# Pythia integration and photonuclear modelling in Geant4

KAW-LDM

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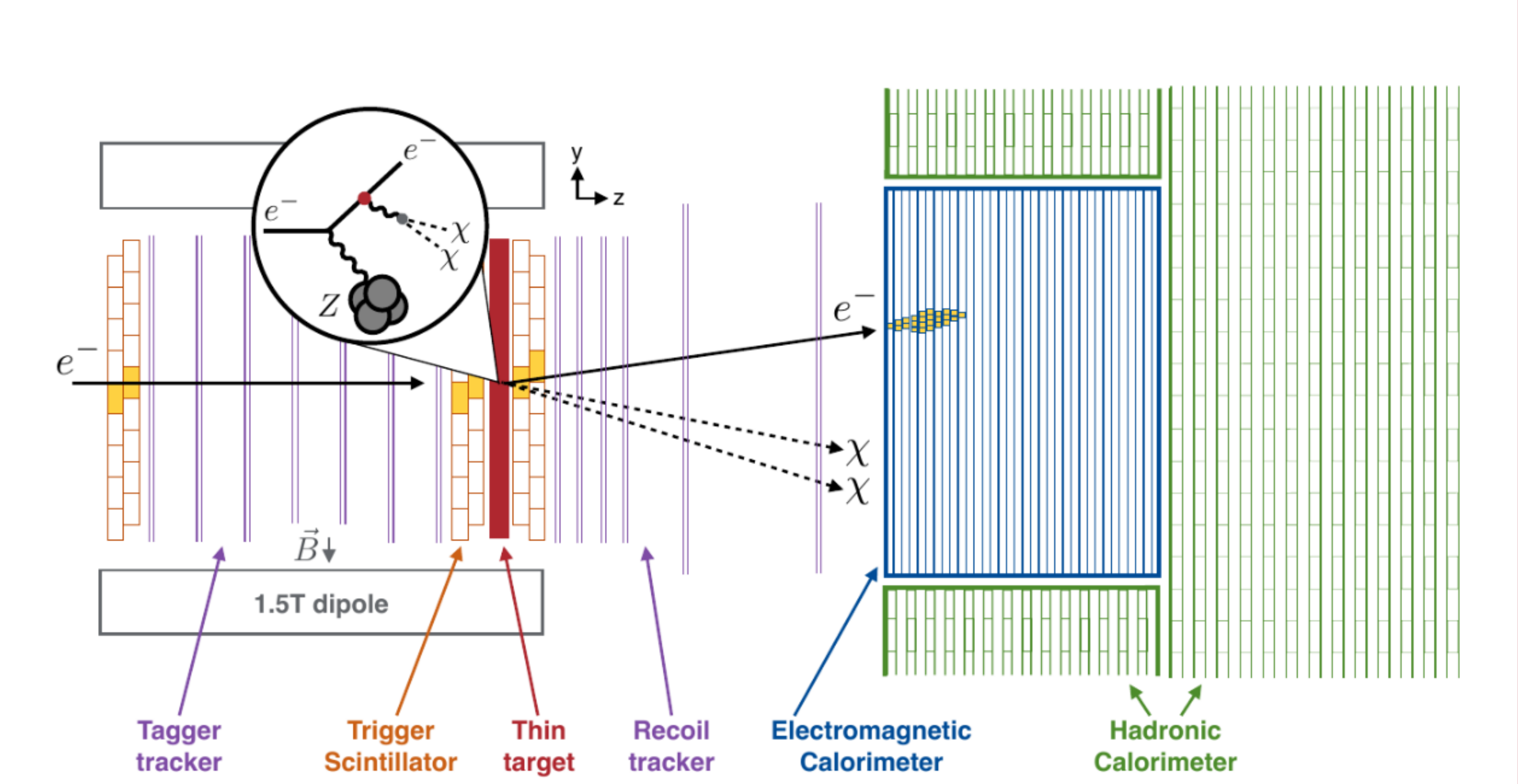
# 1. Part 1: Pythia for signal generation and integration with Geant4

# 1.1. The need for dark matter modelling in detector simulations

- Classic HEP experiments feature high factorization
  - Event generation
  - Detector simulation
- Existing alternatives are lacking in either
  - Treatment of upstream effects
    - Needs to be embedded in Geant4
  - Model flexibility and extensibility
    - Can’t be application-specific



