Vincia

An Antenna approach for final-state radiation

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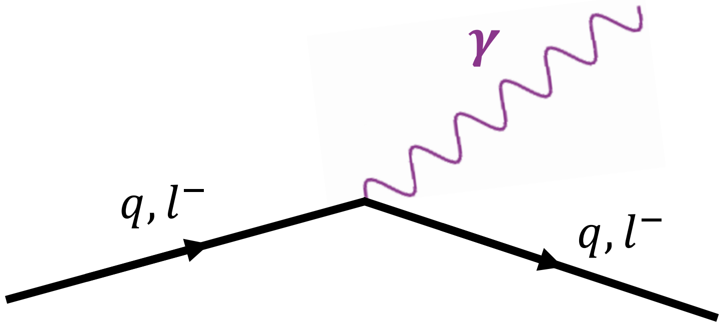
European Physical Society
High-Energy Physics
EPS-HEP conference
July 11, 2025

MONASH University

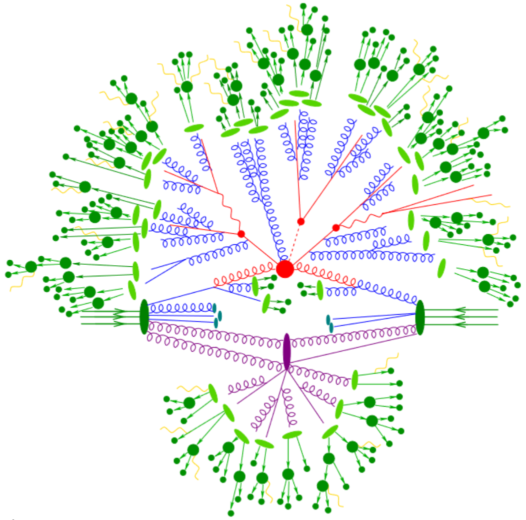
Overview

- Simulation generators
- Theory in a nutshell
- Validation studies
  - $J/\psi \to e^+e^-,\ \mu^+\mu^-$
  - $D^0 \to K^-\pi^+,\ \pi^+\pi^-,\ K^+K^-$
  - $D^+ \to \pi^+\pi^-\pi^+$
- Next steps, interleaving

Final-state radiation in decays



Example collision simulated by PYTHIA8



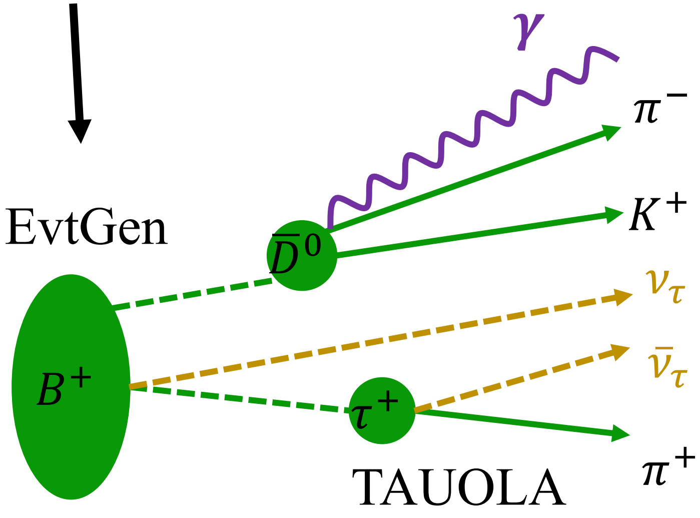
FSR

- Studied using specialised simulation generators (plugins)
- EvtGen: generator specialised in decays of charm and beauty hadrons

⇒ relies on PHOTOS, PHOTONS++, and Vincia generators

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

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



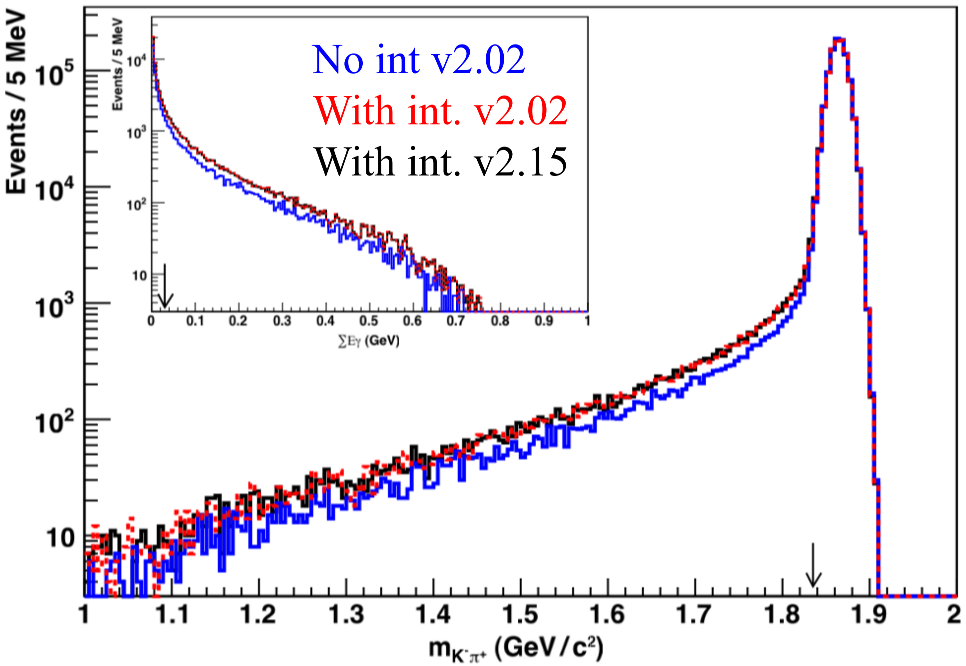
Motivation

- Find alternatives to study systematic effects

$\Rightarrow$ Especially those associated with interference effects

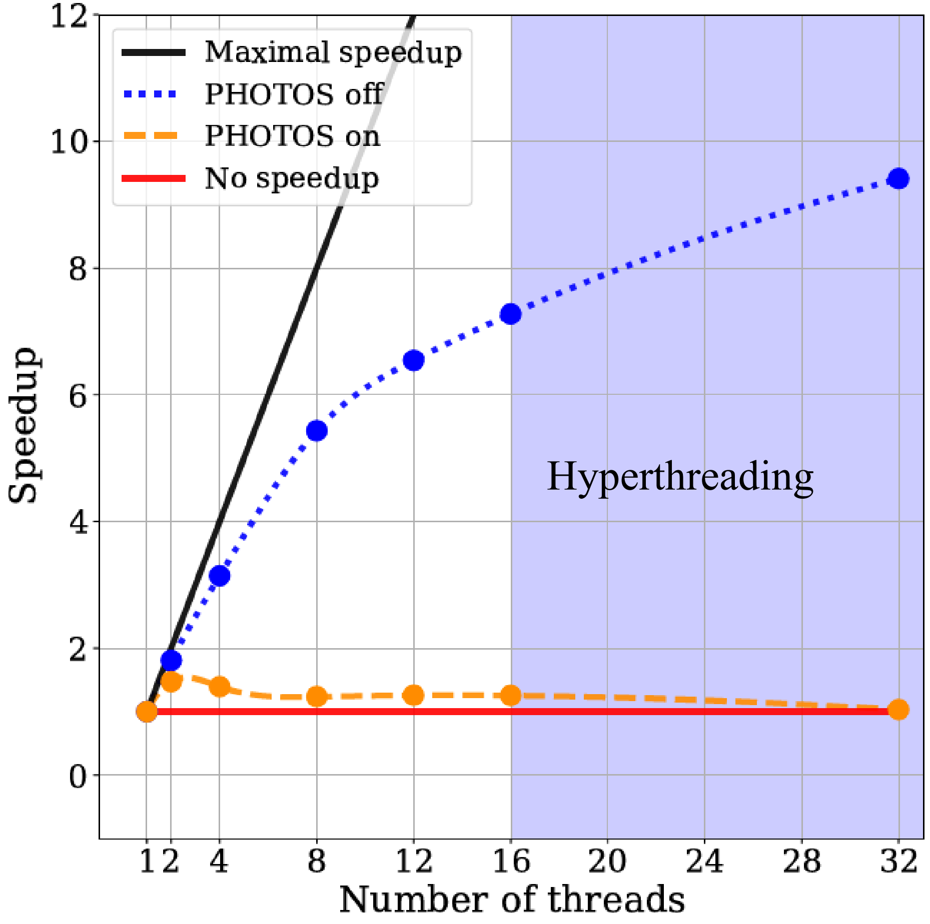
- Find alternatives to exploit multithreaded processing

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



See HFLAV Sec 11.3

EvtGen simulation



		stat.	syst.	FSR

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

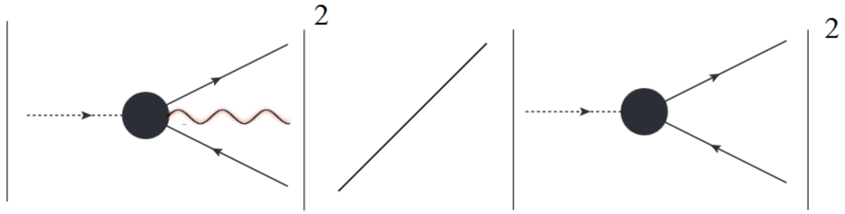
Theory approaches in a nutshell

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

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

Φ: Phase-space of photons

- Example (oversimplified): neutral scalar → e^+e^- (single QED dipole)



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

eikonal term — collinear terms

LO QED

$s_{ij} = 2\,p_i \cdot p_j$
Dot product of 4-momenta

e^--collinear limit — e^+-collinear limit — All Singular Terms — Soft limit

PYTHIA, PHOTOS
DGLAP

$$\frac{P_{e^-\to e^-\gamma}(z_1)}{s_{1\gamma}} + \frac{P_{e^+\to e^+\gamma}(z_2)}{s_{2\gamma}}$$

