First measurements of the (n,Xp)Fe-nat cross sections with the Medley setup at GANIL

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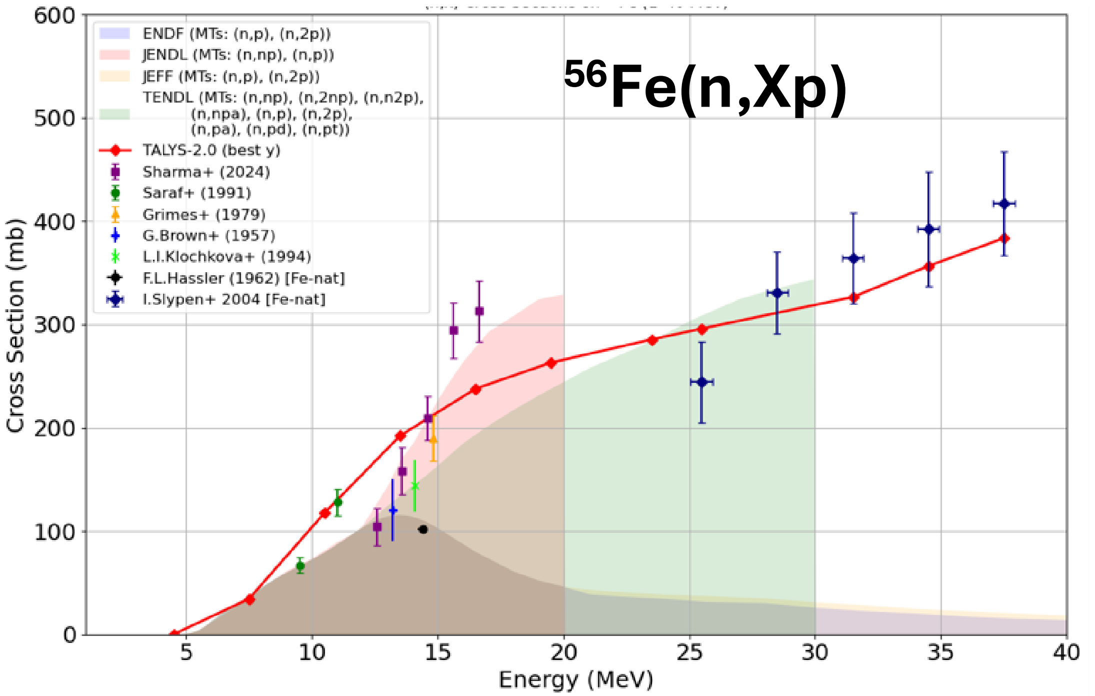
Summary

1. **Introduction:**
    a. Why measuring light ion production for neutron induced reactions
    b. Medley setup and Neutrons for Science (NFS) facility in GANIL
2. **Experimental campaigns**
3. **NFS' neutron flux reconstruction (RADNEXT project)**
4. **Some corrections needed – setup enhancement**
5. **First cross sections**
6. **Next steps**

Introduction: Why measuring light ion production for neutron induced reactions

- Very scarce data for a series of materials
- Several applications
- For some materials, the total cross sections are also scarce



In particular, considering **structural materials**:

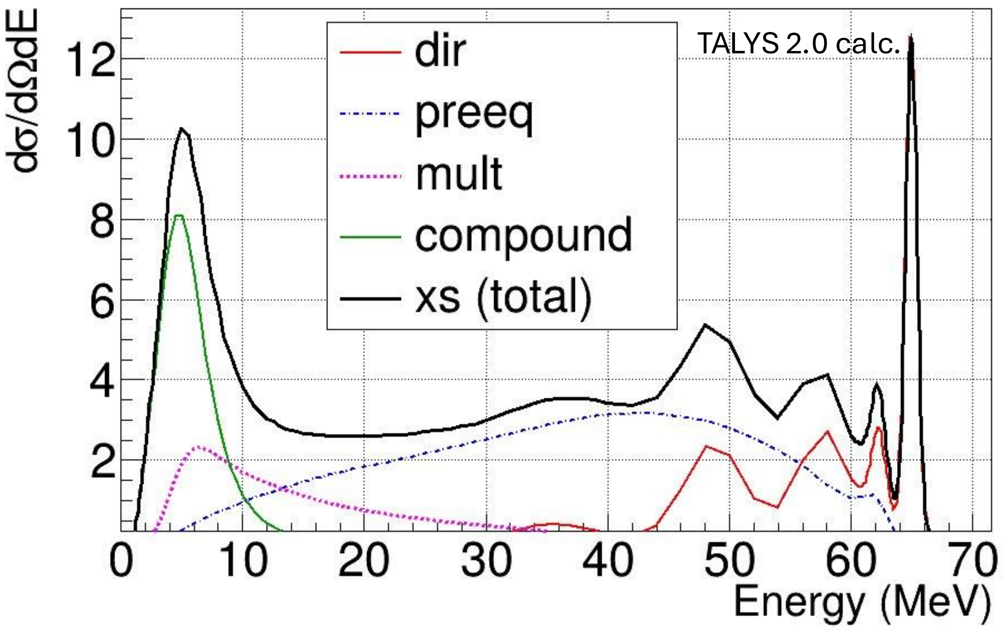
- Swealling and embrittlement of the material due to formation of gas inside it.
- Interpretation of IFMIF-DONES (International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source) data.
- Improving theoretical models for pre-equilibrium emission
- Improving the data evaluations

And more diverse applications:

- Radiation protection
- Dosimetry for aviation and spaceflight, electronics (single-event effects)

Introduction: Why measuring light ion production for neutron induced reactions

Typical double differential cross section (DDX) spectrum:



Three main mechanisms:

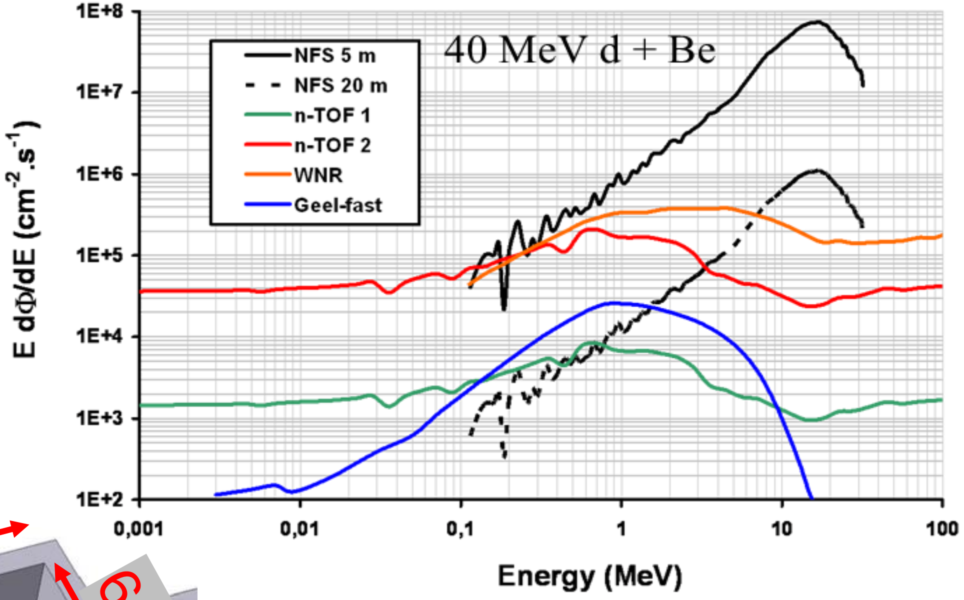
- Compound
  - Very slow
  - Isotropic emission
  - No memory of entrance channel
- Direct
  - Very fast
  - Forward-peaked
  - Few nucleons involved
- Pre-equilibrium
  - Partial equilibrium
  - Multiple nucleons involved
  - Semi-isotropic

