

# FLUKA.CERN HADRONIC EVENT GENERATOR INTERFACE

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Gabrielle HUGO  
for the FLUKA.CERN collaboration  
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# CONTEXT

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## GOAL

Make FLUKA physics models available to the G4 community.

General context: **increasing FLUKA openness and synergies with G4.**

## PROPOSAL

Interface giving access to **FLUKA PEANUT** (hadronic interactions modeling) from G4.

- Give **direct access** to FLUKA Physics from the G4-based user applications and experiments frameworks.

Hadronic interactions modeling is **one of the main targets** of FLUKA Physics integration.

- To be followed by integration of additional FLUKA models (e.g. ion-nucleus).

**First step** in FLUKA code modernization and opening to the community.

- A second step will be to **modularize** the FLUKA code itself, to make it more maintainable, and possibly increase the granularity of the G4 integration.

## DEPENDENCIES

- Interface **can be called in *any* G4 application** (e.g. independent from MOIRA/FLUKA++).
- **Registration to FLUKA and agreement to FLUKA existing license** is obviously needed.

# PROJECT STRUCTURE

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2 distinct projects:

## G4 ↔ FLUKA interface

Standalone repository.

- Transparently follow future FLUKA updates.
- Registration to FLUKA and agreement to its license needed here.  
Need to install FLUKA locally, to be able to link and run the interface successfully.

## G4 side

Created dedicated Model (FlukaNuclearInelasticModel), XSDataSet (FlukaInelasticScatteringXS) [, PhysicsConstructor (FlukaHadronInelasticPhysics), PhysicsList].

The interface can be called:

- At the interaction level  
Incorporated XS and final-state standalone applications as G4 examples.
- As a comprehensive Physics list  
/physics\_lists/select in any G4 application (including MOIRA).

## Integration to G4

Fully open to discussion and G4 team preferences.

- Integrate FLUKA Model and XSDataSet in source/processes/hadronic/cross\_sections and models.
- Integrate to G4 examples the applications calling the FLUKA interface for interaction-level simulations.
- Would it also be useful to integrate the FlukaHadronInelasticPhysics PhysicsConstructor / a template PhysicsList?

# G4 ↔ FLUKA INTERFACE

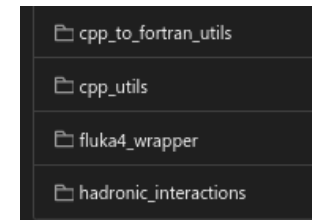
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C++ interface, compatible with FLUKA's latest release.

Presently includes:

- Standalone code, **isolating FLUKA hadron-nucleus interactions modeling**.  
Isolates the necessary FLUKA initializations and calls.  
Returns inelastic scattering XS, and hadron-nucleus interactions final states, as computed by FLUKA.
- A FLUKA project wrapper.  
Contains all needed FLUKA headers and functions in C++  
(and the associated fortran procedures signatures).
- Generic G4 ↔ FLUKA interfacing helpers (particles identification, etc).
- Generic FORTRAN to C++ tools.

Easily extendable (provided extra FLUKA wrappers are added as needed).



# DEVELOPMENTS STATUS

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## Standalone hadronic event generators AT THE INTERACTION LEVEL

Input: projectile type, kinetic energy, target nucleus.

Output: hadron-nucleus interactions cross-sections + final states.

Compiles & provides consistent results versus raw FLUKA calls.

- Compared reaction cross-sections and final states for a wide range of inputs.
- Also made random histories consistent for comparison purposes.
- Results are binwise identical with FLUKA Fortran version.

## FLUKA hadron-inelastic interactions AS A COMPREHENSIVE PHYSICSLIST

Tested both as a standalone G4 application and in MOIRA.

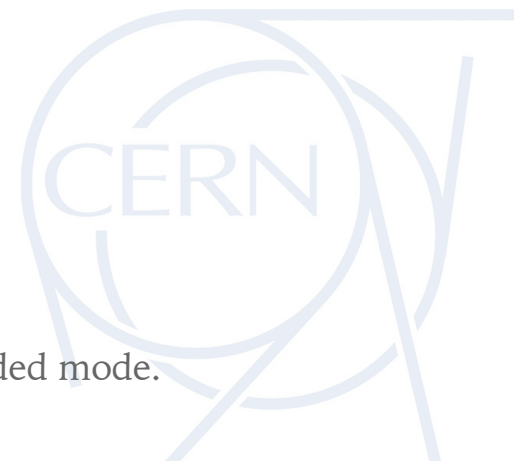
- All default G4 energy and momentum conservation checks now pass successfully.
- Preliminary results are promising (see later slides).
- Still more debugging needed for a wider range of inputs.

### General note:

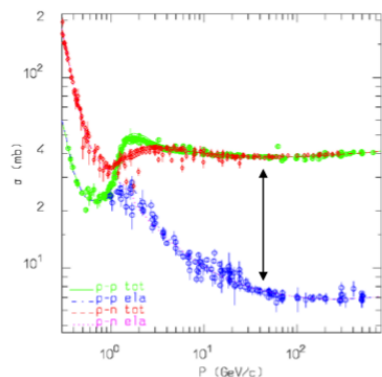
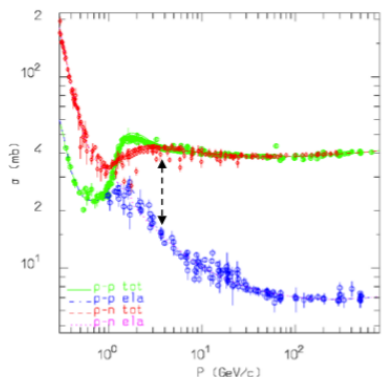
- Single-threaded runs for now.

Could investigate what can be done to run the needed FLUKA sections in multi-threaded mode.

For example: make the COMMON thread-local? OpenMP directives in FLUKA?



# INELASTIC HADRON-NUCLEON REACTIONS



## Intermediate Energies

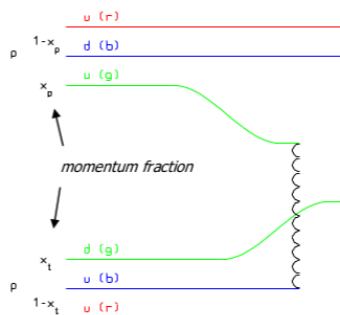
All reactions proceed through an **intermediate state** containing at least one **resonance** (dominance of the  $\Delta(1232)$  resonance and of the  $N^*$  resonances)

$N_1 + N_2 \rightarrow N_1' + N_2' + \pi$  threshold around 290 MeV,  
important above 700 MeV

$\pi + N \rightarrow \pi' + \pi'' + N'$  opens at 170 MeV

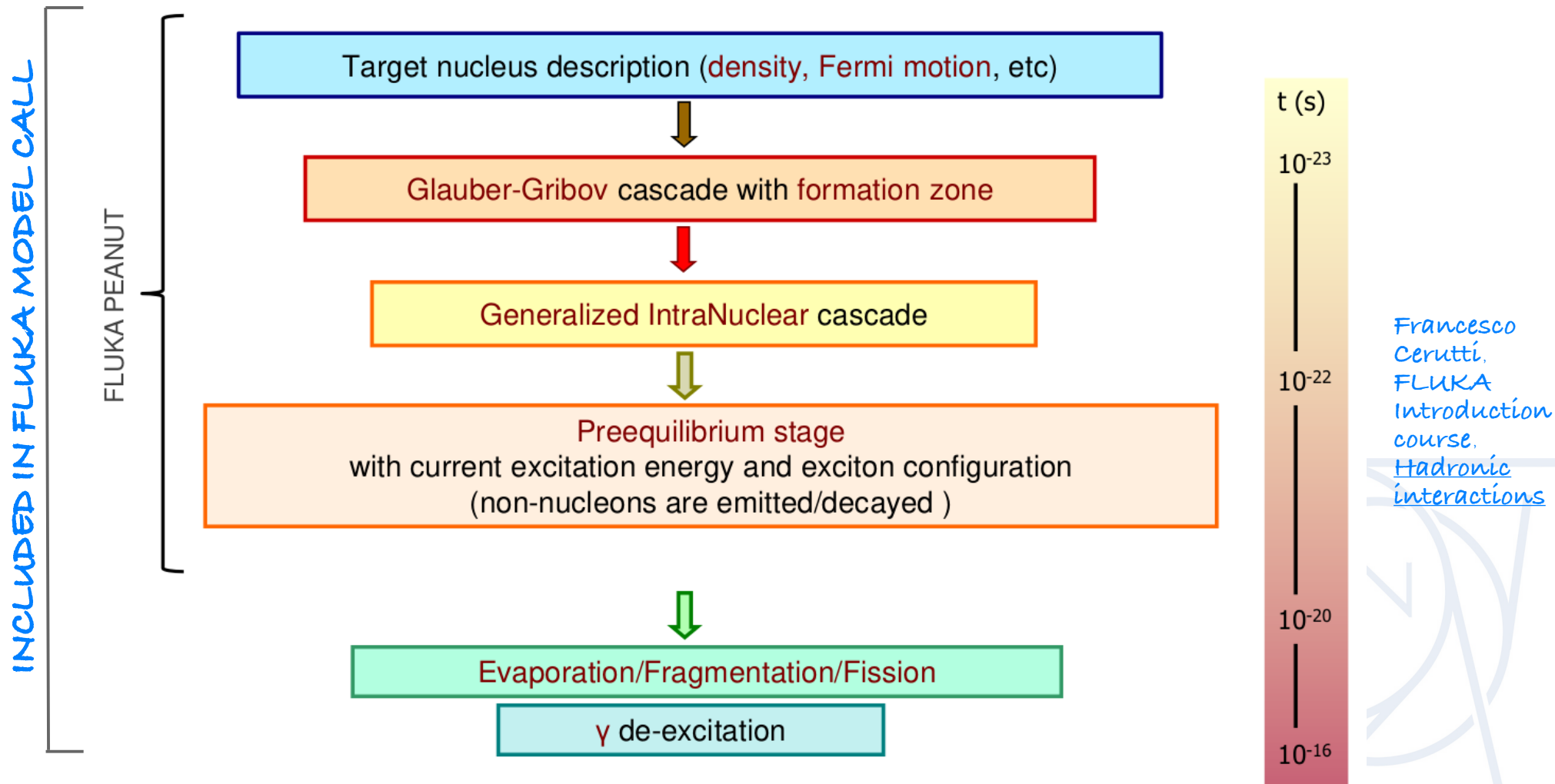
## High Energies: Dual Parton Model/Quark Gluon String Model etc.

**Interacting strings** (quarks held together by the gluon-gluon interaction into the form of a string). Each of the two hadrons splits into 2 **colored partons**  $\rightarrow$  combination into 2 **colorless chains**  $\rightarrow$  2 **back-to-back jets**. Each jet is then **hadronized** into physical hadrons.



