On the track of dark force

A.J. Krasznahorkay

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MTA Atomki, Debrecen

The „Institute for Nuclear Research” in the downtown of Debrecen!

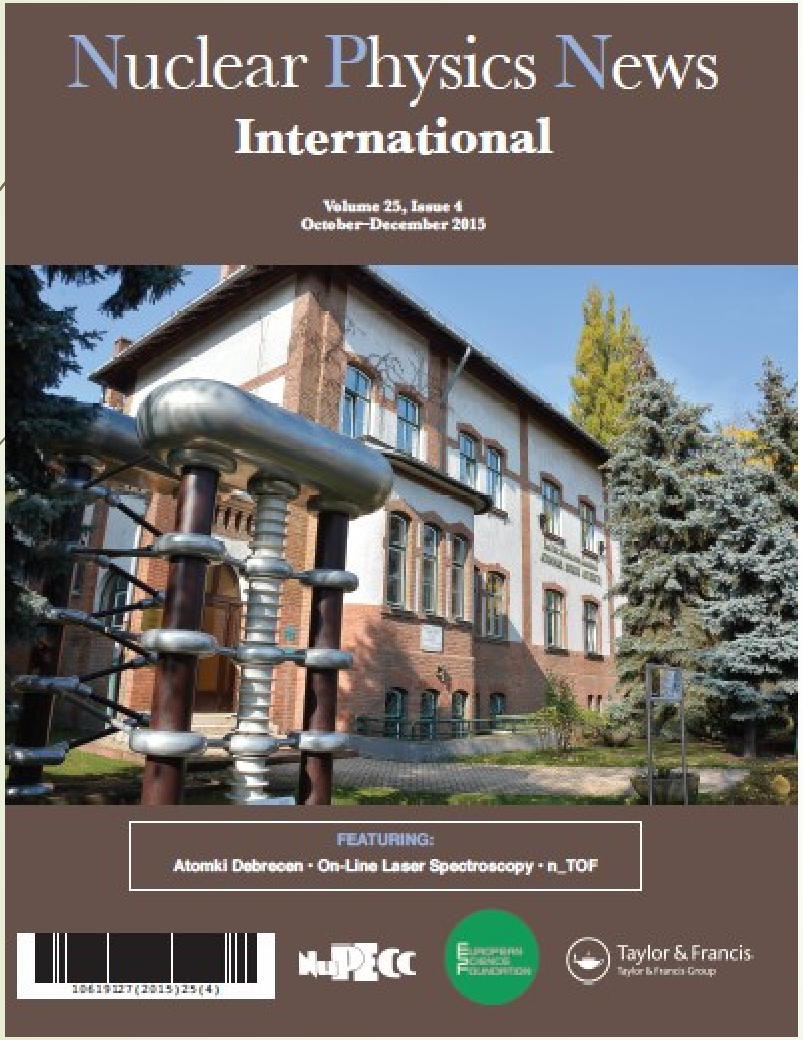
4 main divisions:

- Nuclear Physics Division
- Atomic Physics Division
- Applied Physics Division
- Accelerator Centre

Size: 100 scientists, 100 other staff

www.atomki.mta.hu/en/

http://www.nupecc.org/npn/npn254.pdf



Nuclear Physics in Atomki in the 21st Century

Introduction

Some twenty minutes' walk from the center of Debrecen, Hungary's second largest city, there stands a complex of three two-storeyed red-brick buildings. Originally serving as an orphanage of the reformed church of Hungary, the buildings now have a rather different role: two of them house the physics departments of the University of Debrecen, while the third one is where Atomki, the Institute for Nuclear Research of the Hungarian Academy of Sciences (MTA) was founded in 1954, and where its offices and some of its laboratories are still located. Anyone passing by is reminded of these times by the 800 kV cascade generator, which peacefully rests in the garden after being decommissioned in 1992. But it is not the only reminder there of the historic times.

A plaque indicating that in 2013 this building was declared an Historic Site, the first such memorial in Hungary, by the European Physical Society is another sign of the heroic times of Atomki [1] (see also Figure 1). The plaque commemorates the Debrecen neutrino experiment carried out by A. Szalay and his Ph.D. student, J. Csikai, in 1956, a revolutionary year in Hungary not only from the scientific point of view. The experiment used a cloud chamber to detect the beta decay of ^{6}He, in which the tracks of the electron and of the recoiled ^{6}Li nucleus clearly demonstrate that there must be a third, neutral, particle, invisible to the cloud chamber, carrying away momentum and energy. This observation confirmed the existence of the (anti) neutrino, which, according to the EPS plaque, "laid a brick to the foundation of modern physics."

Alexander Szalay, the father of nuclear research in Hungary, was also the founding director of Atomki. His commitment to nuclear physics, and especially to nuclear experiments, dates back to 1936, when he spent six months with Nobel-laureate Ernest Rutherford at Cavendish Laboratory in Cambridge, UK. Later he also had a pioneering role in prospecting the uranium resources in Southern Hungary. He was the perfect person to be selected as director of a newly established nuclear research institute. In the past sixty years Atomki gradually developed into an institute with a broad research portfolio ranging from nuclear physics to atomic, particle, and environmental physics.

The Debrecen neutrino experiment is symbolic of the past, present, and most probably future activity of Atomki: setting out a clearly defined target and using the methods of nuclear physics to obtain results in a meticulous procedure are all characteristic features of the "Szalay school," as are employing self-made equipment and applying the methodology of nuclear physics in other branches of physics.

A laboratory portrait of Atomki was already presented in *Nuclear Physics News* in 1999 [2], so the present article deals exclusively with activities since the year 2000. The institute has about 200 employees, half of whom are researchers. As an indication of the broad interest of Atomki, many researchers were educated in fields outside physics: mathematics, informatics, chemistry, electrical engineering, and so on. The activity of the institute is distributed among seven main topics (a magic number in Hungarian folklore and mythology), but the effect of nuclear physics is still palpable in the majority of them (Figure 2). The

Figure 1. *The EPS Historic Site plaque commemorating the neutrino experiment at MTA Atomki in 1956.*

Leitmotif of my present talk:

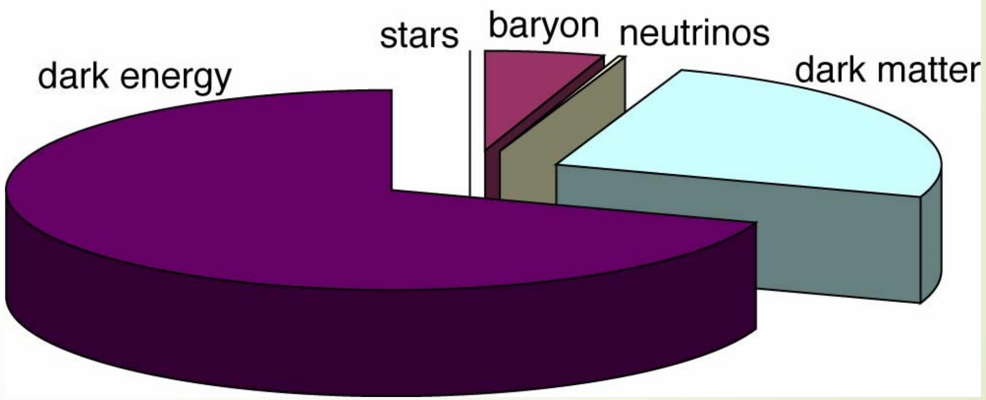
The atomic nucleus is a femto-laboratory including probably all of the interactions in Nature. A real discovery machine like LHC, but at low energy.

In an age of giant accelerators, of complex experiments and of mystifying theories it is a pleasure to report on some simple experiments, made with simple equipment and having a simple interpretation

Robert Hofstadter (Nobel, 1961)

Energy budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%



- It in not short-lived: $t > 10^{10}$ years
- not baryonic: $W_B = 0.04 \pm 0.004$
- not hot: “slow” DM is required to form structure

DARK MATTER: WHAT WE DON'T KNOW

- What is its mass?
- What is its spin?
- What are its other quantum numbers and interactions?
- Is it absolutely stable?
- What is the origin of the dark matter particle?
- Is dark matter composed of one particle species or many?
- How was it produced?
- When was it produced?
- Why does Ω_{DM} have the observed value?
- What was its role in structure formation?
- How is dark matter distributed now?

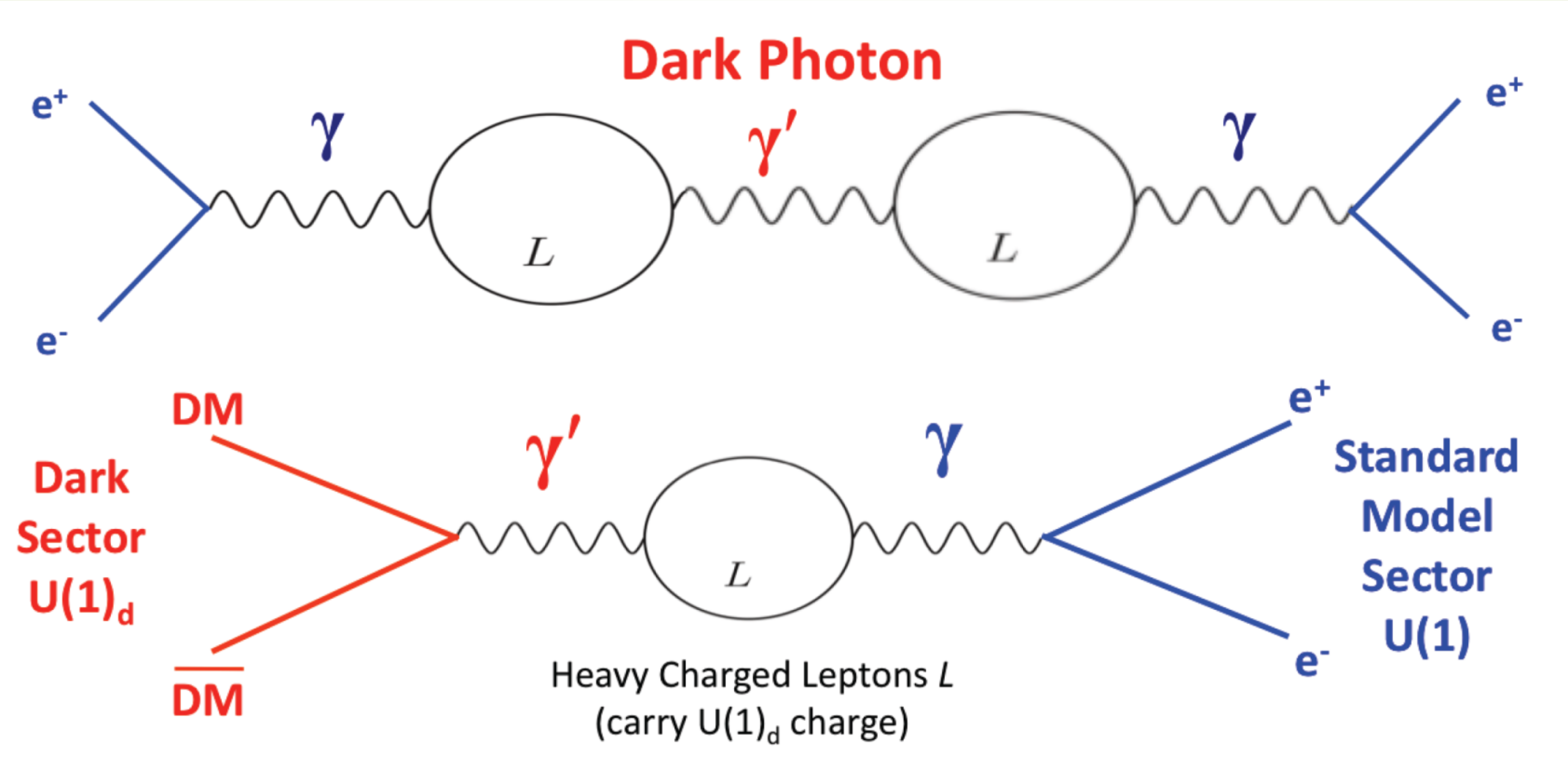
Dark Matter Candidates

- Given the few constraints, it is not surprising that there are many candidates: axions, thermal gravitinos, neutralinos, Kaluza-Klein particles, wimpzillas, self-interacting particles, self-annihilating particles, fuzzy dark matter, superWIMPs,…
- Masses and interaction strengths span many, orders of magnitude
- But independent of cosmology, new particles are required to understand the weak scale. What happens when we add these to the universe?

