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ODDELENIE
ASTRONÓMIE A ASTROFYZIKY
Fakulta matematiky, fyziky a informatiky
Univerzita Komenského
Bratislava

Exposure of extraterrestrial material to cosmic-ray particles

Supervisor: assoc. prof. RNDr. Juraj Tóth, PhD.°
Co-supervisors: prof. RNDr. Jozef Masarik, DrSc.°,
RNDr. Roman Nagy, PhD.°,
*Alicia López Oramas, Ph.D.**

°Comenius University in Bratislava, Slovakia
** Instituto de Astrofísica de Canarias, Spain*

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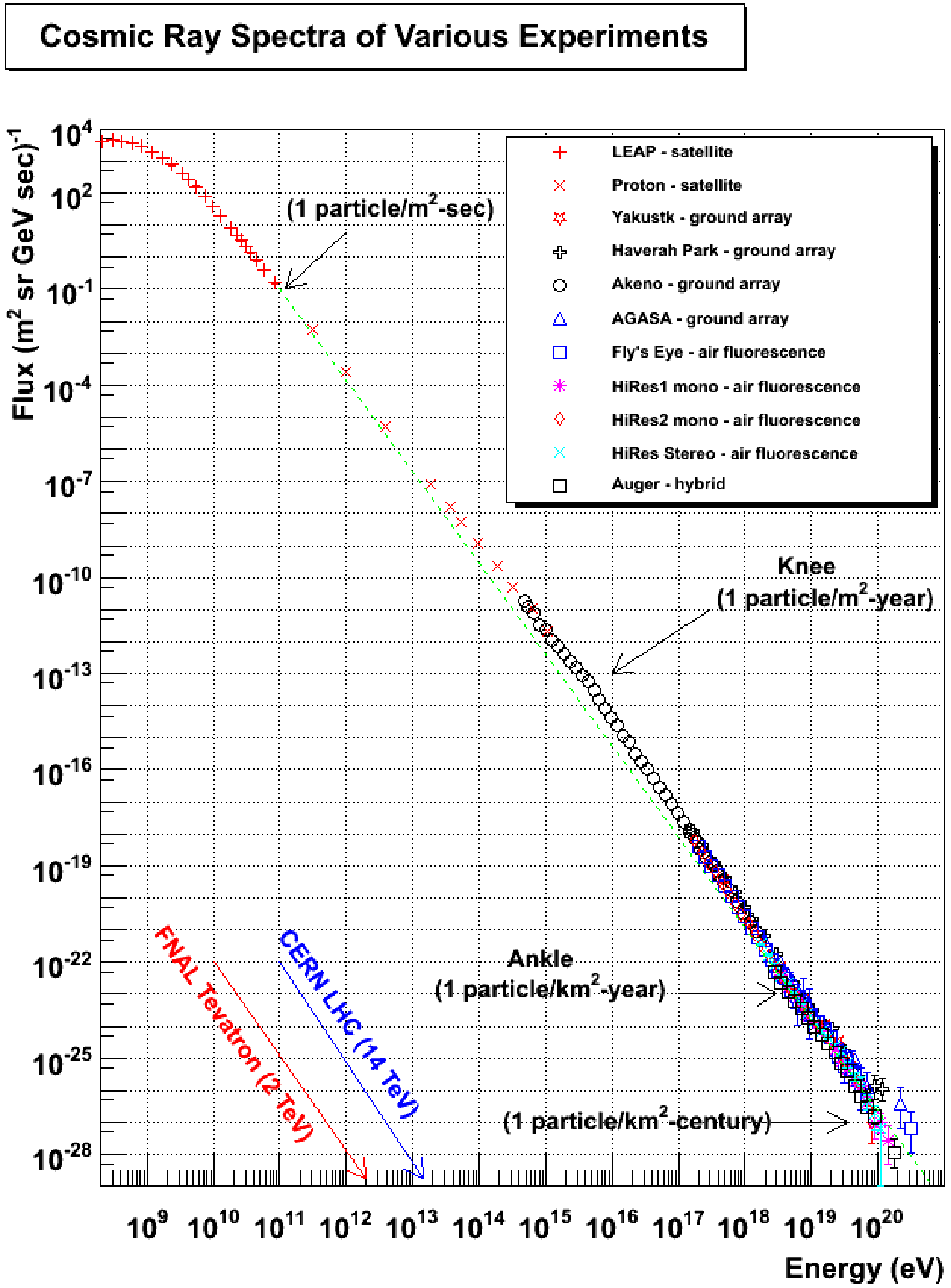
Content

- Cosmic rays – energy spectrum and nature
- Motivation for the creation of the MC simulations based model
- Formation of cosmogenic nuclides
- Model for the calculation of the production rates of cosmogenic nuclides
- Application to the meteorite Knyahinya

Cosmic rays

- Subatomic particles – mainly protons and nuclei of different elements – colliding with the Earth`s atmosphere
- Vast interval of energies from MeV to region up to hundreds of EeV
- Steeply decreasing flux
- Different sources – Sun (lowest energies), galactic sources (energies up to 10^{15}-10^{16} eV), extragalactic sources (highest energies)



Source: https://web.physics.utah.edu/~whanlon/spectrum.html

Motivation- model of the interaction of cosmic-ray particles with material

- Meteoritic and asteroidal material represents the source of valuable information about the history of the Solar System
- Interactions of the material with the cosmic-ray particles lead to the cascades of secondary protons and neutrons within the bodies – Monte Carlo simulations, *Geant4* or *MCNP (Pelowitz et al., 2010) (Pelowitz et al., 2011)*
- Neutrons and protons of high energies bombard target nuclei resulting in the production of cosmogenic nuclides
- Studies of the production rates of cosmogenic nuclides offer information about the exposition time of bodies in Solar System, time from the fall of the sample on the ground, shielding capabilities of the material or the original dimensions of the primary body
- Important applications to meteoritic samples measurements but also nowadays for sample-return missions – OSIRIS-REx, Hayabusa, Hayabusa2 – or future missions oriented in gamma spectrometry of asteroids – Psyche (planned launch October 2023) (Peplowski et al., 2019) – lunar simulations (Masarik et al. 2001) (Li et al., 2017)

Energy spectrum of primary galactic cosmic-ray protons

$$J(E, \theta) = C\frac{E(E+2E_0)(E+K)^{-\gamma}}{(E+\theta)(E+2E_0+\theta)}$$

(Castagnoli & Lal, 1980)

- E is proton kinetic energy in MeV, energy range from 1 MeV up to 20 GeV
- E_0 is the rest energy of a proton, 938 MeV
- θ is the solar modulation parameter in MeV (range from 100 MeV to 1 GeV) - we adopted 550 MeV
- C = $1.244*10^6$ $m^{-2}s^{-1}MeV^{-1}$
- K = $780e^{(-2.5*10^{-4}E)}$
- γ = 2.65, spectral index

Production rates of cosmogenic nuclides

$$Pj\ (R) = \sum_i \frac{c_i N_A}{A_i} \sum_k \int_0^\infty \sigma_{ijk}(E_k) J_k(E_k)\, dE_k$$

(Leya et al., 2000)

- index j represents a type of cosmogenic nuclide within the sample of radius R
- N_A - Avogadro constant
- A_i - the atomic mass of target element *i*
- c_i - the concentration of the target element *i* in g/g
- *k* - the index for the reaction particle type (primary proton, secondary proton and secondary neutron)
- **$\sigma_{i,j,k}(E)$ - the excitation function (or cross section) for the production of nuclide *j* from target element *i* by the reactions induced by particles of type *k***
- J_k - the differential flux density of particles of type *k*

Biggest source of discrepancies

Units of production rates traditionally used in cosmochemistry

Noble gases

Isotope	
^{3}He	
^{21}Ne	
^{22}Ne	
^{38}Ar	
^{39}Ar	

- Calculated production rates in ***s^{-1}.g^{-1}*** or ***Bq.g^{-1}***
- For noble gases more frequently used ***ccSTP g^{-1}.My^{-1}***
- Noble gases do not decay
- Represents the number of generate atoms, cubic-centimeters-at-standard-temperature-and-pressure, over gram of matter over one million of year
- Usually calculated for some specific exposition time – millions of years

Conversion

- Beautiful exercice using the knowledge of molecular physics
- $1\ s^{-1}.g^{-1} = 1.1745*10^{-6}\ ccSTP\ g^{-1}.My^{-1}$

Units of production rates traditionally used in cosmochemistry

Radioactive isotopes (longliving)

. Half-lifes for different radioactive cosmogenic nuclides. Half-lifes for ^{26}Al, ^{36}Cl and ^{41}Ca from http://www.nucleide.org/DDEP_WG/DDEPdata.htm library, on 6.6.2022. ^{10}Be half-life was adopted from (Korschinek et al., 2010). ^{53}Mn half-life was adopted from https://www.chemeurope.com/en/encyclopedia/Isotopes_of_manganese.html.

Isotope	Half-life (years)
^{10}Be	$1.388*10^6$
^{26}Al	717000
^{36}Cl	302000
^{41}Ca	100200
^{53}Mn	$3.7*10^6$

Conversion

- $1\ s^{-1}.g^{-1} = 60\ 000\ dpm.kg^{-1}$

- Calculated production rates in $\boldsymbol{s^{-1}.g^{-1}}$ or $\boldsymbol{Bq.g^{-1}}$
- For radioactive isotopes more frequently used $\boldsymbol{dpm.kg^{-1}}$
- Radioactive isotopes do decay – for long living isotopes, saturation is assumed to be achieved
- Represents the number of decays per minute per 1 kg of matter

Production rates of cosmogenic nuclides

$$P_j(R) = \sum_i \frac{c_i N_A}{A_i} \sum_k \int_0^\infty \sigma_{ijk}(E_k) J_k(E_k)\, dE_k$$

(Leya et al., 2000)

- index j represents a type of cosmogenic nuclide within the sample of radius R
- N_A - Avogadro constant
- A_i - the atomic mass of target element *i*
- c_i - the concentration of the target element *i* in *g/g*
- *k* - the index for the reaction particle type (primary proton, secondary proton and secondary neutron)
- **$\sigma_{i,j,k}(E)$ - the excitation function (or cross section) for the production of nuclide *j* from target element *i* by the reactions induced by particles of type *k***
- J_k - the differential flux density of particles of type *k*

