6th workshop of the Hellenic Institute of Nuclear Physics
New Aspects and Perspectives in Nuclear Physics
Zoom Conference
National and Kapodistrian University of Athens
HINPw6 - 14-16 May 2021

Chasing the X17 Boson
Theory and Experiments

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Outline

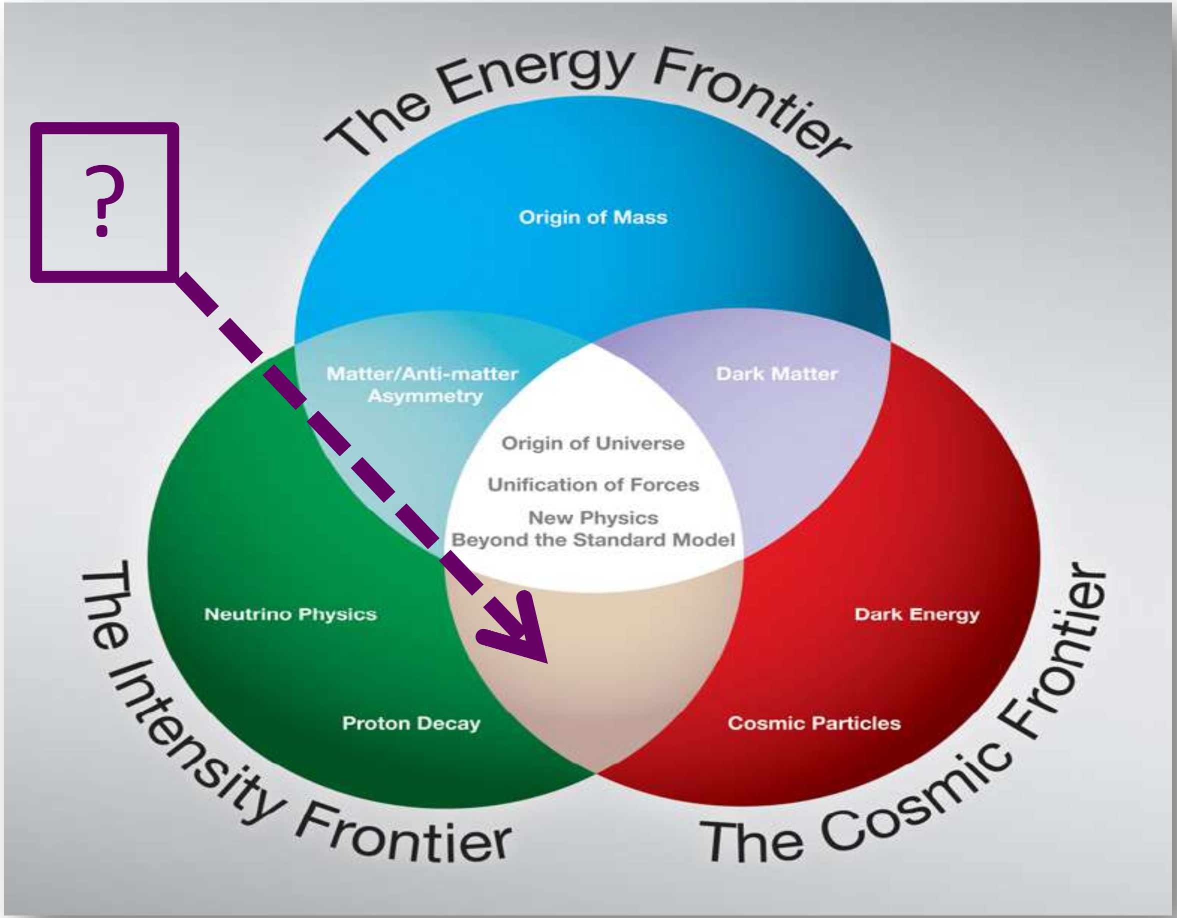
1. ^{8}Be and ^{4}He as physics Lab
2. ATOMKI experiment – results
3. What the theory claim
4. Experimental efforts
5. Summary
6. Some Preliminary Conclusions

Part I (1–2)

Part II (3–4)

Part III (5–6)

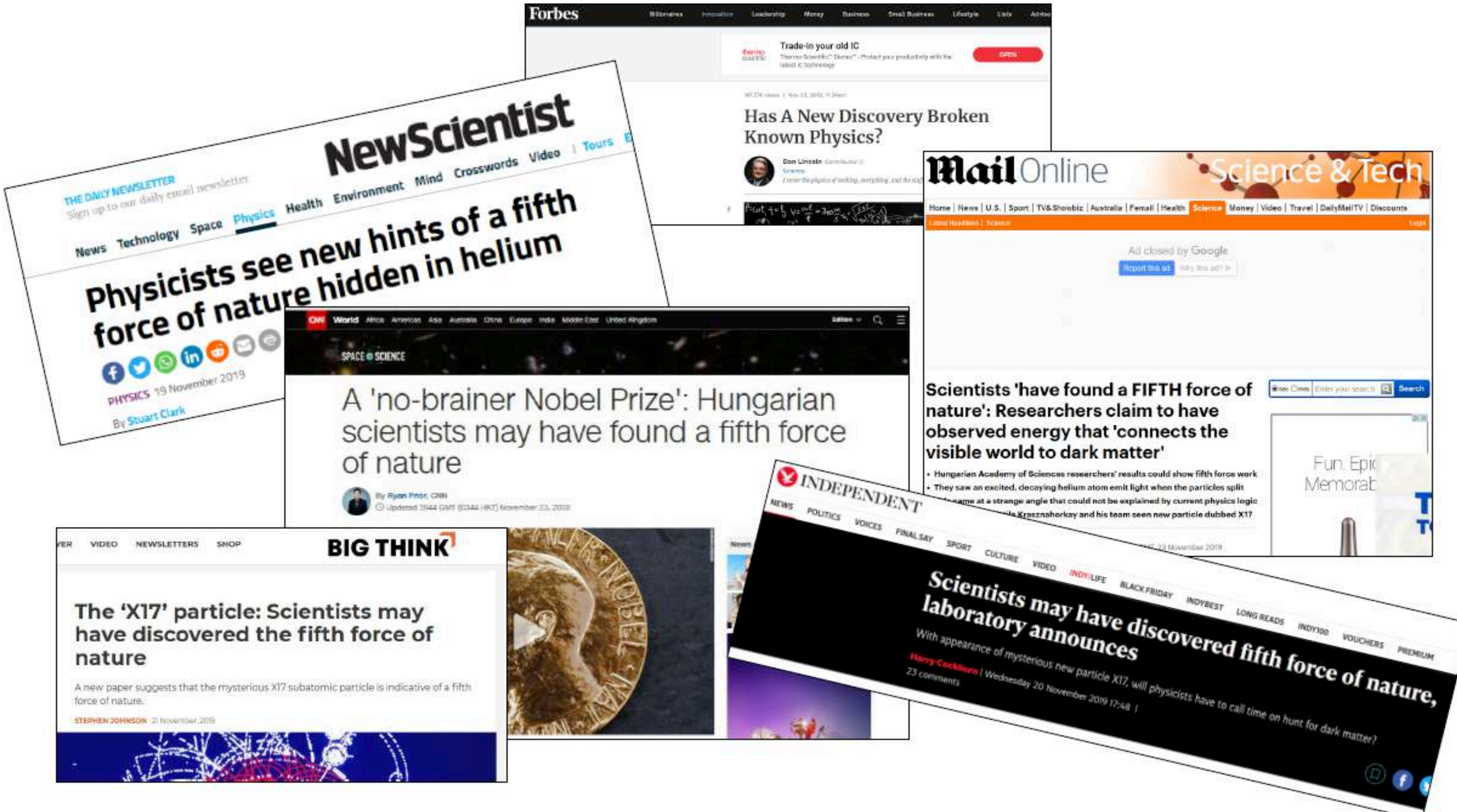
Why are we interested so much ?



