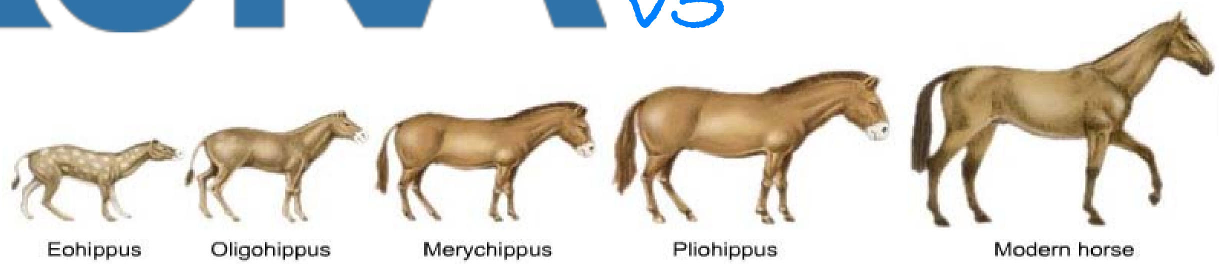
FLUKA v5



THE NEXT FLUKA GENERATION AND ITS TANGIBLE CONVERGENCES WITH GEANT4

Gabrielle HUGO
for the FLUKA.CERN development team

Monday, December 11th 2023

A BIT OF HISTORY

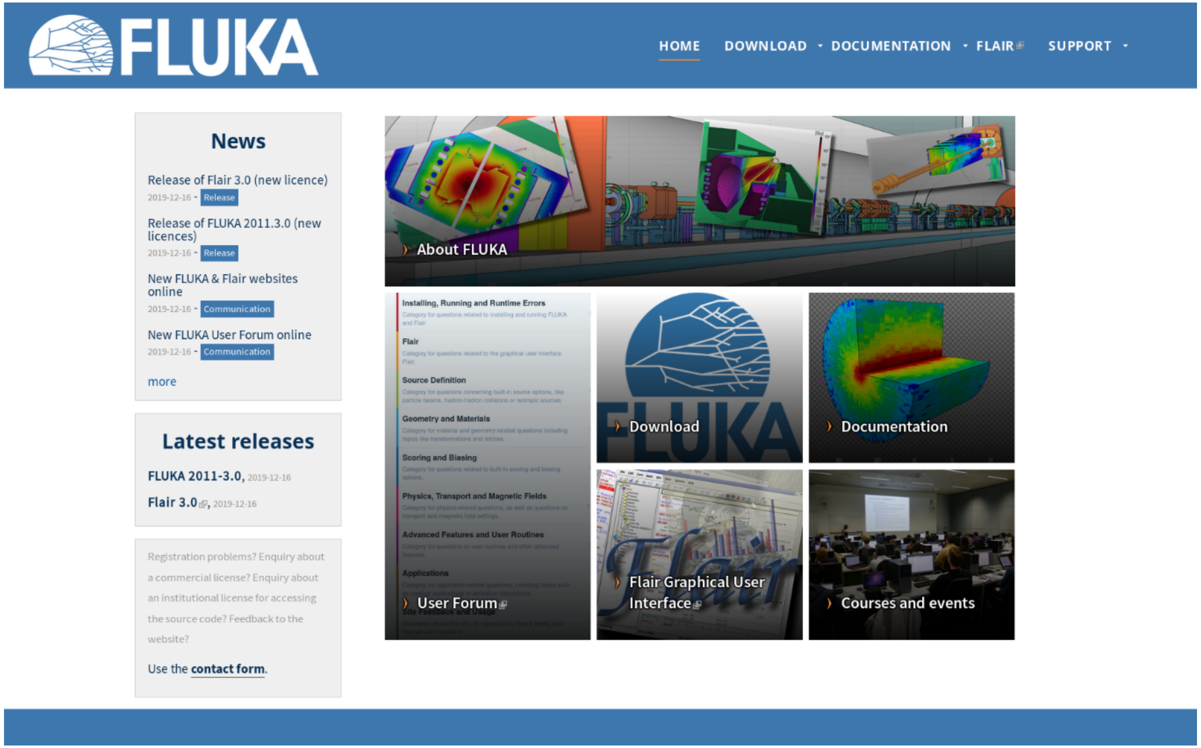
Several FLUKA generations over six decades

- 1st generation. FLUKA was born in the 60s at CERN **with Johannes Ranft**, who wrote a **set of tools for high energy proton accelerators shielding design**. Among these tools, the first cascade code was called FLUKA (FLUktuierende Kaskade).
- Further developed in the 70s **for the SPS**.
- 2nd generation. Tools unified in the 80s into a single hadron cascade code, with **flexible geometry and a modern formulation of the hadron interaction model** (with Leipzig University, Helsinki University).
- 3rd generation. In the 90s: **multiparticle, multipurpose code**. **SSC and LHC design needs** lead to transforming FLUKA from a high-energy code mostly devoted to radiation shielding and beam heating, into a code which could handle most particles of practical interest and their interactions over the widest possible energy range (with INFN).
- From 2003 until August 2019: maintained and developed under a CERN & INFN agreement, **reaching more than** 10,000 registrants. Support for ions interactions (with Houston University and NASA), creation of FLAIR, new neutron cross section library below 20 MeV (including 260 neutron and 42 gamma groups), improved models...

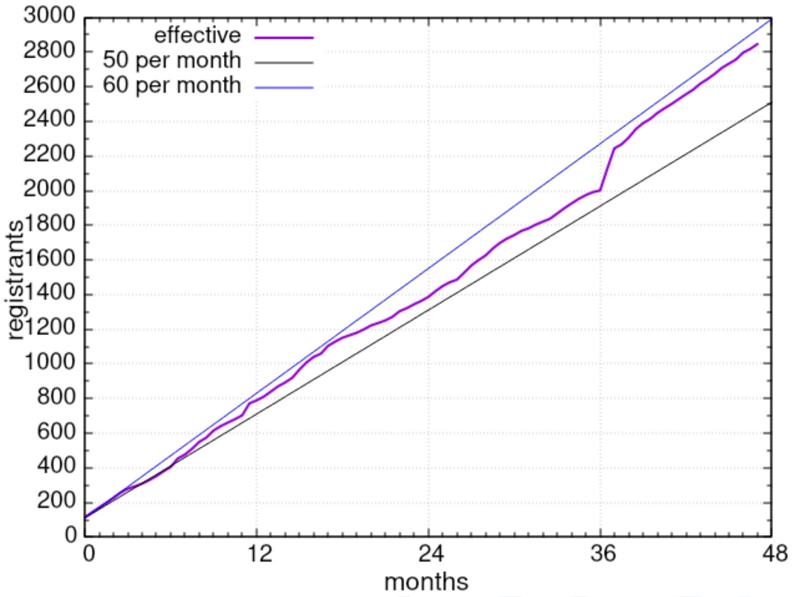
A BIT OF HISTORY

- 4^{th} generation. **From December 2019:** INFN and CERN agreed that they would separately continue the development, maintenance and distribution of FLUKA.
New CERN distribution (FLUKA.CERN) aiming to ensure FLUKA's long-term sustainability within an **international collaboration framework** (already joined by ELI beamlines).

