Probing the X17 existence and properties using proton and neutron beams

Carlo Gustavino
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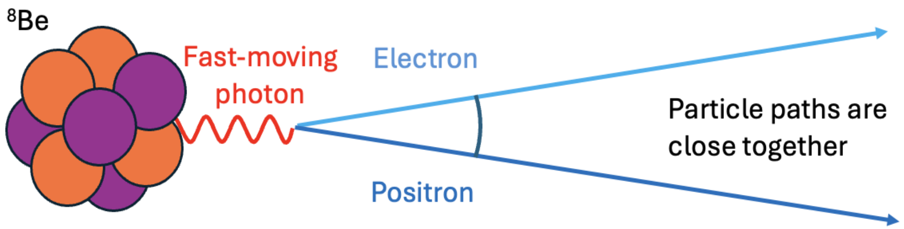
OUTLINE:

- ATOMKI experiments in a nutshell
- Experimental requirements
- n_TOF detector
- The ^{3}He(n,X17)^{4}He experiment at n_TOF
- Other measurements

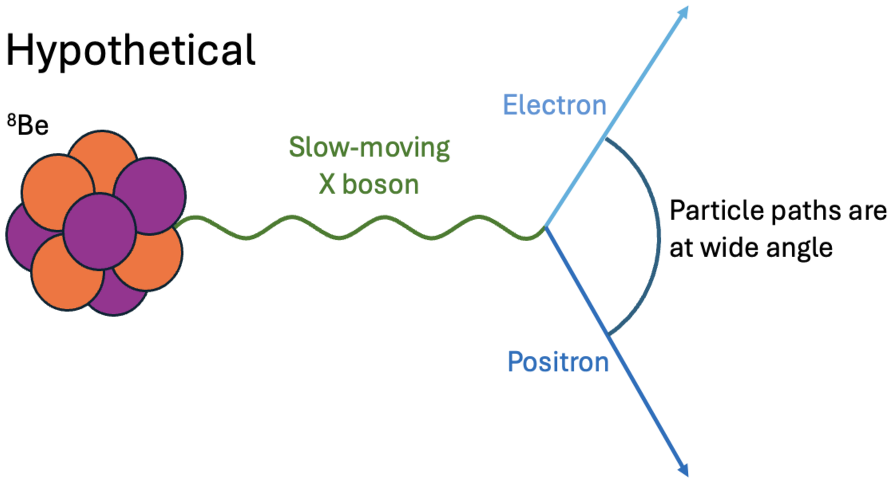
The X17 anomaly

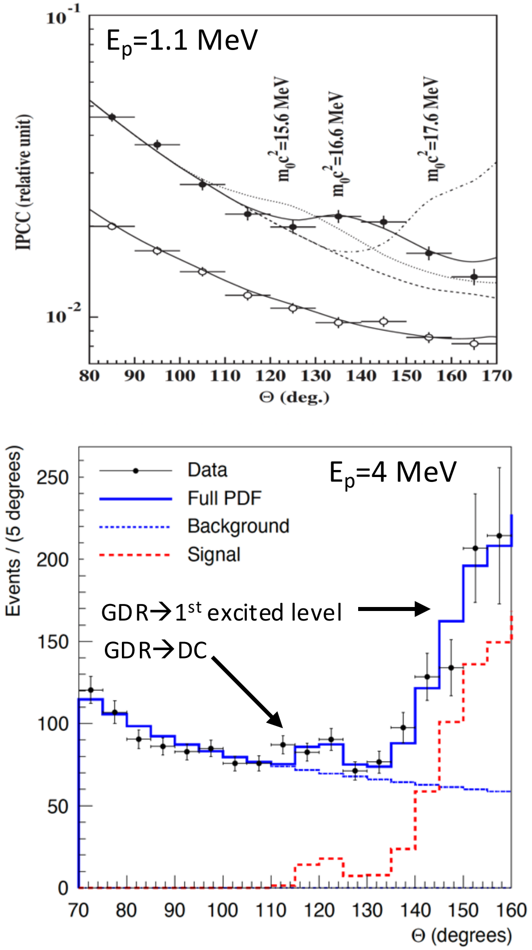
The ATOMKI group observed an excess of e^-e^+ pairs emitted at large relative angle in the $^3H(p,e^-e^+)^4He$, $^7Li(p,e^-e^+)^8Be$, $^{11}B(p,e^-e^+)^{12}C$ nuclear reactions. This excess can be explained with the creation (and decay into e^-e^+ pairs) of a new particle with mass ~17 MeV, called **X17 boson**.

Expected ^8Be Transition

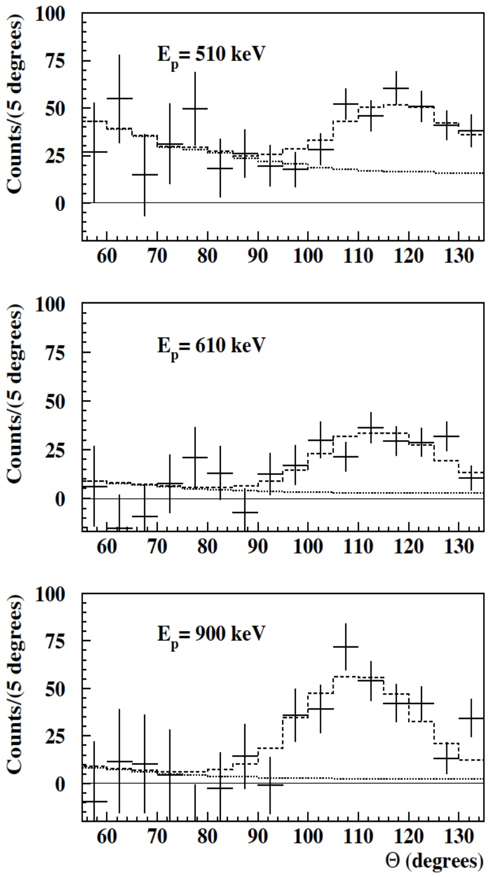


Hypothetical

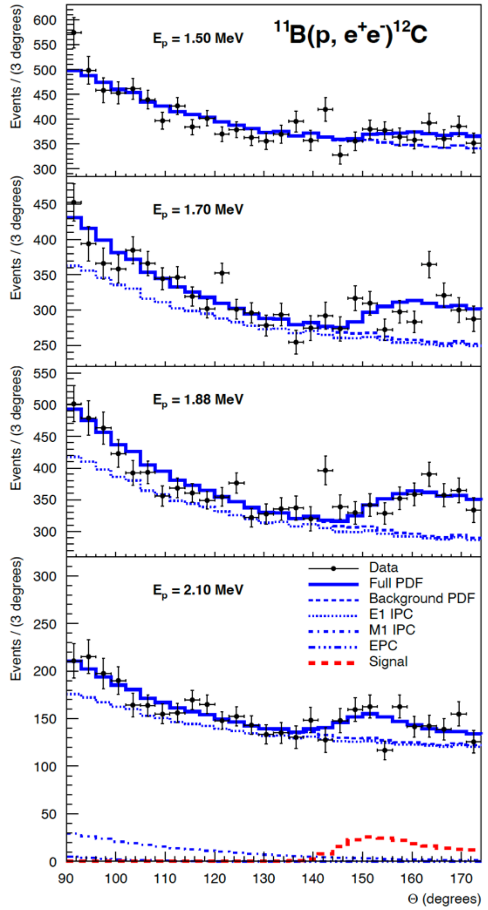




$^7Li(p,e^-e^+)^8Be$



$^3H(p,e^-e^+)^4He$



$^{11}B(p,e^-e^+)^{12}C$

Theoretical Framework in a nutshell

-The first theoretical interpretation of the experimental results was performed by Feng et al (2016). They explained the anomaly with a vector gauge boson X17, which may mediate a fifth fundamental force with some coupling to Standard Model (SM) particles. from searches for $\pi_0 \rightarrow Z' + \gamma$ by the NA48/2 experiment, Feng postulated that the X17 particle couples much more strongly to neutrons than to protons, “protophobic force”.

-This scenario could explain the long standing anomaly on the muon magnetic moment, and also the recent measurement of g_e-2 (Morel 2020), that is compatible with the vector boson hypothesis.

-Ellwanger and Moretti (2016)suggested another interpretation of the experimental results in view of a light, pseudoscalar particle [21]. They predicted about ten times smaller branching ratio in case of the 17.6 MeV transition compared to the 18.15 MeV one.

-Zhang and Miller (2017) investigated the nuclear transition form factor as a possible origin of the anomaly, but they concluded the hypothesis unrealistic for the ^{8}Be nucleus.

-Delle Rose (2019) showed that the anomaly can be described with a very light Z_0 bosonic state, with significant axial couplings.

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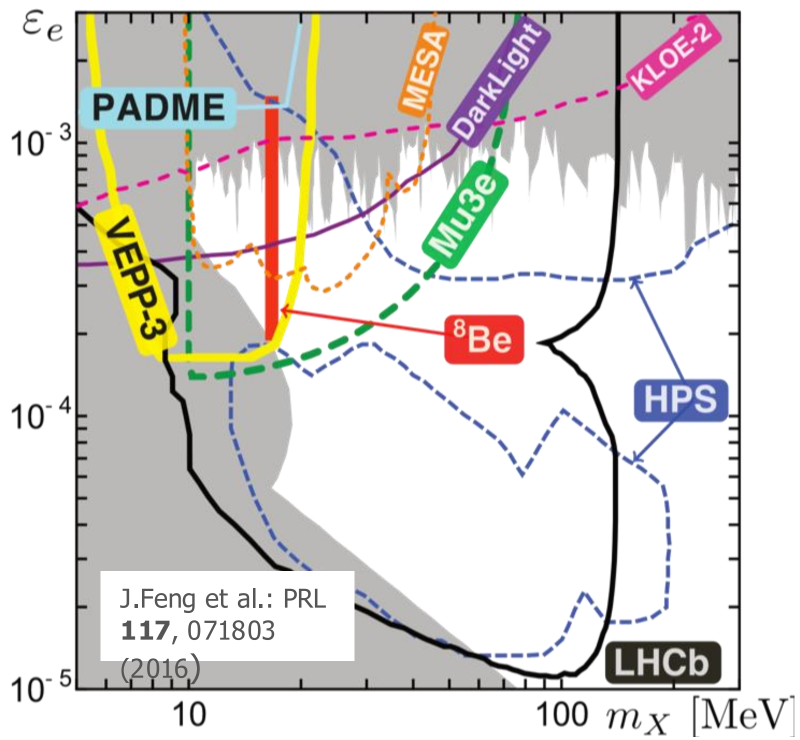
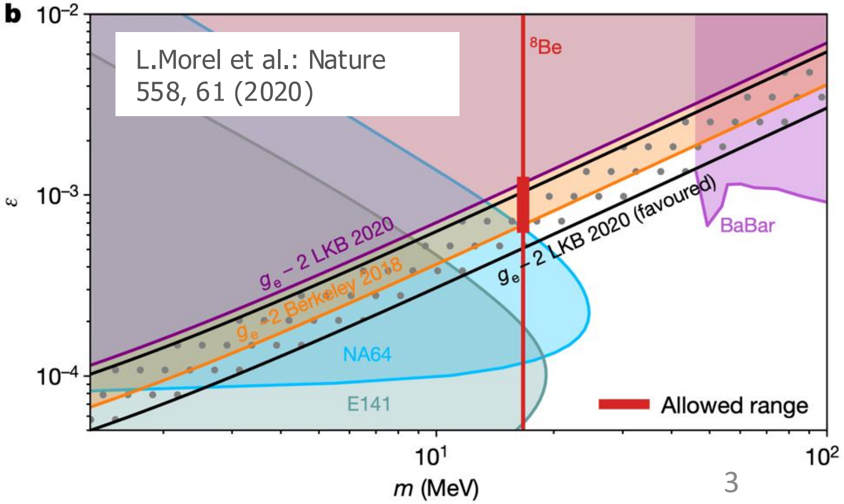


