Experimental and Theoretical Validation of Nuclear Data and Models using different Monte Carlo Codes

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OpenGate Meeting @ Wuppertal
22. Jan. 2020

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1. **Assigned Task**
   - FLUKA simulations
   - Comparison between MC Codes
   - Benchmarking FLUKA-GEANT4

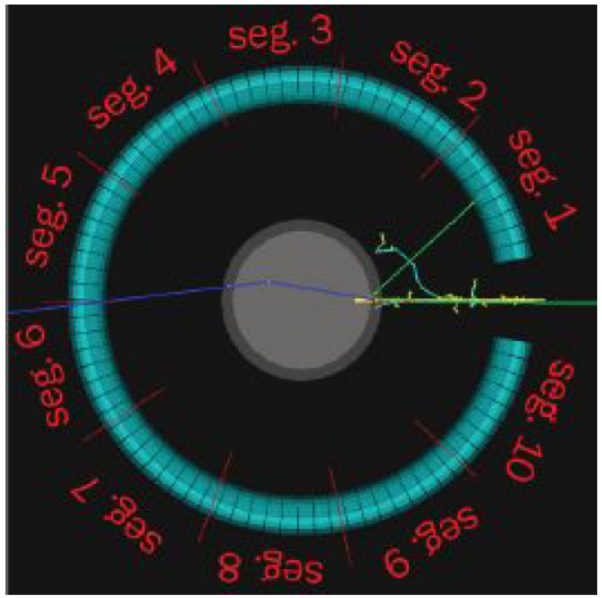
2. **Experimental Validations: Experiment-to-code**
   - Mid/High Energy Application - 62 MeV
   - Low Energy Application - 11 & 12 MeV

3. **Conclusion**

Assigned Task

SIMULATION SETUP AND GEOMETRY

- Proton beam of 1mm dia, (90, 160, 210 MeV)
- Beam directed onto a cylindrical phantom having an elemental composition ($C_5H_8O_2$) and density 1.19 gm/cm^3
- Phantom diameter: 30cm, Height: 20cm
- Detector ring Inner dia: 54.11 cm, Height: 20cm
- Detector material: Plastic scintillator
- Beam entrance opening ratio: 5/85 of ring circumference
- Remaining ring divided into 10 segments to study angular distribution



Simulation Setup

Assigned Task

PROBLEM

Variation in the production yield of secondary particles (neutrons and gammas) in the simulation of a proton beam with two different simulation codes **(Geant4** and **MCNP6).**

Assigned Task

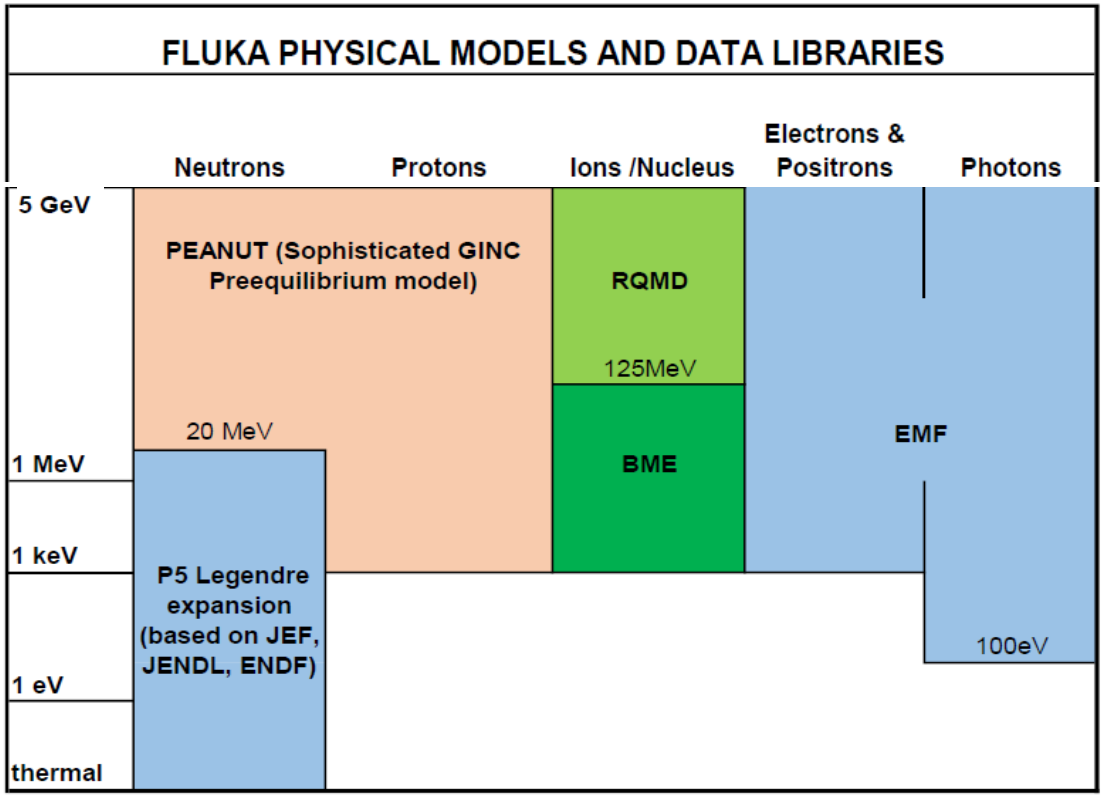
TASK APPROACH

In order to find which simulation results are more closer to reality, same simulation setup was rebuilt on another simulation tool ***FLUKA***, to have a better comparison and reasoning for the observed differences.

