Development of the nuclear reaction and fragmentation models for heavy ion collisions
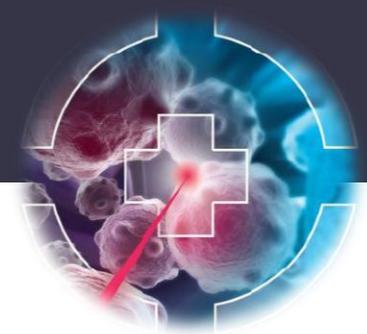
OMA

Giulia Arico'

4-5 June 2018
CERN, Switzerland
OMA topical workshop on Diagnostics
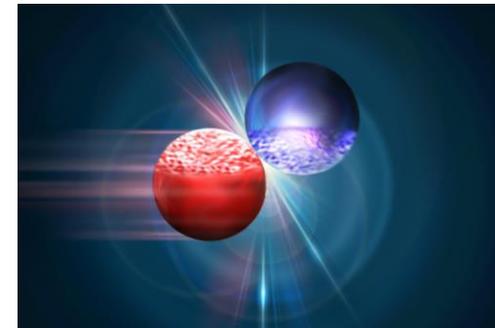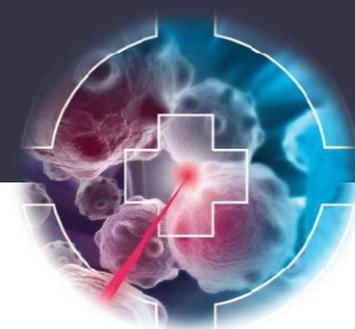for Beam and Patient Monitoring

Overview:

- **Introduction and Aim**
  - Nuclear reactions
  - Hadrontherapy
    - Helium ion therapy

- **Method**

- **Results**

- **Summary**

- **Outlook**

Developments of the nuclear reaction and fragmentation models in FLUKA
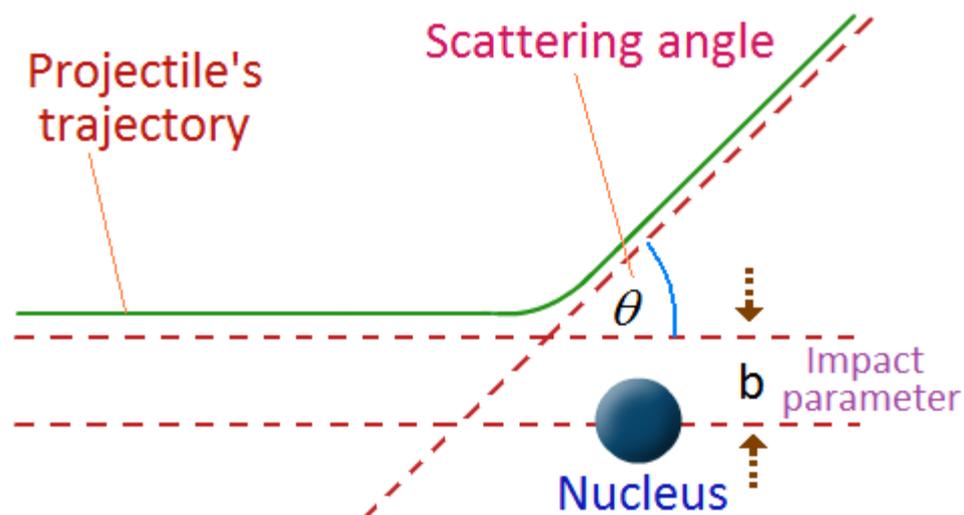
Nuclear reactions

Basic concepts:

Impact parameter:
perpendicular distance between the trajectory of the projectile and the center of the potential field generated by the target nucleus

Elastic scattering

b ≈ 0 : central collision

0 < b < 2R : peripheral collision
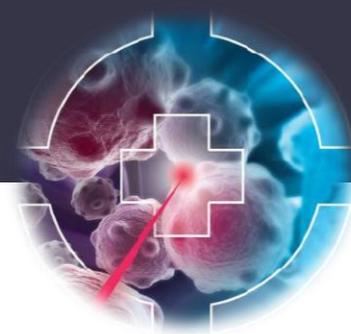
b > 2R : distant collision

R = radius of the colliding nucleus
b = impact parameter

Basic concepts:

Cross section describes the probability that a projectile "interacts" with a target nucleus
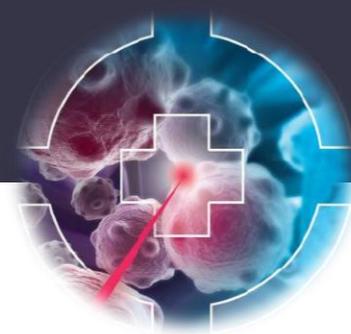
Interaction means either scattering and break up

Different processes have different cross sections

σ is the "area" of the target nucleus within which, if the projectile "falls", a certain reaction channel will take place

σ [cm^2]
1 barn$=10^{-24}$ cm^2

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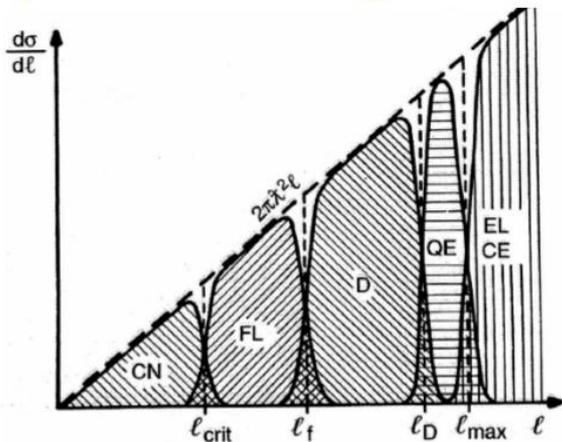OMA topical workshop
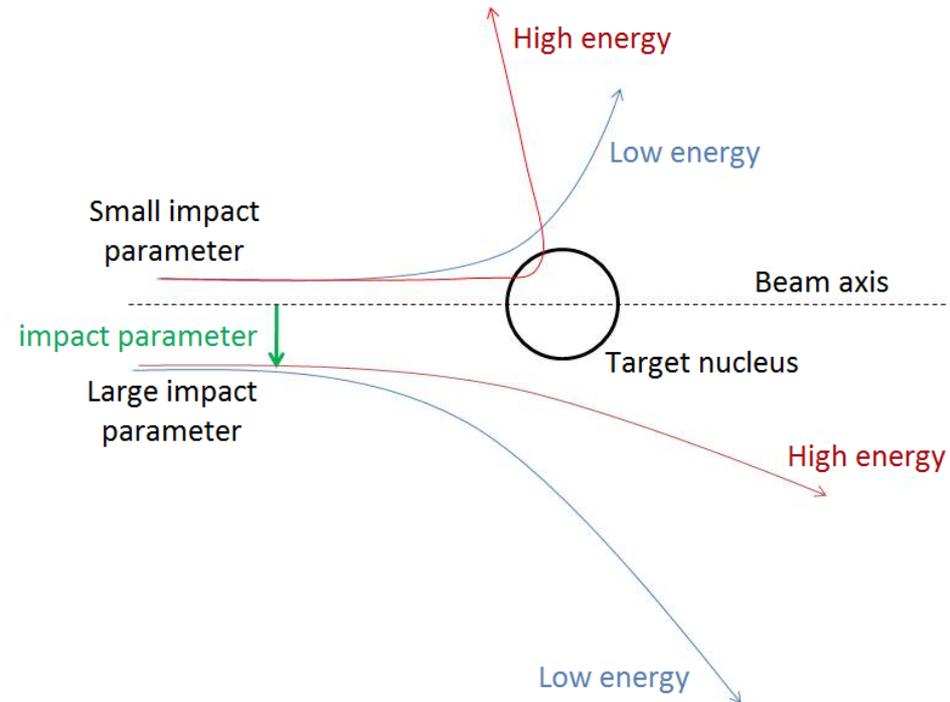
Nuclear reactions