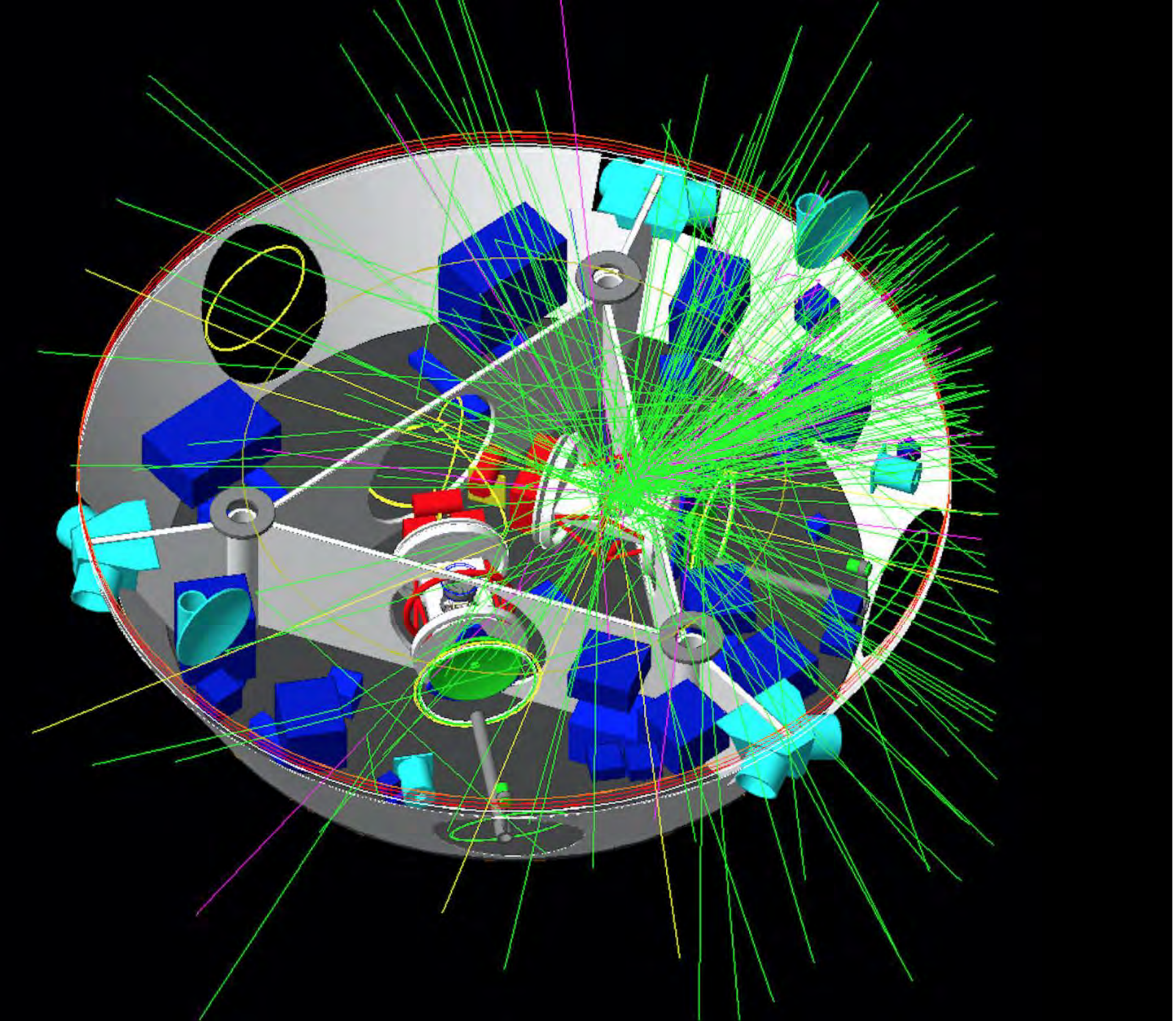
Biggest source of discrepancies

Model

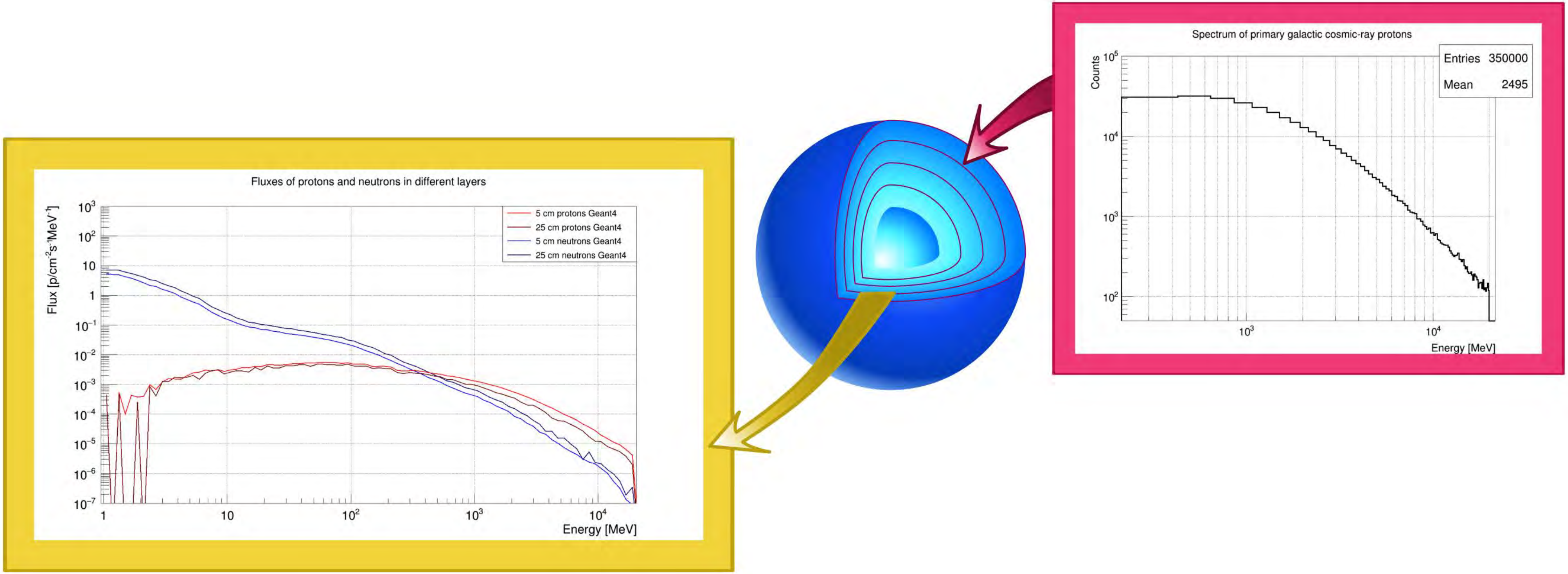
- Based on Geant4 simulation toolkit
- Simulates spherical body with homogeneous density, predefined chemical composition and dimensions with inner concentric shells with predefined incress – first time used on meteorites
- Sphere is isotropically bombared by cosmic rays – in this case protons
- Fluxes of secondary protons and neutrons are calculated in each inner shell
- Using the set of cross sections calculate the production rates for different cosmogenic nuclides

Model
Geant4

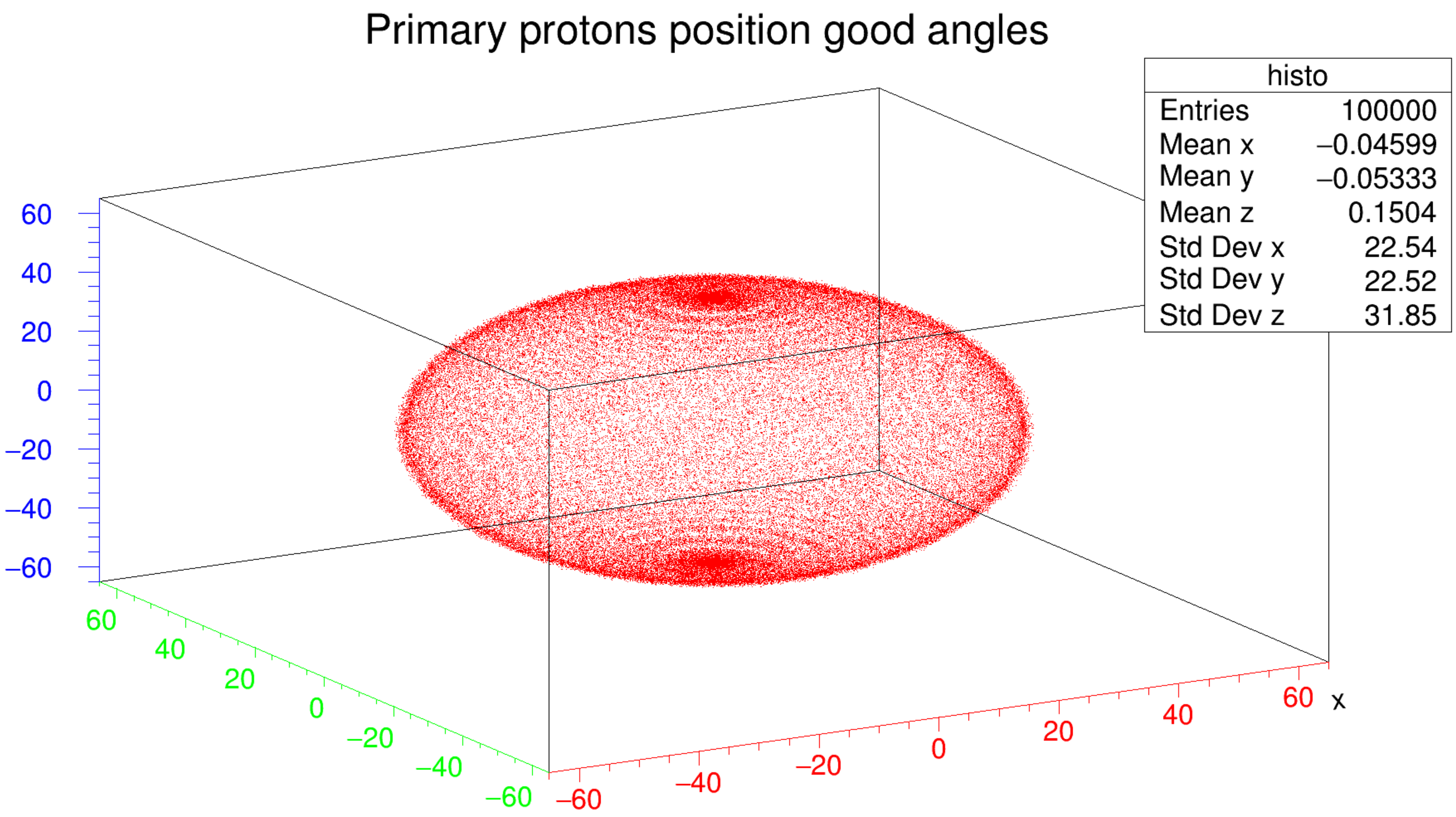
- *Geant4* (GEometry ANd Tracking) Monte Carlo simulation toolkit
- Geant4 is free for download and available at the webpage site https://geant4.web.cern.ch/
- This software simulates the propagation of high-energy particles through matter (Allison et al., 2006), (Agostinelli et al., 2003), (Allison et al., 2016)
- *Geant4* is very versatile and multifunctional software which enables to the user to develop his own geometrical object and the environment exposed to the flux of high-energy particles. The software has been created by international collaboration and is maintained and frequently updated by new packages. It is written in C++ and enables to create the resulting files in *ROOT* (Brun and Rademakers, 1997).



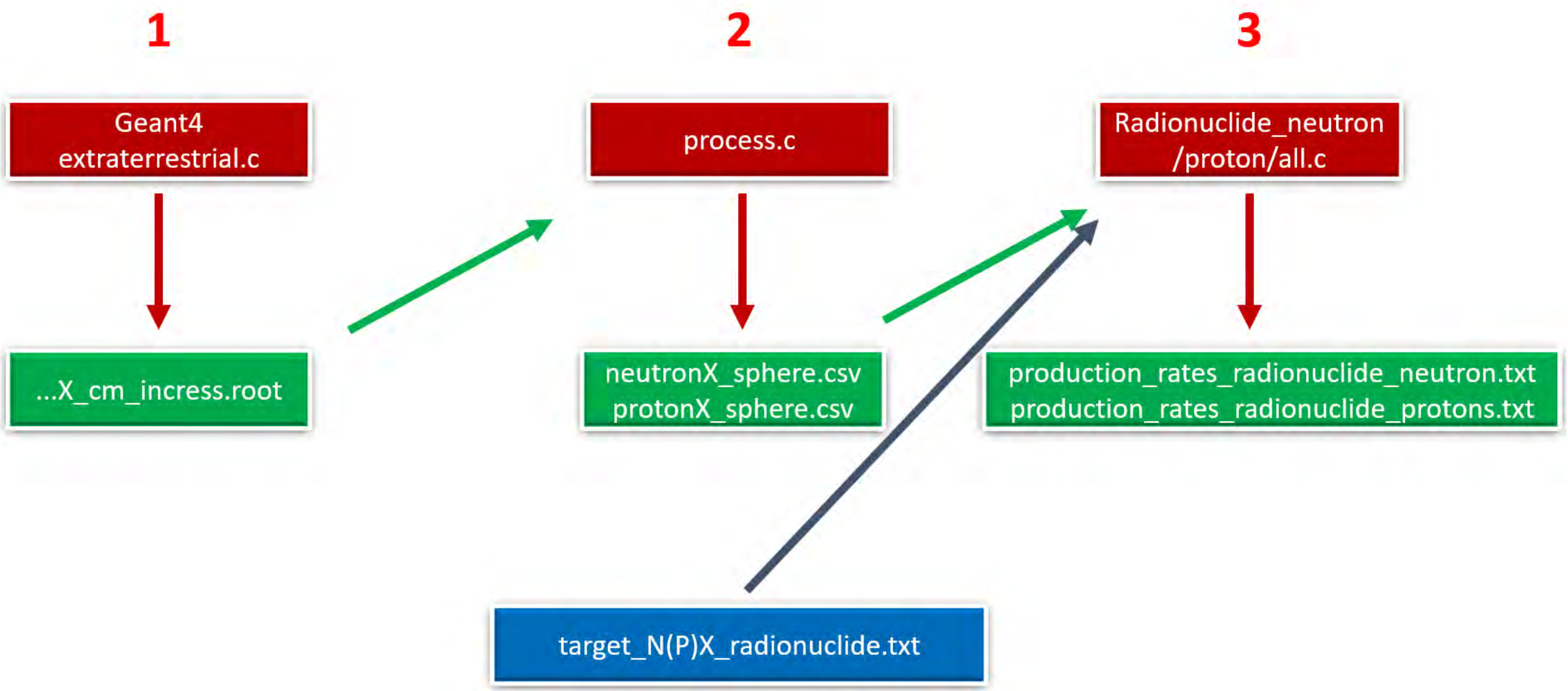
Source:
https://kt.cern/technologies/geant4



Authot: Justína Nováková, Faculty of Natural Sciences, Comenius University in Bratislava


Primary protons position good angles
histo
Entries 100000
Mean x −0.04599
Mean y −0.05333
Mean z 0.1504
Std Dev x 22.54
Std Dev y 22.52
Std Dev z 31.85
60
40
20
0
−20
−40
−60
x

Model Pipeline



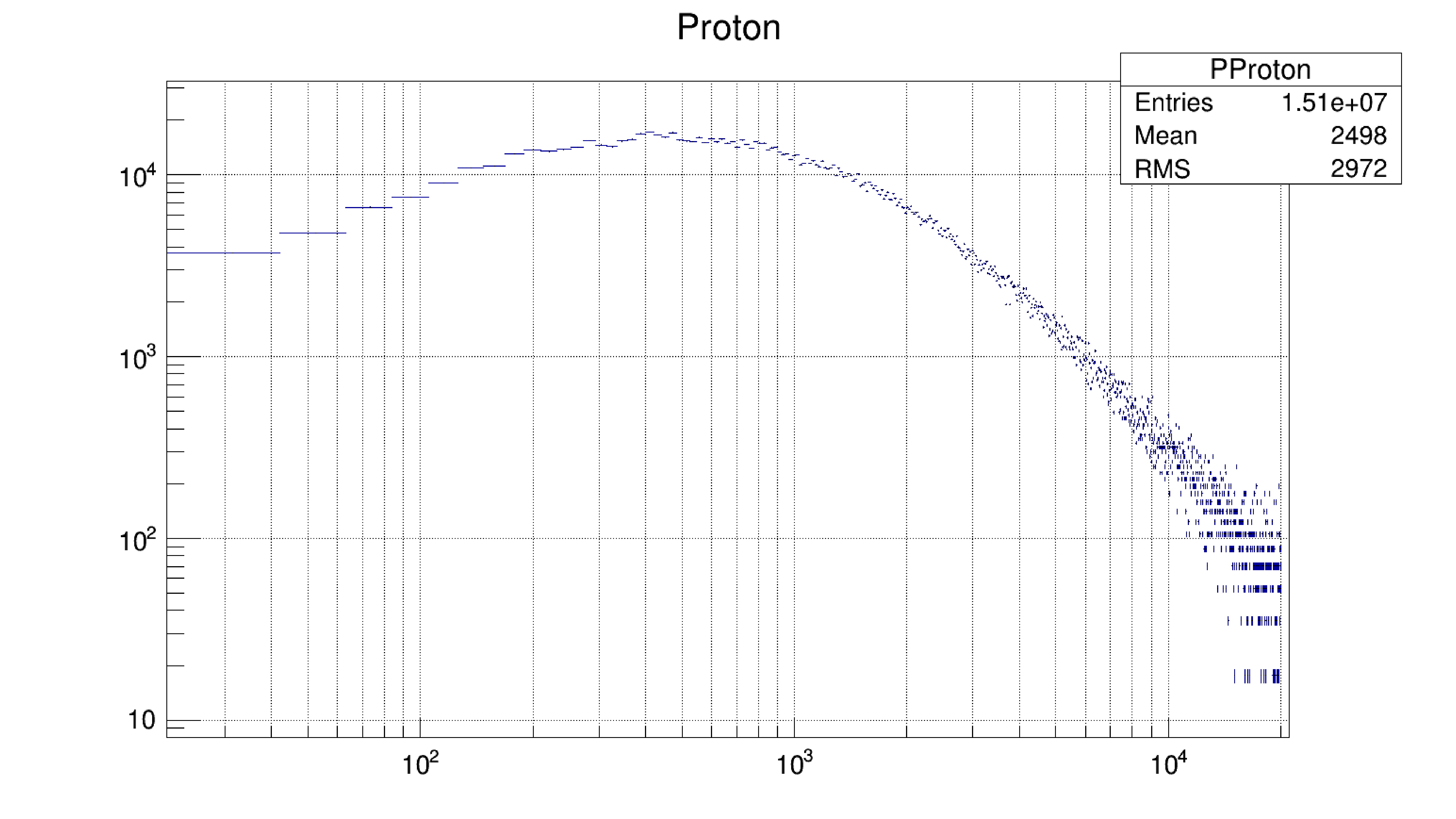
Application – meteorite Knyahinya

Percentual mass abundance of different elements in the Knyahinya meteorite sample

