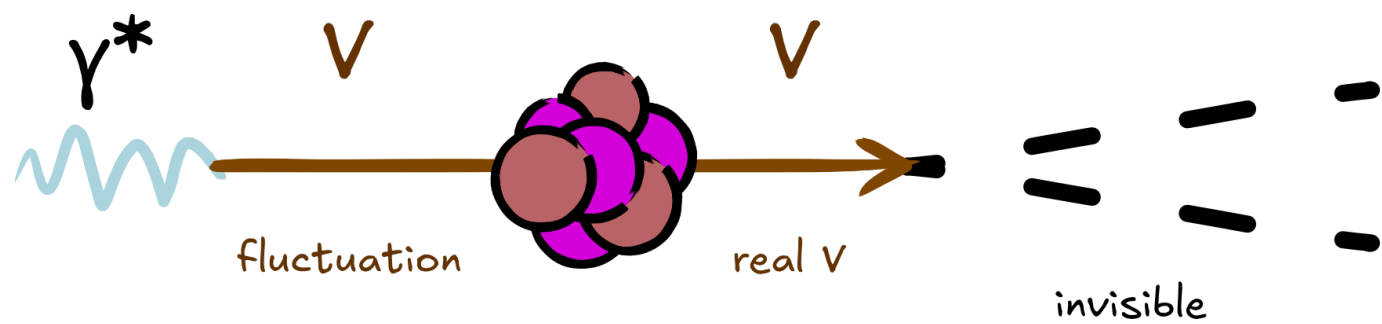
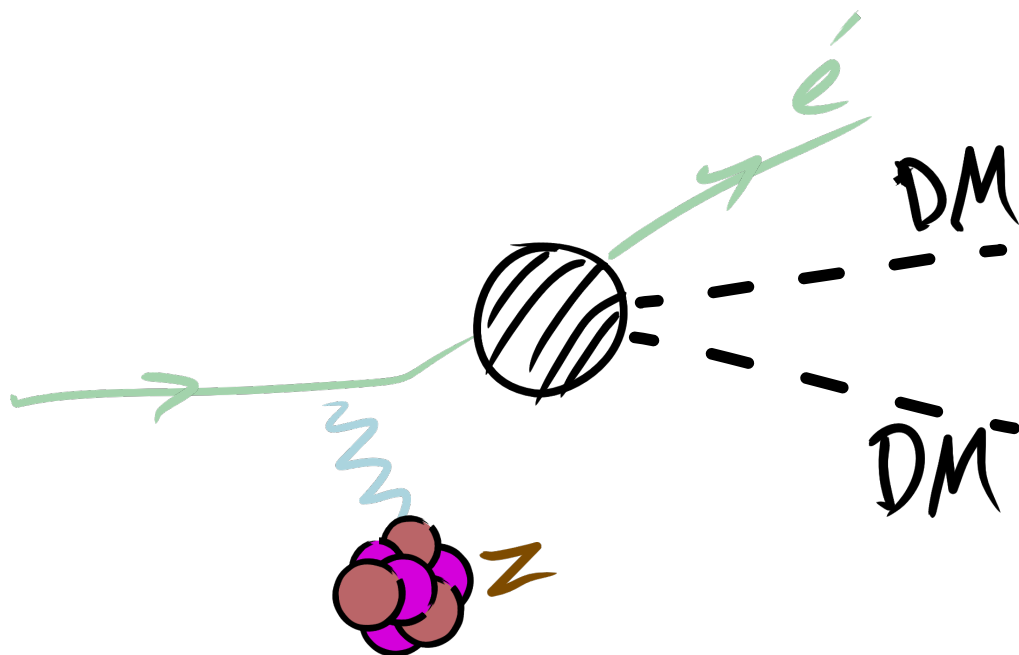
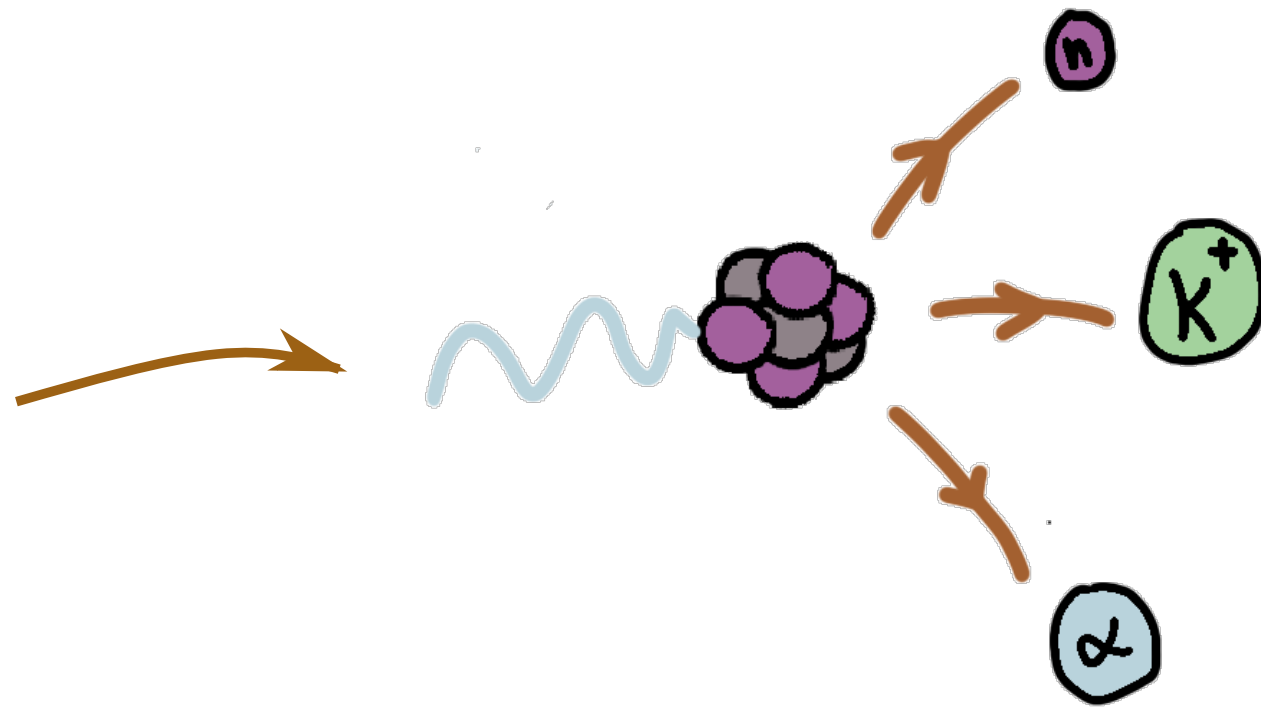
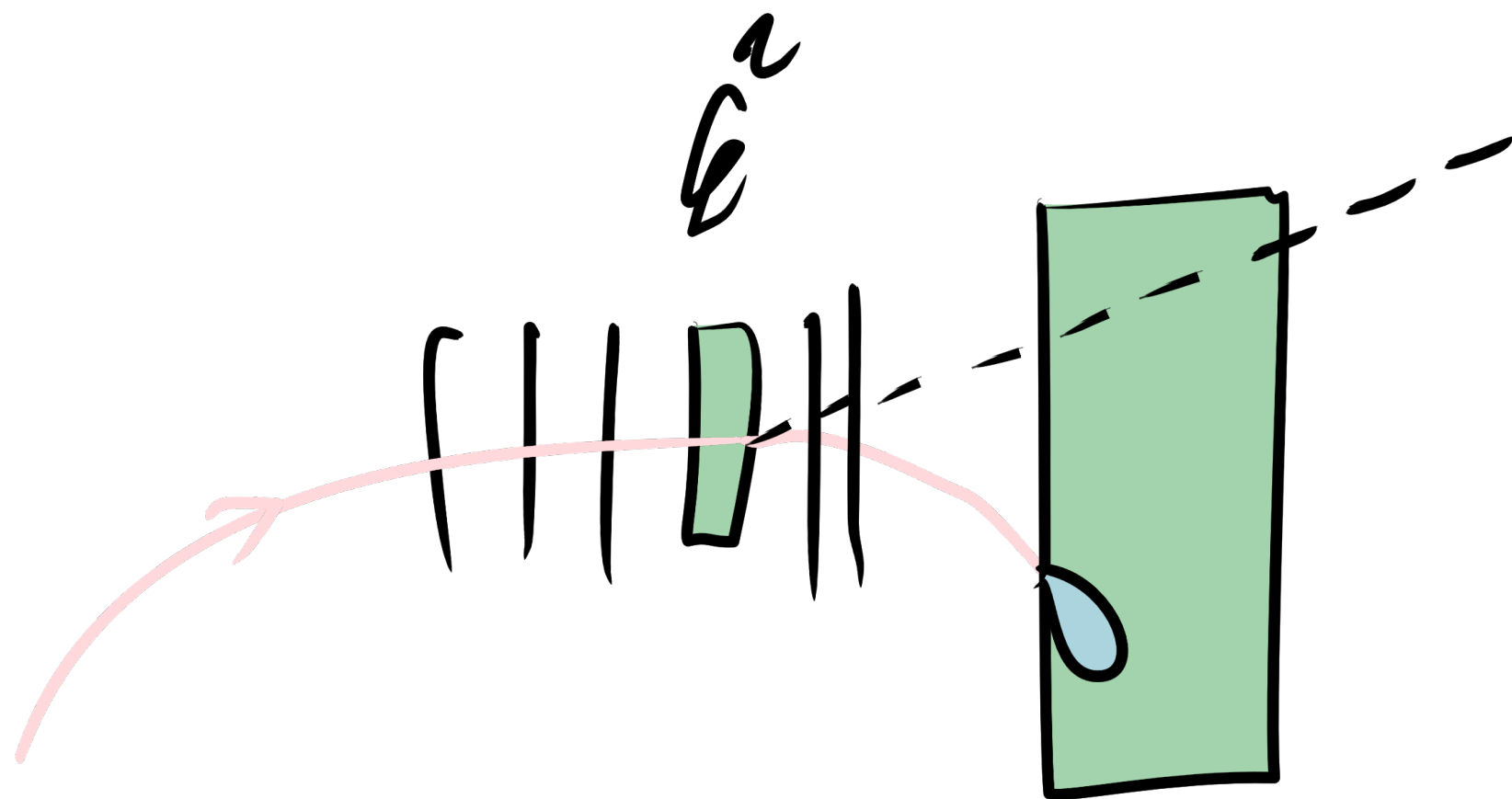