FLUKA

- FLUKA is a fully integrated particle physics Monte Carlo simulation package

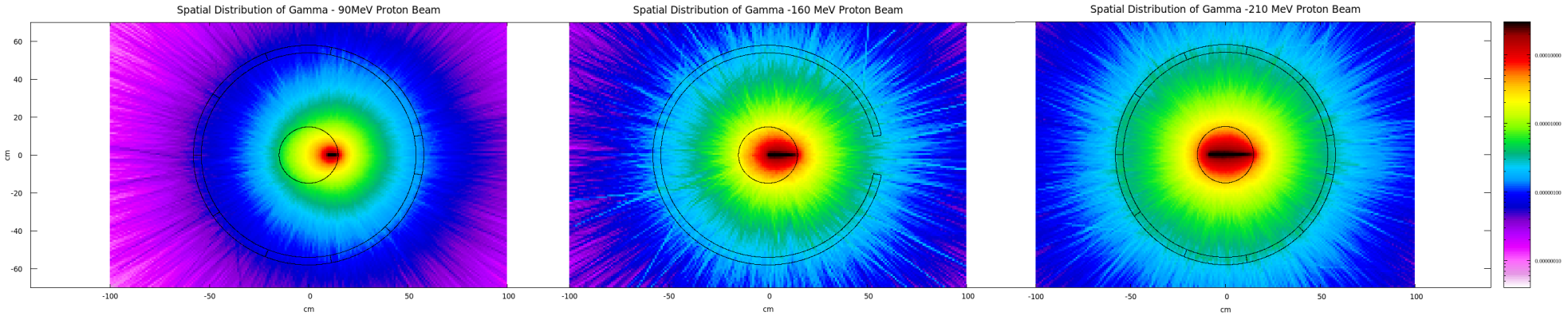
- Applications: high energy physics, shielding, cosmic ray studies, radio-biology, etc.



FLUKA Simulations

ANALYSIS OF INTERACTION DENSITY
(Spatial Distribution of Particles produced per Proton)

