GeNIALE

Geant4 Nuclear Interaction At Low Energy

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Attività di ricerca finanziata con grant giovani CSN5 INFN

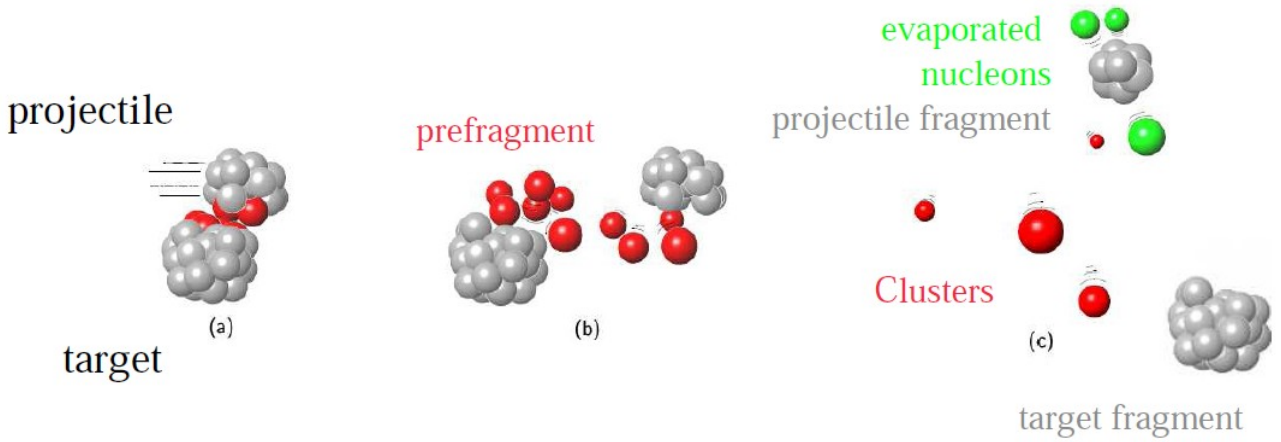
Sapienza, Dipartimento di Fisica. 5 aprile 2017

Outline

- Introduction
- Description of the project
- Some preliminary results
- Next steps

Introduction

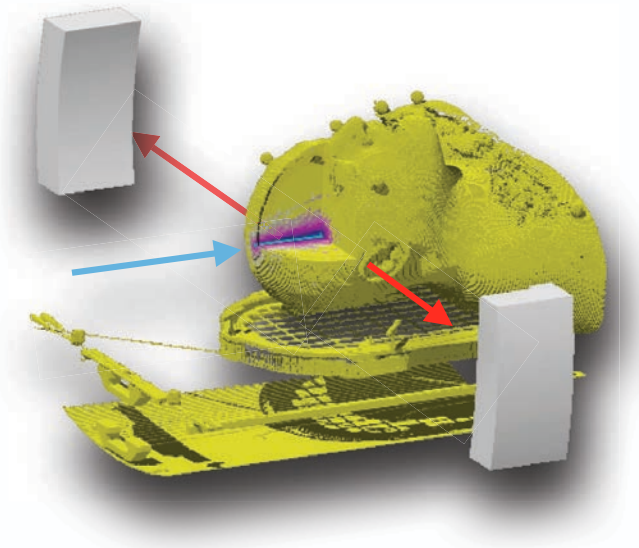
Objectives of the proposal



- Benchmark and **improve** the capacity of Geant4 to simulate **nuclear fragmentation** in the energy range **below 100 MeV/A**

Applications

- Hadrontherapy
- Nuclear Physics experiments (e.g.: FOOT)
- Radiobiology
- High Energy Physics
- and many others…



Applications: hadrontherapy

- Generate input parameters of the treatment planning algorithms
- Validate the dose calculation of such algorithms
- GeNIALE could be useful for MoVe_IT project, aimed at developing an innovative modeling for biologically optimized treatment planning

- Estimate the production of β+ emitters, such as ^{11}C and ^{15}O
- Link the production of prompt γ with the dose distribution

FOOT

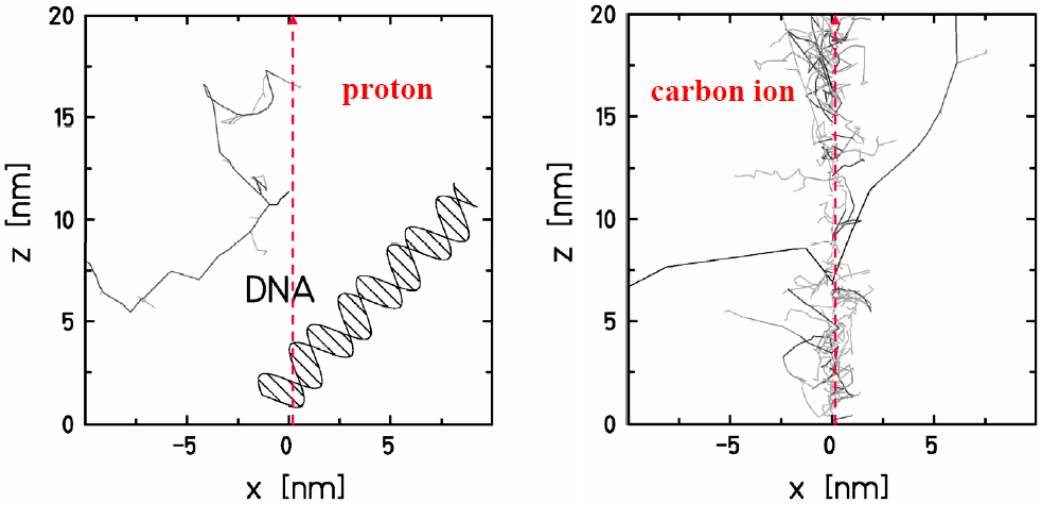
FragmentatiOn Of Target

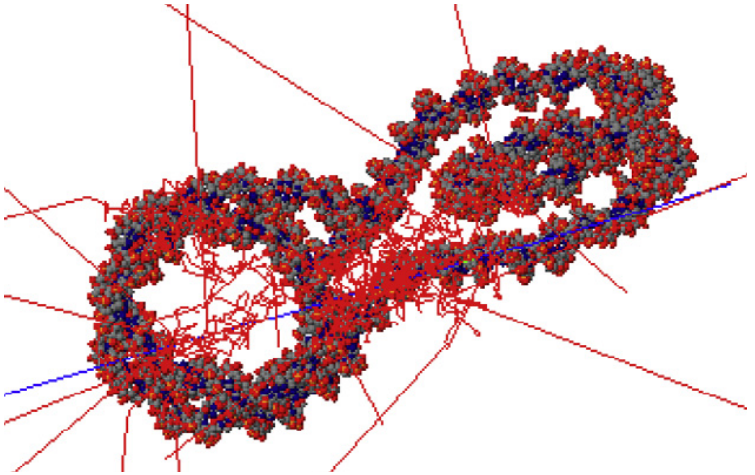
- Will measure the fragmentation cross sections of He, C, O, N, Si and Fe on CH targets
- Energy range between 80 and 400 MeV/A
- GeNIALE will provide a better agreement with the MC simulation for FOOT at, and around, its lower energy range

Applications: radiobiology

- To link the physical dose deposited to the biological effectiveness
- Geant4 has a dedicated package for modeling early biological damage induced by ionizing radiation at the DNA scale (Geant4-DNA)

image from: U. Amaldi and G. Kraft,
Rep. Prog. Phys., vol. 68, no. 8, pp. 1861–1882, Jul. 2005.