Basic concepts:

Nuclear reaction: reactions between an atomic nucleus and a particle

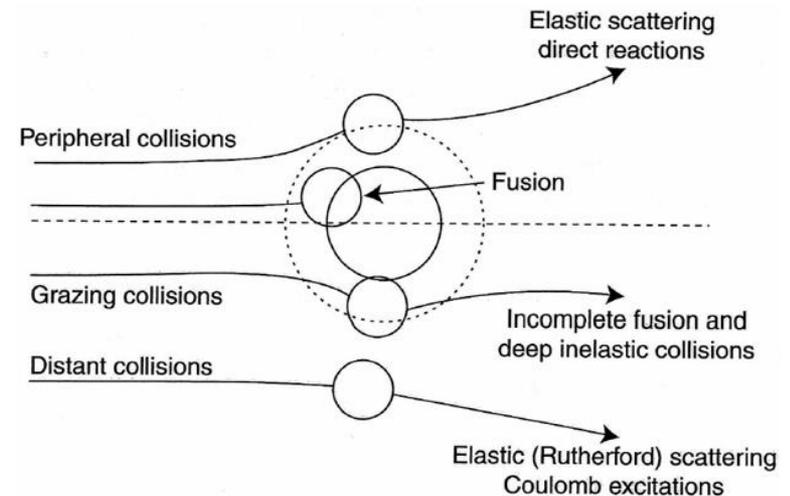**Nuclear transmutation**: new nuclei are formed, P+T → X+R

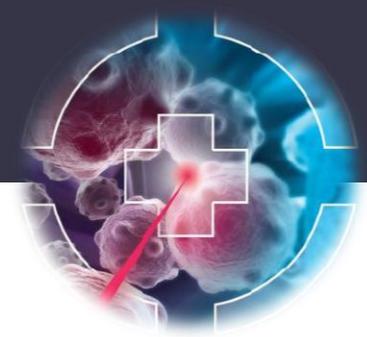**Inelastic scattering**: the nucleus is excited to a higher energy state

Elastic scattering: the nucleus is unchanged
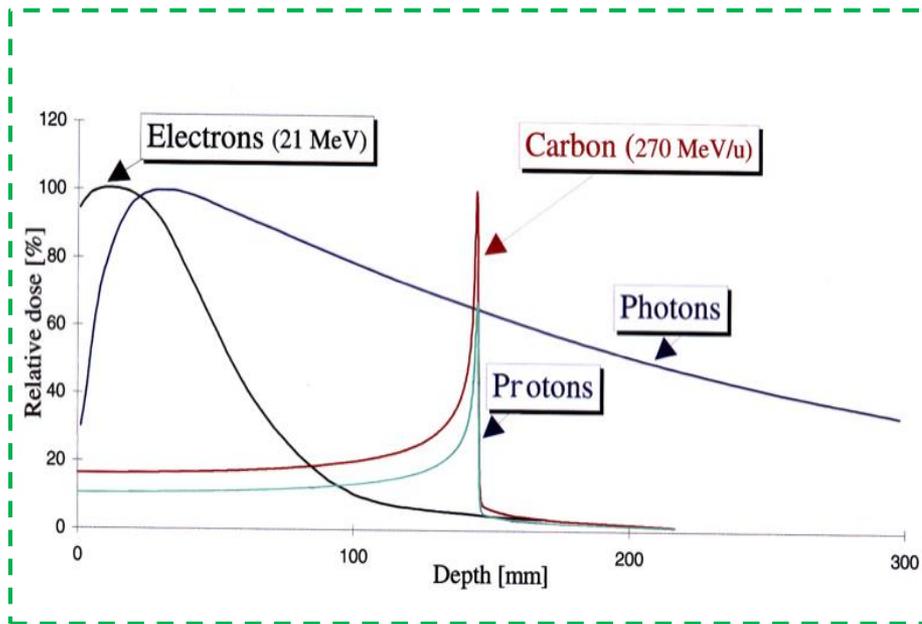

partial cross section vs. angular momentum

- CN: compound nucleus
- FL: fusion-like
- D: deep inelastic
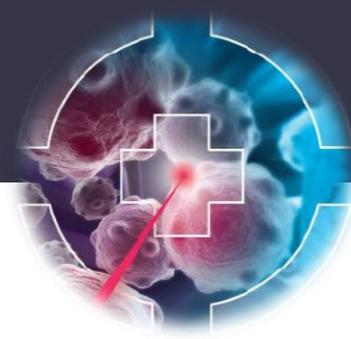- QE: quasi elastic
- CE: Coulomb excitation
- EL: elastic

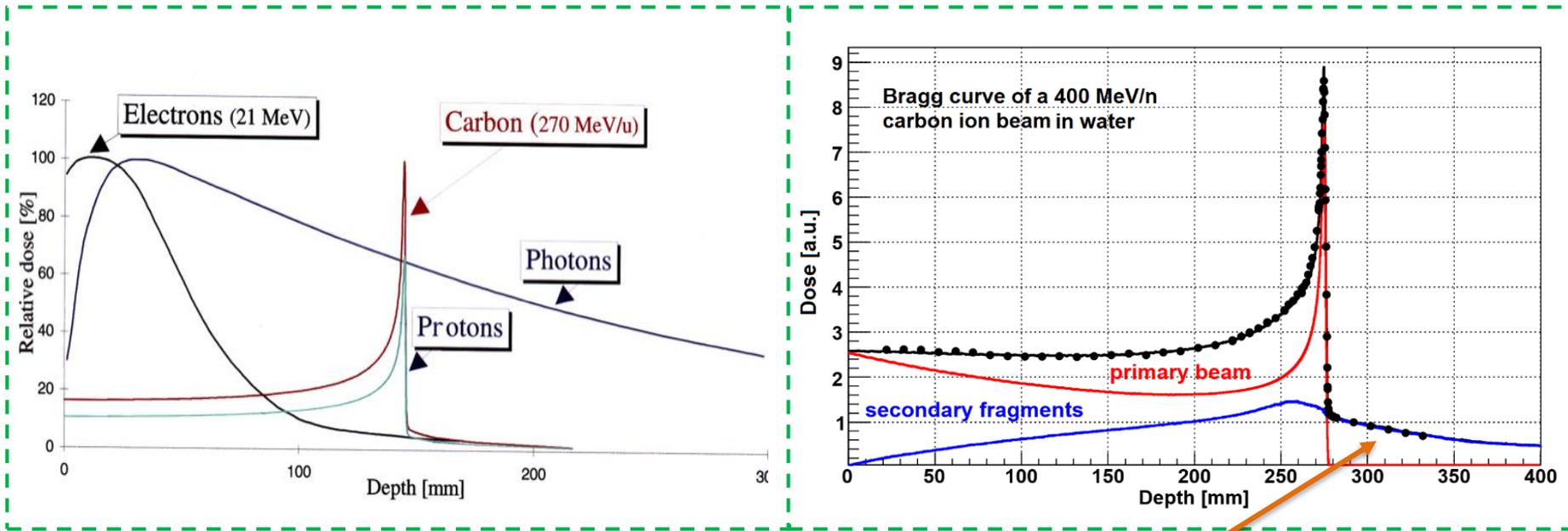**Hadrontherapy** make uses of **protons** and **heavier ions.**
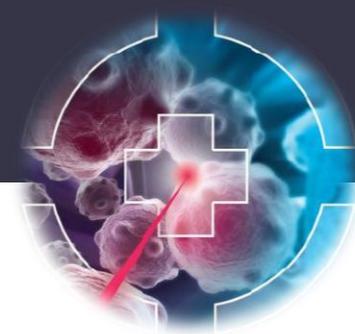**Rationale**: inverse depth-dose profile in comparison to photons and electrons.