# 1.2. Existing alternatives

- Direct placement of events from external event generators into Geant4
  - Typically from LHE files or similar tools
- `DMG4`
  - Models implemented directly in Geant4 code
  - Developed by NA64
- `G4DarkBreM`
  - Scaling MG/ME events generated at higher energies to the electron's current kinematics
  - Novel approach, but well validated w.r.t. MG
  - Developed by collaborators within LDMX, basis of current LDMX simulations

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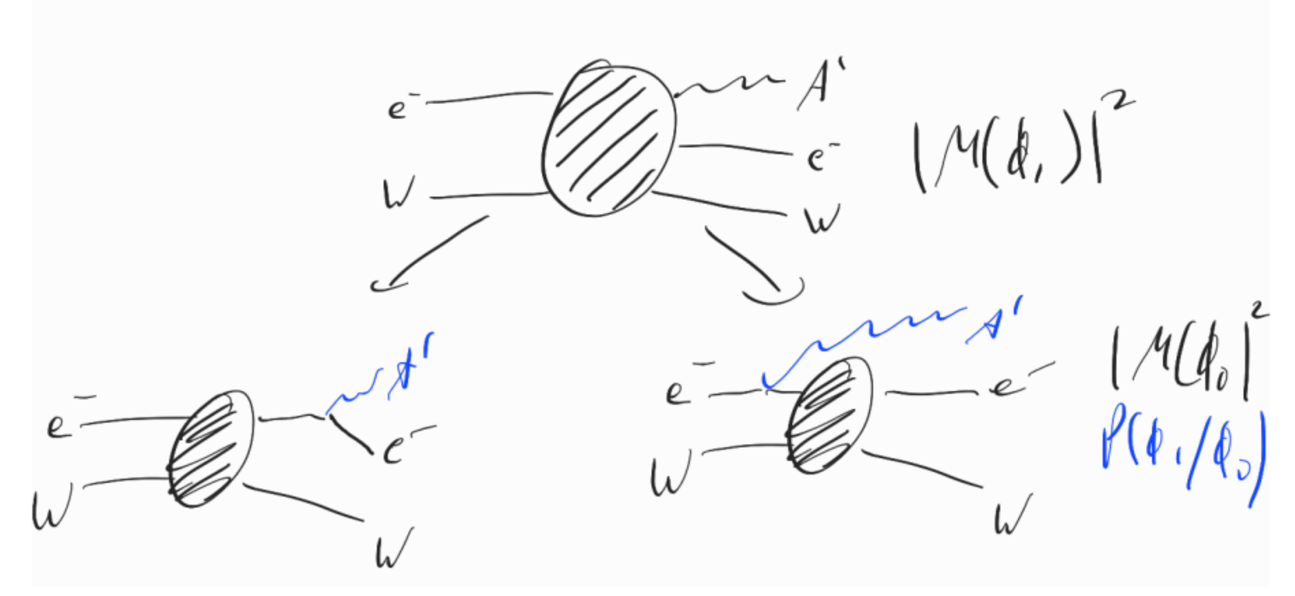
# 1.3. Signal generation with Pythia8

- Use Pythia8 to
  - Generate hard process $eW \rightarrow eW$
  - Generate dark photon radiation with DIRE parton shower
  - Augmented with model-specific corrections from MadGraph
- Embed the whole simulation in Geant4
  - Can directly make use of the efforts from Chalmers



# 1.4. Integration into Geant4

- Geant4 integration is not
  - LDMX-specific
  - Dark matter specific
- Any physics that Pythia can model can be used as a backend in Geant4
  - Hadronic and nuclear interactions are especially interesting from the Geant4 perspective
- Written to not require simulatenous expertise in Pythia and Geant4 for the user