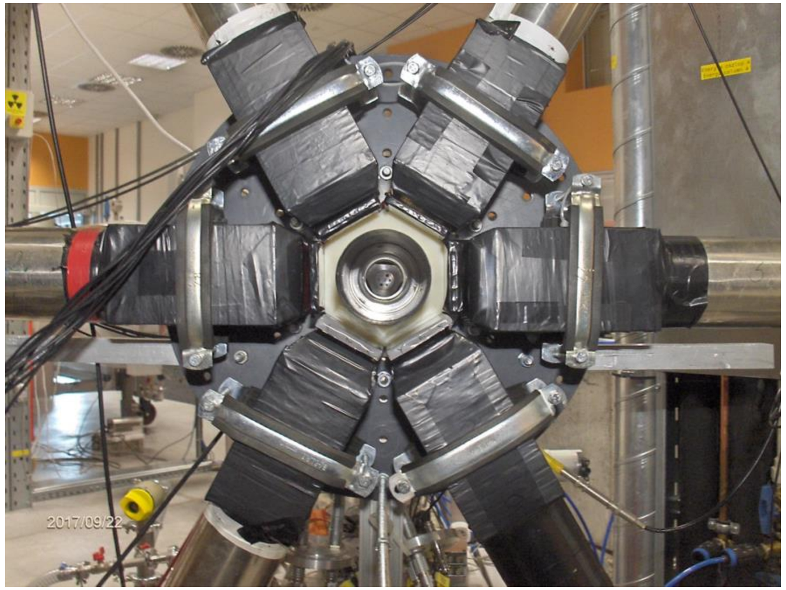


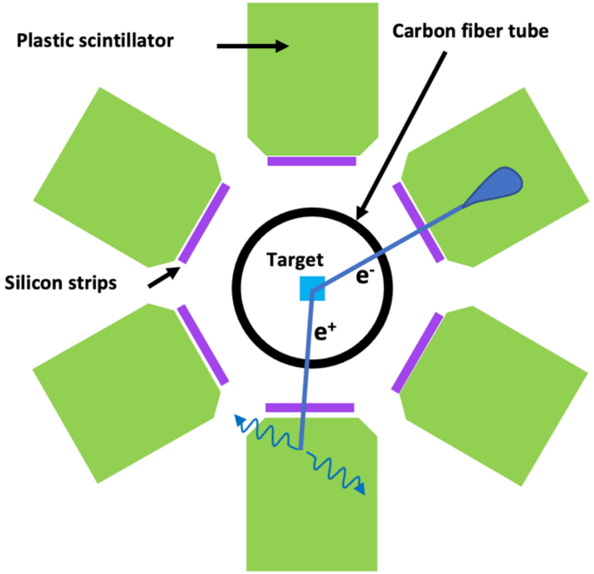
The ATOMKI setup

Let consider the setup used for the **$^{3}H(p,e^{+}e^{-})^{4}He$** experiment.
(similar setup were used in the other experiments)

-Proton beam with Ep<1 MeV (to prevent neutron production)
-^{3}H thin target deposited on a thin Titanium backing
Thin (1 mm thick) carbon fiber tube
→ To limit multiple scattering of ejectiles.
-6 double-sided silicon strip detector 3 mm wide strips, 0.5 mm thick
→measurement of the particle impact point, to deduce the aperture angle
-6 plastic scintillator 82x86x80 mm^3
→ Measure of total kinetic energy of ejectiles

Well suited for electron and positron detection. However:
-Detector acceptance only around 90° with respect to the beam axis
-No tracking.
-No charge and particle identification.





What about X17 quantic numbers?

ATOMKI measurements indicate the existence of a particle with a mass of ~17 MeV. However, the properties of X17 (J^{π}, coupling with ordinary matter,..) are unknown, because of the limited experimental information.

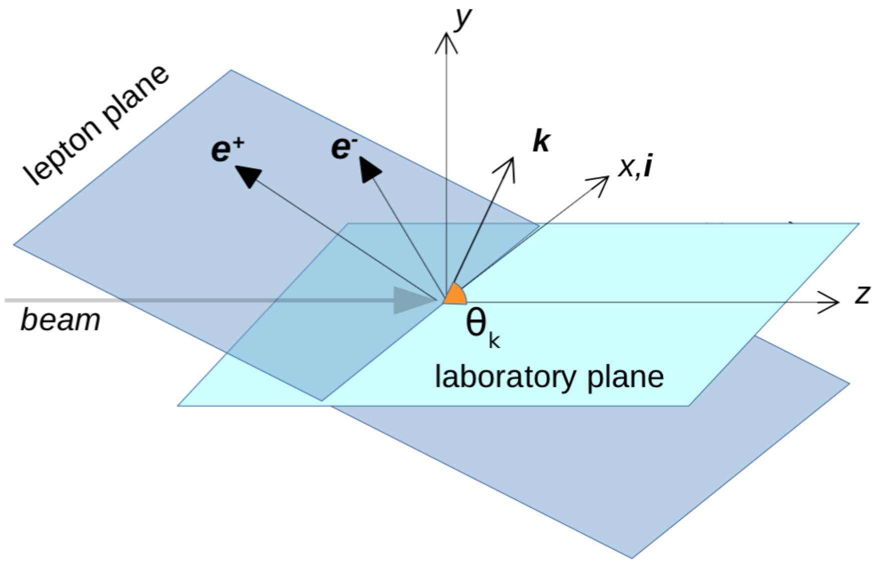
Concerning the $^4He^* \rightarrow {}^4He + X17$ process:

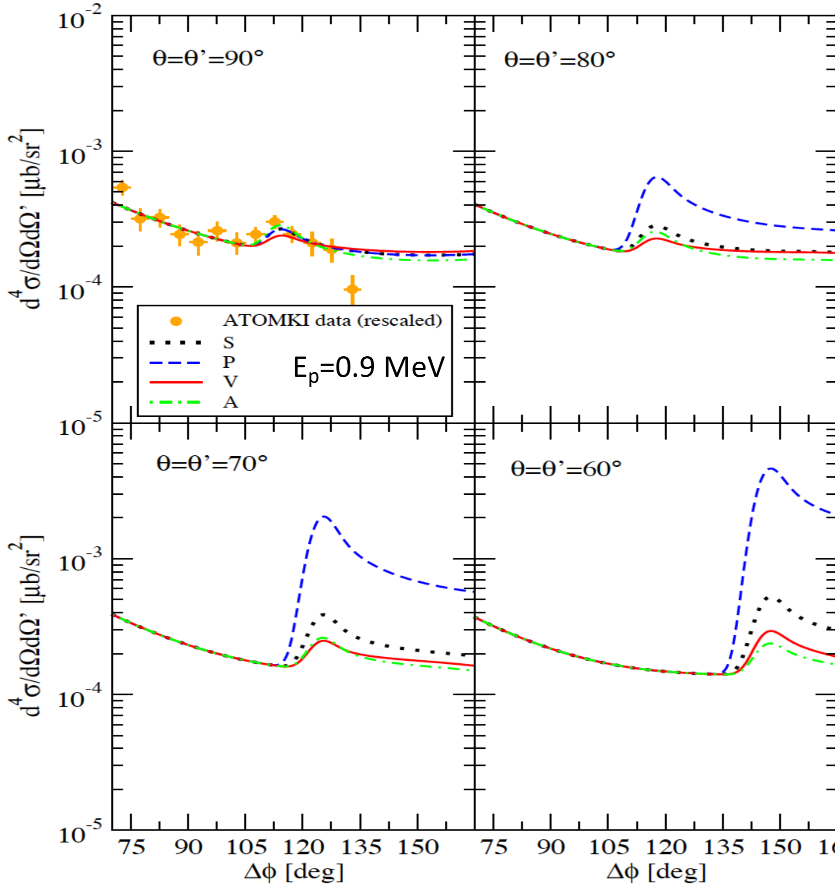
$\hookrightarrow e^+e^-$

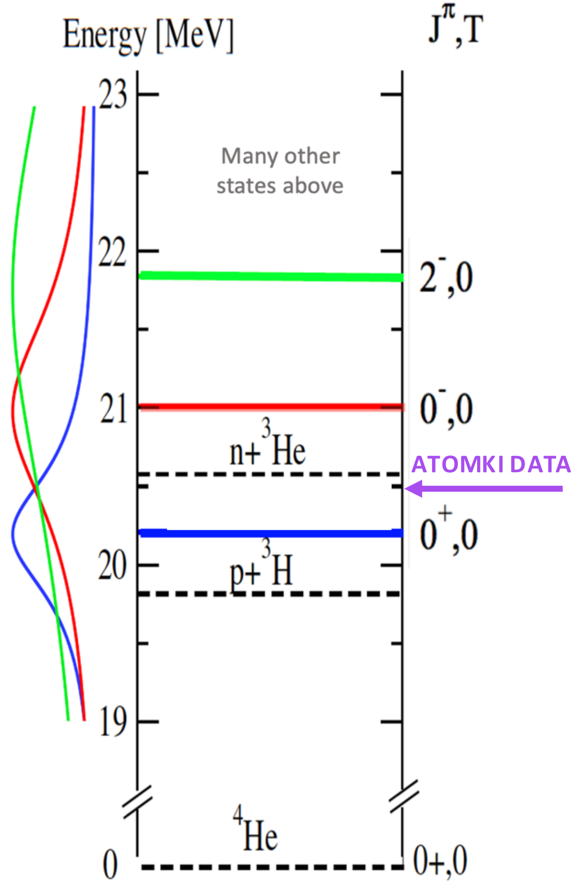
The angular distribution of e^+e^- pairs from the X17 decay strongly depends on its J^{π}

e.g. if it is a Scalar/Pseudoscalar/Vector/Axial Boson

→ Large acceptance detector needed







M. Viviani et al.: PRC 105, 014001 (2022)

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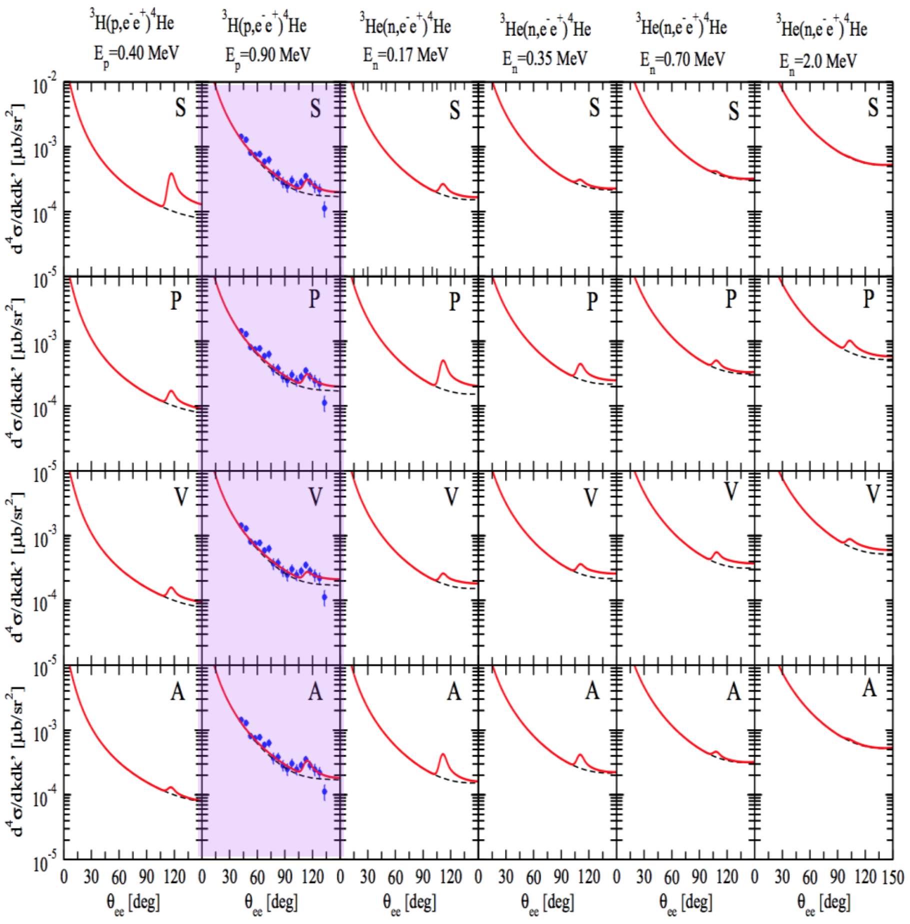
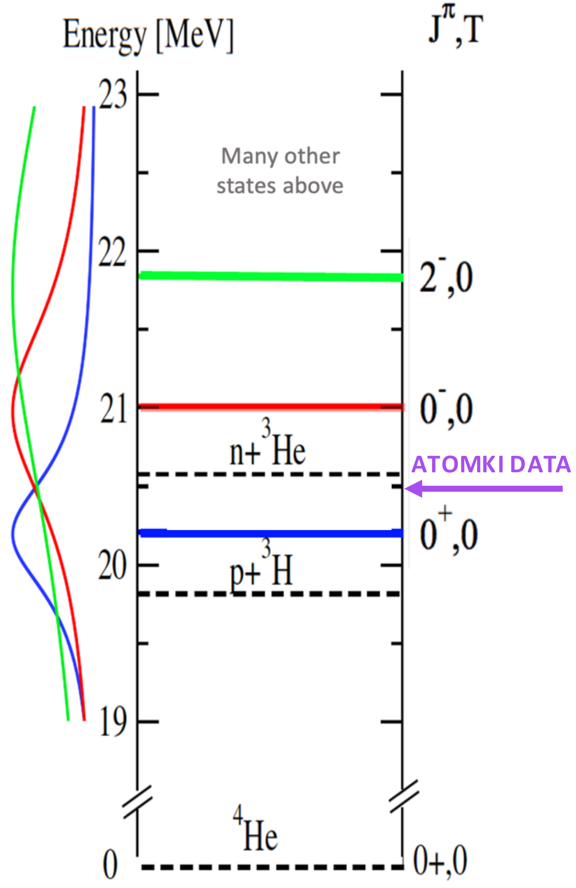
Concerning the $^4He^* \rightarrow {}^4He + X17$ process:

$\hookrightarrow e^+e^-$

The X17 quantic numbers affect the strenght of the excess, by varying the de-excitation energy of $^4He^*$,

→wide energy range of center of mass Energy is desirable.