VINCIA
Antenna

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

HERWIG, SHERPA
YFS

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

Generators: add photons based on $f(\Phi)$

Final-state radiation generators

PHOTOS Barberio-Was 1991, Nanava-Was 2007, Davidson-Przedzinski-Was 2015

- Based on collinear approximation (LO), determines sets of dipoles (assuming spin-1/2)
- Soft (interference) effects and spin dependence through correction weight (NLO for scalar decays)

YFS Yennie-Frautschi-Suura 1961, Krauss-Schönherr 2008 **(basis for Herwig and Sherpa's PHOTONS++)**

- Takes full (multipole) soft interference effects into account
- Scalar QED $\Rightarrow$ spin dependence through Matrix-Element corrections to NLO

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

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

Parton shower concept

Differential probability

$$\frac{\mathrm{d}P^{\mathrm{rad}}}{\mathrm{d}p_\perp^2} = f(p_\perp^2)\ \Delta(p_\perp^2, p_\perp'^2)$$

Splitting function

Sudakov form factor
≙ probability of no radiation
between evolution scales

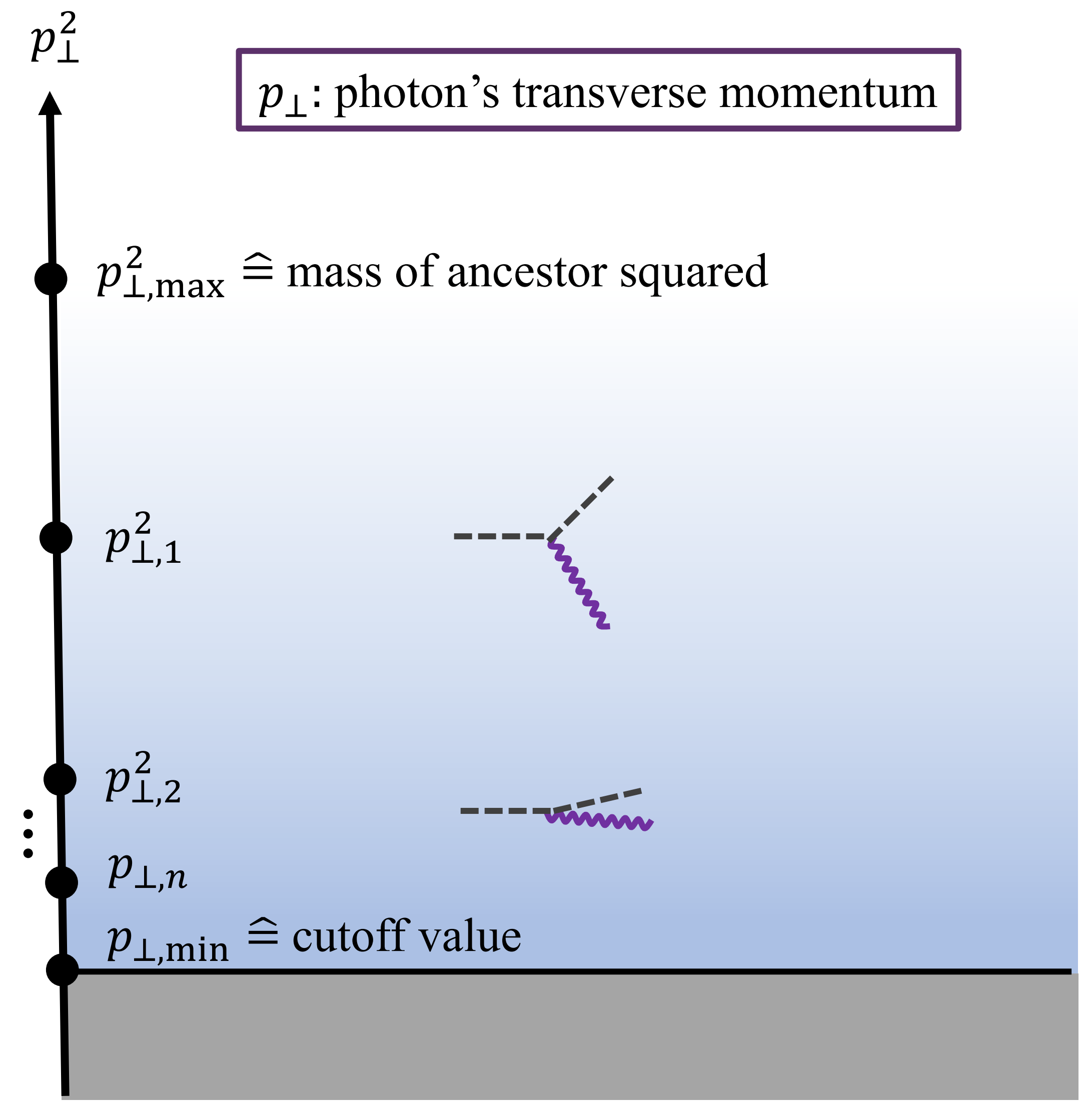
$$\Delta(p_\perp^2, p_\perp'^2) = \exp\left(-\int_{p_\perp^2}^{p_\perp'^2} dk^2 f(k^2)\right)$$

Markov chain: evolution operator based on Sudakov factor.

PRD.84.054003

Algorithm

1. Generate $p_\perp^2$ steps based on evolution operator
2. At each step: accept/reject photons based on Antenna

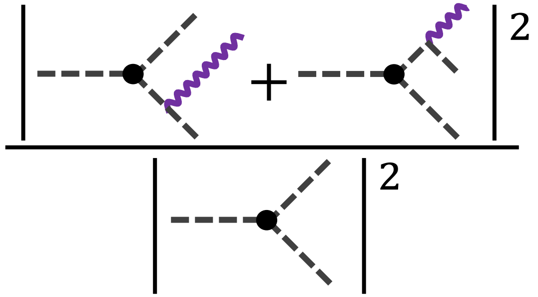


Vincia QED shower for FSR

Giacomo Morgante

- Recently adapted to radiate off hadrons (previously supporting only leptons)
- Matrix-element corrections (MECs) in progress
  - Use FeynRules to model hadron decays (produces universal FeynRules output file)
  - Generate tree-level NLO ME using Madgraph (produces plugin)
  - ⇒ Use it for Antenna function

$$a_{\mathrm{emit}} = \frac{|M_{n+\gamma}|^2}{|M_n|^2} =$$



Technical aspects

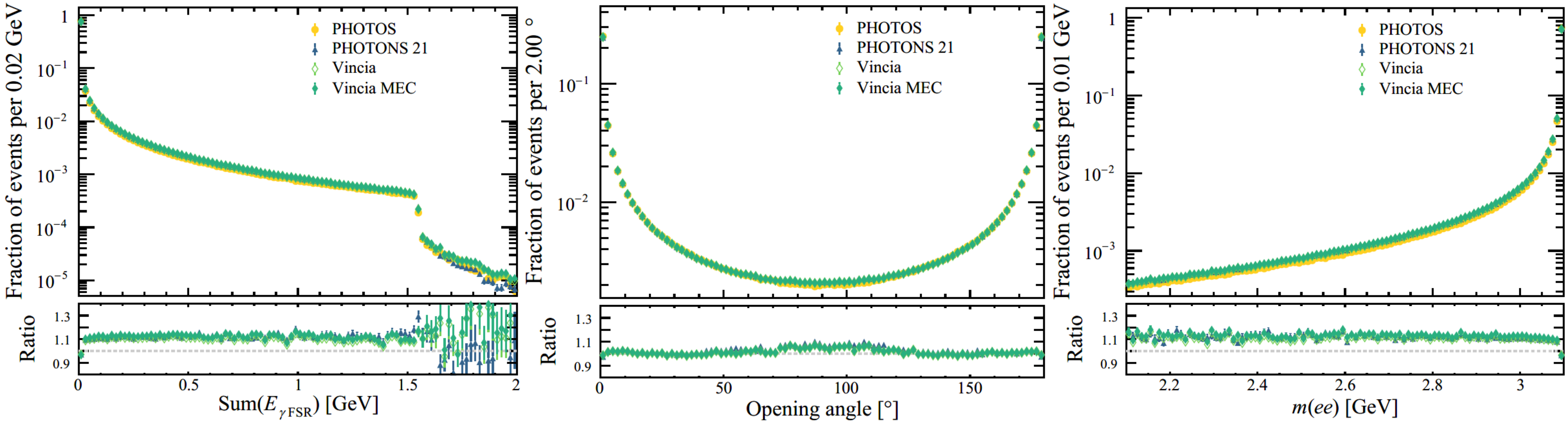
Vincia embedded in Pythia8 → Implementation enables thread safety → EvtGen ↔ Vincia interface based on existing dependency with Pythia8 → Will be part of EvtGen release 3

Comparisons between generators

- Equalize photon p_{T}(Energy) cutoff value (0.1 keV)
- Consider photons only if energy above 0.1 MeV

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

Amount of radiated energy **Angular distribution of photons** **Dielectron mass**

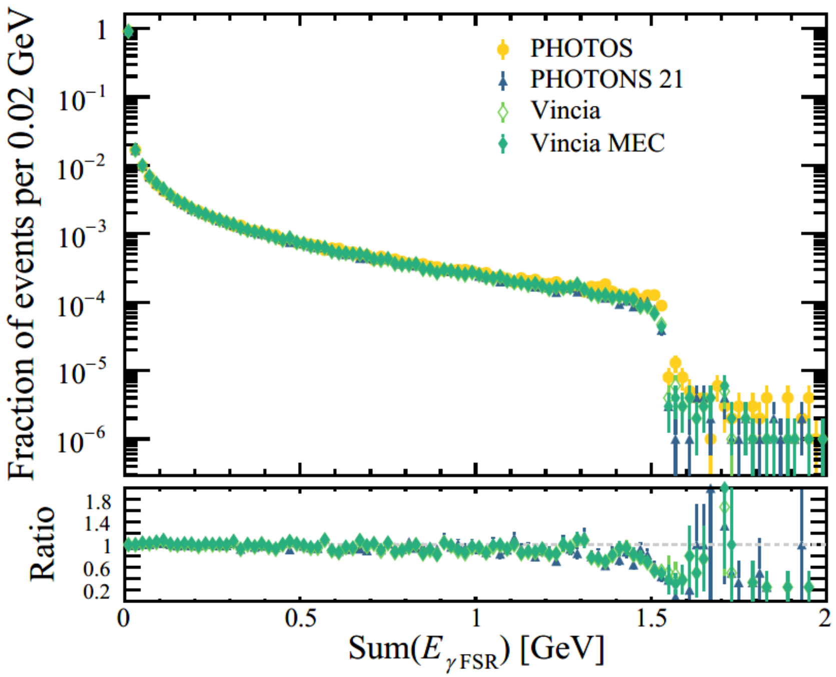


- Good agreement (within ~10%) for energy and angular distributions
- All generators radiate more photons that PHOTOS

