Progress on EvtGen and Pythia developments

EvtGen

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Pythia

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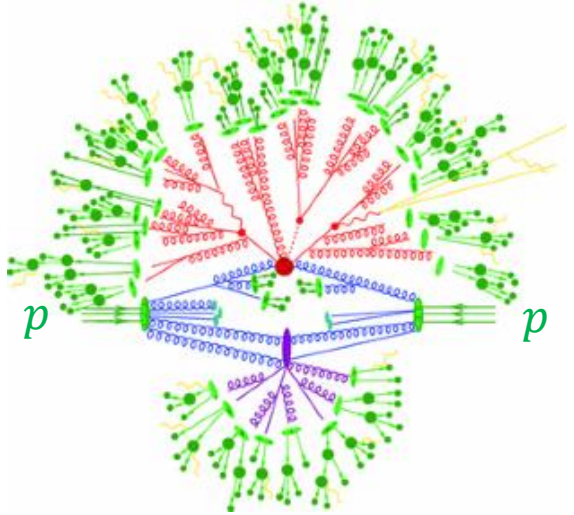
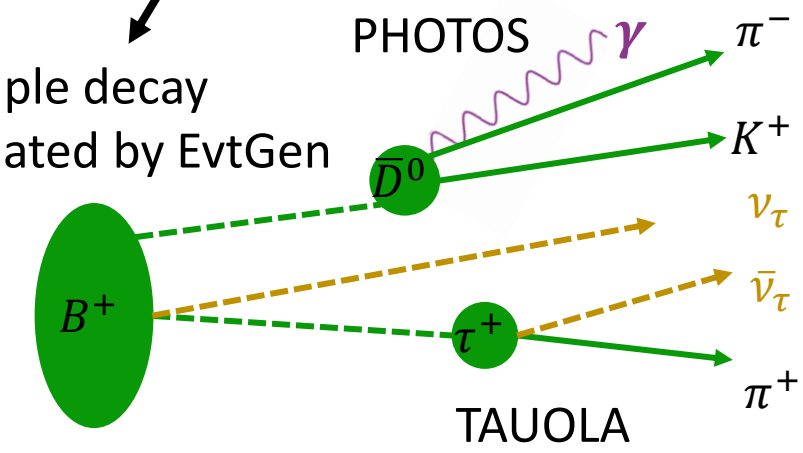
EvtGen

- 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

Example collision simulated by Pythia8



Example decay simulated by EvtGen



Status and plans

- Developed in the 90's, stable over past 10 years (changes mostly additions of new models)
- Physics wise no plan for changes in near future

Challenges for updates

- Various code styles across models (due to contributions from various authors)
- Several code duplications across models (often same kinematics but different form factors)
- Experiments (main users) need generators to be thread-safe as they are moving their simulation frameworks towards multithreading to exploit modern CPUs

Recent developments

- Work on code modernisation, clean-up, removal of duplications, and documentation
- First adaptation of core code towards thread safety (full adaptation to be deployed)
- Implemented global testing framework for validation
- Studies of alternatives for τ and FSR simulation (to be continued)

Testing framework

- Simulation needs testing and validation after structural changes due to code consolidation and implementation of thread safety
- Tests (in different formats) existed only for about 40% of the 130 decay models
- Migrated all tests and added new ones to a common testing framework
- Finalized first working version with tests for all models
- Testing framework helped uncover broken models

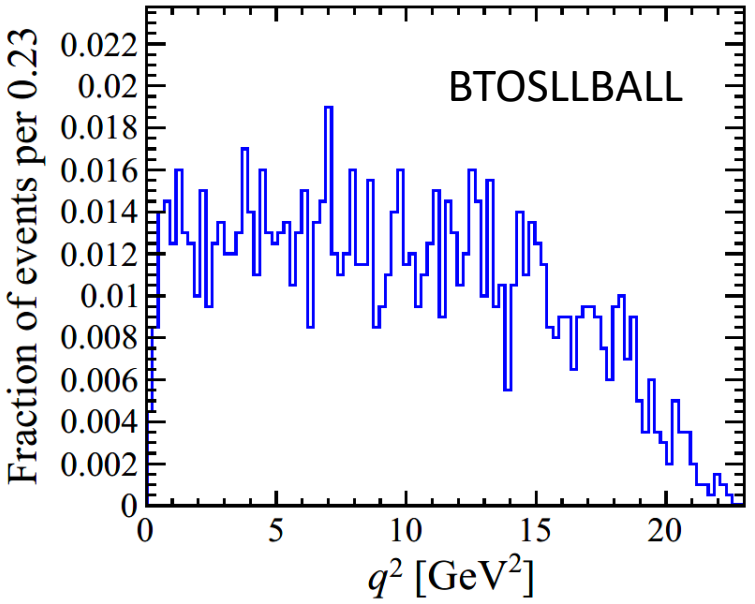
⇒ Repairing them has taken large fraction of recent effort

- Some models support various configurations

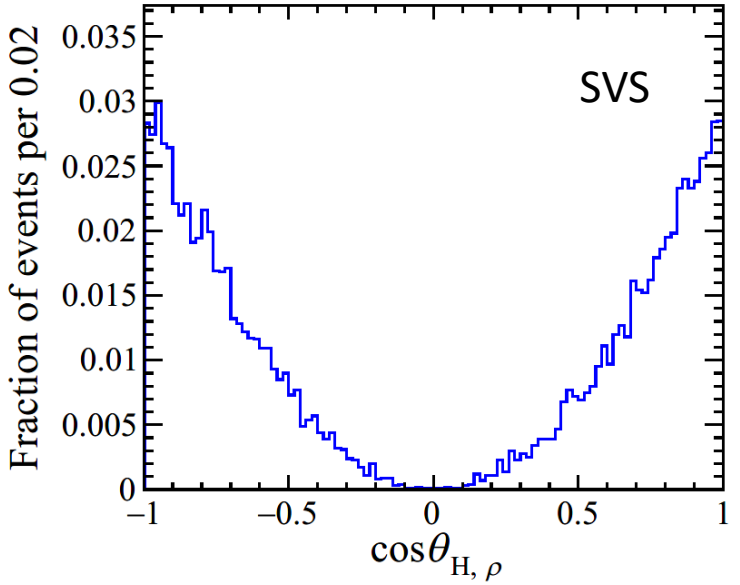
⇒ More tests needed to cover all configurations

