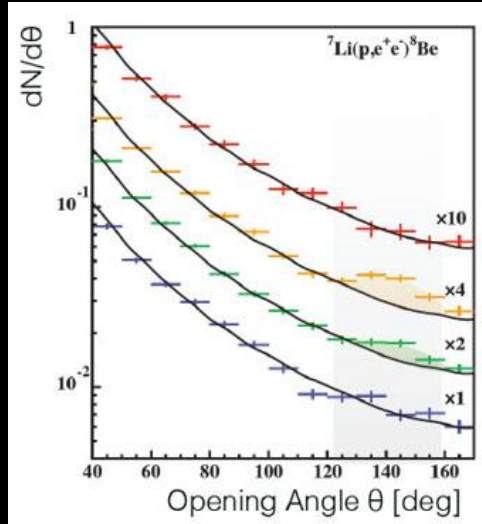
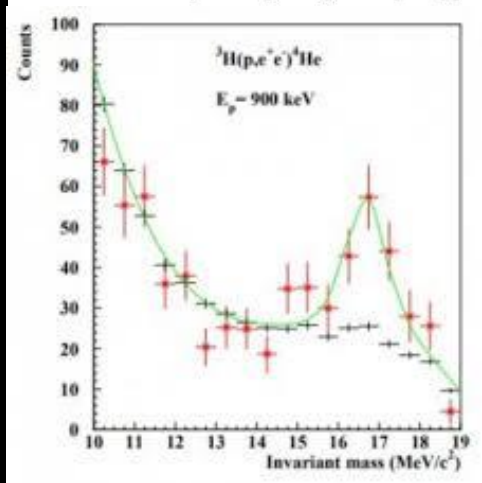
The X17 Boson and the Search for New Physics in Nuclear Transitions

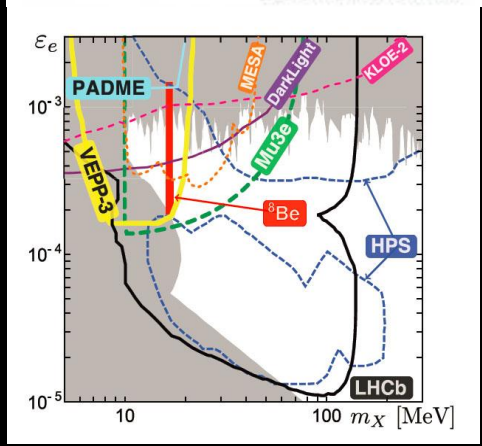
V. Zacek, Université de Montréal

- The ATOMKI Anomalies in ^{8}Be*, ^{4}He*, ^{12}C* and GDR's
- The X17 boson & theor. interpretations
- Ongoing & planned verifications
- The X17 - project at U. of Montreal

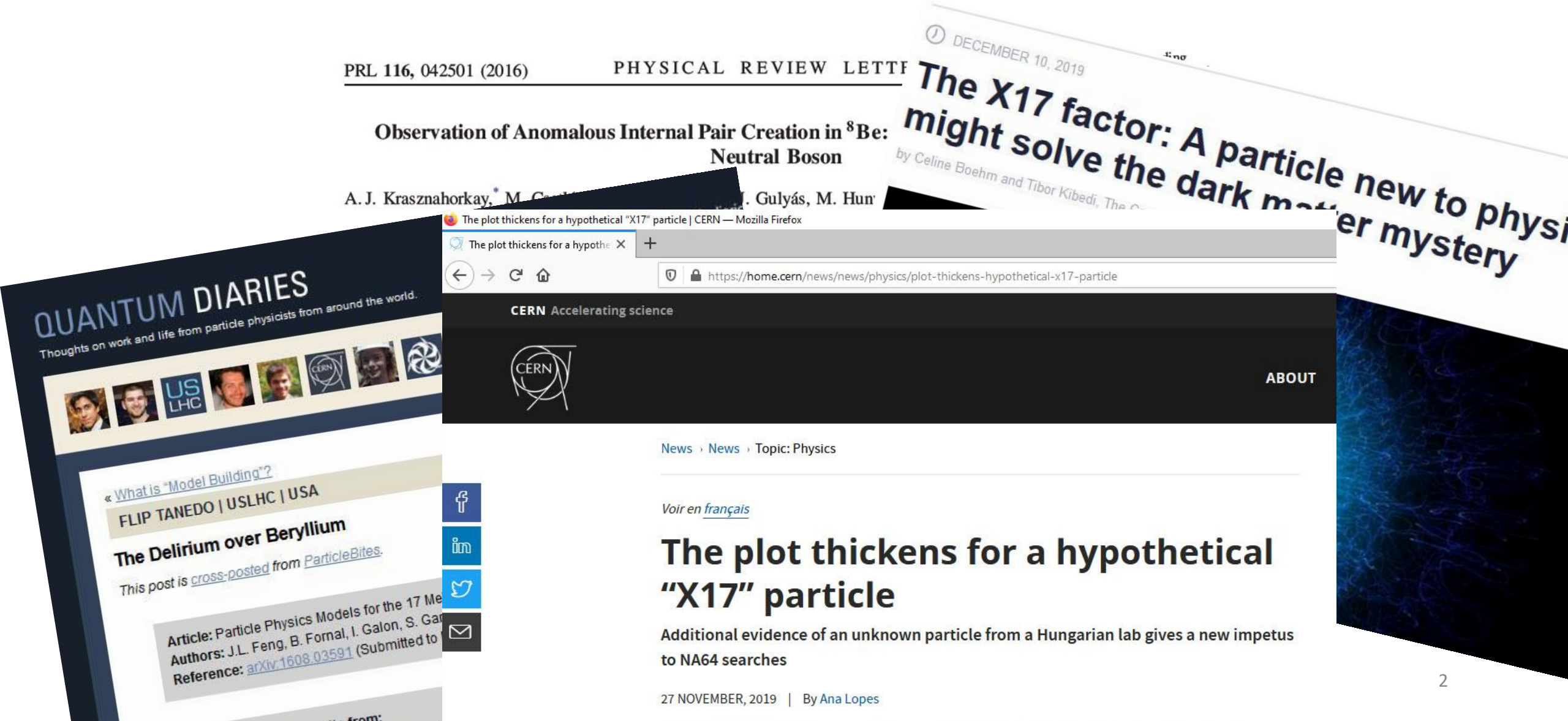
2025 CAP Congress, University of Saskatchevan, Saskatoon (June 8 – 13)





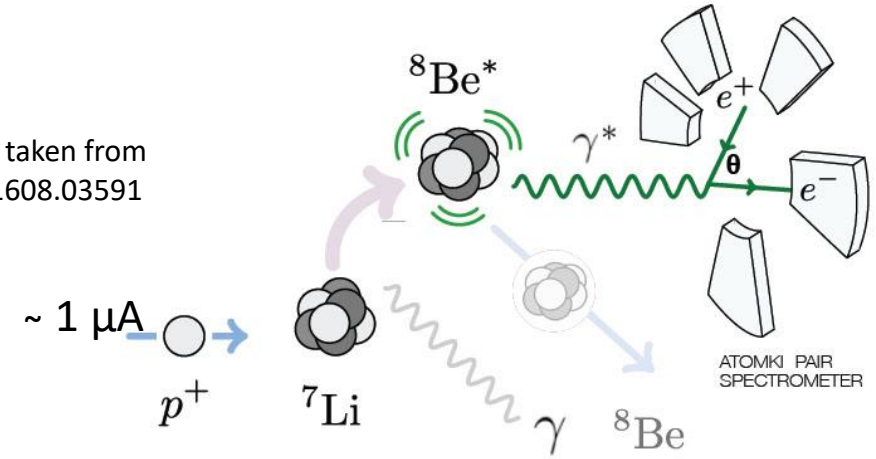


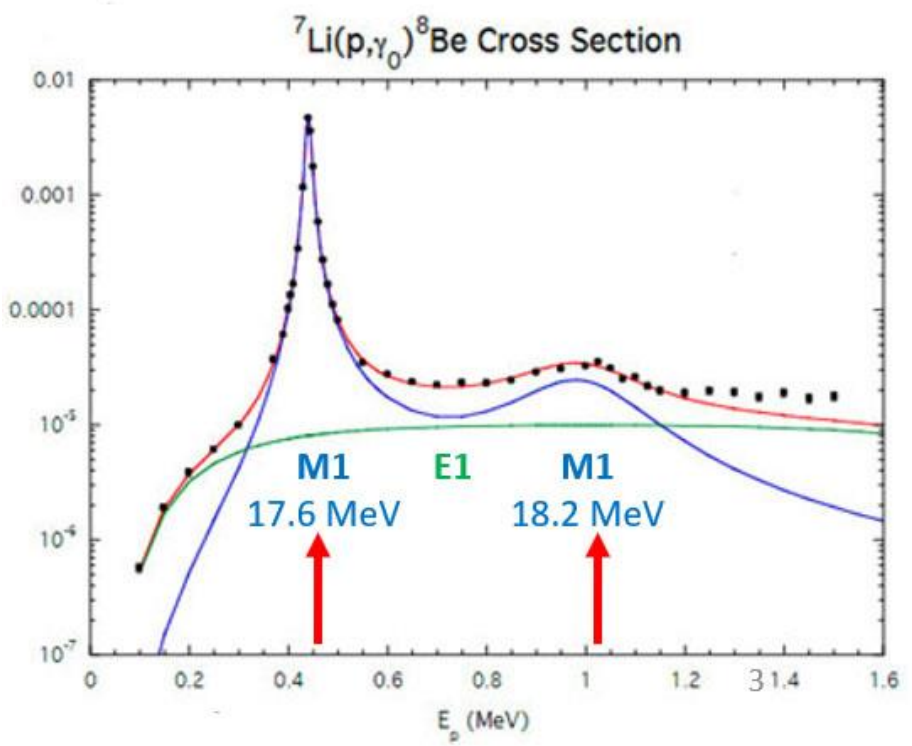
A 7σ Evidence for a New 17 MeV Boson?



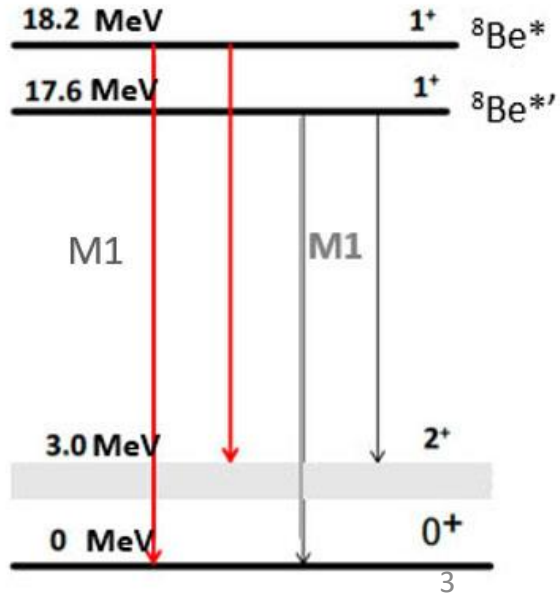
The ATOMKI Experiment!

Figure taken from
arxiv:1608.03591





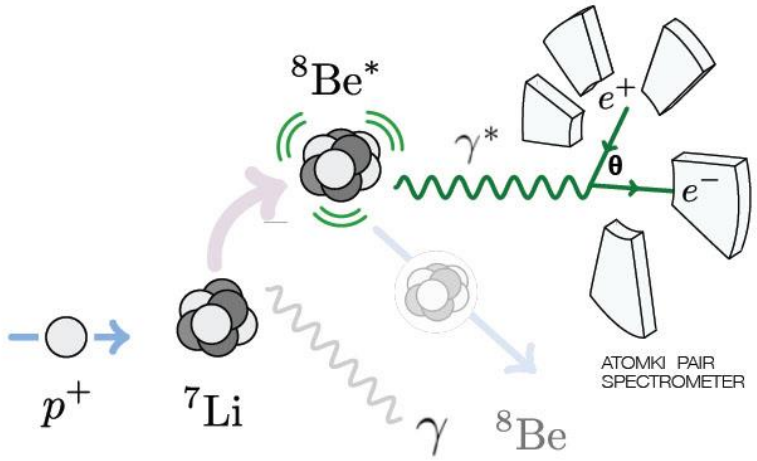
- Photo-production in ^{8}Be* via p +^{7}Li - reaction with high statistics
- Fraction of γ's converted into e^+e^- by Internal Pair Conversion (IPC)
- Measure angular distribution of e^+e^- pairs
- Photons produced on-resonance (M1) & by direct rad. capture (**E1**)

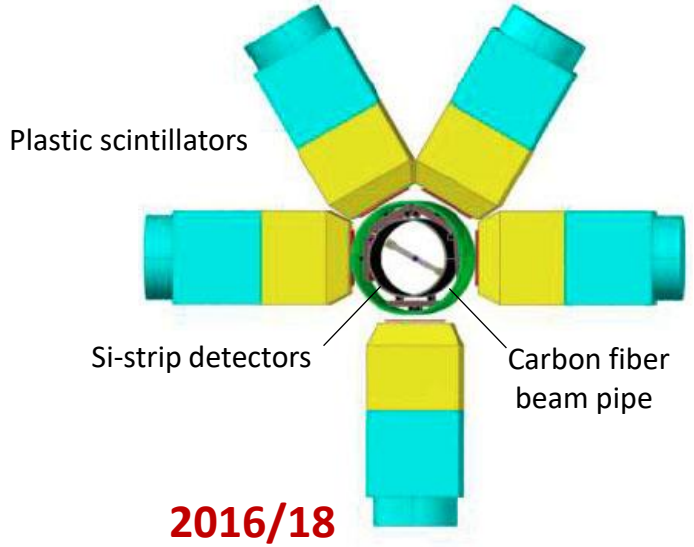


(Graphics J. Feng et al; arxiv:1707.09749)

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501, arXiv:1504.01527 [nucl-ex].

The ATOMKI Experiment!





2016/18

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ATOMKI @ Institute for Nuclear Research, Debrecen, Hungary
2MV Tandetron

(Graphics J. Feng et al; arxiv:1707.09749)

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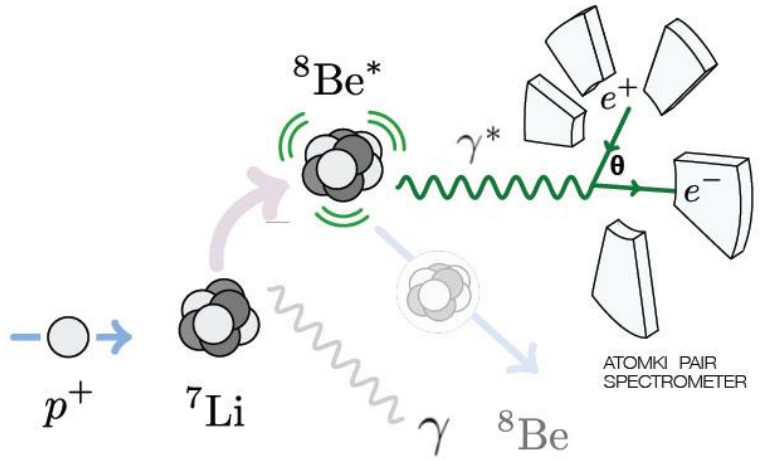

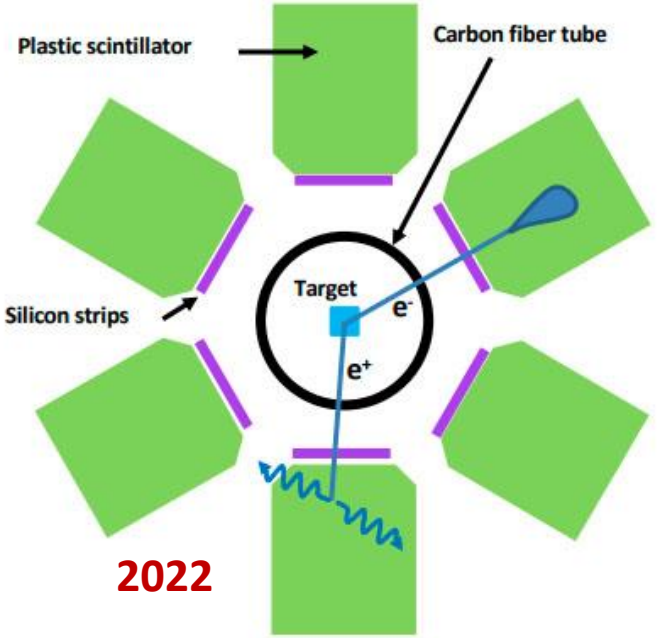

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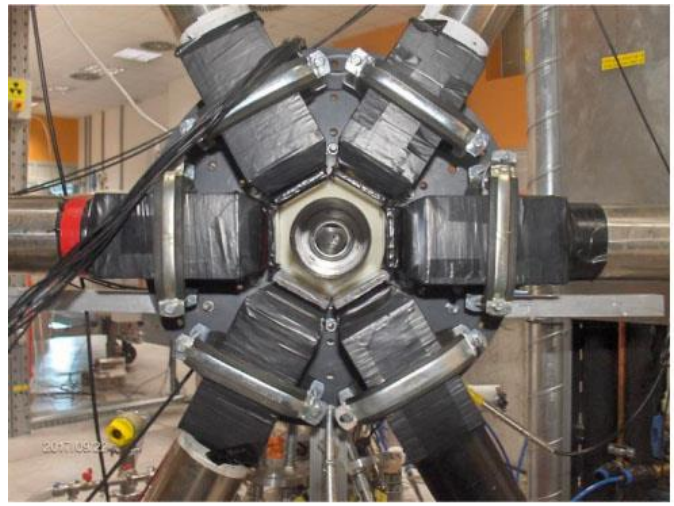

ATOMKI @ Institute for Nuclear Research, Debrecen, Hungary
2MV Tandetron

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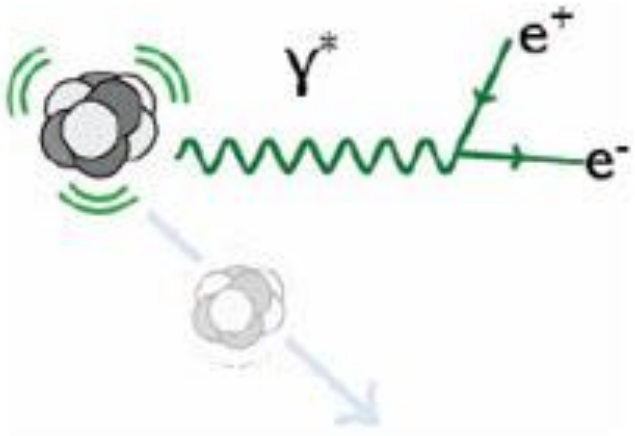
A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501, arXiv:1504.01527 [nucl-ex].

