GEANT4 simulation of the n_TOF spallation target: Neutron production and transport

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Introduction

- GETERUS group, University of Seville:

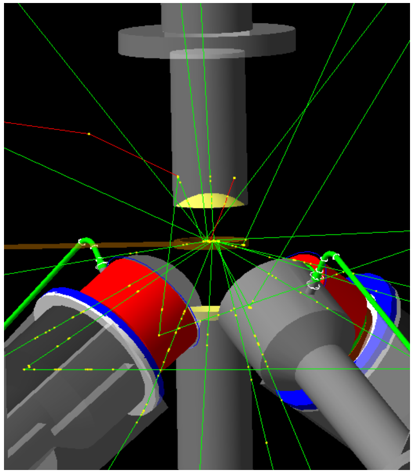
- Members of the n_TOF collaboration (CERN)
  - Validate Geant4 for neutrons with n_TOF Flux

- Members of GEANT4 hadronic group
  - Benchmark for production of neutrons beyond 3GeV

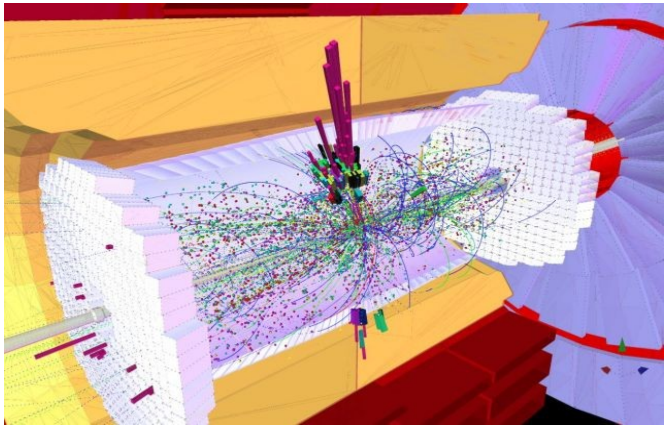
- Involved with CNA (National Accelerators Center)
  - Starting neutron research line in the 3MV TANDEM

Why GEANT4?

- Usually MCNPX/FLUKA to simulate neutron transport
- Explore the capabilities of GEANT4 for neutron production
  - Versatile code with multiple applications
  - Large community of users and extensive support
  - Improved treatment of neutron transport (HP-package)



- GEANT4
  - Developed at CERN: International GEANT4 collaboration
  - Object oriented (C++), modular architecture
  - Allows Customization and extension by the user
  - Extensive documentation and installation guide

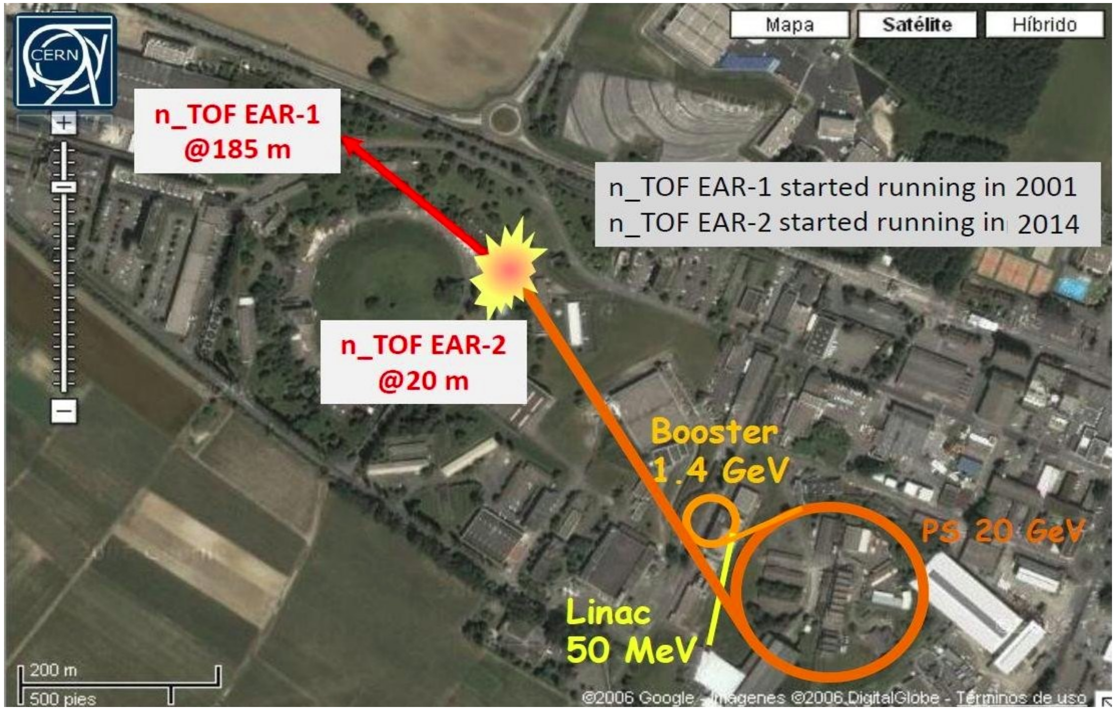


http://geant4.cern.ch

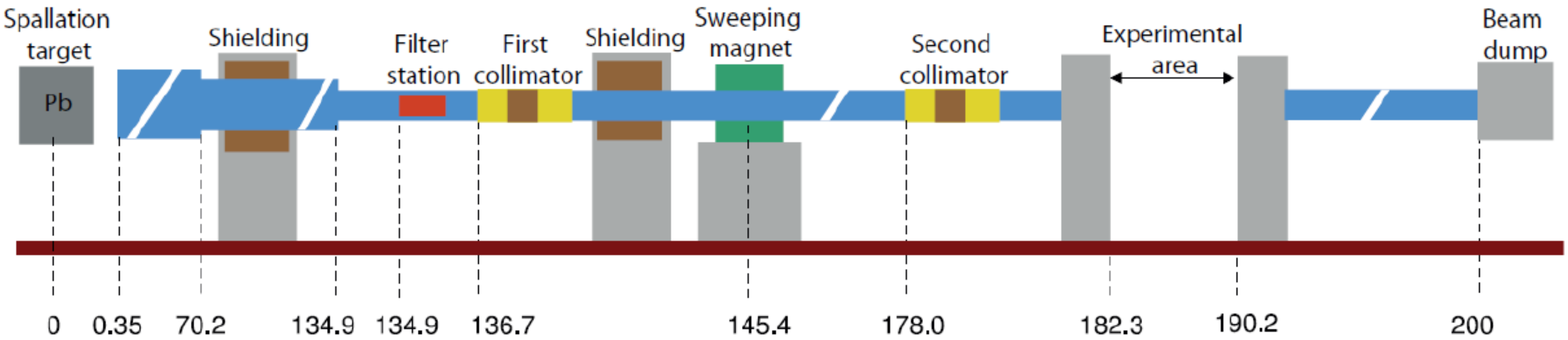
The n_TOF facility at CERN

- High resolution neutron cross section measurements
  - Time of Flight (ToF) Technique
  - **ΔE/E(1keV) :** EAR1 (185m) → $\sim 3\cdot10^{-4}$, EAR2(19m) → $\sim 8\cdot10^{-3}$
  - **Flux** (n/cm^2/pulse)**: EAR1:** $\sim 4\cdot10^{5}$, **EAR2:** $\sim 7.5\cdot10^{6}$
  - Neutron spectrum from **thermal to few GeV** (highest among similar facilities)

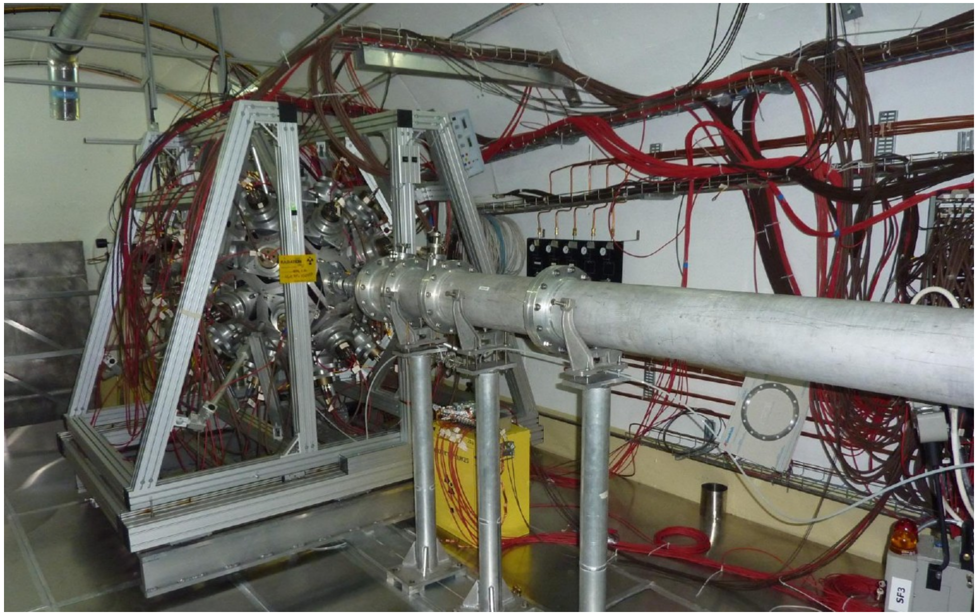
- Applications:
  - Nuclear Technologies
    - ADS, Fast reactors
  - Astrophysics
    - s-process (AGB stars)
  - Basic Nuclear Physics

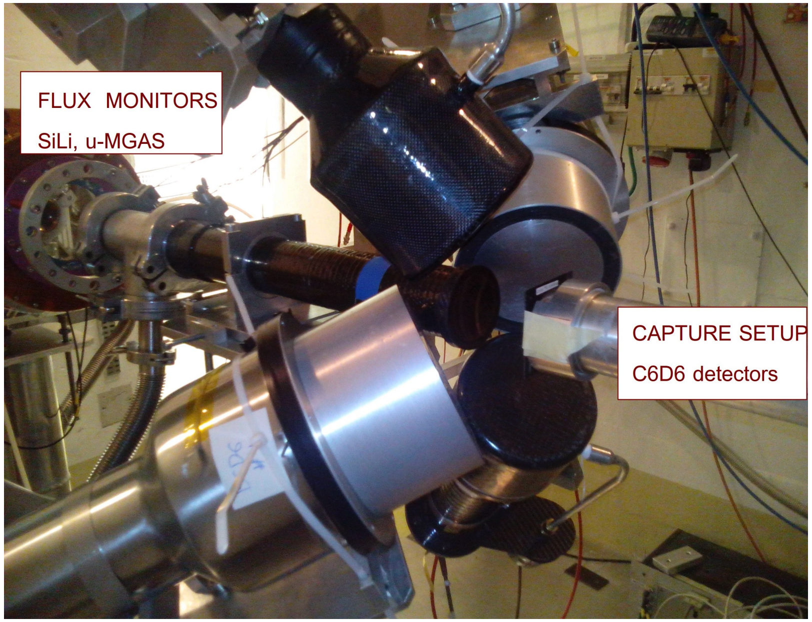


n_TOF EAR1



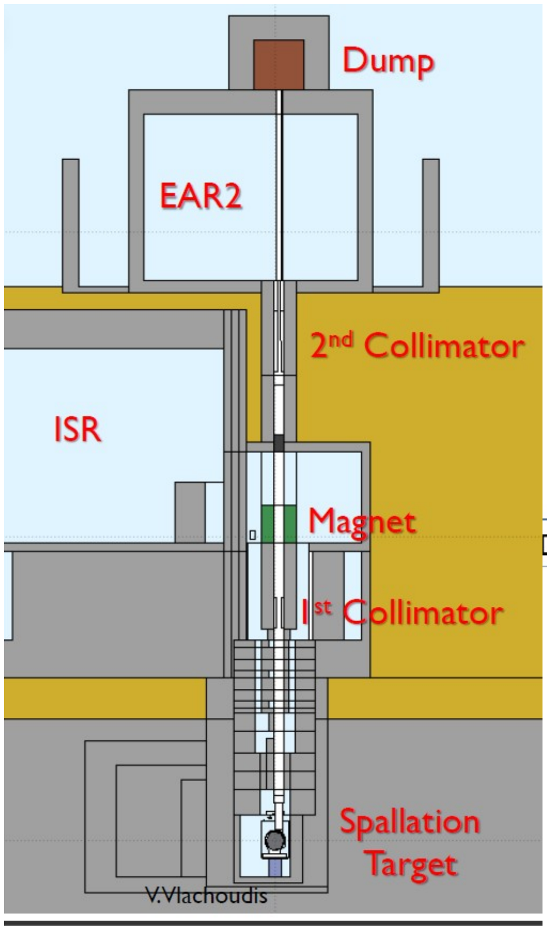
- @ **185m** from spallation target in **forward direction** (10 deg w.r.t proton beam)