# 1.5. Questions/Discussion

# 2. Part 2: Photonuclear reactions with focus on kaon production

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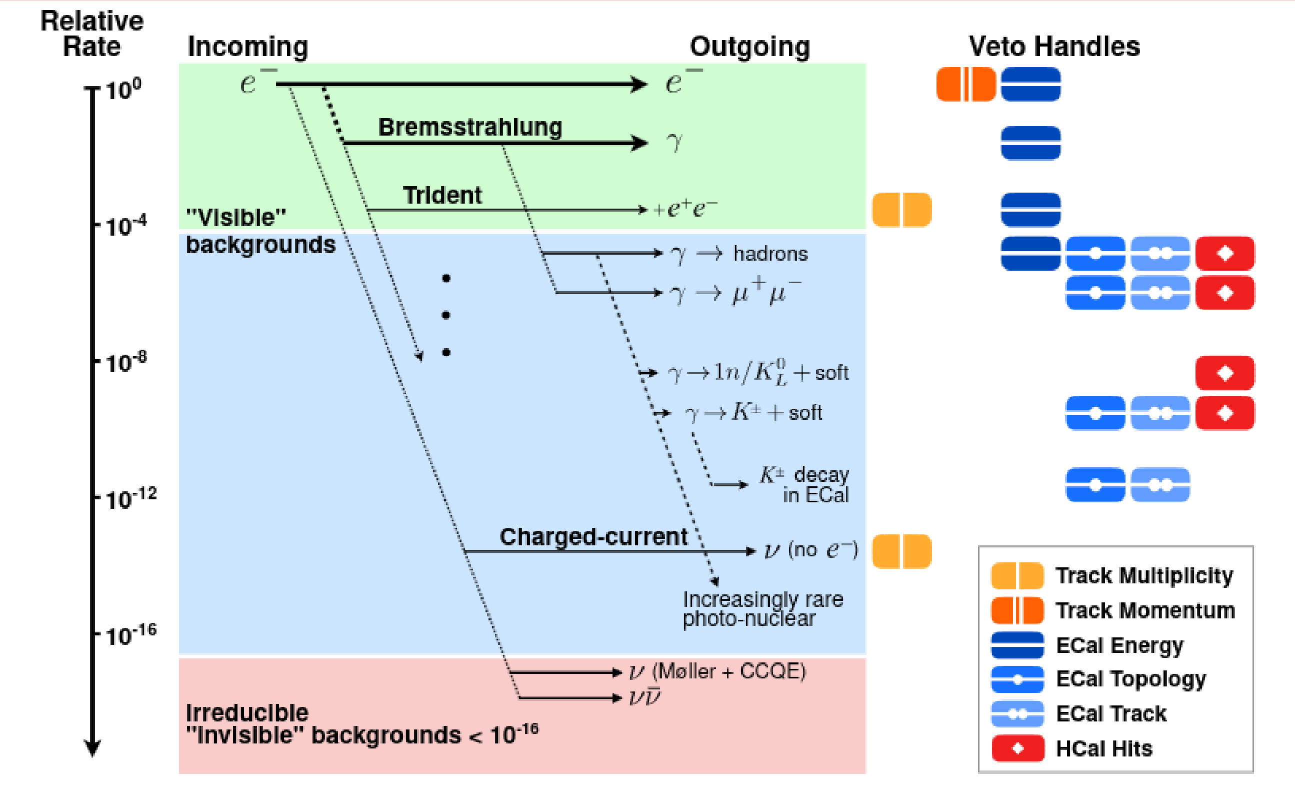
# 2.1. Background

- LDMX is sensitive to rate and topology of rare interaction
- Handled by Geant4's implementation of the Bertini intranuclear cascade
- The typical approach
  - Intranuclear cascades in all major detector simulation frameworks