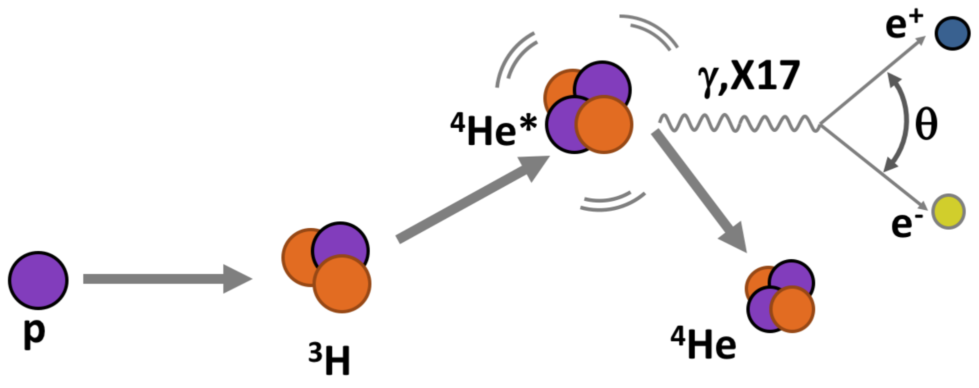


M. Viviani et al.: PRC 105, 014001 (2022)

X17 @ n_TOF

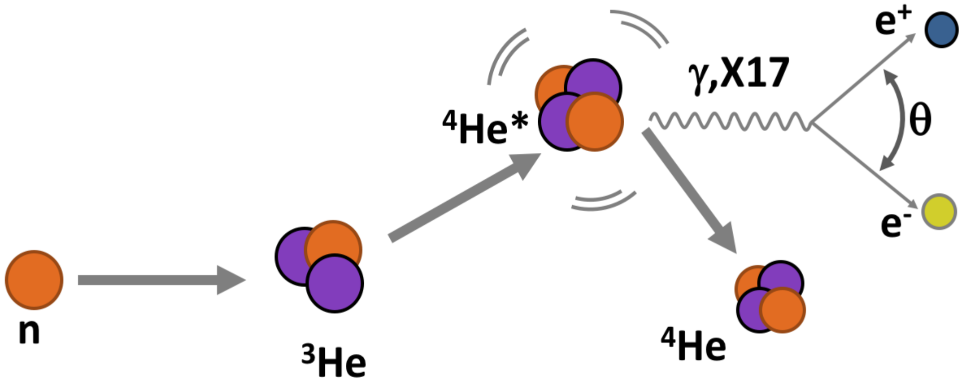
Basic idea: study of excited ^{4}He exploiting both the conjugated reactions:

$^3H(p,e^+e^-)^4He$



ATOMKI REACTION

$^3He(n,e^+e^-)^4He$

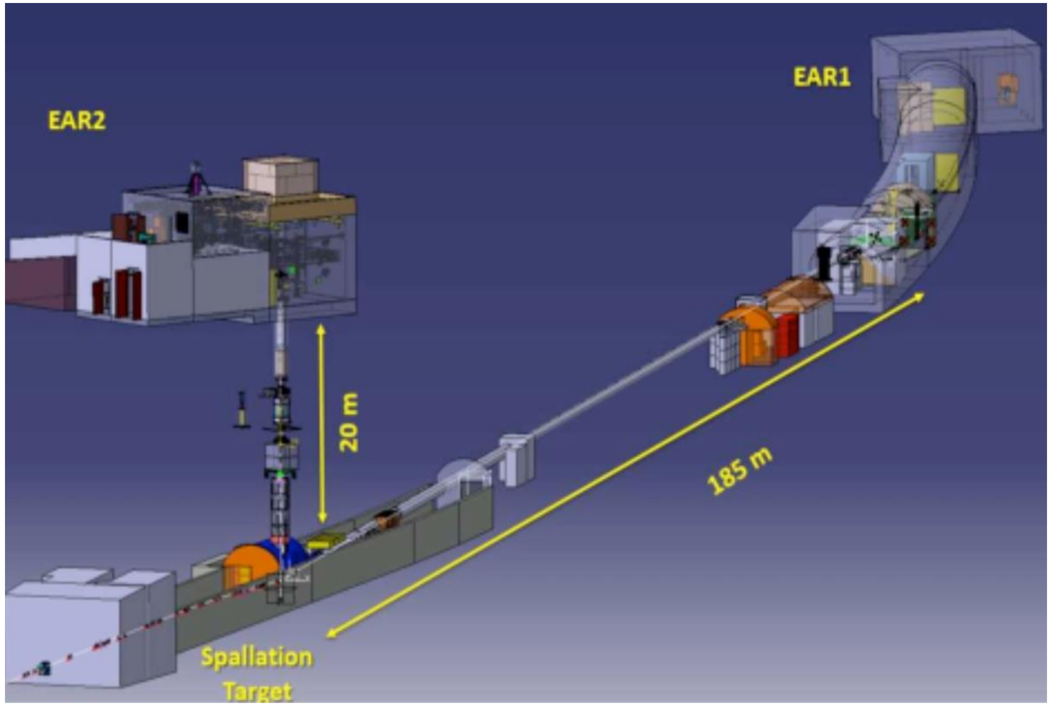


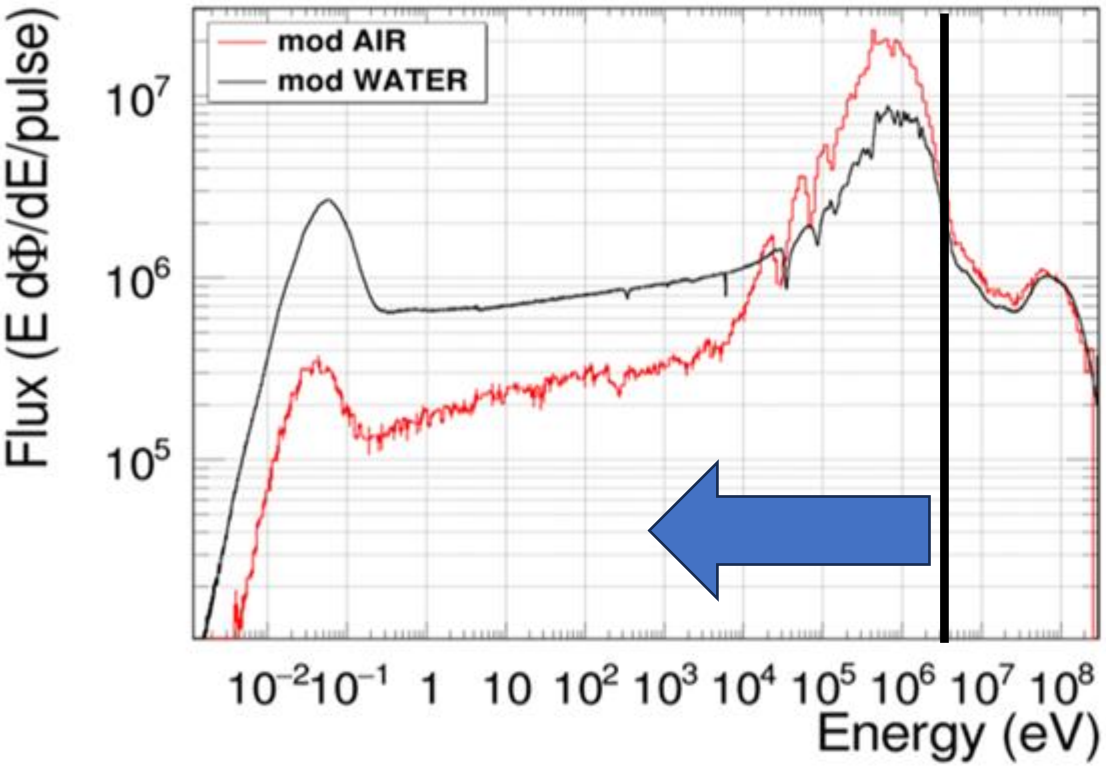
n_TOF REACTION

Physics:

- Probing X17 existence
- X17 Mass, quantic numbers, coupling, life time,..
- proto-phobic nature of the fifth force.
- Data Vs Theoretical nuclear physics

The n_TOF facility

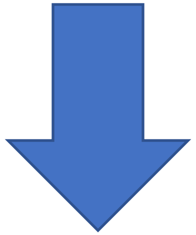




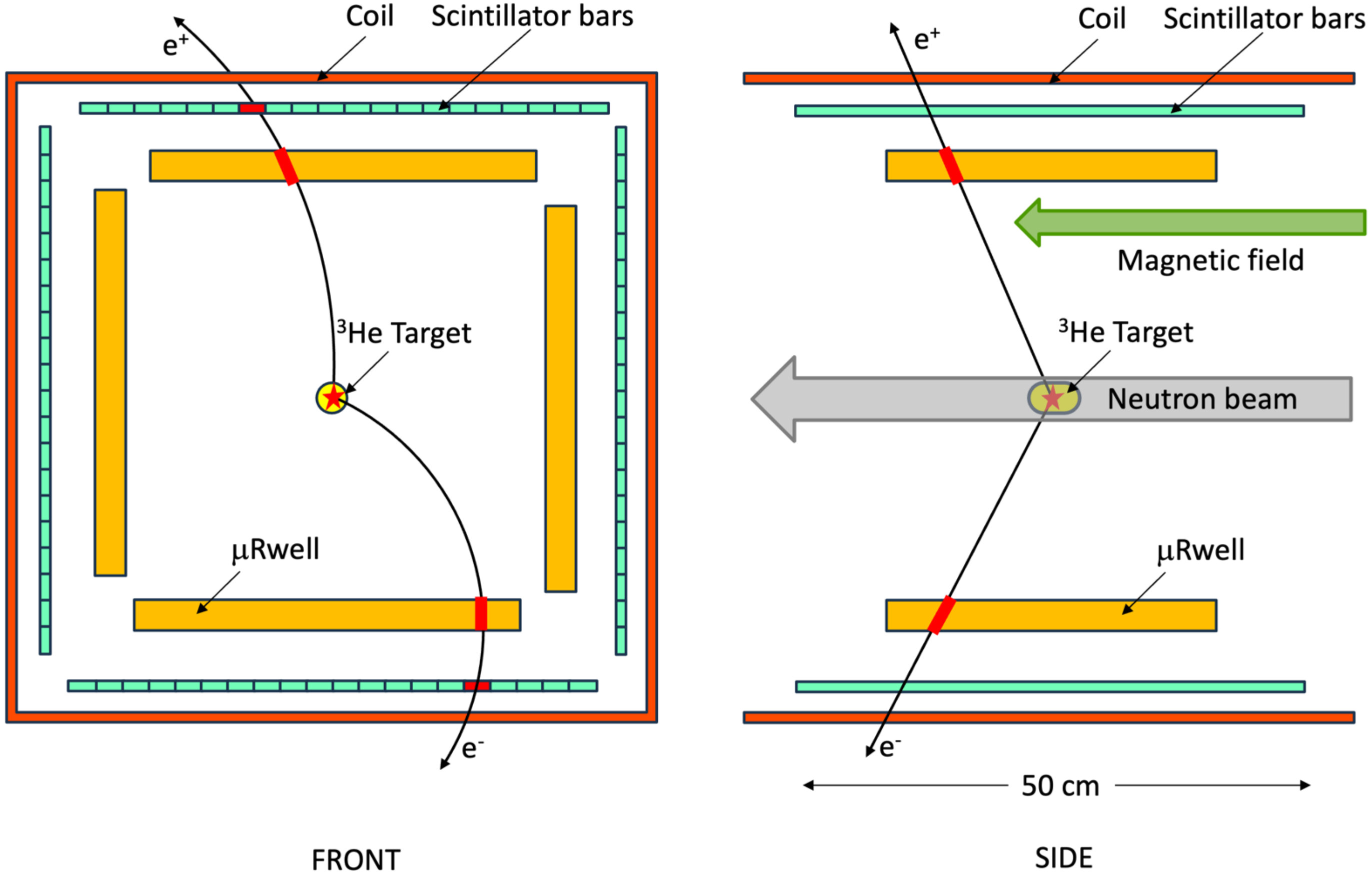
Pulsed neutron beam with a wide energy range $10^{-2}<E<10^8$
The Energy of the interacting neutron is derived with the Time-of-flight technique