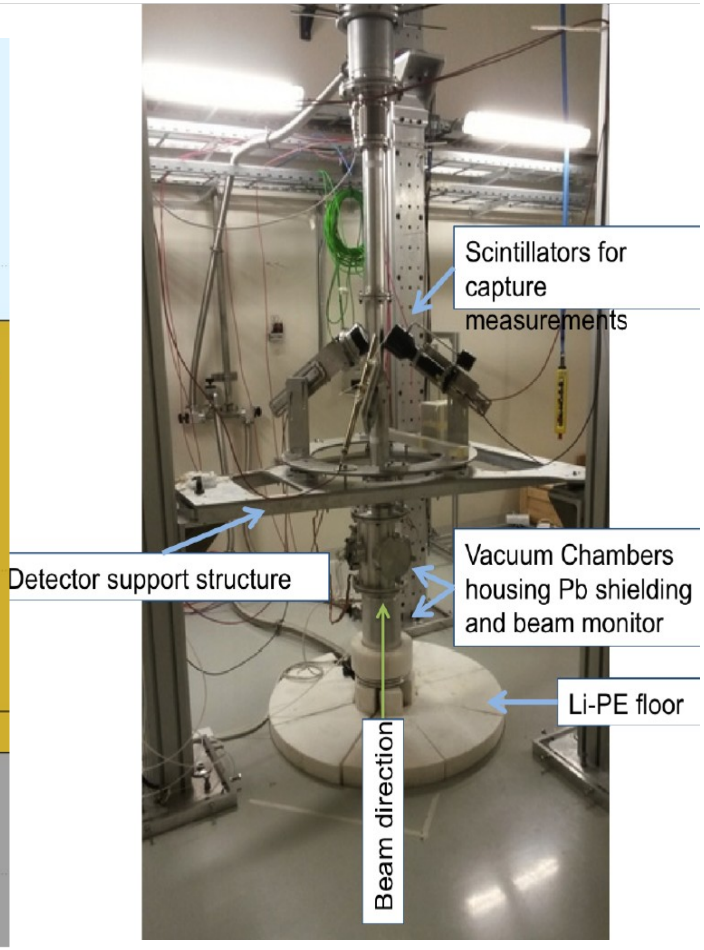




n_TOF EAR2

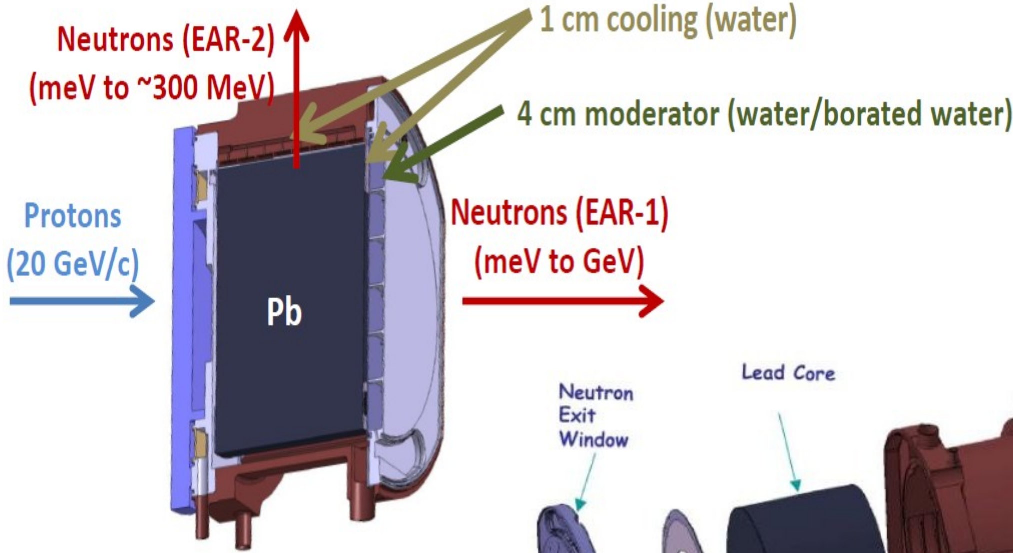
- @ **20m** from spallation target in ***vertical* direction** (90 deg w.r.t proton beam)



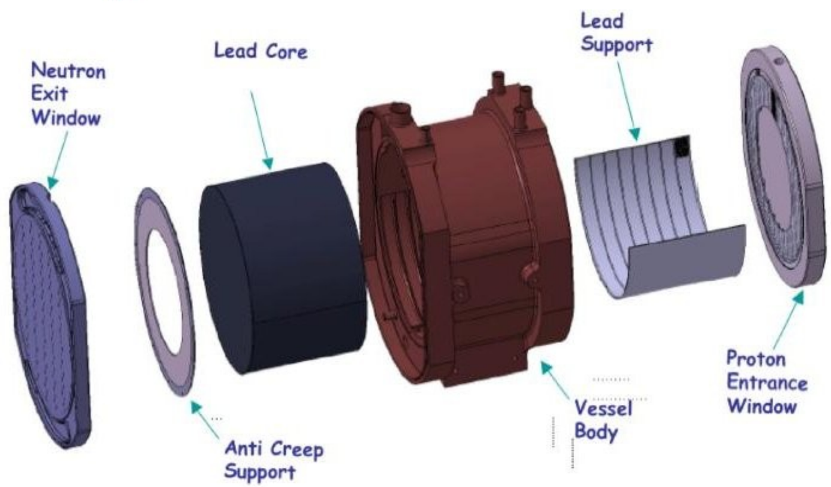


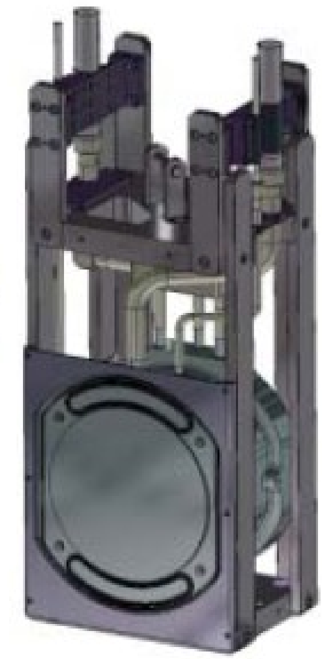
- Neutron Flux EAR1 x ~25
- Expected factor 10 relative background reduction
- Small masses (<mg)
- Highly radioactive samples
- Open to Radiation Damage studies

n_TOF Neutron Source: Pb Spallation Target

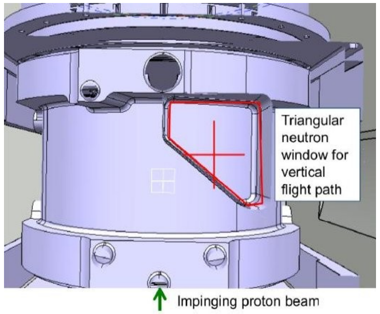


- Water-cooled lead target
- 60cmΦ, 40 cm length
- 400 neutrons/proton (MeV-GeV)





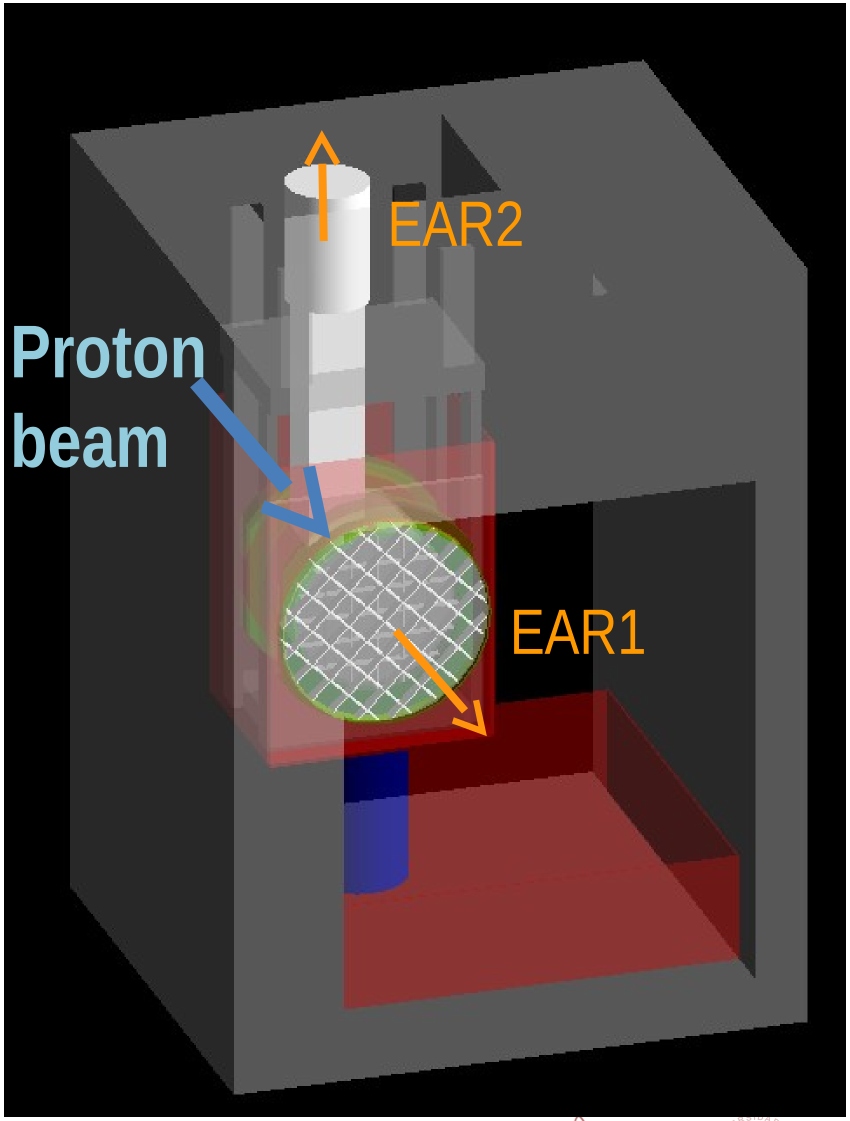
- **EAR1**: 1cm Water+4.35cm Borated Water (1.28% of H_3BO_3) before entering beam-line
- **EAR2**: "triangular" shape entrance to beam line. NO Boron, just water.



Aluminum vessel and support structures from the CAD drawings

nTOF Geant 4

Simulation of n_TOF target

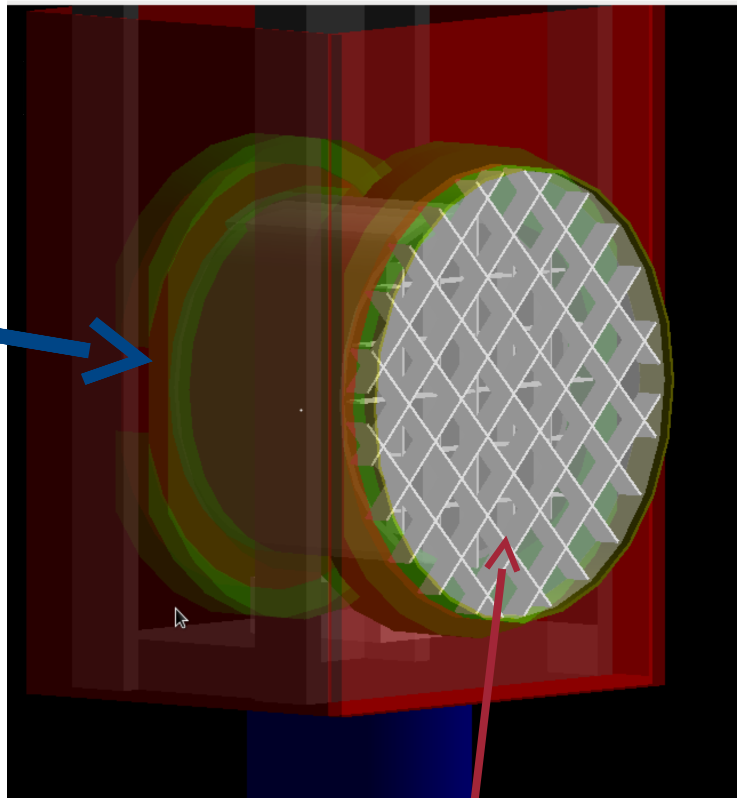


- 10^7 20 GeV/c protons, with an incidence angle of 10 deg
- Gaussian profile proton beam (FWHM=3.53cm)
- Precise implementation of the cooling and moderation layers
- All the components have been implemented following the technical drawings
- Special care in the composition of the Lead target and the surrounding materials

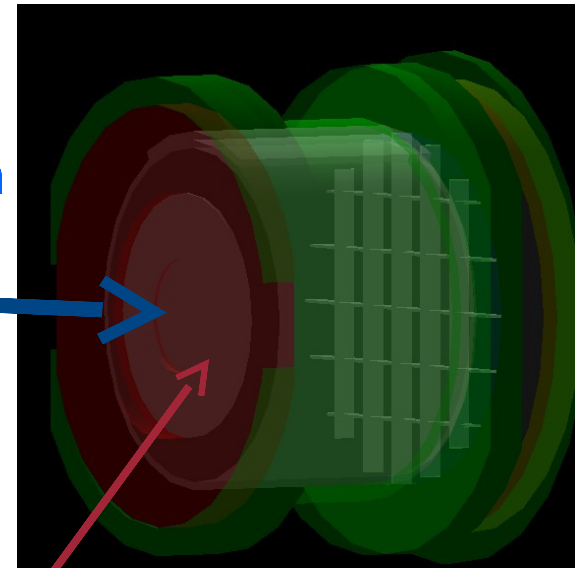
Detailed Geometry Model:

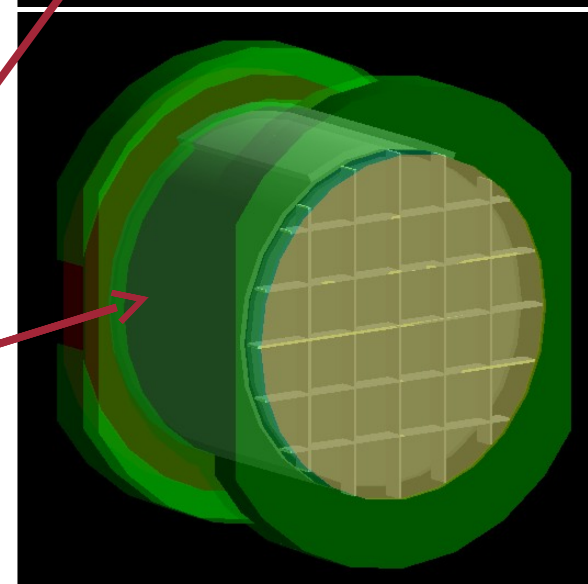
Lead Target with surrounding vessel and structural support (Al-alloys)

