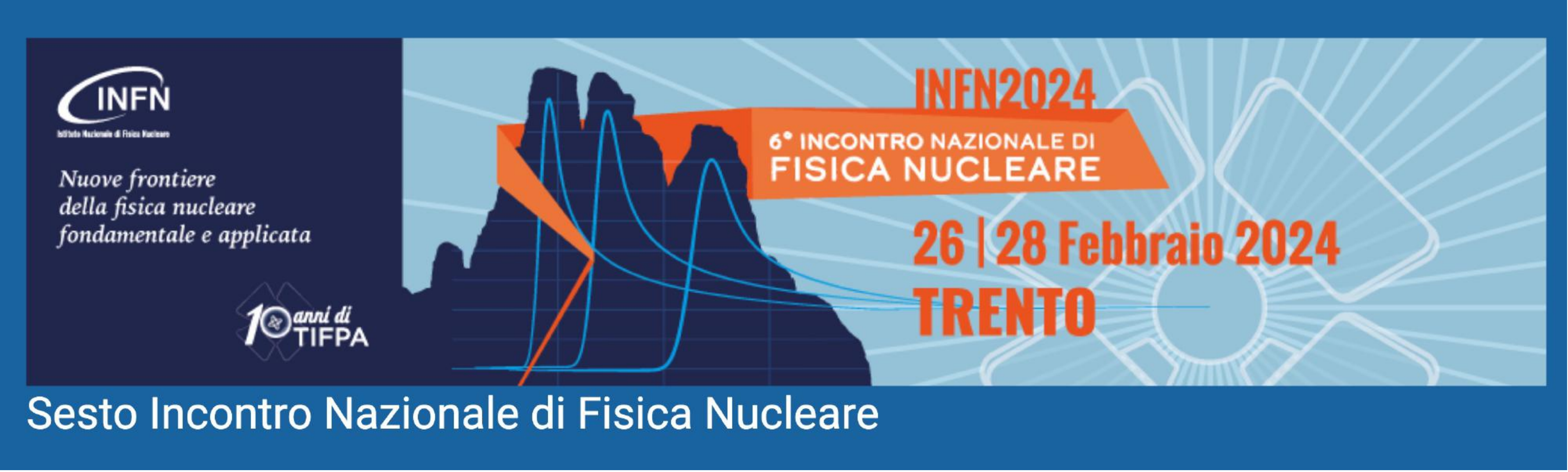



# The X17 boson anomaly: overview and forthcoming experiments

Carlo Gustavino
INFN-Roma

# Introduction

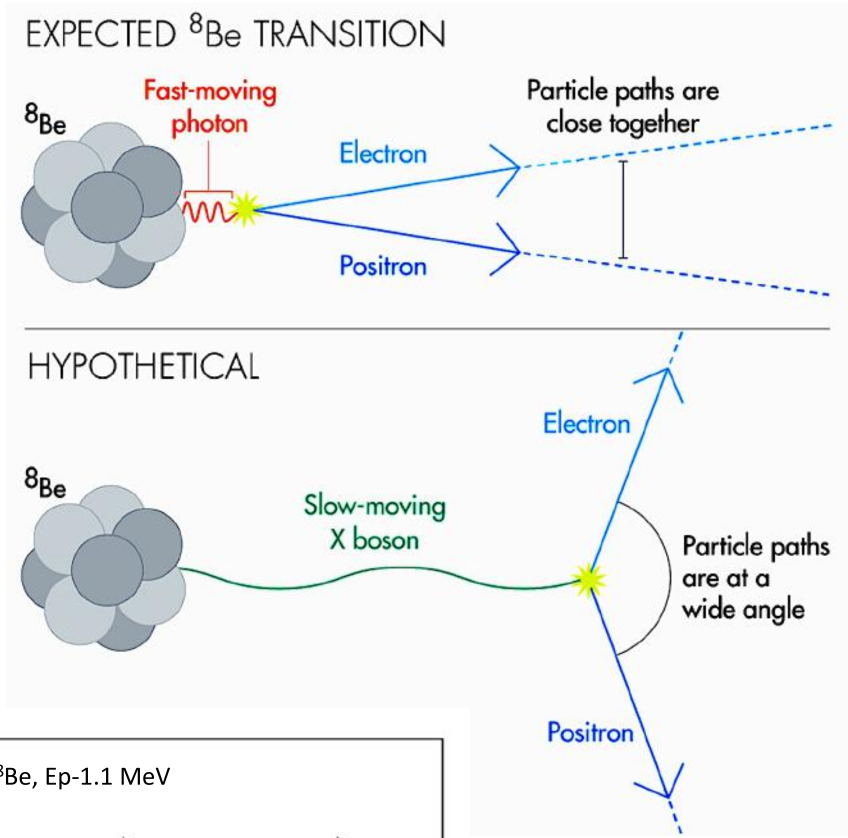
Three anomalies have been recently observed in experiments performed at the 2 MV accelerator of ATOMKI, Debrecen (Hungary). **The anomaly consists in an excess of $e^+e^-$ pairs at large relative angle** in the **$^7Li(p,e^+e^-)^8Be$, $^3H(p,e^+e^-)^4He$** and **$^{11}B(p,e^+e^-)^{12}C$** nuclear reactions.

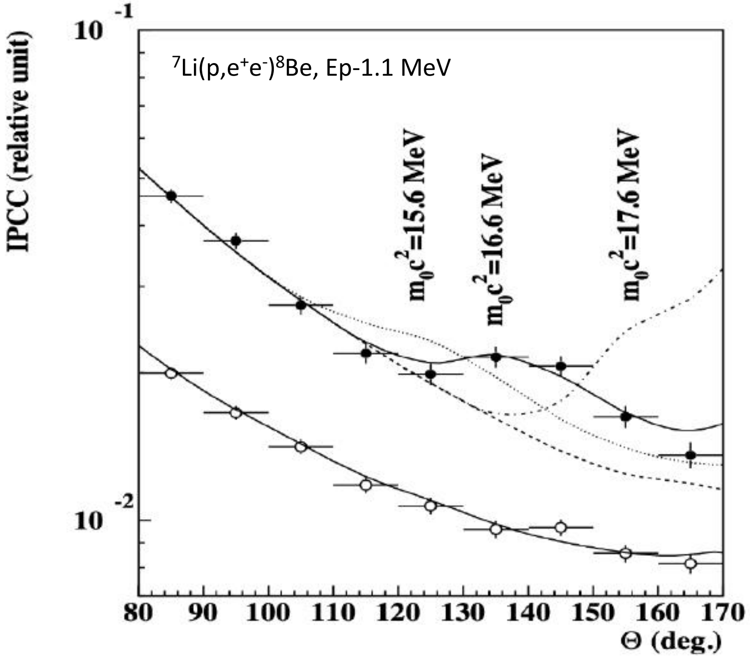
These anomalies have been interpreted as the signature of a BOSON (called X17) with mass $M_{X17}$=17 MeV, not foreseen in the standard model of particle physics.

The X17 boson could be a mediator of a fifth force, characterized by a strong coupling suppression of protons compared to neutrons (protophobic force). Maybe a “portal” to the dark sector.

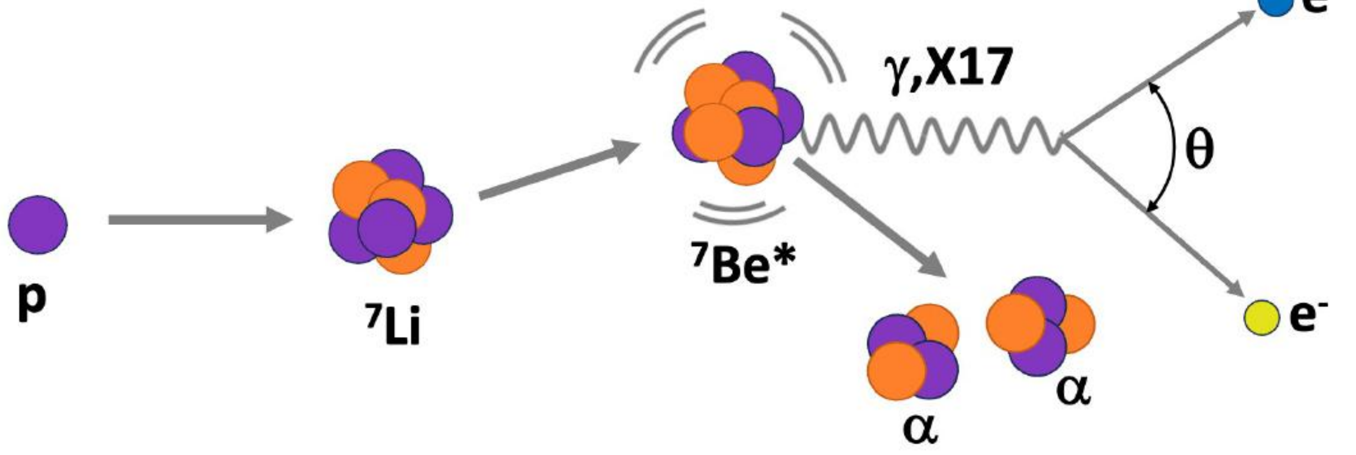
Even more, this scenario could explain, at least partially, the long-standing (recent) anomaly on the muon (electron) magnetic moment.

If confirmed, this new particle could be of extraordinary importance, in particle physics and in Cosmology. Therefore an experimental and theoretical effort is mandatory in order to:
-Confirm/reject the X17 evidence.
-Establish the X17 properties, as **$J^\pi$, $\tau$, coupling…**
-Extend the SM in a a picture in which X17 boson is coherently included