Hadrontherapy make uses of **protons** and **heavier ions.**
However, nuclear interactions between primary ions and
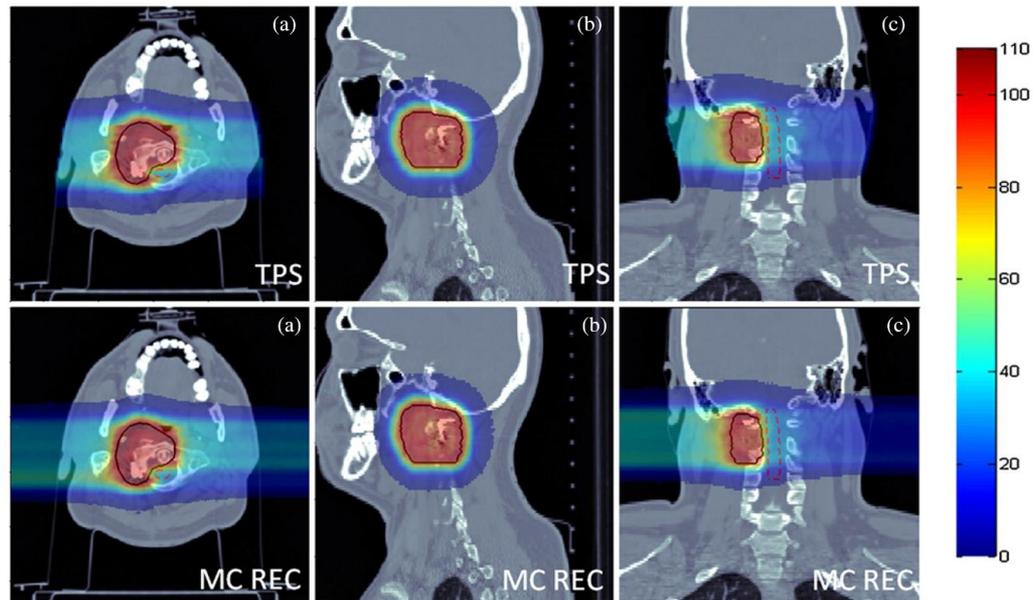patient tissues may cause primary particle **fragmentation**

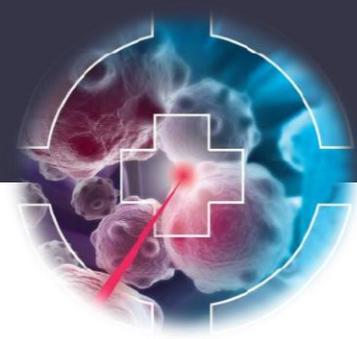*Dose delivered by secondary lighter particles behind the tumor*

Medical applications

At CNAO (Italy), HIT and MIT (Germany), patients are treated with protons and carbon ions.

In those facilities FLUKA is used:

- to **generate input data** for the treatment planning systems
- to **validate the dose calculations**

Helium ion therapy

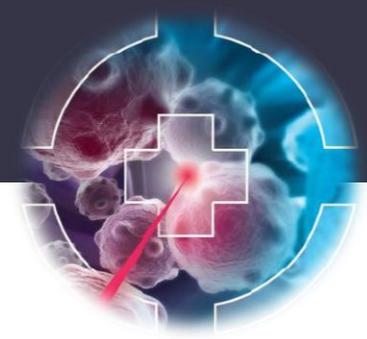The interest on <u>helium ions</u> is growing fast in the last years.

HIT (Germany) is planning to use helium ion beams for radiotherapy in the next future.
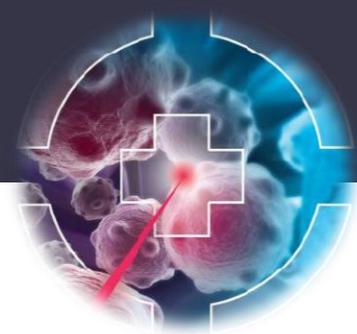
Helium ions vs protons
- ✓ Less scattering
- ✓ Lower penumbra
- ✗ Higher costs

Helium ions vs carbon ions
- ❑ Lower RBE
- ✓ Less fragmentation tail
- ✓ Lower costs

Goal: Improvements of the nuclear reaction cross sections for **helium ions**
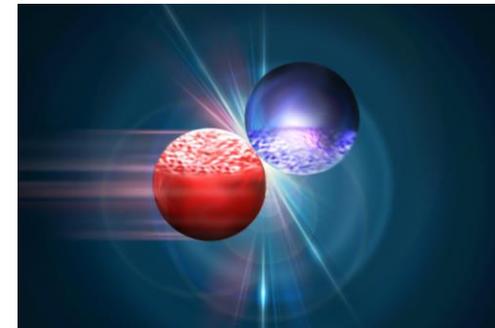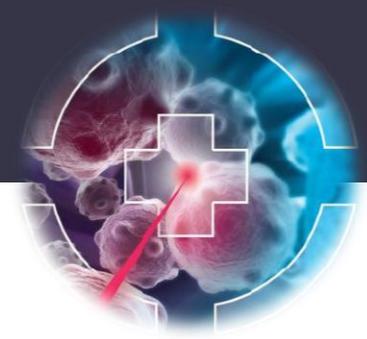 - ➤ **Beneficiary** : HIT and future helium ion therapy centers

Overview

Overview:

- **Introduction and Aim**

- **Method**

  - Experimental setup

  - Analysis

- **Results**

- **Summary**

- **Outlook**

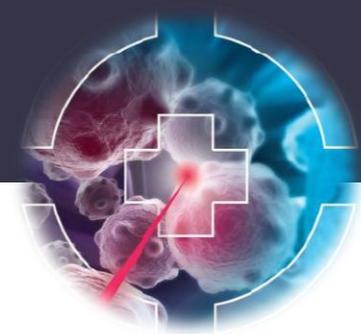**Developments of the nuclear reaction and fragmentation models in** FLUKA

Goal: Improvements of the nuclear reaction cross sections for **helium ions**
  ➢ **Beneficiary** : HIT and future helium ion therapy centers
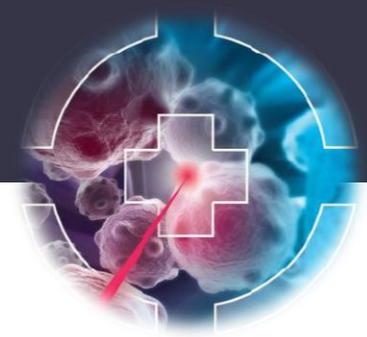
Aim

