Bertini intra-nuclear cascade implementation in GEANT4

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Outline

- Bertini intra-nuclear cascade (INC) models
- GEANT4 5.0 implementation
- Results and conclusion

INC background

- 1947: INC first proposed by R. Serber
- 1948: M. Goldberger made first calculations by hand
- 1958: First computer simulations by N. Metropolis
- 1966: exiton model by J. J. Griffin
- 1968: H. W. Bertini published standard methods to be used in many INC implementations
- 1970's: HETC
- 1990's: INUCL code by N. Stepanov
- 2002: INUCL++

Introduction to Bertini INC

- Physical justification: if the deBroglie wavelenght of the incident particle is comparable to the average intra-nucleon distance, interactions can be treated in terms of particle-particle (N-N) collisions
- Bertini INC solves the Boltzman equation on the average
- Physical foundation comes approximate if $E < 200\ MeV$ or $E > 10\ GeV$
- Pre-equilibrium model developed to support low energy treatment

Basics of INC model steps

1. The spatial point, where the incident particle enters, is selected uniformly over the projected area of the nucleus.

2. N-N cross sections and region-depenent nucleon densities are used to select a path lenght for the projectile particle.

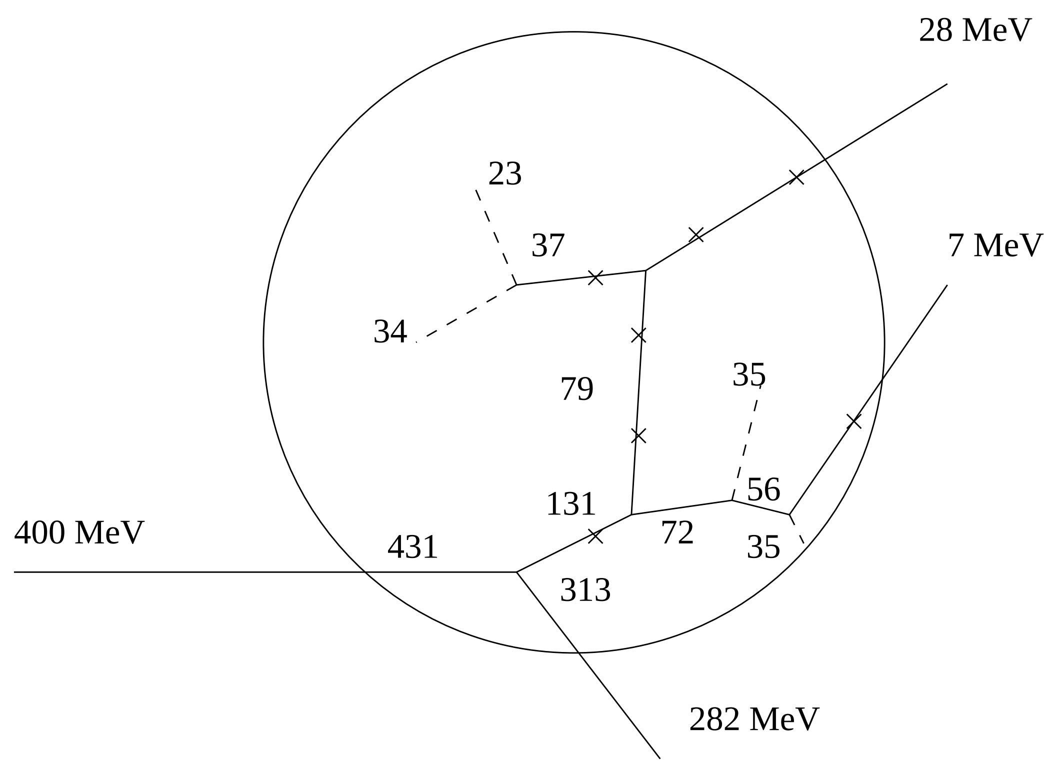
3. The momentum of the struck nucleon, the type of reaction and four momentum of the reaction products are determined.

4. Exiton model is updated as the cascade proceeds.

5. If Pauli exclusion principle allows and
   $E_{particle} > E_{cutoff} = 2\ MeV$,
   step (2) is performed to transport the products.