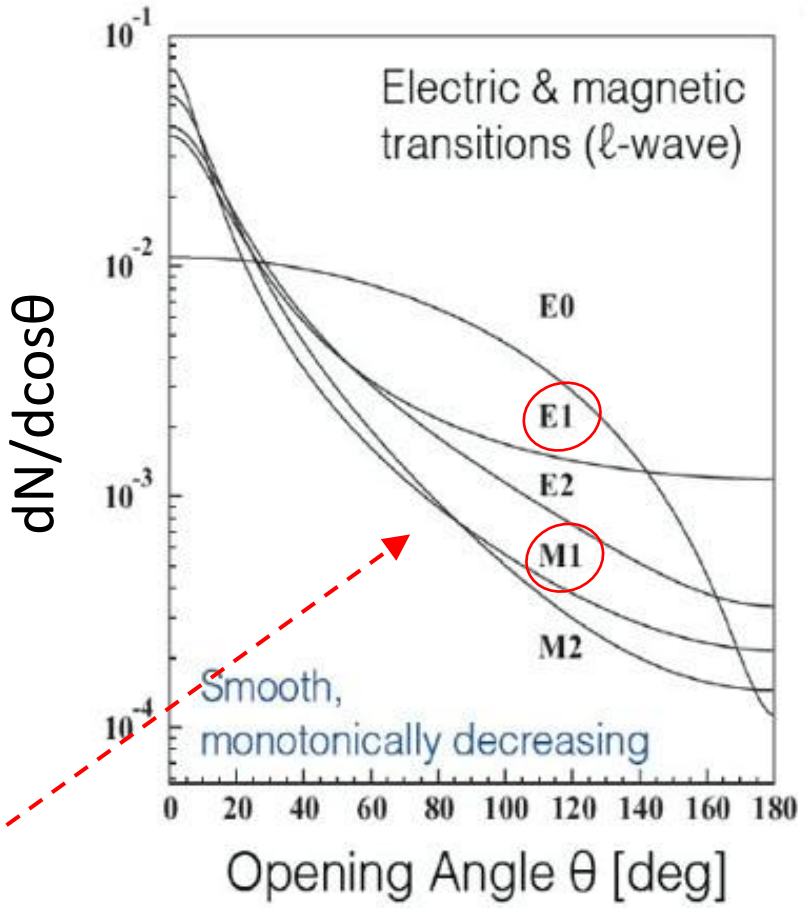
$^{8}Be^{*}$ - Decay and Internal Pair Creation (IPC)



- IPC - Branching ratio:

$$\frac{\Gamma[Be^{*} \rightarrow e^{+}e^{-}]}{\Gamma[(Be^{*} \rightarrow \gamma]} \approx \frac{\alpha}{\pi} \approx 4 \times 10^{-3}$$

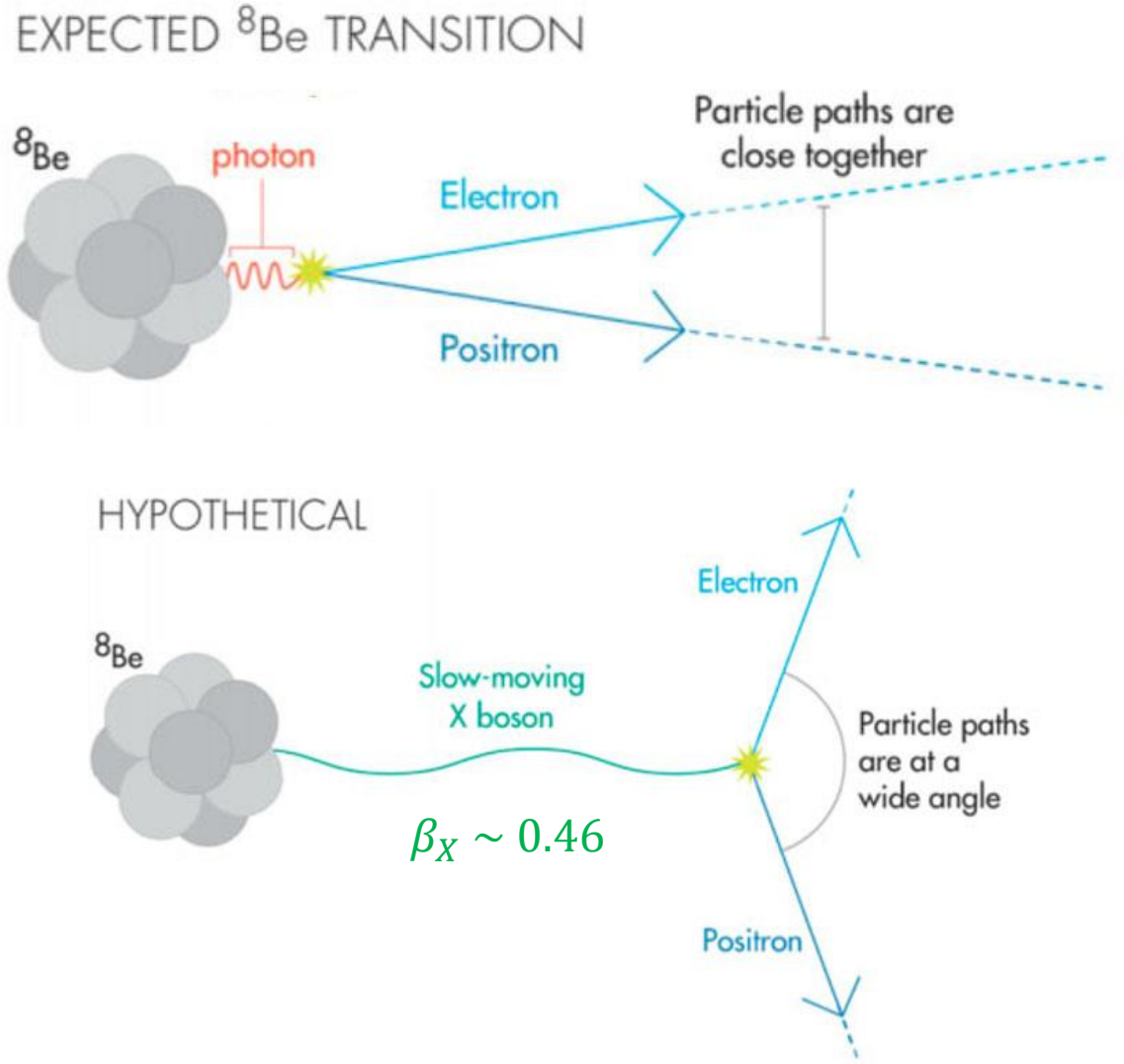
- dN/dcosθ decreases steadily with increasing θ



Gulyas et al.; http://arxiv.org/abs/1504.00489v1

M.E. Rose, PR 76.678 (1949)

^{8}Be* - A Particle Physics Lab ?

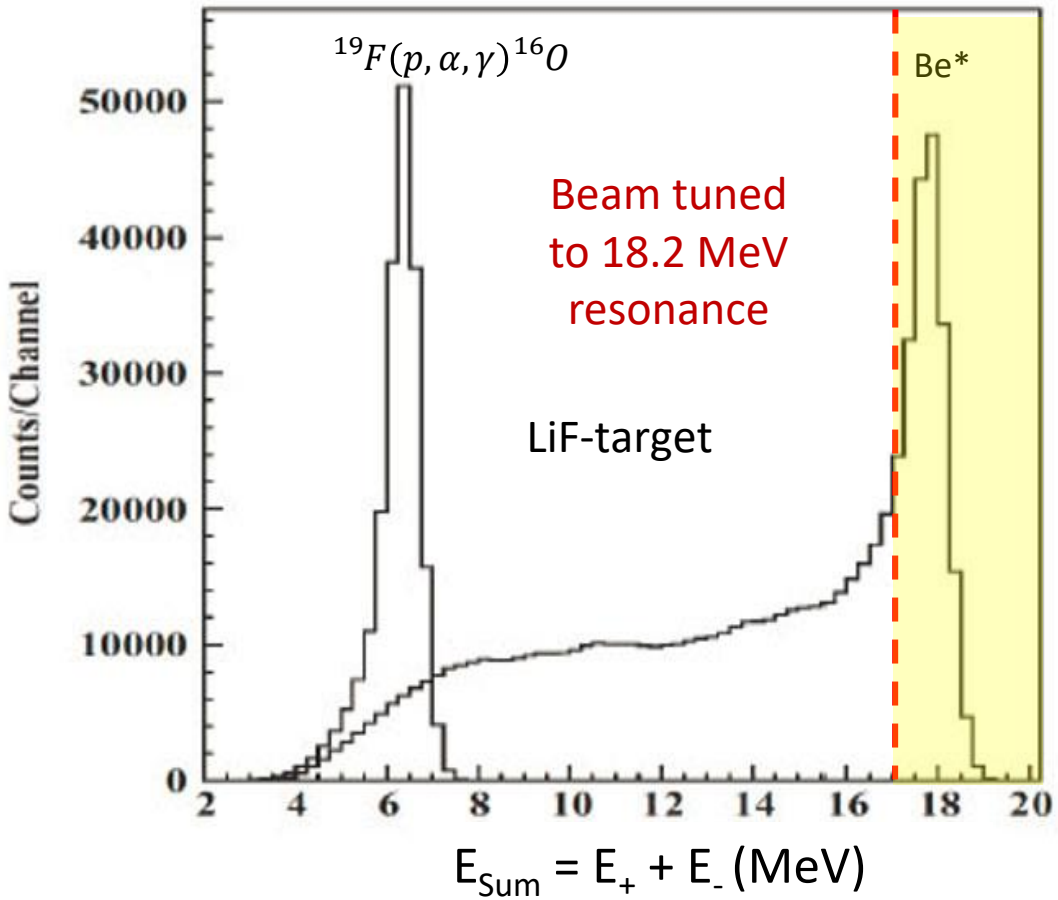


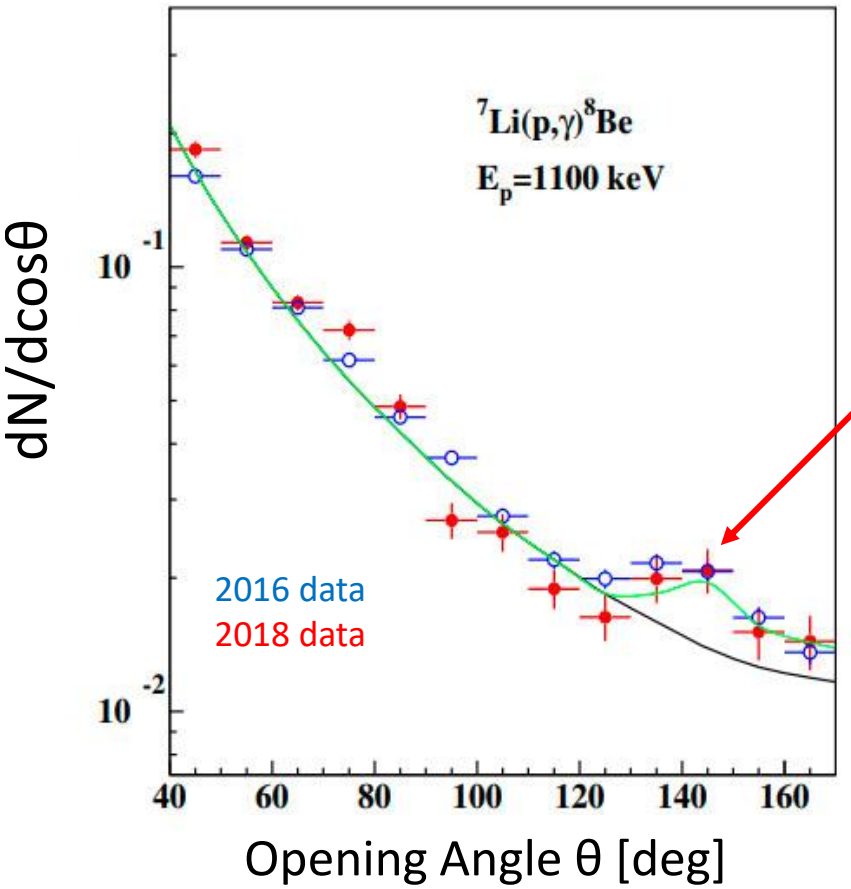
Promising environment to search for new physics at MeV-scale !

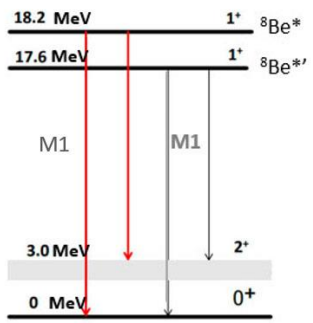
….complementary to accelerator and astroparticle searches

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501
A. J. Krasznahorkay et al.; Acta Physica Polonica B, Vol.50 (2019)

The ATOMKI ^{8}Be* - Experiment 2016/18







The Anomaly!

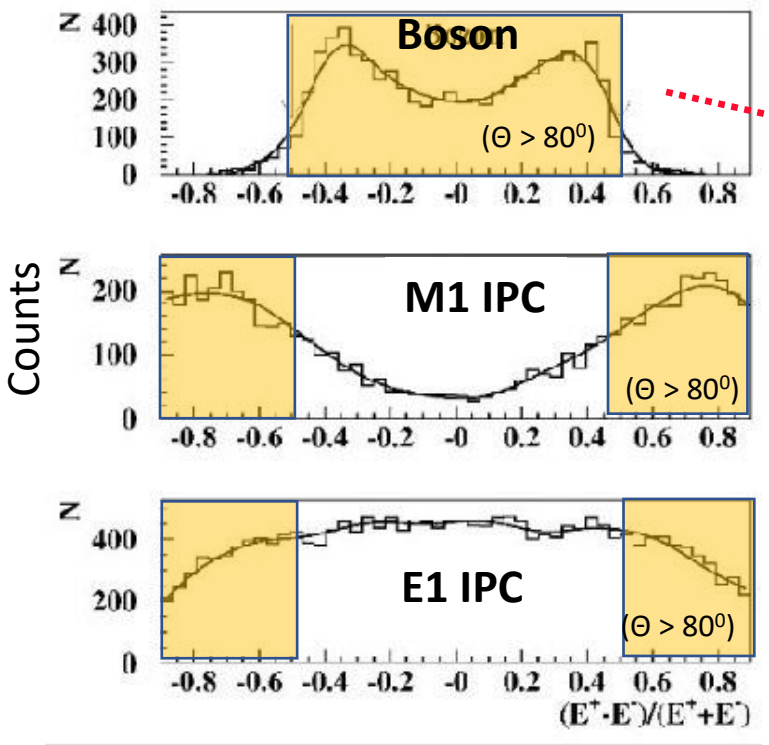
$$\frac{\Gamma(^{8}Be \rightarrow {}^{8}Be\,X)}{\Gamma(^{8}Be \rightarrow {}^{8}Be\,\gamma)} = 5.6 \times 10^{-6}$$

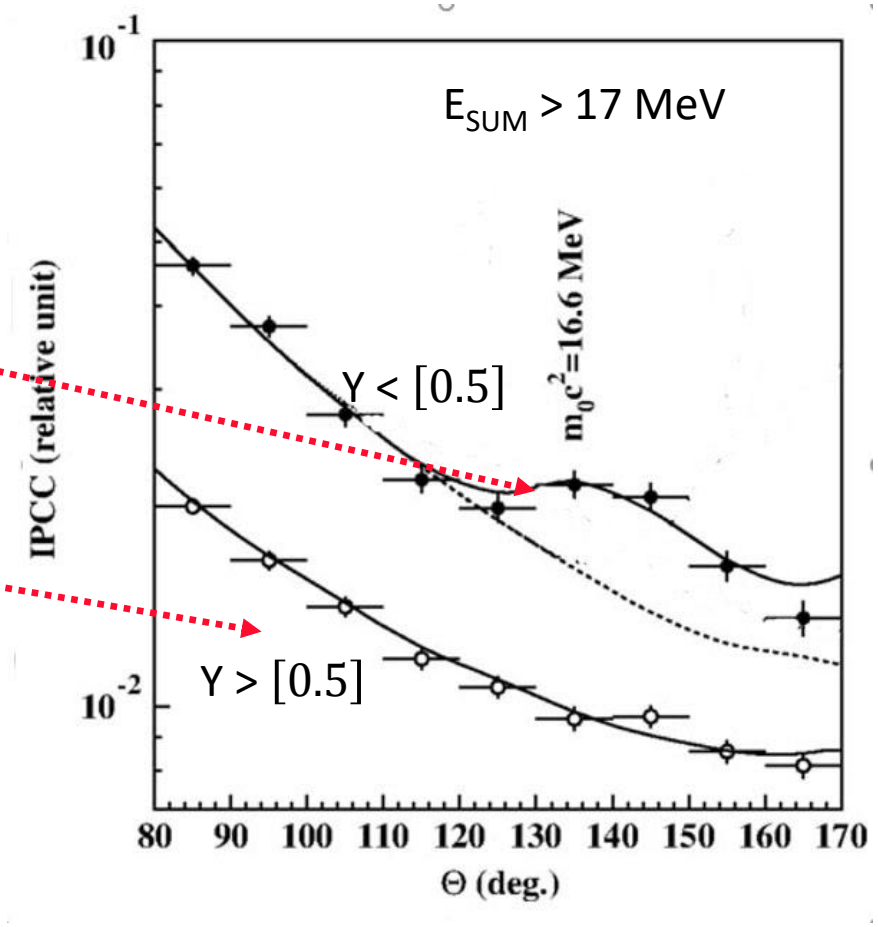
Scale of coupling ε ~ 10^{-3} times electric → BSM !