QCD Backgrounds

But also something entirely different

Hi, I'm Einar!

I work on things like these



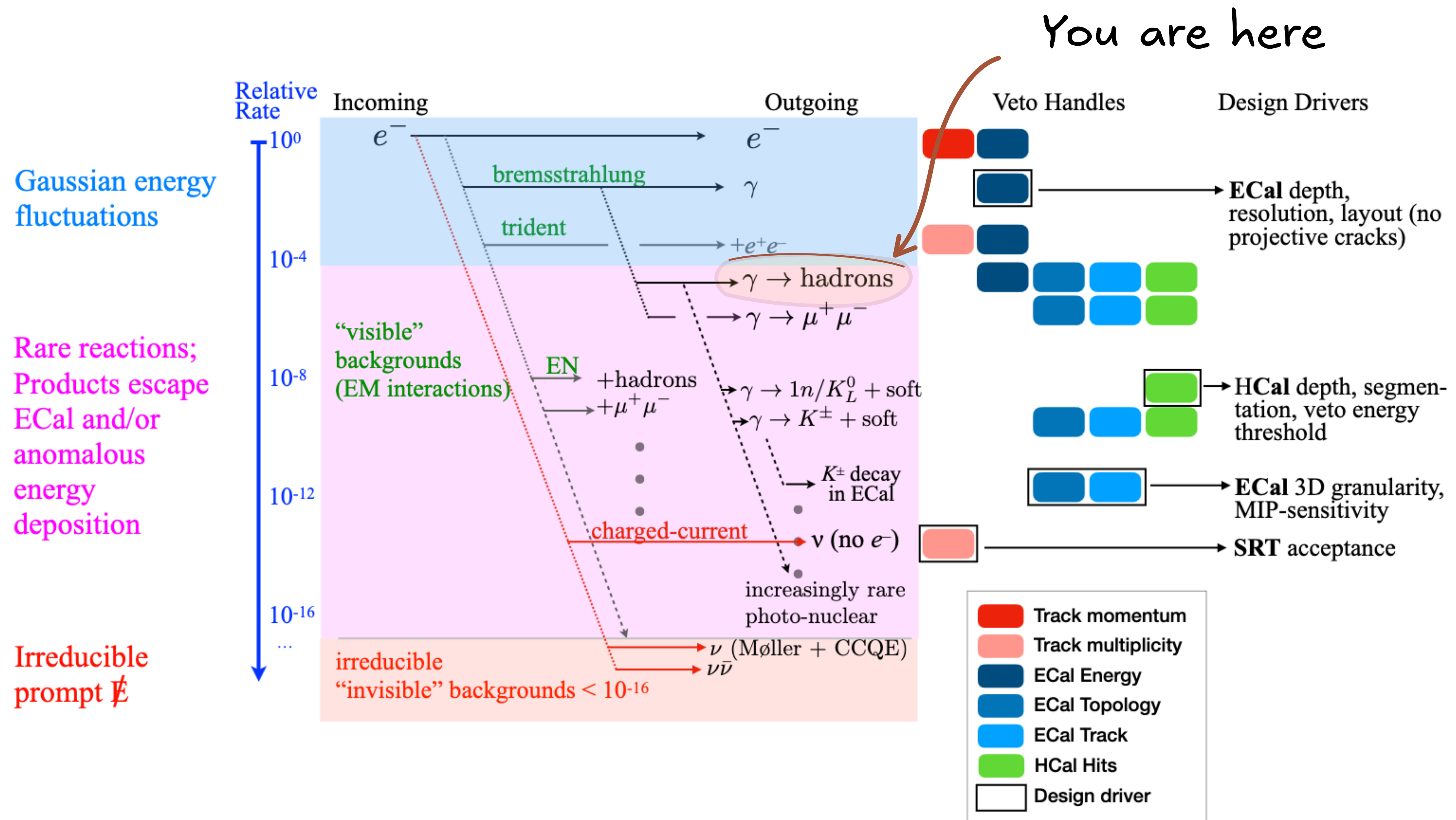


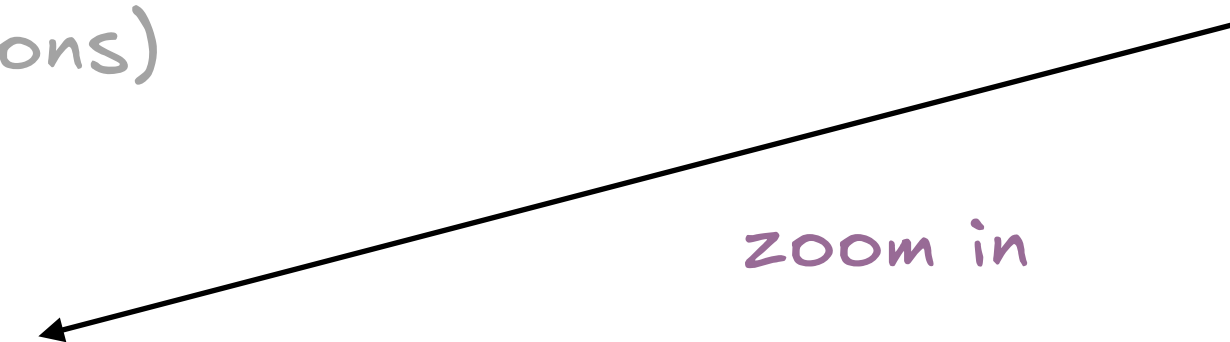
Figure 3.3: An illustration of the potential background sources from Standard Model interactions for the missing-momentum search. Relative rates of each process are shown, in addition to detector subsystems capable of distinguishing each process from a dark matter signal.