Its an open opportunity for

NEW REVOLUTIONARY PHYSICS

The X17 Boson triggered the media



Forbes

Has A New Discovery Broken Known Physics?

Don Lincoln

NewScientist

News Technology Space Physics Health Environment Mind Crosswords Video Tours

Physicists see new hints of a fifth force of nature hidden in helium

PHYSICS 19 November 2019

By Stuart Clark

MailOnline Science & Tech

Scientists 'have found a FIFTH force of nature': Researchers claim to have observed energy that 'connects the visible world to dark matter'

- Hungarian Academy of Sciences researchers' results could show fifth force work
- They saw an excited, decaying helium atom emit light when the particles split

CNN World

SPACE + SCIENCE

A 'no-brainer Nobel Prize': Hungarian scientists may have found a fifth force of nature

By Ryan Prior, CNN

BIG THINK

VIDEO NEWSLETTERS SHOP

The 'X17' particle: Scientists may have discovered the fifth force of nature

A new paper suggests that the mysterious X17 subatomic particle is indicative of a fifth force of nature.

STEPHEN JOHNSON 21 November 2019

INDEPENDENT

NEWS POLITICS VOICES FINAL SAY SPORT CULTURE VIDEO INDY/LIFE BLACK FRIDAY INDYBEST LONG READS INDY100 VOUCHERS PREMIUM

Scientists may have discovered fifth force of nature, laboratory announces

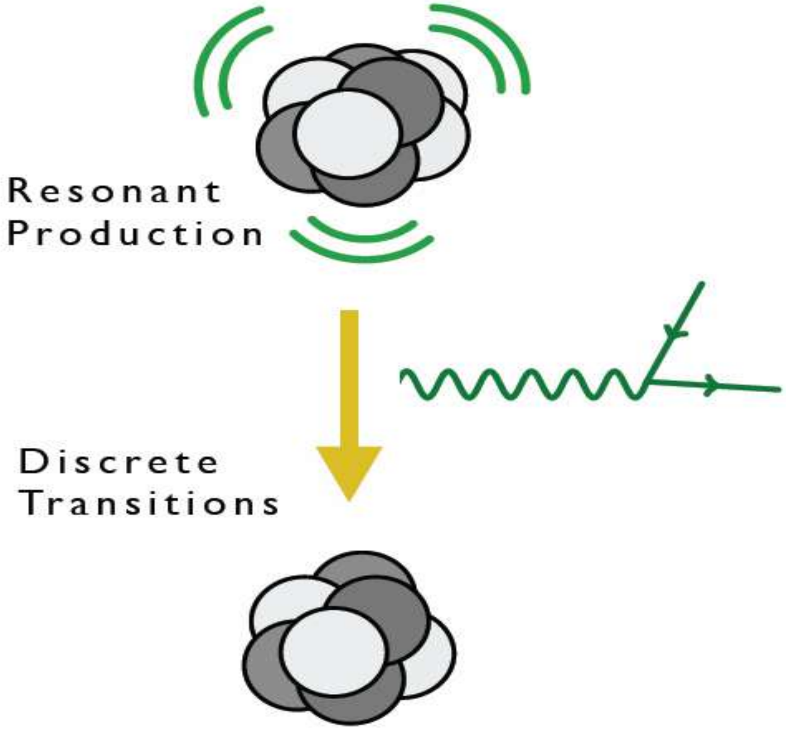
With appearance of mysterious new particle X17, will physicists have to call time on hunt for dark matter?

Harry Cockburn | Wednesday 20 November 2019 17:48 |

23 comments

^{8}Be* and ^{4}He* as a new physics lab

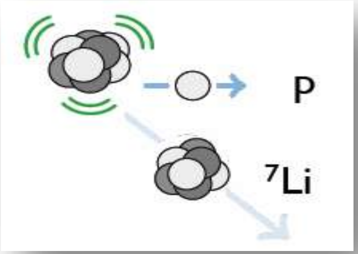
- The ^{8}Be* nucleus is composed of:
 4 protons and 4 neutrons (2p+2n for ^{4}He*).
- Excited states can be produced through p + ^{7}Li (p+^{3}H), with high statistics.
- Excited states decay to ground state with relatively large energies (≈ 20 MeV).
- ^{8}Be* and ^{4}He* nuclear transitions provide interesting probes of light to weakly-coupled particles.



^{8}Be* decay

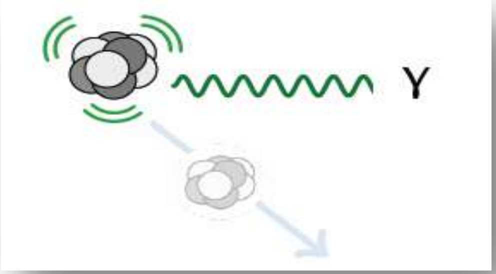
- **Hadronic**

  B(p ^{7}Li) ≈ 100%



- **Electromagnetic**

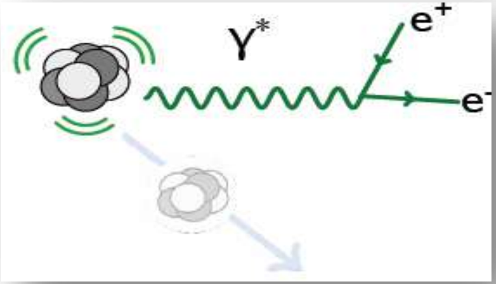
  B(^{8}Be --> γ) ≈ 1.5 x 10^{-5}



- **Internal Pair Creation (IPC)**

  B(^{8}Be --> e^+ e^-) ≈ 5.5 x 10^{-8}

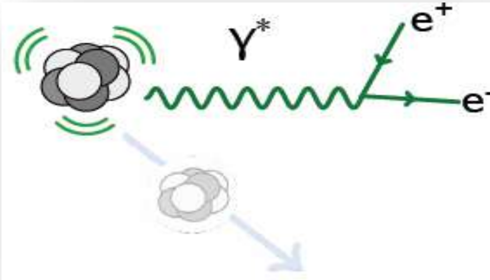
  τ ≤ 10^{-13} sec "short lived"