The ATOMKI ^{8}Be* - Experiment 2016/18

An important variable: the energy asymmetry

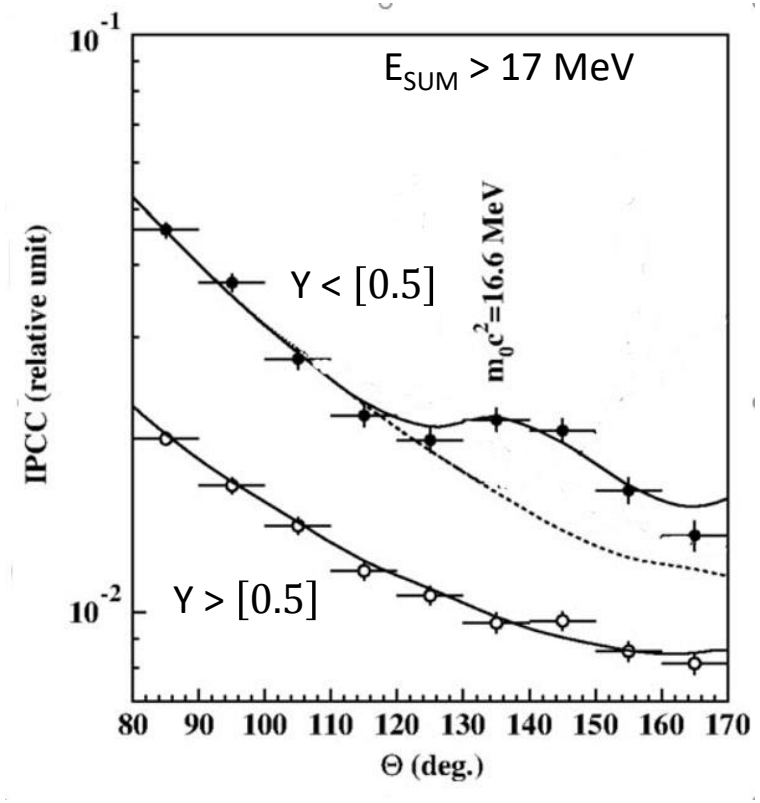
$$y = \frac{E^+ - E^-}{E^+ + E^-}$$

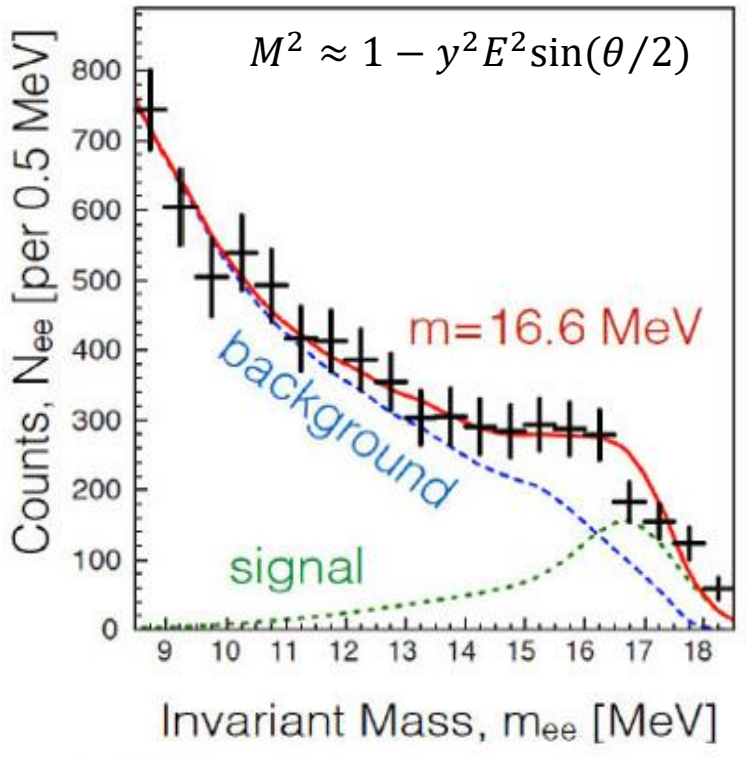




Asymmetry consistent with the decay of a new particle

The ATOMKI ^{8}Be* - Experiment 2016/18



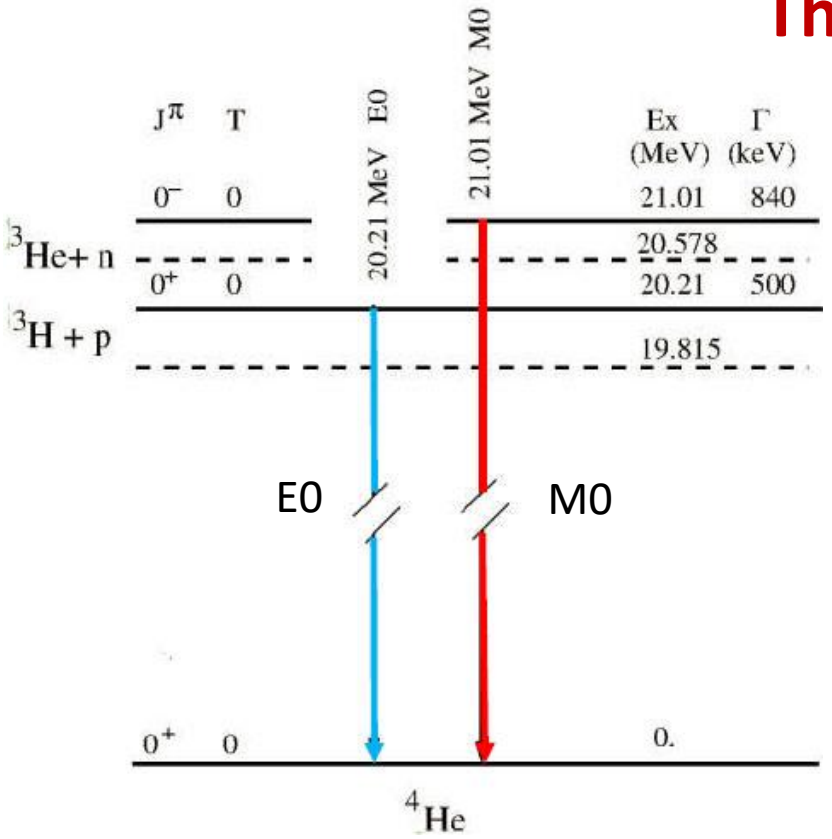


Opening angle, asymmetry and invariant mass consistent with decay of a new particle

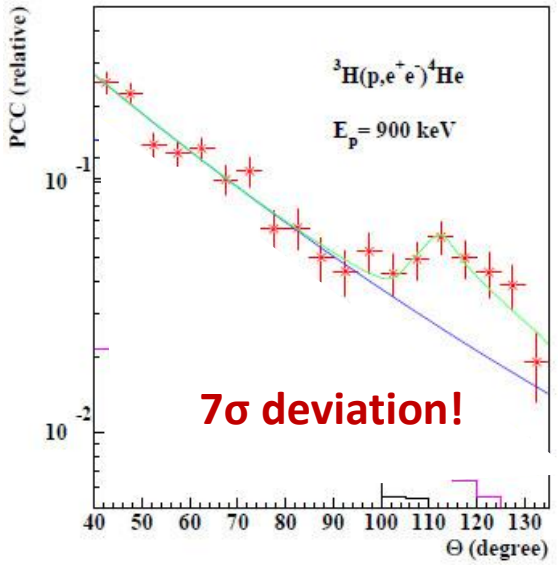
M_X = 16.7 ± 0.35 (stat) ± 0.5 (sys) MeV

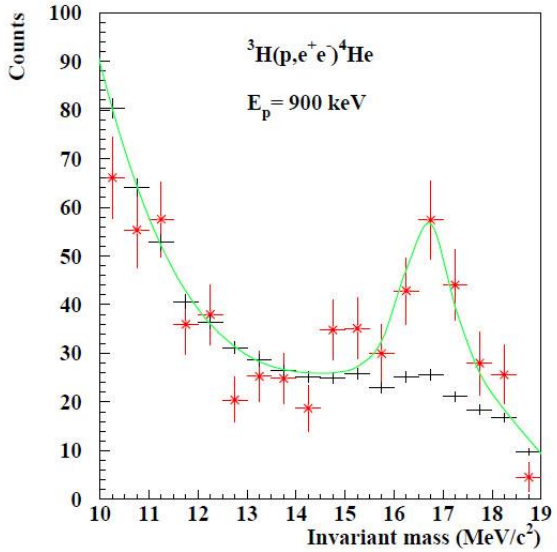
A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501

The ATOMKI ^{4}He* - Experiment 2019/21



Capture via: $p + {}^3H \rightarrow {}^4He^*$
into overlapping 0^+ & 0^- states





Opening angle and invariant mass consistent with decay of new particle as in Be*

M_X = 16.98 ± 0.16 (stat) ± 0.2 (sys) MeV

A. J. Krasznahorkay et al., arXiv:1910.10459v1

….what Particle could it be ? (…as of 2019)

Excited state

Ground state Ang mom. fin. state X - spin

$$J_* = J_{GS} \oplus L \oplus J_X$$

$$P_* = (-1)^L P_{GS} P_X$$

$$J_{GS} = 0$$

$$P_{GS} = +1$$

$$J_* = L \oplus J_X$$

$$P_* = (-1)^L P_X$$

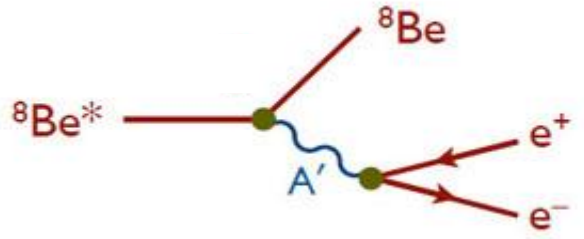
Transition	Vector $(J_X^\pi = 1^-)$	Axial vector $(J_X^\pi = 1^+)$	Scalar $(J_X^\pi = 0^+)$	Pseudo scalar $(J_X^\pi = 0^-)$
^{8}Be: 1^+ 0^+ M1-IS	L=1	L=0,2		L=1
^{8}Be: 1^+ 0^+ M1-IV	L=1	L=0,2		L=1
^{4}He: 0^- 0^+ M0		L=1		L=0
^{4}He: 0^+ 0^+ E0	L=1		L=0	

PS (0^-) difficult to reconcile w. Be & He

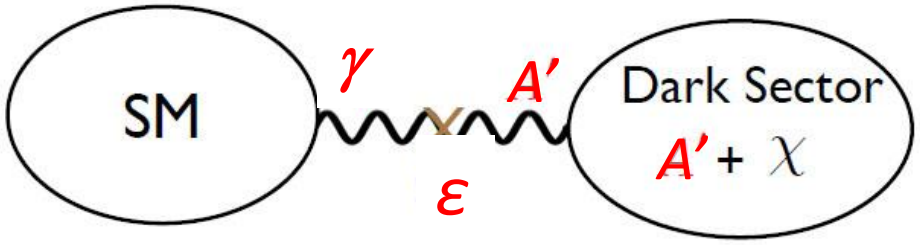
J. L. Feng, et al, *Phys.* arXiv:2006.01151 [hep-ph].

….but X17 with $J^\pi = 1^{+/-}$ could fit the bill !

Maybe a Dark Photon *A'* ($J^{\pi} = 1^{-}$) ?

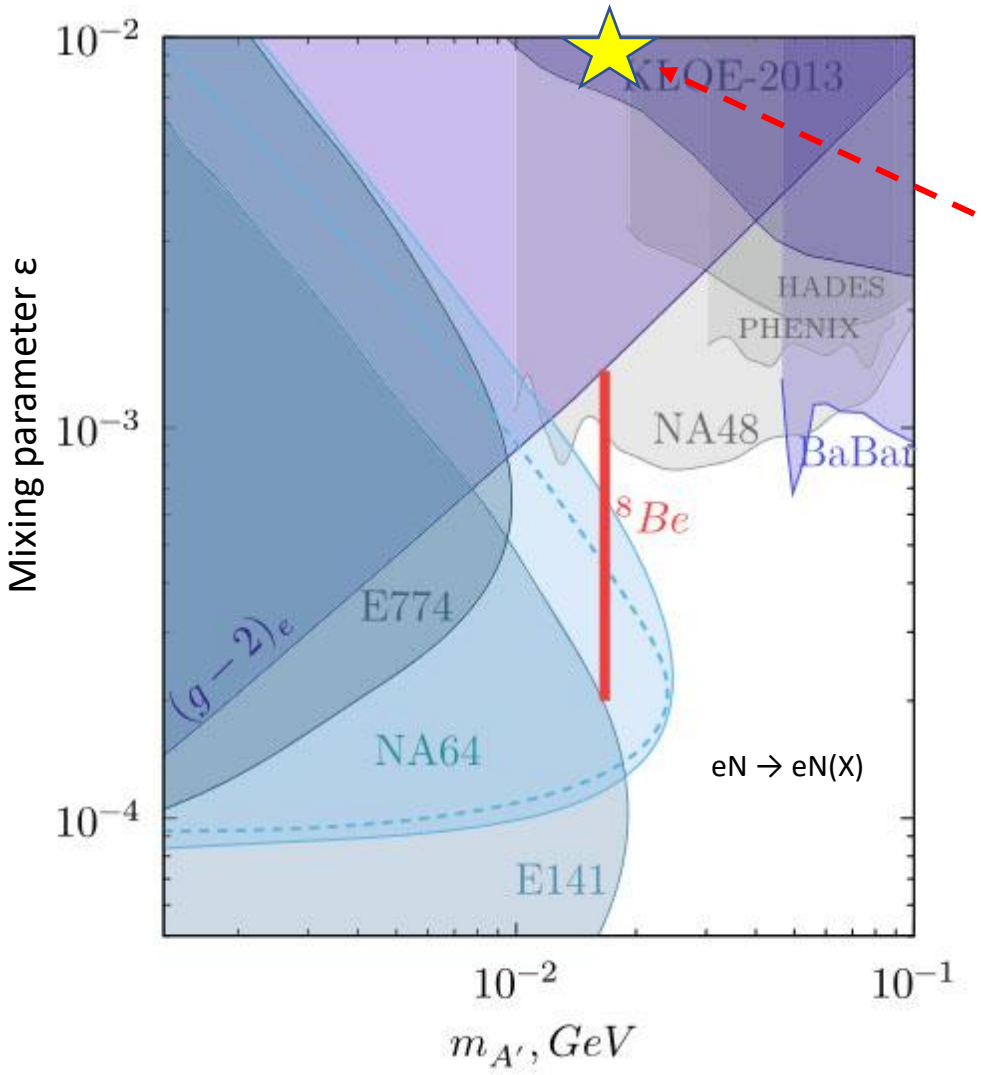


- Interaction with ord. matter mediated by "dark " *A'*
- Gauge boson *A'* mixes kinetically with γ and $\varepsilon \sim 10^{-3}$
- *A'* coupling to SM – particles prop. to ε and SM charges: $\varepsilon e Q_f$
- Vector mediator decays to low mass WIMPs



But…..

But ….it cannot be the Standard Dark Photon



To get the right signal strength in Be/He:

$$|\varepsilon_u + \varepsilon_d| \approx 3.7 \cdot 10^{-3}$$

$$\varepsilon_f = \varepsilon e q_f$$

A' coupling to SM: $\varepsilon \approx 0.01$

"milli-charged" coupling!

