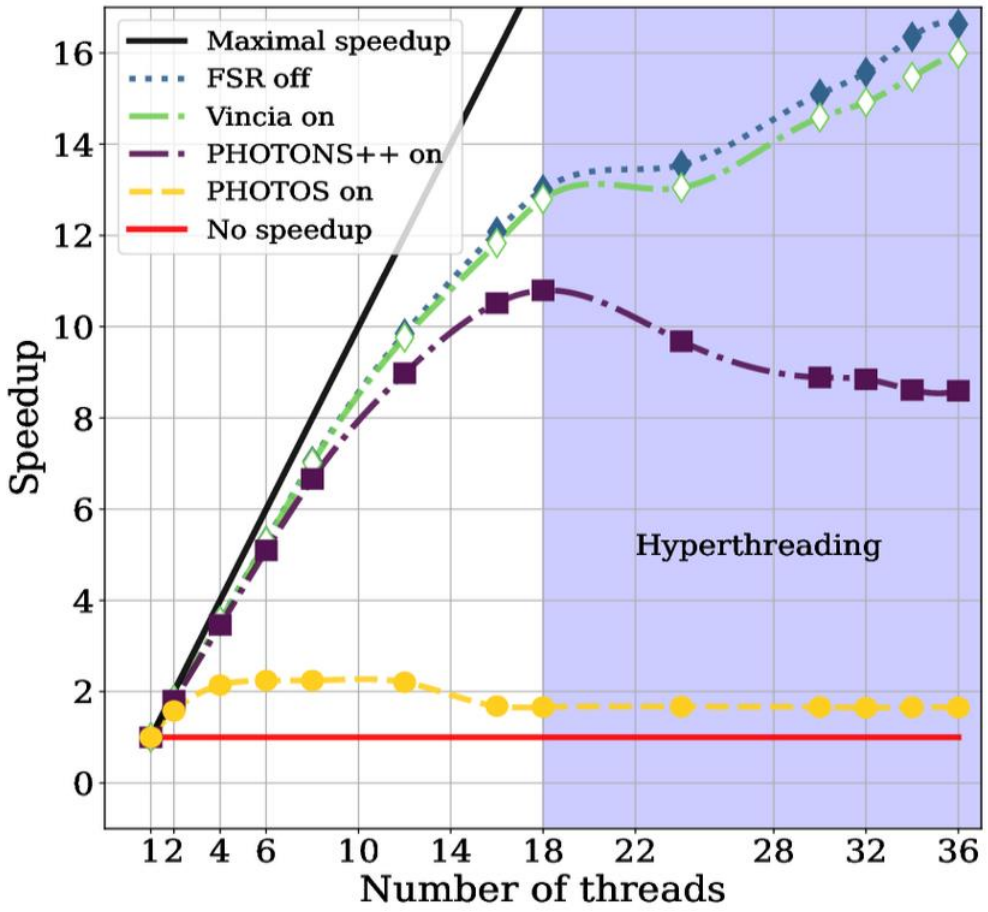
$\Rightarrow$ Benchmark for general use

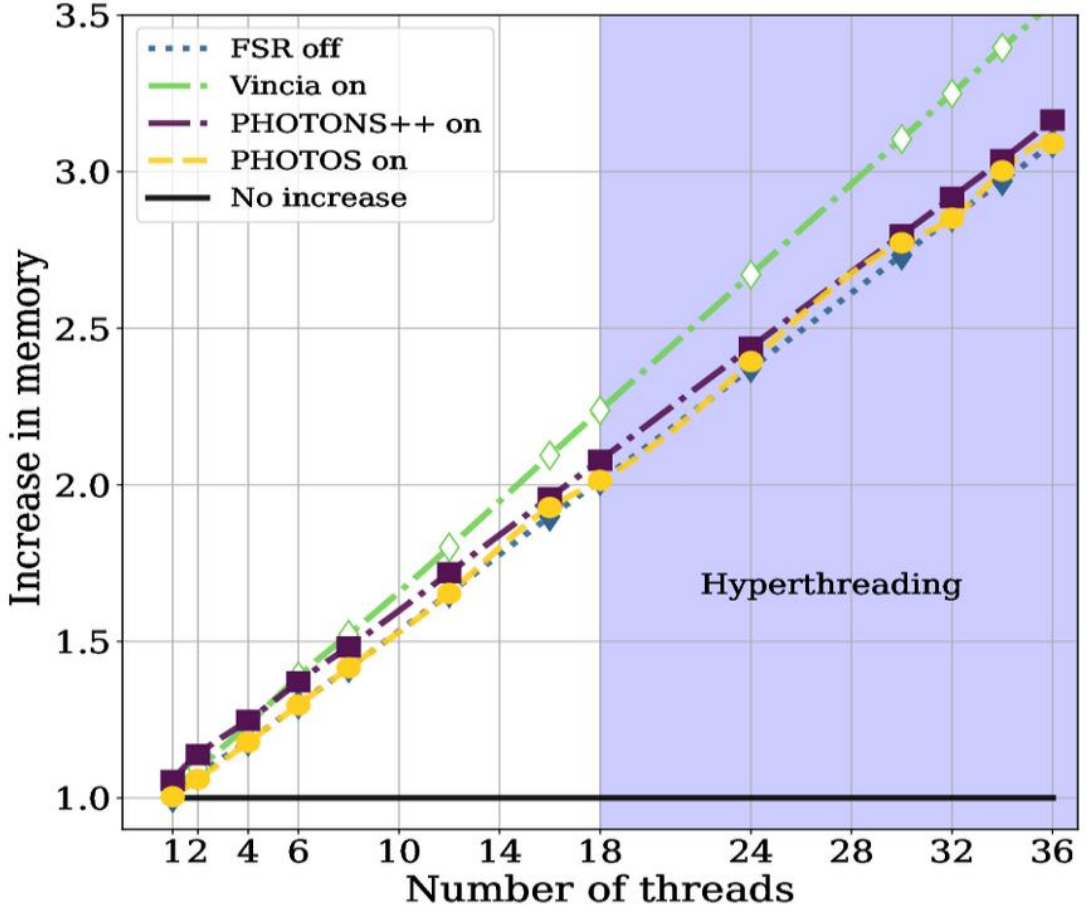


$\Rightarrow$ No large difference between PHOTONS options in generic case

$\Rightarrow$ Potential **speedup** using Vincia or PHOTONS **by about factor 2** (even with MEC)