Proton Beam



Proton Beam



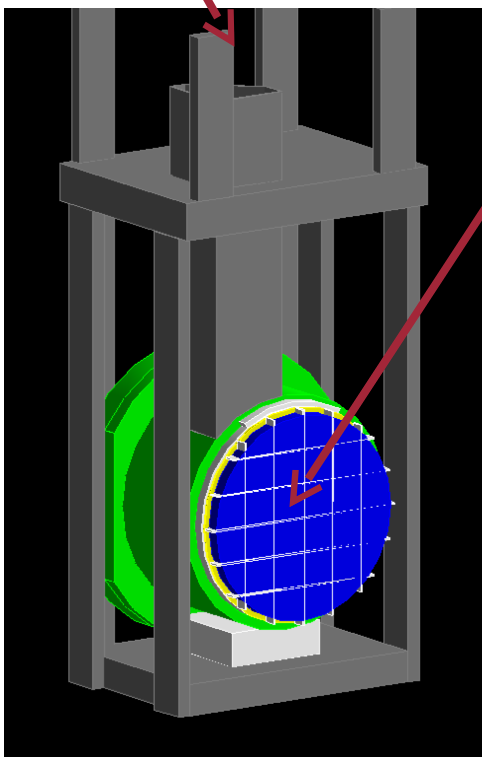


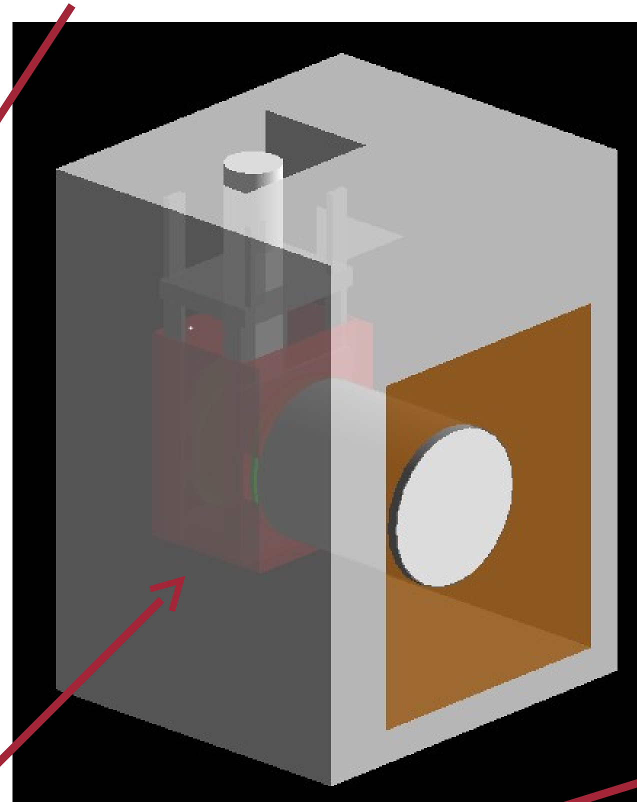
Detail on the proton entrance and neutron exit windows

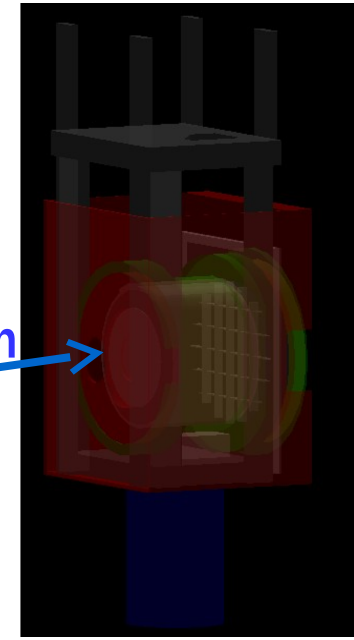
Grid beam line entrance turned 45º

Detailed Geometry Model

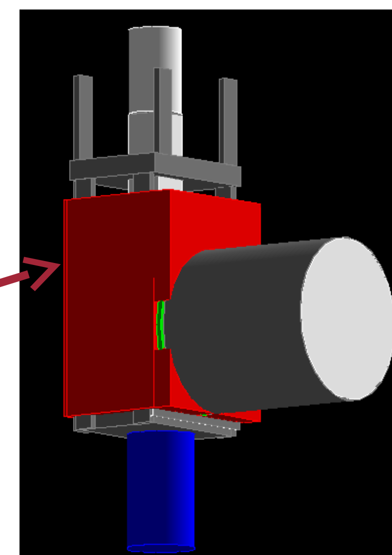
Exit toward EAR2 and Moderator layer with aluminum Support grid







Proton beam



Target support structures, concrete container and beam lines

Notes about Methodology

- **GEANT4** (v. 10.0.3 used) provides a **unique variety of Physics Models**

- **All must be considered** to target the neutron production with 20 GeV p for the 1st time:
  - Fritiof (**FTF**) or Quark-Gluon-String model (**QGS**) **(T > ~10 GeV)**
  - Intranuclear cascade models: Bertini (**BERT**), Binary Cascade Exciton Model+Precompound (**BIC**) or INCL++ (Bertini above 3GeV) (**INCLXX**)
  - Neutron High Precision (**HP**) **below 20 MeV** with thermal scattering (**T**) **(T < 4 eV)** using evaluated data libraries(ENDF VII.0) available at IAEA web site (*).

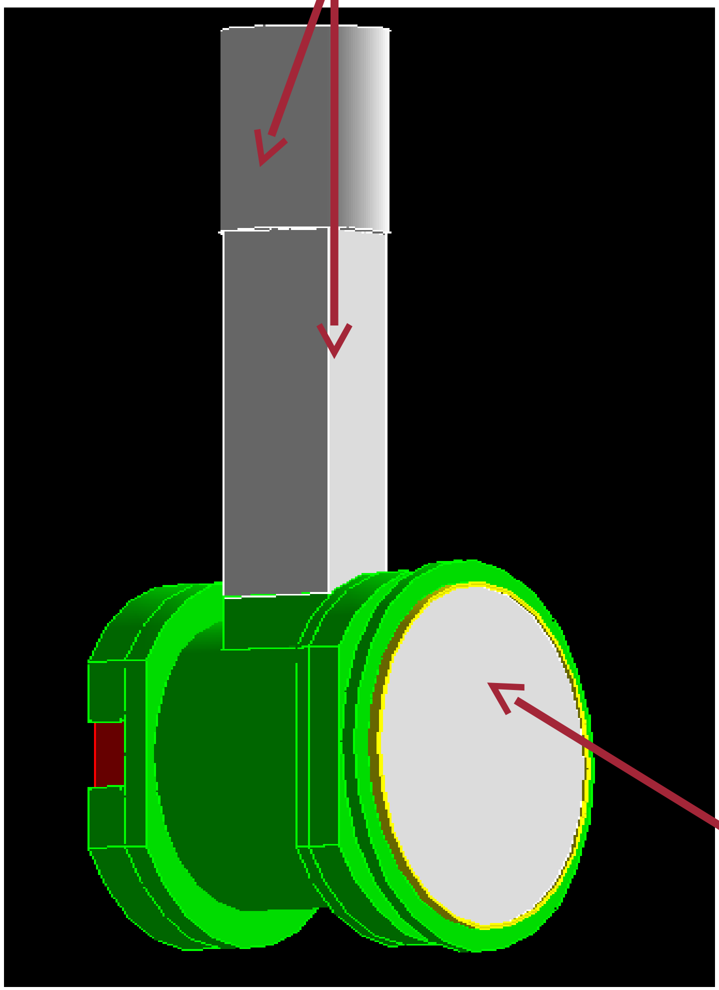
- In order to **validate our results**, comparison with **experimental data** is needed. Experimental data (**) available just far from the target.

- **Optical transport to experimental areas** with a geometric transport code (***)

(*) E. Mendoza et al., IEEE-TNS 61: 2357 (2014)
(**) C. Guerrero et al., EPJ A49: 27 (2013)
(***)V. Vlachoudis

Simulation Output: Scorers @ target exit

EAR2 : 3D scorer, beam line shape



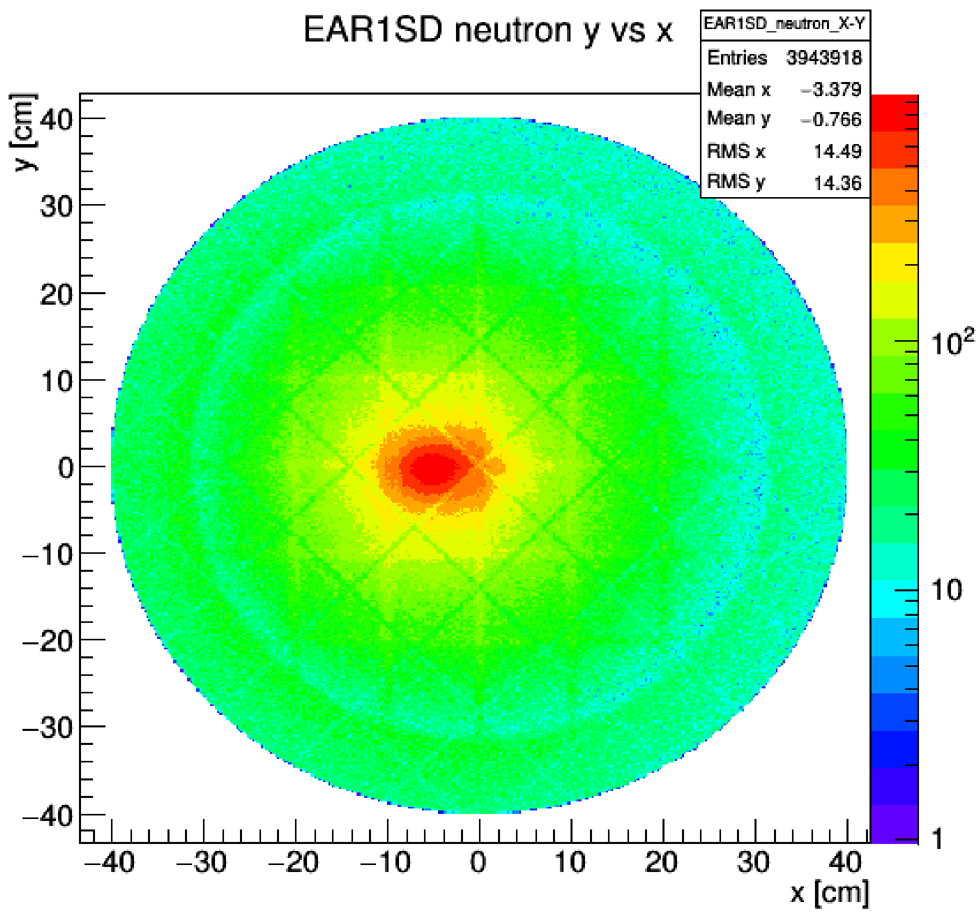
- Scoring surfaces defined as in previous simulations in n_TOF (FLUKA)
- Why? Use previous transport codes to get results at EAR1 and EAR2 from the GEANT4 simulation @ target
- Angular acceptance limited to 4 deg ↔ isotropic spectra within this solid angle
- **Collected information at scorer**: Position, momentum, energy, type of particle and time

EAR1: 2D scorer @ entrance of beam line

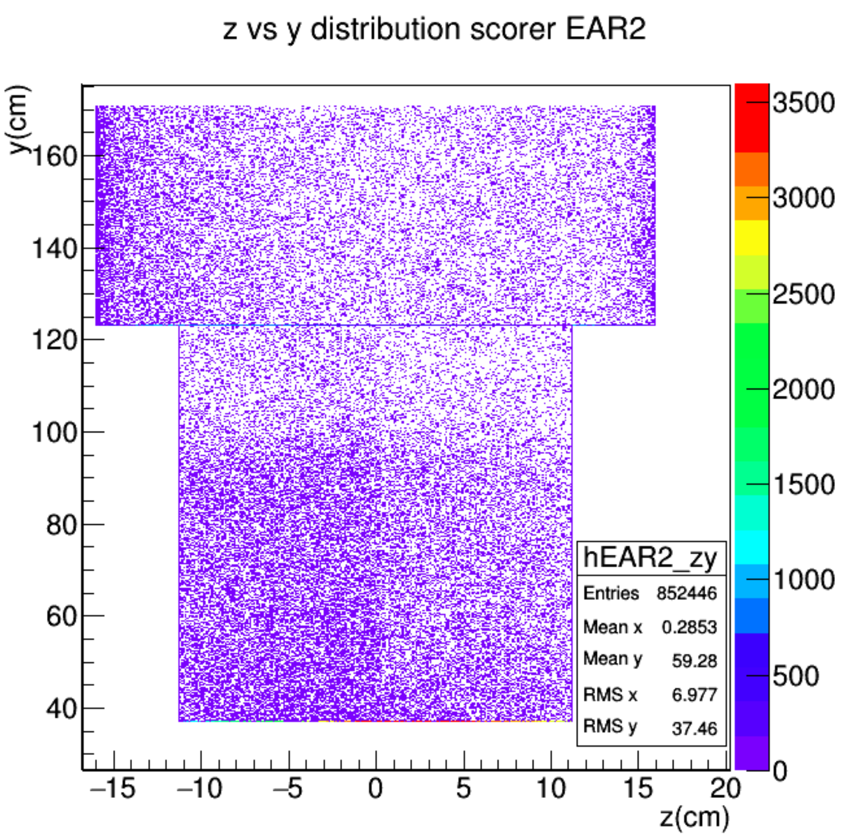
Results at the scorers

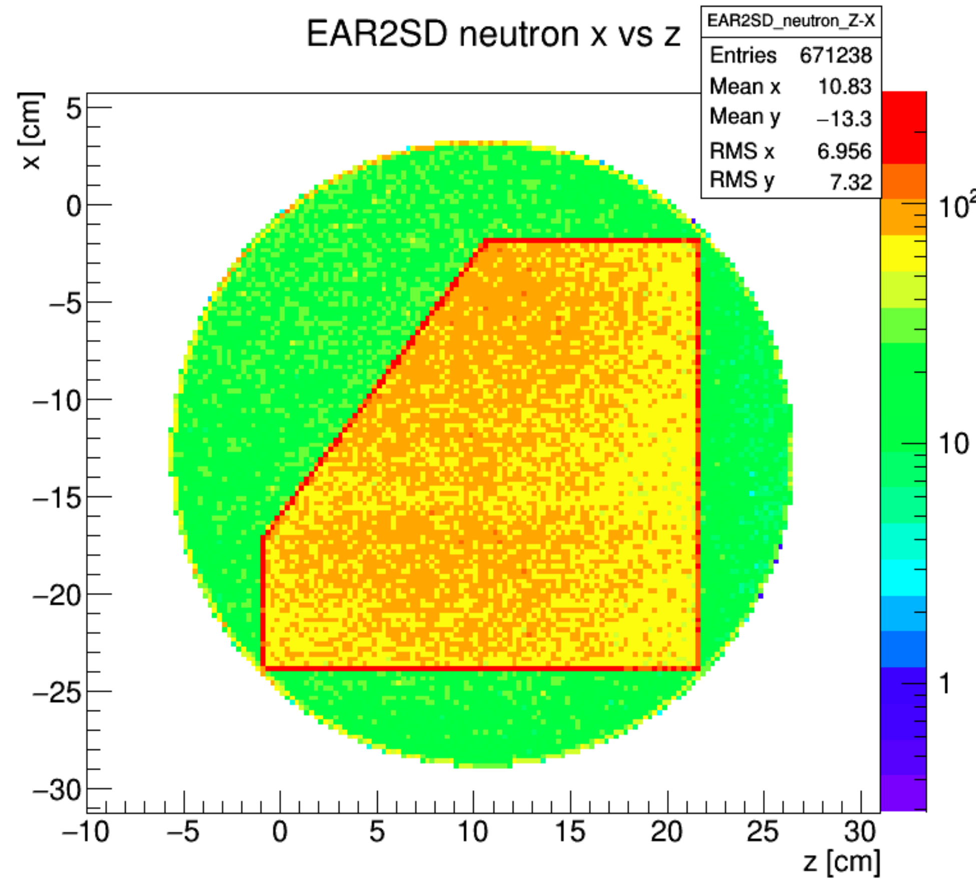
EAR1 Scorer: Spatial Distribution

- Beam off-centered due to 10º angle of incidence
- Border of the Lead Target (30cm radius)
- Al grid in borated water layer: Lack of absorption → Enhanced production
- Shadow of the Al grid in entrance of beam line. Rotated 45º