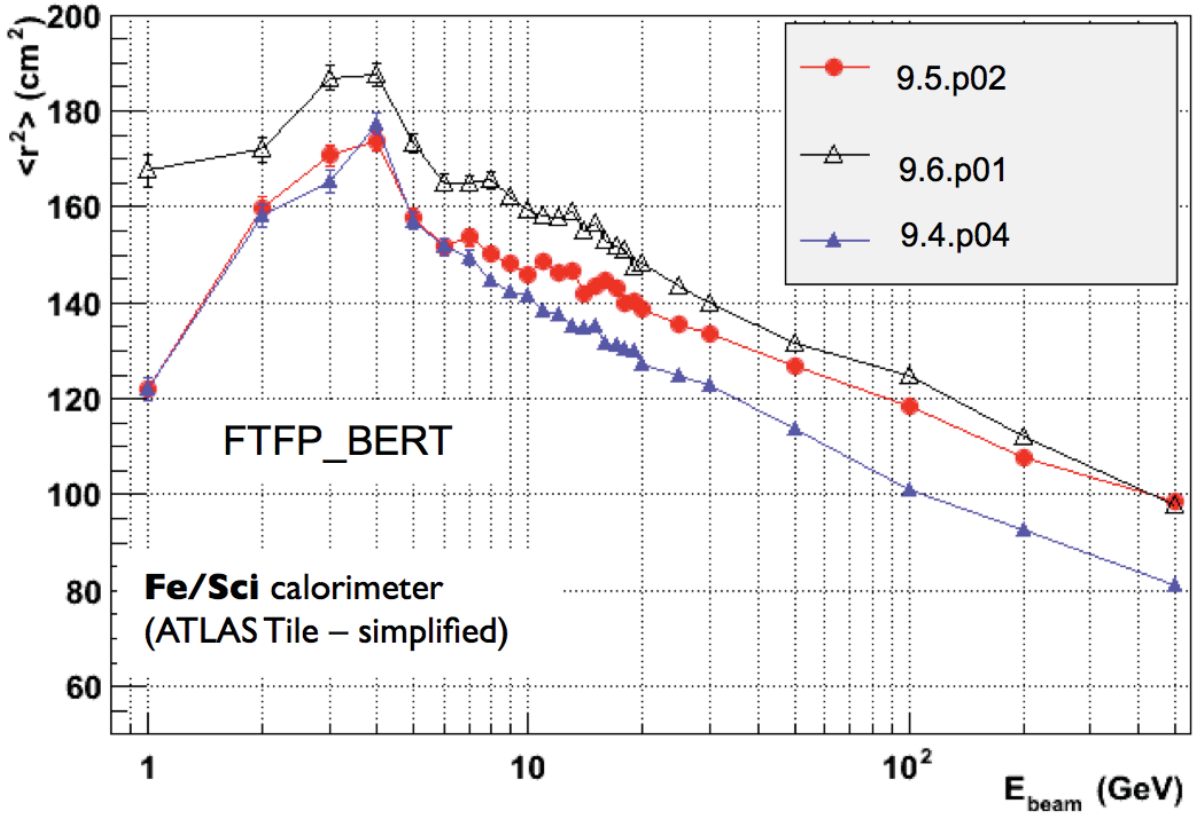




atomistic view of a dinucleosome irradiated by a single 100 keV proton
Image from M. A. Bernal et al Physica Medica, vol. 31, no. 8, pp. 861–874, Dec. 2015.

Applications: hadronic calorimeter simulations

- Lateral pion showers dimensions. Results comparing different Geant4 versions.



[ATLAS TileCal Group; plot from A. Dotti, CHEF 2013]

Further applications

- Radio-protection in space mission
- Shielding for satellites
- Single event upset and radiation damages to electronics
- Simulations for nuclear spallation sources
- Radioactive waste

First slide of the talk “ESA Geant4 R&D Activities from the Geant4 Space User Workshop Hiroshima, 26 August 2015

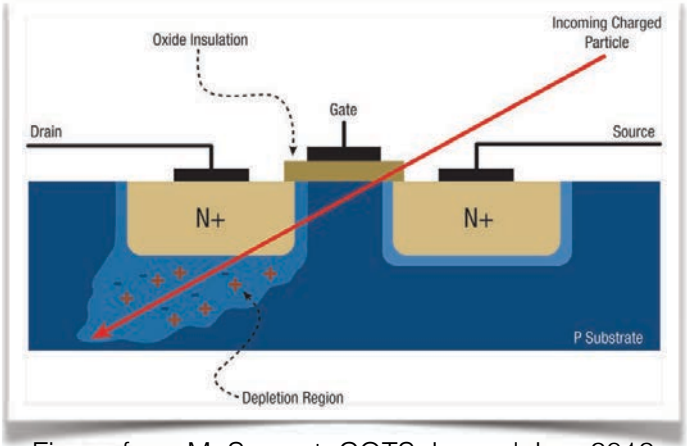


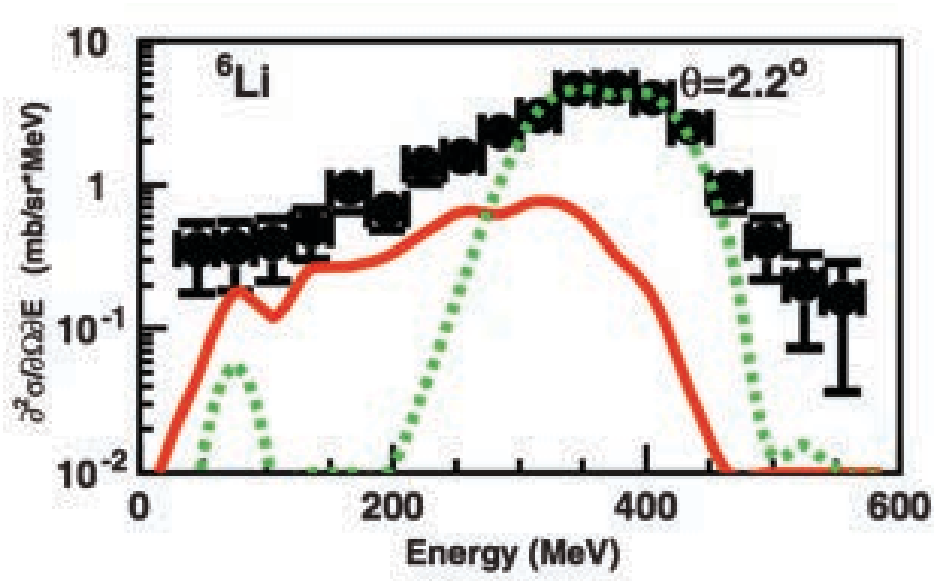
Figure from M. Sawant, COTS Journal Jan. 2012

Problems below 100MeV/A

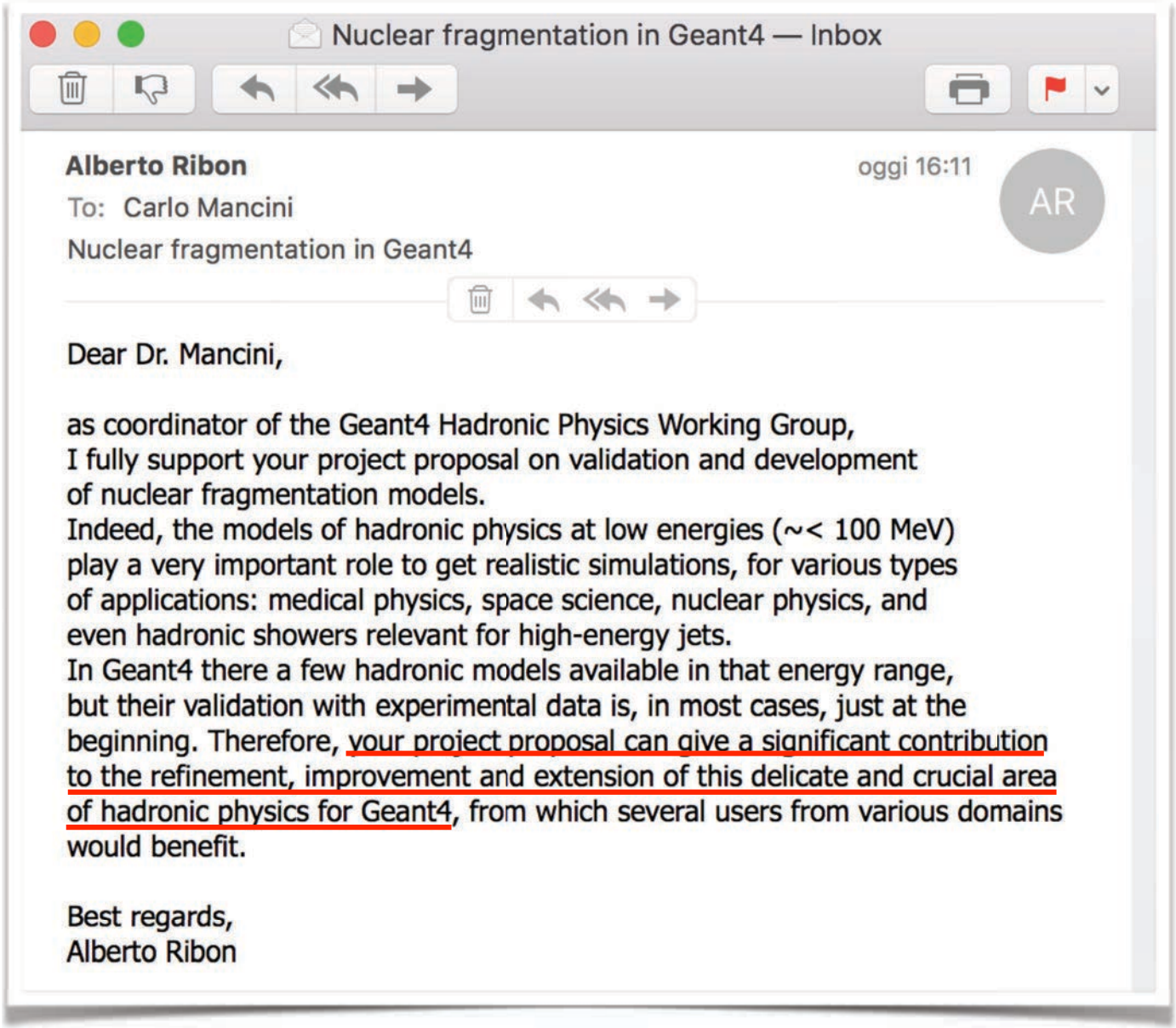
- Braunn et al. have shown discrepancies up to one order of magnitude in ^{12}C fragmentation at 95 MeV/A on thick PMMA target
- De Napoli et al. showed discrepancy specially on angular distribution of the secondaries emitted in the interaction of on 62 MeV/A ^{12}C thin carbon target
- Dudouet et al. found similar results with a 95 MeV/A ^{12}C beam on H, C, O, Al and Ti targets