…but this is excluded by bounds especially from $\pi^0 \to A'\gamma \to \gamma e^+ e^-$ NA48/2

…so this cannot be a "conventional" dark photon

J. L. Feng, et al, *Phys.* arXiv:2006.01151 [hep-ph].

Na64 Eur. Phys. J. C (2020) 80:1159

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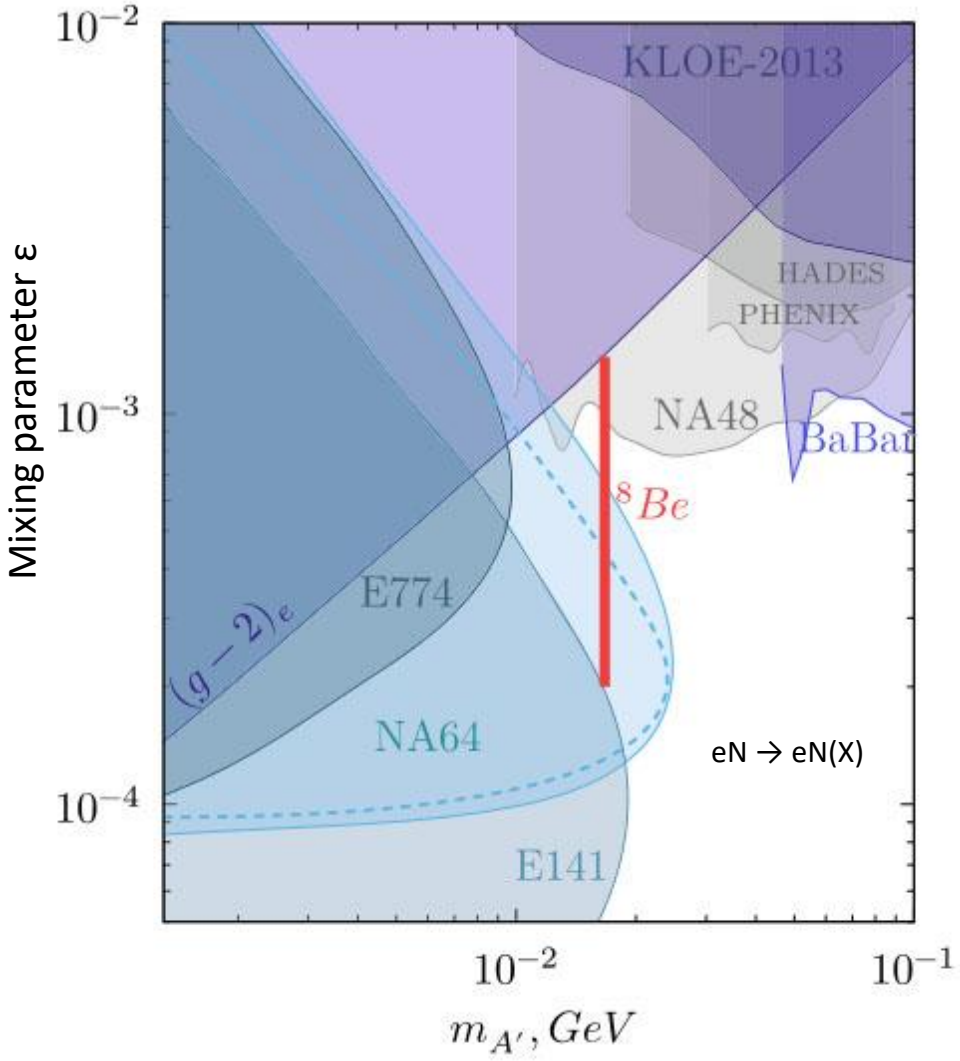
J. L. Feng, et al, *Phys.* arXiv:2006.01151 [hep-ph].



Na64 Eur. Phys. J. C (2020) 80:1159

The anomaly in Be & He can be explained by a "proto-phobic" vector gauge boson with:

Hadronic couplings:

$\varepsilon_u \approx \pm 3.7 \times 10^{-3}$

$\varepsilon_d \approx \mp 7.4 \times 10^{-3}$

$\boldsymbol{\varepsilon_d \approx -2 \times \varepsilon_u}$

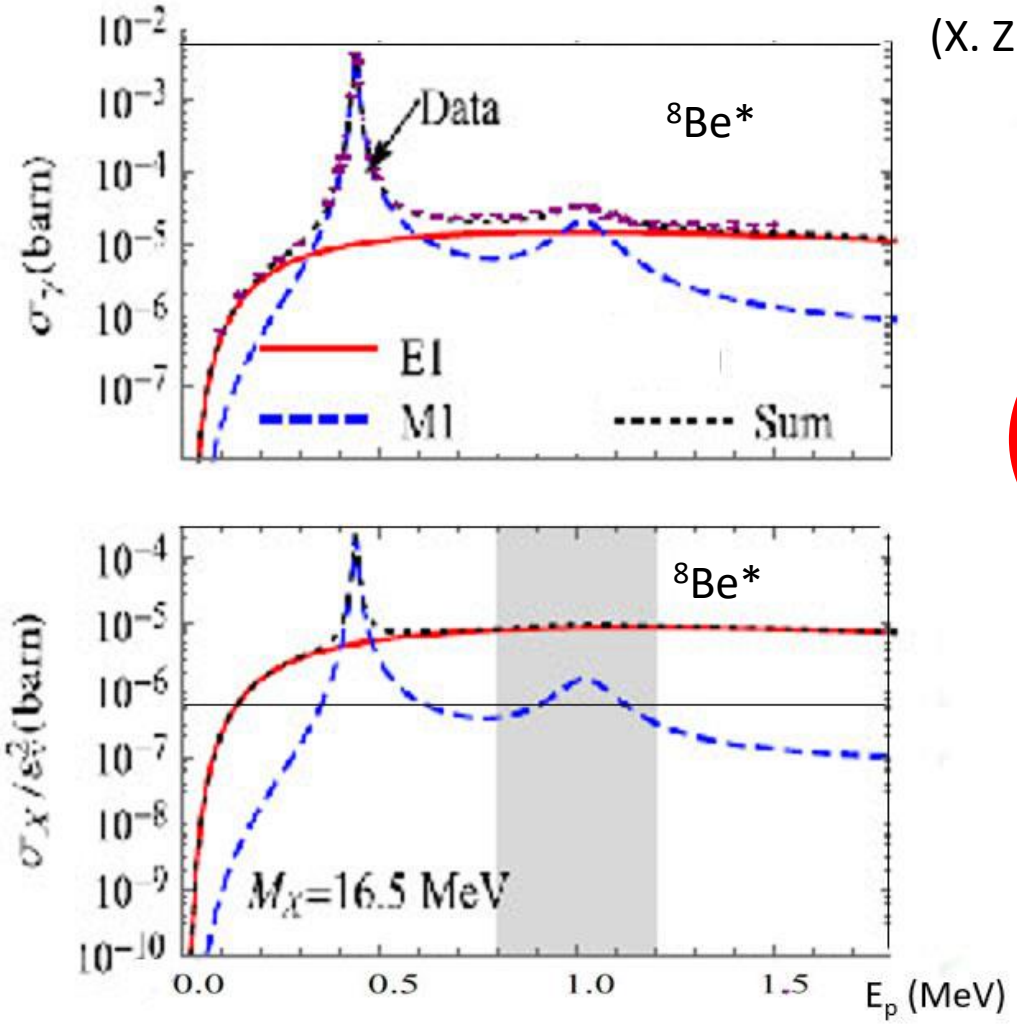
Range ≈ 12 fm → Looks like a force!

Proto-phobic: $\left|\frac{\varepsilon_p}{\varepsilon_n}\right| < 8\%$

J. L. Feng, *Phys. Rev.* **D95** no. 3, (2017) 035017, arXiv:1608.03591 [hep-ph].

But….More Theoretical Insight (2021 +)

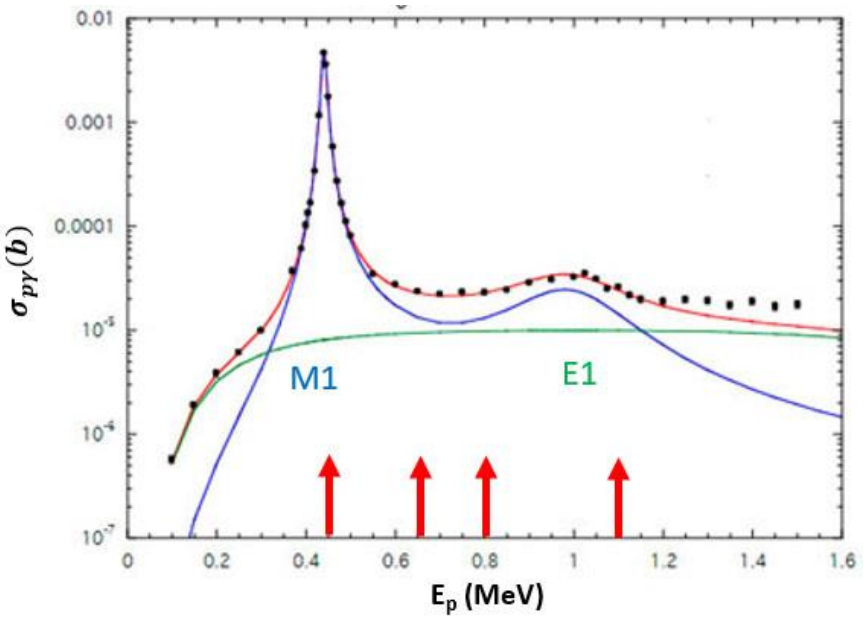
(X. Zhang, G.A. Miller - Physics Letters B 813 136061 (2021))



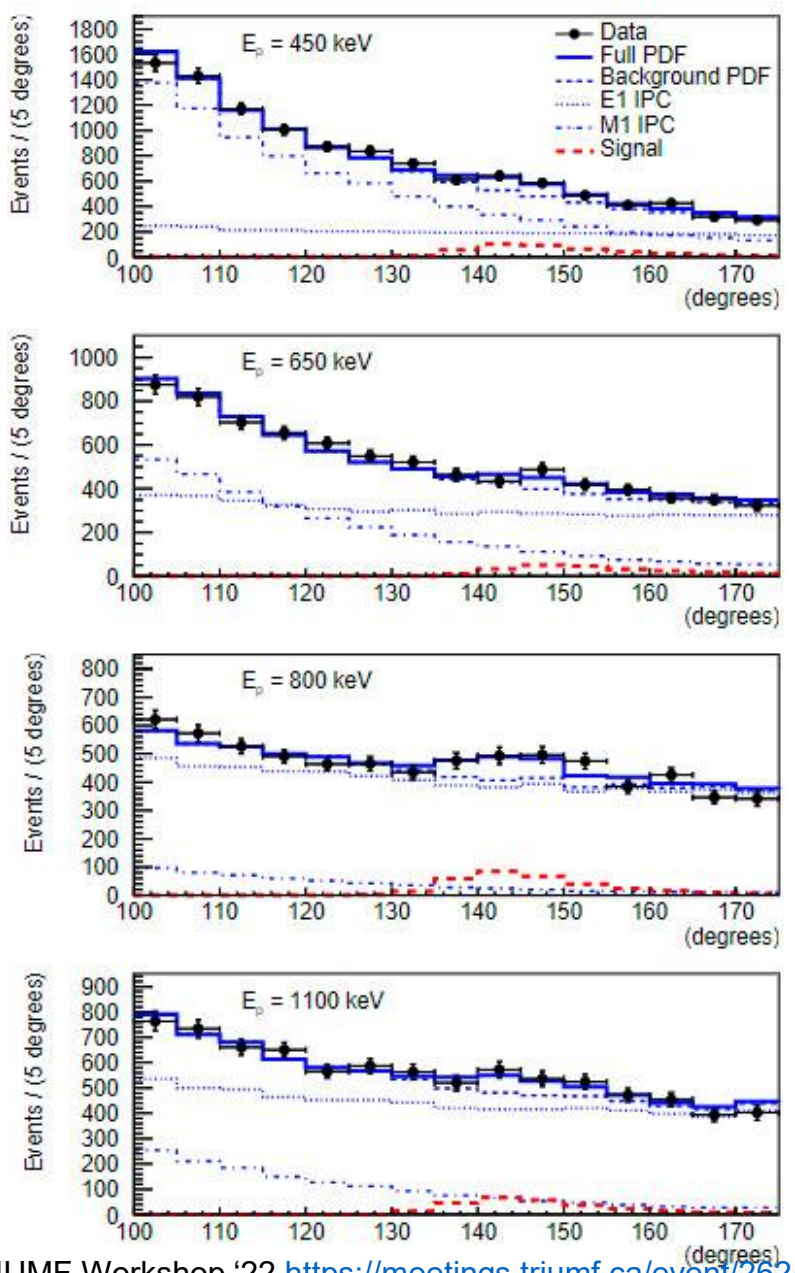
If X17 protophobic, then its production in Be should be dominated by direct capture E1 transitions for all beam energies above the 17.6 MeV resonance!

Check X17 production off- Resonance!

ATOMKI ^{8}Be* Off - Resonance Results (2022)



Protons @ 450, 650, 800, 1100 keV



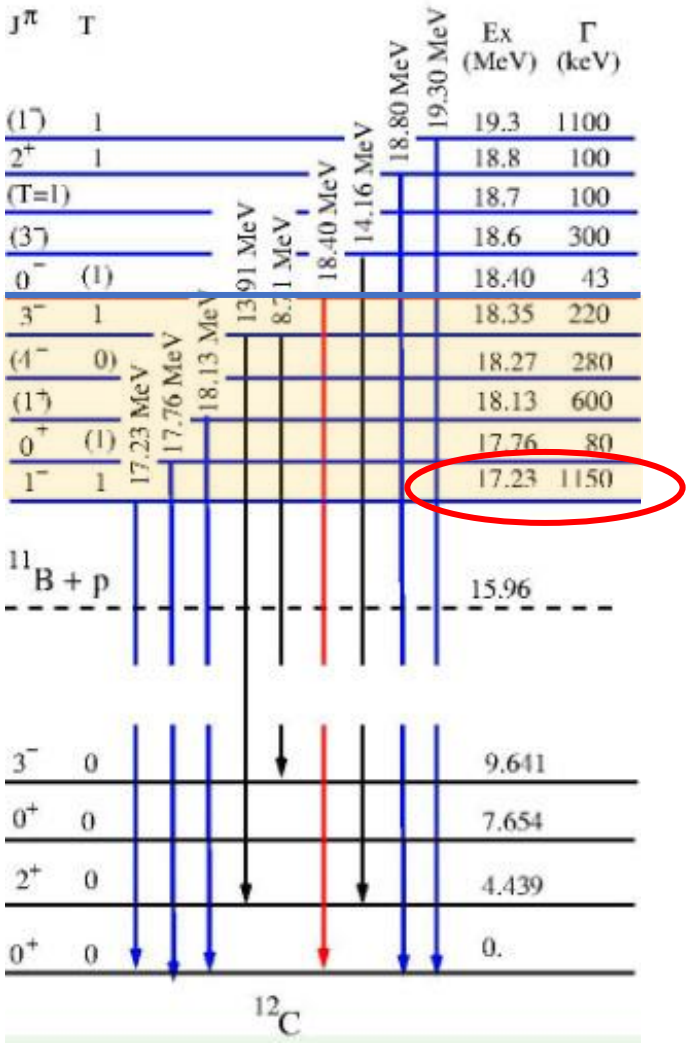
- Peaks around 140^0 correlate w. E1 contribution, rather not w. M1
- Inv. mass around 17 MeV/c^2

X17: protophobic V/AV boson?

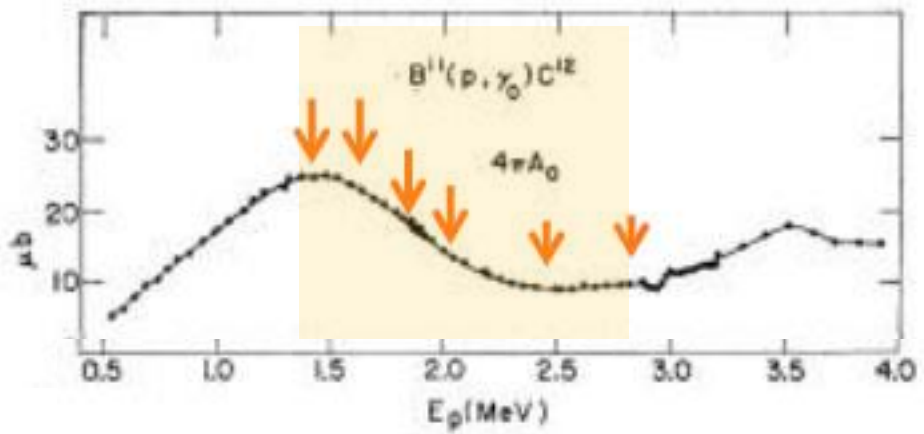
N.J. Sas et al. arXiv: 2205.07744 A. J. Krasznahorkay, TRIUMF Workshop '22 https://meetings.triumf.ca/event/262/timetable/#20220525and

ATOMKI $^{11}B(p,e^+e^-)^{12}C^*$ (2022)

Suggested by J. Feng et al., Phys. Rev. D102, 036016 (2020)

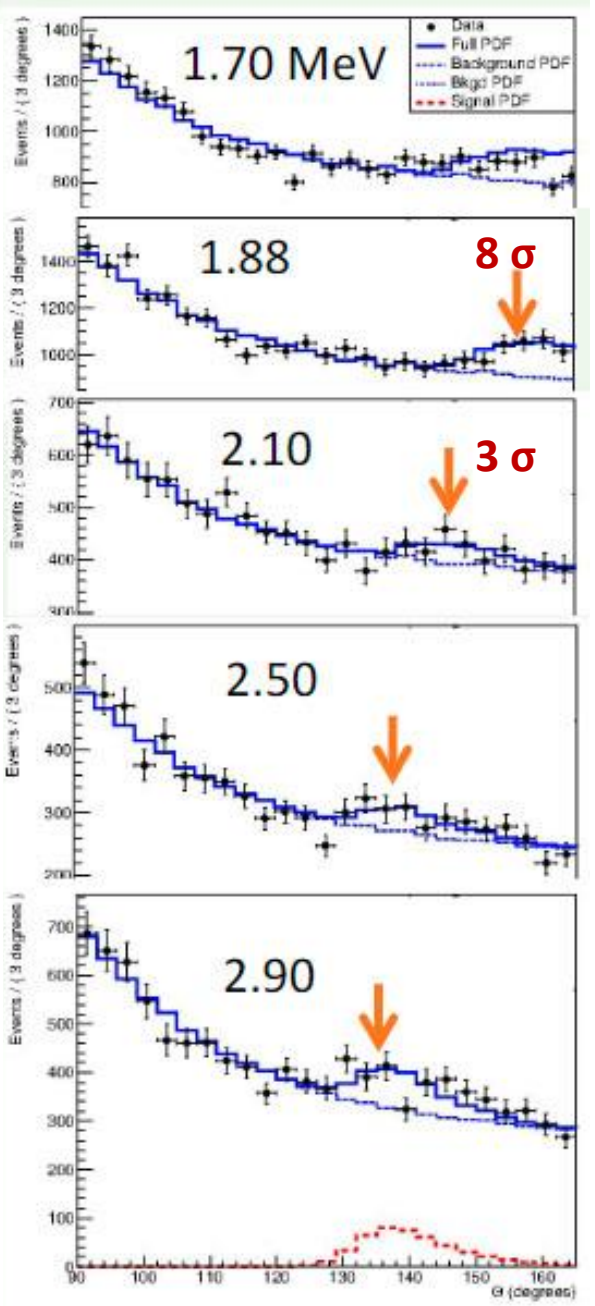


E1 IPC following radiative capture



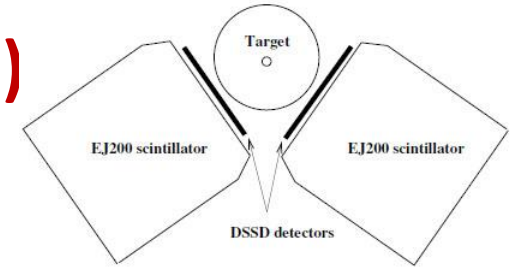
X17 branching ratio relative to E1 contribution appears constant !