The hadronic photon

"A real photon has a complicated nature"

$$|\gamma\rangle_{\text{phys}} = c_\gamma |\gamma\rangle_{\text{bare}} + \sum_{\ell} c_\ell |\ell^+ \ell^-\rangle + \sum_q c_q |q\bar{q}\rangle + \sum_q c_{qg} |q\bar{q}g\rangle + \dots$$

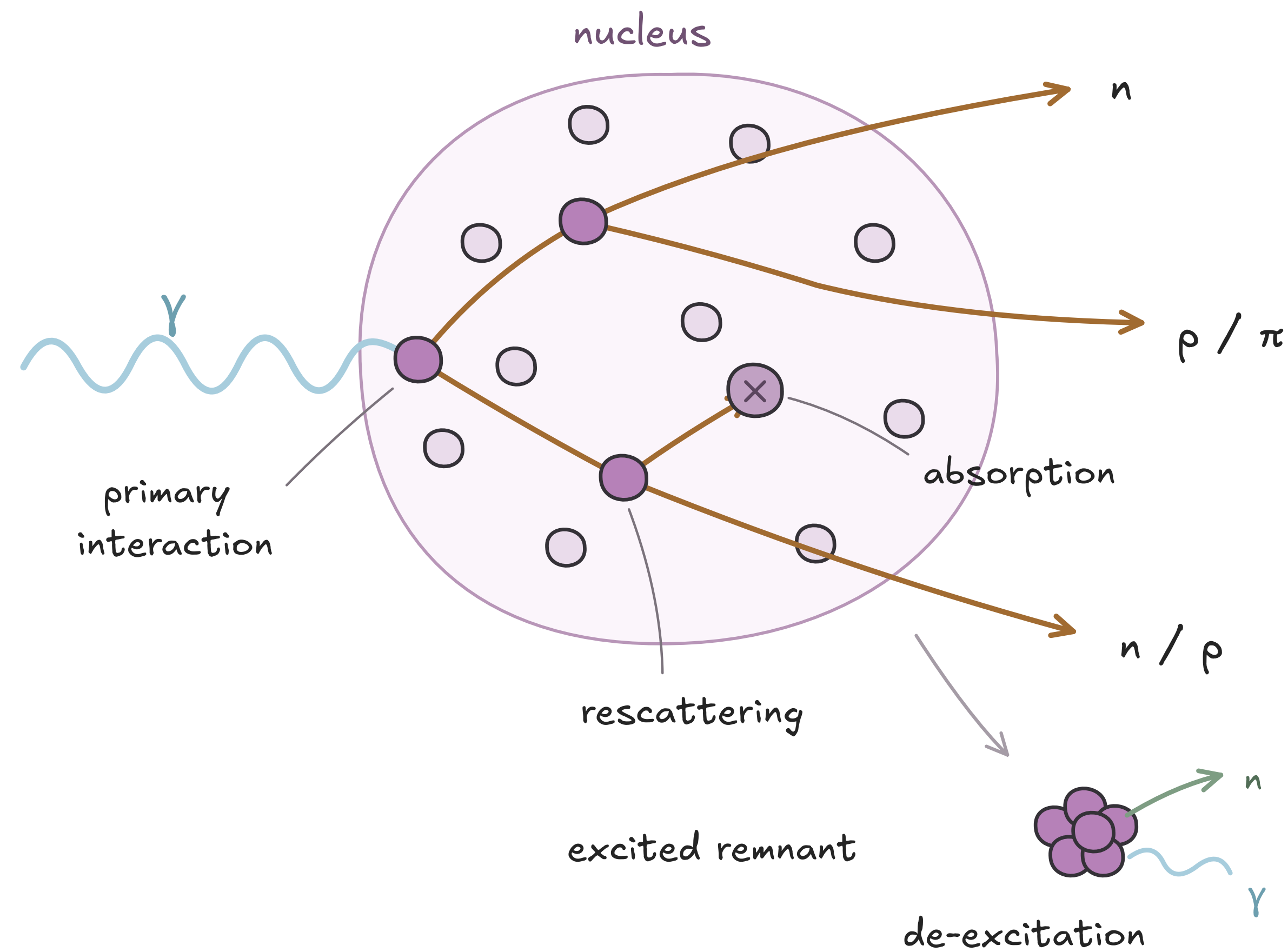
bare photon leptons: irrelevant here
(no strong interactions) hadronic fluctuations



$$\sum_{V=\rho^0, \omega, \varphi, J/\psi} c_V |V\rangle + \sum_q \int_{k_0^2}^{\mu^2} dk^2 c_q(k^2) |q\bar{q}; k^2\rangle + c_{qg} |q\bar{q}g\rangle + \dots$$

vector mesons anomalous continuum higher Fock states
low-mass / VMD higher-mass $q\bar{q}$

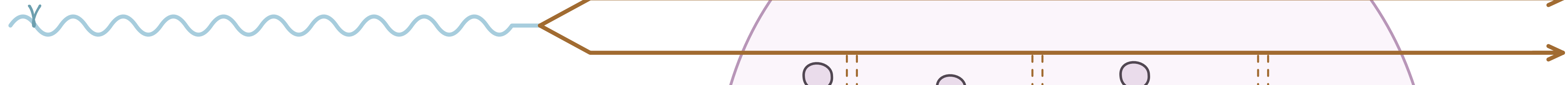
Photonuclear modelling



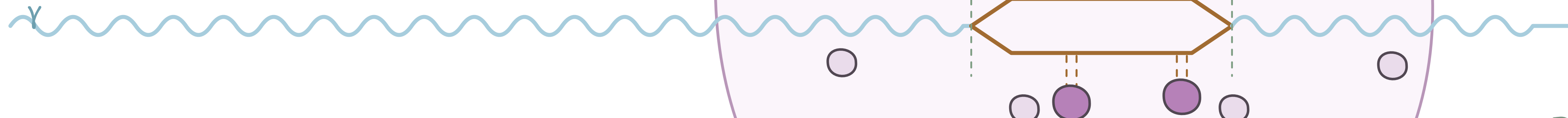
Weird and hard regime

ρ -like fluctuation in W

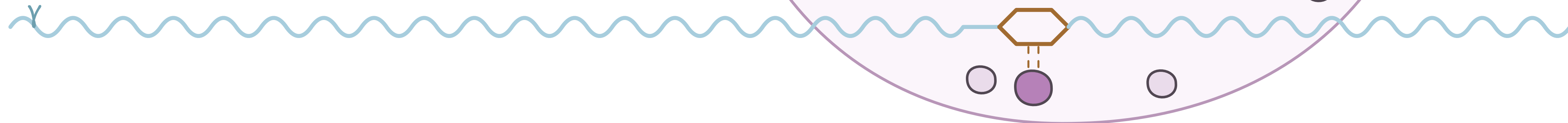
frozen
 $E\gamma \gtrsim 12\text{--}25\text{ GeV}$



