Event Generators and Geant4 Physics Models

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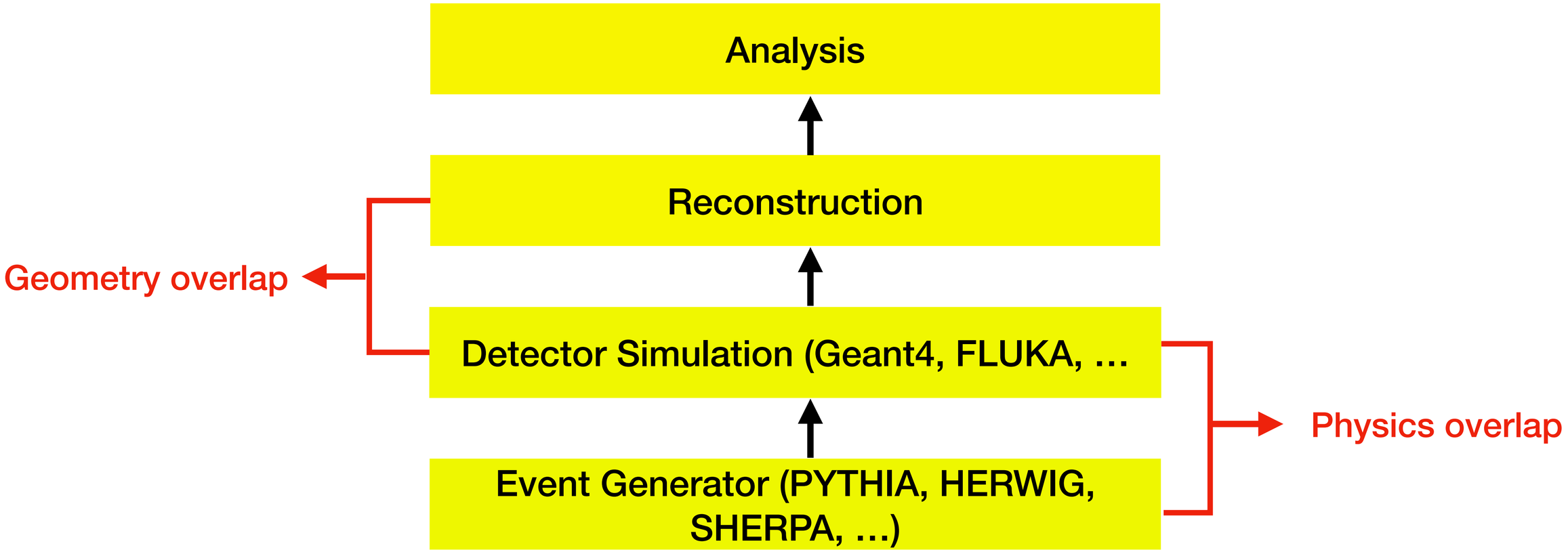
Outline

- Comparing Geant4 to event generators
- Physics content of event generators
- Geant4 physics and process/model organization
- Geant4 as event generator
- References