Nuclei model

- Impulse distribution in each region of concentric spheres follows Fermi distribution with zero temperature
- Pauli exclusion principle (crosses) is taken into account by accepting only secondary nucleons with $E_N > E_{Fermi}$



Cross sections

- Path lengths of nucleons in the nucleus are sampled according to the local density and to free N-N cross sections
- Angles after collisions are sampled from experimental differential cross sections
- For pions the INC cross sections are provided to treat elastic collisions and inelastics channels (π^0p $\rightarrow$ π^+n etc.)
- Pion absorption channels (π^+nn $\rightarrow$ pn etc.)
- Multiple particle production is also implemented

Pre-equilibrium model

- Nucleon states are characterized by the number of exited particles and holes (the exiton model proposed by Griffin)
- INC collisions give rise to a sequence of states characterized by increasing exciton number, leading to a equilibrated nucleus
- Parametrisations of the level density
  (tabulated with both A and Z dependence)

Break-up models

- Fermi break-up is allowed in extreme cases (if $A < 12$ and $3(A - Z) < Z < 6$ or if $E_{excitation} > 3E_{binding}$)
- Simple explosion model decreases exotic evaporation processes
- Phenomenological fission model uses potential minimization (incorporating binding energy paramerization and fission statistical model features)

Evaporation model

- Statistical theory for particle emission
  of the exited nucleus remaining after the INC (by Weisskopf)
- GEANT4 evaporation model for cascade implementation adapts often used computational method developed by Dostrowski
- The main chain of evaporation
  (followed until $E_{cutoff} = 0.1$ MeV)
- The evaporation model ends with γ emission chain
  (followed until $E^{\gamma}_{cutoff} = 10^{-15}$ MeV)

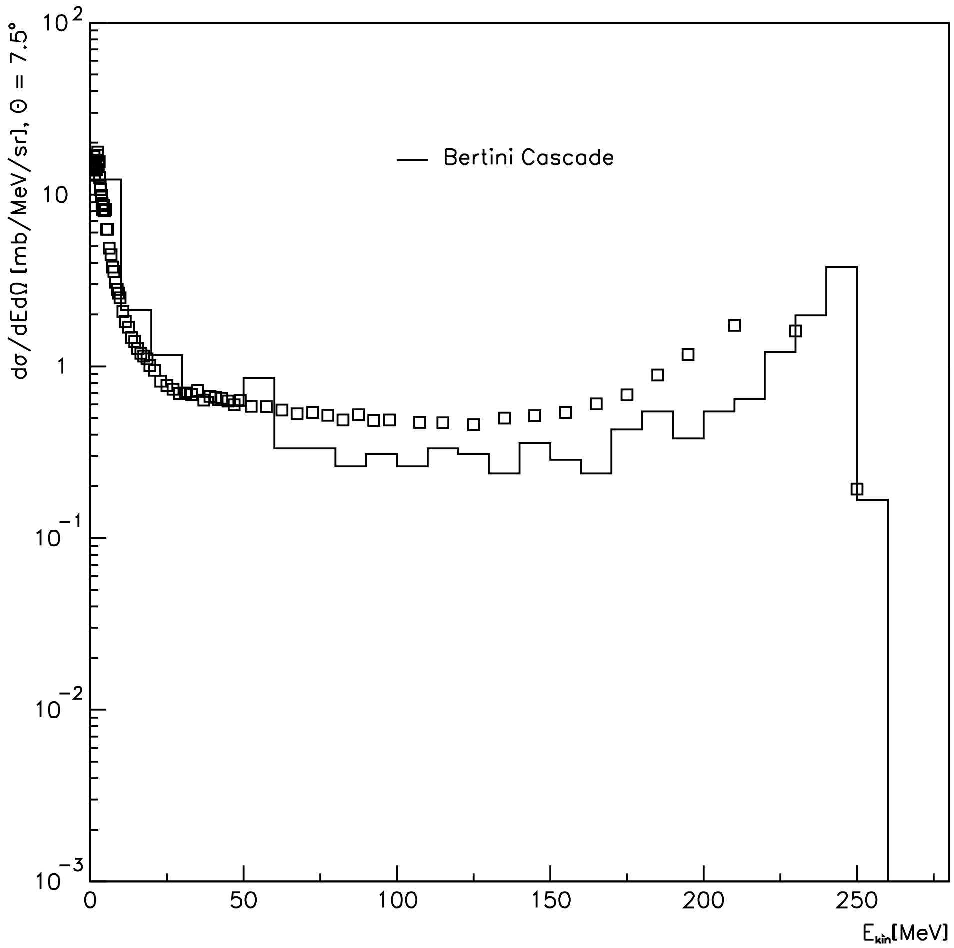
Geant4 5.0 implementation

- Bertini INC is based on re-engineering of INUCL fortran code
- C++ version INUCL++ is a compact stand alone code
- Implemented in GEANT4 hadronics physics framework, which allows modular implementation
- Source code in *processes/hadronic/models/cascade/cascade*
- 16K lines in 32 classes (4K lines for testing and documentation)