Monte Carlo code (FLUKA)
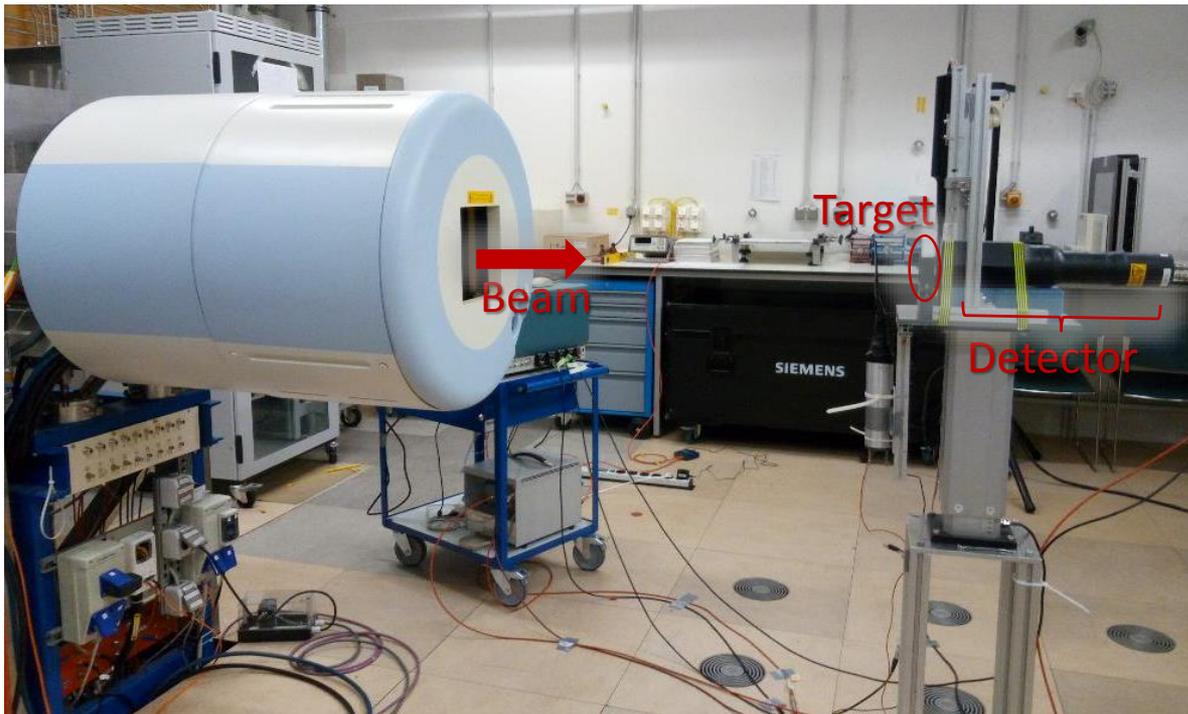Experimental data for benchmarking

Detector for measurements
Helium ion beam

Helium ion beam
Accurate Monte Carlo code for helium ion therapy
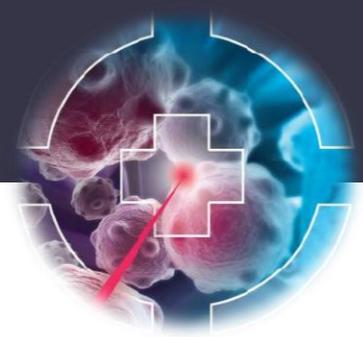Detector for measurements

Incident beam : He ions
Target : thin graphite, silicon, silicon dioxide
Detector : $\Delta E/E$ telescope (developed at GSI)

Exp. setup
mounted @ HIT

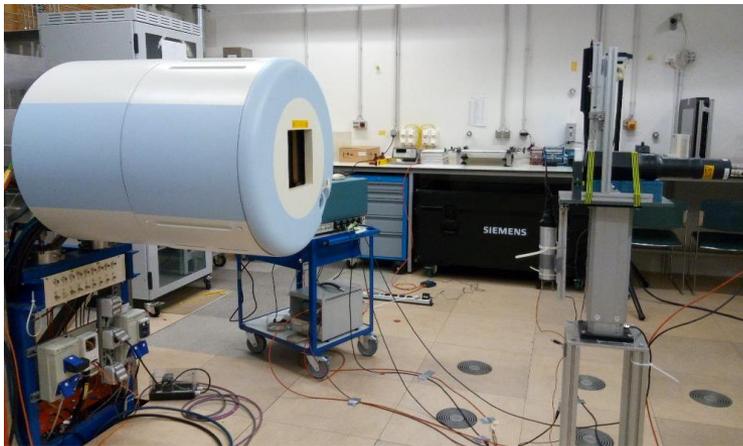**Incident beam** : He ions

Experimental measurements:

mass changing cross sections ($\sigma_{\Delta A}$):
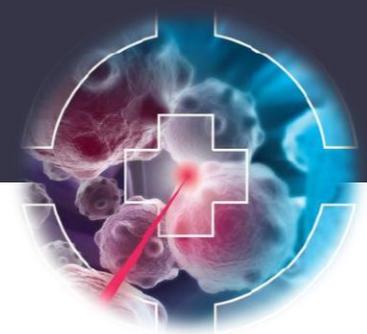
the projectile loses at least one proton

charge changing cross sections ($\sigma_{\Delta Z}$)

the projectile loses at least one nucleon

Note:
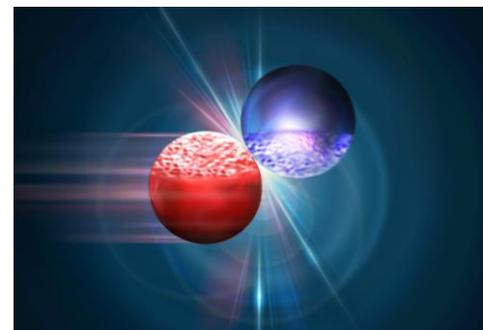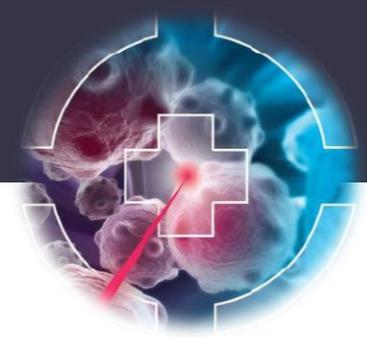Primary helium ions that interact in the target but do not undergo fragmentation are not measured in the experiments

Overview:

- **Introduction and Aim**

- **Method**

- **Results**

  - He+C collisions
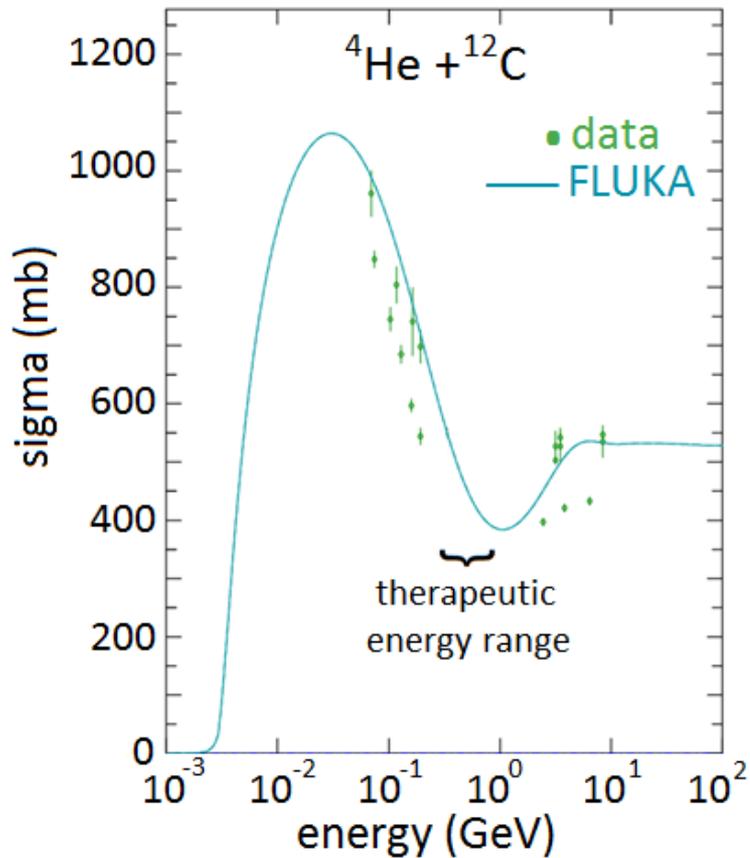
  - He+O collisions

- **Summary**

- **Outlook and Conclusions**

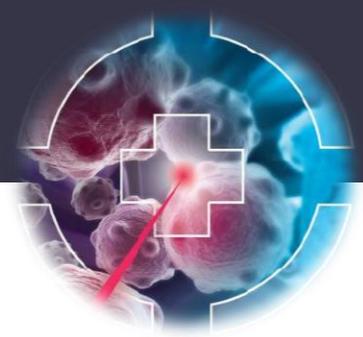**Developments of the nuclear reaction and fragmentation models in** FLUKA

Giulia Arico'
4-5 June 2018
OMA topical workshop

Nuclear reaction cross section curve on C:

Nuclear reaction cross section curve on C:

Experimental GSI data from :
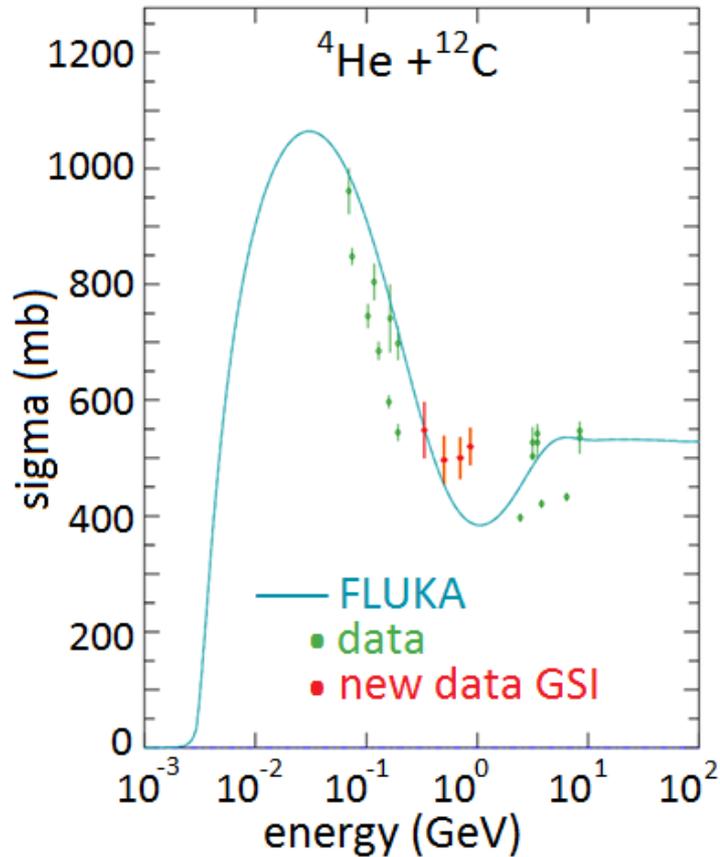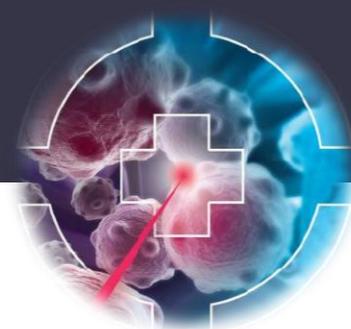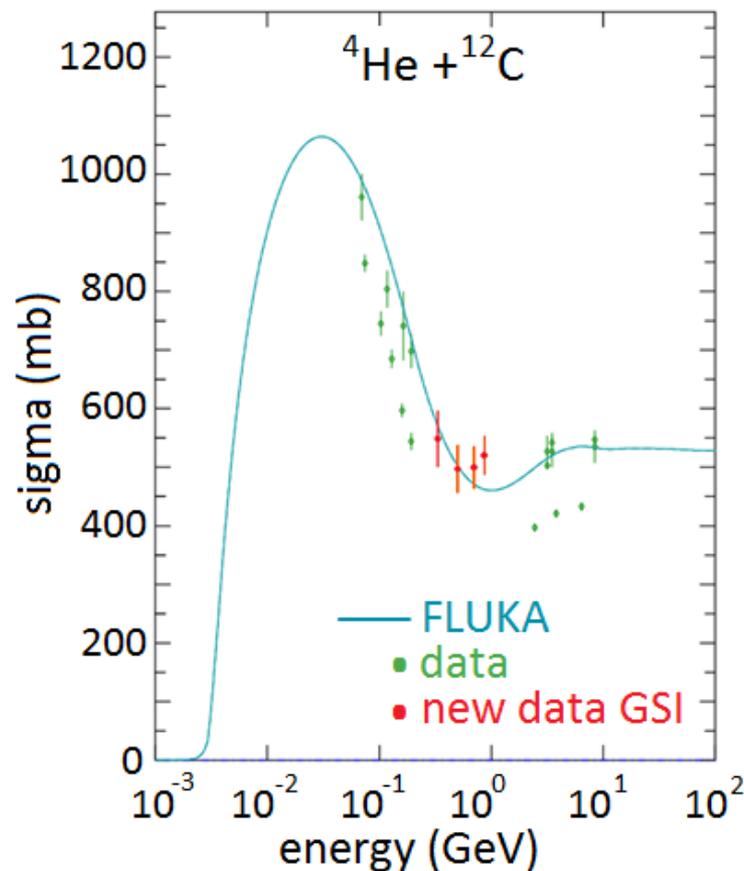Phys. Rev. C 96, 024624 (2017)

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Nuclear reaction cross section curve on C:

Experimental GSI data from :
Phys. Rev. C 96, 024624 (2017)