finite coherence
 $E\gamma \sim 3\text{--}15\text{ GeV}$



short coherence
 $E\gamma \lesssim 2\text{--}5\text{ GeV}$



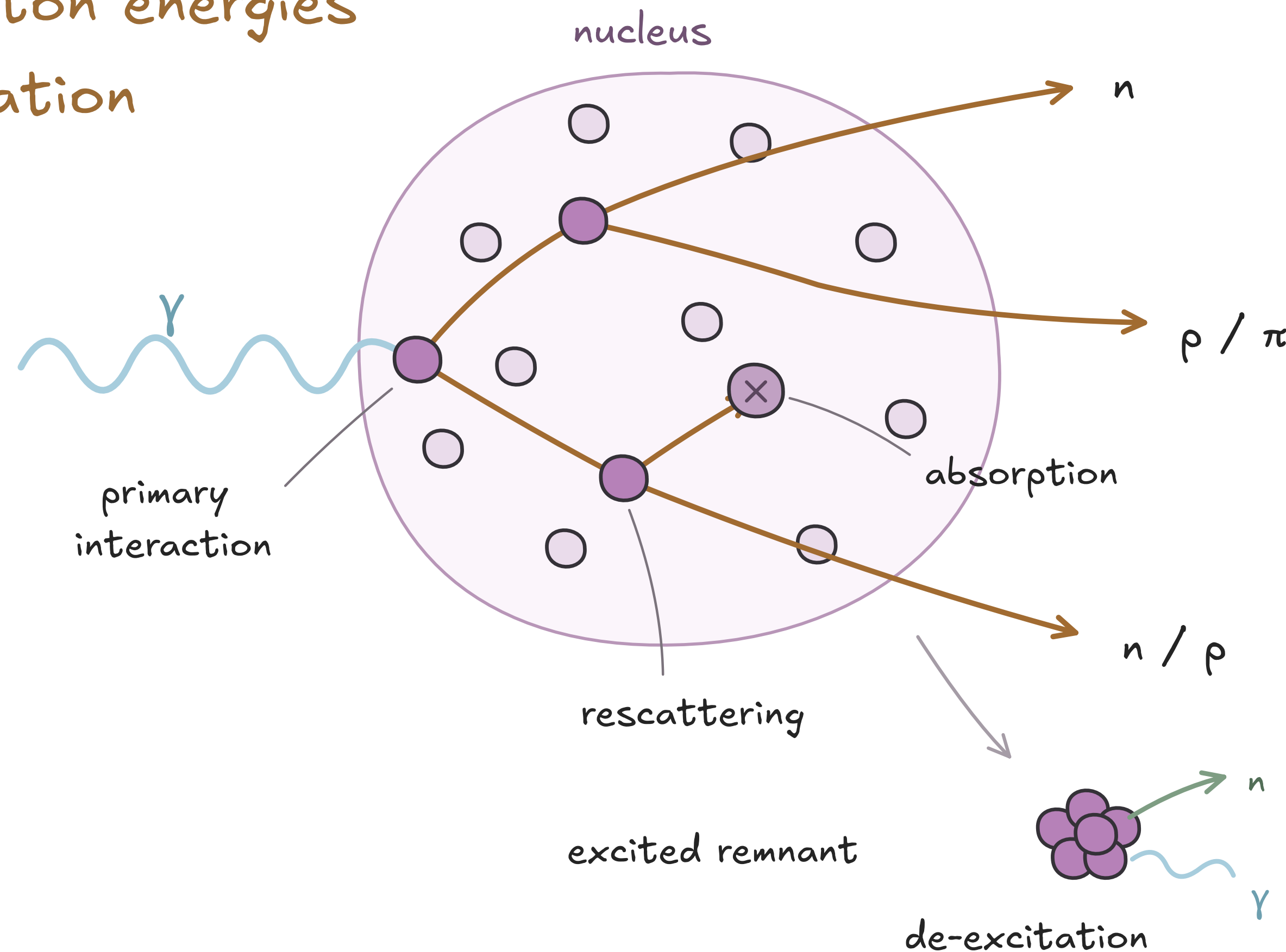
Bertini in LDMX

Bertini for all photon energies
in the LDMX simulation

Semi-classical

Nuclear density shells
Fermi motion
Pauli blocking

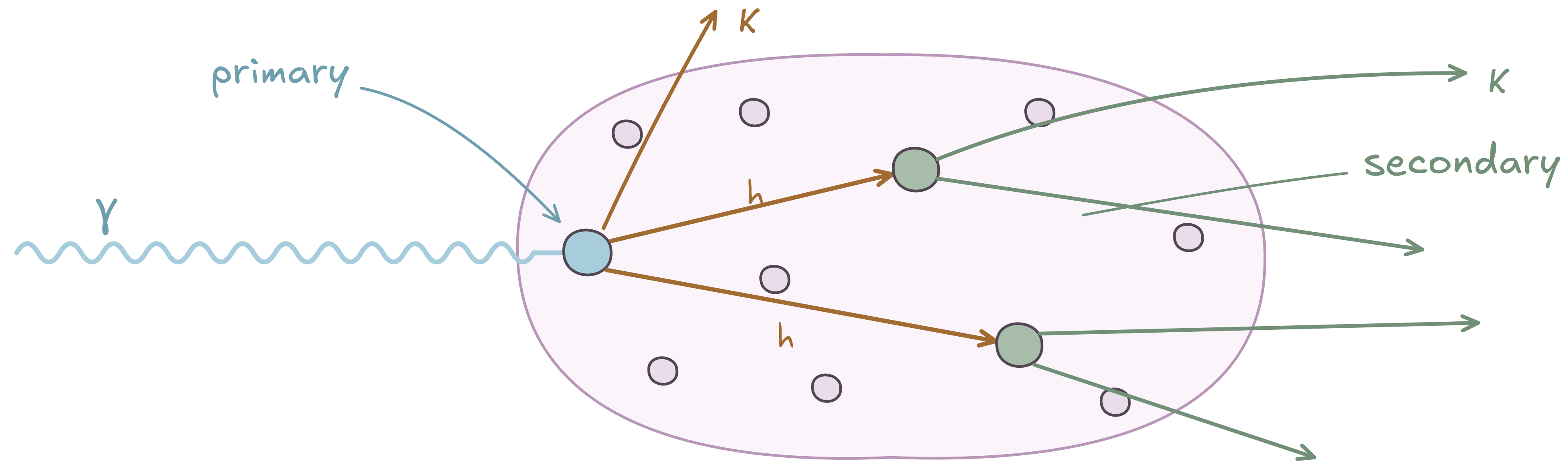
“Very phenomenological” or
“Very data-driven”
depending on who you ask



Early LDMX studies led to
several Bertini corrections.

Most are now included
in upstream Geant4

Biasing rare events: a cautionary tale



Biasing only the primary...

Enhance kaons at the photon vertex;
leave cascade kaons unenhanced.
The primary/secondary mixture shifts.

Better: forced collisions

Geant4 selects a PN reaction in the volume
→ resample the full PN event generator
→ weight the selected events accordingly

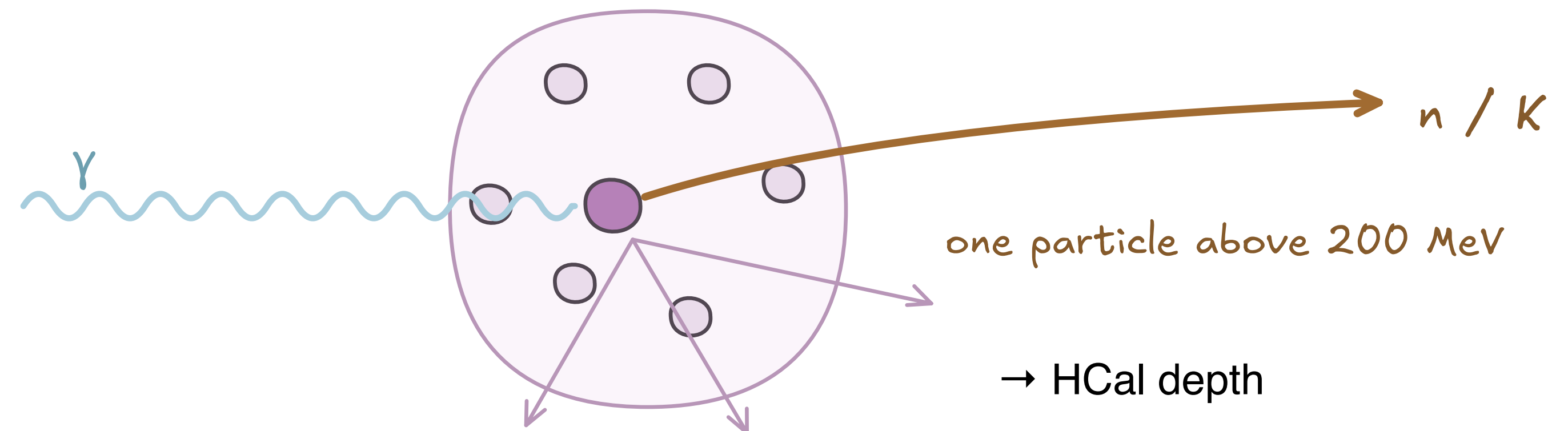
Rare tails beyond LDMX's total PN statistics on a laptop.