⇒ Will require to add new tests for each new model

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



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



Challenges for multithreading in EvtGen

- Internal: structural limitations for multithreading inside EvtGen
  - Global instance of random number generator
  - Global instance of particle properties and decay table

⇒ Needed structural changes identified and first combination of solutions found

- External: limitations from dependences
  - TAUOLA
  - PHOTOS

⇒ Overcoming limitations from dependences are more challenging as they are external

  - TAUOLA and PHOTOS authors currently exploring ways to enable thread safety
  - Exploring use of Pythia8 as alternative to TAUOLA
  - Exploring use of Vincia QED (Pythia8) shower and Sherpa's PHOTONS++ as alternative to PHOTOS

Progress on thread-safety

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

Set of solutions to reach thread-safety (preliminary):

- Converted **static** objects to **static const** where possible
- Global singleton objects made thread-local
- Serialized (mutexed) calls to PHOTOS and TAUOLA

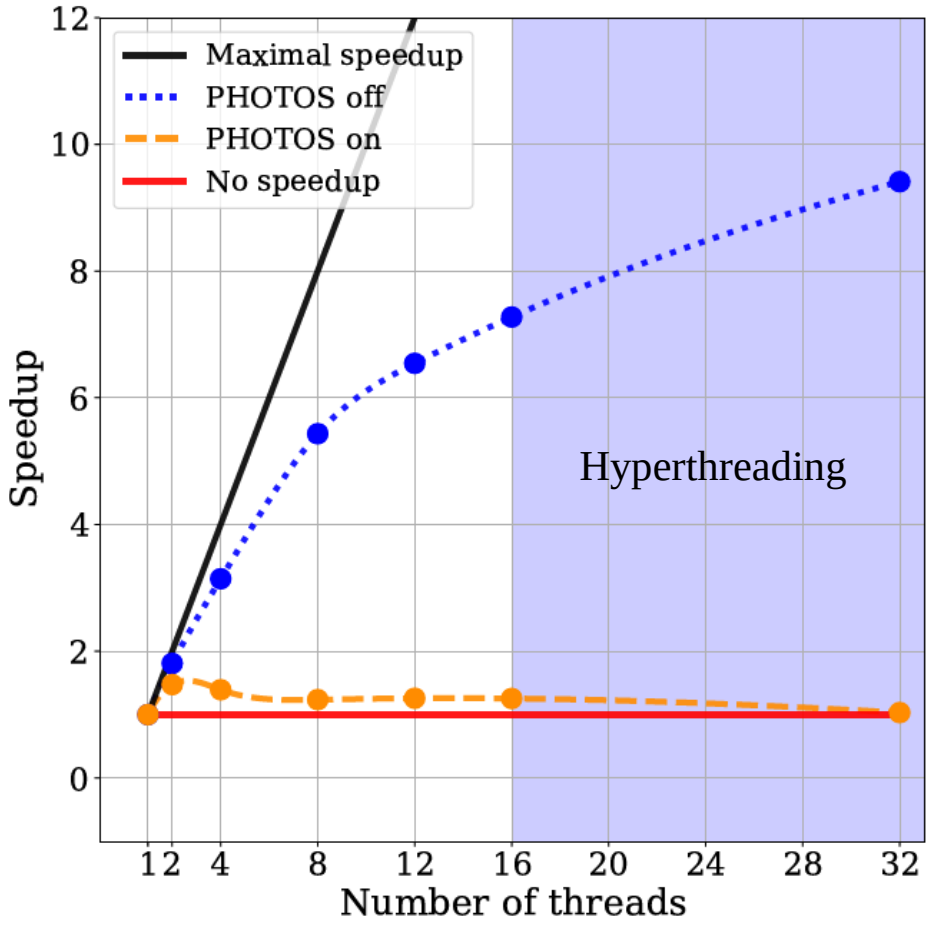
⇒ Deeper structural changes needed to fully exploit multi-threading (plan to continue working on it)

⇒ Current preliminary status reached thread-safety, passing tests for all decay models

⇒ But performance limited by external dependencies

- PHOTOS is used for almost every decay

⇒ Study alternatives for final-state radiation (FSR)



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 (with modern implementations)

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

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

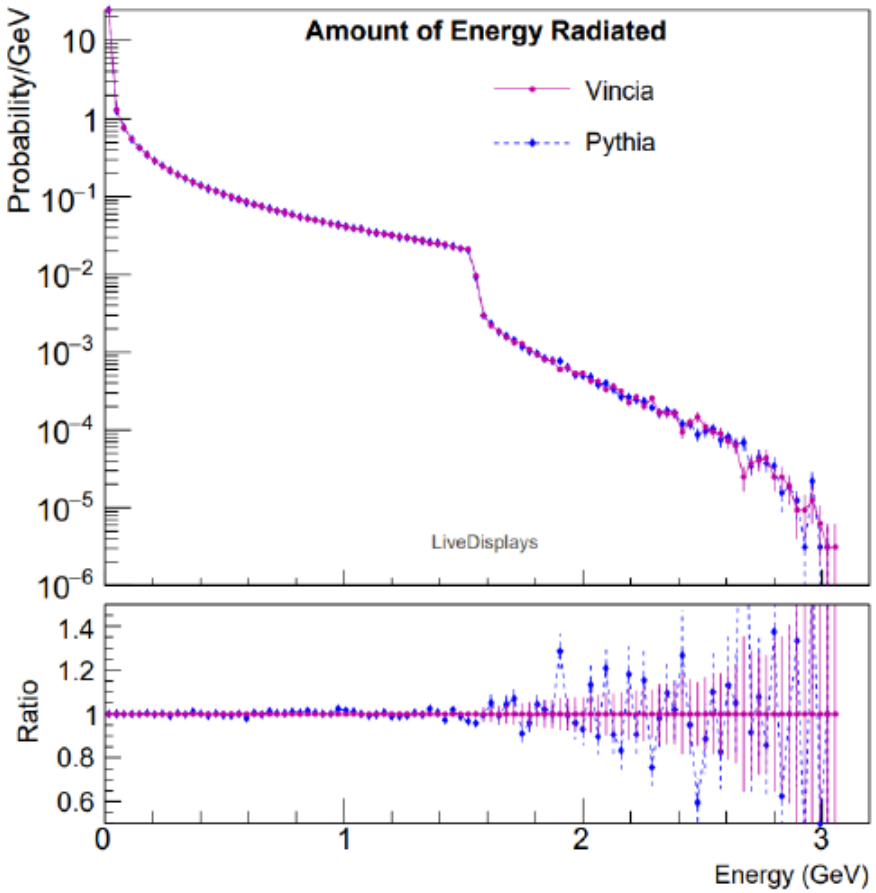
- Takes full (multipole) soft interference effects into account
- Not limited to scalar QED (includes spin dependence)
- Works as parton shower evolution based on antenna approximation (can be interleaved)

