Interfacing to specialist tools in EvtGen

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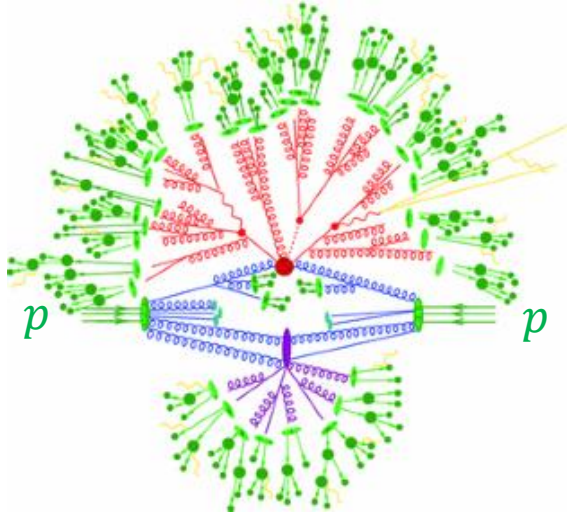
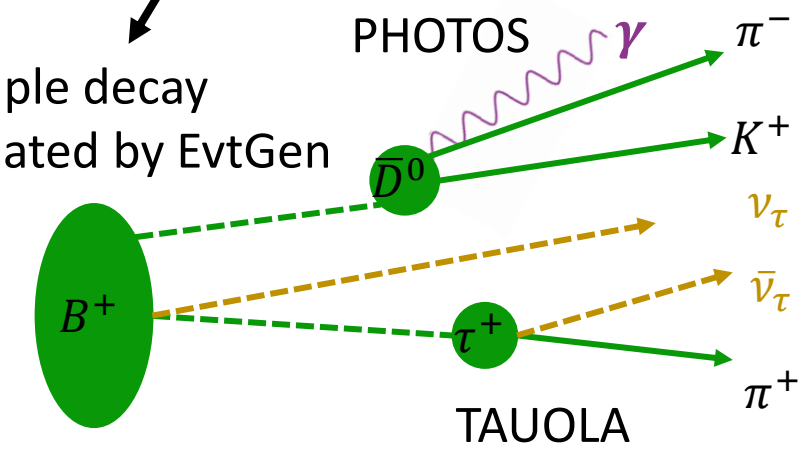
EvtGen generator

- Package specialised for heavy-flavour hadron decays
  - Used as well inside simulation of b jets
- Contains about 130 decay models implementing specific dynamics of various decays
- Maintains detailed decay table with large number of explicit decays
  - Known decay branching fractions do not add up to 100%; Remainder is filled up by generating quark configurations and passing those to Pythia8 for fragmentation
  - Fraction of decays passed to Pythia8 depends on particle (b-baryons rely more on Pythia8 than others)
- τ decays simulated using TAUOLA
- Final-state radiation (FSR) simulated using PHOTOS or Sherpa's PHOTONS++ (new)

Example collision simulated by Pythia8



Example decay simulated by EvtGen



Dependencies across generators

- Extremely heavy "backward" dependencies of whole MC generators to support decay modelling
- Inconsistencies can result from mixing other (typically Pythia) hadron models into another generator's decay chains (and unresponsive to tunes)
- Example dependencies in EvtGen
  - Pythia
  - TAUOLA
  - PHOTOS
  - Sherpa

Interface between EvtGen and Pythia

- EvtGen asks Pythia to decay and hadronise quark configurations in some cases
- Nothing to be put into the event record before Pythia simulation
- Direct translation of EvtGen objects into Pythia event (and back)
- Needs interplay between generators (making sure to avoid double counting)
- Needs matching of particle properties and decay table.