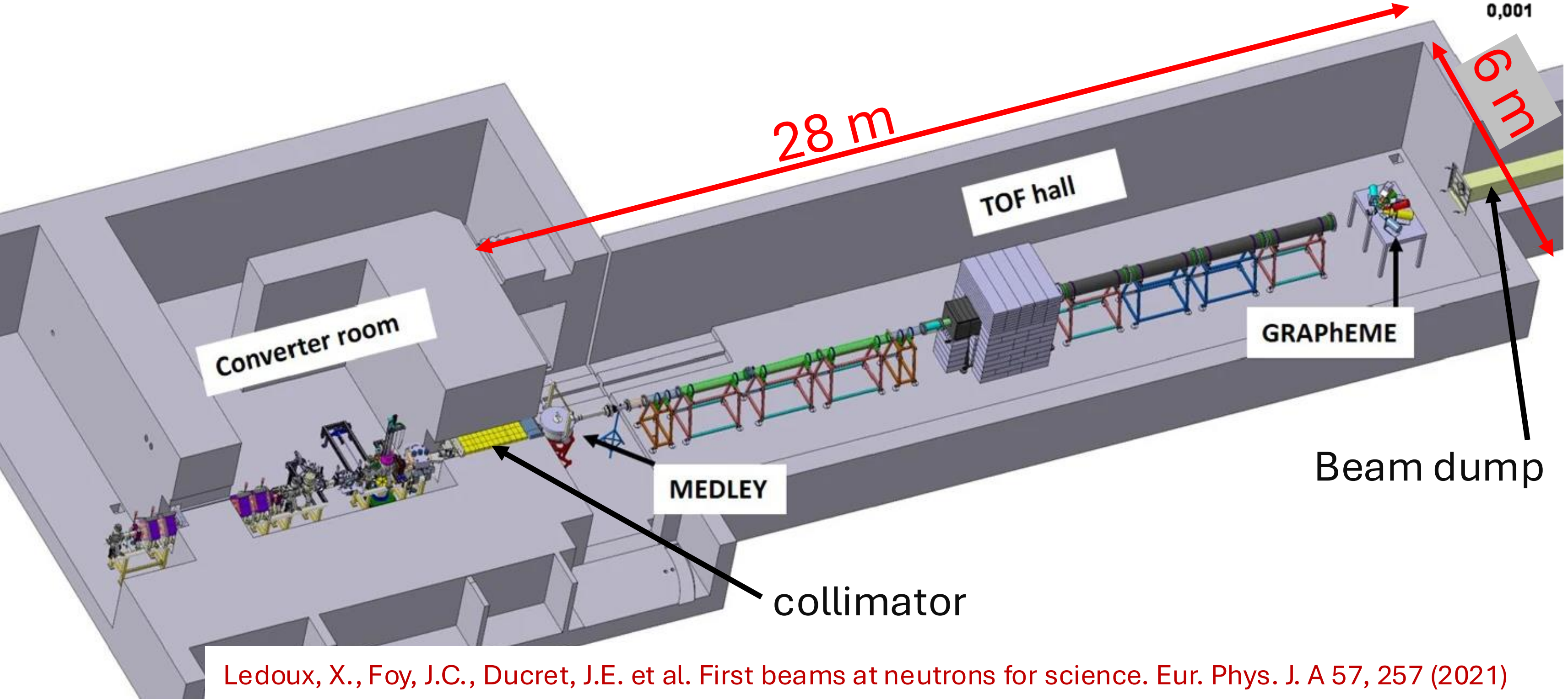
Introduction: Medley setup and **Neutrons for Science (NFS) facility in GANIL**

It is currently operating in Neutron For Science (NFS) facility, in GANIL, France.

- Very intense **white neutron** beam (up to 44 MeV)
- Relatively new facility

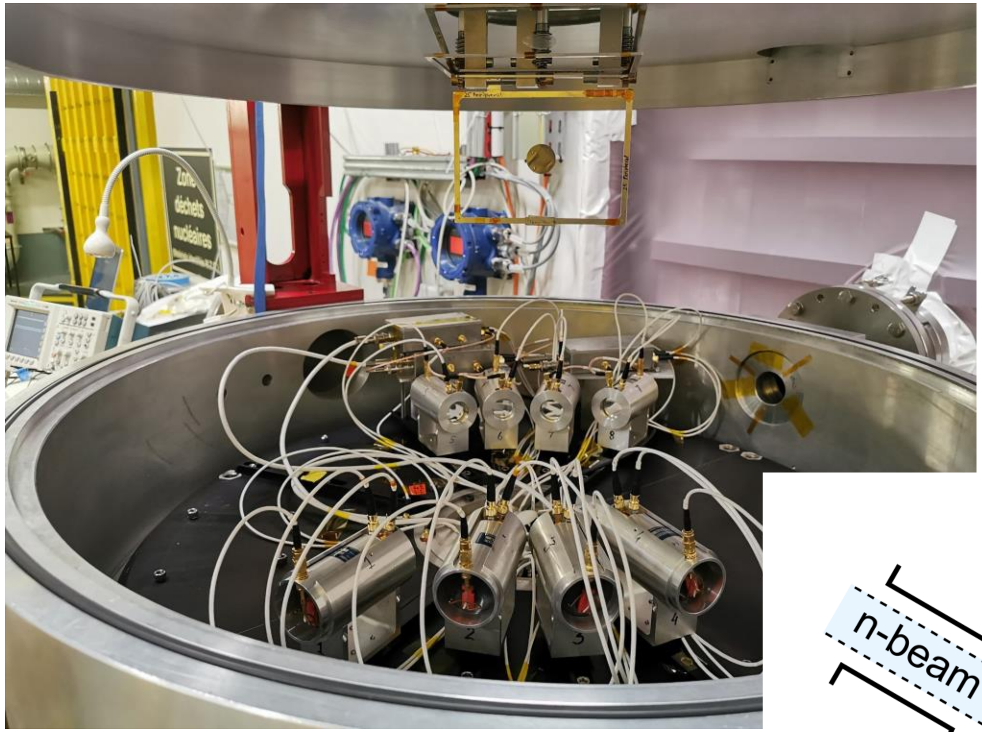
--> Ideal to measure DDXs with a few mb order of magnitude





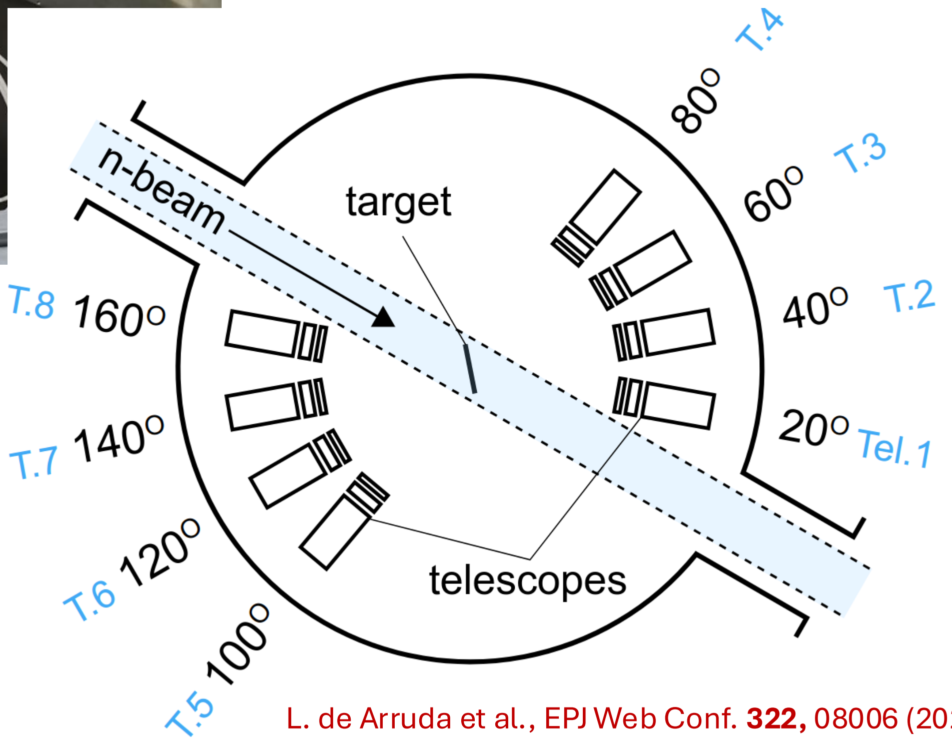
Ledoux, X., Foy, J.C., Ducret, J.E. et al. First beams at neutrons for science. Eur. Phys. J. A 57, 257 (2021)

Introduction: **Medley setup** and Neutrons for Science (NFS) facility in GANIL

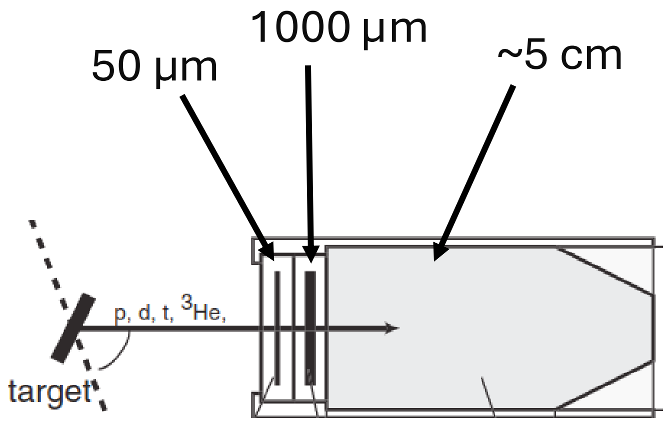


Medley setup was developed in Uppsala University, and is composed of:

- Eight (4x2) three-detector telescopes for PID
- Target holder (supporting up to three targets)
- Rotating table, possibility to exchange detector sets



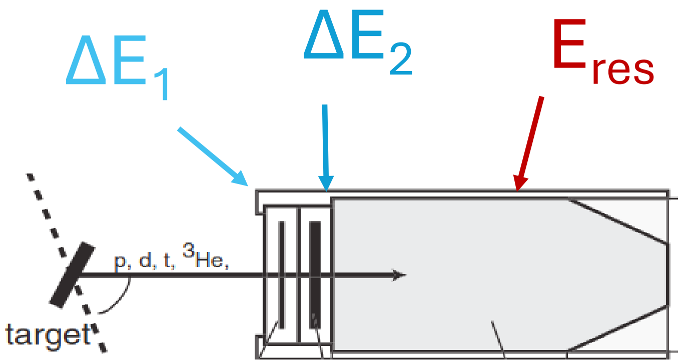
L. de Arruda et al., EPJ Web Conf. **322,** 08006 (2025).