Typical HEP Simulation Flow



Comparison of Geant4 and Event Generators

Event Generators vs. Geant4

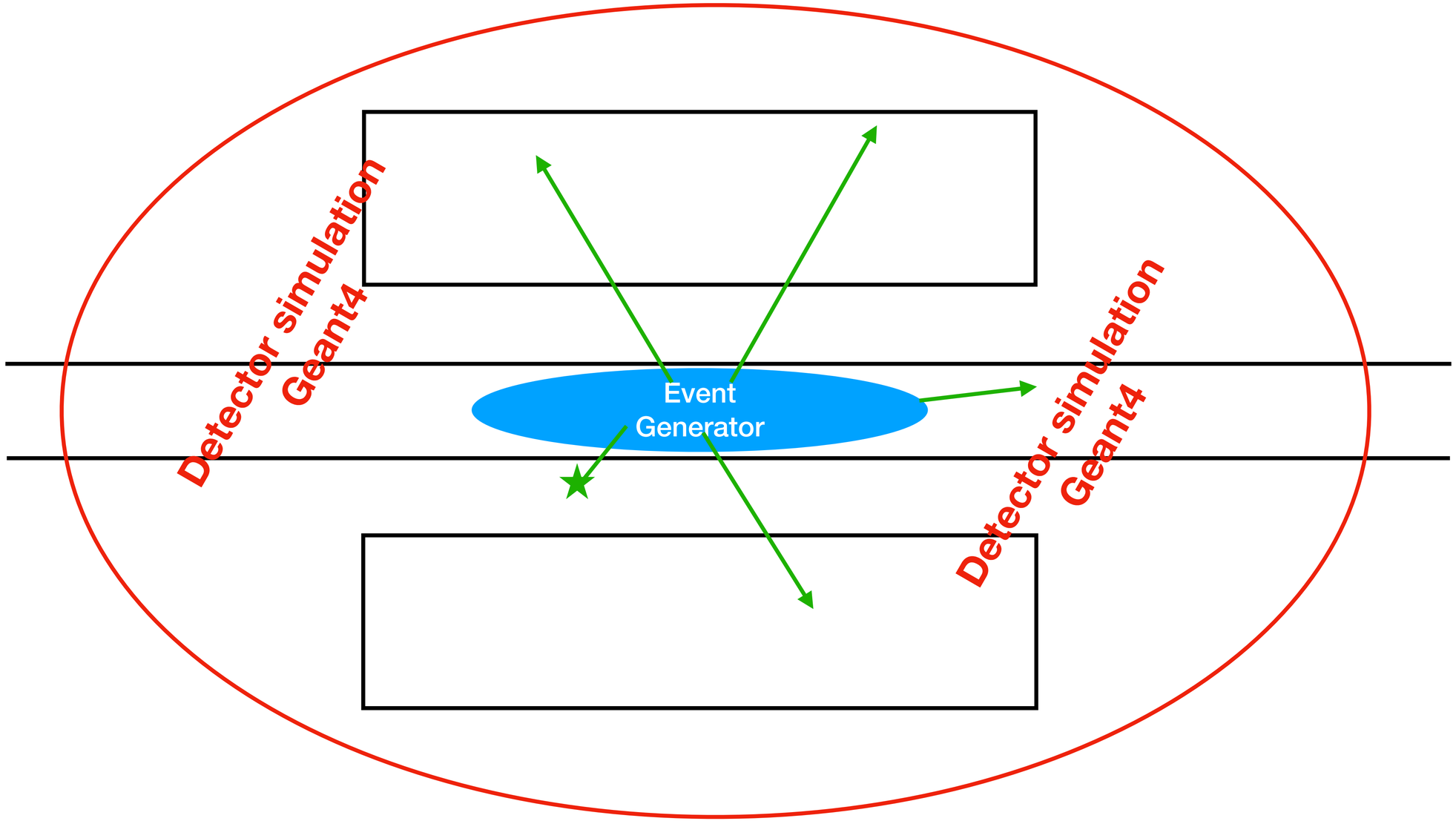
- Event generators
  - colliding beams: Pythia, Herwig, … (pp, ee, ep, …)
  - fixed target: Genie, Neut, … (neutrino interactions), Sibyll (cosmic rays)
  - decay: EvtGen (B, D, τ, semi-leptonic decays)
- Geant4
  - fixed target (particle-nucleus collisions)
  - decay (particle decay, radioactive decay)
  - detailed detector geometry

Geant4 vs. Event generator

- Parameterized and data-driven
- Mostly low to medium energy
- Only physical particles tracked
- Propagates tracks through geometry
- Physics processes can happen anywhere in geometry
- Physics configured mostly by user

- Theory-driven
- Medium to high energy
- Physical and virtual particles
- Does not propagate tracks
- Physics processes occur only in specified regions (beam line, IR, …)
- Physics configured mostly by developer

Event Generator and Geant4 Domains



Use Geant4 When You Have:

- “Trackable” particles
  - real, on-shell particles
  - travel a measurable distance
  - have means of interacting along path
- Interactions outside the IR
  - could use some event generators outside IR (e.g. decay, neutrino)
- A large number of interactions
  - Geant4 faster per interaction than EVG

Physics Overlap

- Some physics of event generators included in Geant4 models
  - Only hadronic models for now (FTF, QGS)
  - For multi-TeV collisions, may be ~TeV collisions outside IR -> need G4 models
  - Some heavy flavor particles (usually handled by EVG) may travel a short distance -> may need interaction along path
- Geant4 provides interfaces for decay generators (B, D, etc.)
- Geant4 neutrino models contain hadron production

Problems Due to Physics Overlap

- Double-counting
  - same interaction may be done both in event generator and Geant4 (e.g. decay)
- Inconsistencies between packages
  - different interaction models for same particle
  - τ, K_0S , D, B
- Hand-off from event generator to Geant4 is not always well-defined
  - energy regions may overlap
- Care required in deciding when to give tracks to Geant4

Physics Content of Event Generators

Collider Generators (Pythia, Herwig)

- Initial state parton showers (not in Geant4)
- Hard scattering (Geant4: -> only up to 1 TeV - di-jets only)
- Decays of H and W (not in Geant4)
- Final state parton showers
- Semi-hard processes
- Hadronization
- Decay

Neutrino Generators (Genie)

- Coherent interactions
- Quasi-elastic interactions
- 2p-2h processes (roughly equivalent to cluster model in Geant4)
- Pion production
- Deep inelastic scattering (in Geant4 up to 1 TeV)
- Final state interactions (not in Geant4)

Nucleus-nucleus Generators (Pythia, Hijing++)

- Merging of nucleus potentials
- Glauber-Gribov multiple scattering of nucleons
- Nucleus-nucleus collisions (hard + soft hadron scattering)
- Intra-nuclear cascade
- Nuclear break-up
- Geant4 QMD model does all of the above but at low-medium energy
- High energy Geant4 nucleus-nucleus model also available

Decay Generators (EvtGen)

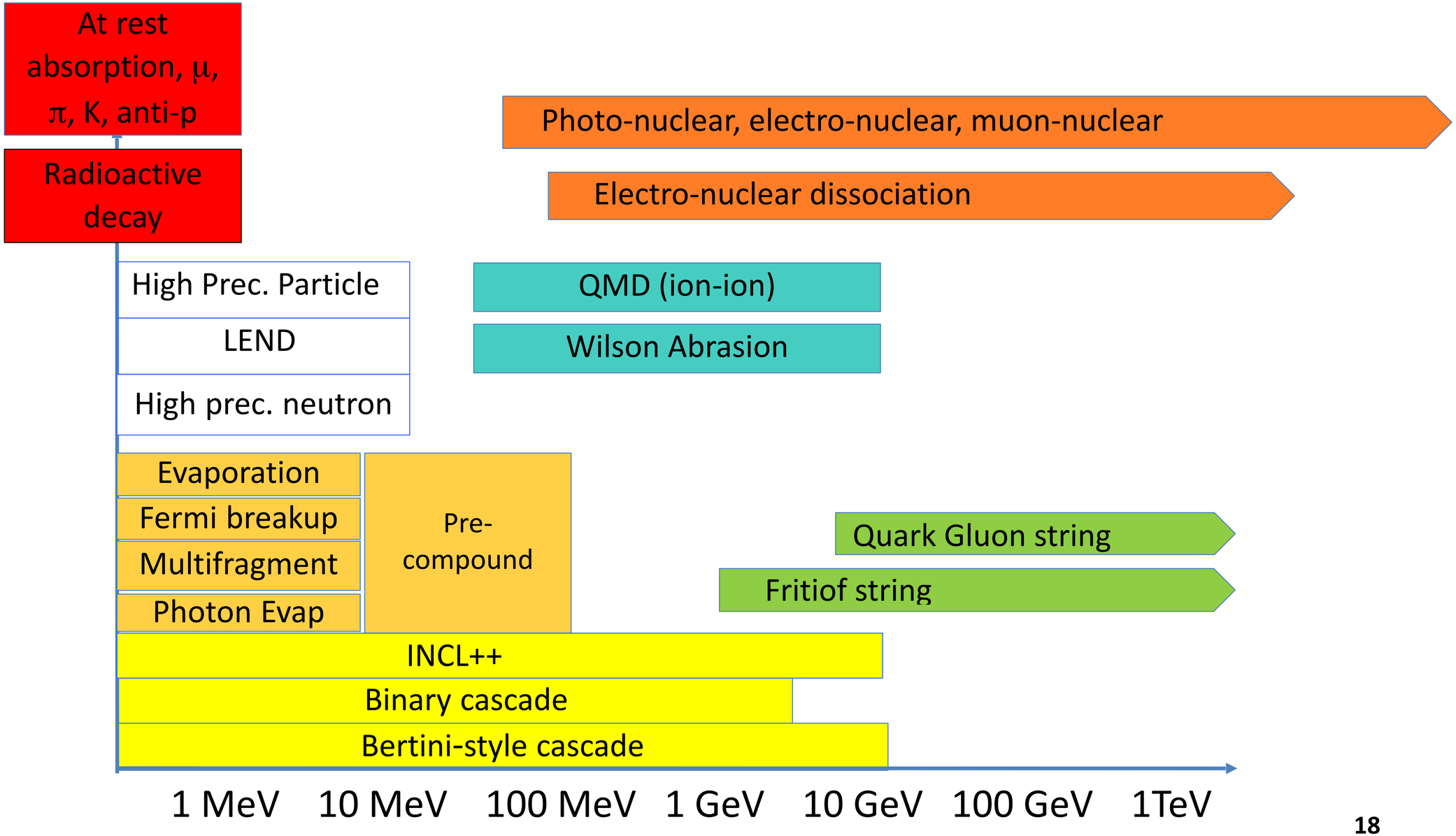
- B, D decays (not in Geant4, but interfaces and predefined decays exist)
- Leptonic
- Semi-leptonic (K, D, B)
- Dalitz
- Other multi-body decays

