# Geant* Hadronic Physics Ideas for the Next 10 Years

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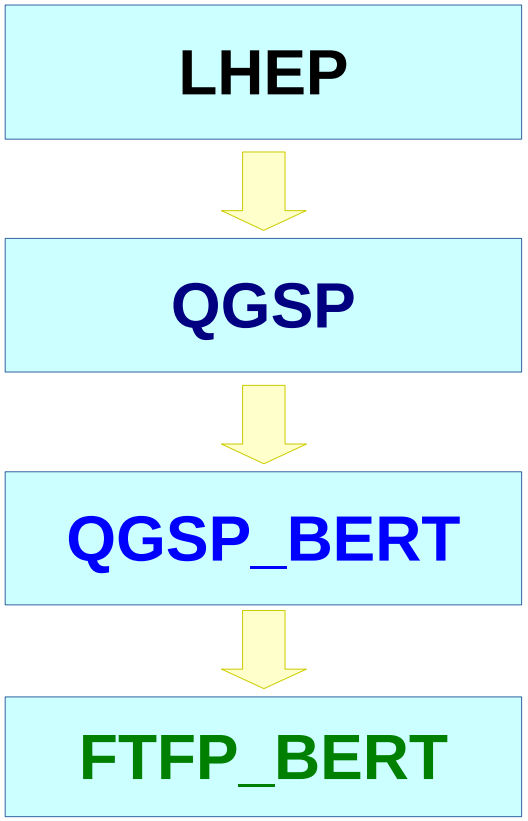
# Outline

- Simulation of hadronic showers: past and future
- Key areas of hadronic physics
  - Cross sections
  - Elastic scattering
  - High-energy string models
  - Intra-nuclear cascade models
  - Precompound & de-excitation models
  - Low-energy hadronic physics (e.g. neutrons)
- Conclusion & Outlook

***Note**: a personal opinion on how Geant* hadronic physics could evolve...*

# Geant4 Evolution in the Simulation of Hadronic Showers in the last ~10 years




Gheisha parameterized model

Theory models (string + precompound/excitation) at high energies

Added intra-nuclear cascade model

Low-energy extension of string model
→ no parameterized model any longer

# Geant* Simulation of Hadronic Showers for the next 10 years ?

**FTFP_BERT**

FTF phenomenological model reaches its best

**QGSP_BERT**

More theory-based string model

**EposP_BertBicIncl**

Extension to very high energies and heavy flavours.
Best combinations of the 3 intra-nuclear cascades (according to the projectile particle and energy)

# Basic Ingredients for Hadronics in HEP

Worth to make a thorough review – theoretical basis, simplified approximations, algorithms

- **Hadronic cross sections**
  - Glauber-Gribov approach
- **Elastic scattering**
  - Diffuse model
- **String models**
  - Fritiof (FTF), Quark-Gluon-String (QGS), EPOS (?)
- **Intra-nuclear cascade models**
  - Bertini (BERT), Binary (BIC), Liege (INCLXX)
- **Precompound/de-excitation models**
  - Critical for CPU & memory performance

- *Other low-energy hadronic models, used in medical, nuclear and space*
  - *Precise transportation of low-energy neutrons, protons, etc.*
  - *Radioactive Decay Model*

# Hadronic Cross Sections

- Cross Sections
  - Critical for CPU performance of hadronic physics simulations
  - Continue to review them and make them more efficient
  - Glauber-Gribov approach seems the most general and promising, at least for high energies
    - Currently under review and rewriting for Geant4 / GeantV

# Elastic Model

- Hadron Elastic Model
  - Need to review cross sections and final-state models
  - Particular important for hadronic showers in scintillator-based calorimeter is neutron – proton elastic scattering
  - DiffuseElastic model approach seems the most promising
    - Will be reviewed and completely rewritten for Geant4 / GeantV