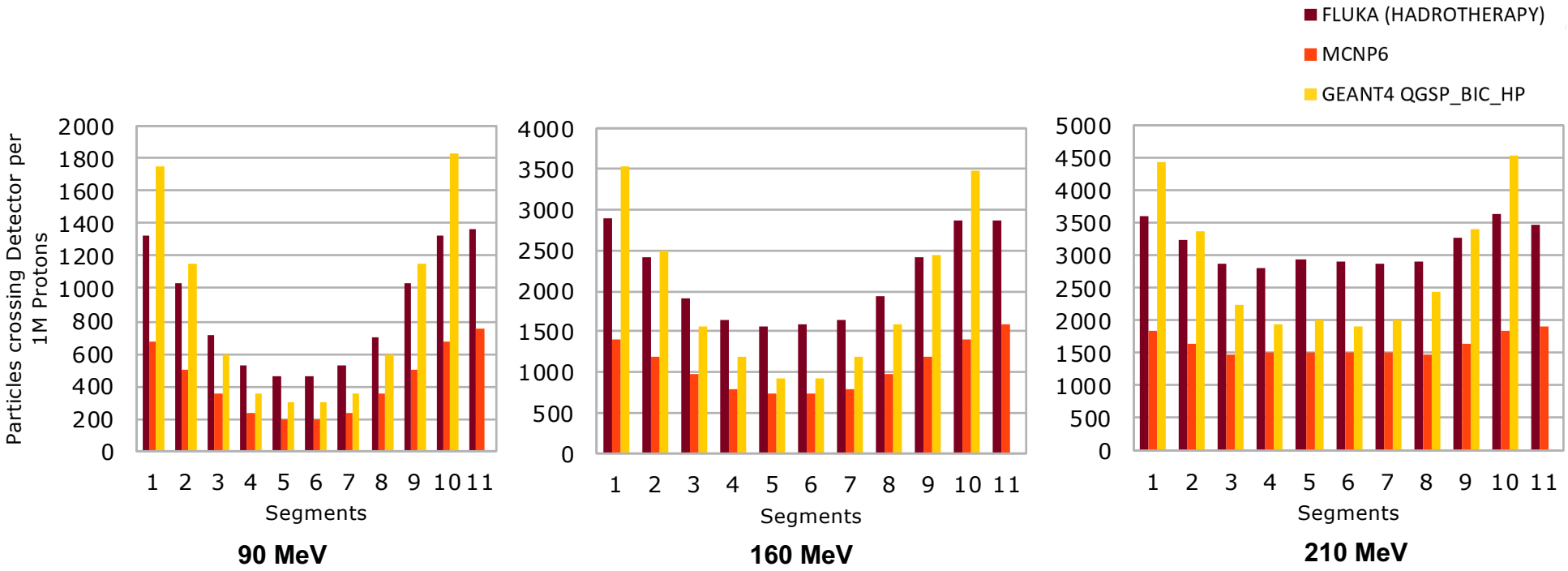
GAMMAS



90 MeV **160 MeV** **210 MeV**

Comparison between MC Codes

ANGULAR DISTRIBUTIONS – GAMMAS YIELD



Experiment-to-Code Validation

COMPREHENSIVE EXPERIMENTAL BENCHMARKING

For Medium energy applications

62 MeV - at LNS, INFN Laboratory, Catania, Italy

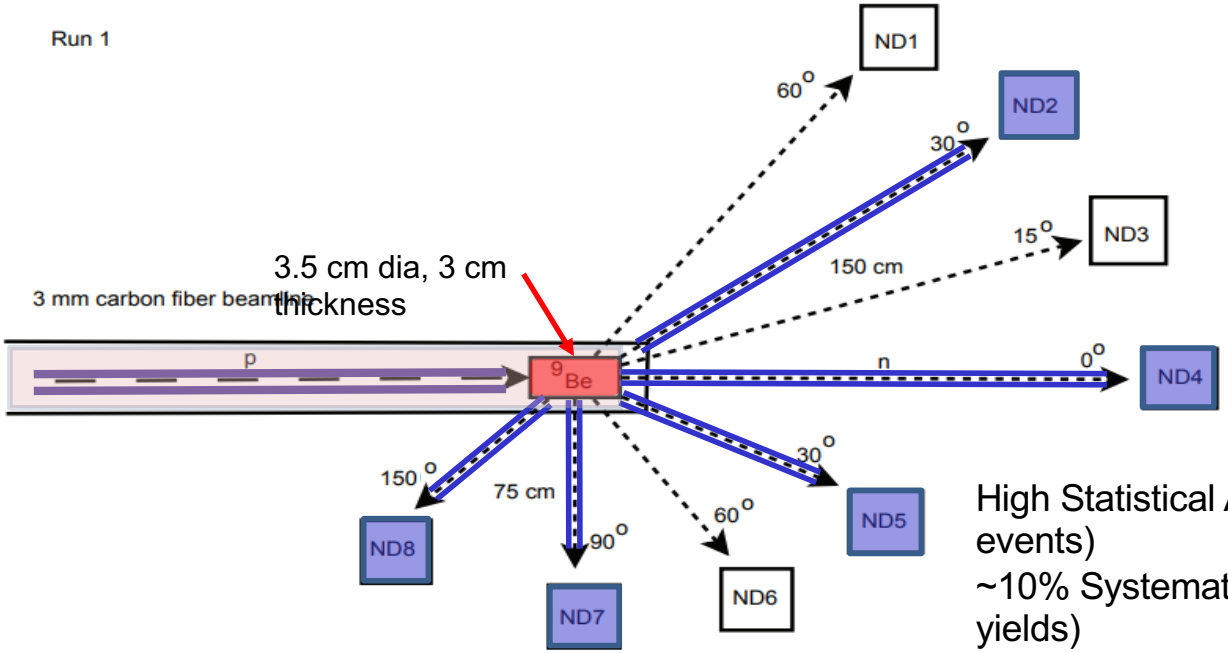
For Low energy applications

12 MeV - at TIARA facility of Japan Atomic Energy Agency

11 MeV - at CYRIC facility, Tohoku University, Japan

Experimental Benchmarking with 62 MeV Protons

LNS, INFN LABORATORY, ITALY

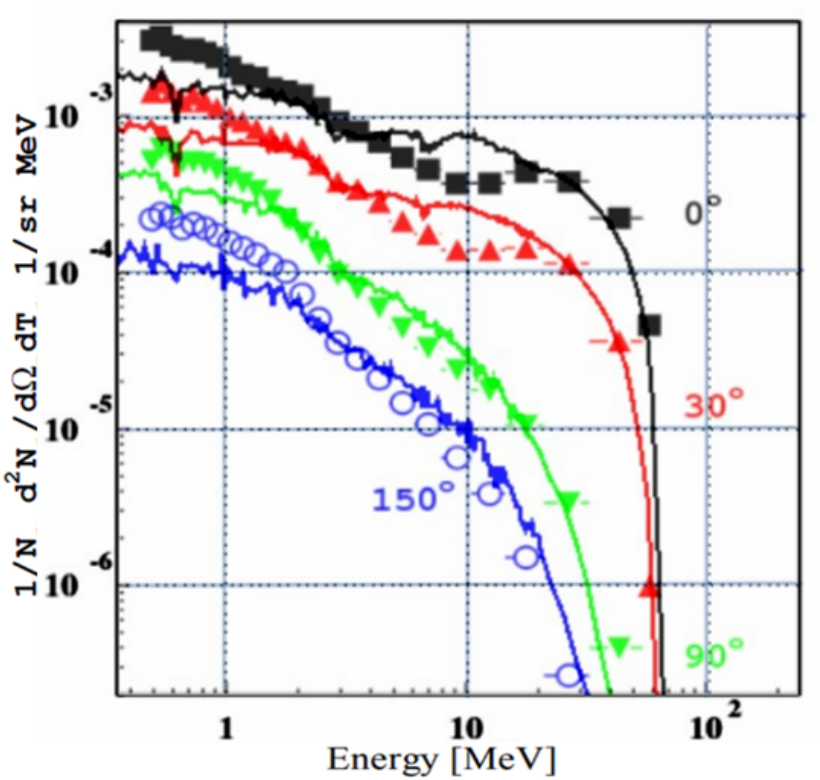


High Statistical Accuracy: ($3x10^5$ to $7x10^6$ events)
~10% Systematic Uncertainties (for diff. yields)
Geant4 MC code for Detector η

Benchmark Experiment:
M. Osipenko, M. Ripani, R. Alba, et.al. "Comprehensive measurement of neutron yield produced by 62 MeV protons on Beryllium target", 3rd Intl. Conf, on ANIMMA, 2013

Experimental Benchmarking with 62 MeV Protons

EXPERIMENT-TO-FLUKA

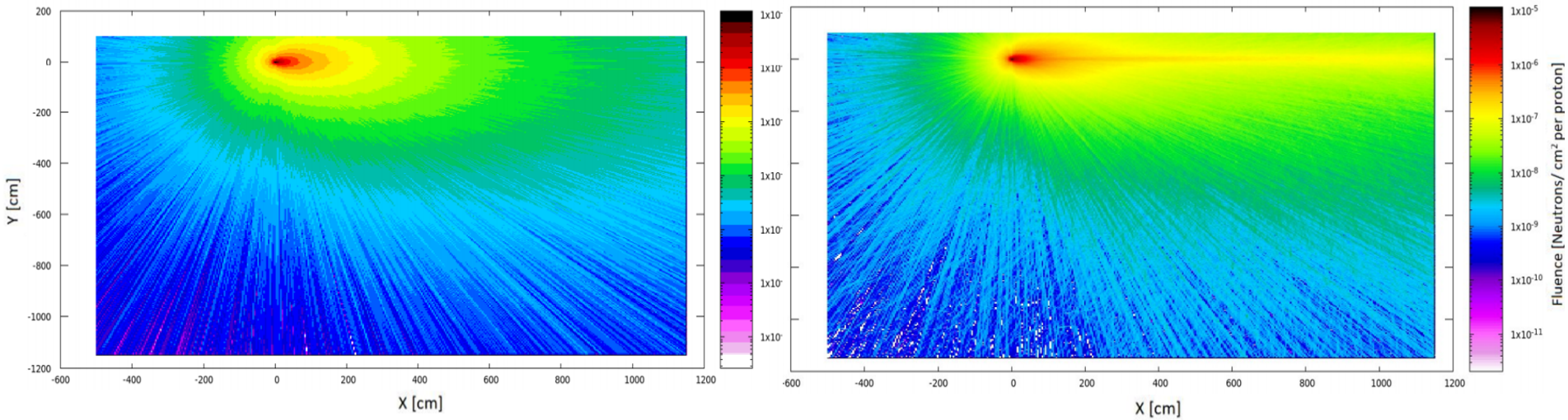


ANALYSIS:

- FLUKA shows a good agreement with experiment.
- It gives more precise estimation for E>20MeV
- Slight overestimation of low energy neutrons in experiment:
  -Neutron Production in air (secondary proton induced neutrons)
- Underestimation of 5-20MeV neutrons in experiment:
  -Neutron Absorption in air (high absorption cross section)

Experimental Benchmarking with 62 MeV Protons

NEUTRON PRODUCTION IN AIR AND VACUUM:

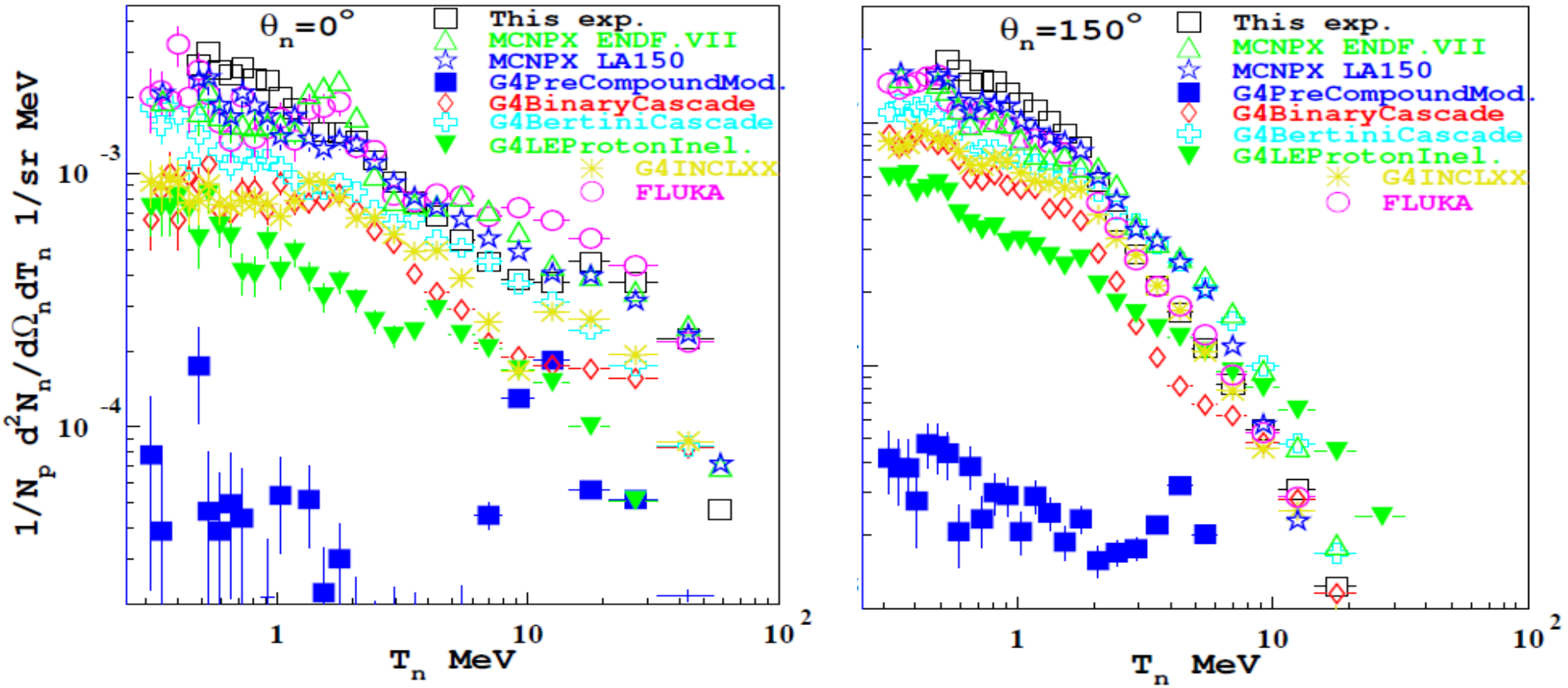


Spatial distribution of Neutron Fluence in Vacuum

Spatial distribution of Neutrons Fluence in Air

Experimental Benchmarking with 62 MeV Protons

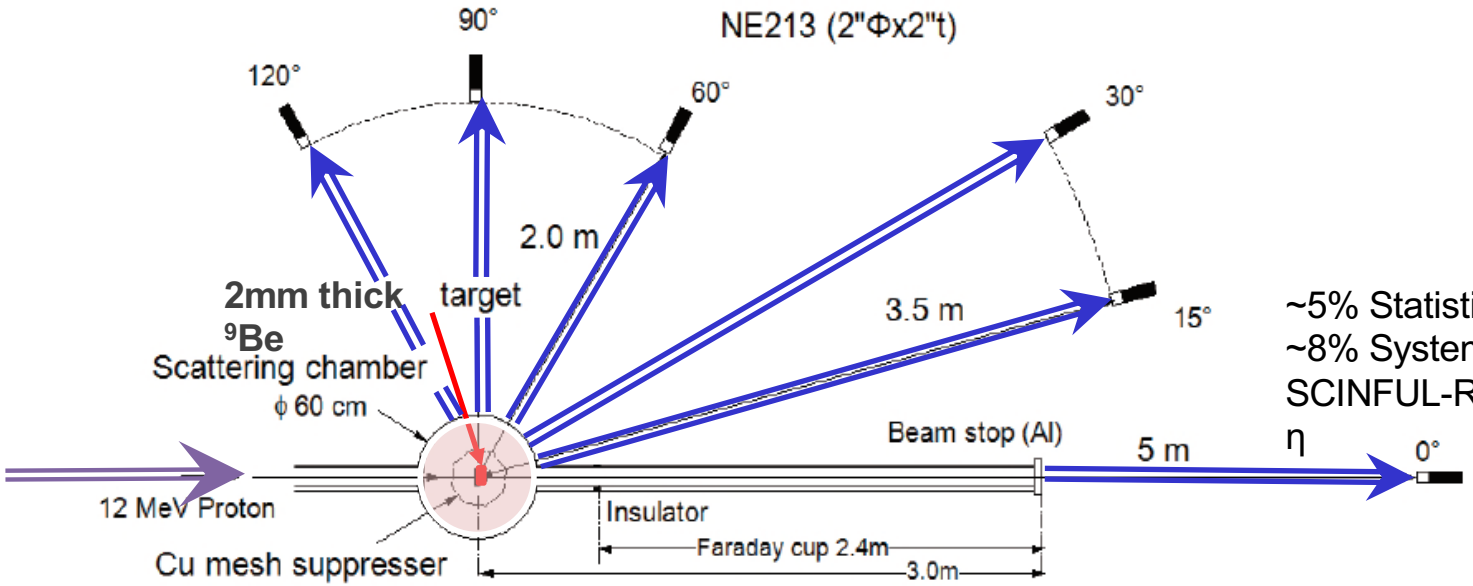
COMPARISON WITH OTHER MODELS



FLUKA PEANUT is precise model for hadron-nucleus reactions within intermediate energies (E>20MeV)