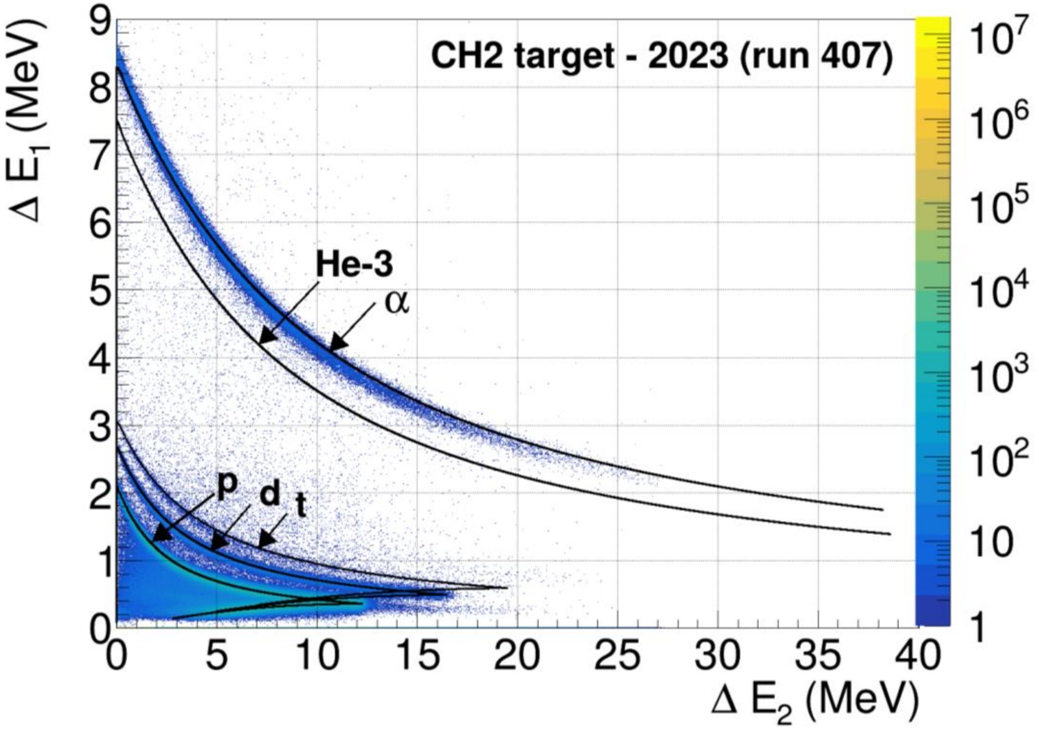


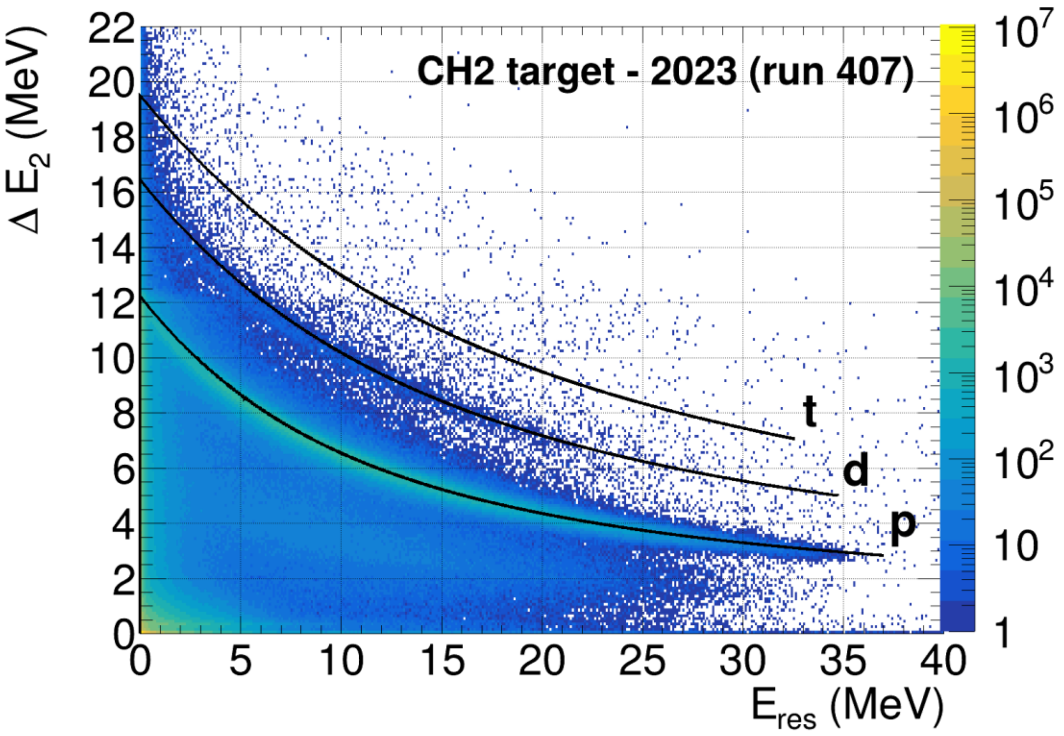
M. Hayashi et al., Proc. ND 2007, p. 1091-1094

Ion identification

- Medley presents high capacity for distinguish H and He isotopes over a wide range
  - Correct combination of detectors
- => ΔE-ΔE-E PID method



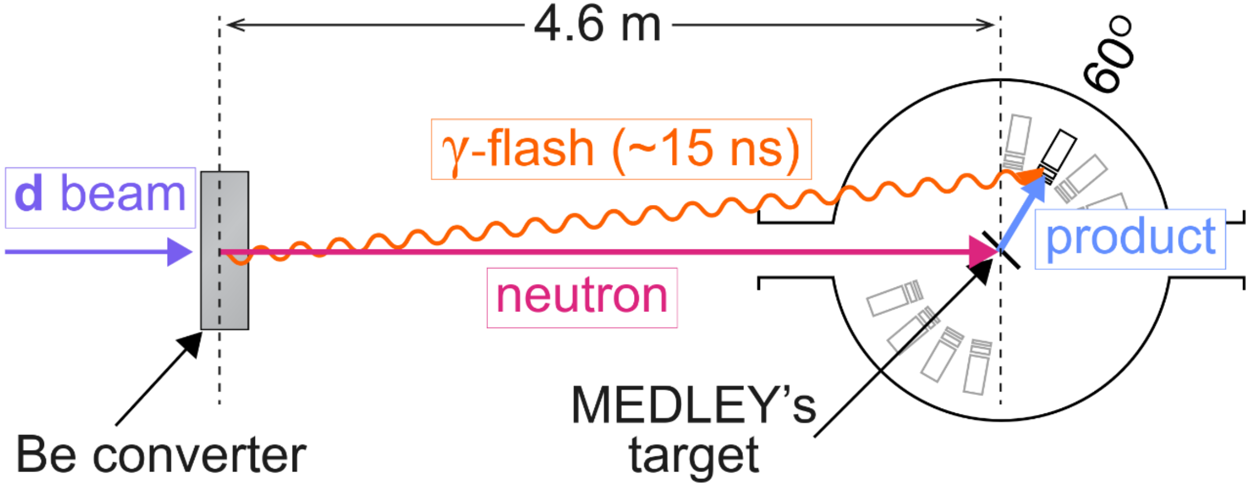


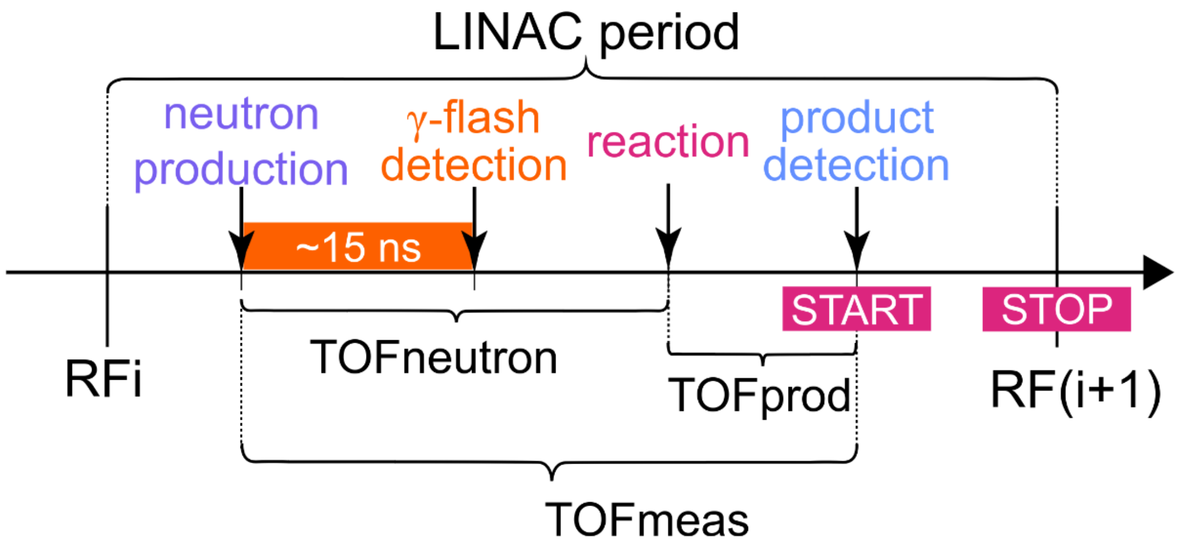


Introduction: **Medley setup** and Neutrons for Science (NFS) facility in GANIL

Time of Flight (ToF) measurement

- ToF measurement is possible given that our Si detectors are sensitive **enough** to the gamma flash generated when the neutron beam is produced
- The setup has a good timing resolution to operate very close to the target, maximizing its efficiency
- The NFS' spectral neutron flux is measured for every experimental campaign; the result is them used to evaluate the DDXs, minimizing systematic errors

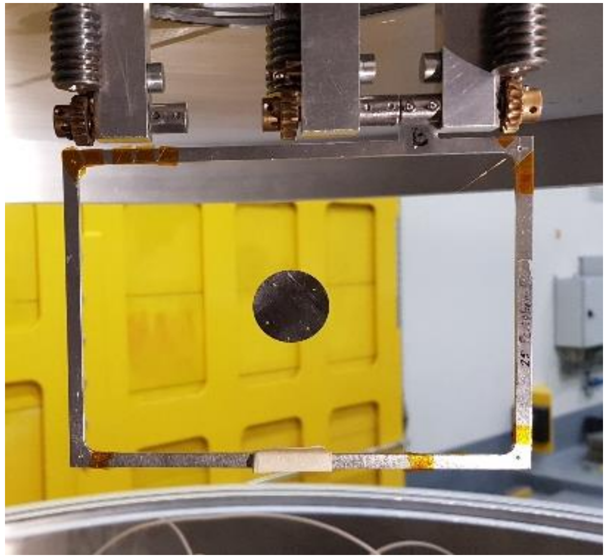




Experimental Campaigns

- Several experiments were carried out with Medley at NFS:

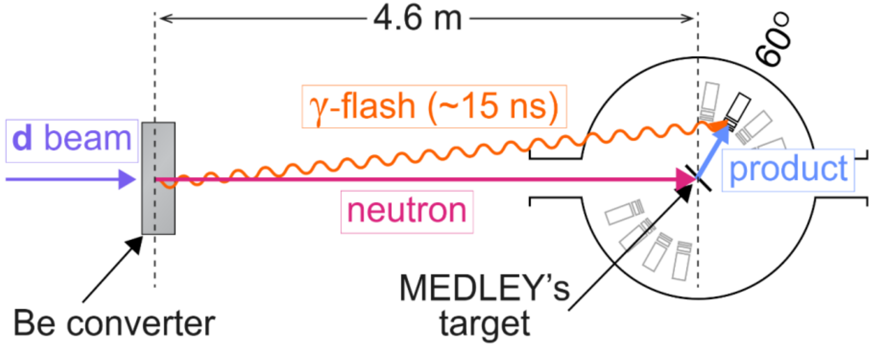
1. **LIONS (Light ION production Studies with Medley) - 2021/2022**
   a. Carbon
2. **GARIC (GAs pRoduction In Chromium by neutrons) - 2022/2023**
   a. Chromium
3. **CATRIN (Characterization of neutron fields at the emerging NFS facility) - 2022 (RADNEXT project) - Fininshed**
   a. Characterization of the neutron flux using Medley
4. **GARROS (Gas pRoduction in iROn by neutronS) - 2024**
   a. Iron
5. **Gas production study in copper - 2024**
   a. Project conducted by collaborators from UKAEA
6. **GARSIO: Gas production in silicon and oxygen by neutrons – Approved**
   a. Silicon and Oxygen

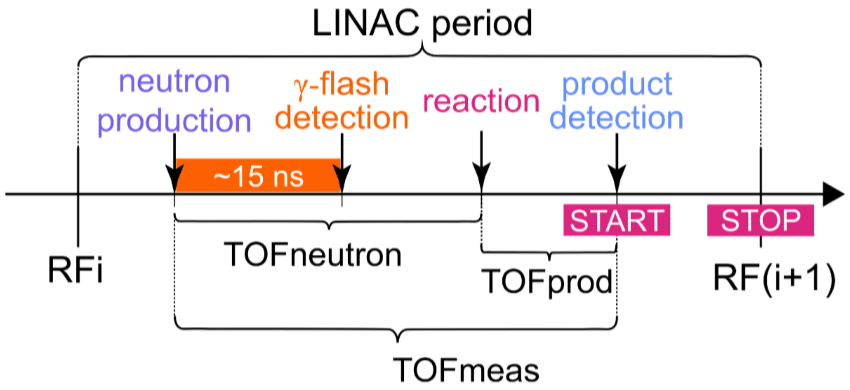


Target installed in Medley.

NFS' neutron flux reconstruction (RADNEXT project)

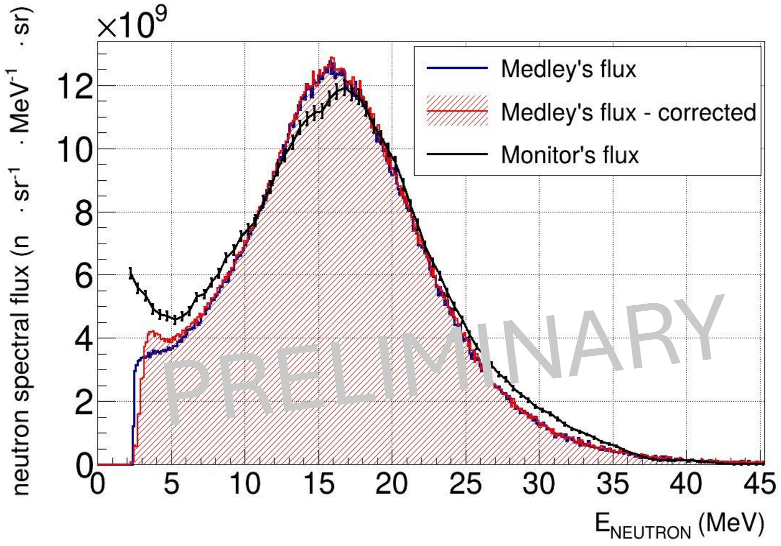
Using a CH_2 and a C target, we can measure the (n,p) elastic scattering. From this point, two methods can be used to obtain the spectral neutron flux:





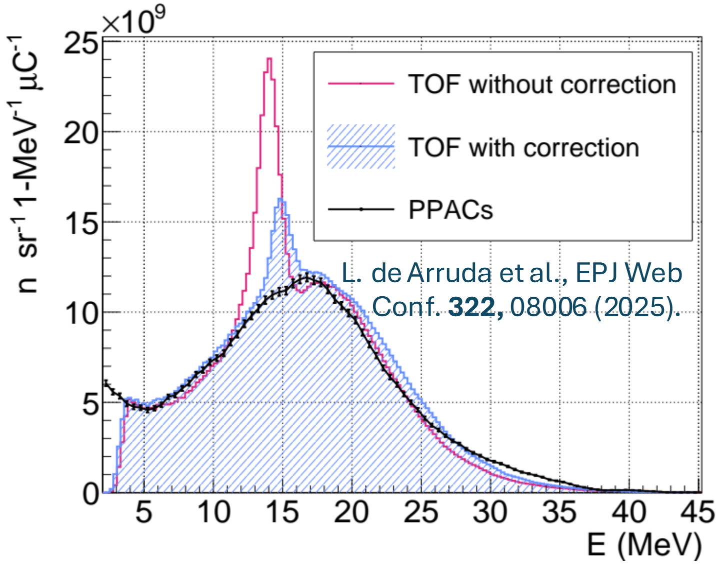
Direct method: reconstruction En from Ep for (n,p) events:

$$E_p = E_n \frac{4 M_p M_n cos^2\theta_{LAB}}{(M_p + M_n)^2}$$



ToF method: From $TOF_{neutron} \Rightarrow E_{neutron}$

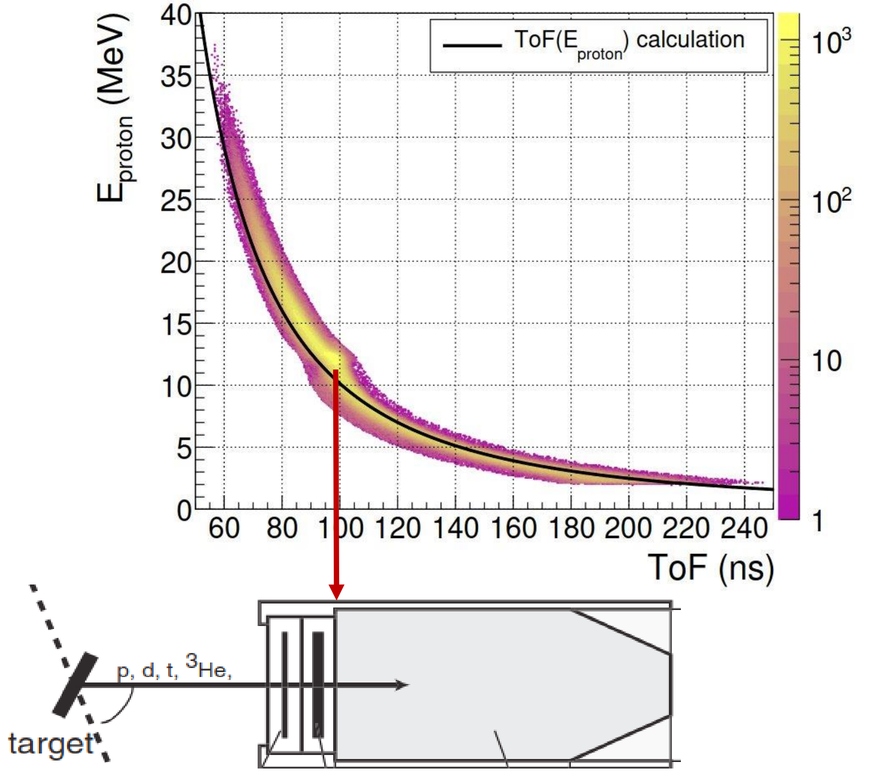
$$N_p(E_n) = \varphi(E_n) \cdot \frac{1}{D^2} \cdot N_H \cdot \frac{d\sigma}{d\Omega}(E_n, \theta_{LAB}) \cdot \Delta\Omega_{tel} \cdot Q$$



Some corrections needed – setup enhancement

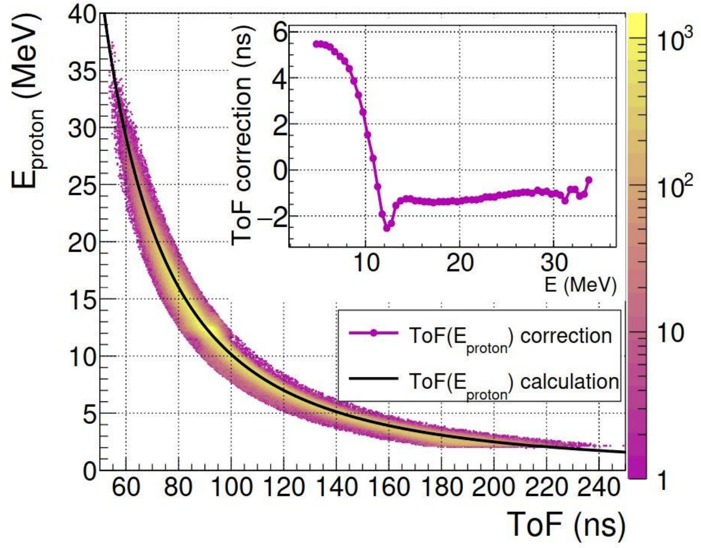
- Timing correction
- Energy correction
- Thick target correction

A difference of pulse shape when the particle punches through the detector* introduces a walk effect on our CFD filter
--> deviation in measured ToF

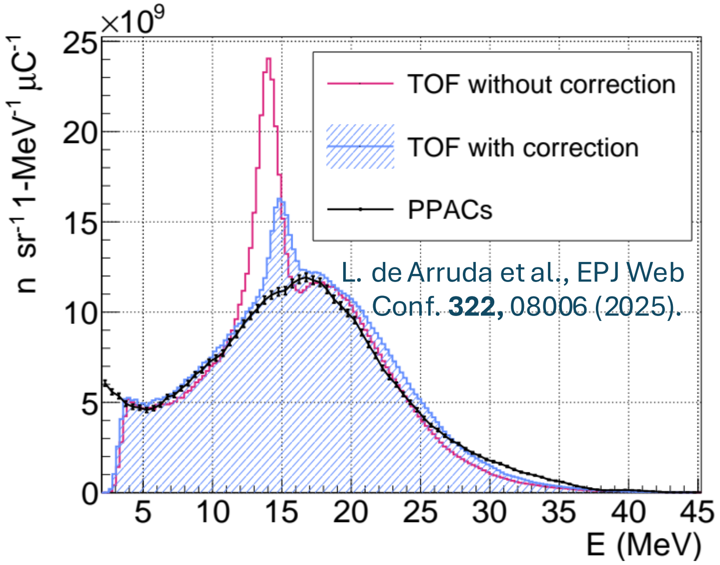


*The second silicon is our timing detector.

First order correction for this effect was produced:



Enhancing the obtained spectral flux (via ToF):

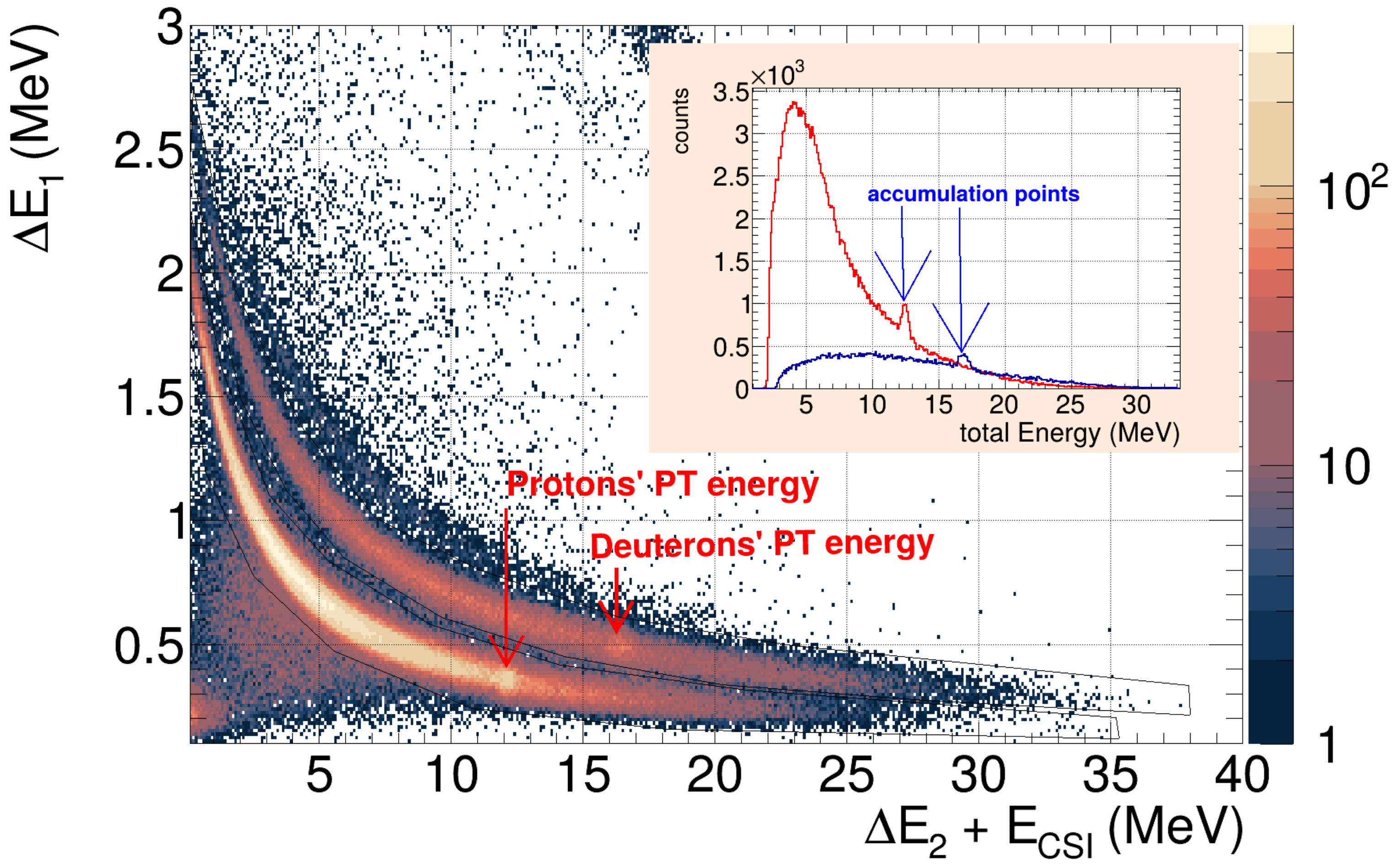


L. de Arruda et al., EPJ Web Conf. **322,** 08006 (2025).

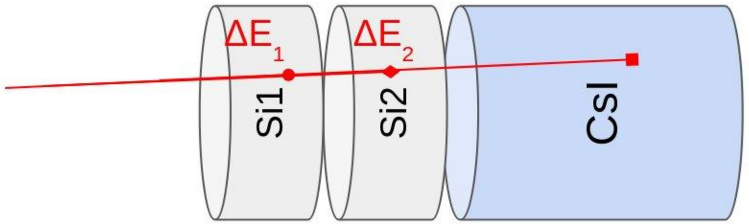
Some corrections needed – setup enhancement