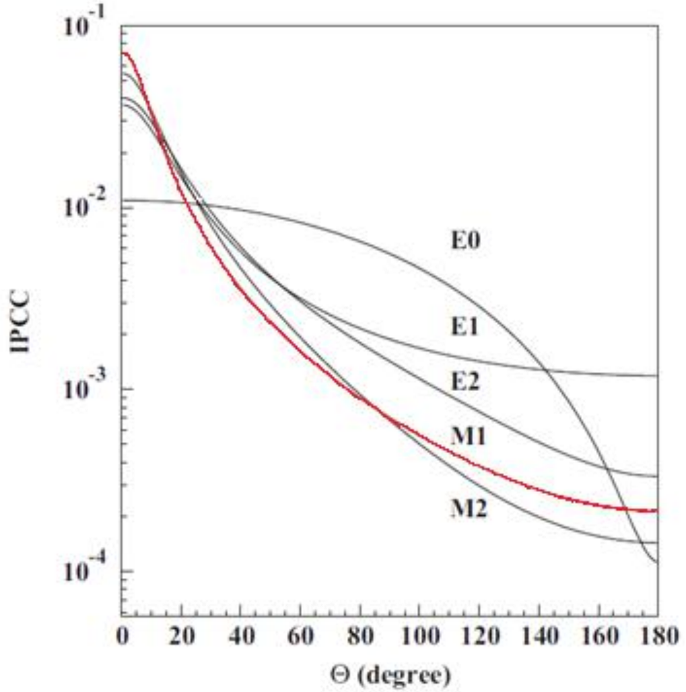


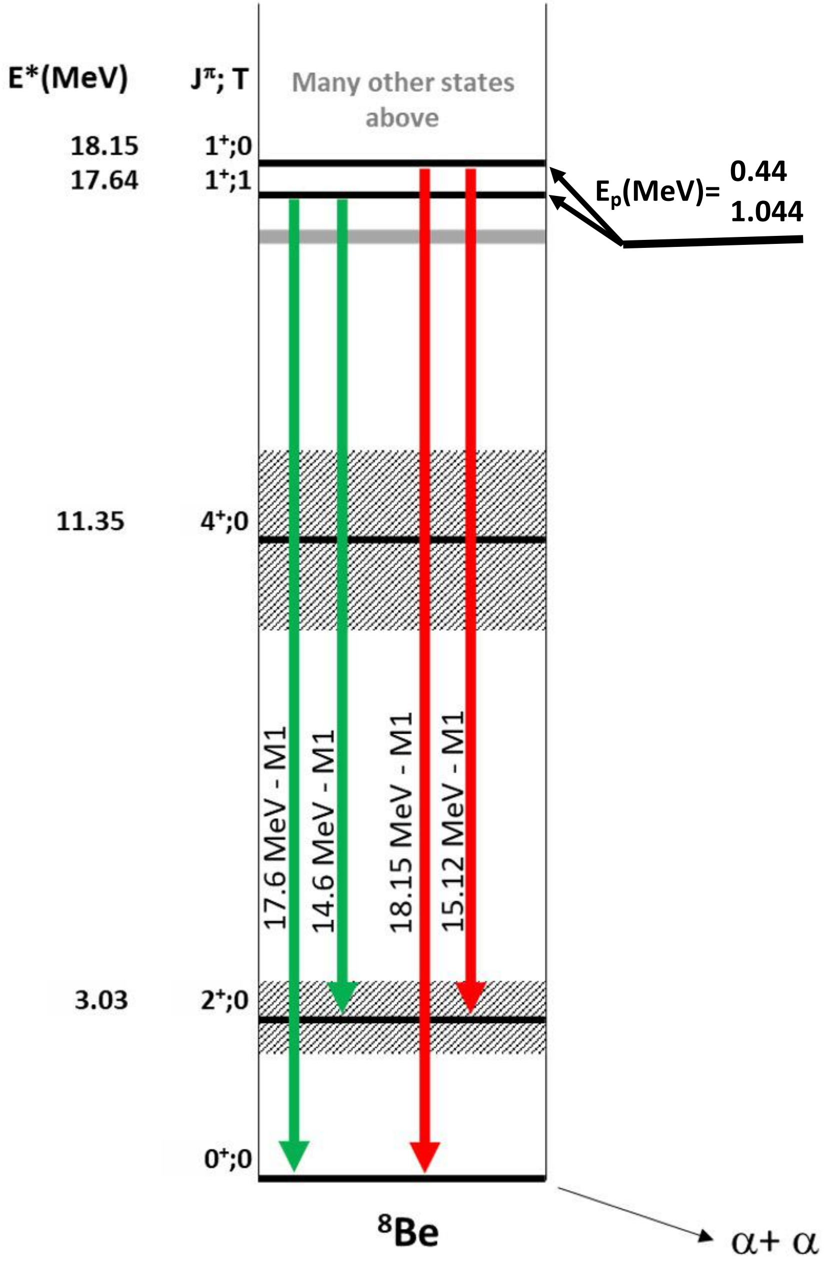



# $^{7}Li(p,e^{+}e^{-})^{8}Be$ reaction at ATOMKI

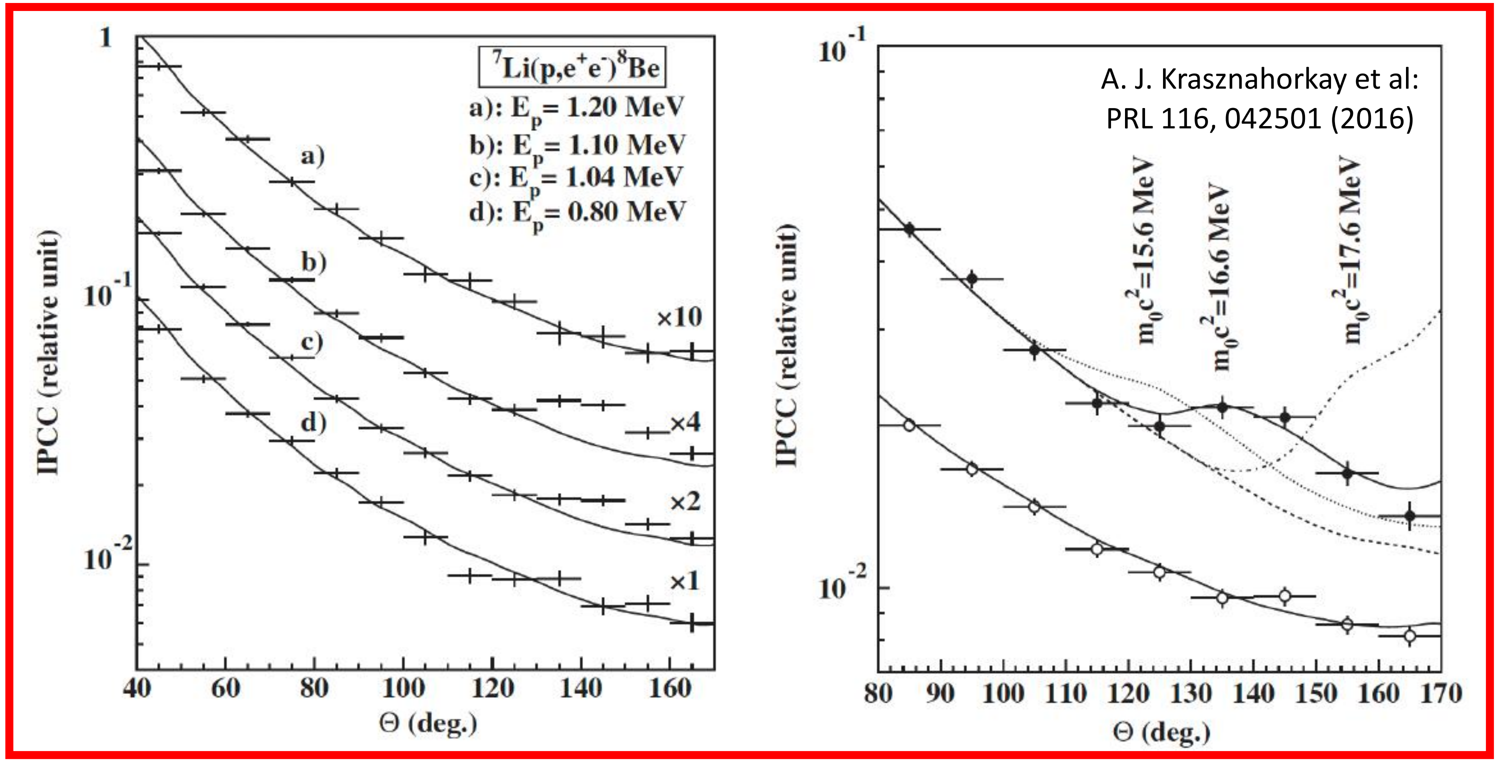


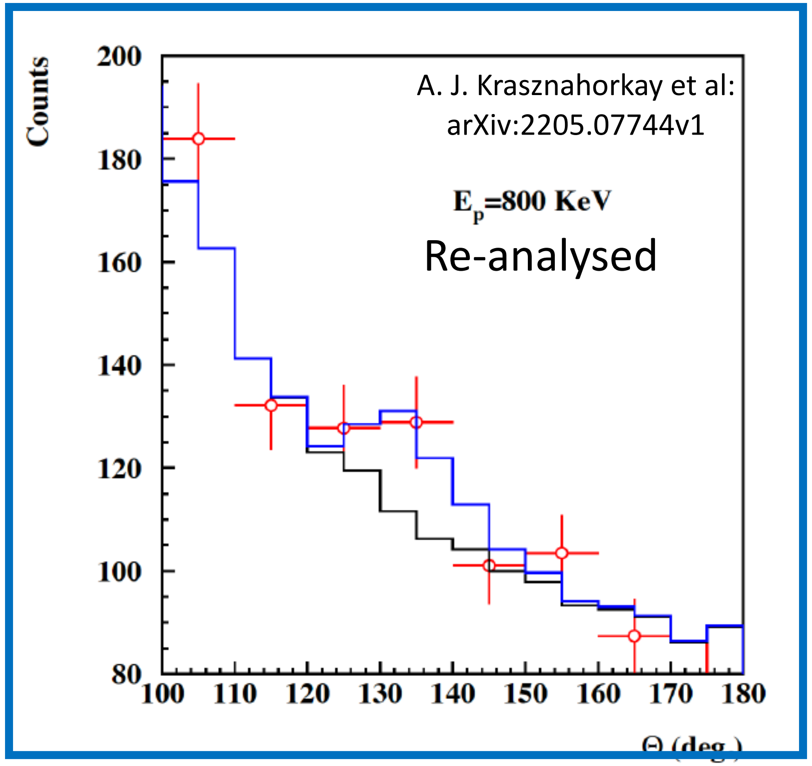

- The reaction $^{7}Li(p,e^{+}e^{-})^{8}Be$ allows to selectively populate the 17.64 MeV and 18.15 MeV resonances. The considered transitions are M1 type.
- In SM, the irreducible background is due to virtual photons converting into $e^{+}e^{-}$ pairs (internal pair convertion, IPC). IPC pairs decreases smoothly with the aperture angle.
- Typically, IPC/$\gamma$s=$10^{-3}$



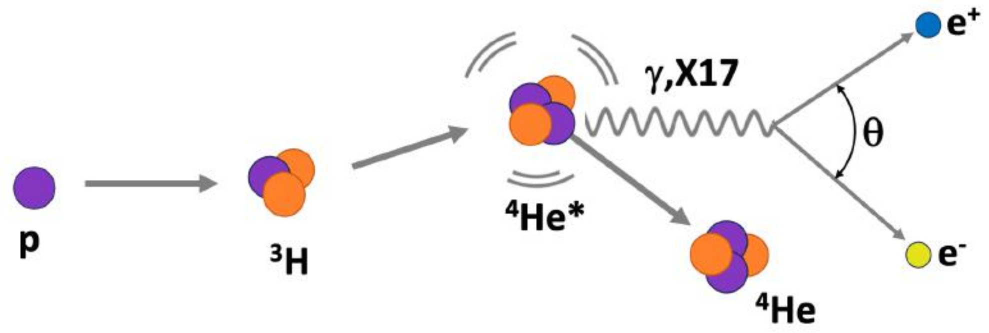
# $^7Li(p,e^+e^-)^8Be$ experiment result

