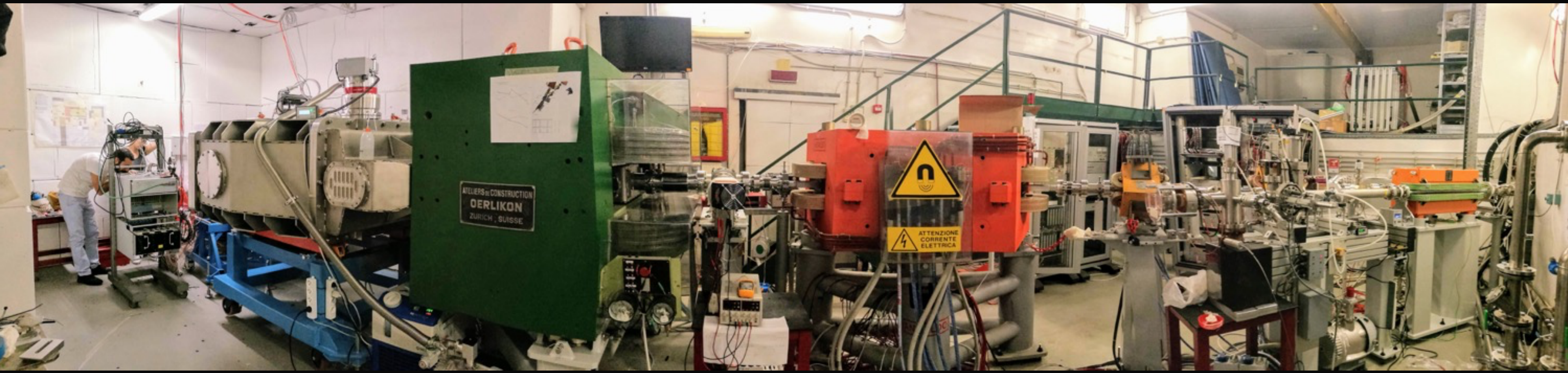
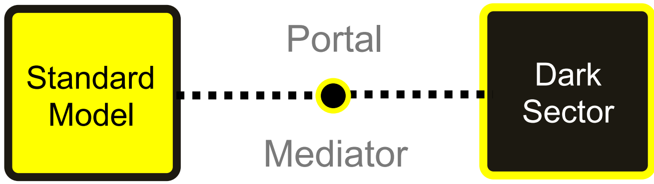
PADME X17 sensitivity update



Mauro Raggi for the PADME collaboration,
Sapienza Università di Roma e INFN Roma

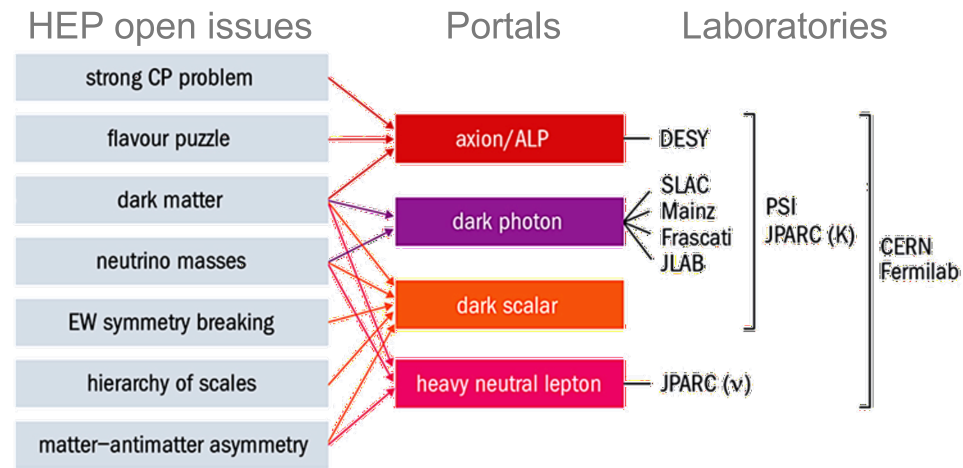
WIFAI workshop Nov 8 – 10, 2023
Dipartimento di Architettura dell'Università Roma Tre

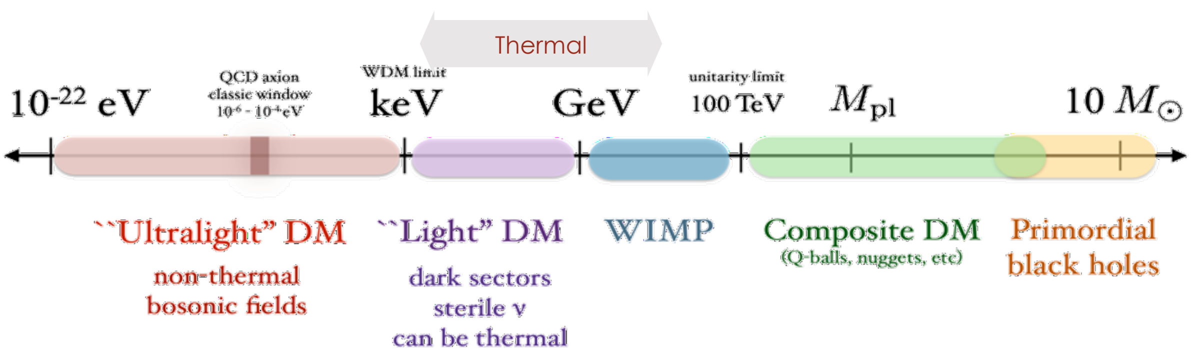
The dark sector paradigm



Feeble, non-gravitational interaction with ordinary matter

- **Dark matter**
- Dark forces
- Other dark particles



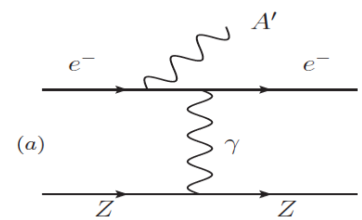


- Dark sector candidates can explain SM anomalies: (g-2)μ, ^{8}Be, proton radius
- The mediator can have a **small mass (MeV -100 MeV)**
- Due to its **small mass** the mediator can be **produced at low energy accelerators**
- It can **decay back to ordinary matter "visible"** on **not "invisible"**

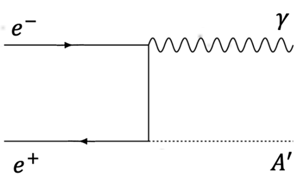
Experimental approaches

- **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 electron/protons** beam is absorbed (NA64, old dump experiments)
  - **Thin target** searching for bumps in ee 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**)

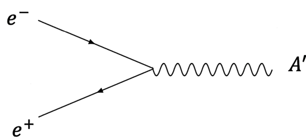
Brems.