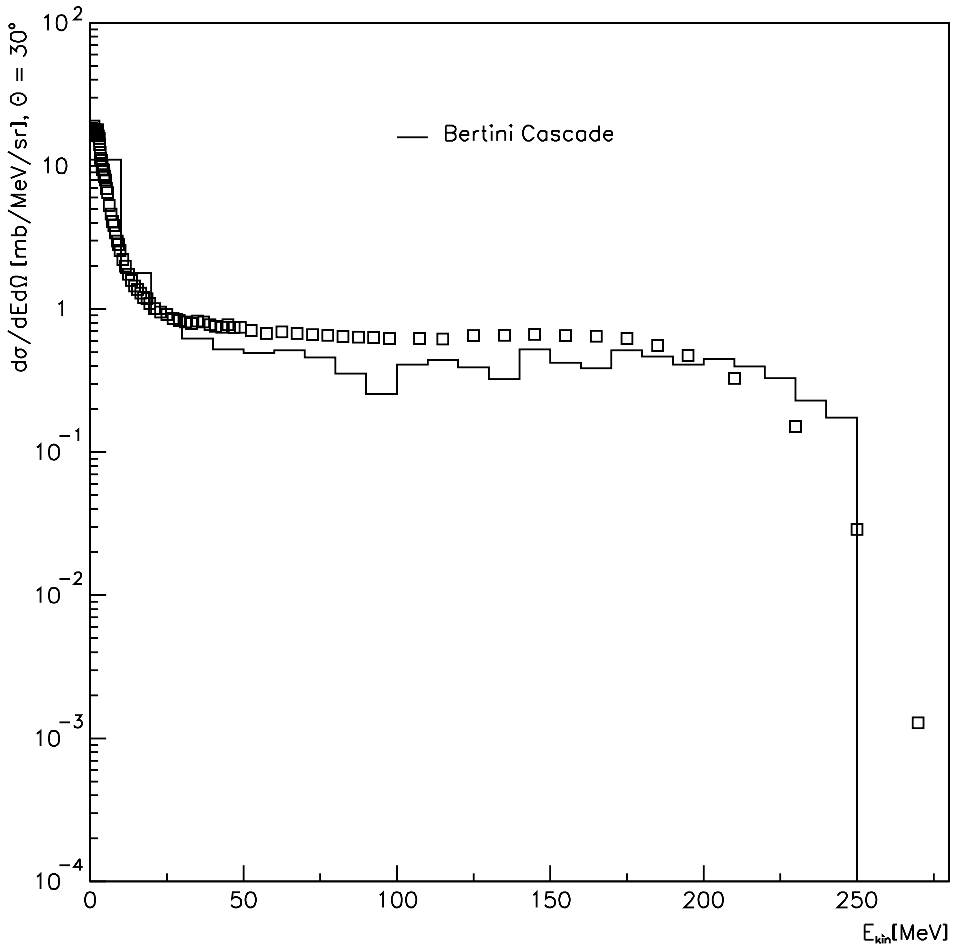
Interfacing Bertini INC models

- Current implementation is quite loosely connected to the Geant4 hadronic framework
- Models are organised into separate classes (*G4IntraNucleiCascader*, *G4Fissioner*, *G4NonEquilibriumEvaporator*, *G4EquilibriumEvaporator* etc.)
- All the models are used collectively through interface method *ApplyYourself* defined in a class *G4CascadeInteface*

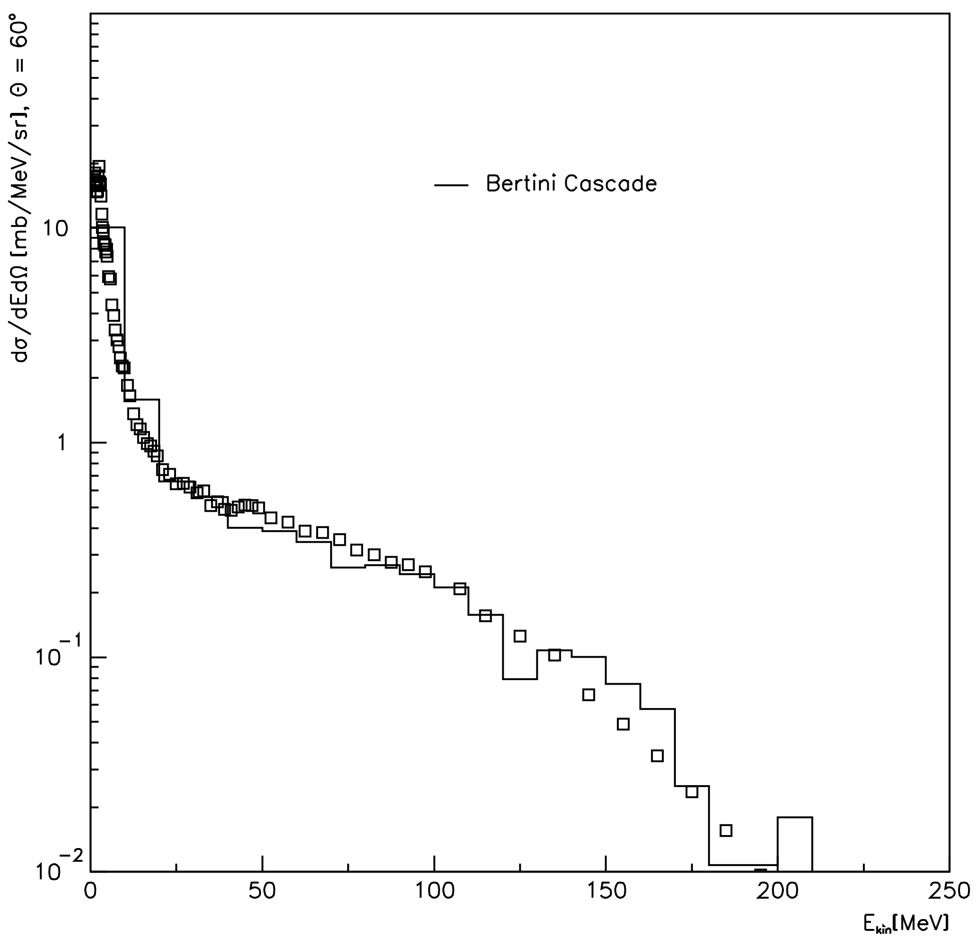
$$p^{256MeV} + \mathbf{Fe} \rightarrow n^{\theta=7.5°} + \mathbf{X}$$