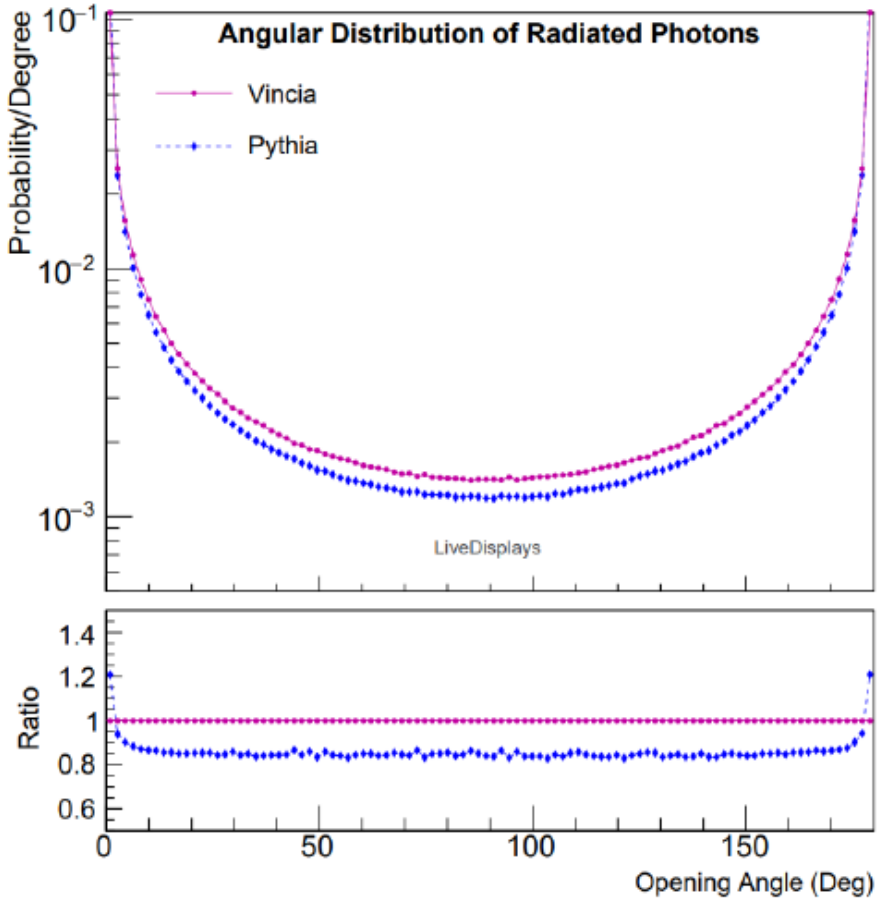
Vincia QED shower for FSR

Giacomo Morgante's Honours Thesis

- Explore use of Vincia's multipole QED shower and compare with Pythia and PHOTOS