FLUKA.CERN website: https://fluka.cern/



FLUKA.CERN registrations since 2019

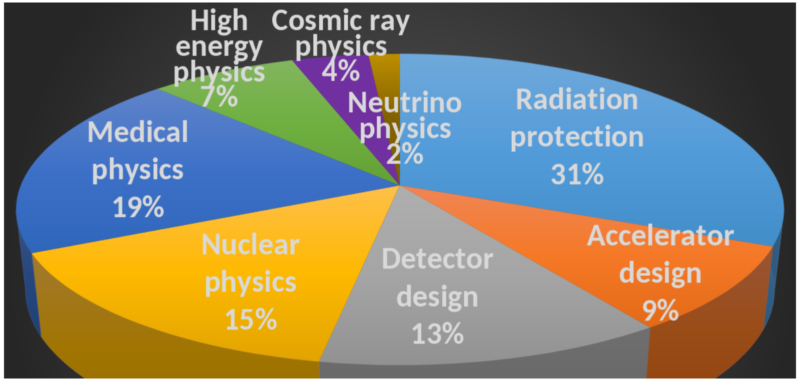


FLUKA CAPABILITIES

- **FLUKA** is a **general purpose Monte Carlo code for the interaction and transport of hadrons, leptons, and photons from keV (with the exception of neutrons, tracked down to thermal energies) to cosmic ray energies in any material.**

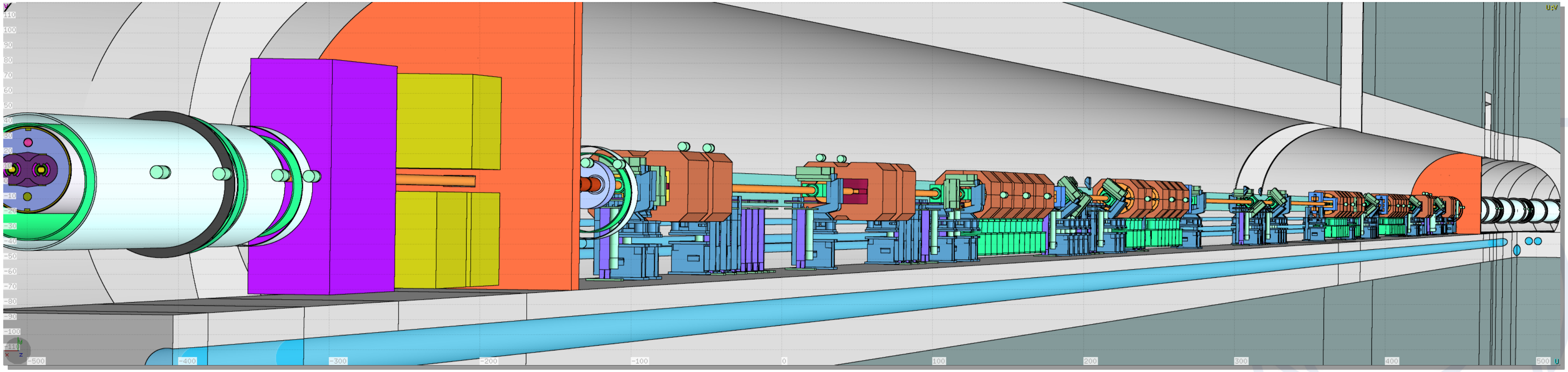
- **Capabilities:**
  - hadron-hadron and hadron-nucleus interactions
  - nucleus-nucleus interactions (including deuterons!)
  - photon interactions (>100 eV)
  - electron interactions (>1 keV; including electronuclear)
  - muon interactions (including photonuclear)
  - neutrino interactions
  - low energy (<20 MeV) neutron interactions and transport
  - particle decay
  - ionization and multiple (single) scattering (including all ions down to 250 eV/u)
  - coherent effects in crystals (channelling)
  - magnetic field, and electric field in vacuum
  - combinatorial geometry and lattice capabilities
  - voxel geometry and DICOM importing
  - analogue or biased treatment
  - on-line buildup and evolution of induced radioactivity and dose
  - built-in scoring of several quantities (including DPA and dose equivalent)

- **Applications:**



FLUKA FOR THE LHC

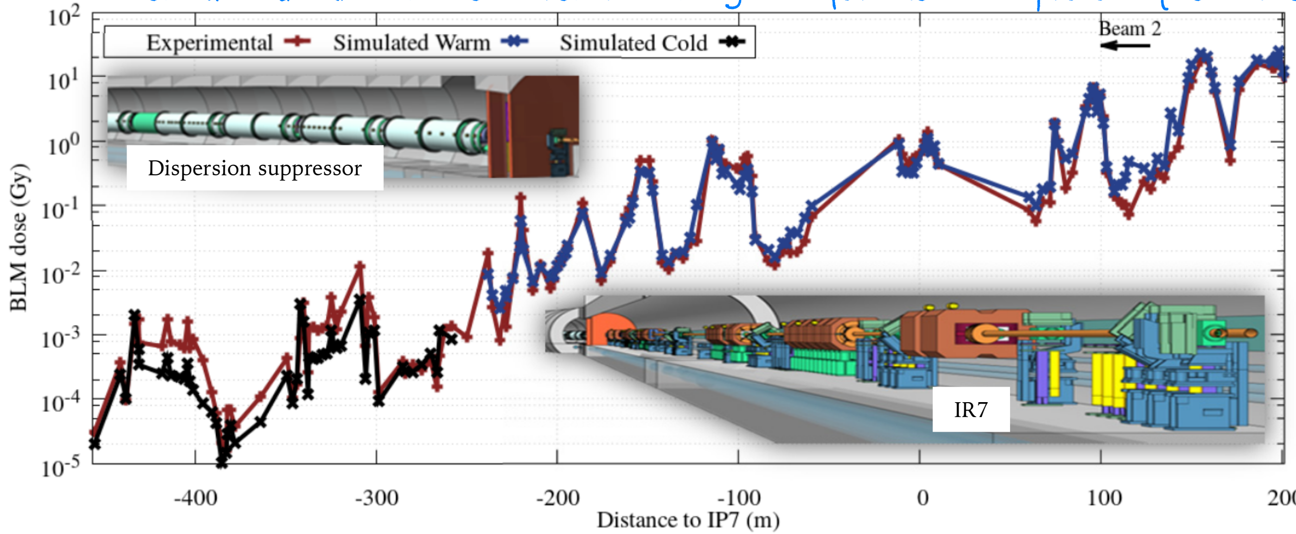
- **Accelerator design studies**, in order to quantify the impact of different kinds of beam losses (collimation, injection/extraction, IP collisions, beam-gas, obstacles, …) on the equipment and evaluate their implications for **operation.**
- Calculate radiation levels and background conditions for **experiments.**
- **Radiation Protection calculations.**



FLUKA geometry model of IR7 (rendering with Flair)

FLUKA EXTENDED BENCHMARKING

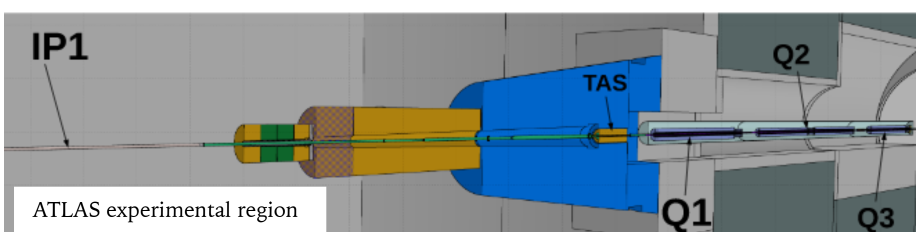
Dispersion suppressor - IR7.
Simulated (FLUKA) and measured BLM signals for the 2015 proton quench test.



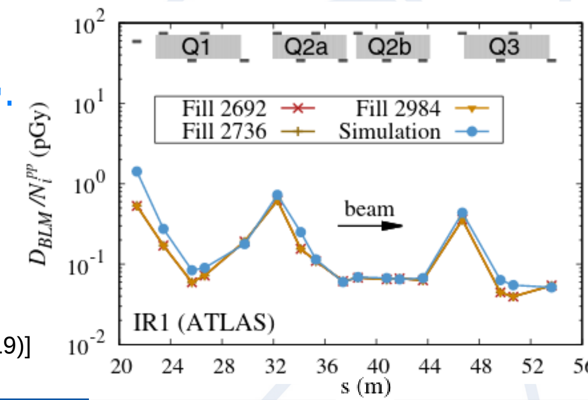
6.5 TeV proton beam

[E. Skordis et al, in Proceedings of IPAC 2017]

ATLAS experimental region.
Simulated (FLUKA) and measured BLM signals along final focus quadrupoles (2012).