- **Exp. data**
- **BIC**
- **G4QMD**

[Plot from De Napoli et al. Phys. Med. Biol., vol. 57, no. 22, pp. 7651–7671, Nov. 2012]



Cross section of the ^{6}Li production at 2.2 degree in a ^{12}C on ^{12}C reaction at 62 MeV/A.



Nuclear fragmentation in Geant4 — Inbox

Alberto Ribon oggi 16:11

To: Carlo Mancini

Nuclear fragmentation in Geant4

AR

Dear Dr. Mancini,

as coordinator of the Geant4 Hadronic Physics Working Group,
I fully support your project proposal on validation and development
of nuclear fragmentation models.
Indeed, the models of hadronic physics at low energies (~< 100 MeV)
play a very important role to get realistic simulations, for various types
of applications: medical physics, space science, nuclear physics, and
even hadronic showers relevant for high-energy jets.
In Geant4 there a few hadronic models available in that energy range,
but their validation with experimental data is, in most cases, just at the
beginning. Therefore, your project proposal can give a significant contribution
to the refinement, improvement and extension of this delicate and crucial area
of hadronic physics for Geant4, from which several users from various domains
would benefit.

Best regards,
Alberto Ribon

- The interest of the Geant4 collaboration for this work has been already manifested by its **Hadronic Physics Working Group Coordinator** and member of the **CERN** Geant4 development team, Alberto Ribon

iThemba LABS

NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

- The iThemba Laboratories are a multidisciplinary facility located near Cape Town, South Africa

- Physics Group at iThemba has a **long-standing experience** in experiments made to measure **nuclear fragmentation** in the low energy regime

Description of the project

Nuclear interactions

- Hadronic interactions are simulated in two different stages:
  - the first one describes the interaction from the collision until the excited nuclear species produced in the collision are in equilibrium
  - the second one, such as the Fermi break-up, models the emission of such excited, but equilibrated, nuclei
- **The entrance channel model characteristics have a larger effect** on particles and fragments production as compared to the choice of the exit channel

[Conclusions from: J. Dudouet et al. Phys. Rev. C, vol. 89, no. 5, p. 054616, May 2014]

GeNIALE target

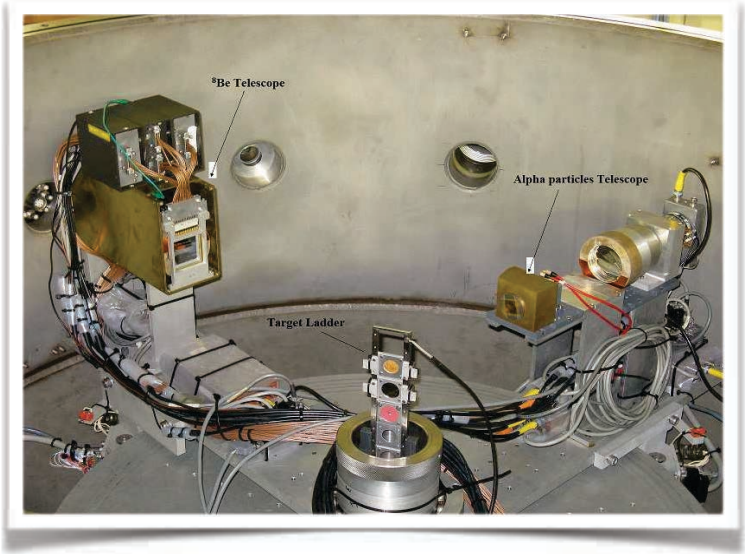
- GeNIALE aims at improving the Geant4 performance in the hadronic interaction below 100 MeV/A
- The core of GeNIALE is the implementation in Geant4 of a new model for the **first stage of the interaction** between a hadron -or a nucleus- and a target nucleus
- Such a model will be coupled with the models already implemented in Geant4 for the second stage, and with the Geant4 framework in general

Suitable models

- **Boltzmann-Uehling-Uhlenbeck (BUU)**
  - describes the time evolution of the density distribution
- **Boltzmann-Langevin (BL)**
  - BUU plus fluctuations in the nucleon-nucleon collisions
- **Antisymmetrized Molecular Dynamics (AMD)**
  - reproduce the molecular dynamics in the nuclear field

Analysis of data from iThemba

- Data on the **fragmentation of ^{12}C and ^{14}N** in the interaction with thin targets of different materials
- 33 MeV/A
- Double differential yields
- With ^{12}C measured the exclusive reaction:
  $^{12}C \rightarrow {}^{8}Be + {}^{4}He$

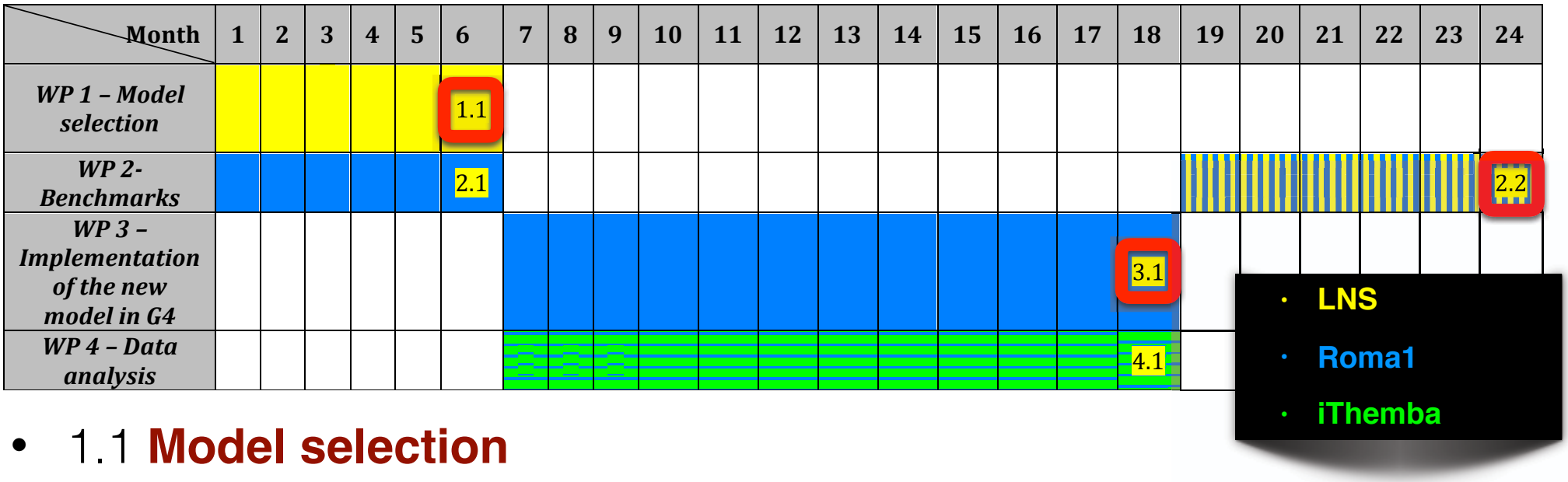


NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

Summary of units

- GeNIALE will be implemented as a collaboration of three units:
- **INFN Roma1**
  - FTE 160%
  - deeply involved in FOOT, and GeNIALE would represent a perfect complement to it
- **INFN LNS**
  - FTE 15% significant **support by the theory group**
  - The Theory group has a long tradition in studying nuclear dynamics. They worked on the models cited in the description of the WP1
- **iThemba Labs (SA)**
  - FTE 25%
  - The Nuclear Physics Group has a long-standing experience in experiments made to measure nuclear fragmentation in the low energy regime
- The project will also be **supported by the CERN Geant4 development group**