Photonuclear final states

one hard hadron

one energetic neutron or kaon
escapes the nucleus

soft nuclear debris remains

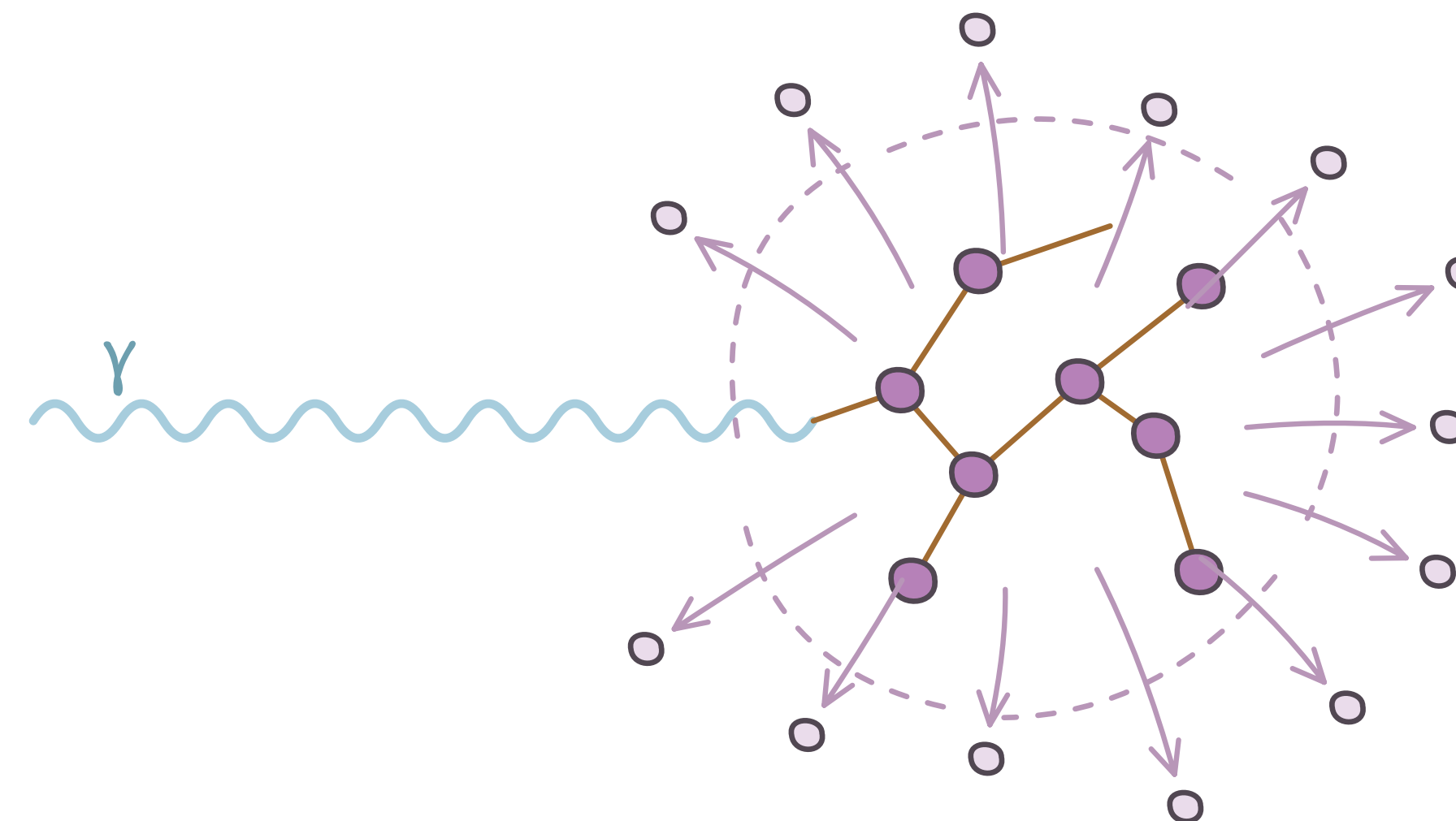


"nothing hard"

a "tungsten bomb"

the cascade breaks up the nucleus
energy shared among many soft particles

none above 200 MeV



many soft nucleons
and fragments

High neutron multiplicity
often near the missing-energy
trigger threshold
→ side-HCal coverage

"hard" > 200 MeV KE

LDMX Simulation

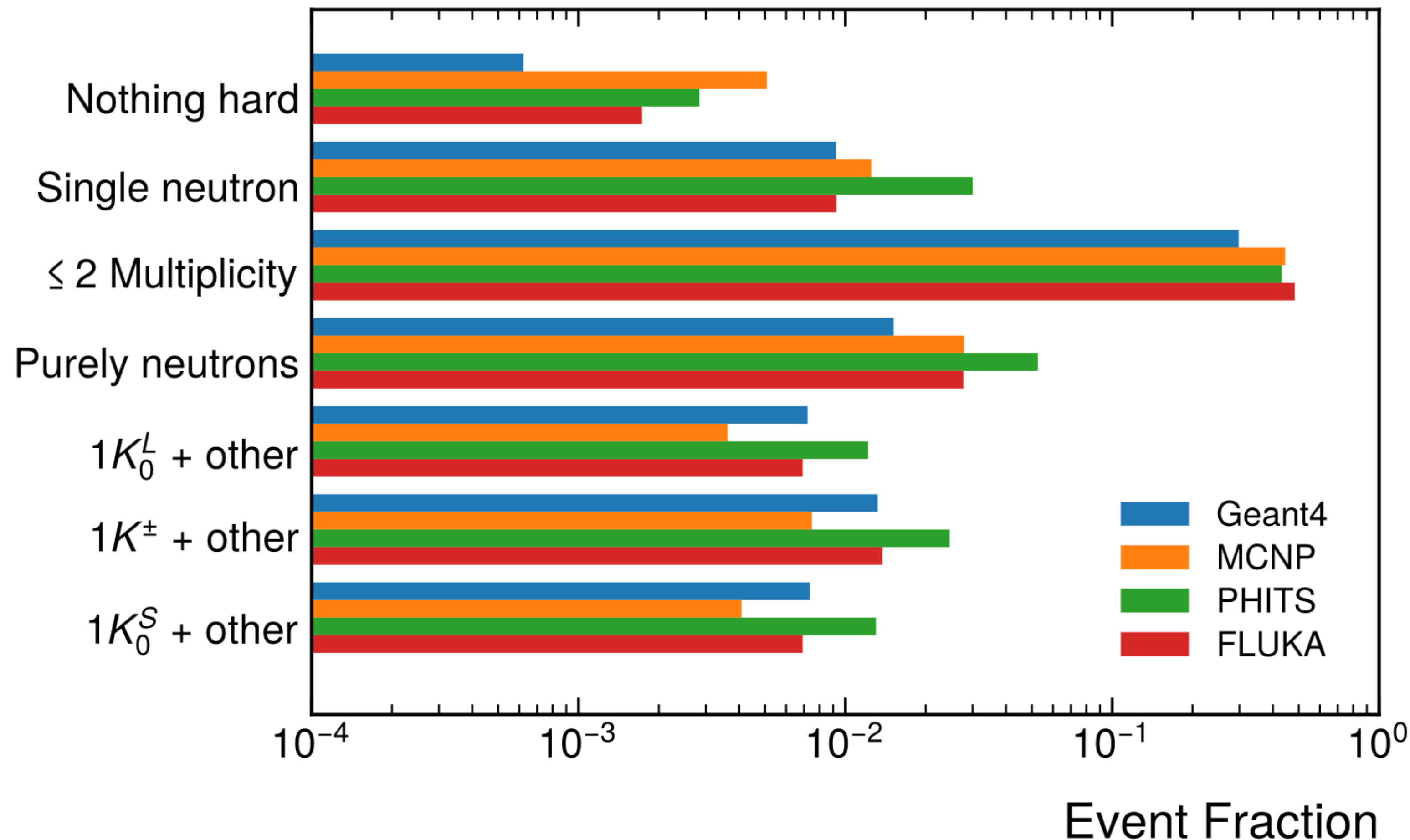


Figure 4.1: Predicted relative rates of photo-nuclear final states from 25000 events generated by the Bertini model in Geant4 (blue), the CEM model in MCNP (orange), the JAM model in PHITS (green), and the PEANUT model in FLUKA (red). Events are classified based on the multiplicity of different particle species with kinetic energy above 200 MeV.

Figure 4.1 · [LDMX design report arXiv:2508.11833](#)

Bertini

Heikkinen, Stepanov & Wellisch (2003)
[Bertini intra-nuclear cascade implementation](#)

CEM — Cascade-Exciton Model

Mashnik & Sierk (2012)
[CEM03.03 User Manual](#)

JAM

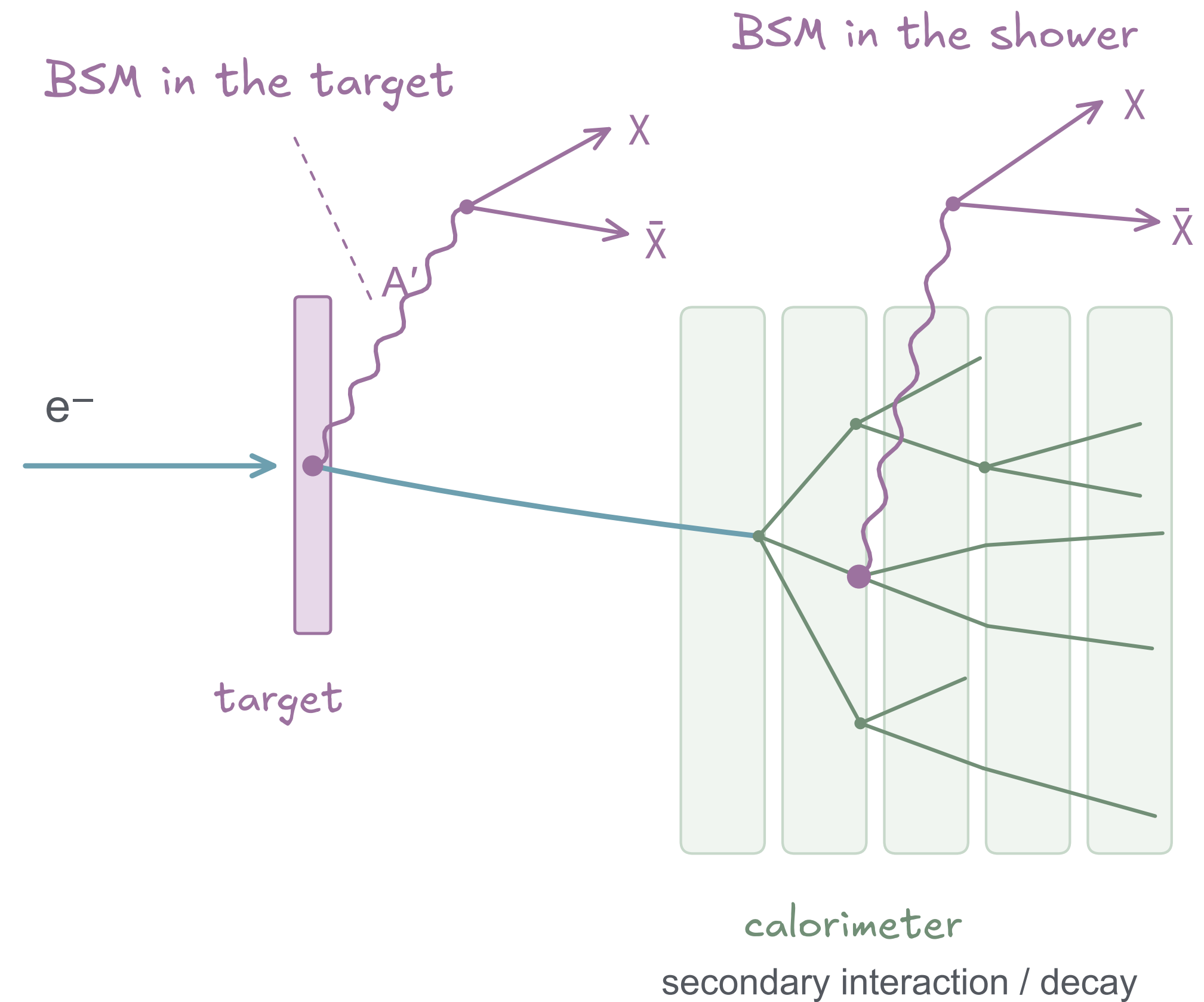
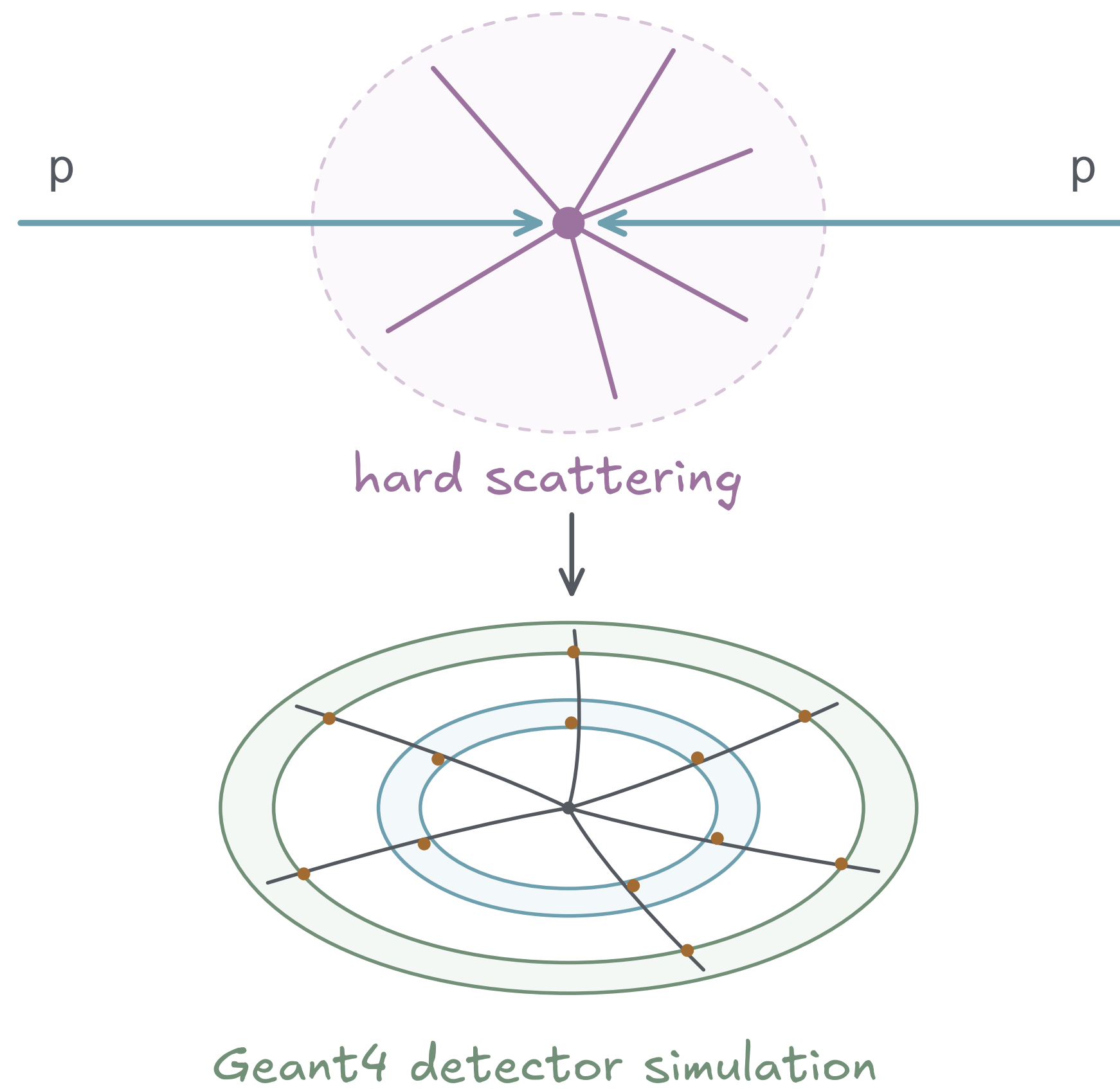
Nara et al. (2000)
[Hadronic cascade model · Phys. Rev. C 61, 024901](#)