Detector requirements

-Large acceptance
-Reconstruction of ejectiles kinematics
-"Light" detector, with a low sensitivity to photons and neutrons

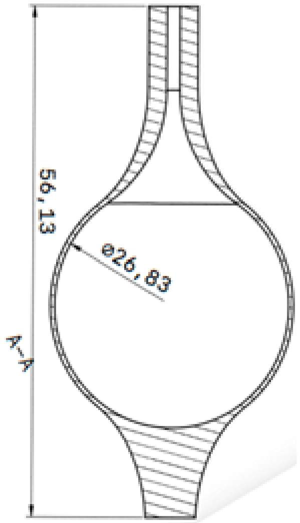


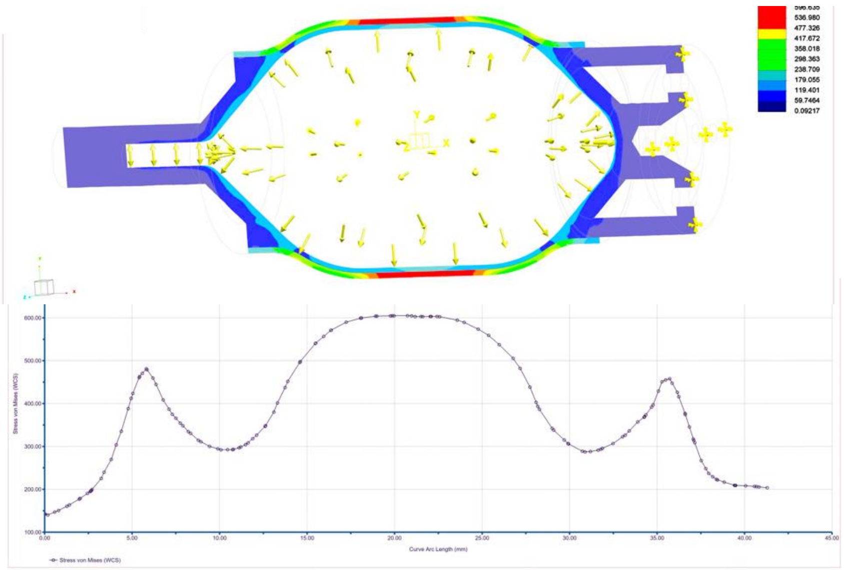
-4 large μRwells with a large (3 cm) ionization gap, 380x460x30mm^3 active volume
→ 3D tracking
-4 planes 50x50 cm^2, each one composed by 20 scintillator bars 3x25x500 mm^3
→ Trigger and neutron energy with TOF technique
-Coil 60 cm long and with a square section 60x60 cm^2 (B = 500 Gauss)
→ charge and momentum reconstruction of ejectiles



The Target

- ^{3}He target (358 bar, 10 cm^{3}) in a quasi-cylindrical cell of 10 cm^{3} Inside a capsule of 0.3 mm SCALMALLOY 0.3 mm thicj reindorced with) 1 mm of carbon fibre, to limit Multiple Scattering and beam induced background.
- SCALMALLOY capsule realized with a 3D printer, to ensure a thight container
- Carbon fibre coat to increase the resistence to pressure.
- First capsules (0.5 mm of SCALMALLOY and 1 mm of carbon fibre) filled with ^{4}He at 200 bar succesfully tested at CERN. No pressure decrease after >3 months of monitoring
- R&D still in progress, to further optimize Pressure Vs thikness of capsule.

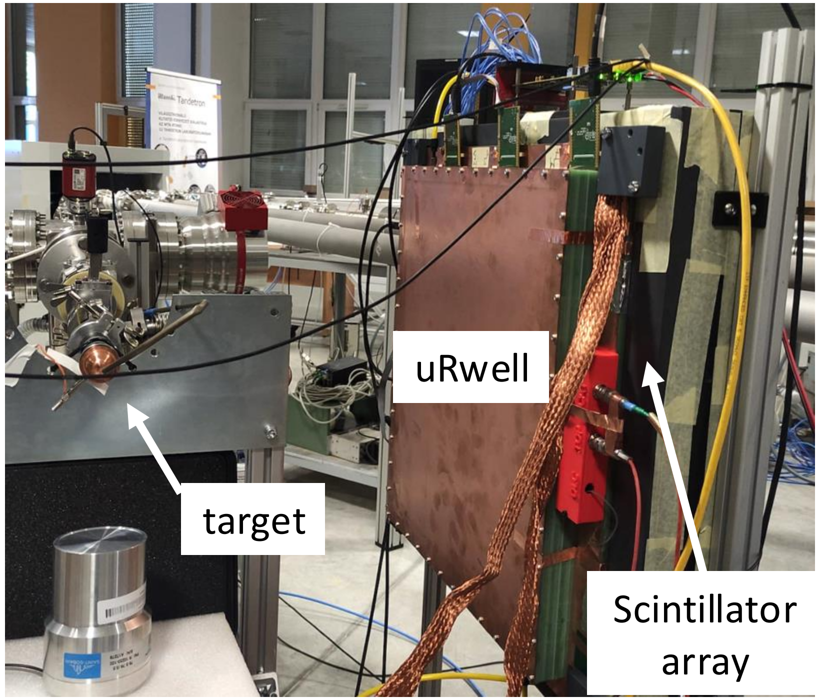


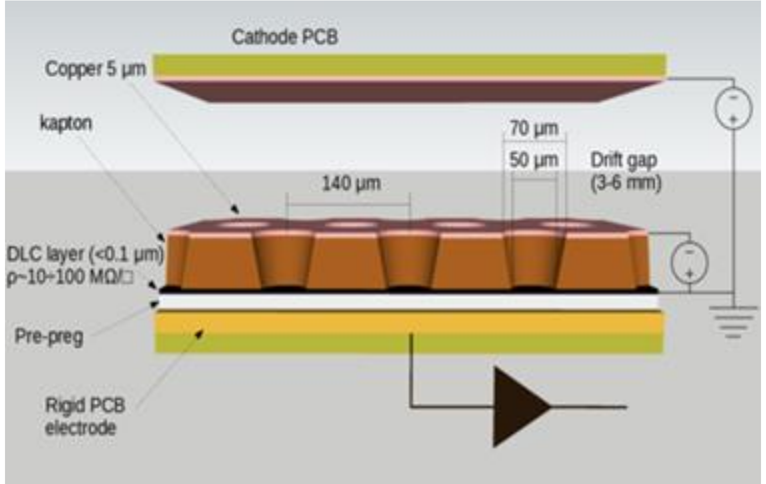


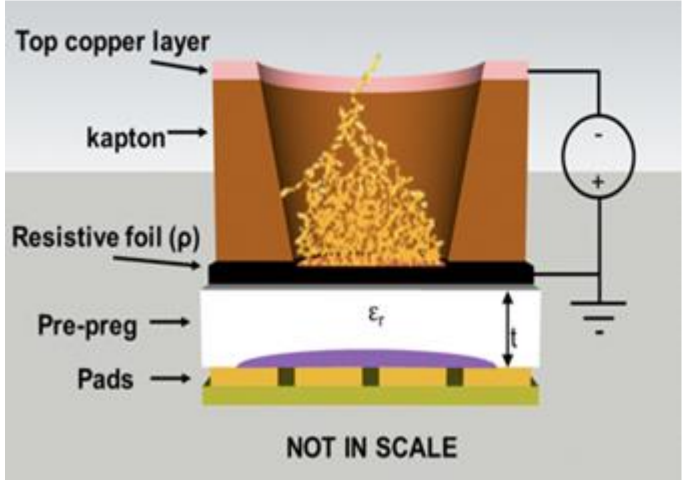
Images by P. Mastinu and E. Musacchio-Gonzales

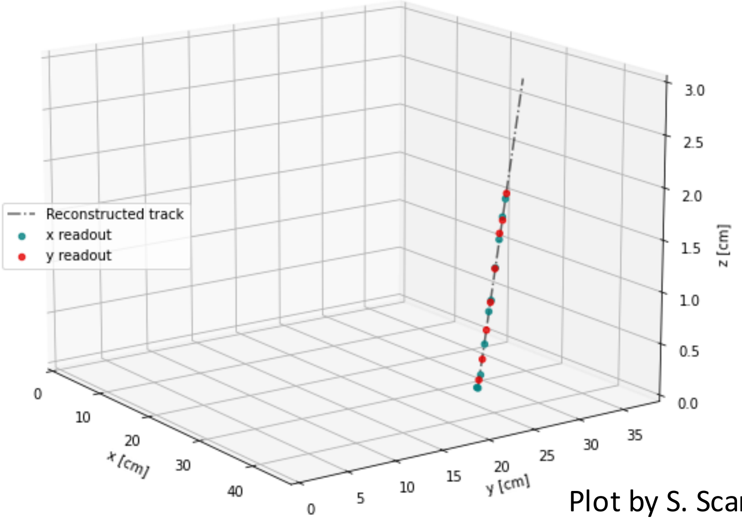
The μRwells

-The μRwells are MPGD like GEM and μMegas.
Our μRwells are equipped with X and Y readout strips, with a pitch 0f 1.7 and 0.7 mm, respectively.
-The 3D reconstruction of the tracks is obtained by operating the chambers In TPC mode (gas gap is 30 mm)
Tested at n_TOF and ATOMKI neutron and proton beams, by using a demonstrator composed by a single μRwell backed with a set of scintillator bars.