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



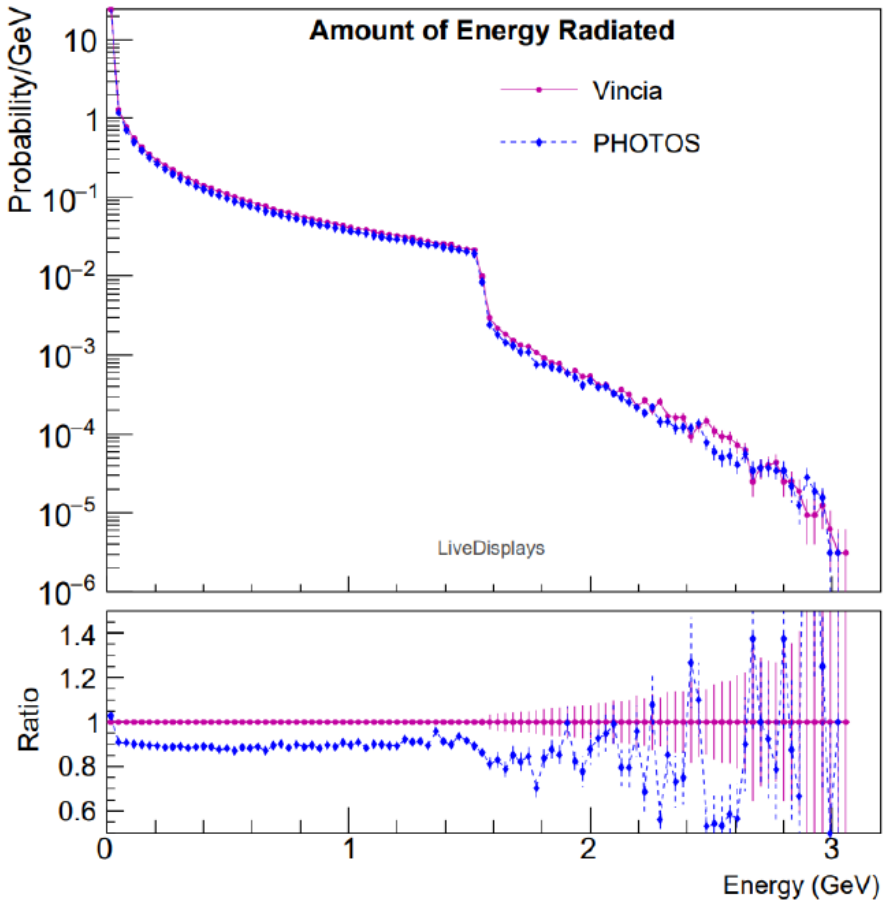


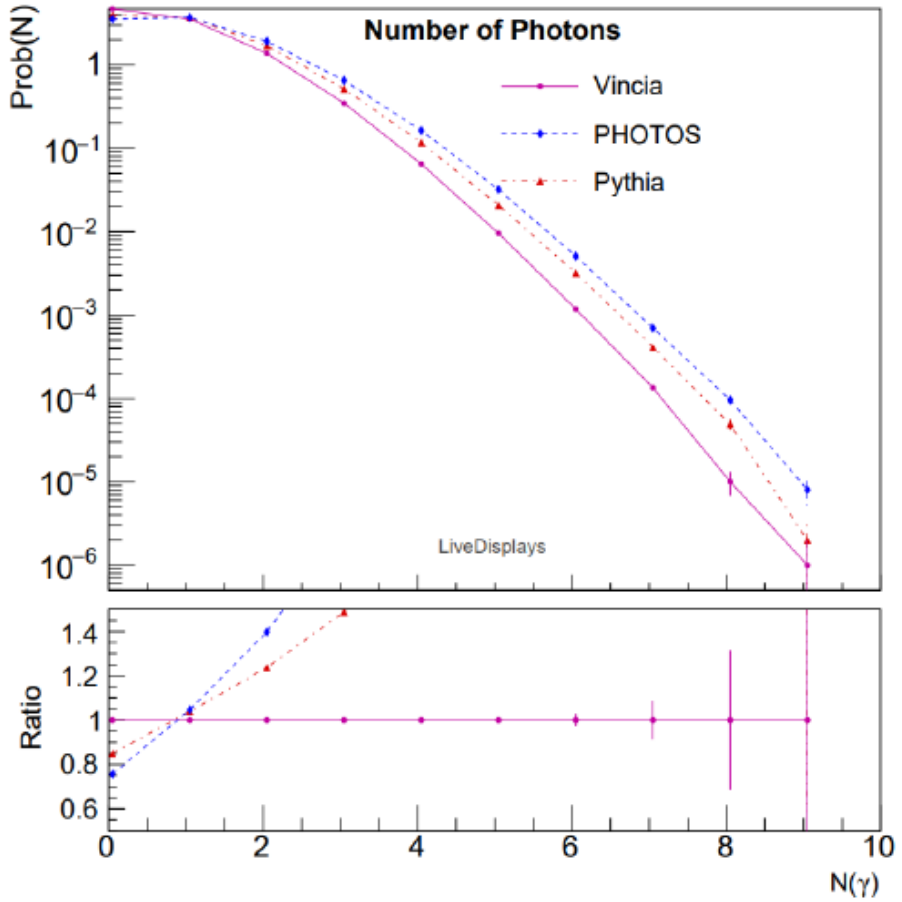
⇒ Good agreement for radiated energy

⇒ Larger impact of collinear singularities on angular distribution in Pythia

Vincia QED shower for FSR