[A. Lechner et al, in Phys. Rev. AB 22, 071003 (2019)]



TOWARDS A NEW FLUKA GENERATION

Present FLUKA results have reached a high level of maturity.
Directly used and benchmarked for the design/construction/operational studies of accelerators over several decades.

However, the present FLUKA code-base (v4), mostly in FORTRAN 77, has margins of improvement:

- General **code readability** (6-letter names, duplication, dead code).
- Rigid **code structure** (lack of modularization).
- Extensive use of **shared variables**, no clear dependencies (when and where is each variable modified?).
- Any typo in a variable name creates a new different variable, silently used (**implicit variable declarations**).
- Locals are initialized to zero through compiler option (hiding **uninitialized variables**).
- **Static memory allocations**.
- Obscure **error messages**.

While maintaining and improving **FLUKA physics performance and its user experience**, we also aim at:

- Long-term maintainability.
- Incorporating further implementations.
- Openness to external contributions.

POSSIBLE PATHS

A complete **transition to another Monte Carlo code** was not an option:

- **Need continuity in the physics results.**
- **Need continuity in the user experience.**
- **Long investment** in FLUKA (models, input files, auxiliary tools, …)

Several paths were envisaged for a **new FLUKA generation (v5)**:

✗ **(1) Continue and evolve the present code**

  * Already operational.
  * Arriving to its limit → adding new features becomes more and more complicated.
  * Requires deep understanding of the code → not easy for external contributors.

✓ **(2) Modernize the present code architecture using existing libraries**

  * Progressive transition.
  * Establish synergies with other codes.
  * Combine with other models if more performant.
  * More flexible licence conditions.
  * Add external dependencies.
  * Transition phase with work in multiple codes.

✗ **(3) Re-write new code from scratch**

  * Very appealing to make a clean design from start.
  * More flexible licence conditions.
  * Would be a very long endeavor to arrive to the same performances.
  * Transition phase with work in multiple codes.

FLUKA 4 VERSUS FLUKA 5: DEVELOPMENT PERSPECTIVE

Entirely re-writing new project from scratch would have been too time-consuming and disruptive.
The progressive, hybrid solution (2) was chosen.

New FLUKA generation (v5):

- **Same FLUKA repository**.
- Make use of the **Geant4 toolkit**. Build **on top technical infrastructure providing same capabilities as FLUKA v4.**
- **Progressively port and re-write common components:** make the re-written modules accessible from both v4 and v5.

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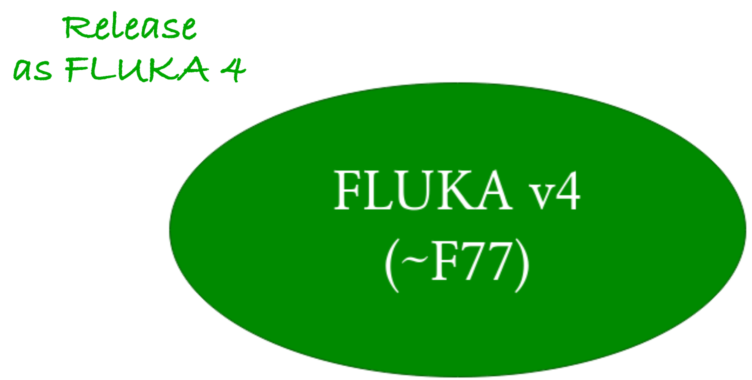

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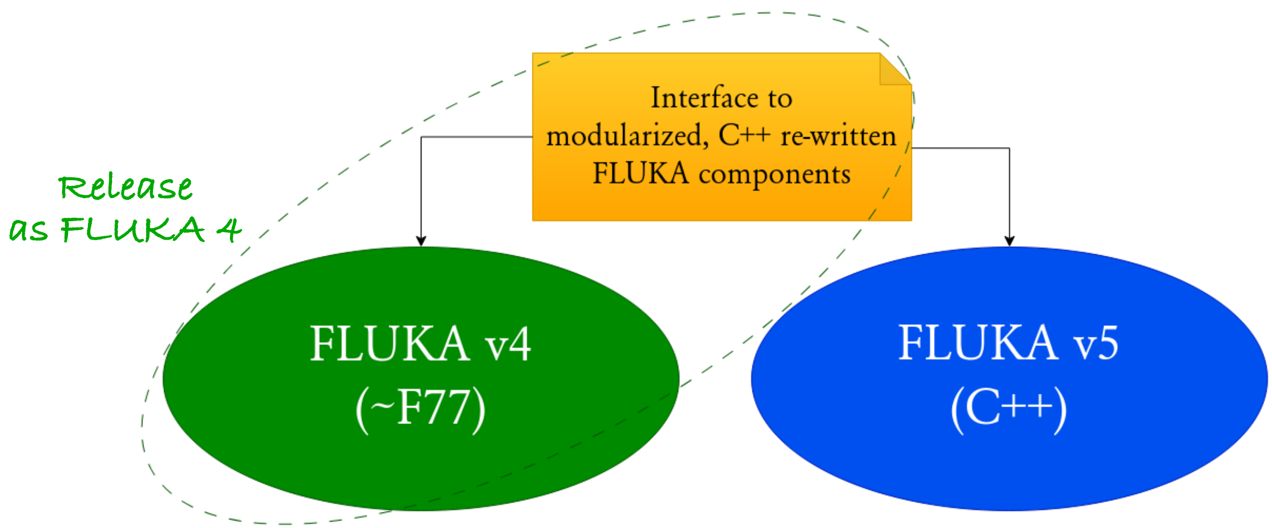

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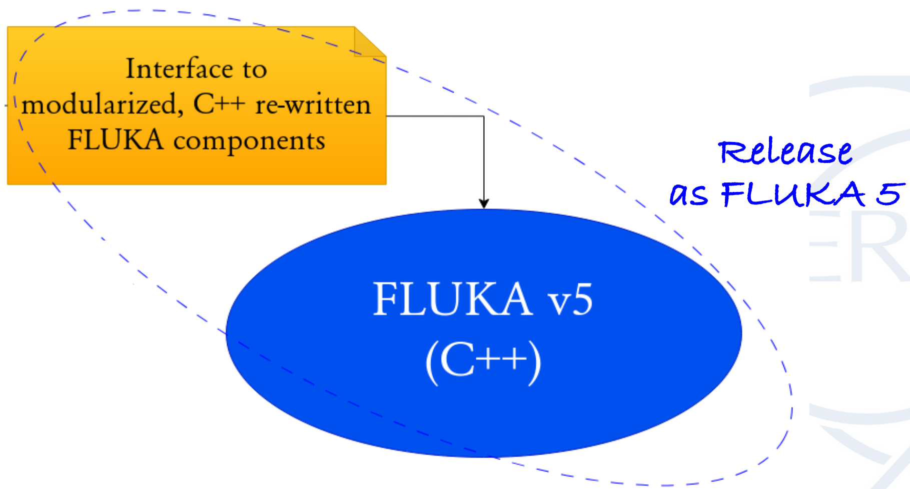
- When equivalent physics performance **is reached, release as FLUKA v5.**



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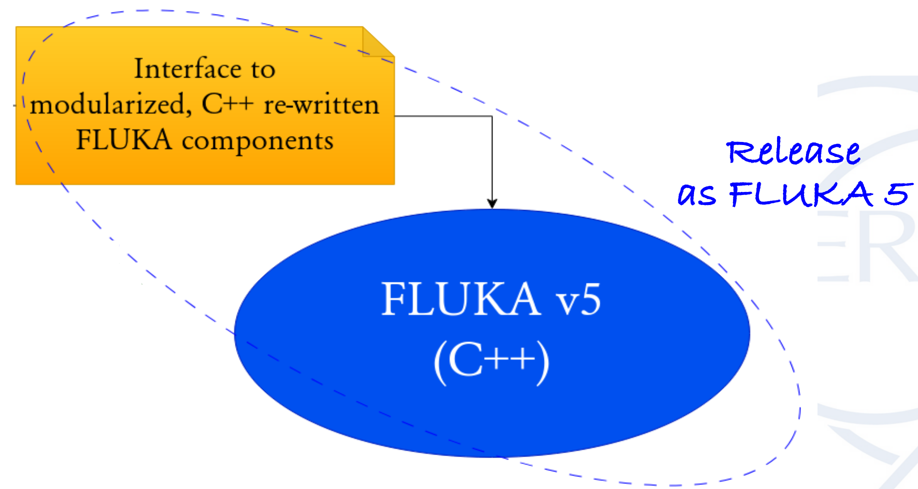
Release scheme continuity

Make use of the Geant4 toolkit



FLUKA 5 VERSUS GEANT4: ORGANIZATIONAL PERSPECTIVE

Different philosophies, at the service of different use-cases:

A SIMULATION TOOLKIT

v5

G4

Modular toolkit.