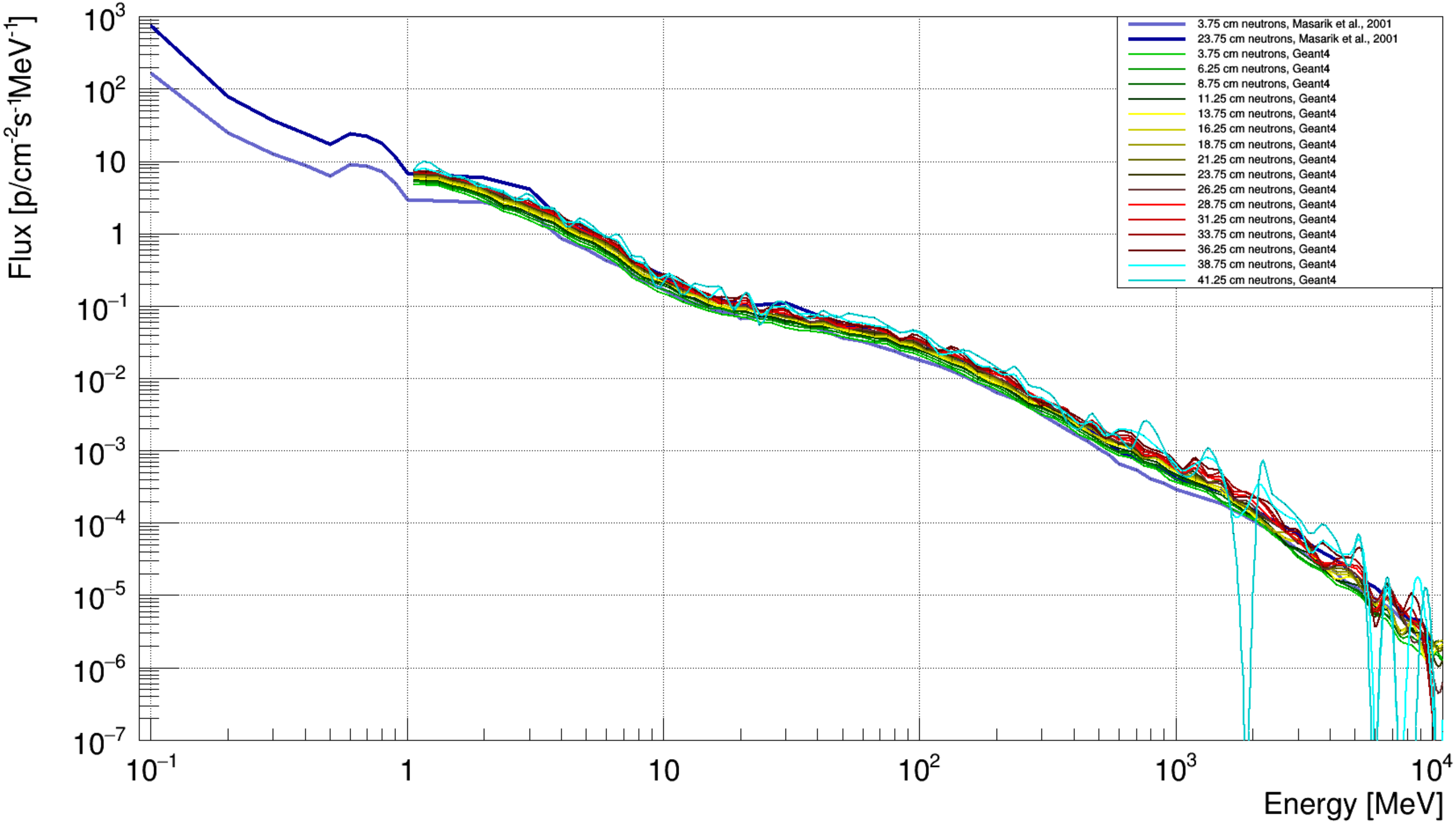
Chemical element	Percentual abundance
Oxygen (O)	42%
Sodium (Na)	0.7%
Magnesium (Mg)	15.05%
Aluminium (Al)	1.19%
Silicon (Si)	21.5%
Phosphorus (P)	0.1%
Sulfur (S)	0.5%
Potassium (K)	0.092%
Calcium (Ca)	1.47%
Titanium (Ti)	0.07%
Chromium (Cr)	0.4%
Manganese (Mn)	0.28%
Iron (Fe)	16.47%
Cobalt (Co)	0.01%
Nickel (Ni)	0.14%

- L/LL5 chondrite, fall 1866, mass 0.5 kg
- Simulated radius – 45 cm
- Considered bulk density – 3.35 g.cm^{-3}
- Injected galactic cosmic-ray protons – 15.1 millions
- Energy distribution according to the semi-empirical spectrum, 0 MeV up to 20 GeV
- 2.5 cm incress – 18 inner shells
- Previously studied using MCNP simulation code (Masarik et al., 2001)
- Exposition time considered – 39 *My*

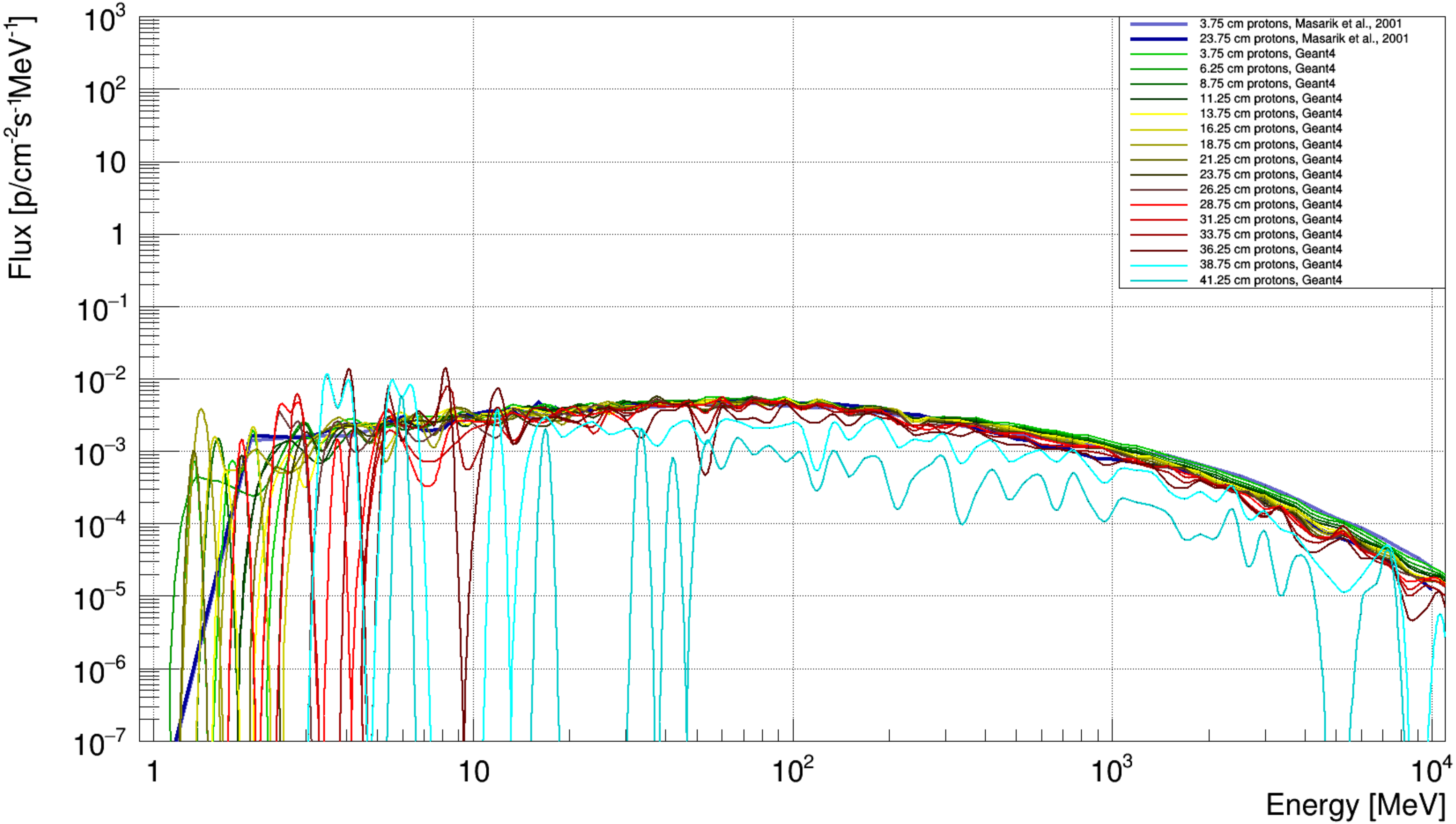
Credit: NHM Vienna, https://www.lpi.usra.edu/meteor/get_original_photo.php?recno=5764120