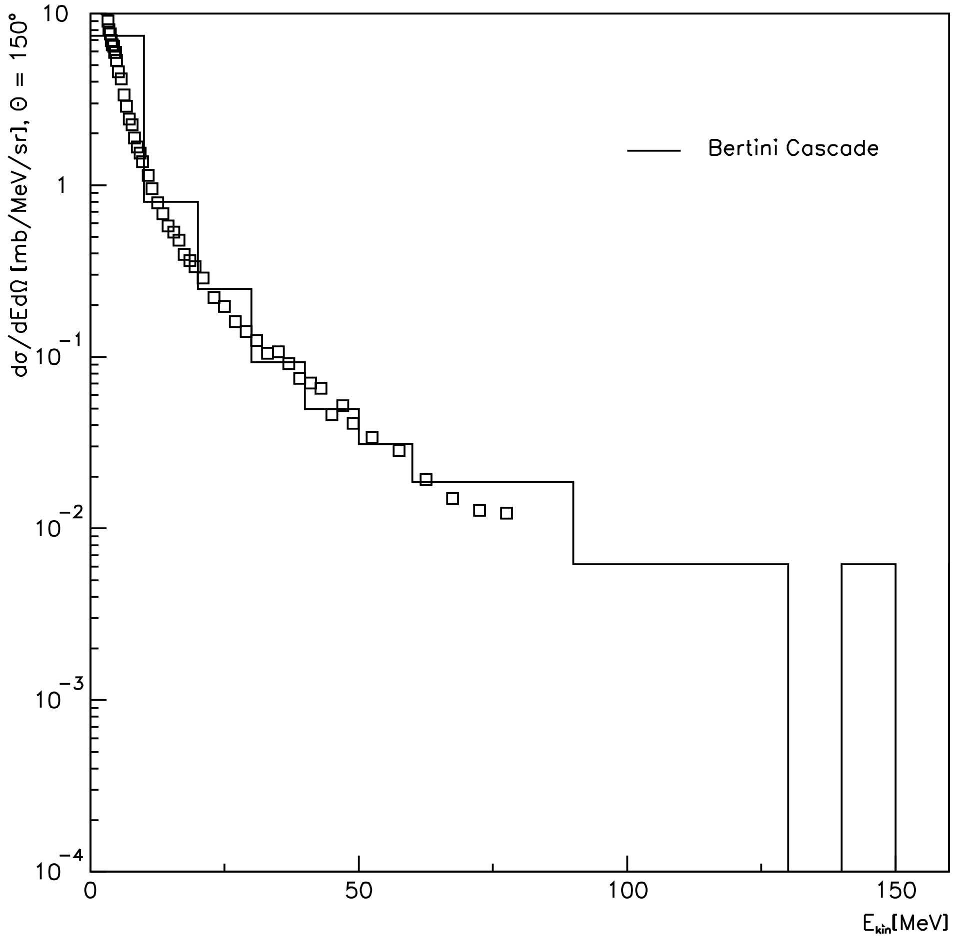
$$p^{256MeV} + \mathbf{Fe} \rightarrow n^{\theta=30^\circ} + \mathbf{X}$$