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



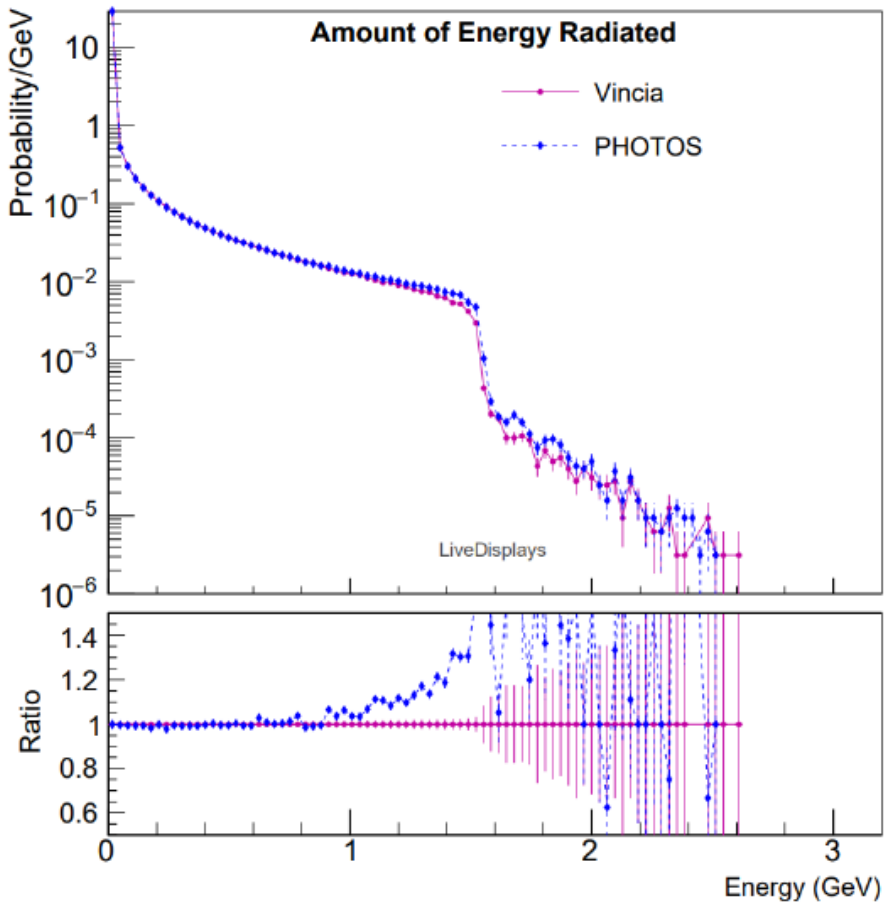


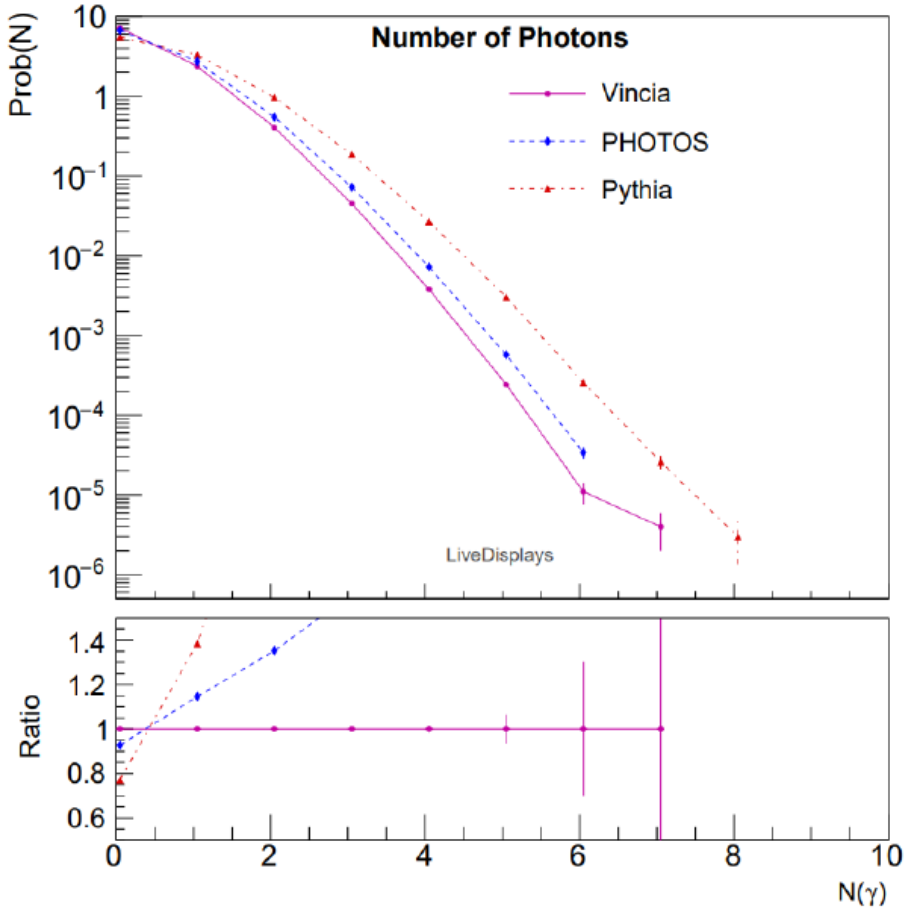
⇒ Vincia tends to radiate fewer but harder photons than PHOTOS

⇒ However, energy cutoff not yet synchronised (0.1 keV in PHOTOS and 1 keV in Vincia)