Average mass 16.88 ± 0.15 MeV
…PS (0^-) ruled out

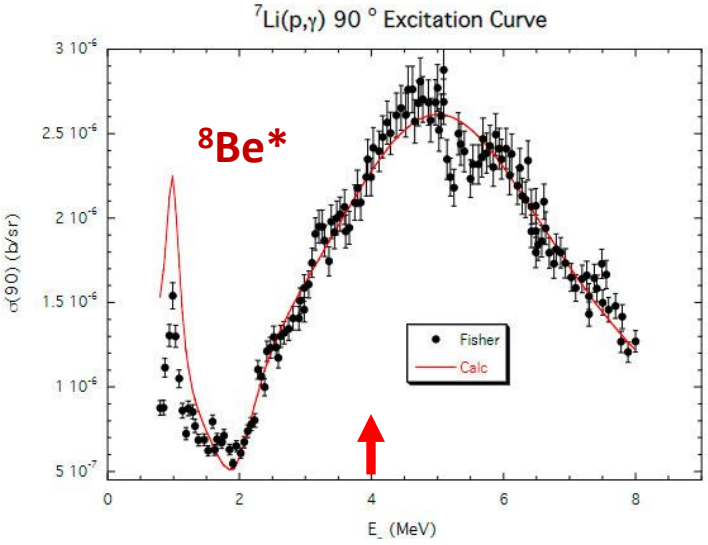


A.J. Krasznahorkay, TRIUMF Workshop '22 https://meetings.triumf.ca/event/262/timetable/#20220525
A. J.Krasznahorkay et al; Arxiv 2205.7744

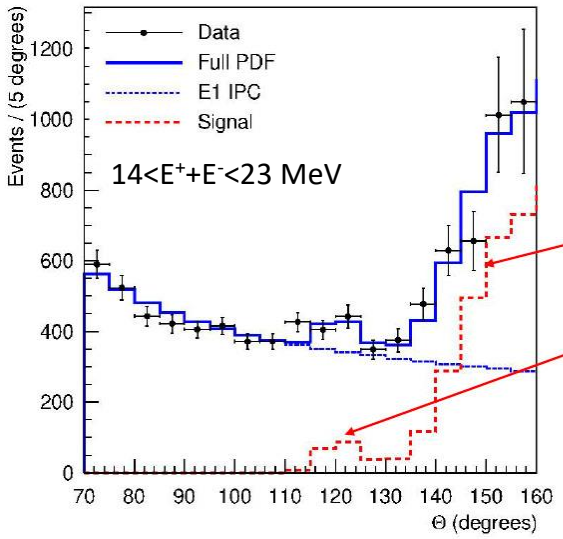
ATOMKI ^{8}Be* Giant E1 - Dipole Resonance* (2023)

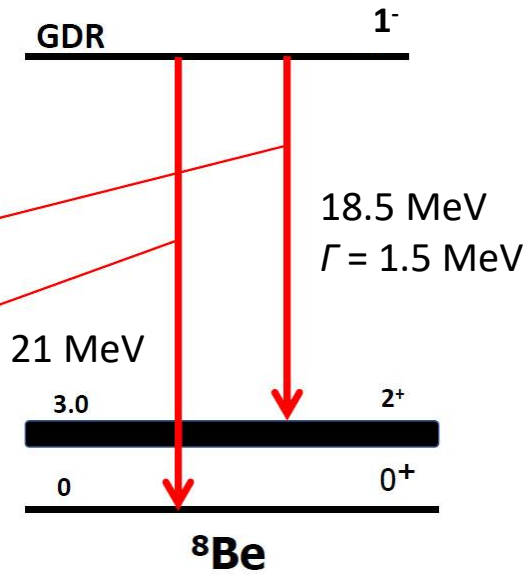


A.J. Krasznahorkay et al. https://arxiv.org/abs/2308.06473



- GDR's are coll. oscillations of protons against neutrons (C. Baldwin, '47)
- GDR excited by proton S-wave capture into ^{8}Be* → decay by E1 – γ's
- Excited at E_p = 4 MeV
- X17 observed in transition to GS and 1st excited state





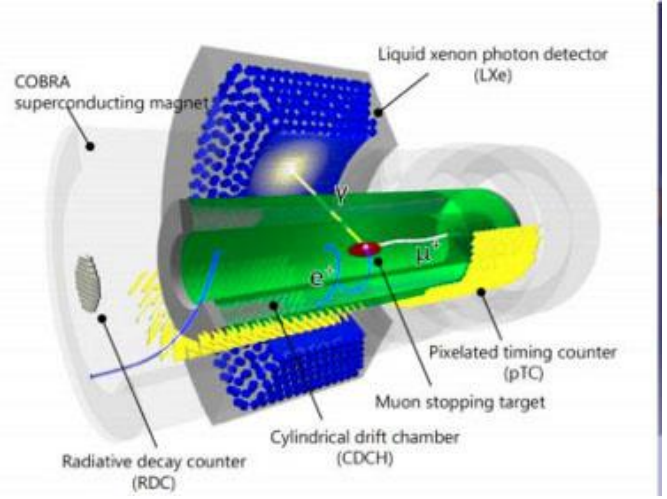
M_X = 16.95 ± 0.48 (stat.) MeV/c^2

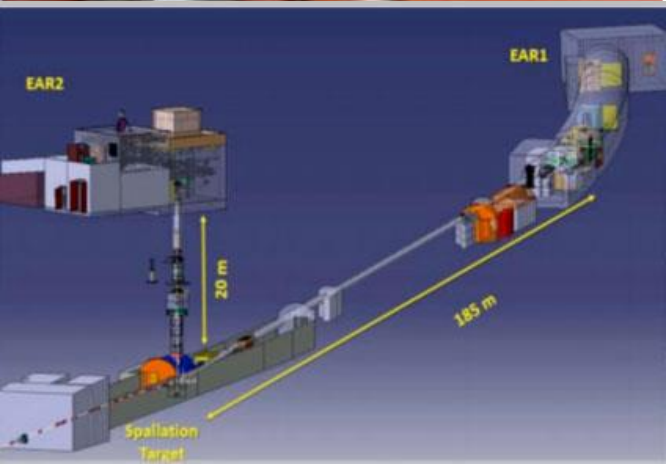
….independent verifications needed !

A.C. Hayes et al – https://arxiv.org/abs/2106.06834 (June 2021) X. Zhang, G.A. Miller – Phys. L. B 813 136061 (2021))

Other Ongoing Efforts

Nuclear physics verifications





MEGII @PSI
$^{7}Li(p,X17)\ ^{8}Be$
MeV Cockroft Walton
Tracking DCH, LXe
Disfav. @ 1.5 σ

X17 @ LNL INFN Legnaro
$^{7}Li(p,X17)\ ^{8}Be$
AN2000 2.5 MV
4 – plastic scint. telescopes
Taking data

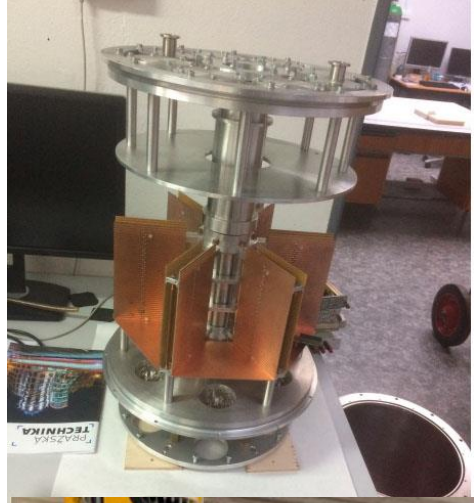
N_Tof @ CERN
$^{3}He(n,X17)\ ^{4}He$
Pulsed n- beam
Dedicated detector

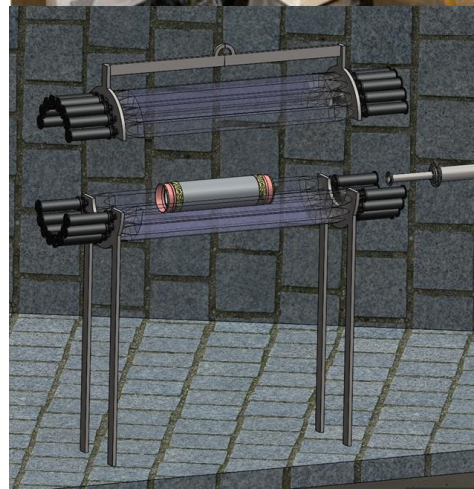
VNU @Hanoi
$^{7}Li(p,X17)\ ^{8}Be$
2-arm spectrometer
4σ effect off resonance
M_X = 16.66 $\pm$ 0.47 MeV/c^2
(w. ATOMKI particip. !)

COPE @ IEAP – CTU Prague
$^{7}Li(p,X17)\ ^{8}Be$
2.5 MeV Van de Graaff
Mag. spectrometer ATOMKI → IEAP
Vertexing with Timepix 3

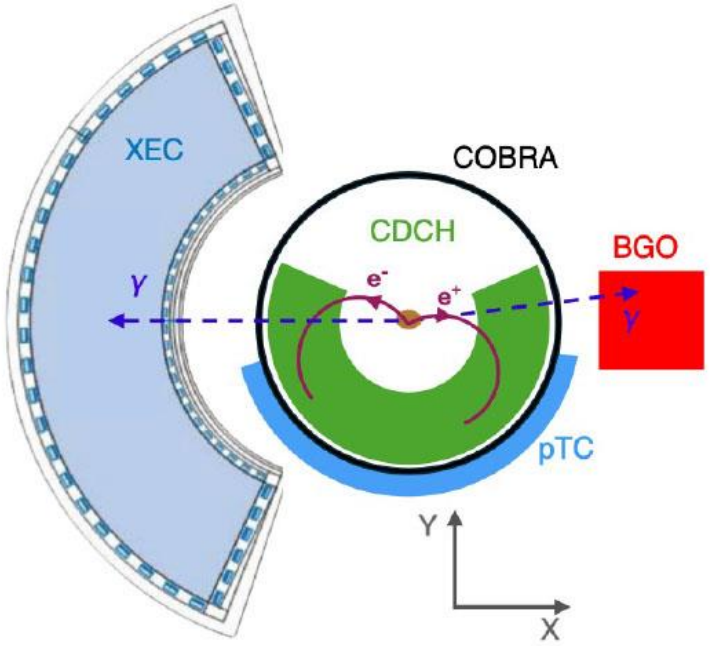
NewJedi @ IJCLab, GANIL, Ithemba
$^{7}Li(p,X17)\ ^{8}Be$; $^{3}H(p,X17)\ ^{4}He$
Vertexing w. DSSSDs;
E- plastic scints.
Ongoing

Project X17 @ U. Montreal
$^{7}Li(p,X17)\ ^{8}Be$;
$^{7}Li(\ ^{3}He,X17)^{10}B$
DAPHNE vertex chamber;
Plastic scints 0.95 4π
Ongoing



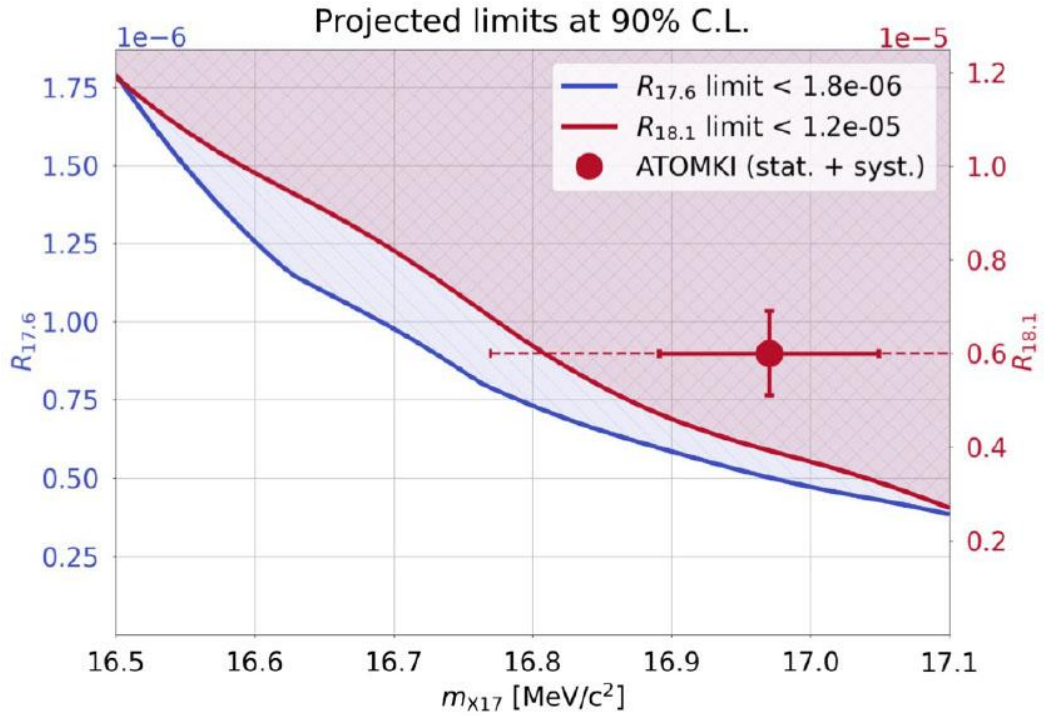


The MEG II Experiment, PSI (2023)



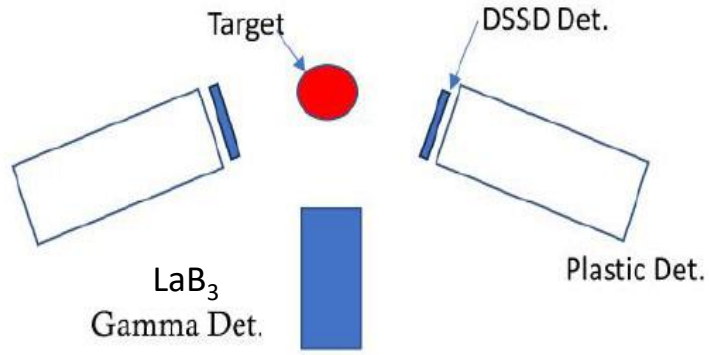
- Designed for $\mu^+ \rightarrow e^+ \gamma$
- Remeasured *Be $^7Li(p, X17)\ ^8Be$ @ 1.08 MeV Cockroft Walton
- Tracking DCH, LXe, 7 µm LIPON target
- Mixed beam H^+, H_2^+, excitation of 17.6 & 18.1 MeV resonances
- No significant signal found…but

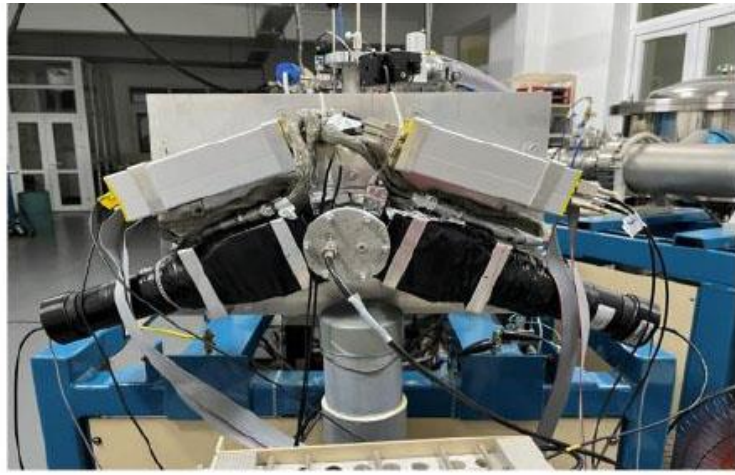
Disfavour ATOMKI at the level of 1.5 σ (p-value 6%)