EAR2 Scorer: Spatial distribution

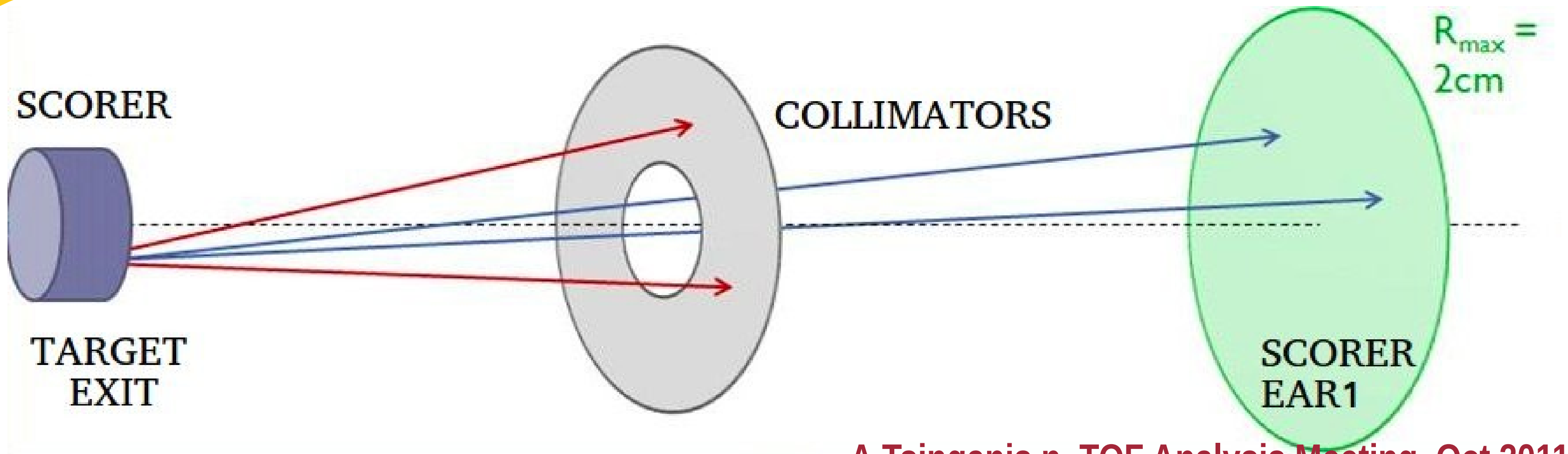




- Spatial distribution on the plane perpendicular to the beam pipe EAR2 shows the shadow of the entrance window
- Projections in the different axis show the structure of the 3D scorer

Transport to experimental areas

Transport Code



A.Tsinganis,n_TOF Analysis Meeting. Oct 2011

- **Real simulation** to the EAR's : **Unaffordable CPU Time**
- ~1300 instances are created for each scored neutron (with $\theta \leq 2^o$) and sent scanning a 2cm radius scorer in EAR1 (185m) or EAR2 (19m)
- Input with the position and dimensions of the collimators in both beam lines
- **Simplified transport**: If a neutron hits a collimator is discarded

Goals: Relevant Results

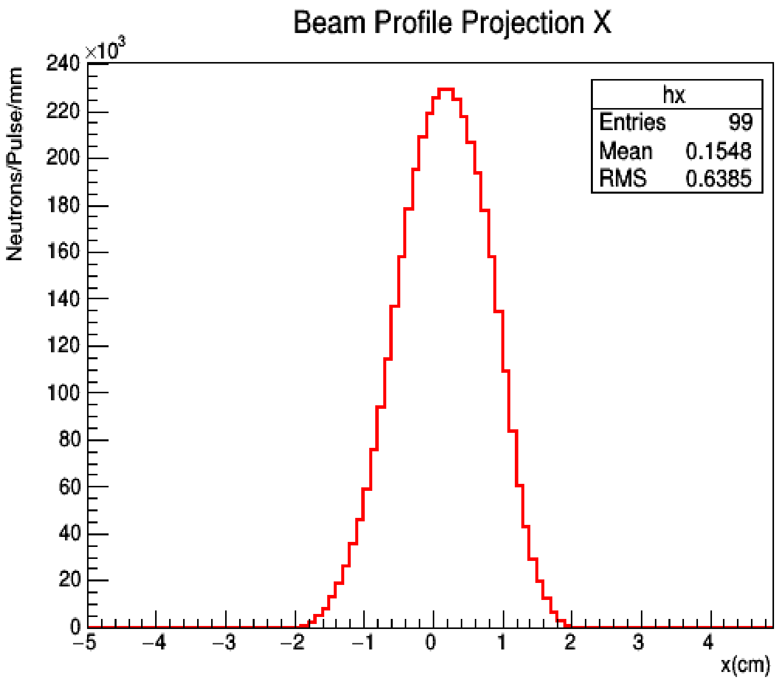
- As a **TOF facility** our goal is to obtain the following results:

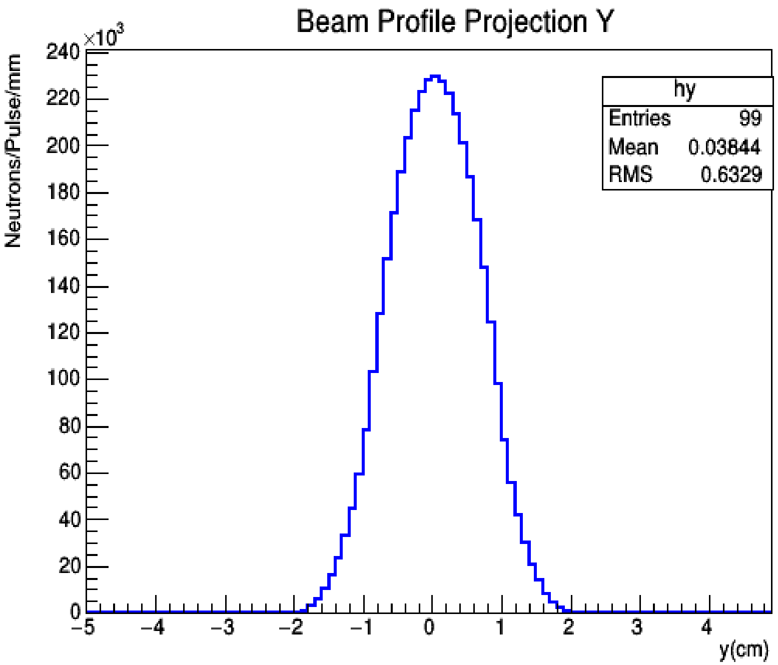
- Energy distribution (Flux) of neutrons arriving to Experimental Areas :
  - **CAN be measured** with FLUX Monitors
  - Used for validation of our simulations

- Relation between Energy and Time of Flight(determines the energy), called **Resolution Function:**
  - **CAN NOT be measured** → Simulations Needed
  - **Intrinsic of the typical moderation time** of neutrons in the target assembly
  - Needed to analyze the experimental resonances

Results @ EAR1

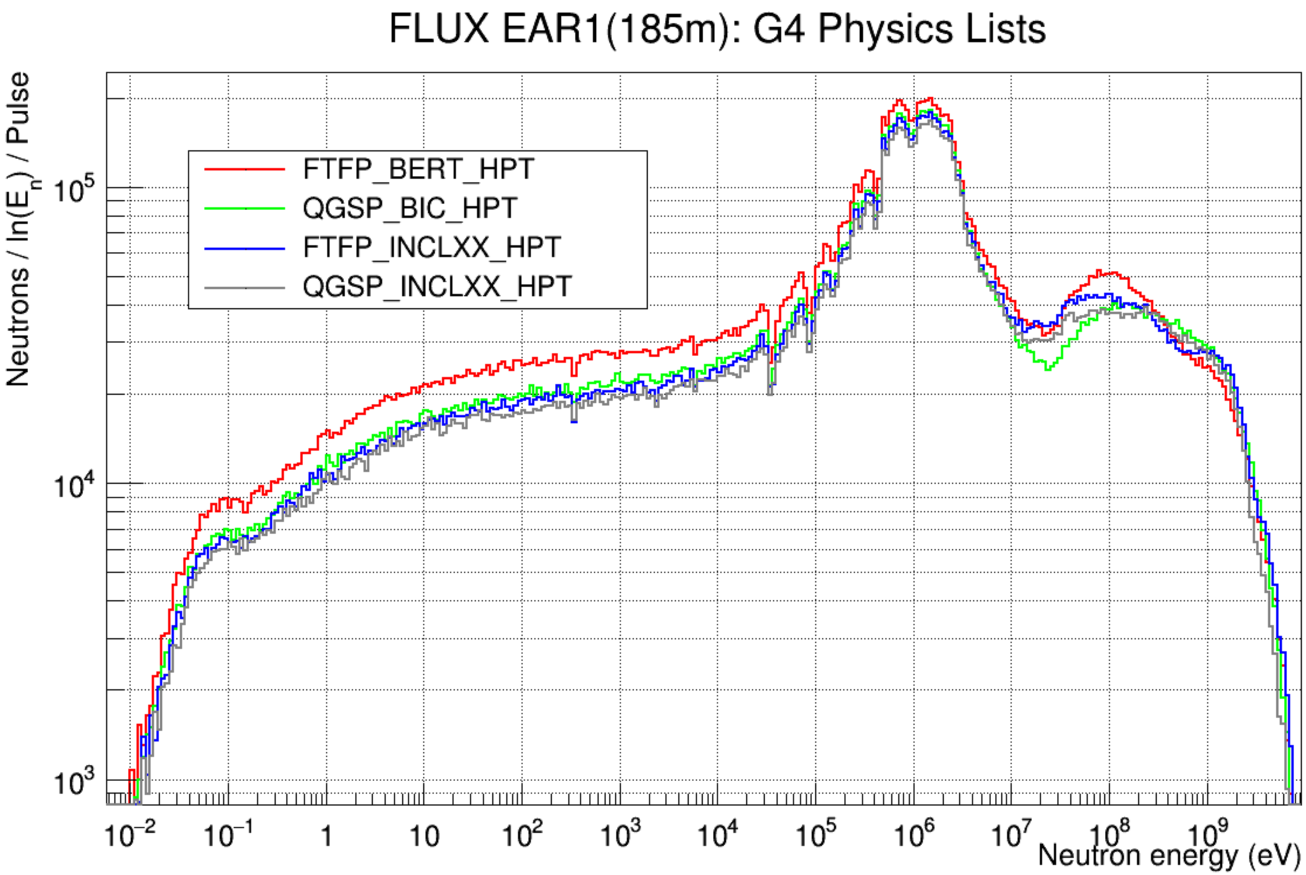
Beam Profile at EAR1





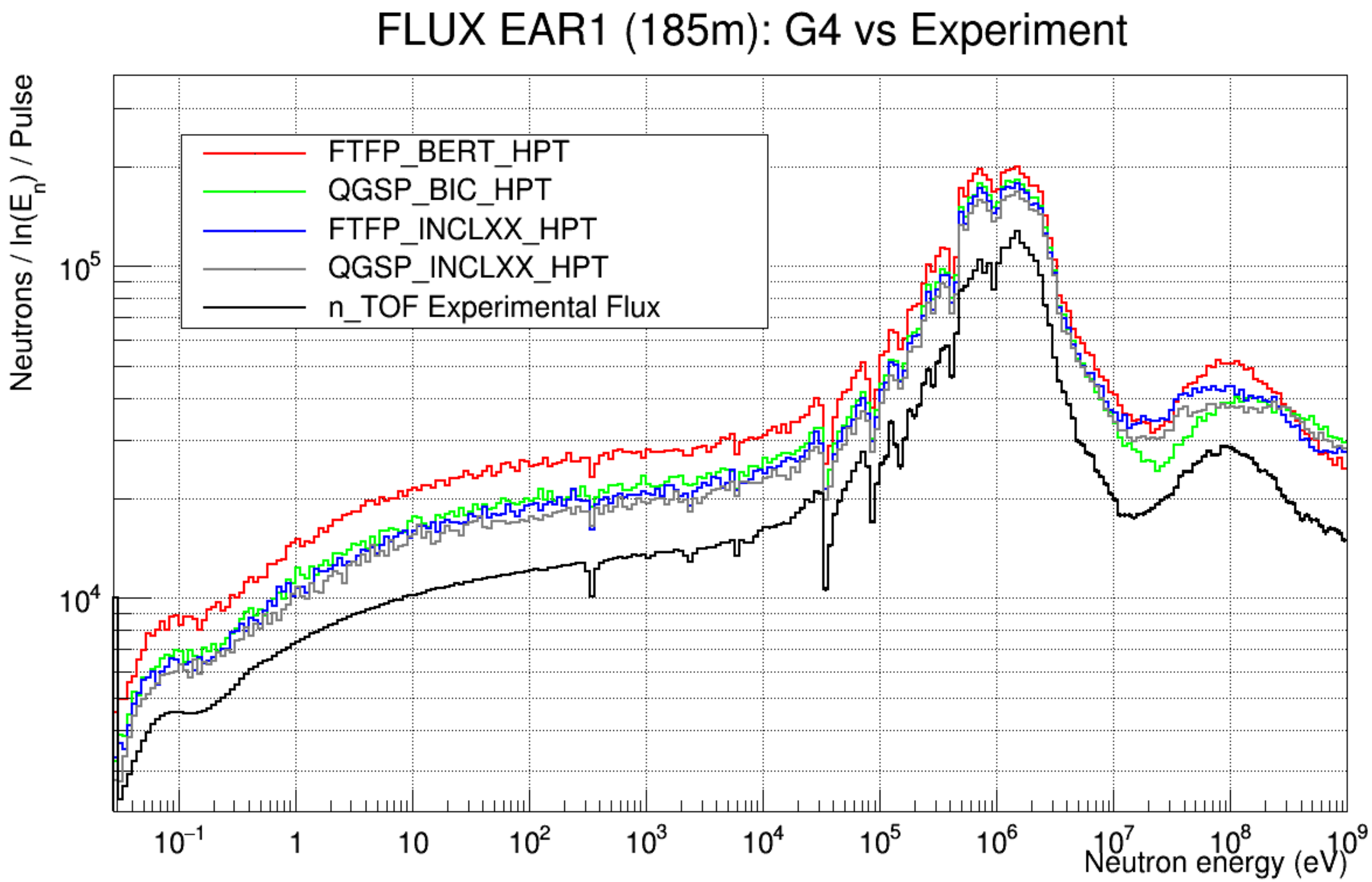
- R=2cm (= Radius scorer) and symmetric (aligned collimation system)
- Off-centered: 0.15cm in X axis, and almost centered in vertical axis
- ~Gaussian Profile : FWHM=1.49-1.50mm