Vincia QED shower for FSR

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



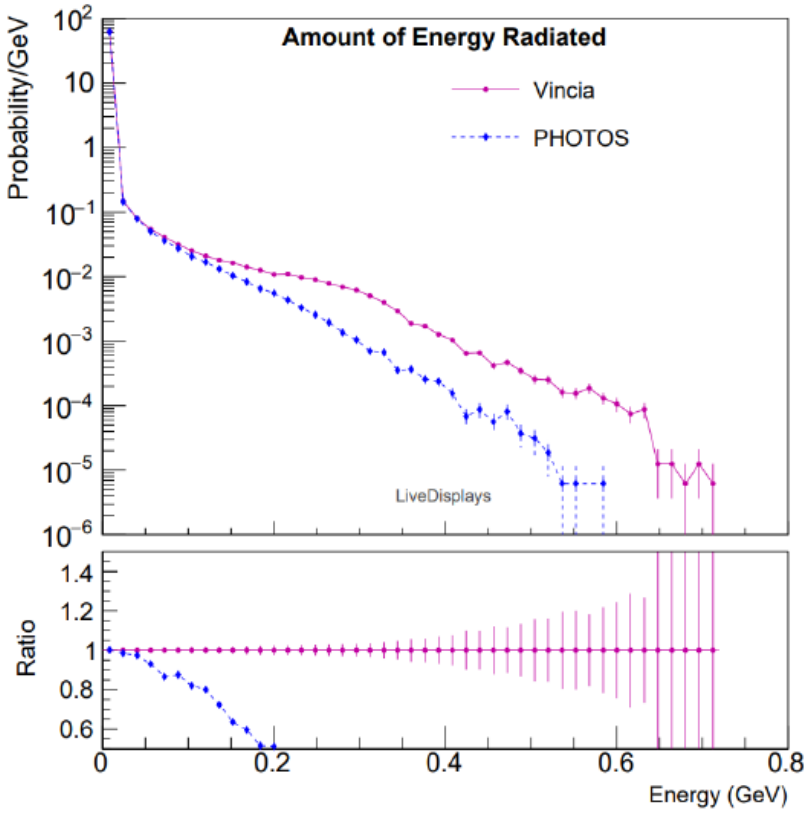


⇒ Good agreement for radiated energy up to 1 GeV

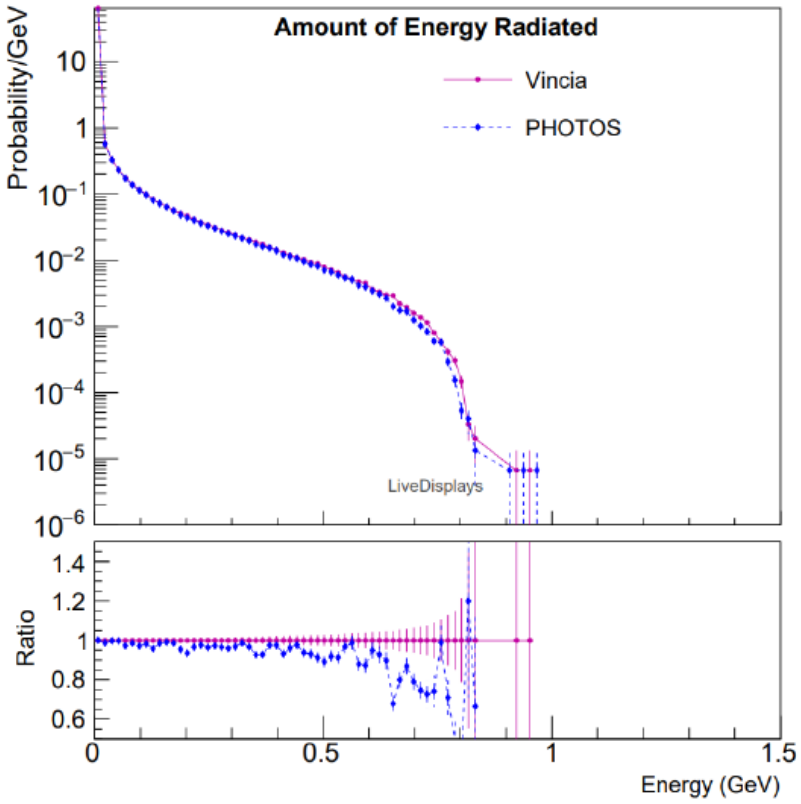
⇒ Vincia tends to radiate fewer photons

Vincia QED shower for FSR

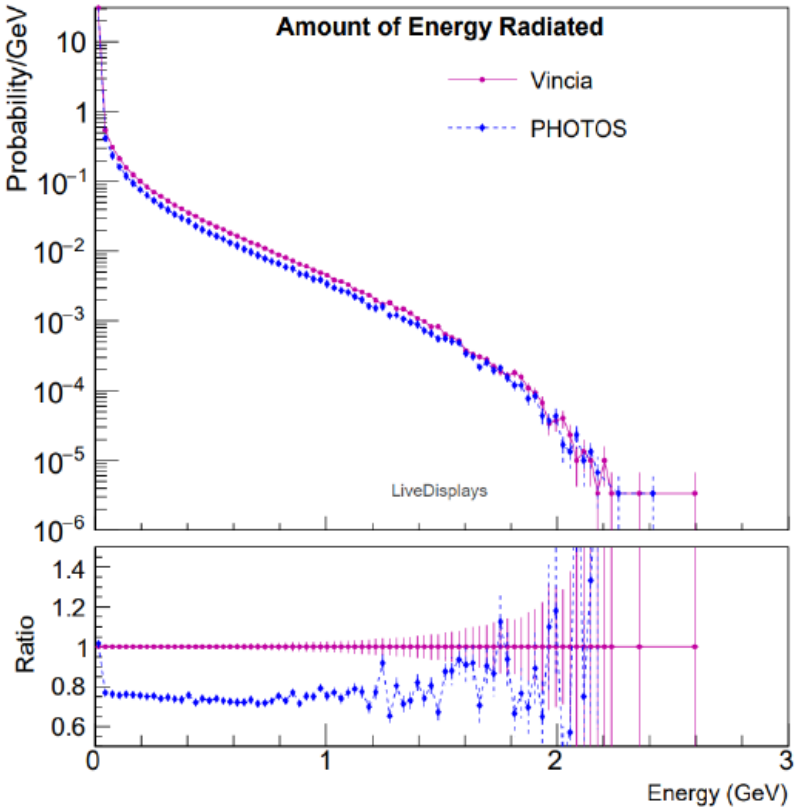
$\rho^+ \to \pi^+\pi^0$



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



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



$\Rightarrow$ Vincia tends to radiate more energy

Vincia QED shower for FSR

- Recently adapted to radiate off hadrons (previously supporting only leptons)
- Matrix-element corrections (form factors, etc) not implemented yet

$\Rightarrow$ Potential main cause for some large discrepancies with PHOTOS

$\Rightarrow$ A lot of room for improvement and validation

$\Rightarrow$ Angular distributions yet to be compared

$\Rightarrow$ However, preliminary results look promising

Technical aspects

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

$\Rightarrow$ Ready to be used, but needs latest Vincia developments (not released yet)

Sherpa's PHOTONS++ for FSR

- PHOTONS++ in Sherpa can simulate emission of soft photons based on YFS approximation
- If switched on, also hard photons
- Algorithm implementation enables thread safety

⇒ Can be explored as alternative to PHOTOS

- Recently started work on EvtGen ↔ Sherpa interface

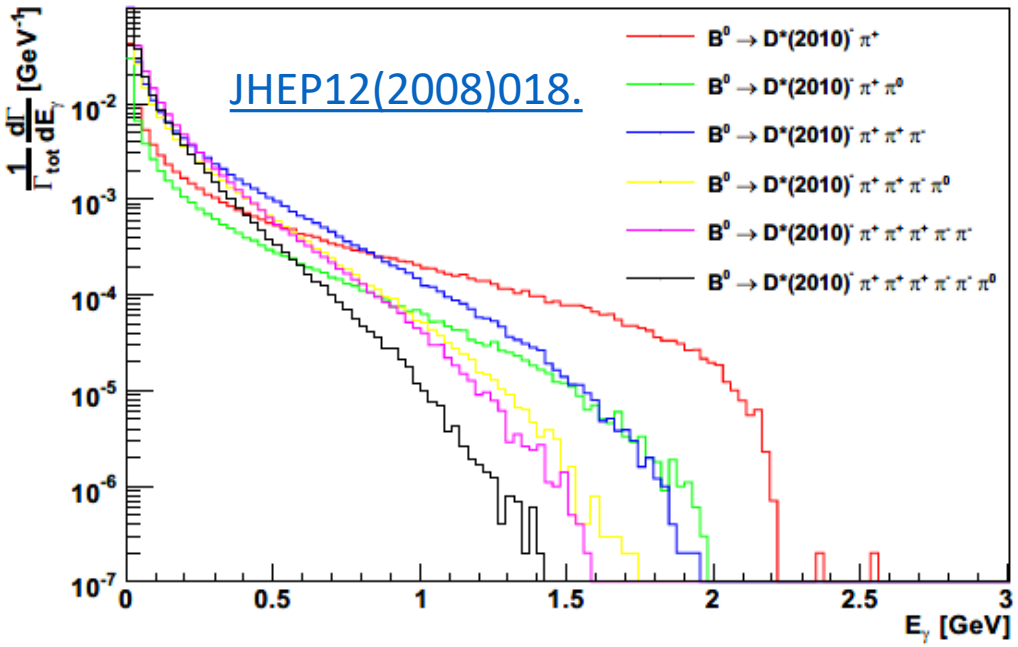
⇒ Skeleton for interface ready

⇒ Need to implement event translation and transfer (currently in contact with M. Schönherr and co.)