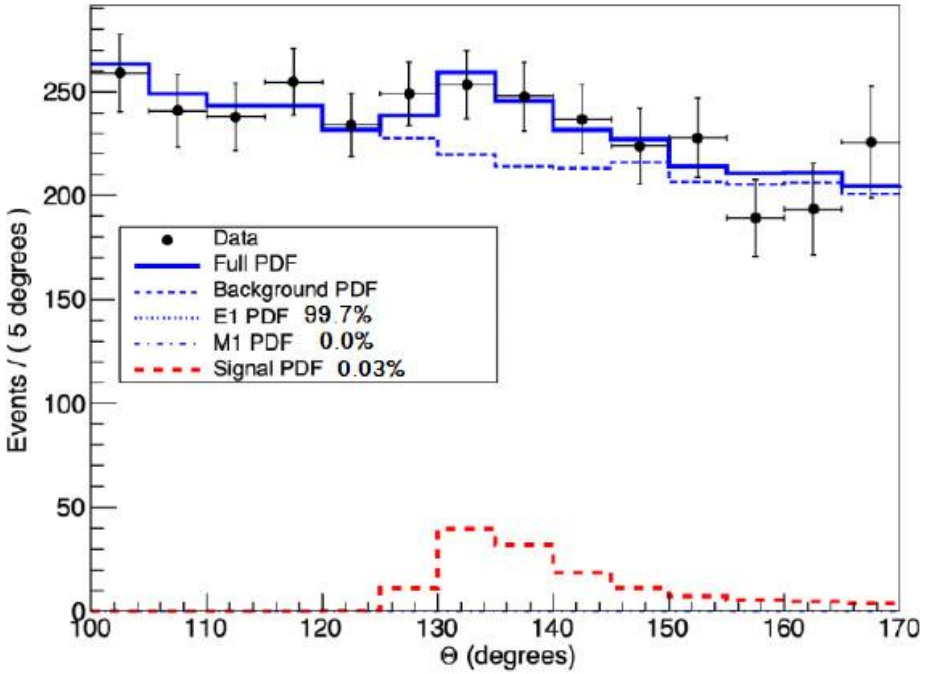


Vietnam U. of Science, Hanoi (in coll. with ATOMKI) (2023)

- 1.7 MV Tandem 1.5 μA,
- LiF & LiO_2 targets
- E_p = 441 keV no effect
- E_p = 1.225 MeV (off res.) → **4 σ effect at 140 deg.**
- X17 produced in direct p capture (E1)







$$\frac{\Gamma(IPC_{E1\to X}}{\Gamma(IPC_{E1\to e^+e^-})} = 2.8 \cdot 10^{-3}$$

$$M_x = 16.95 \pm 0.1 \pm 0.21\ \text{MeV/c}^2$$

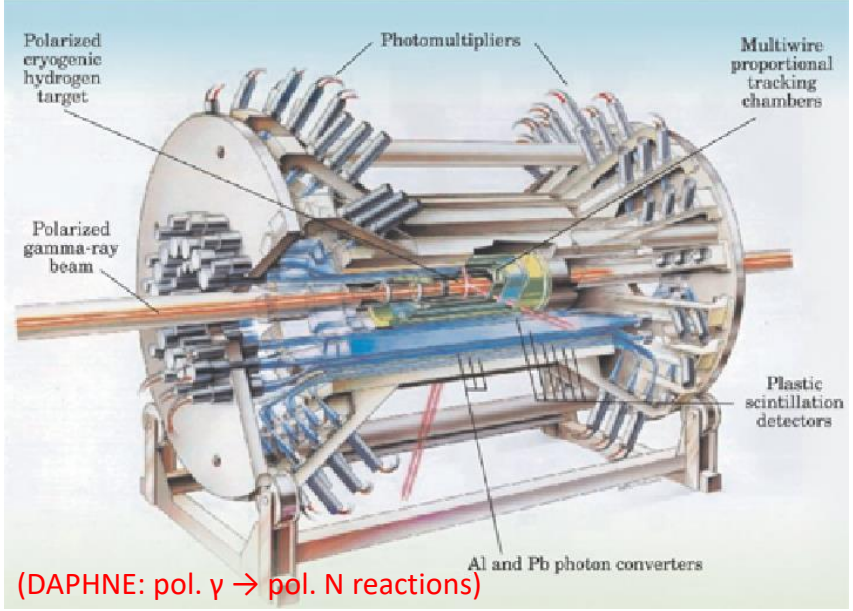
The Montreal X-17 Project

UdeM 6 MV Tandem
Van de Graaff Facility

- E - resolution of 2 Kev for E_p = 0.4 - 1 MeV
- Dedicated Beam Line for X17 – project
- 2 μA proton beam on target (possibly up to 20 μA)

The Montreal X-17 Project

- Uses parts of the DAPHNE experiment (Saclay/Mainz)
- Tracking MWPC chamber & 16 scintillators (NE102A)
- Scints & MWPC generously provided by U. Mainz (Ge)*
- Phototubes, bases and ADC/TDC's borrowed from TRIUMF*



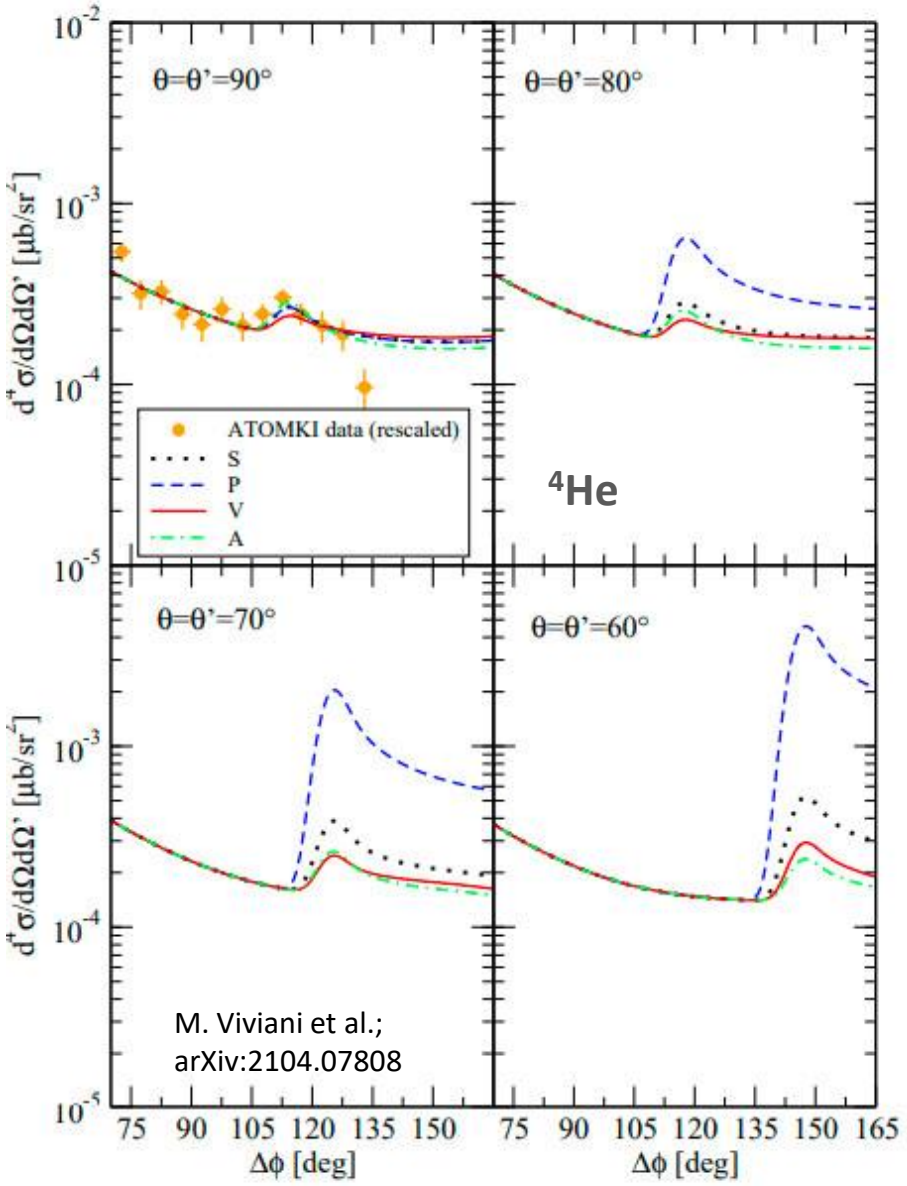
(DAPHNE: pol. γ → pol. N reactions)

*Many thanks to
L. Doria & U. Mainz
D. Bryman & TRIUMF

Large solid angle coverage: 0.95 x 4π
Angular res.: $\Delta\theta \sim 2^0$ (FWHM)

Motivation #1: Increased Angular Acceptance!

M. Viviani et al., arXiv:2104.07808v1



If X17 produced in direct E1-capture (^{8}Be, ^{4}He,^{10}B, ^{12}C..)

↓

Polar angular distribution of the e^+e^- pair depends on the X17 quantum numbers (L=0,1,2…)

↓

Large angular acceptance allows discrimination btw. different options

↓

Aim at close to 4π solid angle coverage

Motivation #2: Other nuclei!

$^{7}Li(p,\gamma)\,^{8}Be$

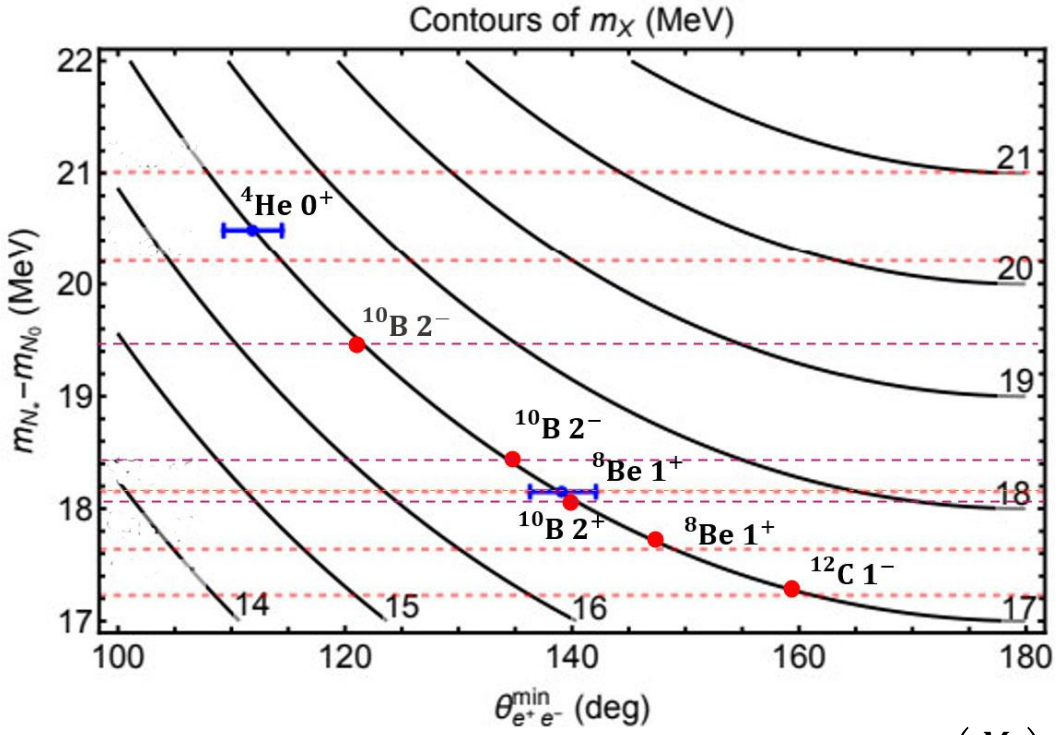
$^{11}B(p,\gamma)^{12}C$

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

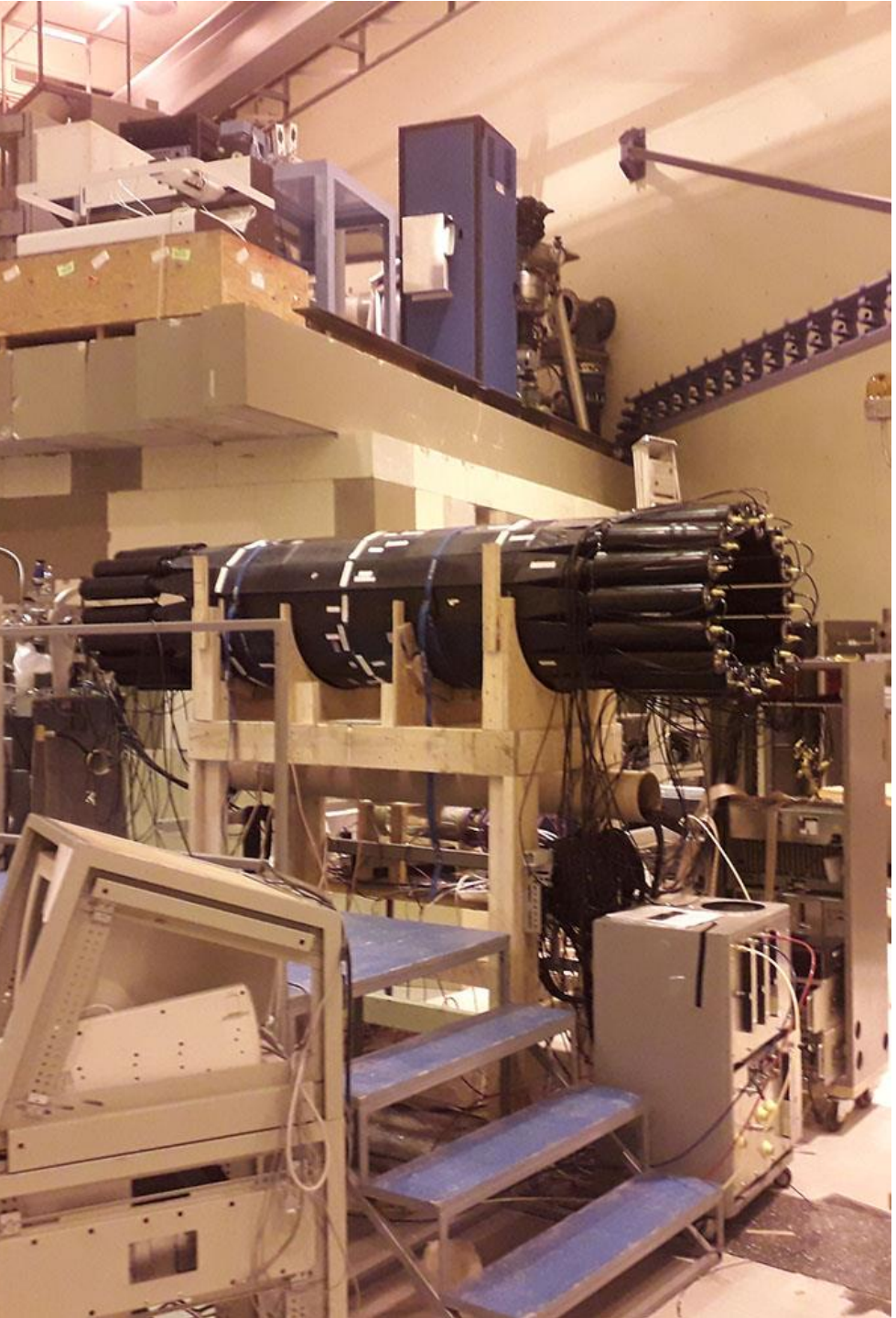
$^{7}Li(\,^{3}He,\gamma)^{10}B$

N_*	$J^{P_*}_*$	T_*	Γ_{N_*} (keV)
^{8}Be(18.15)	1^+	0	M1 IV 138
^{8}Be(17.64)	1^+	1	M1 IS 10.7
^{12}C(17.23)	1^-	1	E1 IV 1150
^{4}He(21.01)	0^-	0	M0 840
^{4}He(20.21)	0^+	0	E0 500
^{10}B(19.3)	2^- (-3^+)	1	E1 280
^{10}B(18.1)	$2+$ (-1^+)	1	M1 < 600
^{10}B(18.4)	2^- (-3^+)	1	E1 280
^{10}B(17.0)	1^- (-2^+)	1	E1 280

^{3}He beam available at Montreal !

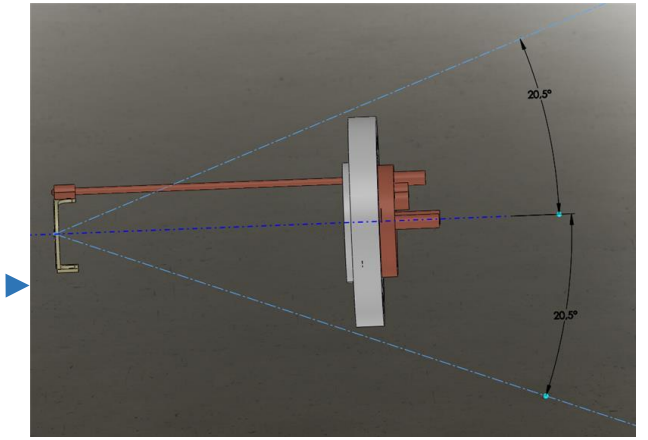


$$\theta = 2\,sin^{-1}\left(\frac{M_x}{E_x}\right)$$



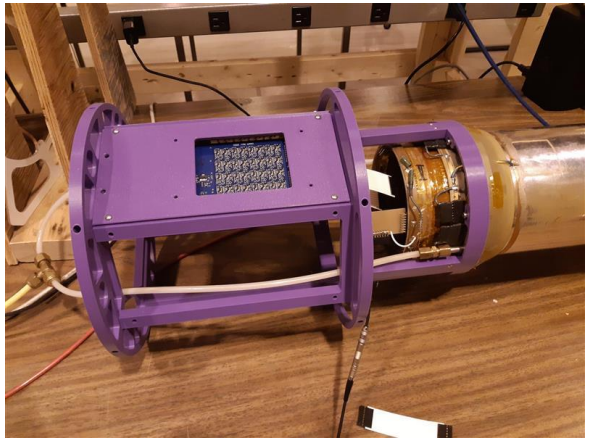
Status Set-UP

p - beam



Beam & Target:

- 10 µA on target demonstrated
- 500 nm LiF on 10µm Cu backing



Scintillators:

- All 16 scints. installed & calibr.
- DAQ (VF48)& trigger system working

MWPC:

- Wire & strip r/o ready & tested
- 480 preamp & DAQ channels ready
- Problems w. some wire sections

ΔE counters :

- 8 Scint. plates (1mm) w. SiPM r/o

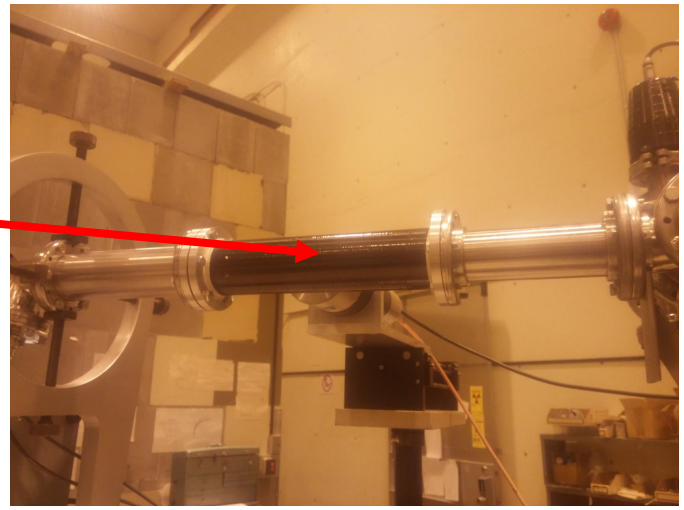
On-going data taking:

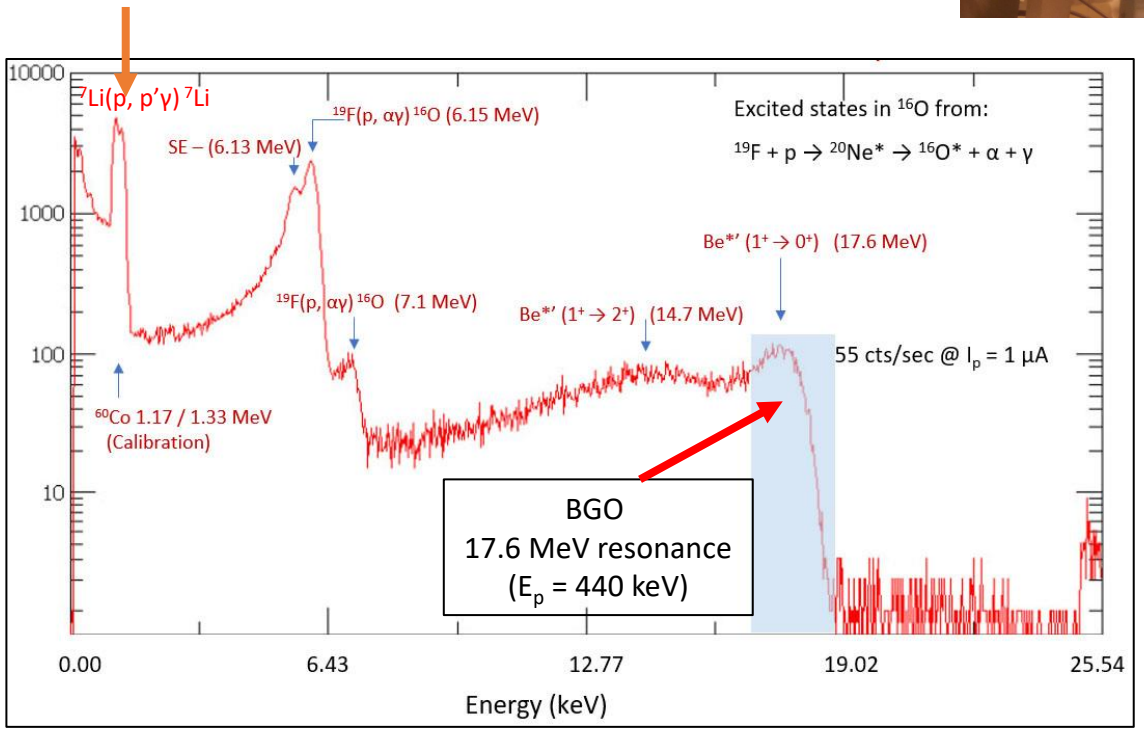
- Test runs for IPC spectroscopy

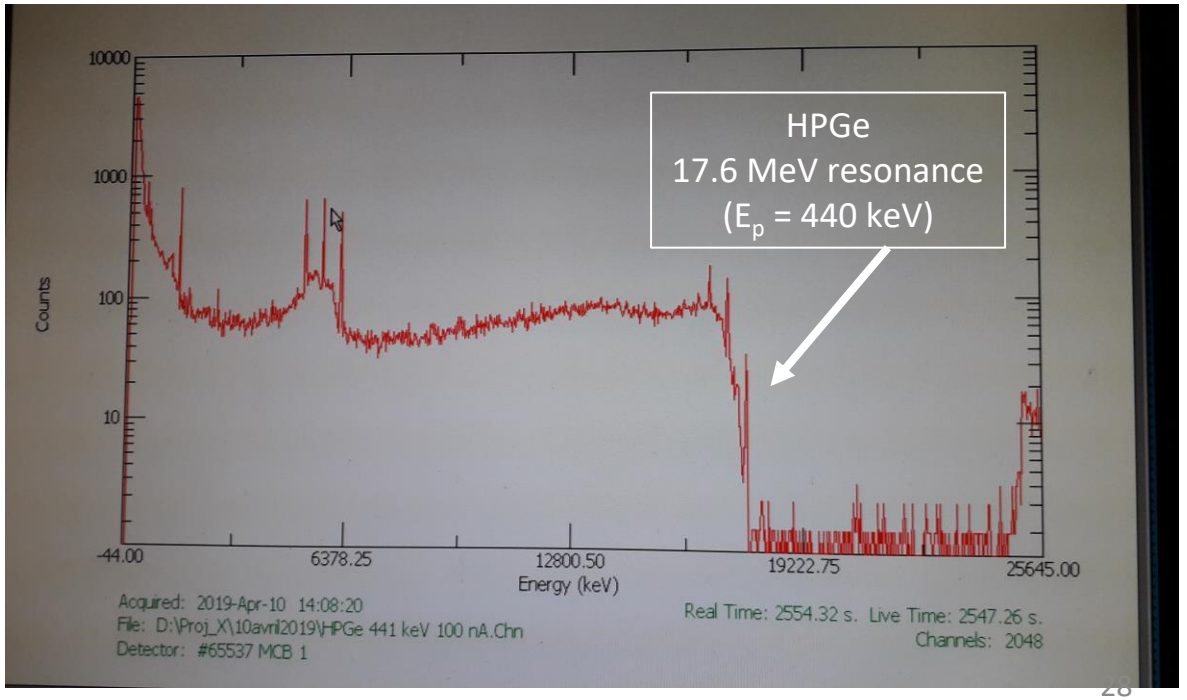
Test – Beam Measurements

Exploring Be* physics

- 0.8 mm thick C-beam pipe
- Target: 0.2 µm LiF (52 µg/cm^2)
- Beam current: I_p = 2 µA







Geant 4 Simulations : ^{8}Be* (IPC & X17)

- Measured BGO rates @ I_p = 2μA extrapolated to 0.9 x 4π – coverage:

E_γ = 478 keV: $R_\gamma = 5.7 \times 10^5\ s^{-1}$

$$\frac{\sigma\ ^7Li(p,\gamma)\ ^8Be^*}{\sigma\ ^7Li(p,\gamma)\ ^7Li} = 7.5 \times 10^{-4}$$

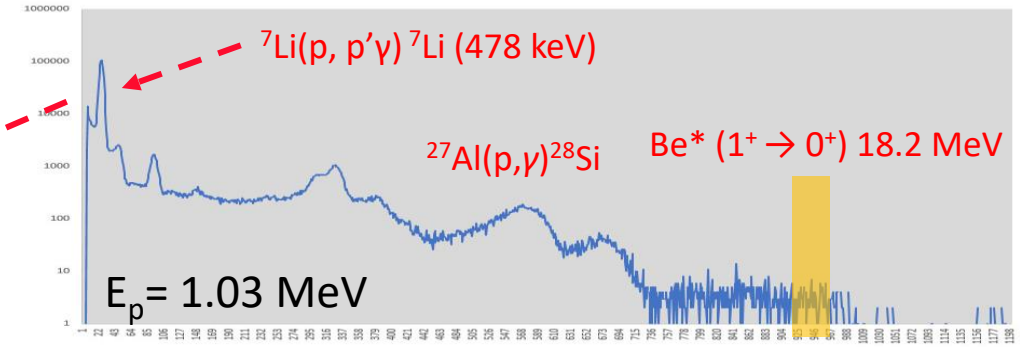
R_{IPC} (18.2 -> GS) = 1.7 s^{-1}

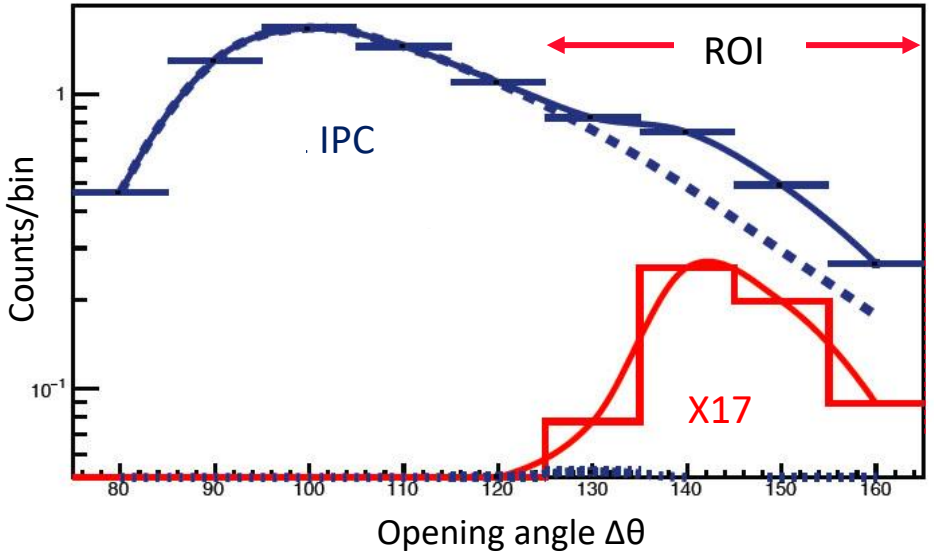
Geant4

R_{IPC} (in ROI) = 15 h^{-1}

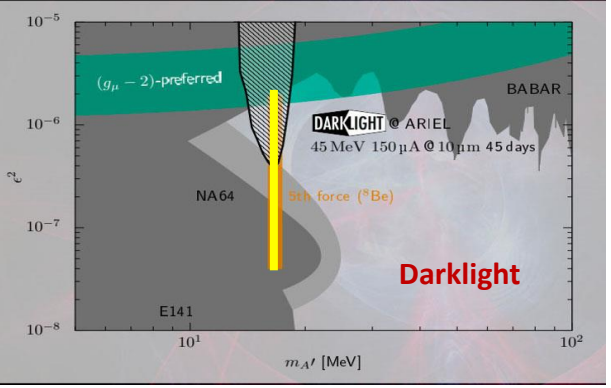
R_{X17} (in ROI) = 9 h^{-1}

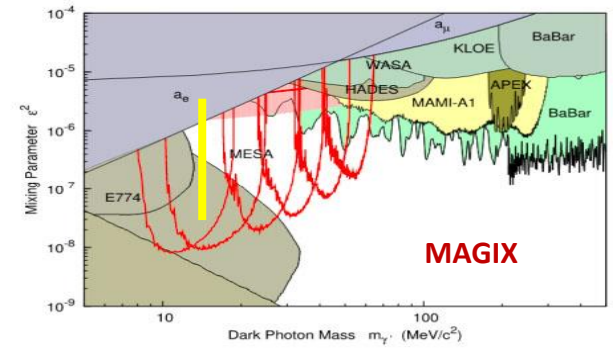
(Data taking 1 - 2 weeks @ I_p = 2μA)

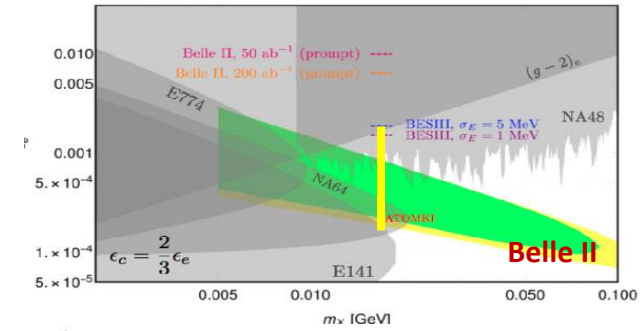


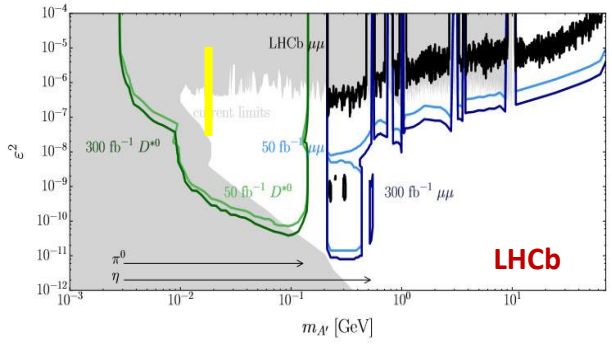


(Expected $R_{trigger}$ (E_γ > 1 MeV; $E_1 \wedge E_2$) = 200 Hz)



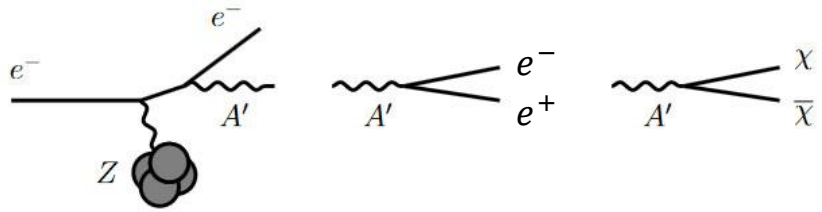






Where Else Can We look?

Searches @ accelerators and beam dumps



Darklight @ Ariel, TRIUMF radiative production; 30 MeV, later 45 -50 MeV

JlabX17@Jefferson L., 2 – 3 GeV e^- ;

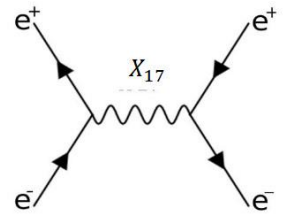
MAGIX @ MESA γd → pn + A' → e^+e^- > 2024/25

LDMX@JLAB/SPS? - operates > 2024, statistics!

NA64 @CERN/SPS – needs detector upgrade, statistics!