Searching for weakly interacting massive particles (WIMP)

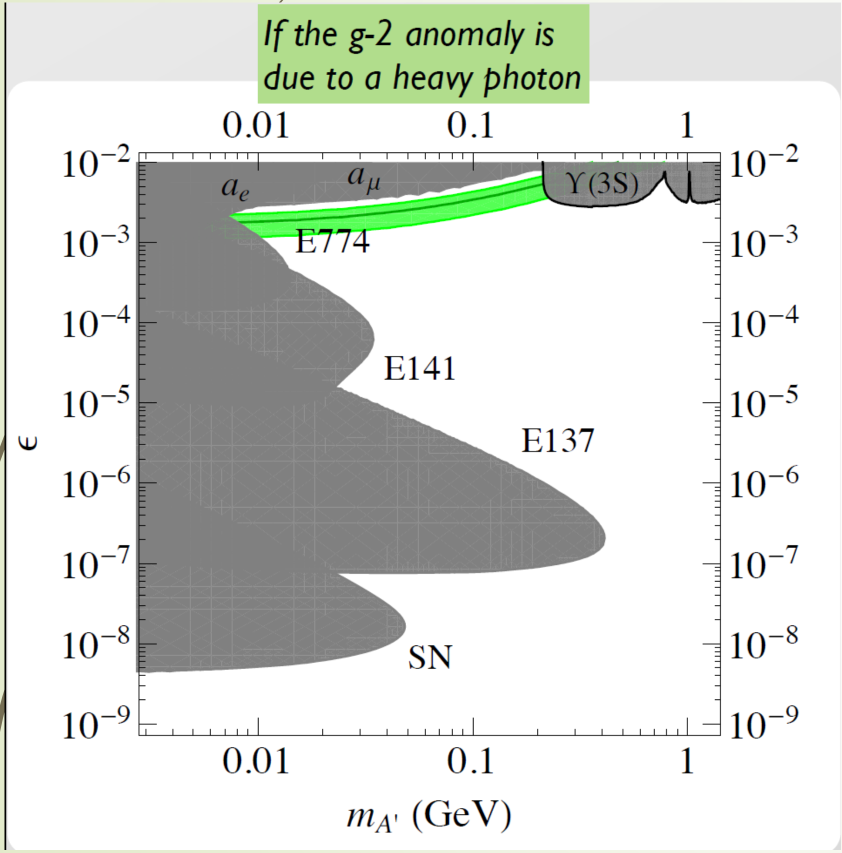
- Scientists' biggest search for dark matter to date just turned up nothing
- They were the currently considered most viable candidate for dark matter
- Searching for light dark matter (1 MeV/c^2 – 1 GeV/c^2) → Something like a ***dark photon*** is very well theoretically motivated
- Kinetic mixing from the vector portal: if there is an additional U(1) symmetry in nature, there will be mixing between the photon and the new gauge boson (Holdom, Phys. Lett B166, 1986)

Dark Photon

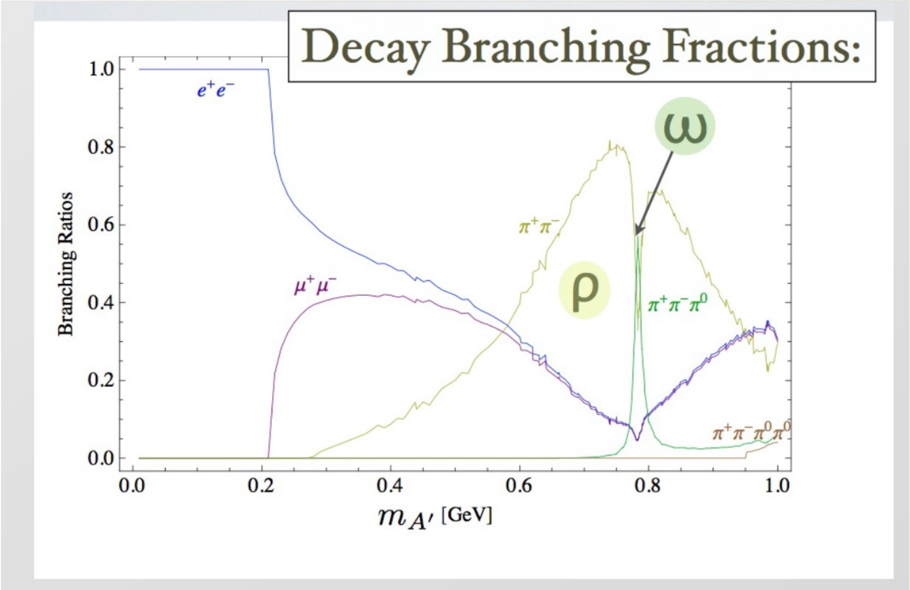


Feynman graphs depicting interactions via a hypothetical Dark Photon γ’.
Up: Kinetic mixing model;
Down: Interaction between the Standard Model sector and the Dark Sector via a Dark Photon. The loop denotes a pair of charged leptons, which couple both to the Standard Model photon as well as the Dark Photon.

Dark photons and the g-2 anomaly



Branching ratio

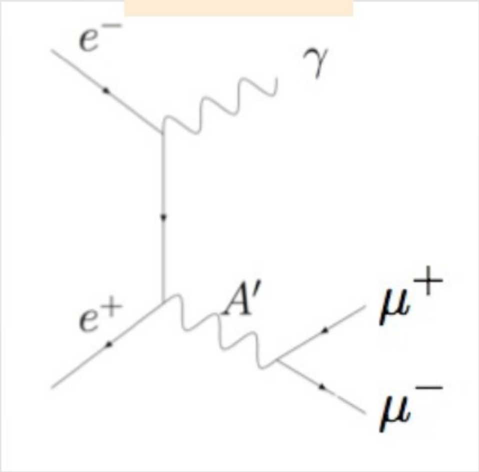


Lifetime

$$\gamma c\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2$$

Wherever there is a photon there is a dark photon...

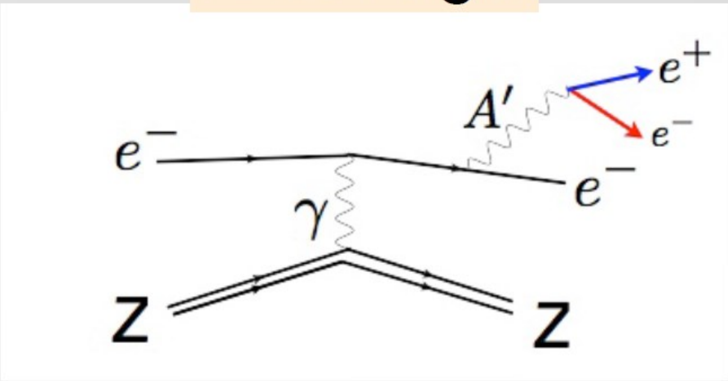
Collider



$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

$O\ ab^{-1}$ per ~~decade~~ month

Fixed Target



$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

$O\ ab^{-1}$ per day

...much higher backgrounds

Dark Force searches in the Labs

https://sites.google.com/site/zprimeguide/ Hye-Sung Lee (JLAB)

Many searches for Dark Force in the Labs around the world (ongoing/proposed).

Typical searches for Dark Force exploit the small Z' coupling to the SM particles (rather than using the DM particles).

Particularly attractive: One of the New physics scenarios that can be tested with Low-energy experimental facilities (Nuclear/Hadronic physics labs).

[Dark force carrier Z' scale (GeV) ≈ 1/1000 × Typical new physics scale (TeV)]

"various Low-E Labs" "LHC"

PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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(Received 7 April 2015; published 26 January 2016)

Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV$/c^2$ and $J^\pi = 1^+$ was created.

Evidence for a Protophobic Fifth Force from ^{8}Be Nuclear Transitions

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Phys. Rev. Lett. 117, 071803

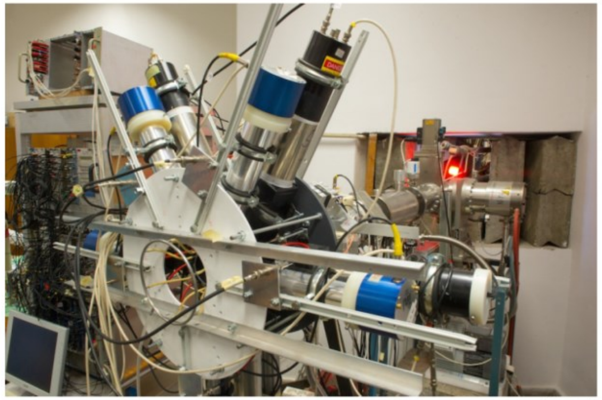
NATURE | NEWS

Has a Hungarian physics lab found a fifth force of nature?

Radioactive decay anomaly could imply a new fundamental force, theorists say.

Edwin Cartlidge

25 May 2016



MTA-Atomki

Physicists at the Institute for Nuclear Research in Debrecen, Hungary, say this apparatus — an electron-positron spectrometer — has found evidence for a new particle.

Print

A laboratory experiment in Hungary has spotted an anomaly in radioactive decay that could be the signature of a previously unknown fifth fundamental force of nature, physicists say – if the finding holds up.

The Atomki anomaly | symmetry magazine http://www.symmetrymagazine.org/article/the-at...