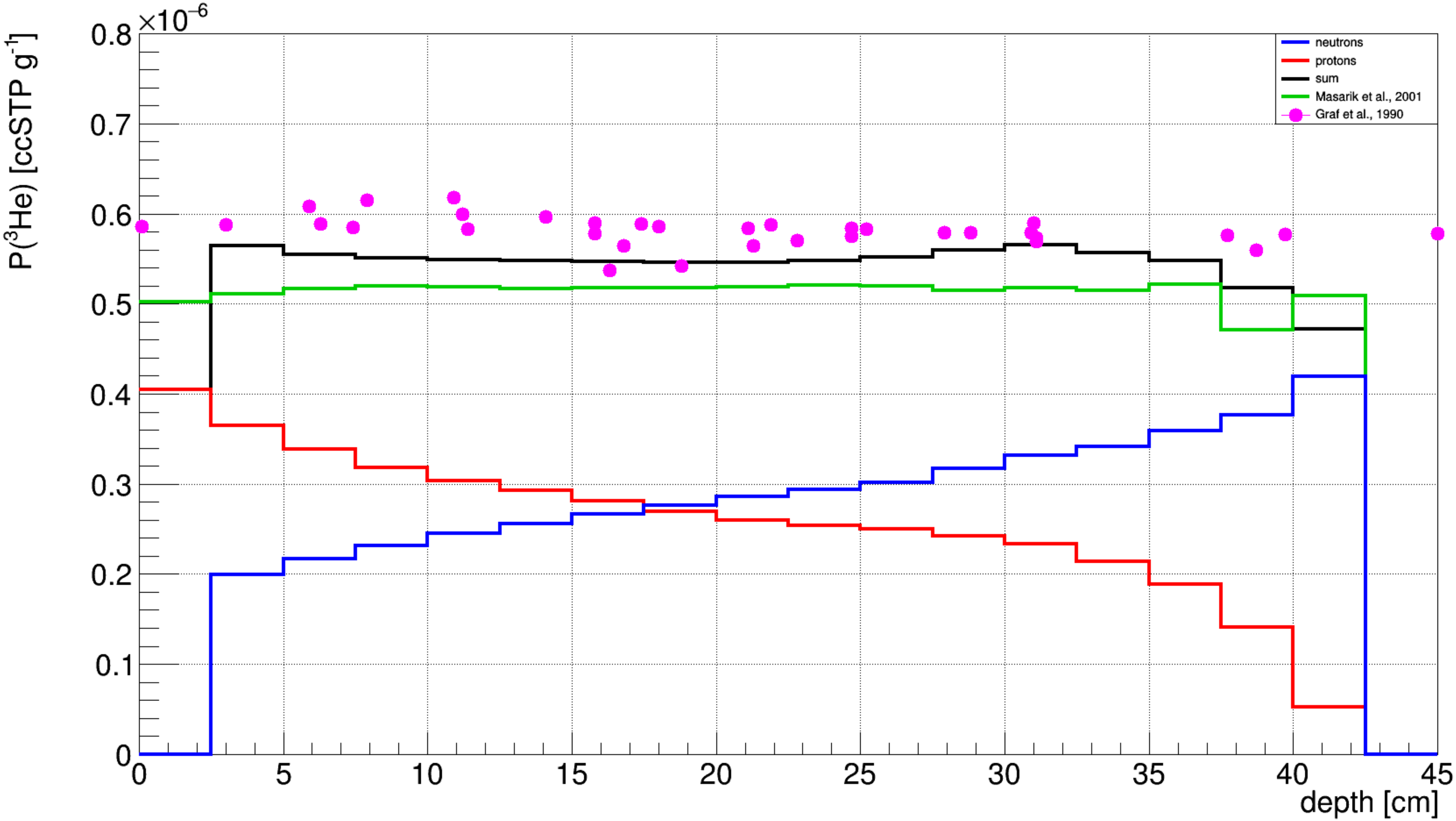


Proton
PProton
Entries 1.51e+07
Mean 2498
RMS 2972
10
10^2
10^3
10^4

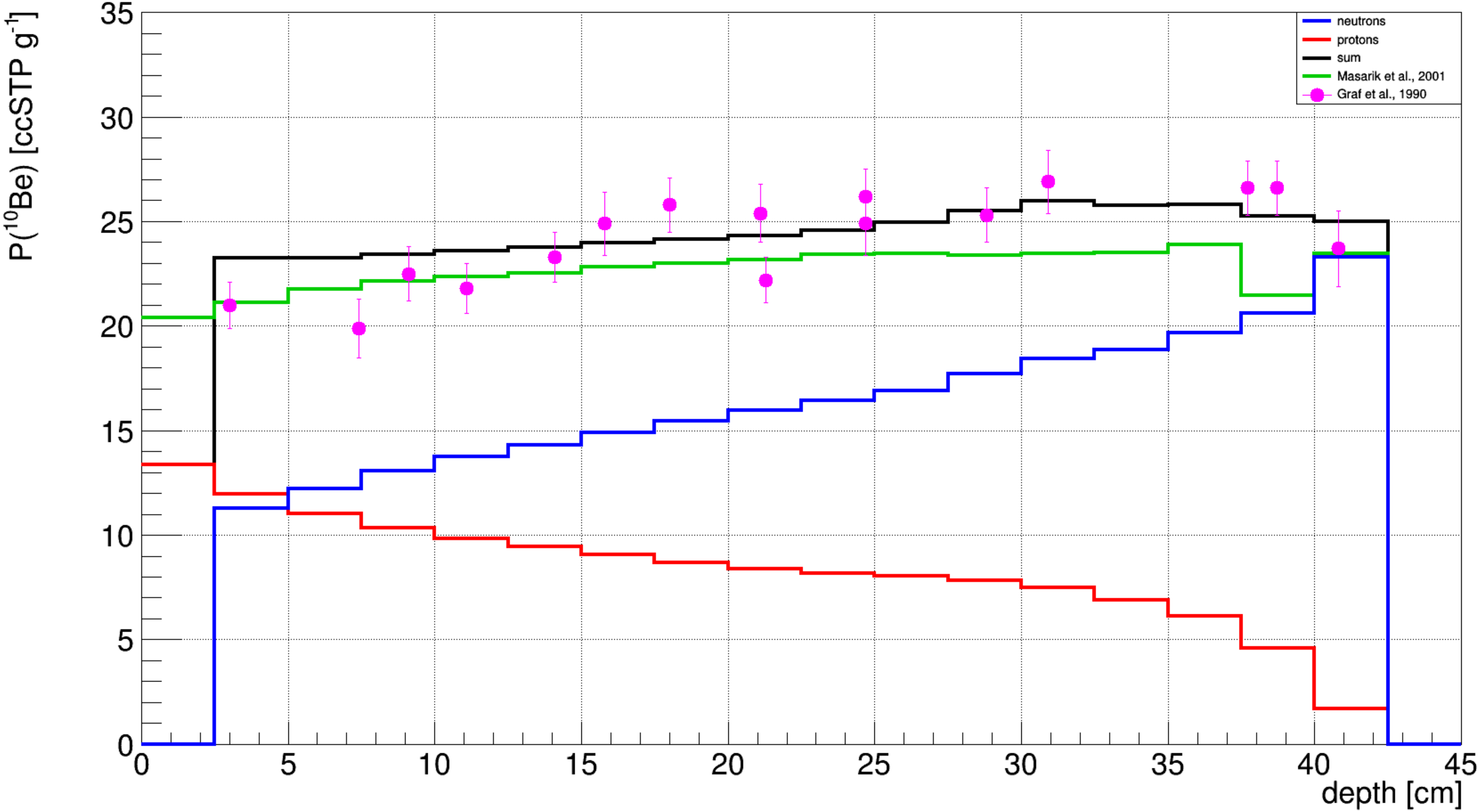


Flux [p/cm-2s-1MeV-1]
Energy [MeV]
3.75 cm neutrons, Masarik et al., 2001
23.75 cm neutrons, Masarik et al., 2001
3.75 cm neutrons, Geant4
6.25 cm neutrons, Geant4
8.75 cm neutrons, Geant4
11.25 cm neutrons, Geant4
13.75 cm neutrons, Geant4
16.25 cm neutrons, Geant4
18.75 cm neutrons, Geant4
21.25 cm neutrons, Geant4
23.75 cm neutrons, Geant4
26.25 cm neutrons, Geant4
28.75 cm neutrons, Geant4
31.25 cm neutrons, Geant4
33.75 cm neutrons, Geant4
36.25 cm neutrons, Geant4
38.75 cm neutrons, Geant4
41.25 cm neutrons, Geant4

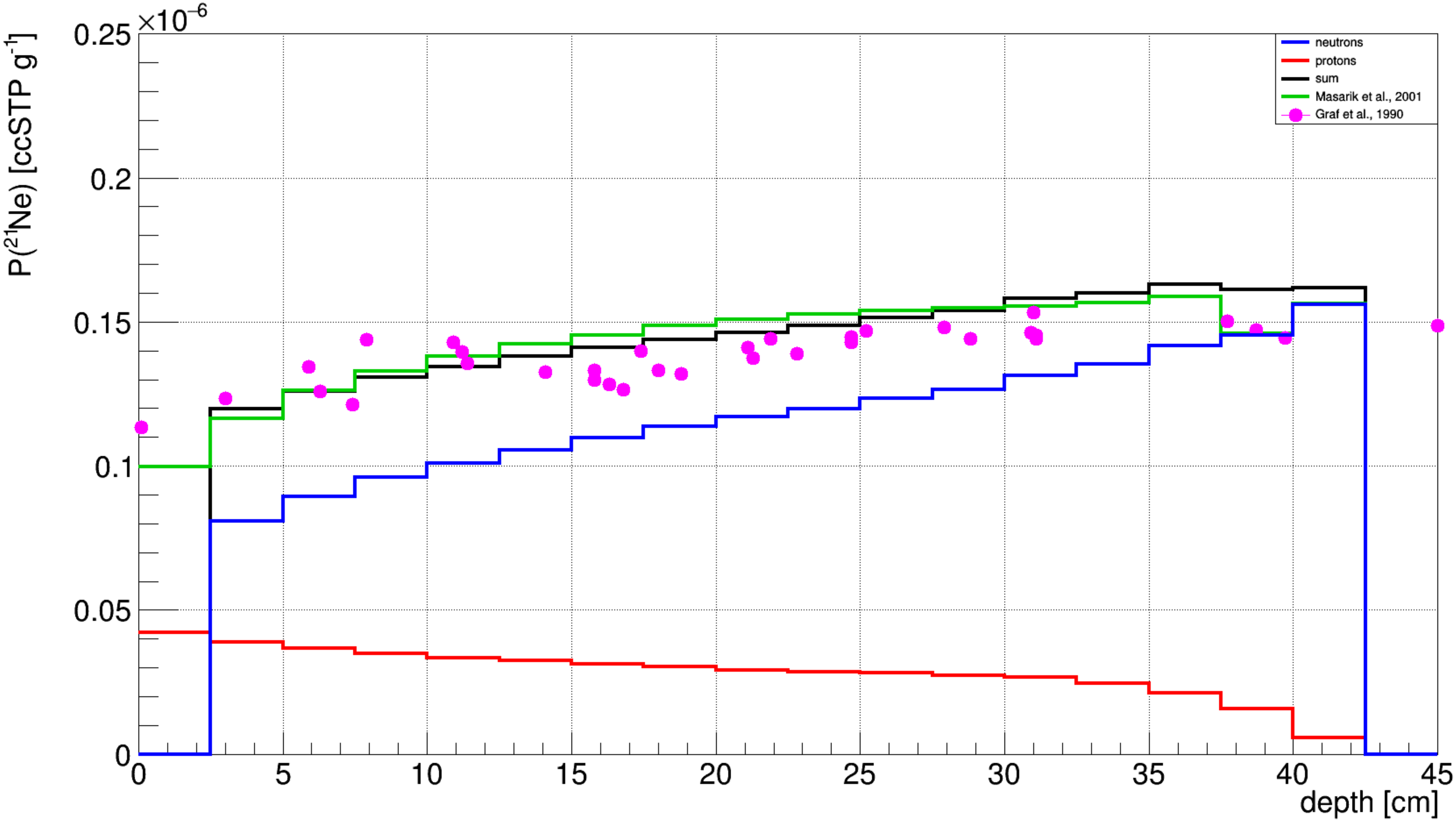

Flux [p/cm^{-2}s^{-1}MeV^{-1}]
Energy [MeV]
3.75 cm protons, Masarik et al., 2001
23.75 cm protons, Masarik et al., 2001
3.75 cm protons, Geant4
6.25 cm protons, Geant4
8.75 cm protons, Geant4
11.25 cm protons, Geant4
13.75 cm protons, Geant4
16.25 cm protons, Geant4
18.75 cm protons, Geant4
21.25 cm protons, Geant4
23.75 cm protons, Geant4
26.25 cm protons, Geant4
28.75 cm protons, Geant4
31.25 cm protons, Geant4
33.75 cm protons, Geant4
36.25 cm protons, Geant4
38.75 cm protons, Geant4
41.25 cm protons, Geant4



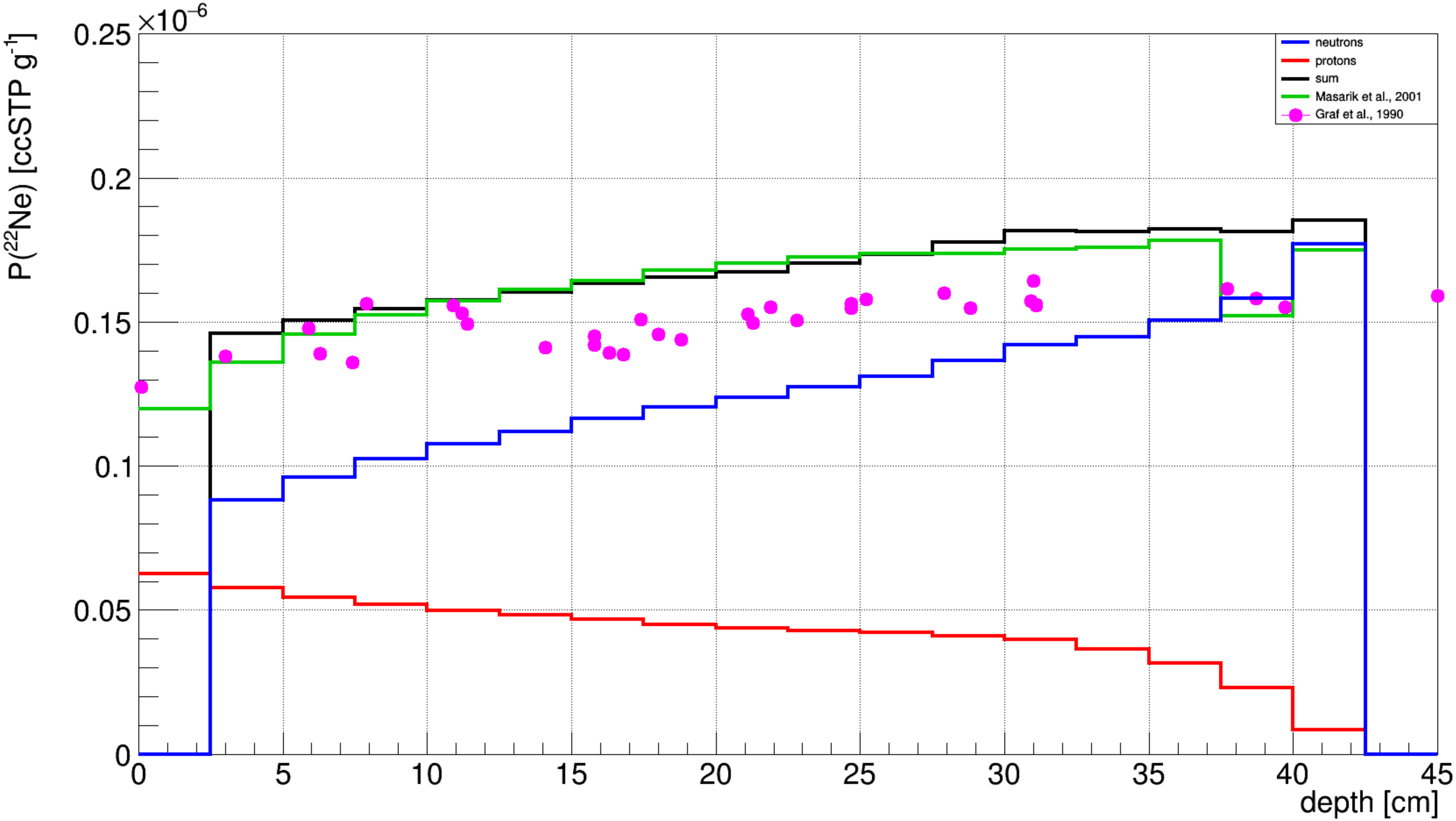
×10^-6
P(³He) [ccSTP g⁻¹]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
Graf et al., 1990