…also

PADME@Frascati - res. production, results Run III



…also

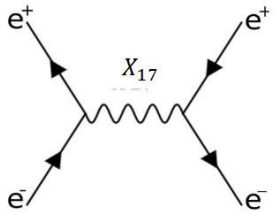
Belle II: $D^{+*} \rightarrow D^+ + A'$; $A' \rightarrow e^+e^-$; statistics! >2025

LHCb: ; $D^{0*} \rightarrow D^0 + A'$; $A' \rightarrow e^+e^-$ after upgrade 2025

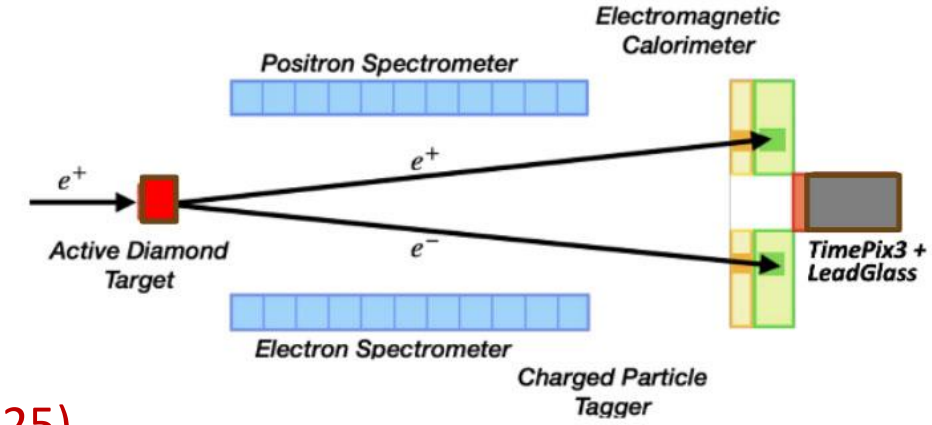
PHOTON II @ Dubna; p + N → $\gamma\gamma$ + else 2024

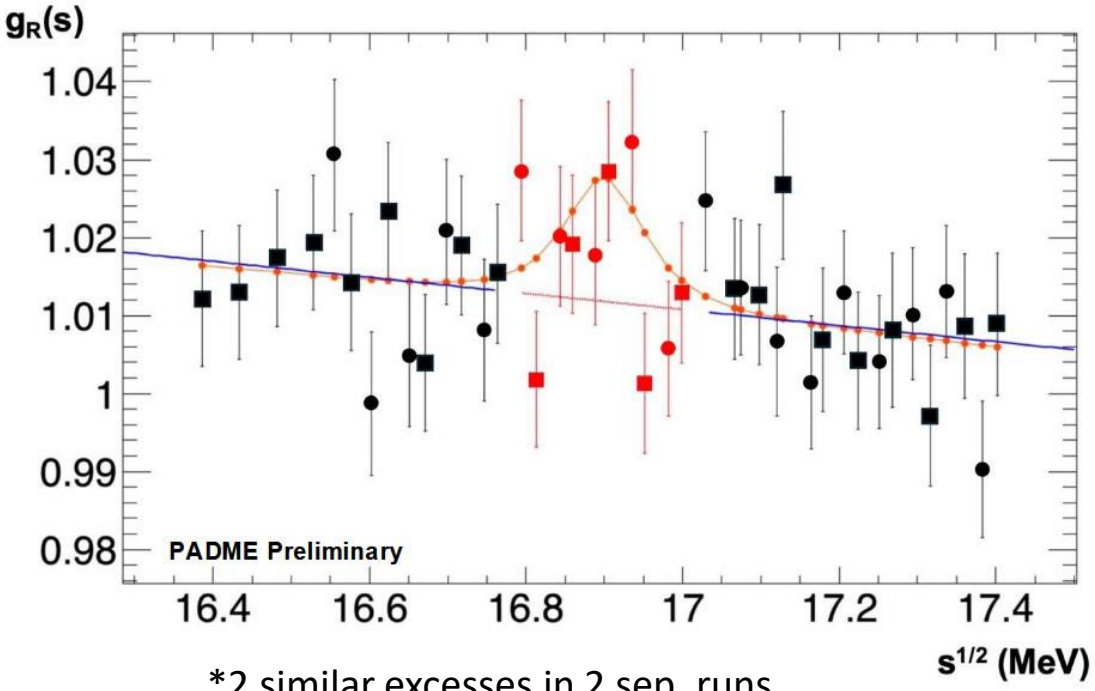
Window of opportunity for fast moving new intitatives !

The PADME Run III Experiment, Frascati (2023)



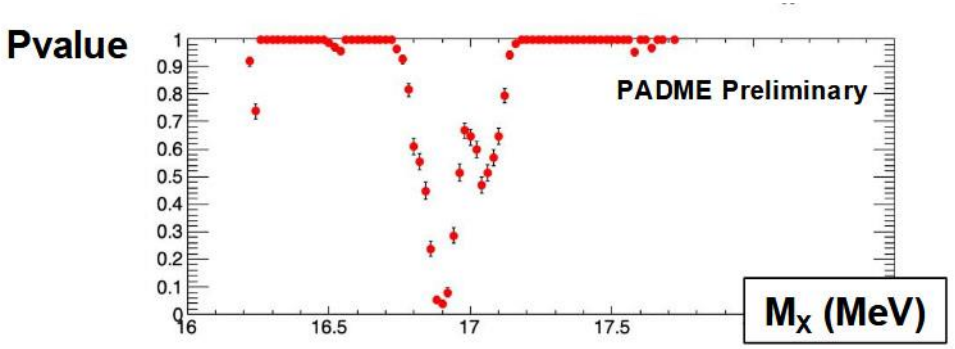
- Search for resonant production of X17
- e^+ annihilation on fixed target e^-
- E_{e+} : 265 – 300 MeV → $\sqrt{s}$ = 16.9 – 18.8 MeV)
- Compton profiles of e^- included in analysis
- Blinded analysis → 1st results LDMA Genova (2025)



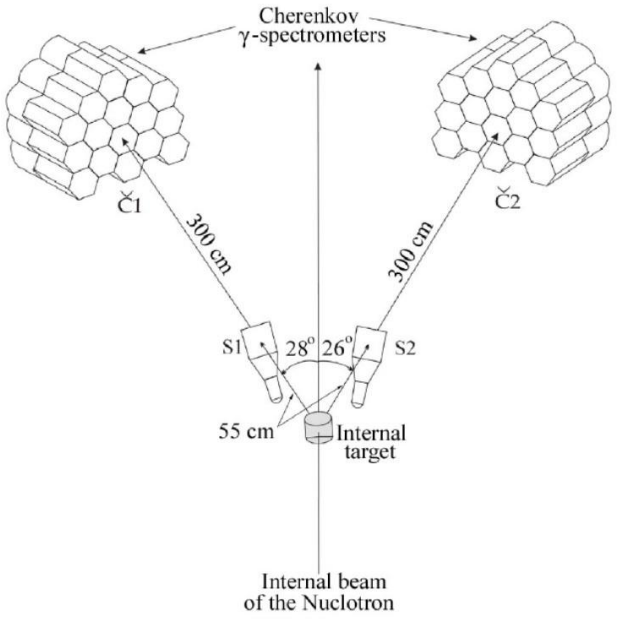


*2 similar excesses in 2 sep. runs

Excess* of e+e- at
√s = 16.9 MeV/c²
1.86 σ (2.5 σ local)



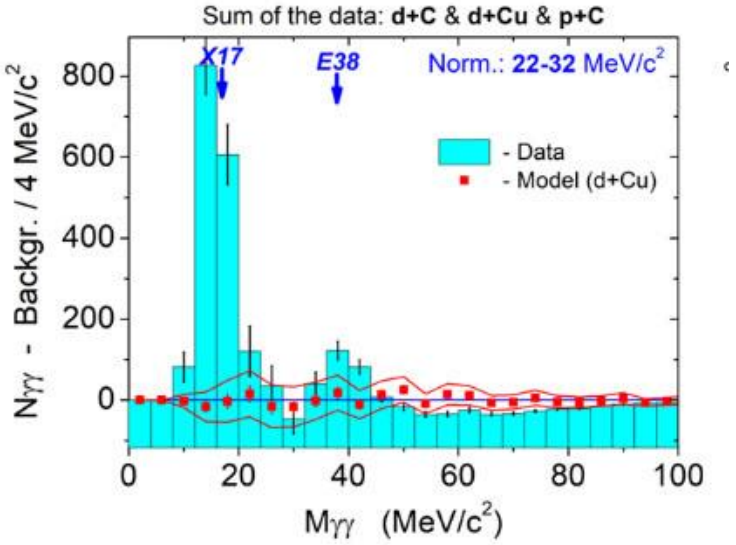
The PHOTON II Experiment @ JINR- Dubna (2023)

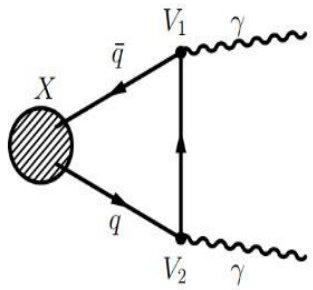


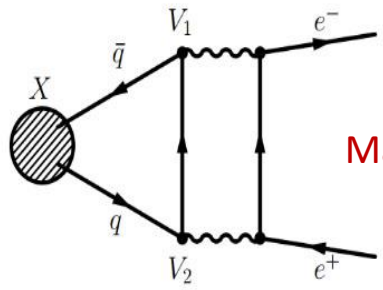
- Two arm γ – Pb glass calorimeter (η-meson production etc)
- $p + C \rightarrow \gamma + \gamma + x$ @ 5.5 GeV/c /nucl.
- $d + C \rightarrow \gamma + \gamma + x$ @ 2.75 GeV/c / nucl.
- $d + Cu \rightarrow \gamma + \gamma + x$ @ 3.83 GeV/c /nucl.
- Determine invariant mass of γ - pairs

Observe "enhanced structure" at inv. masses of 17 and 38 MeV/c2

2γ decay excludes V(1$^-$) boson (Landau-Yang)







Maybe "QED meson ? "

Maybe indication of composite nature of X17 & E38

(C.-Y. Wong; arXiv:2201.09764v2)

What's Going On ?

(June 2025)

- **Systematic effects?** Unlikely!

  - Anomaly in ^{8}Be, ^{4}He, ^{12}C, GDR with consistent kinematics and different apparatus and more than 5σ

  - Possibly seen also by PADME, Hanoi, Dubna

- **Nuclear physics effects?** Unlikely !

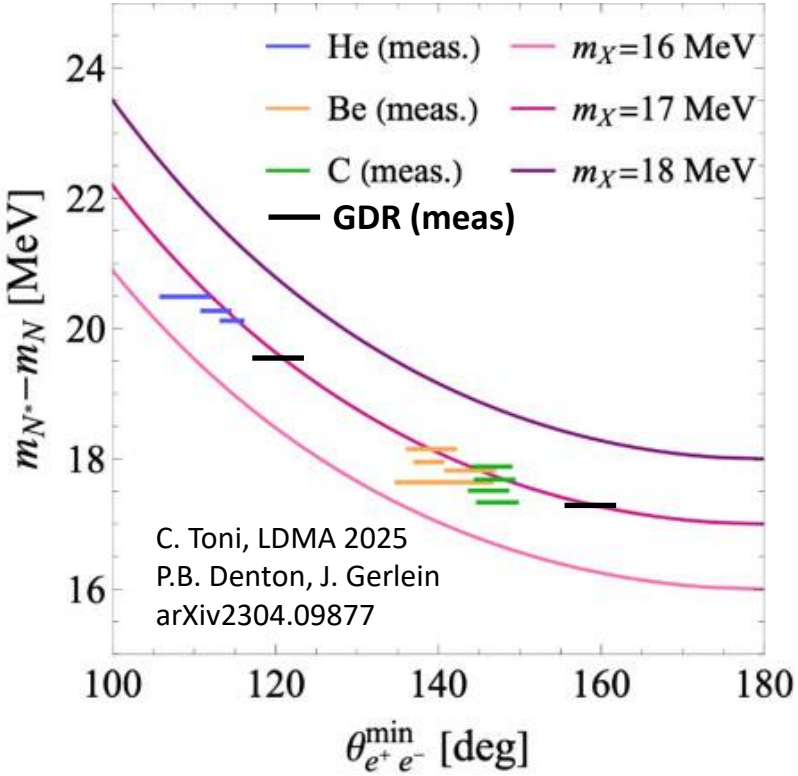
  - Modelling w. EFT→ nuclear form factors too large[1]

  - Nuclear decay chain w. subsequent conversion 2 γ's to e+e- pair[2] → very unlikely

  - Ab initio No-Core Shell Model with Continuum (NCSMC) [3] : → no bump, smooth background consistent w. measurements

- **A QED Meson?** Maybe?

  - $q\bar{q}$ interact in QED[4], open string isoscalar QED meson @ 17.9 MeV and isovector @ 36.4 MeV (Dubna?)



1) X. Zhang, G.A. Miller PLB 773 (2017) 159 2) B. Koch, Nucl. Phys.A 1008 122143 (2021) 3) P. Gysbers et al., Phys. Rev. C 110, 015503 4) C.Y. Wong, JHEP 08(2020)165

BSM : A New Particle ?

(June 2025)

Transition		Mass (MeV/c^2)	Vector ($J_X^\pi = 1^-$)	Axial vector ($J_X^\pi = 1^+$)	Scalar ($J_X^\pi = 0^+$)	Pseudo sc. ($J_X^\pi = 0^-$)
^{8}Be: 1^+ 0^+ M1	ATOMKI	17.17±0.07±0.2	L=1	L=0,2	excl	L=1
^{8}Be: dir. cap. E1	ATOMKI	16.95±0.10±0.21	L=0,2	L=1	L=1	excl.
^{8}Be 1^- 0^+ GDR E1	ATOMKI	16.95±0.48±0.35	L=0,2	L=1	L=1	excl.
^{8}Be: dir. cap. E1	VNU UoS	16.66±0.47±0.35	L=0,2	L=1	L=1	excl.
^{4}He: 0^+ $/^-$ 0^+ E0/ M0	ATOMKI	16.94±0.12±0.21	L=1	L=1	L=0	L=0
^{12}C 1^- 0^+ E1	ATOMKI	17.03±0.11±0.2	L=0,2	L=1	L=1	excl.
^{8}Be: 1^+ 0^+ M1	MEGII	< 16.81	L=1	L=0,2	excl	L=1
Resonant prod.	PADME	16.9±0.02±0.05				
$p + N \rightarrow \gamma\gamma$ + else	Dubna JNR	16.66±0.47	excl.			

M_x = 16.88 +- 0.05 MeV/c^2

Global fit by F. Arias-Aragon et al. arXiv: 2504.11439

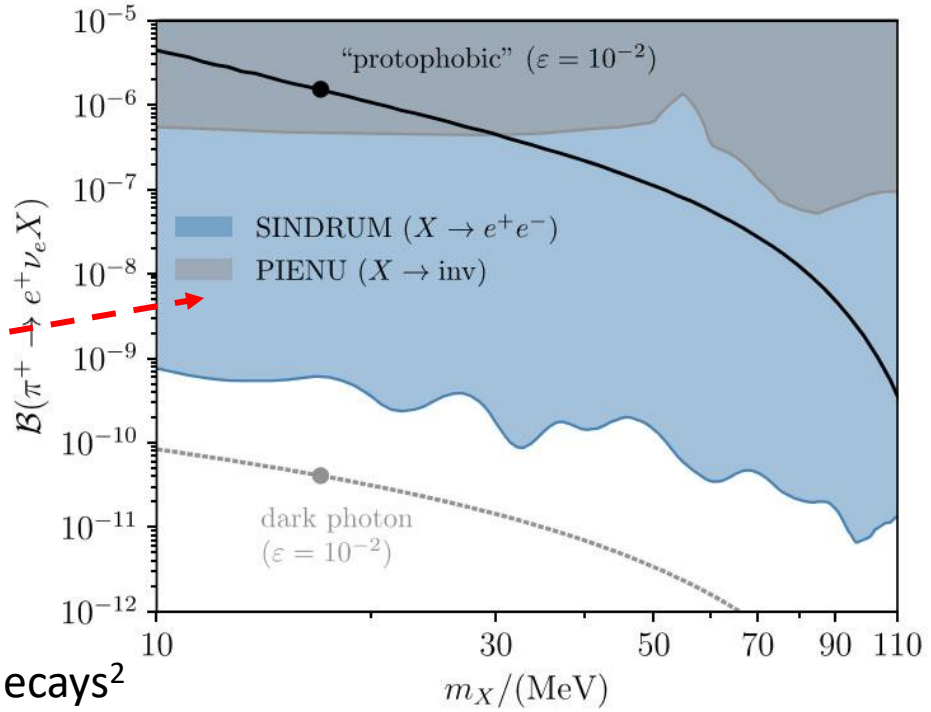
^{12}C, GDR, dir. capture E1 rule out PS !

V or AV interpretation?

BSM : A New Particle ?

(June 2025)

- **PS (0^-)** QCD axion ruled out by C - data & direct E1 capture
  also excluded by NA62 $(K^+ \to \pi^+ XX \to e^+e^-e^+e^-)$
- **V(1^-)** coupling in Be/He in 4σ tension w. ^{12}C
  - proto-phobic[1] to be consistent w. NA48 → not a dark - photon
  -but proto-phobic V(1^-) excluded[2] by limits on $\pi^+ \to e^+\nu_e X$
- **AV (1^+)** can explain Be / He / GDR
  - Some tension with ^{12}C, but possible (nucl. matrix elem. uncertain)[1]
  - Chiral EFT[3]: isoscalar (18.15 MeV ok)
  - Constrains by SINDRUM, PIENU but still regions compatible w. π – decays[2]
  - Relation to other anomalies[4]? $(g-2)_\mu$, p- charge radius, KTeV anomaly in $\pi^0 \to e^+e^-$, self interacting DM….



….AV solution favoured ?

Minimal Interpretation[2]:
X17 boson would be a mediator of a local $U(1)_{Qx}$ gauge symmetry associated w. SM or Dark Sector quantum numbers Q_X

[1]Feng et al.; PRL 117.071803) [2]M. Hoster, M. Pospelov (arXiv:2306.15077) [3]J. Kozaczuk, D.E. Morrissey,S. R. Stroberg arXiv:1612.01525v2 2016 [4]D. Barducci, C. Toni (arXiv:2212.06453)

Conclusions

- Intriguing results by the ATOMKI collaboration in Be*, He*, (C*?)
- UdeM – experiment for independent & timely verification
- Extend to other states & nuclei: ^{10}B(17.8), ^{12}C (17.2)….E1 GDR's (?)
- Large solid angle increases coverage of param. space (V, AV P, PS)
- Other searches: New JEDI, NuCReX17, Darklight, MAGIX, Na64, SHiP, SeaQuest, LHCb, PADME…