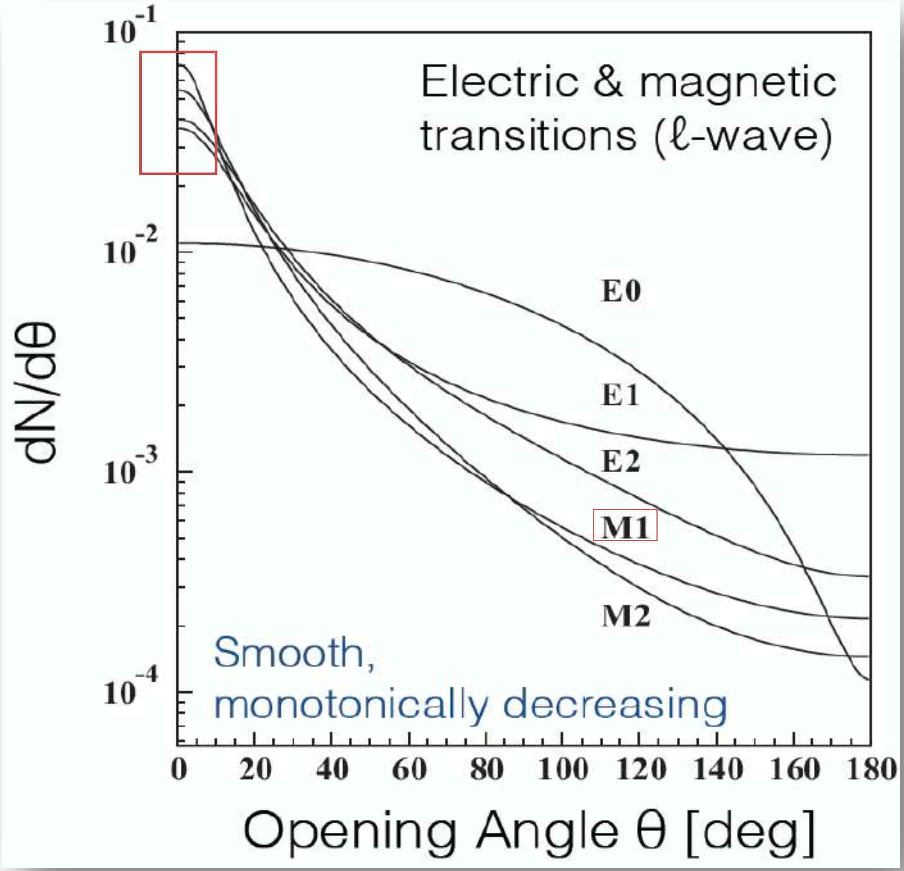
^{8}Be* decay

- Internal Pair Creation (IPC)

  B(^{8}Be --> $e^+ e^-$) ≈ 5.5 x 10^{-8}



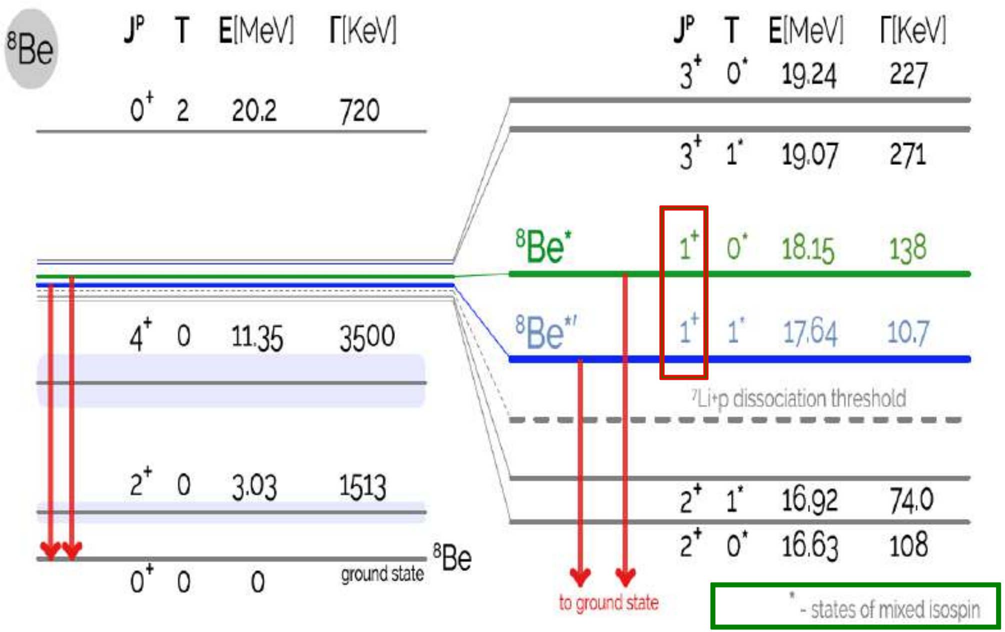
For e^+e^- pair produced by a virtual photon the dN/dθ sharply peaks at low θ and is expected to decreasing monotonically as a function of θ.



Gulyas et al. (2015); Rose (1949)

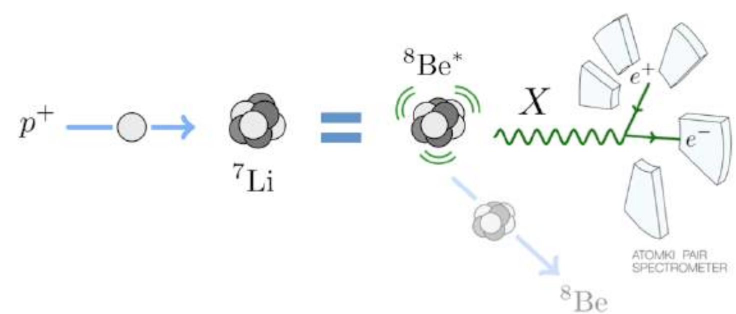
The $^{8}Be^{*}$ spectrum

- Many excited states with different spins and isospins.
- Of special interest: the **$^{8}Be^{*}$ (18.15)** and **$^{8}Be^{*\prime}$ (17.64)** states.
- Almost 1 μA proton beam with $0.441 \leq E_p \leq 1.20$ MeV strikes a thin ^{7}Li foil target.



Tilley et al. (2004) and Wiringa et al. (2013)

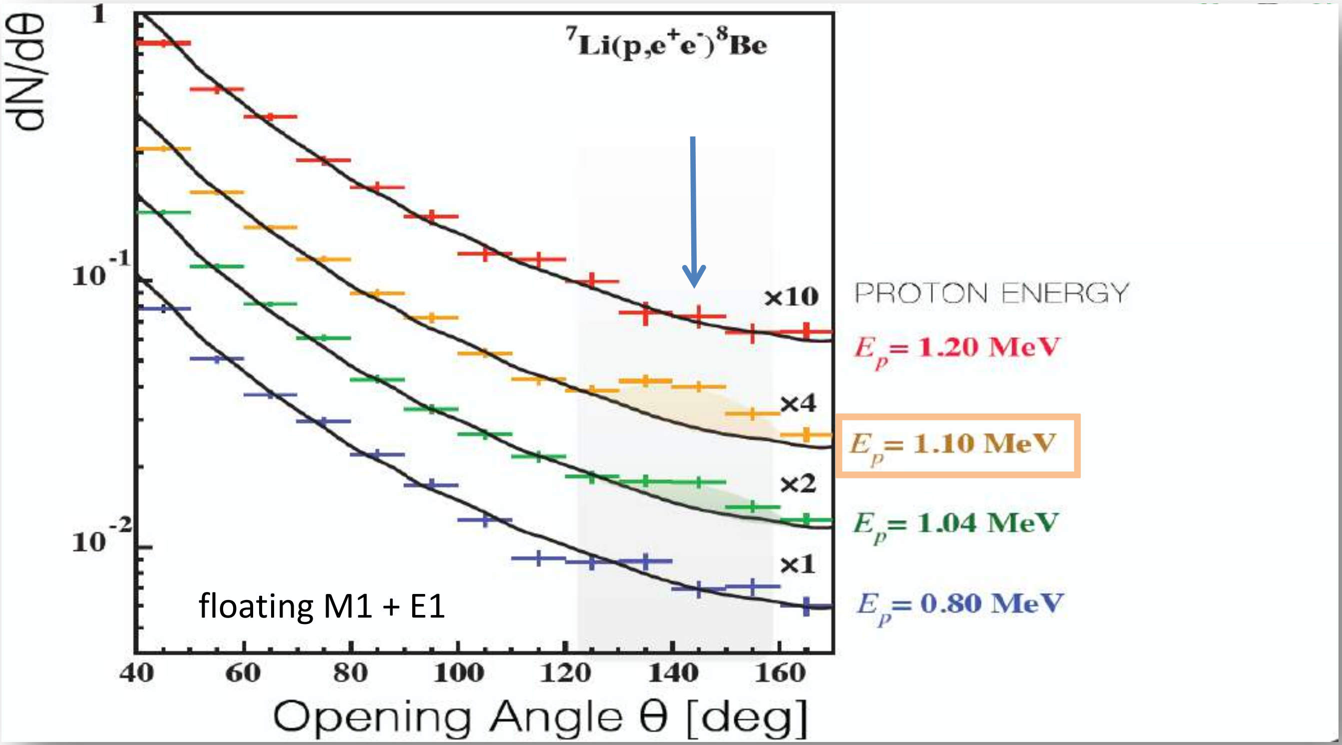
15μg/cm^2 thick LiF_2
700 μg/cm^2 thick LiO_2
evaporated on 10μm Al backings