Allow users to **develop applications** relying on a **common core base**.

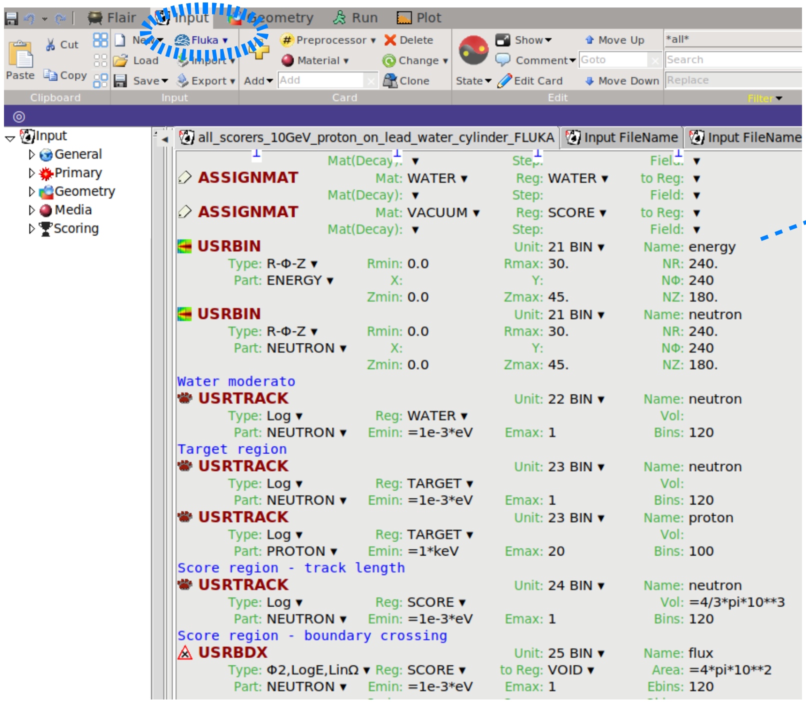
FLUKA 5

Fully integrated application

- Continuity with **FLUKA v4 user experience** (Flair, tools…)
- **Technical infrastructure: continuity with FLUKA v4 features** (geometry & navigation, scoring, biasing…)
  Make it possible to use input files "converted" from v4.
- **1 FLUKA "physics list": Fixed set of physics models** which ensure **continuity with FLUKA v4 physics**.

FLUKA 4 VERSUS FLUKA 5: USER PERSPECTIVE

FLUKA v4

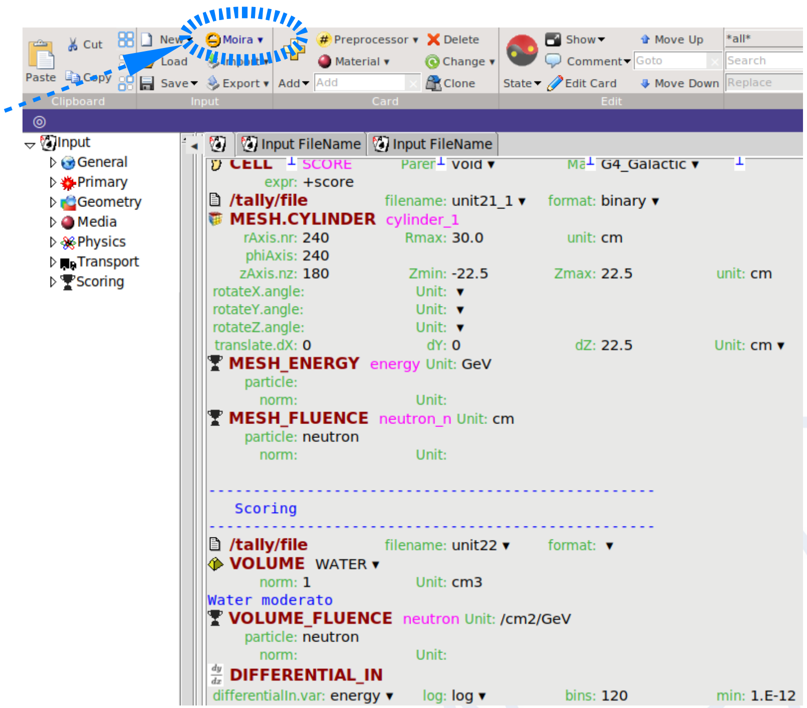


Available to the user:

- FLUKA v4 physics
- No G4 physics list

Convert FLUKA v4 input files with Flair

FLUKA v5



"Converted" input files are directly compatible with FLUKA v5.

Available to the user:

- 1 FLUKA physics list
- All G4 physics lists

FLUKA 5 STATUS

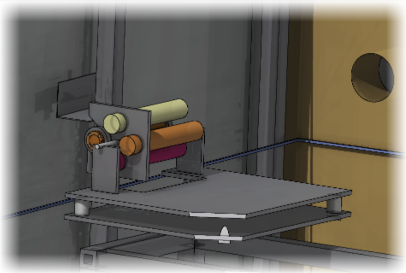
Access to FLUKA 4 physics:

- Hadron-nucleus inelastic interactions from PEANUT.
- Ion-ion inelastic interactions from BME/RQMD/DPMJET.

BME: 1MeV/n → 125 MeV/n [± 25 MeV/n]
RQMD: 125 MeV/n [± 25 MeV/n] → 5 GeV/n [± 0.5 GeV/n]
DPMJET: from 5 GeV/n [± 0.5 GeV/n]

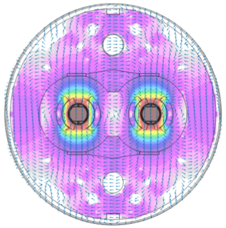
Geometry & navigation:

- Support of FLUKA v4 geometry features, such as bodies (can be infinite!), zones, volumes flat hierarchical structure.
- Extension to the GDML format and custom navigator.


Targets at the CHARm facility

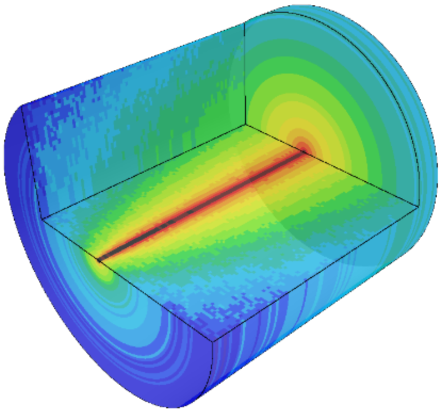
Magnetic fields:

- Multipoles.
- 2D/3D interpolated fields.
- User-defined.


MBRB

Scoring:

Quantities: energy deposition, fluence, current, reaction product yields
Differential (1D or 2D) in: kinetic energy, solid angle, charge, time, LET.
Fully **custom scorers and histogram** classes.
Geometry: per **volume** / through a **boundary** / in a **mesh** (Cartesian and cylindrical modes)
Radioactive decay modeling: can import irradiation profiles and cooling time.
Event by event scoring.