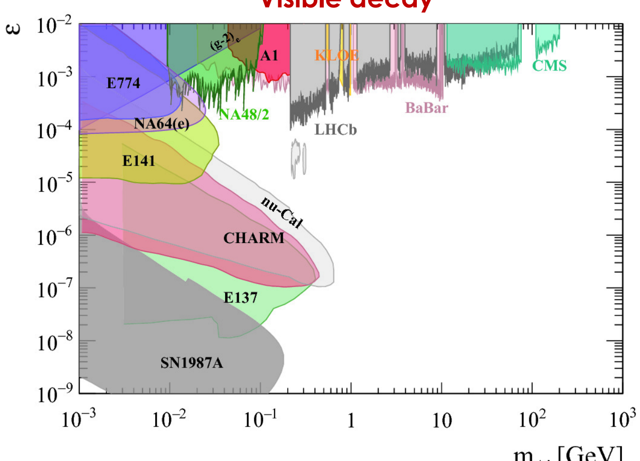
Associated production



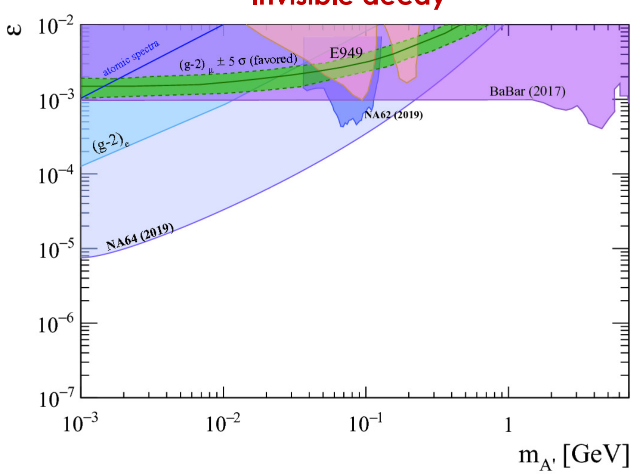
Resonant

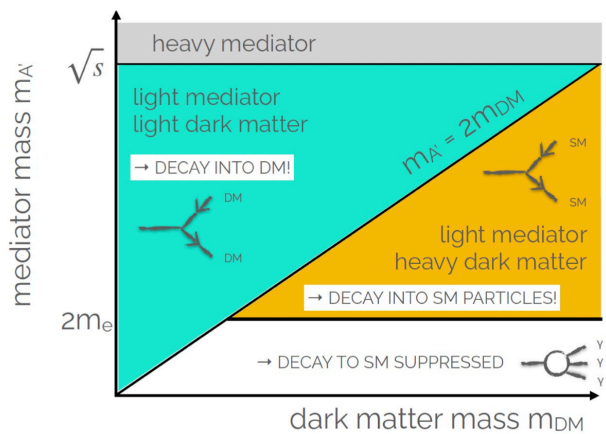


Visible decay



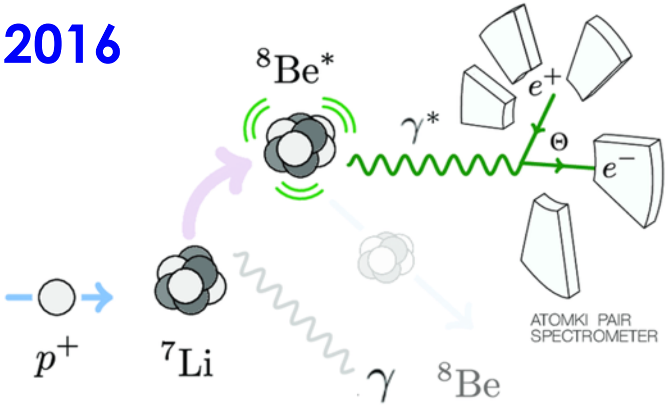
Invisible decay

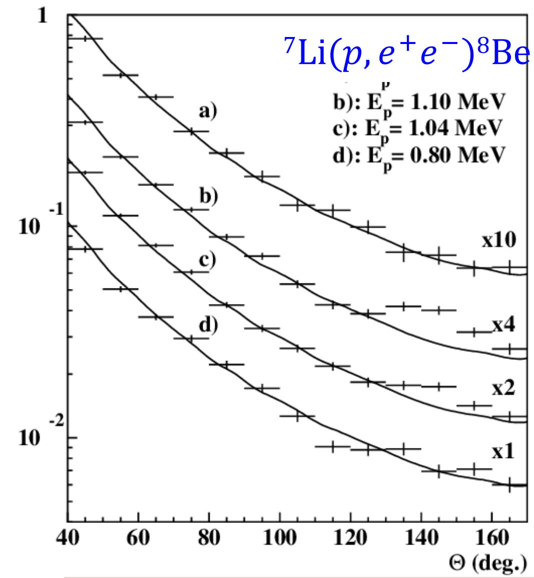




The ^{8}Be and ^{4}He Atomki anomaly

2016

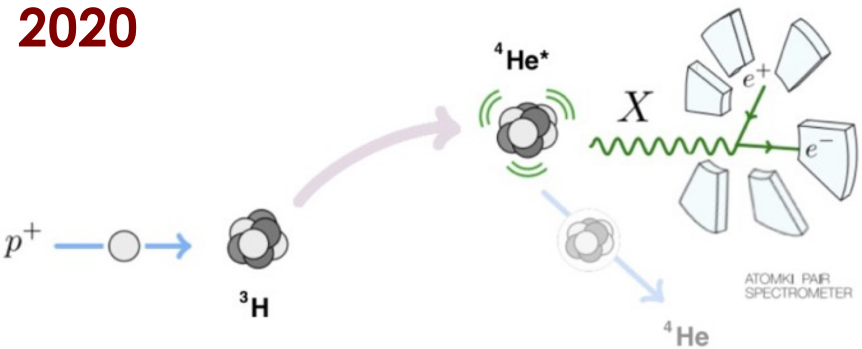


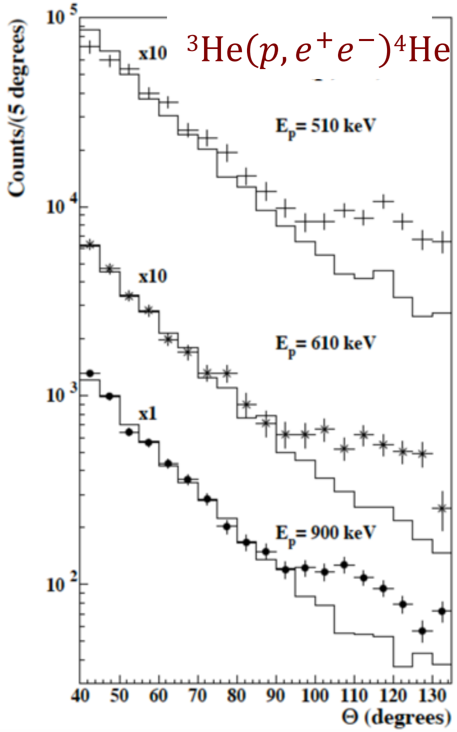


$m_X c^2 = 17.01 \pm 0.16(\mathrm{tot})$ MeV

PRL 116, 042501 (2016)

2020





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

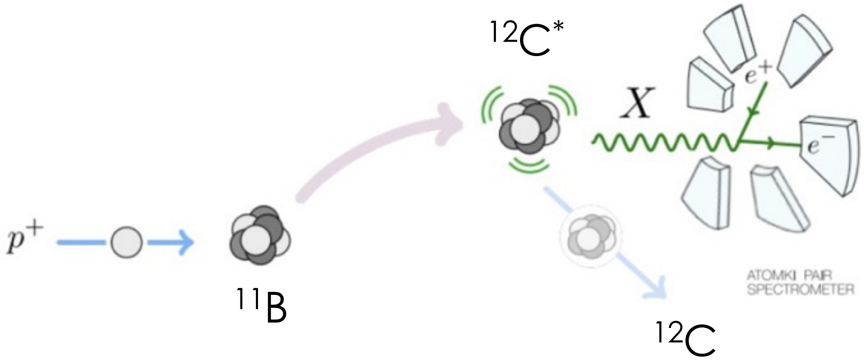
Phys. Rev. C 104, 044003 (2021)

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



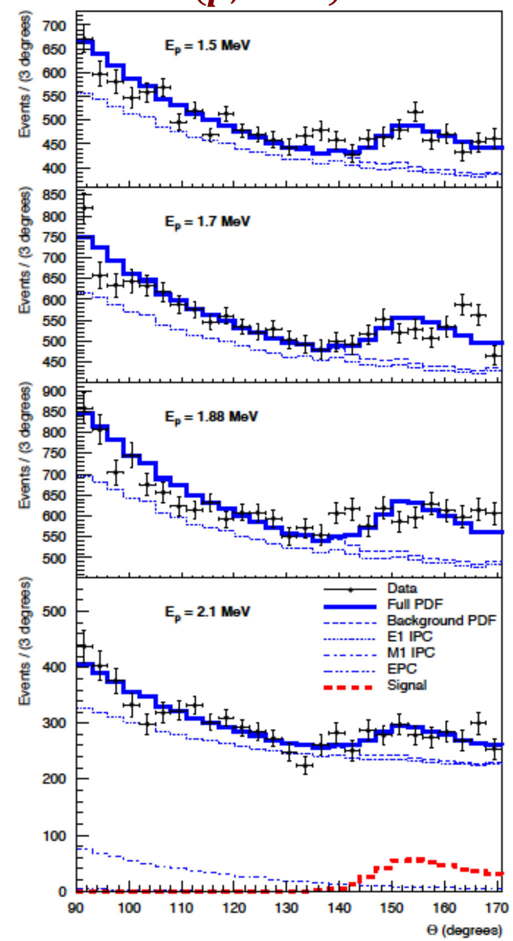
E = 17.23 MeV excited state of ^{12}C

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 high significance

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



On the nature of X17

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

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

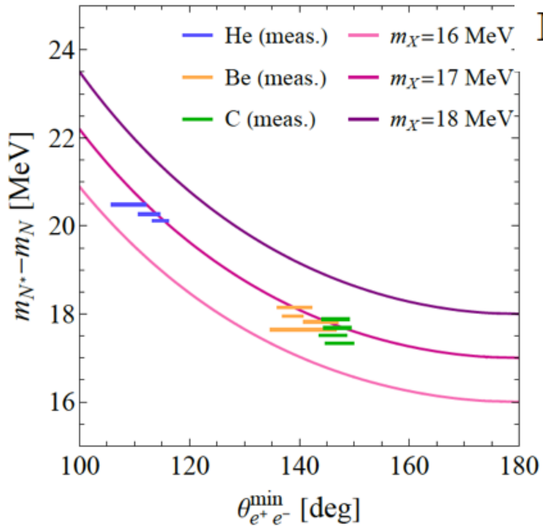
Jonathan L. Feng,* Tim M. P. Tait,† and Christopher B. Verhaaren‡
Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

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



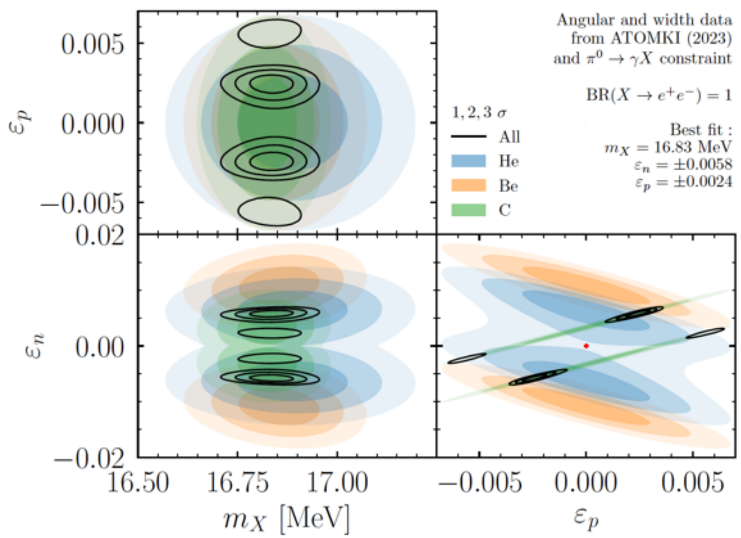
Neutrino Constraints and the ATOMKI X17 Anomaly

[Phys. Rev. D **108**, 015009](#)

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

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



Using width for each element: 3 measurements

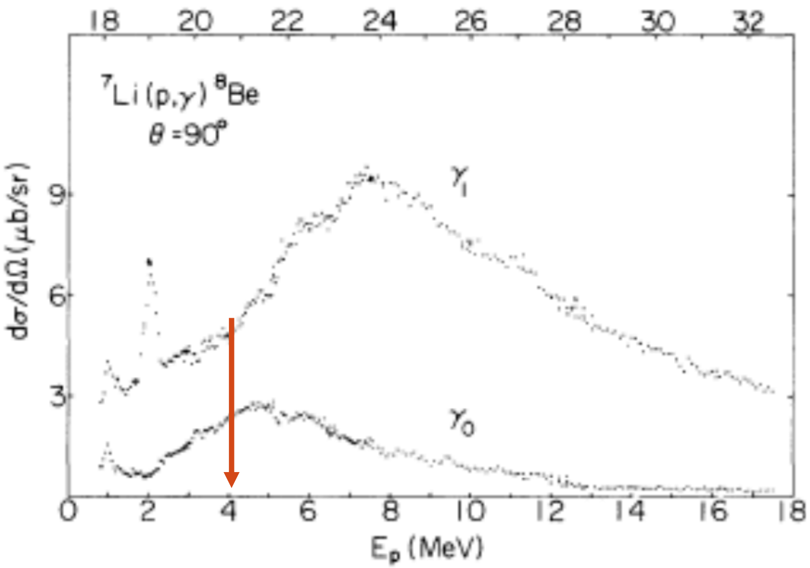
Next, we add in to the analysis the latest width information from each element and include a prior on ε_p since X needs to couple to protons and/or neutrons on the production size. There is a stronger constraint

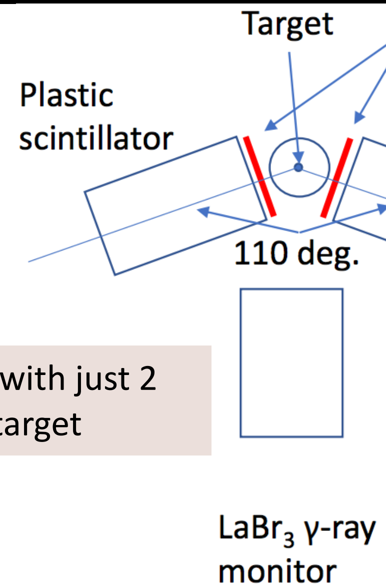
see the next section for more information. We find an okay fit to the data at the same mass $m_X = 16.83$ MeV, $\varepsilon_n = \pm 5.8 \times 10^{-3}$, and $\varepsilon_p = \pm 2.4 \times 10^{-3}$, see fig. 2. We note that the signs of ε_n and ε_p must be the same due to the non-trivial degeneracy structure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

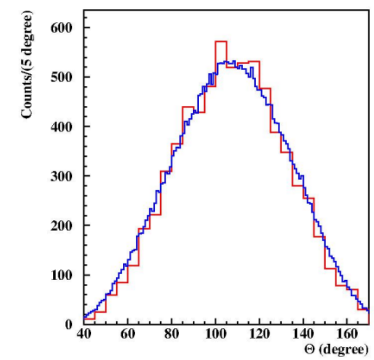
Anomaly on the ^{8}Be GDR

ATOMKI moved it's experiment on the 8Be Giant Dipole Resonance
Bombarding energy is now ~4 MeV on ^{7}Li target. [arXiv:2308.06473v1]