Experimental Benchmarking with 12 MeV Protons

TIARA FACILITY, JAEA



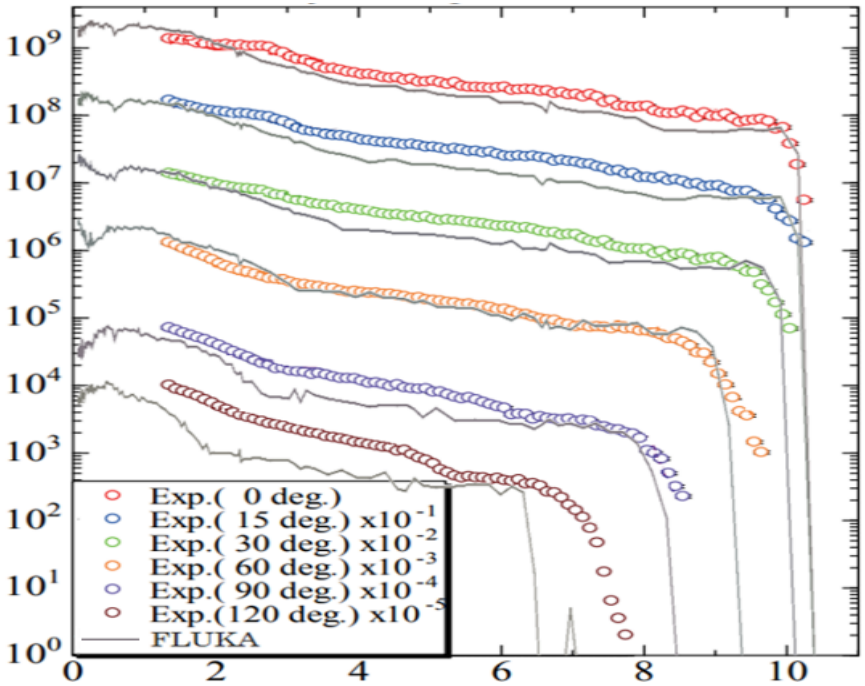
Setup in HB-1 course

~5% Statistical Uncertainties
~8% Systematic Uncertainties
SCINFUL-R MC code for Detector η

Benchmark Experiment:
Hagiwara M, et al. ''Measurement of neutron and gamma-ray yields on thick targets bombarded with 12 MeV protons''. Proc. of the 2011 Symp. on Nuclear Data: JAEA-Conf 2012-001; 2011 Nov 16–17; Tokai, Japan: JAEA; 2012. p. 111–116.

Experimental Benchmarking with 12 MeV Protons

EXPERIMENT-TO-FLUKA

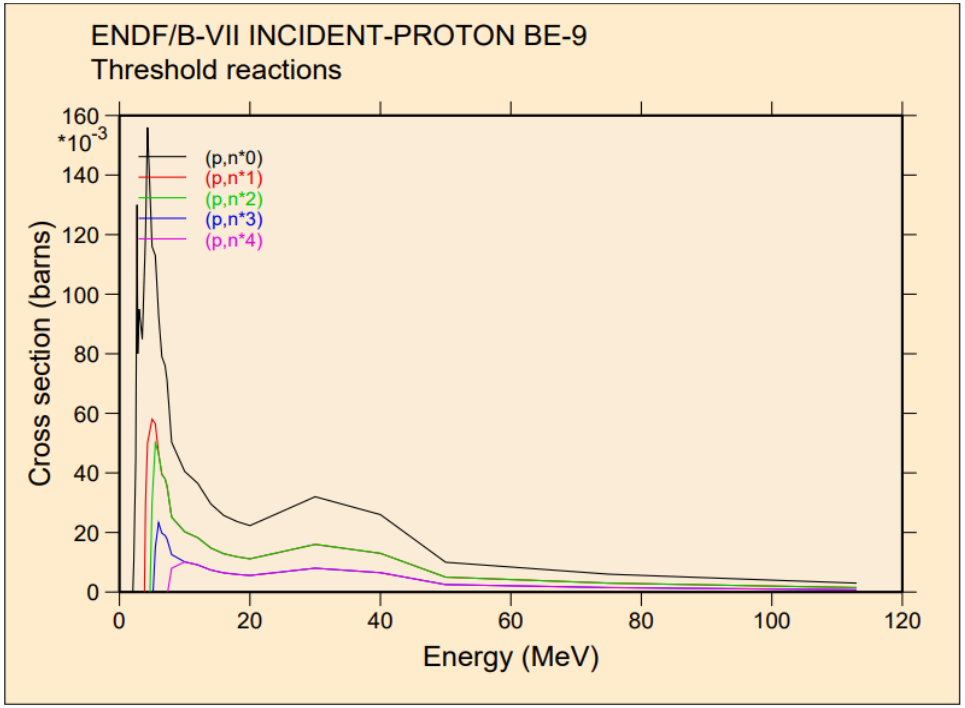


ANALYSIS:

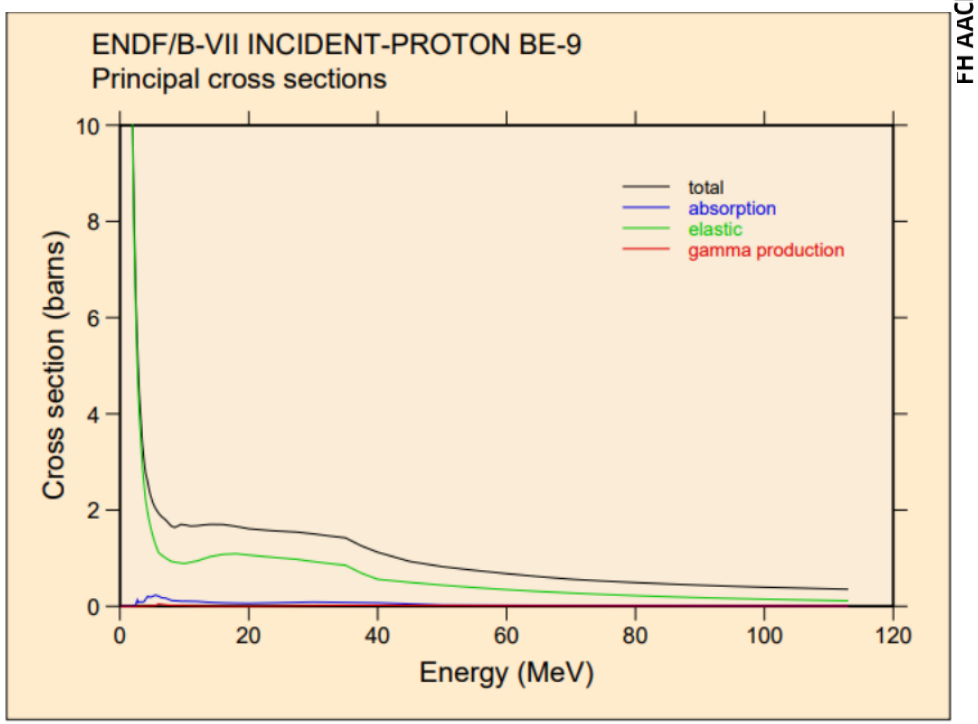
- FLUKA shows acceptable agreement at lower angles.
- Fits precisely well at 60°
- Slight deviation at lower angles:
  - Effect of air
  - Difference in Data library
- Deviations at higher angles: geometrical effect of target
  - In simulation : 2mm x 4mm x 4mm -
  - In experiment: 2mm x ? x ?