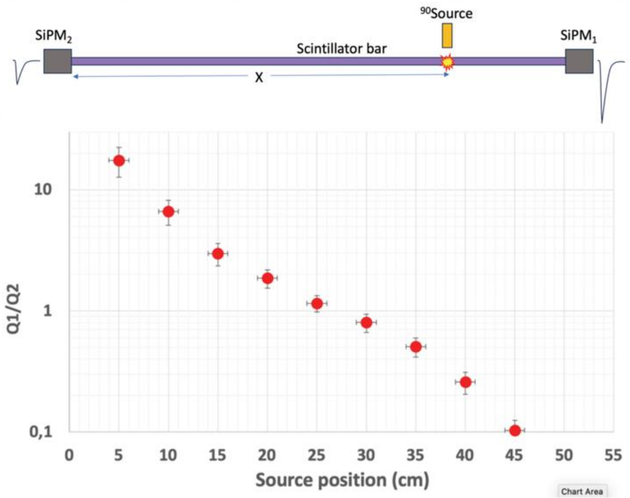


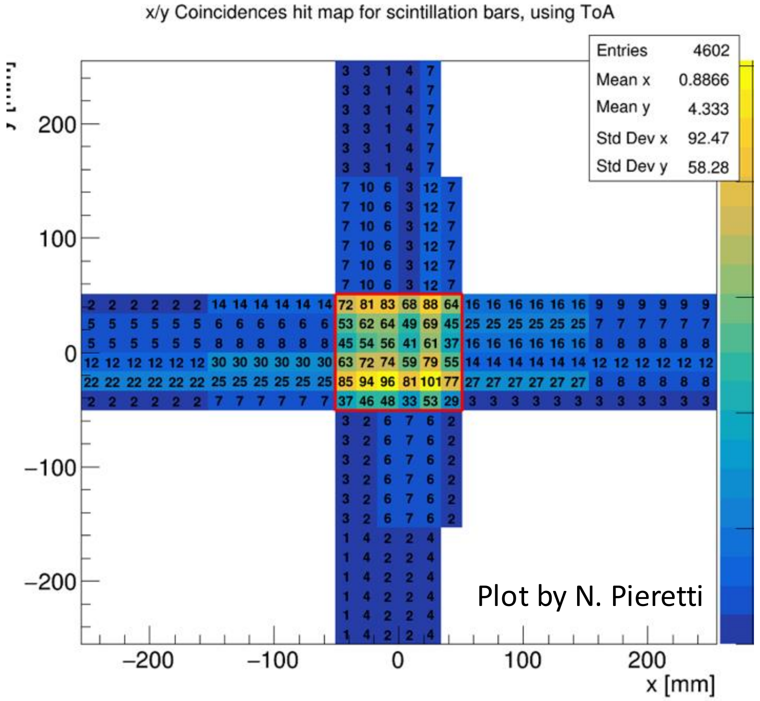


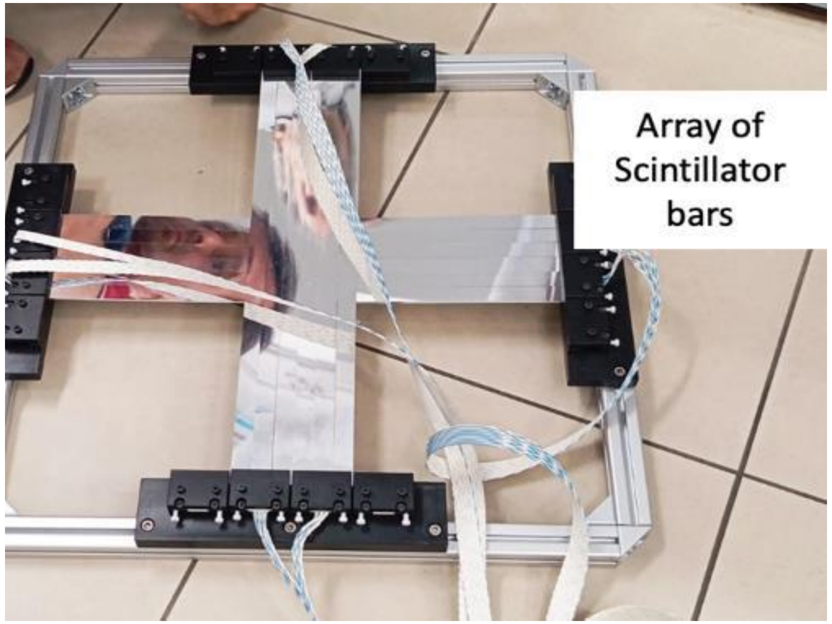
Plot by S. Scarpellini

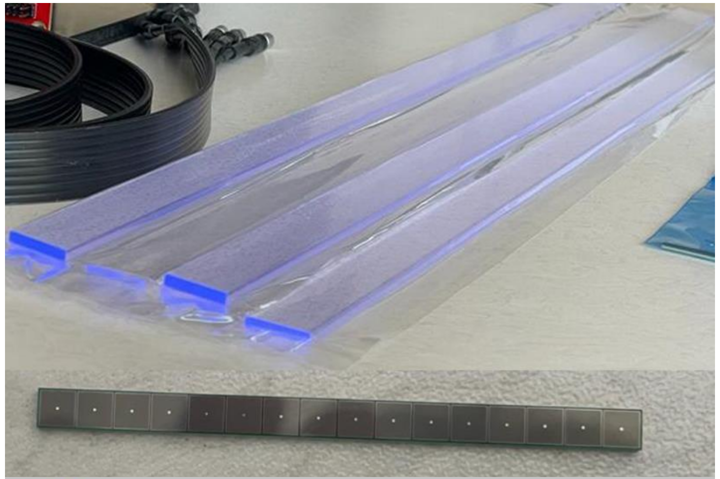
The scintillator system

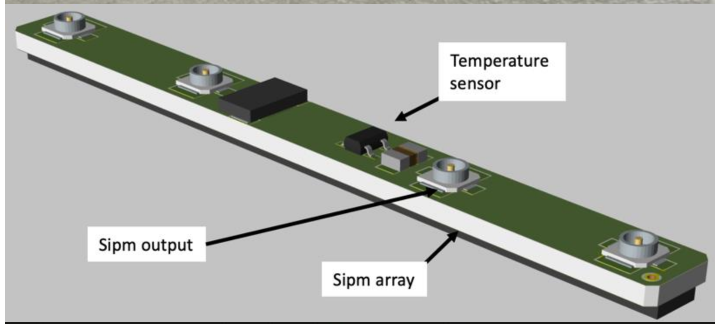
-Commercial scintillator bars by SCIONIX, 50x2.5x0.3 cm^3
-readout performed with array of SiPM by Hamamatsu.
Tested at n_TOF and ATOMKI neutron and proton beams.

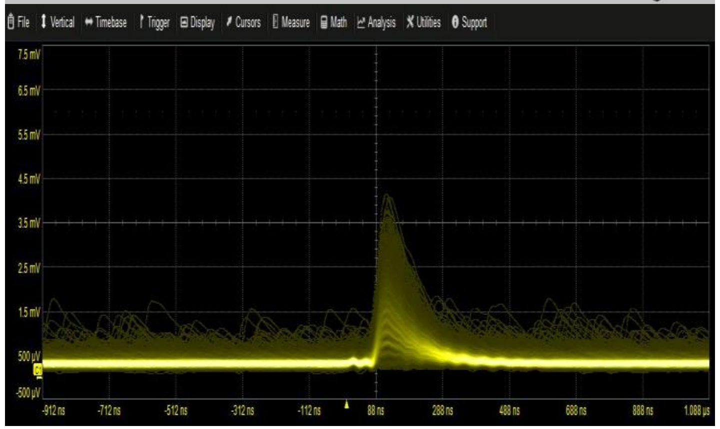






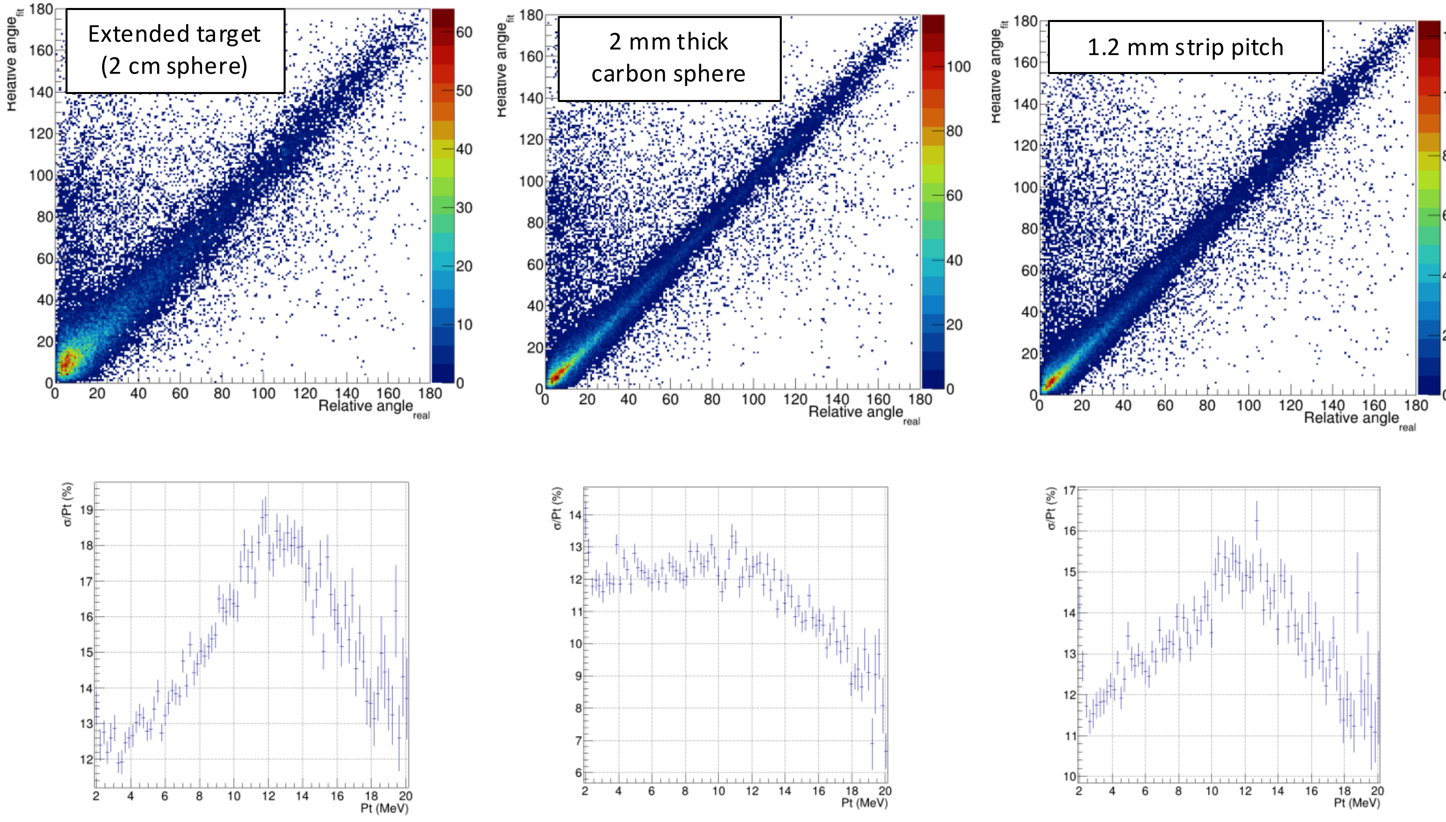




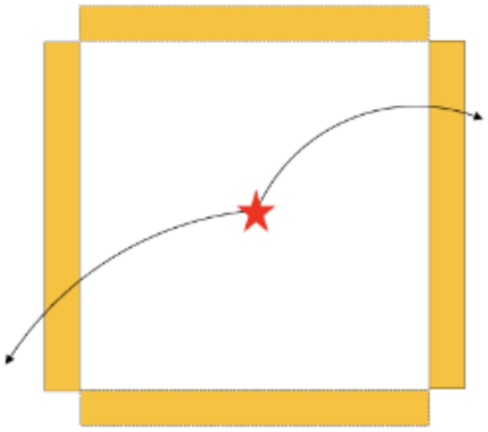


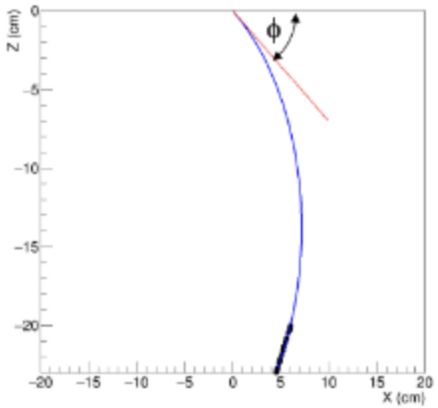
The magnet

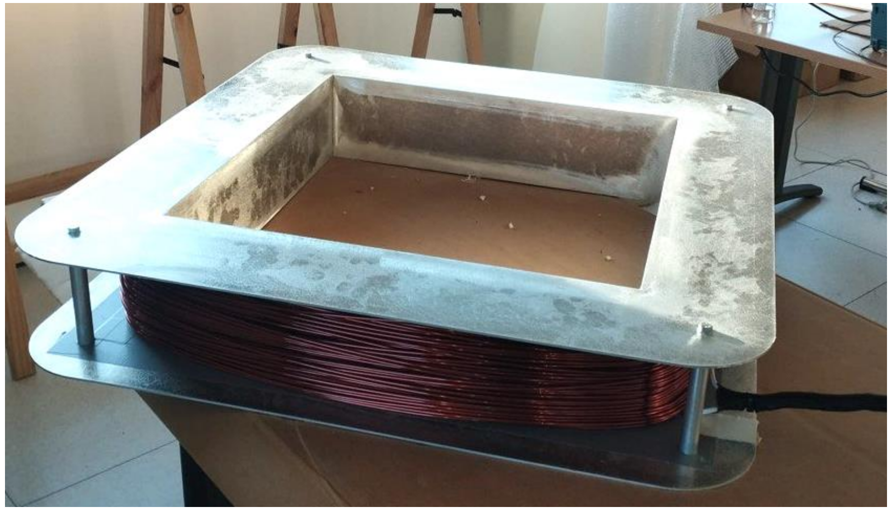
The magnet demonstrator has been realised and caracterised. Tests at n_TOF with the neutron beam and at LNL with the proton one in 2025). Simulations provide an overall momentum reconstruction of ejectiles at the 20% Level.