Flux at EAR1: G4 Physics Lists



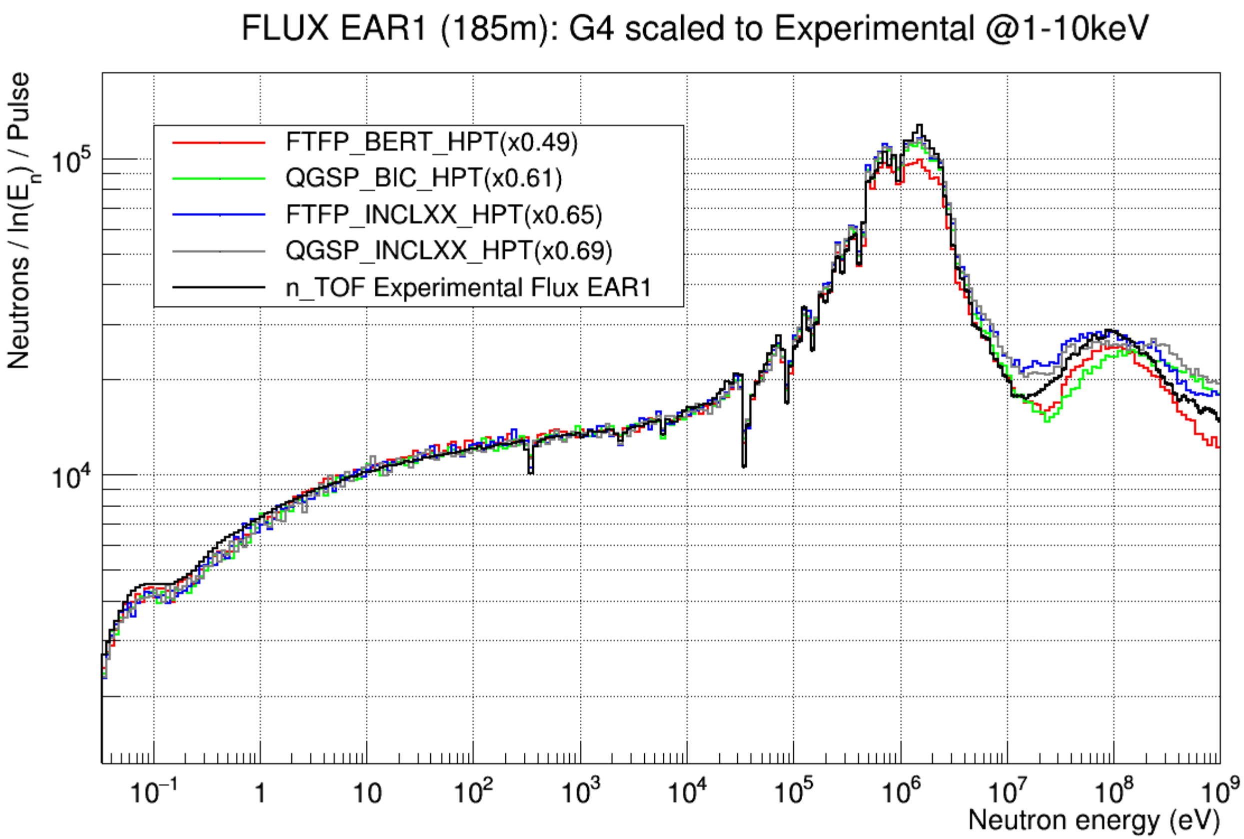
- Deviations in the integral flux of one the G4 Physics Lists, FTFP_BERT
- The other Physics List agree with each other within a few percent.
- Main differences in shape in the region above 20MeV: No role of neutron HP

Flux at EAR1:G4 vs. Experimental results



- All the Physics Lists give a global yield larger than the experiment
- The deviation ranges from 30% for QGSP_INCLXX to 50% for FTFP_BERT
- Transport code might not reflect all the flux loss → More relevant to focus on the **shape**

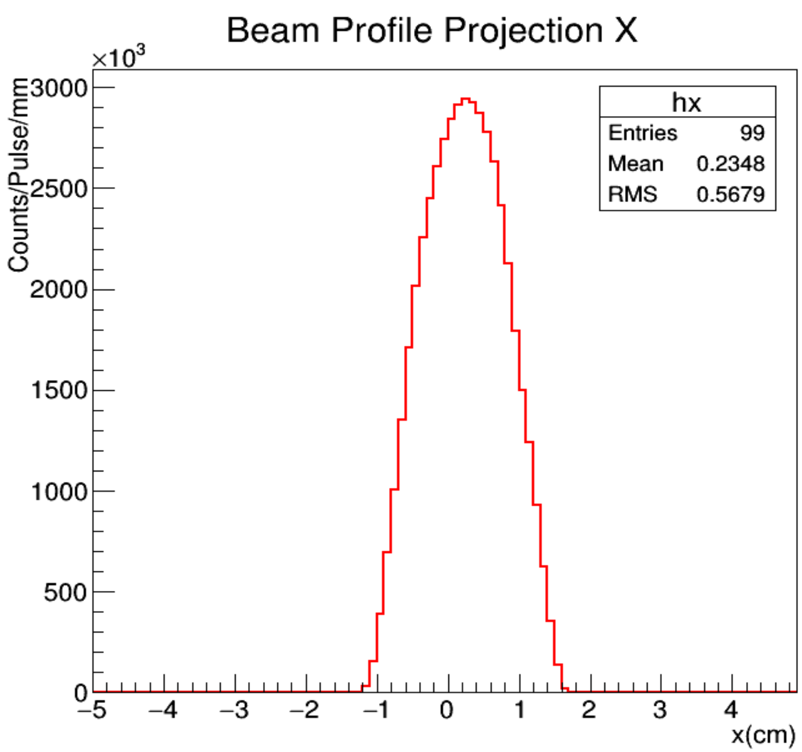
Flux at EAR1: G4 vs. Experimental results

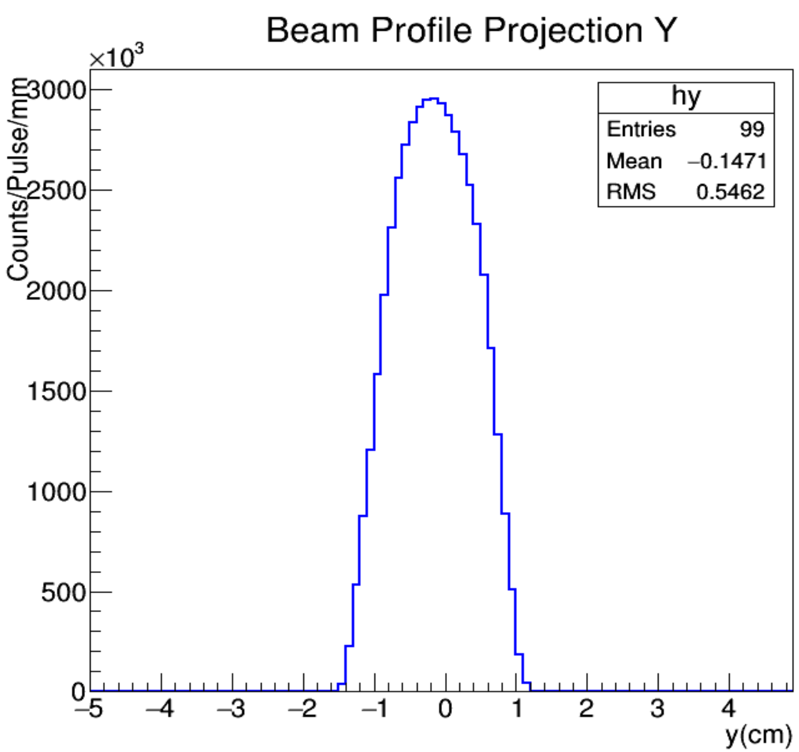


- Normalization to epithermal range (1-10keV) ↔ Most reliable range in the measured flux
- Shape better appreciated: Reproduction of dips in the flux from Al- alloys: Al, Mn, ...etc
- Good reproduction of the thermal/epithermal ratio
- Largest deviations above 10MeV, experimental flux within average simulated results

Results @ EAR2

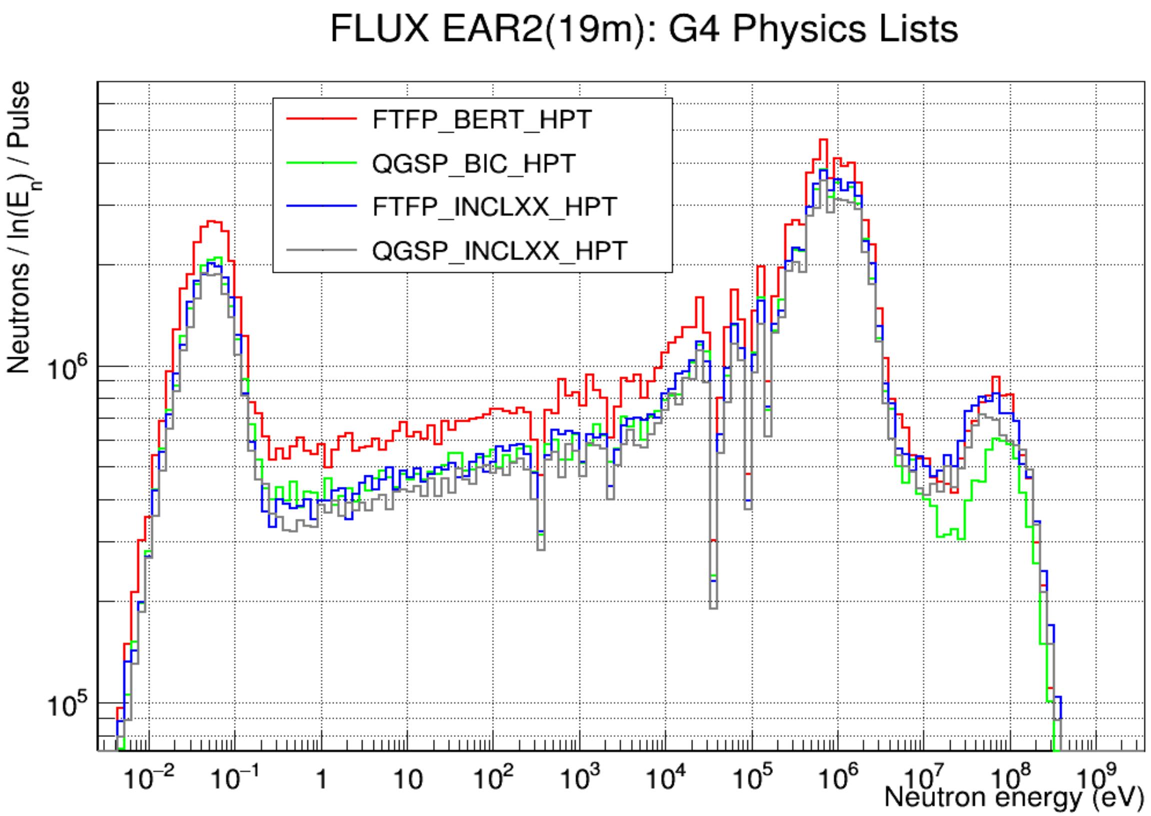
Beam Profile at EAR2





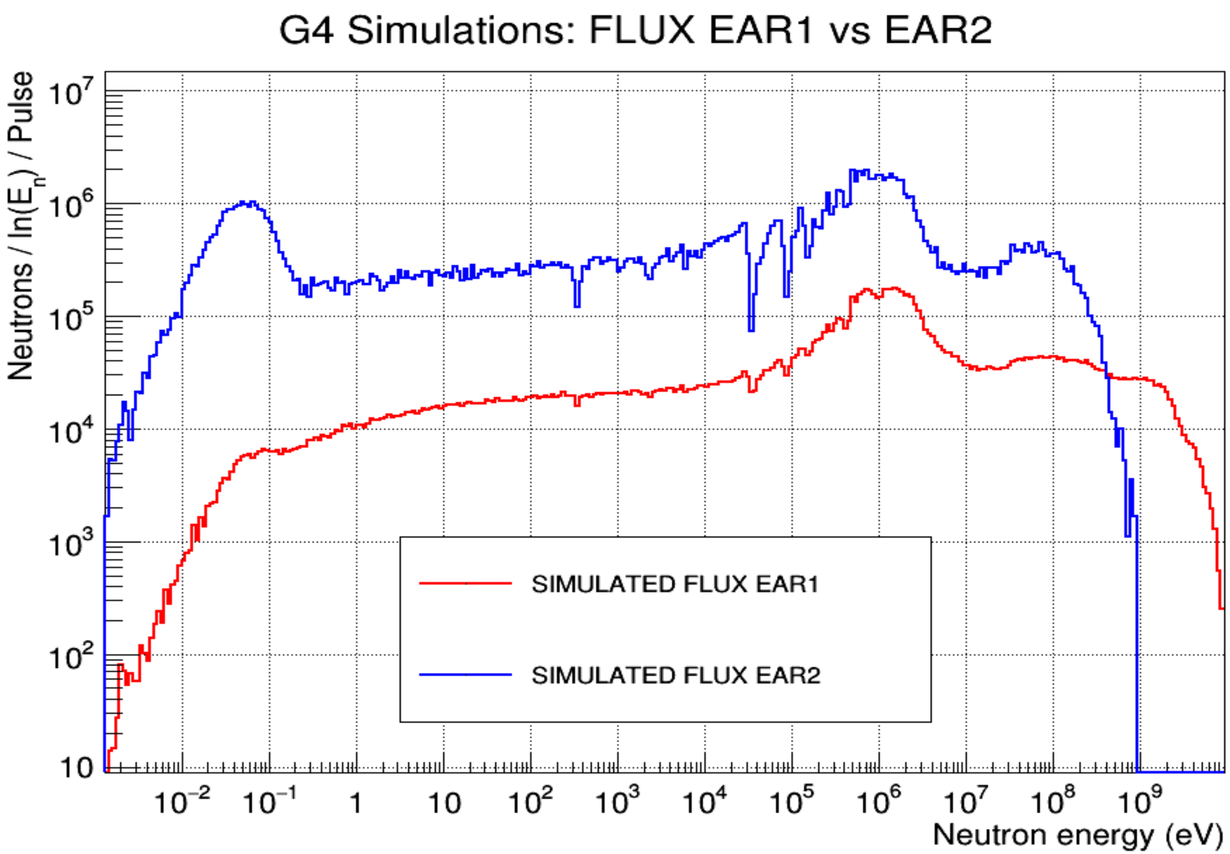
- Considered the real misalignment of the two first collimators
- Off-centered: 0.23cm in X axis, and -0.15cm in Y axis
- FWHM ~20mm