# String Models

- Consolidate **FTF**
  - Reaching its full maturity: only small improvements seem possible
- Improve and extend **QGS**
  - Useful to provide an alternative, more theory-based, to the phenomelogical FTF model, for hadronic showers
  - Naturally valid to higher energies than FTF, up to a few TeV
- C++ rewrite of EPOS inside Geant* ?
  - Will open the possibility to cover interactions to much higher energies (multi TeV), useful for accelerator applications, FCC-hh, and even extremely high-energy cosmic rays
  - Will include treatment of hadronic interactions for charmed and bottom hadrons, useful for interactions of boosted particles in trackers for LHC & FCC

# Intranuclear Cascade Models

- Bertini (**BERT**)
  - The current Geant4 workhorse, reasonably good and fast
    - Porting this to GeantV as first, quick approach
  - Significantly improved and extended in recent years, expected to remain stable in the next future
- Binary (**BIC**)
  - Stable since many years; extensions and improvements are possible but unlikely to happen
- Liège (**INCL**XX)
  - State-of-the-art for spallation studies
  - Recent extension to higher energies and under further development
    - 3 –-> 20 GeV , inclusion of η , η' , strange hadrons , etc.

---> Possibility to use a combination of them (according to projectile and energy) to get the best precision & speed

# Precompound / De-excitation

- Not only important for physics – even for high-energy jets – but also critical for computing performance
- Physics and code implementation have been carefully revisited and improved in the recent past
  - Not expected major changes in the next future, but certainly further consolidation and validation
  - Additional physics effects (e.g. correlation of emitted gammas), revision of models currently not used (e.g. multi-fragmentation), and perhaps even new, specialized models will be driven by medical, nuclear and space applications
    - Many requests for specific reactions (e.g. fragmentation of 12C when interacting with different materials) : current models (cascade, precompound and de-excitation) provide often only rough simulations, not enough for certain applications

# Low-energy Hadronic Physics

- Not used for HEP analyses, but useful for activation, radiation and shielding studies, and with a growing interest in: medical physics, nuclear physics, space science
- High-precision transportation of low-energy neutrons
  - Moving to the new Livermore approach and format
  - Under revision and complete rewriting for Geant4 / GeantV : one of the areas where vectorization can boost performance
- High-precision transportation of low-energy charged particles (protons, deuterons, tritons, He3 and alphas)
  - First implementation needs consolidation and extensive validation
- Radioactive Decay model
  - Undergoing a major revision and extension
  - Nuclear groups interest to develop & share their specialized codes

# Other Hadronic Challenges / Opportunities

- Nucleus-Nucleus
- Hyper-nuclei physics
- Antiproton physics
- Spin physics
- Electromagnetic dissociation of nuclei
- Gamma-nuclear & lepton-nuclear
- Neutrinos
- Exotica
  - Monopoles
  - Dark matter
  - R-hadrons
  - Q-balls

# Guiding Lines

- Whenever possible, prefer **theory-based approach** to phenomenological / parametrized / data-driven approach
  - Safer extrapolation outside known data
  - Lattice QCD could in principle replace all hadronic models, but in practice it is still limited to static properties of hadronic physics, not yet usable for dynamic properties that we need
- **Common development** between Geant4 and GeantV
  - Allows to optimize effort and make results available earlier to users
  - Allows to smooth out and shorten the transition between simulation engines, given that the new one is tested against the previous one
- The community should consider to invest on **more people** working full time on hadronic physics simulation
  - Huge work, expertise requires continuous effort for a long time
    - Common Geant* development reduces man-power need, but still requires more effort than Geant4 alone where we are already man-power limited

# Summary & Outlook

- The main work of Geant* hadronic physics for the next years is to **consolidate** the **physics** and the **algorithms** of the existing models, as well as the **validation testing suite**
  - Aim for common developments Geant4 & GeantV with a strong emphasis to rewrite common modules whenever feasible
    - GeantV allows also to test them in a streamlined hadronic framework

- Besides strengthening the capabilities for the “traditional” application domains of Geant* – HEP, medical, space – new domains could be opened
  - Very high-energy cosmic rays : possible with EPOS inclusion
  - Activation, Radiation, Shielding : all ingredients are available, but need more refinements, validations and user support
  - More low-energy nuclear applications : e.g. ISOLDE experiments