Energy deposited in Pb target by a proton pencil beam at 10 GeV

FLUKA 5 STATUS

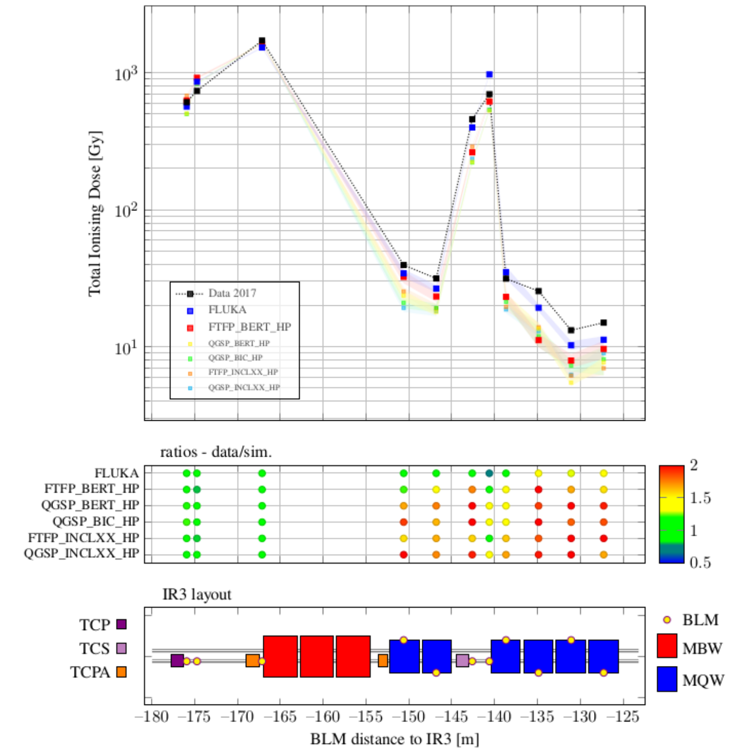
Random engine / seeding:
Possibility to restart a simulation at a crashed event with no I/O.

Biasing:
Region importance, weight windows, interaction length biasing.

Event generator mode:
On-demand XS and FS at the interaction level.

User can write and build his own code, dynamically loaded at runtime.

Flair compatibility:
Input files conversion from v4, geometry visualization, run, post-processing.



BLM benchmarks in IR3

Distribution:
Source and binaries. Binaries: users can run on *any x86_64 Linux distribution* after download, without *any build*.

Testing:
CI in progress (multi-platform build & tests). Integration into the **FLUKA extensive testing suite (FLUKAVAL)**.

Use:
Alpha testers in the collaboration are already using/testing FLUKA v5 framework:
inter-comparison studies for CHARM, nTOF, LHC collimation.

FLUKA 5: ROADMAP

General maintenance and debugging of the existing features.

Extend coverage of FLUKA v4 features
(missing scoring capabilities, radiation to electronics effects, geometry, reports by users…).

Plug-in pointwise neutron treatment:
- Only available in FLUKA 4 for now.

Make FLUKA 4 physics databases available to FLUKA 5.

Modularize the present FLUKA v4 components.
Callable from both FLUKA v4 and v5.
Interfaces and generic wrappers to these modules.
Notably: hadronic, electromagnetic, evaporation…

Extend CI, integration into FLUKAVAL.

Simplify input file format. Create users guide.

Extend distribution within the collaboration.

EXAMPLE SYNERGY WITH GEANT4:

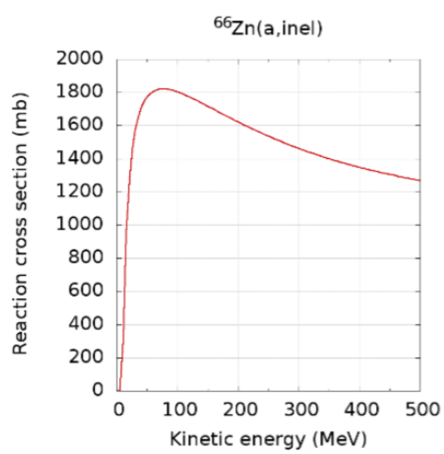
INTERFACE TO FLUKA 4
HADRON-NUCLEUS INELASTIC INTERACTIONS

INTERFACE TO FLUKA 4 HADRON-NUCLEUS INELASTIC INTERACTIONS

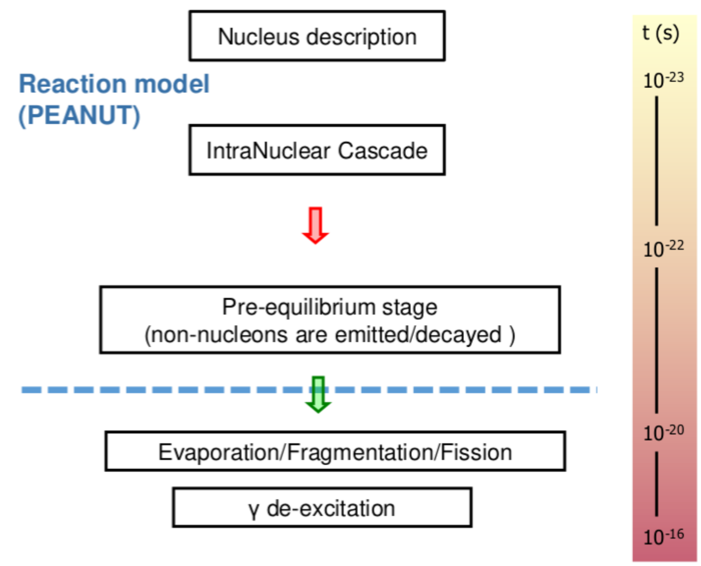
INCLUDED IN INTERFACE

i. To decide the process occurrence

Reaction cross section (typically parametrized)



ii. To decide the reaction final state



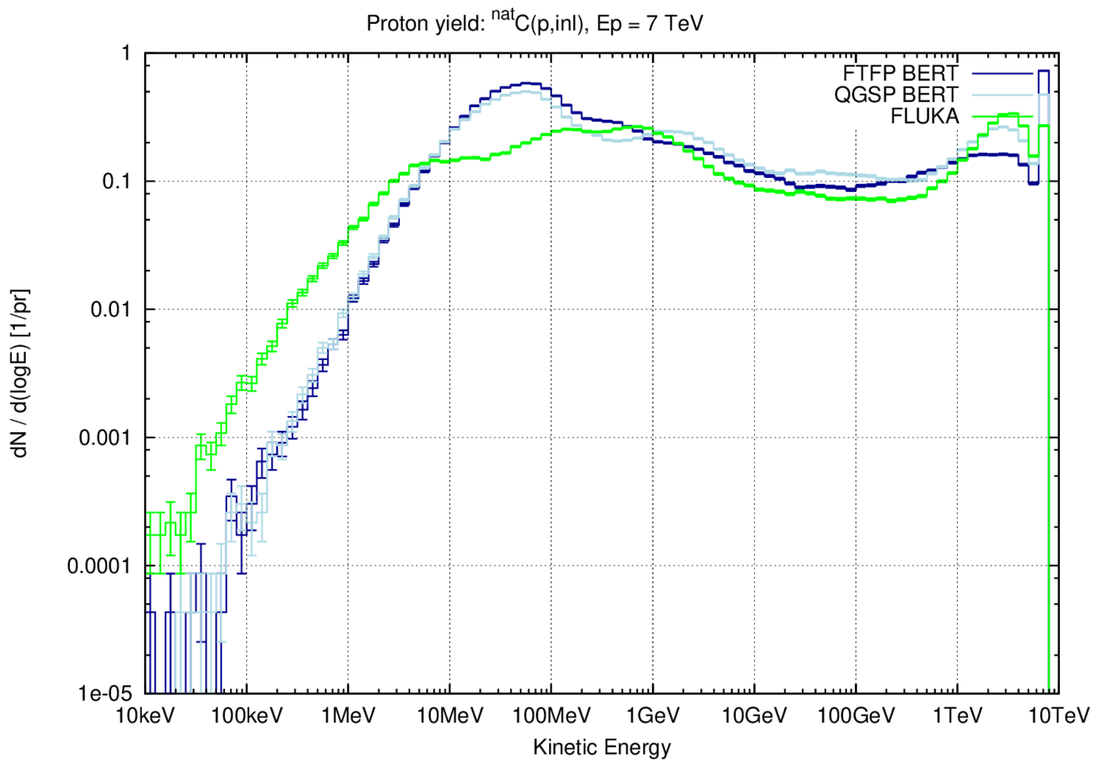
- **Accessible from both Geant4 and FLUKA5**.
- **Integrated in FLUKA 5**: one **can now access FLUKA 4 hadron-nucleus inelastic physics.**
- **Integrated in Geant4**: from **11.2.0 beta release (June 2023) onwards**. Includes:
  - The **interface itself**.
  - **2 G4 examples applications** demonstrating how to use it (at the interaction and physics list level).
  - Extension so that results can be **visualized by Flair**.