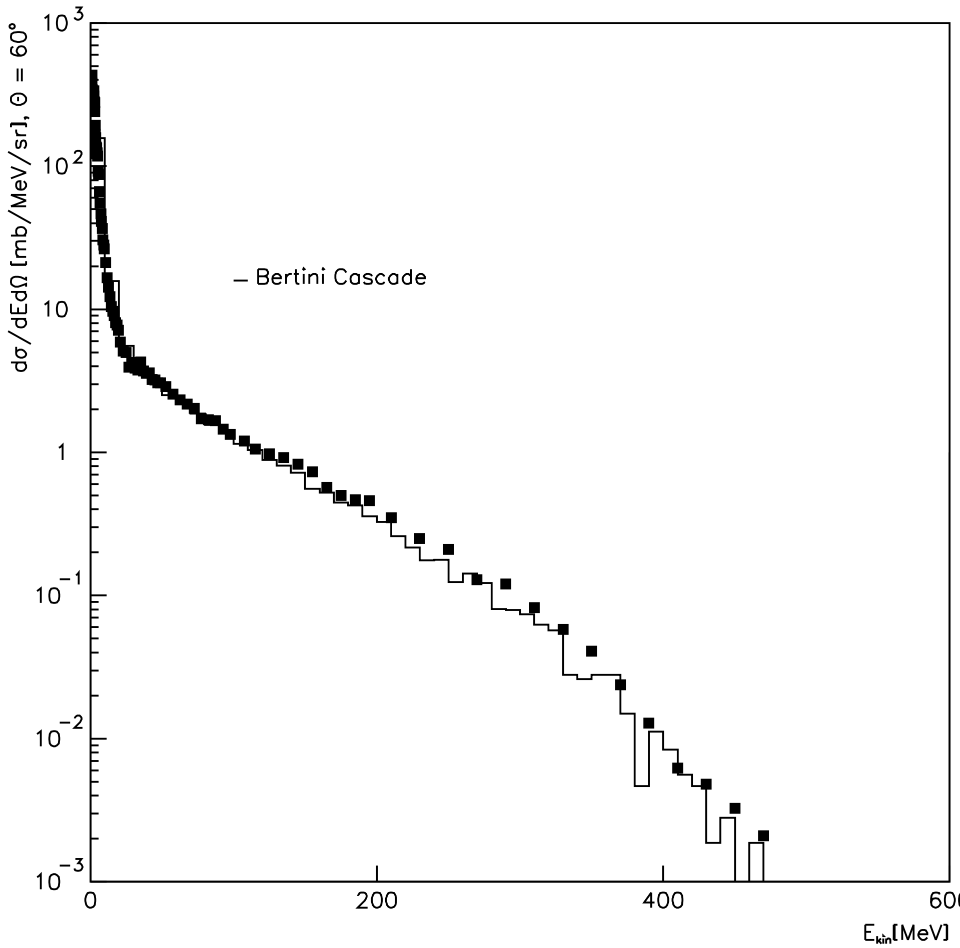
$$p^{256MeV} + \mathbf{Fe} \rightarrow n^{\theta=60^\circ} + \mathbf{X}$$



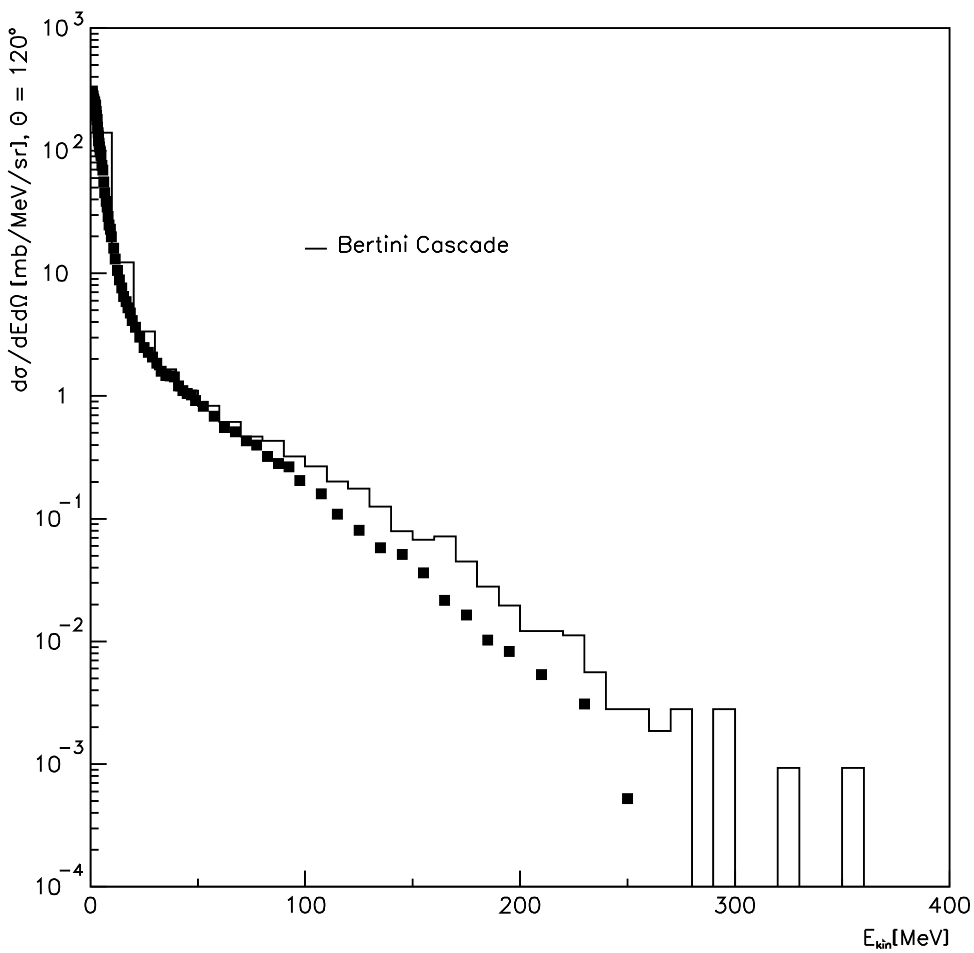
$$p^{256MeV} + \mathbf{Fe} \rightarrow n^{\theta=150^\circ} + \mathbf{X}$$