Gantt chart with the time line of the WPs



- 1.1 **Model selection**
- 2.1 Benchmark of the existing models
- 2.2 **Benchmark of the implemented model**
- 3.1 **Implementation of the model in Geant4**
- 4.1 Analysis of the data on ^{12}C and ^{14}N fragmentation

Preliminary results

The first two deliverables

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WP 1 – Model selection						1.1																		
WP 2- Benchmarks						2.1																		2.2
WP 3 – Implementation of the new model in G4																		3.1						
WP 4 – Data analysis																		4.1						
Milestone						1.1												3.1						2.2

- **Month 6 - Milestone 1.1** The LNS unit will chose the most suitable model for the entrance channel stage of the hadronic interaction for Geant4 in the energy range of interest

- **Month 6 - Deliverable 2.1** The Roma1 unit will benchmark the models already existing in Geant4 with the data published in literature

Models already implemented in Geant4 for the entrance channel

- **Binary Intra-nuclear Cascade (BIC)** “participating” particles, are tracked in the nucleus. The interactions are between them and an individual nucleon of the nucleus.

- **Quantum Molecular Dynamics (QMD)** all the nucleons are considered as “participants”, scattering between them is included

- **Liège Intranuclear Cascade (INCL++)** The nucleons are modeled as a free Fermi gas in a static potential well. The particles are assumed to propagate along straight-line trajectories until an interaction

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Recently implemented in Geant4

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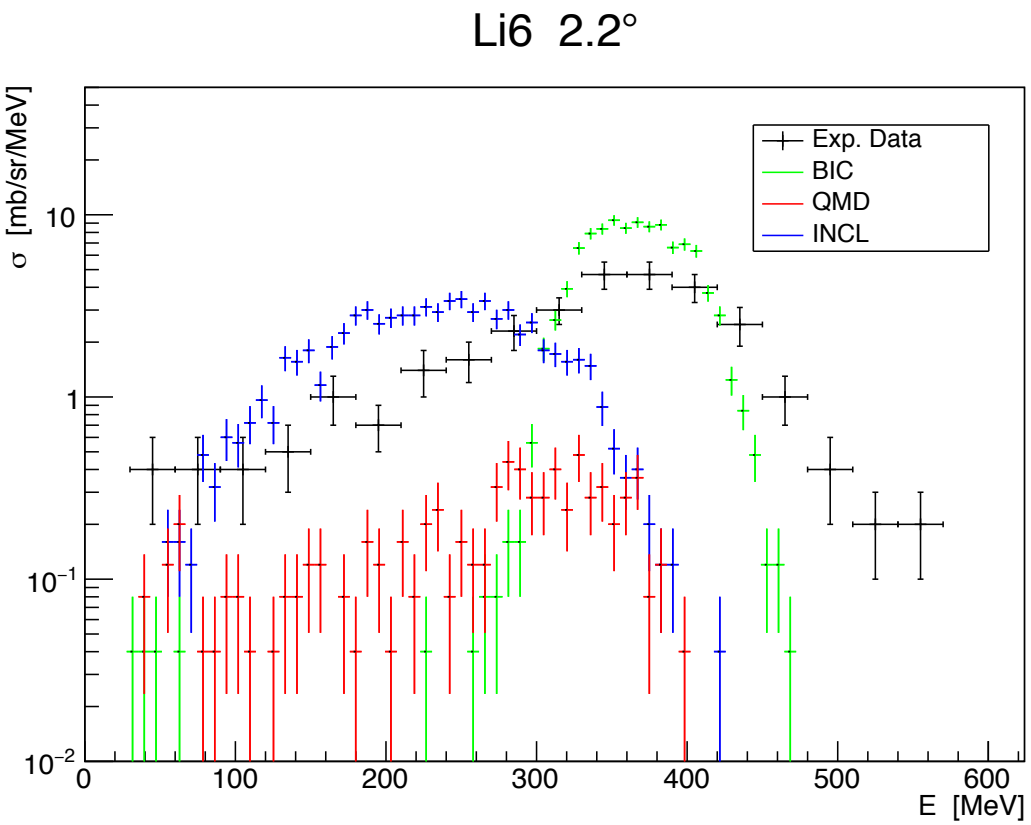
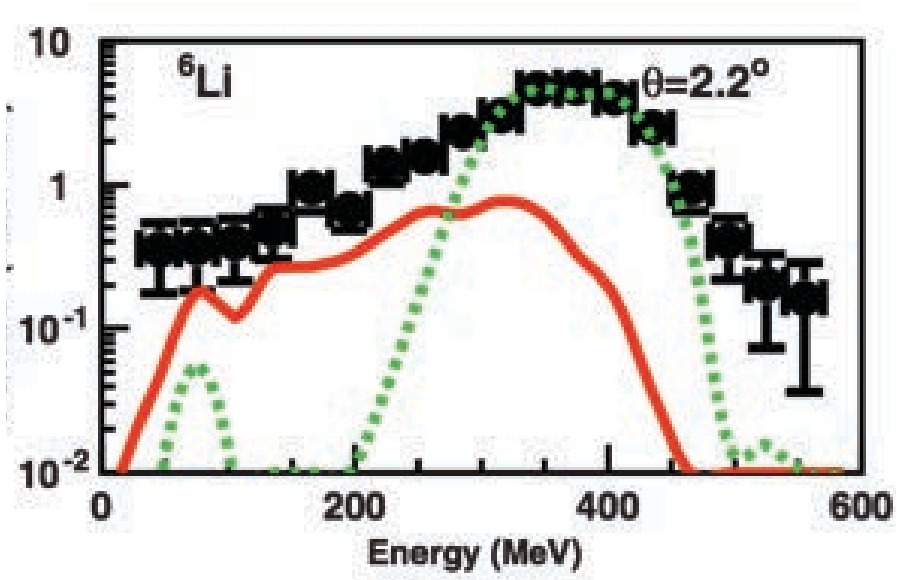
Update on the models already implemented in G4