Flux at EAR2: G4 Physics Lists



- Flux up to 300MeV, in EAR1 → few GeV : Forward Component
- Smaller differences in the high energy region than in EAR1: Relevance of directionality
- No experimental flux in EAR2 officially released

EAR1 vs EAR2



- FTFP_INCLXX_HPT compared for both EAR's
- Simulated Flux EAR2 x~15-20 Flux EAR1
- Thermal Peak just in EAR2 due to the absence of B-10
- Larger dips in the keV-MeV region in EAR2's Flux
- Flux extends to 300-400 MeV in EAR2 and 5GeV in EAR1

Global Neutron Yield

NEUTRONS SCORED per 1000 protons				
	EAR1(2º)	EAR1(4º)	EAR2(2º)	EAR2(4º)
QGSP_BIC_HPT	98.9	394.0	15.9	67.1
FTFP_BERT_HPT	118.0	469.0	20.2	85.2
QGSP_INCLXX_HPT	91.5	364.8	14.8	62.2
FTFP_INCLXX_HPT	98.2	391.7	16.3	68.6

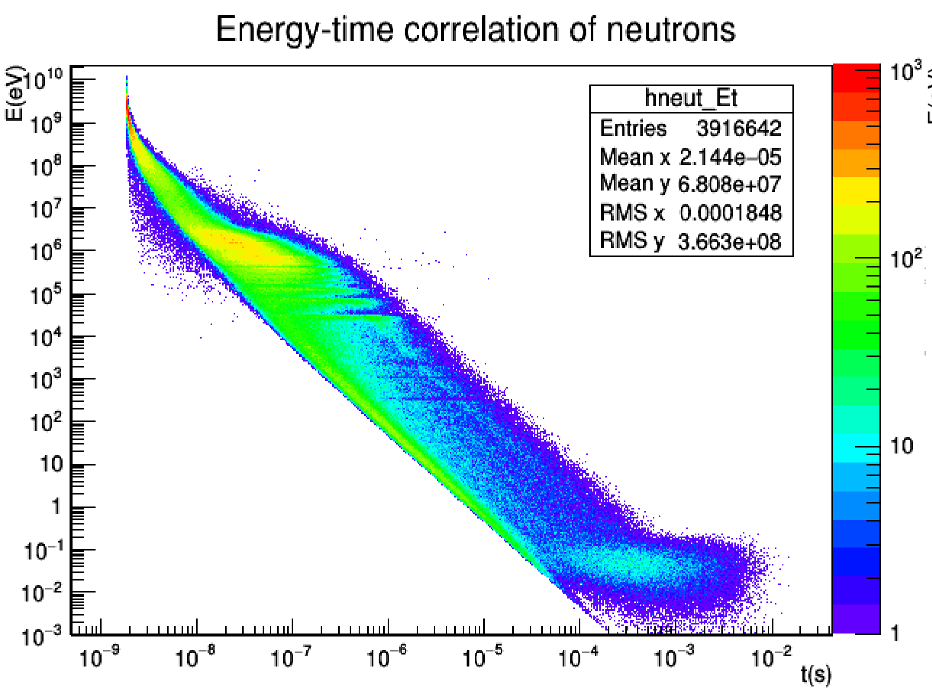
NEUTRON YIELD RATIOS				
FTFP_BERT/QGSP_BIC	1.19	1.19	1.27	1.27
QGSP_INCLXX/QGSP_BIC	0.92	0.93	0.93	0.93
FTFP_INCLXX/QGSP_BIC	0.99	0.99	1.02	1.02

- FTFP_BERT_HPT and QSGP_INCLXX_HPT provide the largest/smallest production (22-28% deviation)
- The yield ratios are independent of the angular acceptance (within 1%) for angles < 4º
- Besides FTFP_BERT_HPT, the other PL's give the same global production within 7%

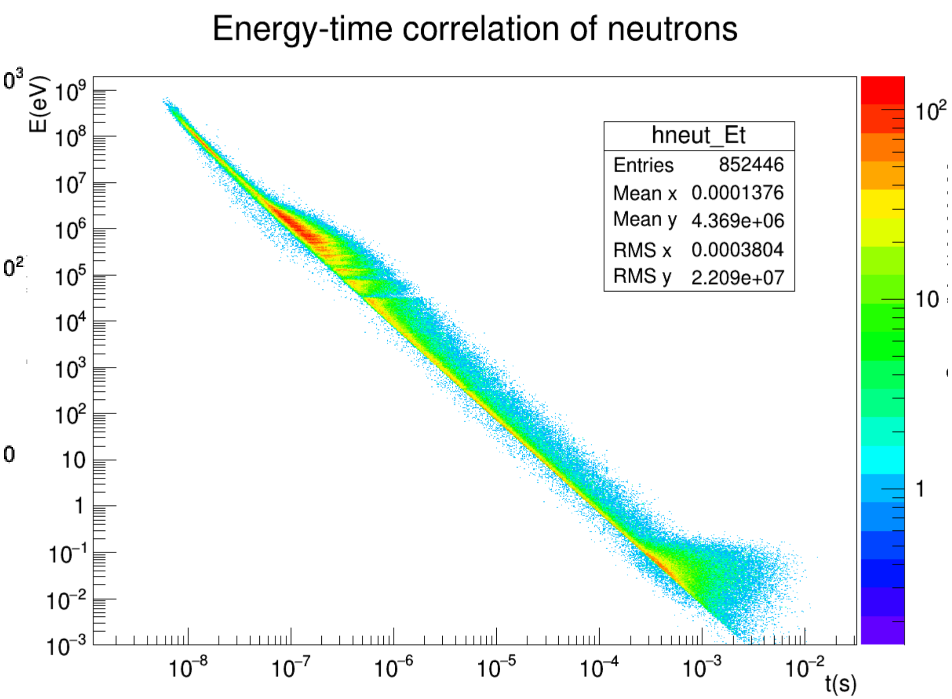
Resolution Function

- Energy- time relation of neutrons @ target exit (θ<4º)

EAR1



EAR2

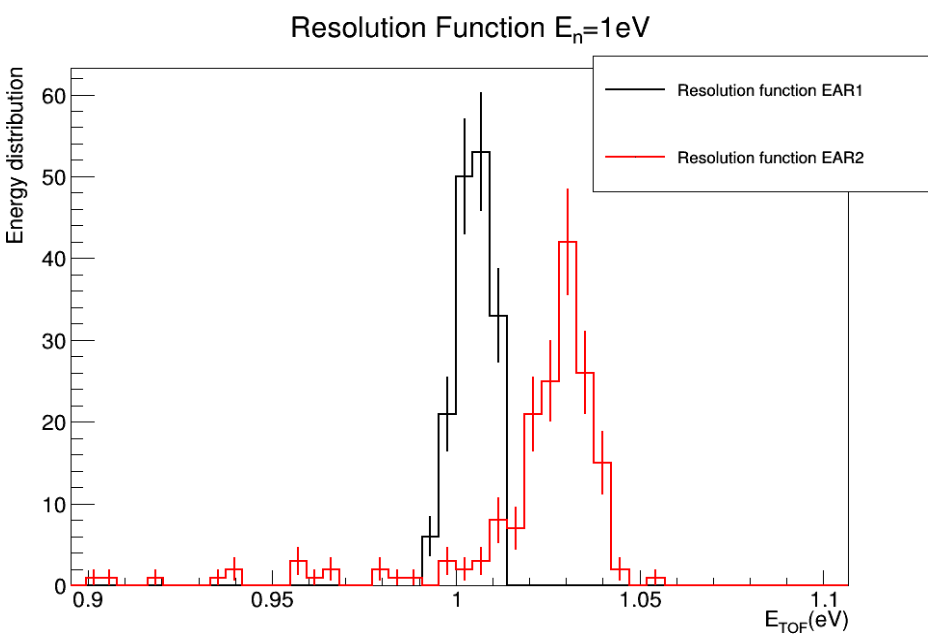


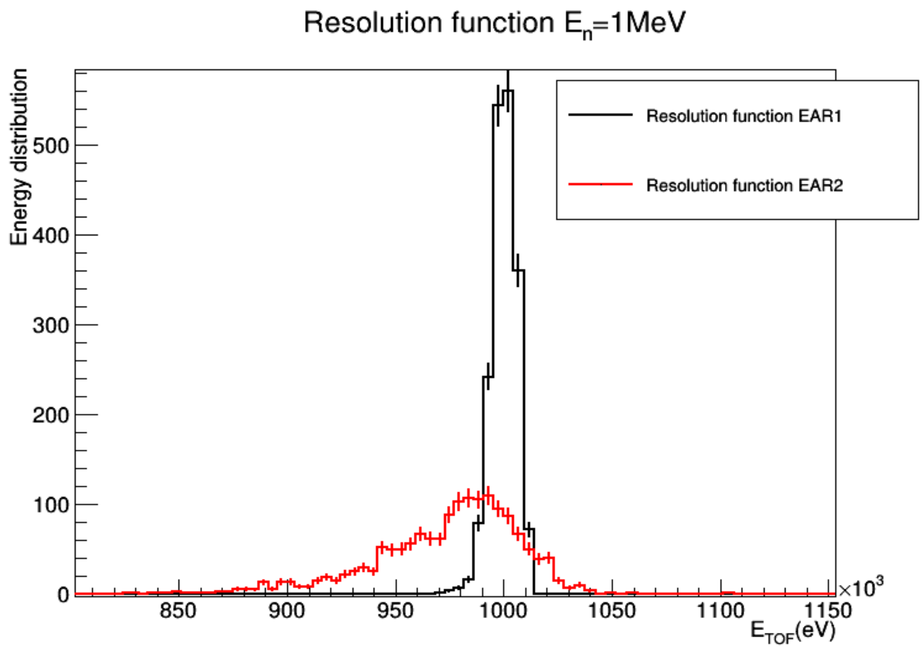
- **Resolution Function**=Energy dependent time distribution of neutrons with the same energy
- Obtained from the projection of the E-t correlation for a certain neutron energy.
- EAR2: To avoid false structures due to the 3D scoring, we get the time at 150 cm above the target

Resolution Function

- **TOF or Energy(TOF) distribution for neutrons of a certain energy**

EAR1 vs EAR2





- After **adding the TOF** corresponding to each neutron Energy:
- EAR2 worse resolution than EAR1 due to the shorter flight path
- EAR2 larger shifting of energy reconstructed from TOF
- In general, distribution width increases with energy → Worse resolution

Summary and conclusions

Summary and Conclusions

- We have **explored and confirmed the good performance of GEANT4** to simulate the neutron production and transport, in an energy range beyond previous works.
- The results are needed both for n_TOF (Resolution Function of EAR2) and **validation of the capabilities of GEANT4** to simulate neutron transport using different officially released Physics Lists .
- The geometry of the **target assembly** has been **implemented in detail**. At the level of the target exit we have scored the neutrons that leave towards EAR1 and EAR2.
- We have obtained the two **most relevant quantities**: **FLUX** and **RESOLUTION FUNCTION** at EAR1 (185m forward) and EAR2 (19m upwards)
- GEANT4 **is able to reproduce the shape of the experimental flux** and agrees with the global neutron flux within the expected accuracy of 30-50%.

Outlook

- Next step will be to confirm the good **reproduction** of the final experimental neutron **flux for EAR2**(*)

- The obtained **resolution function for EAR2** will be used for the capture measurements in the starting campaign of n_TOF.

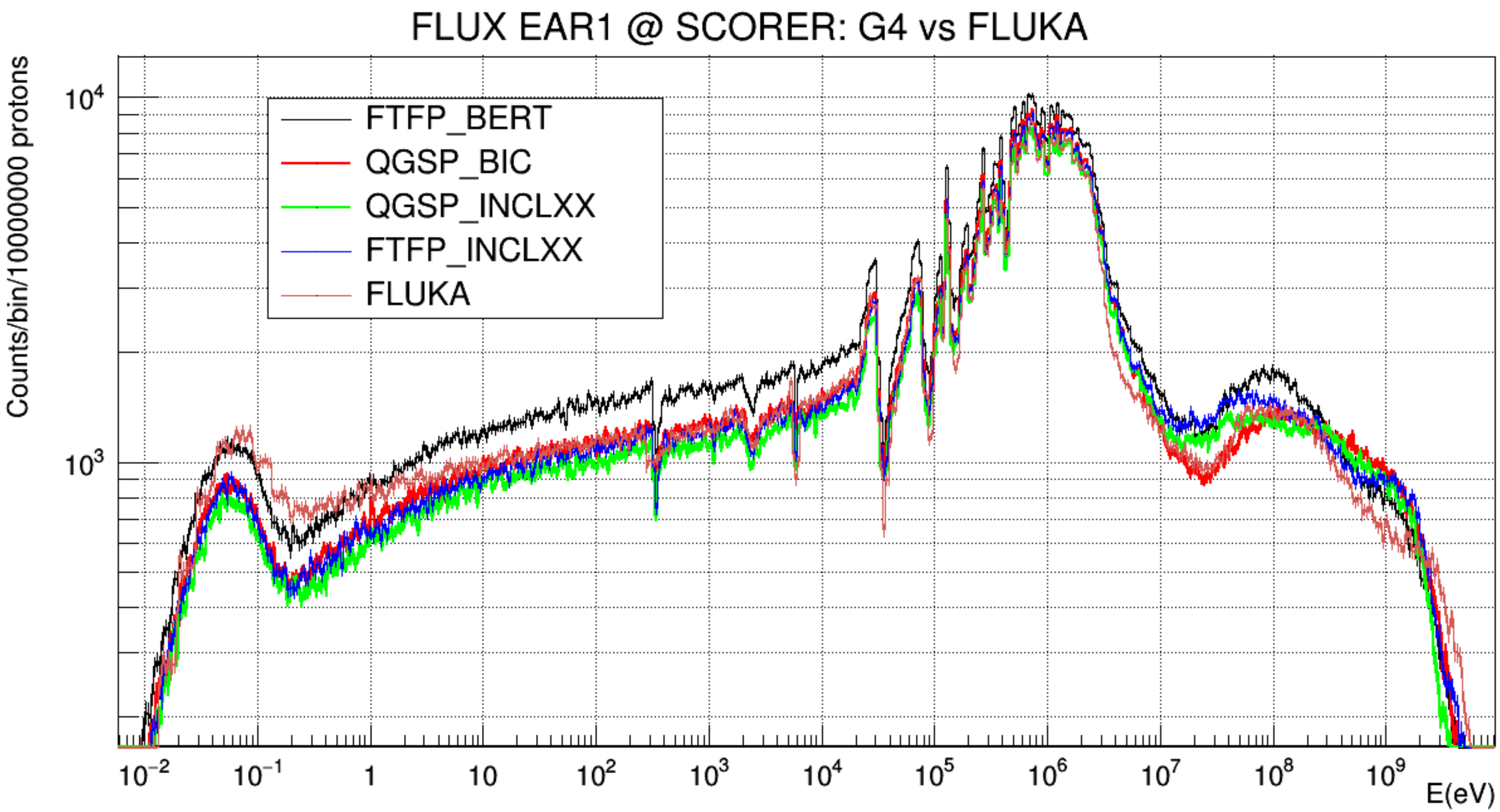
- There is also a **work in progress** to provide more information about the main **neutron production channels** and the origin of the different neutron yield at the level of physics model providing a **benchmark for Geant4**.