Feng et al. Phys. Rev. Lett. 117, 071803 (2016)

The ATOMKI anomaly results

- A bump at near the **140⁰** was observed as one passes through the ^{8}Be* resonance.
- Background Fluctuations Probability: 5.6 x 10^{-12} ---> (6.8σ)



Feng et al. Phys. Rev. Lett. 117, 071803 (2016)

Krasznahorkay et al. PRL 116, (2016)

The ATOMKI anomaly results

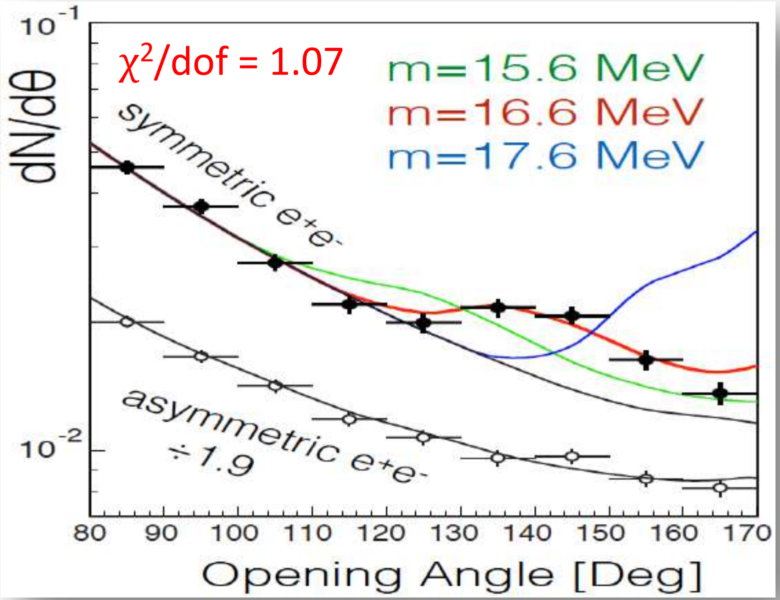
- The θ (and m_{ee}) distributions can be explained by postulating a new particle and the decay **^{8}Be* --> ^{8}Be+X**, followed by **X -- > e^+e^-**
- Best fit parameters: $M_X = 16.7 \pm 0.35\,(\text{stat}) \pm 0.5\,(\text{sys})\ \text{MeV}$

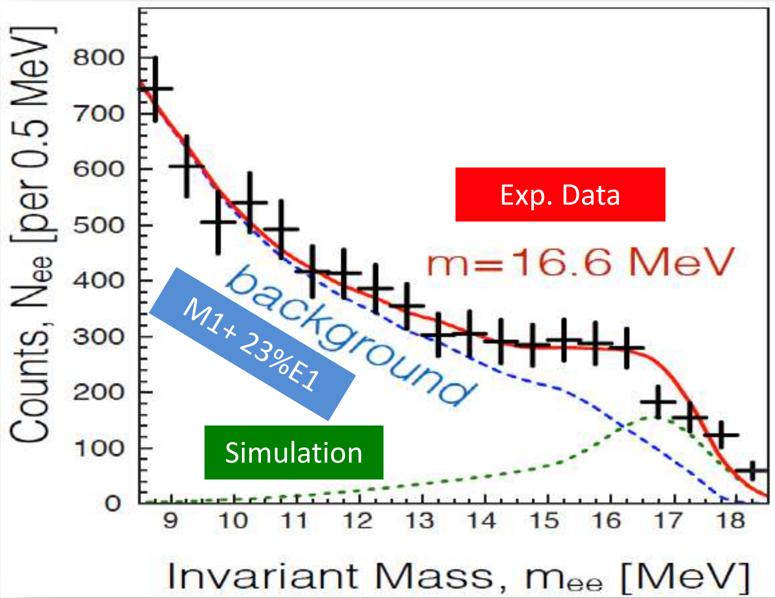
$$\mathcal{B} \equiv \frac{\text{BR}(^8\text{Be}^* \to X + {}^8\text{Be})}{\text{BR}(^8\text{Be}^* \to \gamma + {}^8\text{Be})} \times \text{BR}(X \to e^+e^-) = 5.8 \times 10^{-6}$$

1

Krasznahorkay et al. PRL 116, (2016)

Feng et al. Phys. Rev. Lett. 117, 071803 (2016)



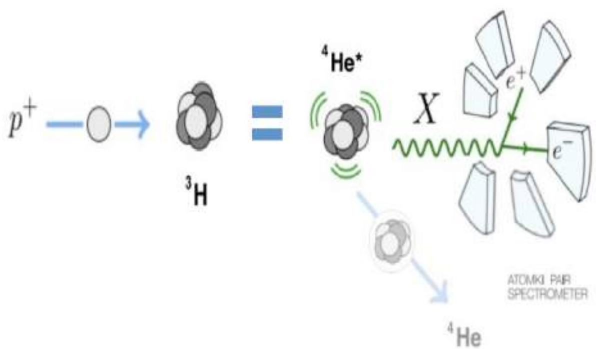


Same anomaly using another target (^{3}H)

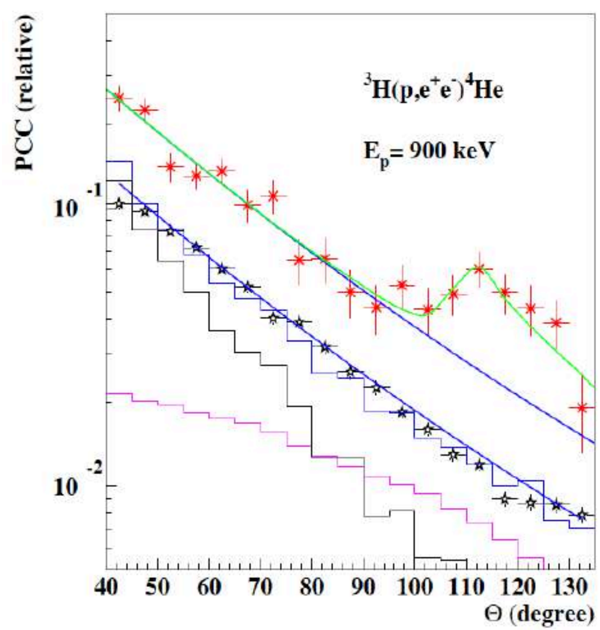
$^3H(p,\gamma)^4He^*$

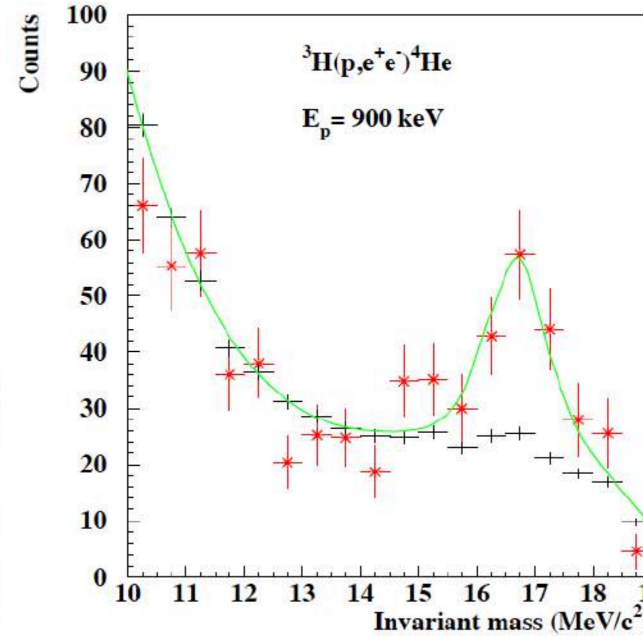
- A proton beam E_p = 900 keV with a typical current of 1.0 μA was strikes on a ^{3}H target.
- e^+e^- pairs showed a peak at **115^0**, supporting the creation and decay of the X17 particle with mass of **m_X = 16.84 ± 0.16(stat) ± 0.20(syst) MeV** (7.1σ)

Feng et al. Phys. Rev. Lett. 117, 071803 (2016)



^{3}H target absorbed in a 3mg/cm^2 thick Ti layer evaporated onto a 0.4 mm thick Mo disk.