Francesco  
Cerutti,  
FLUKA  
Introduction  
course,  
Hadronic  
interactions

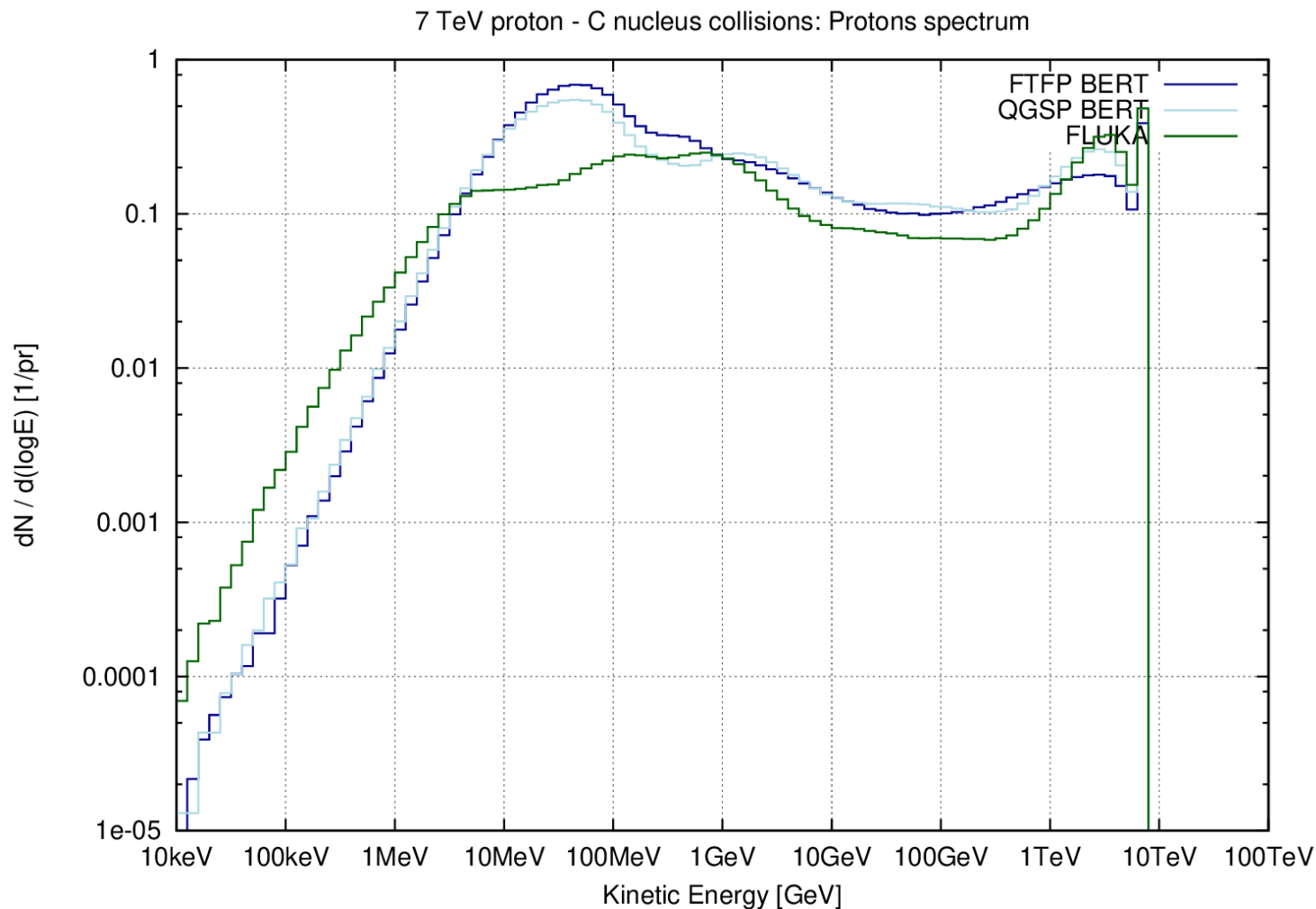
# FLUKA INELASTIC HADRON-NUCLEUS INTERACTION MODELING: PEANUT



# G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: FINAL STATES

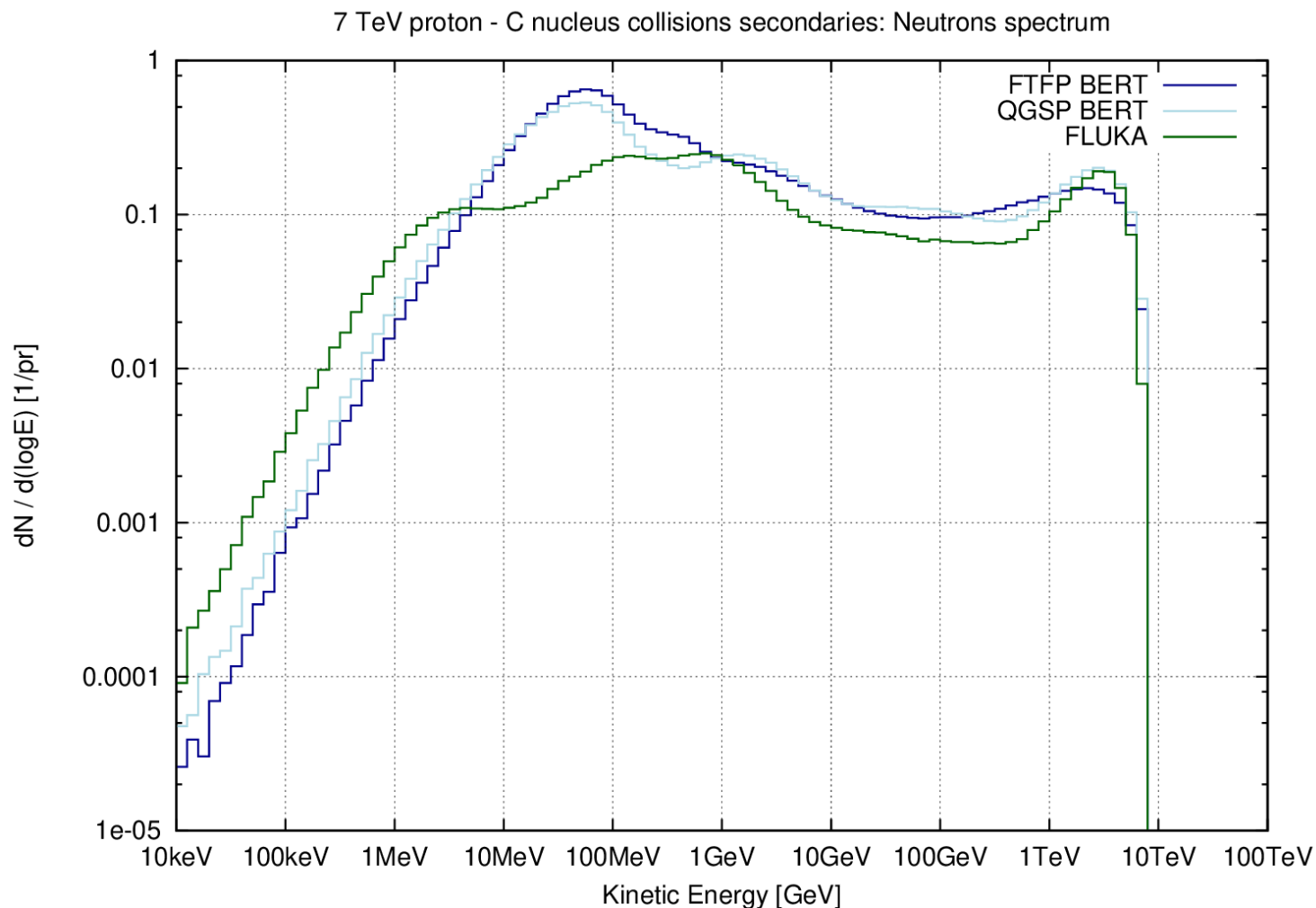
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# G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: FINAL STATES



7 TeV proton - C  
nucleus collisions.  
1 000 000 collisions.

# G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: FINAL STATES



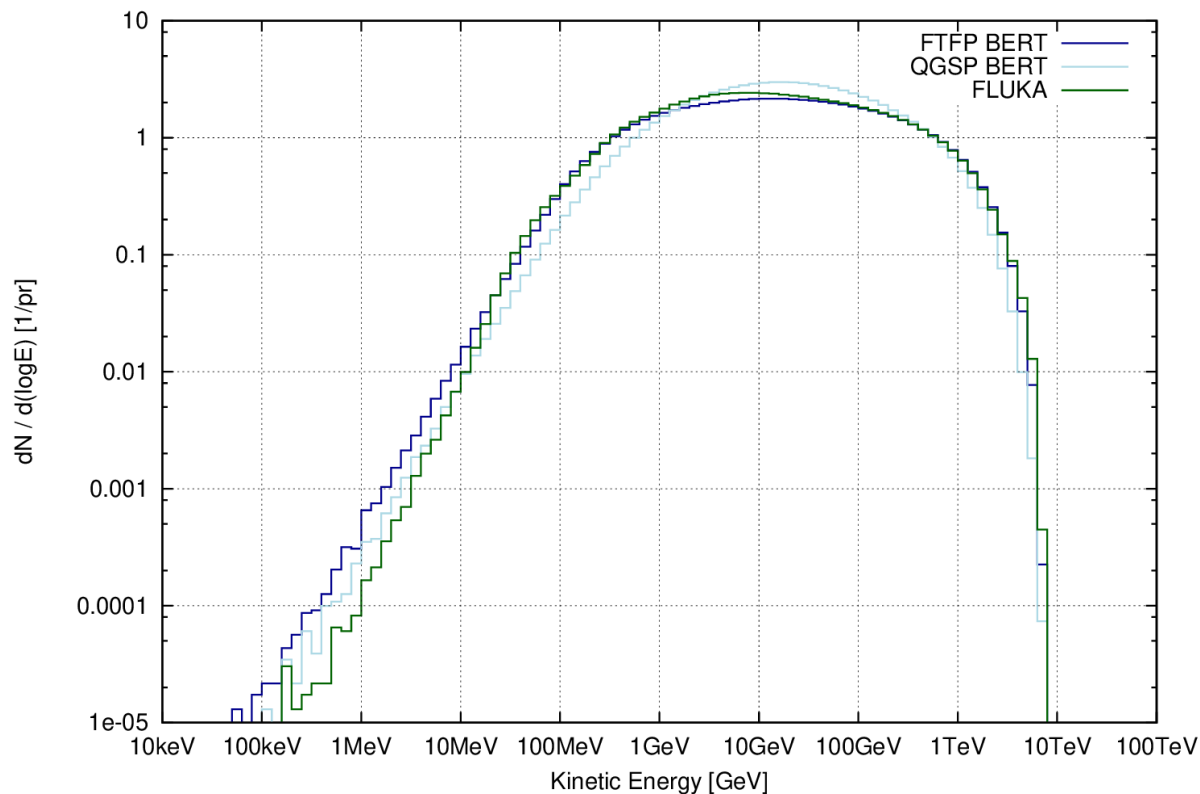
7 TeV proton - C  
nucleus collisions.  
1 000 000 collisions.