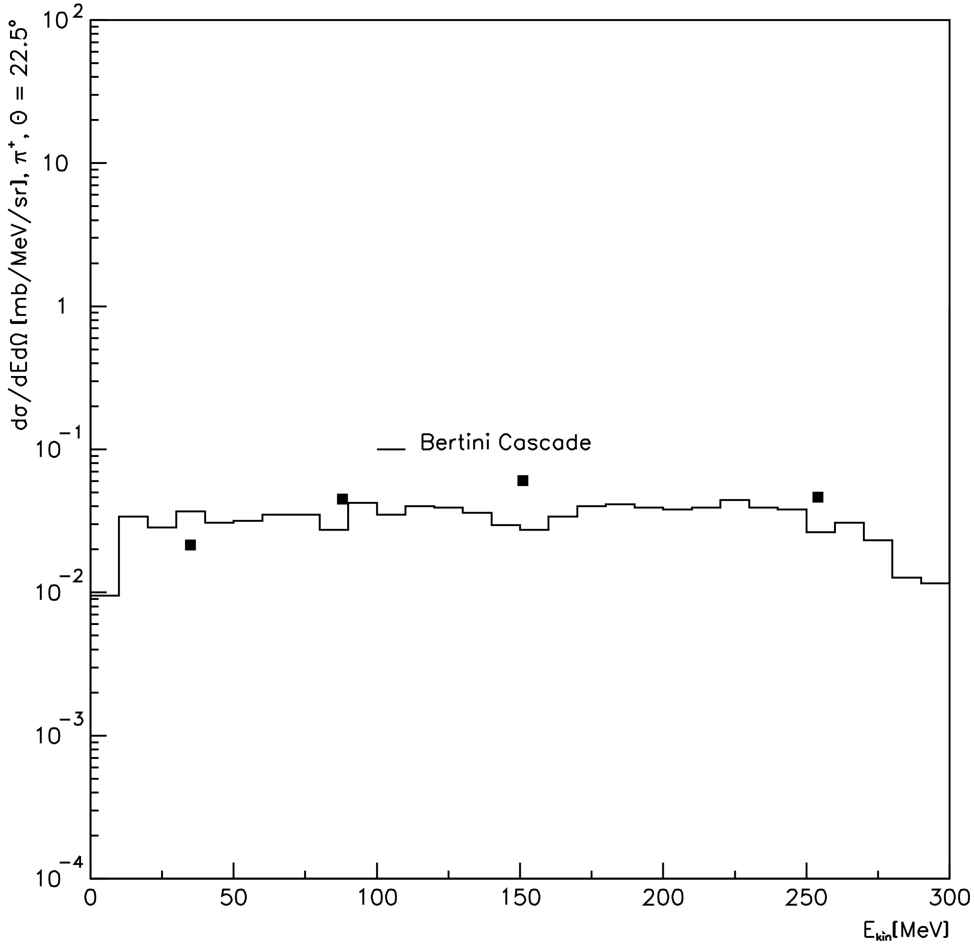
$$p^{597MeV} + \mathbf{Pb} \rightarrow n^{\theta=60^\circ} + \mathbf{X}$$