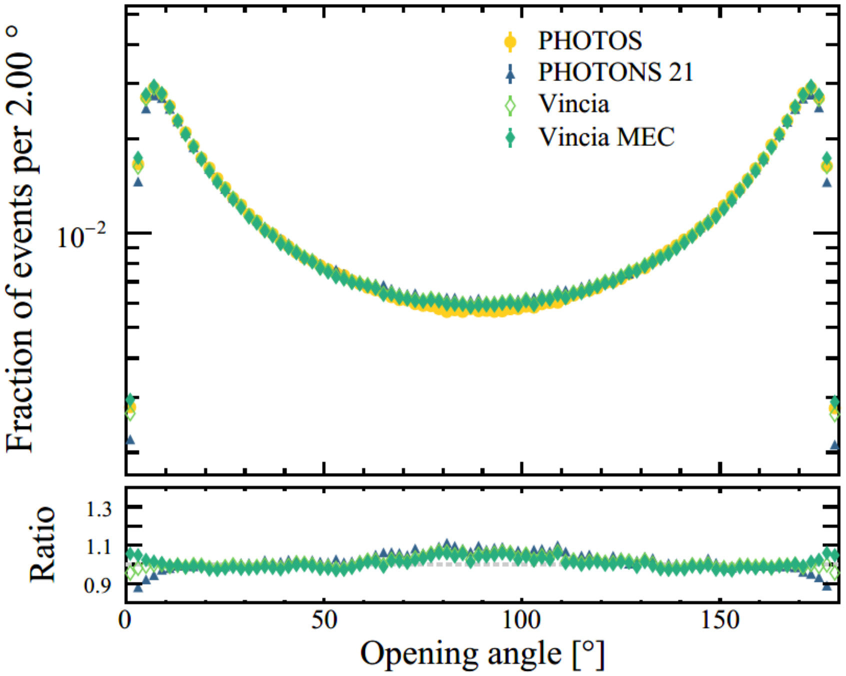
Comparisons between generators

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

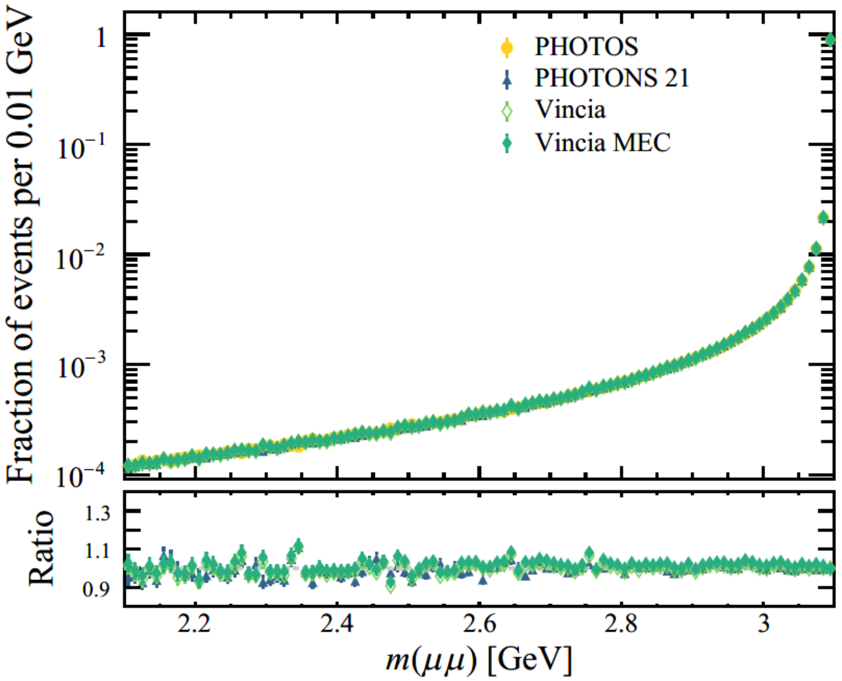
Amount of radiated energy



Angular distribution of photons



Dimuon mass

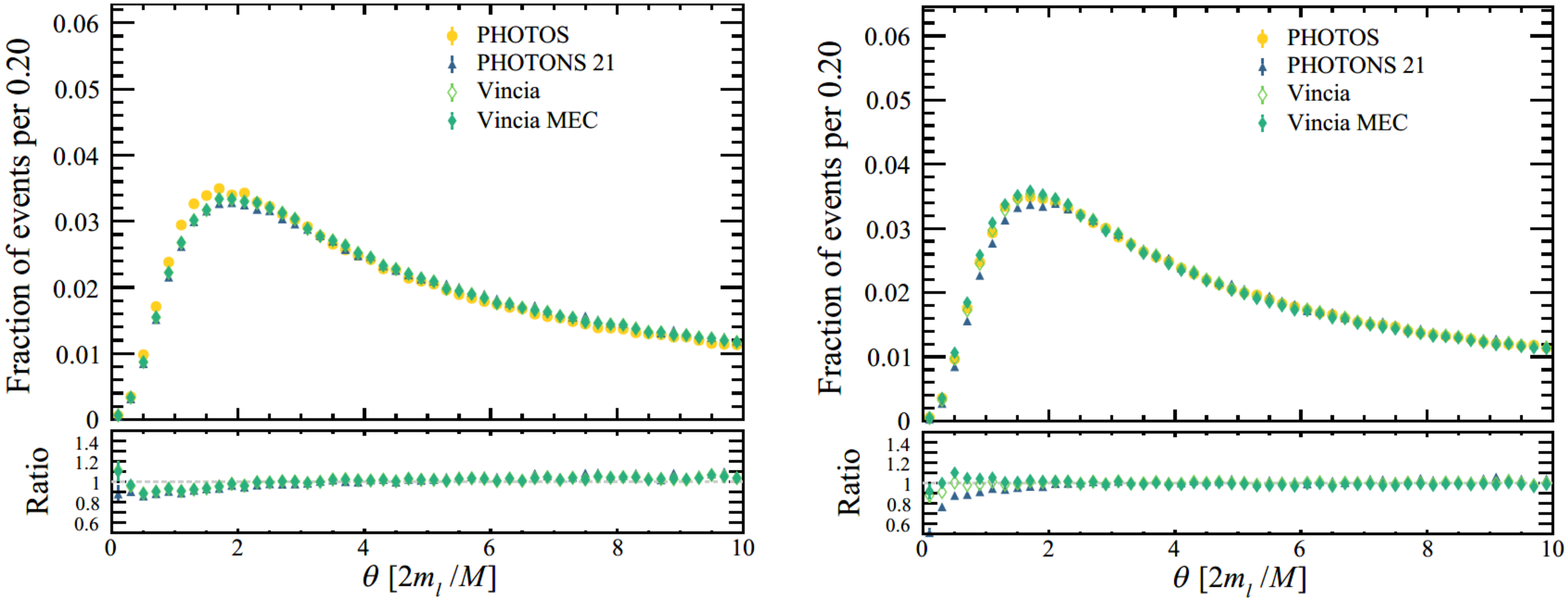


- Good agreement among generators

Dead cone angle

Combination of phase space and mass corrections ⇒ dead cone for $\theta \lesssim \frac{m}{E}$

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

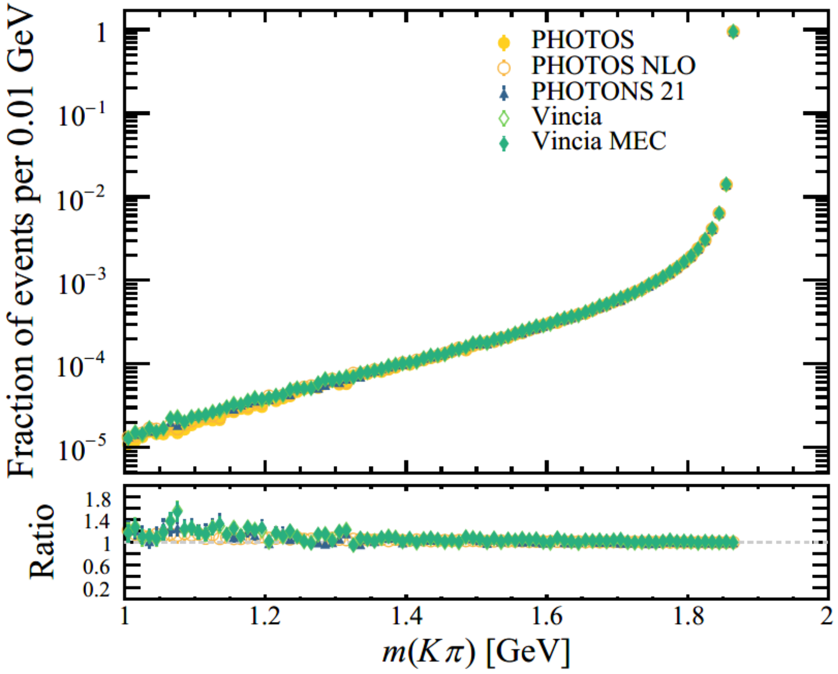


- Electrons: dead cone slightly narrower with PHOTOS
- Muons: dead cone slightly wider with PHOTONS++