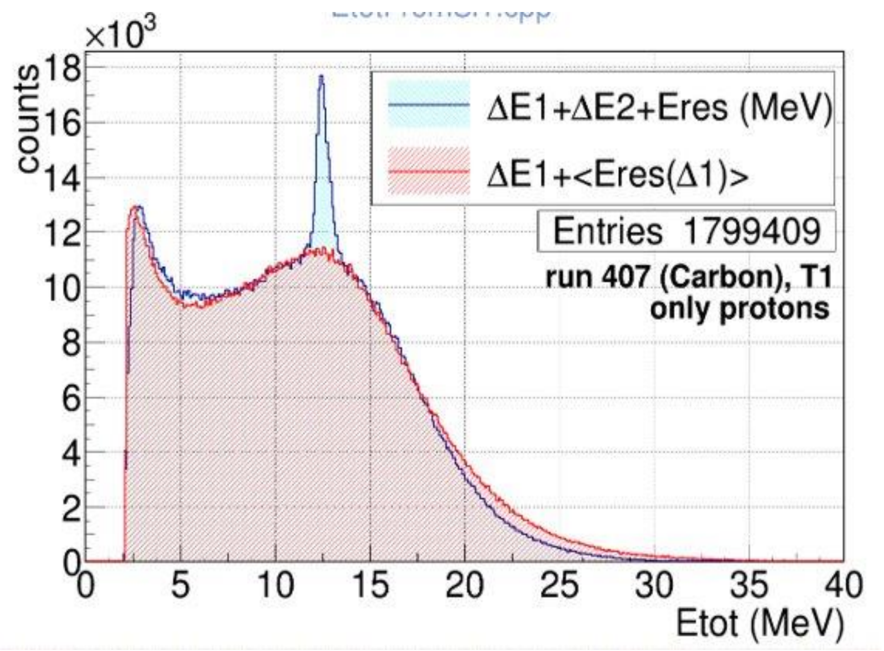
- Timing correction
- Energy correction
- Thick target correction

It is also needed to correct for the energy lost between the Si2 and the CsI (matching problem):



It is carried out by calculating the expected remaining energy for an **identified particle** to correct the events' total energy:

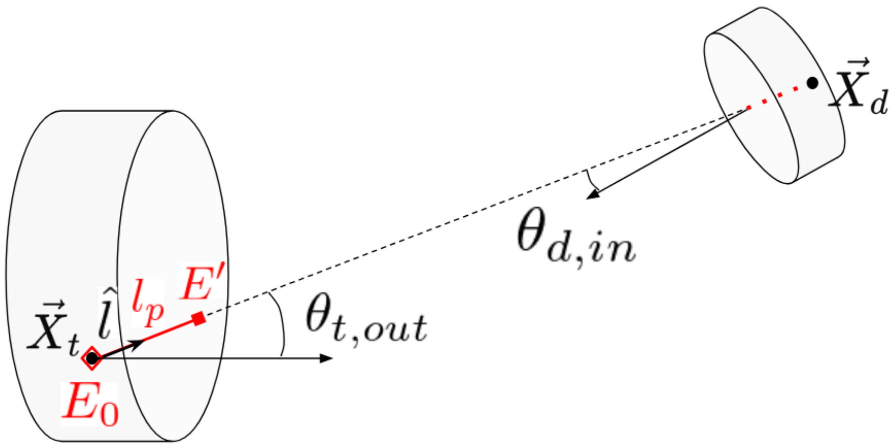




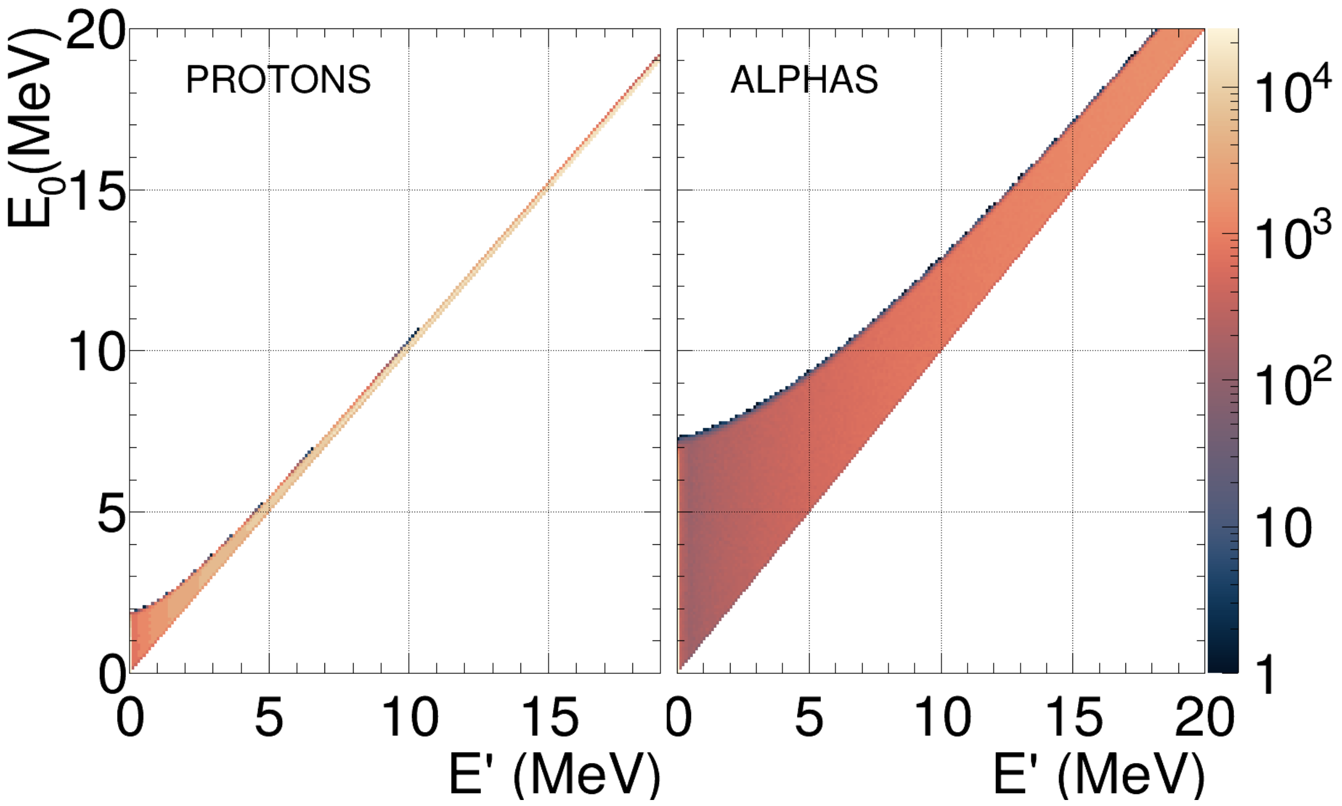
Some corrections needed – setup enhancement

- Timing correction
- Energy correction
- Thick target correction

We need to correct our measurements for the losses of energy within the target:



- This is done using Monte Carlo method together with Eloss tables.