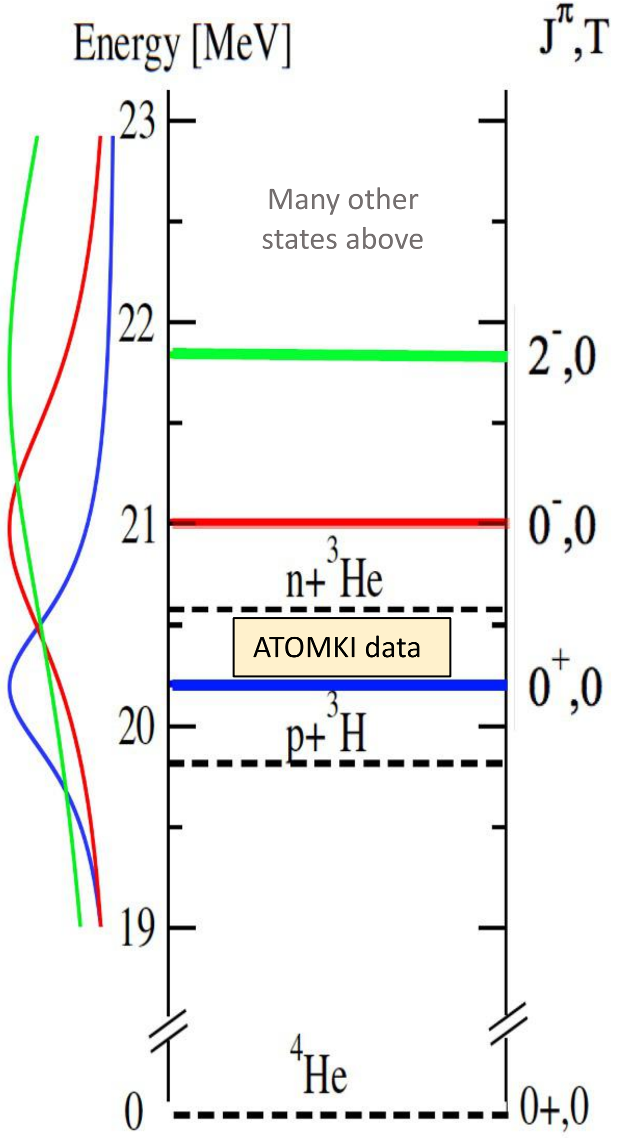


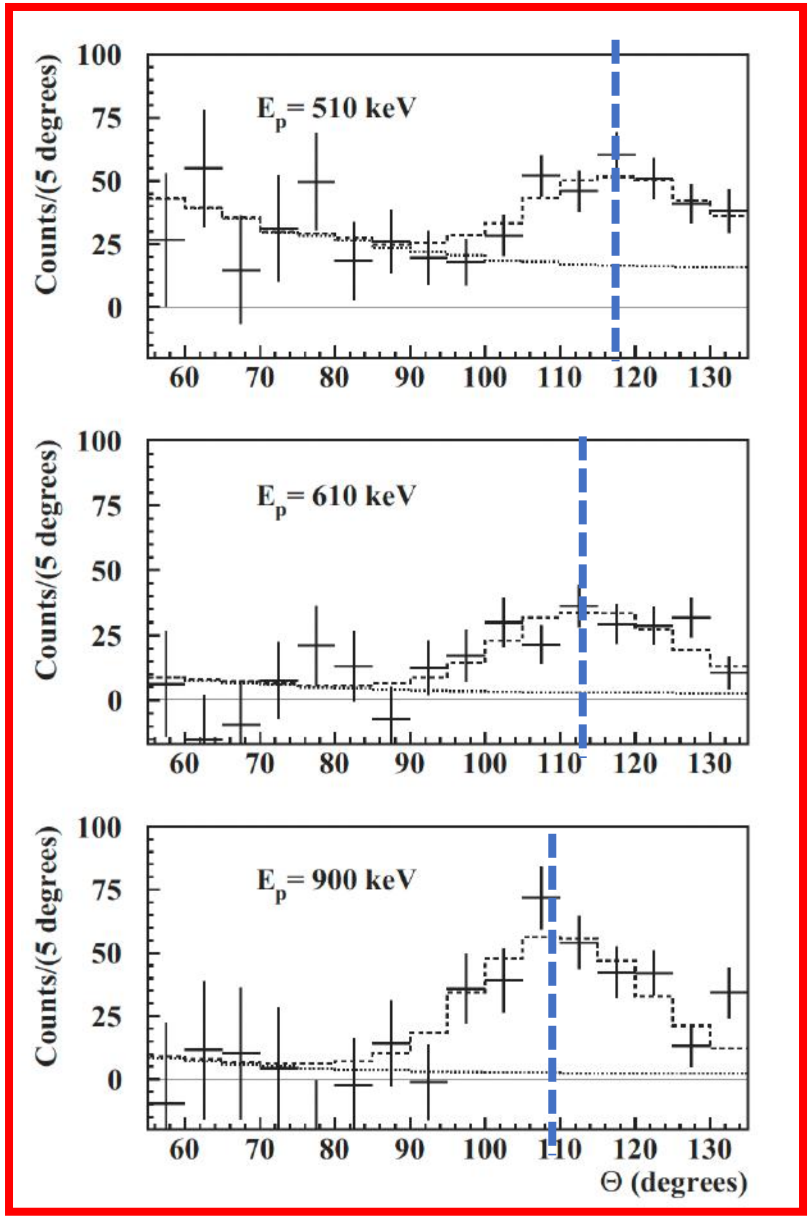




- Clear counting excess for $\theta_{e+e-}$~140° for $E_p$ populating yje 18.2 resonance
- This anomaly has been interpreted as the signature of a BOSON (hereafter X17) not foreseen in the standard model of particle physics, with **$M_{X17}\pm\Delta M_{stat}\pm\Delta M_{syst}$ (MeV)=16.70±0.35±0.50**
- The excess is broadened by the of e+e- **multiple scattering** in the carbon tube and in the target backing.
- No excess populating the 17.6 Clear counting excess populating the 18.2 resonance, for $\theta_{e+e-}$~140° resonance, making very puzzling the data interpretation. However
- *A recent measurement and the re-analysis of old data shows that the excess is also at 17.6 MeV (See arXiv:2205.07744v1)*

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




- Counting excess for $\theta_{e+e-}$ 110°
- Remarkably, the excess moves towards smaller angles increasing the energy, in agreement with the creation of a 17 MeV particle
- **$M_{X17} \pm \Delta M_{stat} \pm \Delta M_{syst}$ (MeV)=16.94±0.12±0.21**

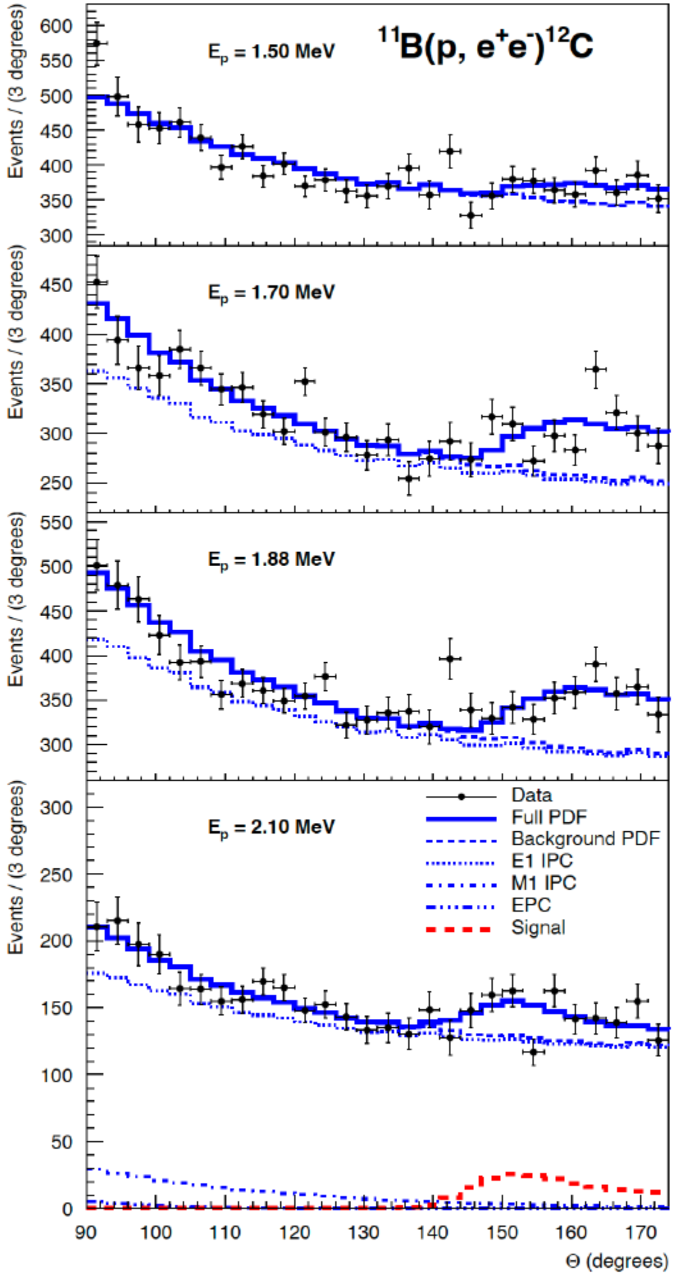
N.B. Target heating (Tritium evaporation) makes this measure problematic because of safety rules

PHYS. REV. C 104, 044003 (2021)

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

-The three reactions studied at ATOMKI provide a compatible with scenario in which is kinematics indicates the creation of a 17 MeV boson decaying into $e^+e^-$ .
-The excess of the $^7Li(p,e^+e^-)^8Be$ has been confirmed (~4σ) by a (not so) different team using a (not so) different setup. arXiv:2401.11676v1 [nucl-ex] 22 Jan 2024.
*-Apart from that, the ATOMKI anomaly is presently not confirmed neither excluded by other experiments/groups.*
*-While kinematics is very convincing, property of X17 ( $J^\pi$, life-time, coupling with ordinary matter,..) largely unknown because of the limited experimental informations.*

| | $E_p$ (MeV) | $B_x$ $\times 10^{-6}$ | Mass (MeV/$c^2$) | Confidence |
|---|---|---|---|---|
| $^{12}C$ | 1.50 | 1.1(6) | 16.81(15) | $3\sigma$ |
| | 1.70 | 3.3(7) | 16.93(8) | $7\sigma$ |
| | 1.88 | 3.9(7) | 17.13(10) | $8\sigma$ |
| | 2.10 | 4.9(21) | 17.06(10) | $3\sigma$ |
| | Averages | 3.6(3) | 17.03(11) | |
| $^8Be$ | Previous [14] | 5.8 | 16.70(30) | |
| $^4He$ | Previous [28] | 5.1 | 16.94(12) | |
| | Predicted [30] | 3.0 | | |




Phys. Rev. C **106**, L061601 (2022)

# 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.

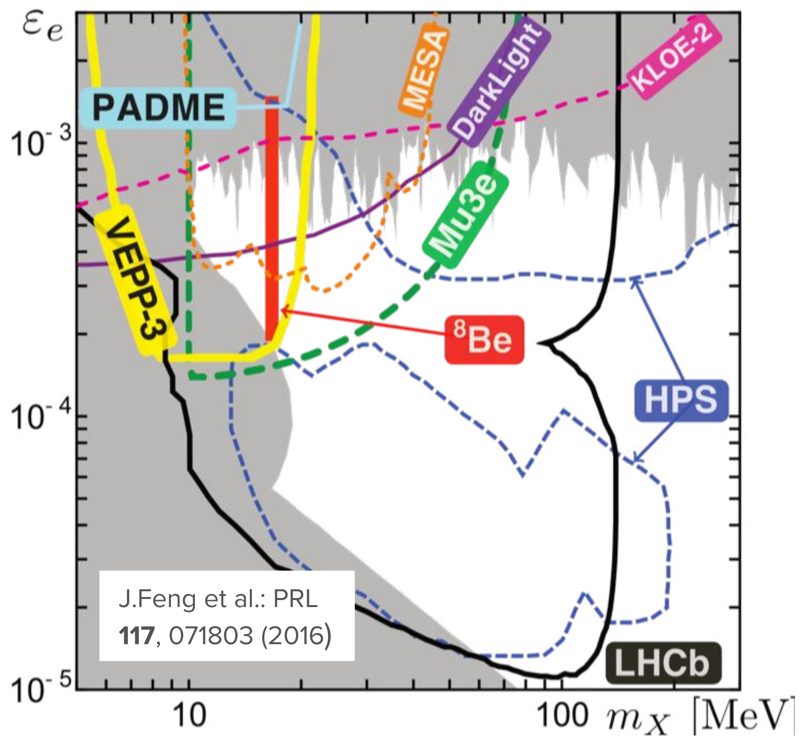
-Ellwanger and Moretti (2016)suggested another interpretation of the experimental results in view of a light, pseudoscalar particle [21]. They predicted about ten times smaller branching ratio in case of the 17.6 MeV transition compared to the 18.15 MeV one.