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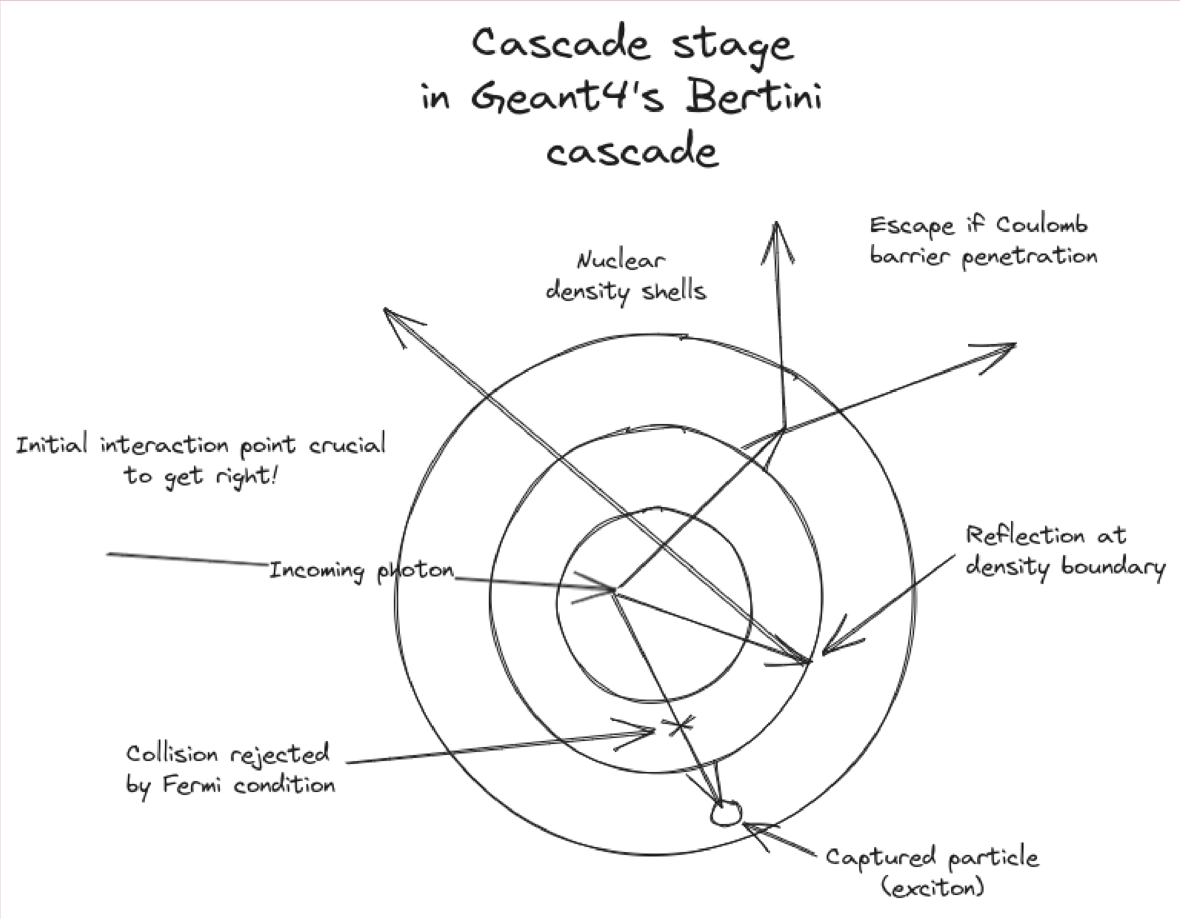
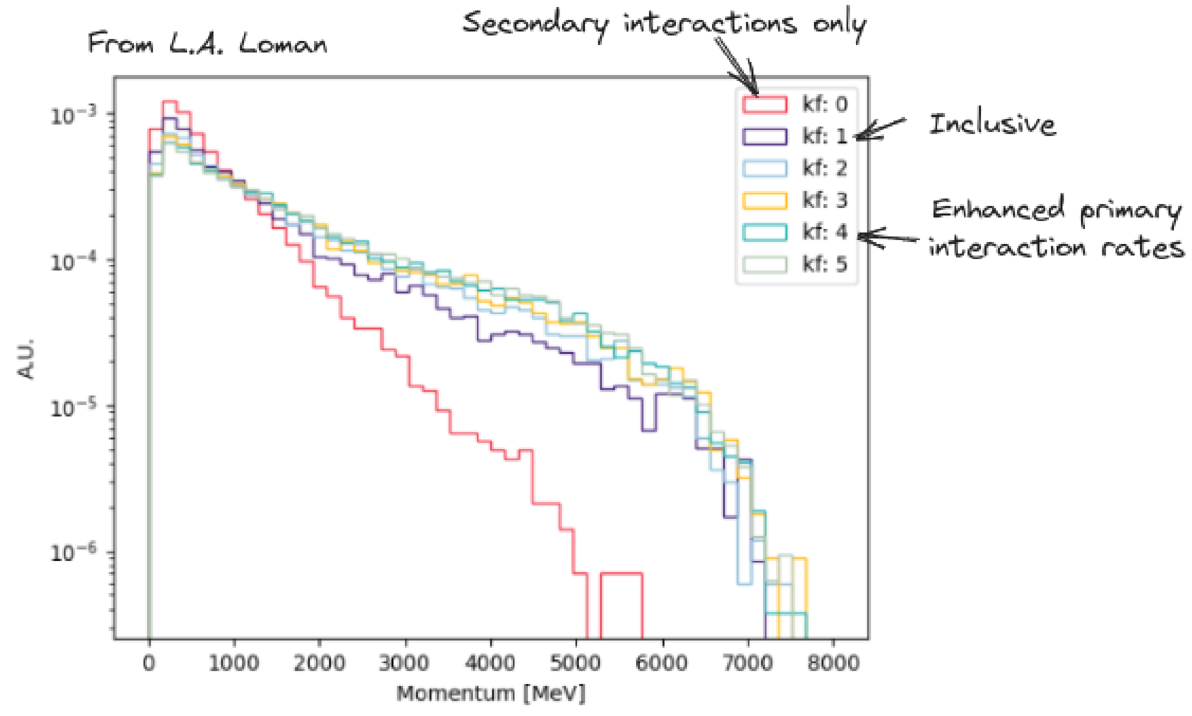
# 2.2. Intranuclear cascades