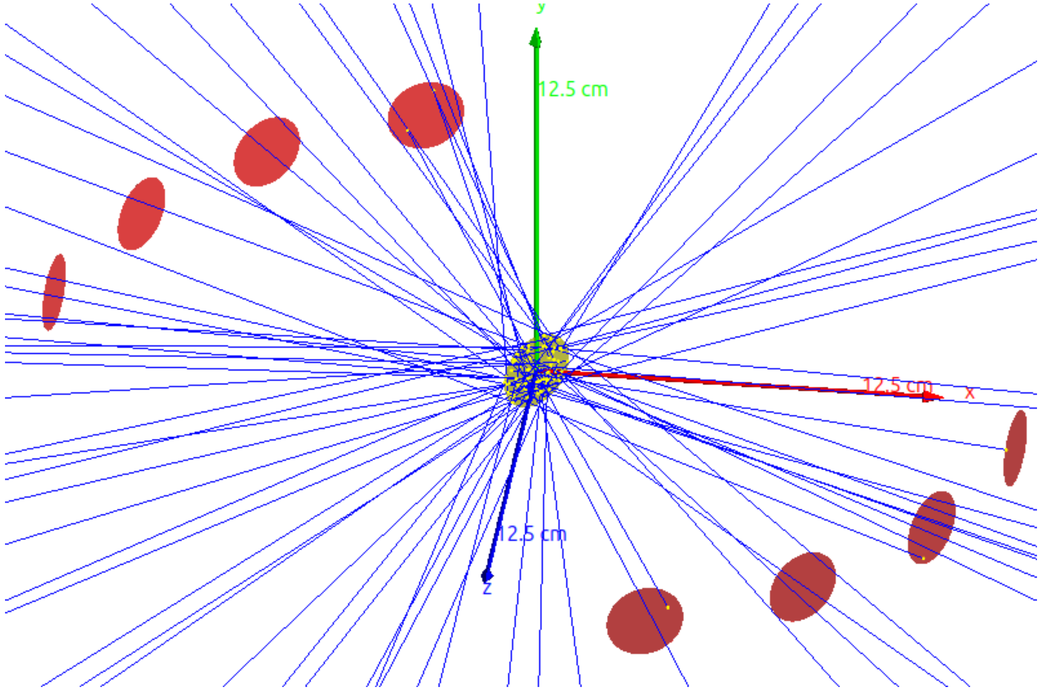
- The idea is to produce a response function to deconvolve E0 from E'

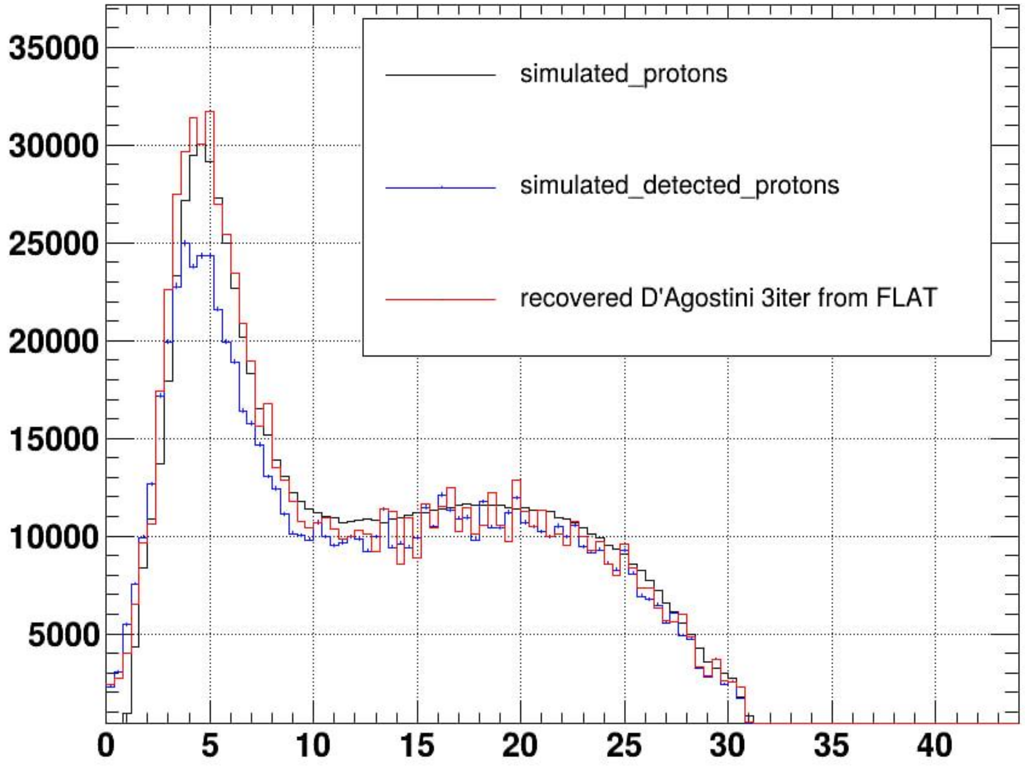
Some corrections needed – setup enhancement, V2

- Timing correction
- Energy correction
- Thick target correction

- Geant4 calculations to encompass more detailed physics.
- Reconstruction uses Bayesian approach (D'Agostini's method).
- Some fine-tunning still needed, validation (using TALYS) is promising.

We need to correct our measurements for the losses of energy within the target:

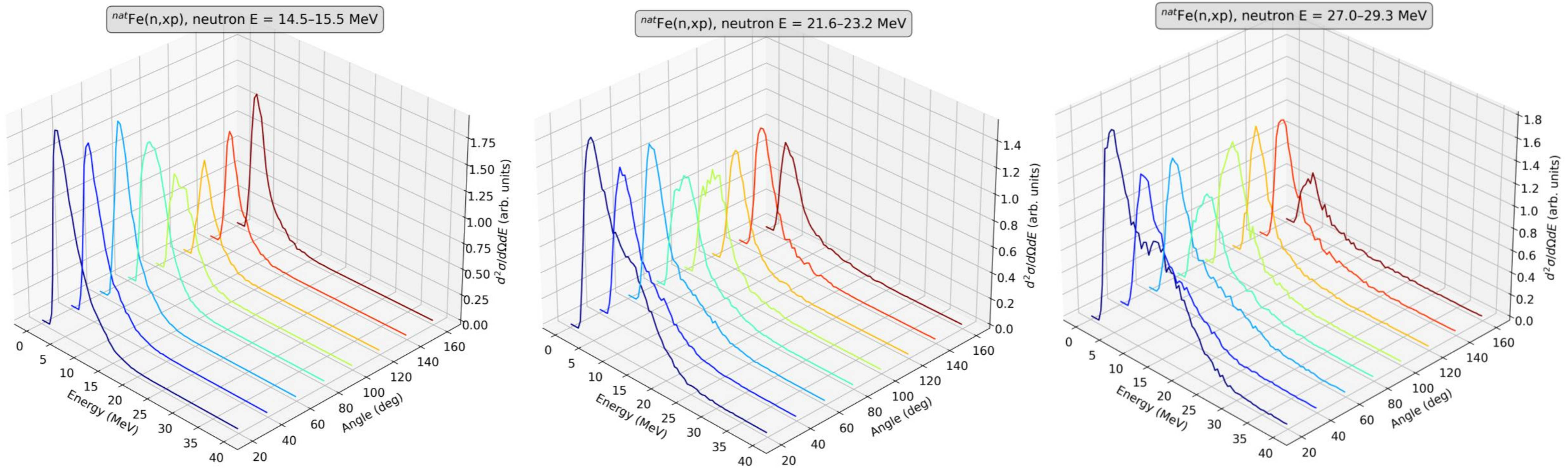




- The idea is to produce a response function to deconvolve E0 from E'

Preliminary cross sections

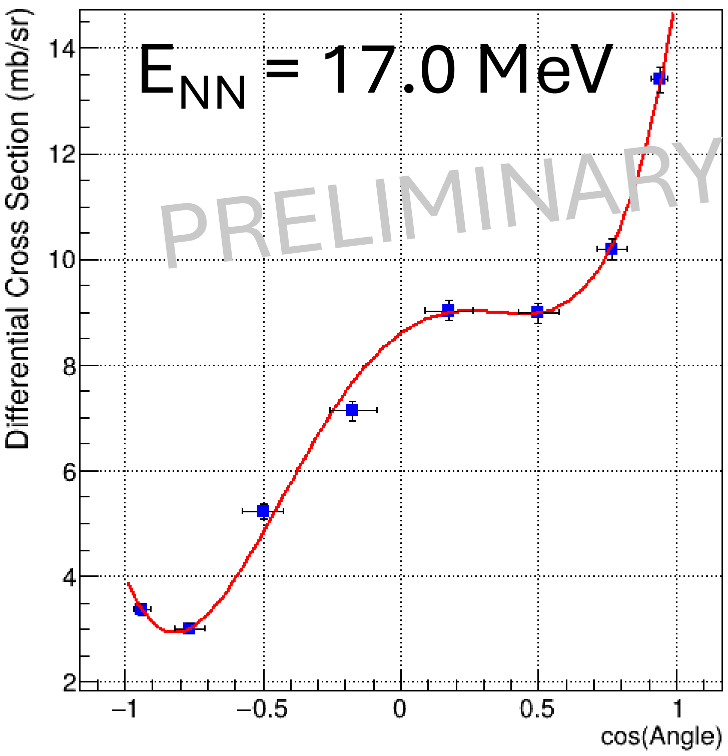
Fe(n,Xp) double differential cross sections