A. Krasznahorkay et al. (2019) arXiv:1910.10459v1

What kind of new particle can it be ?

- **Scalar Particle** ($J^P = 0^+$): then L = 1 and $P=(-1)^L$: IS NOT A SCALAR (P - violation)
- **Pseudoscalar Particle** ($J^P = 0^-$) and L = 1 : POSIBILTY EXIST if $g' \approx g_{SM(Higgs)}$
- **Vector Particle** ($J^P = 1^-$) : THE MOST COMMON CONDIDIATE if $g' \approx 10^{-3}$
- **Axial-Vector Particle(Pseudovector)** ($J^P = 1^+$): POSIBILTY EXIST if $g' \approx 10^{-4}$

The couplings of the X17 Boson
to the SM particles remains an open question !

Candidates for the new X17 boson

A possible existence of the X17 boson, triggered an enhanced theoretical and experimental interest in nuclear and particle physics community (2016 - today).

Zhang and Miller: explored the nuclear transition form factors as a possible origin of the anomaly: Concluded that the required form factor is unrealistic for the ^{8}Be nucleus.

Phys. Lett. B773 159 (2017)

In an additional work, they concluded that the X17 production is dominated by direct capture transitions both in ^{8}Be and ^{4}He without going through any nuclear resonance.

Phys. Lett. B 813 136061 (2021)

Feng and co-workers: claim that a 16.7 MeV, $J^{P} = 1^{-}$ vector gauge boson may mediate a fifth fundamental force, with some coupling restrictions to the Standard Model (SM) particles.
Phys. Rev. Lett. 117, 071803 (2016) - Phys. Rev.D 95, 035017 (2017)

The NA48/2 experiment: set constraints on such a new particle, notably from searches for $\pi_0 \rightarrow Z' + \gamma$ requiring the couplings of the Z′ to up and down quarks to be “protophobic”. Subsequently, many studies of such models have been performed including an extended two Higgs doublet model. **Phys. Lett. B 746, 178 (2015)**

Candidates for the new X17 boson

Ellwanger and Moretti: Claim that the X17 boson could indeed be a $J^P = 0^-$ pseudoscalar particle, if it was emitted with L = 1 orbital momentum. They predicted about 10 times smaller branching ratio in case of the 17.6 MeV transition compared to the 18.15 MeV.
JHEP 11 39 (2016)

Alves and Weiner: revisited experimental constraints on QCD axions in the O(10 MeV) mass window. Axions or axion like particles (ALPs) are expected to decay predominantly also by the emission of e^+e^- pairs. **High Energy Phys. 92,(2018)**

Luigi Delle Rose and co-workers: claim that the anomaly can be described with a very light Z_0 bosonic state, stemming from the $U(1)_0$ symmetry breaking, with significant axial couplings. **Phys. Rev. D 96, 115024 (2017) - Phys. Rev. D 96, 115024 (2017) - Phys. Rev. D 99 055022 (2019)**

C. Hati, J. Kriewald, J. Orloff and A.M. Teixeira: they investigated anomalies in ^{8}Be nuclear transitions and their connection with $(g\text{-}2)_{e,\mu}$ **JHEP: 235 (2020)**

The VPL (Veselský - Petousis - Leja) model

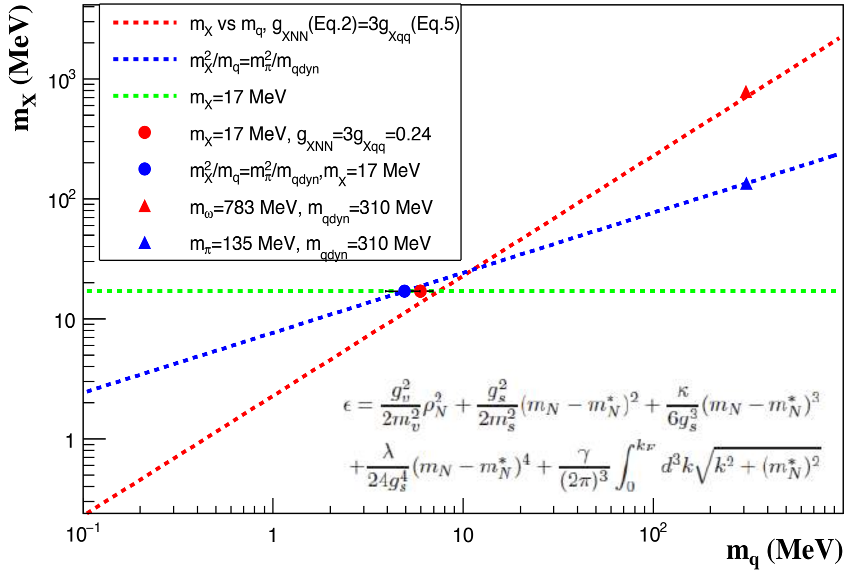
- We present a hypothesis that the anomaly in the folding angle distribution of electron-positron pairs, emitted in the decay of the excited levels of nucleus ^{8}Be and ^{4}He can be related to the cluster structure of the decaying state.

- We present a hypothesis that the potentially observed boson with rest mass m_X=17 MeV can mediate the nucleon-nucleon interaction at the low-energy regime of QCD, in the weakly bound cluster states p+^{7}Li and p+^{3}H.

- We present a possible EoS of symmetric nuclear matter corresponding to the vector meson mass m_V=17 MeV, obtained using RMF theory of nuclear force, QHD-I with physically relevant incompressibilities K_0=245-260 MeV and couplings g_v, g_s lower than unity.

- Based on concepts of chiral symmetry breaking, we show that reduction of the rest mass of a pseudoscalar particle from physical value m_π=135 MeV to m_X=17 MeV is equivalent to reduction of the quark mass from dynamical value ~ 310 MeV down to current quark mass ~ 5 MeV.

arXiv: 2004.09758v3



$$\left(\frac{m_N}{m_s}\right)^2 g_s^2 = 357.4$$
$$\left(\frac{m_N}{m_v}\right)^2 g_v^2 = 273.8 \qquad (2)$$

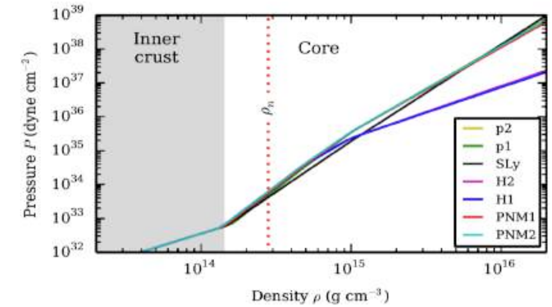
$$\frac{m_X^2}{m_{q,curr}} \simeq \frac{m_\pi^2}{m_{q,dyn}} \qquad (4)$$

$$g_{Xqq} = \frac{g_A m_{q,curr}}{f_\pi} \qquad (5)$$

K_0	m_v	m_s	g_v	g_s	κ	λ
MeV	MeV	MeV			MeV	
245	17.	25.58	0.2407	0.4666	0.0039	-0.001396
250	17.	25.58	0.2417	0.4703	0.00398	-0.001316
260	17.	25.58	0.2417	0.4684	0.00374	-0.001204