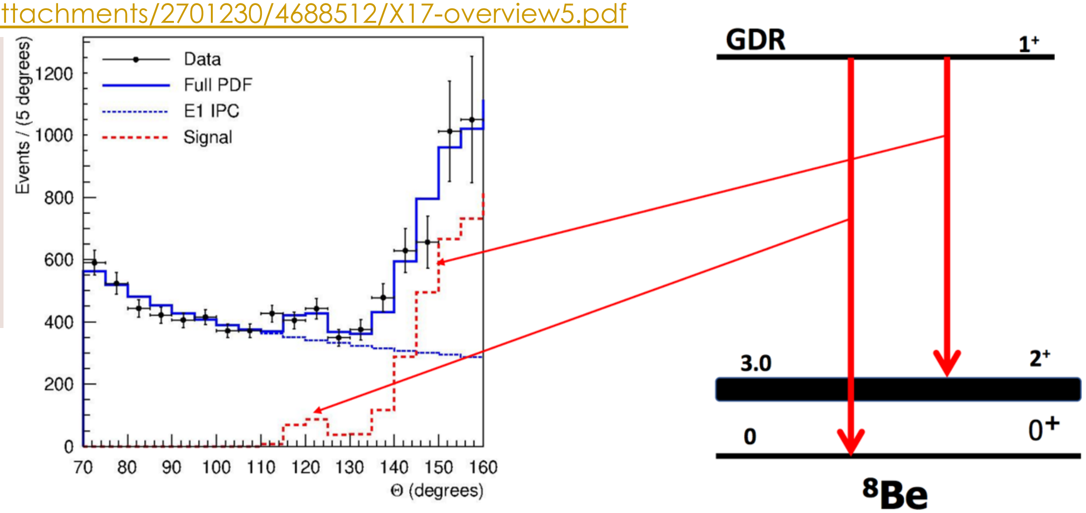


New spectrometer with just 2 arms very close to target



https://indico.cern.ch/event/1258038/contributions/5538279/attachments/2701230/4688512/X17-overview5.pdf

Two anomalous peak observed:
~120° and >140°
compatible with different GDR decays to lower energy states 2$^+$ and 0$^+$
Observed angles are again compatible with 17 MeV mass.

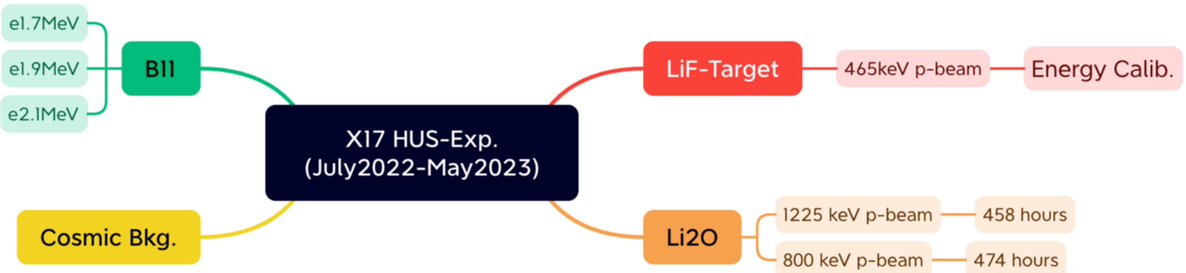


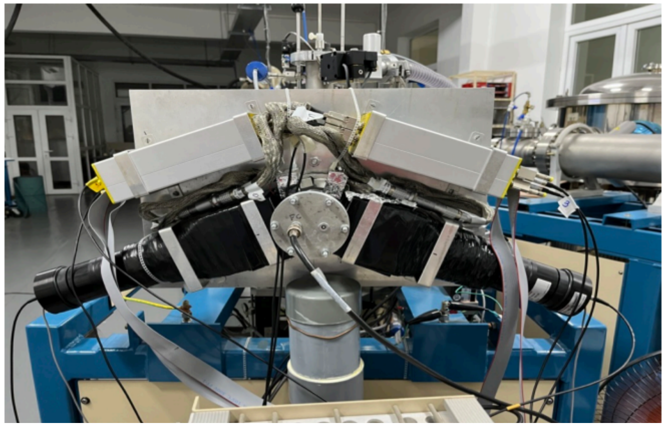
Confirmation by Vietnam group

IPC experiment repeated by Hanoi University using pelletron accelerator

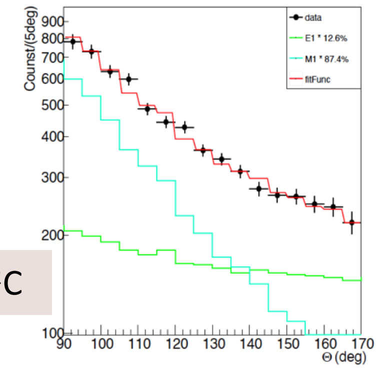
2 arm spectrometer like the one used by ATOMKI on the giant resonance

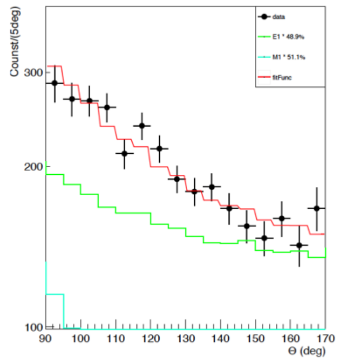
^{12}C and ^{8}Be tested at different bombarding energies

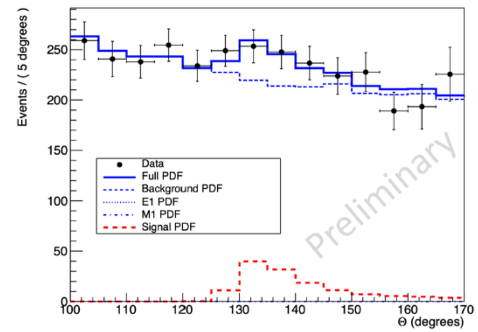




Anomaly confirmed in both ^{8}Be and ^{12}C

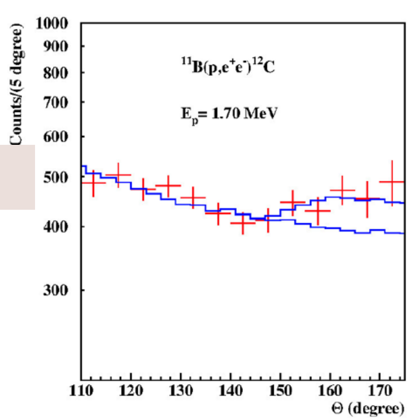


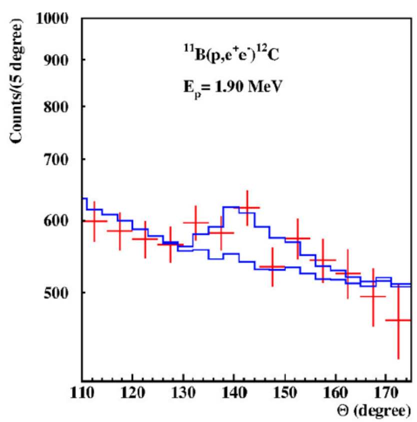


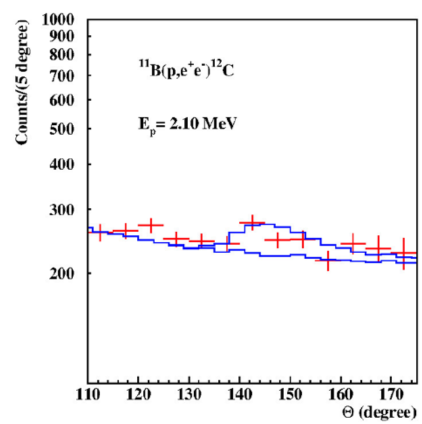


Talk given at ISMD 2023

https://indico.cern.ch/event/1258038/contributions/5538280/attachments/2700698/4687589/X17%20HUS%20ISMD2023.pdf





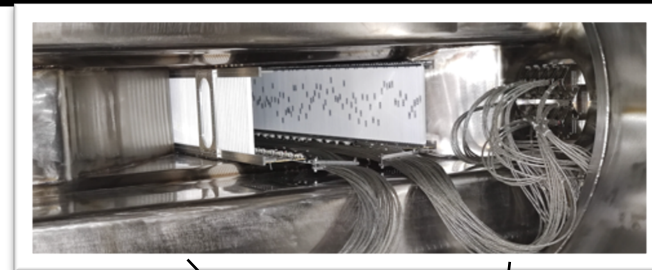


PADME Run I and Run II setup

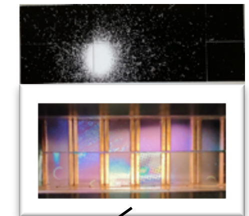
- Positron beam of ~**0.5 GeV/c**
  - LINAC repetition rate 50 Hz
  - Macro-bunches maximum length $\Delta t \lesssim$**300 ns**
- Number of annihilations proportional to:

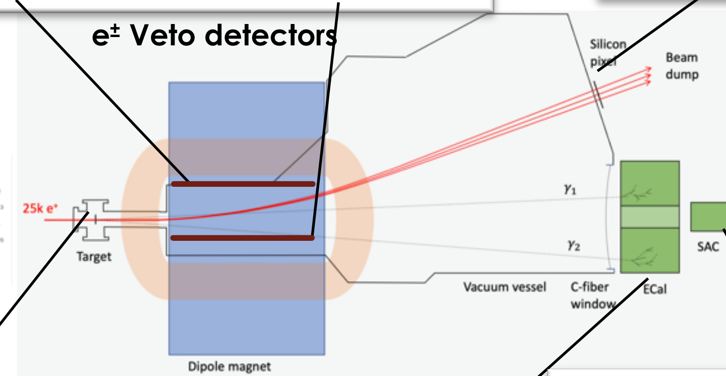
$$N_{beam}^{e^+} \times N_{target}^{e^-}$$

  - 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

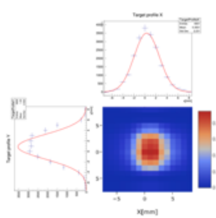


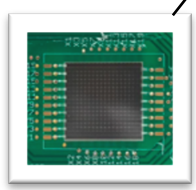
Silicon **pixel** (TimePix3)



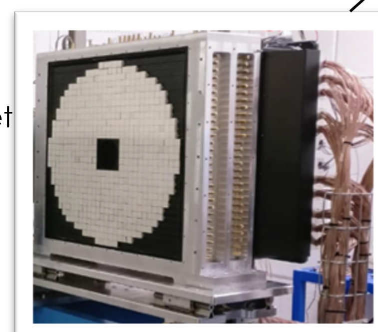


SAC





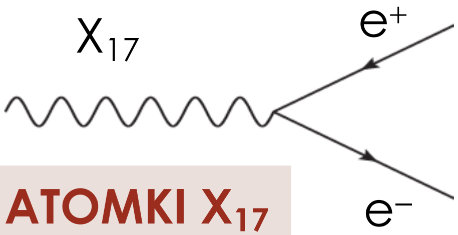
Active **diamond** target
100 μm thick



BGO calorimeter (ECAL)

small angle calo
SAC PbF_2

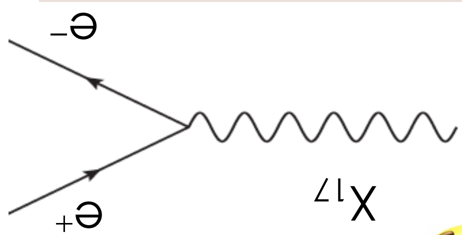
PADME X17: the resonance search



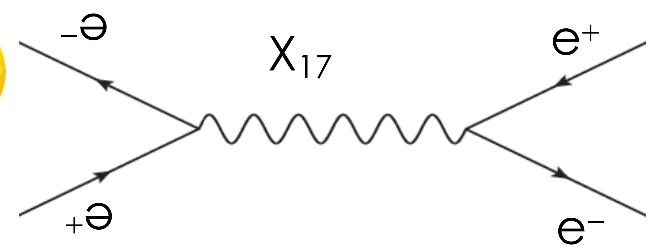
ATOMKI X_{17}

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

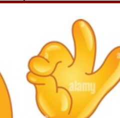
Extremely small Γ_{X17} $\Gamma_{A'} \simeq \epsilon^2 \alpha m_{A'}/3$ $<10^{-2}$ eV

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!

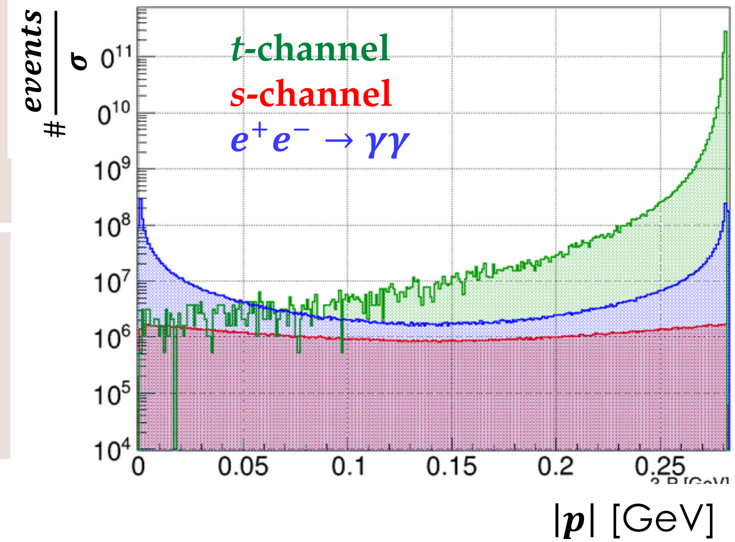


The mass scan X17 search strategy

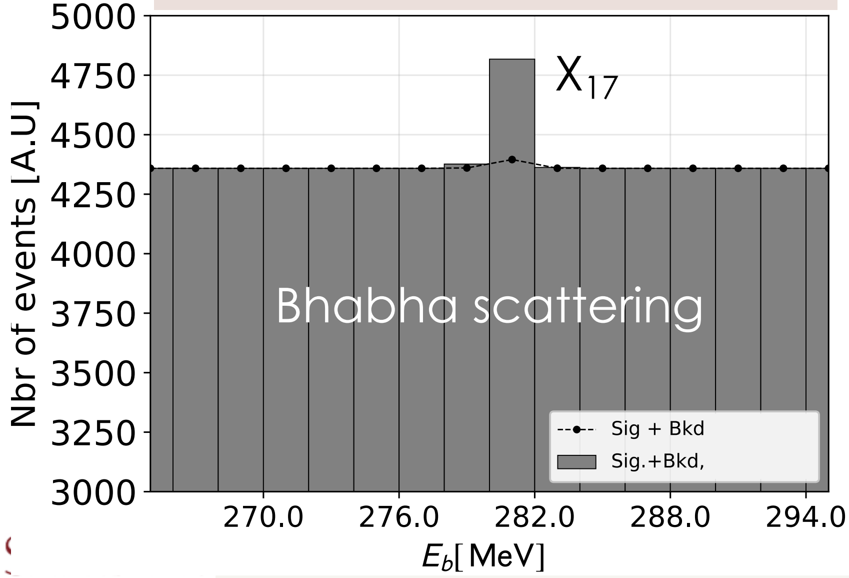
PADME, can use resonant X17 production process

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

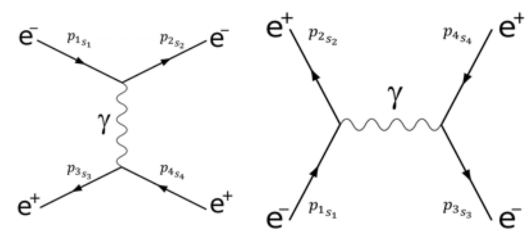
- Completely data driven no theory or MC input
- Signal should emerge on top of **Bhabha** BG in one or more points of the scan.
- Background estimated from surrounding bins



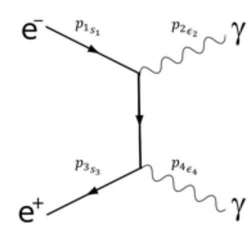
Cartoon view of the technique



Bhabha scattering



t channel   *s* channel



$e^+e^- \to \gamma\gamma$

PADME Run III on resonance data set

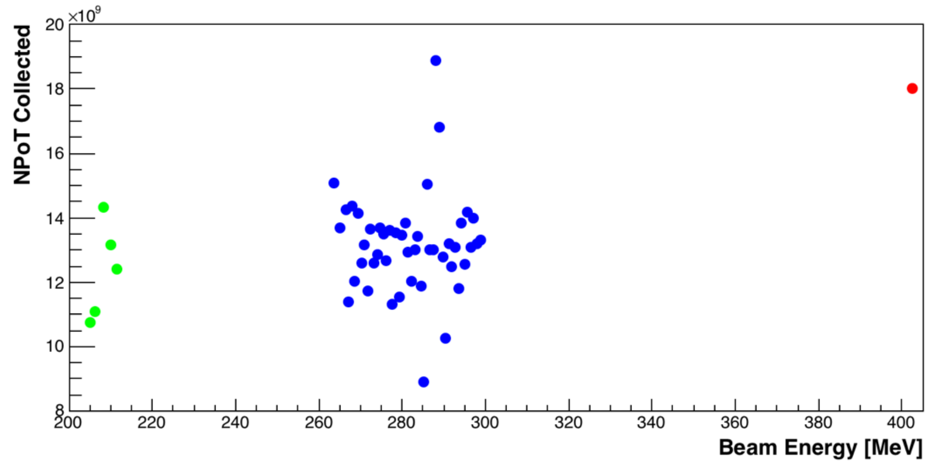
Run III PADME data set contains **3 subset**
- **On resonance: 47 points (263-299) MeV**
- **Below resonance: 5 points (205-211) MeV**
- **Over resonance: 1 energy 402. MeV**

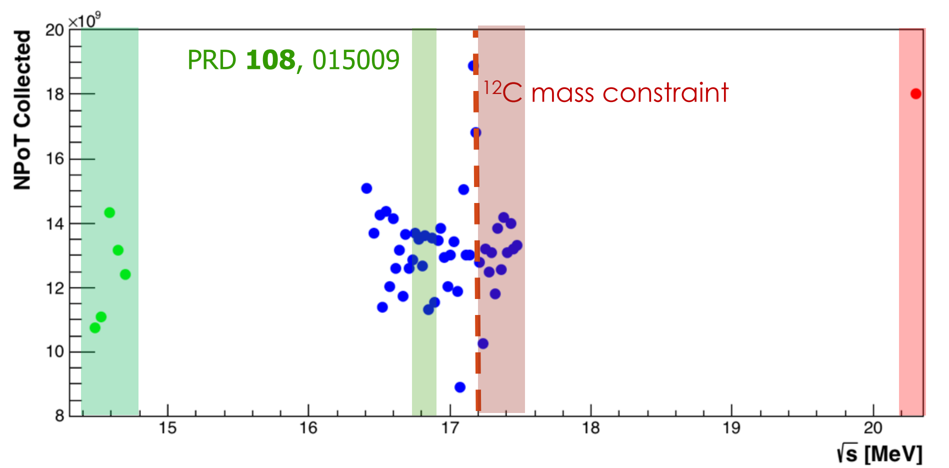
On resonance points **spaced** by **~0.75 MeV**
Point spacing equal to the energy resolution
Mass region 16.4 MeV<M_{X17}<17.5 MeV
statistics >1x10^{10} PoT per point
The PADME precision on M_{X17} measurement:
ΔM_{X17}=(17.47-16.36)/47 ~ 20 KeV

Below resonance **spaced** by **~1.5 MeV**
Statistics >1x10^{10} PoT per point
Used to validate analysis method

1 over resonance energy **5 different runs**
Statistics ~0.4x10^{10} PoT per run ~2E10 total
Used to validate NPoT measurement stability

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



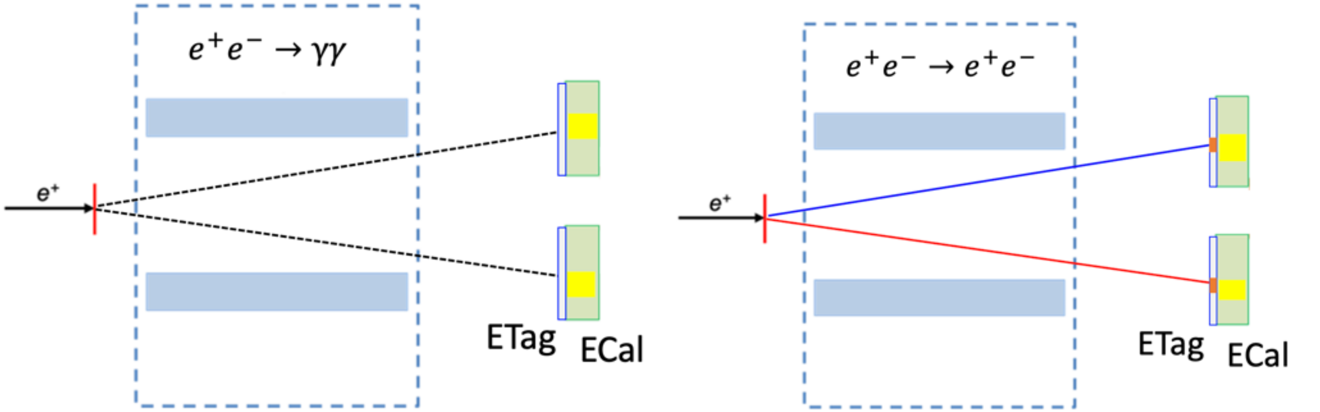


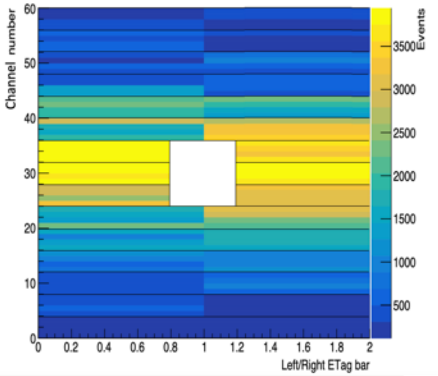
GREEN mass range fit results in PRD **108**, 015009
Dots mass values explored by PADME
17.2 MeV mass limit imposed by ^{12}C observation

PADME Run III modified setup

- Using PADME veto is impossible to reconstruct $e^+ e^-$ mass having no vertex info
- Idea: identify $e^+e^- \to e^+e^-$ 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

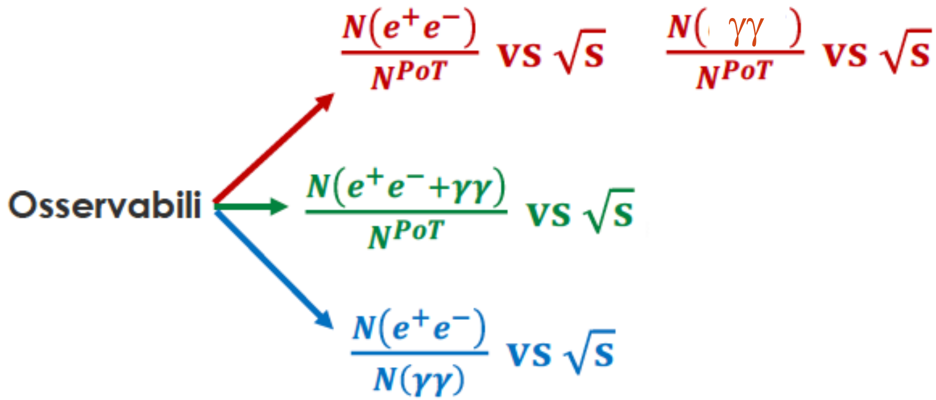




- Thanks to the enhanced production cross section can reduce N_{POT}/bunch by factor 10.
- Much lower pile-up and better energy resolution

X17 observables at PADME

Several different observables can be used with different systematics



N(2cl)/NPoT ⟹ existence of X17
High statistical significance (small sensitivity loss due to small only 20% $\gamma\gamma$ BG)
No ETag related systematic errors

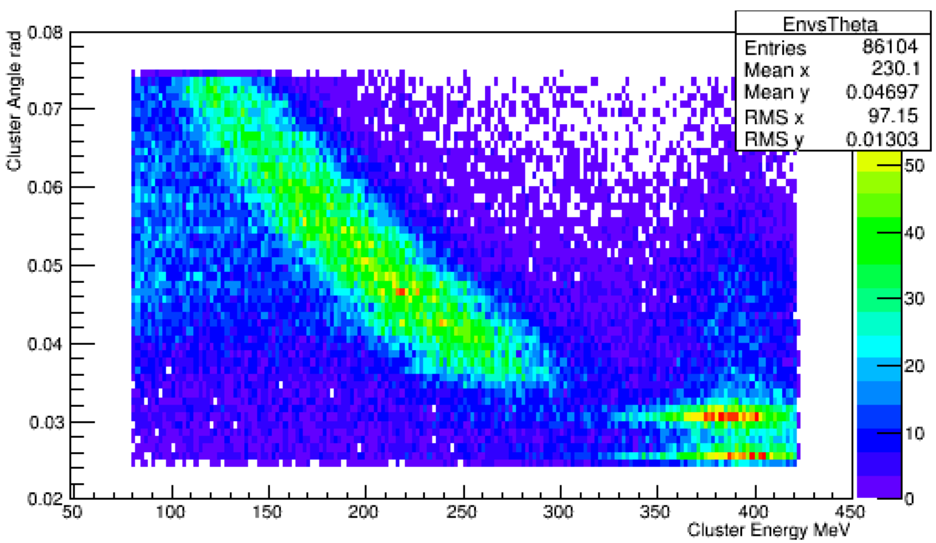
N(ee)/N($\gamma\gamma$) ⟹ existence of X17
Lower statistical significance due to smaller $\gamma\gamma$ cross section
Do not depend on N_{PoT} (no N_{PoT} systematic) error dominated by tagging efficiency

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}

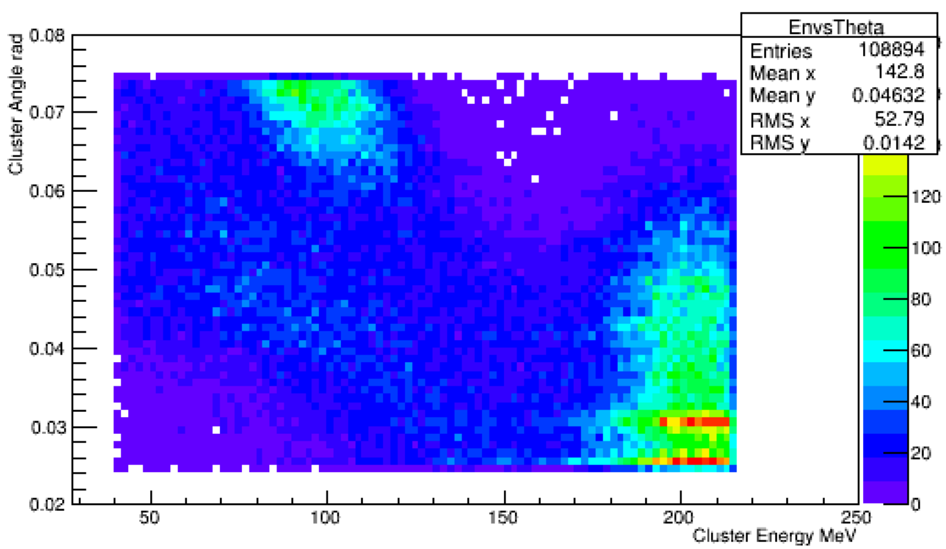
First look at Run III off resonance data set

- **PADME collected two off resonance data sets:**
  - Over Resonance: 402 MeV 5 Runs for a total of 1.2E10 POT (1w of October 22)
  - Below Resonance: 205-211 MeV 5 energies for a total of 6.5E10 POT (last w of Nov. 22)
- **First selection aimed at N(2cl)/NPoT studies:**
  - 2 in time clusters in the Dt < 5ns 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

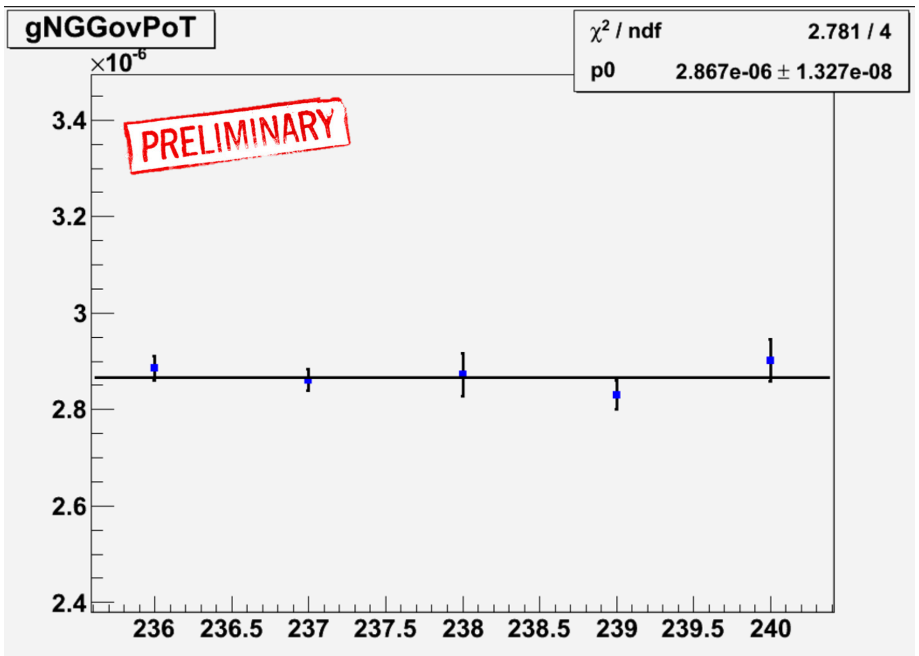


Below Resonance: 205 MeV



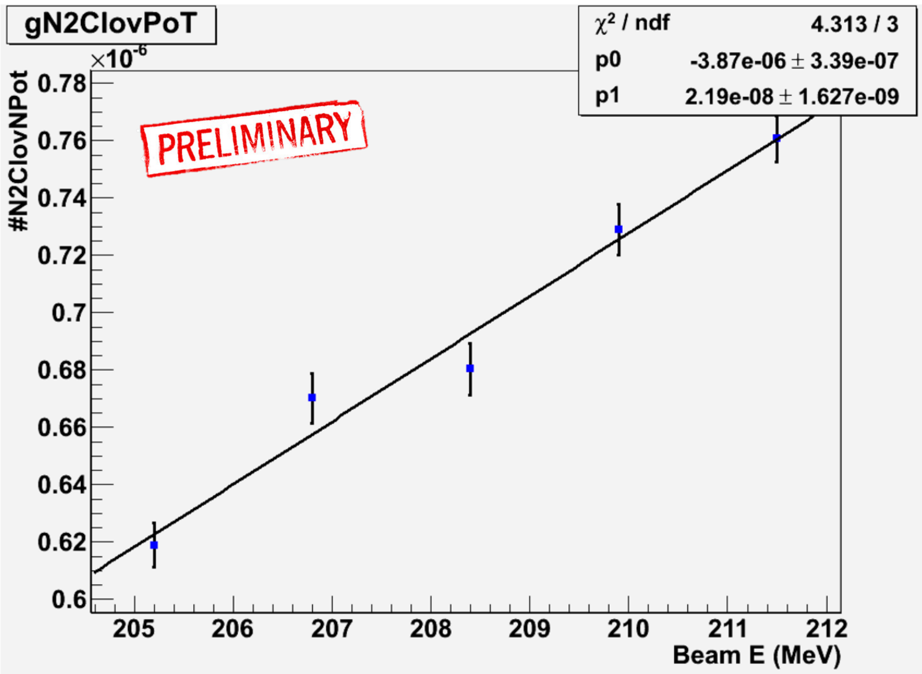
First look out of resonance data sets

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

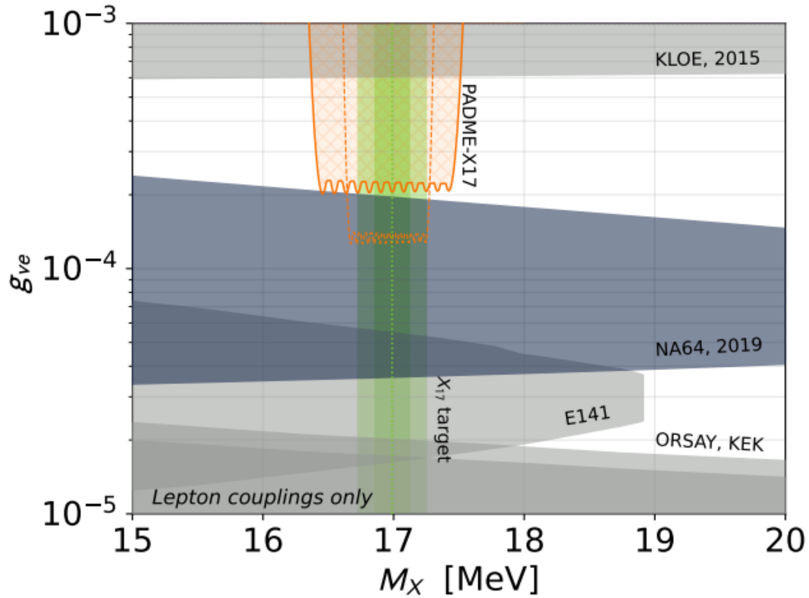


- **RMS <1%** over the 5 energies
  - computed on residuals wrt the fit
- Good χ^2 of the linear fit
  - Trend due to acceptance
  - Trend is reproduced by MC
- Vertical scale arbitrary:
  - No acceptance correction applied

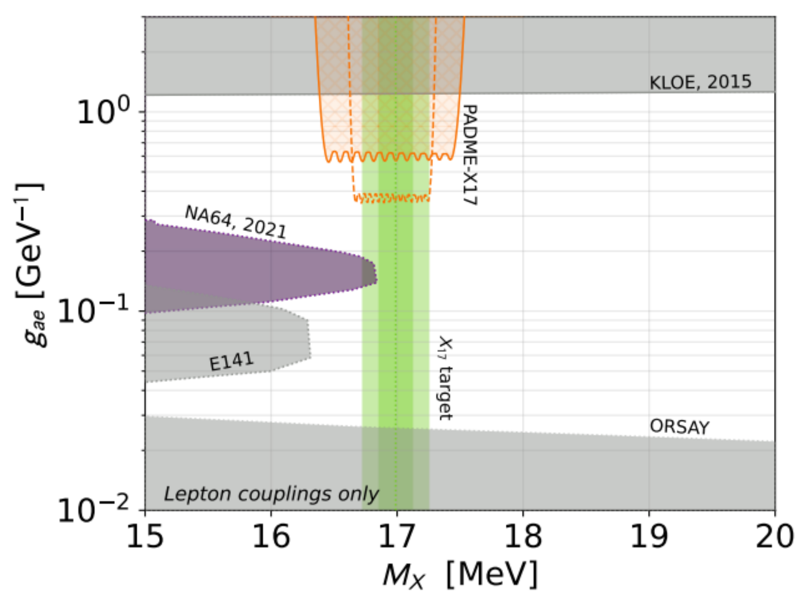
PADME expected limits: June 2022

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

Vector X17



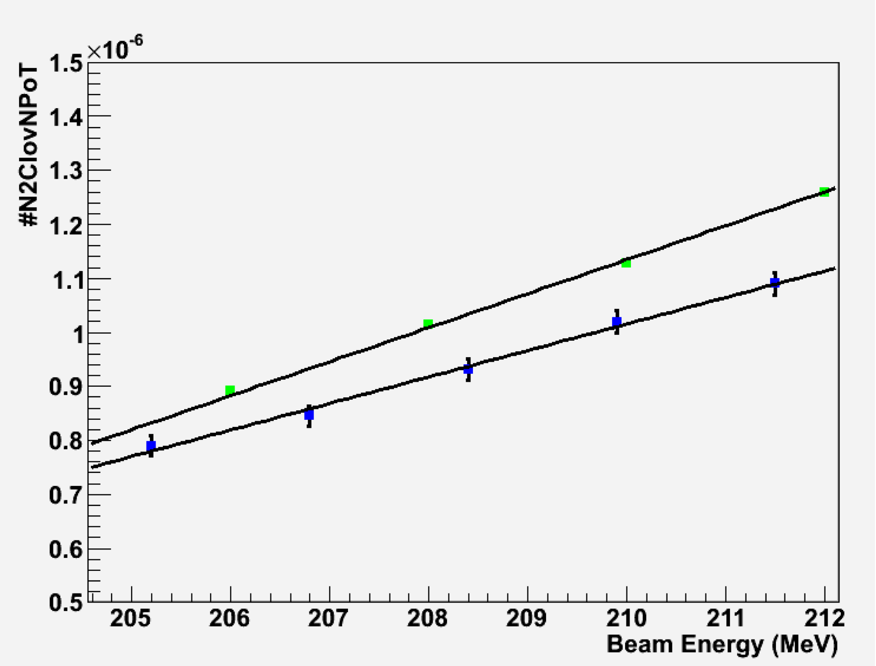
Pseudo scalar X17



- 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
- What can we really achieve with PADME Run III data set.

Sensitivity Update: the technique

- Updated are based on the following new information
  - **Actual number of POT** and energy point from Run III (real data)
  - MC simulations of the energy resolution energy by energy (full Geant4)
  - MC driven estimates of the total background and acceptance (ToyMC)



- **Toy MC** and full **Geant4** simulation comparison on the below resonance energy region show reasonable agreement
  - Used ToyMC for the predictions of signal acceptance and BG.

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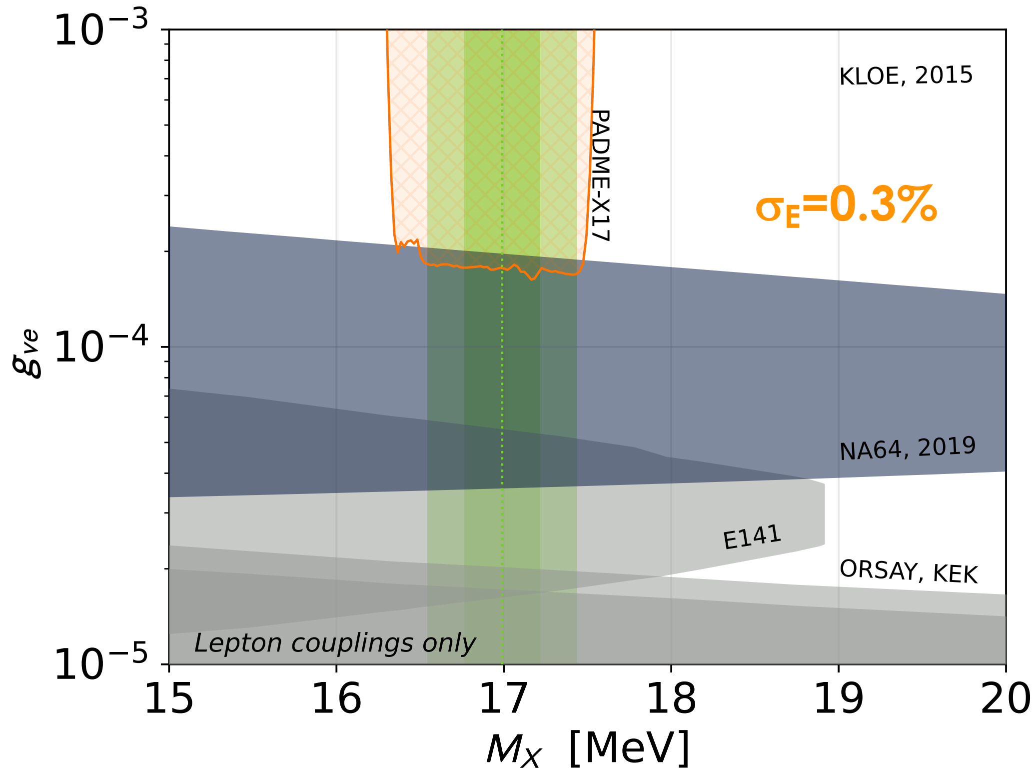
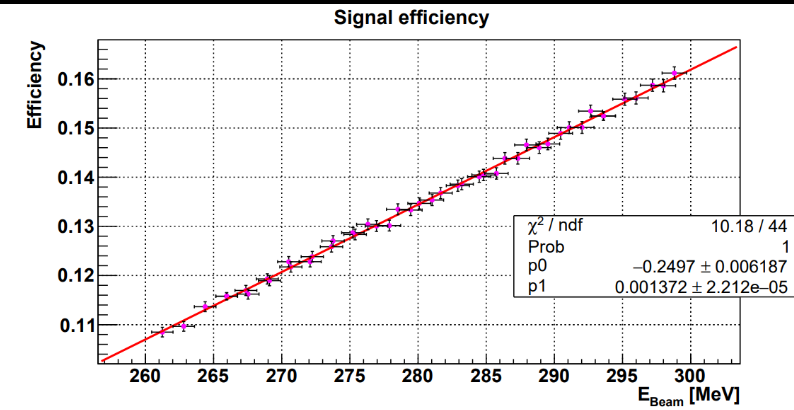
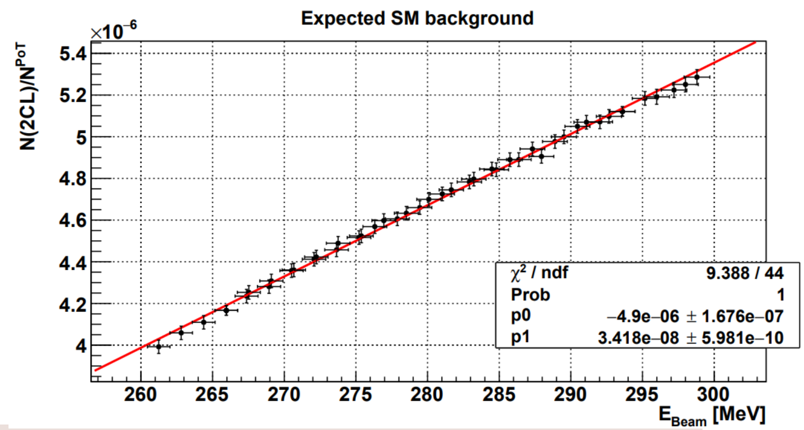
Updated sensitivity estimates: theory



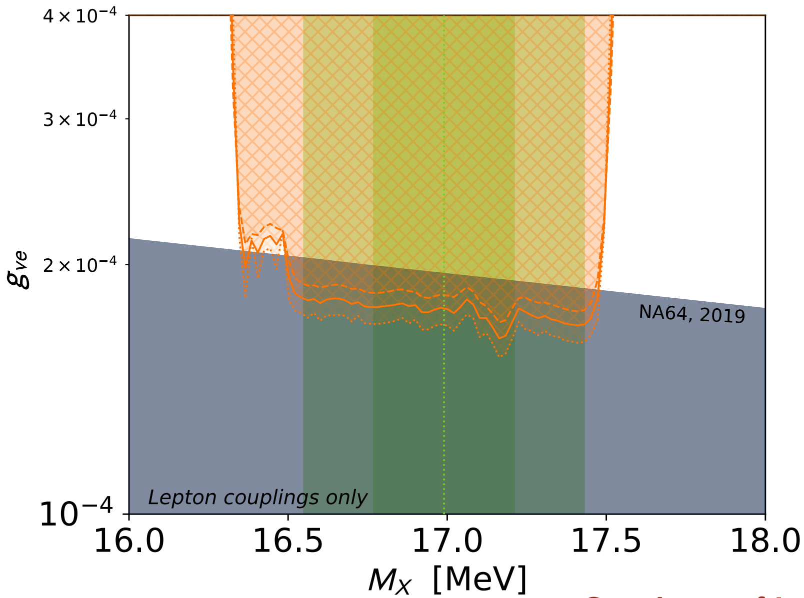
Courtesy o f L. Darme' and G. Grilli di Cortona

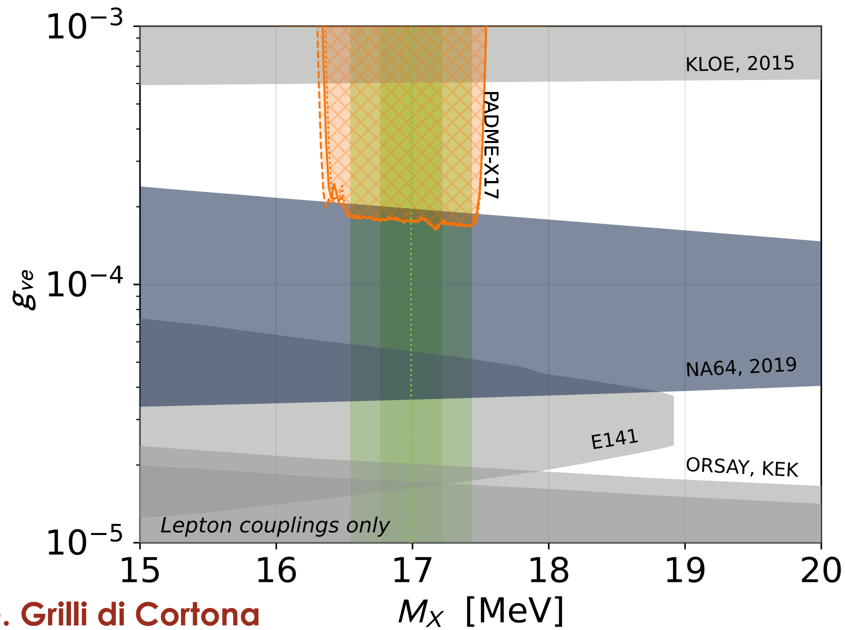




- Based on the following input from PADME experiment:
  - **Actual number of POTs** and **energy** points from Run III data set
  - **MC driven total background and acceptance** estimates
  - Conservative estimate of the **beam energy spread σ_E=0.3%**

Systematic errors check theory





Courtesy o f L. Darme' and G. Grilli di Cortona

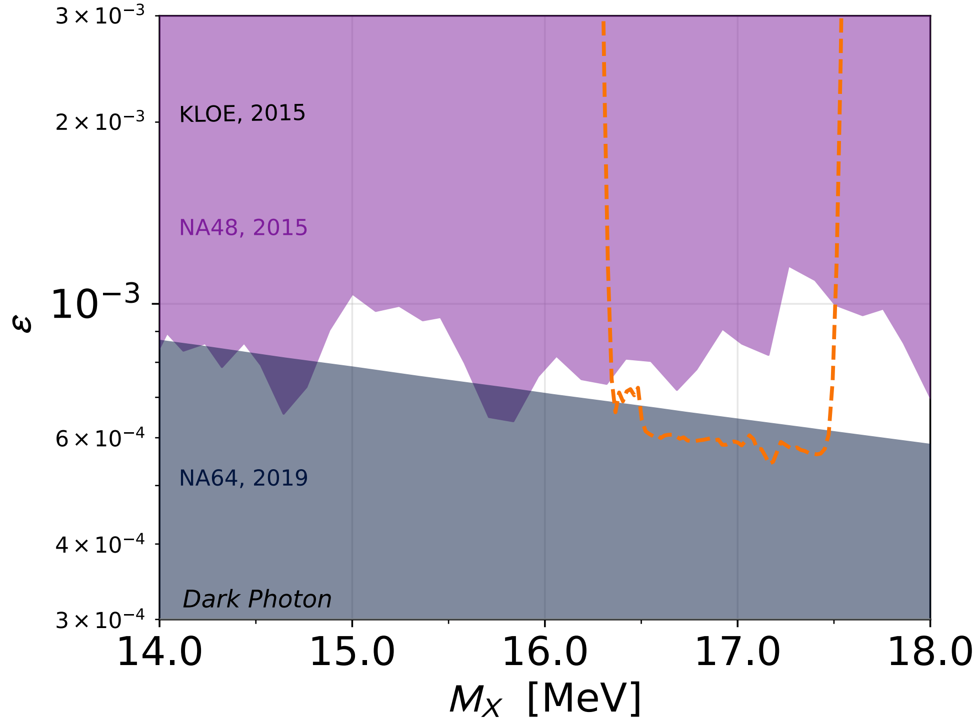
- The main systematic effect is expected to come from beam energy spread
  - **Standard values used in the plots is 0.3%, 0.25% dotted, 0.35% dashed**
  - MC simulations suggest that the actual value is below 0.25% and precisely known

$$N_{X_{17}}^{perPoT} \simeq \frac{g_{Ve}^2}{2m_e} \ell_{tar} \frac{N_A \rho Z}{A} f(E_{res}, E_{beam})$$

- Energy scale changes the scan position on the mass by negligible amonunt
  - MC simulations indicate a beam energy scale accuracy of ~1.5 MeV
  - ~(20-30) KeV in the mass scale and it is barely visible

The dark photon: theory prediction

A'–> e⁺e⁻



Courtesy o f L. Darme' and G. Grilli di Cortona

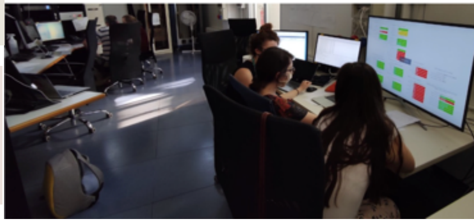
- The **PADME exclusion limit** will provide also the **best constraint on general Dark Photon visible decays scenario** in the 17 MeV region
  - NA48/2 limit using $\pi 0 \to \gamma e^+ e^-$ points extracted from HEPData: https://www.hepdata.net/record/ins1357601

Conclusions

- **PADME Run III at the X_{17} CoME**, successfully terminated
  - 47 different energy points collected + side bands
  - High quality data collected for **16.35 MeV <M_{X17}<17.5 MeV**
  - Beam and BhaBha backgrounds are under control

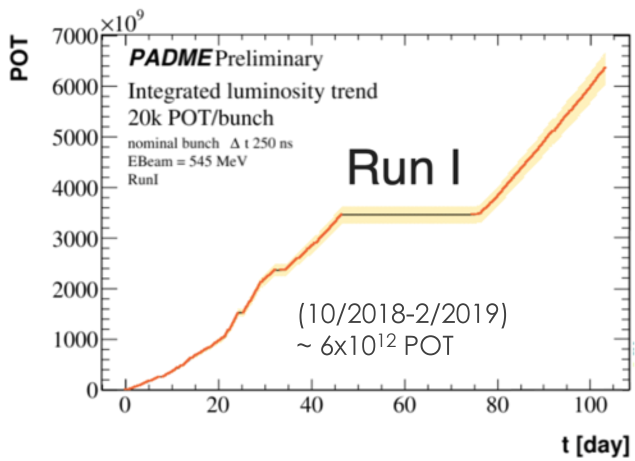
- Stability of the ratio **#2Clusters/N_{PoT} on off resonance data <1%**
- Next steps towards final result:
  - Move into the closer sidebands (M_{X17}>17.25 MeV ?)
  - Improve data/MC agreement

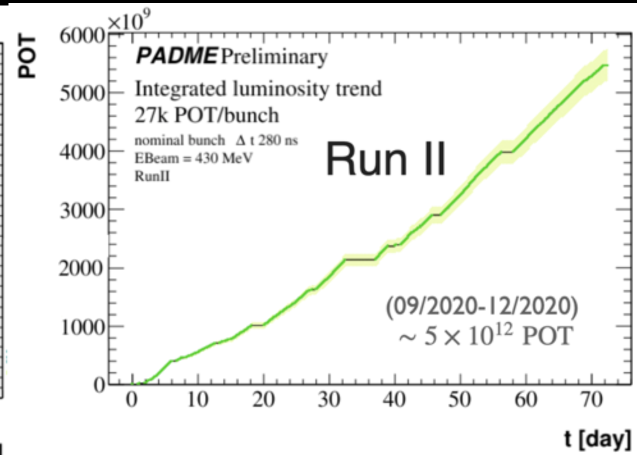
- **Analysis strategy papers in preparation (expected by mid Dec.)**
- Expect a result on the X17 signal region by summer 2024

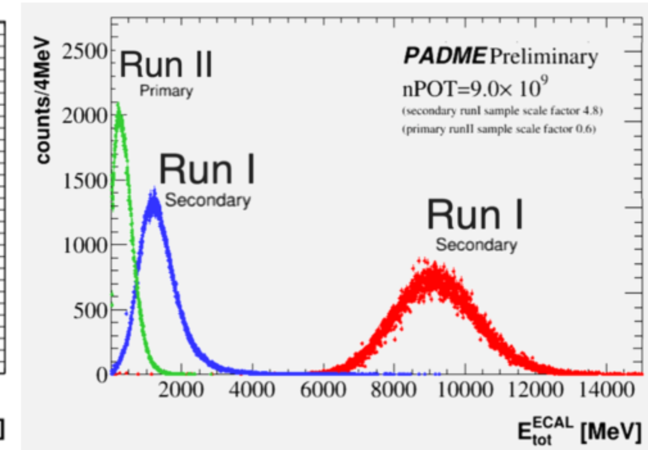


We plan to continue exploring visible dark sector scenarios BTF beam line in the near future. Stay tuned!

PADME data taking periods 2018-20

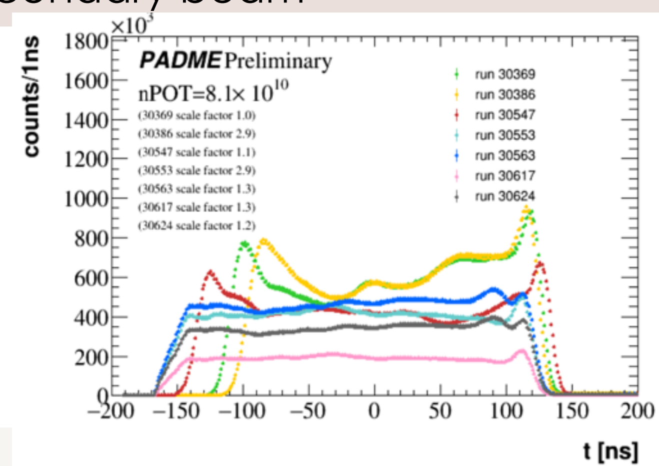






- Two physics runs **Run I Oct. 2018 Feb. 19** and **Run II Set-Dec 2020**
  - Hard simulation work to understand BG in between Run I and Run II.
- Run II wrt Run I
  - Slightly lower beam momentum in Run II, 430 MeV/c, wrt to Run I, 490 MeV/c
  - **Improved vacuum separation** between experiment and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

- During Run II itself
  - Improved bunch length and structure



Improving production rates

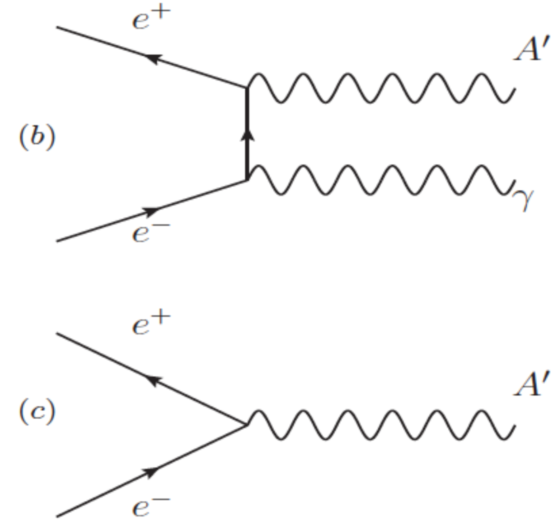
- We need higher production cross section!
- Can move from associated to resonant production
  - b) Radiative annihilation O(α^2)

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

  - c) Resonant annihilation O(α)

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

Positron beams



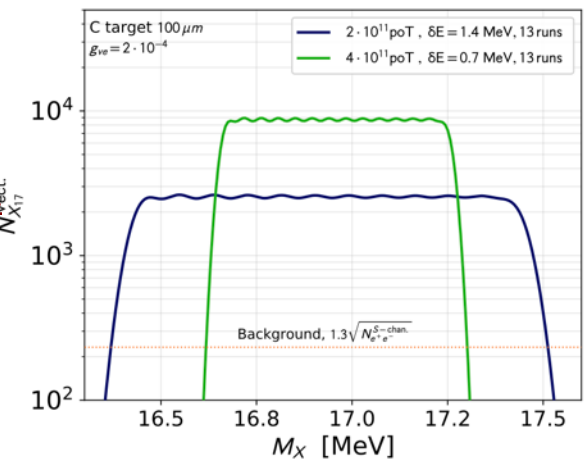
- **Resonant:** Profit for a higher production in a tiny mass region

$$\mathcal{N}_{X_{17}}^{\rm Vect.} \simeq 1.8\cdot 10^{-7} \times \left(\frac{g_{ve}}{2\cdot 10^{-4}}\right)^2 \left(\frac{1\ \rm MeV}{\sigma_E}\right)$$

$$\mathcal{N}_{X_{17}}^{\rm ALP} \simeq 5.8\cdot 10^{-7} \times \left(\frac{g_{ae}}{\rm GeV^{-1}}\right)^2 \left(\frac{1\ \rm MeV}{\sigma_E}\right)$$

Darmé et al. Phys. Rev. D 106,115036

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



Summary on X17 constraints

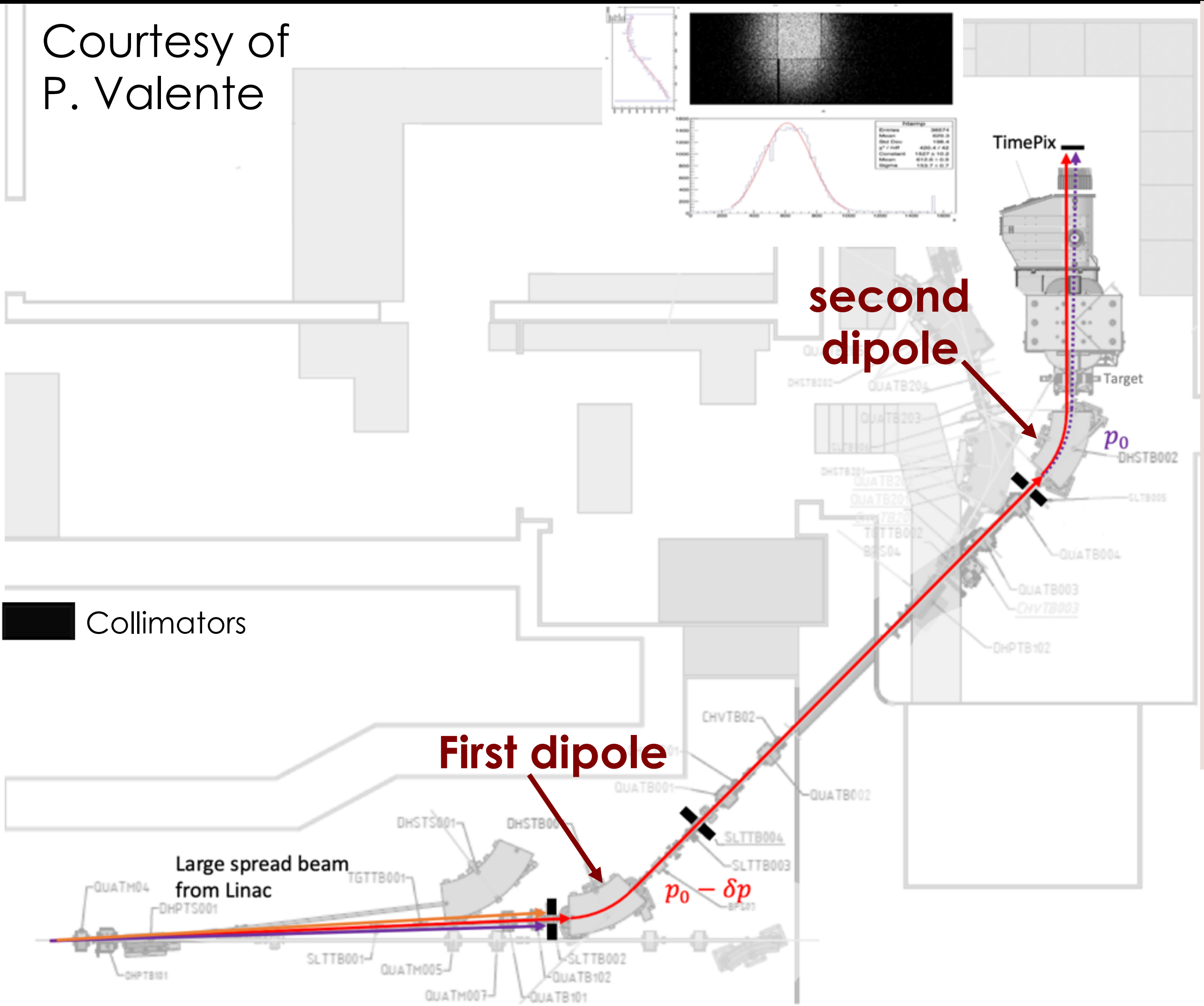
To summarize this section, a model with a vector mediator explaining the ATOMKI anomaly at a minimum needs to fulfill the following requirements:

- 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



Use the first dipole magnet and collimators to select energy

- dp ∝ collimator aperture.

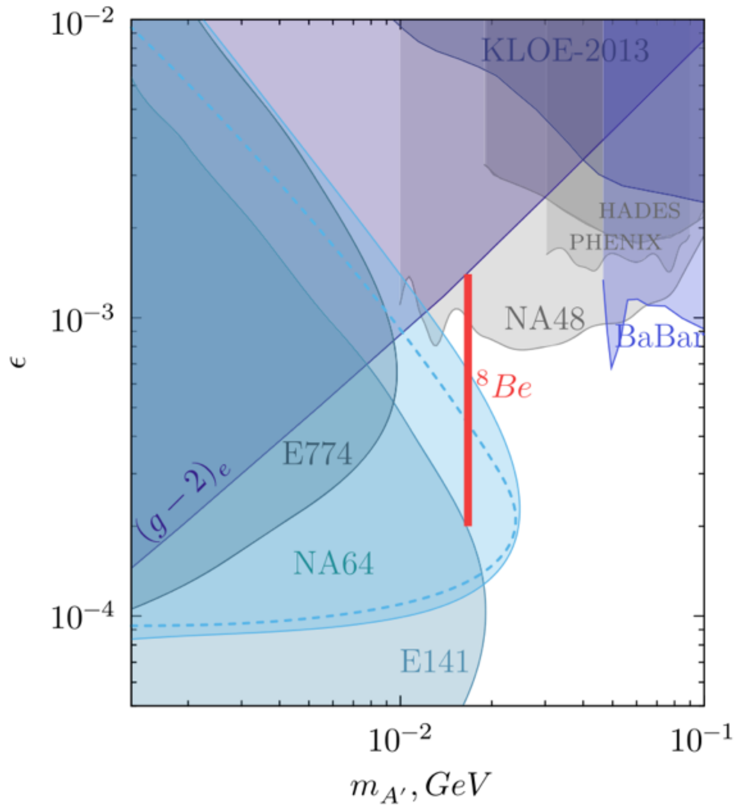
Change the first dipole magnet current to change the energy

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

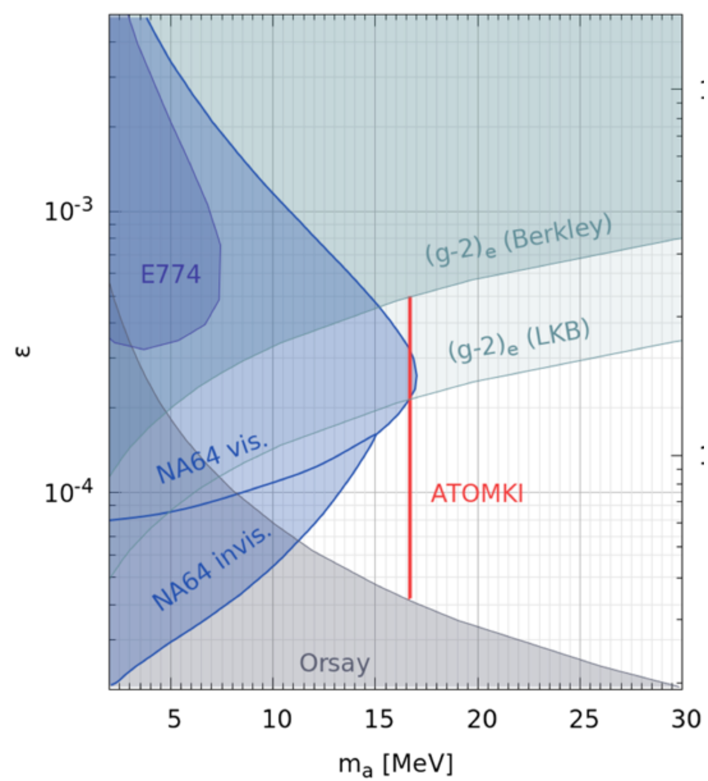
Measure the displacement at the target and timePix to measure the energy step performed

Current constraints on X17 from leptons

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



Phys. Rev. D 104, L111102 (2021)



X17 as a vector particle:

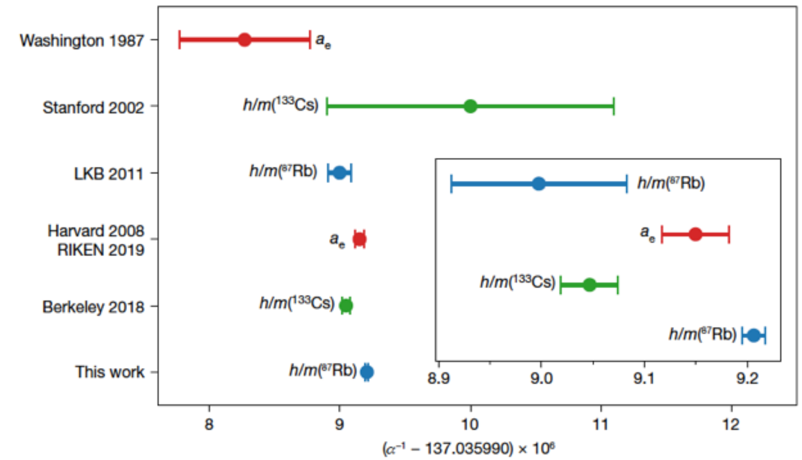
- LKB $(g\text{-}2)_e$ bound weaker for vector and model dependent
- NA48/2 bound not valid for “protophobic” X17
- Still a lot of free parameter space for vector X17

X17 as pseudo scalar particle:

- $(g\text{-}2)_e$ 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 $a_{e,exp}$.