INTERFACE TO FLUKA 4 HADRON-NUCLEUS INELASTIC INTERACTIONS

- The **interface includes**:
  - **Standalone code, isolating inelastic scattering XS and hadron-nucleus inelastic interactions final states**, as computed by FLUKA 4.
  - **FLUKA 4 wrappers** and **helper tools**.
  - General **utilities to interface FLUKA to Geant4 world** (particles identification, random numbers…).
  - **G4 physics list & related classes** to plug-in the work into a G4 environment.

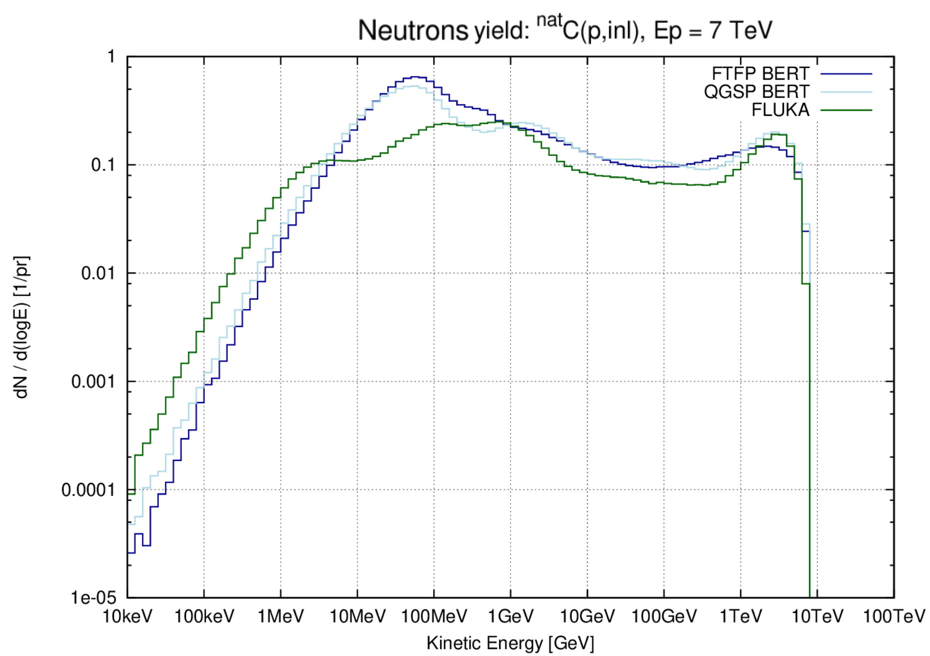
- **Gives access to the FLUKA models:**
  - At the **single interaction level**.
  - At the **physics list level**.

G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: FINAL STATES



7 TeV proton – C nucleus collisions.

1 000 000 events.



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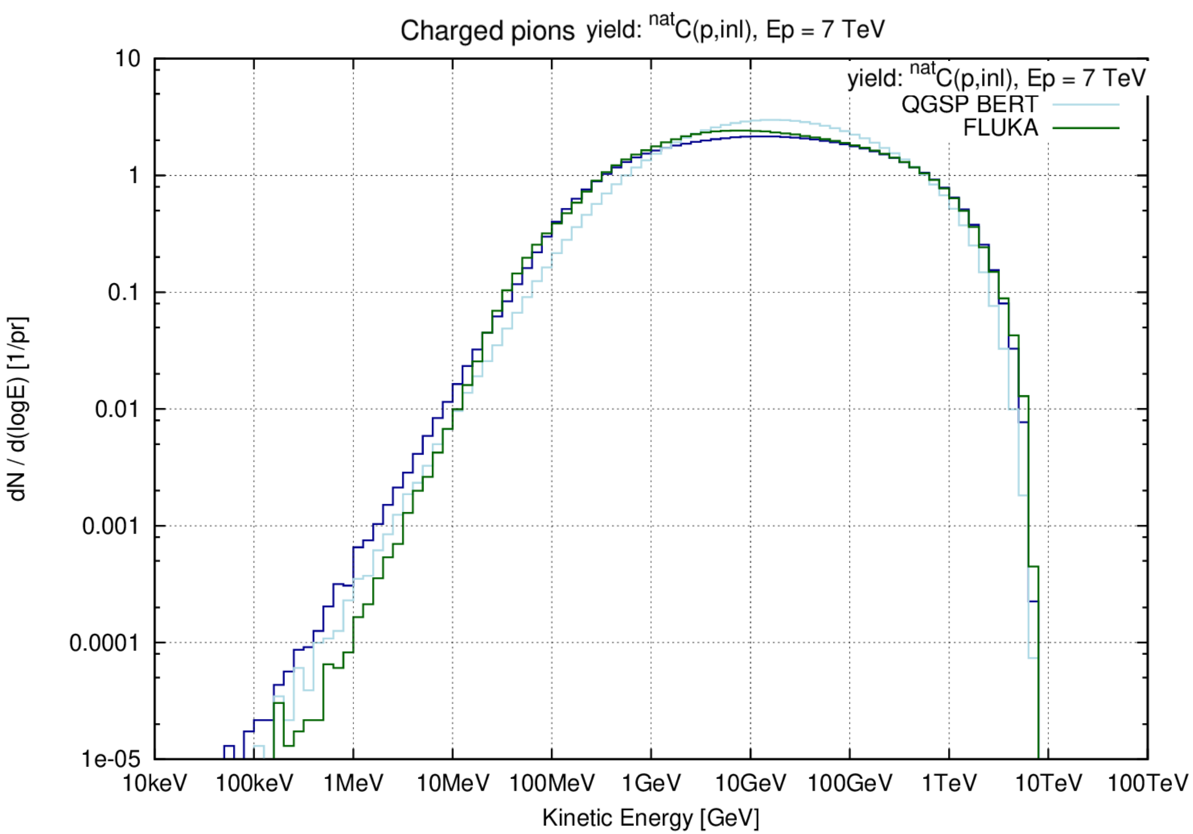