Performance with multithreading





⇒ Better performance with new FSR alternatives

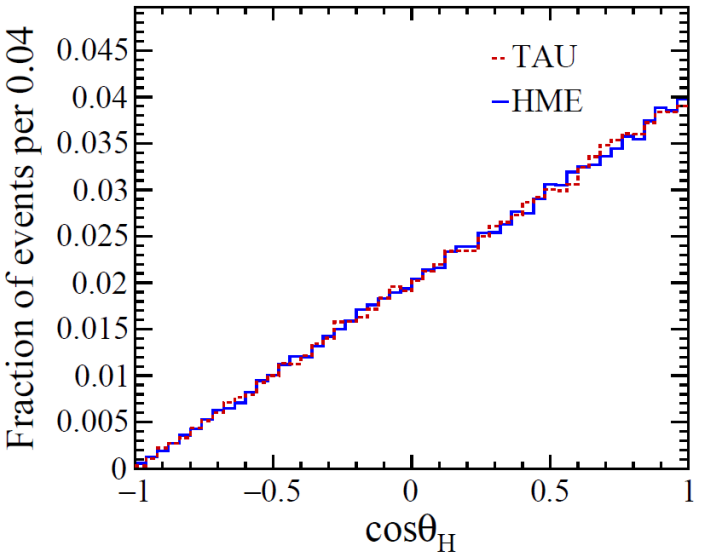
⇒ Deeper structural changes needed to fully exploit multithreading with increased memory sharing