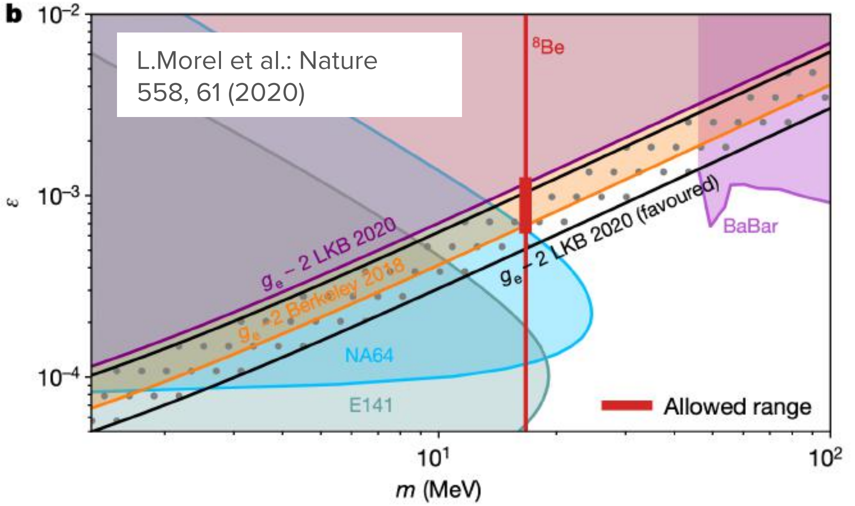
-Zhang and Miller (2017) investigated the nuclear transition form factor as a possible origin of the anomaly, but they concluded the hypothesis unrealistic for the $^8$Be nucleus.

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

-....

-....



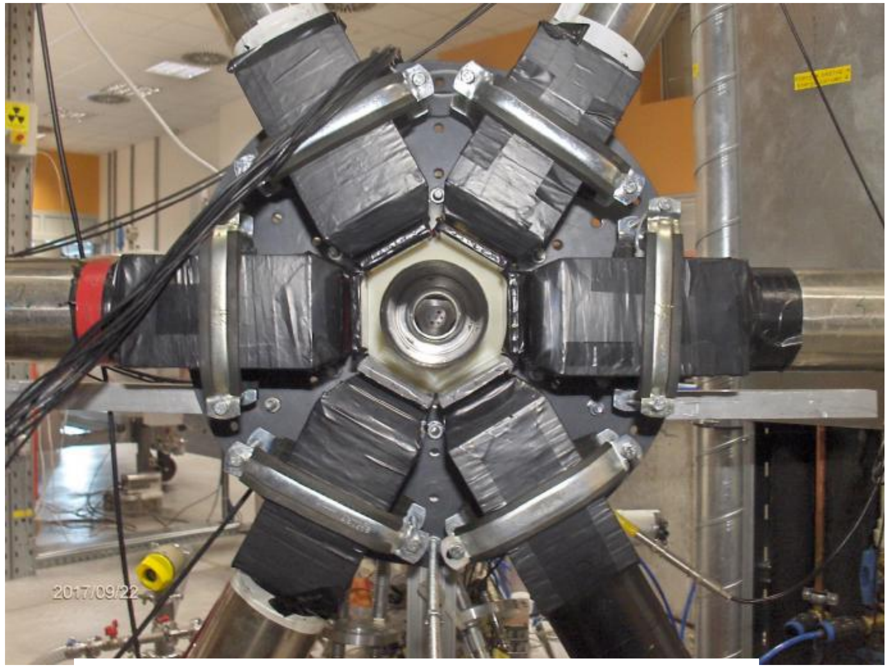
# The ATOMKI Setup

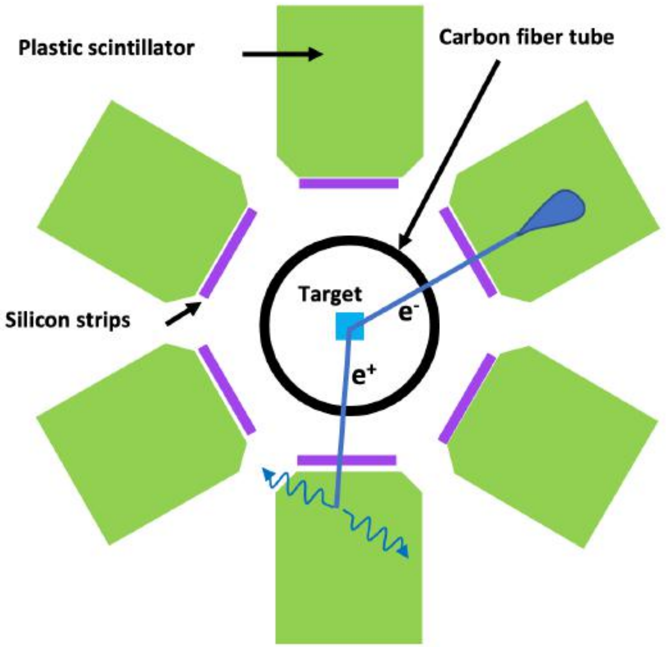
Let consider the **$^3H(p,e^+e^-)^4He$** experiment. The setup is projected to measure the **aperture angle of ejectiles and their energy :**

- ❖Proton beam up 2 MeV (ATOMKI Tandetron)
- ❖$^3H$ thin target deposited on a thin Titanium backing
- ❖1 mm thick carbon fiber tube
- ❖6 plastic scintillator 82x86x80 $mm^3$
- ❖6 double-sided silicon strip detector (3 mm wide strips, 0.5 mm thick)

However:

- ❖No tracking
- ❖No particle identification
- ❖Detector acceptance only around 90° with respect to the beam axis
- ❖Narrow Energy window for proton beam

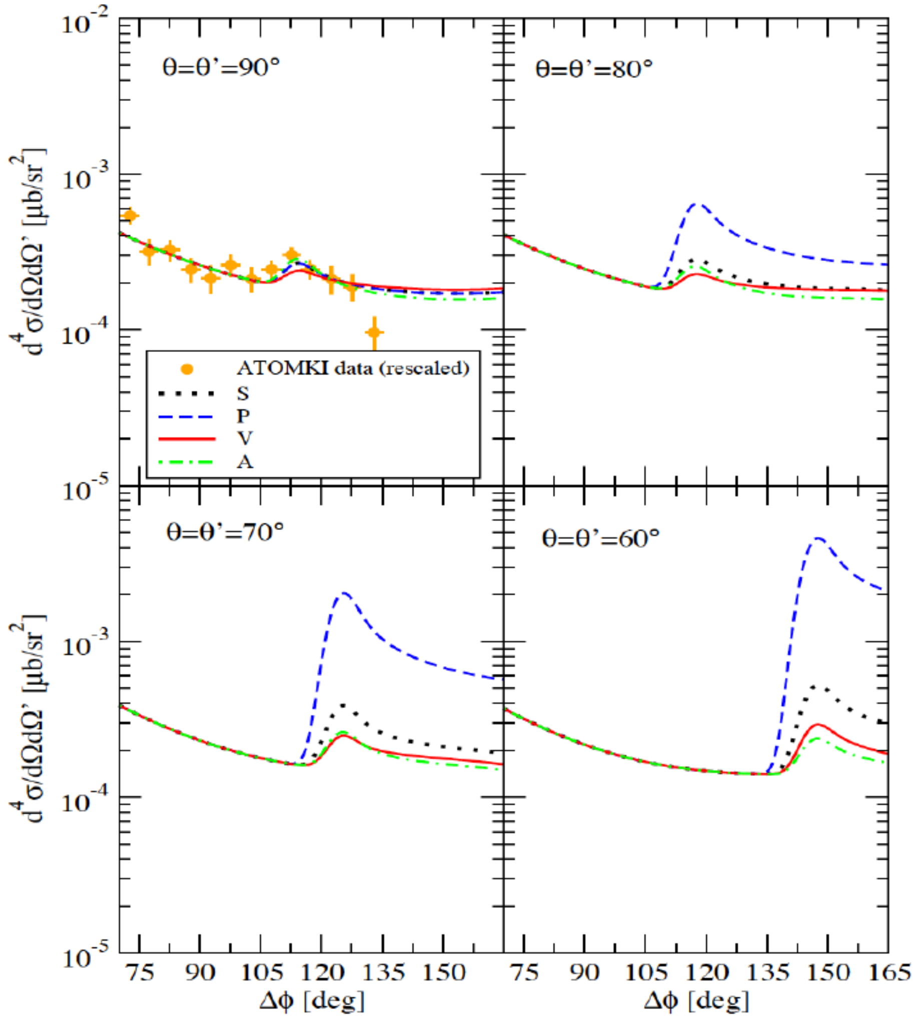


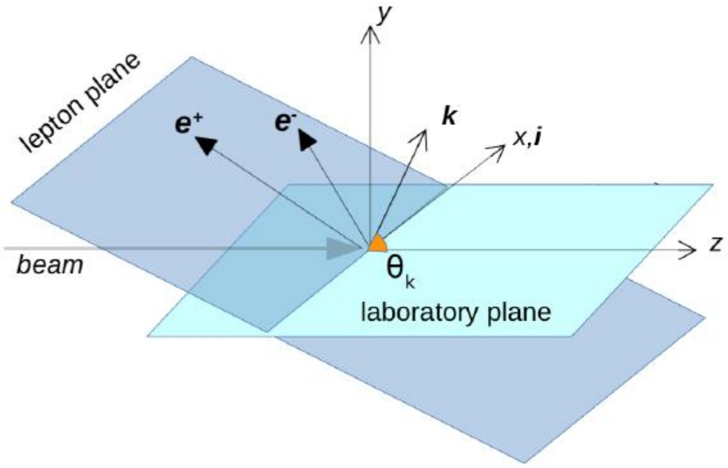
# Detector acceptance

In addition to having an higher statistics, a detector with a large acceptance is useful to probe the quantic number of X17, e.g. if it is a Scalar/Pseudoscalar/Vector/Axial Boson. As shown in a recent ab-initio calculation in which the de-excitation of $^4$He*→γ, X17 is considered , the angular distribution of e+e- pairs from the X17 decay strongly depends on its quantum numbers.

Predictions normalized to the ATOMKI data with ejectiles emitted at 90° with respect to the beam axis, $E_p$=900 keV