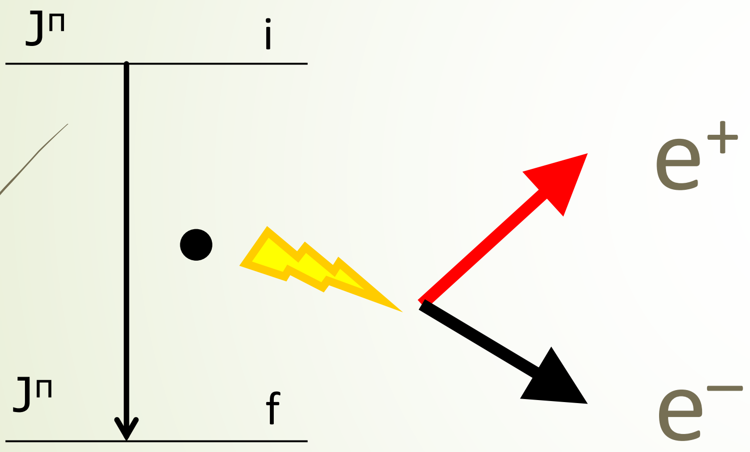
symmetry dimensions of particle physics

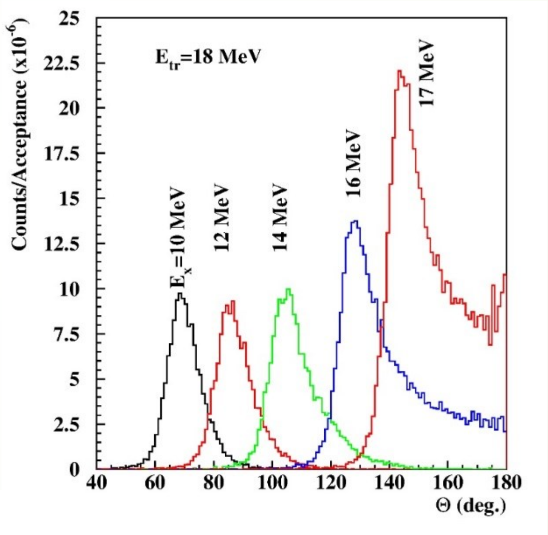
Scientists at the Large Hadron Collider aren't the only ones investigating a possible sign of a new particle.

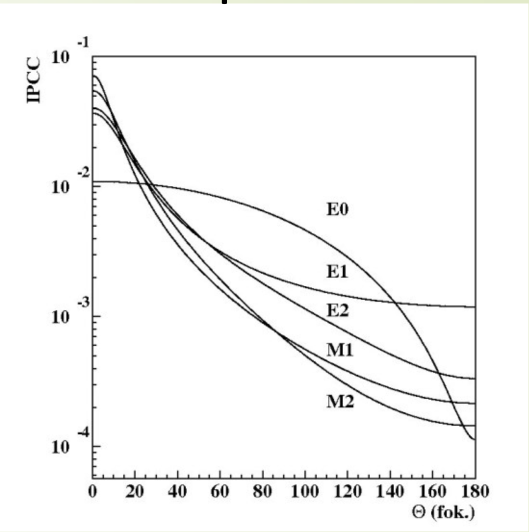
In a result published in *Physical Review Letters* earlier this year, scientists on the Atomki nuclear physics experiment in Hungary claimed to have turned up potential evidence of a particle that could point to an entirely new fundamental force of nature.

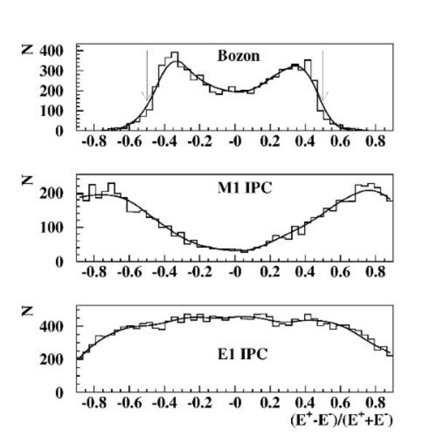
Searching for the e^+-e^- decay of the dark photon in nuclear transitions

Two body decay of a moving particle / e^+-e^- internal pair creation







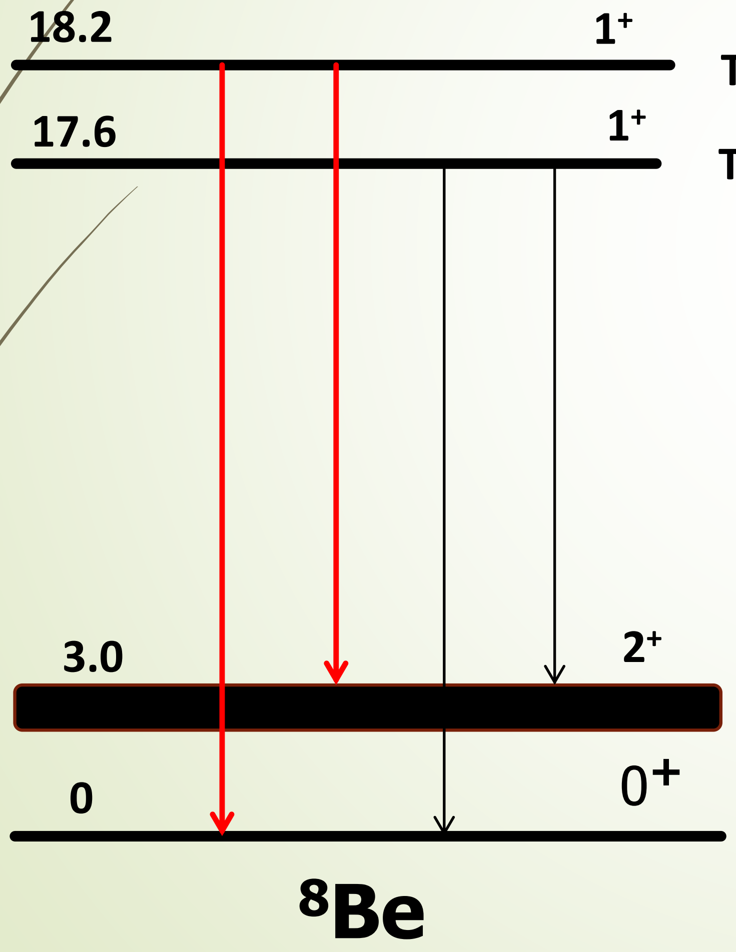


M.E. Rose Phys. Rev. 76 (1949) 678

E.K. Warburton Phys. Rev. B133 (1964) 1368.

P. Schlüter, G. Soff, W. Greiner, Phys. Rep. 75 (1981) 327.

Study the ^{8}Be M1 transitions

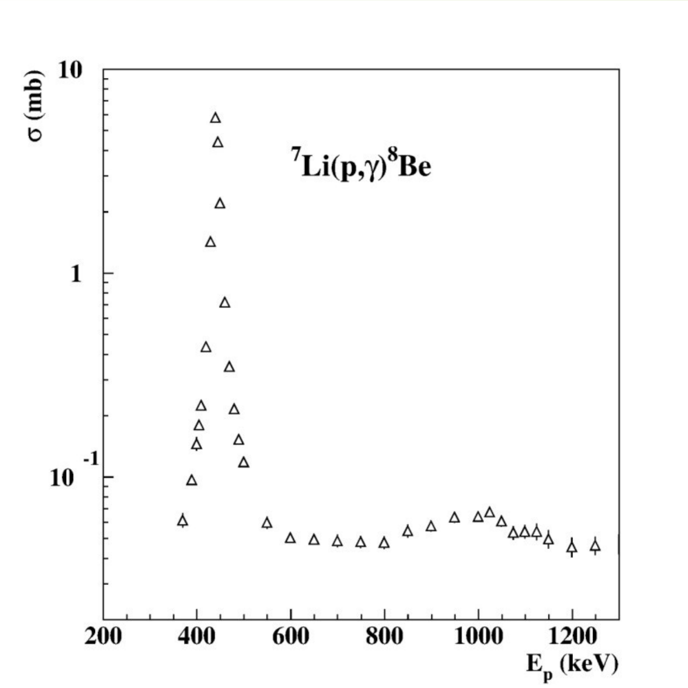


T=0 Ep= 1030 keV

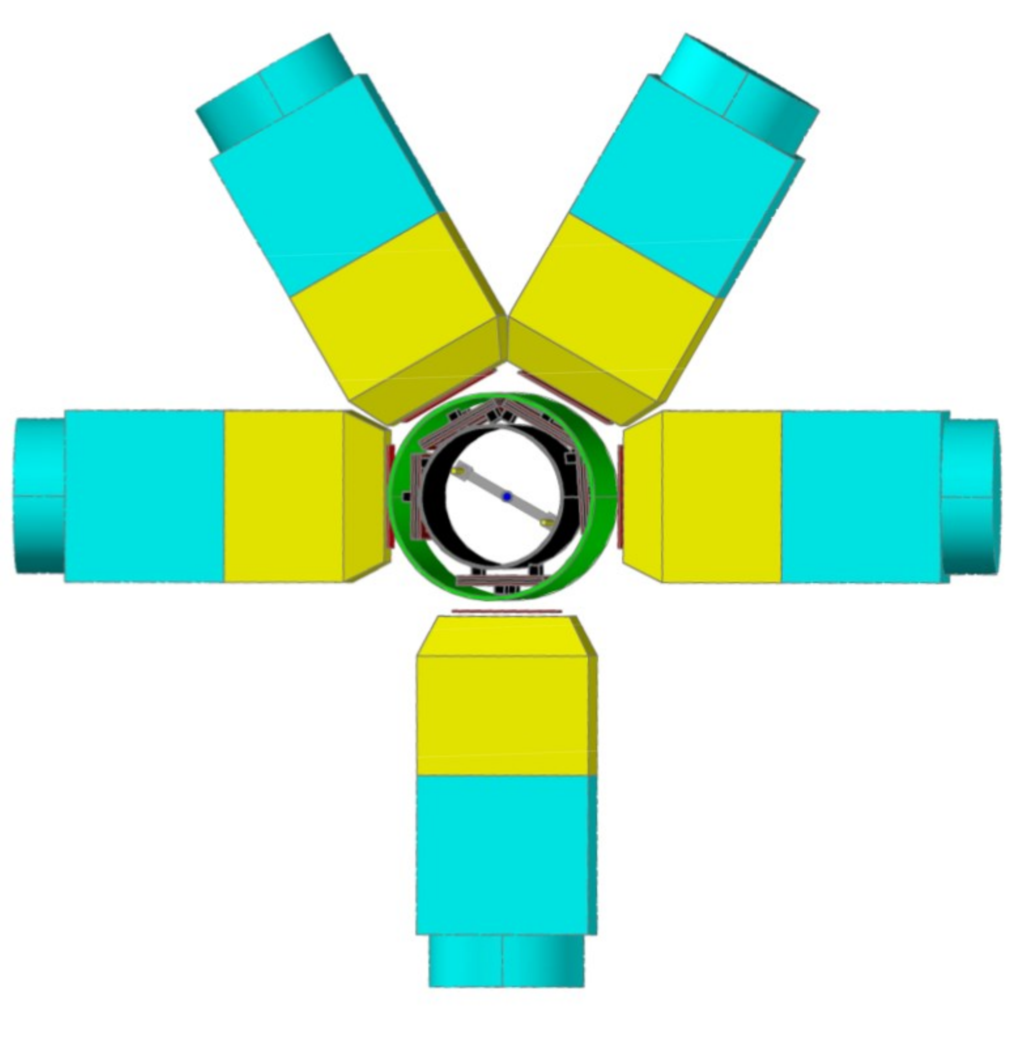
T=1 Ep= 441 keV

Excitation with the $^7Li(p,\gamma)^8Be$ reaction

^{7}Li, p3/2$^-$ + p

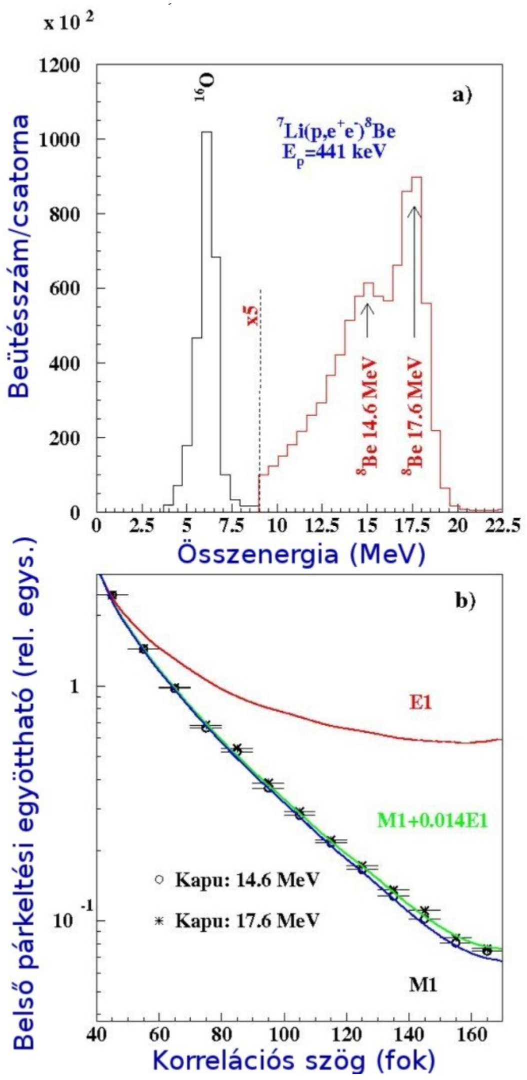


Geometrical arrangement of the scintillator telescopes (NIM, A808 (2016) 21)