Plots by R. Mucciola







15x60x60 cm^3 magnet demonstrator

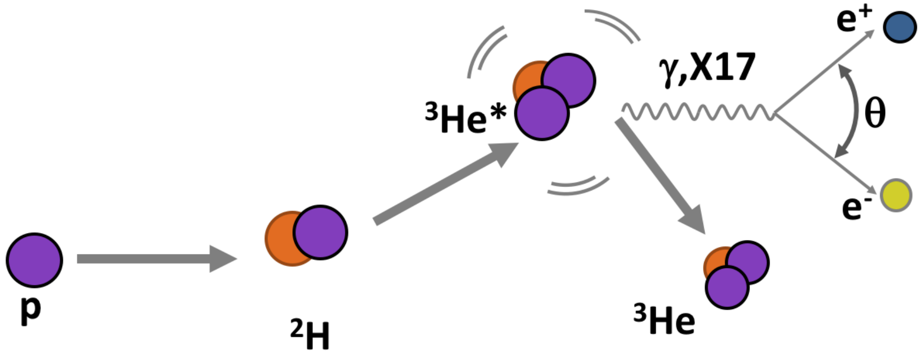
Conclusions

Stay tuned! Many groups are working to probe the existence of the X17 boson claimed by the ATOMKI group.

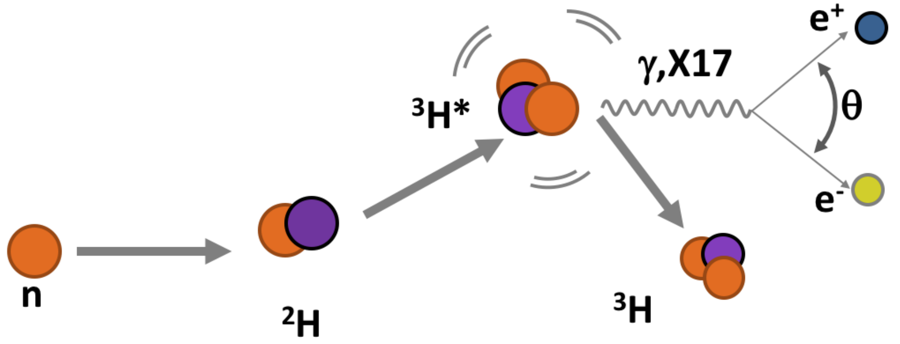
The experimental goal of n_TOF approach is to perform the first measurement of the **$^{3}He(n,e^{+}e^{-})^{4}He$** process at the n_TOF facility and the $^{7}Be(p,e^{+}e^{-})^{8}Be$ reaction **in the 2nd half of 2025**

The proposed detection setup is well suited for proton-induced reactions as well. For instance, it can be used to repeat the ATOMKI experiments such as the **$^{3}H(p,e^{-}e^{+})^{4}He$**, **$^{11}B(p,e^{-}e^{+})^{12}C$** nuclear reactions in a wider energy region, with a large acceptance and with improved kinematic reconstruction.

Finally, low sensitivity to neutrons suggests its use to study for the first time the **$^{2}H(n,e^{+}e^{-})^{3}H$** and **$^{2}H(p,e^{+}e^{-})^{3}He$** reactions. In these latter cases, the iso-specular structure of the ^{3}He and ^{3}H nuclei and the different numbers of neutrons and protons involved in the two reactions can be studied to investigate the isospin dependency of the X17-nucleon interaction, as the alleged “proto-phobicity”.
M. Viviani et al.: arXiv:2408.16744v1 [nucl-th] 29 Aug 2024.



$^{2}H(p,e^{+}e^{-})^{3}He$ (Q=5.5 MeV)



$^{2}H(n,e^{+}e^{-})^{3}H$ (Q=6.3 MeV)

Probing the X17 existence and properties using proton and neutron beams

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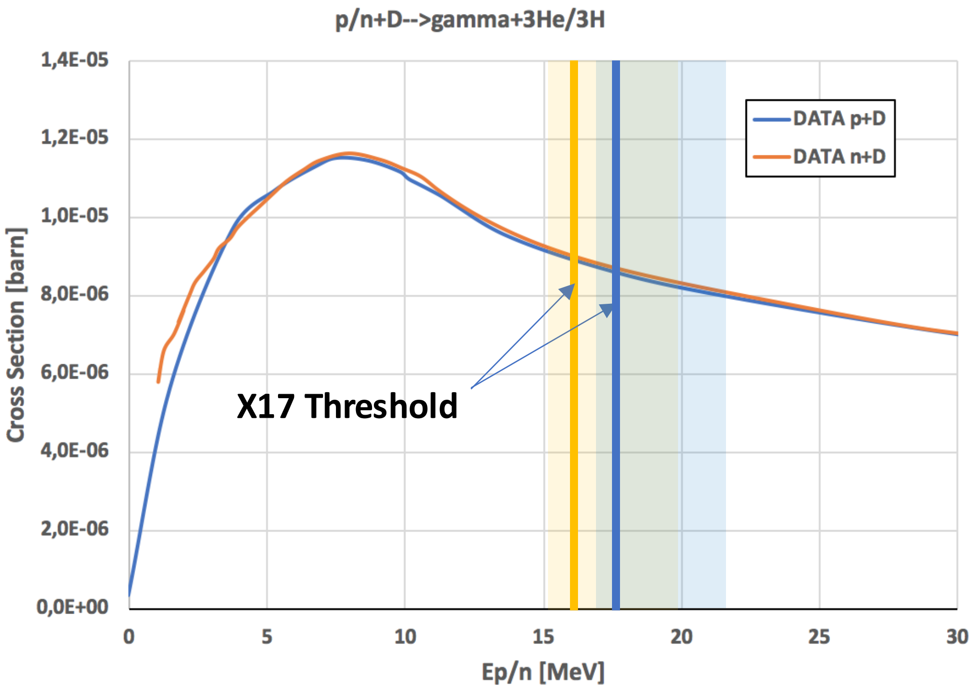
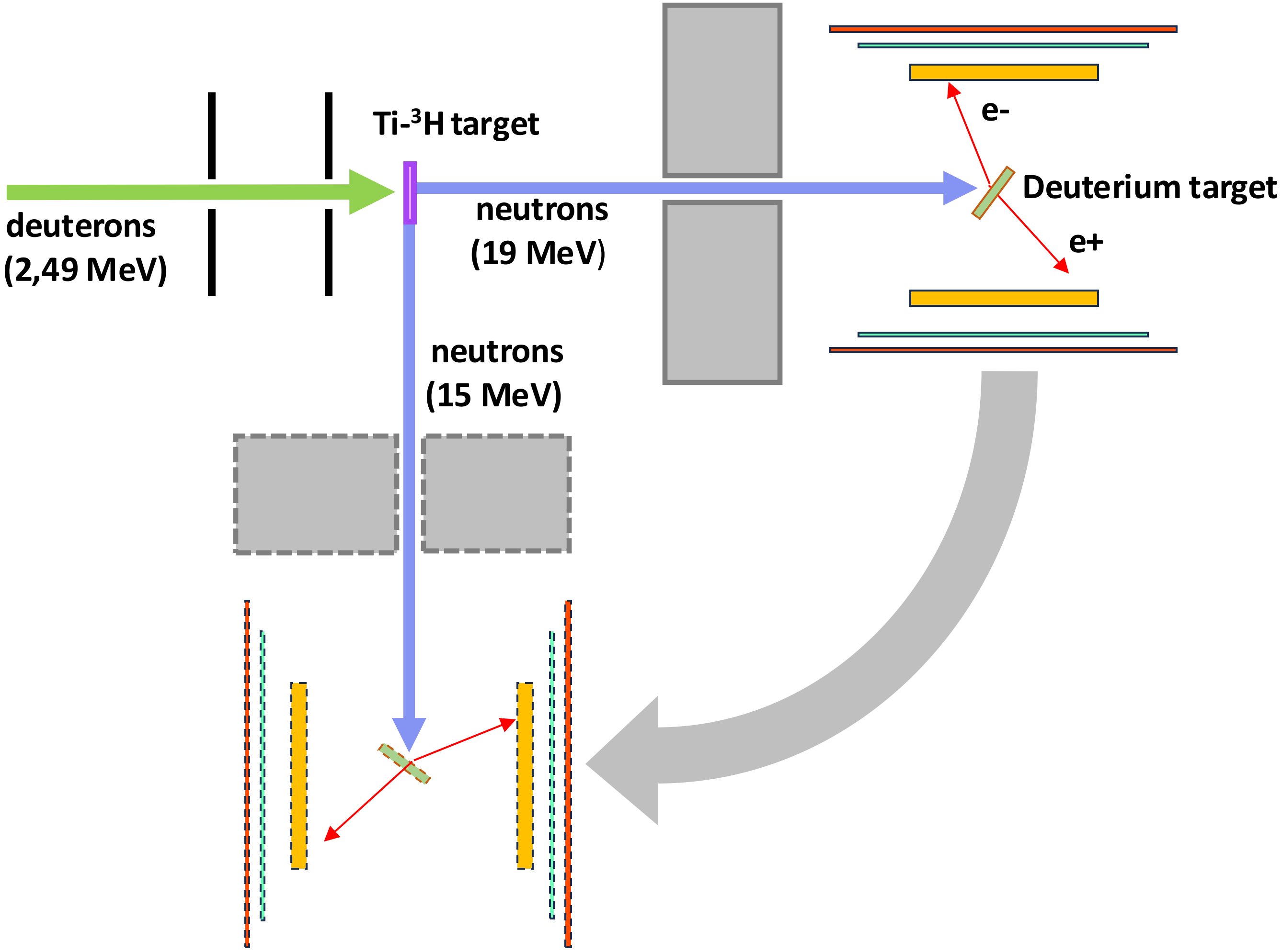
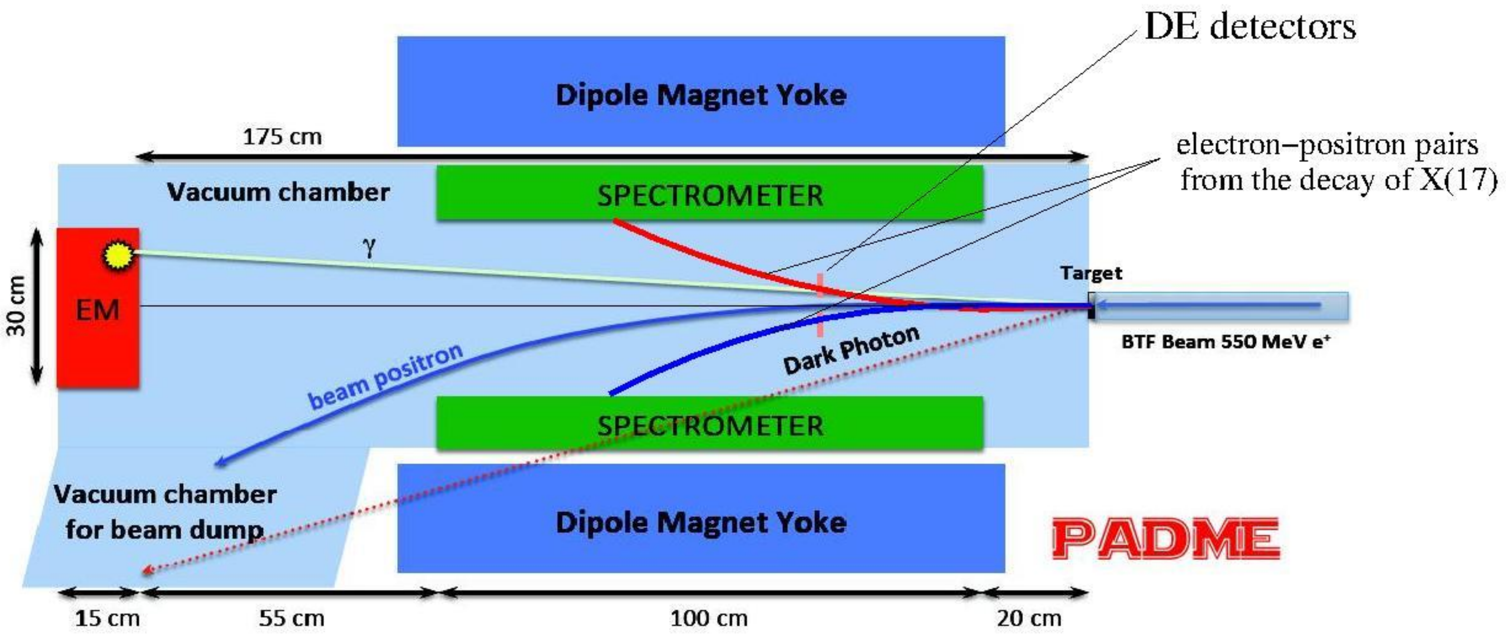
SPARES