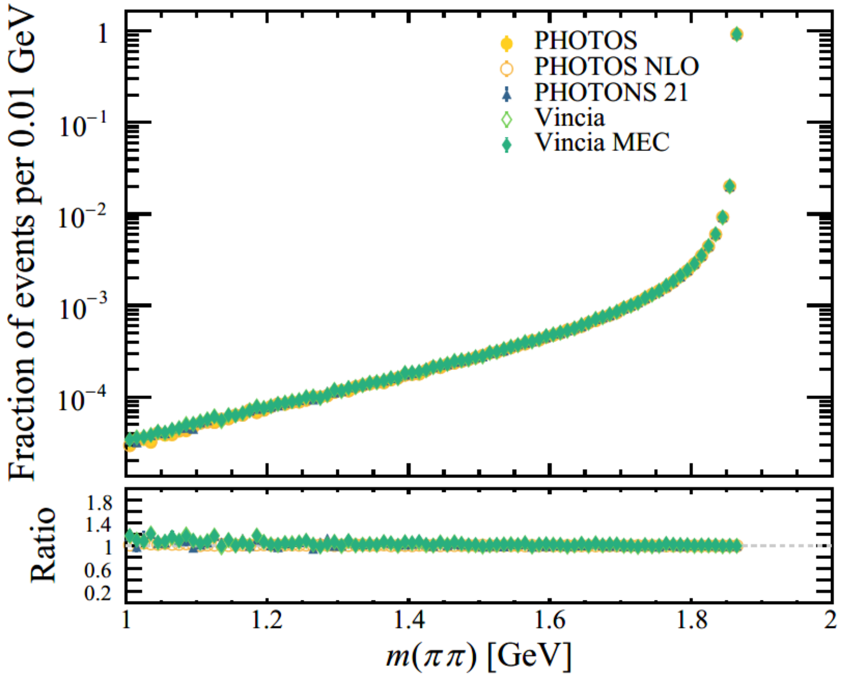
Comparisons between generators

Dihadron invariant mass

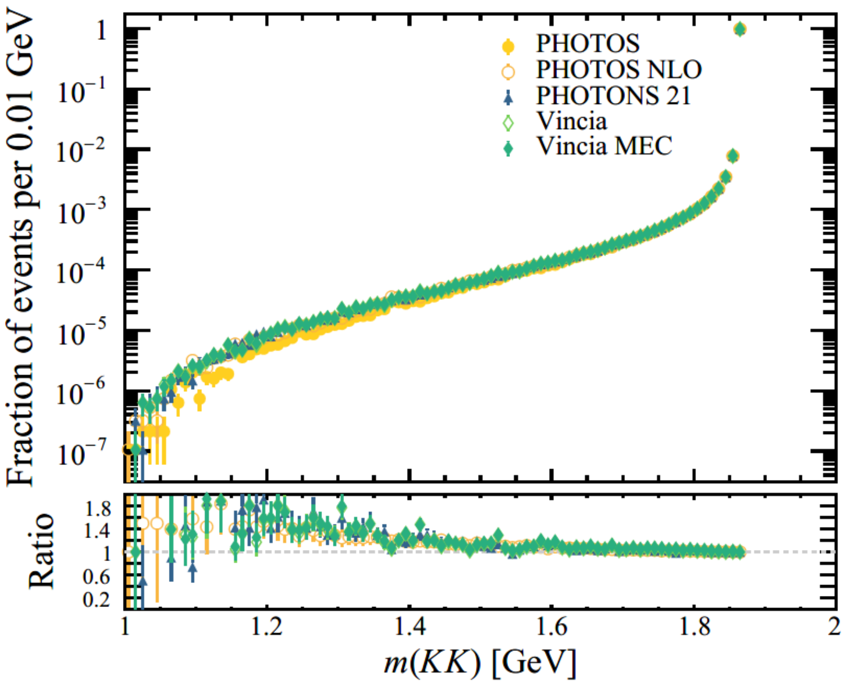
$D^0 \to K^-\pi^+$



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



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

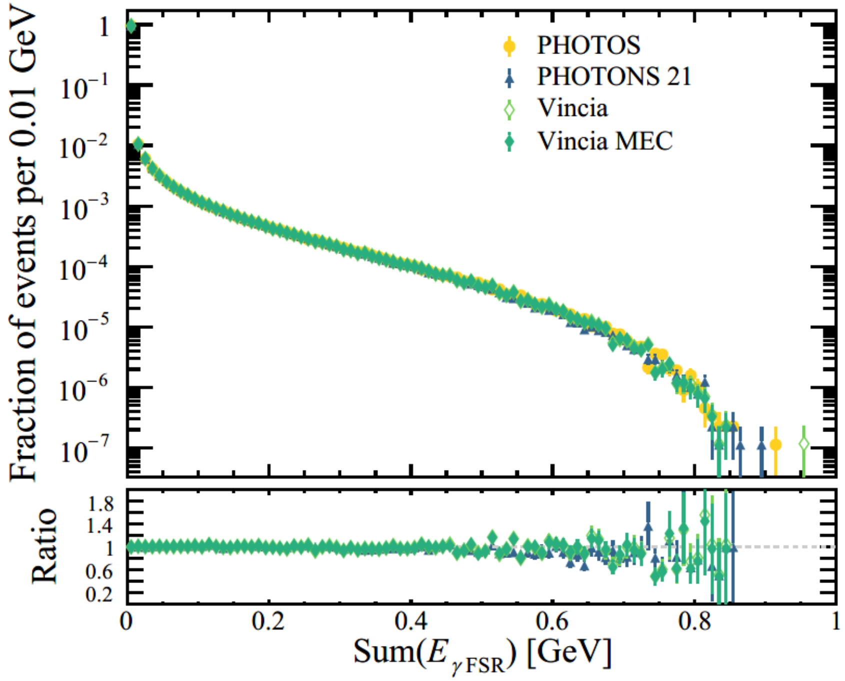


- Excellent agreement among generators, especially with NLO ME corrections

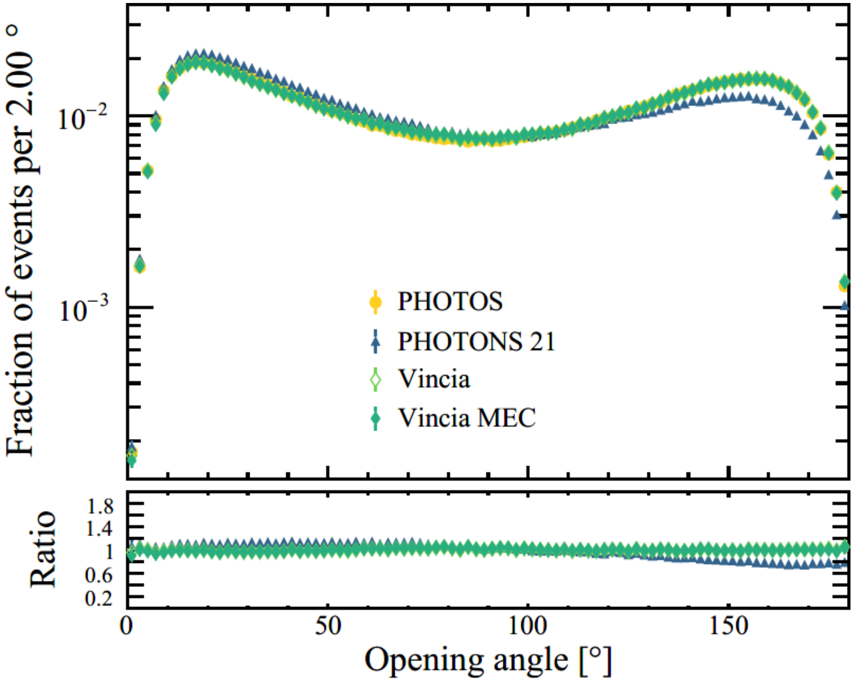
Three-body study

$D^+ \to \pi^+\pi^-\pi^+$

Amount of radiated energy

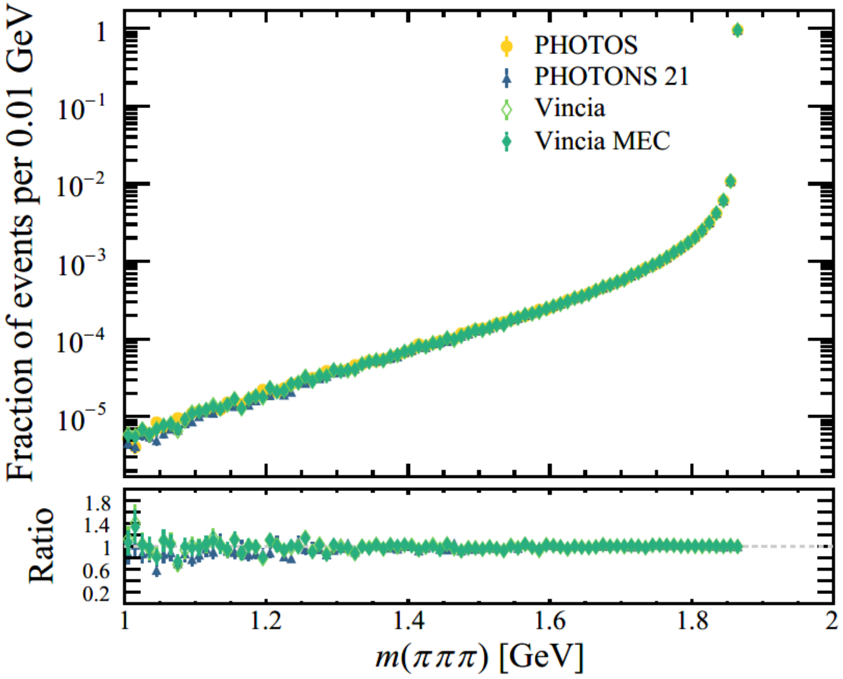