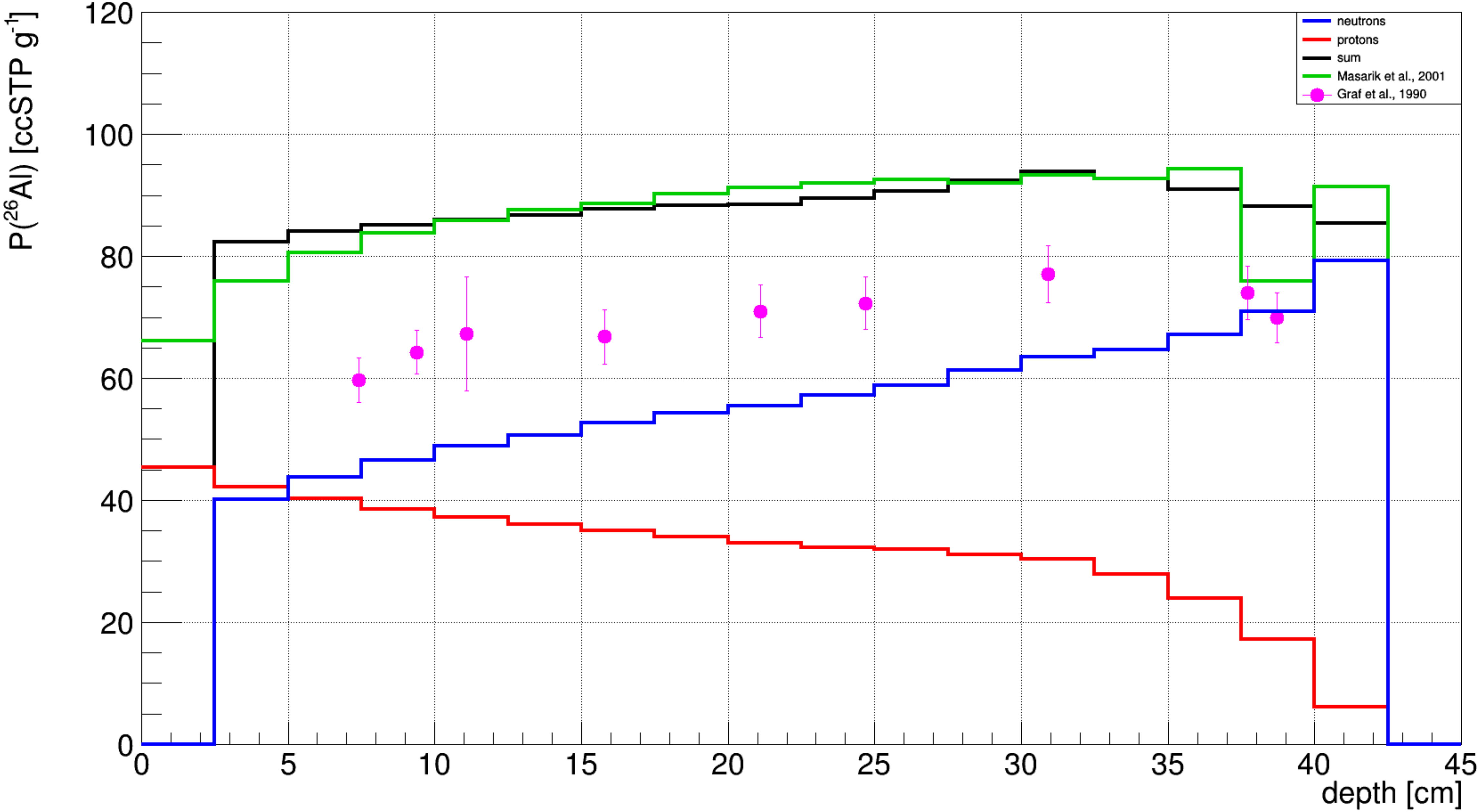


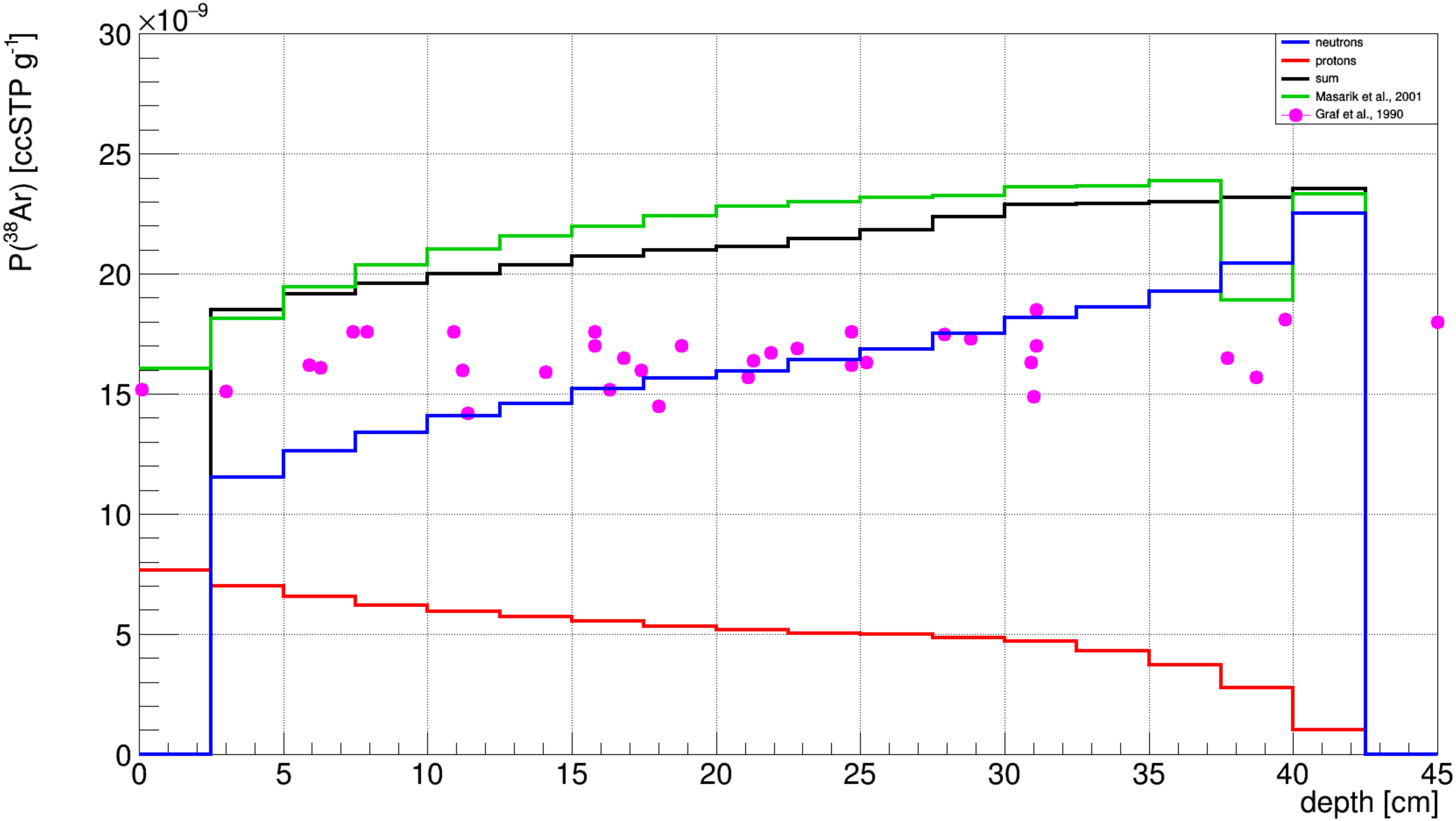
neutrons
protons
sum
Masarik et al., 2001
Graf et al., 1990
P(^{10}Be) [ccSTP g^{-1}]
depth [cm]
0
5
10
15
20
25
30
35
40
45



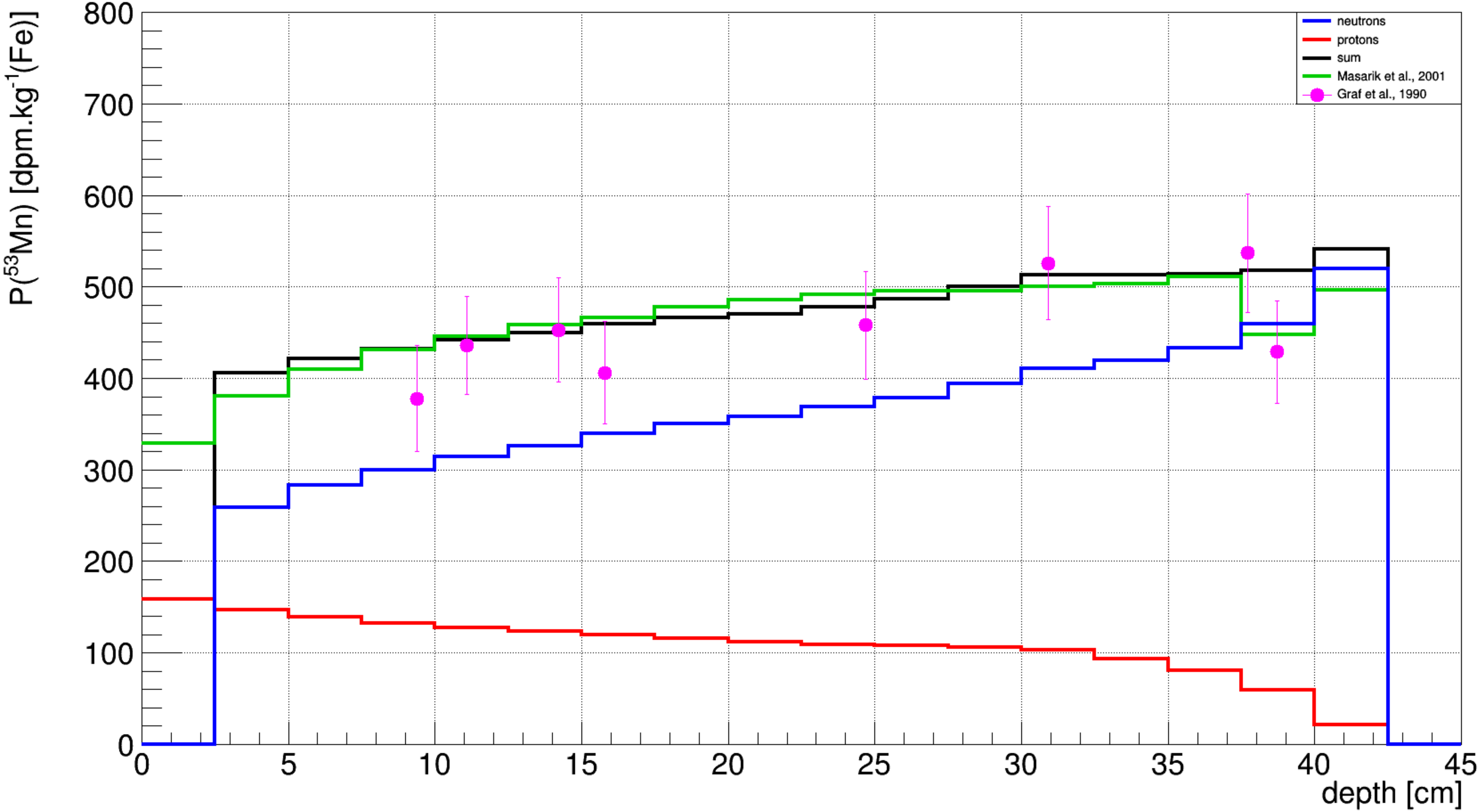
P(^{21}Ne) [ccSTP g^{-1}]
$\times 10^{-6}$
0.25
0.2
0.15
0.1
0.05
0
5
10
15
20
25
30
35
40
45
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
Graf et al., 1990


P(^{22}Ne) [ccSTP g^{-1}]
×10^{-6}
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
Graf et al., 1990

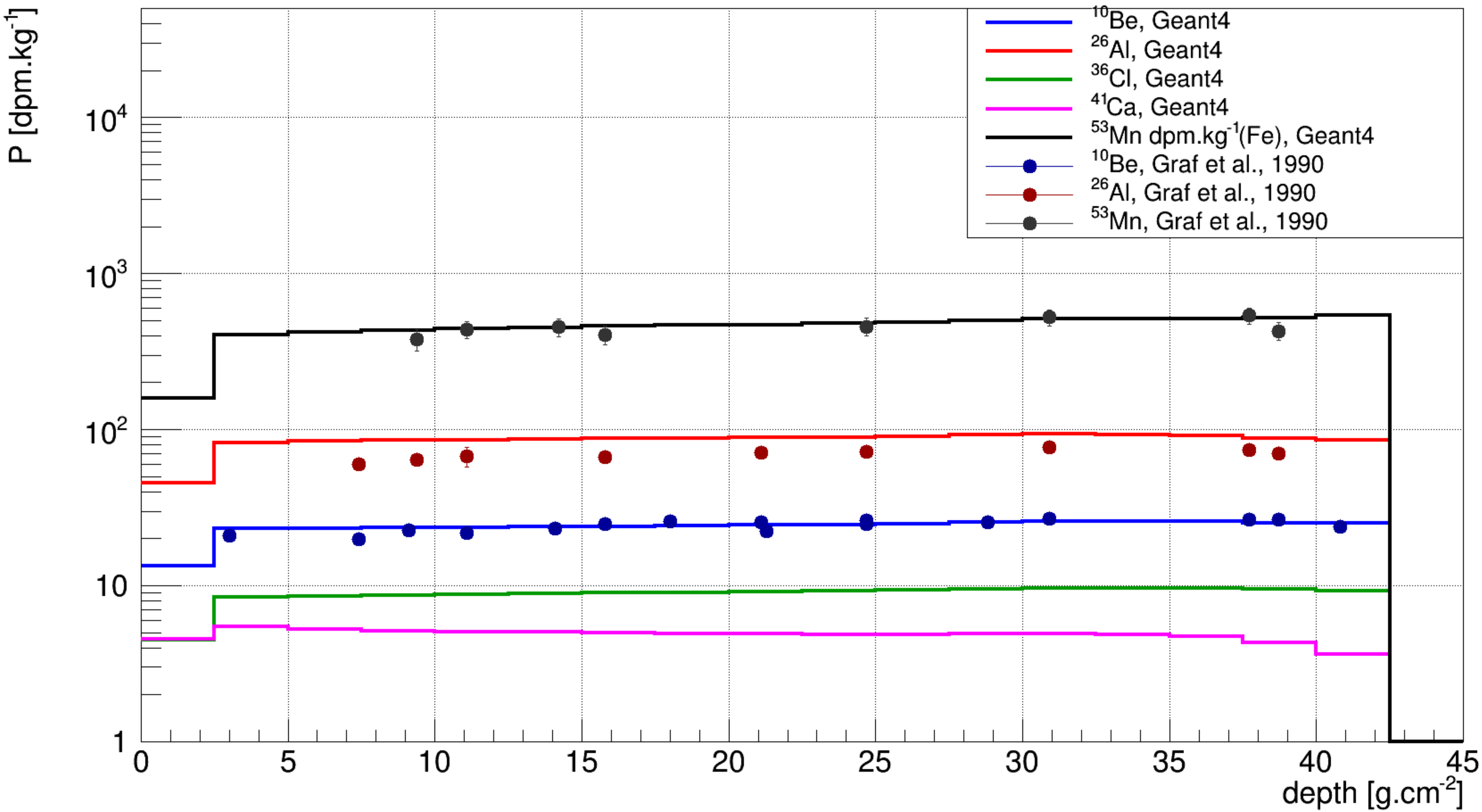

P(^{26}Al) [ccSTP g^{-1}]
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
45
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
Graf et al., 1990



neutrons
protons
sum
Masarik et al., 2001
Graf et al., 1990
P(^{38}Ar) [ccSTP g^{-1}]
$\times 10^{-9}$
depth [cm]
0
5
10
15
20
25
30
35
40
45



P(^{53}Mn) [dpm.kg^{-1}(Fe)]
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
Graf et al., 1990


P [dpm.kg^{-1}]
depth [g.cm^{-2}]
^{10}Be, Geant4
^{26}Al, Geant4
^{36}Cl, Geant4
^{41}Ca, Geant4
^{53}Mn dpm.kg^{-1}(Fe), Geant4
^{10}Be, Graf et al., 1990
^{26}Al, Graf et al., 1990
^{53}Mn, Graf et al., 1990
1
10
10^2
10^3
10^4
0
5
10
15
20
25
30
35
40
45

Conclusion

- Development of the model for the calculation of the production rates of cosmogenic nuclides in spherical bodies with predefined chemical composition, dimension and density
- Model is based on the MC simulation toolkit Geant4 – first time application to meteoritic samples
- Application to meteorite Knyahinya – well studied sample, measured and previously simulated using MCNP (Masarik et al., 2001) simulation software
- Model gives comparable results to the previous MCNP model outputs and is in good agreement with the measured data
- Even better agreement for ^{10}Be isotope than older MCNP model
- Huge versatility of the model

Sources and recommended literature

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Thank you very much for your attention