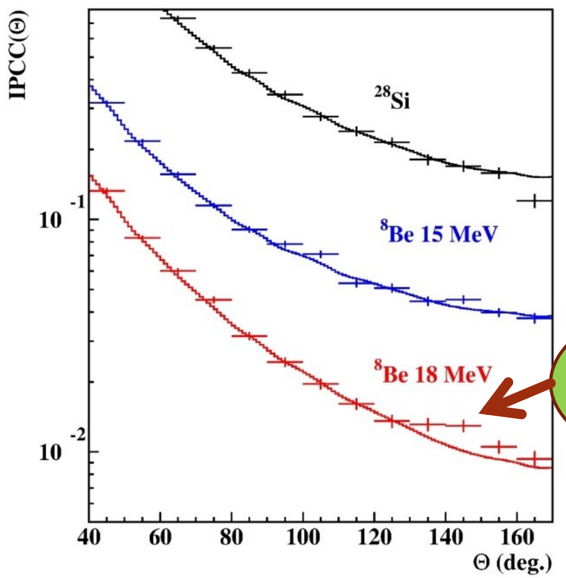


Results

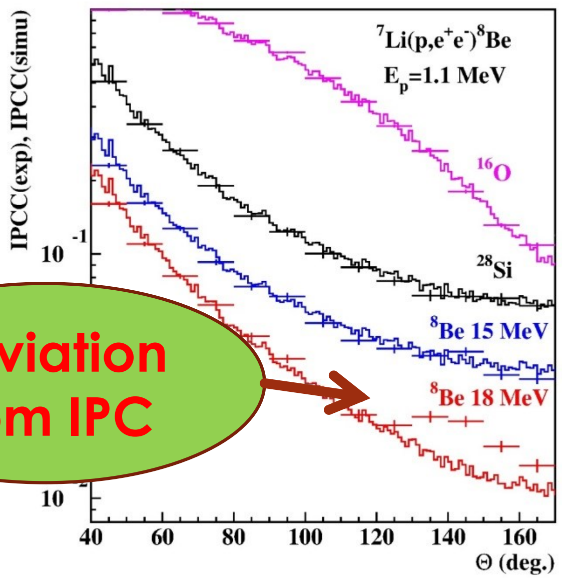
e^+ - e^- sum energy spectra and angular correlations



Ep=1.04 MeV



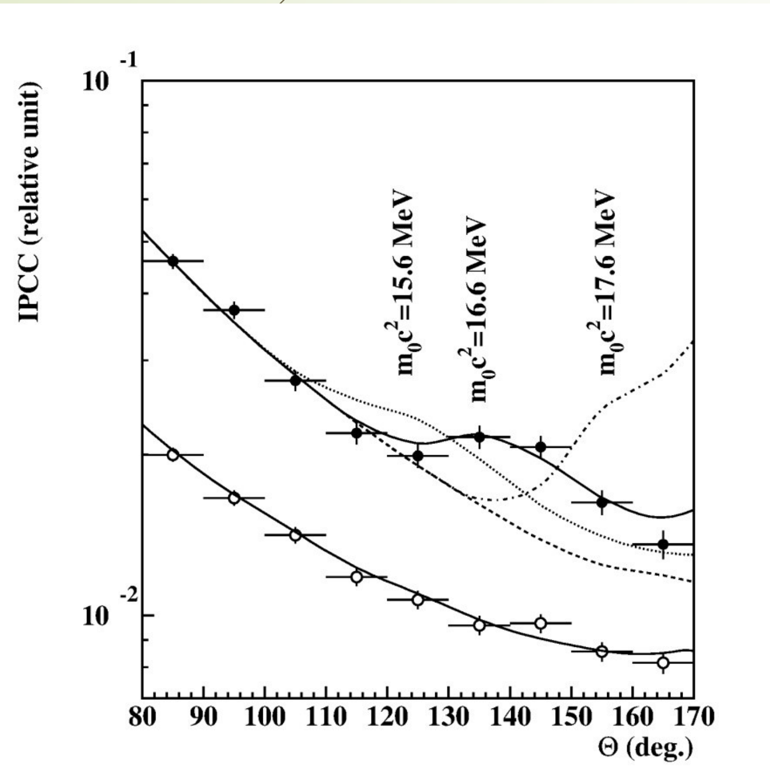
Ep=1.10 MeV

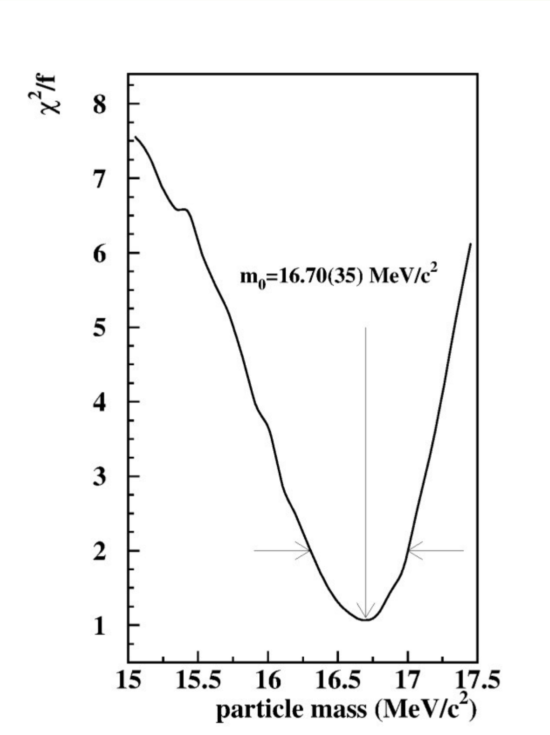


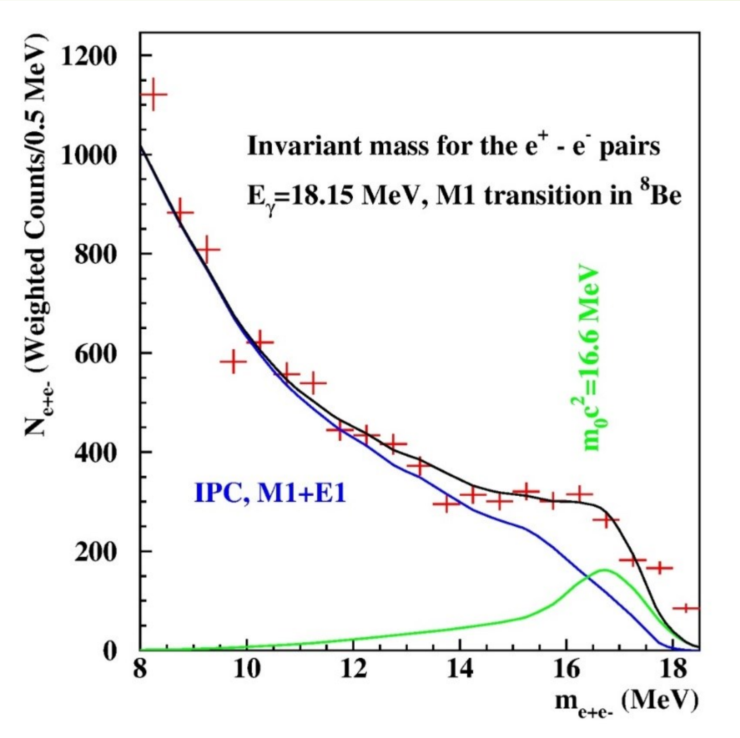
Deviation from IPC

- **Can it be some artificial effect caused by γ-rays?**
- **Can it be some nuclear physics effect?**
- **…**