Angular distribution of photons



Angle with respect to hardest particle

Tripion mass

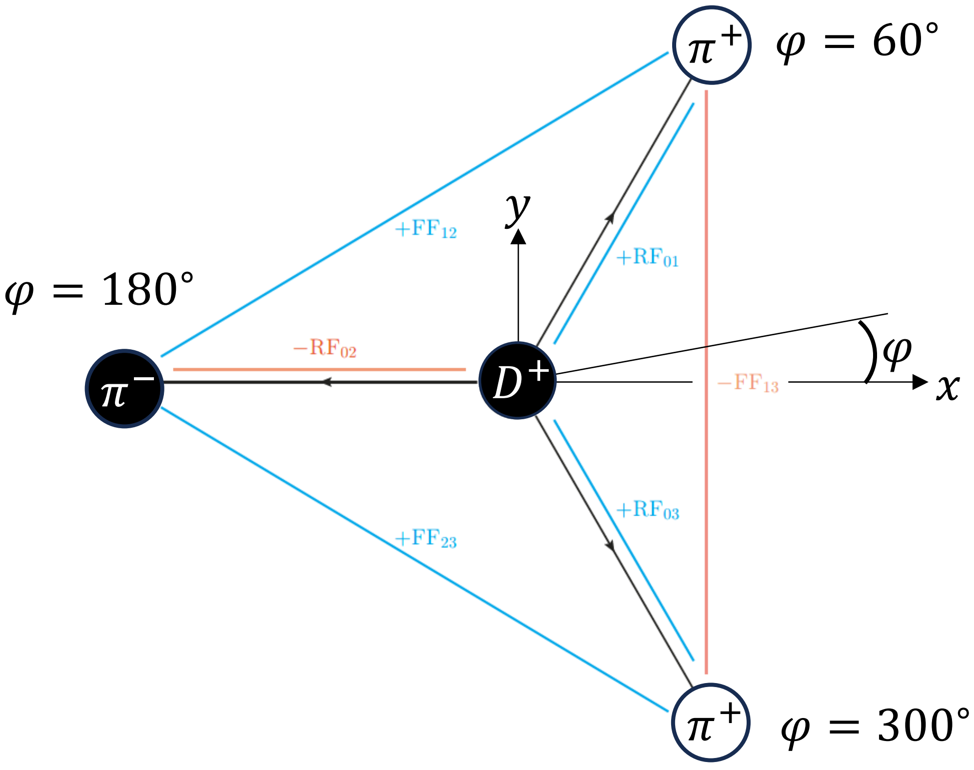


- Good agreement between generators
- PHOTONS++ tends to radiate fewer photons in backwards direction (to be checked)

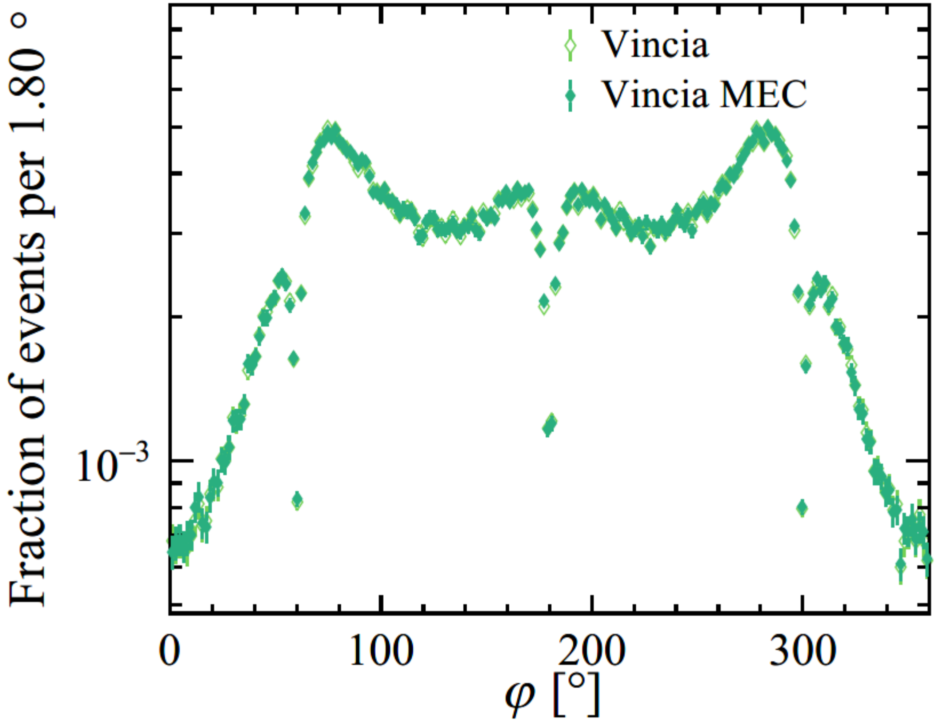
Three-body study

Enforce a specific geometric configuration

Generated geometric configuration



Angular distribution of radiated energy

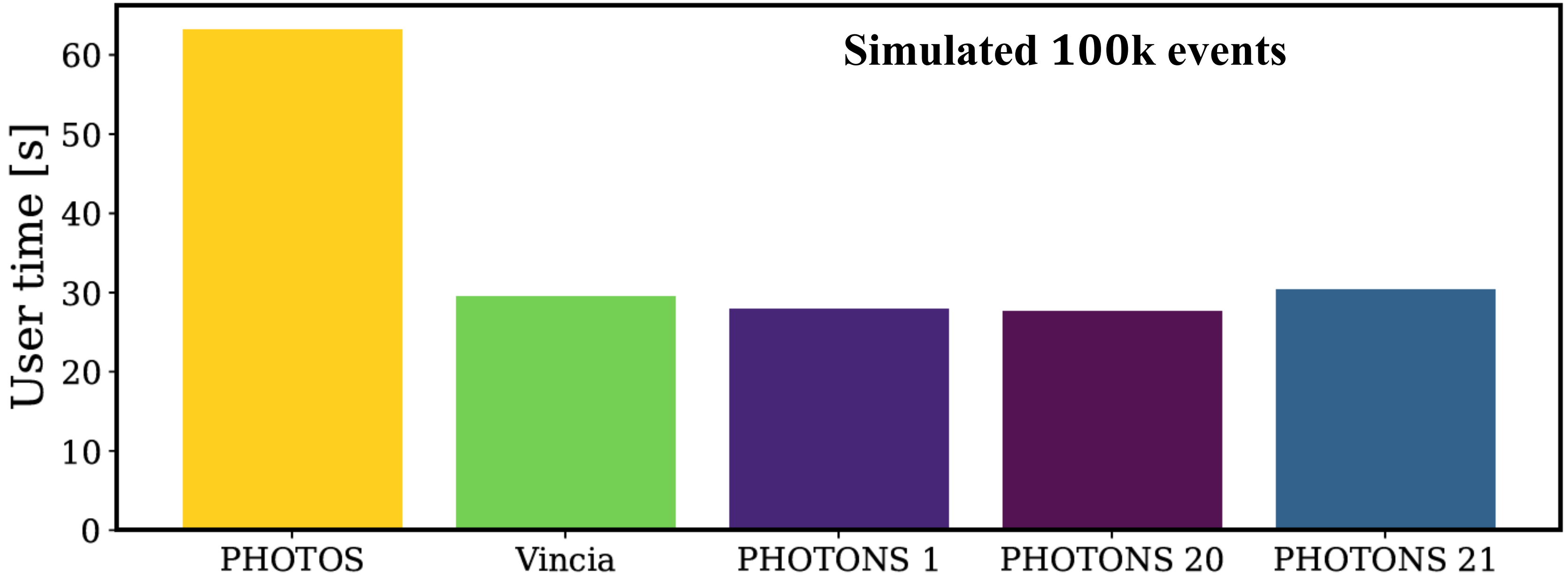


$\Rightarrow$ Expected decrease in radiation collinear with decay products in parent's frame