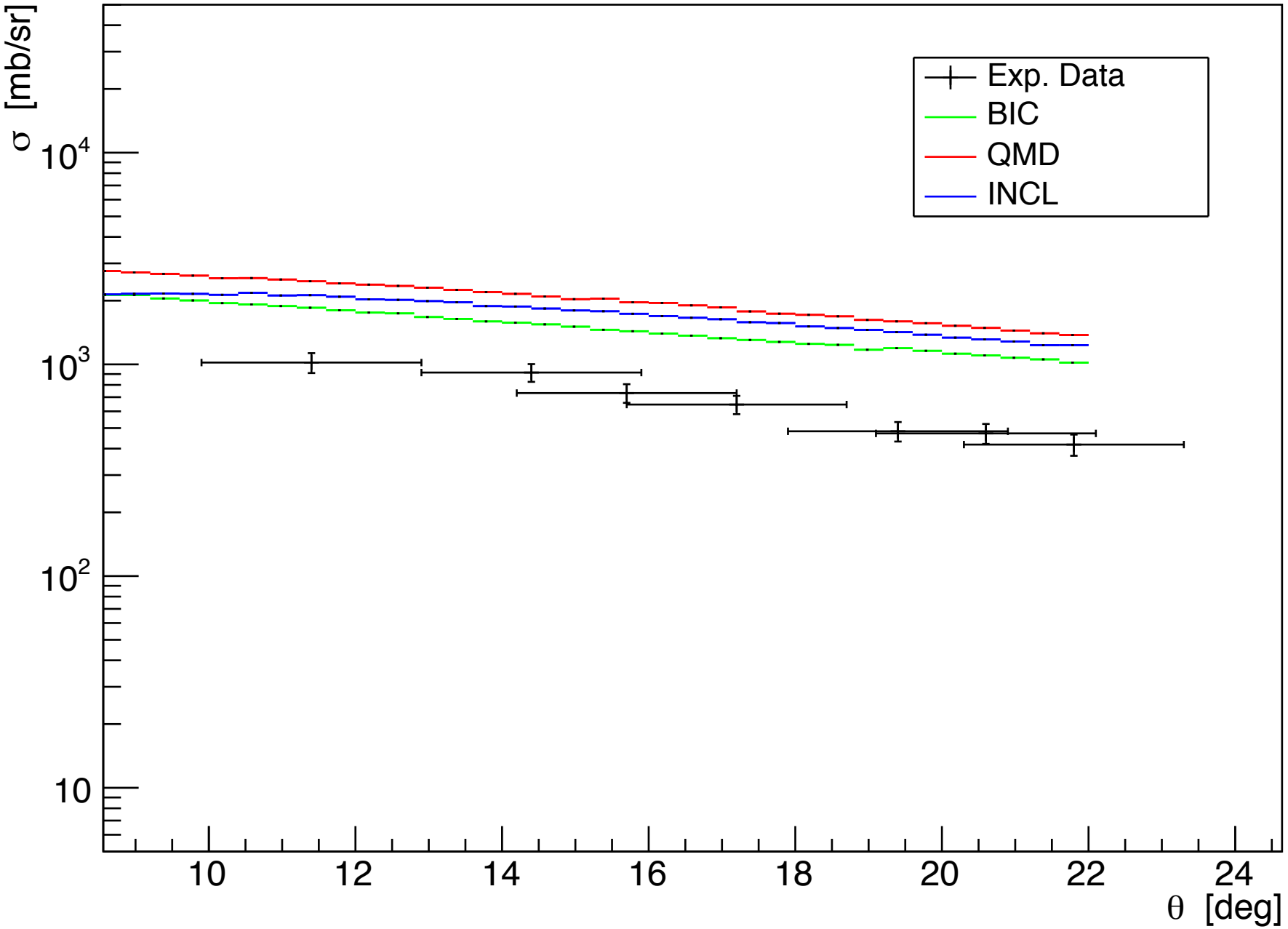
- **Exp. data**
- **BIC**
- **G4QMD**



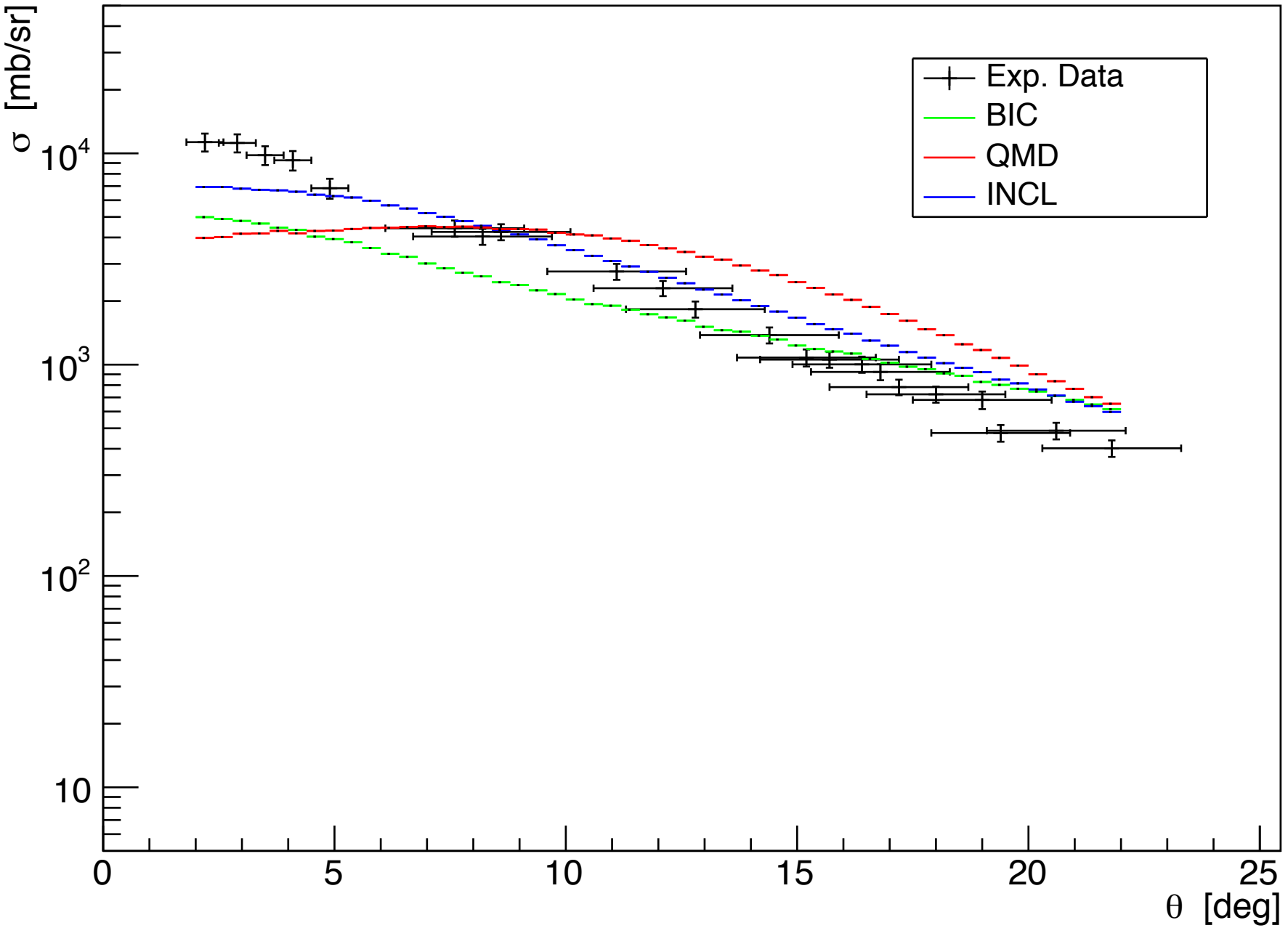
Cross section of the ^{6}Li production at 2.2 degree in a ^{12}C on ^{12}C reaction at 62 MeV/A.

[De Napoli et al. Phys. Med. Biol., vol. 57, no. 22, pp. 7651–7671, Nov. 2012]