- Treat nucleus as gas of free nucleons
  - Collisions between cascade particles and nucleons
- Occurs in stages
  - Cascade: Free particle collisions
  - Pre-equilibrium: Exciton evaporation
  - Compound nucleus: Equilibrium evaporation phase
- Main difference between modeles
  - Nuclear effects



# 2.3. Production of kaons in intranuclear cascades

- Two sources:
  - $\gamma + N$ (Primary)
  - subsequent $h + N$ (Secondary)
- Rates of challenging kaon events in agreement between the two major HEP detector simulation frameworks
  - Modest disagreement with others
- Primary crucial for LDMX, but secondary not negligible

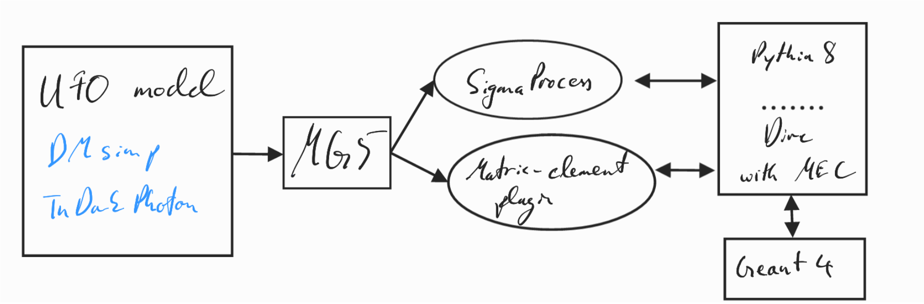



(a) Momentum $K_L^0$

# 3. Backup

# 3.1. Pythia8

## Integration of model and tools




- Generate process and matrix-element plugin code libraries ONCE per UFO model, using MadGraph
- Then build and run Geant4 + Pythia (linking to MG5-generated code)



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# Pythia8

## PYTHIA 8 — GEANT 4 interface: Status & prospects

- First implementation of UFO → MADGRAPH → PYTHIA 8.3 → GEANT 4 running
  - Generate eW process based on MADGRAPH process library in PYTHIA 8.3
  - Allow for DIRE's generic dark photon shower emissions
  - Correct generic dark photon emission pattern to specific dark matter model (TnDarkPhoton)
  - Run and access generated events through GEANT
- Next steps
  - Validation and first signal simulation results
  - Comparison to fixed-order signal results
- Opportunities
  - Look at visible decays
  - Alternative target modeling (ANGANTYR, photoproduction, MADGRAPH for eA, ...)
  - Exploit generic GEANT PYTHIA interface



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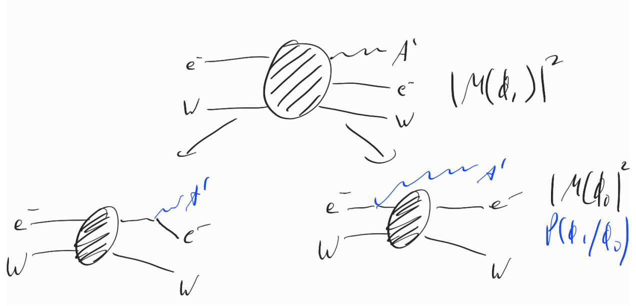
# Pythia8

## PYTHIA signal for dark bremsstrahlung

Use DIRE's dark photon shower with iterated matrix element corrections. Possible advantage over MADGRAPH: Sudakov factors from shower, ME corrected to give right emission pattern. Multiple emissions. All orders.