A word on timing

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

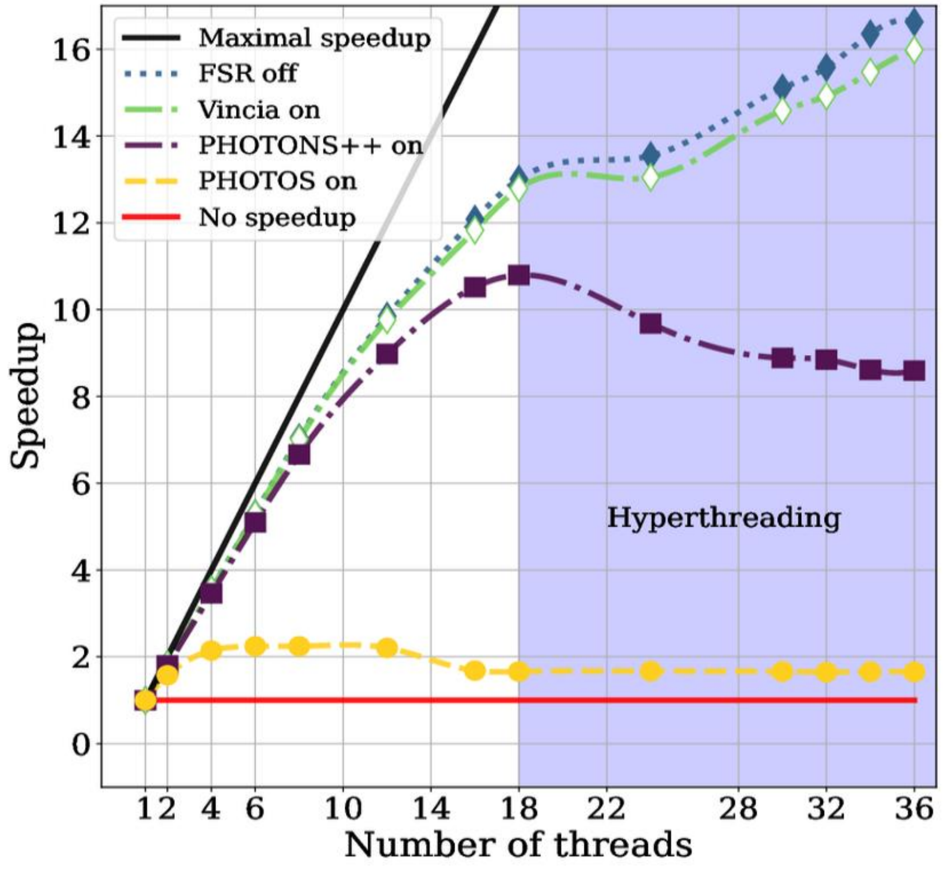
$\Rightarrow$ Benchmark for general use

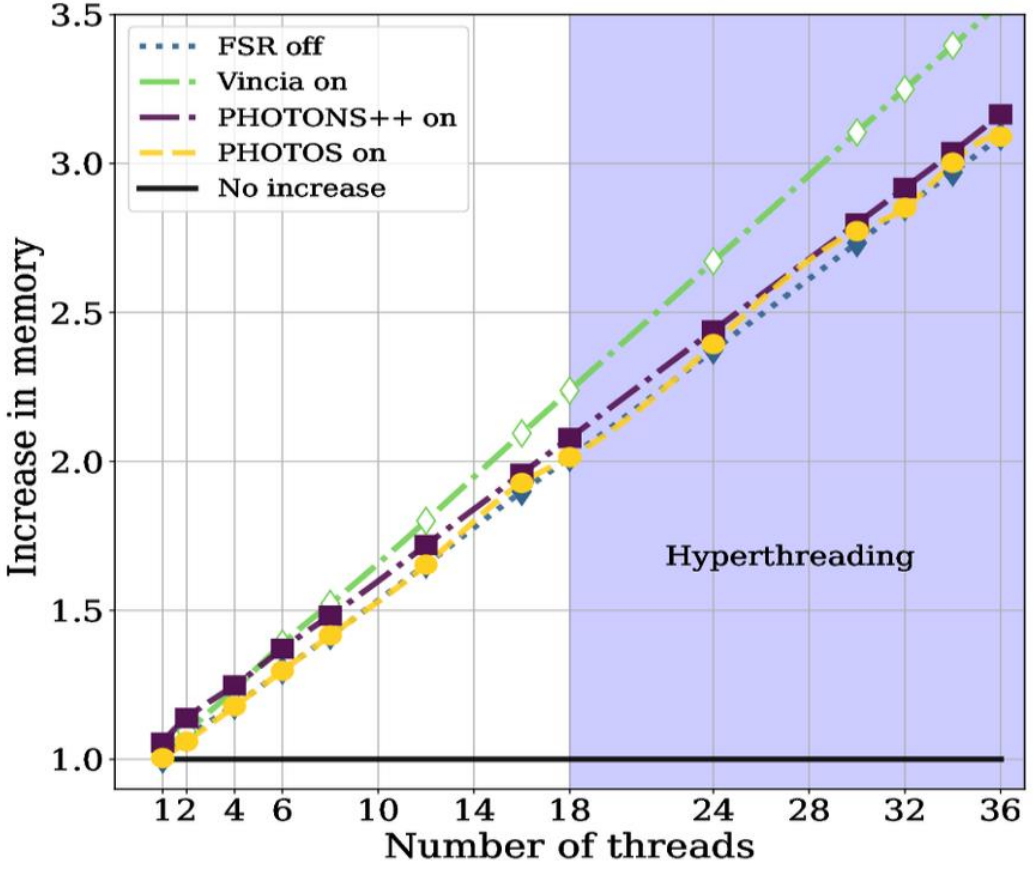


$\Rightarrow$ No large difference between PHOTONS options in generic case

$\Rightarrow$ Potential speedup using Vincia or PHOTONS by about factor 2

Checks with vincia-qed branch





$\Rightarrow$ Best performance with Vincia!

Next step: 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 $E_\gamma < \Gamma$

$\Rightarrow$ Effect kicks in for offshell resonances

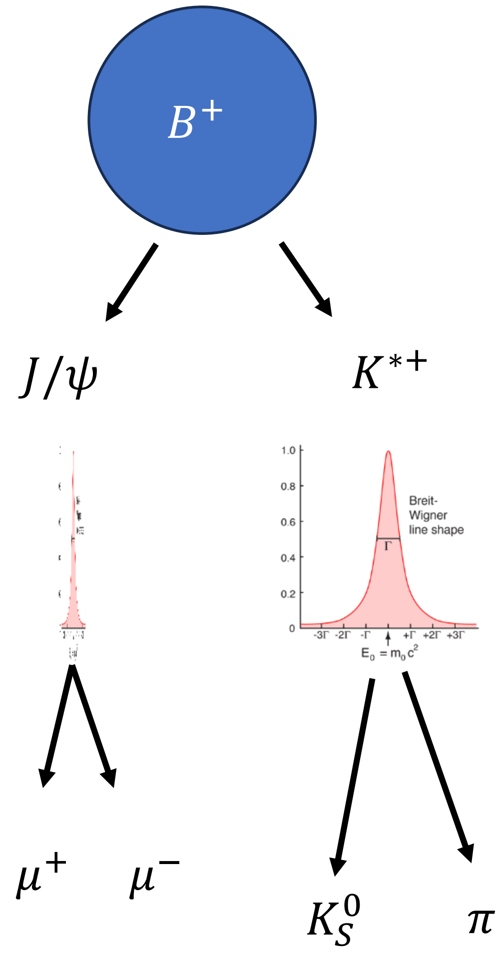
$\Rightarrow$ Can distort resonance shape in regions far from pole (tails)

$\Rightarrow$ Can give rise to interference effects

$\Rightarrow$ Will affect kinematic distribution of final-state particles

$\Rightarrow$ Not considered in conventional approach

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

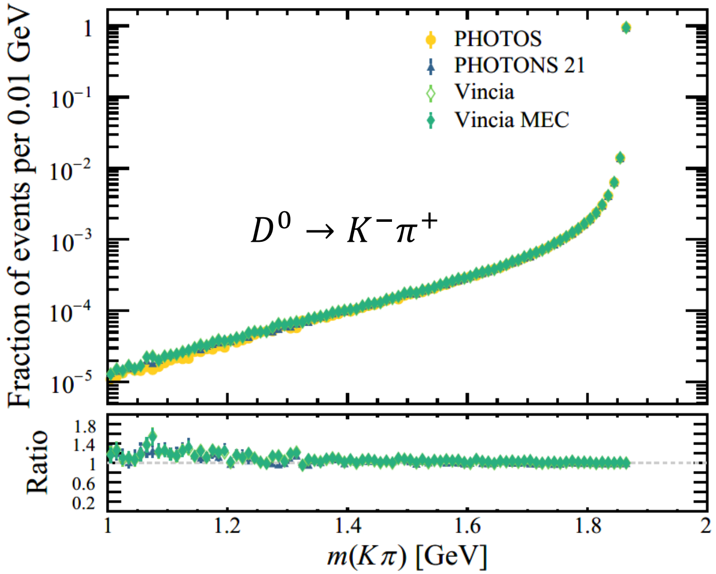


Effect more relevant for resonances with large widths

Summary and outlook

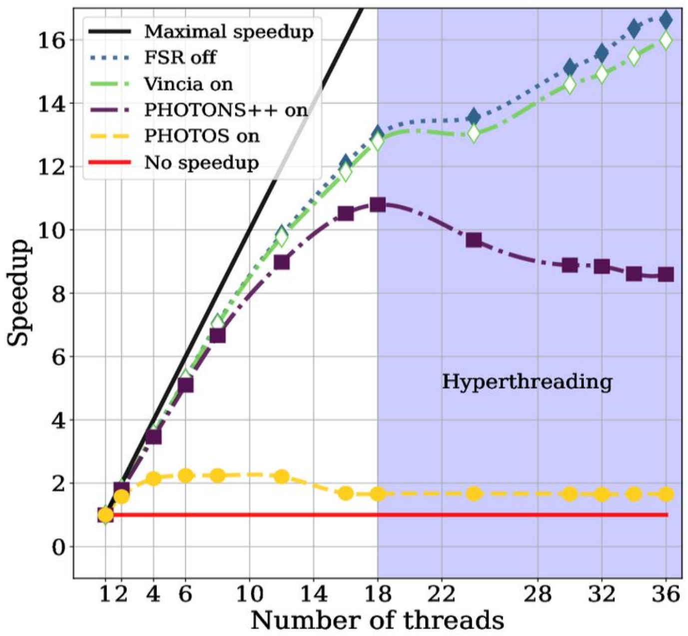
New **Vincia generator** for QED final-state radiation simulation

- Recently adapted to radiate from hadrons
- Currently developing and validating ME corrections
- Results show agreement with other generators
- Efficient use of multi-threading



Availability

- Already (without ME corrections) in Pythia 8.13
- In upcoming EvtGen release 3
- Publication in preparation!



Thanks!