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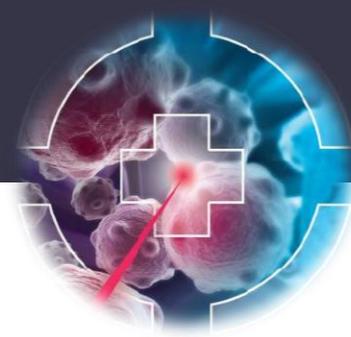4-5 June 2018
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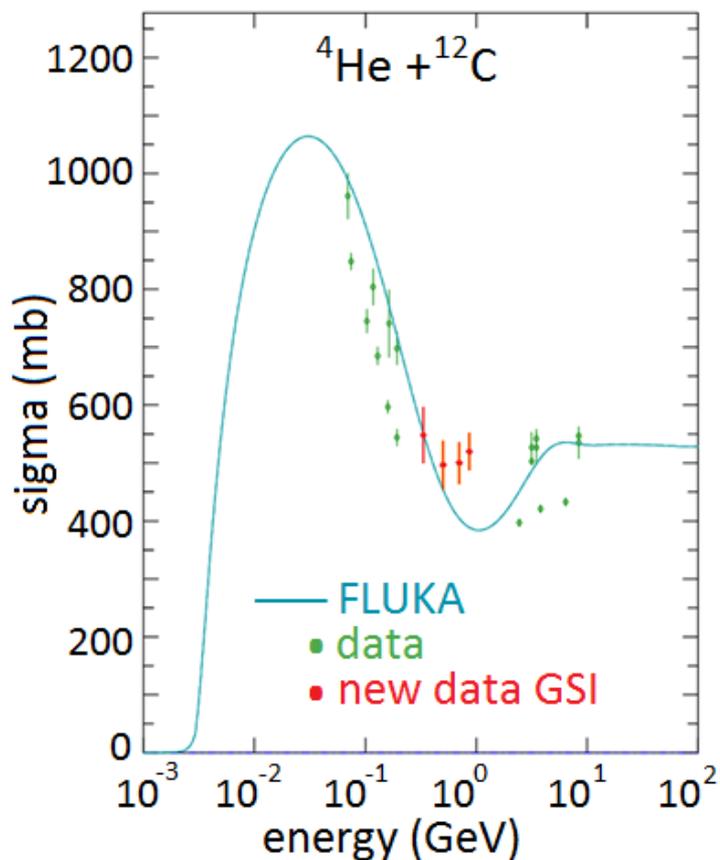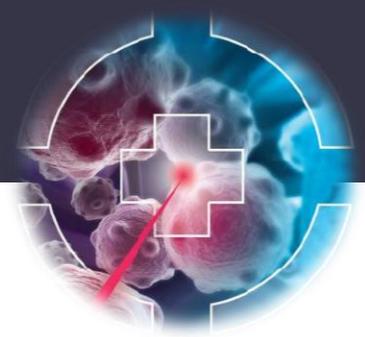
Nuclear reaction cross section curve on O:

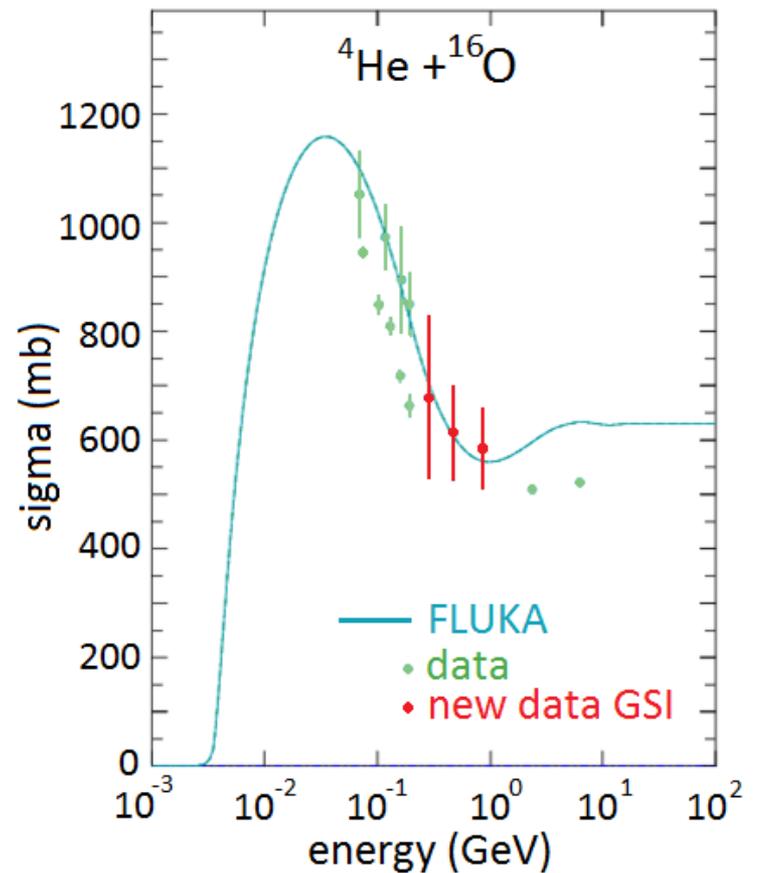Measurements of nuclear reaction cross sections for He+O systems are changeling.
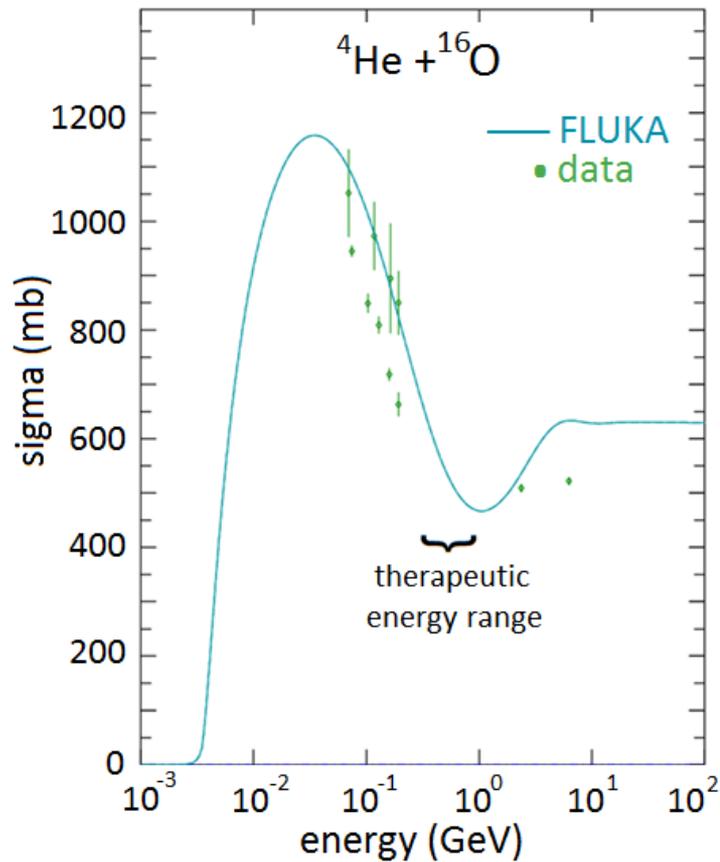
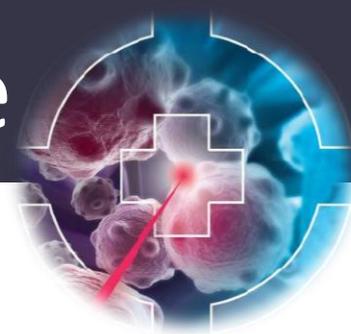Cross section values can be obtained by comparison, e.g. using:

- Al and Al_2O_3 targets
- Si and SiO_2 targets

Not recommended: H and H_2O targets, due to the not negligible elastic scattering component on H