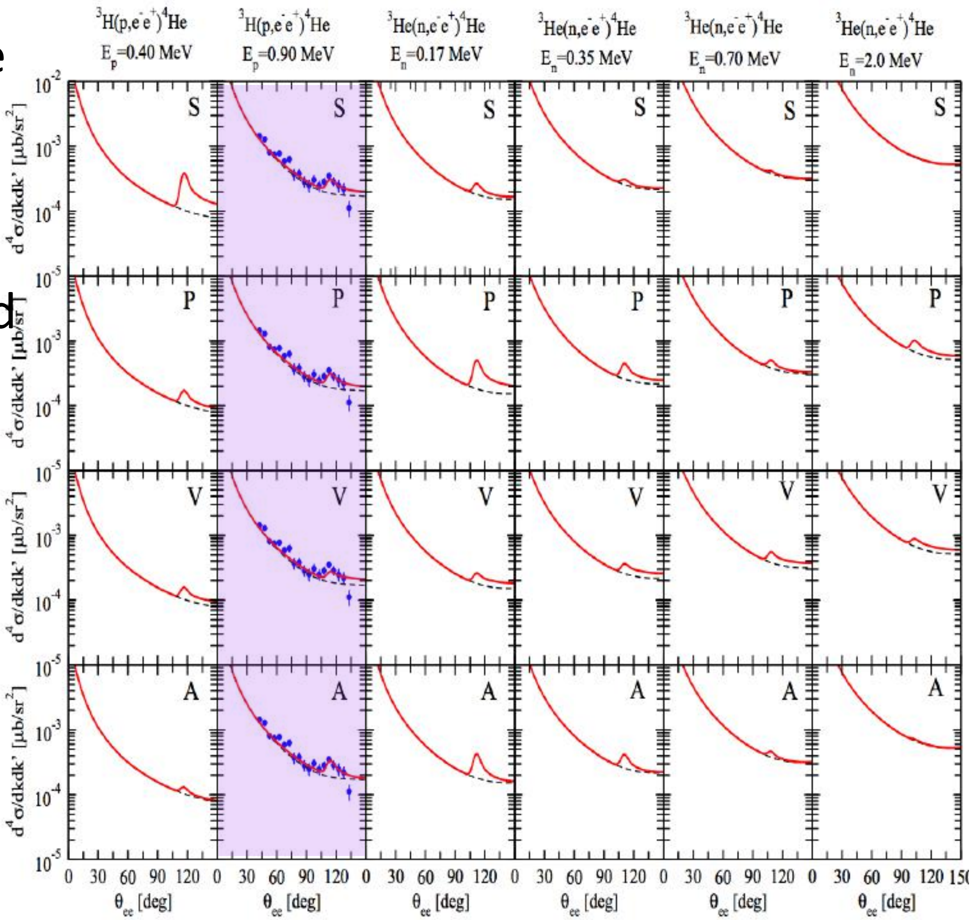

M. Viviani et al.: PRC 105, 014001 (2022)



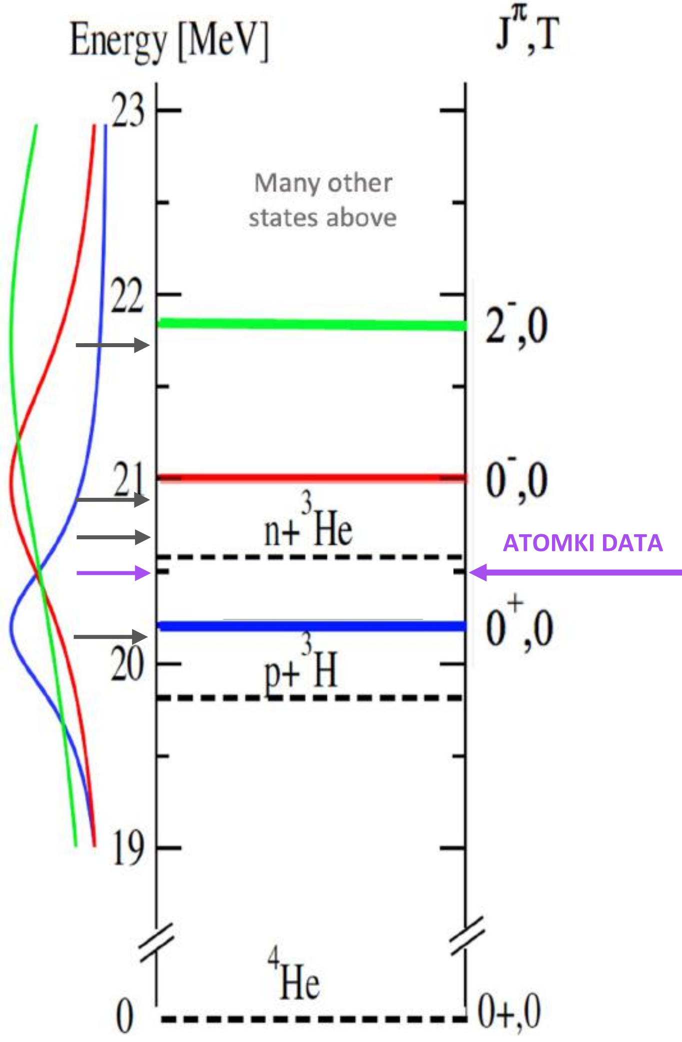
# Beam energy range

Measurements in a broad energy range allow to scan different decay modes to probe the X17 properties.
The ab-initio calculation the de-excitation of $^4He^* \rightarrow \gamma$, X17 is considered at different energies with pairs emitted at 90° respect to the beam axis.

Predictions normalized to the ATOMKI data with ejectiles emitted at 90° with respect to the beam axis, $E_p$=900 keV




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



# Hunting down the X17 puzzle: an overview of worldwide efforts


Shedding light on X17, Rome, September 2021.
*The first workshop able to gather the X17 "community" worldwide.*

**The ATOMKI spectrometer**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Coffe Break**
*Aula Magna, Centro Ricerche Enrico Fermi*

**8Be IPC with the MeGII experiment** ← $^8$Be at MEG II
*Aula Magna, Centro Ricerche Enrico Fermi*

**IPC with TPC**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Experiments on 8Be IPC at INFN Legnaro Laboratory** ← $^8$Be at LNL
*Aula Magna, Centro Ricerche Enrico Fermi*

**The searching for 4He anomaly at N-TOF experiment** ← X17 at n_TOF
*Aula Magna, Centro Ricerche Enrico Fermi*

Session: Experiments on IPC

**X17 production mechanisms at accelerators**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Searching for X17 in pi0 decays at NA48/2**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Recent results on X17 searches in NA64**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Searching X17 with positrons at PADME** ← X17 at PADME
*Aula Magna, Centro Ricerche Enrico Fermi*

**Searching for X17 at JLab**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Coffee Break**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Searching for X17 at MAGIC**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Prospects for X17 searches at Mu3e**
*Aula Magna, Centro Ricerche Enrico Fermi*

Session: Searches for X17

**Theoretical introduction to possible interpretations** *Jona*
*Aula Magna, Centro Ricerche Enrico Fermi*

**A U(1)' solution of the 17 MeV anomaly** *L*
*Aula Magna, Centro Ricerche Enrico Fermi*

**X17 Parameter Space Motivated by Theoretical Interpretations of ATOMKI**
*Aula Magna, Centro Ricerche Enrico Fermi*

**Coffee Break**
*Aula Magna, Centro Ricerche Enrico Fermi*

**The nuclear physics aspects of the ATOMKI anomaly and the protophobic vector boson explanation**
*Aula Magna, Centro Ricerche Enrico Fermi*

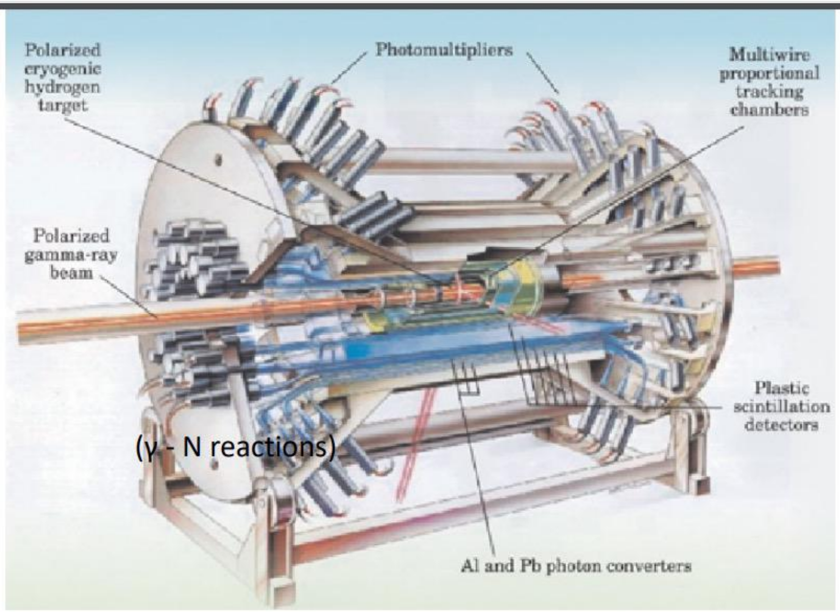
**QCD axion interpretation of the X17 anomalies** *Dan*
*Aula Magna, Centro Ricerche Enrico Fermi*

**Quark-antiquark QED meson description of X17 and other anomalous particles** *C*
*Aula Magna, Centro Ricerche Enrico Fermi*

Session: Theoretical works

# 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 → $0.95 \times 4\pi$**

*Many thanks to

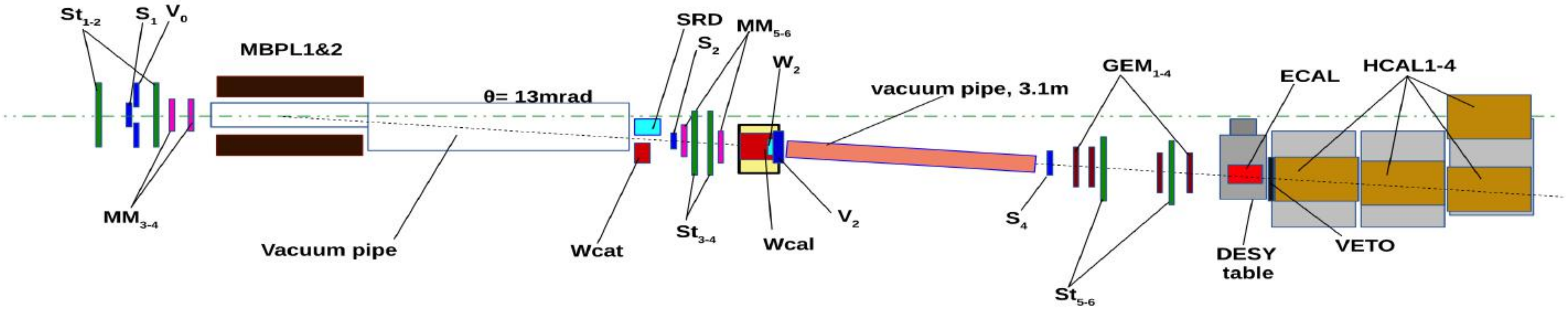
# The NA64 experiment at CERN

- 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

# Searching for the X(17) in particle decays at the Belle-II experiment

Precise measurements of weak interaction parameters using a high intensity $e^+e^-$ collider, study exotic hadrons, and search for new phenomena beyond the Standard Model of particle physics.

Searches for dark-matter related particles are pursued looking at deviation over a standard Physics "background".

- Araki et al. discussed the feasibility of detecting the gauge boson of the U(1) symmetry, which possesses a mass in the range between MeV and GeV, at the **Belle-II experiment**. They have found that the Belle-II experiment can examine a part of the parameter region that evades the current experimental constraints and, at the same time, is favored by the observation of the muon anomalous magnetic moment.

  (Phys. Rev. D 95, 055006 (2017))

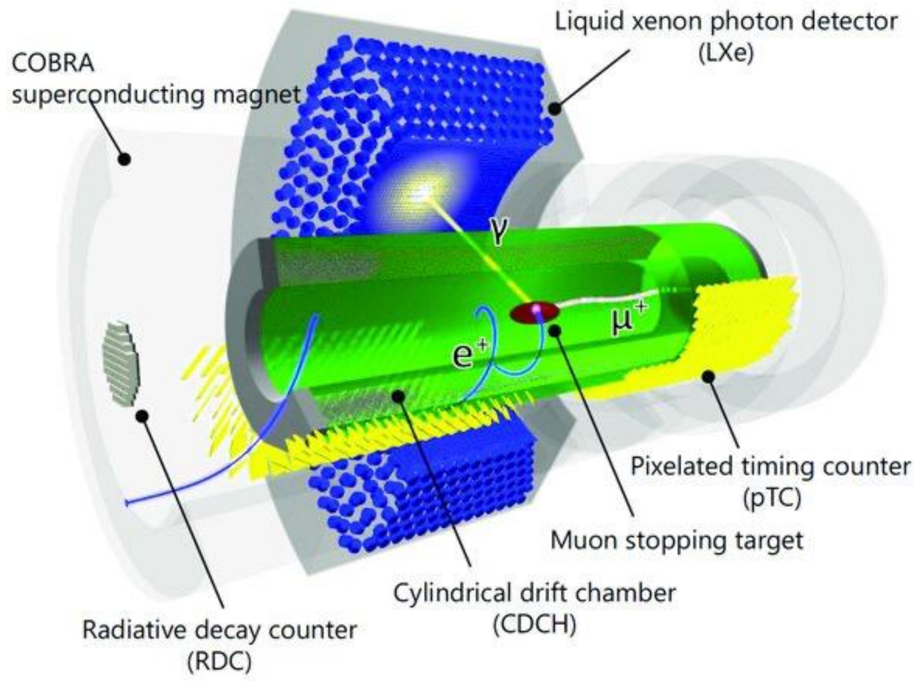
- Rare leptonic kaon and pion decays $K^+(\pi^+) \to \mu^+\nu_\mu e^+e^-$ can also be used to probe a dark photon of mass O(10)MeV. Cheng-Wei Chiang evaluated the reach of future experiments for the dark photon with vectorial couplings to the standard model fermions except for the neutrinos, and show that a great portion of the preferred 16.7-MeV dark photon parameter space can be decisively probed.

  (Physics Letters B 767 (2017) 289)

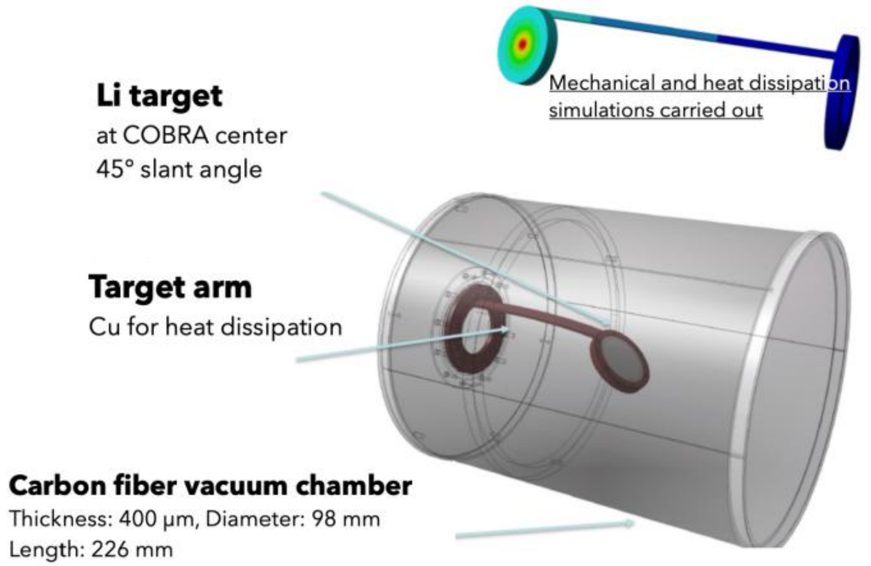
# X17 Search by Italian groups

# 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 (3-5$\sigma$ signal expected)




*Courtesy of F. Renga MEG II collab.*

# 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

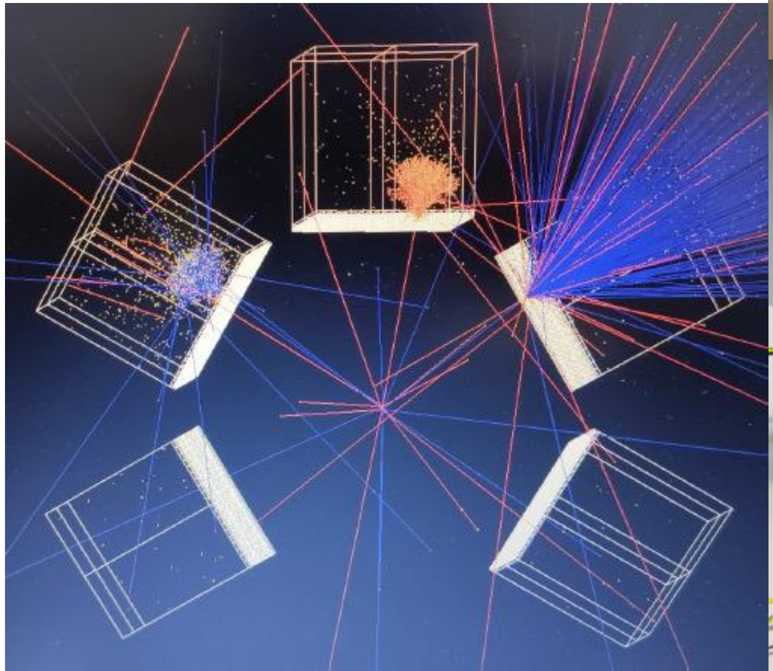
Beam line: AN2000 at LNL

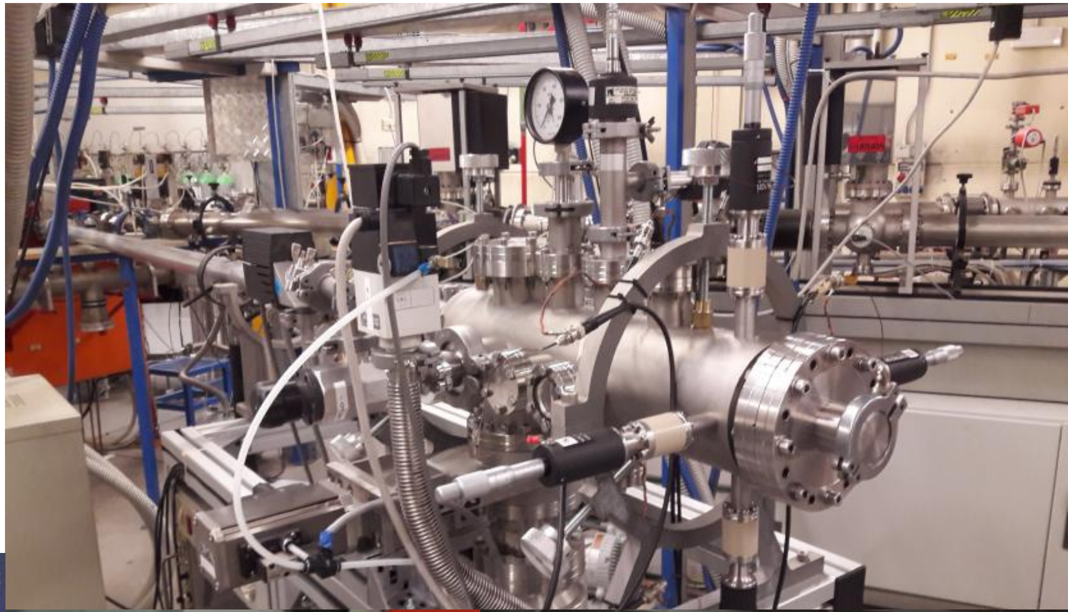
- Proton energy 200 – 2000 keV
- Beam current up to 1 $\mu$A

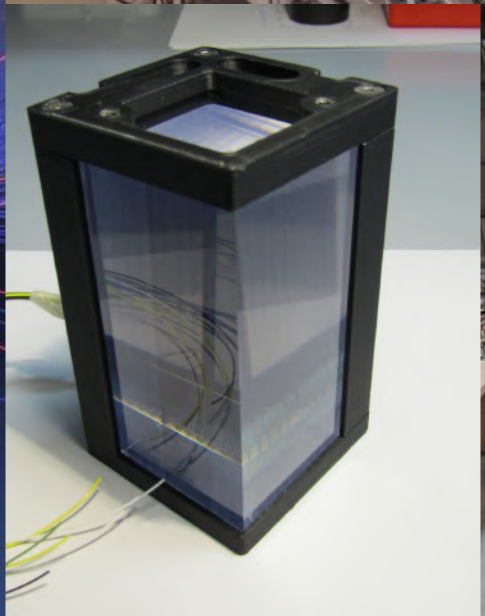
Target:

- One dedicated beamline

$E_p$=2 MeV I~1 uA



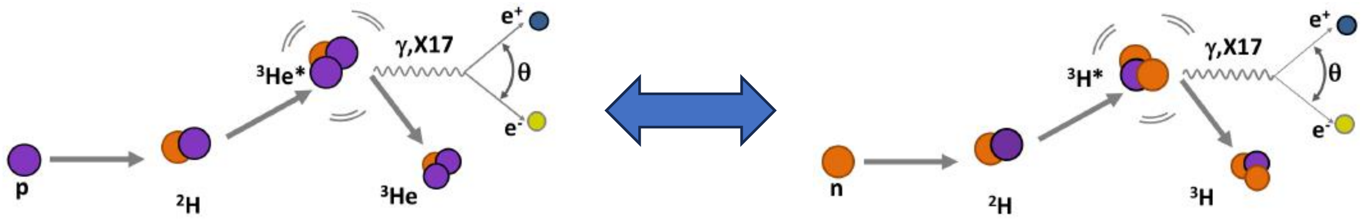


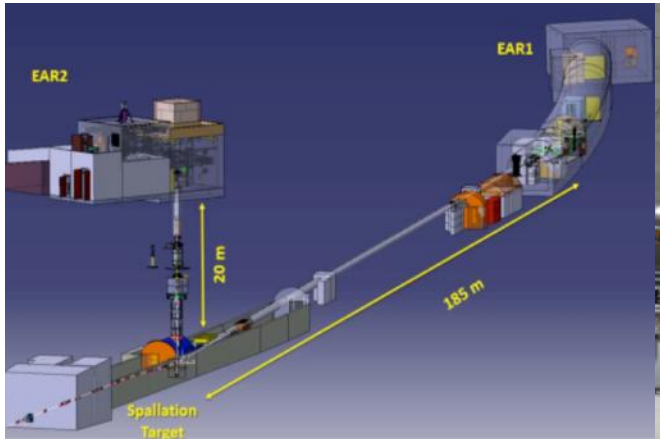


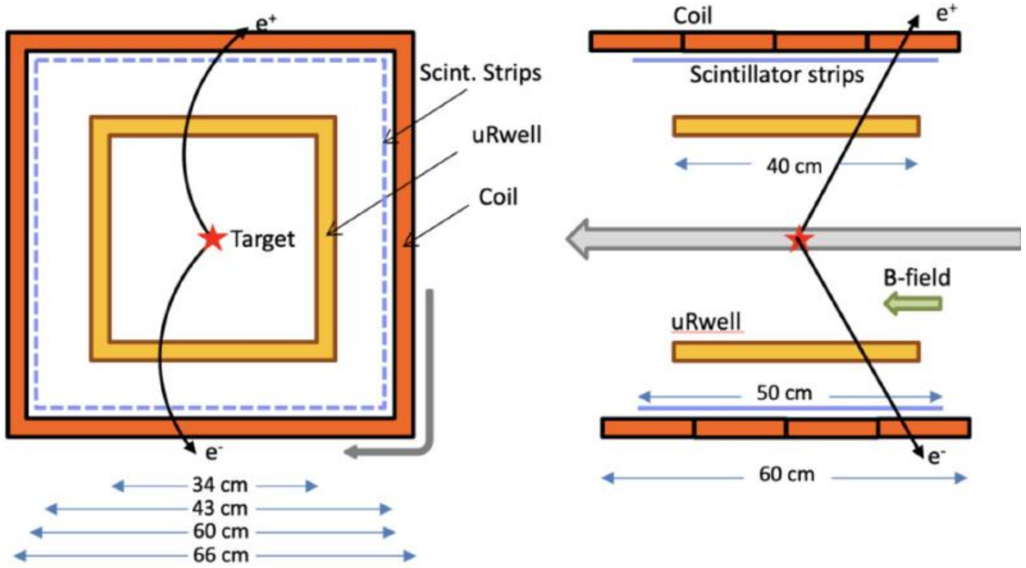
*Courtesy of T. Marchi*

# The n_TOF X17 detector

Experimental program under study:
$^3He(n,e^+e^-)^4He$ (New!)
$^3H(p,e^+e^-)^4He$
$^2H(p,e^+e^-)^3He$ (New!)
$^2H(n,e^+e^-)^3He$ (New!)
$^7Li(p,e+e-)^8Be$
With a detector with:
Large acceptance
Low sensitivity to photons and neutrons
Reconstruction of 4-momenta of ejectiles
Large acceptance Detector composed by:
-4 large μRwells (3D tracking)
-4 planes of scintillator bars (trigger)
-Magnetic Coil
Facility:
n_TOF, Demokritos, iThemba… (neutrons)
LNGS, ATOMKI, LNL…(protons)

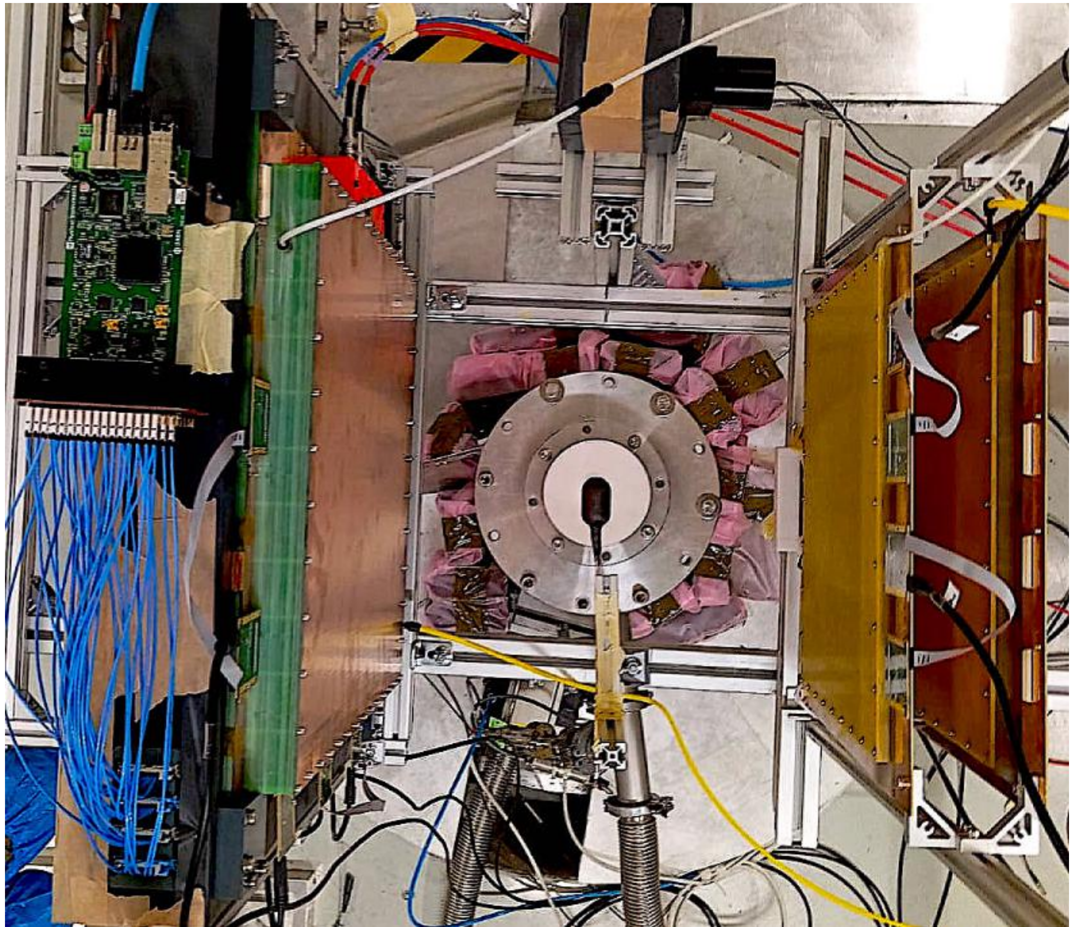


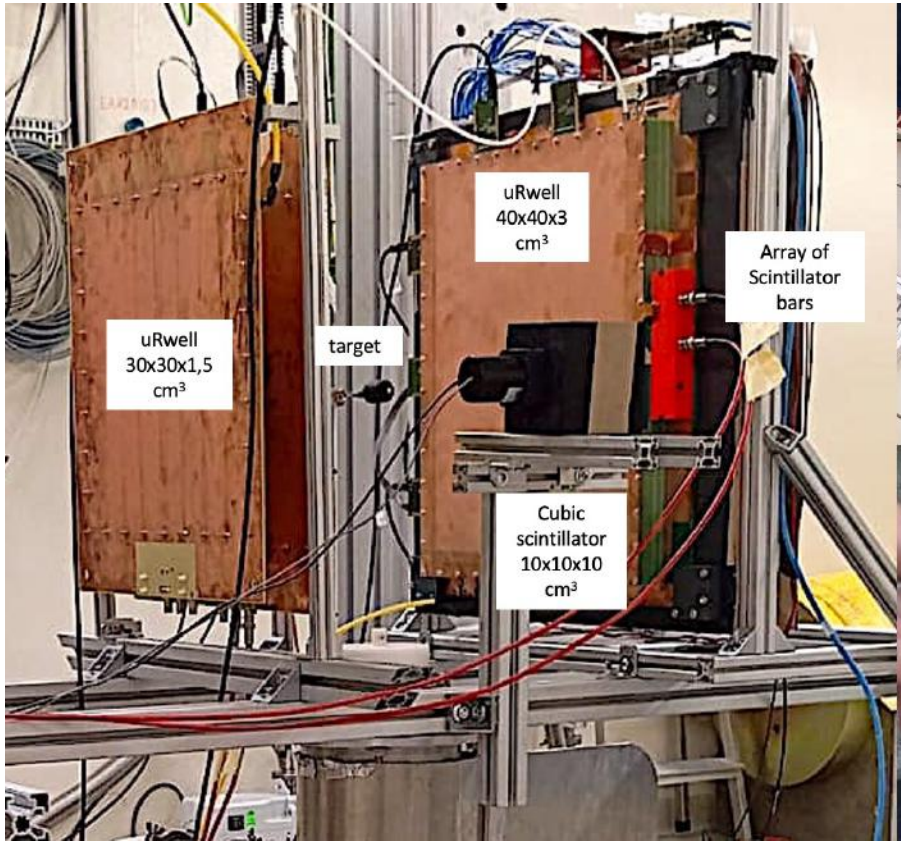



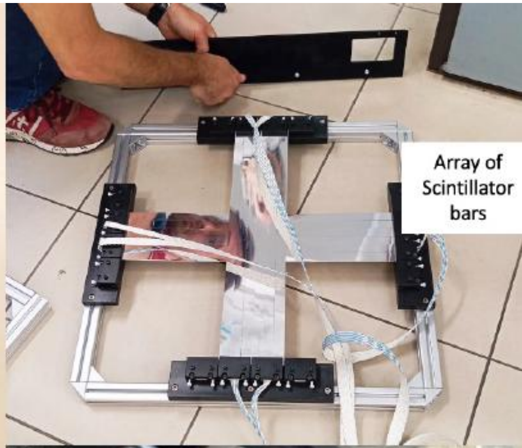



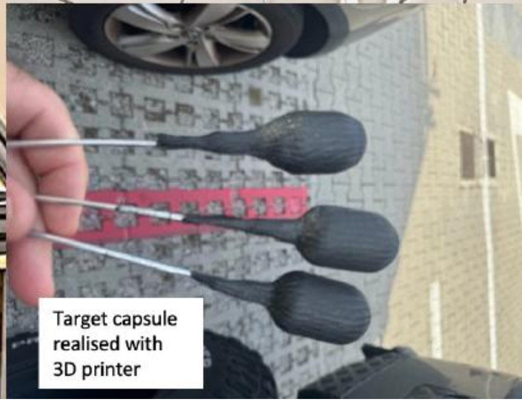
# The n_TOF X17 detector demonstrator

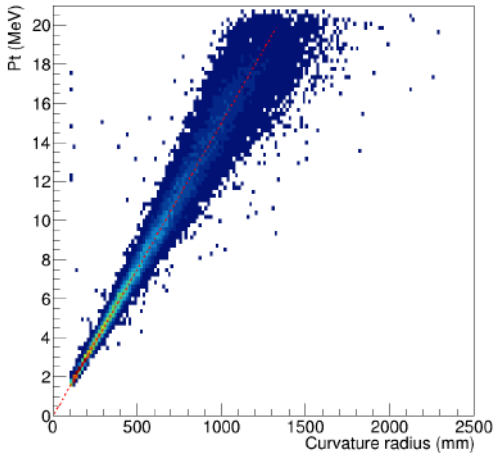
Tests of Demonstrator (1/4 of the final detector):
Neutron beam of N_TOF at CERN (October 2023)
Proton beam of ATOMKI, Debrecen (May 2024)

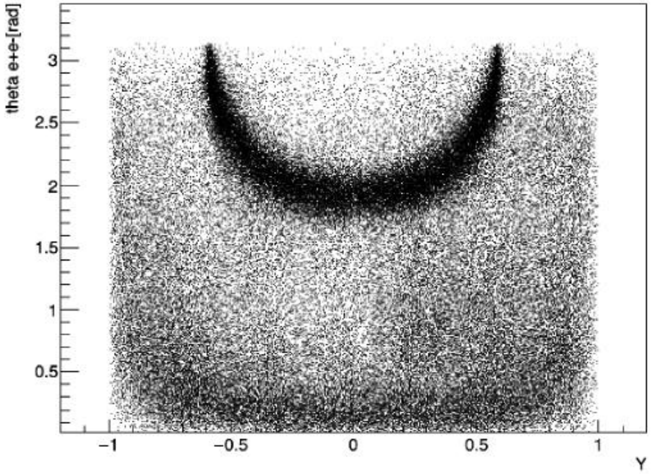




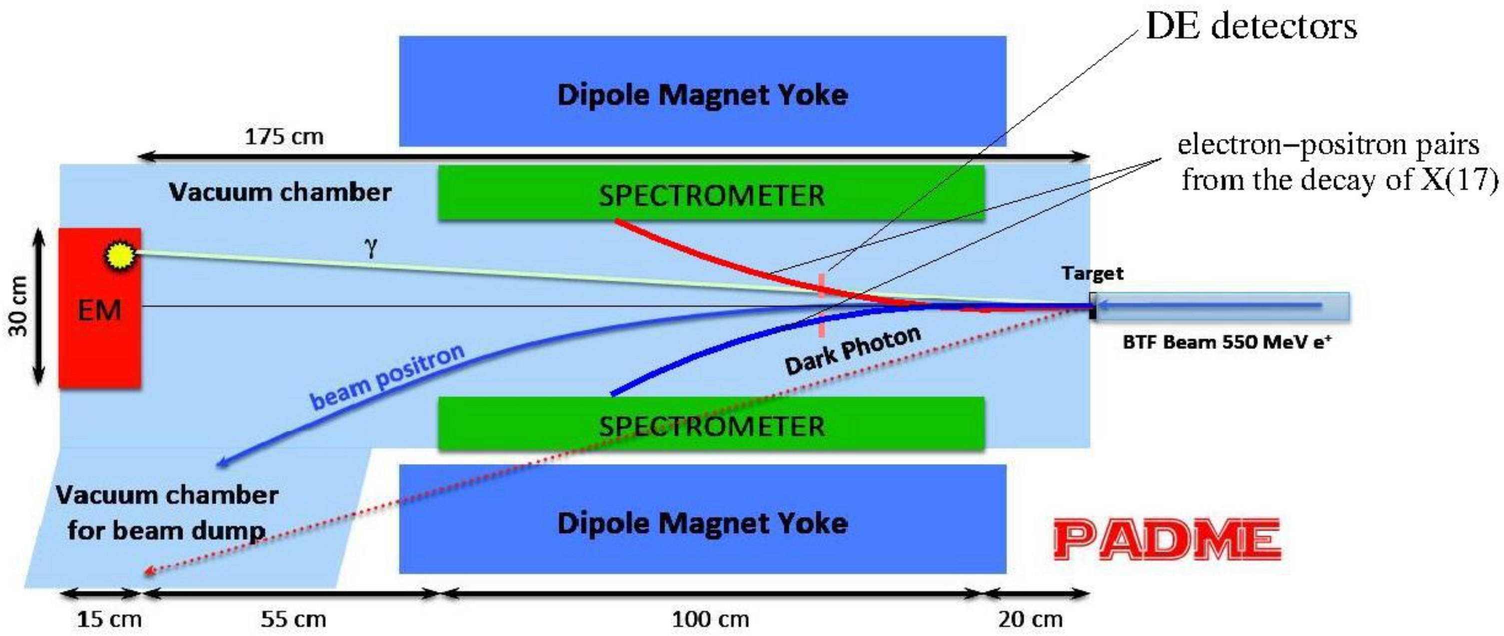



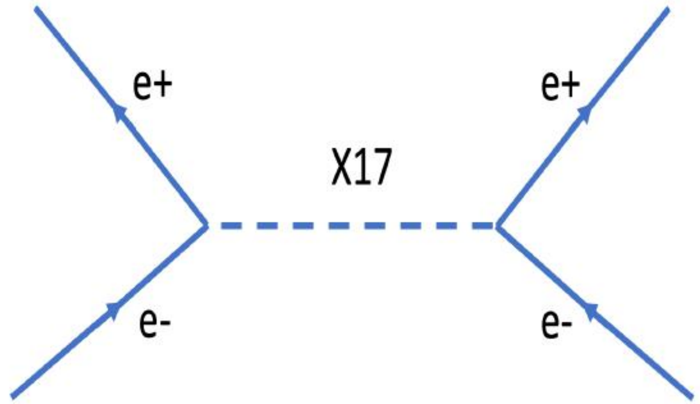



# Search for the X17 at PADME in Frascati




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 $\mathbf{E_{cm} = M_{X17}}$