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Model PhysicsList

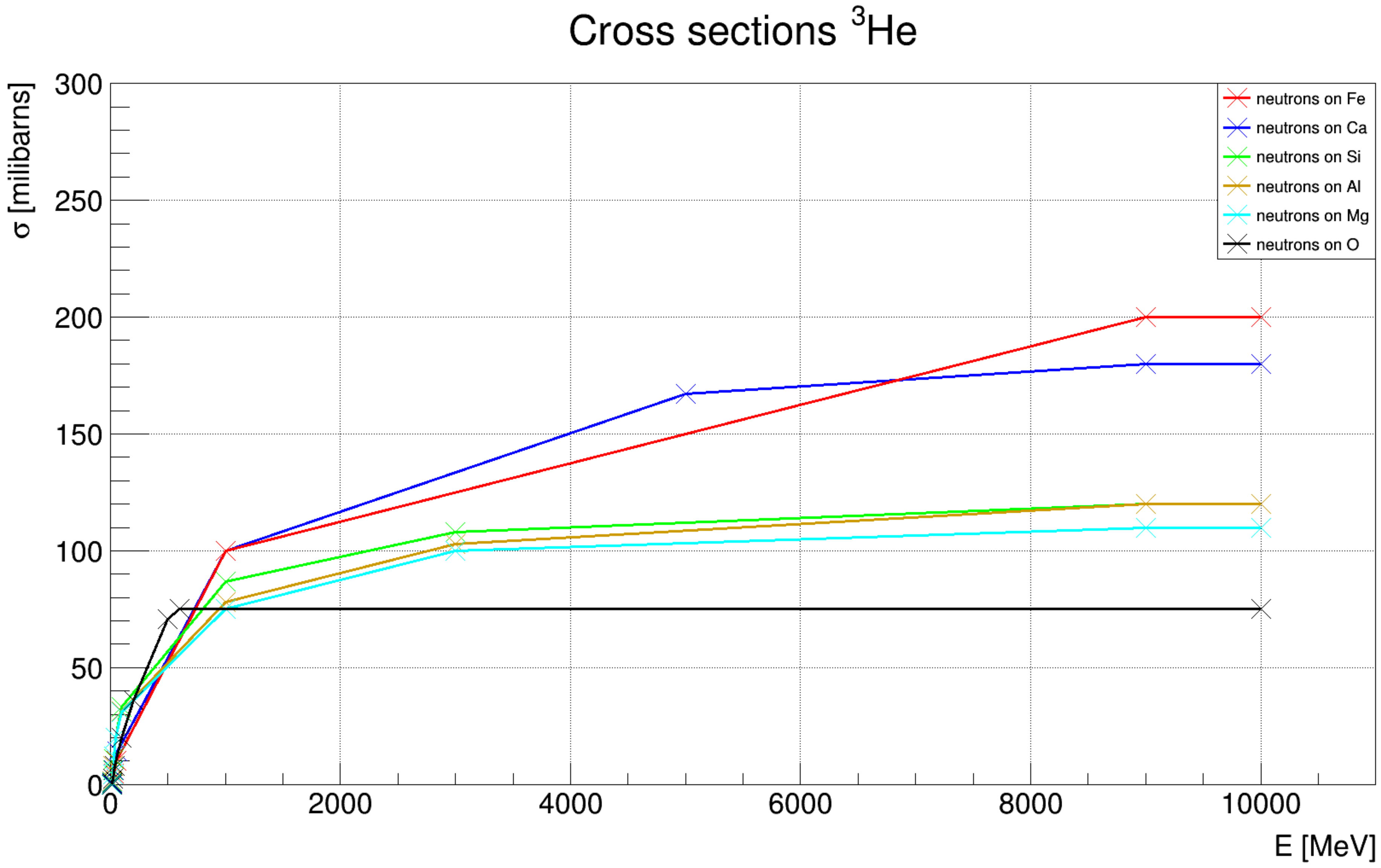
This guide is a description of the physics lists class which is one of the mandatory user classes for a GEANT4 application. For the most part the “reference” physic lists included in the source distribution are described here as well the modularity and electronic options. Some use cases and areas of application are also described.

QGSP_BIC can be used for collider physics applications, as an alternative to the recommended physics list FTFP_BERT.
It is can also be used for cosmic ray applications where good treatment of very high energy particles is required. Note, however, that is not suited to very high energy collisions of order 10 TeV or more.

Related Physics Lists

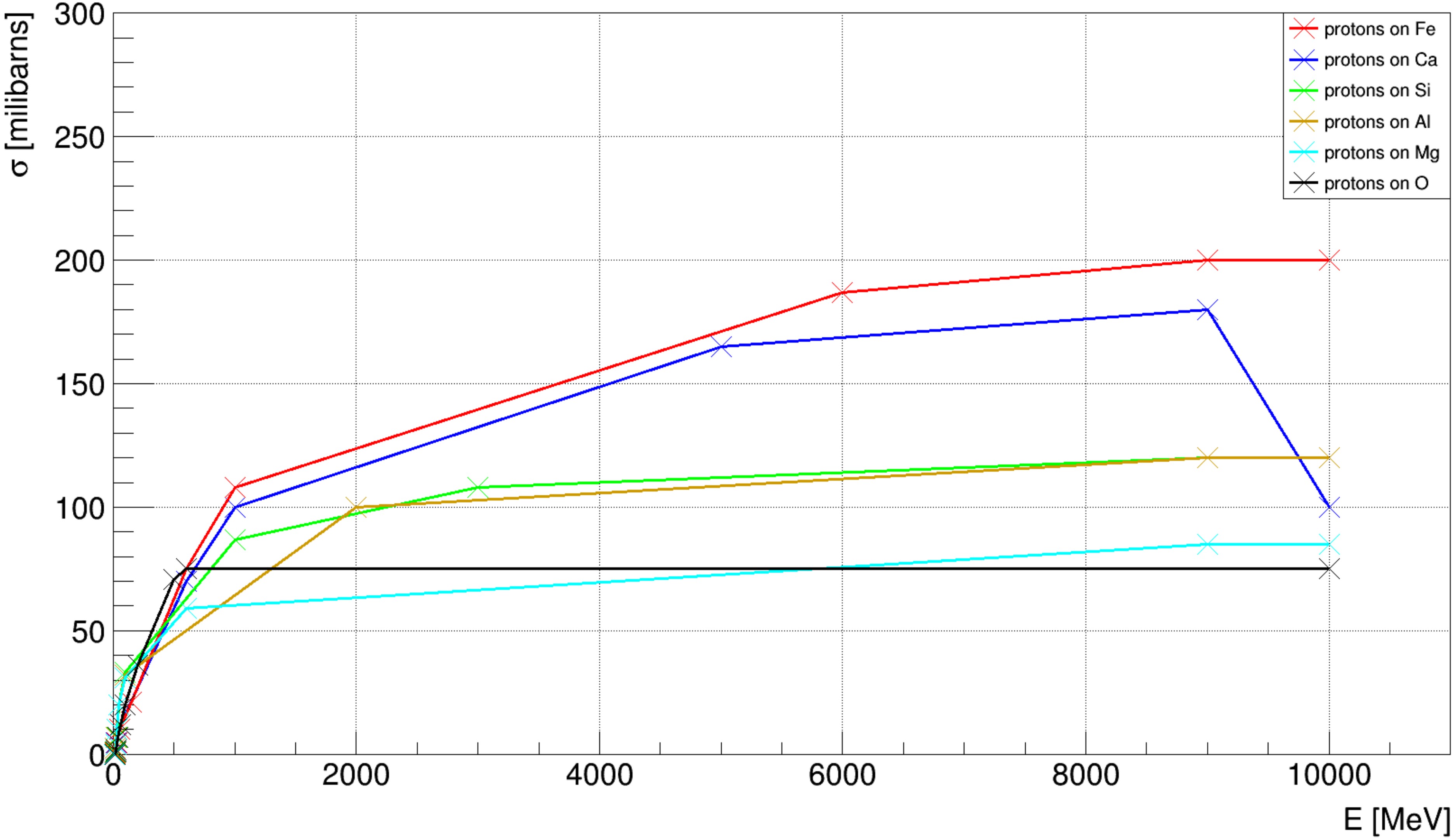
- **QGSP_BIC_HP**: identical to QGSP_BIC except that neutrons of 20 MeV and lower use the High Precision neutron models and cross sections to describe elastic and inelastic scattering, capture and fission. The G4NDL database is required for this physics list. Moreover, RadioactiveDecay is activated.
- **QGSP_BIC_AllHP**: identical to QGSP_BIC_HP except that for protons and light ions (d, t, He3, and alpha), ParticleHP is used below 200 MeV.
- **Electromagnetic options**: different configurations of electromagnetic physics are available Inelastic models), which may be used instead of the default electromagnetic physics.

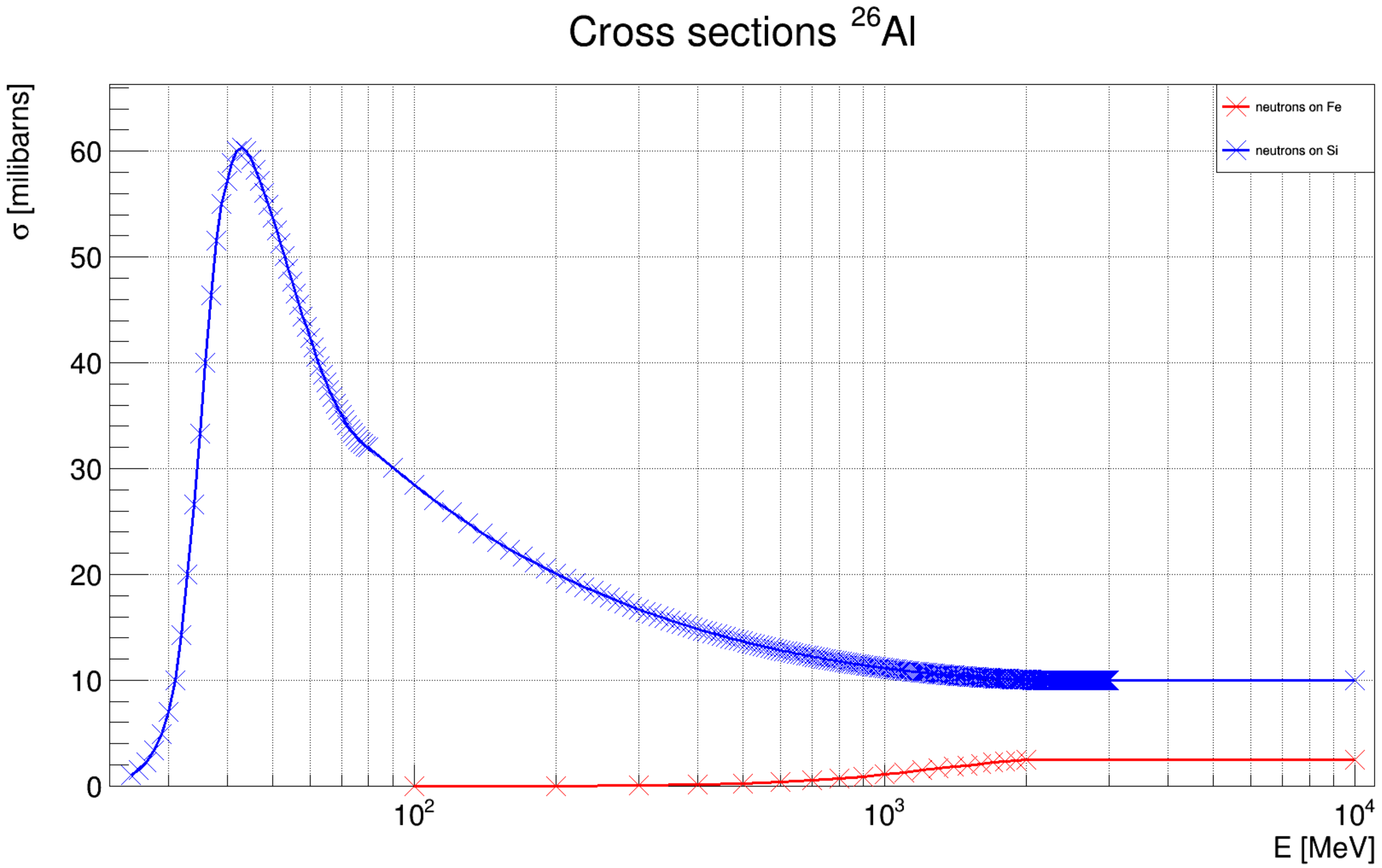
https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsListGuide/html/reference_PL/QGSP_BIC.html



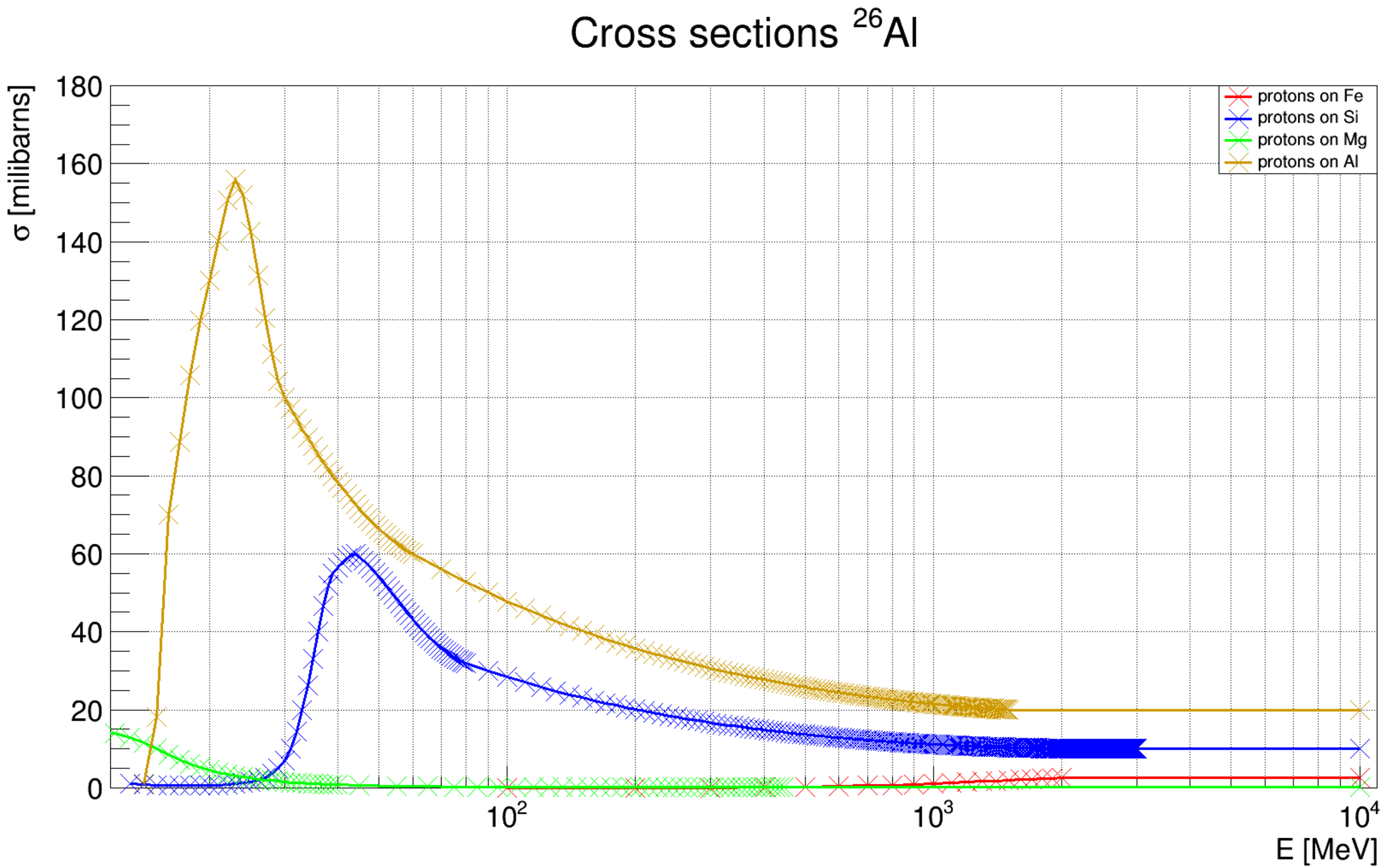
Cross sections ^{3}He
σ [milibarns]
300
250
200
150
100
50
0
0
2000
4000
6000
8000
10000
E [MeV]
neutrons on Fe
neutrons on Ca
neutrons on Si
neutrons on Al
neutrons on Mg
neutrons on O