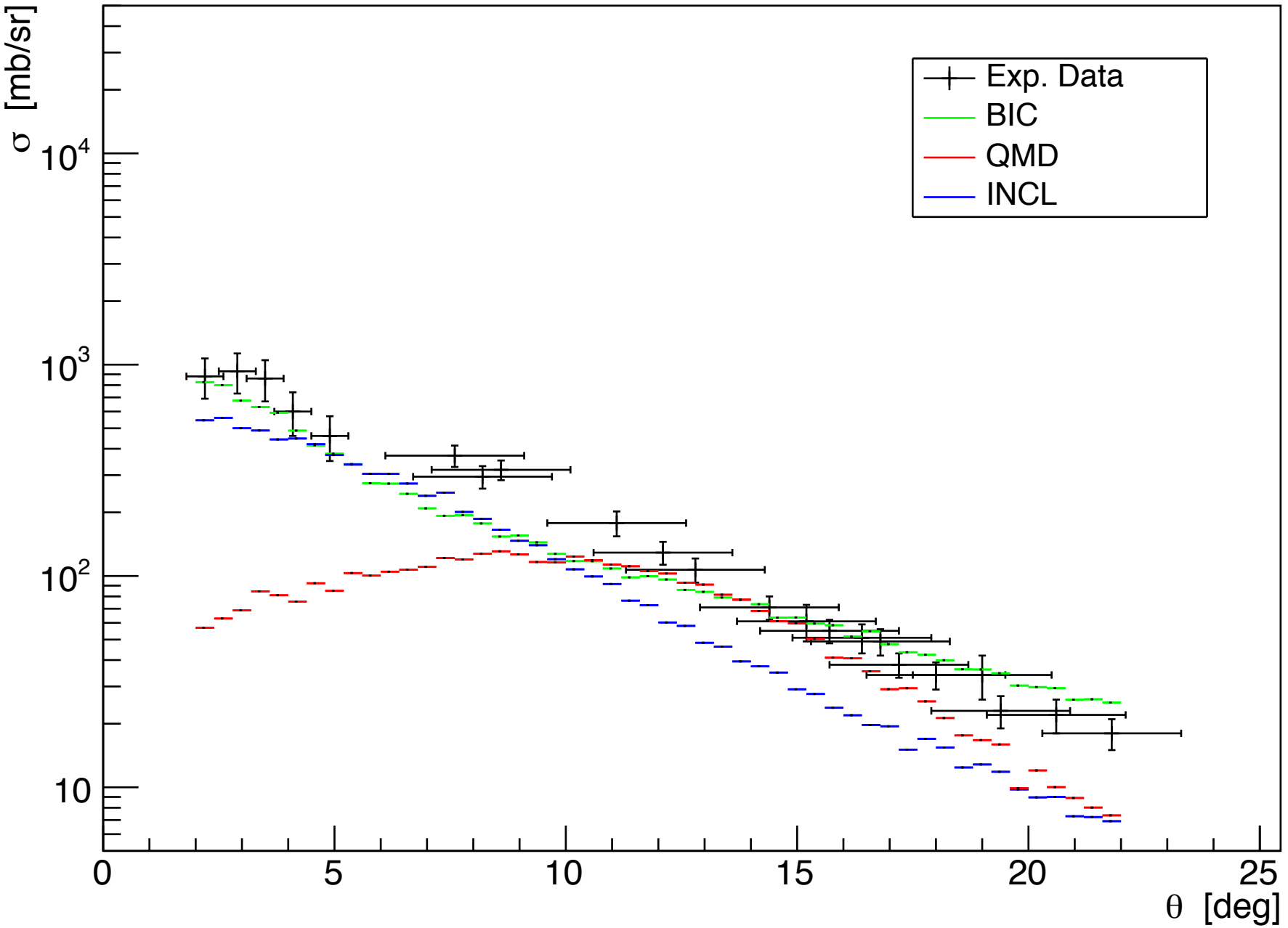
H1


σ [mb/sr]
10⁴
10³
10²
10
10
12
14
16
18
20
22
24
θ [deg]
Exp. Data
BIC
QMD
INCL

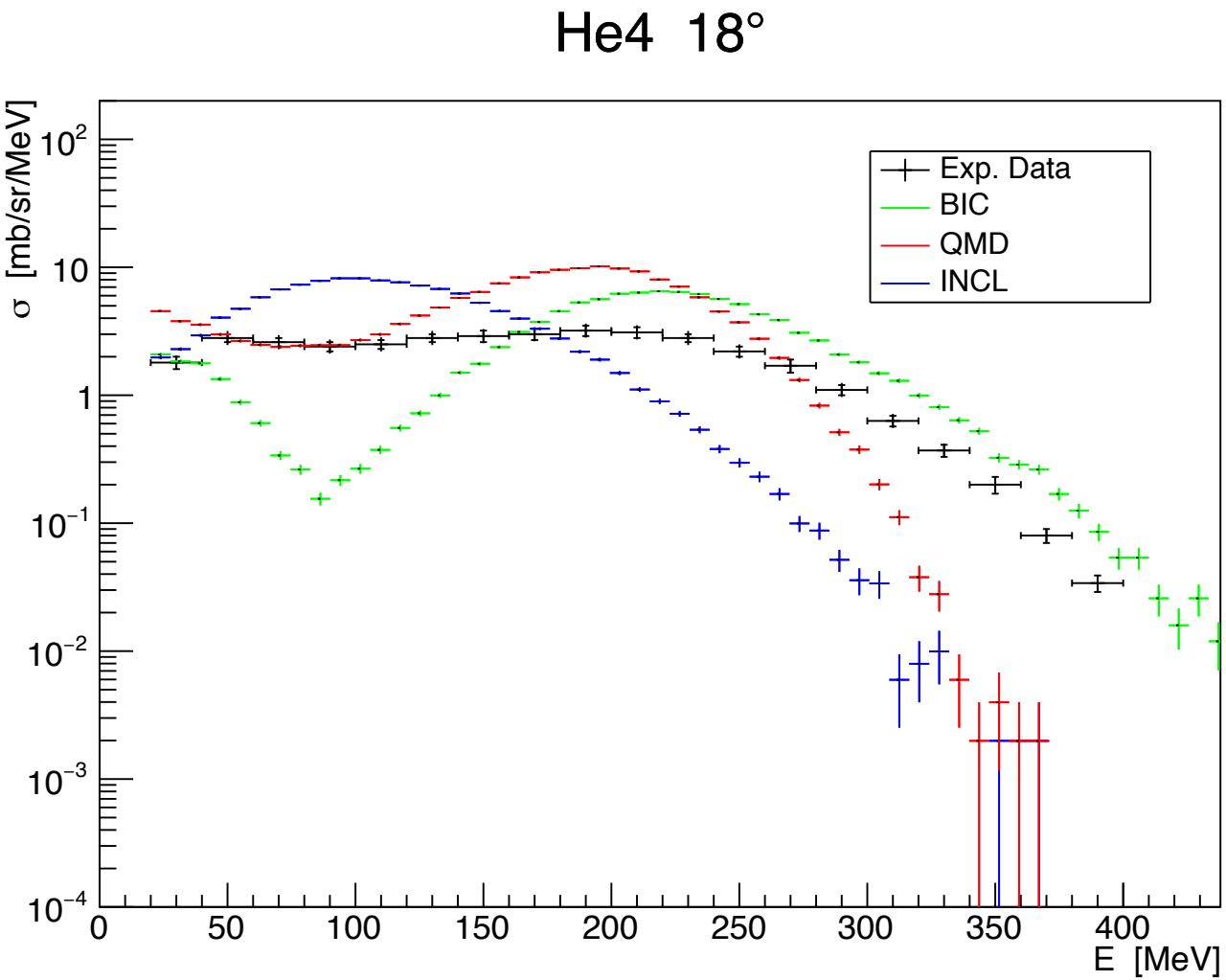
He4

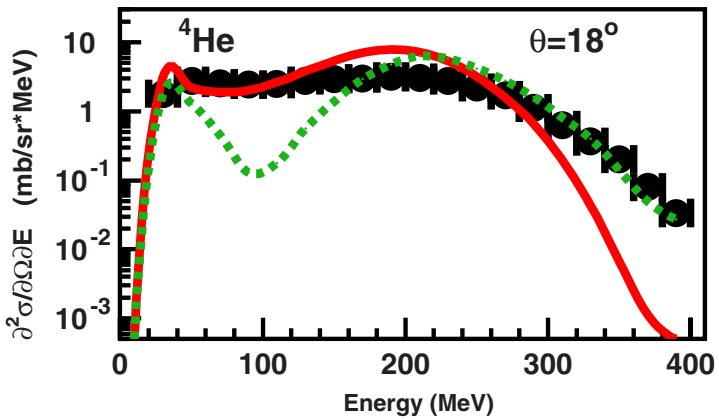


Li6

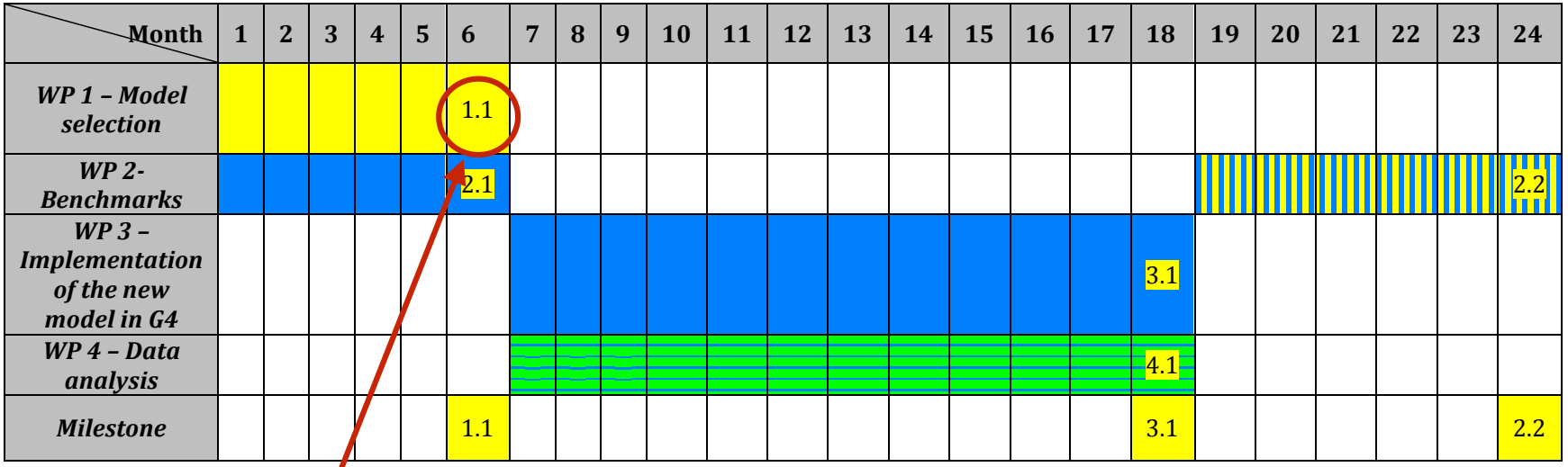


Double differential cross section





The first two deliverables



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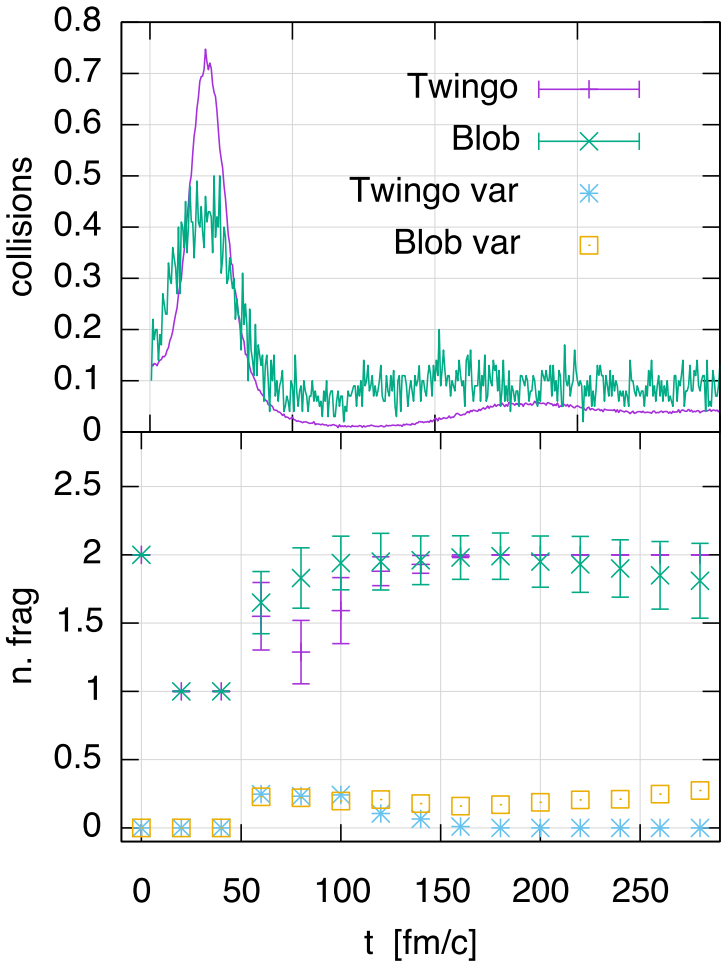
Blob and Twingo

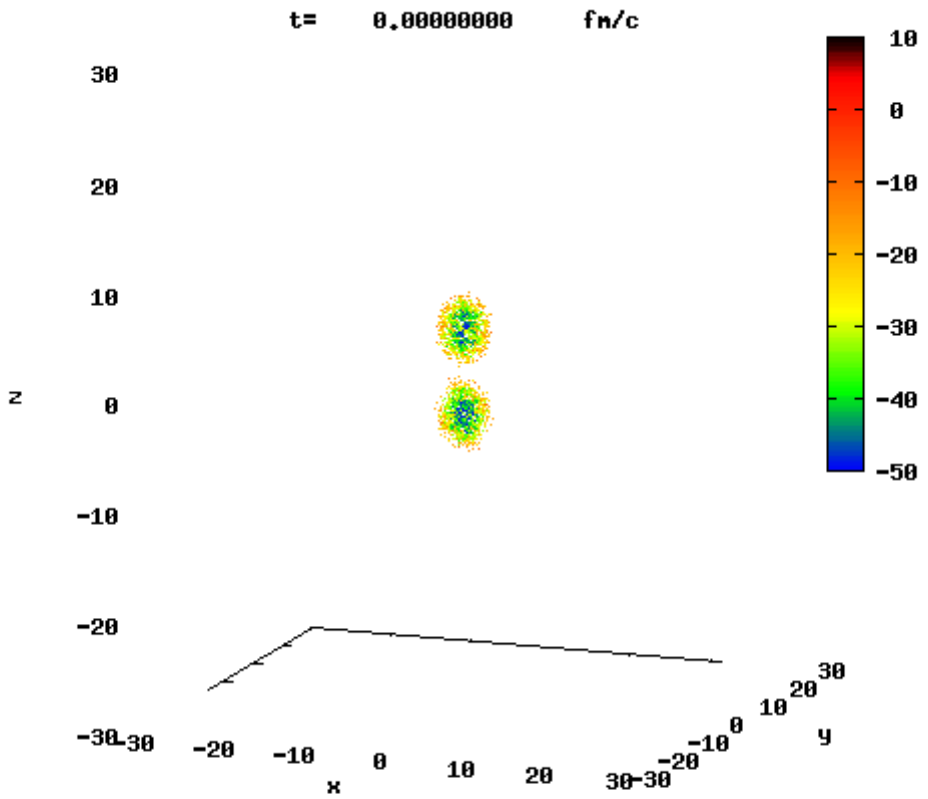
- **Twingo** is a BUU model
  - Developed by **Maria Colonna** (LNS, Catania)
- **Blob** is a BL model
  - Derived from Twingo
  - Implemented by **Paolo Napolitani** (IPN, Orsay)

Blob and Twingo

- We have done a first run simulating ^{12}C-^{12}C interaction at 62 MeV/n using Twingo and Blob
- Both produces all the hot fragments before 150 fm/c
- To compare with experimental data it is necessary to couple them with a de-excitation model