Experimental Benchmarking with 12 MeV Protons

DIFFERENCE IN DATA LIBRARY:



Proton induced cross section

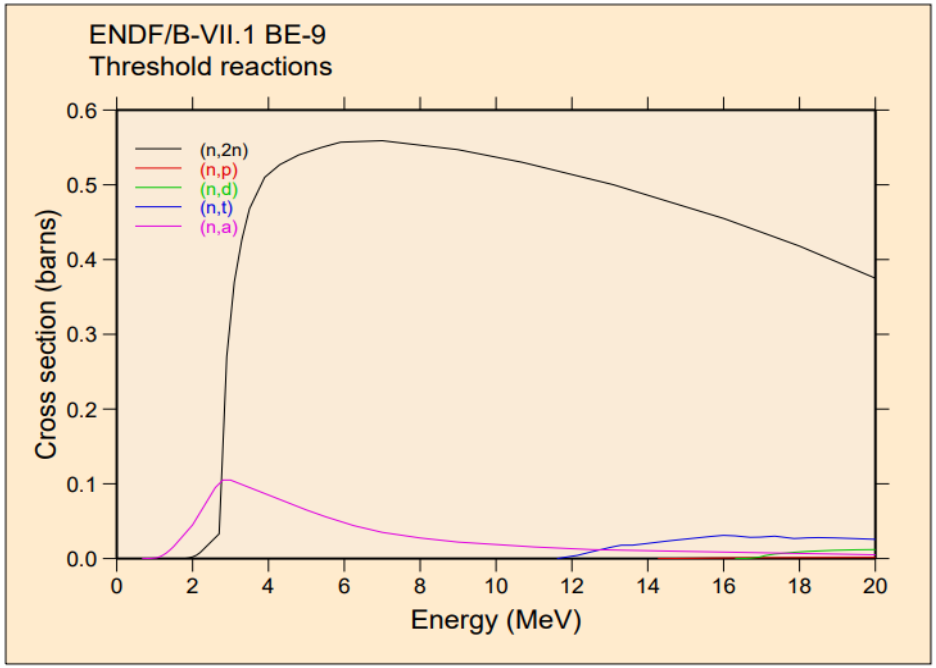


Proton elastic cross section

- High elastic cross section in low energy region results in high yield of low energy neutrons.
- Neutrons are produced through different reaction channels; also from recoiled protons, and (n,2n) channel

Experimental Benchmarking with 12 MeV Protons

DIFFERENCE IN DATA LIBRARY:

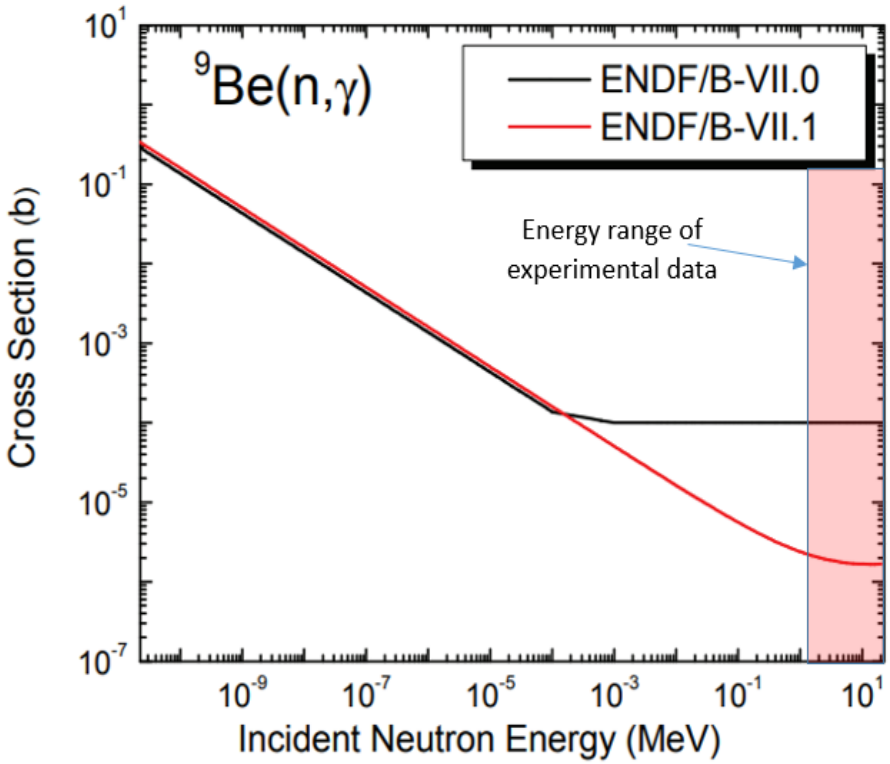


n-induced cross section

Rise in (n,2n) cross section above 2.5 MeV; (n,2n) > (p,n) cross section

Experimental Benchmarking with 12 MeV Protons

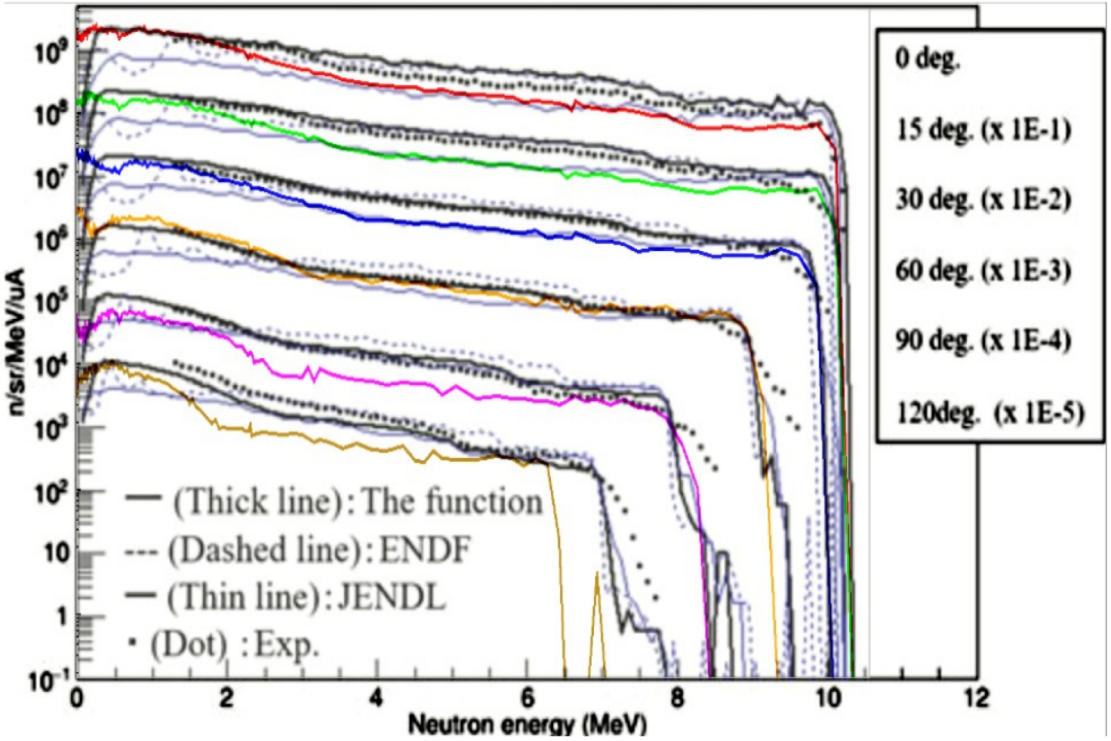
DIFFERENCE IN DATA LIBRARY:



- For n-incuded reactions with ^{9}Be FLUKA uses ENDF/B–VII.0 for n < 20MeV
- Difference in neutron capture cross-section could also be a possible reason for slightly low neutron yield with FLUKA.
- FLUKA B-VII.0: High neutron capture cross-section, low neutron yield

Experimental Benchmarking with 12 MeV Protons

EXPERIMENTAL COMPARISON WITH FLUKA, RANS FUNCTION AND DATA LIBRARIES



Function was developed at RANS, RIKEN

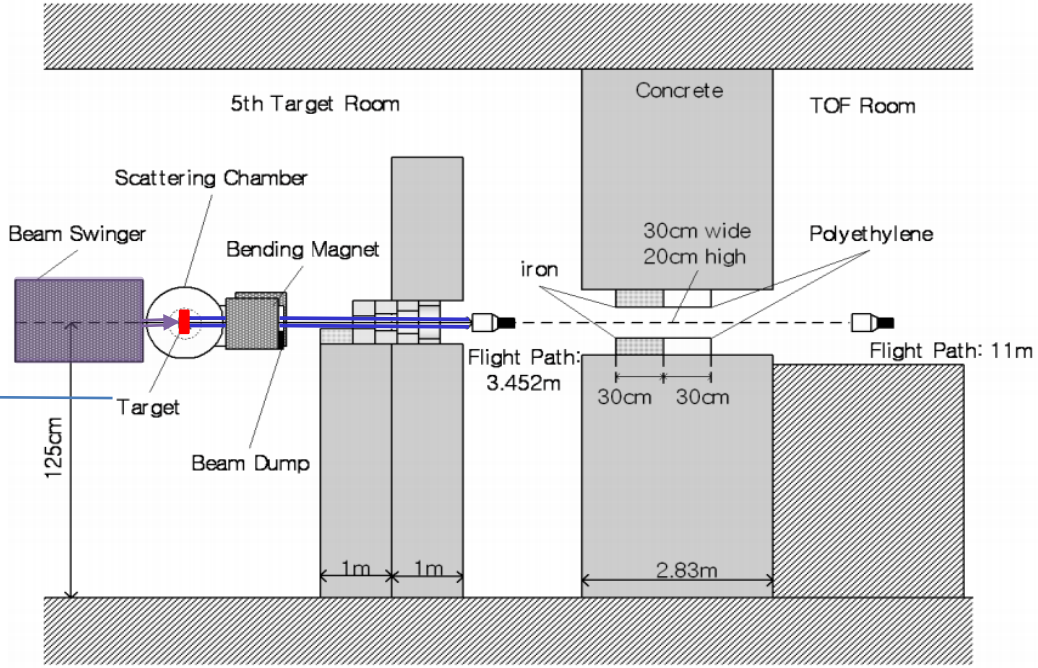
Analysis:

- RANS (RIKEN) function fits well with slight overestimation of 14%.
- ENDF and JENDL underestimated up to 35%.
- Similarly, FLUKA also underestimates within same deviation range at lower angles
- FLUKA gives more deviations at higher angles.