Geant4 Physics and Process/Model Organization

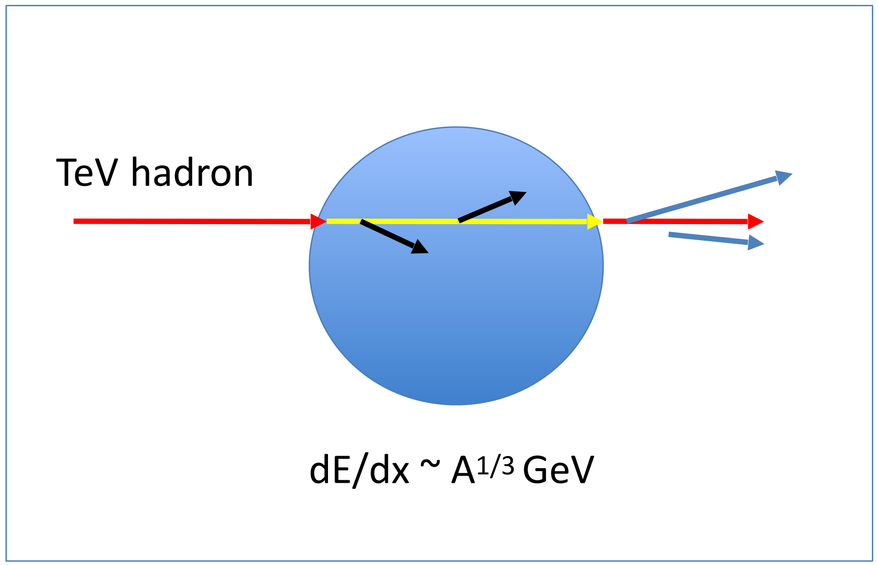
Physics Processes Provided by Geant4

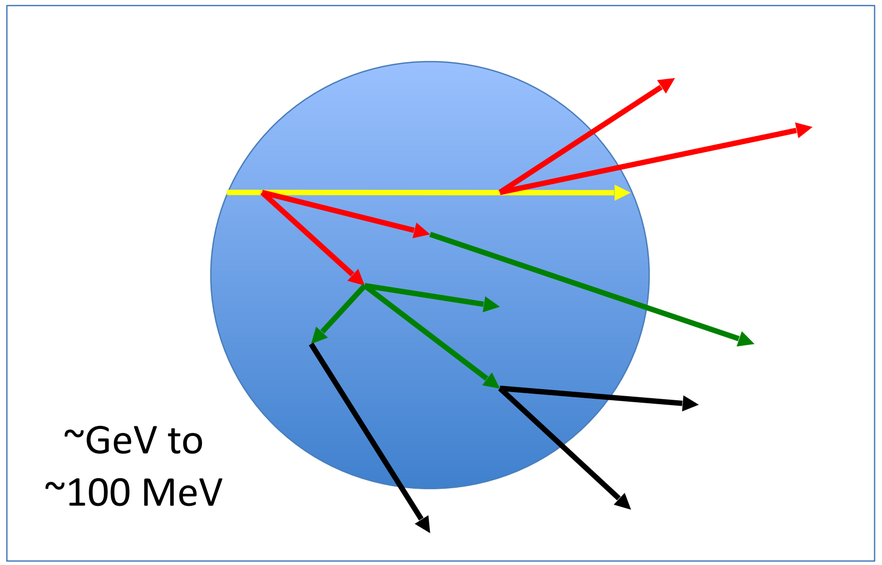
- Electromagnetic physics
  - “standard”: the default processes valid between ~keV and PeV
  - ”low energy”: processes available for ~100 eV to 1 PeV
  - Geant4 DNA: valid down to ~eV (but only for selected materials)
  - optical photons
- Weak interactions
  - decay of subatomic particles
  - radioactive decay of nuclei
- Hadronic physics
  - pure strong interaction physics valid from 0 to ~1 TeV
  - electro- and gamma-nuclear interactions valid from 10 MeV to ~TeV
  - high precision neutron (and other particles) package valid from thermal energies to ~20 MeV

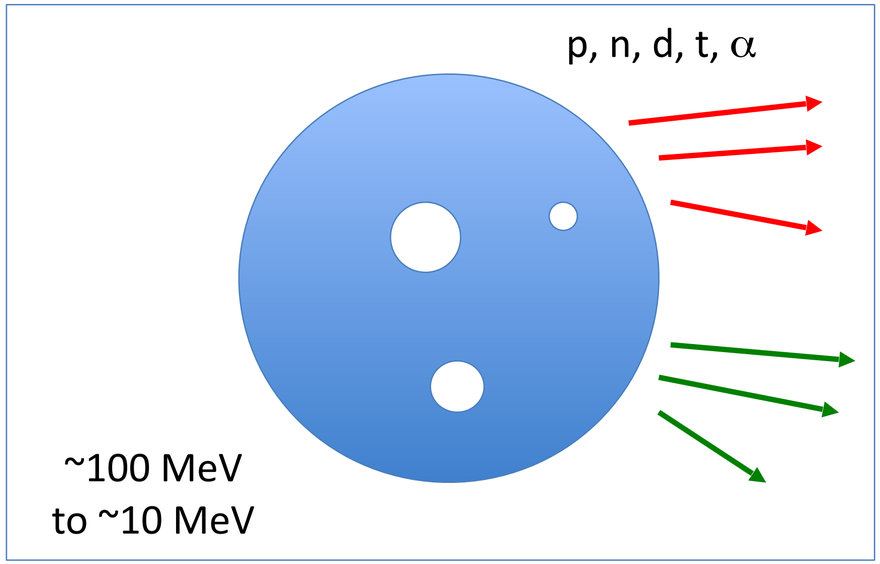
Partial Inelastic Hadronic Model Inventory

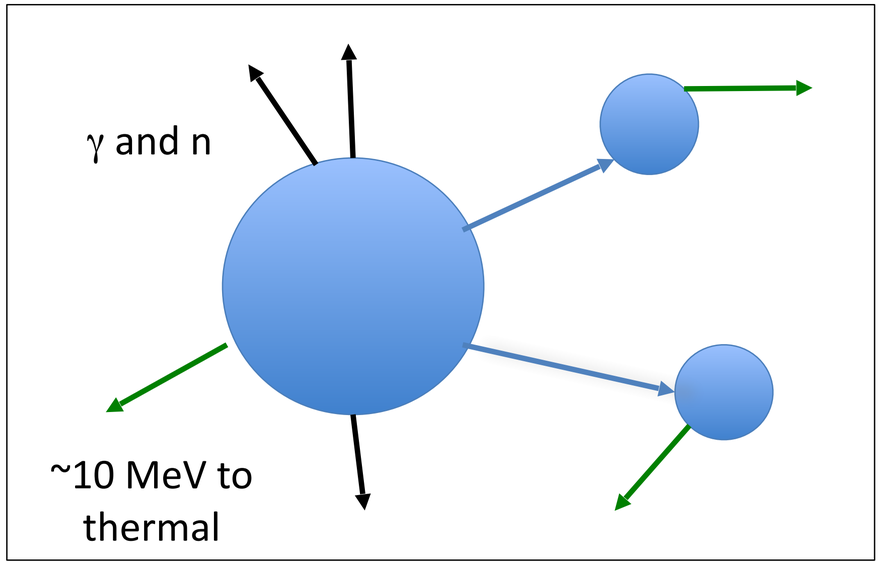


Hadronic Interactions from TeV to meV







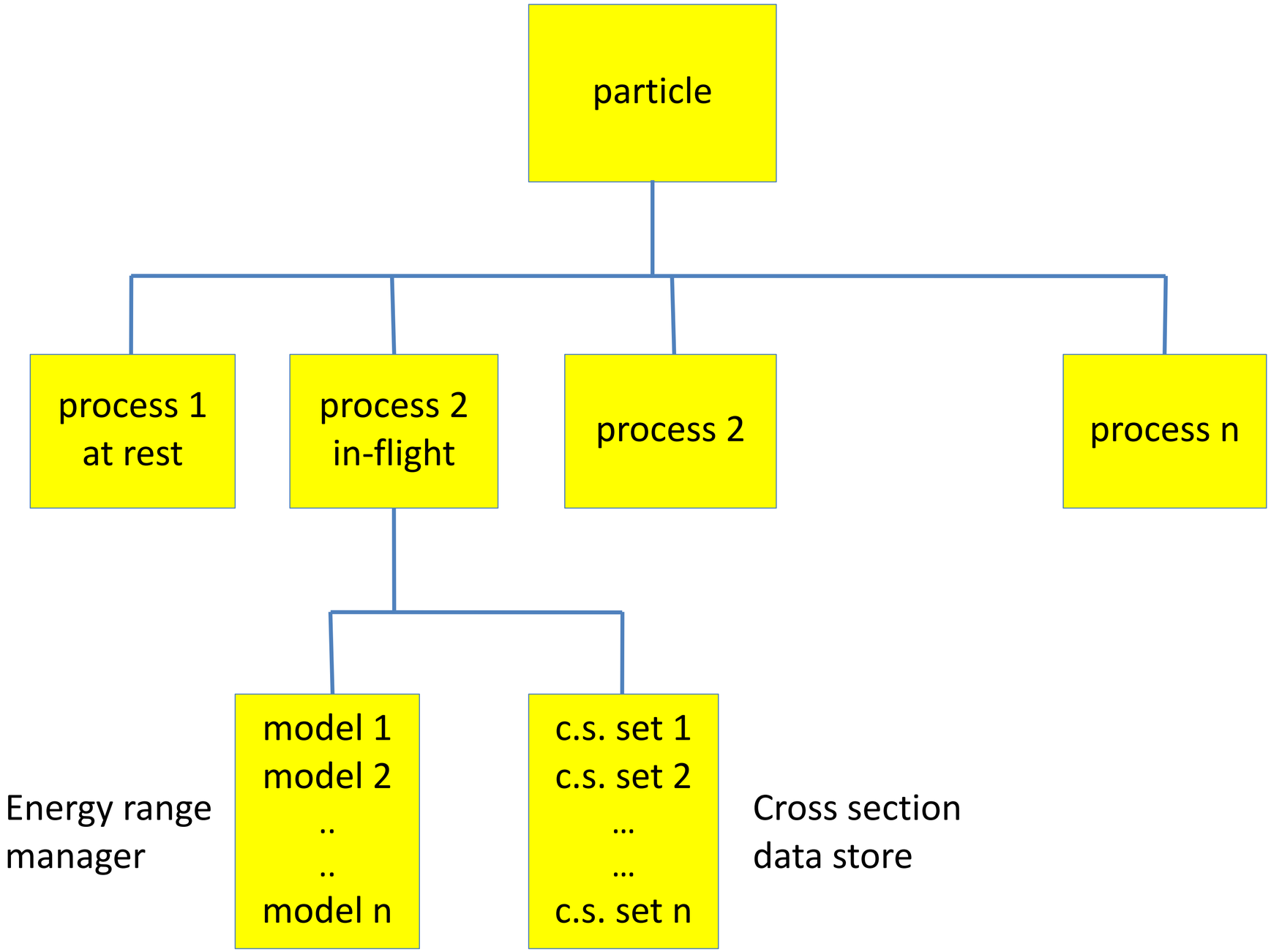


EM Processes/Models in Geant4

- Gamma incident
  - Compton
  - photo-electric
  - pair production
- Optical photon incident
- e+/e- incident
  - multiple scattering
  - bremsstrahlung
  - ionization and energy loss
  - annihilation
- Muon incident
  - bremsstrahlung
  - e+/e- pair production
  - muon-nuclear interaction
  - standard”: the default processes valid between ~keV and PeV
- Hadron incident
- Polarized processes for gamma, e+, e-

Processes and Models

- Play generally similar roles in Geant4 and event generators
  - Process: type of interaction
  - Model: a way of implementing a process
- HEP event generator: hadronization process can be implemented by Lund model or cluster model
- Geant4: hadronic interaction process can be implemented by Fritiof model or quark-gluon string model


particle
process 1
at rest
process 2
in-flight
process 2
process n
model 1
model 2
..
..
model n
c.s. set 1
c.s. set 2
…
…
c.s. set n
Energy range
manager
Cross section
data store

Physics Lists in Geant4

- A physics list is a collection of all processes and models needed to do a simulation
- User has theoretical control of assembly
  - Practical problem: too many processes and models to choose from
- Experts can custom design physics for a given use case
  - Very flexible
  - Can develop their own processes/models
  - Can choose to optimize speed in cases where physics does not have to be precise
- Geant4 developers have supplied several physics lists for LHC experiments and other users
  - Each could be considered as an event generator in its own right

Geant4 as an Event Generator

Where Geant4 Could Be Used Instead of Generators

- Neutrino interactions (biasing details to be worked out, no detailed inelastic models yet)
- Some decays (radioactive decay, …)
- Cosmic rays (some geometry problems to be overcome)
- Interface generators to Geant4 (decay, neutrino, …)
- Geant4 interfaced to event generators (neutrino-induced hadronic interactions)

Fixed Target or Decay Experiments Could Use Geant4 As Event Generator

- “event generator” in Geant4 is simple particle gun
  - no physics, just a user-implemented particle source - could be quite detailed
- $E_{cm} < 1$ TeV due to limitations in Geant4 high energy models
- Projectiles: all long-lived hadrons (p, n, π, K, Λ, Σ, …), γ, e^a, μ^a, ν^b, nuclei, muonic atom
  - a: electron and muon nuclear models somewhat rudimentary - full lepton scattering formalism not implemented
  - b: neutrino models under development

Summary

- Typical usage
  - event generator -> Geant4 track propagation -> reconstruction -> analysis
  - some use cases employ event generators outside the initial interaction
- Significant physics overlap between Geant4 and event generators
  - most of the overlap in hadronics and decay
  - could be some in neutrino event generators
  - Interfaces in both directions G4 - evtgen , evtgen - G4
  - hand-off from event generator to Geant4 is not always well-defined
- Geant4 provides physics processes, models and physics lists for a wide range of physics
  - flexible design allows lots of user choice
  - in many cases Geant4 can function as an event generator

Event Generator References

- A good set of lectures on event generators
  - https://www.hep.phy.cam.ac.uk/theory/webber/MCnet/MClecture1.pdf
  - https://www.hep.phy.cam.ac.uk/theory/webber/MCnet/MClecture2.pdf
  - https://www.hep.phy.cam.ac.uk/theory/webber/MCnet/MClecture3.pdf
  - https://www.hep.phy.cam.ac.uk/theory/webber/MCnet/MClecture4.pdf
- Documentation on Specific Event Generators (to name a few)
  - Pythia (high energy) : https://pythia.org/latest-manual/Welcome.html
  - Herwig (high energy) : https://herwig.hepforge.org/
  - EvtGen (decay) : https://evtgen.hepforge.org/
  - Genie (neutrino) : https://www.genie-mc.org
  - Heavy ion collisions: https://www.sciencedirect.com/science/article/abs/pii/S2405601417302857

Geant4 References

- Geant4 documentation: https://geant4.web.cern.ch/docs/
- Main papers:
  - (2016) Recent Developments in Geant4: https://www.sciencedirect.com/science/article/pii/S0168900216306957
  - (2006) Geant4 Developments and Applications, https://ieeexplore.ieee.org/xpls/abs_all.jsp?isnumber=33833&arnumber=1610988&count=33&index=7
  - (2003) Geant4 - A Simulation Toolkit: https://www.sciencedirect.com/science/article/pii/S0168900203013688
- Physics content:
  - https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/html/index.html
- Users' Guides
  - Application developers: https://geant4-userdoc.web.cern.ch/UsersGuides/ForApplicationDeveloper/html/index.html
  - Toolkit developers: https://geant4-userdoc.web.cern.ch/UsersGuides/ForToolkitDeveloper/html/index.html