The X17 boson and the Neutron Star structure

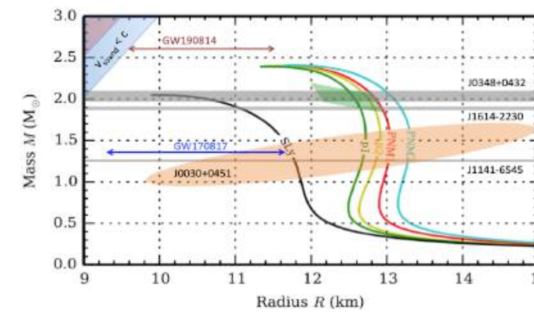
- The reported X17 MeV boson has been investigated in the context of its possible influence to the neutron star structure.
- We implemented the m_V=17 MeV to the nuclear equation of state using different incompressibility values K_0=245 MeV and K_0=260 MeV solving the Tolman-Oppenheimer-Volkov equations.
- We estimated an upper limit of $M_{TOV} \approx 2.4 M_\odot$ for a non-rotating neutron star with span in radius 11.5 km ≤ R ≤ 14 km.
- Moving away from the β-equilibrium with admixture of 10% protons we simulated possible softening of equation of state due to hyperons, we saw that our estimated limits fit quite well inside the newest reported studies, coming from the neutron stars merge procedure.



$$\epsilon = \frac{g_v^2}{2m_v^2}\rho_N^2 + \frac{g_s^2}{2m_s^2}(m_N - m_N^*)^2 + \frac{\kappa}{6g_s^3}(m_N - m_N^*)^3 + \frac{\lambda}{24g_s^4}(m_N - m_N^*)^4 + \frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\sqrt{k^2 + (m_N^*)^2}$$

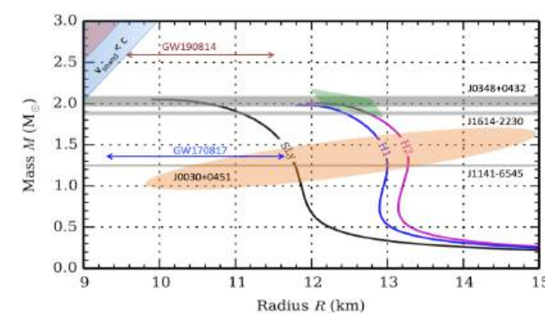
$$\frac{dP}{dr} = \frac{-G}{c^2}\frac{(P+\epsilon)(m + \frac{4\pi r^3 P}{c^2})}{r(r - \frac{2Gm}{c^2})}$$

$$\frac{dm}{dr} = 4\pi r^2 \frac{\epsilon}{c^2}$$



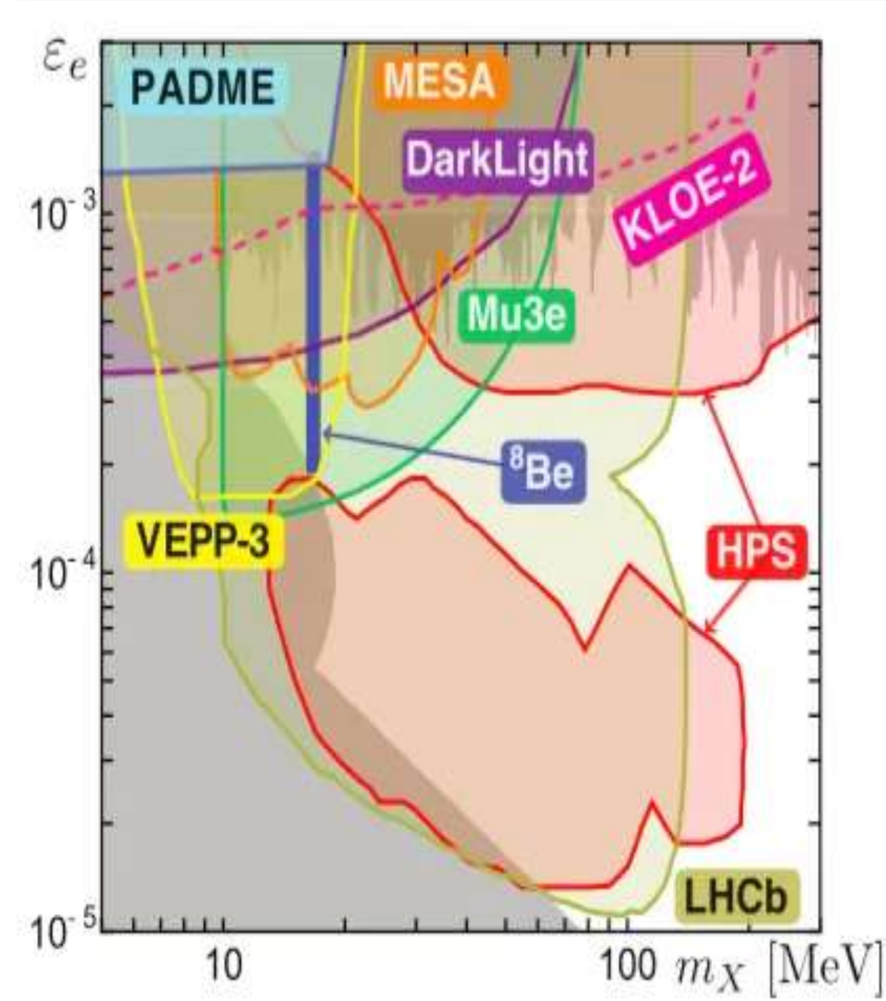
$$P = \frac{g_v^2}{2m_v^2}\rho_N^2 + \frac{g_s^2}{2m_s^2}(m_N - m_N^*)^2 + \frac{\kappa}{6g_s^3}(m_N - m_N^*)^3 + \frac{\lambda}{24g_s^4}(m_N - m_N^*)^4 + \frac{1}{3}\frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\frac{k^2}{\sqrt{k^2 + (m_N^*)^2}}$$

Models	a_0	Γ_1	Γ_2	Γ_3	K_0(MeV)	Note
PNM1	34.600	3.350	3.170	2.497	245	Pure.nucl.matt
H1	34.600	3.350	2.570	1.497	245	Hyperons sim
p1	34.553	3.470	3.307	2.546	245	10% of protons
PNM2	34.642	3.348	3.040	2.534	260	Pure.nucl.matt
H2	34.642	3.348	2.440	1.534	260	Hyperons sim
p2	34.593	3.530	3.177	2.500	260	10% of protons



arXiv: 2008.02733v1

The LHCb experimental efforts



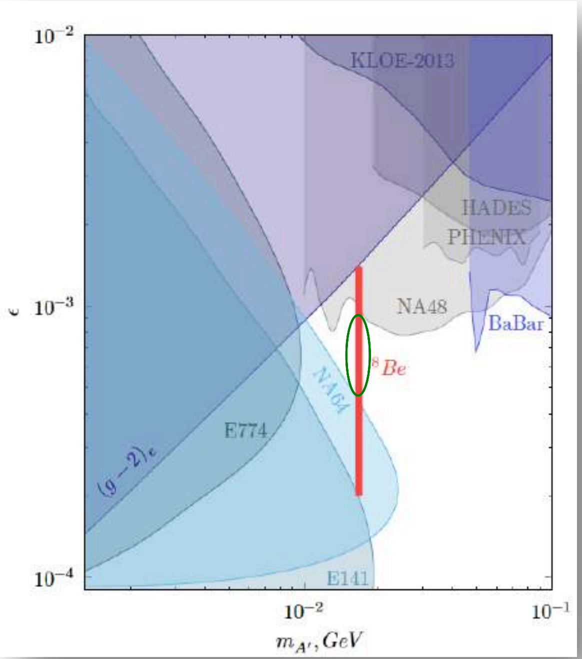
- **The LHCb experiment** will search for dark photon-like particles with masses and interaction strengths that were previously unexplored.