How can we understand the peak like deviation? Fitting the angular correlations





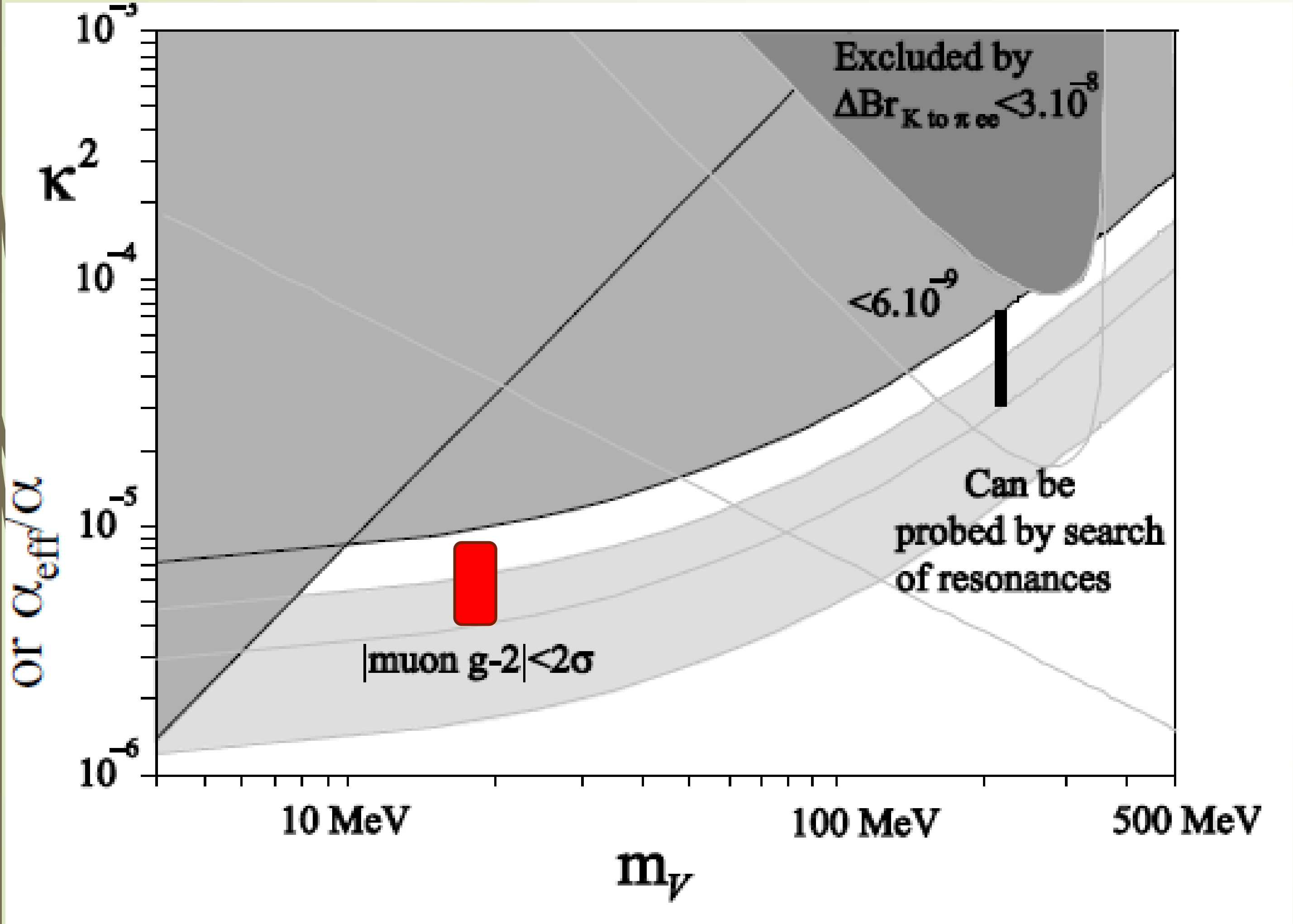


Experimental angular e^+e^- pair correlations measured in the ^{7}Li(p,e^+e^-) reaction at Ep=1.10 MeV with -0.5< y <0.5 (closed circles) and |y|>0.5 (open circles).

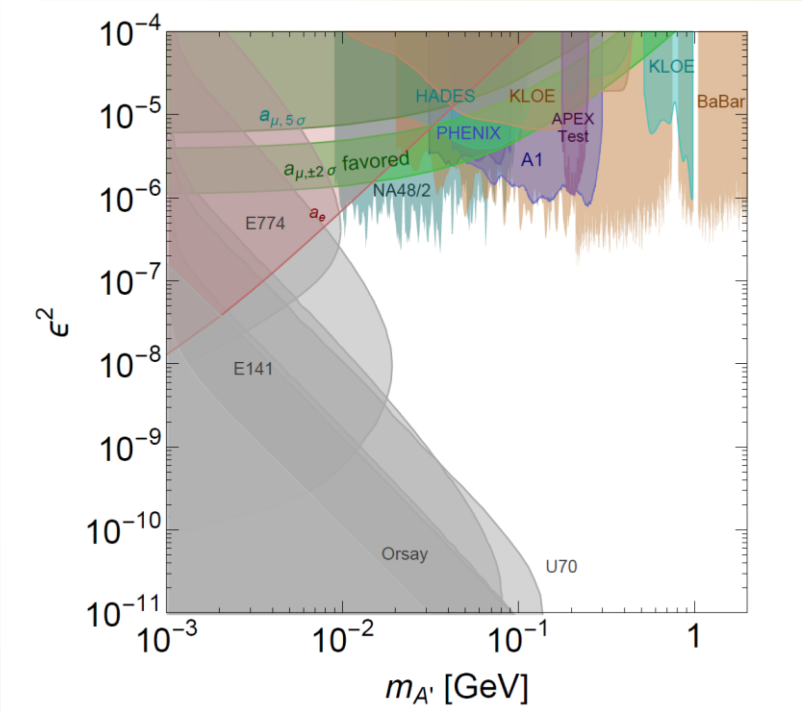
Determination of the mass of the new particle by the X^2/f method

Invariant mass distribution plot for the electron-positron pairs

The coupling constant



Search for a dark photon in the $\pi^0 \rightarrow e^+e^- \gamma$ decay, NA48/2 Collaboration, Phys. Lett. B 746, 178 (2015). → exclusion limit



Introduction of the protophobic fifth force (J. Feng et al.PRL 117, 071803, (2016))

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - X^\mu J_\mu ,$$

$$\varepsilon_p = 2\varepsilon_u + \varepsilon_d \qquad \varepsilon_n = \varepsilon_u + 2\varepsilon_d$$

Branching ratio: $\frac{B(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, X)}{B(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\, \gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.6 \times 10^{-6}$

$\Rightarrow$ $|\varepsilon_p + \varepsilon_n| \approx 0.011$ $\quad |\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$

Pion decay: $|2\varepsilon_u + \varepsilon_d| < \varepsilon_{\max} = 8 \times 10^{-4}$

$\Rightarrow$ $-2.3 < \frac{\varepsilon_d}{\varepsilon_u} < -1.8 , \quad -0.067 < \frac{\varepsilon_p}{\varepsilon_n} < 0.078$

Evidence for a Protophobic Fifth Force from ^{8}Be Nuclear Transitions

Feng et al., arXiv:1604.07411 [hep-ph]

- dark photon ✗
- scalar ✗
- axion ✗
- protophobic gauge boson ✓

$$\mathcal{L} \supset -X^{\mu} \sum_{f} e\, \varepsilon_f\, \bar{f} \gamma_{\mu} f$$

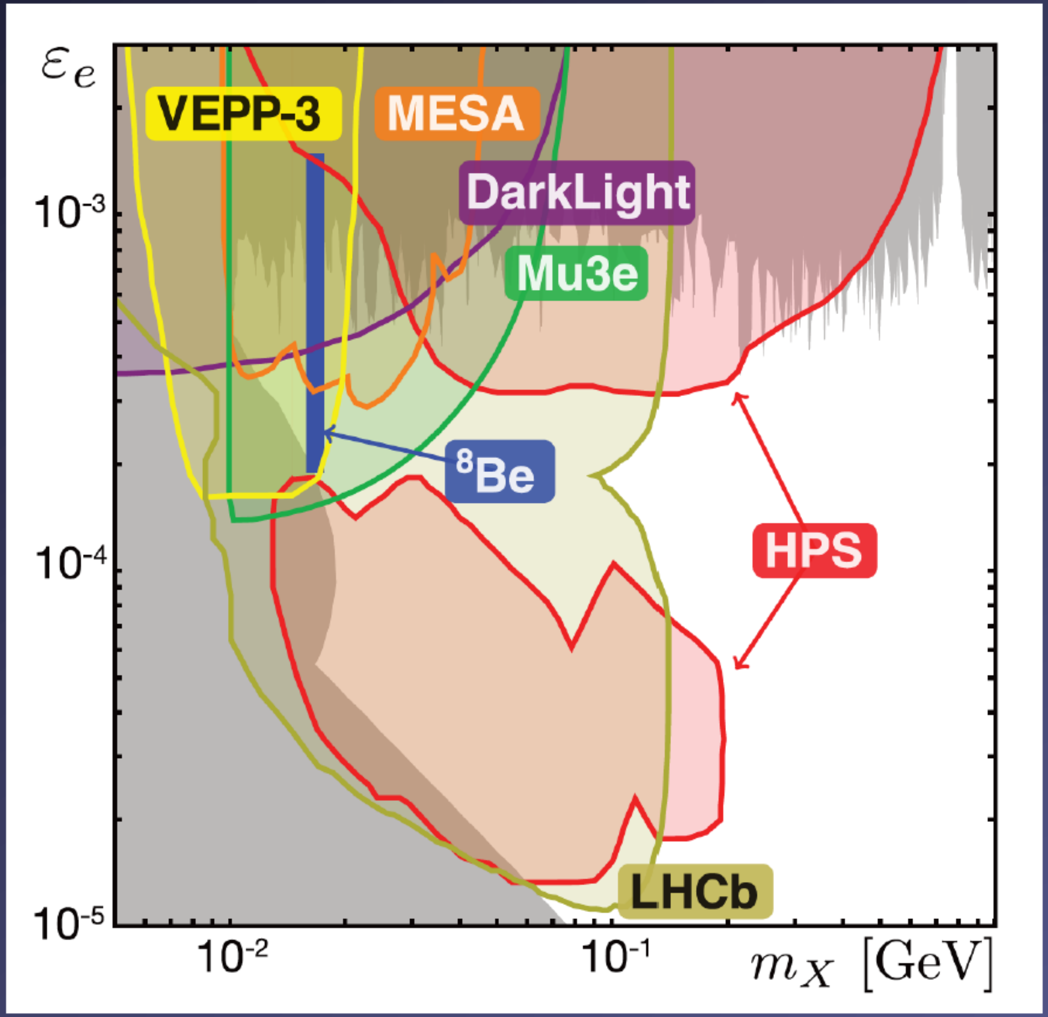
$$\varepsilon_u = -\frac{1}{3}\varepsilon_n \approx \pm 3.7 \times 10^{-3}$$