Cross sections ^{3}He



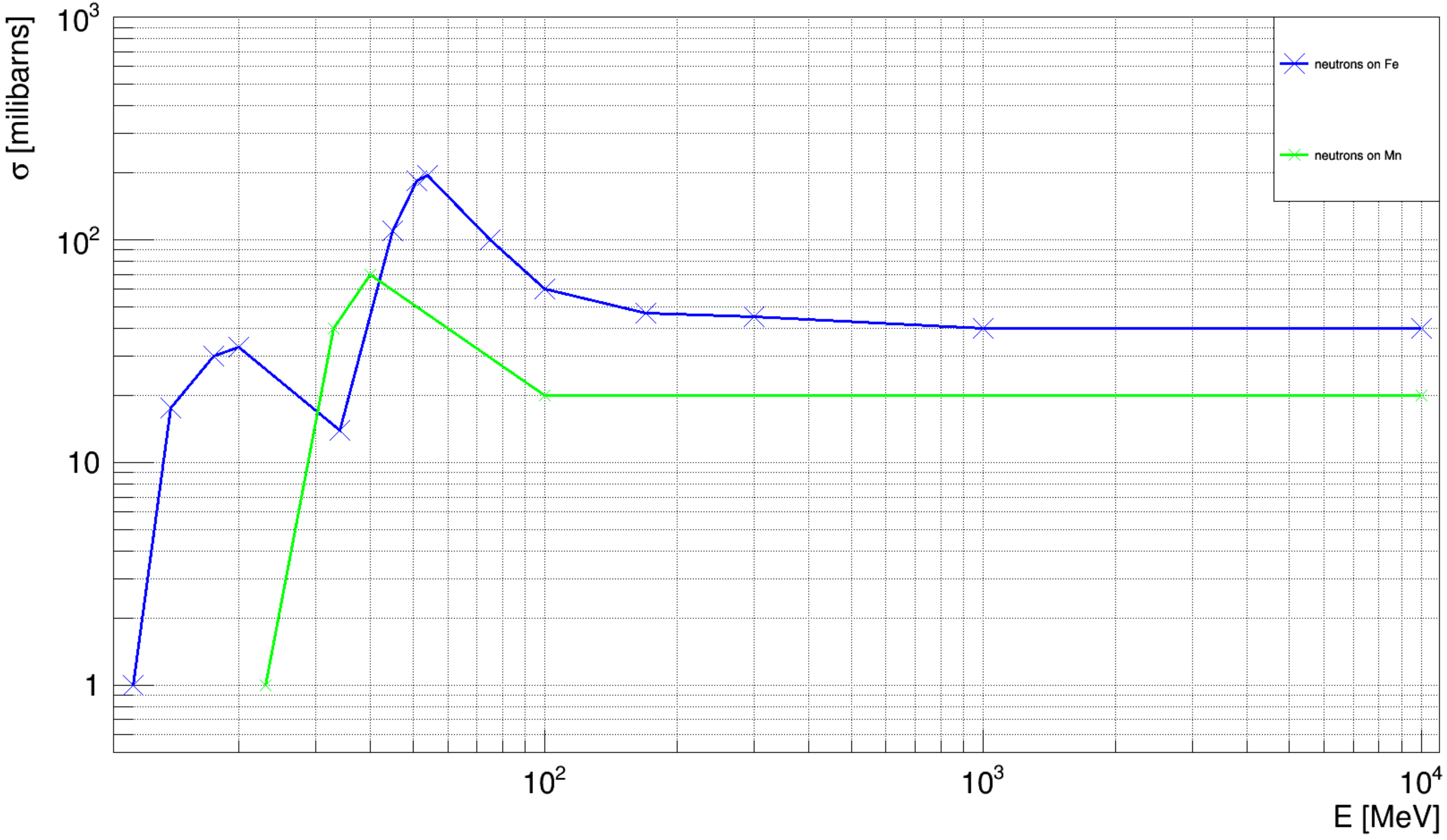


Cross sections ^{26}Al
σ [milibarns]
60
50
40
30
20
10
0
10^2
10^3
10^4
E [MeV]
neutrons on Fe
neutrons on Si

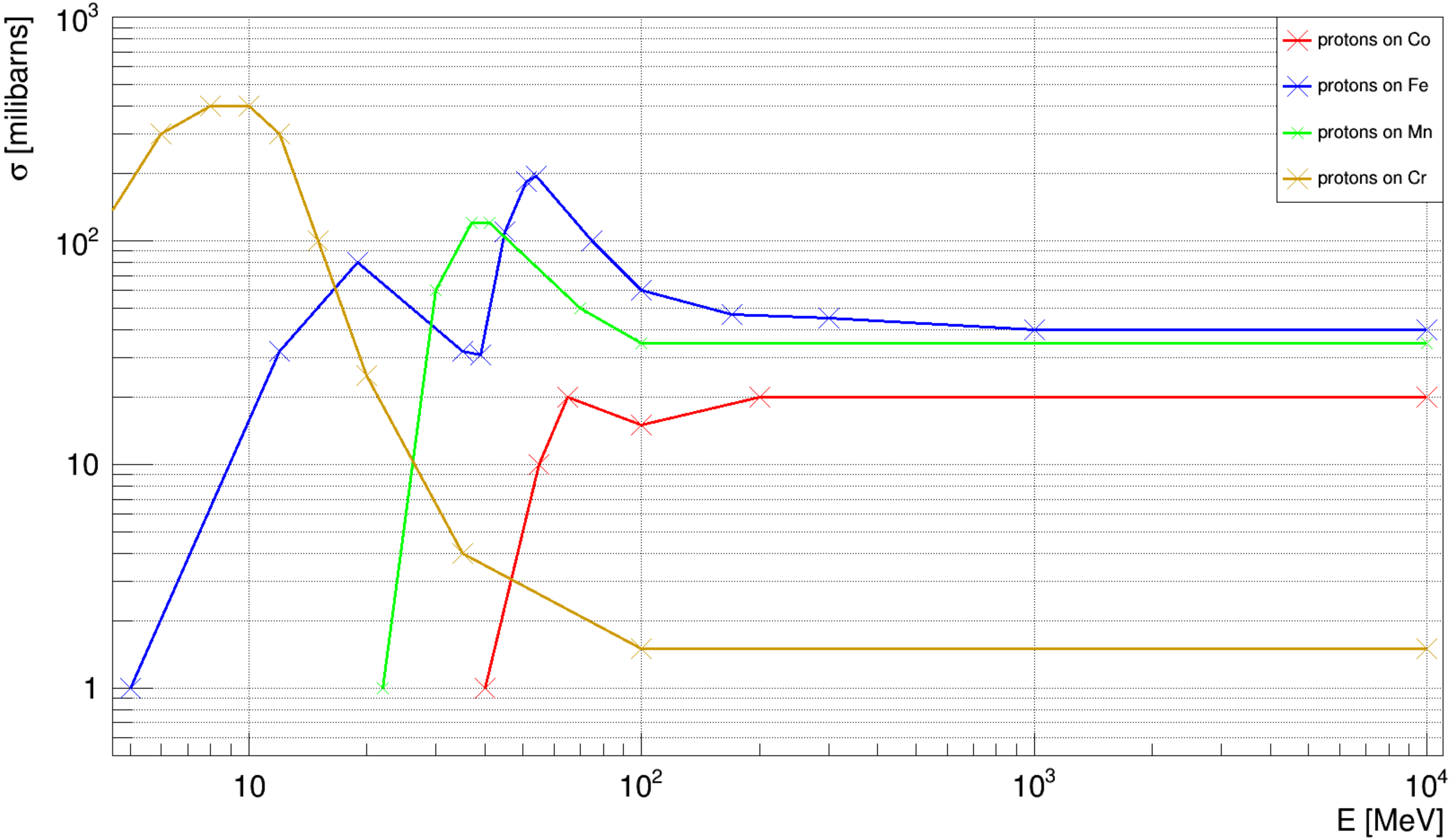


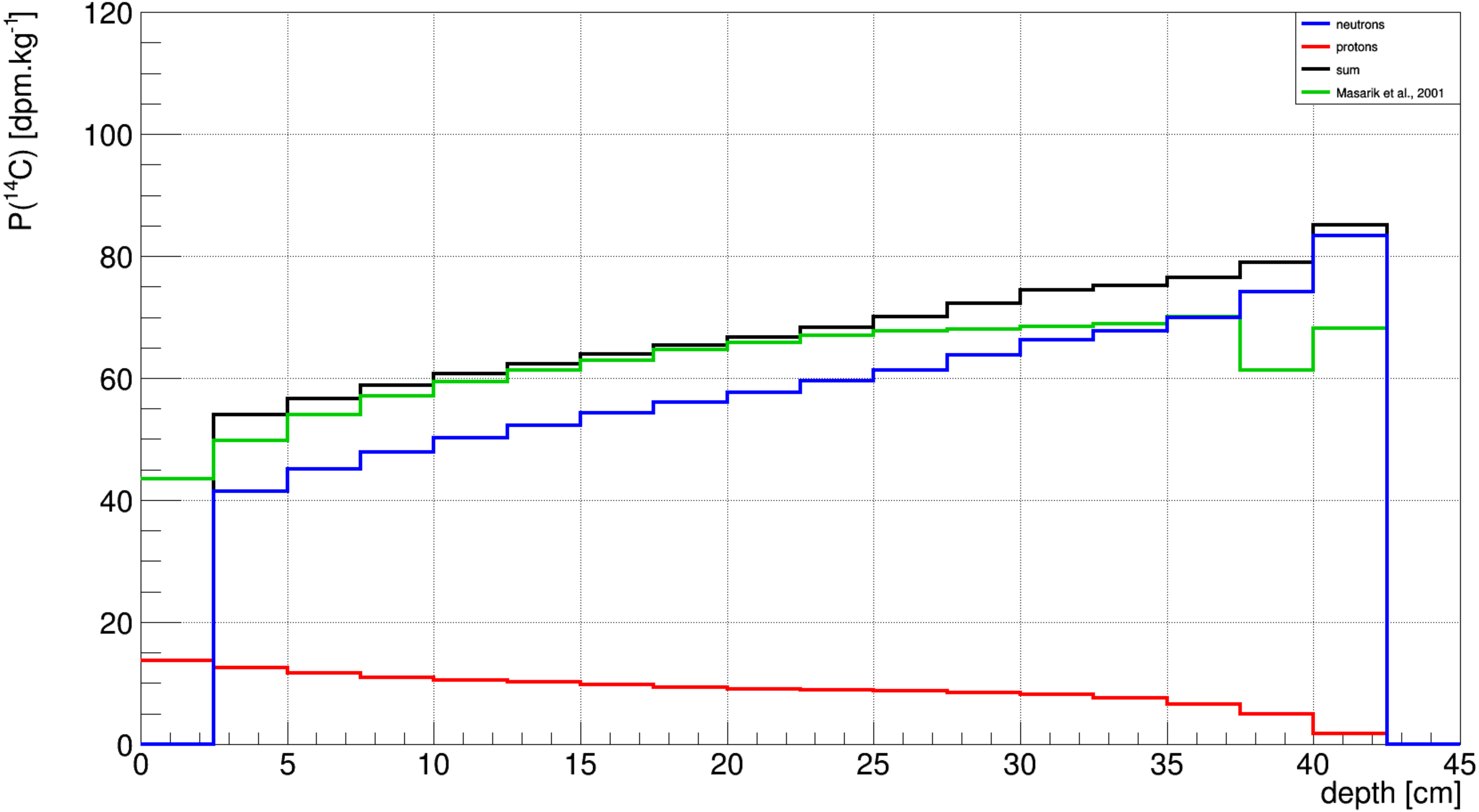
Cross sections ^{26}Al
σ [milibarns]
180
160
140
120
100
80
60
40
20
0
10^2
10^3
10^4
E [MeV]
protons on Fe
protons on Si
protons on Mg
protons on Al