- The proposed research makes use of the LHCb's ability to pinpoint the production position of charged particle pairs and the copious amounts of D mesons produced at Run 3 of the LHC.

- As seen in the figure, the LHCb with this search thoroughly covers the ATOMKI anomaly region.

PhysRevLett.117.071803

The NA64 experimental negative results



NA64 Collaboration
PhysRevD.101.071101

An intriguing possibility is that in addition to gravity a new effective force between the dark sector and visible matter, transmitted by a new vector boson A' (dark photon), might exist.

$$L = L_{SM} - \frac{1}{4} F^{DM}_{\mu\nu} F^{\mu\nu}_{DM} - \frac{\varepsilon}{2} F^{DM}_{\mu\nu} F^{\mu\nu} + \left| D^{\mu}\varphi \right|^2 - V(\varphi)$$

$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ x $U(1)_D$

$$\varepsilon^2 \equiv \frac{\alpha'}{\alpha}$$

Such A' could have a mass **$m_{A'} \leq 1$ GeV**, associated with a spontaneously broken gauge **$U(1)_D$** symmetry, and would couple to the Standard Model (SM) through kinetic mixing term with the ordinary photon parameterized by the mixing strength **ε << 1**

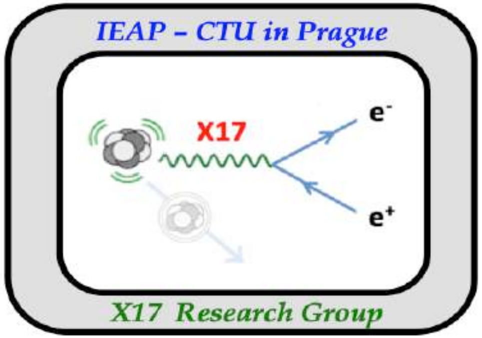
The 90% C.L. exclusion areas in the ($m_{A'}$ - ε) plane from the NA64 experiment (light blue area). For the mass of 16.7 MeV, the excluded coupling region by NA64 is: **$1.3\times10^{-4} \leq \varepsilon \leq 4.2\times10^{-4}$**

The region $4.2\times10^{-4} \leq \varepsilon \leq 1.4\times10^{-3}$ is still unexplored

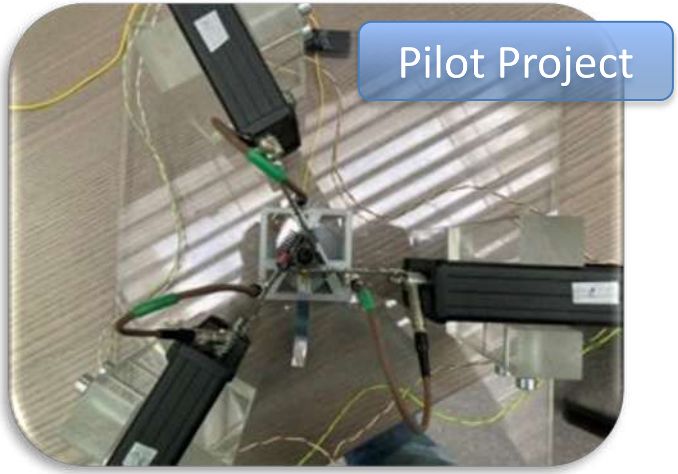
Researching ATOMKI anomaly @ IEAP - CTU

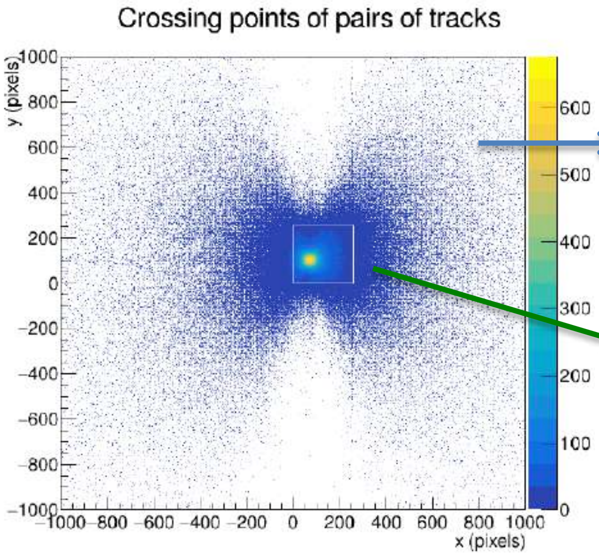
The IEAP - CTU - X17 research group:

B. Ali
B. Bergmann
P. Broulím
P. Burian
L. Fajt
Z. Kohout
P. Mánek
L. Meduna
H. Natal da Luz
V. Petousis
S. Pospíšil
R. Sýkora
T. Sýkora
M. Veselský



- At IEAP-CTU, a group of physicists and engineers trying to understand and to test the anomaly at the VdG facility.
- A 3 years research Grant has been awarded for that research and running since February 2021.



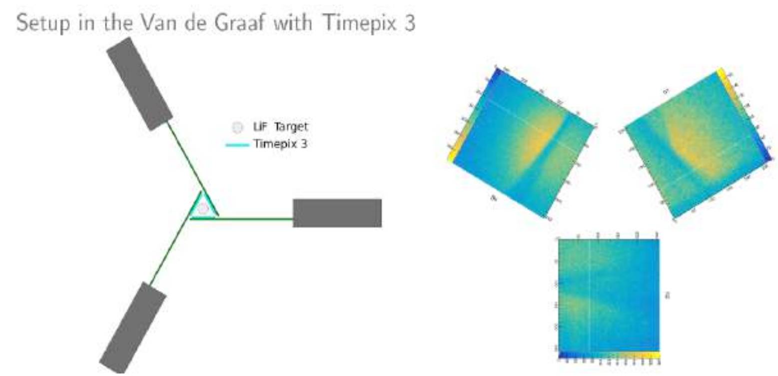


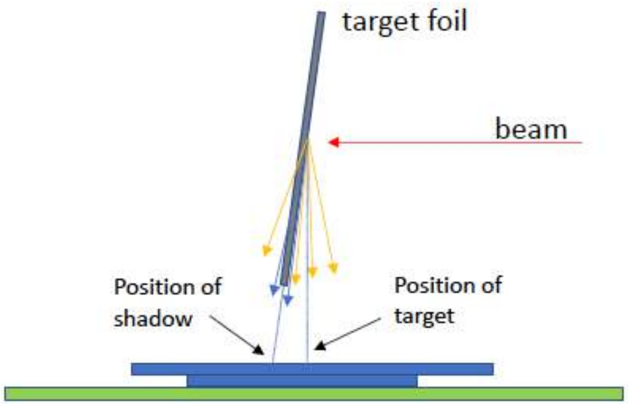
Every point represents a crossing point of 2 tracks in the same detector

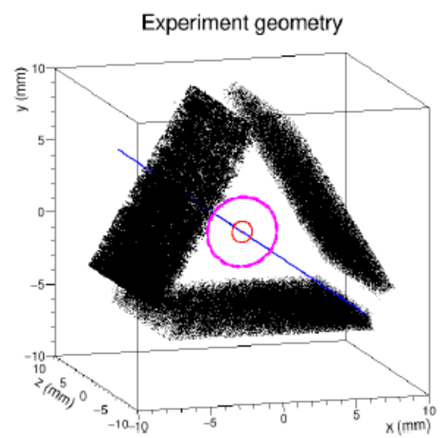
Reconstruction of the target position in the frame of the detectors physical dimensions.