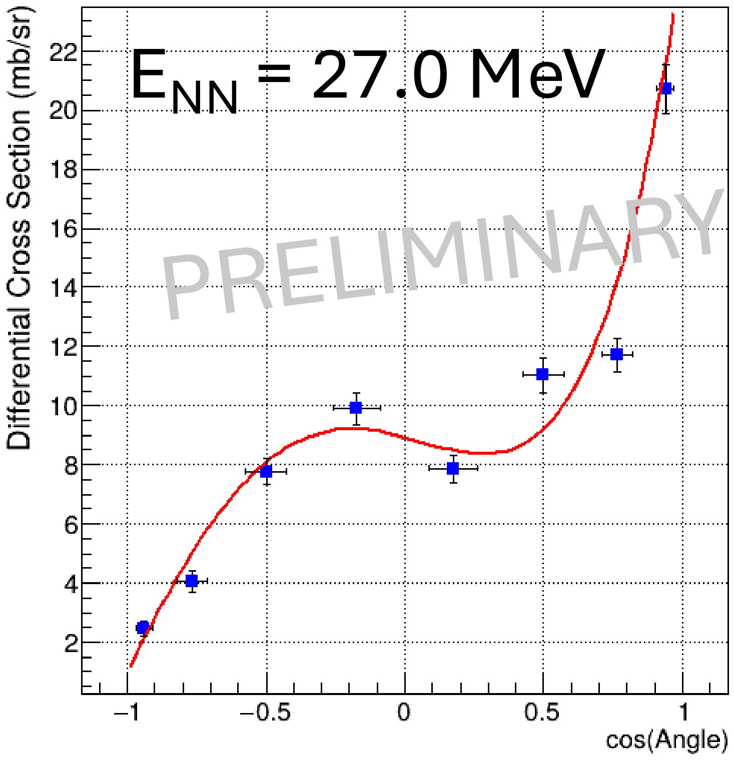


- The first results with DDX were successfully obtained

Preliminary cross sections

Proton differential cross sections – angular

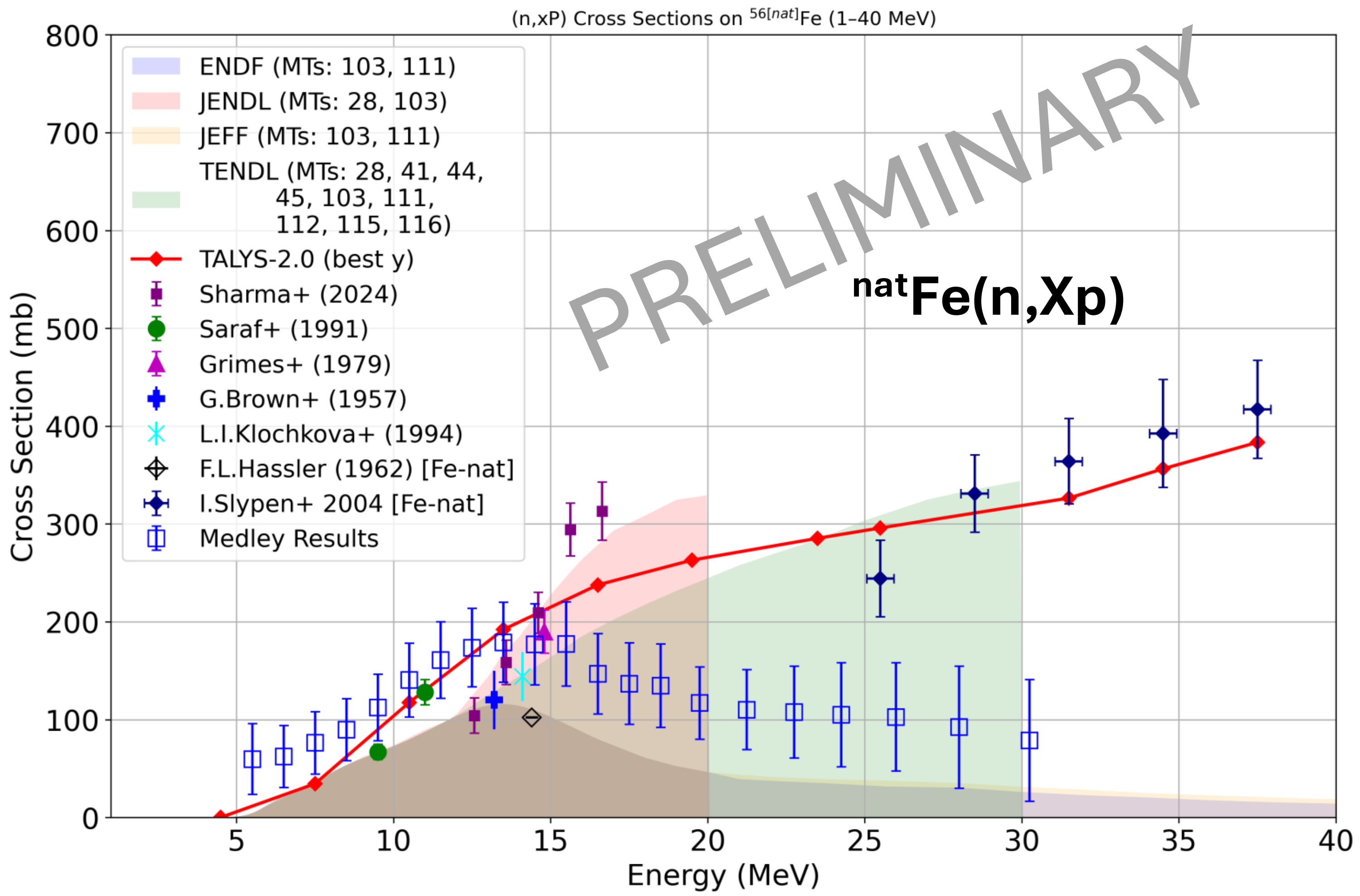




- Integrating in dE we can obtain the angular differential cross section as a function of neutron energy
- Fitting Legendre's polynomials allow us to obtain the total cross section for each neutron energy

Preliminary cross sections

Proton total cross sections – First results



- Comparison of the total proton production cross section show some agreement with the models
- Some uncertainties still need to be considered
- Some corrections for accounting the detector thresholds are needed

Summary and next steps

- Medley proved to work properly under white neutron beam, providing a good amount of valuable data which is under analysis.
- Several challenges were identified and solved; the first results were obtained.
- Some exclusive channels were observed: possibility to obtain exclusive cross sections
- Fine tuning of the methods and techniques for treating the data are being carried out.

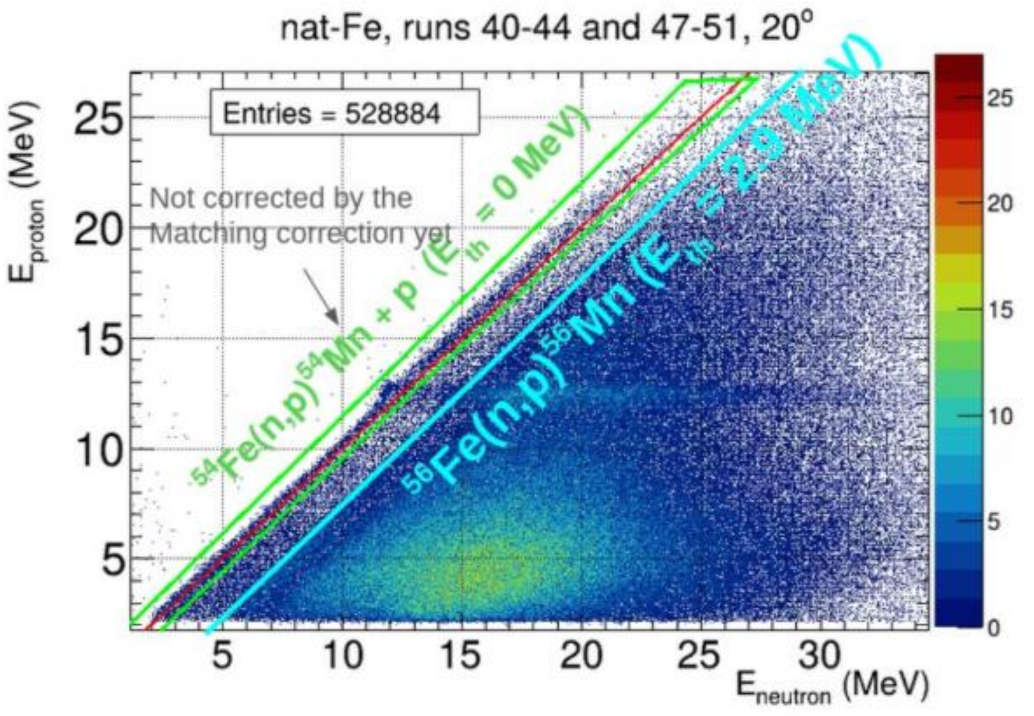


Figure 15: *There is also the possibility of eventually providing exclusive cross sections for some cases like ^{54}Fe(n,p)^{54}Mn and ^{56}Fe(n,p)^{56}Mn, but some extra assessment need to be done in order to confirm if we have enough available statistic.*

Thank you for your attention!

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