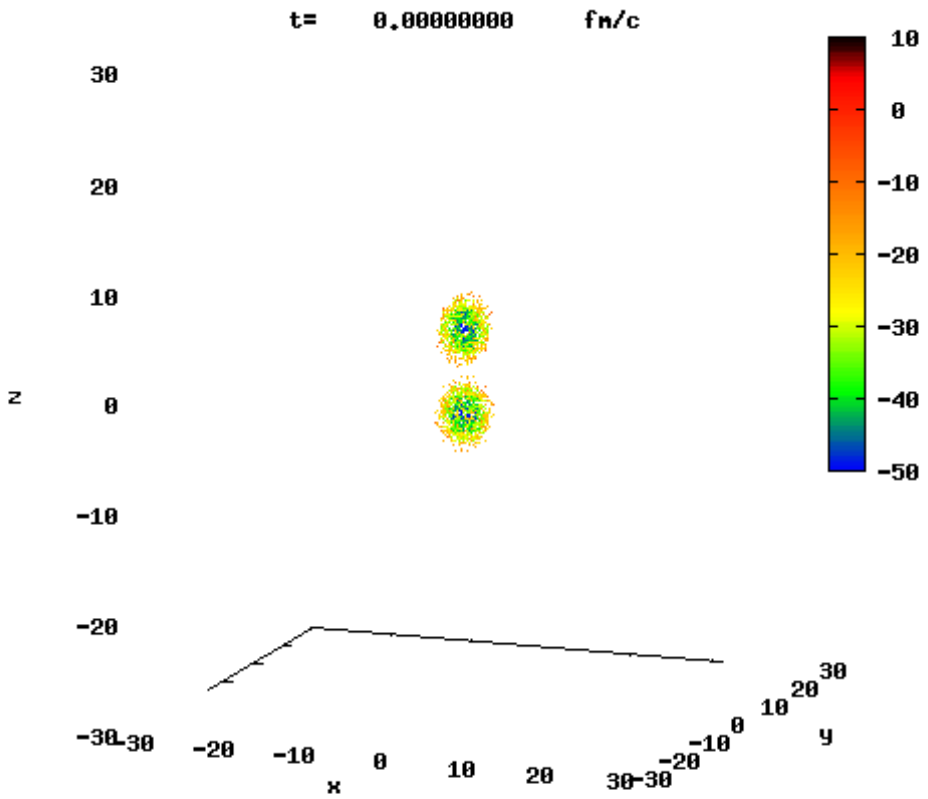


Blob and Twingo



Blob

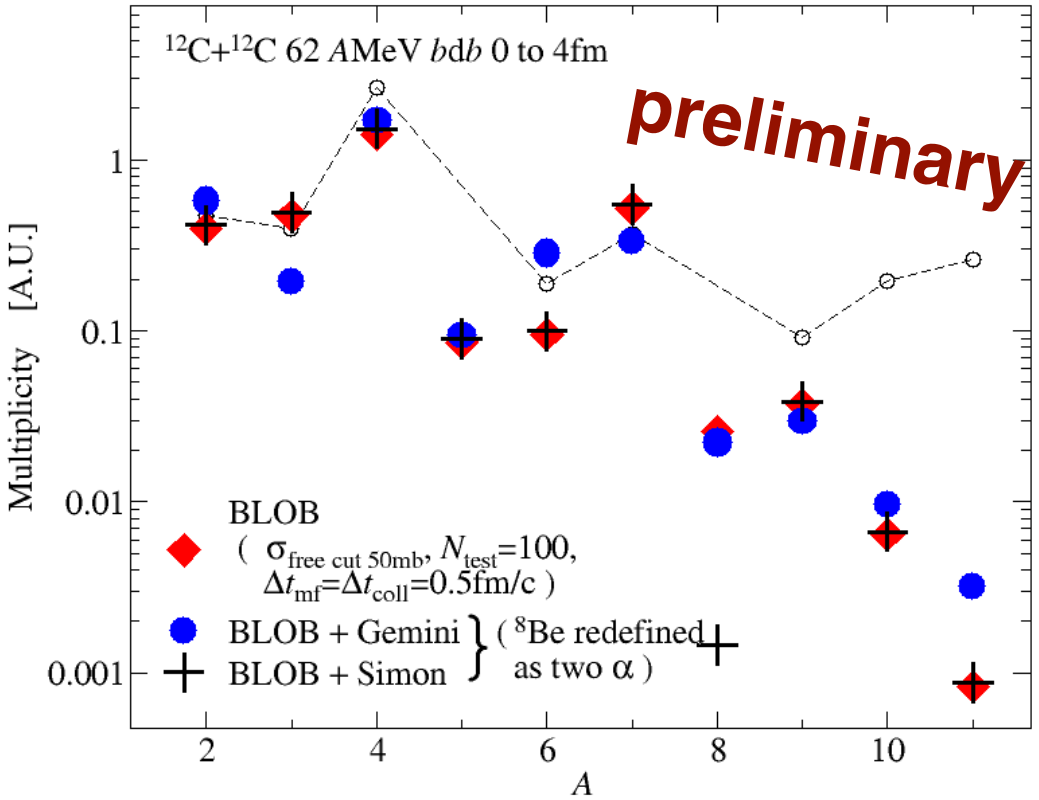
100 test particles per nucleon
^{12}C on ^{12}C at 62 MeV/n



Twingo

First preliminary results from Blob

- With **Paolo Napolitani**, we coupled **Blob** with two exit channel models (Gemini and Simon)
- Only central collisions (b from 0 to 4 fm)



experimental data points from [De Napoli et al. Phys. Med. Biol., vol. 57, no. 22, pp. 7651–7671, Nov. 2012]

Next steps

Work on the benchmark

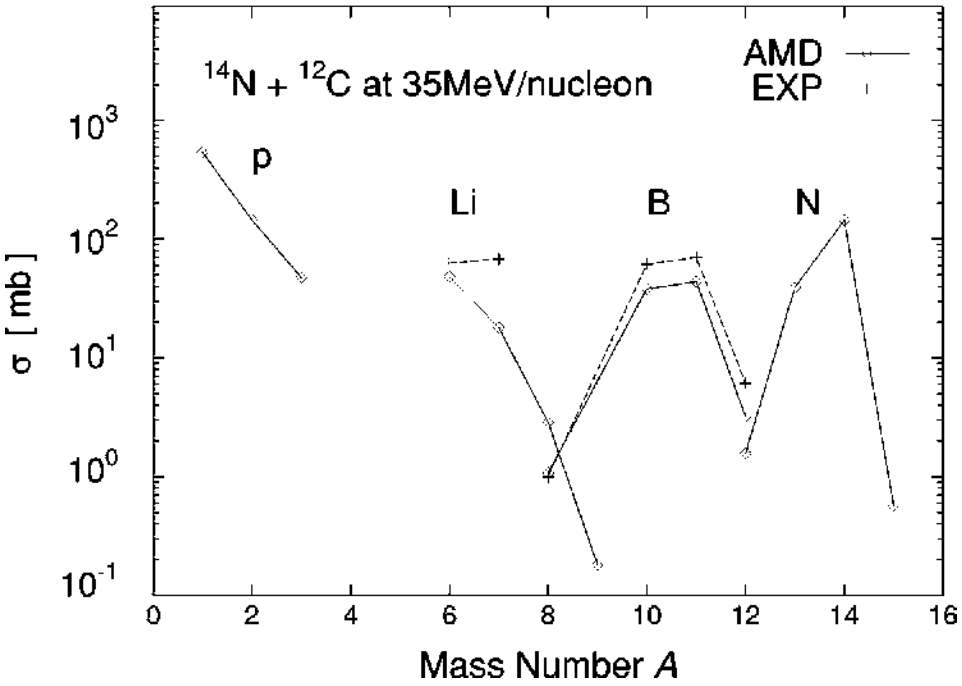
- Adapt the code to Geant4 v 9.4.1(the same of the paper by De Napoli et al., 2012)
- Compare the results of BIC and G4QMD of G4 v 9.4.1 (2012) and G4 v 10.03.1 (actual version)

Work on the models

- Simulate the interaction up to b=12 fm
- Do the same simulation with Twingo
  (but also with G4QMD, BIC and INCL++)
- Compare angular and energy spectra for
  Intermediate-mass fragments of Blob and Twingo
  with experimental data
- Couple Blob and Twingo with other exit channel
  models (Abla, Gemini++)

Work on the models

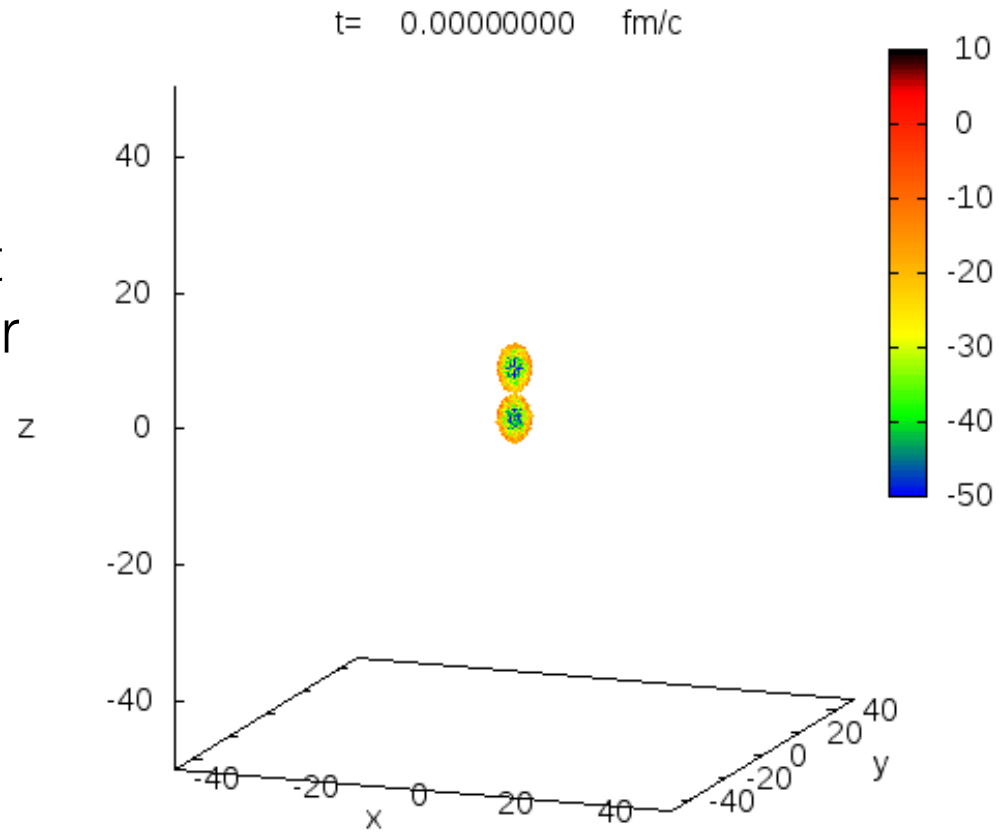
- Simulate the interaction of ^{14}N on ^{12}C at 35 MeV/n to compare with the AMD model made by A. Ono



[H. Takemoto, H. Horiuchi, and A. Ono, Phys. Rev. C, vol. 57, no. 2, pp. 811–821, Feb. 1998]

Work on the models

- Test the results with an higher number of test particle for the mean field (allowing to use a different number of test particles for the collision term)
- Test the stability with peripheral collisions
- Try to speed up the simulation



400 test particles per nucleon for mean field and 40 for the collision term

Summary

- This project covers **a gap which needs to be filled**:
  - implementation of a low energy hadronic interaction **model developed by LNS** theory group
  - **unique** in Geant4
- Has a **lot of applications**:
  - related to several INFN activities e.g.: **FOOT**, **MoVe_IT**
- Fragmentation data at 33 MeV/A will be analyzed
- Will strengthen **international collaborations** between two of the research centers with the highest expertise in the field (LNS and iThemba)

thank you for your attention!