Plugins for τ decays

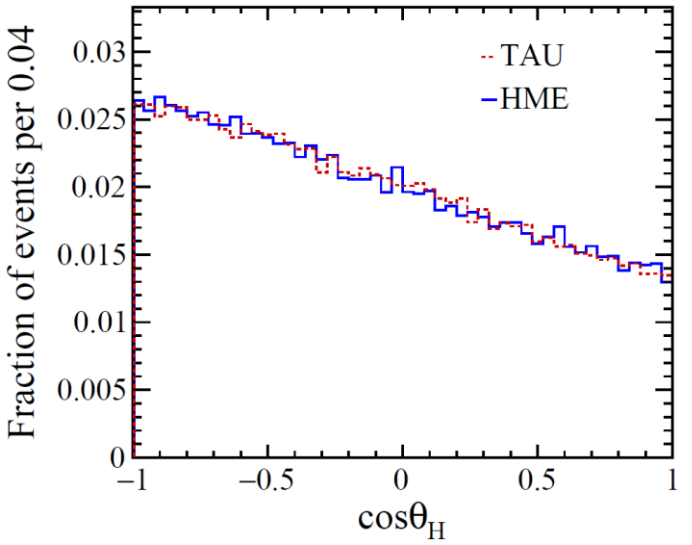
- EvtGen $\leftrightarrow$ TAUOLA interface based on HEPMC
- Spin-state information of τ not propagated
  - TAUOLA reconstructs spin info from ancestors
  - Needed for analyses sensitive to τ polarization
- Simulation of τ decays with spin-state propagation possible with PYTHIA8 using HME (helicity-matrix element) model

  $\Rightarrow$ Prototyped EvtGen $\leftrightarrow$ Pythia interface with spin-density matrix propagation
- Generalisation of helicity/spin basis conversion has turned out challenging (but wish to continue work)

$B^+ \rightarrow \tau^+(\rightarrow \pi^+\bar{\nu}_\tau)\,\nu_\tau$



$B^+ \rightarrow \tau^+\left(\rightarrow \mu^+\nu_\mu\bar{\nu}_\tau\right)\nu_\tau$



EvtGen releases

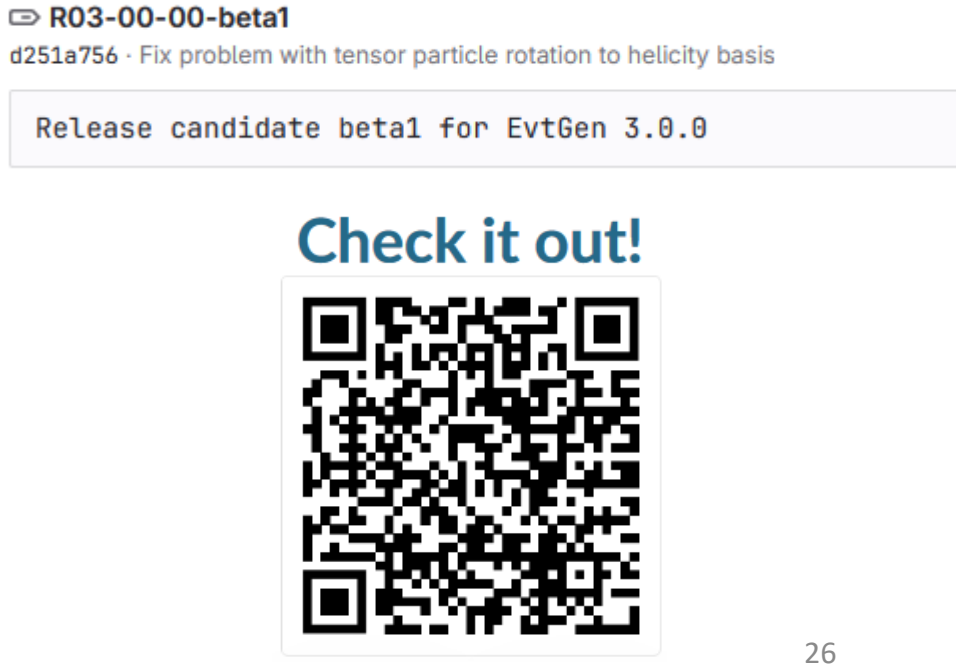
Release with latest subversion R02-02-03 (Sep 2024)

- Fixed RNG interface issue with Pythia8 310
- Fixed bug with tensor particle rotation to helicity basis

After the long campaign released R03-00-00-beta1 (Oct 2024) for users to test

- Implemented **thread safety**
- Implemented new **testing framework**
- Added Sherpa's PHOTONS++ as **FSR alternative**
- **Fixed** various **decay models** (removed obsolete ones)

Physics validation passed for all models with/without FSR when multithreading.