⇒ Requires tuning (for instance of cut-off energy)

⇒ And validation of physics output

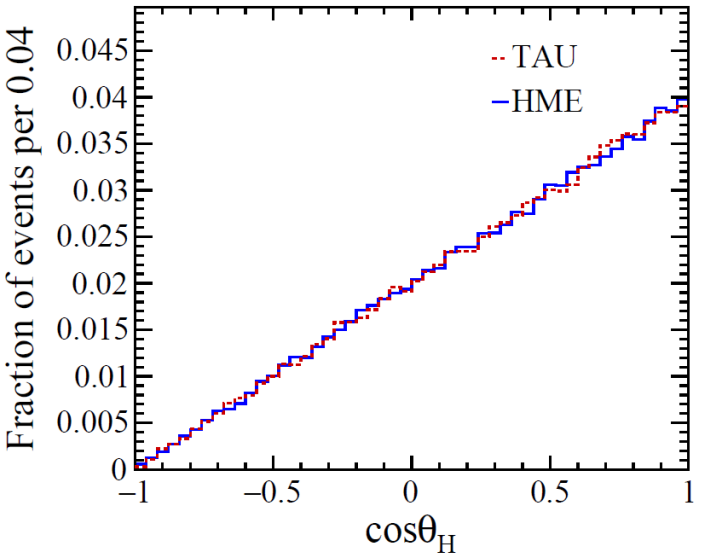
Energy of radiated soft photon



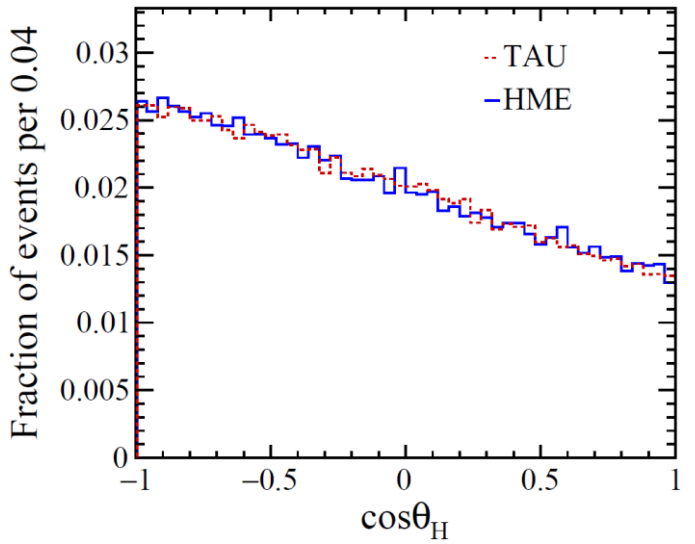
Pythia 8 for τ decays

- In addition to multithreading limitations, spin-state information of τ not propagated between EvtGen and TAUOLA:
  - 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.
- Main EvtGen $\leftrightarrow$ Pythia interface ready
- Generalization of conversion of helicity/spin basis (and initialization) not yet finalized (interesting also for interface with TAUOLA)

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



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



Pythia status and plans

- General purpose generator for simulation of collision events of particles (electrons, protons, photons, heavy nuclei) at high-energies.
- Contains models for several aspects: hard/soft interactions, parton distributions, initial/final-state parton showers, multiparton interactions, fragmentation and decay.

Rencently worked on different aspects aimed at making simulation of b-hadron faster:

- B enhancement
- Doubly-heavy hadrons in Pythia

} To be continued

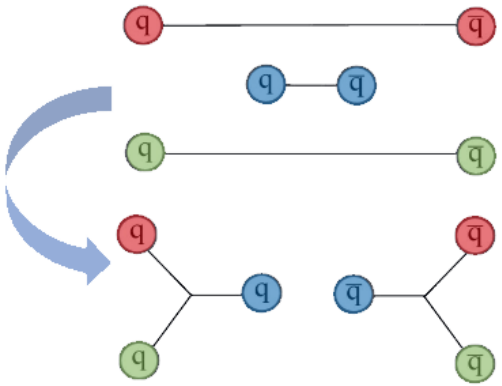
Interests for future developments:

- Optimizing simulation for colour-reconnection modes

Improving colour-reconnection models

- QCD-based colour-reconnection models with junction agree well with collision data (without particular tuning)

CR junction: choose "shortest" string configuration



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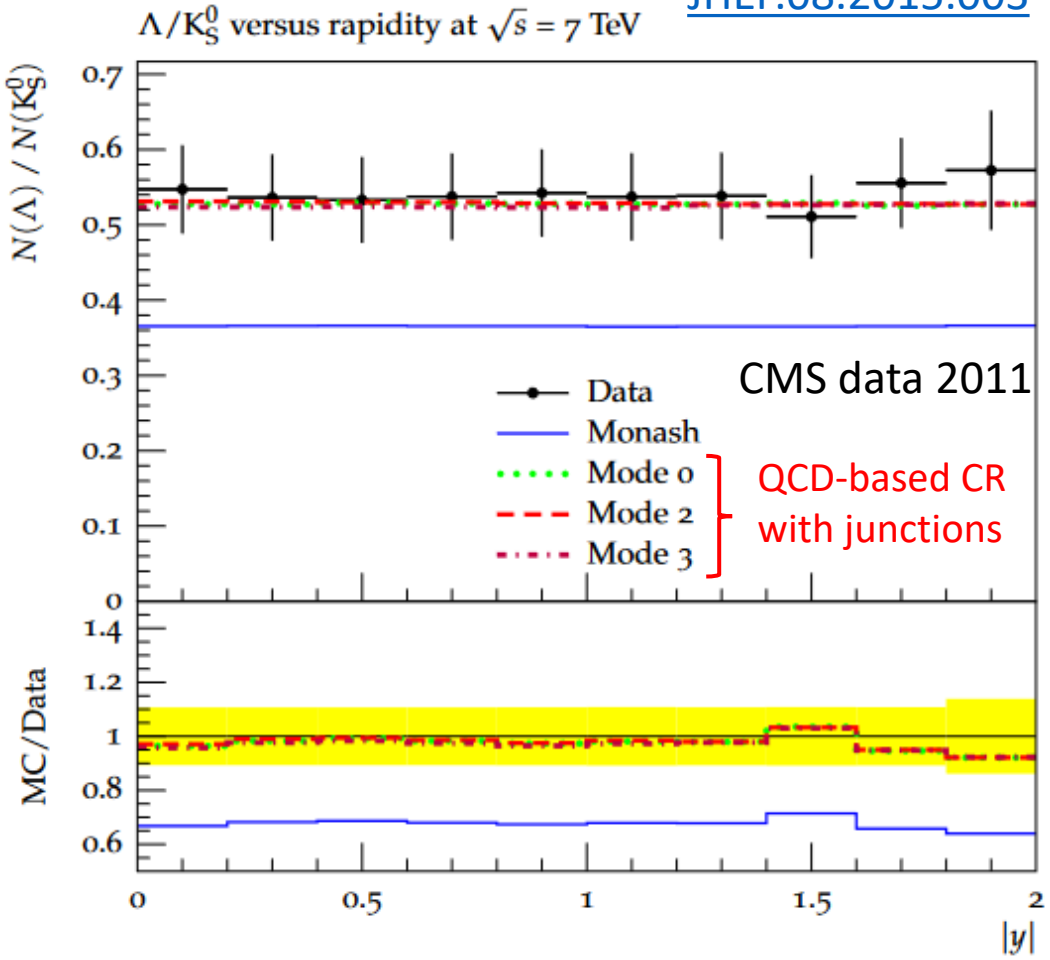