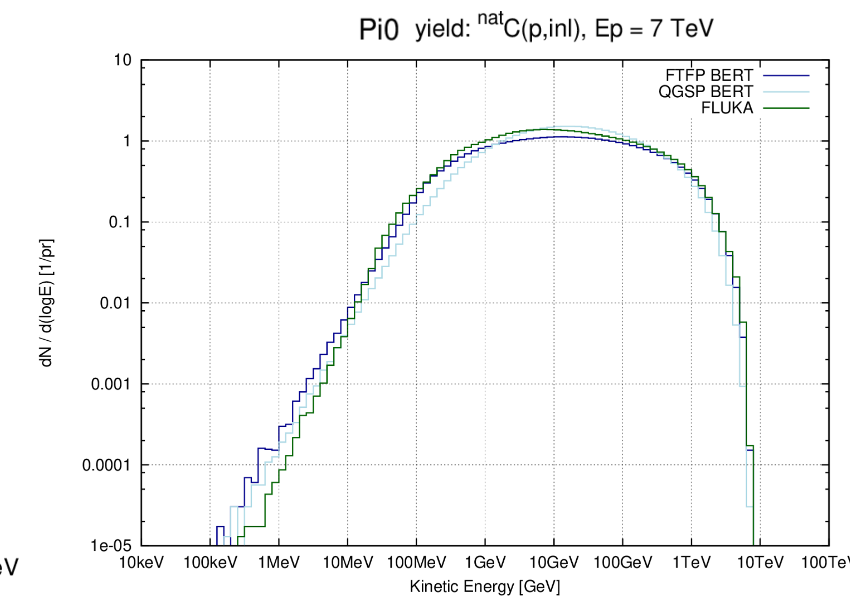

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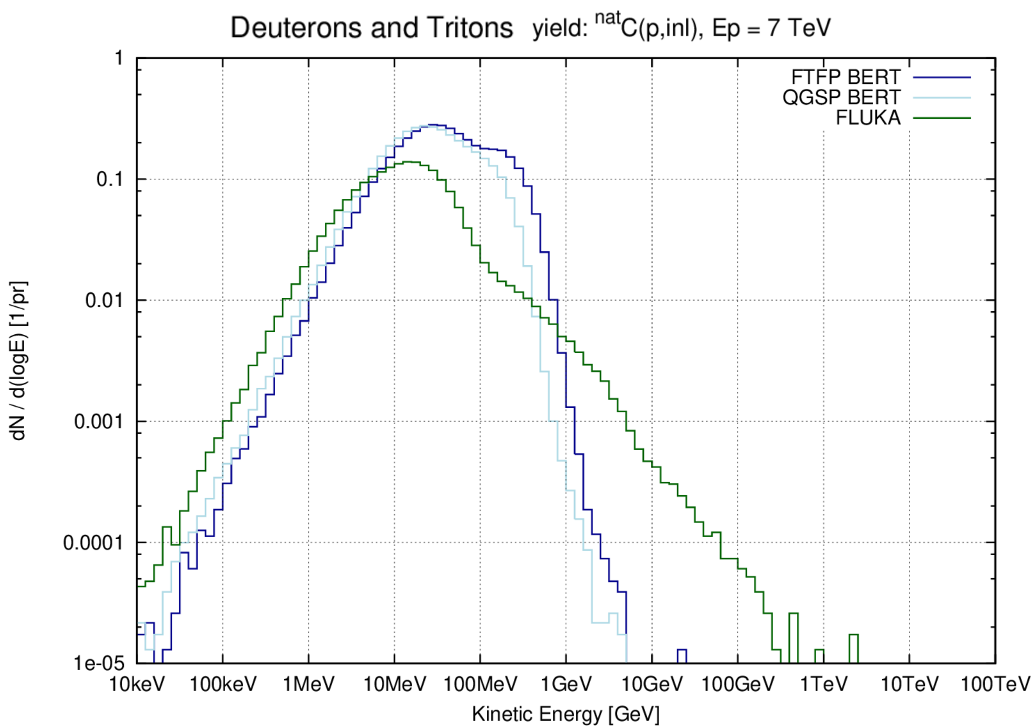
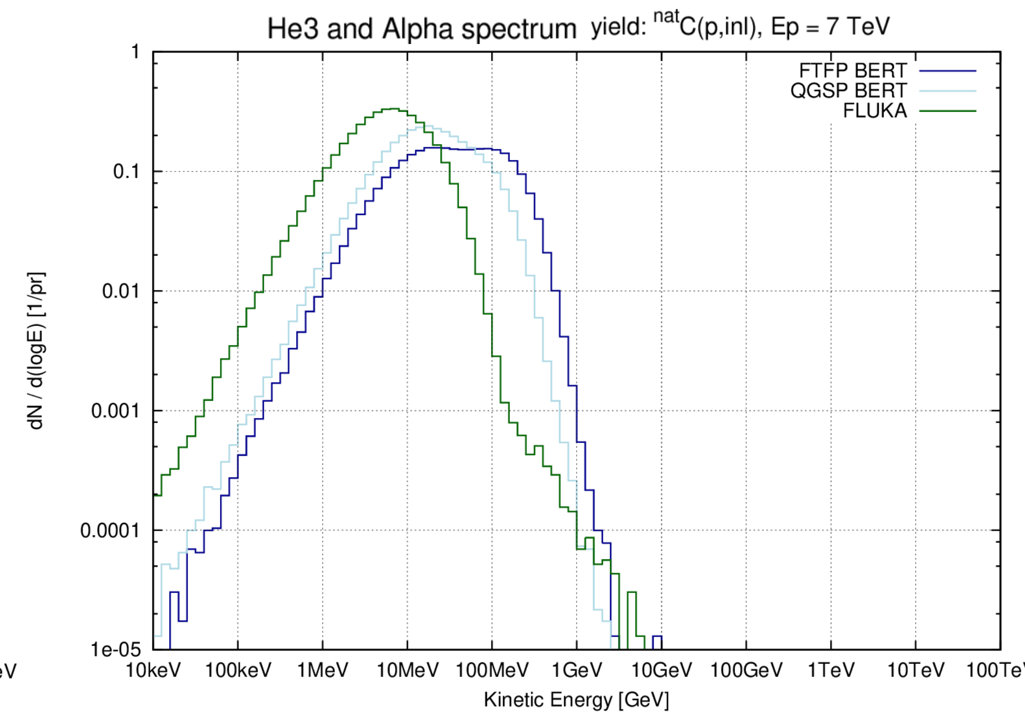
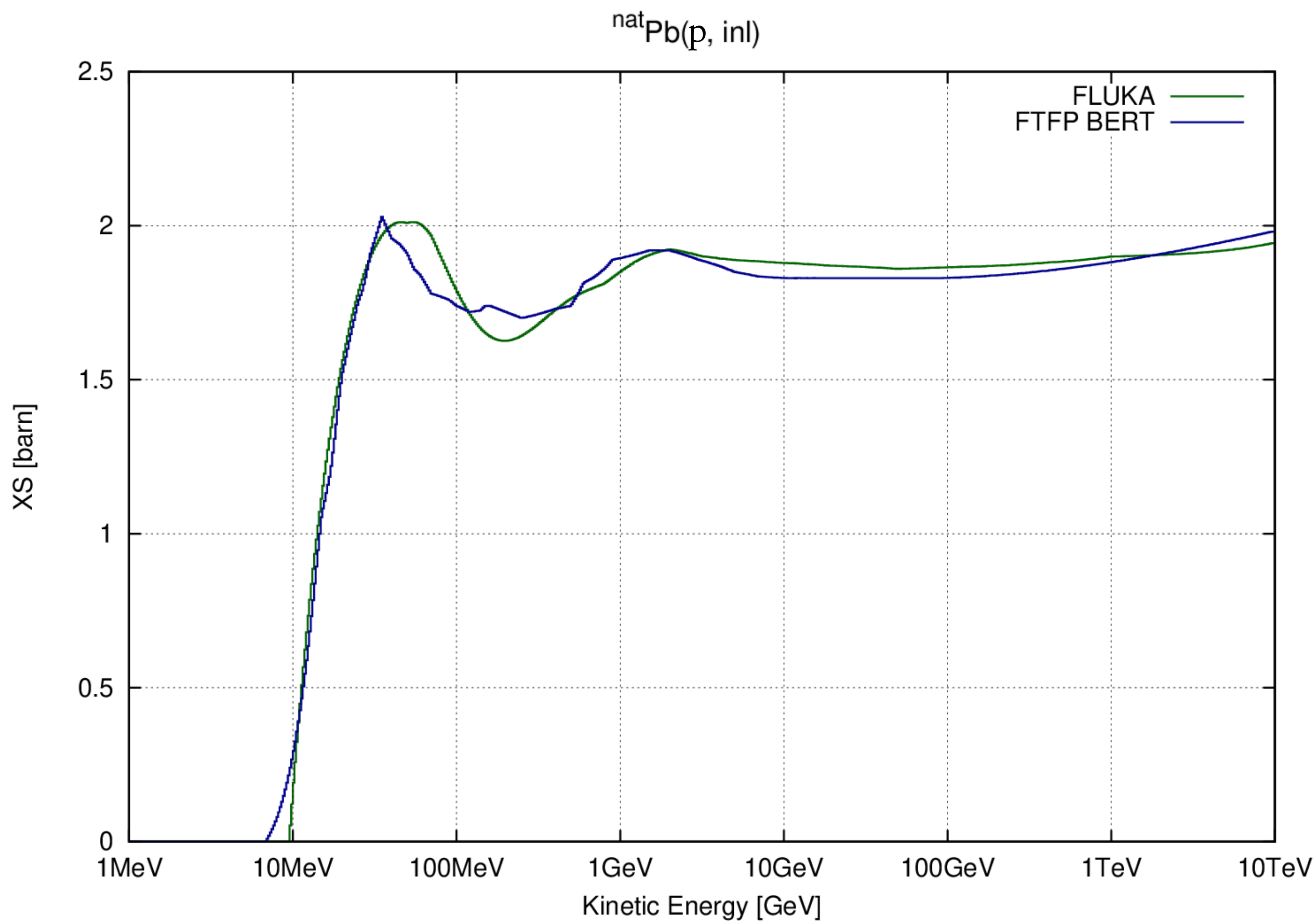