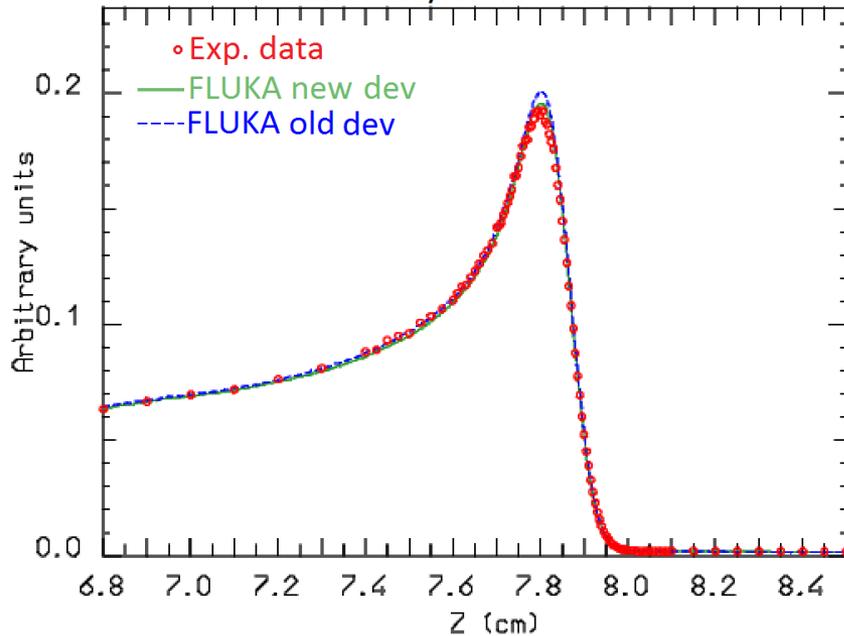**Nuclear reaction cross section curve on O:**

Assessment of the projectiles ^{4}He ions that undergo a nuclear reaction in the target without changing their mass or charge (i.e. no fragmentation)

Calculated with FLUKA simulations

→ not considered in the experiments

Correction factor needed to obtain the *total* nuclear reaction cross sections

Depth-dose curves

⁴He at 100 MeV/n and 190 MeV/n in water

Normalization to the area subtended by the curve

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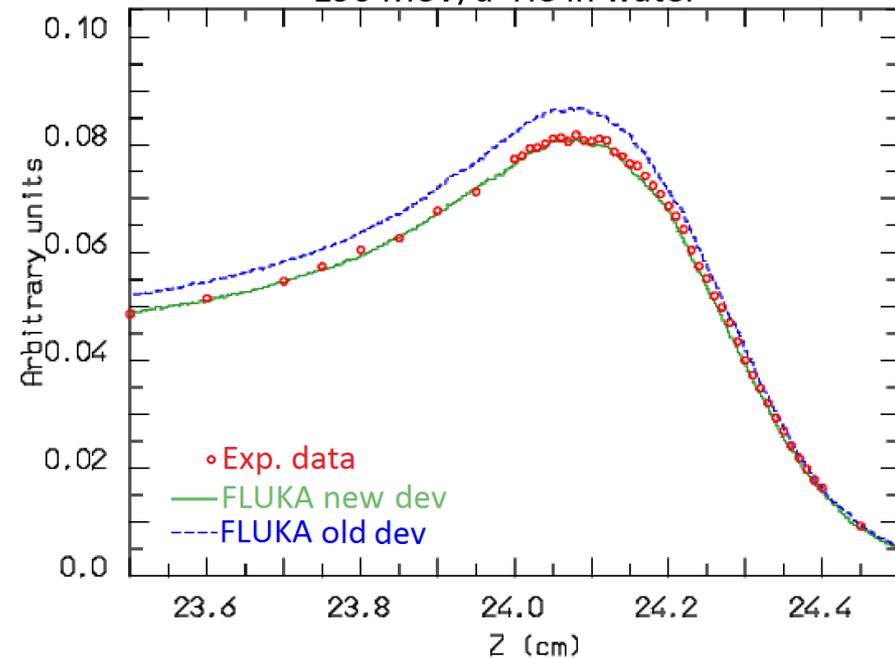OMA topical workshop

Depth-dose curves (zoom)

^{4}He at 100 MeV/n and 190 MeV/n in water

100 MeV/u ^{4}He in water
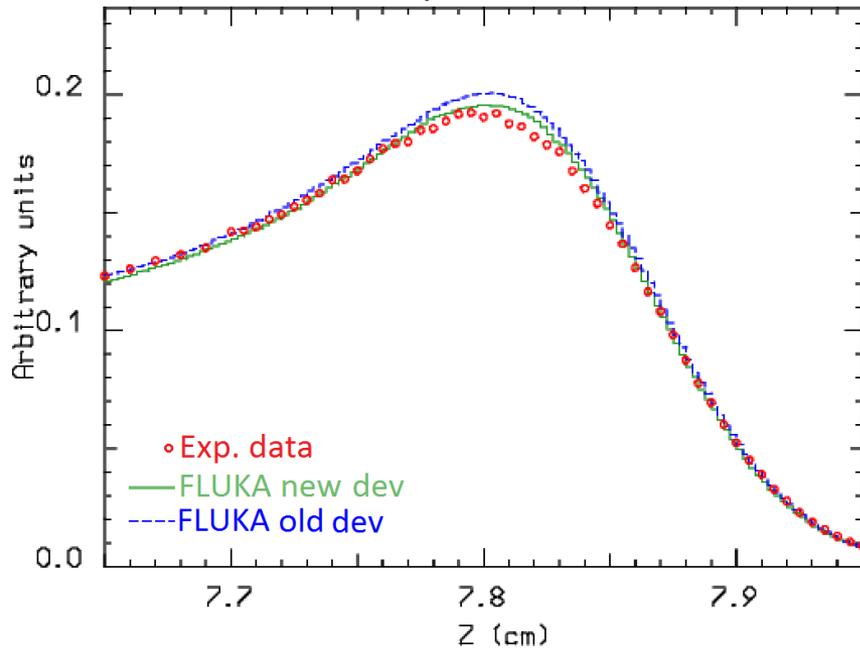
190 MeV/u ^{4}He in water

○ Exp. data
— FLUKA new dev
-- FLUKA old dev

Normalization to the area subtended by the curve

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OMA topical workshop

Preliminary results on dose

Depth-dose curves (zoom)

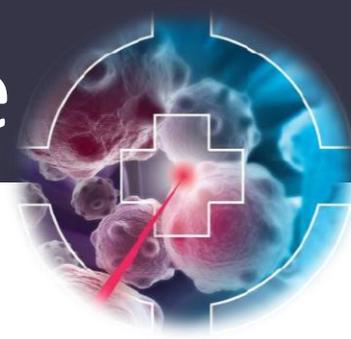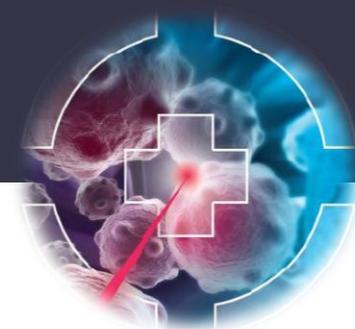### ^{4}He at 100 MeV/n and 190 MeV/n in water