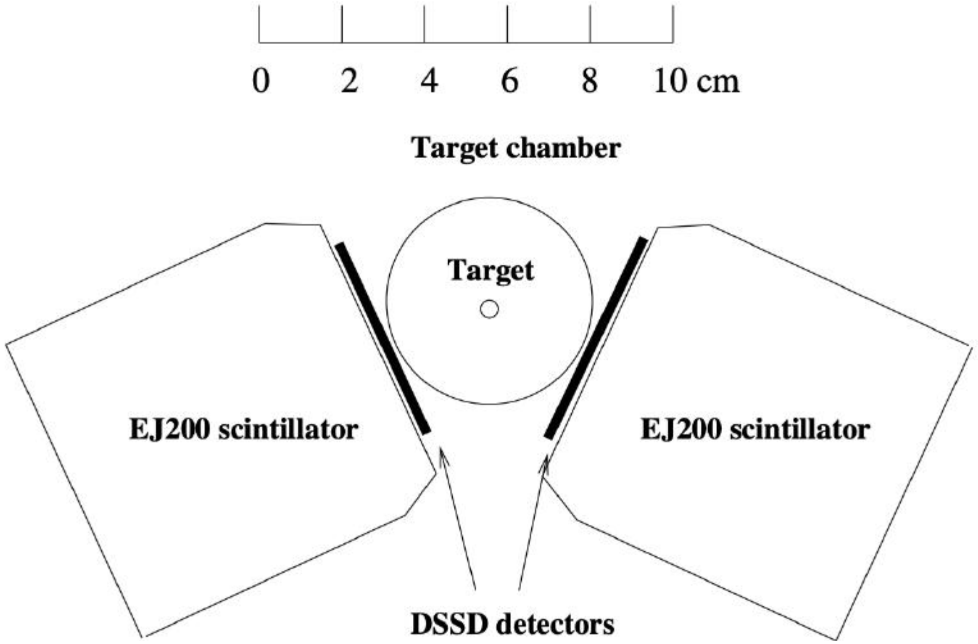
# Summary

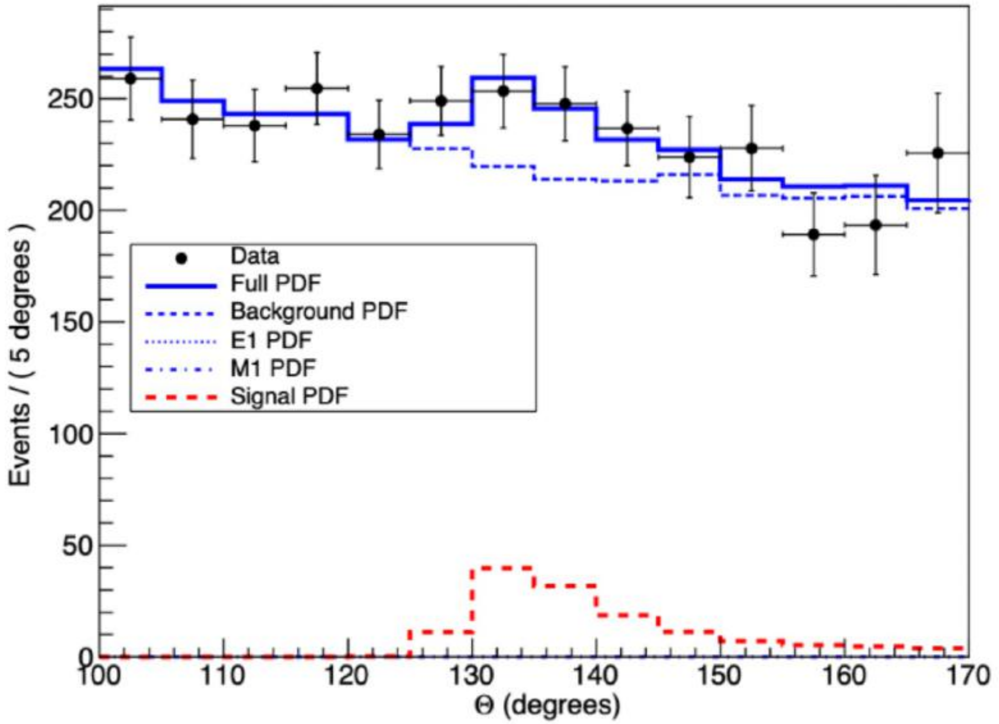
- Unexplained anomalies in the IPC angular correlation distribution have been reported for specific transitions in $^{8}Be$, $^{4}He$ and $^{12}C$
- However, the observations have been performed by the same group, using similar setups
- Several interpretations have been proposed, including the existence of an unknown vector boson mediator of a new fundamental force, triggering speculations about its impact on the Dark Matter sector and the concordance with  the measured anomalies of magnetic moment anomalies of muon/electron (assuming a Vector X17 boson).
- There is a worldwide effort to for  experiments able to confirm/reject the X17 existence.
- Italian research groups are strongly involved in the endeavor: few nuclear physics experiments and European experiments with a major Italian contribution…

Stay tuned, data are coming!

# SPARES

Tran The Anh et al.:
“Checking the 8Be anomaly with a two-arm electron positron pair spectrometer”;  arXiv:2401.11676v1 [nucl-ex] 22 Jan 2024 .

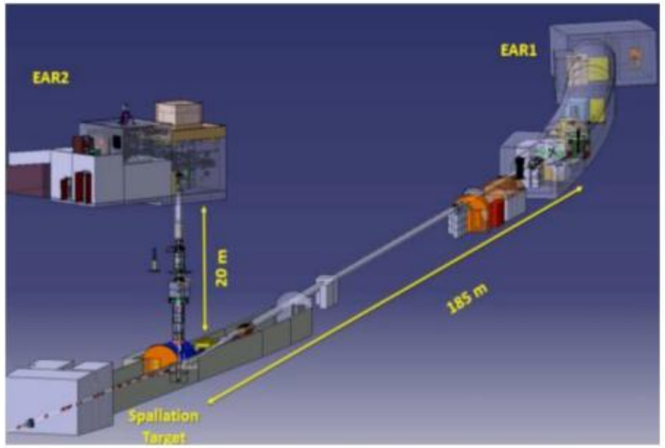


## Physics:

- Probing X17 existence
- X17 Mass, quantic numbers, coupling, life time,..
- proto-phobic nature of the fifth force.
- First measurement of σ(E) $^{3}He(n,e^{+}e^{-})^{4}He$
- Data Vs Theoretical nuclear physics

## Two setups for deep investigation of the $^{4}He$ case




- **n_ToF @ CERN: pulsed neutron beam in a wide energy range (thermal<$E_n$<100 MeV).**
- **Time of flight to establish the single neutron energy (10-$10^8$ eV)**
- **dedicated detector**

$^{3}He(n,X17)^{4}He$ **(new!)** → $e^{+}e^{-}$

Measurements:
2022-24 (CERN LoI approved)

- **LUNA-MV @ LNGS: high intensity proton beam and low bacground**
- **Terminal Voltage ≈ 0.2 – 3.5 MV**
- **$I_{max}$ ≈ 100 μA of protons**
- **Underground operation**
- **dedicated detector**

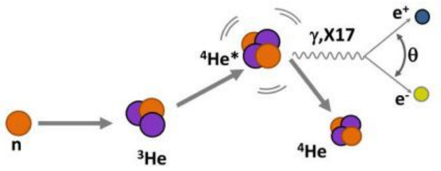
$^{3}H(p,X17)^{4}He$ → $e^{+}e^{-}$

Measurements:
2023-5 (LoI in preparation)

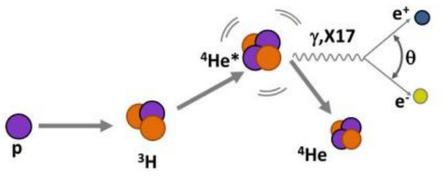
**Two steps:**

1. n+3He at n_TOF
2. p+T (coniugate of n+3He),
   n+7Be (coniugate of p+7Li),
   n+D, p+D etc.

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



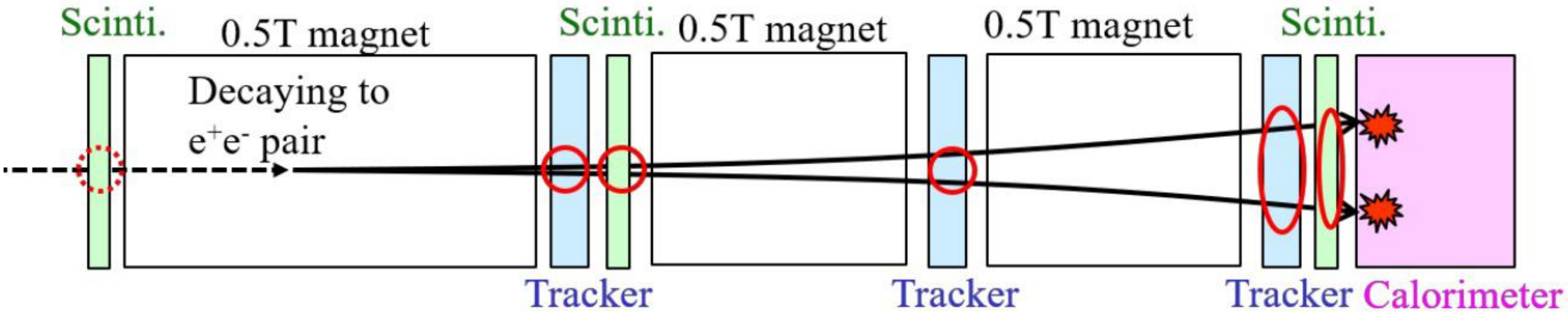

$^{3}H(p,e^{+}e^{-})^{4}He$




**goals**: cover a wide energy range and use a large acceptance, compact and versatile detector.

# Forward Search Experiment

- FASER (Forward Search Experiment is designed to study the interactions of high-energy neutrinos and search for new, as-yet-undiscovered light and weakly interacting particles. Such particles are dominantly produced along the beam collision axis and may be long-lived particles, travelling hundreds of metres before decaying. The existence of such new particles is predicted by many models beyond the Standard Model that attempt to solve some of the biggest puzzles in physics, such as the nature of dark matter and the origin of neutrino masses.
- FASER is located along the beam collision axis, 480 m from the ATLAS interaction point, in an unused service tunnel that formerly connected the SPS to the LEP collider – an optimal position for detecting the particles into which light and weakly interacting particles will decay



# The **DarkLight** experiment at JLAB

- The DarkLight experiment proposes to search for dark photon through complete reconstruction of the final states of electron–proton collisions. In order to accomplish this, the experiment requires a moderate-density target and a very high intensity, low energy electron beam.
- Projected reaches in mass and coupling for upcoming experiments near the Beryllium-8 anomaly. Note that these are taken in the fully protophobic limit, so the sensitivities of experiments that search for the dark photon through hadronic probes are heavily suppressed. The DarkLight projection marks the region where an anomaly yields a $5\sigma$ with 1 $ab^{-1}$ of data, which is readily achievable with anticipated luminosities.