G4 ↔ FLUKA COMPARISONS AT THE INTERACTION LEVEL: XS



INTEGRATION AT THE PHYSICS LIST LEVEL

PHYSICS LIST

*Class **G4_HP_CernFLUKAHadronInelastic_PhysicsList** : public **G4VModularPhysicsList***

```
RegisterPhysics( new G4EmLivermorePhysics( ver ) );           // G4 EM physics
RegisterPhysics( new G4EmExtraPhysics( ver ) );               // G4 synchroton 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 G4RadioactiaveDecayPhysics( ver ) );     // G4 radioactiave 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 AT THE PHYSICS LIST LEVEL

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 Physics 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 AT THE PHYSICS LIST LEVEL

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 Physics list with FLUKA interface:

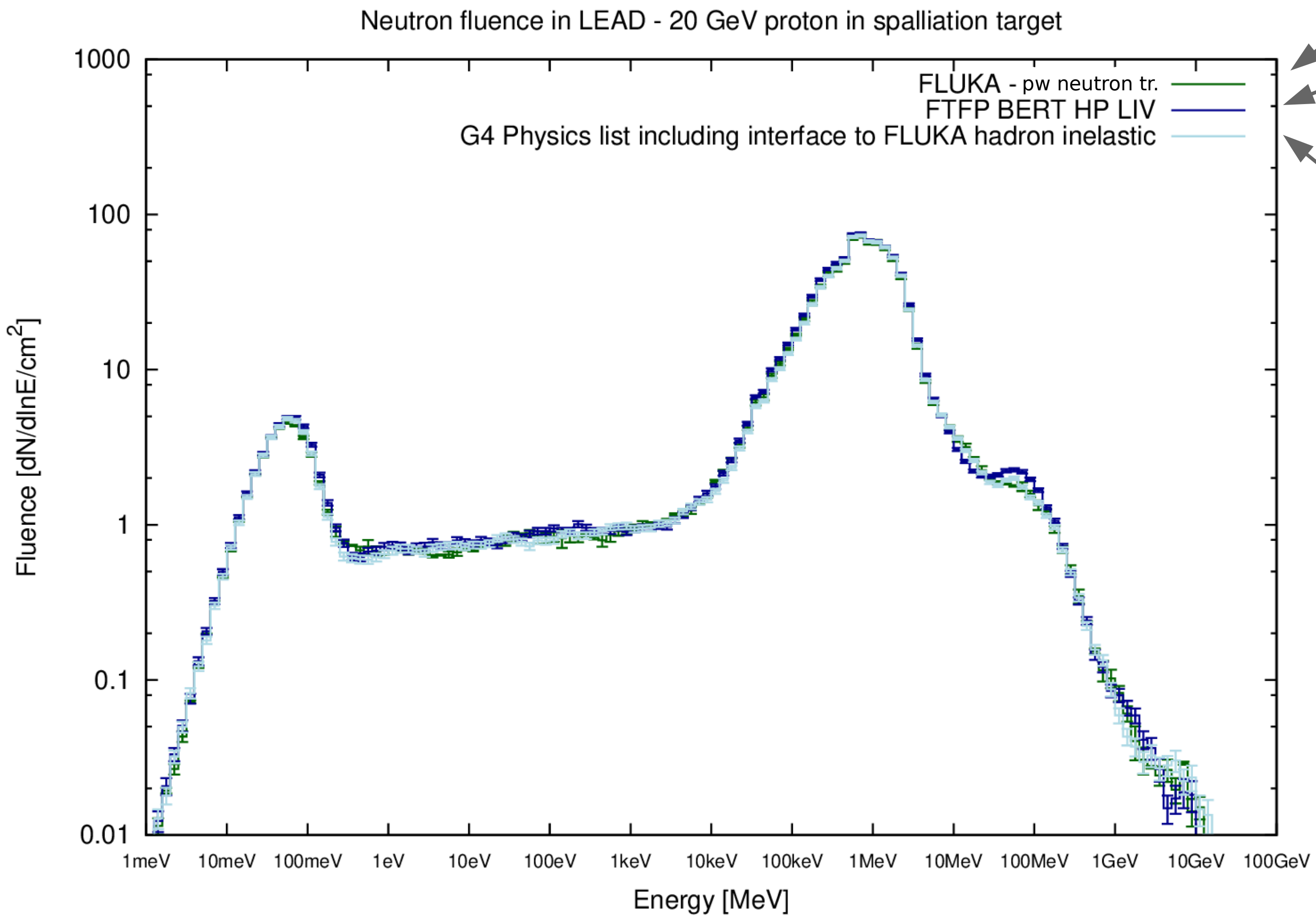
```
---------------------------------------------------
                           Hadronic Processes for proton

  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 AT THE PHYSICS LIST LEVEL



FLUKA 4 run

Run on FLUKA 5 framework with FTFP_BERT_HP LIV

Run on FLUKA 5 framework with the FLUKA physics list

Physics lists available in FLUKA 5 framework:

- All G4 Physics lists.
- FLUKAPhysicsList: Development physics list, bound to progressively incorporate ~all of FLUKA 4 physics.

CONCLUSION AND OUTLOOK

- FLUKA is being **progressively re-written**, while ensuring a **continuous release scheme**.
  The **identity of FLUKA is preserved**: a **fully integrated application**, giving the user access to a **fixed set of physics models**, which underwent **strict quality insurance processes**.

- The **FLUKA v5 technical infrastructure is based on Geant4**.
  It incorporates **custom implementations** (geometry & navigation, scoring, biasing…) to **ensure continuity in the FLUKA features**.
  This makes it possible to run on input files converted from FLUKA v4.

- The **FLUKA physics models are progressively being modularized and re-written** to make up a single FLUKA physics list.

- **Synergies among communities**:
  The **Geant4 users community** will have easier **access to the FLUKA models**, as was done with the interface to hadron-nucleus inelastic interactions (via the **FLUKA physics list**).
  The **FLUKA users community** will have direct access to the **Geant4 physics lists** for their studies, in addition to the FLUKA physics (via the **FLUKA v5 framework**, based on Geant4).

- **Outlook**:
  The **technical infrastructure** is in an **advanced state**. Still missing features, and significant **debugging and testing** needed. Starts being **released internally**.
  The **modularization of the FLUKA v4 components is starting**.