$$\varepsilon_d = \frac{2}{3}\varepsilon_n \approx \mp 7.4 \times 10^{-3}$$

$$2 \times 10^{-4} \lesssim |\varepsilon_e| \lesssim 1.4 \times 10^{-3}$$

$$|\varepsilon_\nu \varepsilon_e|^{1/2} \lesssim 7 \times 10^{-5}$$

Future discovery prospects



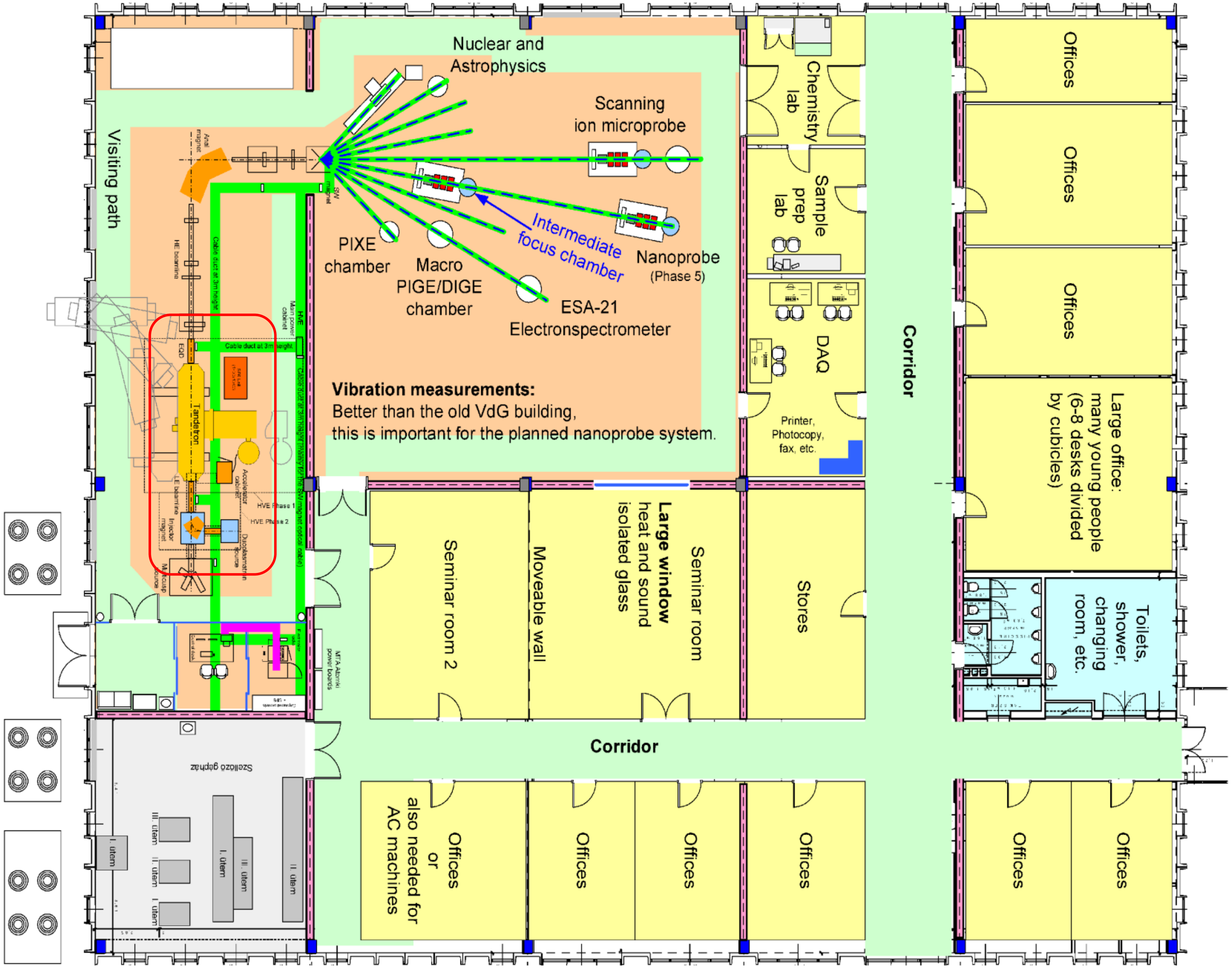
An open laboratory…

2.0 MV Medium-Current Plus Tandetron Accelerator System (High Voltage Eng., The Netherland)

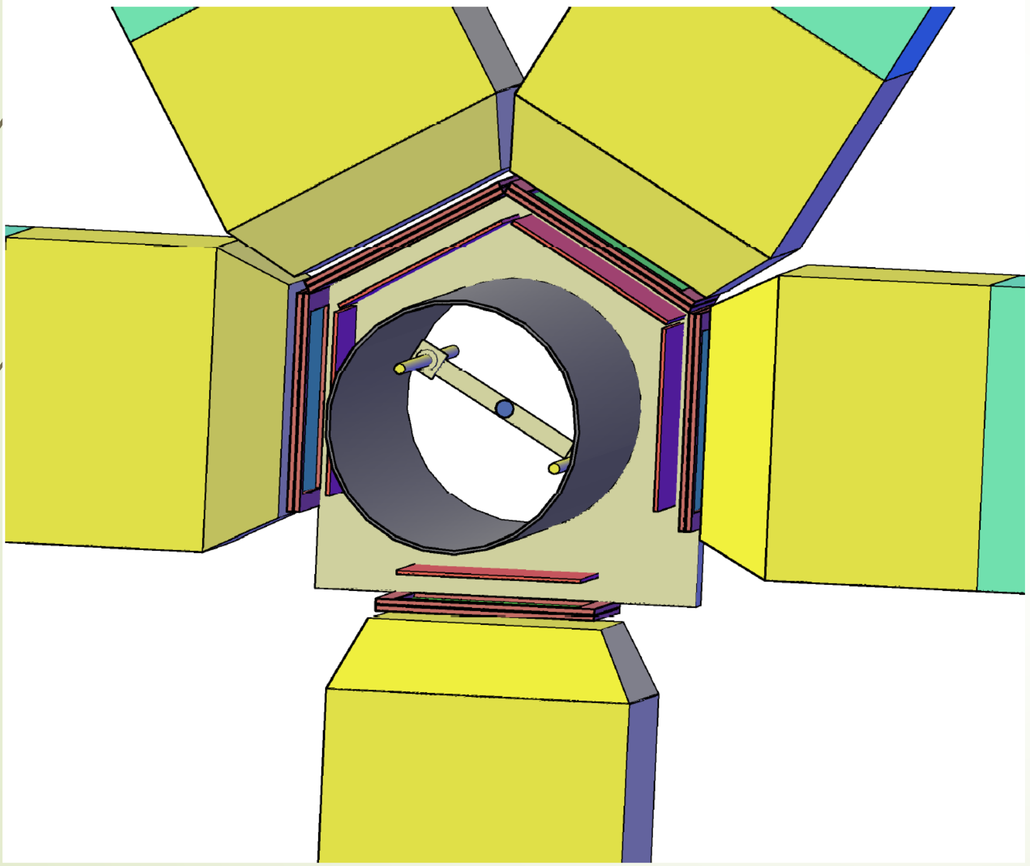
Support: Hungarian Academy of Sciences and Nuclear Power Plant of Paks City

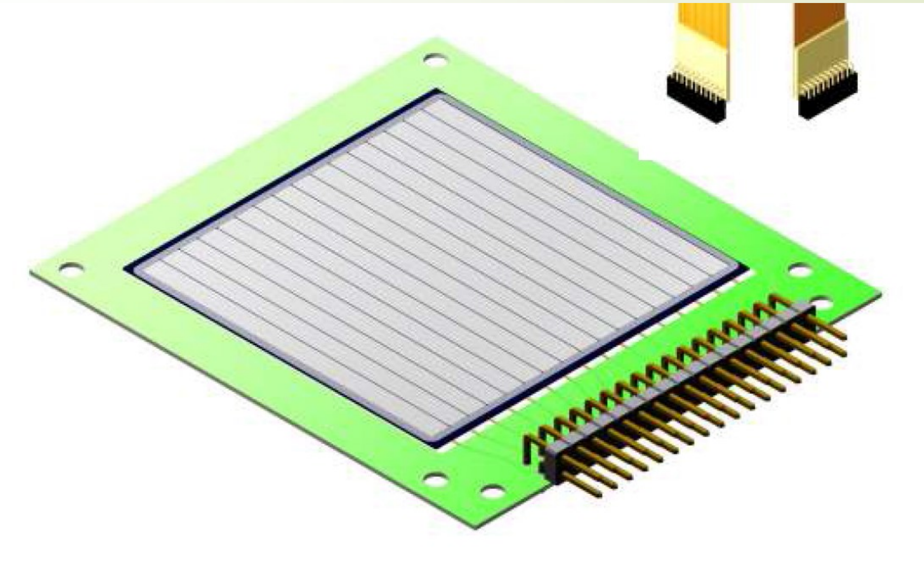
Main spec

- TV ripple: 25 $V_{RMS,}$ TV stability: 200 V (GVM), 30 V (SLITS)
- Beam current capability at 2 MV: 200 μA proton, 40 μA He
- Beam brightness: guaranteed 10 Amp(rad)$^{-2}$m^{-2}eV$^{-1,}$ expected 20 Amp(rad)$^{-2}$m^{-2}eV^{-1}

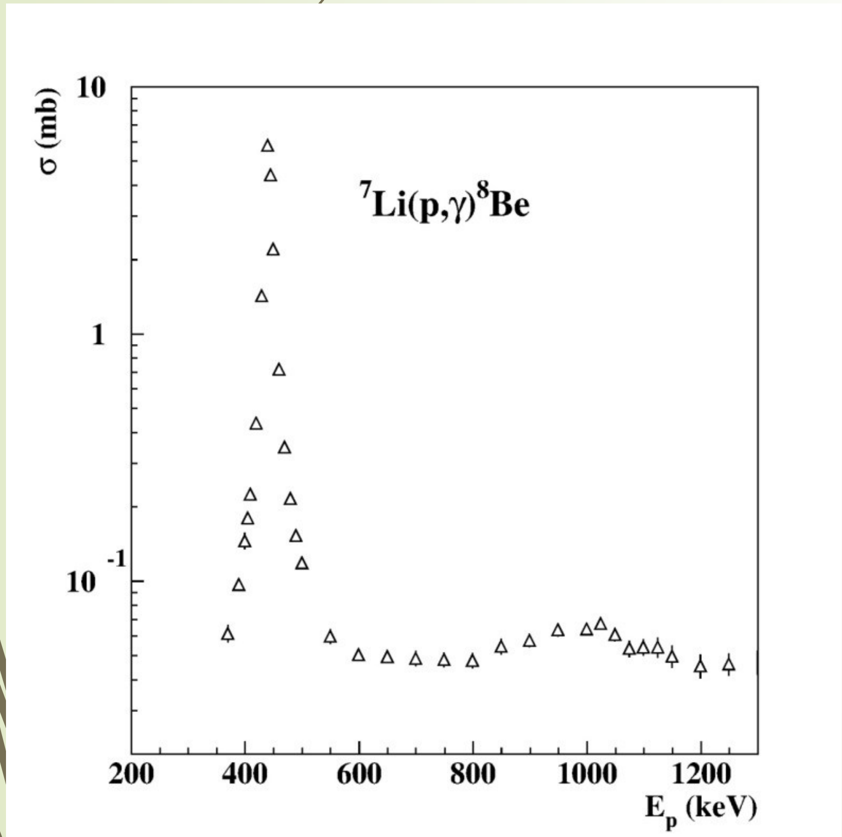

Nuclear and Astrophysics
Scanning ion microprobe
PIXE chamber
Macro PIGE/DIGE chamber
Intermediate focus chamber
Nanoprobe (Phase 5)
ESA-21 Electronspectrometer
Vibration measurements:
Better than the old VdG building,
this is important for the planned nanoprobe system.
Visiting path
Tandetron
Chemistry lab
Sample prep lab
DAQ
Printer, Photocopy, fax, etc.
Corridor
Offices
Large office: many young people (6-8 desks divided by cubicles)
Toilets, shower, changing room, etc.
Seminar room 2
Moveable wall
Large window heat and sound isolated glass
Seminar room
Stores
Corridor
Offices or also needed for AC machines
Offices
Offices
Offices
Offices
Offices
Szellőző gépház