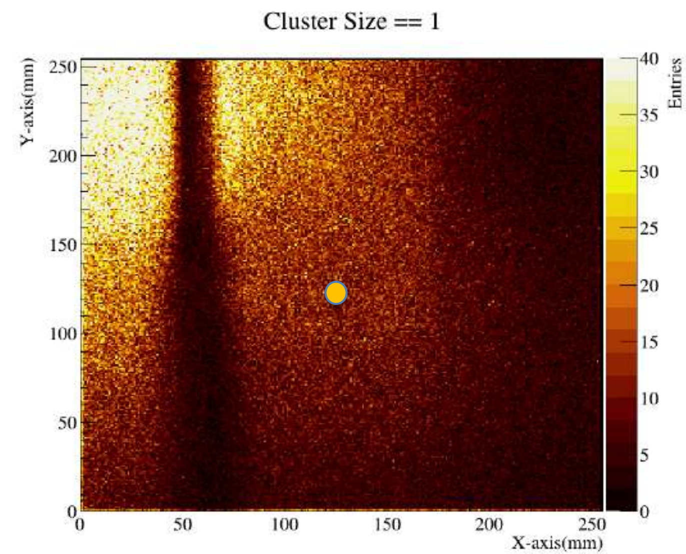
Researching ATOMKI anomaly @ IEAP - CTU

- Testing the proton beam conditions
- Testing target efficiency and its alignment
- Developing data analysis framework
- Solving problems with TimePix3, TPC's and MWPC

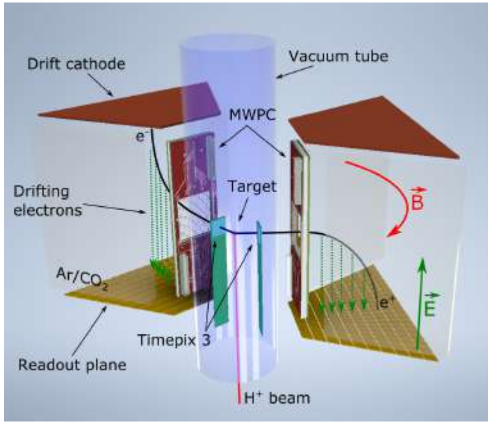




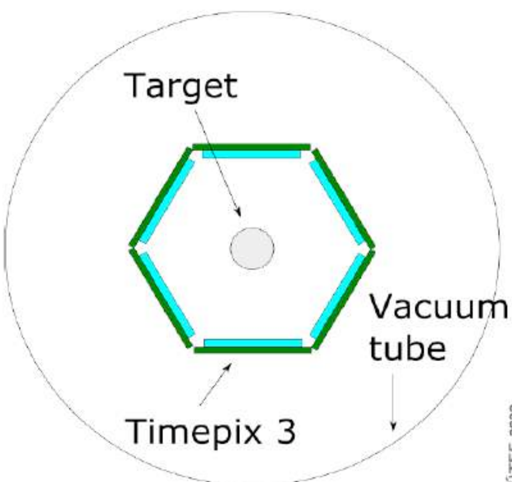


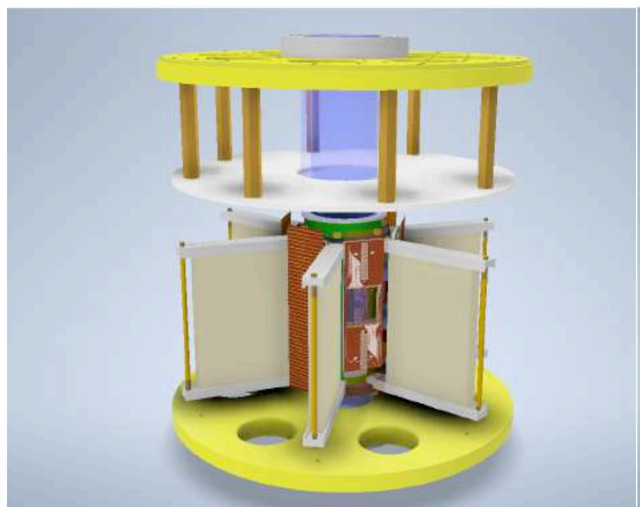


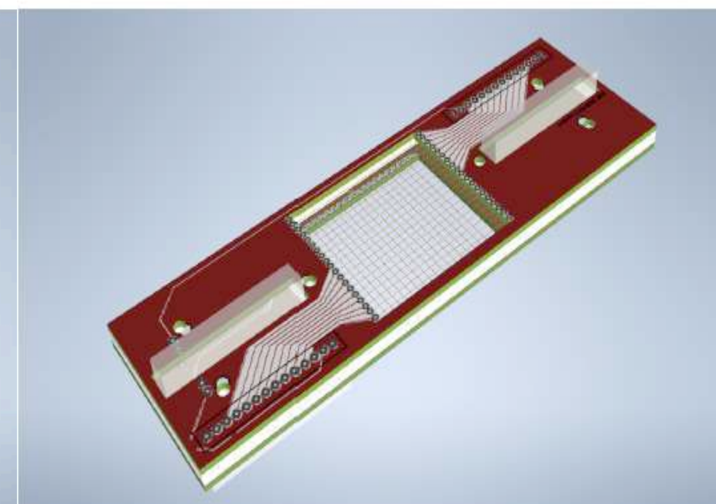
Researching ATOMKI anomaly @ IEAP - CTU



Setup currently in Prague.







In Summary

(1) As a yet unidentified nuclear physics experimental problem ?

(2) As a yet unidentified nuclear theory effect ?

(3) As a yet unidentified particle physics problem ?

WHAT COULD BE ?

In Summary

(1) Nuclear Experiment

- The excess consists of hundreds of events in each bin and is comparable to the background, this is not a statistical fluctuation.
- The excess is not a "last bin" effect: bump, not smooth excess.
- Comparable bump for 17.64 MeV state but smaller in excess should eventually appear.
- Nuclear experiments can confirm or exclude this.

(2) Nuclear Theory

- Must explain the X17 mass "bump" originated from the 18.15 MeV IPC.
- Must simultaneously explain lack of similarly-sized bump in (isospin-mixed) 17.64 IPC transition–decay.

(3) Particle Physics

- If it's a new particle, what kind can it be and what about its couplings to the SM?
- Is it consistent with all other experiments ?
- Particle experiments can confirm or exclude the reported anomaly ?

(LHCb, FASER, CODEX-b expressed already great interest)

Some Preliminary Conclusions

- There is currently a **6.8σ** anomaly in **^{8}Be*** and recently **7.1σ** in **^{4}He*** nuclear decays.
- The data are beautifully fit with χ^2/dof = 1.07 by a new particle interpretation.
- A “bump” at 17.64 MeV ^{8}Be*’ is phase-space suppressed, but should eventually appear.
- The parameters $m_X \approx 17$ MeV, $\varepsilon_n \approx (2\text{-}10)\times10^{-3}$, $\varepsilon_e \approx (2\text{-}14)\times10^{-4}$ provide an interesting argument for future experiments.
- A possible new physics explanation, consistent with all other constraints, may also explain the (g-2)μ anomaly (?)
- Further work is needed in nuclear and particle experiments and theory.
- In future negative results may disfavor new physics, but the road to reject or to confirm the X17 existence is still open before us, so good ideas and complementary probes are welcome.

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Thank you