# G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: FINAL STATES

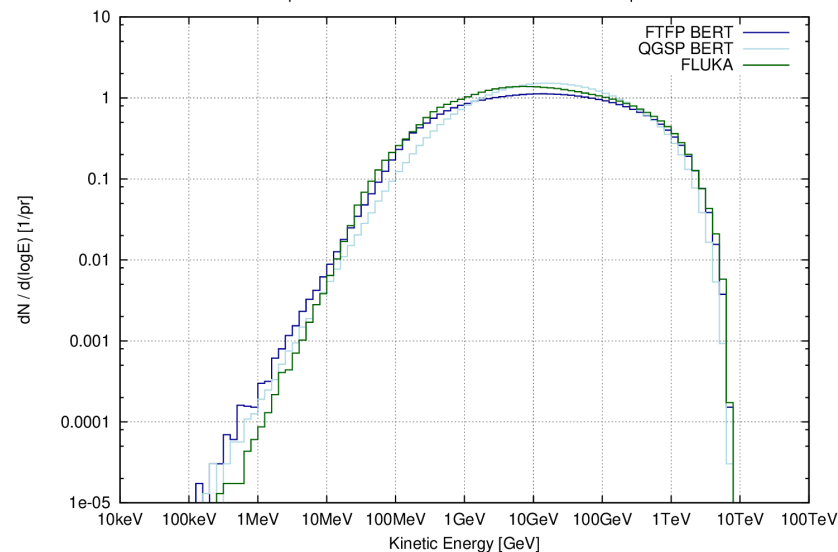
7 TeV proton - C nucleus collisions.

1 000 000 collisions.

7 TeV proton - C nucleus collisions secondaries: Charged pions spectrum



7 TeV proton - C nucleus collisions secondaries: Pi0 spectrum

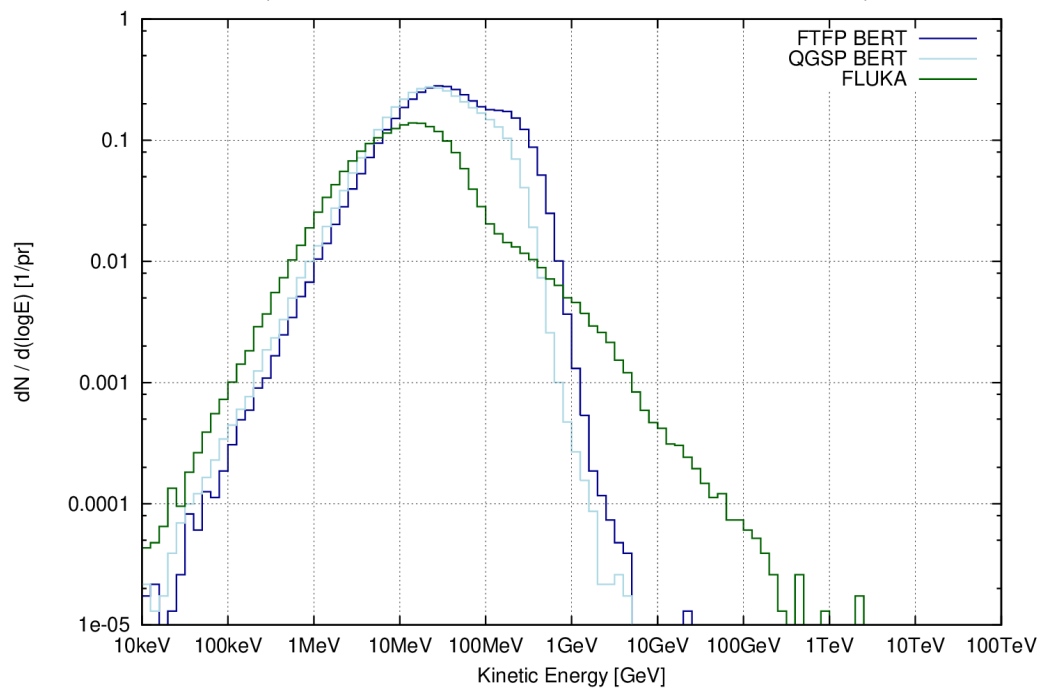


# G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: FINAL STATES

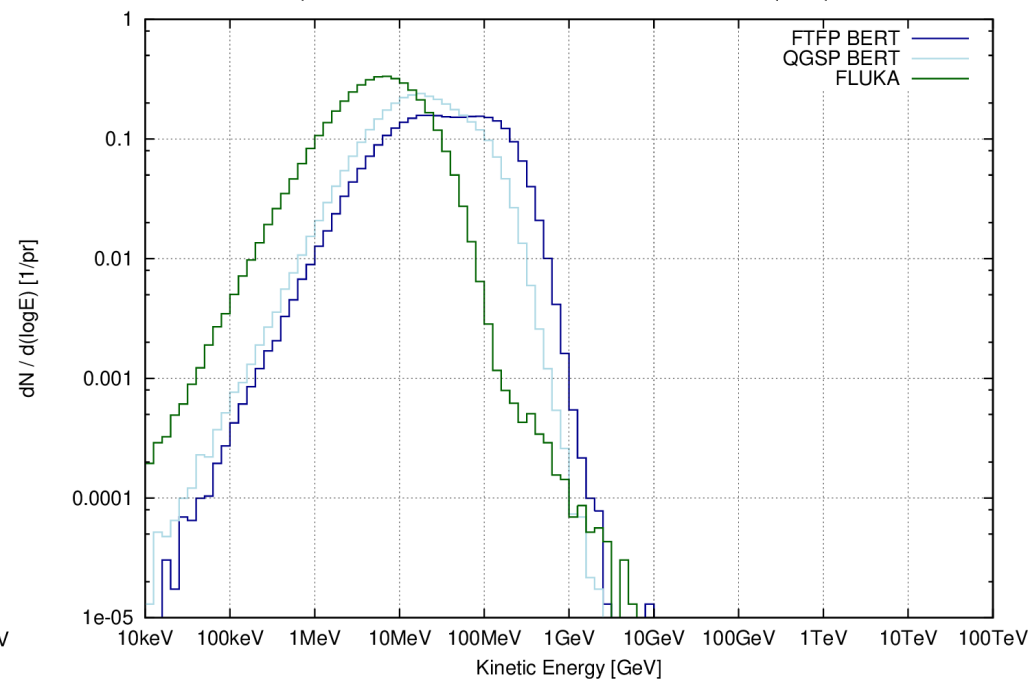
7 TeV proton - C nucleus collisions.

1 000 000 collisions.

7 TeV proton - C nucleus collisions secondaries: Deuterons and Tritons spectrum



7 TeV proton - C nucleus collisions secondaries: He3 and Alpha spectrum



# G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: CROSS-SECTIONS

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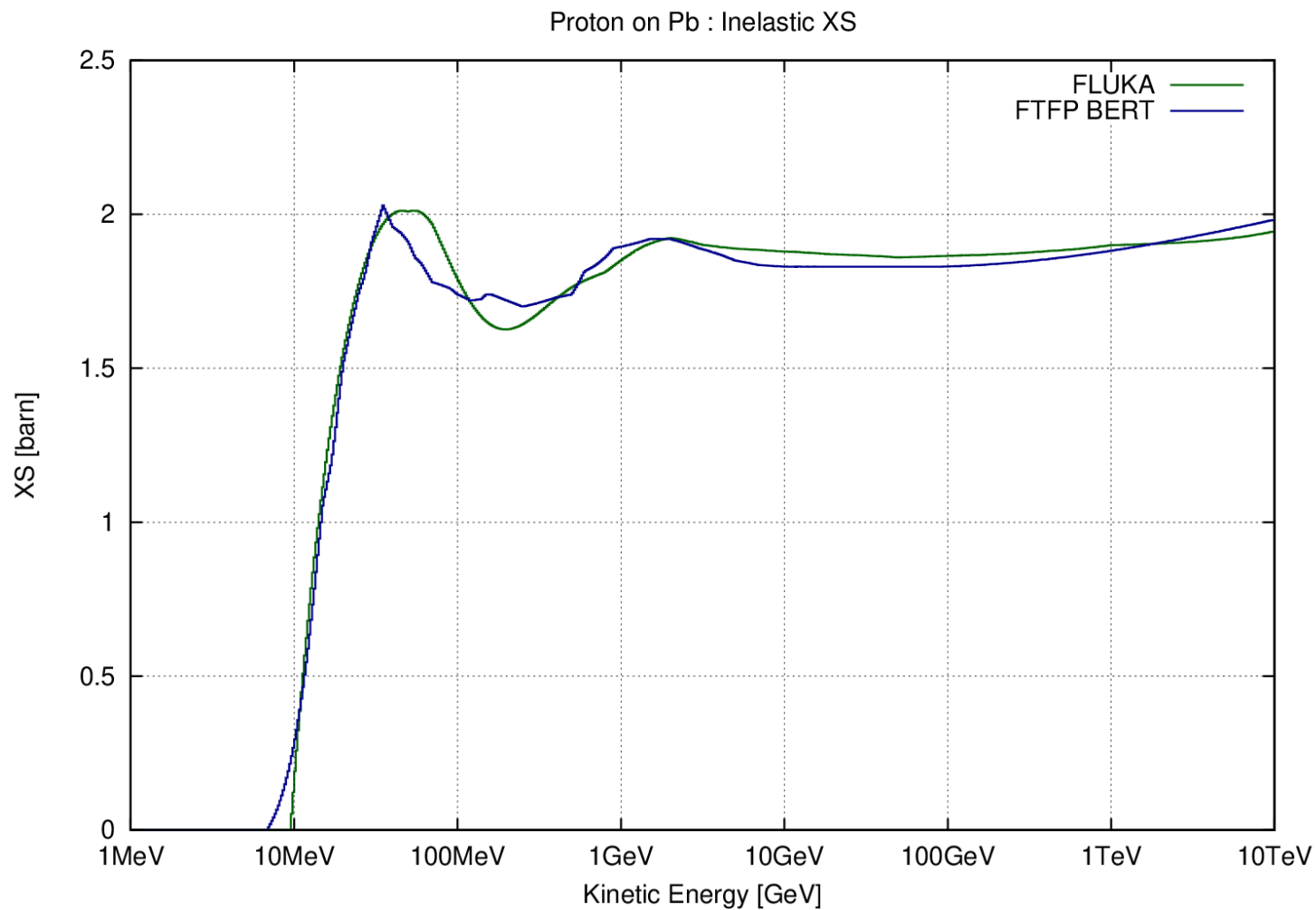
# XS STANDALONE APPLICATION

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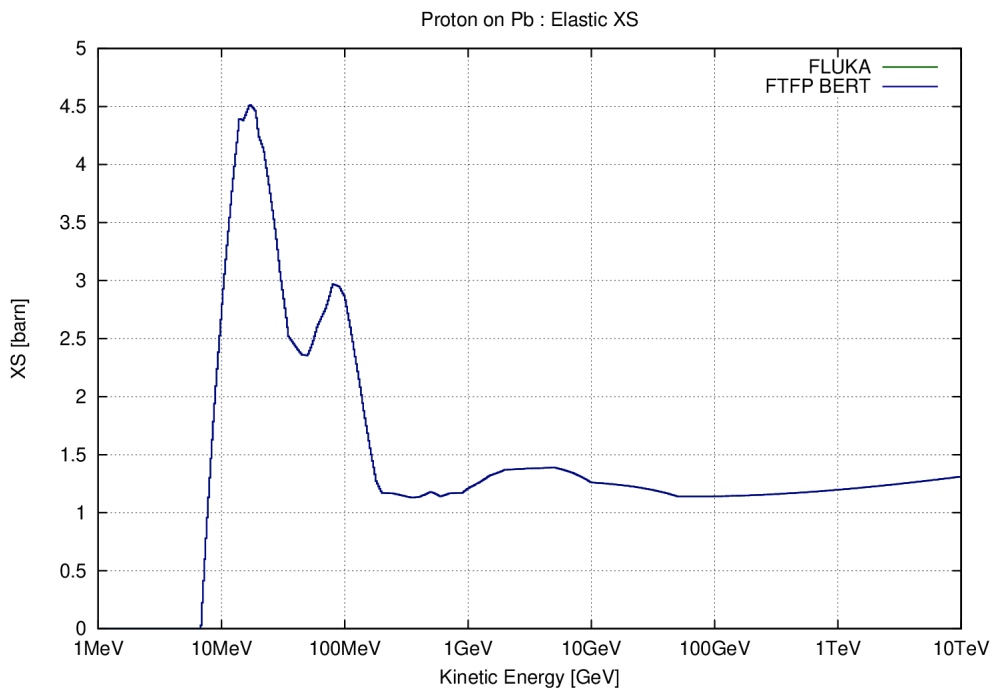
- Created **standalone G4 application to printout XS for given particle and target material.**  
Supports any G4 Physics List + G4 interface to FLUKA hadron inelastic interactions.
- Based on **one of the G4 examples.**
- Complementary to the standalone G4 application to printout final state.
- Integrated **scoring from MOIRA** for easy integration with **Flair**.
- Possible, but not compulsory relevant, to integrate in a complete G4 application:
  - **not event-based**: work is done at the end of the run.
  - **independent from the input geometry**: only target material matters.



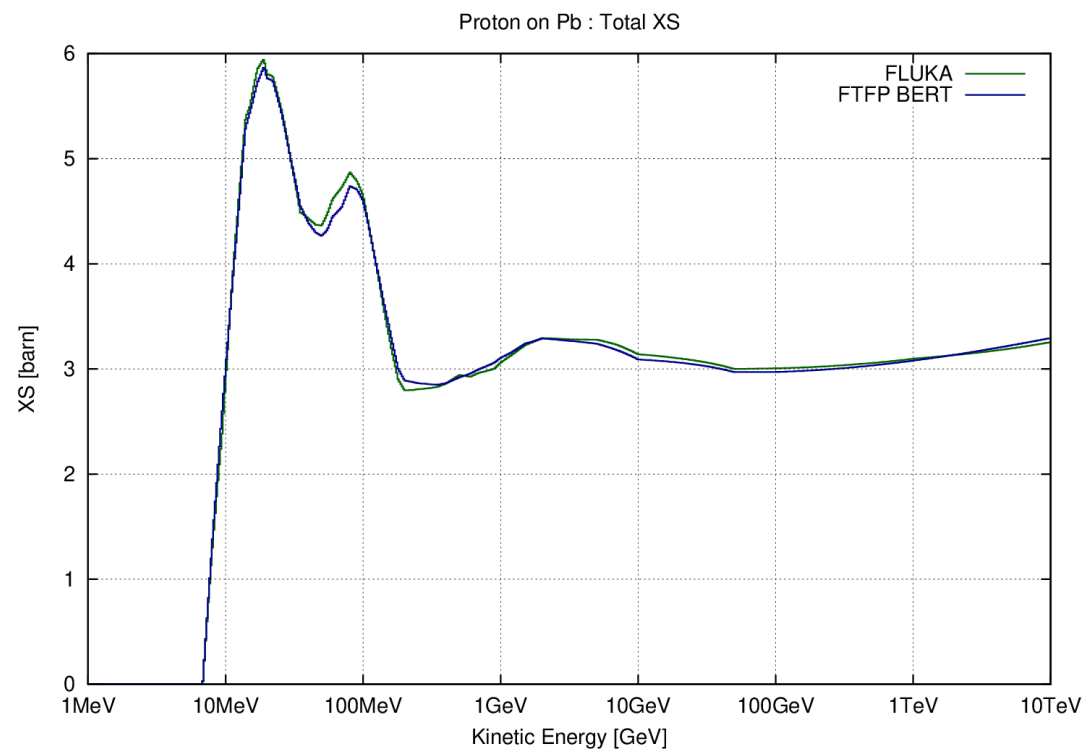
# PROTON ON Pb: INELASTIC XS



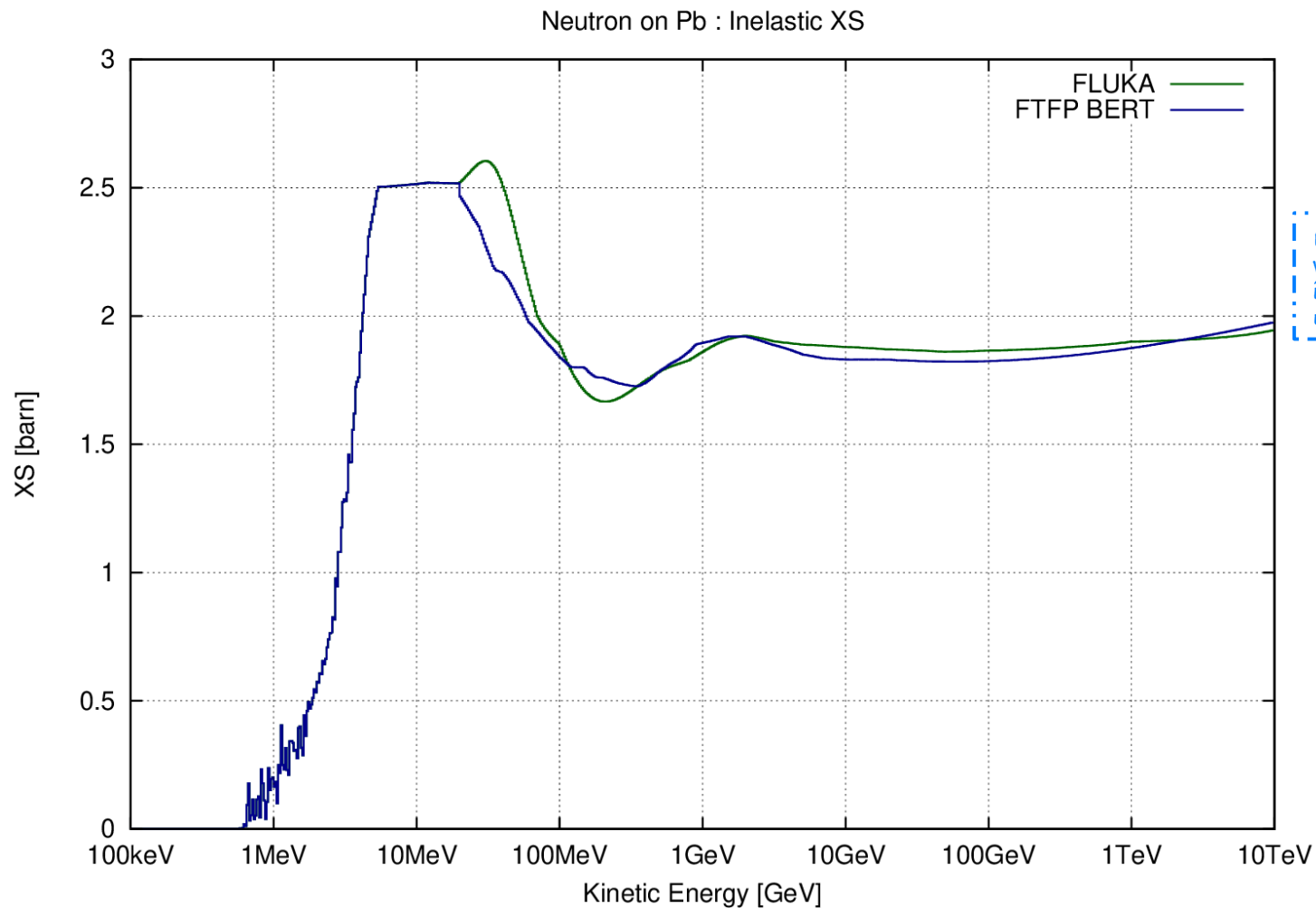
# PROTON ON Pb: ELASTIC AND TOTAL XS



Elastic XS with the FLUKA interface follows G4 elastic XS!!

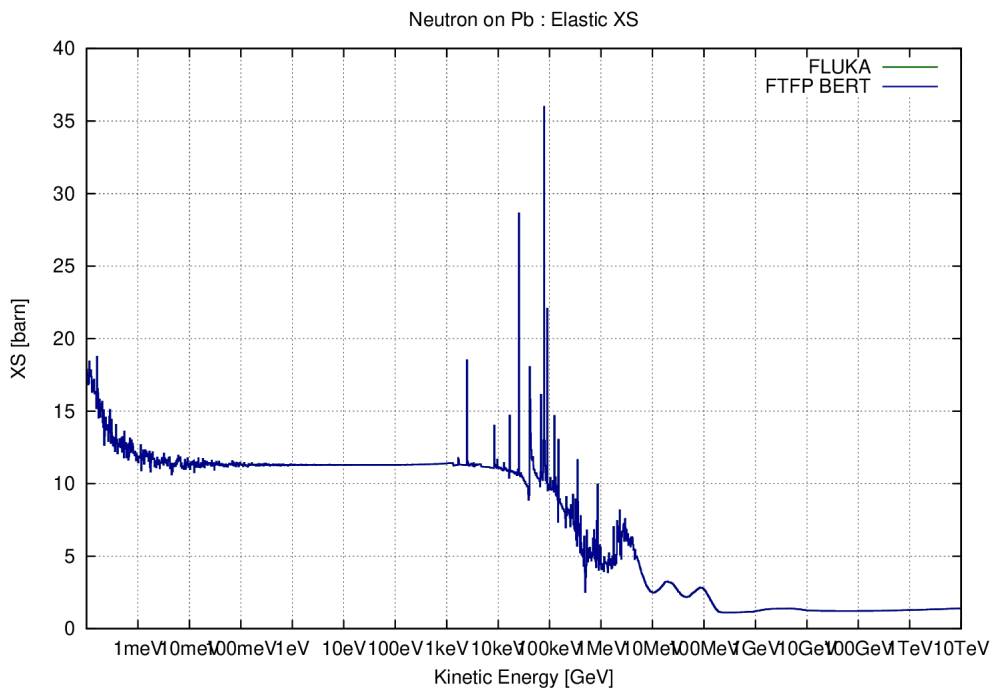


# NEUTRON ON Pb: INELASTIC XS

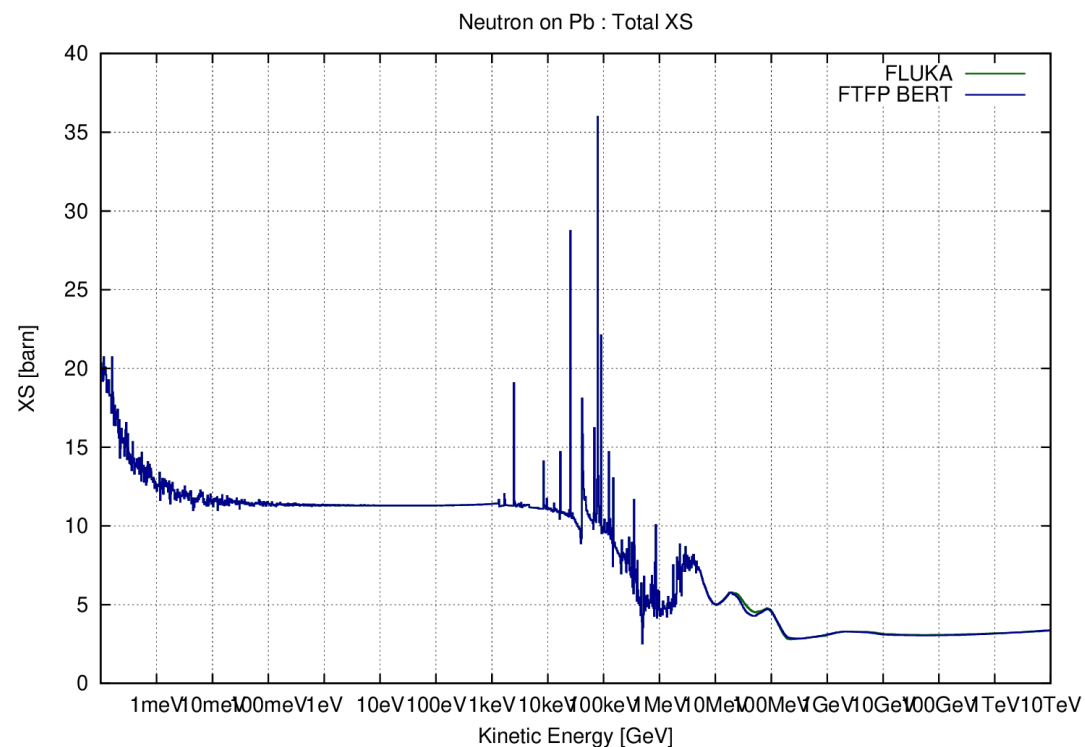


Inelastic neutron XS  
with the FLUKA  
interface follows G4 XS  
under 20 MeV.

# NEUTRON ON PB: ELASTIC AND TOTAL XS



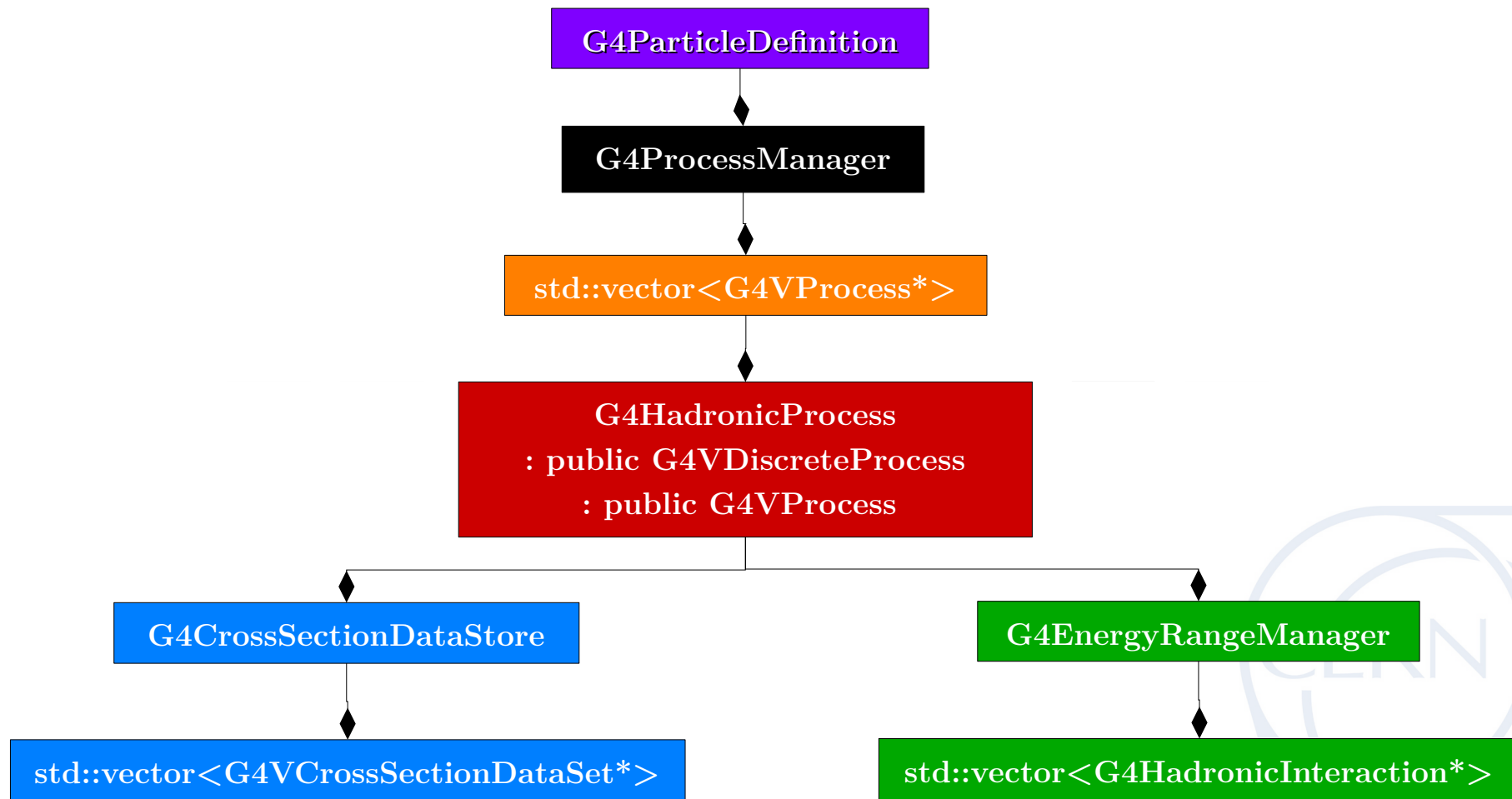
Elastic XS with the FLUKA interface follows G4 elastic XS!!  
Also true for capture XS and fission XS (for any material).



# INTERFACE TO FLUKA HADRON INELASTIC INTERACTIONS: INTEGRATION IN ANY G4 APPLICATION EXAMPLE OF MOIRA INTEGRATION

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# G4 XS AND INTERACTION MODELS: OWNERSHIP DESIGN



# G4 XS AND INTERACTION MODELS: RUNTIME

## INITIALIZATION: PHYSICS PROCESS REGISTRATION

In each Physics constructor:

- **XS and Interaction models** are constructed.
- *ConstructParticle()* defines the relevant particles.
- *ConstructProcess()* associates:  
particle <-> processes manager <-> processes <-> XS and interaction models.

The *G4RunManager* calls the physics list's *ConstructParticle()* and *ConstructProcess()*.

## FOR EACH G4 STEP

Competitive process to find the shortest step length provided by all continuous and discrete processes:  
*G4SteppingManager::DefinePhysicalStepLength()* calls *ComputeCrossSection(dynamicParticle, material)*.

Run the selected process: *G4SteppingManager::InvokePostStepDoItProcs()*.

Checks that there is 1 or 2 models defined for this projectile, at this energy, and for this material!  
If 2 models, make a linear interpolation.

Update the final state, as defined by the selected process's model(s).  
*result = theInteraction->ApplyYourself(thePro, targetNucleus)*

Run  
time

# INTEGRATION IN ANY G4 APPLICATION: EXAMPLE OF MOIRA INTEGRATION

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- Created complete G4 physics list, incorporating the inelastic hadronic interaction from FLUKA.  
Calls the interface to FLUKA when relevant.
- Initially based on FTFP BERT HP LIV, with hadronic inelastic processes replaced.
- Can be called from any G4 application, including MOIRA.
- Running it with MOIRA allowed to further debug the FLUKA interface in a realistic scenario.



# FLUKA INELASTIC HADRONIC INTERACTIONS: INTEGRATION IN FULL PHYSICS LIST

## PHYSICS LIST

Class **FLUKAPhysicsList** : public **G4VModularPhysicsList**

```
RegisterPhysics( new G4EmLivermorePhysics( ver ) ); // G4 EM physics
RegisterPhysics( new G4EmExtraPhysics( ver ) ); // G4 synchrotron radiation & GN physics
RegisterPhysics( new G4HadronElasticPhysicsHP( ver ) ); // G4 hadron elastic physics HP
RegisterPhysics( new FLUKAHadronInelasticPhysics( ver ) ); // FLUKA hadron inelastic physics
RegisterPhysics( new G4IonPhysics( ver ) ); // G4 ions physics
RegisterPhysics( new G4StoppingPhysics( ver ) ); // G4 stopping physics
RegisterPhysics( new G4DecayPhysics( ver ) ); // G4 decay physics
RegisterPhysics( new G4RadioactiveDecayPhysics( ver ) ); // G4 radioactive decay physics
```

## PHYSICS CONSTRUCTOR

Class **FLUKAHadronInelasticPhysics** : public **G4VPhysicsConstructor**

Construct and register at least one process, for each supported particle.

## FLUKA CROSS SECTION DATA SET

Class **FLUKAInelasticScatteringXS** : public **G4VCrossSectionDataSet**.

Calls to FLUKA inelastic scattering cross-sections computation placed here!

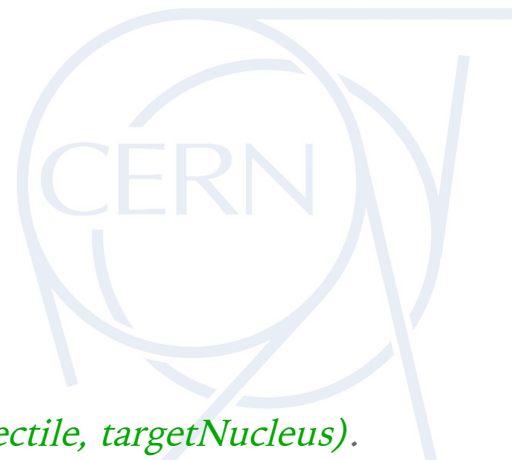
More precisely, it is injected in **FLUKAInelasticScatteringXS::ComputeCrossSection**.

## FLUKA HADRONIC MODEL

Class **FLUKANuclearInelasticModel** : public **G4HadronicInteraction**

Calls to the FLUKA nuclear inelastic model placed here, to inject the final state.

More precisely, the final state is set in **FLUKANuclearInelasticModel::ApplyYourself(projectile, targetNucleus)**.



# INTEGRATION IN ANY G4 APPLICATION

## Example of neutron processes:

### G4 FTFP BERT HP LIV:

#### Hadronic Processes for neutron

```
Process: hadElastic
  Model:      hElasticCHIPS: 19.5 MeV ---> 100 TeV
  Model:      NeutronHPElastic: 0 eV ---> 20 MeV
  Cr_sctns:    NeutronHPElasticXS: 0 eV ---> 20 MeV
  Cr_sctns:    G4NeutronElasticXS: 0 eV ---> 100 TeV

Process: neutronInelastic
  Model:      FTFP: 3 GeV ---> 100 TeV
  Model:      BertiniCascade: 19.9 MeV ---> 6 GeV
  Model:      NeutronHPInelastic: 0 eV ---> 20 MeV
  Cr_sctns:    NeutronHPInelasticXS: 0 eV ---> 20 MeV
  Cr_sctns:    G4NeutronInelasticXS: 0 eV ---> 100 TeV

Process: nCapture
  Model:      NeutronHPCapture: 0 eV ---> 20 MeV
  Model:      nRadCapture: 19.9 MeV ---> 100 TeV
  Cr_sctns:    NeutronHPCaptureXS: 0 eV ---> 20 MeV
  Cr_sctns:    G4NeutronCaptureXS: 0 eV ---> 100 TeV

Process: nFission
  Model:      NeutronHPFission: 0 eV ---> 20 MeV
  Model:      G4LFission: 19.9 MeV ---> 100 TeV
  Cr_sctns:    NeutronHPFissionXS: 0 eV ---> 20 MeV
  Cr_sctns:    ZeroXS: 0 eV ---> 100 TeV
```

### G4 Physic list with FLUKA interface:

#### Hadronic Processes for neutron

```
Process: hadElastic
  Model:      hElasticCHIPS: 19.5 MeV ---> 100 TeV
  Model:      NeutronHPElastic: 0 eV ---> 20 MeV
  Cr_sctns:    NeutronHPElasticXS: 0 eV ---> 20 MeV
  Cr_sctns:    G4NeutronElasticXS: 0 eV ---> 100 TeV

Process: neutronInelastic
  Model:      FLUKANuclearInelasticModel: 20 MeV ---> 100 TeV
  Model:      NeutronHPInelastic: 0 eV ---> 20 MeV
  Cr_sctns:    NeutronHPInelasticXS: 0 eV ---> 20 MeV
  Cr_sctns:    FLUKAInelasticScatteringXS: 0 eV ---> 100 TeV

Process: nCapture
  Model:      NeutronHPCapture: 0 eV ---> 20 MeV
  Model:      nRadCapture: 19.9 MeV ---> 100 TeV
  Cr_sctns:    NeutronHPCaptureXS: 0 eV ---> 20 MeV
  Cr_sctns:    G4NeutronCaptureXS: 0 eV ---> 100 TeV

Process: nFission
  Model:      NeutronHPFission: 0 eV ---> 20 MeV
  Model:      G4LFission: 19.9 MeV ---> 100 TeV
  Cr_sctns:    NeutronHPFissionXS: 0 eV ---> 20 MeV
  Cr_sctns:    ZeroXS: 0 eV ---> 100 TeV
```

# INTEGRATION IN ANY G4 APPLICATION

## Example of proton processes:

### G4 FTFP BERT HP LIV:

Hadronic Processes for proton

```
Process: hadElastic
  Model:          hElasticCHIPS: 0 eV ---> 100 TeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV

Process: protonInelastic
  Model:          FTFP: 3 GeV ---> 100 TeV
  Model:          BertiniCascade: 0 eV ---> 6 GeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV
```

### G4 Physic list with FLUKA interface:

Hadronic Processes for proton

```
Process: hadElastic
  Model:          hElasticCHIPS: 0 eV ---> 100 TeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV

Process: protonHadronInelastic
  Model: FLUKANuclearInelasticModel: 0 eV ---> 100 TeV
  Cr_sctns: FLUKAInelasticScatteringXS: 0 eV ---> 100 TeV
```



# INTEGRATION IN ANY G4 APPLICATION

## Example of pi+/pi- processes:

### G4 FTFP BERT HP LIV:

#### Hadronic Processes for pi+

```
Process: hadElastic
  Model:          hElasticGlauber: 0 eV ---> 100 TeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV

Process: pi+Inelastic
  Model:          FTFP: 3 GeV ---> 100 TeV
  Model:          BertiniCascade: 0 eV ---> 6 GeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV
```

#### Hadronic Processes for pi-

```
Process: hadElastic
  Model:          hElasticGlauber: 0 eV ---> 100 TeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV

Process: pi-Inelastic
  Model:          FTFP: 3 GeV ---> 100 TeV
  Model:          BertiniCascade: 0 eV ---> 6 GeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV

Process: hBertiniCaptureAtRest
```

### G4 Physic list with FLUKA interface:

#### Hadronic Processes for pi+

```
Process: hadElastic
  Model:          hElasticGlauber: 0 eV ---> 100 TeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV

Process: pi+HadronInelastic
  Model: FLUKANuclearInelasticModel: 0 eV ---> 100 TeV
  Cr_sctns: FLUKAInelasticScatteringXS: 0 eV ---> 100 TeV
```

#### Hadronic Processes for pi-

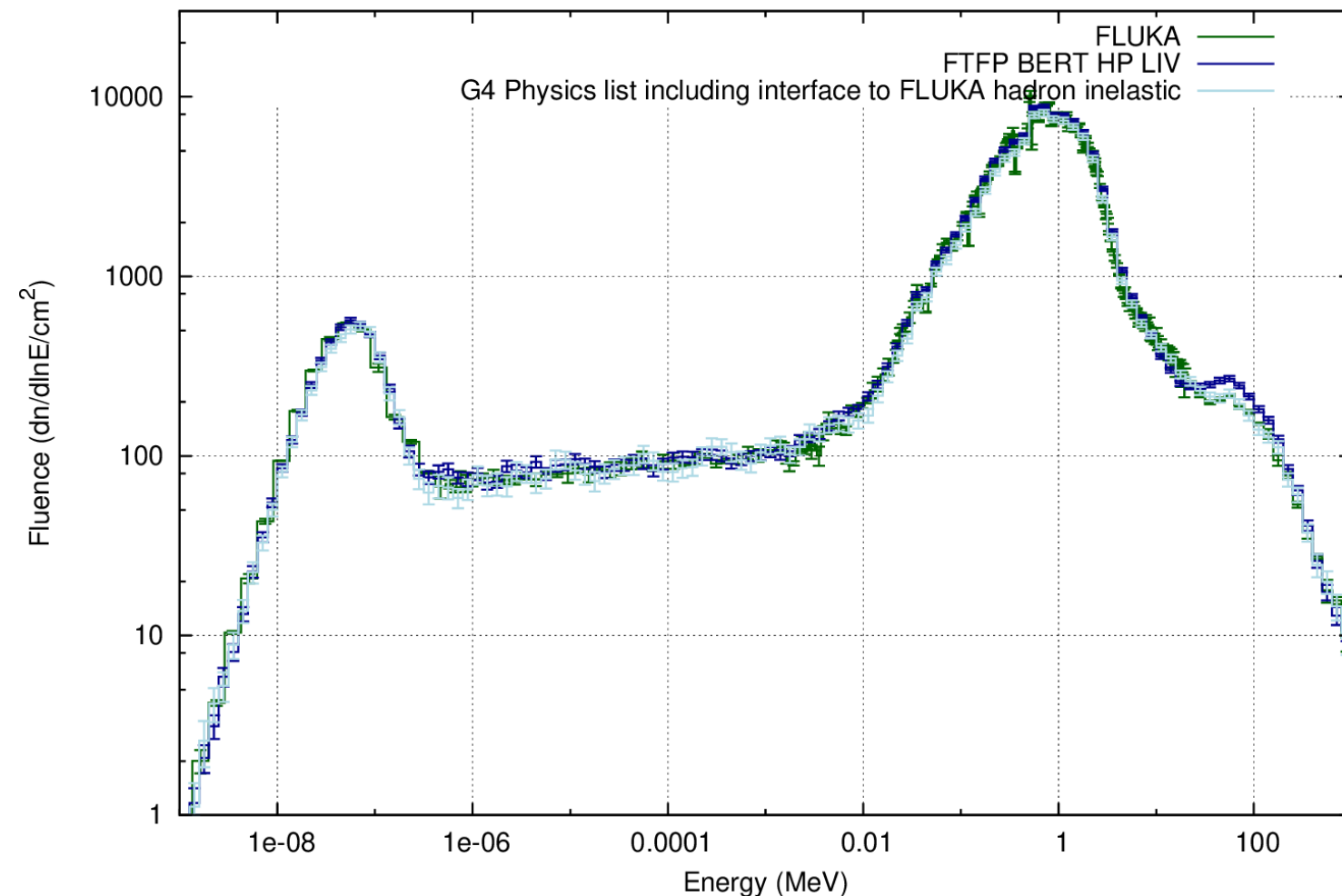
```
Process: hadElastic
  Model:          hElasticGlauber: 0 eV ---> 100 TeV
  Cr_sctns: BarashenkovGlauberGribov: 0 eV ---> 100 TeV

Process: pi-HadronInelastic
  Model: FLUKANuclearInelasticModel: 0 eV ---> 100 TeV
  Cr_sctns: FLUKAInelasticScatteringXS: 0 eV ---> 100 TeV

Process: hBertiniCaptureAtRest
```

# MOIRA INTEGRATION: 20 GEV PROTON GUN ON PB TARGET

Neutron fluence in LEAD, 20 GeV proton on Pb-WATER



Preliminary results  
600 events.