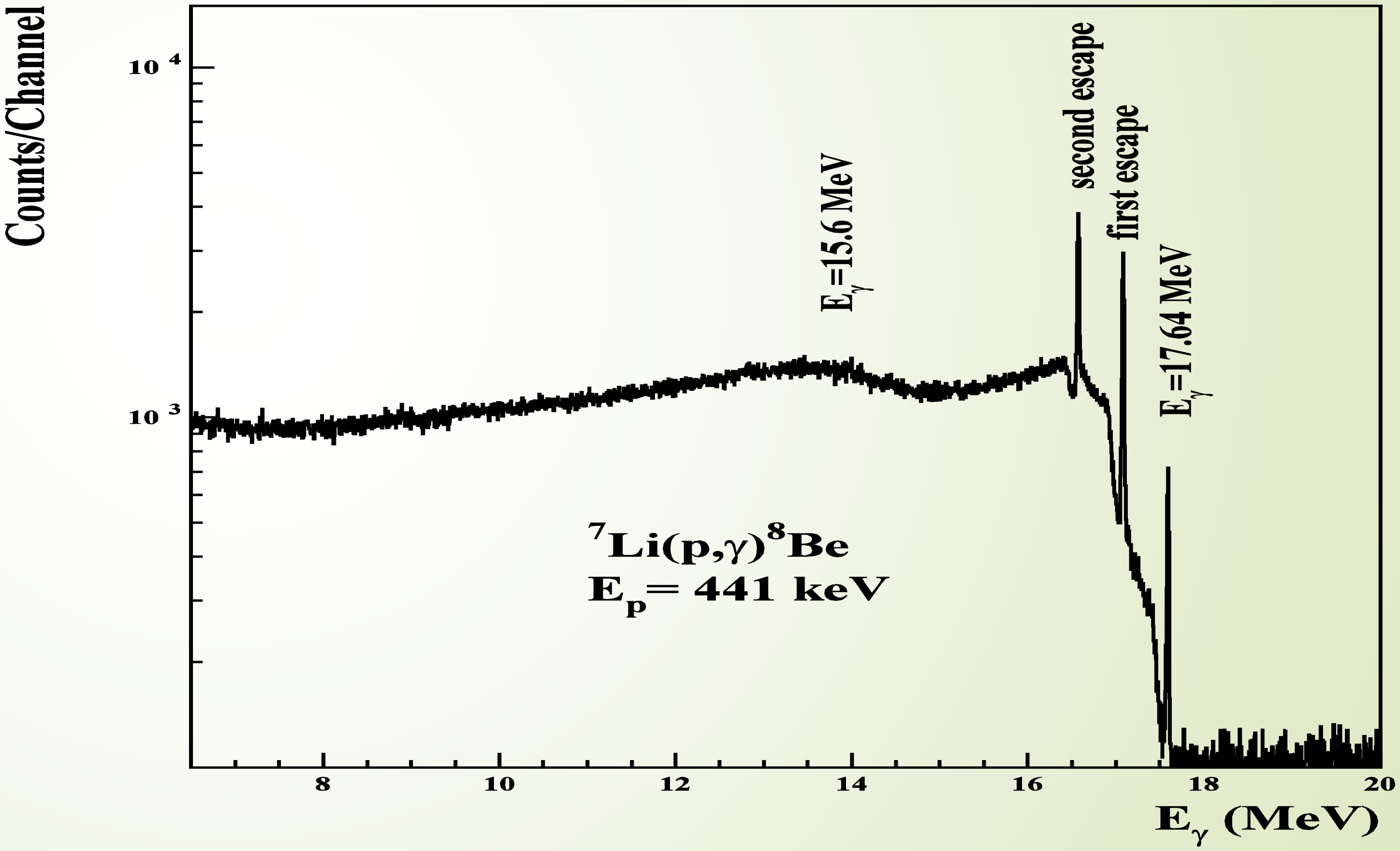
The upgraded spectrometer with Double sided Silicon Strip Detectors (DSSD)



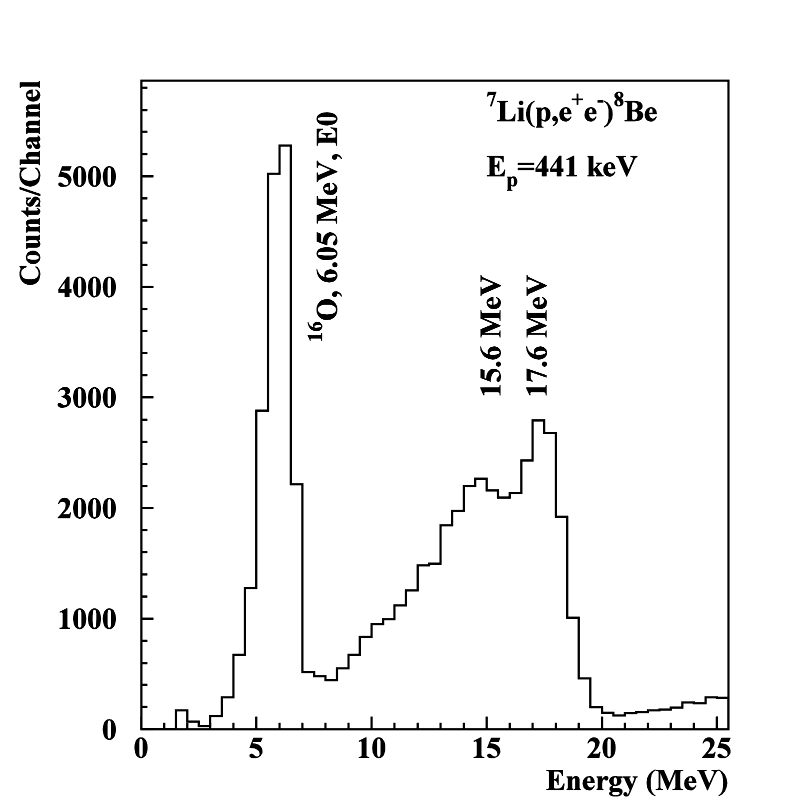


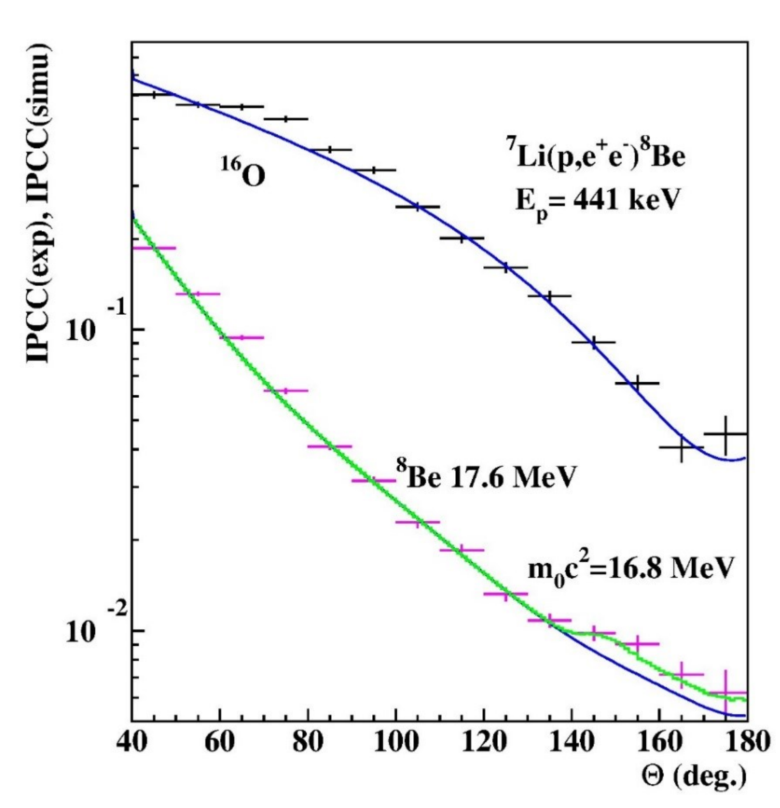
γ-spectrum measured on the 441 keV resonance