- Consider matrix element state $|\mathcal{M}(\Phi_0)|^2$
- Parton-shower produces branching according to $P(\Phi_1/\Phi_0)|\mathcal{M}(\Phi_0)|^2 \mathrm{d}\Phi_1$
- Apply MEC factor to recover full fixed-order matrix element (model-specific!)

$$\mathcal{R}(\Phi_1) = \frac{|\mathcal{M}(\Phi_1)|^2}{\sum_{\Phi'_0} P(\Phi_1/\Phi'_0)|\mathcal{M}(\Phi'_0)|^2}$$

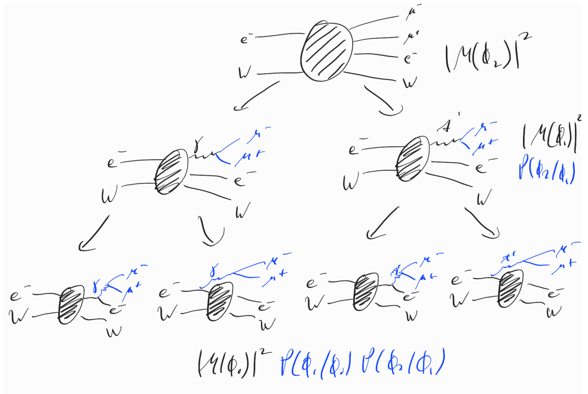


# Pythia8

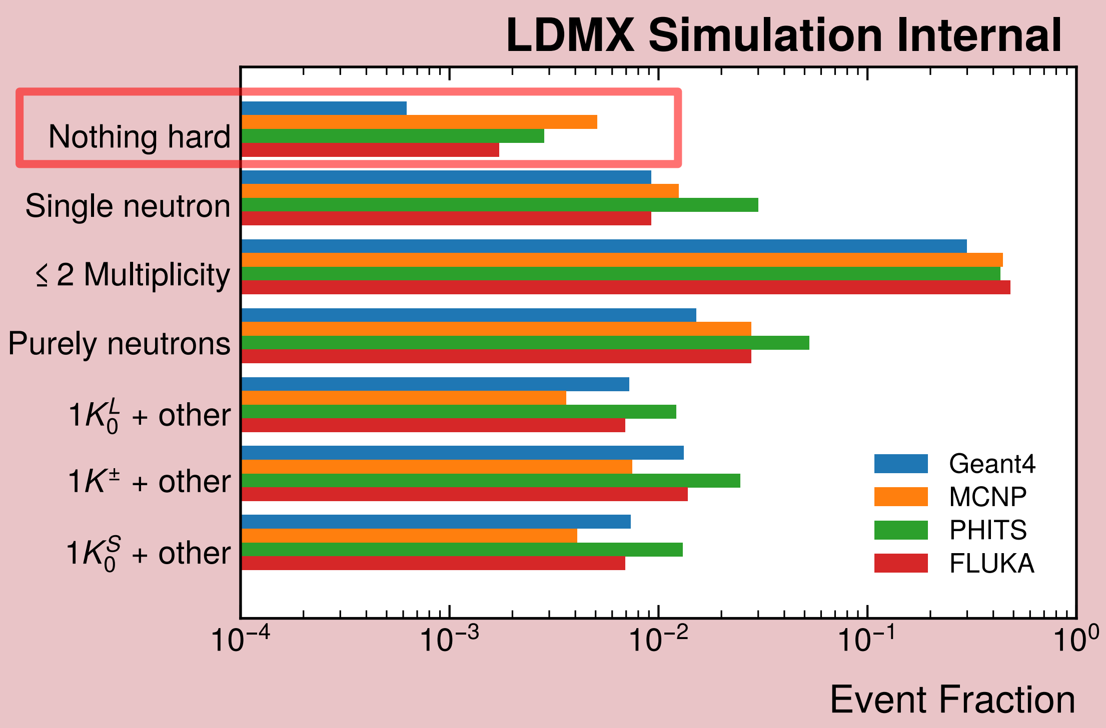
## PYTHIA 8 signal for visible final states

- Iterate, taking all possible PS histories into account
- Includes interference between $\gamma$ and $A'$ channels

$$\mathcal{R}(\Phi_2) = \frac{|\mathcal{M}(\Phi_2)|^2}{\sum_{\Phi_1'} P(\Phi_2/\Phi_1')\mathcal{R}(\Phi_1') \sum_{\Phi_0'} P(\Phi_1'/\Phi_0')|\mathcal{M}(\Phi_0')|^2}$$



# 3.2. Photonuclear

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