# ANNEX

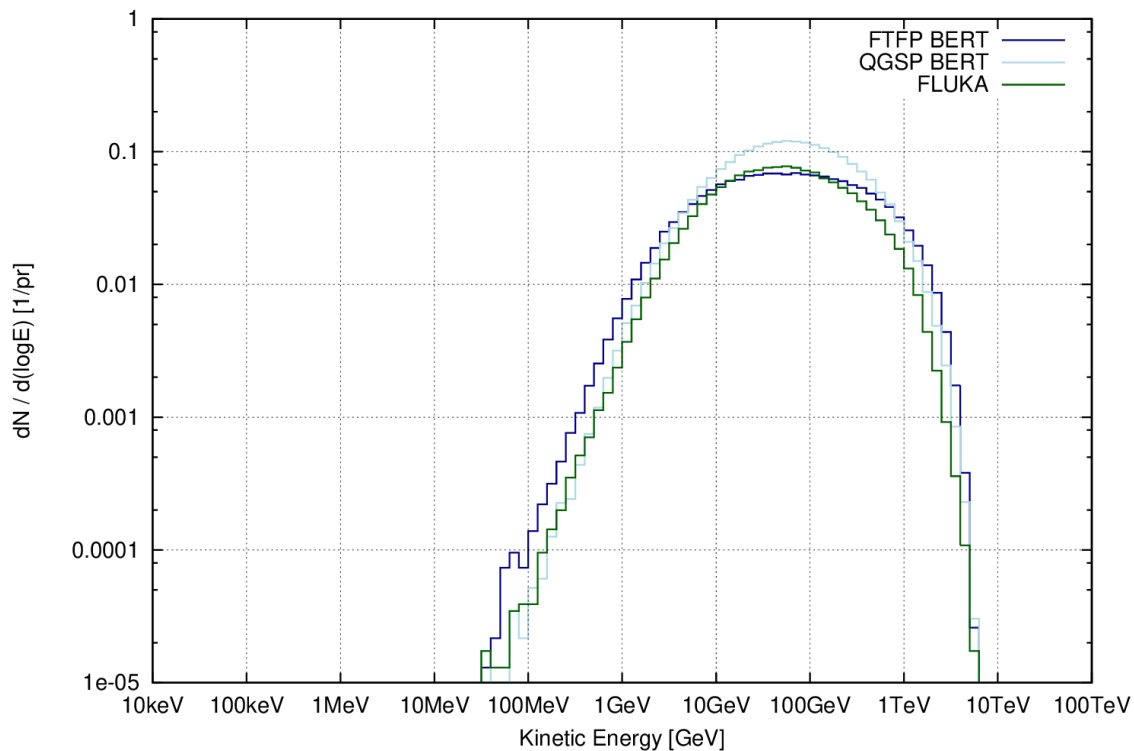
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# 7 TEV PROTON ON C INTERACTIONS

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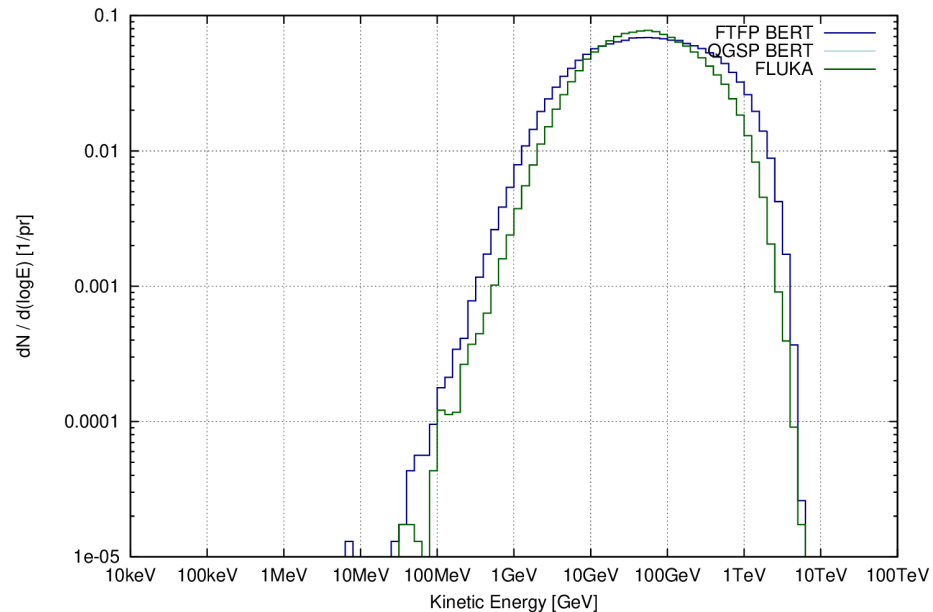
# 7 TEV PROTON ON C: SECONDARIES SPECTRA

7 TeV proton - C nucleus collisions secondaries: Antiprotons spectrum



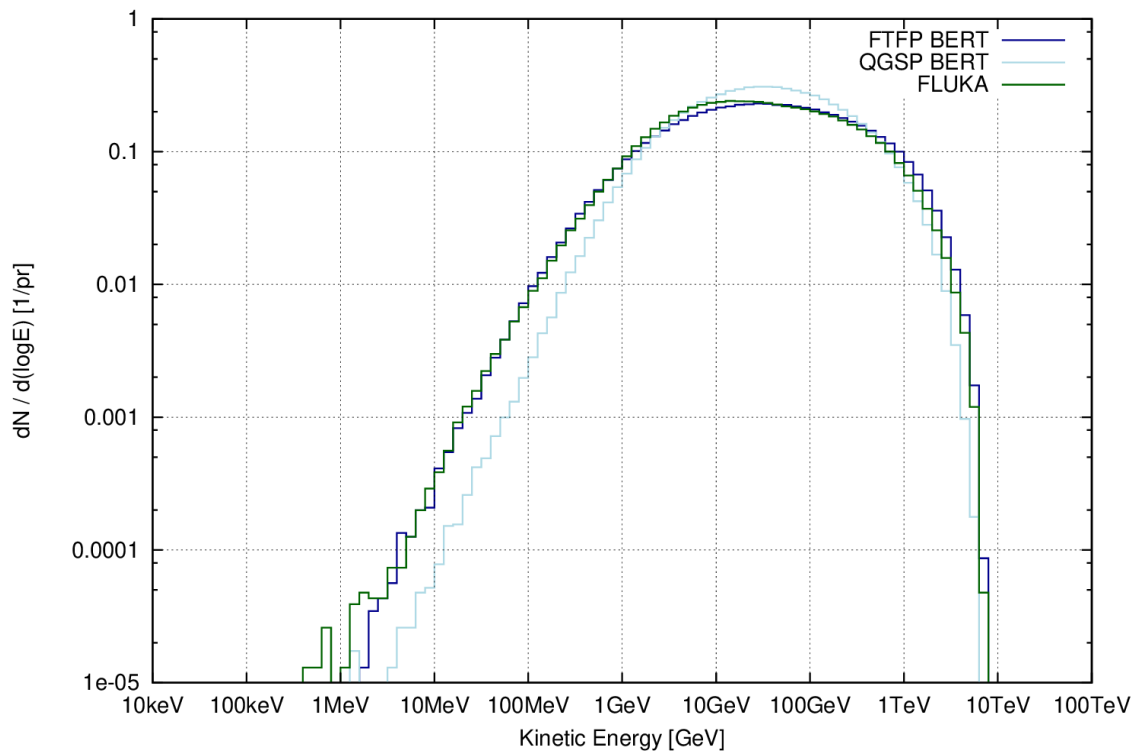
1 000 000 events.