- Ongoing simulations with **Geant4 latest version 10.1.1**, which includes a newer and extended version of INCL++.

(*)M.Barbagallo, M. Sabate, T.Wright,n_TOF Analysis Meeting. Feb 2015

Thanks for your attention !!

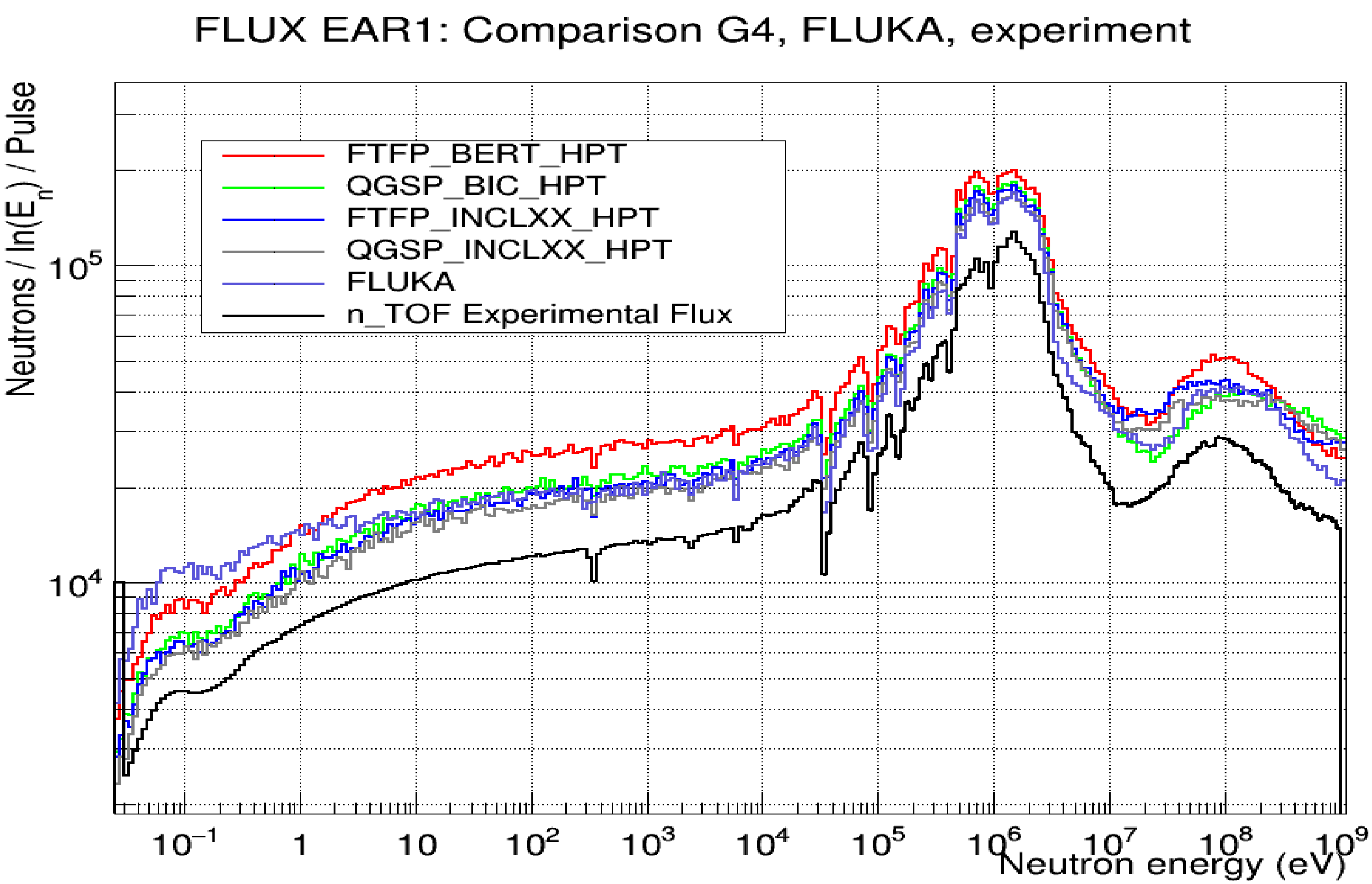
Comparison to FLUKA @ scorer EAR1



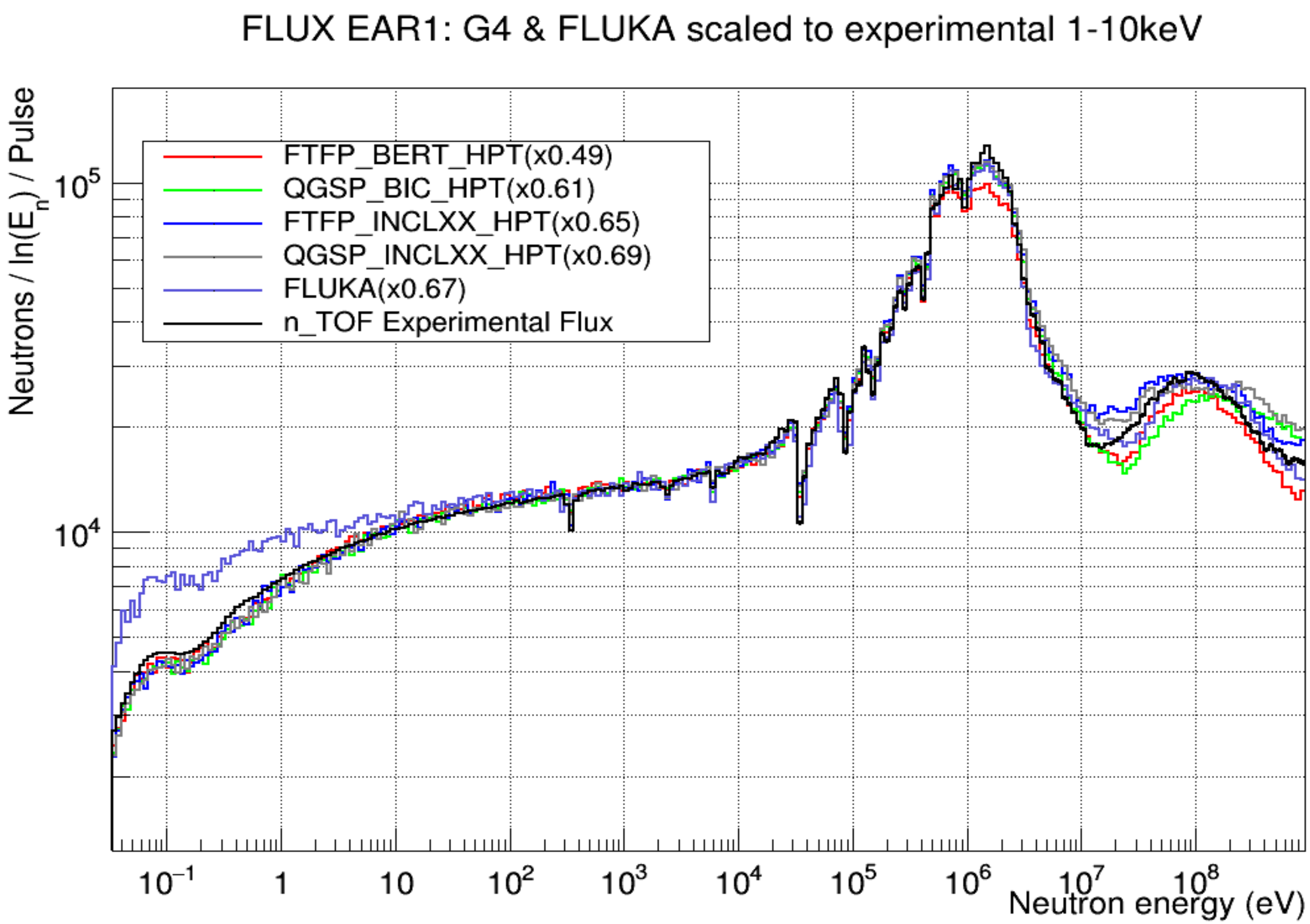
nTOF

Geant 4

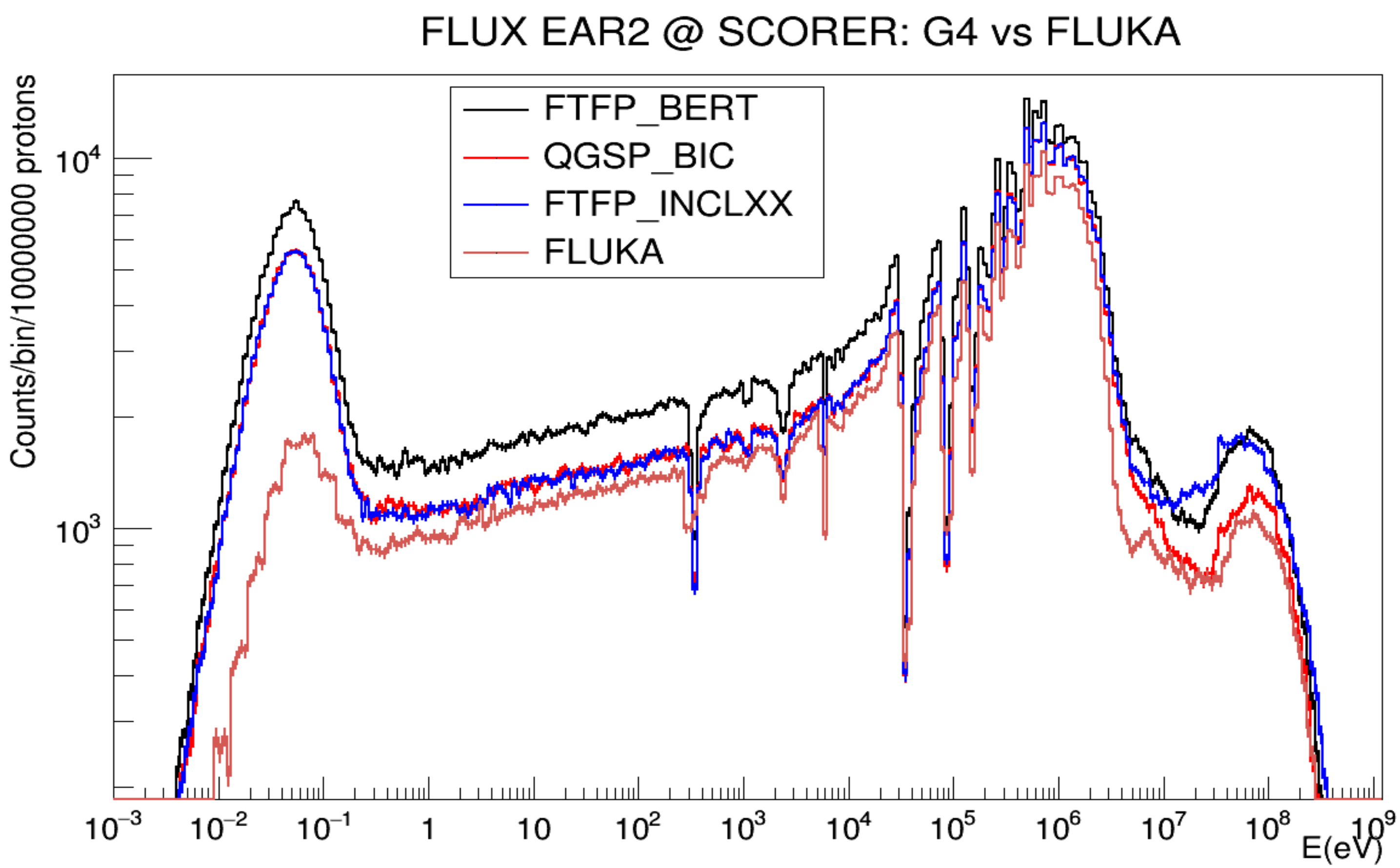
Comparison to FLUKA @ EAR1



Comparison to FLUKA @ EAR1