PEANUT

Ferrari & Sala (1998)
[The Physics of High Energy Reactions](#)

Now for something
completely-ish different

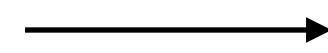
Traditional collider factorization



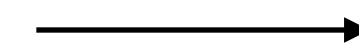
See also: [DMG4 \[1\]](#) · [PETITE \[2\]](#) · [G4DarkBreM \[3\]](#)

FTF

String excitation



Hadronization



Decays

Bertini

Nuclear transport



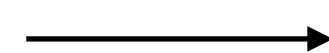
Collision model



Cascade continues

And the other way around

Event generator



Excited remnant

Geant4 nuclear
de-excitation /
Final state interactions

Done in the neutrino
community with GENIE



Putting your simulation in a detector

1. Raw LHE events with wrong production...

2. Write your own model in Geant4 code (DMG4)

3. Scale LHE events (G4DarkBreM)

4. Convince Geant4 to implement it

5. Fancier techniques like PETITE

Why not just run the event generator?

Everyone ends up doing the same thing in incompatible ways

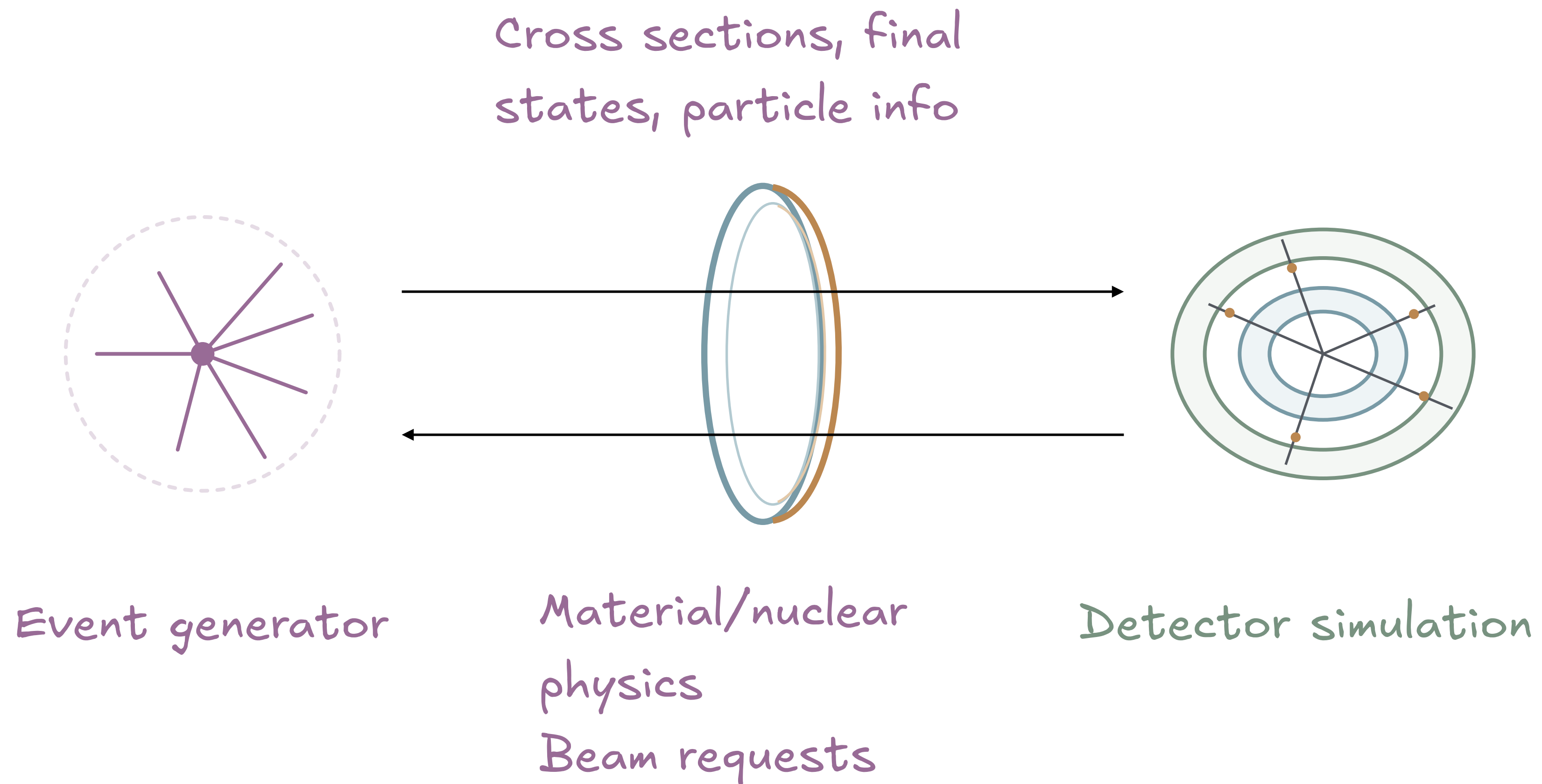
Usually: You have that one thing about your calculation that is "special" (e.g. why doesn't LDMX use DMG4?)

Embedding event generators directly

Straight forward in principle, rarely done in practice

Requires simultaneous knowledge (or cooperation) about
the event generator and Geant4

Solution is to build portals



Shorthand for: Translations & Dealing with all the technical faff

Castalia: A portal between PYTHIA8 and GEANT4

Einar Elén^{a,*}, Luis Sarmiento Pico^a

^a *Lund University, Department of Physics, Box 118, 221 00 Lund, Sweden*

Abstract

We present Castalia (from the Castalian spring where pilgrims and priests would cleanse themselves before consulting Pythia, the oracle at Delphi), a C++17 software library that bridges the physics modeling capabilities of the general purpose Monte Carlo event generator PYTHIA8 [1] into the detector transport infrastructure of GEANT4 [2, 3, 4]. Traditionally, event generation and particle transport is treated as an entirely factorized process. While such a scheme is natural at collider experiments, it is not a foundational necessity and the hard distinction in fact prevents new developments in one area from benefiting the other. Moreover, the factorisation fundamentally breaks down in several important contexts such as fixed target and beam dump, and future high energy collider experiments, as well as cosmic ray physics.

Castalia allows physicists familiar with PYTHIA8 and its surrounding ecosystem to directly contribute to GEANT4 applications without being familiar with the GEANT4 internals, as well as for GEANT4 application developers to embed a physics model written in a PYTHIA8 program into their GEANT4 application without having to rewrite the model in GEANT4. Longer term, we aim for Castalia to be able to both extend and enhance the capabilities of existing GEANT4 and PYTHIA8 modeling with the strengths of the other. We illustrate these two goals with a selected subset of Castalia's capabilities: A dark photon-like model for a scenario like the SHiP [5] experiment with dark mediator production in the initial scattering, within hadronic showers, and through the decays of neutral mesons, and a comparison of the building blocks for hadronic models in GEANT4 between the built in GEANT4 alternatives and what PYTHIA8 offers.

Similar work ongoing in FLUKA.CERN

Why Pythia?

Isn't that a high-energy generator?

Low-energy programme

Ironically, originally developed for extreme-energy cosmic ray showers in air and hadronic rescattering.

General-purpose, already everywhere

MadGraph and the wider generator ecosystem; already embedded in simulation chains.