7 TeV proton - C nucleus collisions secondaries: Antineutrons spectrum

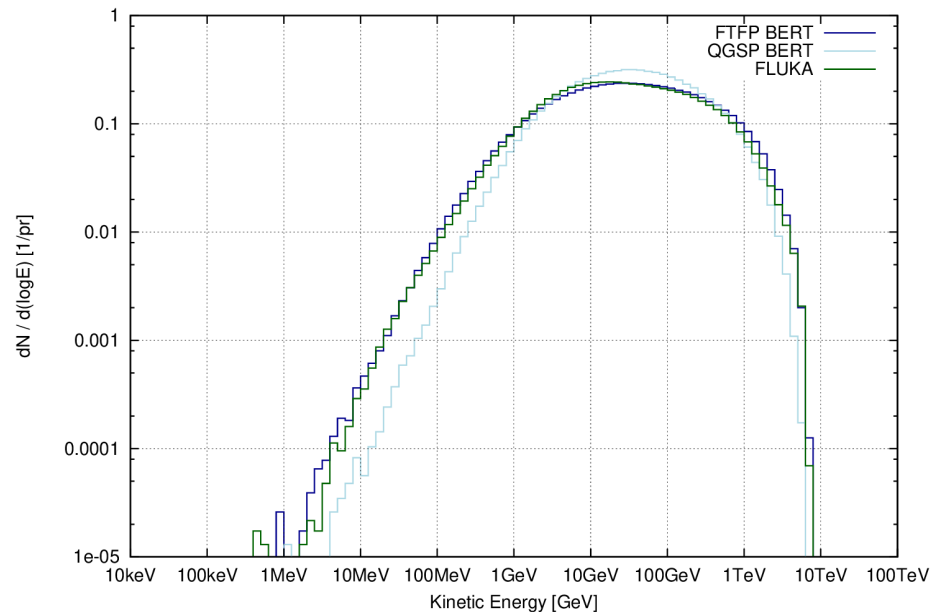


# 7 TEV PROTON ON C: SECONDARIES SPECTRA

7 TeV proton - C nucleus collisions secondaries: K0 spectrum

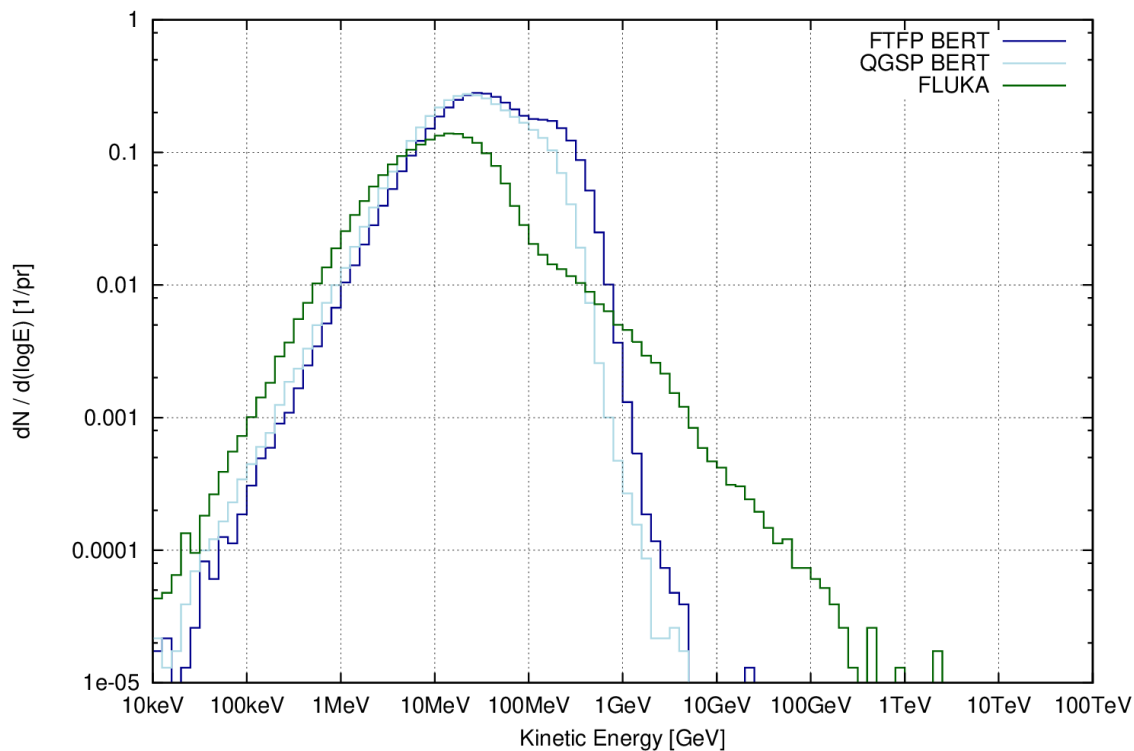


7 TeV proton - C nucleus collisions secondaries: Charged kaons spectrum



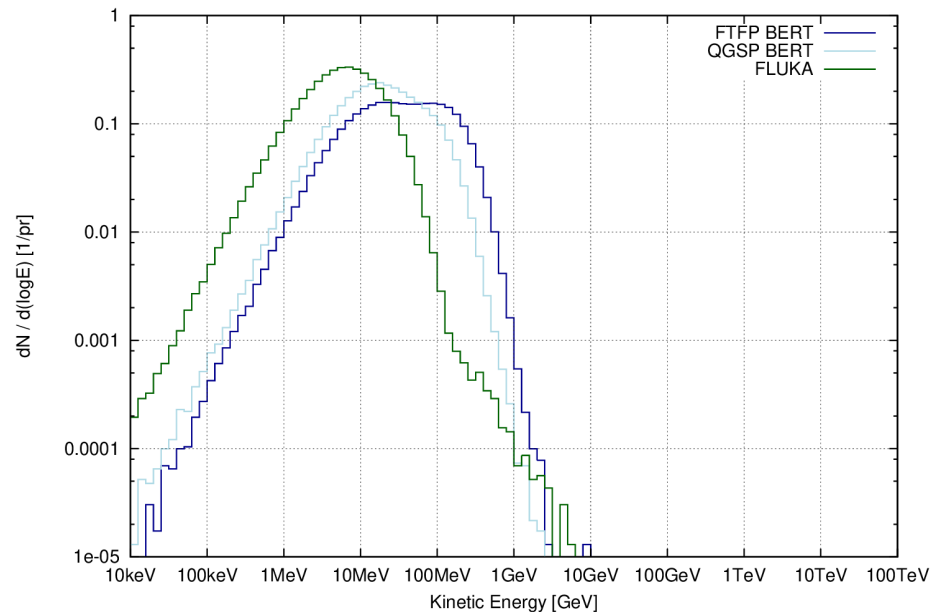
# 7 TEV PROTON ON C: SECONDARIES SPECTRA

7 TeV proton - C nucleus collisions secondaries: Deuterons and Tritons spectrum



1 000 000 events.

7 TeV proton - C nucleus collisions secondaries: He3 and Alpha spectrum

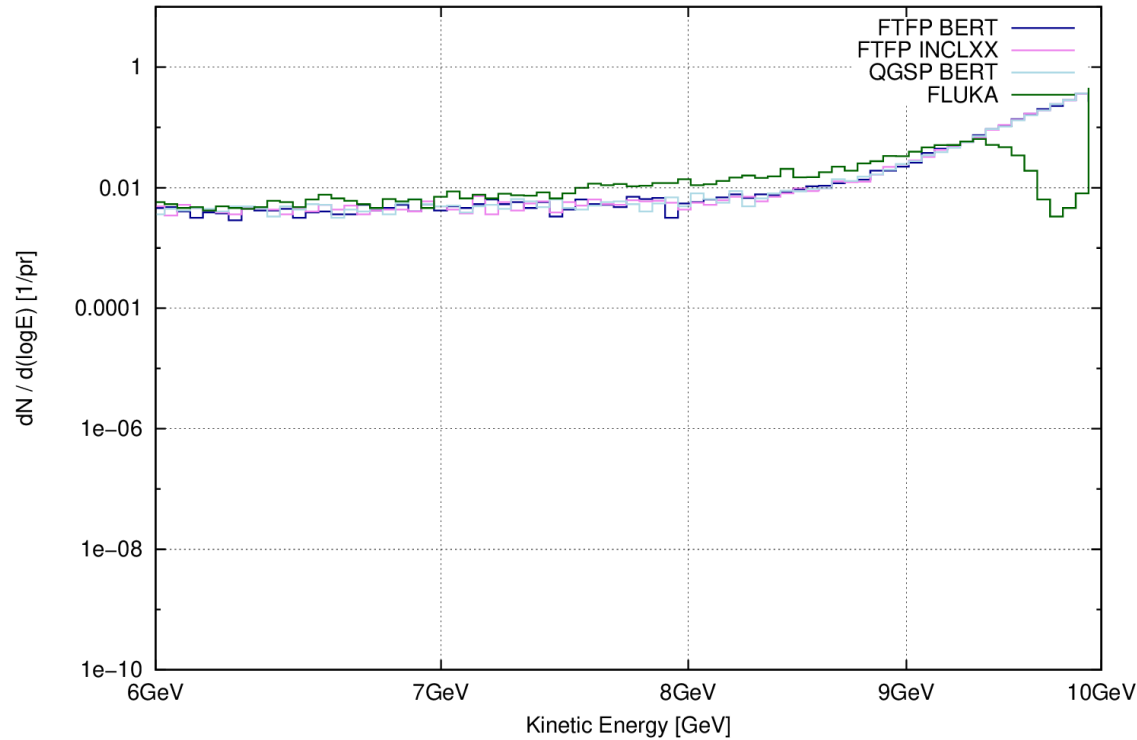


# FLUKA VS G4 DISCREPANCIES TO INVESTIGATE

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# 10 GEV PROTON ON AL: SECONDARIES SPECTRA (TAN(THETA) <= 0.01)

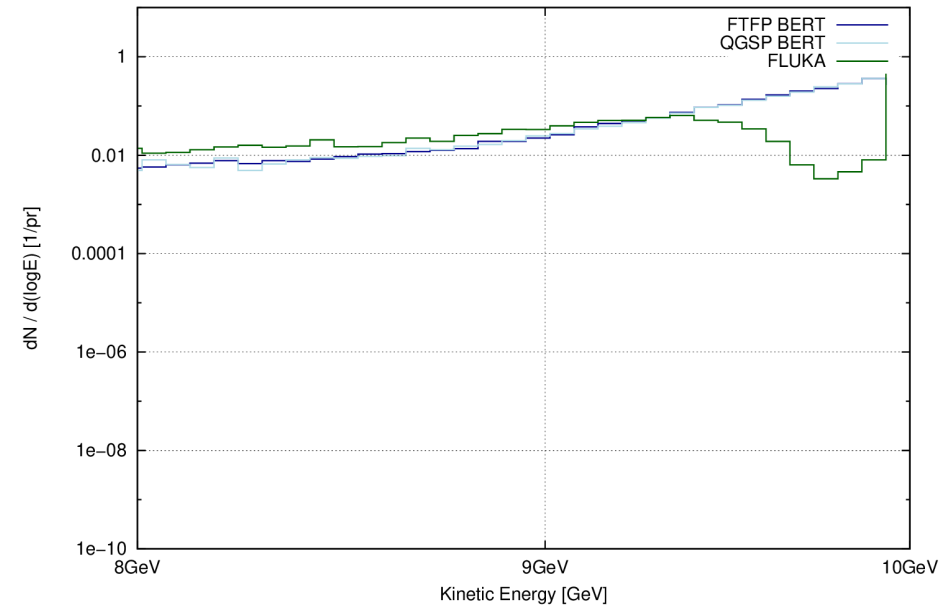
10 GeV proton – Al nucleus collisions: Protons spectrum (tan(theta) <= 0.01)



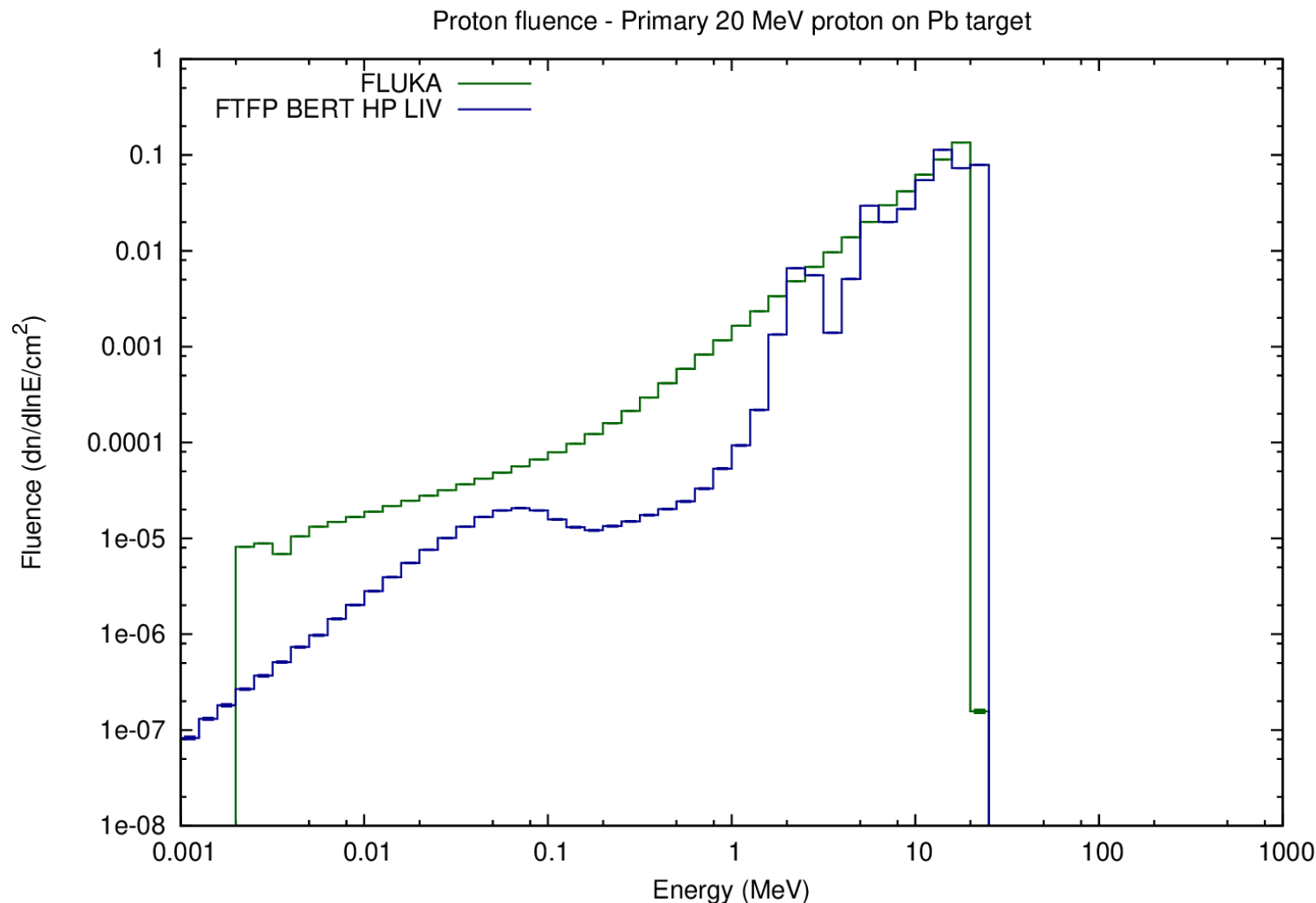
1 000 000 events.

AT THE INTERACTION LEVEL !

10 GeV proton – Al nucleus collisions secondaries: Neutrons spectrum (tan(theta) <= 0.01)



# FLUKA VERSUS G4 PROTON FLUENCE DISCREPANCY IN PB BELOW 10 MEV



~ 600 events.