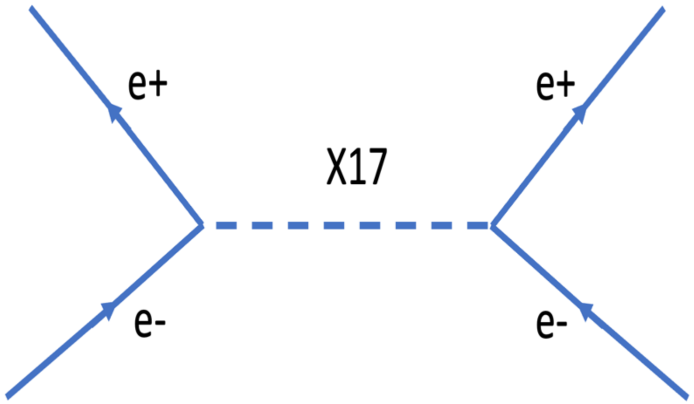
Possible Setup at DEMOKRITOS for $^{2}H(n,X17 \rightarrow e^{+}e^{-})^{3}He$





Search for the X17 at PADME in Frascati





PADME (Positron Annihilation into Dark Matter Experiment) is devoted to the Dark Photon search, exploiting the e^+ beam with $E_{beam} \leq 550$ MeV

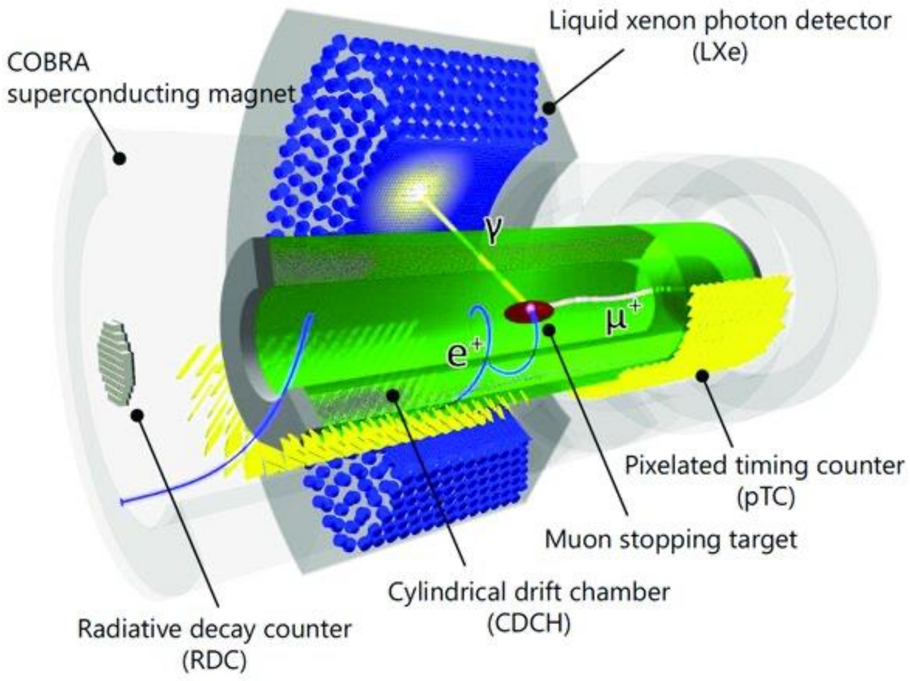
Regarding the X17, an experiment is running using a diamond target and positron with energy around 250 MeV

47 different energy points collected data collected for 16.35 MeV $< M_{X17} < 17.5$ MeV

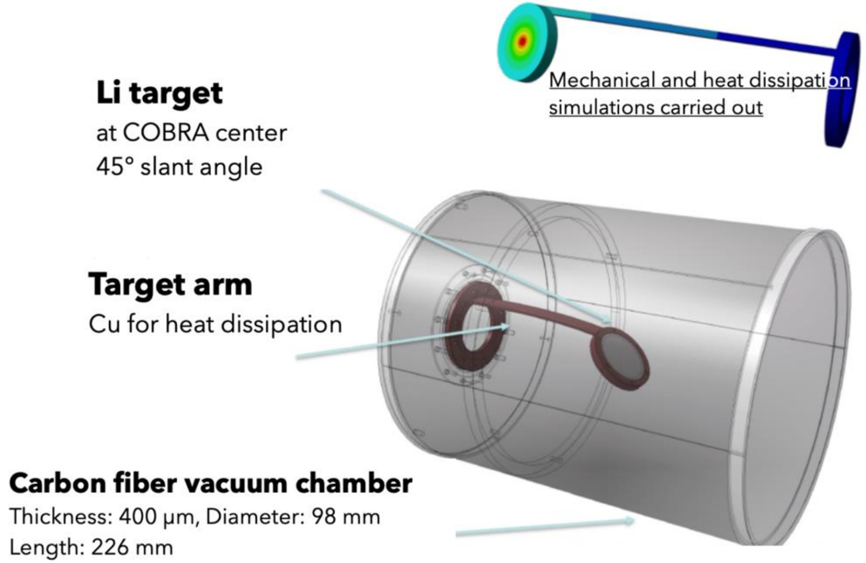
Analysis to see the X17 excess over the BhaBha scattering background, at $\mathbf{E_{cm} = M_{X17}}$

The $^{7}Li(p,e^{+}e^{-})^{8}Be$ experiment with the MEGII apparatus

- Proton from a ~1 MeV accelerator used for calibration
- Magnetic field to measure particle momenta
- Cylindrical drift chamber
- LXe detector
- 400 µm-thickness carbon fibre vacuum chamber to minimize multiple scattering
- 5 µm LiF target on 10 µm copper (@ INFN Legnaro)
- >2 µm LiPON target on 25 µm copper (@ PSI)
- 4 weeks of DAQ in February 2023
- 300k reconstructed e+e- pairs



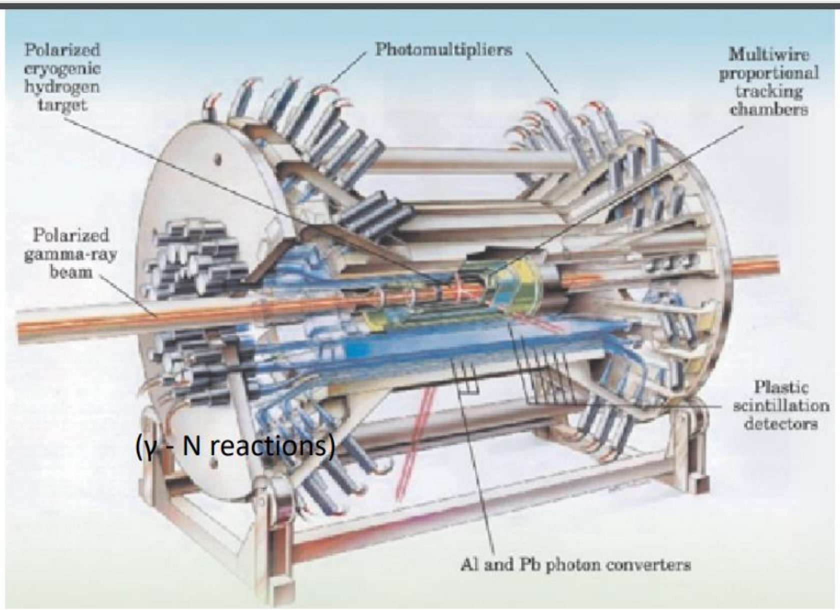
Aiming at unblinding at the beginning of 2024 (3-5σ signal expected)



Courtesy of F. Renga MEG II collab.

The Montreal X-17 Project

- Use parts of the DAPHNE experiment (Saclay/Mainz*)
- Tracking MWPC chamber & 16 scintillators (NE102A)
- Scints & MWPC from U. Mainz → now @ Montreal
- Phototubes and some ADC/TDC's borrowed from TRIUMF



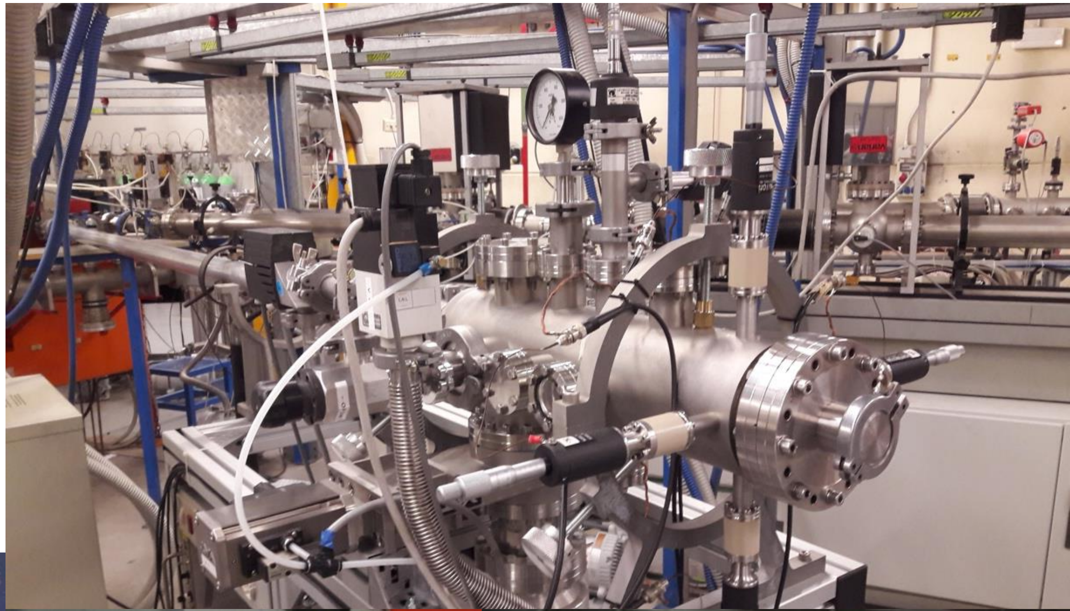
Large solid angle coverage → 0.95 x 4π

*Many thanks to
L. Doria & N. Mainz!?

The Aipac8Be apparatus at LNL

Design of a new setup for IPC measurements in low energy nuclear reactions:

- Improve angular resolution by reducing material budget.
- Improve angular coverage and measure out-of-plane correlations
- Improve confidence on target composition.
- Allow future coupling with a magnetic field.
- Can operate in vacuum



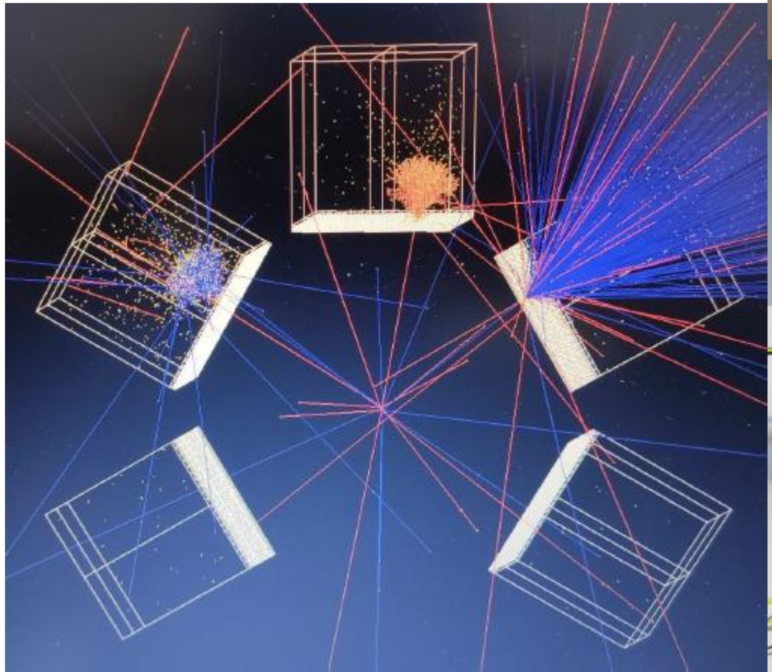
Beam line: AN2000 at LNL

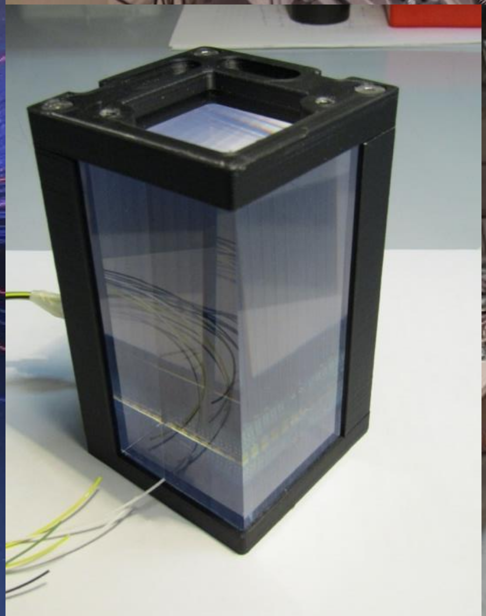
- Proton energy 200 – 2000 keV
- Beam current up to 1 μA

Target:

- One dedicated beamline

E_p=2 MeV I~1 uA

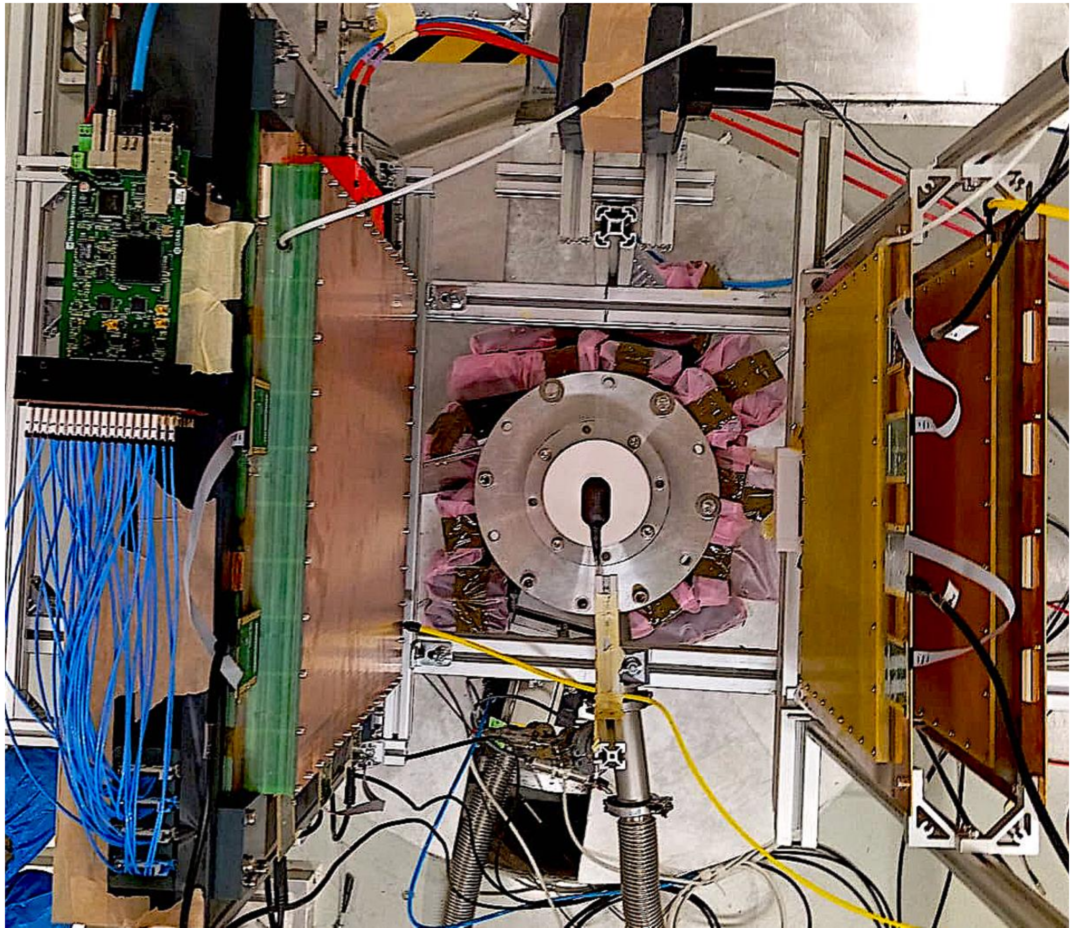


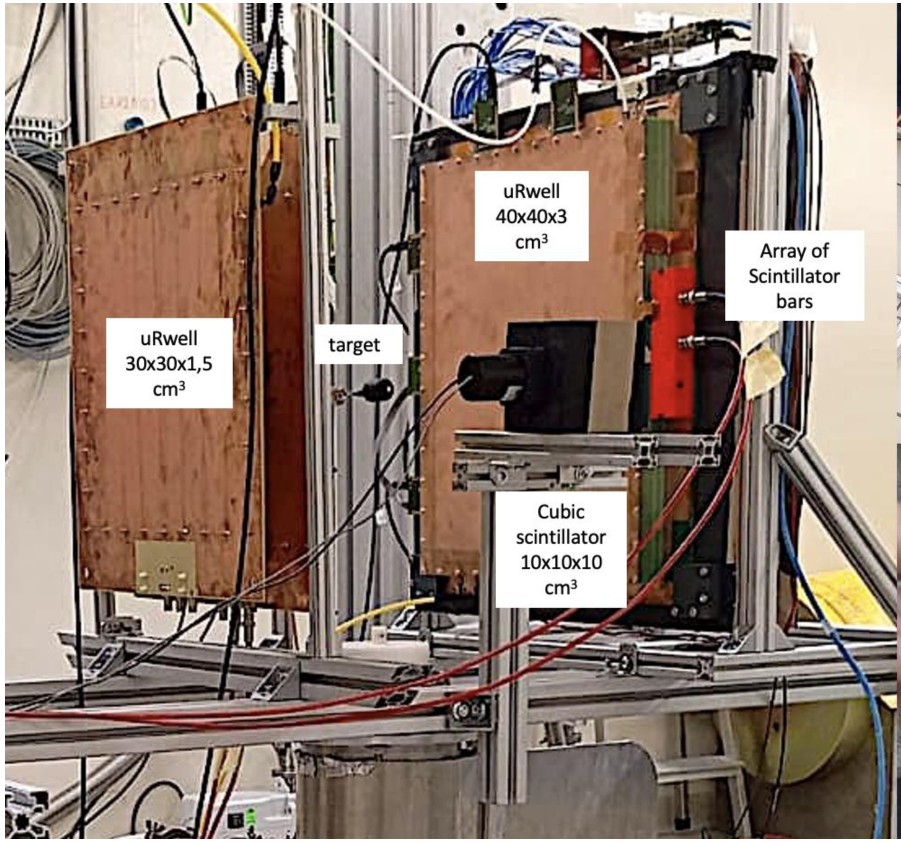


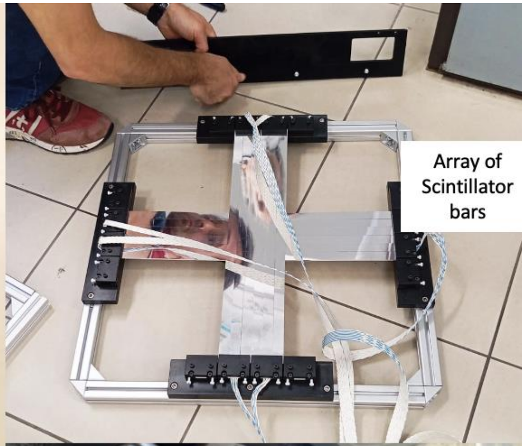
Courtesy of T. Marchi

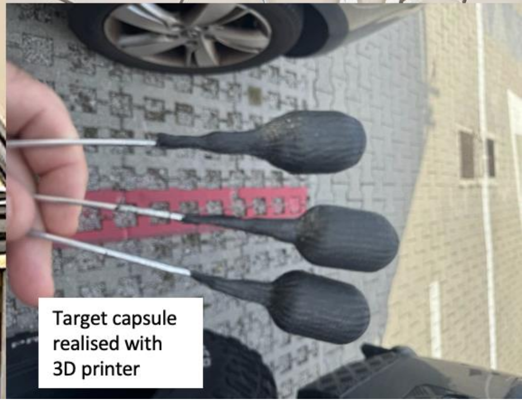
The n_TOF X17 detector demonstrator

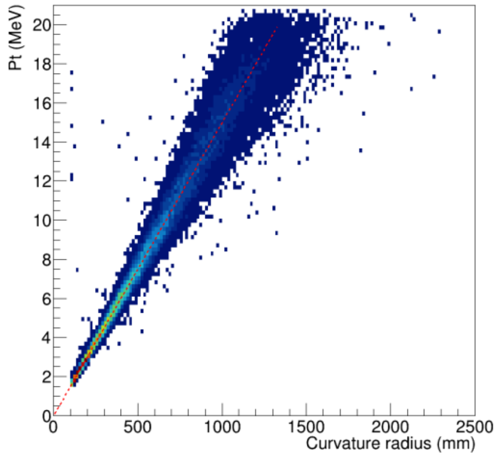
Tests of Demonstrator (1/4 of the final detector):
Neutron beam of N_TOF at CERN (October 2023)
Proton beam of ATOMKI, Debrecen (May 2024)

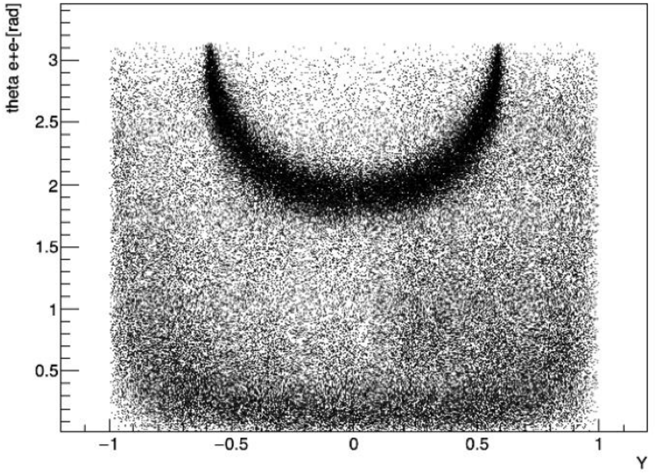












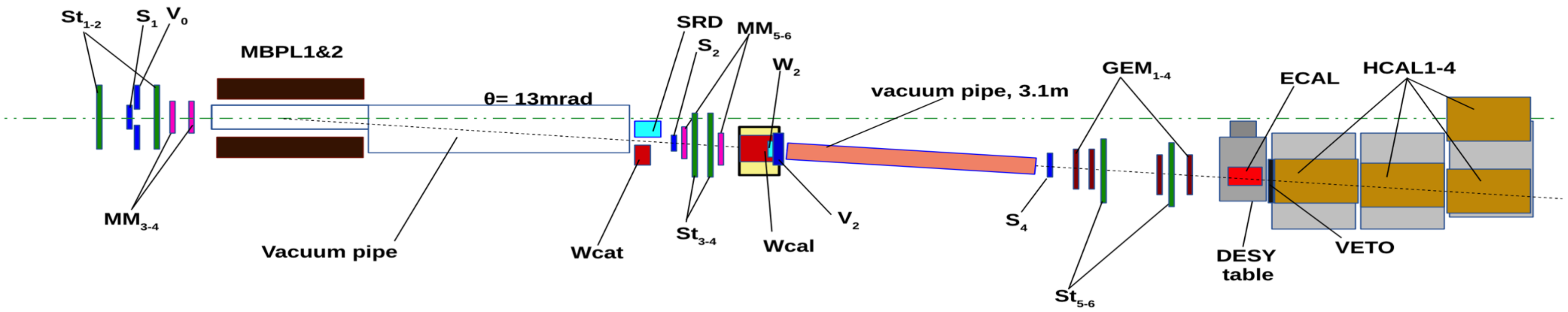
The NA64 experiment at CERN

- Electron beam with E_{beam}=100-150 GeV in a beam dump.
- The main aim of the NA64 experiment is to search for unknown particles from a hypothetical “dark sector”. These particles could be dark photons, which would carry a new force between visible matter and dark matter, in addition to gravity, or they could make up dark matter themselves.
- For these searches, NA64 directs an electron beam of 100–150 GeV energy from the Super Proton Synchrotron (SPS) onto a fixed target. Researchers then look for unknown dark- sector particles produced by collisions between the SPS beam’s electrons and the target’s atomic nuclei. The search can either be done by looking for ordinary particles, such as electrons, into which the new particles would decay, or for the “missing” collision energy the dark-sector particles would carry away.
- NA64 also searches for axions and axion-like particles that could explain the puzzling symmetry properties of the strong force or serve as a mediator of a new force. The experiment looks for the production of such particles in interactions between high-energy photons generated by the SPS beam’s electrons in the target and virtual photons from the target’s atomic nuclei.

The NA64 experiment at CERN

The ^{8}Be excess and search for the $X \to e^+e^-$ decay of a new light boson with NA64

S.V. Donskov, S.N. Gninenko, M.M. Kirsanov, D.V. Kirpichnkov



"Search for a hypothetical 16.7 MeV gauge boson and dark photons in the NA64 Experiment at CERN". *Physical Review Letters*. **120** (23): 231802, (2019).

Search for Axionlike and Scalar Particles with the NA64 Experiment, D. Banerjee *et al.* (NA64 Collaboration)
Phys. Rev. Lett. **125**, 081801 – Published 17 August 2020

https://www.youtube.com/watch?v=J1P5r3IvVrM