Plans for the future

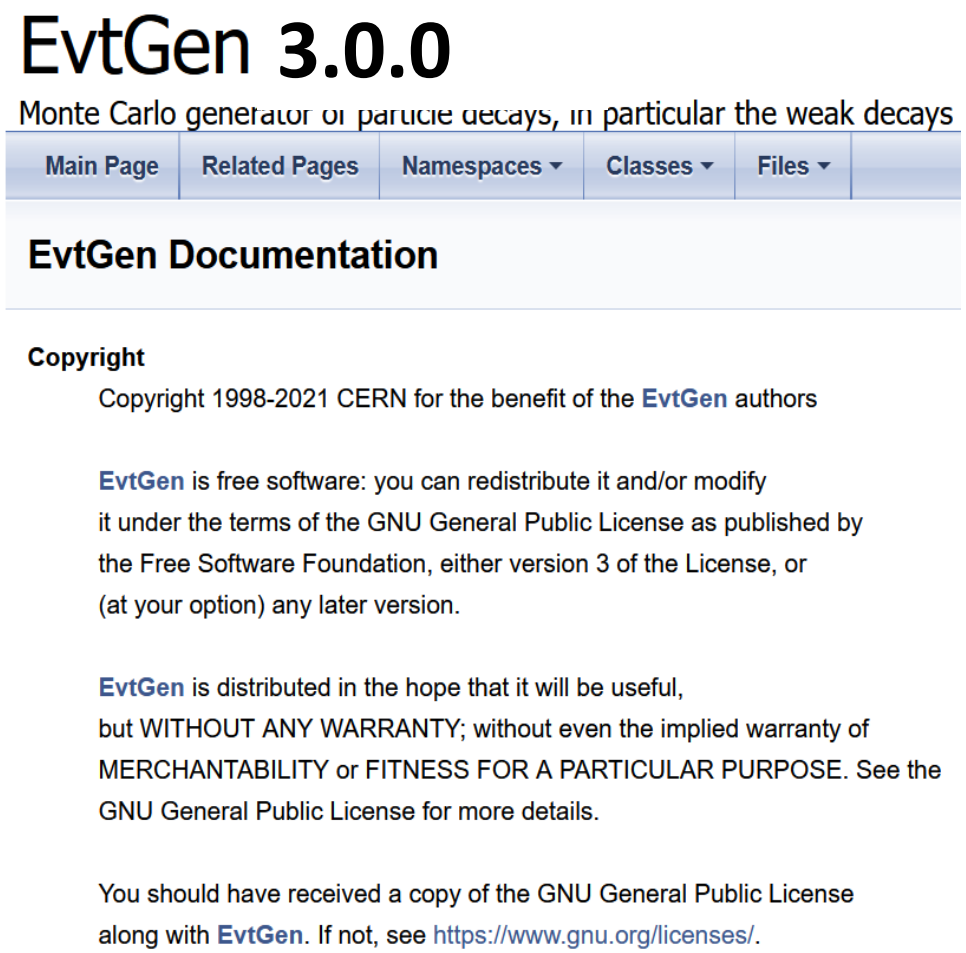
Immediate

- Include Belle II decay table
- Vincia for FSR
- Improve Doxygen documentation
- Prepare main Journal article

Long-term

- Add further models as requested by community
- Implement alternatives for τ particle simulation (fix spin propagation)
- Implement structural modifications to fully exploit multi-threading
- Provide event weights for alternative decay tables
- Interleave Vincia FSR with entire decay chain

https://evtgen.hepforge.org/doc/doxygen/test


EvtGen 3.0.0

Monte Carlo generator of particle decays, in particular the weak decays

Main Page | Related Pages | Namespaces | Classes | Files

EvtGen Documentation

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Summary and outlook

- EvtGen — essential tool to study heavy-flavour particle decays in multiple experiments
- After long modernisation campaign ⇒ R03-00-00-beta1

⇒ New general **testing framework**

⇒ Implemented **thread safety**

(full exploitation of multi-threading will require further structural changes)

⇒ Performance limited by external dependencies

⇒ Implemented Sherpa's PHOTONS++ (and working on Vincia) as **alternative for FSR**

- Various projects for future developments (τ-spin propagation, event weights, …)

⇒ Contributions from the community very welcome

- Full release 3.0.0 expected by summer 2025 (and paper by year's end)

Stay tuned!

https://evtgen.hepforge.org

evtgen@projects.hepforge.org