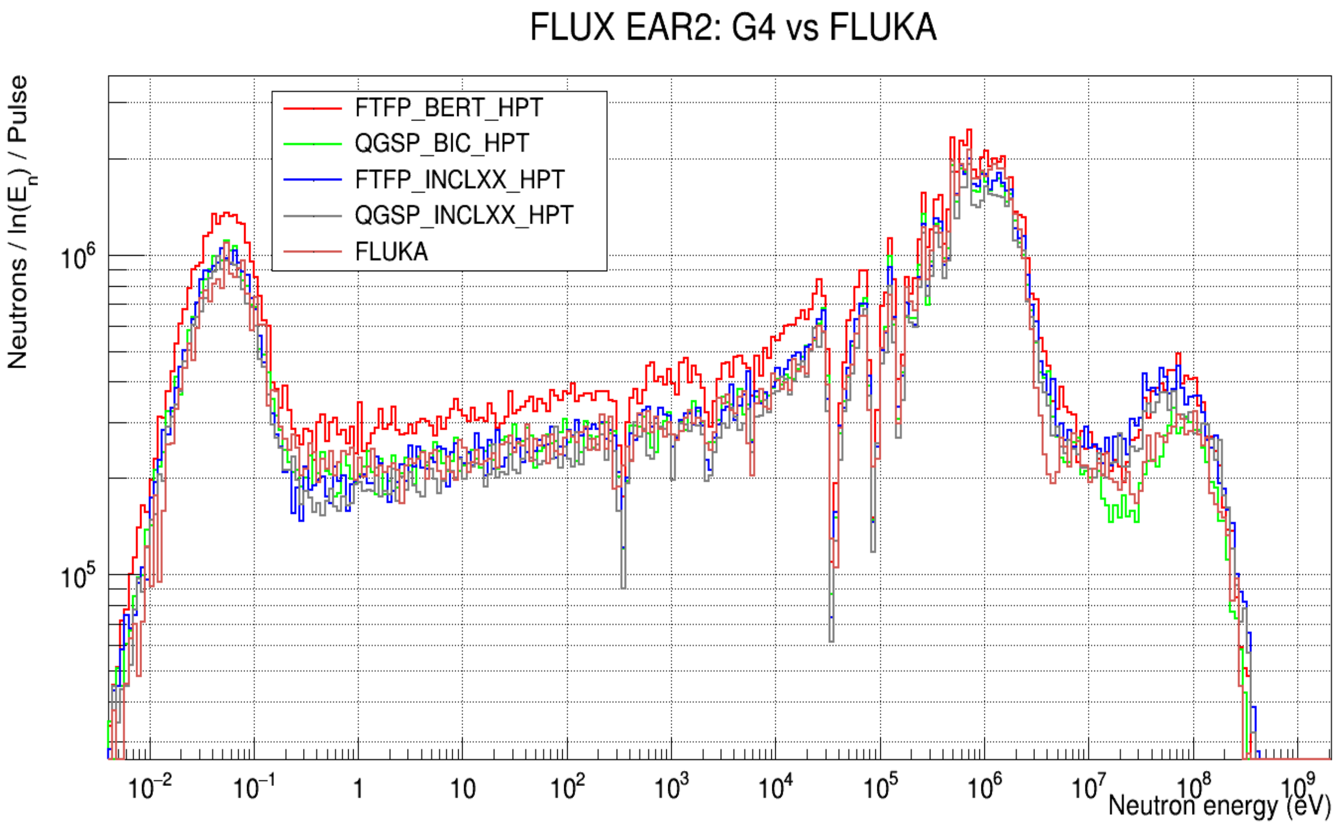


Comparison to FLUKA @ scorer EAR2

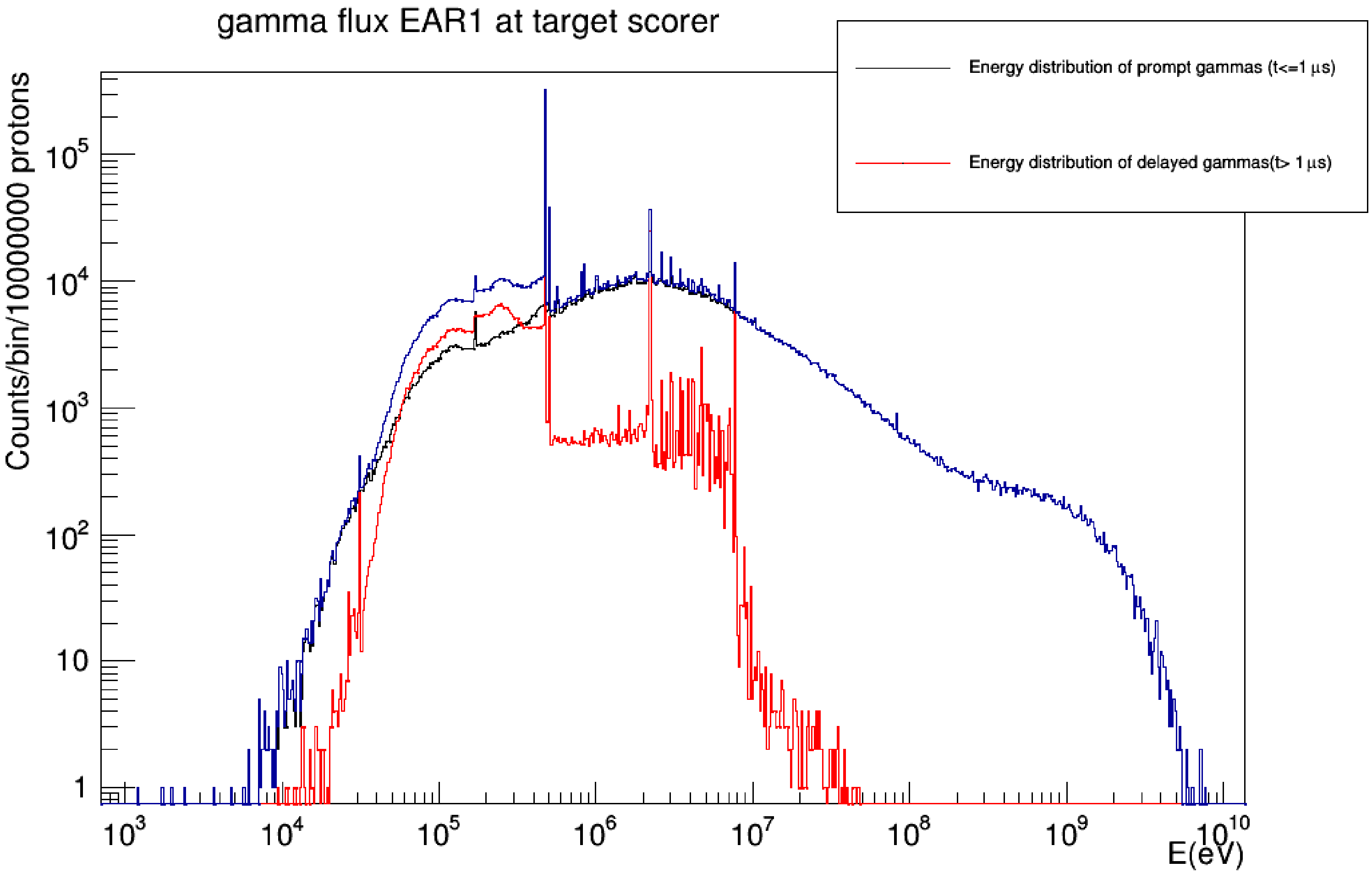


nTOF Geant 4

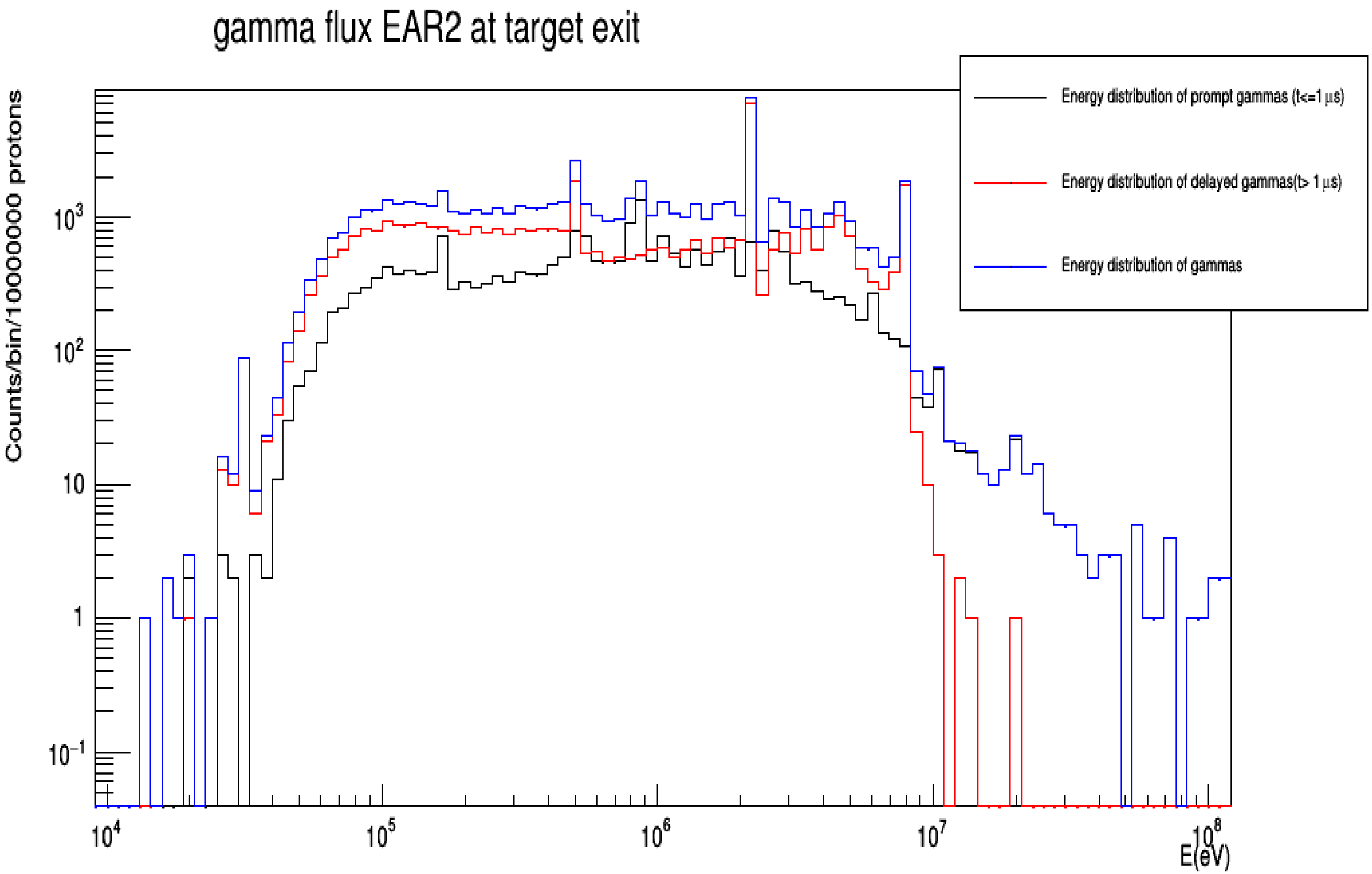
Comparison to FLUKA @ EAR2



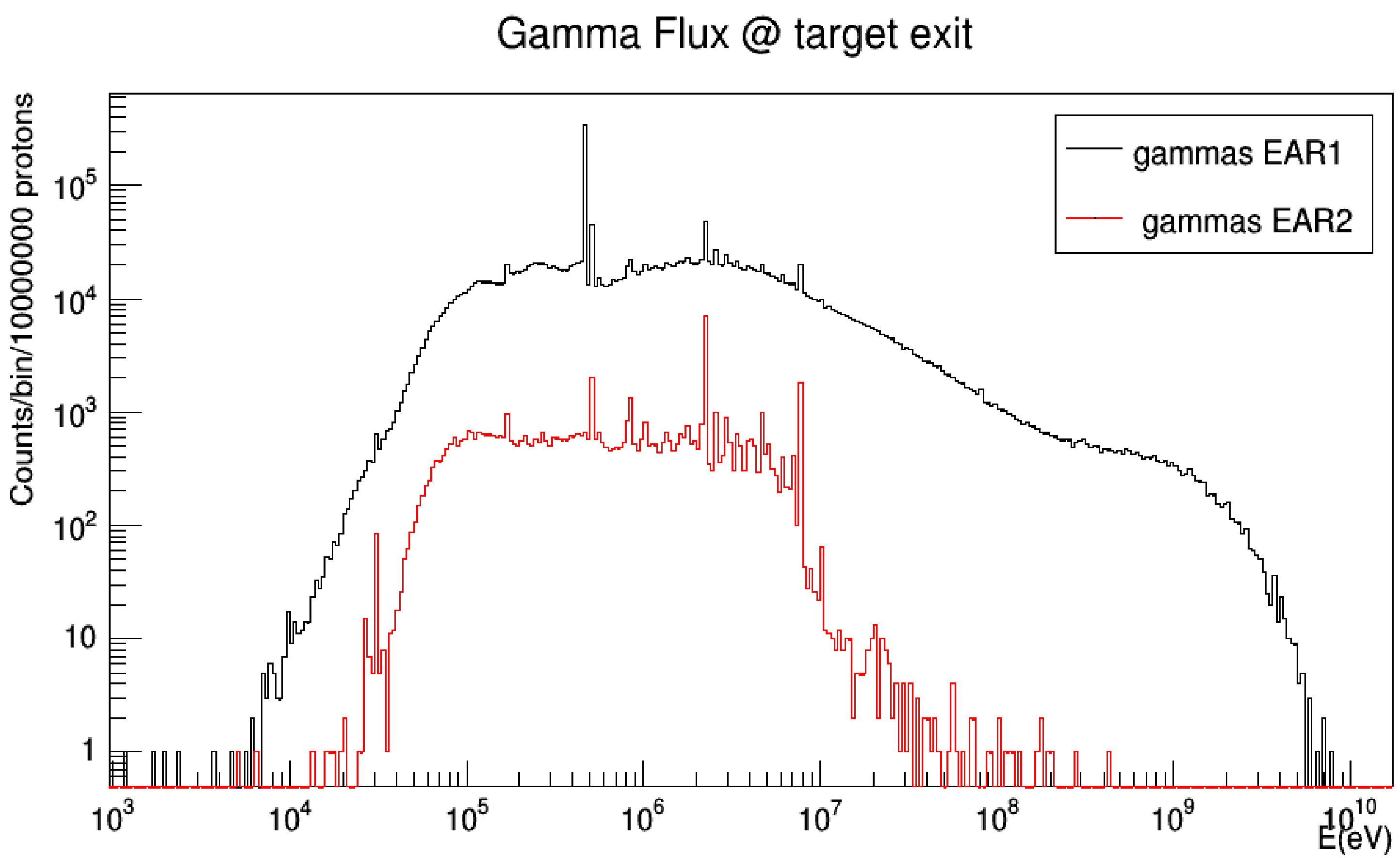
Gamma flux EAR1



Gamma flux EAR2



Gamma flux EAR1 vs EAR2



NEUTRON YIELD RATIOS				
	EAR1(2º)	EAR1(4º)	EAR2(2º)	EAR2(4º)
QGSP_BIC/FLUKA	1.03	1.03	1.26	1.33
QGSP_INCLXX/FLUKA	1.23	1.22	1.60	1.69
FTFP_INCLXX/FLUKA	0.95	0.95	1.18	1.24