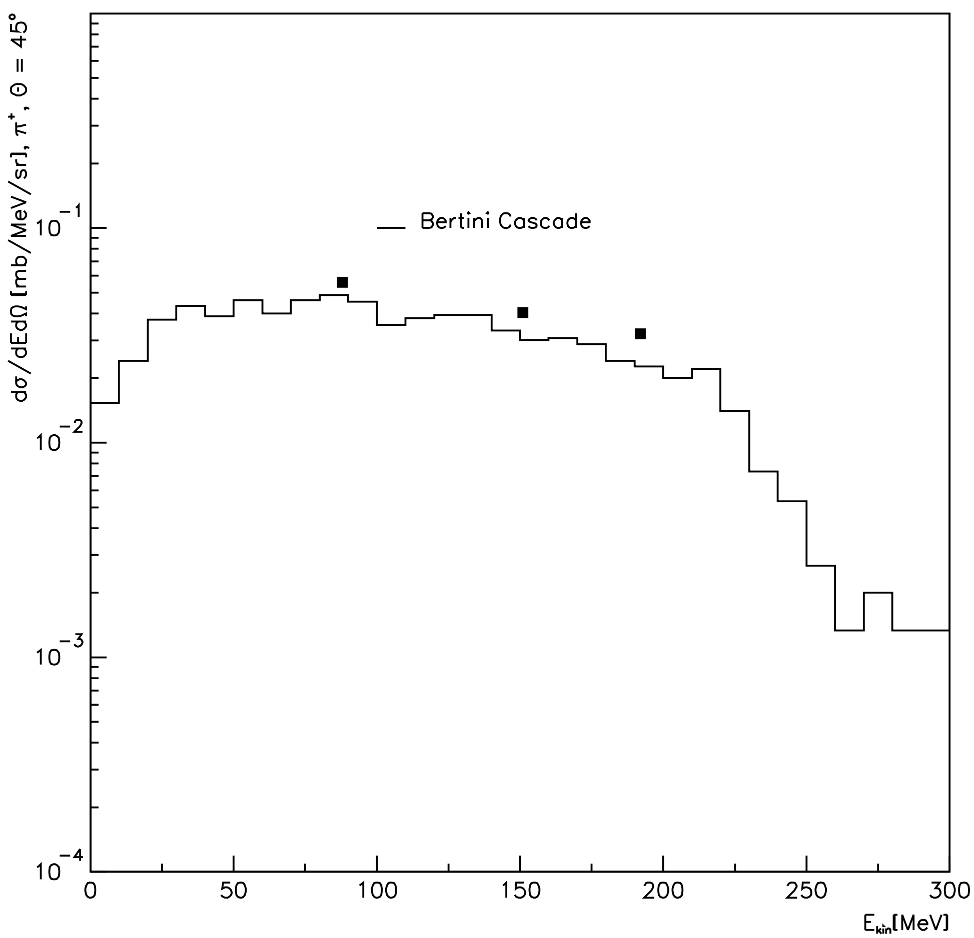
$$p^{597MeV} + \mathbf{Pb} \rightarrow n^{\theta=120^\circ} + \mathbf{X}$$



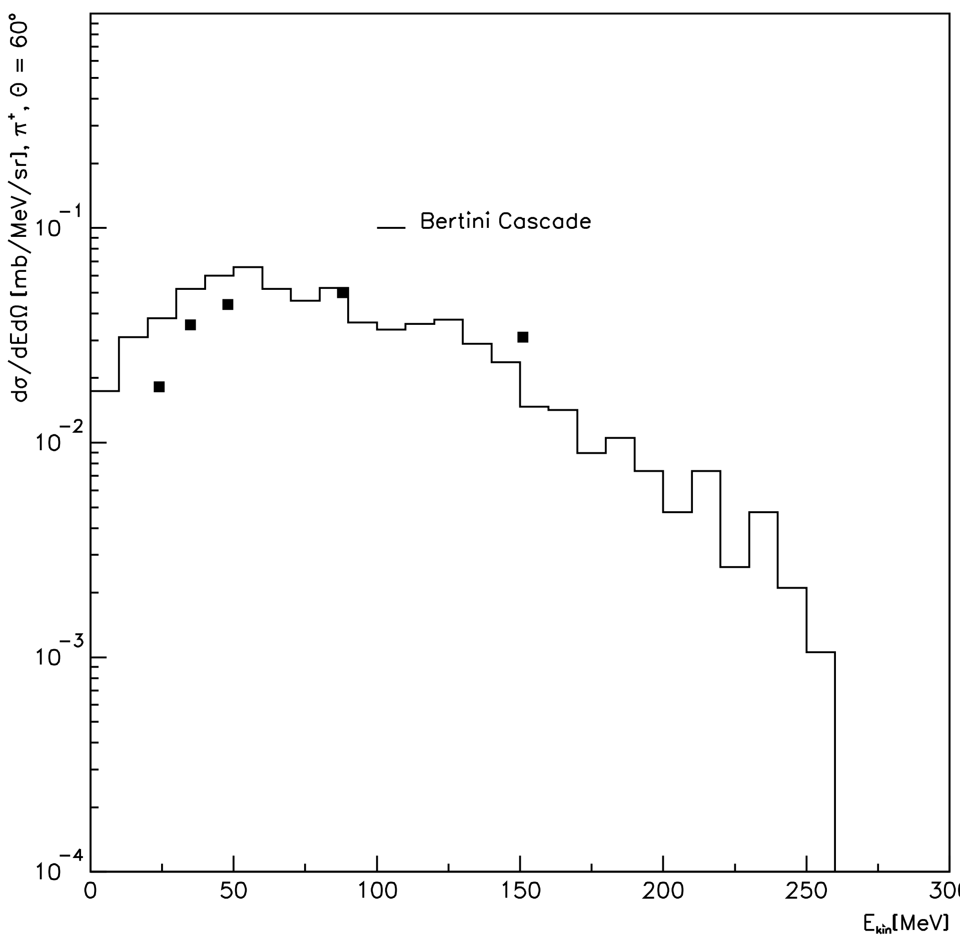
$$p^{597MeV} + \mathbf{Pb} \rightarrow \pi^{+\theta=22.5^\circ} + \mathbf{X}$$



