Search for the resonant X17 boson production in PADME Run III

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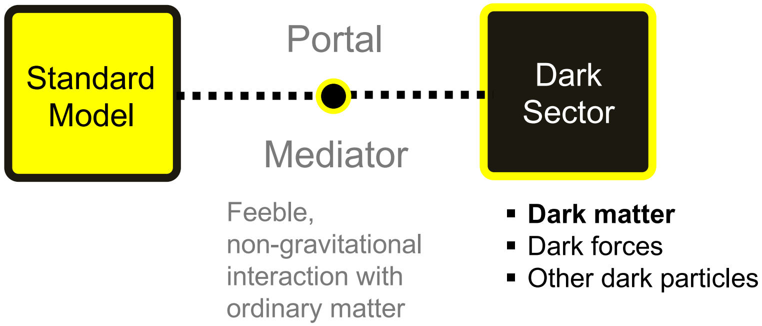
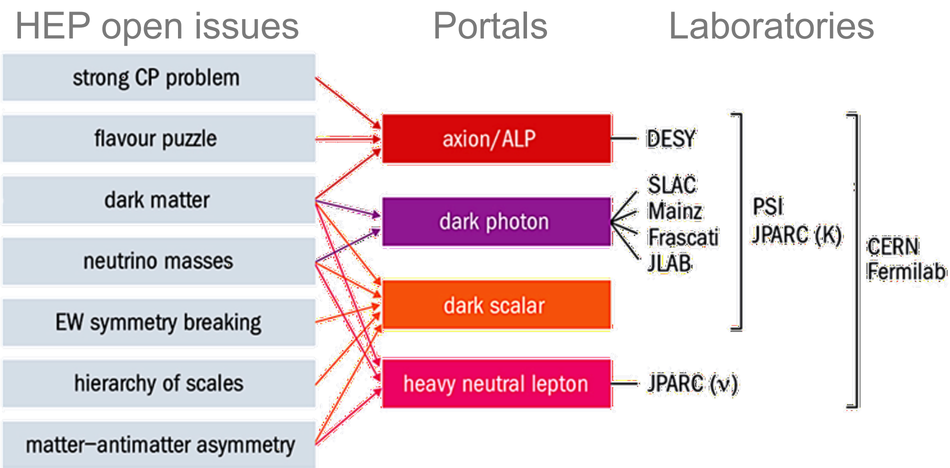
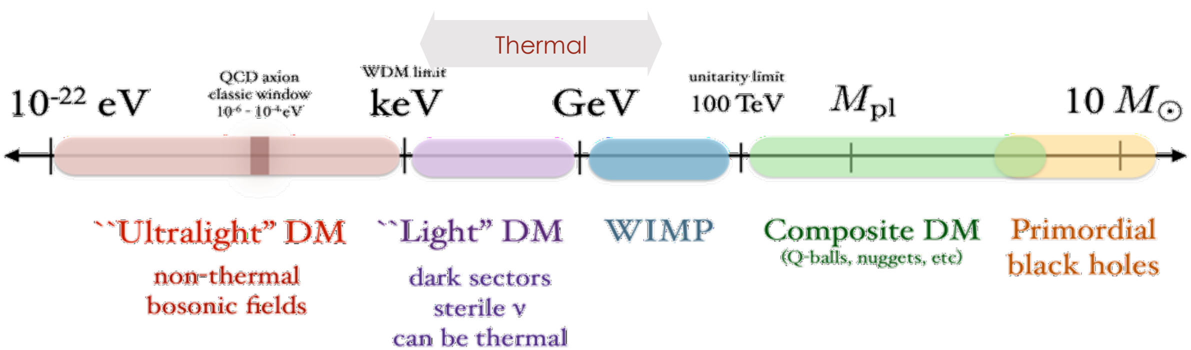
ISMD2023 Conference
Róbert Campus of MATE in Gyöngyös, Hungary Aug 21 – 26, 2023

The dark sector paradigm







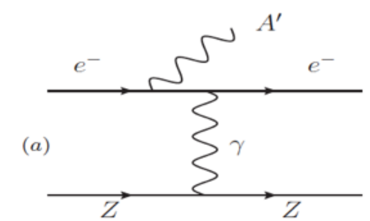
- Dark sector candidates can explain SM anomalies: (g-2)μ, ^{8}Be, proton radius
- The mediator can have a **small mass (MeV -100 MeV)**
- Due to its **small mass** the mediator can be **produced at low energy accelerators**
- It can **decay back to ordinary matter "visible"** on **not "invisible"**

Experimental approaches

- **Electron beam experiments production**
  - **Just A'-strahlung**
- **Positron based experiments**
  - **A'-strahlung**
  - **Associated production $e^+e^- \to A'(\gamma)$**
  - **Resonant production $e^+e^- \to e^+e^-$**

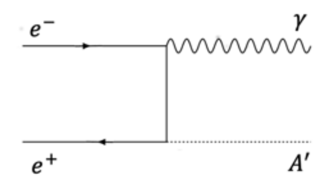
- **Visible decays:** $A' \to e^+e^-$ $A' \to \mu^+\mu^-$
  - **Thick target electrons/protons** beam is absorbed (NA64, old dump exp.)
  - **Thin target**   searching for bumps in e^+e^- invariant mass
- **Invisible searches: $A' \to \chi\chi$**
  - **Missing energy/momentum**: A' produced in the interaction of an electron beam with **thick/thin target** (NA64/LDMX)
  - **Missing mass**: $e^+e^- \to A'(\gamma)$ search for invisible particle using kinematics (Belle II, **PADME**)

Brems.



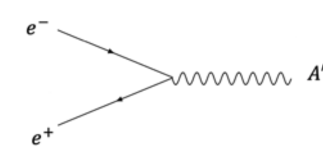
dump and thin target

Associated production



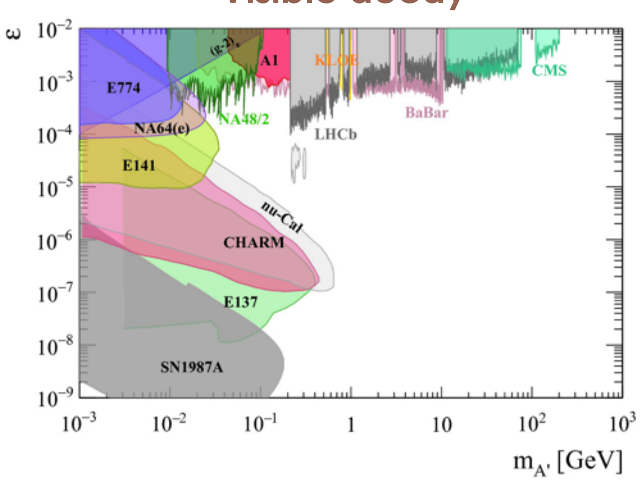
Colliders

Resonant

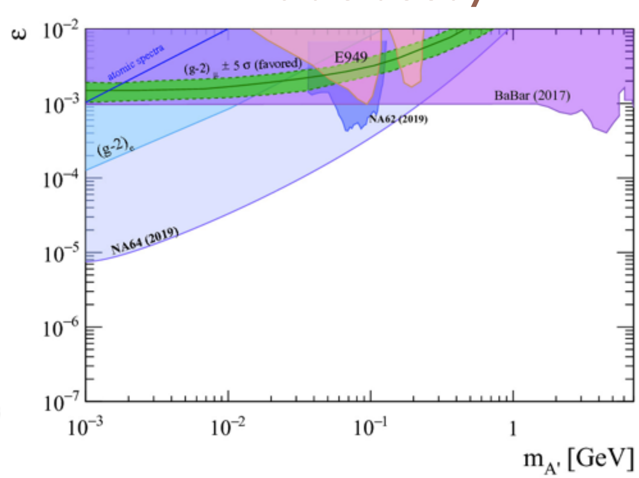


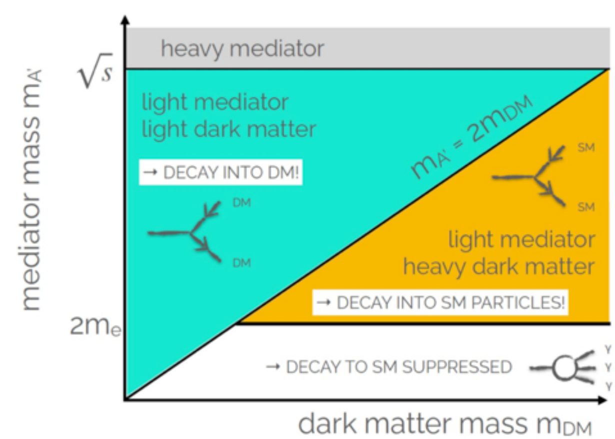
Never used!

Visible decay



Invisible decay



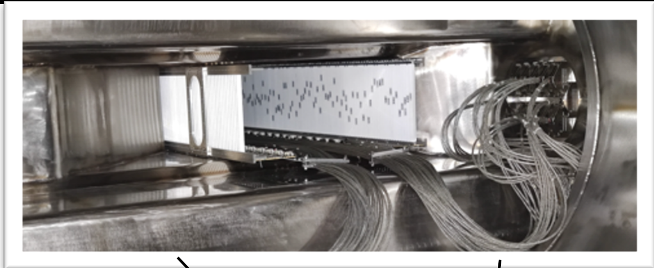


PADME Run I and Run II setup

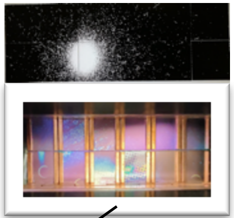
- Positron beam of ~**0.5 GeV/c**
  - LINAC repetition rate 50 Hz
  - Macro-bunches maximum length $\Delta t \lesssim$ **300 ns**
- Number of annihilations proportional to:

$$N^{e^+}_{beam} \times N^{e^-}_{target}$$

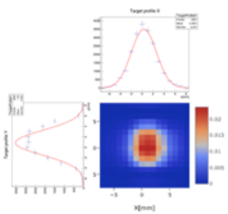
  - Limited **intensity**, due to pile-up, ~**3·10⁴ pot/pulse**
- Dipole **magnet** in order to
  - Sweep away non-interacting positrons
  - Tag positrons losing energy by Bremsstrahlung
- Scintillating bar **veto** detectors placed inside vacuum vessel
  - Positron and electron detectors inside the magnet gap
  - Additional veto for e^+ irradiating soft photons at beam exit

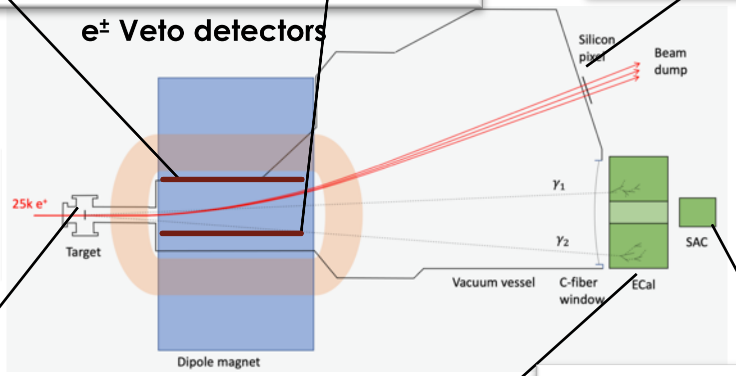


Silicon **pixel** (TimePix3)

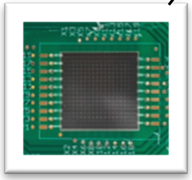


e± Veto detectors

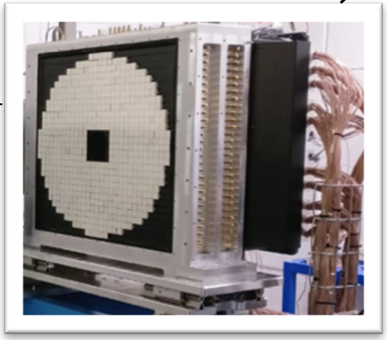




SAC



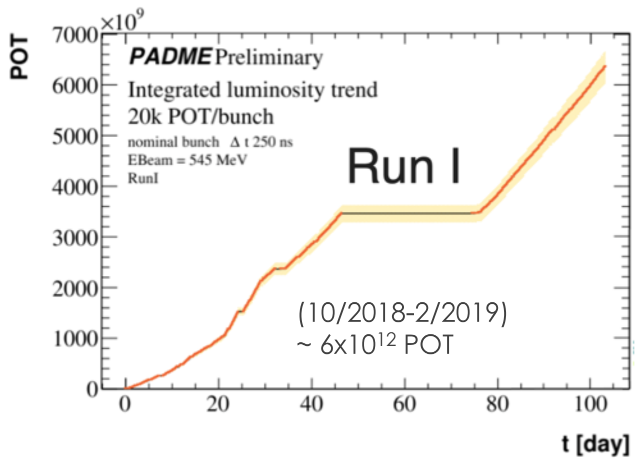
Active **diamond** target
100 μm thick

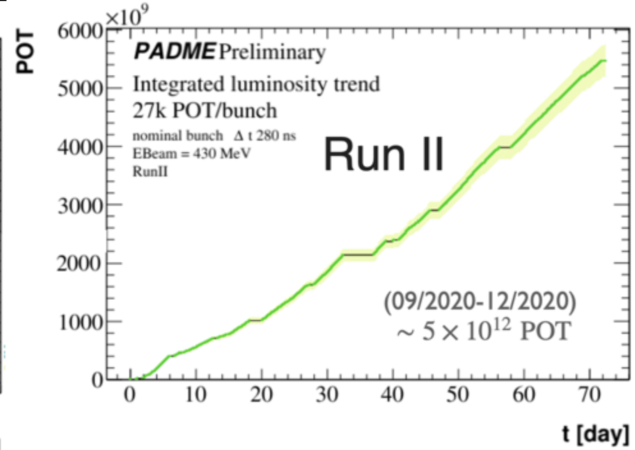


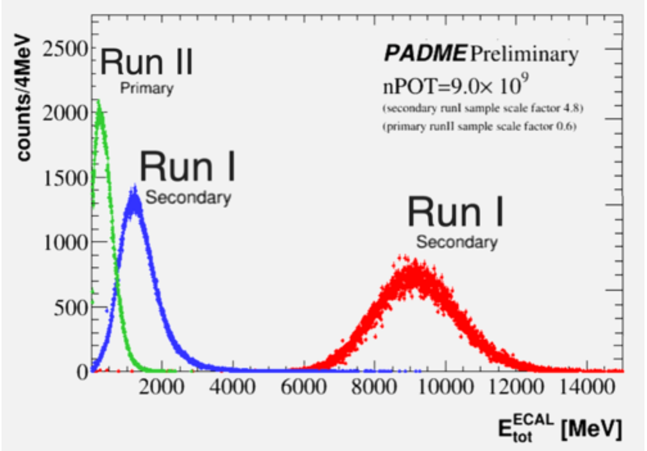
BGO calorimeter (ECAL)

small angle calo
SAC PbF$_2$

PADME data taking periods 2018-20

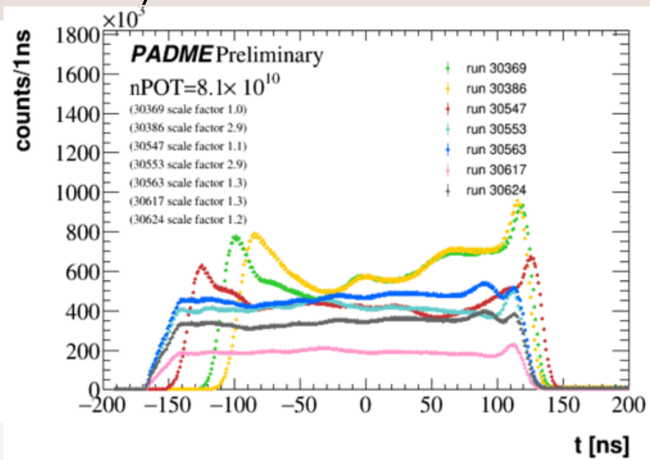






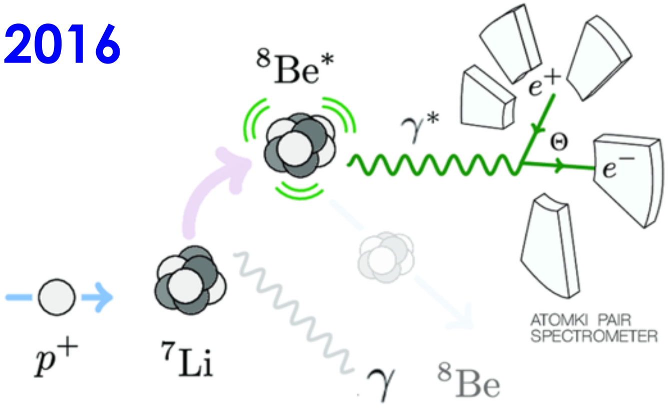
- Two physics runs **Run I Oct. 2018 Feb. 19** and **Run II Set-Dec 2020**
  - Hard simulation work to understand BG in between Run I and Run II.
- Run II wrt Run I
  - Slightly lower beam momentum in Run II, 430 MeV/c, wrt to Run I, 490 MeV/c
  - **Improved vacuum separation** between experiment and beamline
  - Less beam-induced background with primary wrt secondary beam

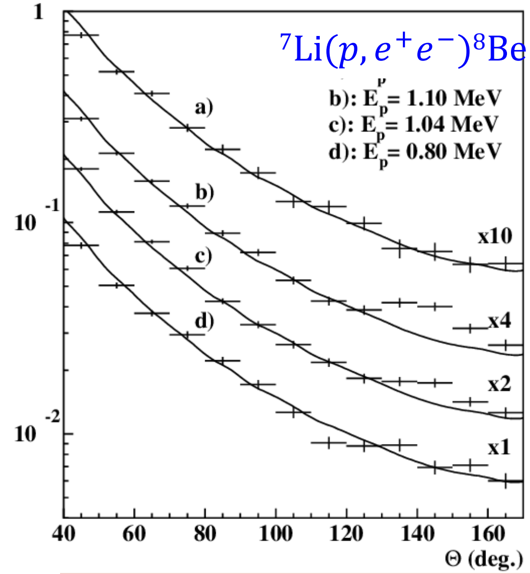
- During Run II itself
  - Improved bunch length and structure



The ^{8}Be and ^{4}He Atomki anomaly

2016

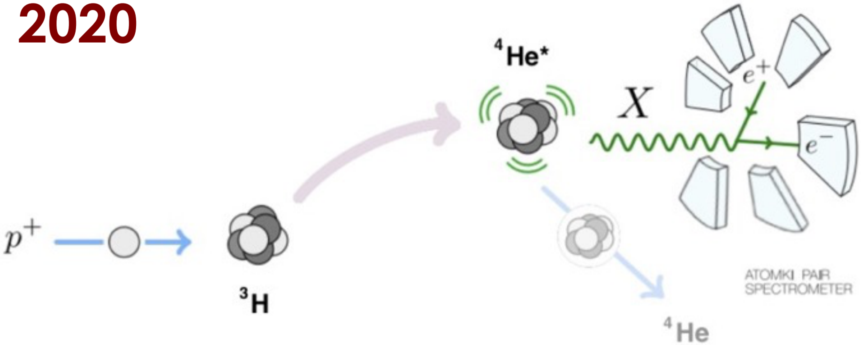


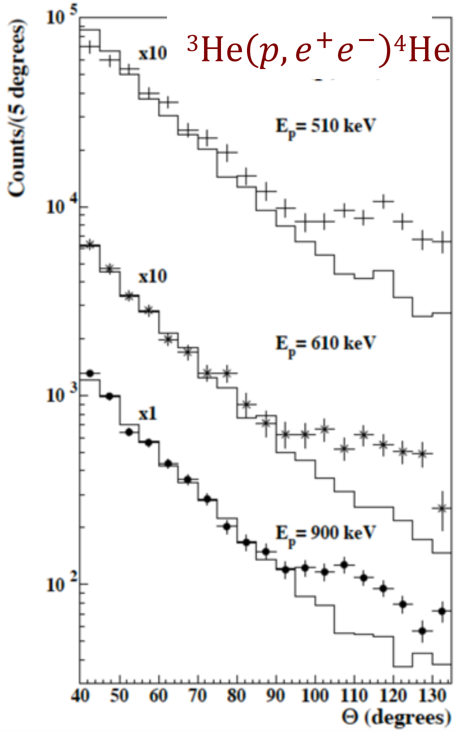


$m_X c^2 = 17.01 \pm 0.16(\text{tot})$ MeV

PRL 116, 042501 (2016)

2020





$m_X c^2 = 16.98 \pm 0.16(\text{stat}) \pm 0.20(\text{syst})$ MeV

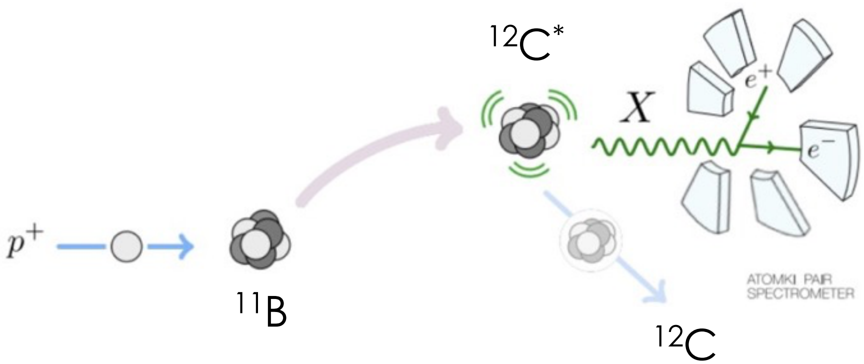
Phys. Rev. C 104, 044003 (2021)

ATOMKI has confirmed the anomalous peak in the angular distribution of internal pair creation in **^{8}Be with a similar** one in the **^{4}He** transitions, with different kinematics but at the **same invariant mass value.**

The ^{12}C anomaly and the vector portal

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

Phys. Rev. C 106, L061601
Dec 2022



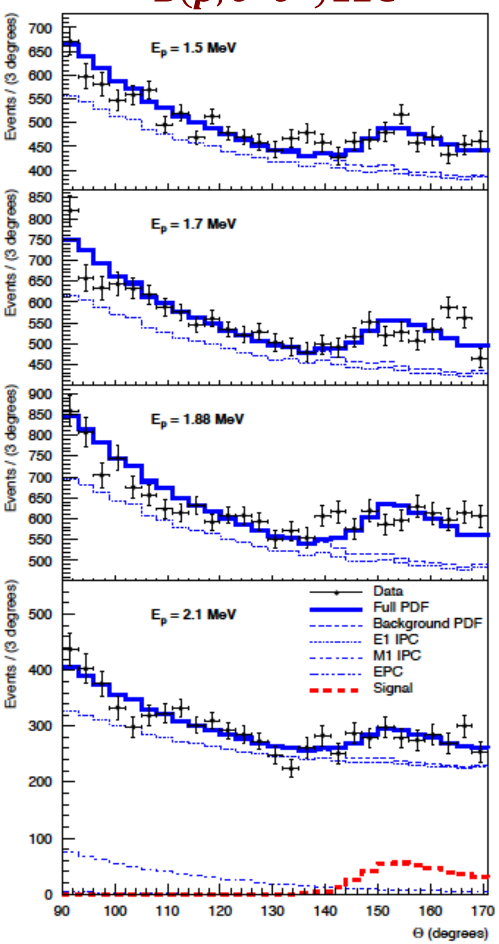
E = 17.23 MeV excited state of ^{12}C

TABLE I. X17 branching ratios (B_x), masses, and confidences derived from the fits.

E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [31]	5.1	16.94(12)	
Predicted [33]	3.0		

4 different p bombarding energies with strong significance

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



On the nature of X17

PHYSICAL REVIEW D **102,** 036016 (2020)

Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies

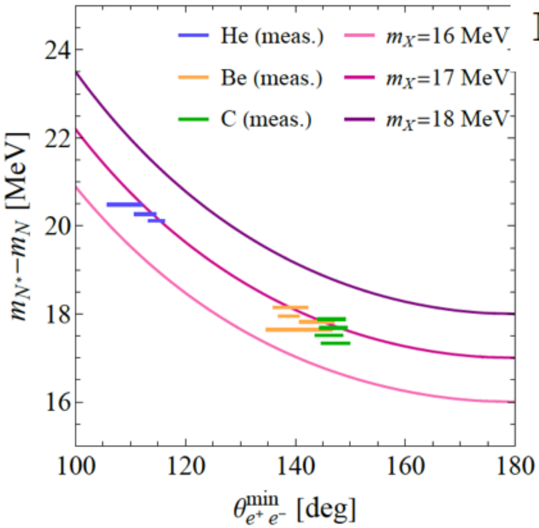
Jonathan L. Feng,* Tim M. P. Tait,† and Christopher B. Verhaaren‡
Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

J. Feng and collaborators suggested that the X17 should be observed in ^{12}C transitions
X17 observations in ^{12}C will point to a vector or axial vector nature for X17
Pseudo Scalar X17 killed by ^{12}C observation now confirmed

TABLE III. Nuclear excited states N_*, their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators are defined. The operator subscripts label the operator's dimension and the partial wave of the decay, and the superscript labels the X spin. For example, $\mathcal{O}_{4P}^{(0)}$ is a dimension-four operator that mediates a P-wave decay to a spin-0 X boson.

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	…	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	…	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	…	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)	…

On the mass of X17



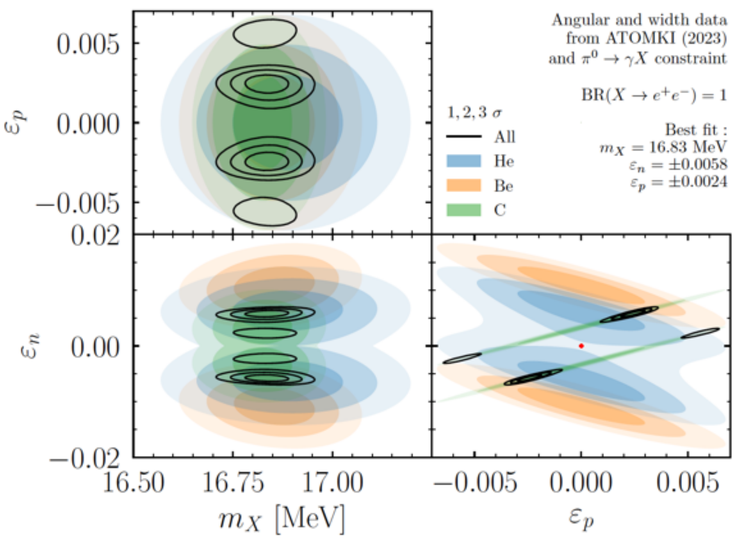
Neutrino Constraints and the ATOMKI X17 Anomaly

arXiv:2304.09877v1

Using angular data only: 11 measurements

An analysis with the angular data alone of 11 different measurements finds that the data is well described by a new particle of mass $m_X = 16.85 \pm 0.04$ MeV with an internal goodness-of-fit of 1.8σ calculated from Wilks' theorem at $\chi^2/dof = 17.3/10$. We use only the best fit

$$\theta_{ee}^{min} \approx 2\arcsin\left(\frac{m_{X17}}{m_{N*} - mN}\right)$$



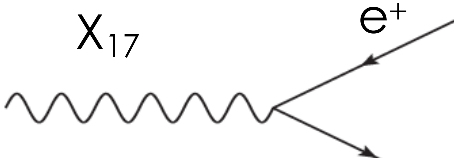
Using width for each element: 3 measurements

Next, we add in to the analysis the latest width information from each element and include a prior on ε_p since X needs to couple to protons and/or neutrons on the production size. There is a stronger constraint

see the next section for more information. We find an okay fit to the data at the same mass $m_X = 16.83$ MeV, $\varepsilon_n = \pm 5.8 \times 10^{-3}$, and $\varepsilon_p = \pm 2.4 \times 10^{-3}$, see fig. 2. We note that the signs of ε_n and ε_p must be the same due to the non-trivial degeneracy structure shown clearly in the $\varepsilon_n - \varepsilon_p$ panel of fig. 2. We have confirmed that the

data are consistent and point to M_{X17}=16.85±0.04 MeV

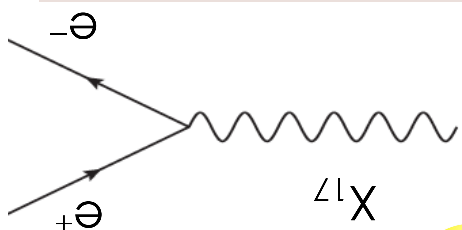
As simple as possible: the resonance search



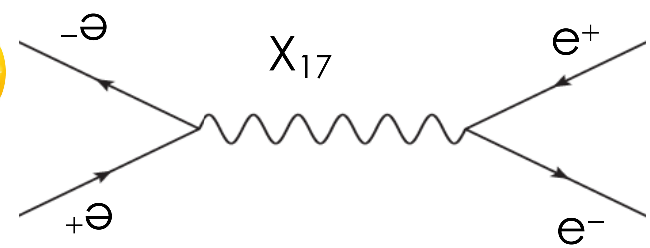
ATOMKI X_{17}

PHYSICAL REVIEW D 97, 095004 (2018)

Just flip the diagram



and connect!



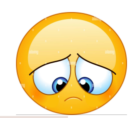
No model dependence just electron coupling!

Extremely high production rate Breit-Wigner enhancement

$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak} \frac{\Gamma^2_{A'}/4}{(\sqrt{s} - m_{A'})^2 + \Gamma^2_{A'}/4} \qquad \sigma_{\rm peak} = 12\pi/m^2_{A'}$$

Lowest possible α suppression

Extremely small Γ_{X17} $\Gamma_{A'} \simeq \epsilon^2 \alpha m_{A'}/3$ $<10^{-2}$ eV

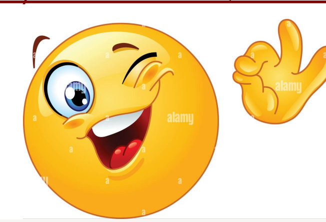


We need a lot of positrons in very limited COM energy range

Darmé et al. Phys. Rev. D 106,115036

We can have >1E10 e^+ in 20KeV CoM energy at LNF!

Ok let's do that!

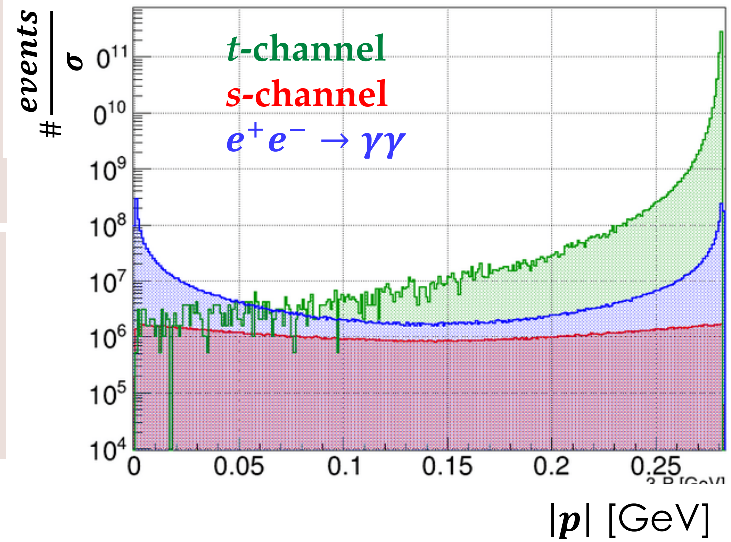


The mass scan X17 search strategy

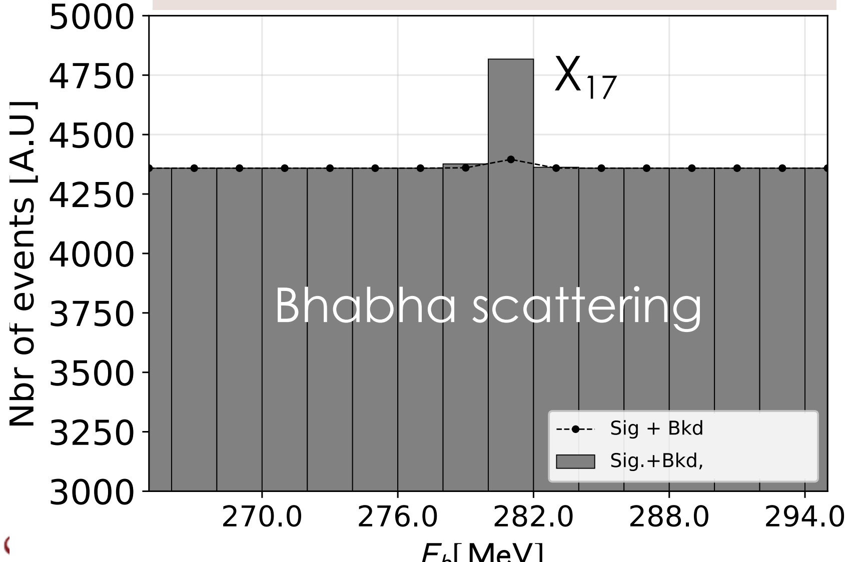
PADME, can use resonant X17 production process

- Extremely effective in producing X17 but in a very small mass range
- Scan E_{beam}=260–300 MeV in <1 MeV steps

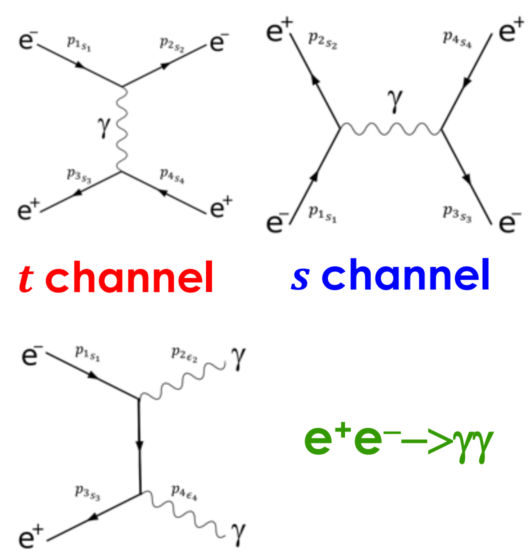
- Completely data driven no theory or MC input
- Signal should emerge on top of **Bhabha** BG in one or more points of the scan.
- Background estimated from surrounding bins



Cartoon view of the technique



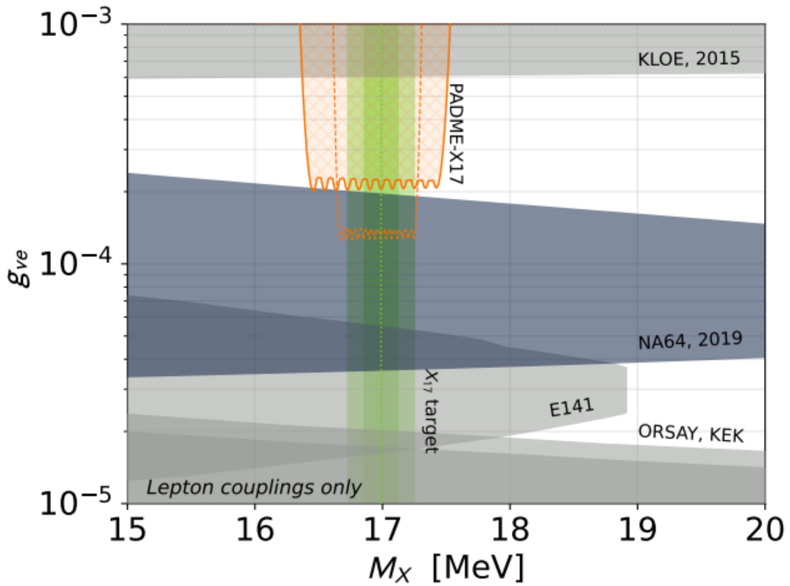
Bhabha scattering



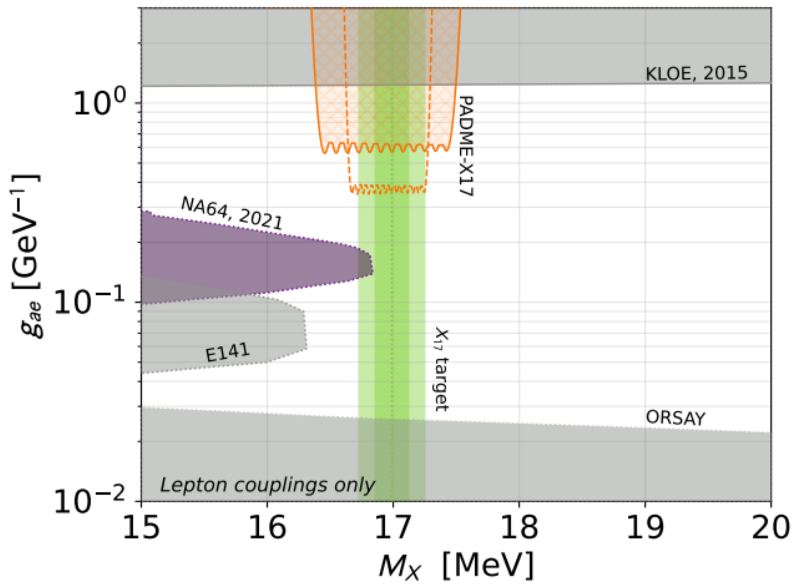
PADME expected limits

L. Darmé, M. Mancini, E. Nardi, M. Raggi
Darmé et al. Phys. Rev. D 106,115036

Vector X17



Pseudo scalar X17



- BG from SM Bhabha scattering under control down to ε = few 10^{-4}
- Challenge is to achieve an extremely precise luminosity measurement and systematic errors control (<1%)
- ~1E10 POT per each energy point
- PADME maximum sensitivity in the vector case
- Actual data set very close to optimistic scenario in the wide mass region

PADME Run III on resonance data set

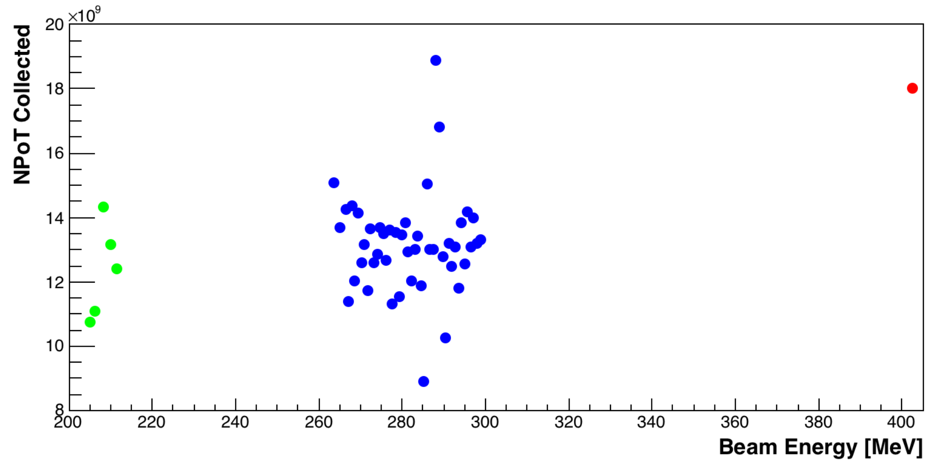
Run III PADME data set contains **3 subset**
- **On resonance: 47 points (263-299) MeV**
- **Below resonance: 5 points (205-211) MeV**
- **Over resonance: 1 energy 402. MeV**

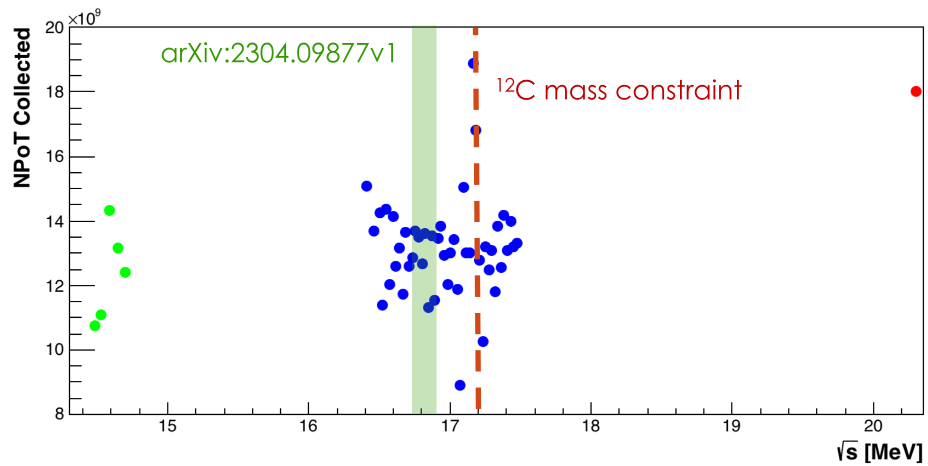
On resonance points **spaced** by **~0.75 MeV**
Point spacing equal to the energy resolution
Mass region 16.4 MeV< M_{X17} <17.5 MeV
statistics > 1×10^{10} PoT per point
The PADME precision on M_{X17} measurement:
ΔM_{X17} =(17.47-16.36)/47 ~ 20 KeV

Below resonance **spaced** by **~1.5 MeV**
Statistics > 1×10^{10} PoT per point
Used to validate analysis method

1 over resonance energy **5 different runs**
Statistics ~ 0.4×10^{10} PoT per run ~2E10 total
Used to validate NPoT measurement stability

~10 different masses >17.2 MeV
Is this mass region excluded by ^{12}C?
Closer sidebands to explore before the box



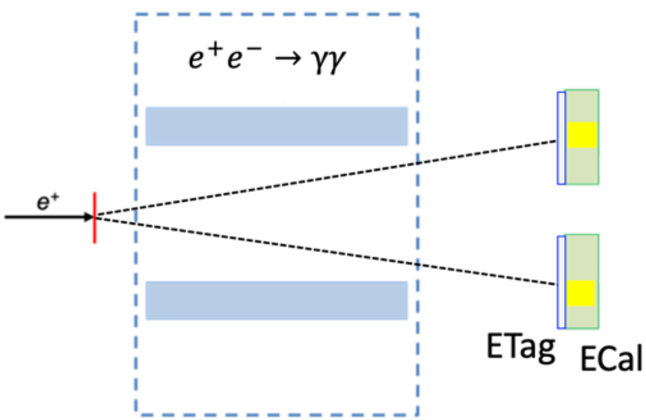


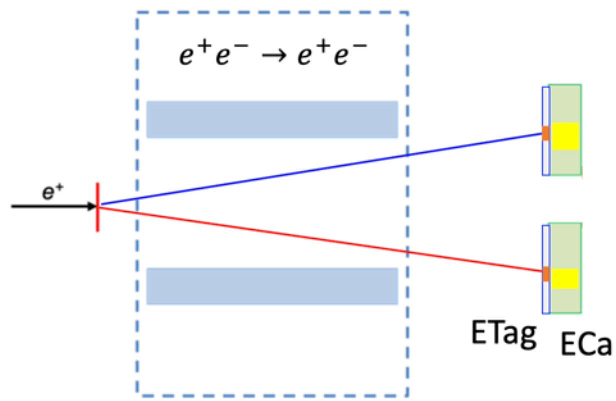
RED Combined Be,He,C Atomki mass ranges
GREEN mass range fit results in arXiv:2304.09877v1
Dots mass points explored by PADME
Mass limit imposed by ^{12}C observation

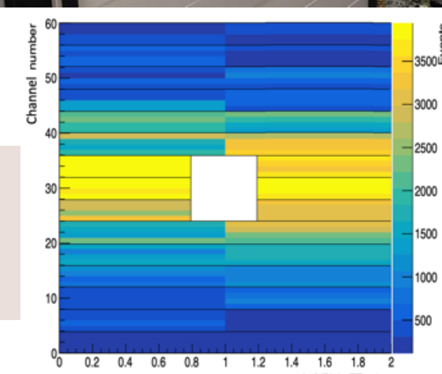
PADME Run III modified setup

- Using PADME veto is impossible to reconstruct $e^+ e^-$ mass having no vertex info
- Idea: identify $e^+e^-\rightarrow e^+e^-$ using the BGO calorimeter only, as for $\gamma\gamma$ events in Run II

- Switch the PADME dipole **magnet off**
- Both positron and electron will reach the ECal
  - Can measure precisely (3%) electron-positron pair momentum and angles
  - Can reconstruct invariant mass of the pairs precisely (small pile-up)
- **Identify clusters** in ECal from photons or electrons
  - New detector, plastic scintillators, similar to PADME vetos (Electron tagger, ETag) with vertical segmentation and covering the fiducial region of ECal







- Thanks to the enhanced production cross section can reduce N_{POT}/bunch by factor 10.
- Much lower pile-up and better energy resolution

X17 observables at PADME

Several different observables can be used with different systematics

Osservabili:

- $\frac{N(e^+e^-)}{N^{PoT}}$ vs $\sqrt{s}$ $\frac{N(\gamma\gamma)}{N^{PoT}}$ vs $\sqrt{s}$
- $\frac{N(e^+e^-+\gamma\gamma)}{N^{PoT}}$ vs $\sqrt{s}$
- $\frac{N(e^+e^-)}{N(\gamma\gamma)}$ vs $\sqrt{s}$

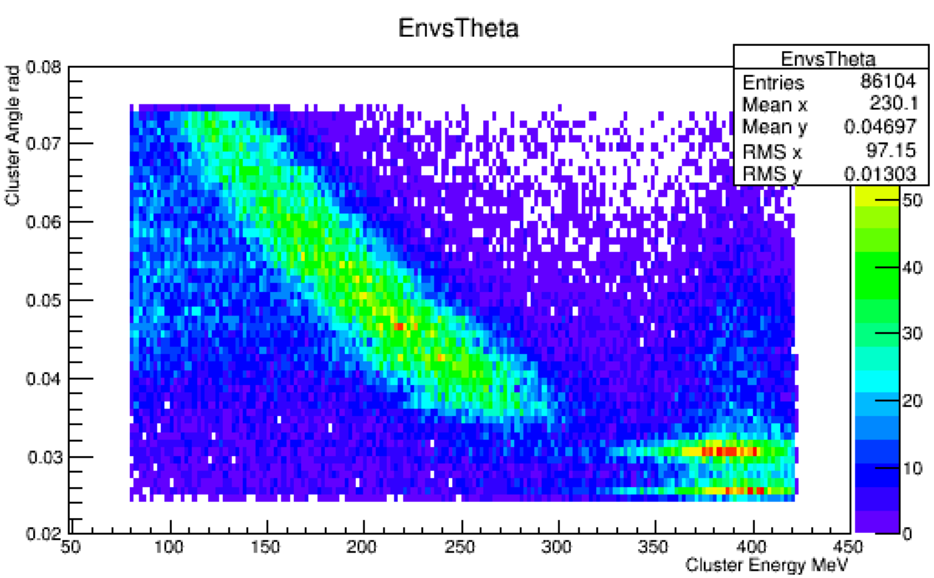
N(2cl)/NPoT ⟹ existence of X17
High statistical significance (small sensitivity loss due to small $\gamma\gamma$ BG)
No ETag related systematic errors

N(ee)/N($\gamma\gamma$) ⟹ existence of X17
Lower statistical significance due to smaller $\gamma\gamma$ cross section
Do not depend on N_{PoT} (no N_{PoT} systematic) error dominated by tagging efficiency

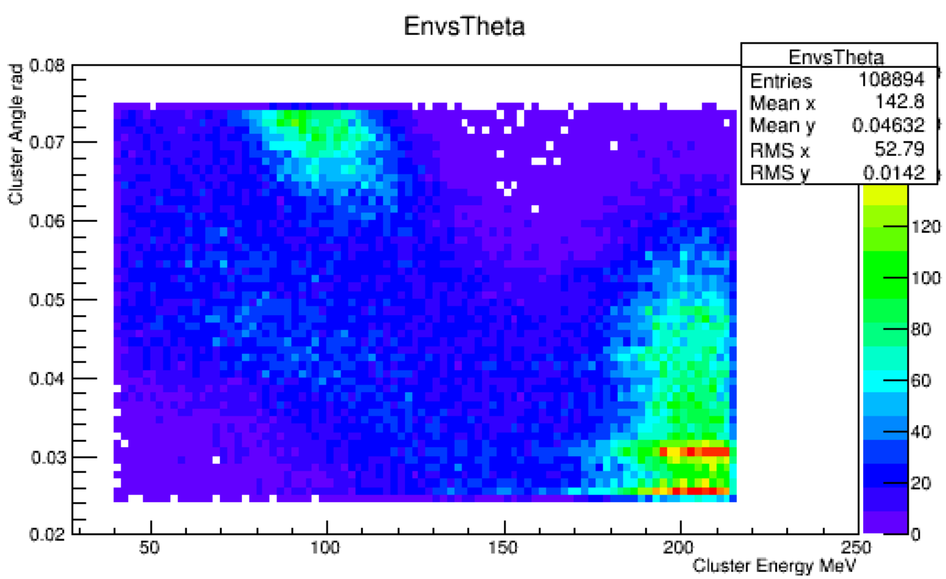
N_{e+e-}/N_{PoT} ⟹ vector nature of X_{17}
Systematic errors due to ETag tagging efficiency stability and N_{PoT}
$N_{\gamma\gamma}/N_{PoT}$ ⟹ pseudo-scalar nature of X_{17}
Systematic errors due to ETag tagging efficiency stability and N_{PoT}

First look at Run III off resonance data set

- PADME collected **two off resonance** data sets:
  - **Over Resonance: 402 MeV** 5 Runs for a total of **1.2E10 POT (collected 1w of October 2022)**
  - **Below Resonance: 205-211** MeV 5 energies for a total of **5E10 POT (last w of November 2022)**
- First selection aimed at **$N(2cl)/N_{PoT}$** studies:
  - 2 in time clusters in the $\Delta t < 5$ns in Ecal
  - Energy and radius cuts, reasonable Centre of Gravity
  - Cluster energy vs angle correlation compatible with a 2 body final state.



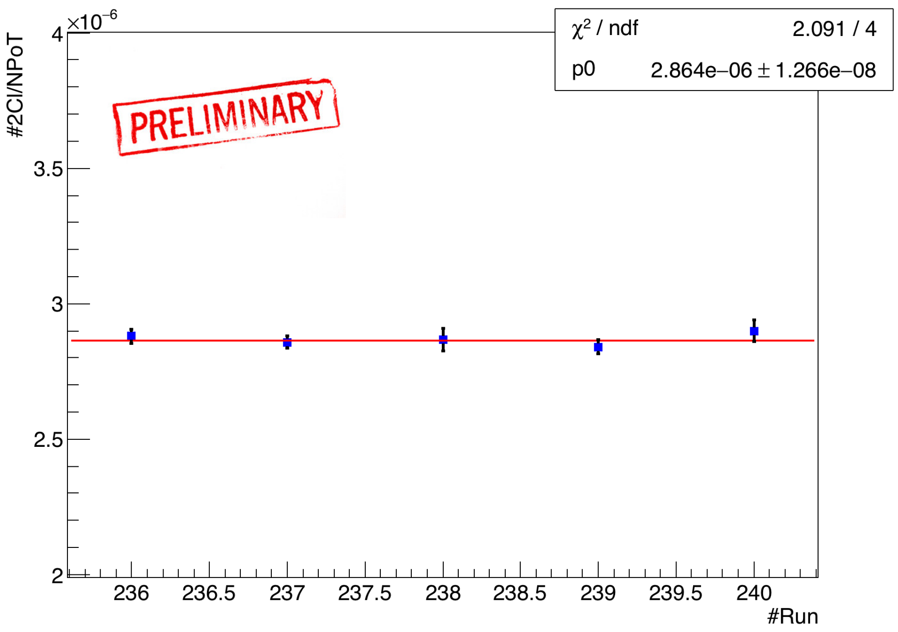
Over Resonance: 402 MeV



Below Resonance: 205 MeV

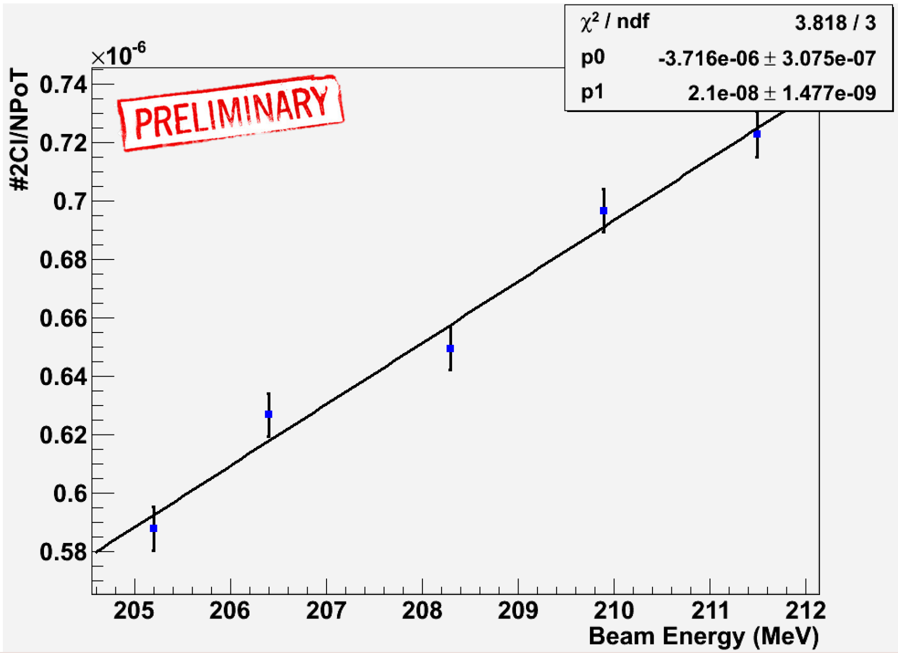
First look out of resonance data sets

Over resonance 402 MeV



- **RMS ~0.7%** over the 5 runs
  - compatible with pure statistic
- Constant **fit has a good χ^2**
  - No significant systematic errors
- Vertical scale arbitrary:
  - No acceptance correction applied

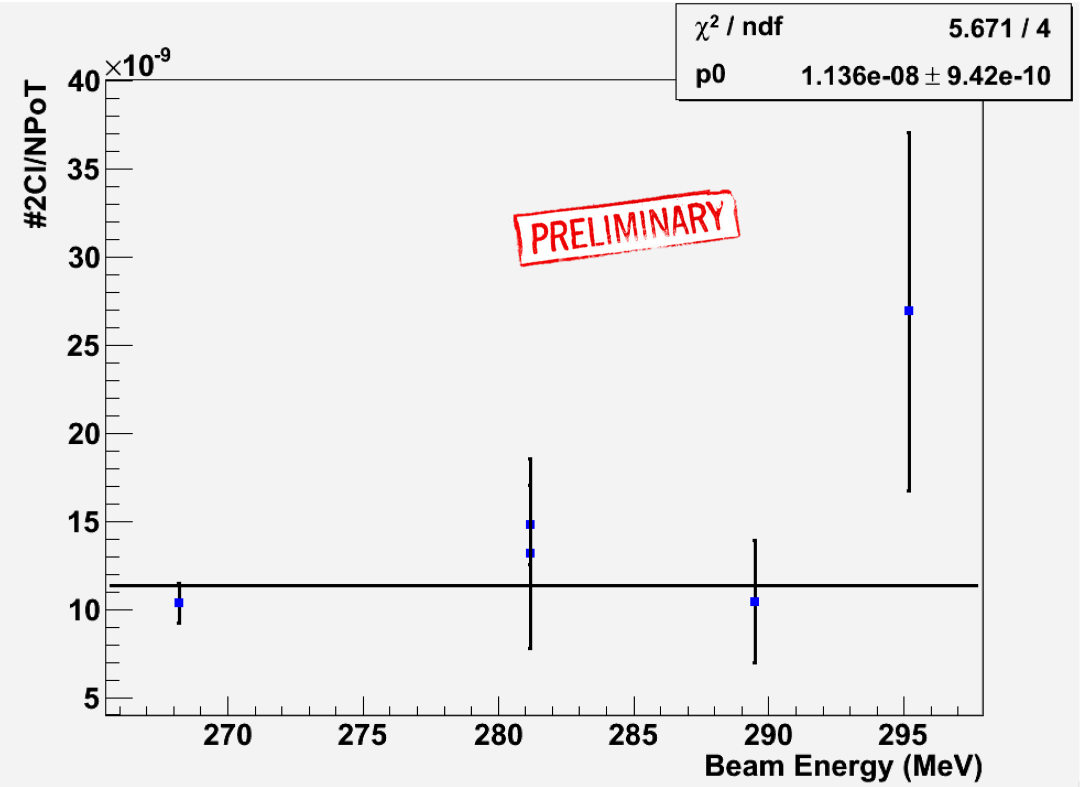
Below resonance



- **RMS <1%** over the 5 energies
  - computed on residuals wrt the fit
- Good χ^2 of the linear fit
  - Trend due to acceptance
  - Trend is reproduced by MC
- Vertical scale arbitrary:
  - No acceptance correction applied

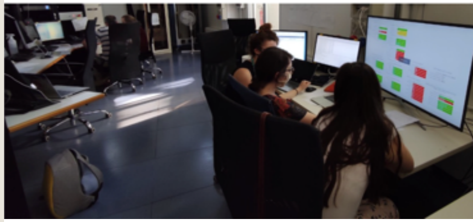
Beam background estimates

- **No target** data set is used **to measure the beam background** contamination in the data samples
  - The set contains data collected at different beam energies.
- Running the **same selection code** on the no target data we can get the contamination from beam halo background in the signal selection
  - **#2Cl(Data)/#2Cl(noTarget) = 3E-6/1E-8** is a few permille
  - **Background level seems stable.**



Conclusions

- PADME performed two physics runs, collecting ~$5 \cdot 10^{12}$ POT each
- **PADME Run III at the X_{17} CoME**, successfully terminated
  - 47 different energy points collected
  - High quality data collected for **16.35 MeV <M_{X17}<17.5 MeV**
  - Beam and BhaBha backgrounds are under control



- Data quality variable identified allowing to reject beam instabilities
- Stability of the ratio **#2Clusters/N_{PoT} on off resonance data <1%**
- Next steps:
  - Move into the closer sidebands (M_{X17}>17.25 MeV ?)
  - Improve data/MC agreement

We would like to thank the **LINAC and BTF teams** and all the **LNF accelerator division** for the excellent efficiency and quality of the machine operation during PADME Run III.

Improving production rates

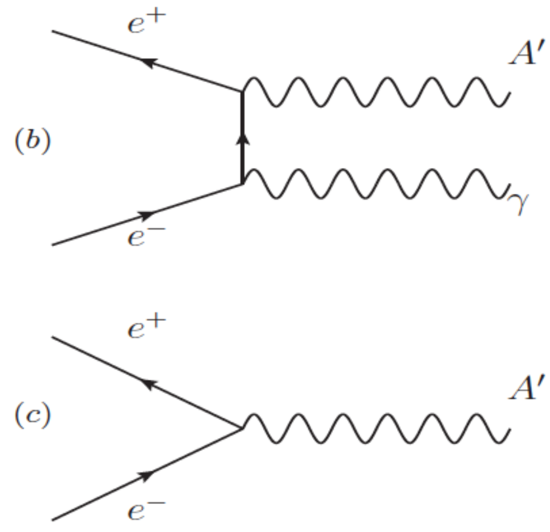
- We need higher production cross section!
- Can move from associated to resonant production
  - b) Radiative annihilation $O(\alpha^2)$

$$\sigma_{nr} = \frac{8\pi\alpha^2}{s}\left[\left(\frac{s-m_{A'}^2}{2s}+\frac{m_{A'}^2}{s-m_{A'}^2}\right)\log\frac{s}{m_e^2}-\frac{s-m_{A'}^2}{2s}\right]$$

  - c) Resonant annihilation $O(\alpha)$

$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak}\frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2+\Gamma_{A'}^2/4} \qquad \sigma_{\rm peak} = 12\pi/m_{A'}^2$$

Positron beams



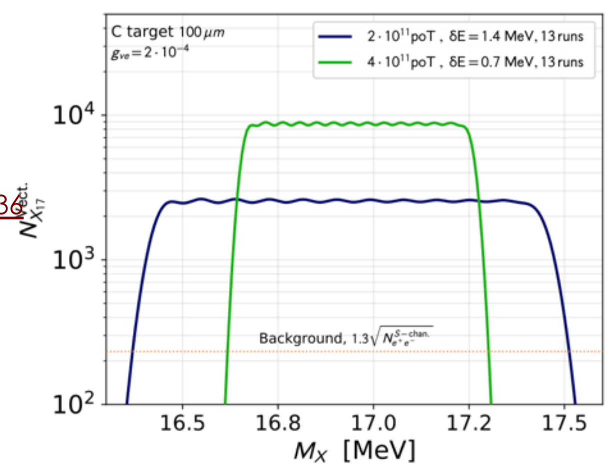
- **Resonant:** Profit for a higher production in a tiny mass region

$$N_{X_{17}}^{\rm Vect.} \simeq 1.8\cdot10^{-7} \times \left(\frac{g_{ve}}{2\cdot10^{-4}}\right)^2 \left(\frac{1\ \rm MeV}{\sigma_E}\right)$$

$$N_{X_{17}}^{\rm ALP} \simeq 5.8\cdot10^{-7} \times \left(\frac{g_{ae}}{\rm GeV^{-1}}\right)^2 \left(\frac{1\ \rm MeV}{\sigma_E}\right)$$

Darmé et al. Phys. Rev. D 106,115036

  - **Thousands** of events with just **1E10 PoT**



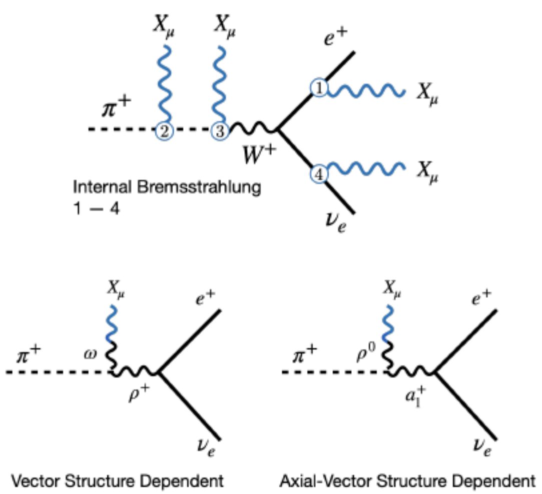
On the vector hypothesis

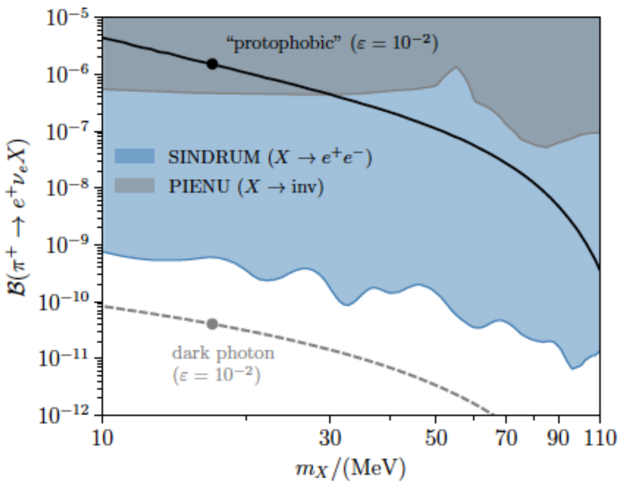
Pion decay constraints on exotic 17 MeV vector bosons

Matheus Hostert[1,2,3] and Maxim Pospelov[1,2]

arxiv.2306.15077.pdf

We derive constraints on the couplings of light vector particles to all first-generation Standard Model fermions using leptonic decays of the charged pion, $\pi^+ \to e^+ \nu_e X_\mu$. In models where the net charge to which X_μ couples to is not conserved, no lepton helicity flip is required for the decay to happen, enhancing the decay rate by factors of $\mathcal{O}(m_\pi^4/m_e^2 m_X^2)$. A past search at the SINDRUM-I spectrometer severely constrains this possibility. In the context of the hypothesized 17 MeV particle proposed to explain anomalous ^{8}Be, ^{4}He, and ^{12}C nuclear transitions claimed by the ATOMKI experiment, this limit rules out vector-boson explanations and poses strong limits on axial-vector ones.





Summary on X17 constraints

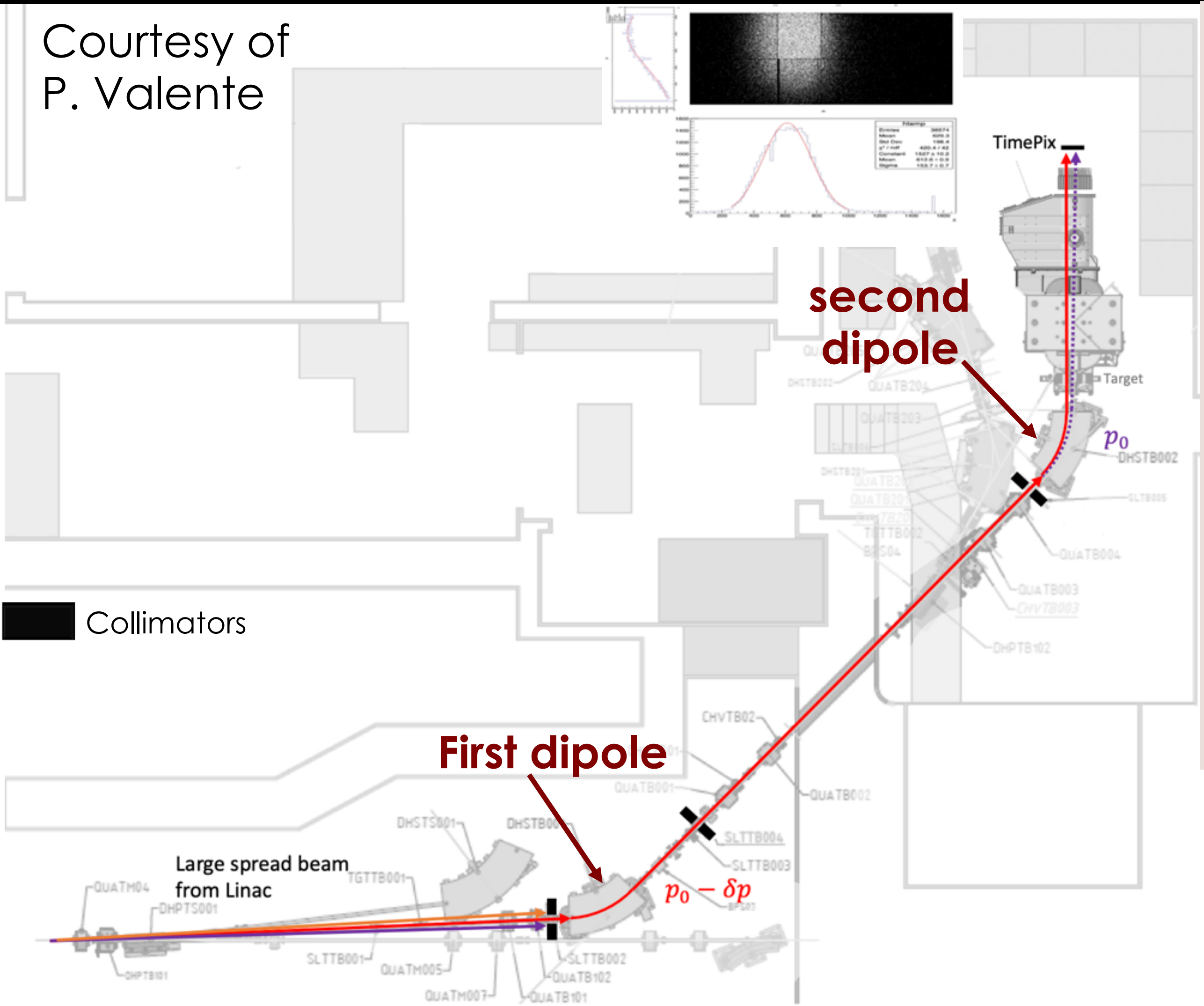
To summarize this section, a model with a vector mediator explaining the ATOMKI anomaly at a minimum needs to fulfill the following requirements:

- feature a vector mediator with mass $m_X \approx 17$ MeV,
- X needs to couple to neutrons with strength $|\varepsilon_n| \approx 0.0058$,
- X needs to couple to protons with strength $|\varepsilon_p| \approx 0.0024$,
- the product of neutron and proton couplings of X need to fulfill $\varepsilon_n \varepsilon_p > 0$,
- the coupling of X to electrons needs to be either $|\varepsilon_e| \in [0.63, 1.2] \times 10^{-3}$ or $|\varepsilon_e| < 10^{-12}$ for $\mathrm{BR}(X \to e^+e^-) = 1$, and
- the coupling of X to electron neutrinos needs to be smaller than $|\varepsilon_{\nu_e}| < 3 \times 10^{-6}$.

Finally, a new mediator that explains the ATOMKI anomaly is only required to couple to first generation fermions; if it also couples to the other generation potentially more constraints need to be taken into account.

Obtaining energy steps and resolution

Courtesy of P. Valente



Collimators

Use the first dipole magnet and collimators to select energy

- dp ∝ collimator aperture.

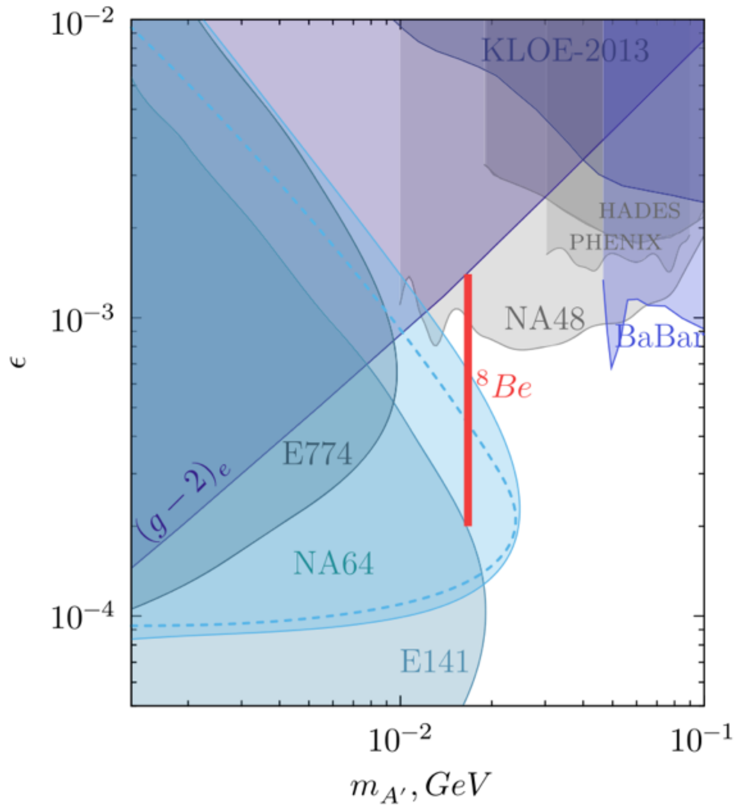
Change the first dipole magnet current to change the energy

Correct the trajectory using second dipole to put the beam back on axis at PADME

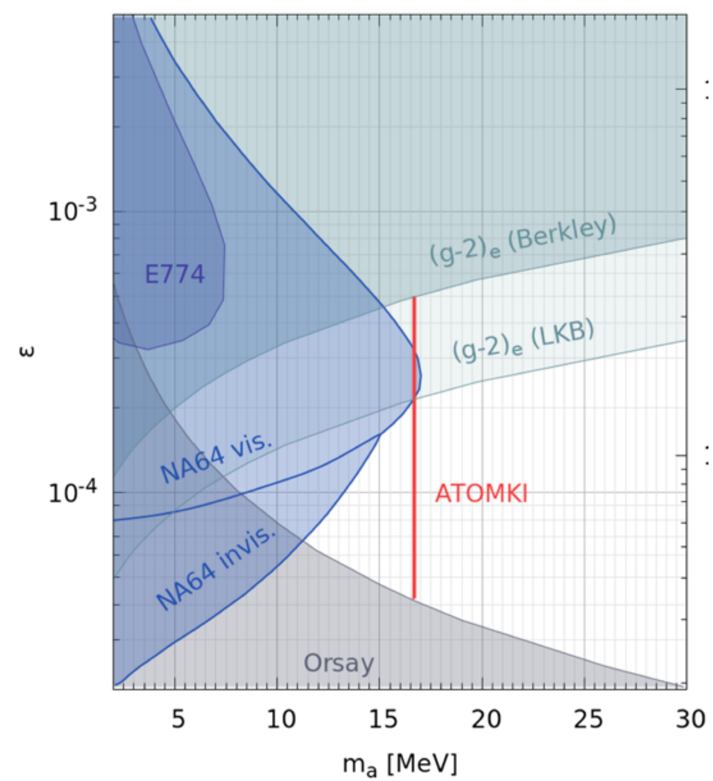
Measure the displacement at the target and timePix to measure the energy step performed

Current constraints on X17 from leptons

Phys. Rev. D 101, 071101 (R) (2020)



Phys. Rev. D 104, L111102 (2021)



X17 as a vector particle:

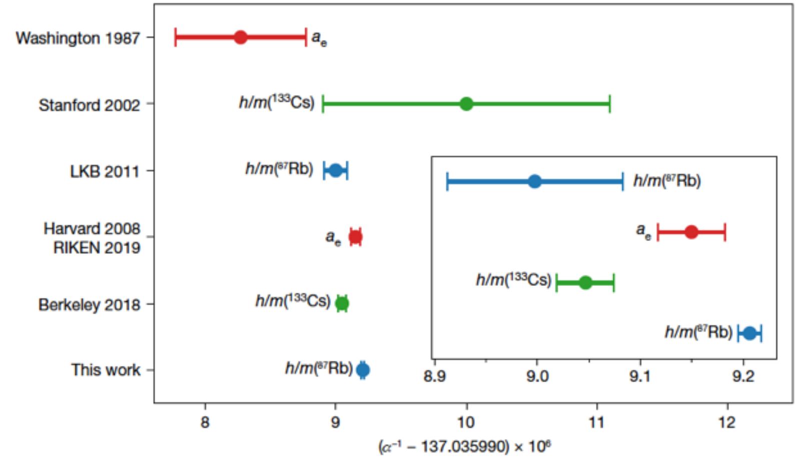
- LKB $(g-2)_e$ bound weaker for vector and model dependent
- NA48/2 bound not valid for "protophobic" X17
- Still a lot of free parameter space for vector X17

X17 as pseudo scalar particle:

- $(g-2)_e$ bound stronger for pseudo scalars
- Still model dependent and with big data uncertainties
- Almost unconstrained parameter space for X17

g-2e anomaly

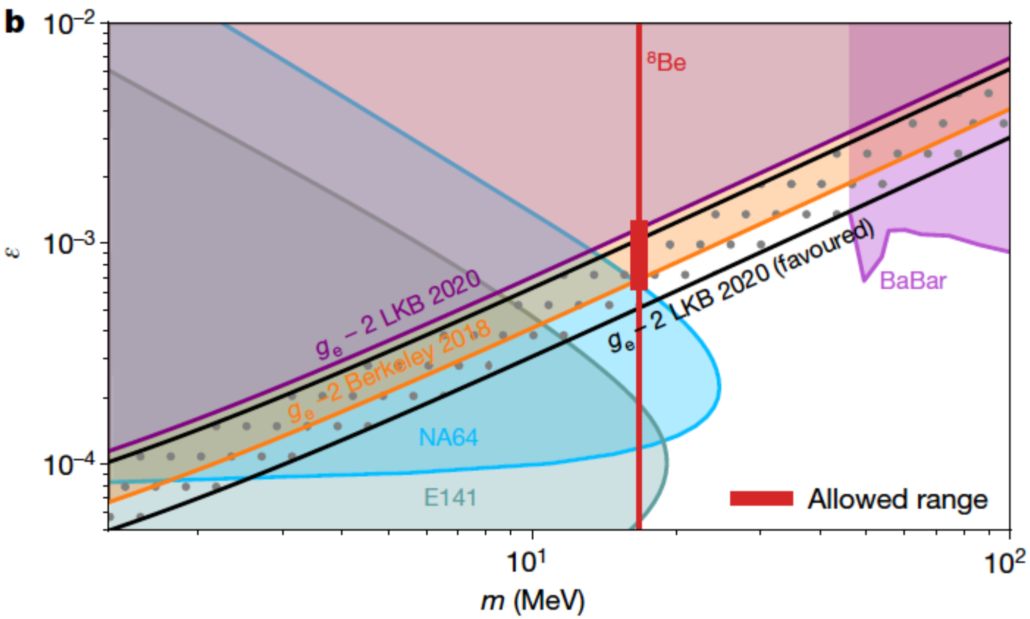
- Significant discrepancy in the last two results on the α determination
- Produce a modified $(g\text{-}2)_e$ exclusion which allows a region of existence of X17



$$\alpha^{-1} = 137.035999206(11).$$

The uncertainty contribution from the ratio $h/m(^{87}Rb)$ is 2.4×10^{-11} (statistical) and 6.8×10^{-11} (systematic). Our result improves the

https://www.nature.com/articles/s41586-020-2964-7



experimental measurement $a_{e,exp}$ (ref. [9]) gives $\delta a_e = a_{e,exp} - a_e(\alpha_{LKB2020}) = (4.8 \pm 3.0) \times 10^{-13}$ ($+1.6\sigma$), whereas comparison with caesium recoil measurements gives $\delta' a_e = a_{e,exp} - a_e(\alpha_{Berkeley}) = (-8.8 \pm 3.6) \times 10^{-13}$ (-2.4σ). The uncertainty on δa_e is dominated by $a_{e,exp}$.