Cross sections ^{53}Mn

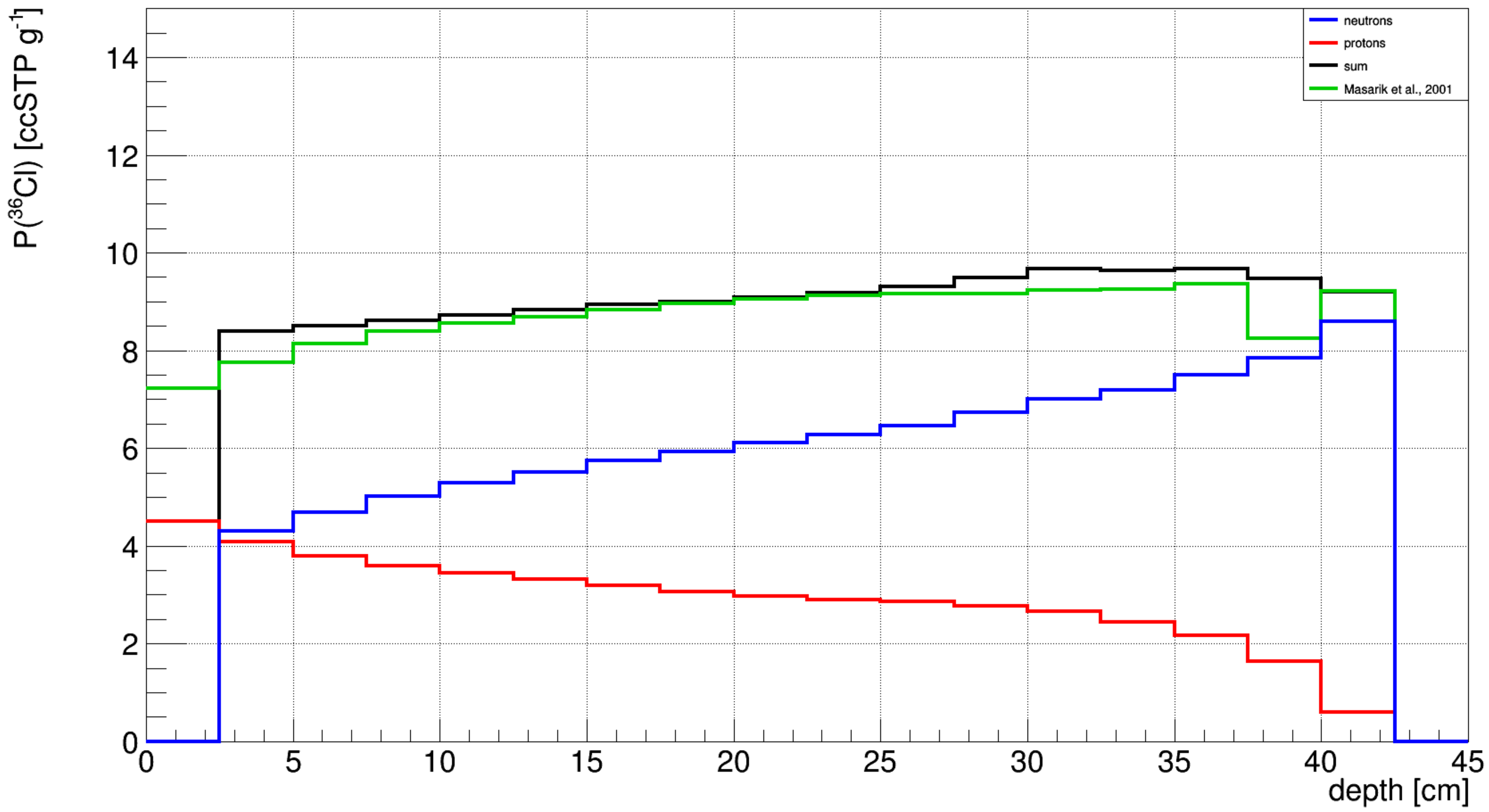


Cross sections ^{53}Mn

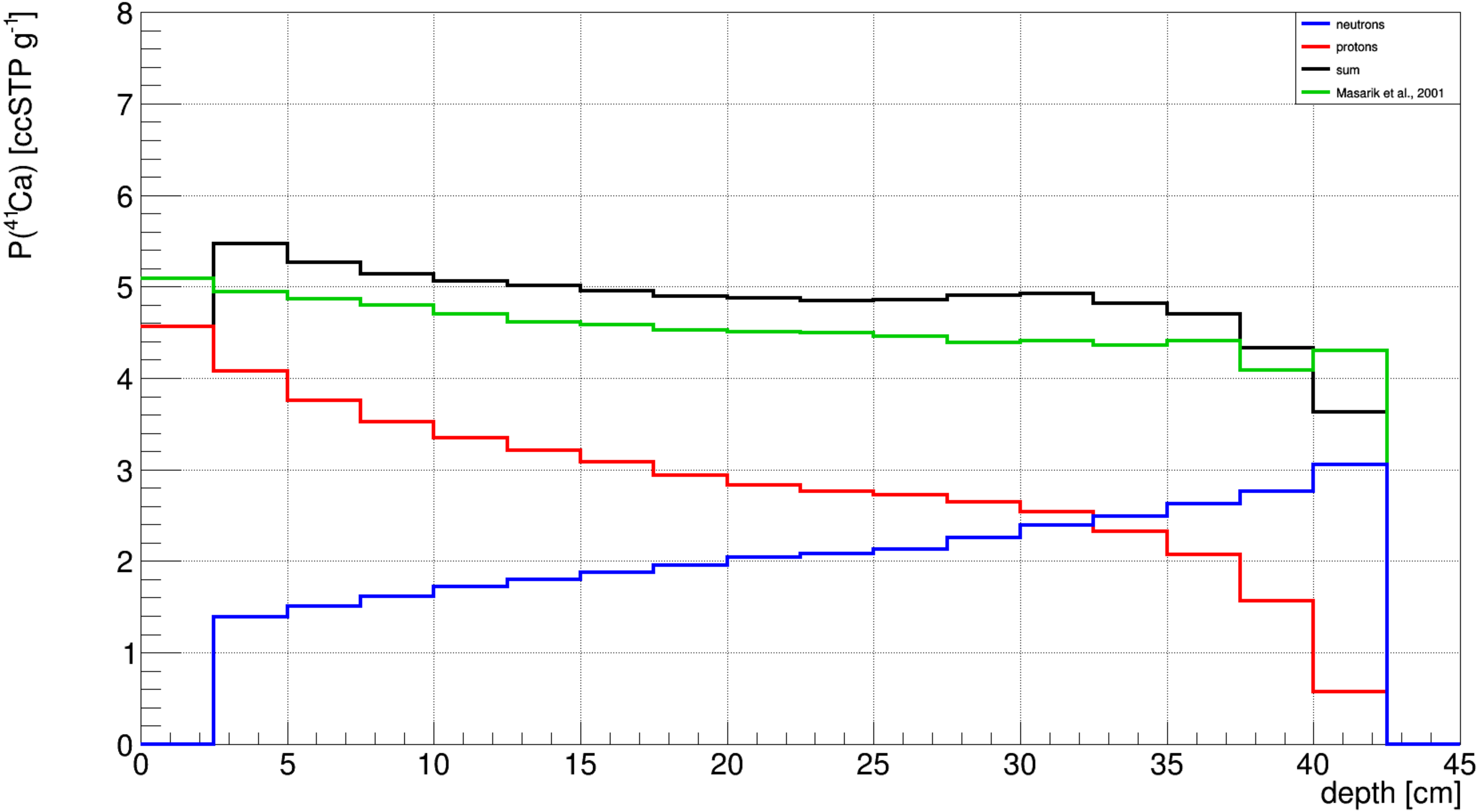




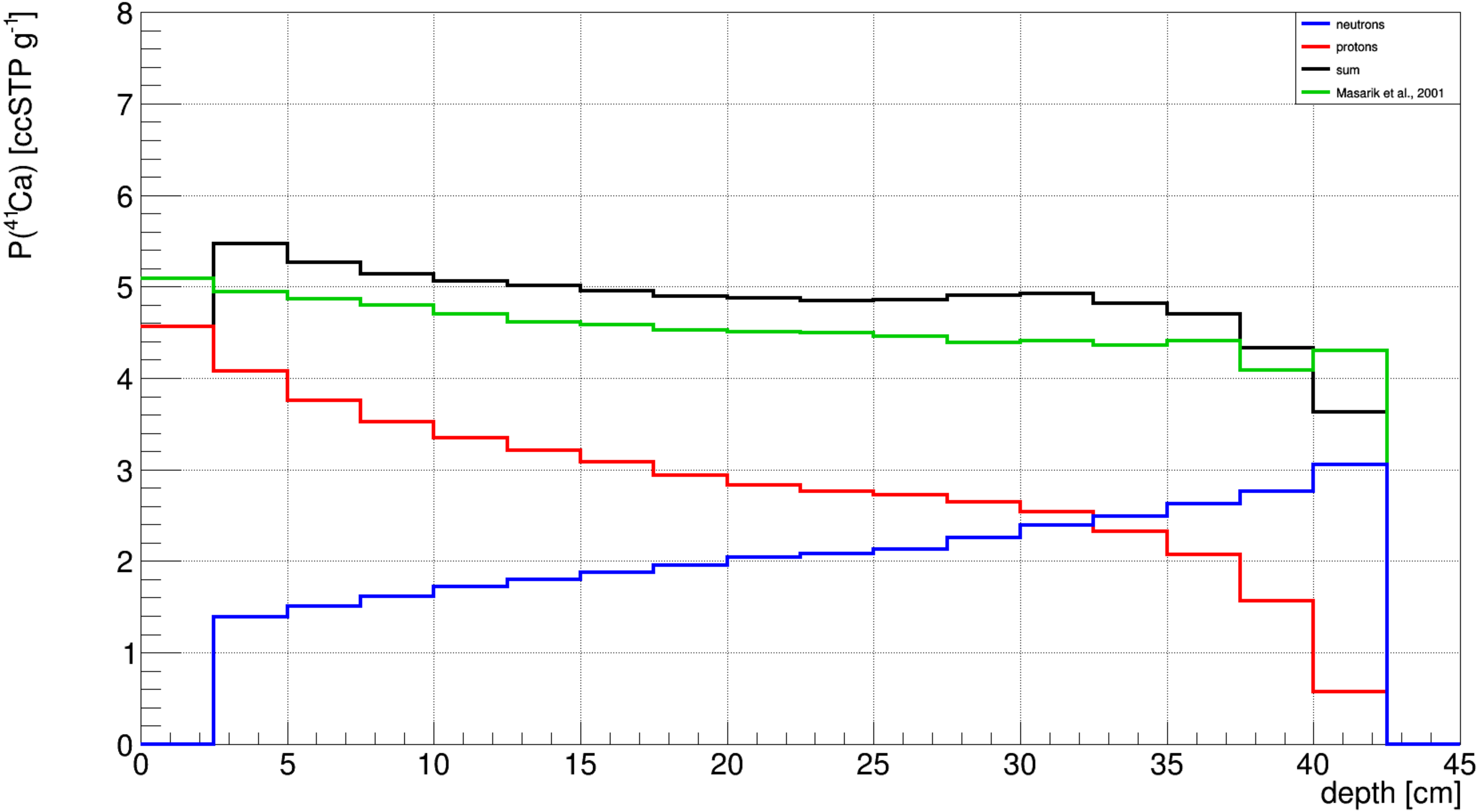
P(14C) [dpm.kg-1]
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
0
20
40
60
80
100
120
0
5
10
15
20
25
30
35
40
45

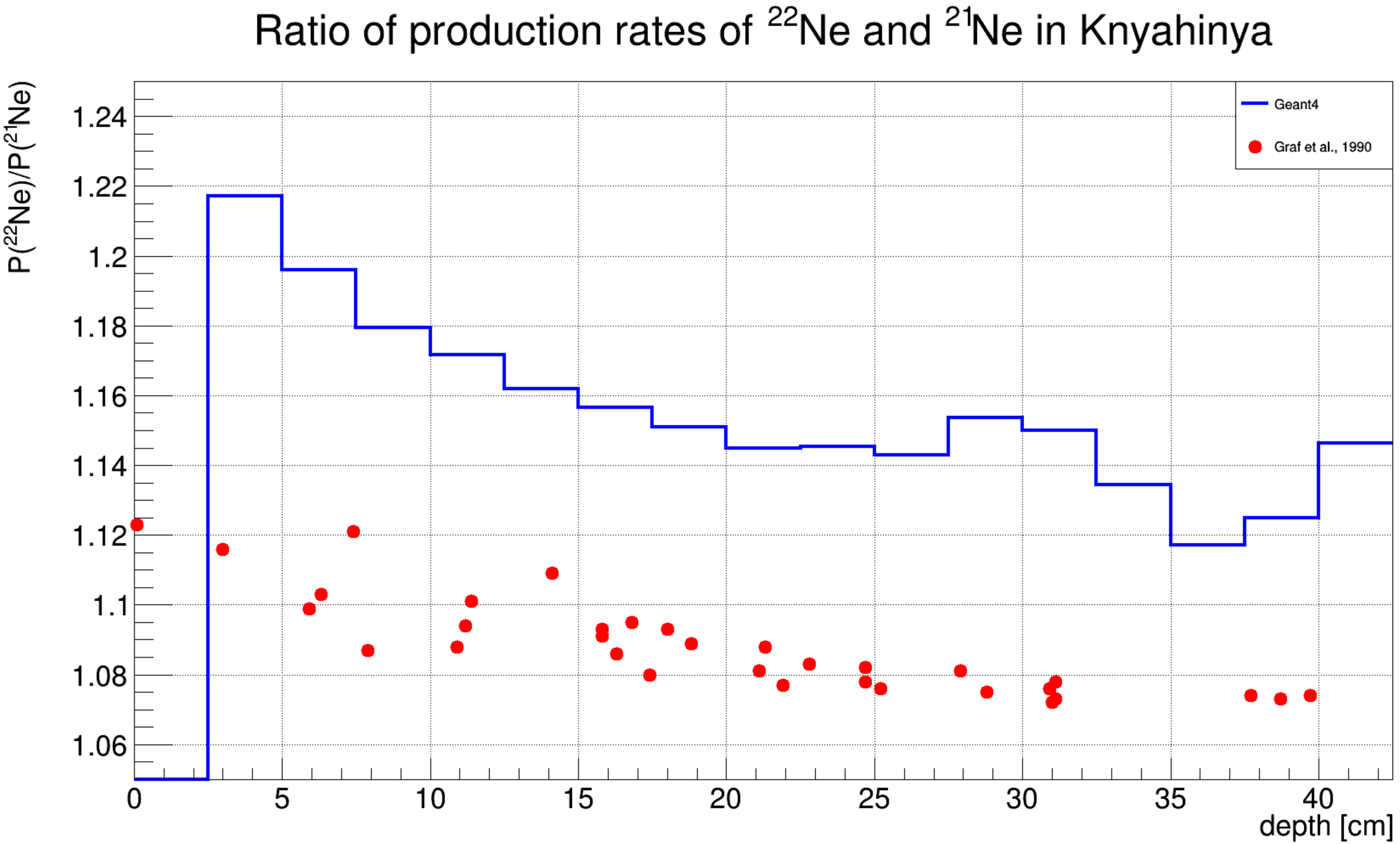


P(^{36}Cl) [ccSTP g^{-1}]
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
0
2
4
6
8
10
12
14
0
5
10
15
20
25
30
35
40
45



neutrons
protons
sum
Masarik et al., 2001
P(41Ca) [ccSTP g-1]
depth [cm]
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35
40
45


P(^{41}Ca) [ccSTP g^{-1}]
depth [cm]
neutrons
protons
sum
Masarik et al., 2001
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35
40
45



Ratio of production rates of ^{22}Ne and ^{21}Ne in Knyahinya
$P(^{22}Ne)/P(^{21}Ne)$
1.24
1.22
1.2
1.18
1.16
1.14
1.12
1.1
1.08
1.06
0
5
10
15
20
25
30
35
40
depth [cm]
Geant4
Graf et al., 1990