- However inefficient and CPU expensive
- Structural changes and efficient alternative algorithm for minimization identified (link)

⇒ Need to be implemented and tested, but promising for enhancement of baryon production

Summary and outlook

EvtGen:

- Continue work towards thread safety

$\Rightarrow$ Finalized common testing framework for validation

$\Rightarrow$ Converged on preliminary set of solutions to enable thread-safety of generator (full exploitation of multi-threading will require further structural changes)

$\Rightarrow$ Performance limited by external dependencies

$\Rightarrow$ Started exploring Vincia QED and Sherpa's PHOTONS++ as alternatives for FSR

$\Rightarrow$ τ decays: plan to iron out basis conversion for Pythia8 (interesting also for TAUOLA)

Pythia:

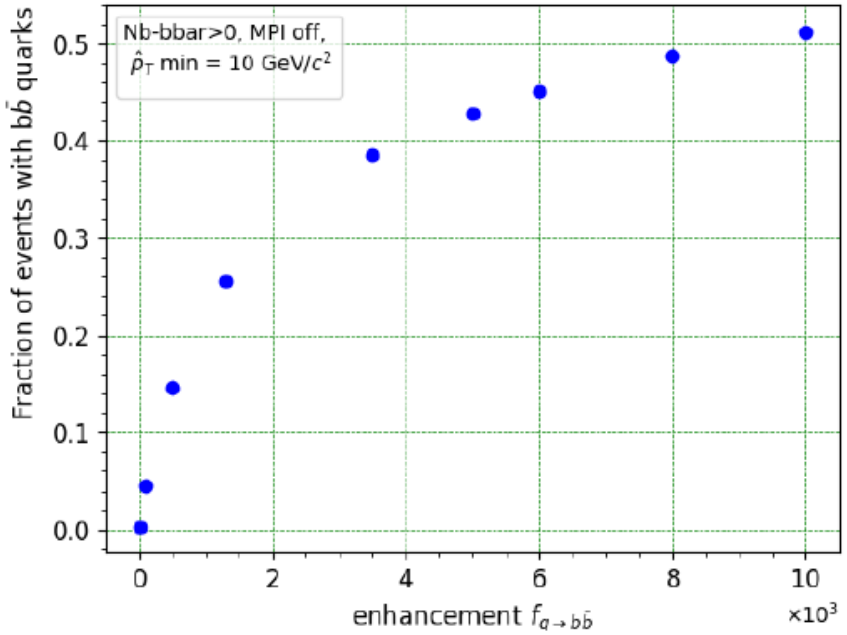
- Recently enabled Vincia QED shower to radiate off hadrons
- Work on enhancement of b-hadron production to make simulation faster

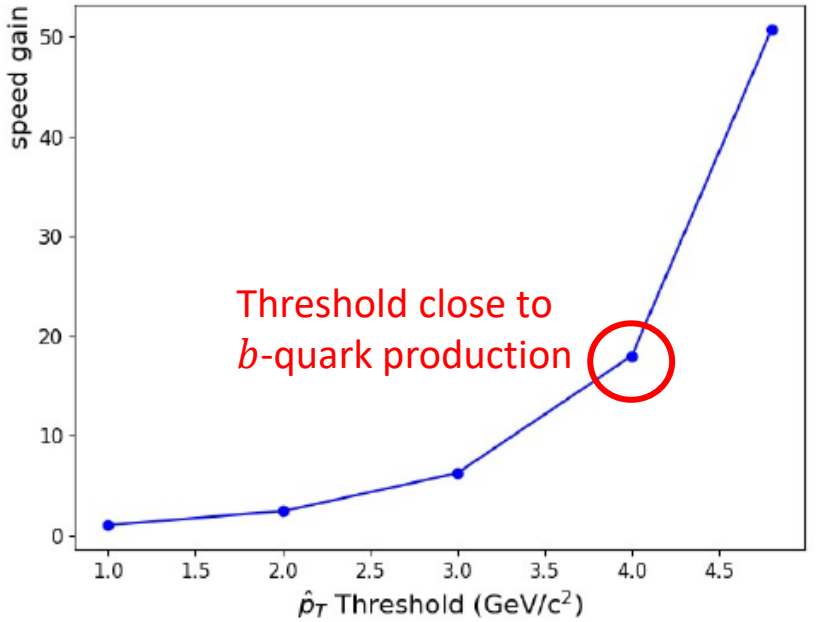
$\Rightarrow$ Interest on improving implementation of colour-reconnection models

Backup

B enhancement

- Goal: make b-hadron production faster (in LHCb simulation)
- Particularly important for cases where generator consumes more CPU time than detector simulation
- Examples: production of $B_s, B_c, \Xi_{cc}, \Omega_{bb}$
- Produced b-hadrons should still be kinematically unbiased
- Module made flexible for user to enhance $g \to c\bar{c}, b\bar{b}$ splitting
- About to be ready to tested within LHCb simulation framework GAUSS





Proof of Principle via standalone Pythia

Double-heavy hadrons in Pythia

- Pythia currently not employed for B_c or other double heavy hadrons at LHCb
- Exploring ways to increase efficiency by vetoing events without desired heavy-quark composition at early simulation stage
- Possible vetoes based on presence of correctly colour-connected heavy quarks
- Currently comparing geometrical B_c distributions with dedicated generators like BcVegPy which currently has a limited list of supported production mechanisms
- $\Delta\phi$ sensitive to production mechanism
  - $\Rightarrow$More mechanisms available in Pythia 8 and thus more uniform distributions

$\Delta\phi$: angle between B_c and $X_{b(c)}$ hadron on transverse plane