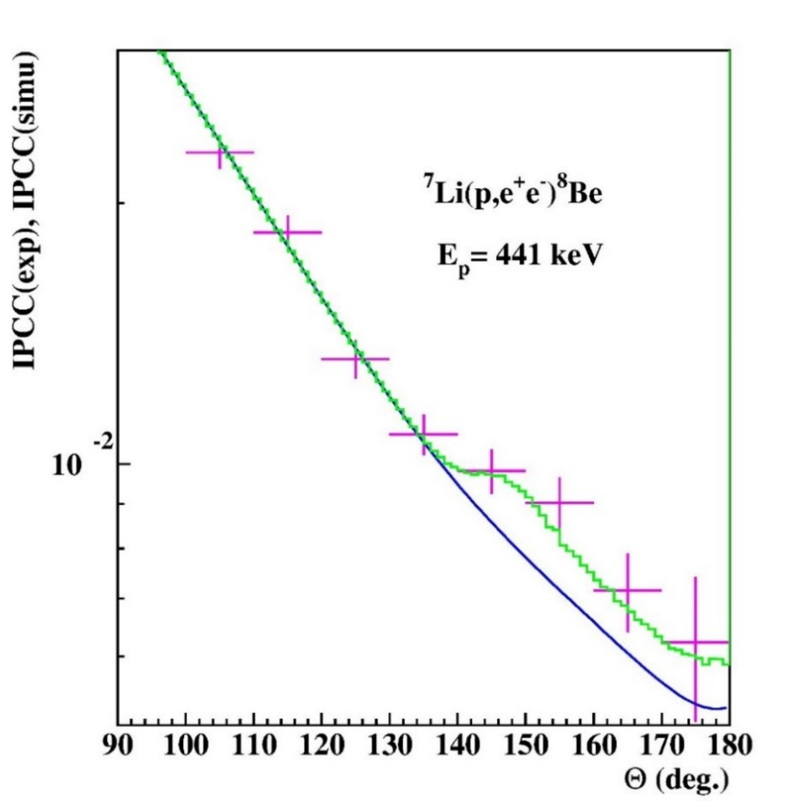




New results for the 17.6 MeV transition

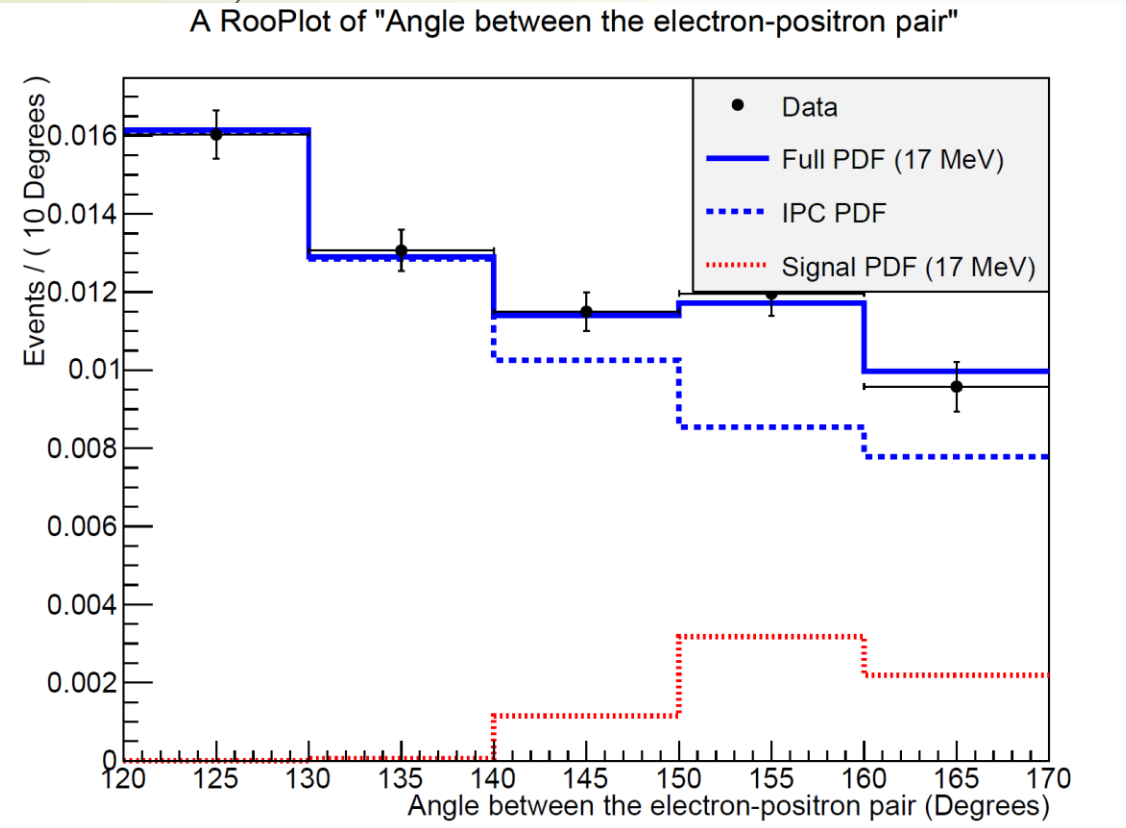


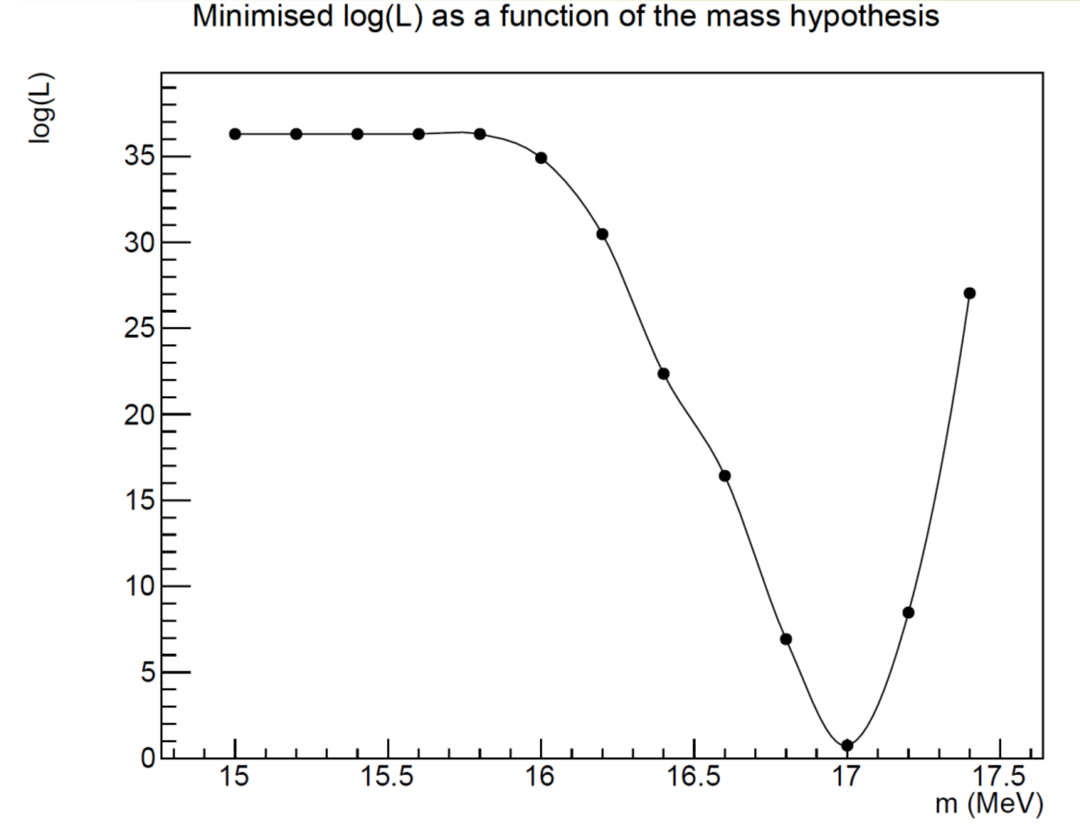




→The prediction of Feng et al., is correct.

Fitting the data with the standard RooFit code



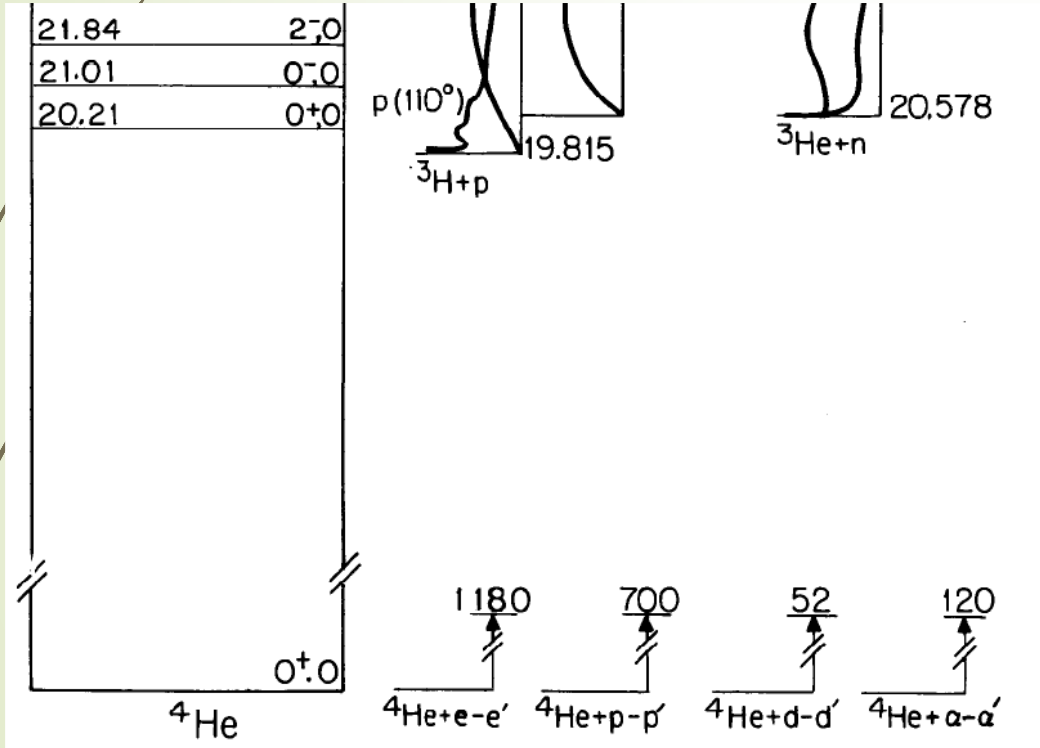


To be continued ...

- Support from the Hungarian National Development Agency (~ 1.5 MEur)
- More telescopes, even bigger efficiency
- Si DSSD detectors for tracking the particles
- LaBr3 detectors and an AGATA detector for γ-ray measurements

- Constraining the mass of the particle
- Can we see anything in the 17.6 MeV transition?
- Constraining the lifetime of the particle
- Can we see particle creation in E1 transitions ($^{11}B(p,\gamma)^{12}C$) ? Parity conservation?

Study the γγ-decay of the 16.7 MeV boson



- Landau-Yang theorem: a vector boson is not allowed by two gamma emission
- U. Ellwanger and S. Moretti, Possible Explanation of the Electron Positron Anomaly at 17 MeV in $_8Be$ Transitions

  Through a Light Pseudoscalar
  arXiv:1609.01669v2
- 1+ vector boson → 0- pseudoscalar boson
- L=1 emission between the 1+ and 0+ states
- M. Suffert and R. Berthollet, Nucl. Phys. A318, 54 (1979)
- **Doubly radioactive neutron capture in ^{3}He**

Promising Outlook

IPC:

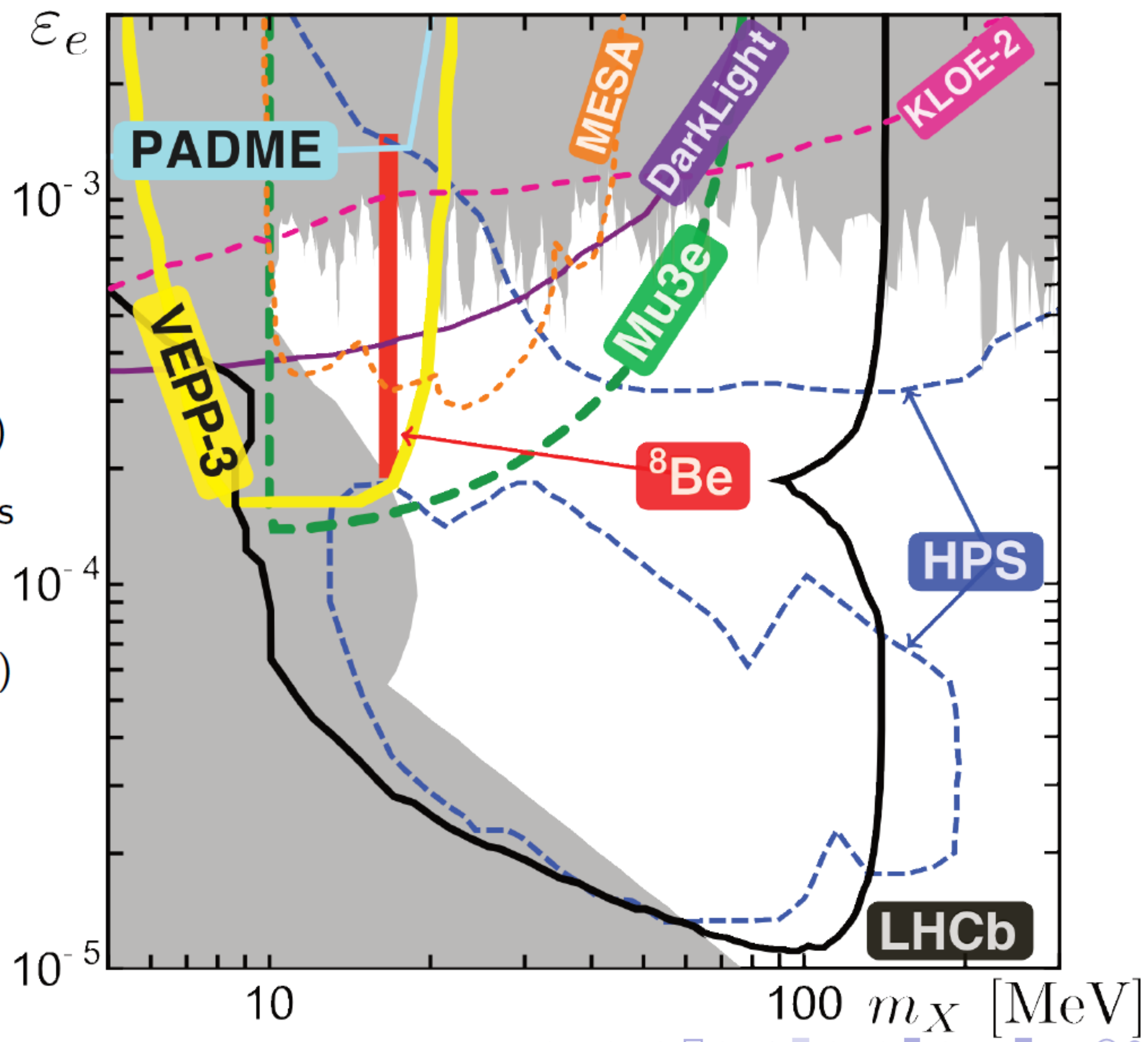
- verify ^{8}Be
- ^{10}B : 19.3 MeV
- ^{10}Be : 17.79 MeV

More Exp:

- TUNL (HIGS facility γ *Nuc*)
- TREK@JPARC: K^+ Decays
- SHIP
- SeaQuest (Gardner & Holt)
- VdG UK
- BESIII (arXiv:1607.03970)

Prob UV

- ATLAS, CMS



Thank you very much for your attention