Angantyr: sophisticated Glauber–Gribov

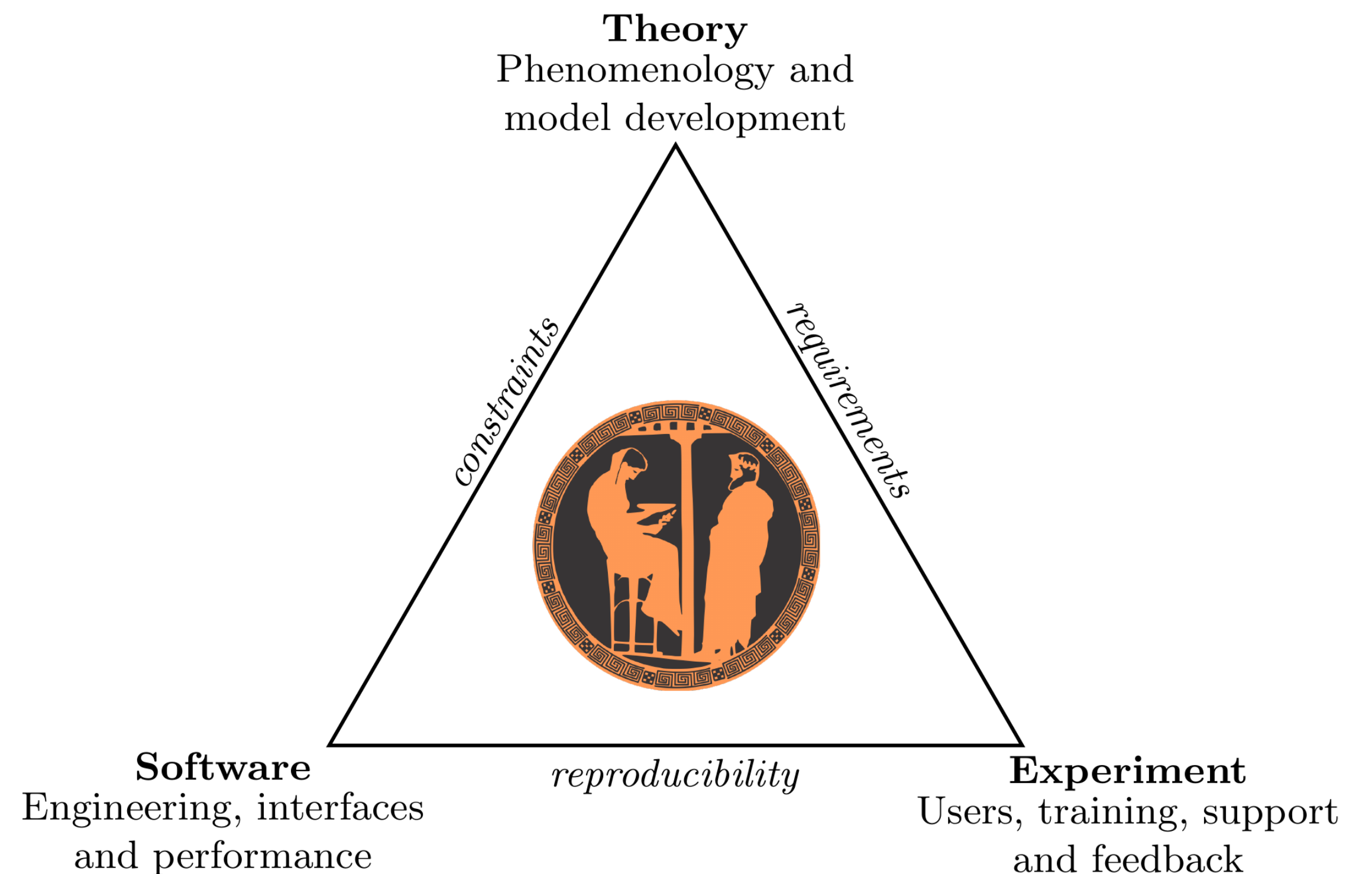
General hadron–nucleus and nucleus–nucleus collisions.

PythiaCascade: simpler hA & AA modelling

Still a big step up from using pp for signals in a nuclear target.

Rapid beam changes

New projectile and energy inside the shower, without repeated initialisation costs.



C. Bierlich, L. Lönnblad & T. Sjöstrand

[The PYTHIA Facility \(2026\), Fig. 2 · arXiv:2603.01744 \[4\]](#)

Simplest example: $\sim$ Dark photon production for SHiP

```
Pythia8::Pythia pythia{};

// 400 GeV fixed-target beam
pythia.readString("Beams:frameType = 3");
pythia.readString("Beams:pzA = 400.0");
pythia.readString("Beams:pzB = 0.0");

// Hidden U(1), Drell-Yan production
pythia.readString("HiddenValley:Ngaug = 1");
pythia.readString("HiddenValley:ffbar2Zv = on");
pythia.readString("4900023:m0 = 1.0");
pythia.readString("4900023:mMin = 0.0");
pythia.readString("4900023:mayDecay = off");
```

```
cst::DiscreteProcess process{"hA2Zv"};

// Same physics configuration
process.readString("HiddenValley:Ngaug = 1");
process.readString("HiddenValley:ffbar2Zv = on");
process.readString("4900023:m0 = 1.0");
process.readString("4900023:mMin = 0.0");
process.readString("4900023:mayDecay = off");
```

If you can write the left hand side, you get the detector simulation for free

A MadGraph model in the detector

Dark bremsstrahlung: $e^- Z \rightarrow e^- Z A'$

```
// MadGraph-exported SigmaProcess: illustrative class name  
auto sigma = std::make_shared<SigmaDarkBrem>();
```

```
auto* process = new cst::DiscreteProcess{"DarkBrem"};  
process->setSigmaPtr(sigma);  
process->readFile("dark-brem.cmnd");
```

```
G4Electron::Definition()->GetProcessManager()  
->AddDiscreteProcess(process);
```

Model-specific particle and target setup omitted

The main limitation for arbitrary BSM calculations

Phase space integration

Usual solution

B&K phase space maps + VEGAS

Quick and dirty, one-size-fits-all

Single map + normalizing flows

without machine learning

Leading into the next session...

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[Fully Geant4 compatible package for the simulation of Dark Matter in fixed target experiments](#)

Comput. Phys. Commun. 269, 108129 (2021) · [arXiv:2101.12192](#)

[2] PETITE — N. Blinov et al.

[Dark fluxes from electromagnetic cascades](#)

JHEP 07 (2024) 022 · [arXiv:2401.06843](#)

[3] G4DarkBreM — T. Eichlersmith et al.

[Simulation of dark bremsstrahlung in Geant4](#)

Comput. Phys. Commun. 287, 108690 (2023) · [arXiv:2211.03873](#)

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[The PYTHIA Facility](#)

[arXiv:2603.01744 \(2026\)](#)

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[A High Efficiency Photon Veto for the Light Dark Matter eXperiment](#)

JHEP 04 (2020) 003 · [arXiv:1912.05535](#)

[7] T. Åkesson et al.

[Photon-rejection Power of the Light Dark Matter eXperiment in an 8 GeV Beam](#)

JHEP 12 (2023) 092 · [arXiv:2308.15173](#)

[8] Geant4 Physics Reference Manual

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[13] T. Åkesson et al. (LDMX Collaboration)

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CHEP 2003 · arXiv:nucl-th/0306008

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[CEM03.03 User Manual](#)
Los Alamos report LA-UR-12-01364 (2012)

[11] JAM — Y. Nara et al.
[Study of relativistic nuclear collisions at AGS energies from p+Be to Au+Au with hadronic cascade model](#) · Phys. Rev. C 61, 024901 (2000)

[12] PEANUT — A. Ferrari and P. R. Sala
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Vol. 2, p. 424 (1998)

[14] G. A. Schuler and T. Sjöstrand
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[15] Lisa Andersson Loman

[Validation of simulation with enhanced kaon production to investigate kaon background for LDMX](#)

MSc thesis, Lund University (2023) · Chapters 4–6

Earlier kaon-enhancement study.

Later primary/secondary and collision-biasing work is discussed separately.

Appendix