Backup

PHOTOS for FSR

PHOTOS Interface in C++

Comput. Phys. Commun. **199**, 86 (2016) arXiv: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] $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-(\gamma)$ — *Eur. Phys. J. C* **50**, 53–62 (2007)
- [5] $B \to K\pi(\gamma)$ — *Eur. Phys. J. C* **51**, 569–583 (2007)
- [6] $W \to l\,\nu$ and $\gamma^* \to \pi^+\pi^-$ — *Eur. Phys. J. C* **70**, 673–688 (2010)

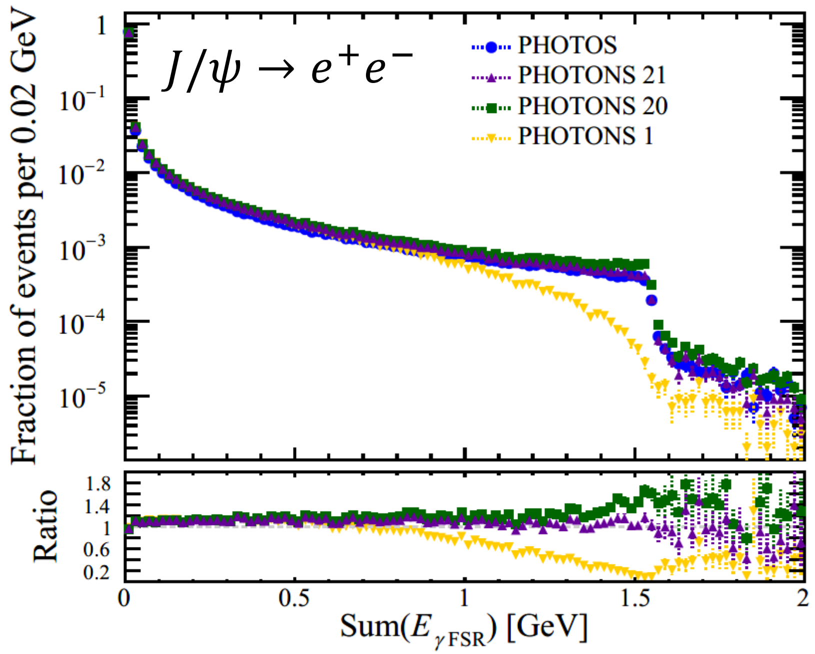
Sherpa's PHOTONS++ for FSR

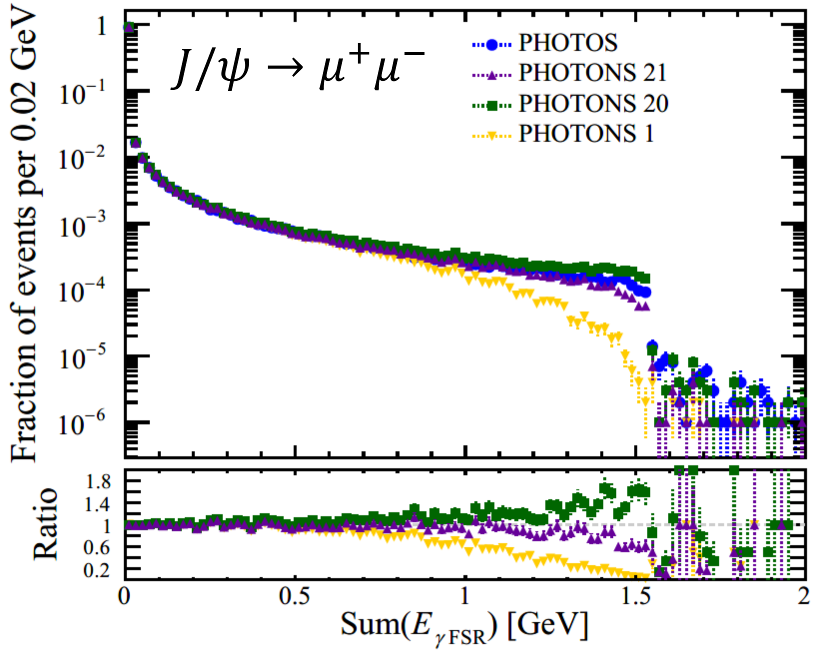
- PHOTONS++ in Sherpa can simulate emission of soft photons based on YFS approximation (mode 1)
- If switched on also hard photons based on collinear approximation (mode 2)
  - Approx. matrix-element corrections (mode 20) or
  - Exact matrix-element corrections (mode 21)
- With mode 1: fewer hard photons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

$\Rightarrow$ Implemented switches for systematic studies

New in EvtGen R03-00-00-beta1!

Amount of radiated energy



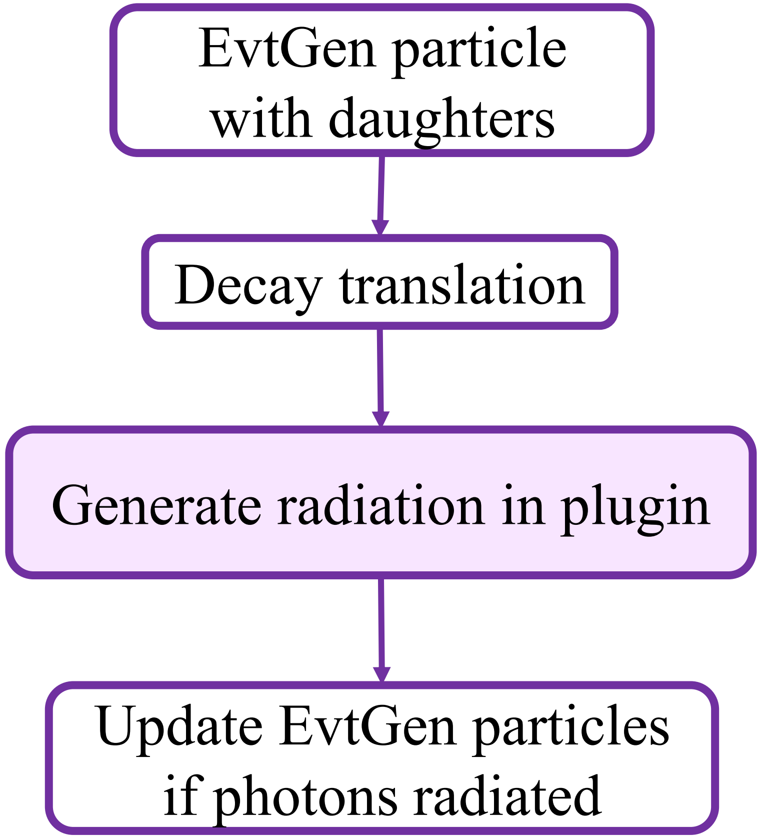


Interfaces between EvtGen and Plugins

- 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

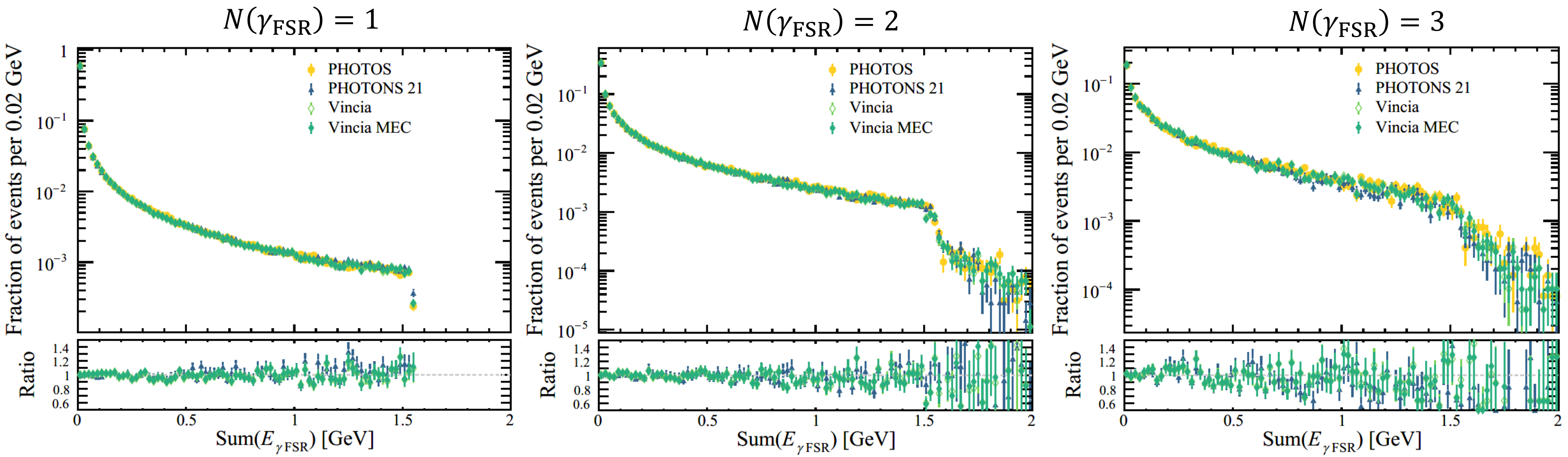
Workflow



Comparisons between generators

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

Amount of radiated energy

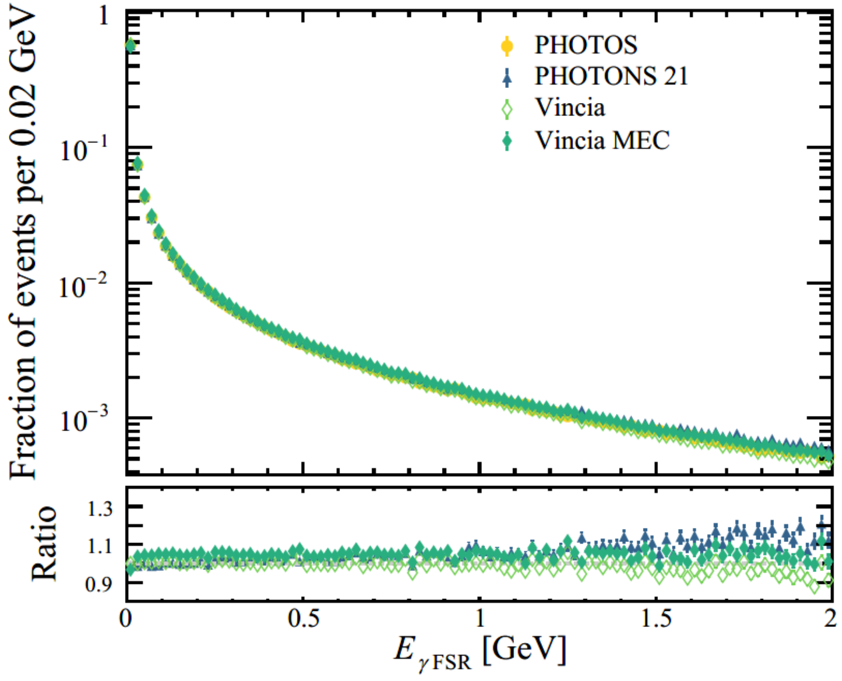


- Energy range above $M_{J\psi}/2$ kinematically accessible only for events with more than one photon

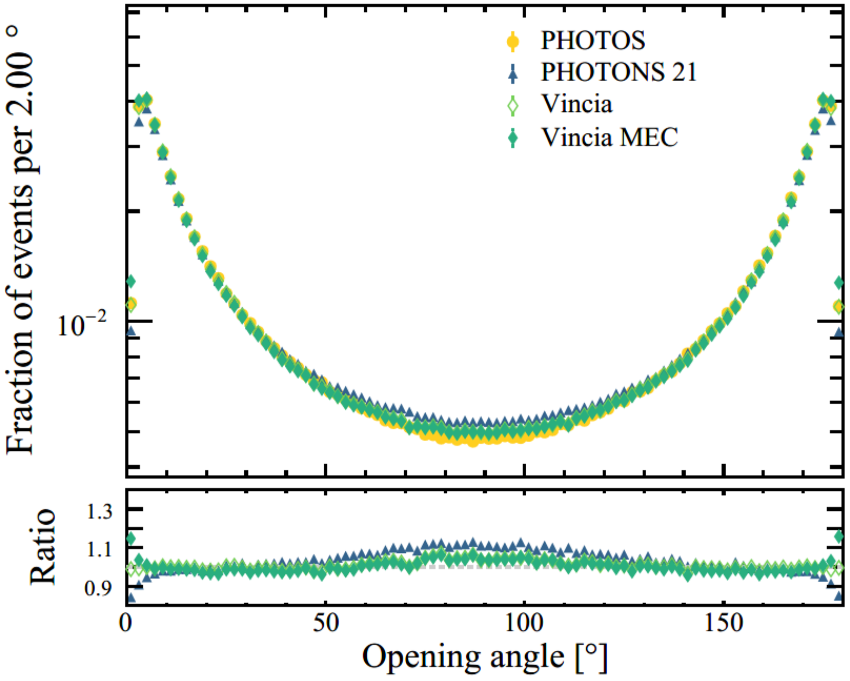
Comparisons between generators

$B_s^0 \to \mu^+\mu^-$

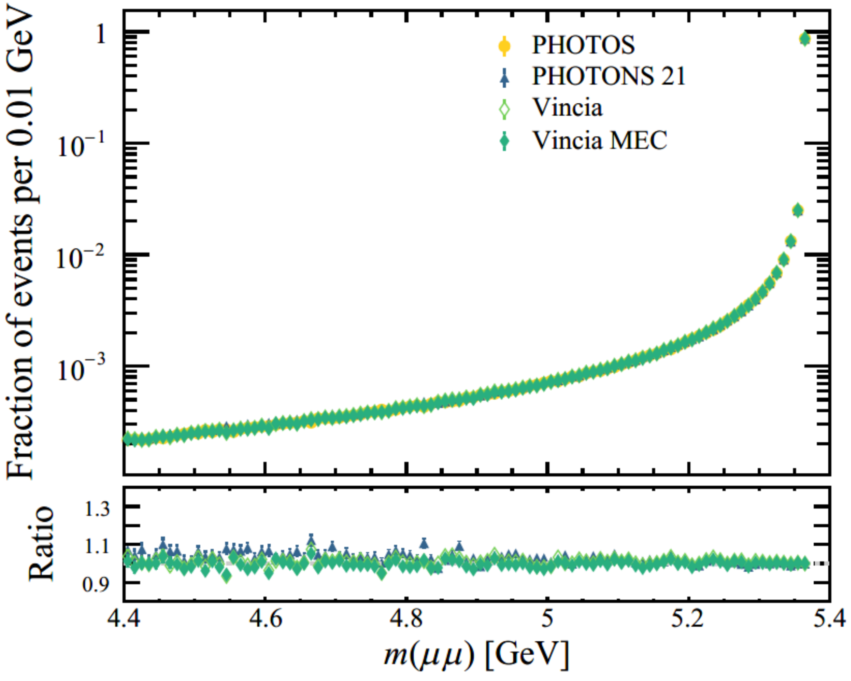
Amount of radiated energy



Number of photons



Dimuon mass

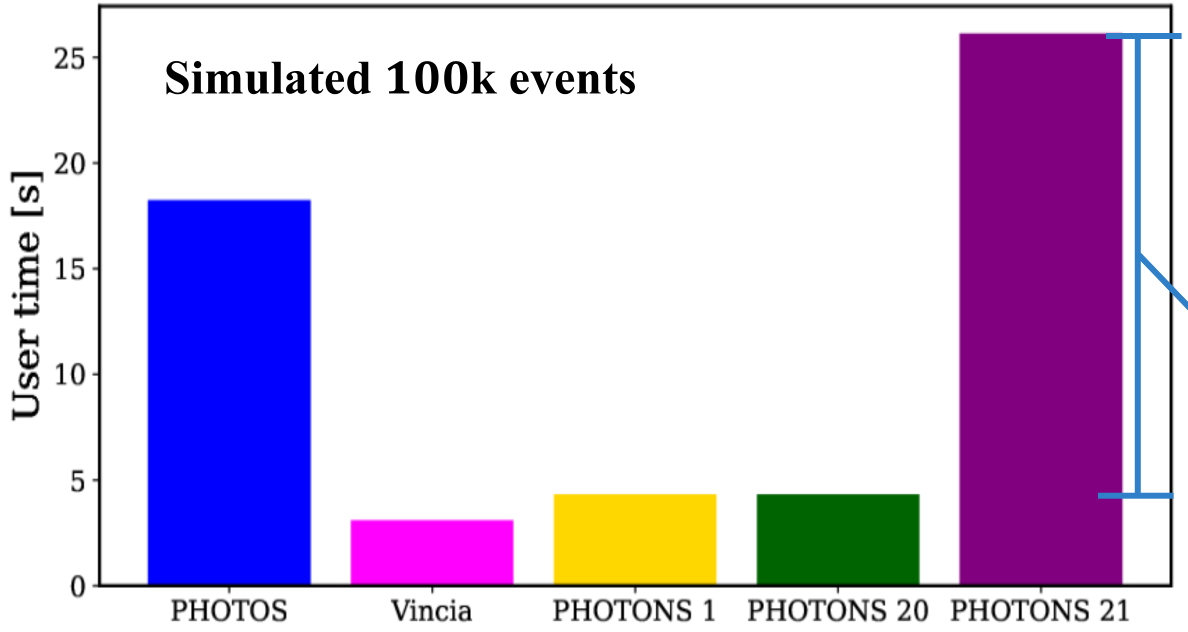


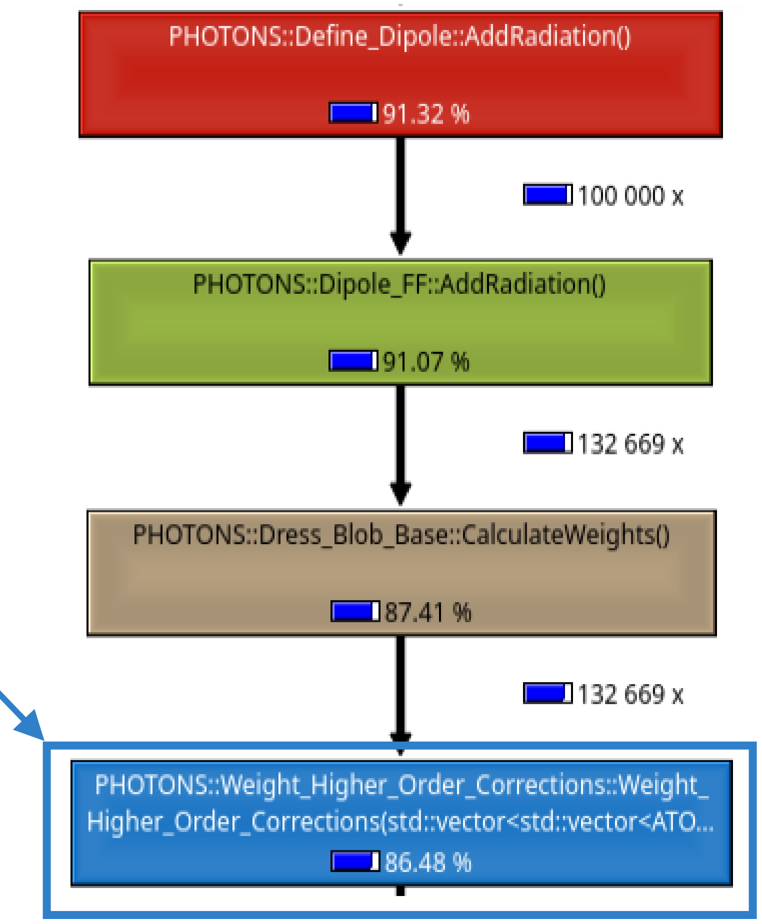
- Good agreement (within ~10%) among generators

A word on timing

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

$\Rightarrow$ Collinear singularities enhanced due to small electron mass





$\Rightarrow$ Largest consumption by exact matrix-element calculation

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

$\Rightarrow$ Potential speedup using Vincia or PHOTONS by about factor 4

Vincia parton shower with NLO

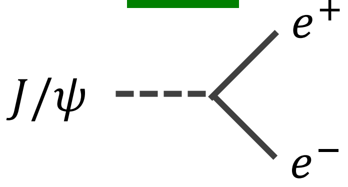
M_n^l = QED amplitude for n legs and l loops

… = Shower approximation

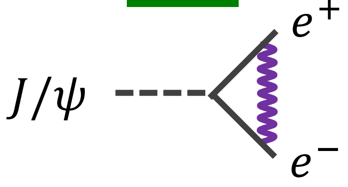
$$B_n = |M_n^0|^2$$
$$V_n = 2\mathrm{Re}[M_n^0 M_n^{1*}] + \int \mathrm{d}\phi \, \left|M_{n+1}^0\right|^2$$
$$W_n = |M_n^1|^2 + 2\mathrm{Re}[M_n^2 M_n^{0*}] + \int \mathrm{d}\phi \, V_{n+1}$$

B_n , V_n and W_n are all finite
For n resolved partons

LO M_2^0



M_2^1



Loops and legs diagram ≙ coefficients of perturbative series