Example from general Decay table

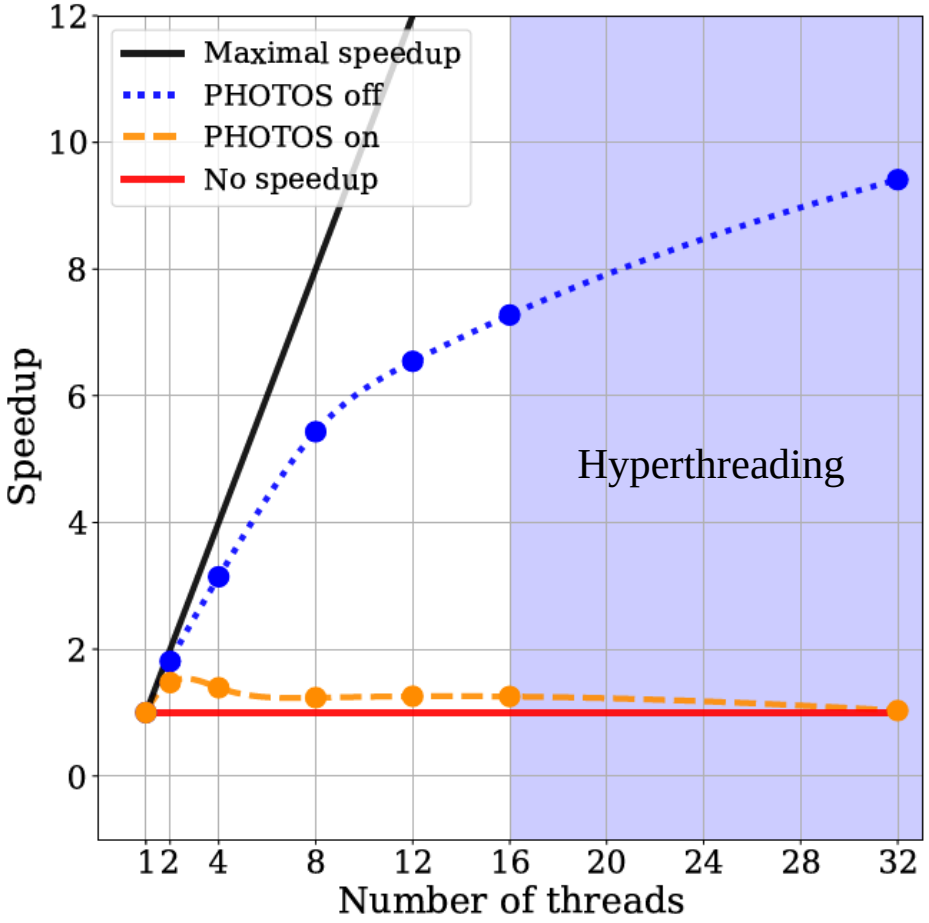
```
Decay Omega_b-
#                  SemiLeptonic Decays
  0.05460    Omega_c0      e-    anti-nu_e                PHSP;
  0.05460    Omega_c0      mu-   anti-nu_mu               PHSP;
  0.02000    Omega_c0      tau-  anti-nu_tau              PHSP;
#                  Hadronic Decays with Xi_c+
  0.00600    Omega_c0      pi-                            PHSP;
  0.02200    Omega_c0      pi-     pi+       pi-          PHSP;
  0.00055    Omega_c0      K-                             PHSP;
  0.02200    Omega_c0      D_s-                           PHSP;
  0.0011     D0            Xi-                            PHSP;
#
  0.00047    Omega-        J/psi                          PHSP;
  0.00038    Omega-        psi(2S)                        PHSP;
#                  filling out with inclusives
0.68192 d anti-u s cs_0 PYTHIA 43;
0.10910 d anti-u d cs_0 PYTHIA 43;
0.02728 d anti-u s su_0 PYTHIA 43;
Enddecay
```

Interface between EvtGen and PHOTOS

- Evtgen decay tree (particle with daughters) translated into HEPMC event (and back)
- PHOTOS translates HEPMC event internally (and back)
- PHOTOS core is not thread safe

⇒ Mutexed calls when making EvtGen thread safe

⇒ Major limitation in performance since almost every decay calls FSR simulation



Final-state radiation generators

- Treat the effect of FSR as a correction to the Born-level decay rate (or cross section)

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

Φ: Phase-space of photons

- Example (oversimplified): neutral scalar $\rightarrow e^+e^-$ (single QED dipole)

From talk by Peter Skands

LO QED $\propto \frac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}} + \frac{1}{M_0^2}\left(\frac{s_{\gamma e^+}}{s_{e^-\gamma}} + \frac{s_{e^-\gamma}}{s_{\gamma e^+}} + 2\right)$

eikonal term — collinear terms

$s_{ij} = p_i \cdot p_j$
Dot product of 4-momenta

PYTHIA
DGLAP
e^--collinear limit
e^+-collinear limit
$\frac{P_{e^-\rightarrow e^-\gamma}(z_1)}{s_{1\gamma}} + \frac{P_{e^+\rightarrow e^+\gamma}(z_2)}{s_{2\gamma}}$

VINCIA
Antenna
All Singular Terms
$\frac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}} + \frac{1}{M_0^2}\left(\frac{s_{\gamma e^+}}{s_{e^-\gamma}} + \frac{s_{e^-\gamma}}{s_{\gamma e^+}}\right)$

Soft limit
HERWIG, SHERPA, PHOTOS
YFS
$\frac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}}$

Final-state radiation generators

Pythia QED

- Determines “best” set of dipoles (no genuine multipole effects)
- Works as parton shower evolution interleaved with QCD, MPI, …

YFS – Yennie-Frautschi-Suura 1961 (basis for PHOTOS, Herwig, Sherpa’s PHOTONS++)

- Takes full (multipole) soft interference effects into account
- Scalar QED, no spin dependence (but taken into account via ME corrections)
- Adds a number of photons to final state with predetermined kinematics (no interleaving)

Vincia QED Kleiss-Verheyen 2017, Brooks-Verheyen-Skands 2020

- Takes full (multipole) soft interference effects into account
- Not limited to scalar QED (includes spin dependence)
- Works as parton shower evolution based on antenna approximation (can be interleaved)

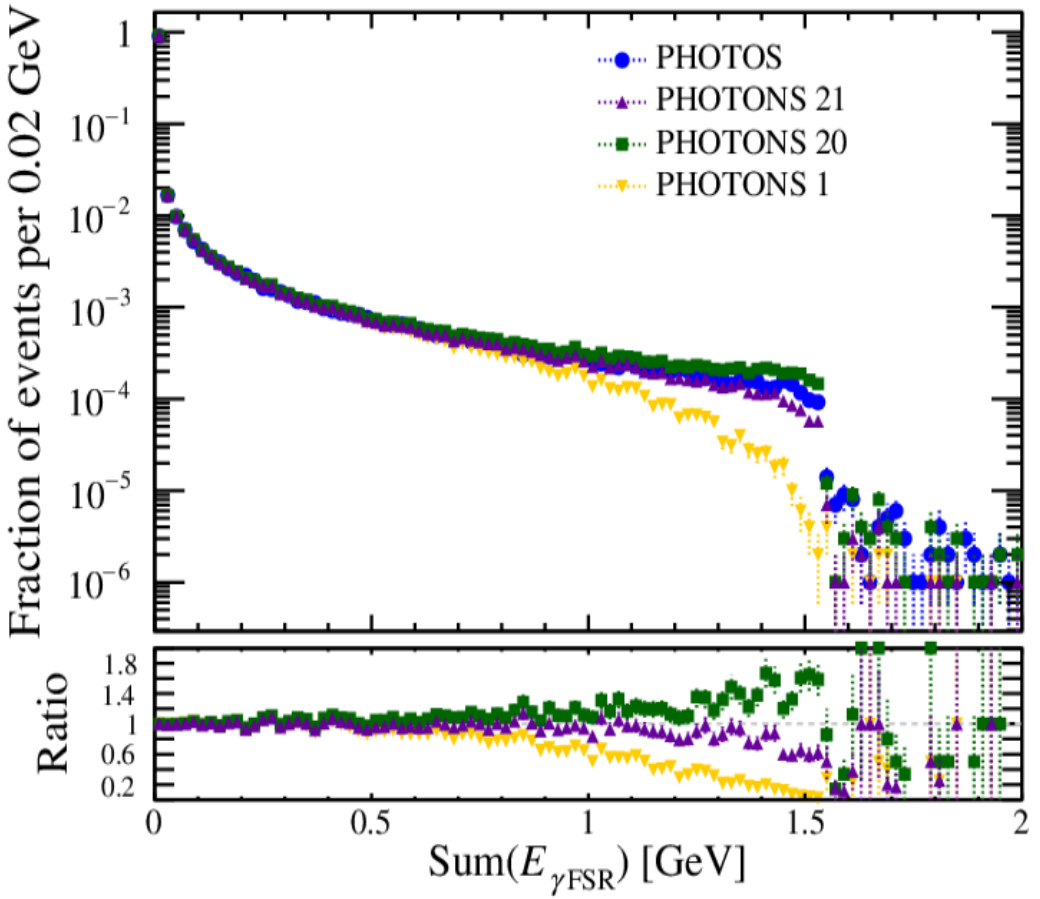
Sherpa's PHOTONS++ for FSR

- 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), with
  - Approx. matrix-element corrections (mode 20) or
  - Exact matrix-element corrections (mode 21)
- Using option 1, observed fewer hard photons with respect to PHOTOS (note that PHOTOS has matrix-element corrections implemented)
- Generally good agreement with PHOTOS using options 20 and 21

⇒ Will enable user to switch between options for systematic studies

Amount of radiated energy

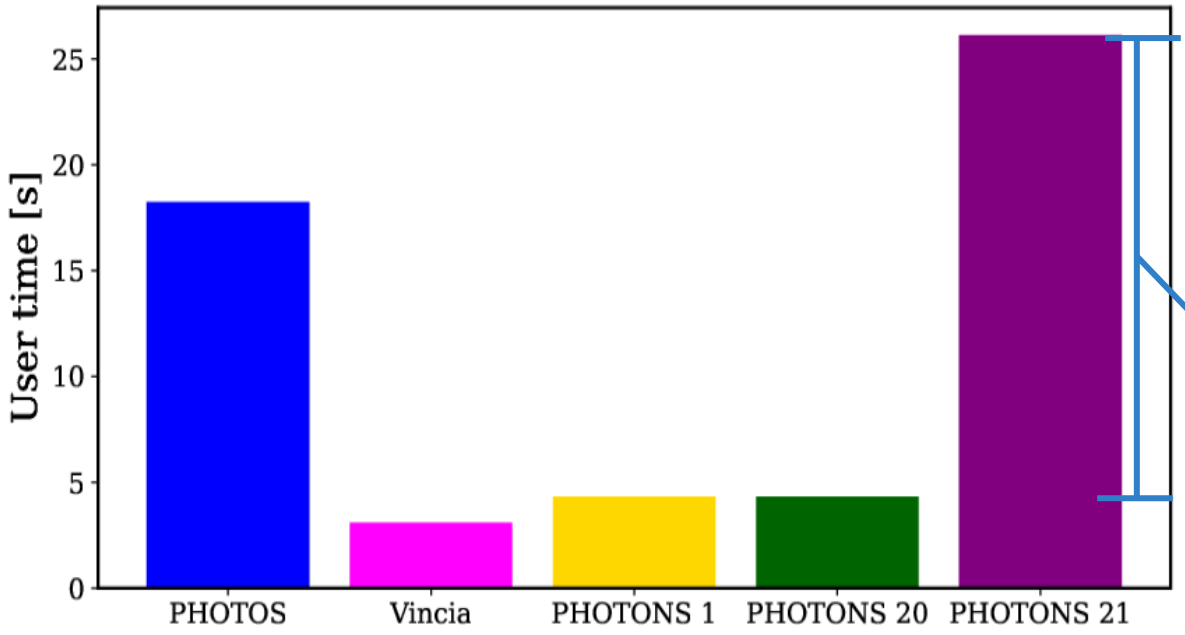
$J/\psi \to \mu^+\mu^-$

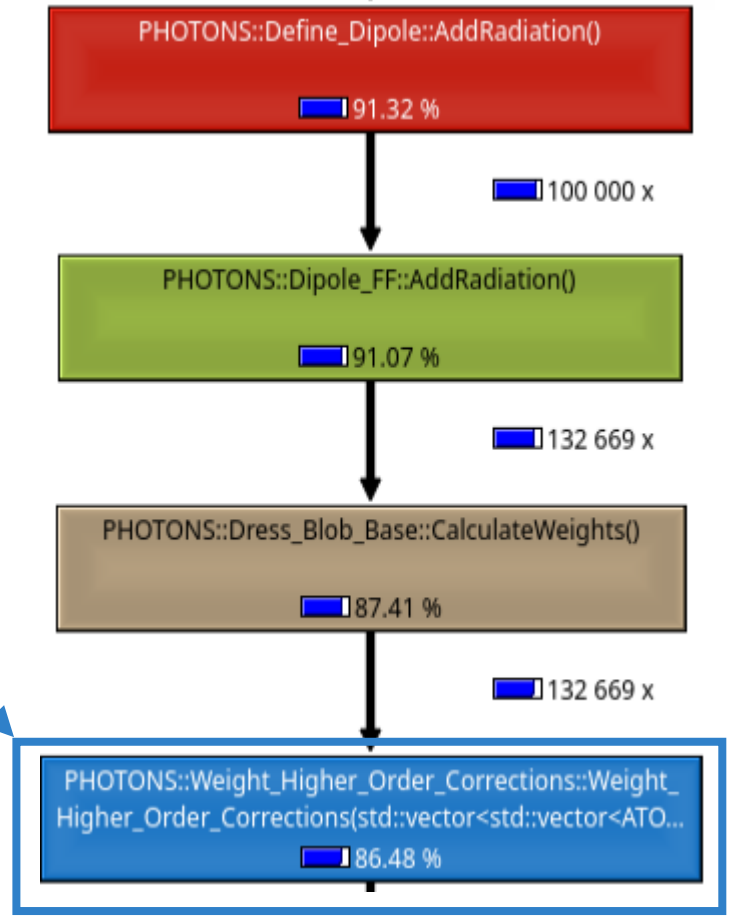


A word on timing

- 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

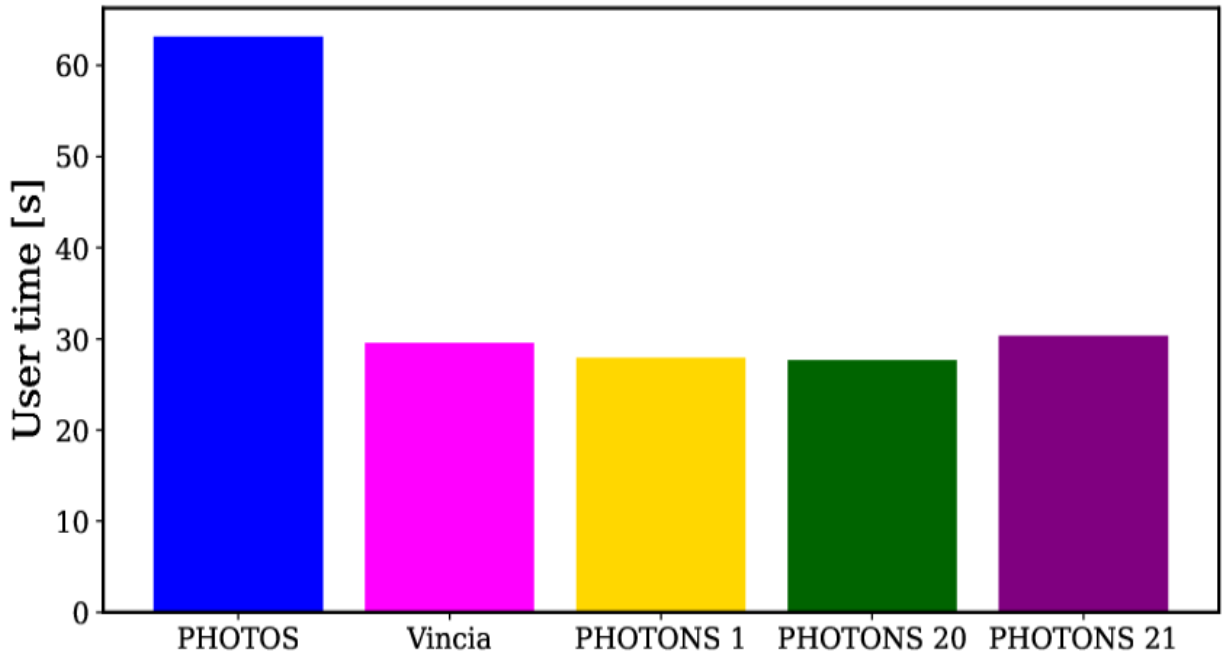
⇒ Good precision/time trade-off for option 20 (will use as default)

⇒ 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

Interface between EvtGen and Sherpa

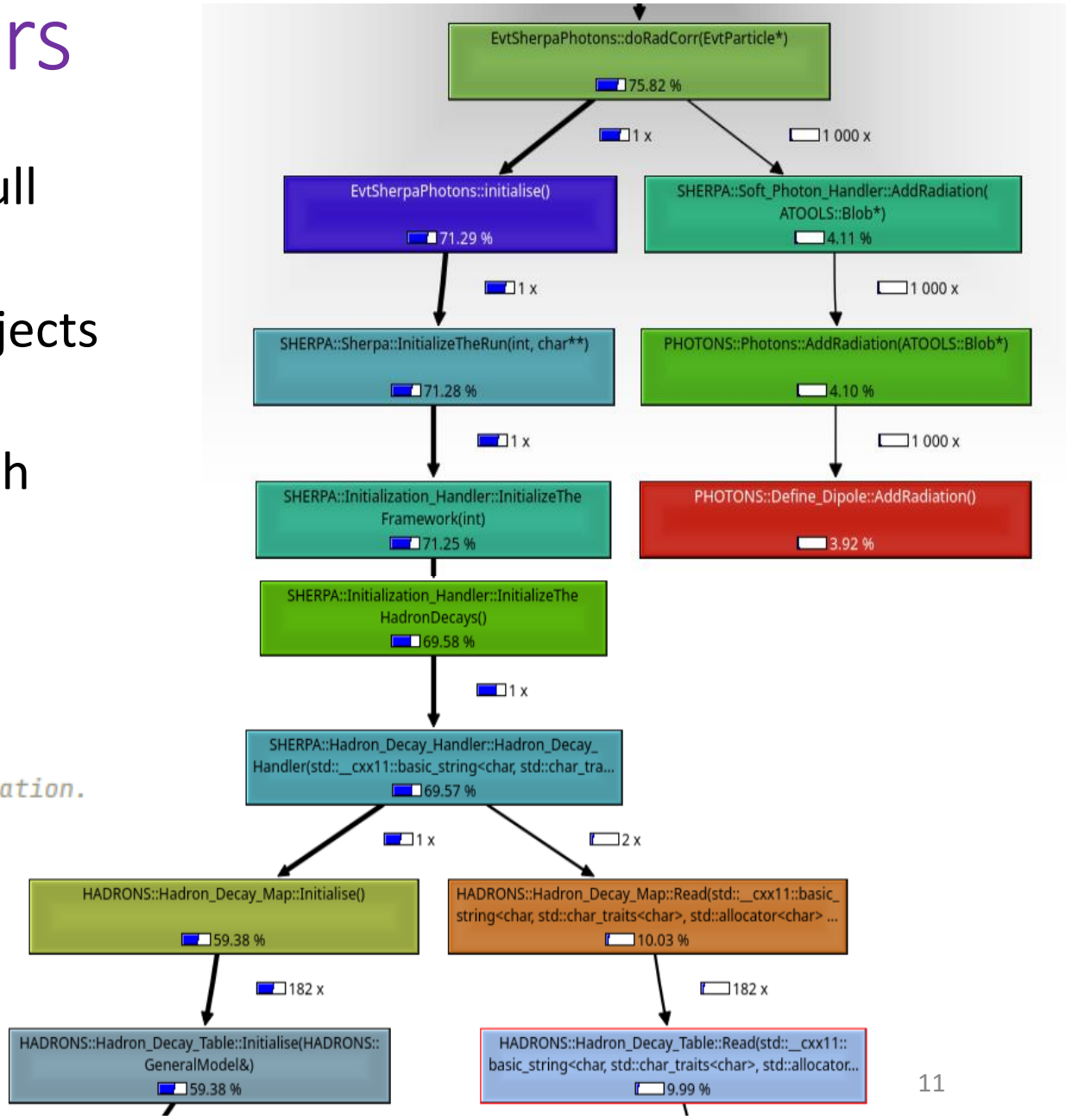
- Included dependency with Sherpa into EvtGen
- Developed EvtGen ↔ Sherpa interface (support Sherpa 2.x.x releases)
- EvtGen particle with its daughters translated into Sherpa blob (and back)
- Updates Sherpa's KF_Table to include custom EvtGen's particles
- Included into master branch and part of next release
- A few aspects need to be ironed out/investigated
  - Use in multi-threaded environment
  - Photon rate in hadronic tau decays seems underestimated
  - Support virtual photon splitting (once Sherpa 3 is out)

Initialisation of afterburners

- For external dependencies EvtGen creates full Pythia/Sherpa objects
- Would be useful to initialise only needed objects (shower/soft-photon handler)
- Example: Sherpa's initialisation takes as much time as $\sim 10^4$ decay events
- Several initialised objects are not used

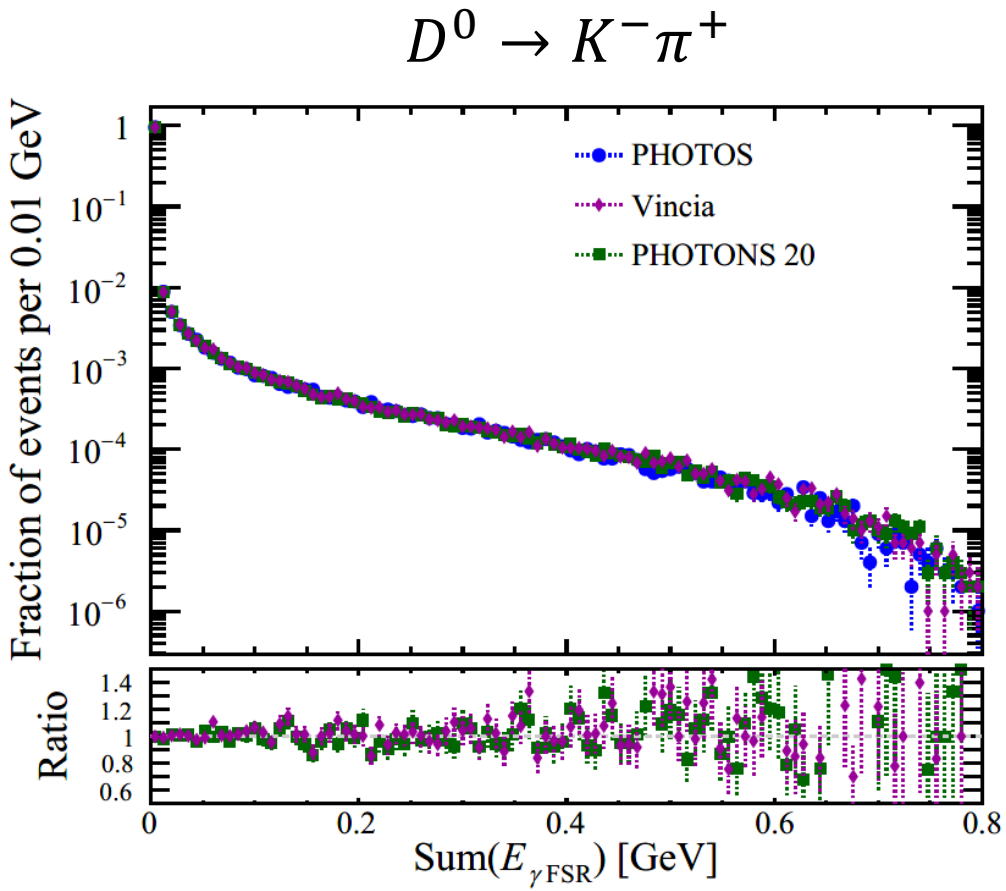
```
// Vector containing the configuration strings for Sherpa
// INIT_ONLY=6 intialises the Sherpa objects without launching simulation.
std::vector<std::string> m_configs{ "Sherpa", "INIT_ONLY=6" };

// Create instance and initialise Sherpa.
m_sherpaGen = std::make_unique<SHERPA::Sherpa>();
m_sherpaGen->InitializeTheRun( argv.size(), &argv[0] );
m_sherpaGen->InitializeTheEventHandler();
```



Ideas for future FSR generation

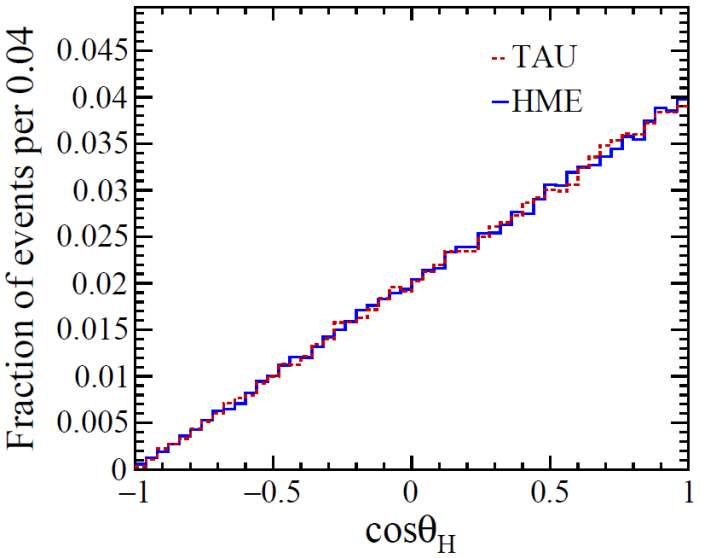
- FSR added by passing decay tree step-by-step (node-by-node) to the FSR generators
- Vincia QED shower (inside Pythia) currently being developed to simulate QED radiation off hadrons
- Prototyped EvtGen ↔ Vincia interface using existing Pythia dependency (step-by-step)
- Idea exists to propagate full decay chain to Vincia to simulate radiation standalone
- Could simulate interference and resonance interleaving effects



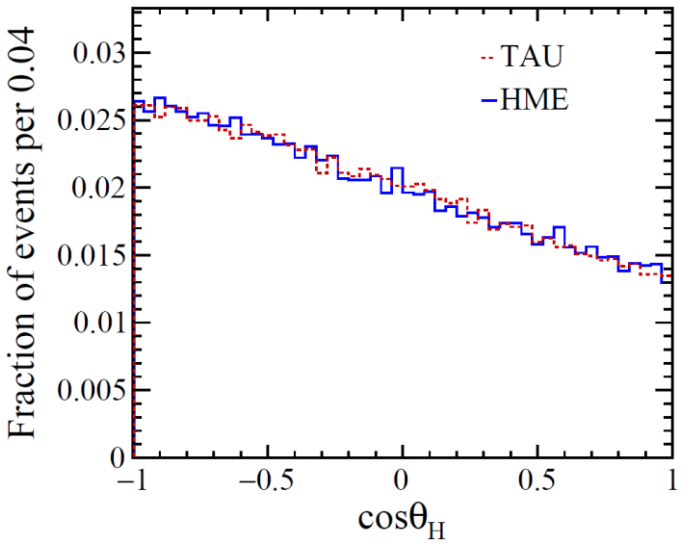
Plugins for τ decays

- EvtGen ↔ 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) amplitude model
- Prototyped EvtGen ↔ Pythia interface propagating spin-density matrix
- Generalisation of helicity/spin basis conversion has been showstopper

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



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



Decay table and custom IDs

- General Decay table does not consider uncertainties in branching fractions
- Each user can have custom general Decay table
- Currently no possibility to provide uncertainty or weighting variation for decays
- Challenges: Inconsistencies, PDG BFs not adding up to 1, theory uncertainties (form factors, etc)
- Particle ID standards: some particle IDs used in EvtGen are outside the standard range

Example from general Decay table

```
Decay B0
#
# b -> s gamma
#
0.0003118   Xsd    gamma     BTOXSGAMMA 2 ;
#
Decay Xsd
1.00000 d anti-s PYTHIA 42;
Enddecay
```

Summary and discussion

EvtGen

- FSR: introduced new alternative using Sherpa's PHOTONS++
- FSR: envisaged plans for full decay-chain propagation with Vincia
- τ decays: explore Sherpa as alternative, check interface between HERWIG EvtGen

General

- Possibility of a "bidirectional" API between main generator and specialist afterburners?