Experiment with 11 MeV Proton Beam

CYRIC FACILITY, TOHOKU UNIVERSITY, JAPAN

^{9}Be 2mm thick x
30mm x 30mm



Angular measurements:
0◦, 15◦, 30◦, 45◦, 60◦, 90◦ and 110◦

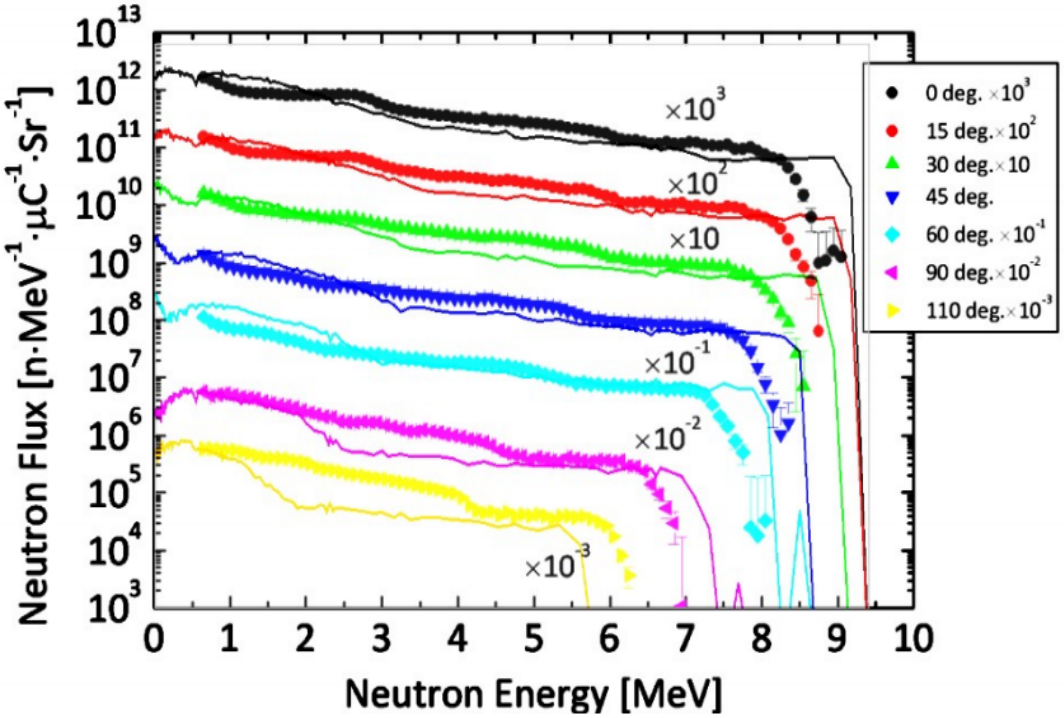
<10% Statistical Uncertainties
<13% Systematic Uncertainties
SCINFUL-R MC code for Detector η

Benchmark Experiment:
So Kamada, et. al.; “Measurement of Energy-angular Neutron Distribution for 7Li, 9Be(p,xn) Reaction at EP = 70 MeV and 11 MeV”, Journal of the Korean Physical Society, 2011.

Experimental Benchmarking with 12 MeV Protons

CYRIC FACILITY, TOHOKU UNIVERSITY, JAPAN

EXPERIMENT-TO-FLUKA



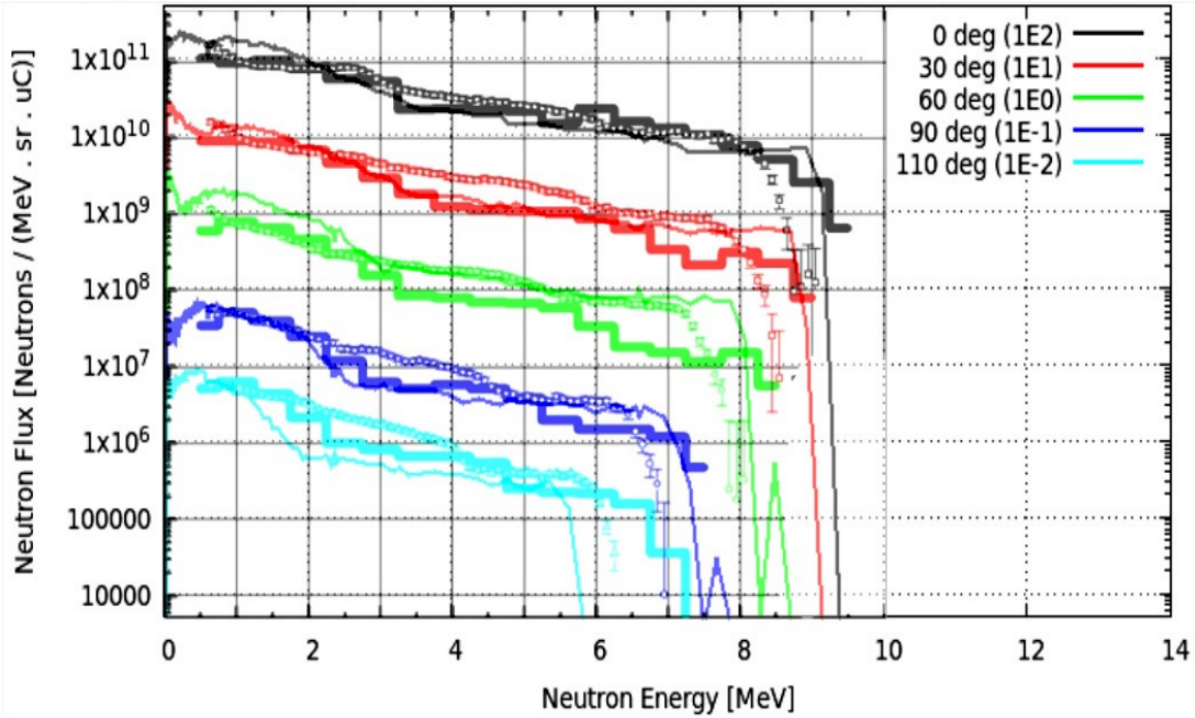
ANALYSIS:

- FLUKA shows a good agreement.
- Deviations observed in high energy due to experimental uncertainties (as FLUKA had good agreement in 12MeV BM)
- Slight deviation in yield:
  - -Effect of air
  - -Data library

Experimental Benchmarking with 12 MeV Protons

CYRIC FACILITY, TOHOKU UNIVERSITY, JAPAN

EXPERIMENTAL COMPARISON WITH FLUKA AND MCNPX



Analysis:

- FLUKA is closer to experiment than MCNP at lower angles.
- Deviations at higher angles could be a combined effect of:
  - high statistical errors (simul.)
  - secondary proton interaction with air

Conclusion

1. Discrepancies were found in:
   - Physical Models and
   - Data Libraries when employed in different simulation codes

2. Experimental benchmarking determined the accuracies of the numerical methods and suggested:
   - the appropriate choice of MC code and
   - the **appropriate selection of the Data library and physical models**

Conclusion

- in 62 MeV experiment:
  - GEANT4 models had high deviations
  - MCNP was close to experiment (Data libraries)
  - FLUKA was the most accurate (PEANUT model fits precisely well for n > 20MeV)

- in 11/12 MeV experiments:
  - MCNP and PHITS produce close results with experiments.
  - FLUKA also agrees with experiments within the same deviation range.
  - RANS function produces closest results to experiment.