

Studies on final state radiation

Final-state radiation team

Fernando Abudinén, Giacomo Morgante, Peter Skands

EvtGen team

Fernando Abudinén, Michal Kreps, Thomas Latham, John Back

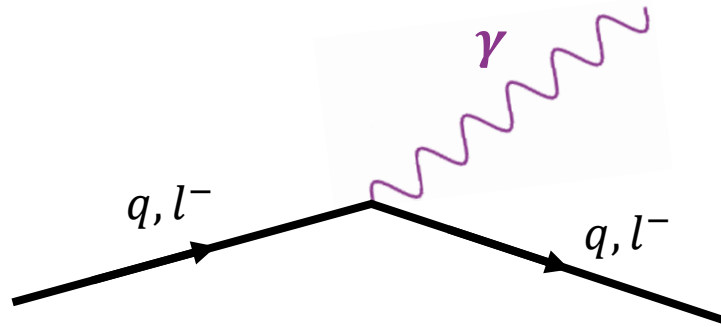


MONASH
University

MWAPP meeting
March 17, 2025



Final-state radiation in decays

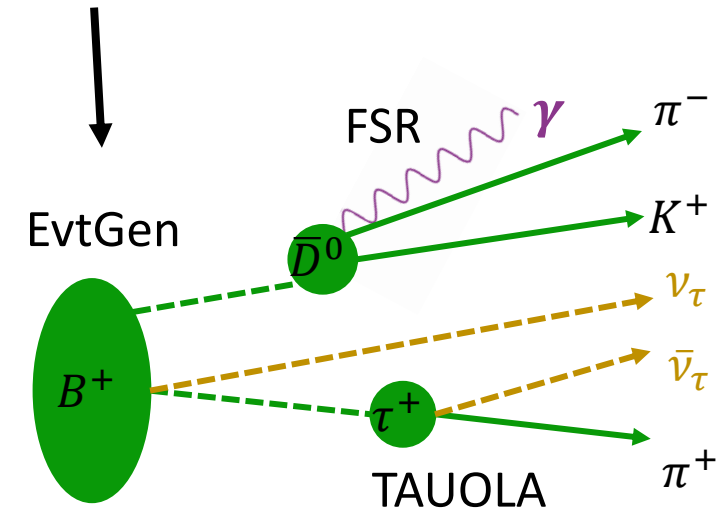
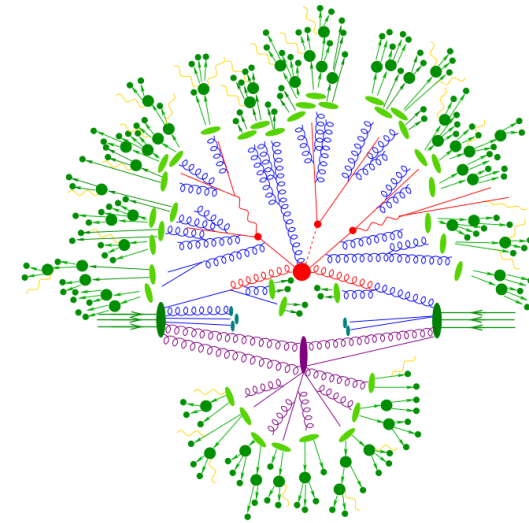


- Studied using specialised simulation generators (plugins)
- EvtGen generator relies on [PHOTOS](#) or [PHOTONS++](#) generators

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

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

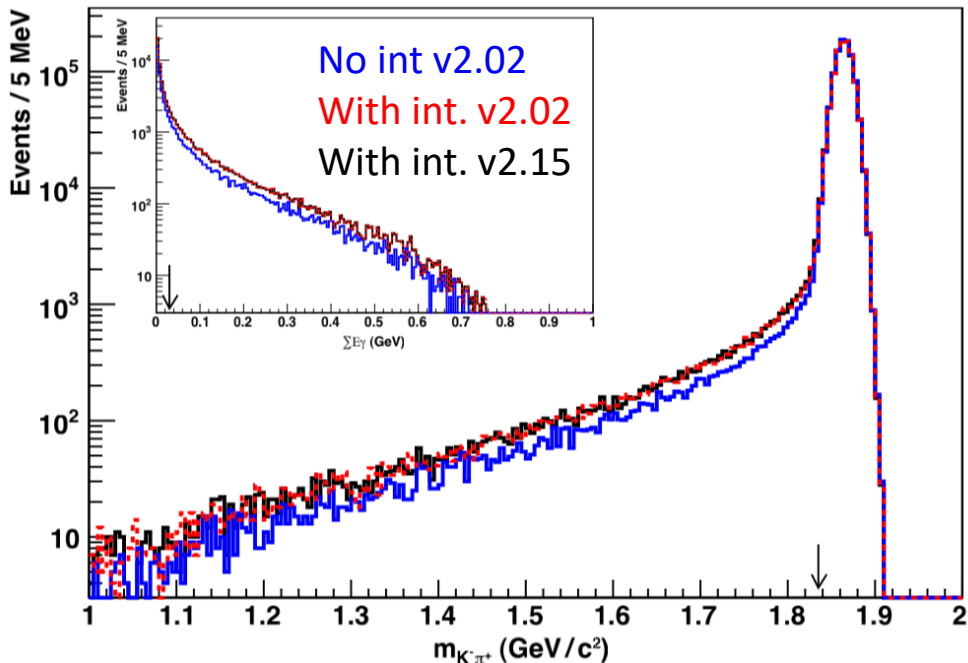
Example collision
simulated by PYTHIA8



Motivation

- Find alternatives to exploit multi-threading
- Find alternatives to study systematic effects
- ⇒ Especially those associated with interference effects

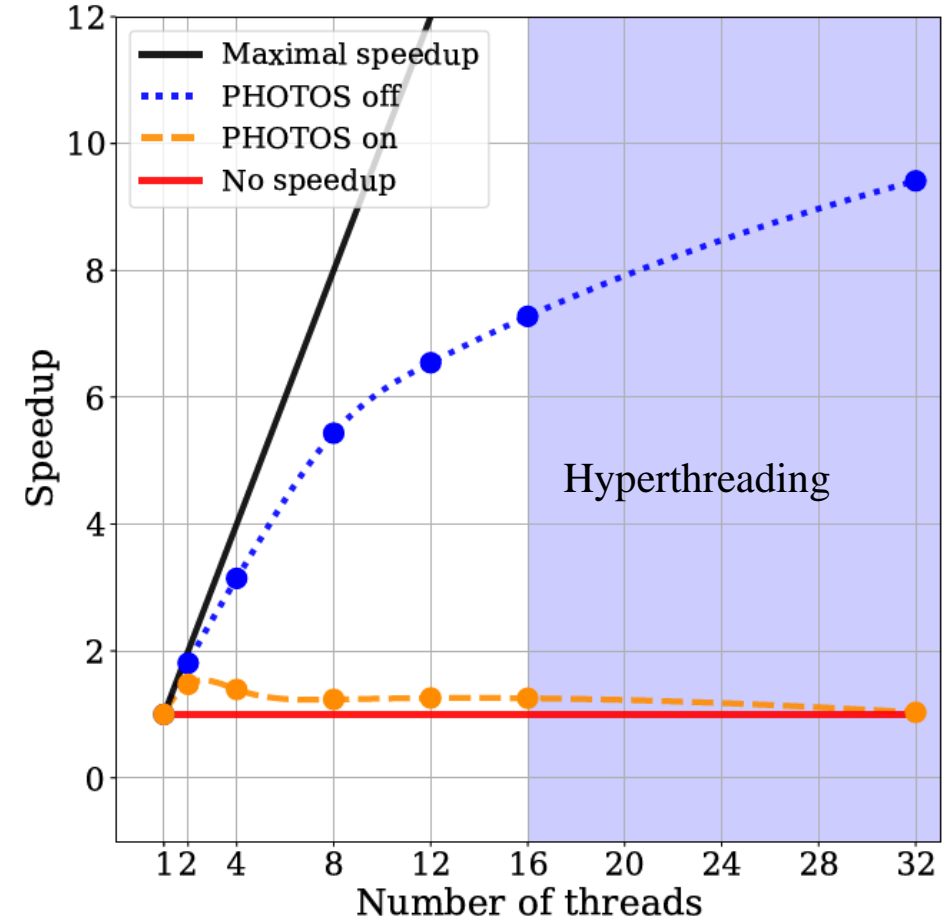
$D^0 \rightarrow K^+ \pi^-$ simulation with PHOTOS



See [HFLAV](#) Sec 11.3

$$\begin{aligned}
 \mathcal{B}(D^0 \rightarrow K^- \pi^+) &= (3.999 \pm 0.006 \pm 0.031 \pm 0.032) \%, \\
 \mathcal{B}(D^0 \rightarrow \pi^+ \pi^-) &= (0.1490 \pm 0.0012 \pm 0.0015 \pm 0.0019) \%, \\
 \mathcal{B}(D^0 \rightarrow K^+ K^-) &= (0.4113 \pm 0.0017 \pm 0.0041 \pm 0.0025) \%.
 \end{aligned}$$

EvtGen simulation



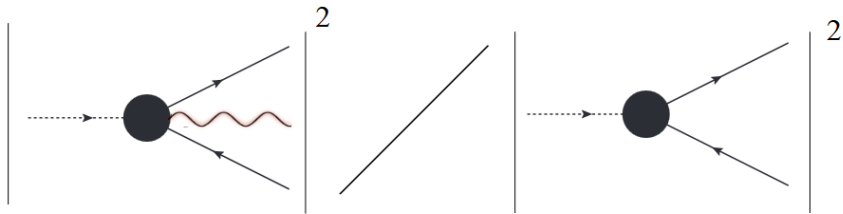
stat. syst. FSR

Final-state radiation generators

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

$$d\Gamma^{\text{radiative}} = d\Gamma^{\text{Born}} f(\Phi) d\Phi \quad \Phi: \text{Phase-space of photons}$$

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



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

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

$$\frac{2s_{e^-e^+}}{s_{e^-}\gamma s_{\gamma e^+}}$$

From [talk](#) by Peter Skands

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)

PHOTOS for FSR

PHOTOS Interface in C++

Comput. Phys. Commun. **199**, 86 (2016) [arXiv:1011.0937](https://arxiv.org/abs/1011.0937)

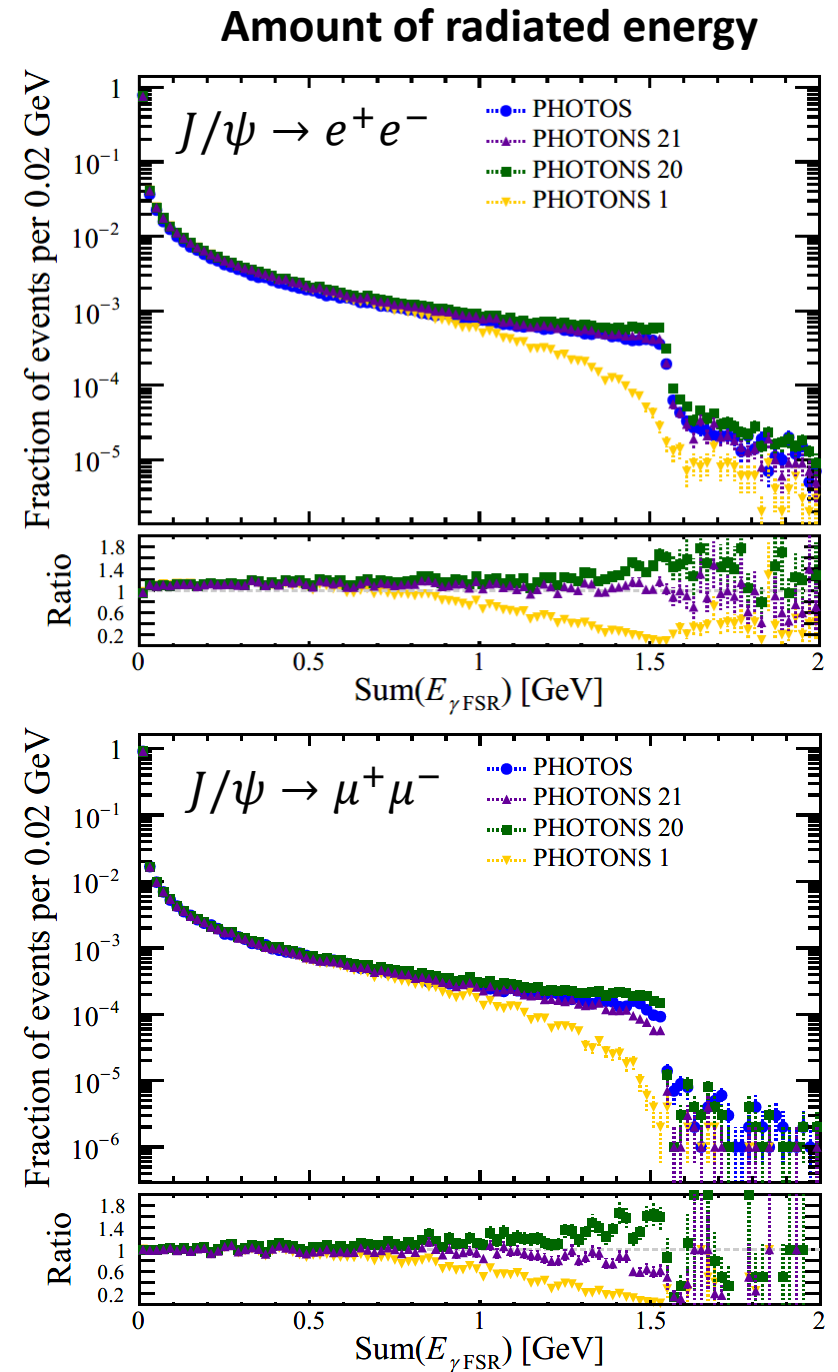
For a long time, PHOTOS Monte Carlo [1, 2] has been used for the generation of bremsstrahlung in the decay of particles and resonances. Over the years the program has acquired popularity and it evolved into a high precision tool [3]. Since 2005, when multi-photon radiation was introduced [4] into the program (version 2.15), there were no further public upgrades of the program until 2010. The efforts were concentrated on documentation and new tests; phase space treatment was shown to be exact [5] and for several processes [3, 5, 6] an exact matrix element was studied with the help of optional weights. Benchmark distributions, including comparisons with other simulation programs, were collected on the MC-TESTER [7] (special program devoted to tests) web page [8]¹.

- [3] $e^+e^- \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-(\gamma)$ [Eur. Phys. J. C **50**, 53–62 \(2007\)](#)
- [5] $B \rightarrow K\pi(\gamma)$ [Eur. Phys. J. C **51**, 569–583 \(2007\)](#)
- [6] $W \rightarrow l\nu$ and $\gamma^* \rightarrow \pi^+\pi^-$ [Eur. Phys. J. C **70**, 673–688 \(2010\)](#)

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

See talk by Giacomo

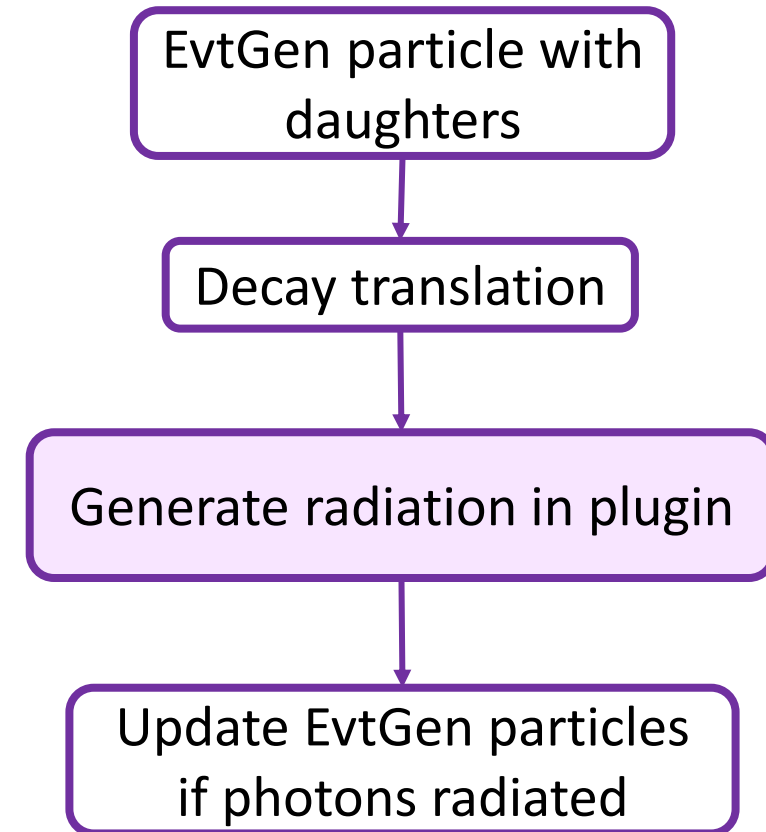
Technical aspects

- Vincia is embedded in Pythia8
 - Algorithm implementation enables thread safety
 - Developed EvtGen ↔ Vincia interface based on existing dependency with Pythia8
- ⇒ Not in EvtGen release yet (needs Vincia in Pythia8 release)

Interfaces between EvtGen and Plugins

- EvtGen objects translated
 - Into intermediate HepMC events (for PHOTONS)
 - 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 \Rightarrow **mutex**
 - Need to mutex also HepMC translation (for PHOTOS)

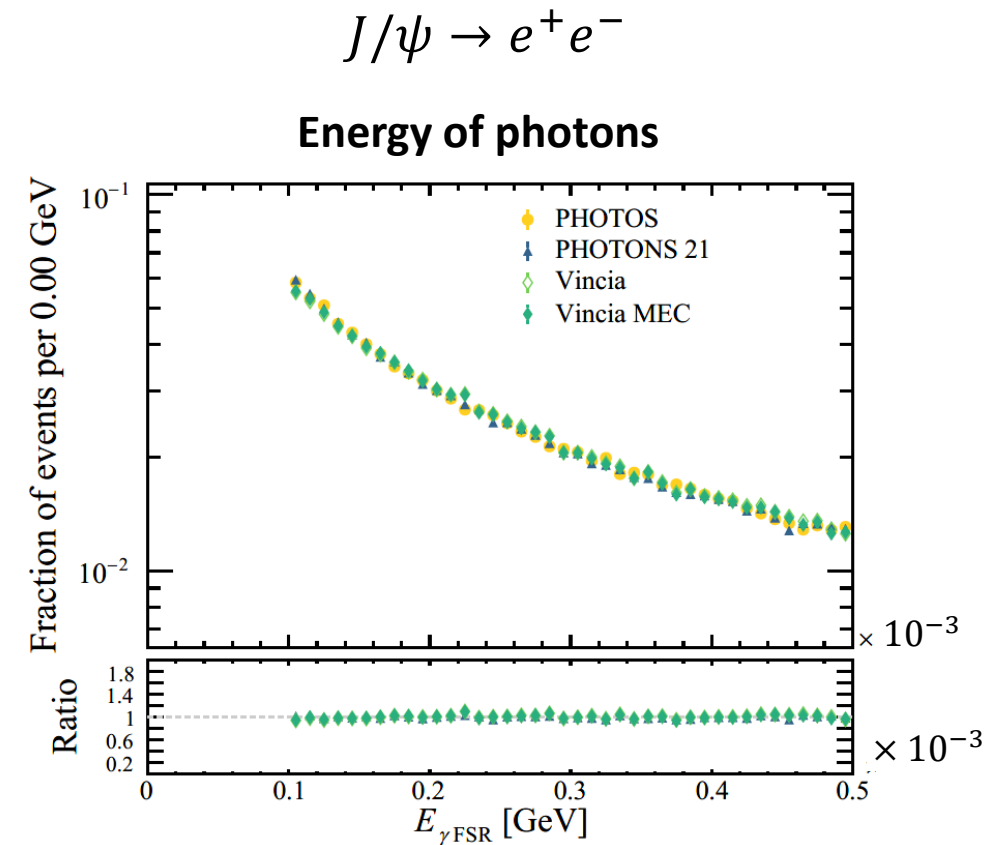
Workflow



Review (for Sherpa) by Marek Schönherr and Frank Krauss

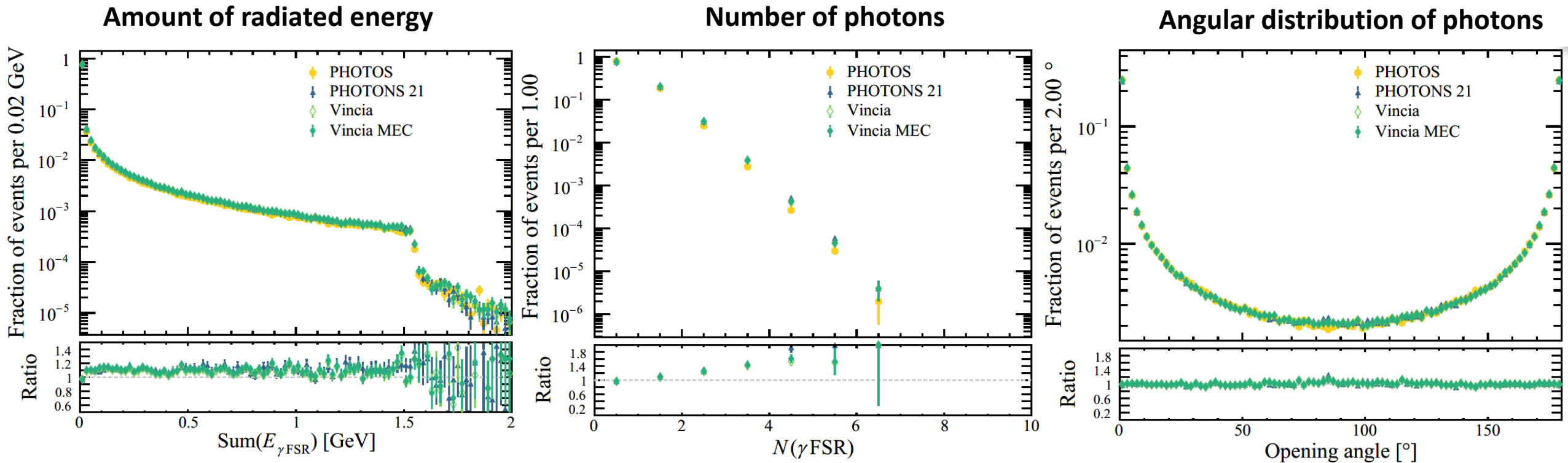
Comparisons across generators

- Compare PHOTOS, PHOTONS++ with Vincia simulation with/out MEC
 - Equalize photon pT(Energy) cutoff value (0.1 keV)
 - Fill histograms only if photon energy above 0.1 MeV
- Vincia MECs obtained from [Madgraph](#)
 - Currently generated manually for specific decays
- Compare CPU consumption and multithread speedup



Comparisons between generators

$$J/\psi \rightarrow e^+e^-$$

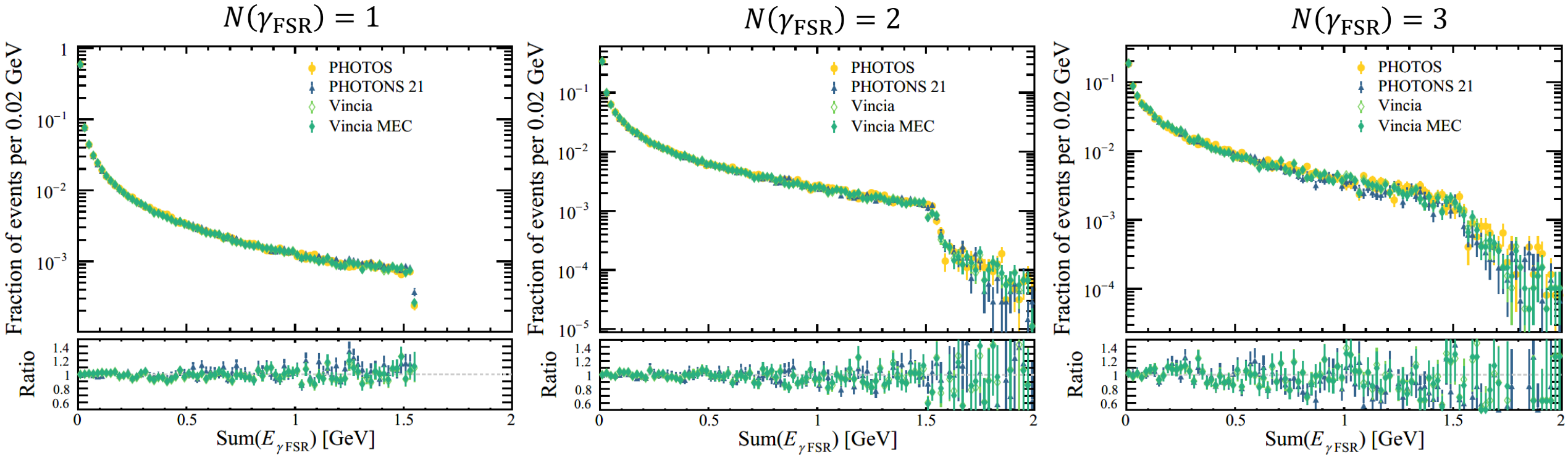


- Good agreement (within $\sim 10\%$) for energy and angular distributions
- All generators radiate more photons than PHOTOS

Comparisons between generators

$$J/\psi \rightarrow e^+e^-$$

Amount of radiated energy

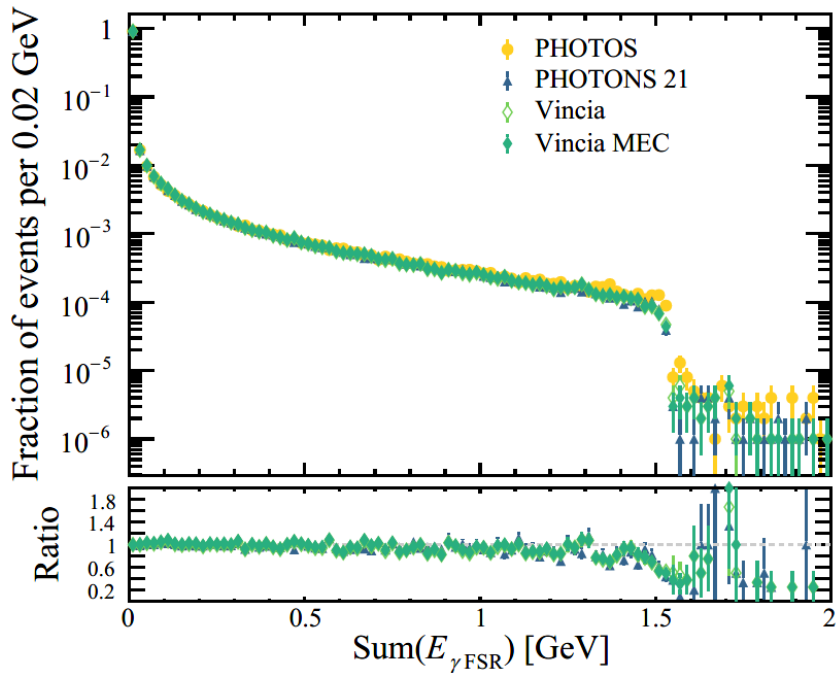


- Energy range above $M_{J\psi}/2$ kinematically accessible for events with more than one photon

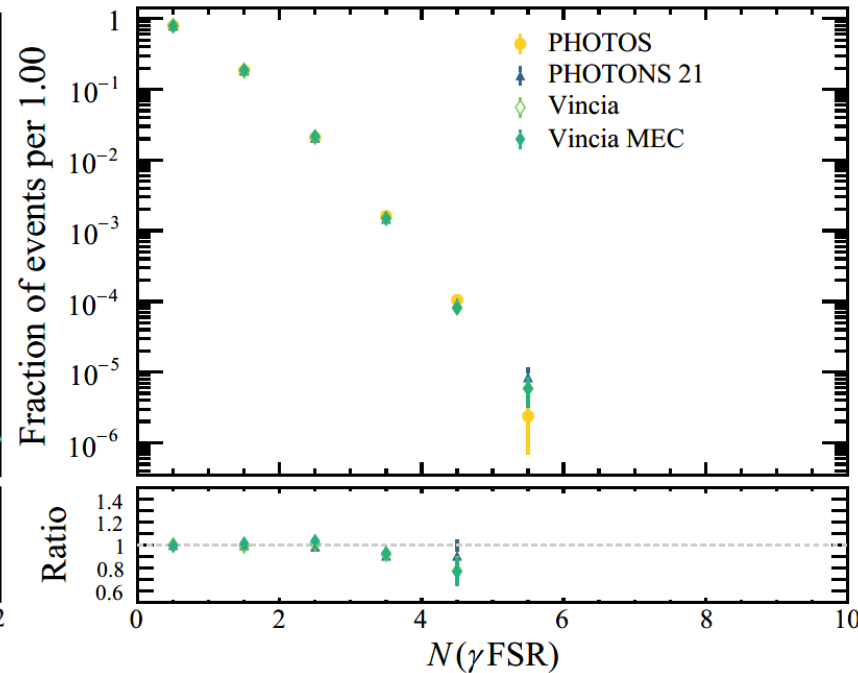
Comparisons between generators

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

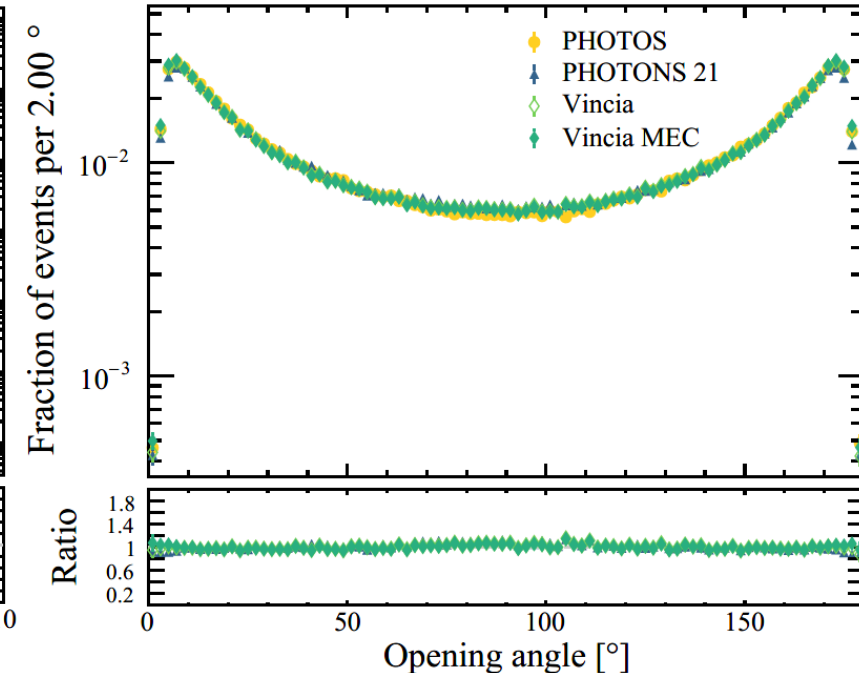
Amount of radiated energy



Number of photons



Angular distribution of photons

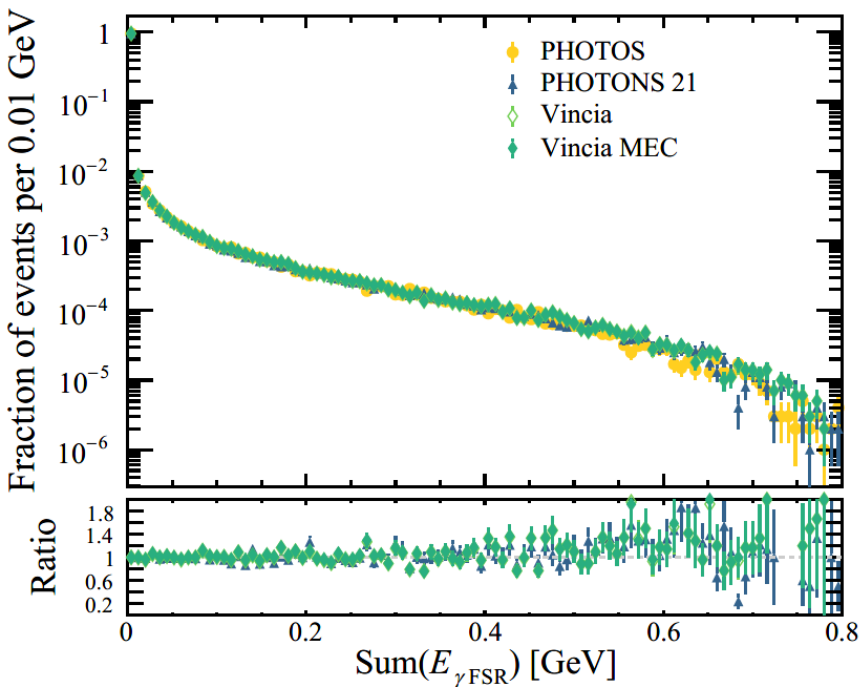


- Good agreement for all distributions

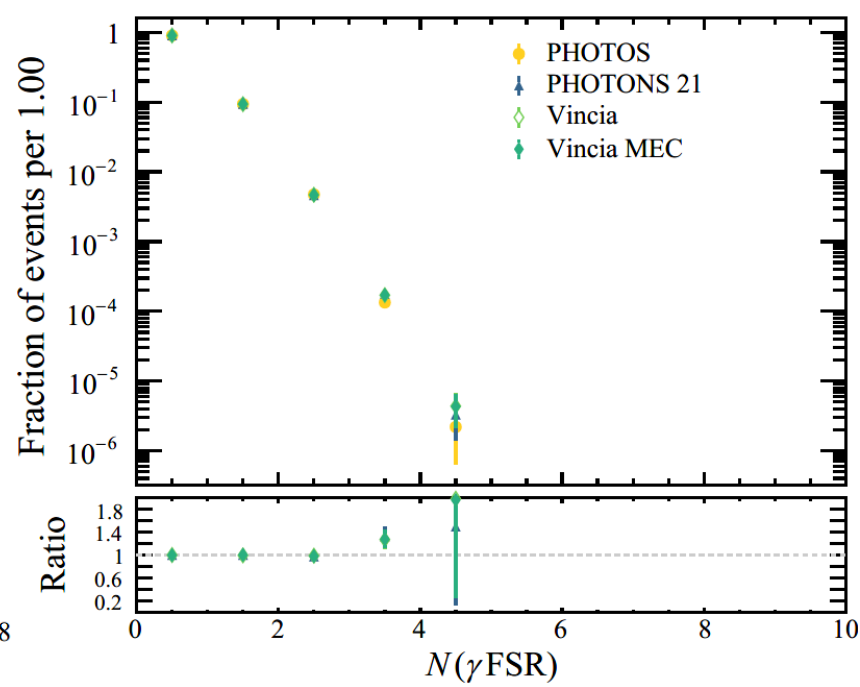
Comparisons between generators

$$D^0 \rightarrow K^- \pi^+$$

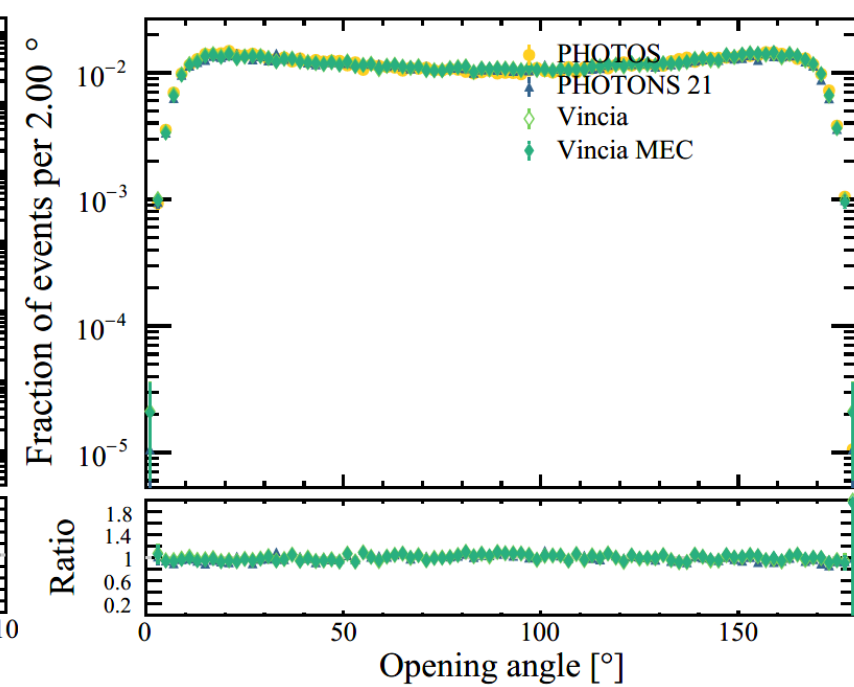
Amount of radiated energy



Number of photons



Angular distribution of photons

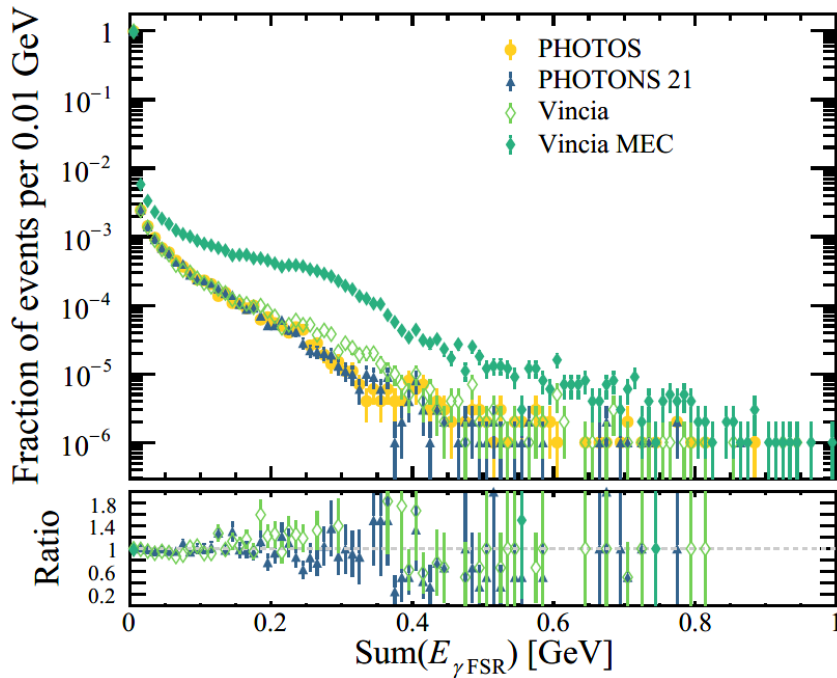


- Good agreement among generators

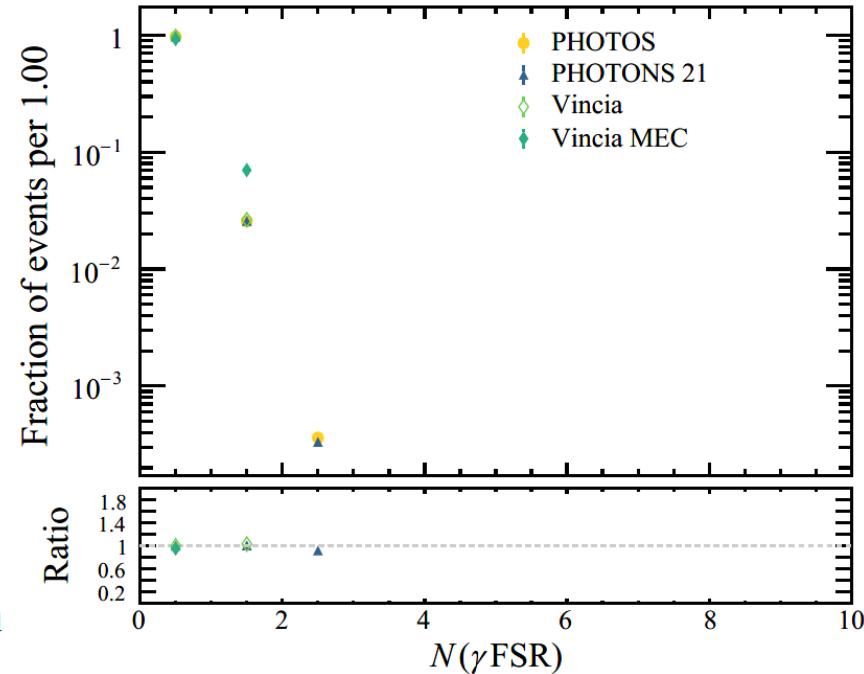
Comparisons between generators

$$\rho^+ \rightarrow \pi^+ \pi^0$$

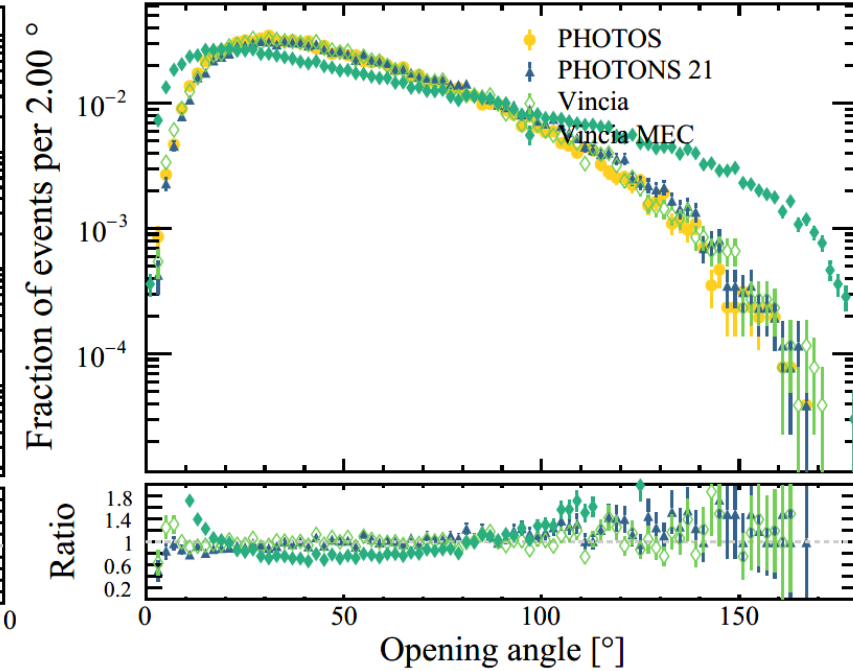
Amount of radiated energy



Number of photons



Angular distribution of photons

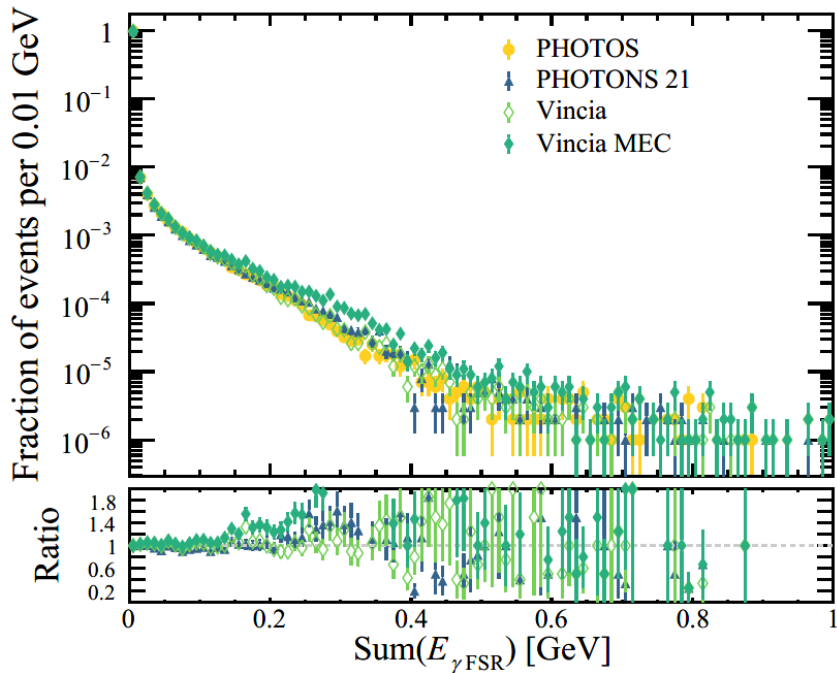


- Angular distribution and effect of MEC to be understood

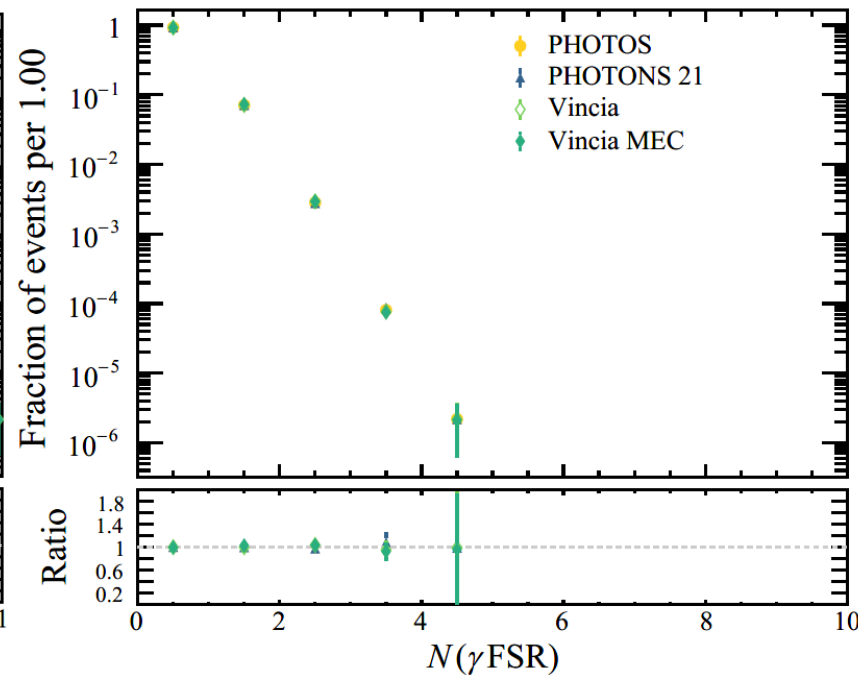
Comparisons between generators

$$\rho^0 \rightarrow \pi^+ \pi^-$$

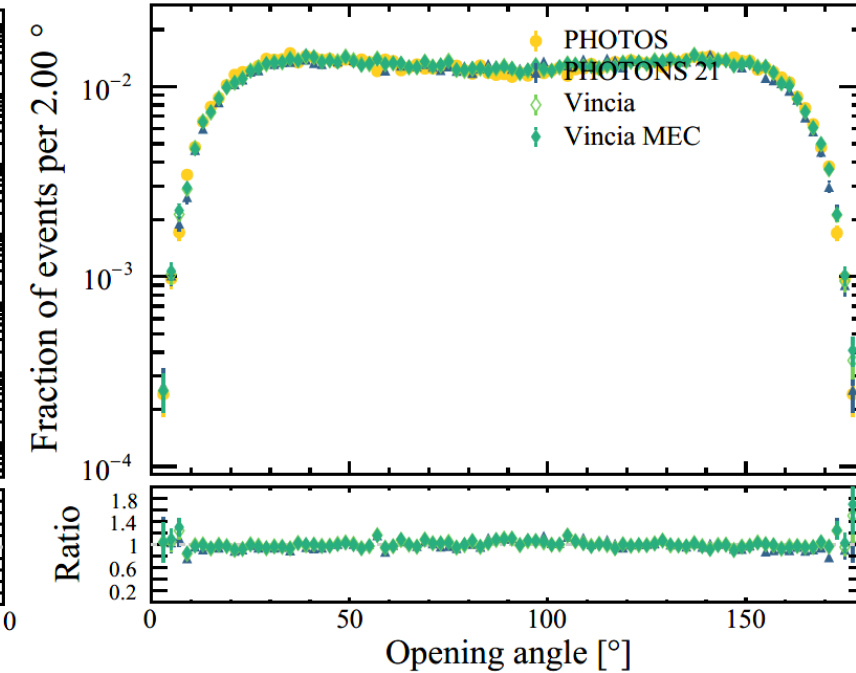
Amount of radiated energy



Number of photons



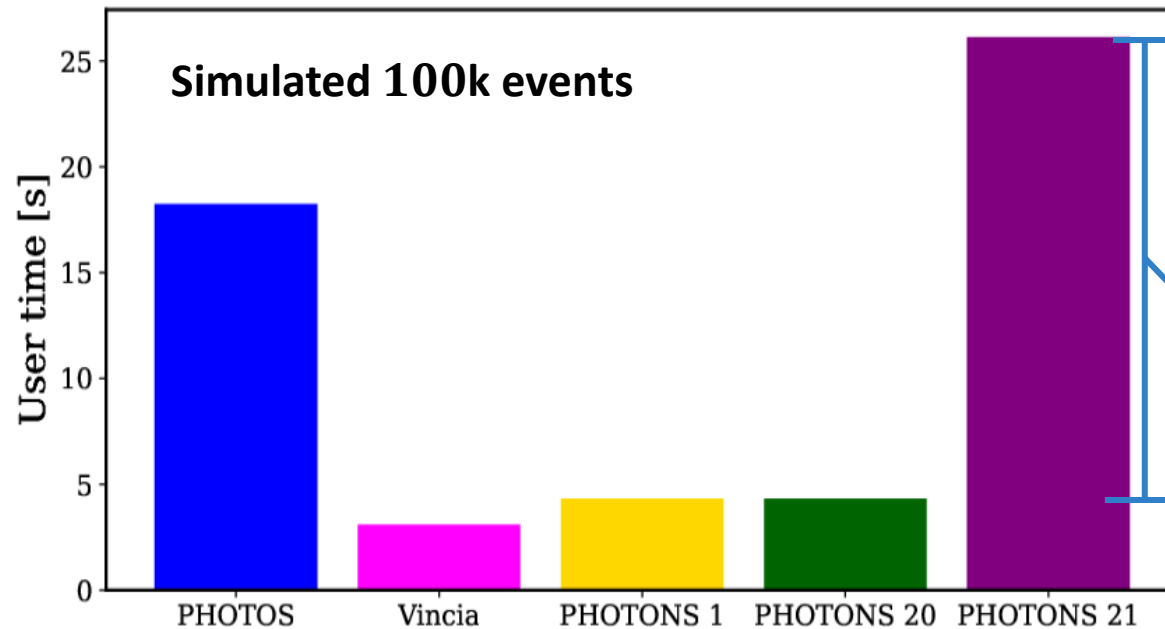
Angular distribution of photons



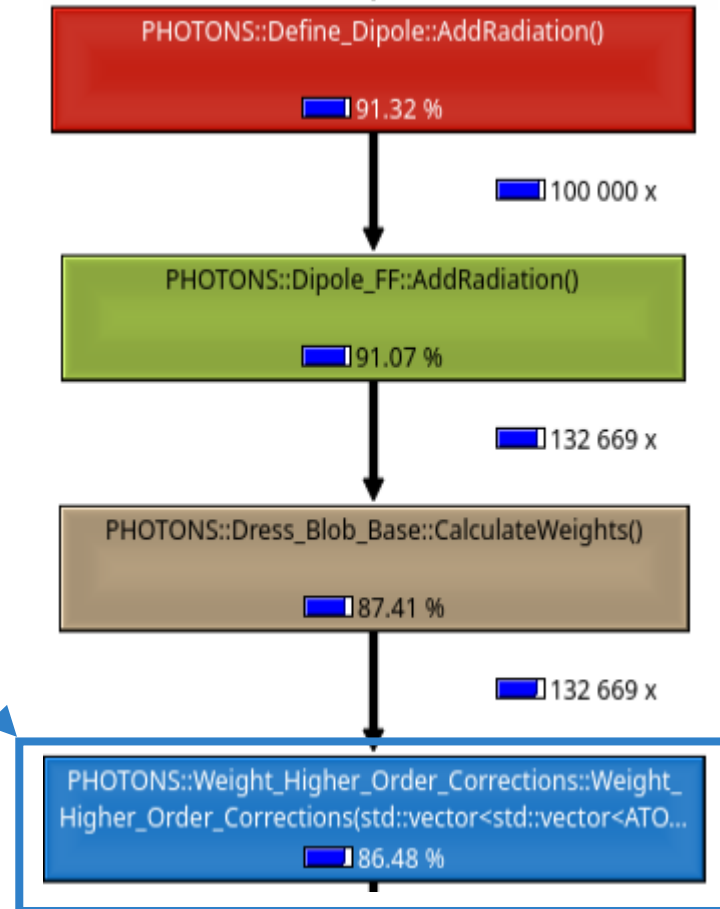
- Generally good agreement among generators
- Larger effect of MEC on tail

A word on timing

- Compare simulation time using $J/\psi \rightarrow e^+e^-$ decay as benchmark
- ⇒ Collinear singularities enhanced due to small electron mass

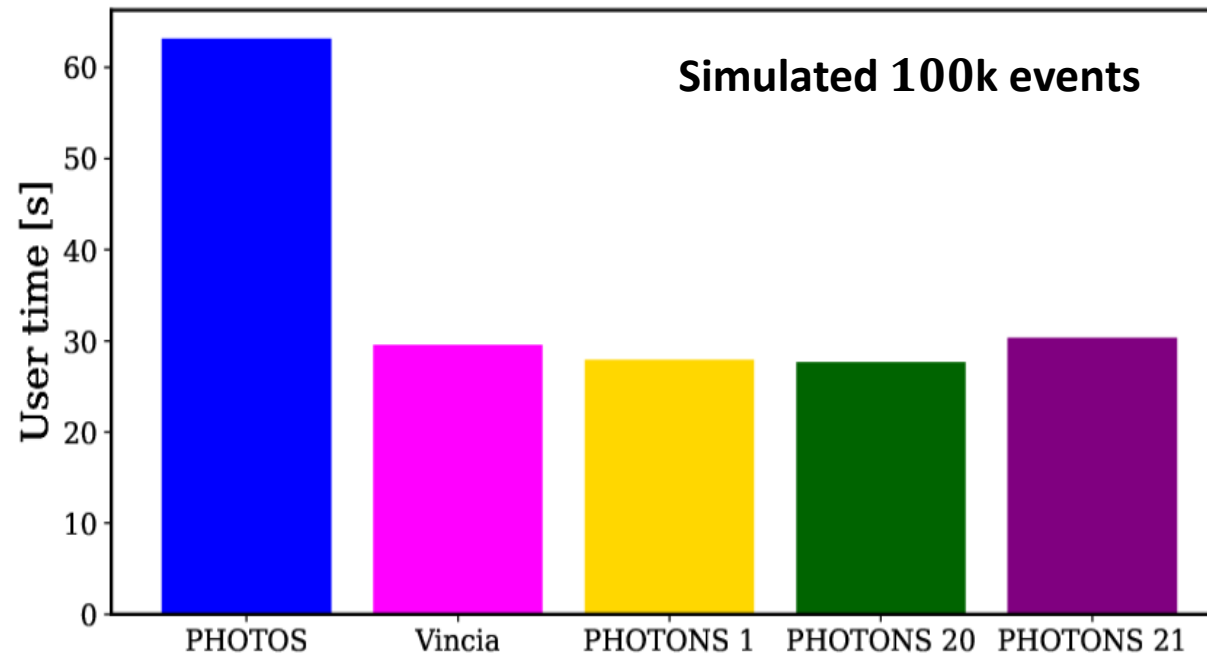


- ⇒ Largest consumption by exact matrix-element calculation
- ⇒ Good precision/time trade-off for option 20 (will use as default)
- ⇒ Potential speedup using Vincia or PHOTONS by about factor 4



Another word on timing

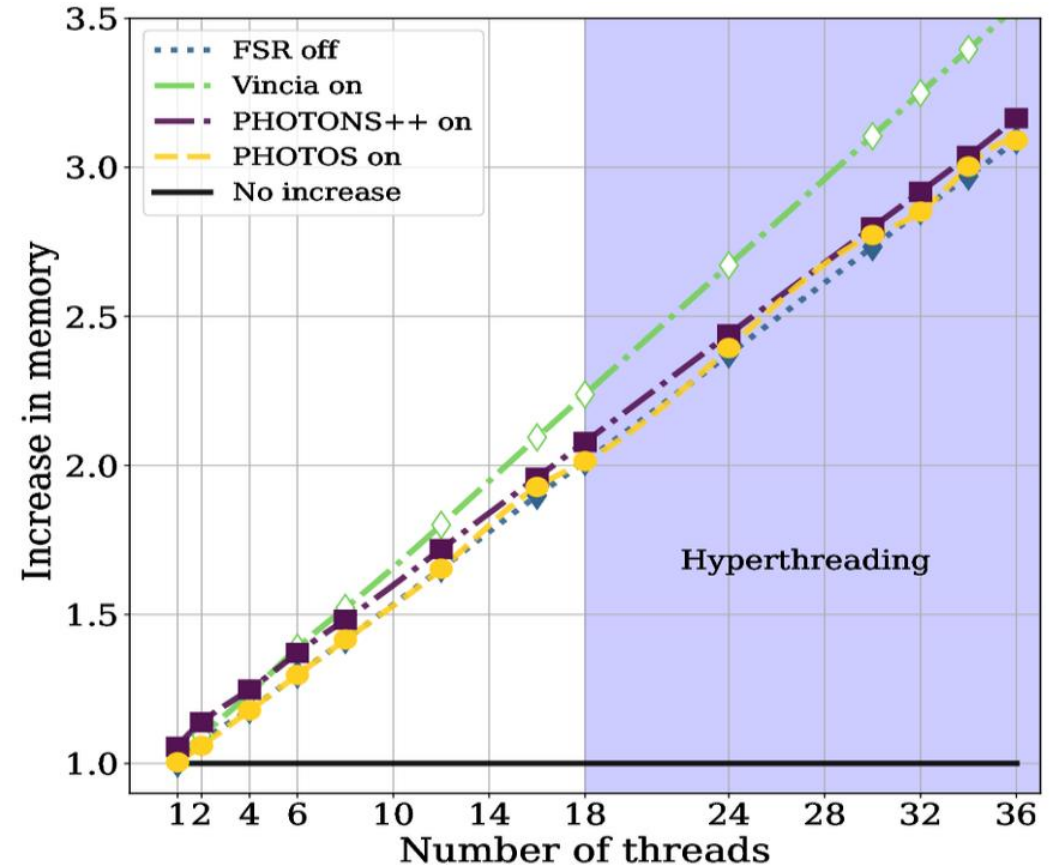
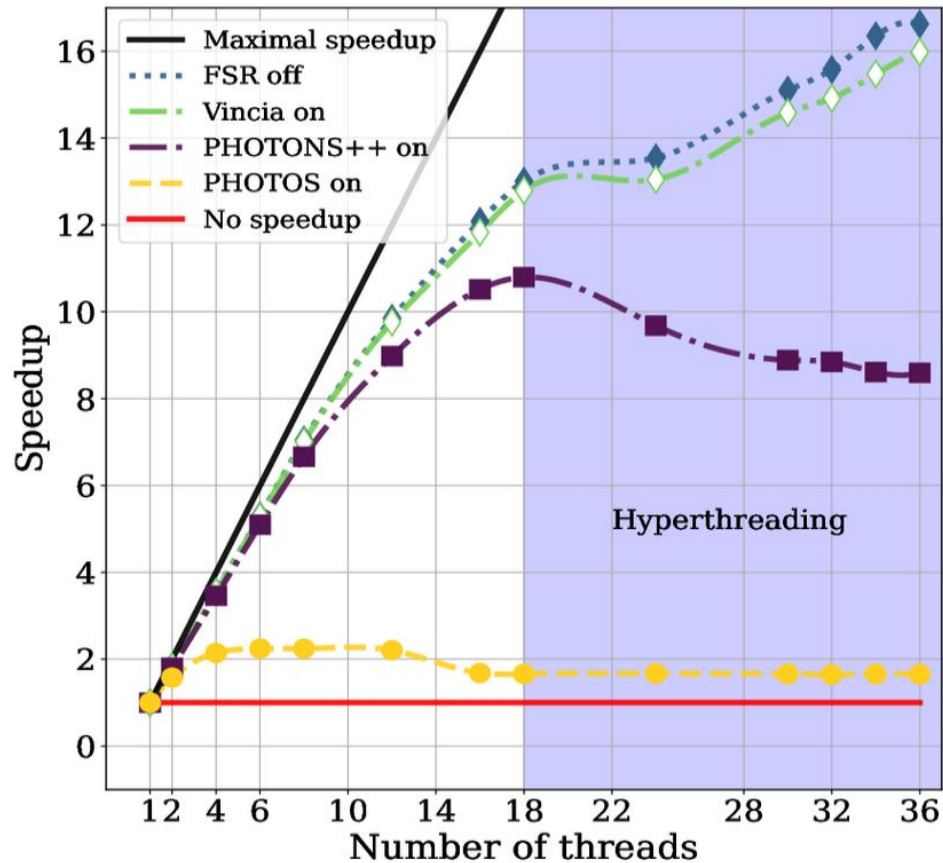
- Compare simulation time when simulating generic $\Upsilon(4S) \rightarrow B\bar{B}$
⇒ Benchmark for general use



- ⇒ No large difference between PHOTONS options in generic case
- ⇒ Potential speedup using Vincia or PHOTONS by about factor 2 (even with MEC)

Checks with vincia-qed branch

$$B_S^0 \rightarrow \phi(\rightarrow K^+ K^-)\mu^+ \mu^-$$



⇒ Best performance with Vincia!

⇒ All tests passed with multi-threading without mutexing

Interleaving of FSR

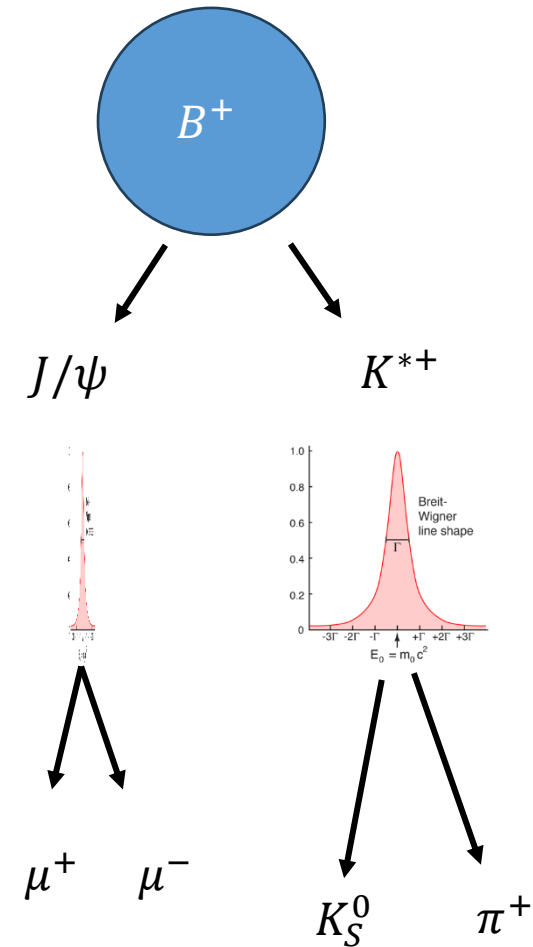
Conventional FSR simulation

- Treat decay nodes sequentially
- Assume all particles have narrow widths

In a time evolution, photons can resolve resonances for $E_\gamma < \Gamma$

- ⇒ Effect kicks in for offshell resonances
- ⇒ Can distort resonance shape in regions far from pole (tails)
- ⇒ Can give rise to interference effects
- ⇒ Will affect kinematic distribution of final-state particles
- ⇒ Not considered in conventional approach

- Vincia can simulate the interleaving if provided with full decay chain



Effect more relevant for resonances with large widths

Summary and outlook

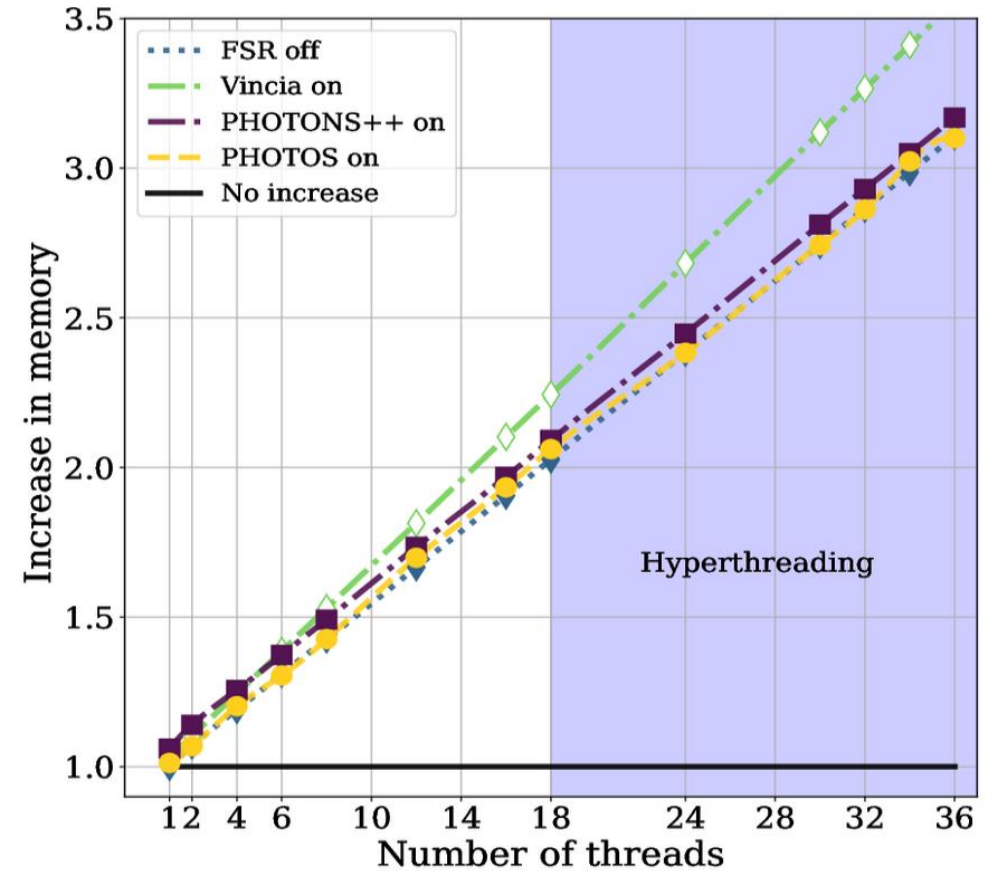
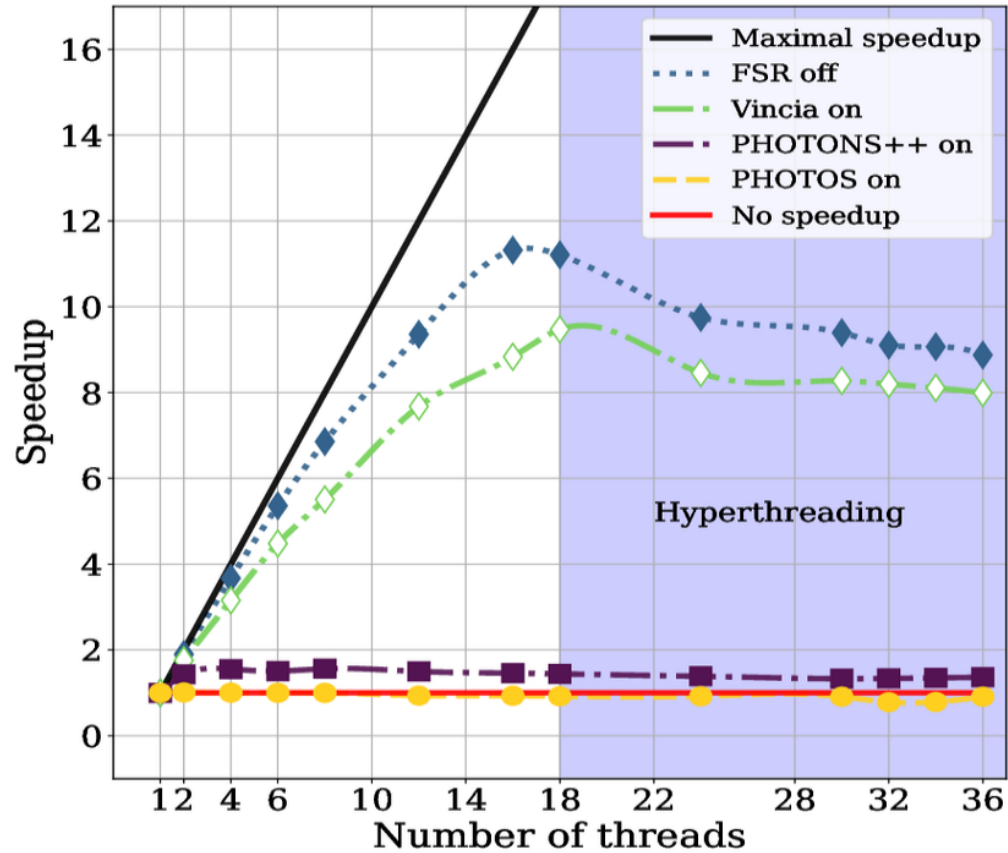
- Implemented Sherpa PHOTONS++ as FSR alternative
 - ⇒ Validation shows good agreement between generators
 - ⇒ Speed-up $\sim 2 \times$ PHOTOS (single-threaded)
 - ⇒ Part of [R03-00-00-beta1](#)
 - Developed EvtGen \leftrightarrow Vincia interface
 - ⇒ First physics validation shows good agreement
 - ⇒ Efficient use of multi-threading
 - ⇒ Currently developing and validating ME corrections
 - ⇒ Plan to work on implementation of interleaving
 - ⇒ Study virtual photon splitting $\gamma^* \rightarrow \ell\ell(hh)$
 - EvtGen and Vincia journal articles
 - Vincia merge-request into Pythia8
- } In preparation

Backup

Checks with vincia-qed branch

$$J/\psi \rightarrow e^+e^-$$

StdLib



⇒ Best performance with Vincia!