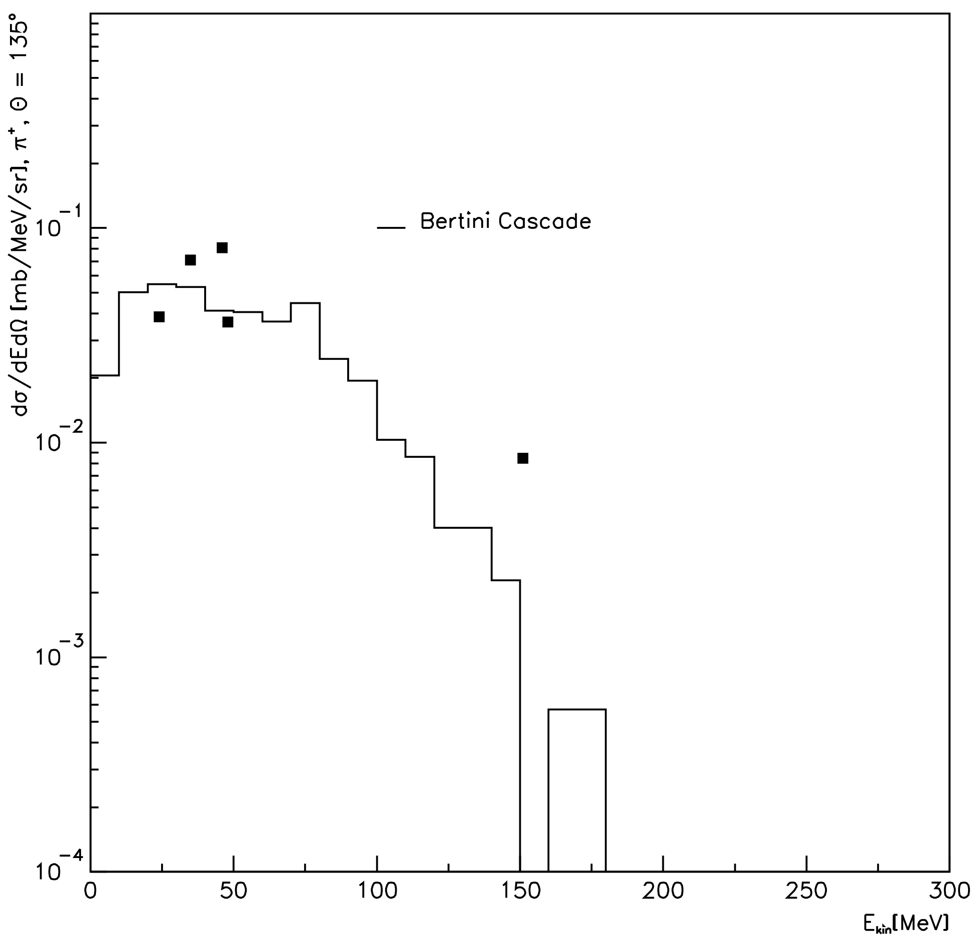
$$p^{597MeV} + \mathbf{Pb} \rightarrow \pi^{+\theta=45^\circ} + \mathbf{X}$$



$$p^{597MeV} + \mathbf{Pb} \rightarrow \pi^{+\theta=60^\circ} + \mathbf{X}$$



$$p^{597MeV} + \mathbf{Pb} \rightarrow \pi^{+\theta=135^\circ} + \mathbf{X}$$



Conclusion

- We have released a Bertini INC model in Geant4 5.0
- Exitons, pre-equilibrium, nucleus explosion, fission, and evaporation are modelled
- Particles treated: γ, π, n, p, and nuclear isotopes
- We have tested the code in a energy range 60 MeV - 10 GeV