Normalization to the area subtended by the curve

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4-5 June 2018
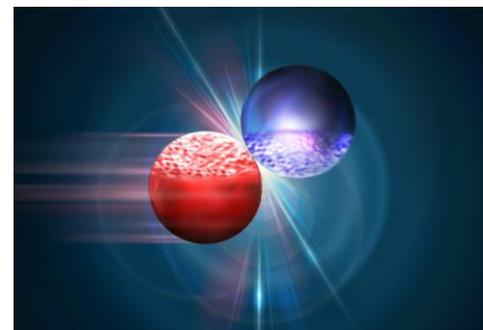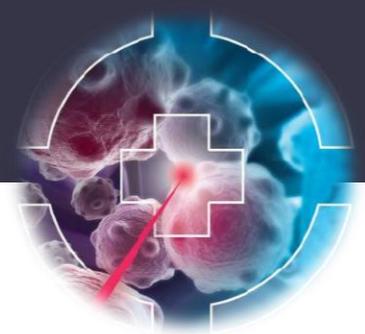OMA topical workshop
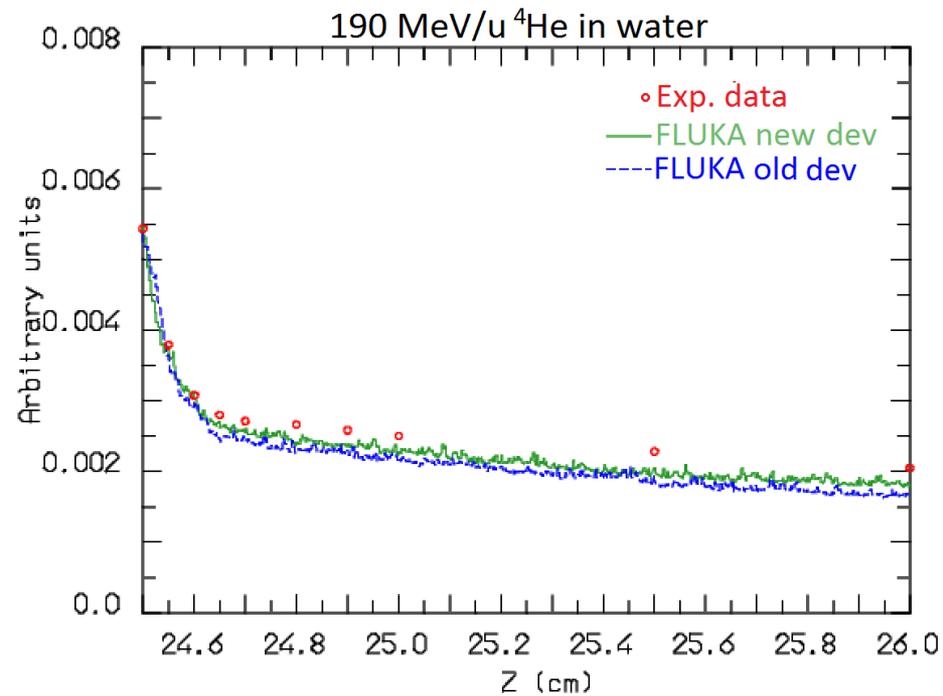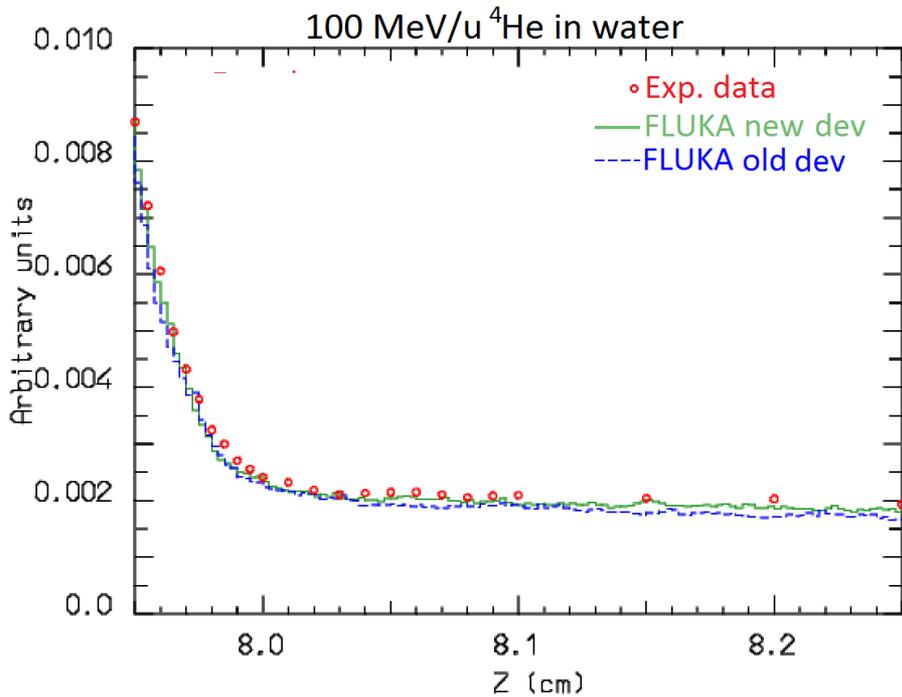
Overview:

- **Introduction and Aim**

- **Method**

- **Results**

- **Summary**

- **Outlook**

**Developments of the nuclear reaction and fragmentation models in** FLUKA

Summary

Helium ion therapy can be a viable alternative to proton and carbon ion therapy.

➢ Prior to the use of helium ions for clinical applications, their physical and biological properties have to be well known

➢ Improvements on the nuclear reaction cross section curves were needed for accurate dose calculations

Summary
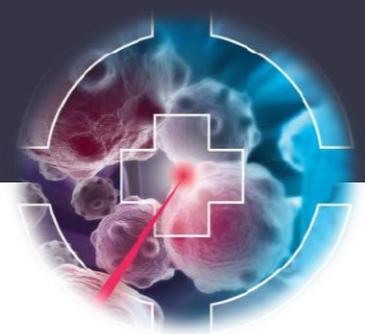
➢ New experimental data in the therapeutic energy range were used to benchmark the FLUKA nuclear reaction cross section curve

➢ An additional renormalization factor was considered in the FLUKA model to take into account all primary ^{4}He ions which undergo nuclear reactions without changing their mass and charge (not measured in the experiments)

Conclusions and Outlook
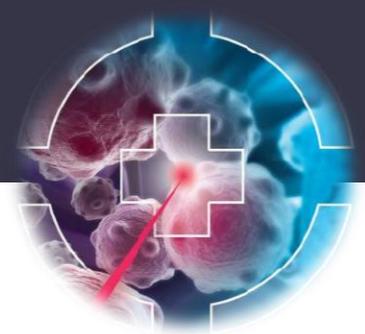
➤ The new refined nuclear reaction cross section curves for ^{4}He ions in C and O will be included in the next FLUKA release and used for clinical applications at HIT.

➤ Nuclear reaction cross sections measurements with different target materials and beam energies will be investigated, for use e.g. for detectors, astrophysics, space radiation...

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12-13 March 2018
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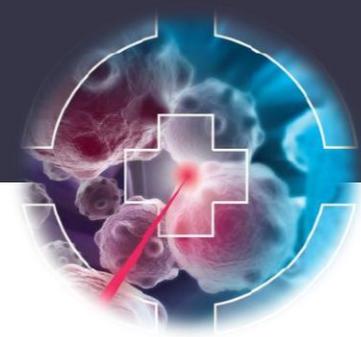
Thanks for your attention

Acknowledgments: