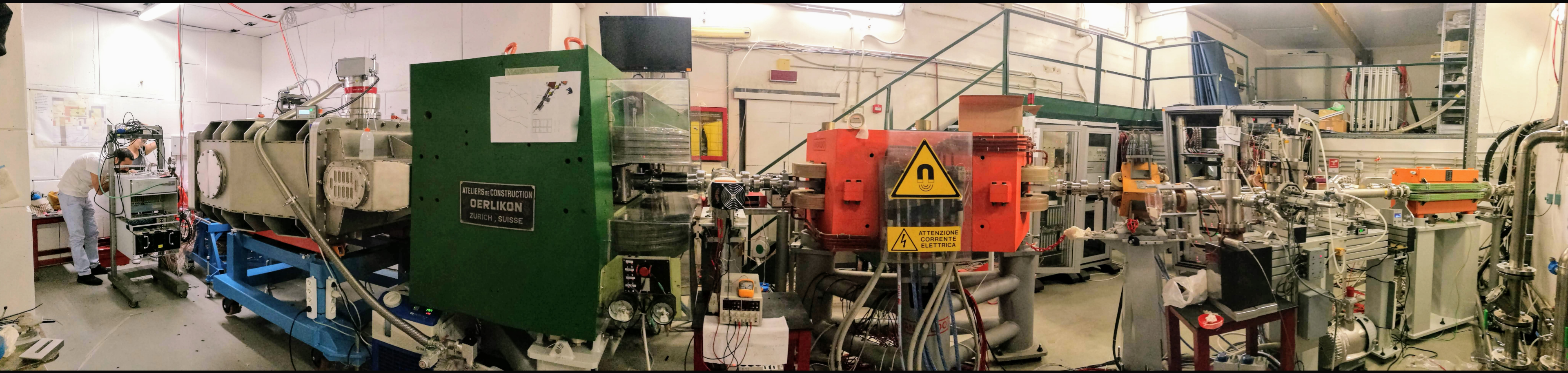
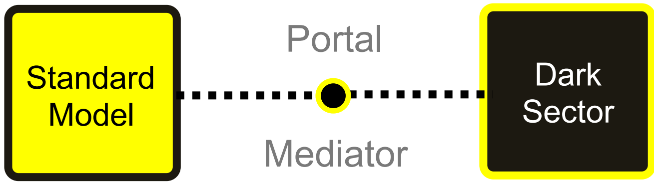
The PADME experiment



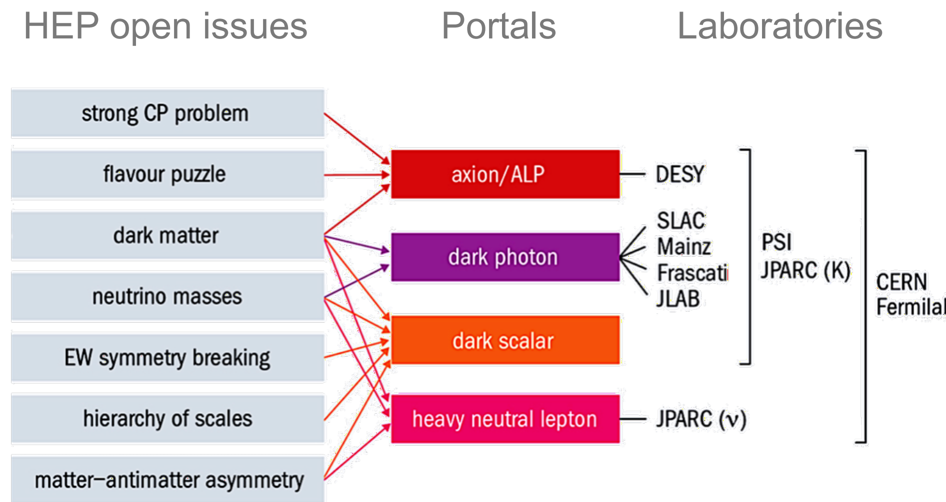
Mauro Raggi for the PADME collaboration,
Sapienza Università di Roma e INFN Roma
Workshop on status and perspectives of physics at high intensity
9–11 Nov 2022 LNF

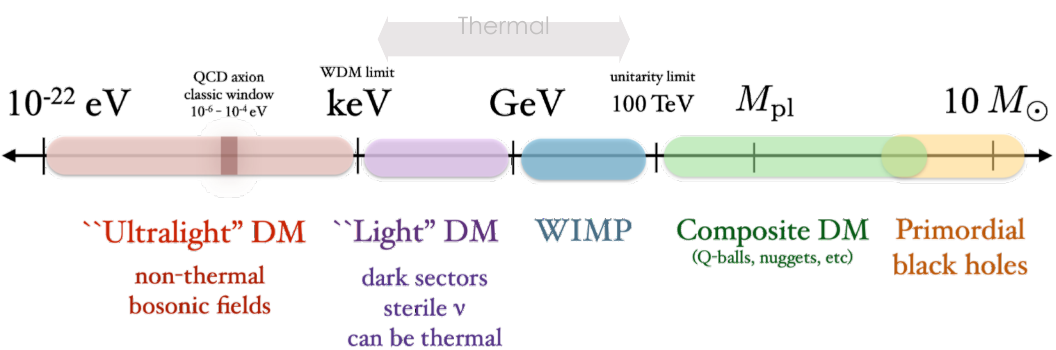
The dark sector paradigm



Feeble, non-gravitational interaction with ordinary matter

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





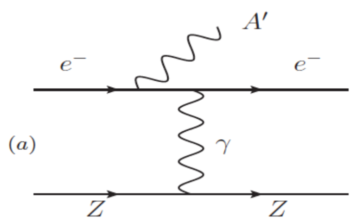
- Dark sector candidates can explain SM anomalies: (g-2)μ, ^{8}Be, proton radius
- The mediator can have a **small mass (MeV -100 MeV)**
- Due to its **small mass** the mediator can be **produced at low energy accelerators**
- It can **decay back to ordinary matter "visible"** on **not "invisible"**

Experimental approaches

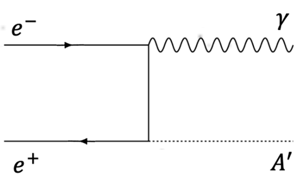
- **Electron beam experiments production**
  - **Just A'-strahlung**
- **Positron based experiments**
  - **A'-strahlung**
  - **Associated production $e^+e^- \rightarrow A'(\gamma)$**
  - **Resonant production $e^+e^- \rightarrow e^+e^-$**

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

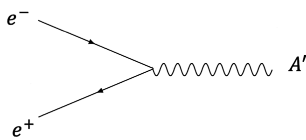
Brems.



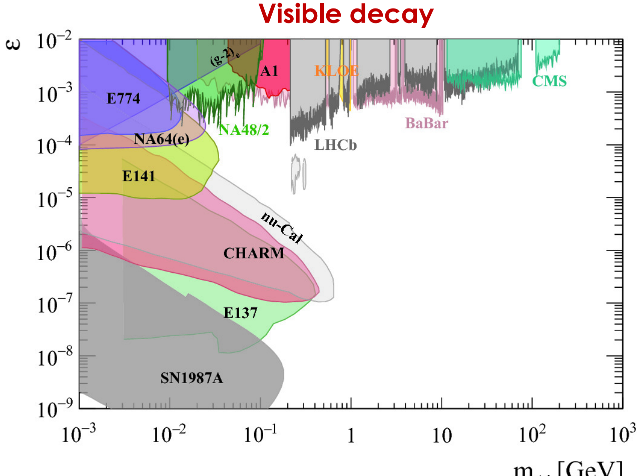
Associated production



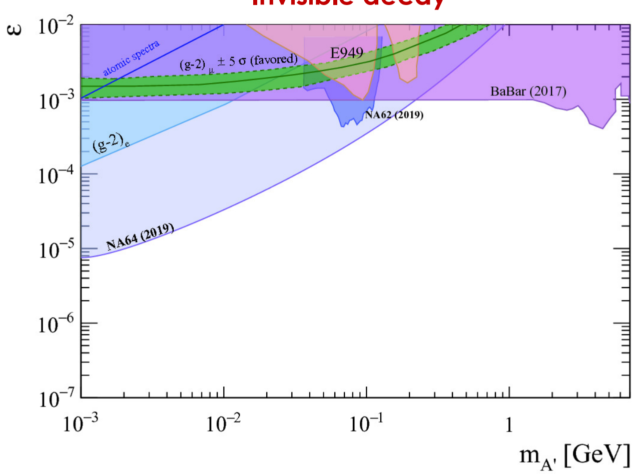
Resonant

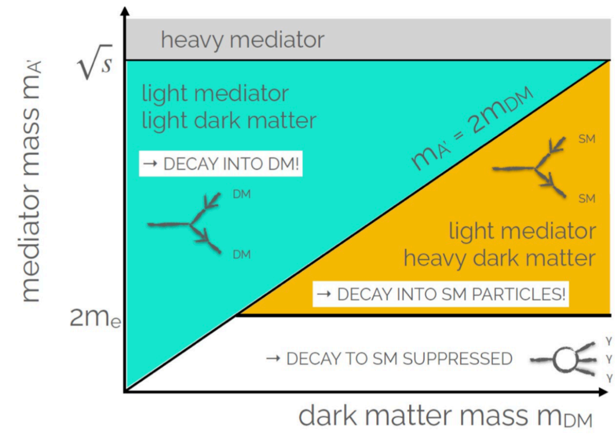


Visible decay



Invisible decay



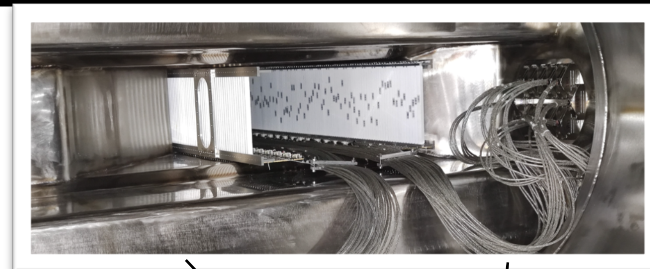


PADME Run I and Run II setup

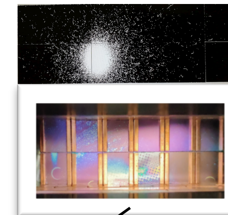
- Positron beam of ~**0.5 GeV/c**
  - LINAC repetition rate 50 Hz
  - Macro-bunches maximum length $\Delta t \lesssim$**300 ns**
- Number of annihilations proportional to:

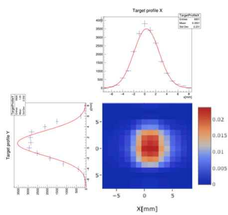
$$N_{beam}^{e^+} \times N_{target}^{e^-}$$

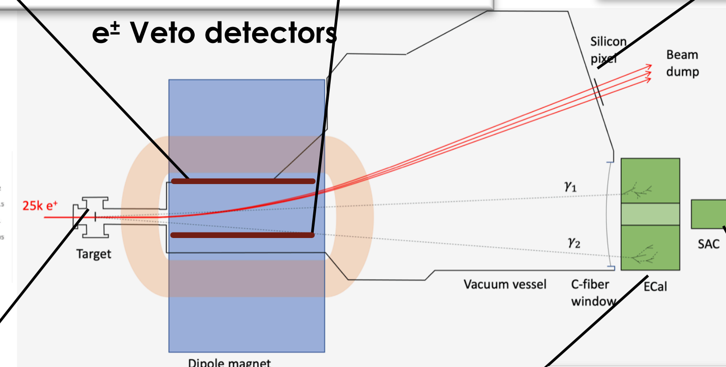
  - Limited **intensity**, due to pile-up, ~**3·10^4 pot/pulse**
- Dipole **magnet** in order to
  - Sweep away non-interacting positrons
  - Tag positrons losing energy by Bremsstrahlung
- Scintillating bar **veto** detectors placed inside vacuum vessel
  - Positron and electron detectors inside the magnet gap
  - Additional veto for e^+ irradiating soft photons at beam exit



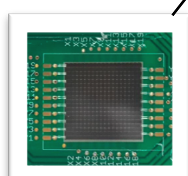
Silicon **pixel** (TimePix3)



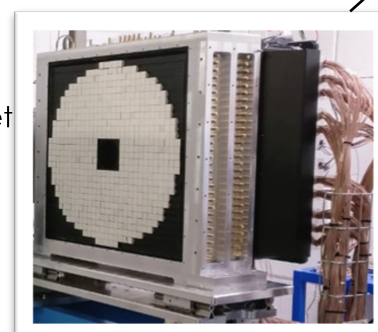




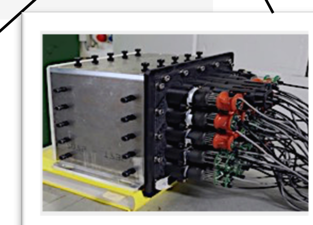
SAC



Active **diamond** target
100 μm thick

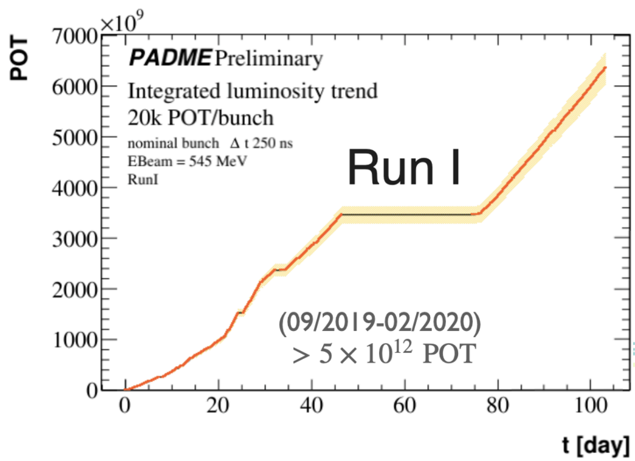


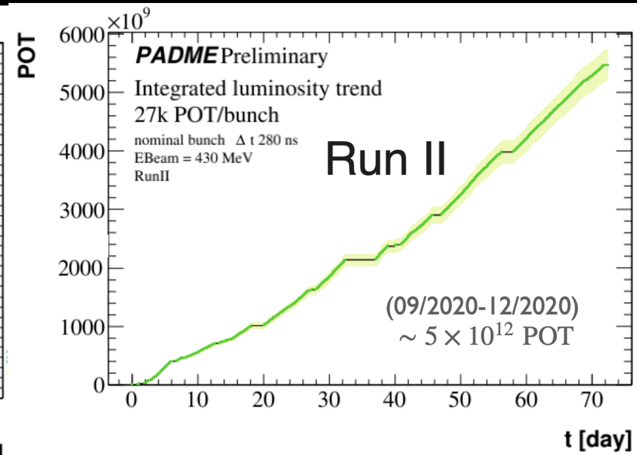
BGO calorimeter (ECAL)

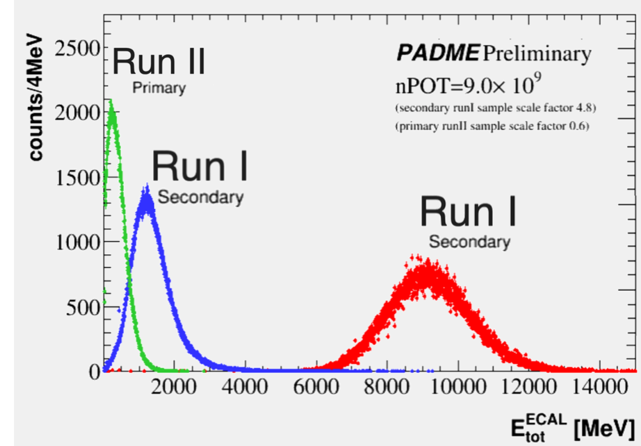


small angle calo
SAC PbF_2

PADME data taking periods

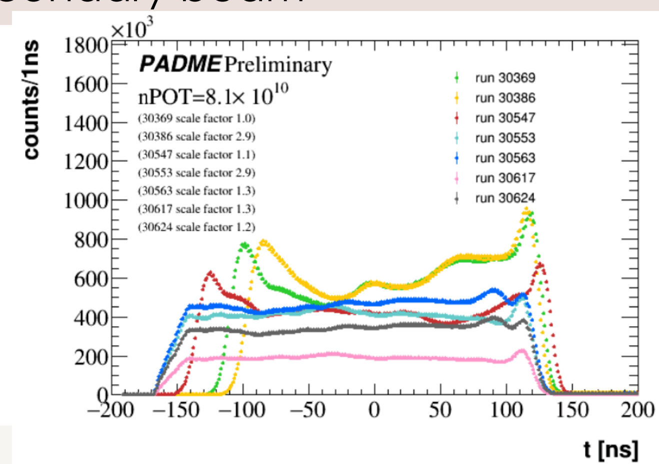






- Two physics runs **Run I Oct. 2018 Feb. 19** and **Run II Set-Dec 2020**
  - Hard simulation work to understand BG in between Run I and Run II.
- Run II wrt Run I
  - Slightly lower beam momentum in Run II, 430 MeV/c, wrt to Run I, 490 MeV/c
  - **Improved vacuum separation** between experiment and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

- During Run II itself
  - Improved bunch length and structure

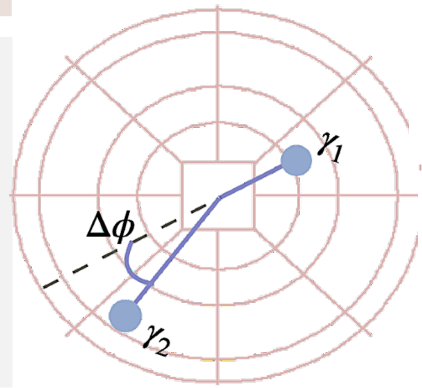


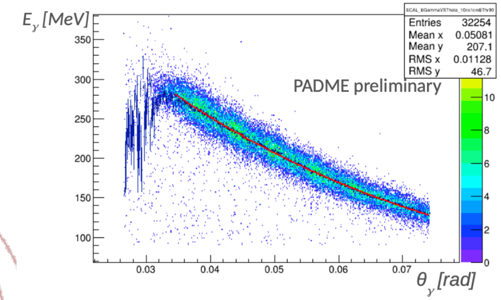
SAPIENZA
UNIVERSITÀ DI ROMA

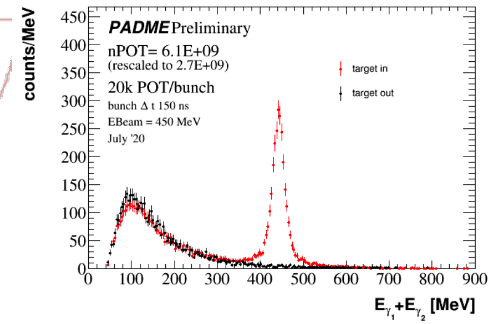
First physics result: $\sigma(ee\to\gamma\gamma)$ at $\sqrt{s}$=20 MeV

- Normalization for single photon analysis
- Independent determination of luminosity
- **SM Cross-section measurement**

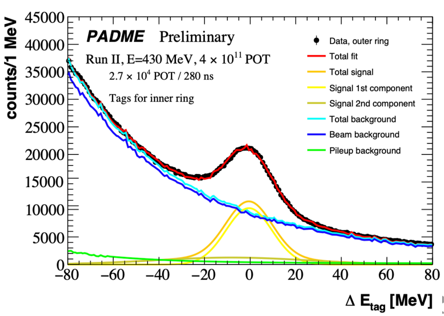
- Tag-and-probe method on two back-to-back clusters
  - Exploit energy-angle correlation $E_\gamma = f(\vartheta_\gamma)$
  - Count tag photons with $E_\gamma - f(\vartheta_\gamma) \sim 0$
  - Match using $E_{\gamma 1} + E_{\gamma 2} = E_{beam}$ and count probes
- Single photons selection
  - Subtract background from **no target** runs
  - $E_\gamma - f(\vartheta_\gamma) \sim 0$ and $m^2_{miss} \sim 0$



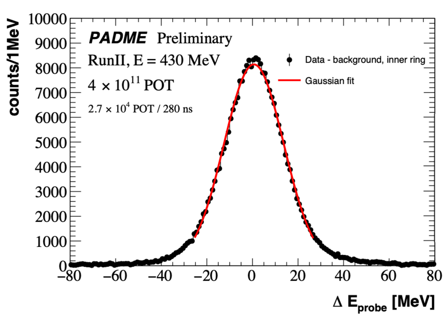




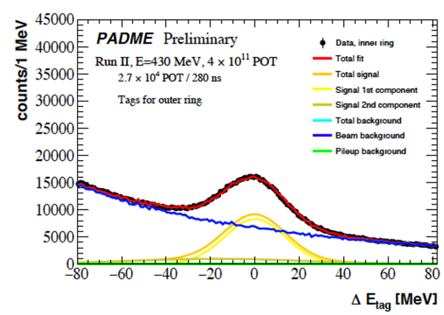
Tag photons selection

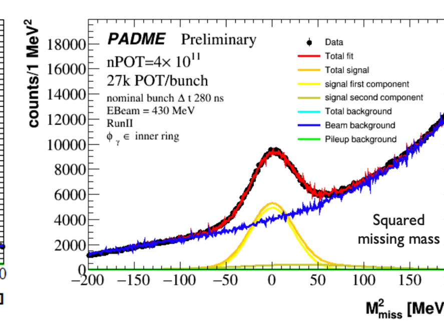


Probe photons



Single photon selection





PADME $\sigma(e^+e^- \rightarrow \gamma\gamma)$ results

PADME 2020 (10% of 2020 data set)

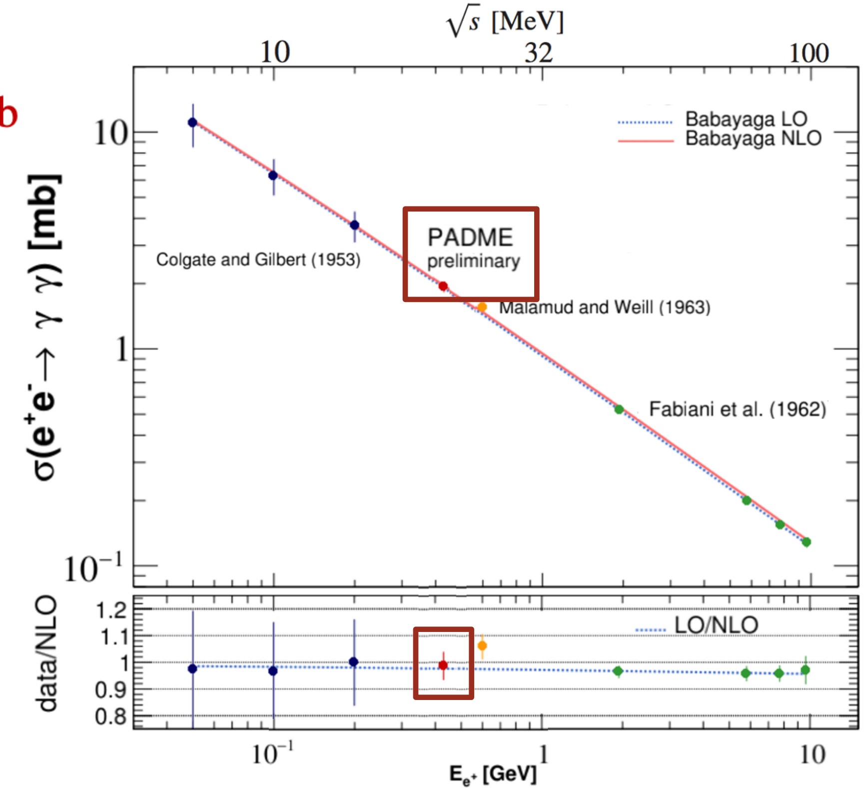
$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst})$ mb

Full details, see talk by **I. Oceano** at Moriond 2022

https://moriond.in2p3.fr/2022/EW/slides/3/2/5_IOceano.pdf

good agreement with NLO QED prediction:

QED @NLO $\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.9573 \pm 0.0005\ (\text{stat}) \pm 0.0020\ (\text{syst})$ mb

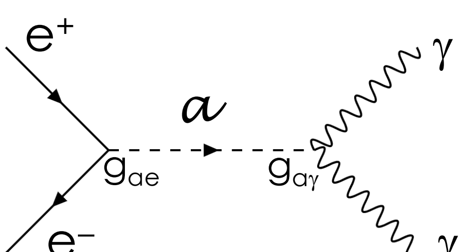


- **First direct measurement** of $e^+e^- \rightarrow \gamma\gamma$ below 1 GeV
- Both **Gilbert '53** and **Malamud '63** measure e^+ disappearance rates
- Error dominated by luminosity measurement large room for improving.

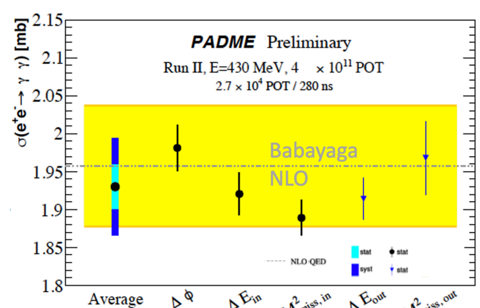
https://arxiv.org/abs/2210.14603

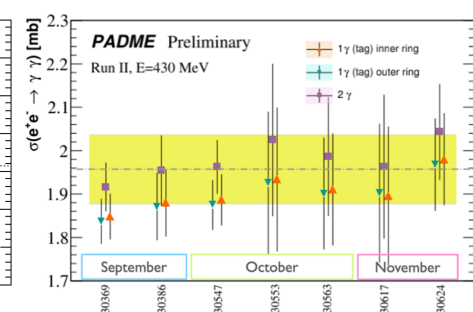
Submitted to PRD

- Can constrain ALPs with both g_e and g_γ couplings
- Including X17 with g_{ae} and $g_{a\gamma}$ couplings



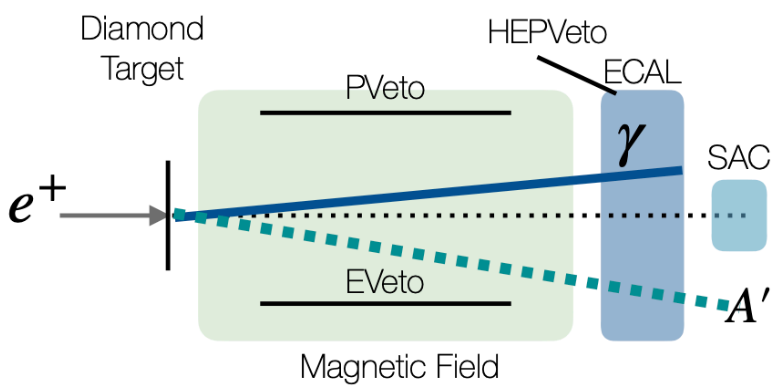
JHEP 06 (2021) 009



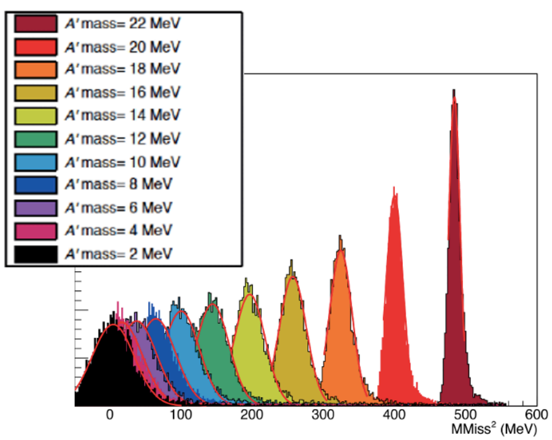


A' to invisible signature Run II analysis

Signal:



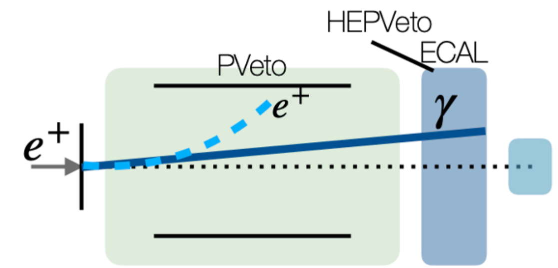
Knowing the beam momentum $\underline{p}_{e^+}$,
compute: $m^2_{miss} = (\underline{p}_\gamma - \underline{p}_{e^+} - \underline{p}_{e^-})^2$



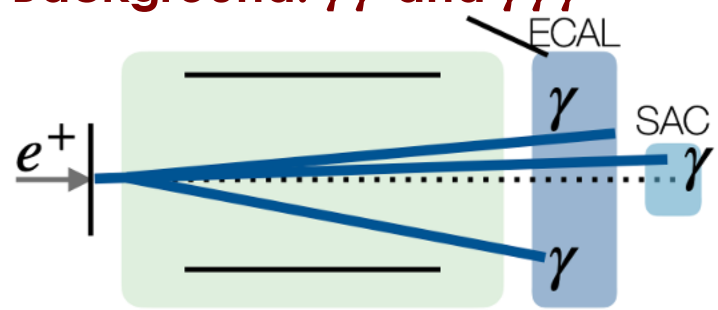
Normalize to $\gamma\gamma$ channel:

$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma\gamma)}\frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon\delta$$

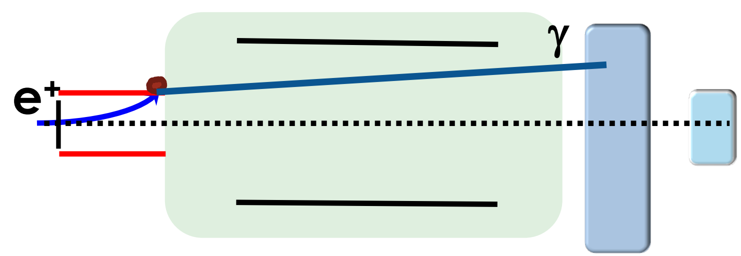
Background: Bremsstrahlung



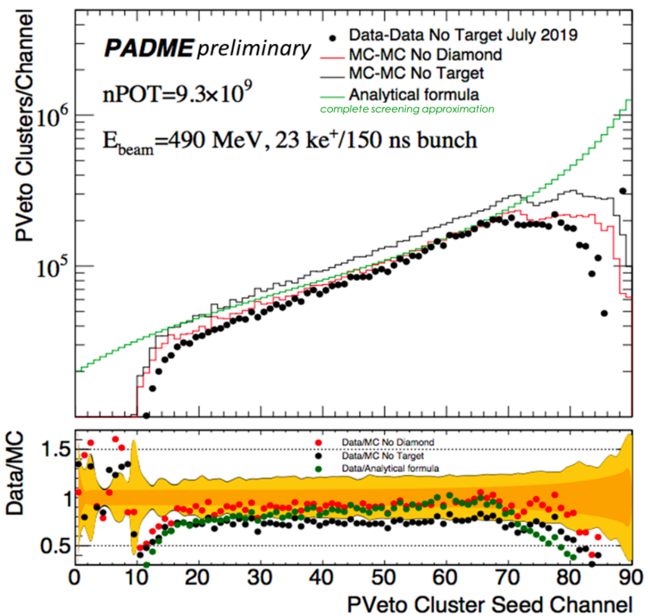
Background: $\gamma\gamma$ and $\gamma\gamma\gamma$



Background: beam crash



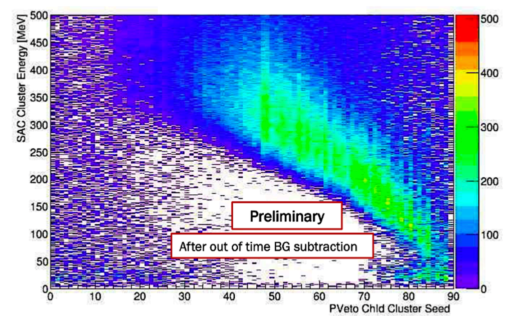
Single photon events



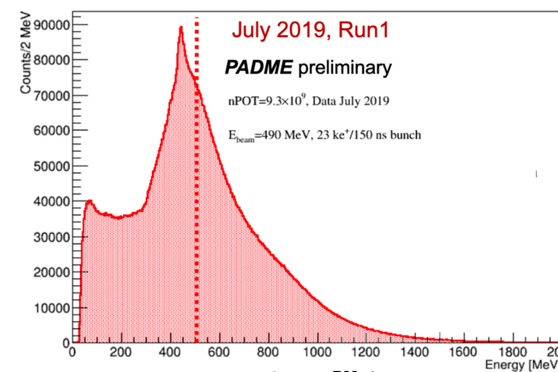
- Essential for dark photon analysis

Physics backgrouns dominated by Bremsstrahlung:

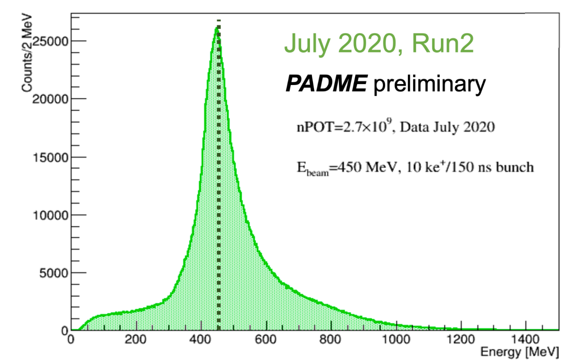
- Measured with no-target runs and subtracted
- Bremstrahlung photon distribution in agreement with **Monte Carlo simulation** and **analytical calculation**
- Main systematic uncertainties:
  - Background normalization
  - Positron momentum scale
  - n POT calibration



Veto momentum vs. SAC energy
490 MeV, primary beam, $\Delta t < 1$ ns



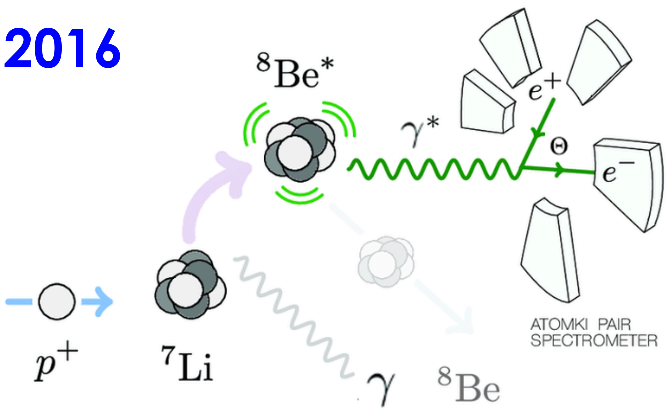
$p_{\gamma}^{ECal} + p_{e^+}^{PVeto}$

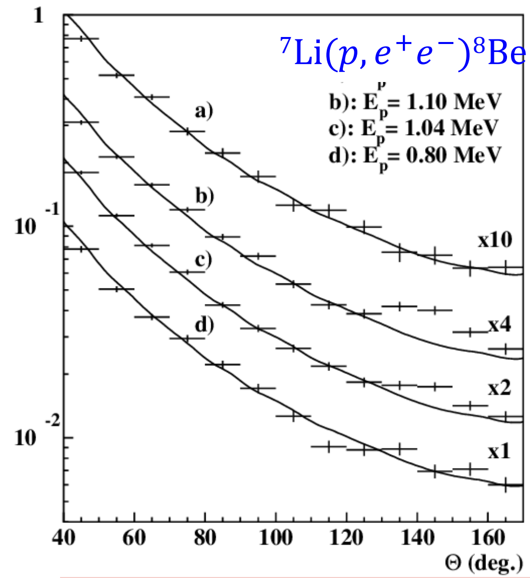


$p_{\gamma}^{ECal} + p_{e^+}^{PVeto}$

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

2016

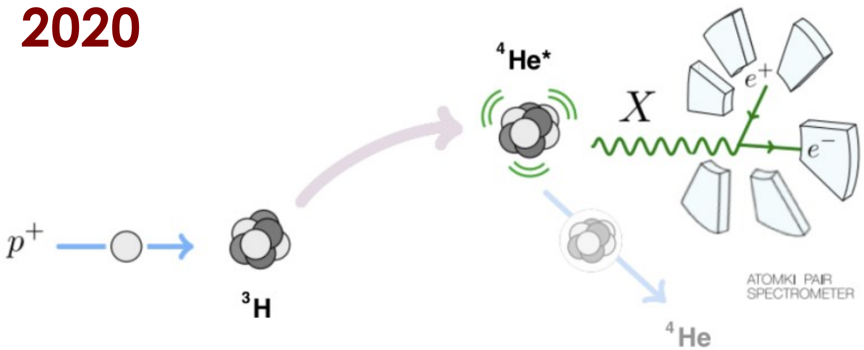


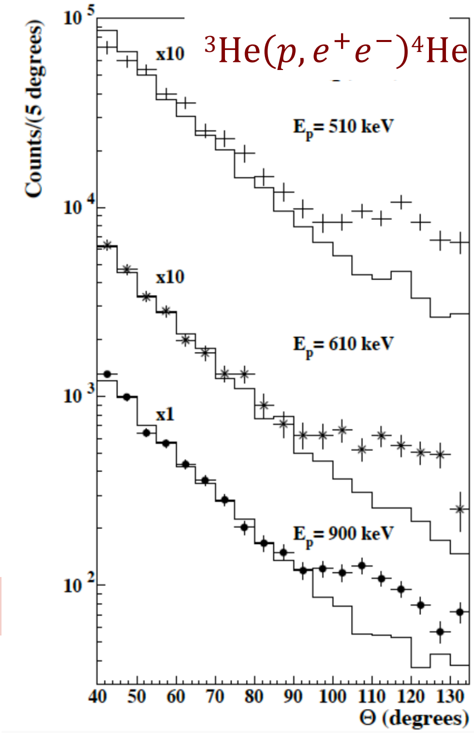


$m_X c^2 = 17.01 \pm 0.16(\text{tot})$ MeV

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

ArXiv:2209.10795v1

Sept 2022

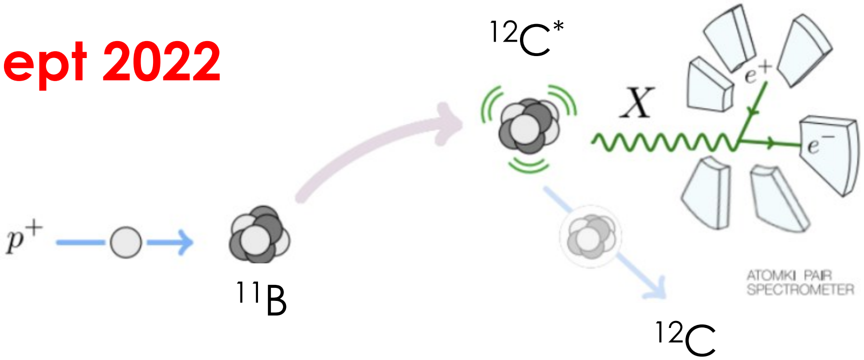
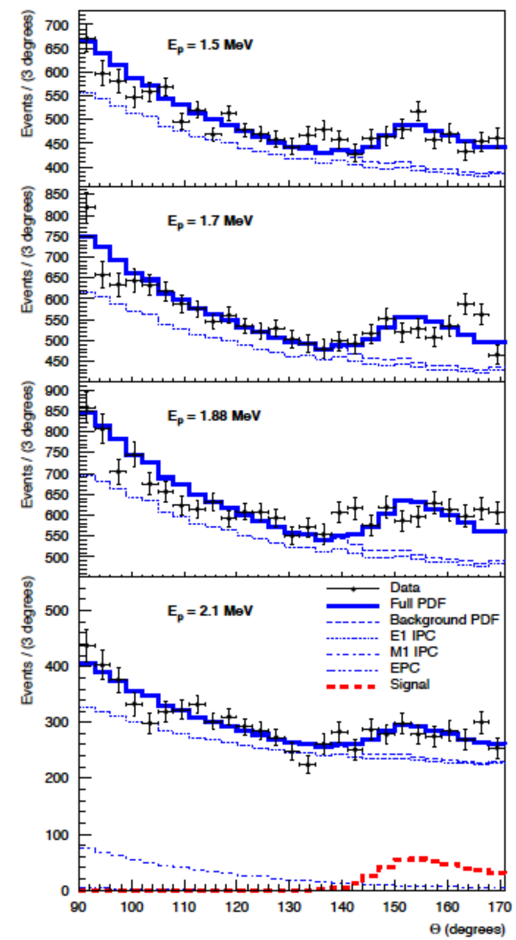


TABLE I. X17 branching ratios (B_x), masses, and confidences derived from the fits.

E_p (MeV)	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
1.5	2.7(2)	16.62(10)	8σ
1.7	3.3(3)	16.75(10)	10σ
1.88	4.1(4)	16.94(10)	11σ
2.1	4.7(9)	17.12(10)	6σ
Averages	3.4(3)	16.86(17)	
Previous [1]	5.8	16.70(30)	
Previous [21]	5.1	16.94(12)	
Predicted [16]	3.0		

4 different bombarding energies with strong significance

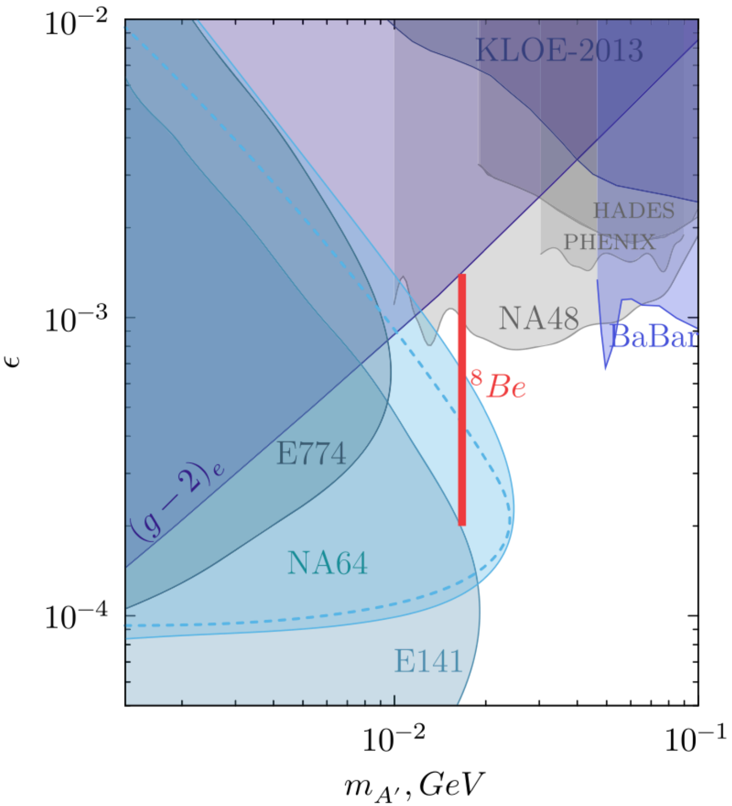
$^{11}\mathrm{B}(p, e^+e^-)^{12}\mathrm{C}$



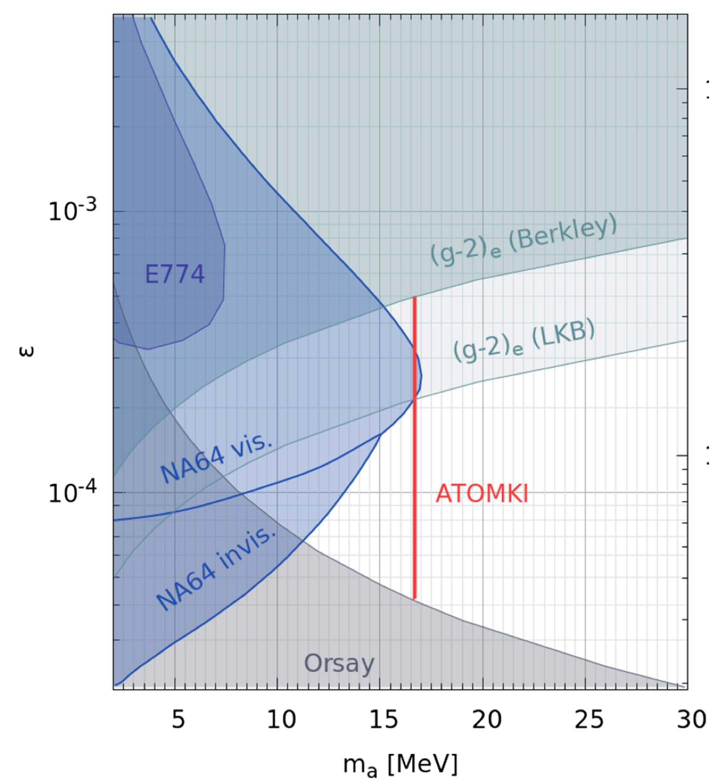
E=17.23 MeV excited state of ^{12}C

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

On the nature of X17

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

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

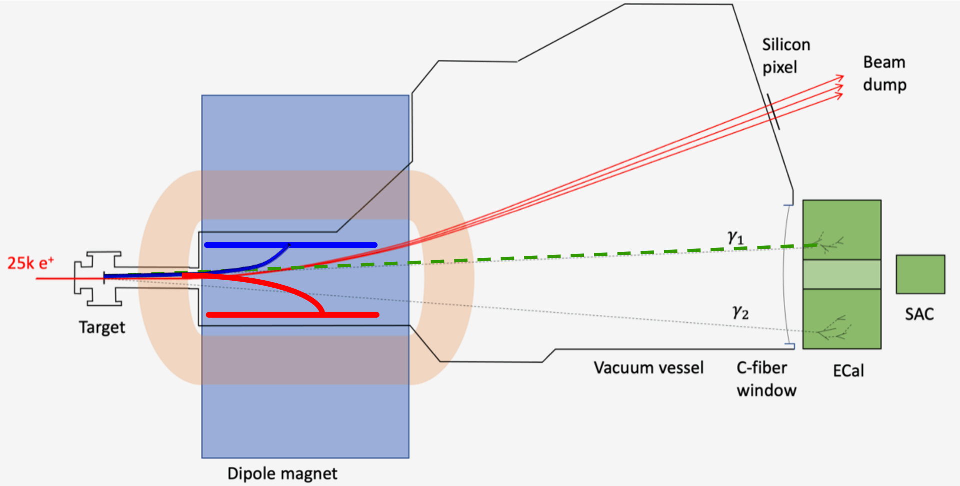
Jonathan L. Feng,* Tim M. P. Tait,† and Christopher B. Verhaaren‡
Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

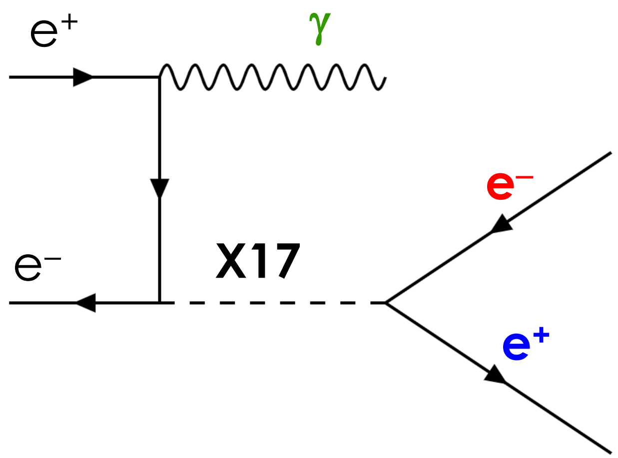
Feng and collaborators suggested that the X17 should be observed in ^{12}C transitions
X17 observations in ^{12}C will point to a vector or axial vector nature for X17

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)	…

PADME X17 searches on Run II data





Final state $e^+e^- \to X_{17}\gamma \to e^+e^-\gamma$

- Use radiative return E_{beam} =430 MeV
- small contribution from $\gamma\gamma$
- Large beam γ background reducing the sensitivity

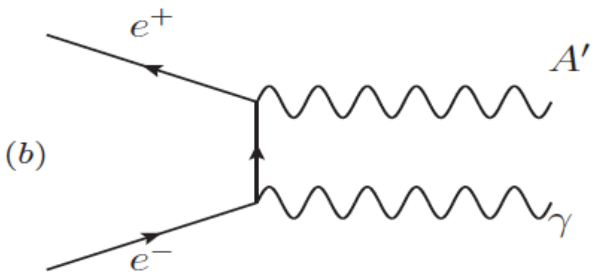
Try to identify pairs of leptons using PADME veto

- Large BG from BhaBha scattering
- Large beam background increasing combinatorics BG
- Lepton invariant mass not accessible

How can we make our life easier?

- We need higher production cross section!

Positron beams

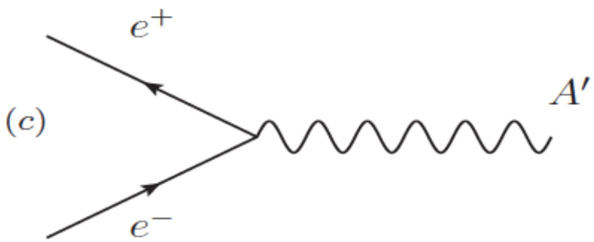


- Can move from associated to resonant production
  - b) Radiative annihilation $O(\alpha^2)$

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

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

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



- Profit for a higher production in a tiny mass region

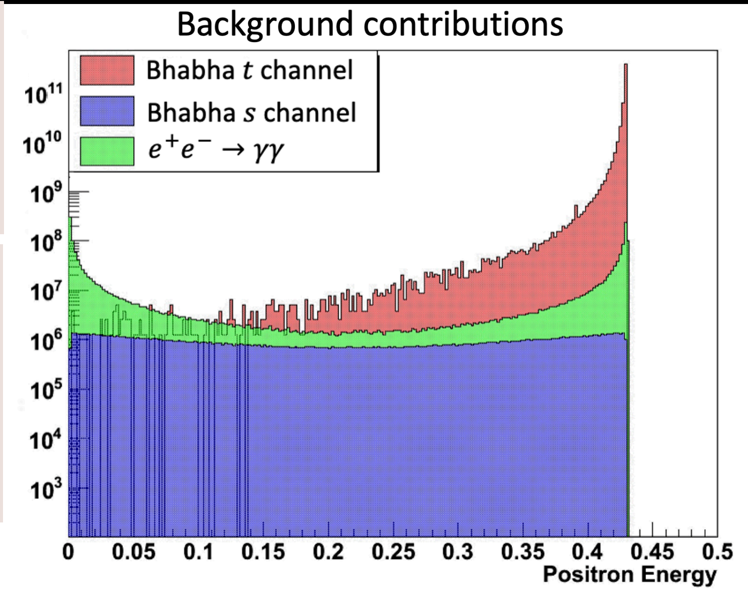
$$\mathcal{N}_{X_{17}}^{\rm Vect.} \simeq 1.8\cdot 10^{-7} \times \left(\frac{g_{ve}}{2\cdot 10^{-4}}\right)^2 \left(\frac{1\ {\rm MeV}}{\sigma_E}\right) \qquad \mathcal{N}_{X_{17}}^{\rm ALP} \simeq 5.8\cdot 10^{-7} \times \left(\frac{g_{ae}}{{\rm GeV}^{-1}}\right)^2 \left(\frac{1\ {\rm MeV}}{\sigma_E}\right)$$

The mass scan X17 search strategy

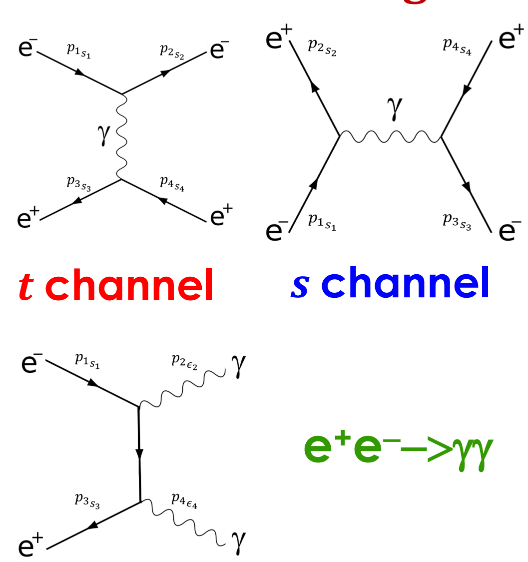
PADME, can use resonant X17 production process

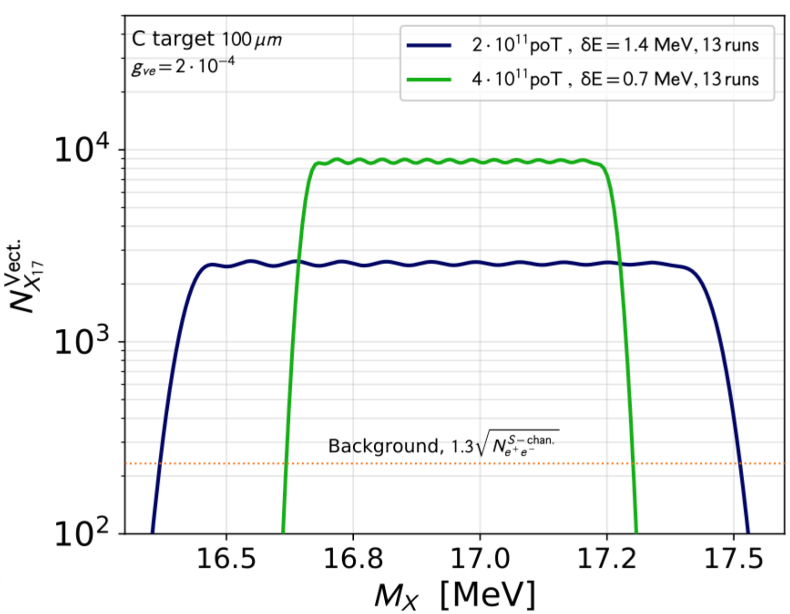
- Extremely effective in producing X17 but in a very small mass range
- Scan E_{beam}=260–300 MeV in ~1.5 MeV steps

- Need only ~10^{10} POT per point
- Signal should emerge on top of **Bhabha** BG in one point of the scan.
- Critical parameter for signal to background optimization: **beam energy spread**



Bhabha scattering

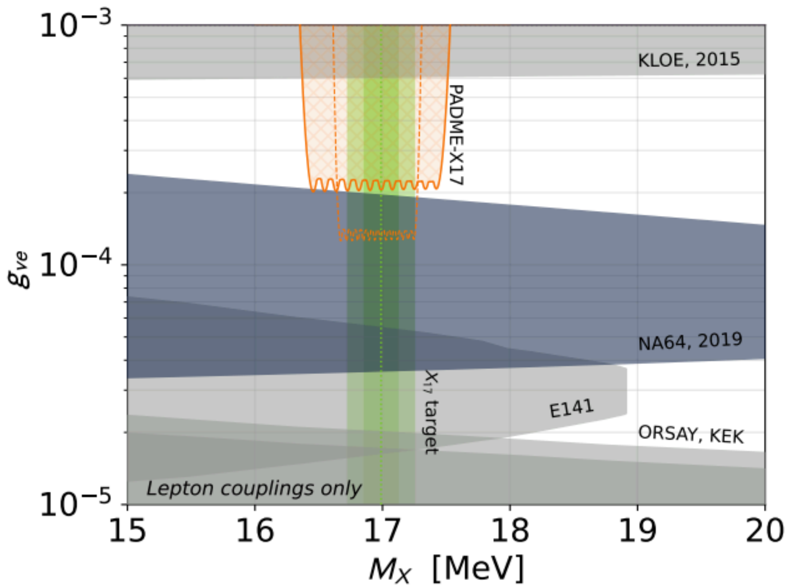




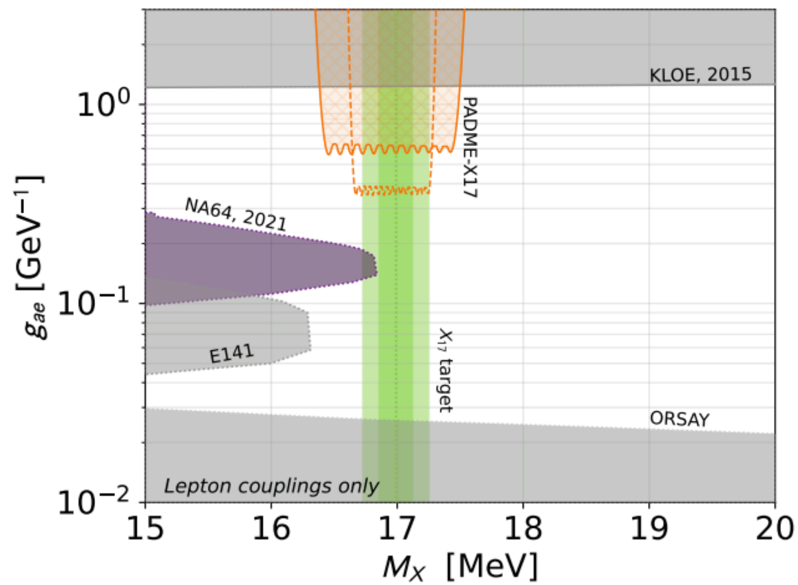
PADME expected sensitivity

L. Darmé, M. Mancini, E. Nardi, M.R.
https://arxiv.org/pdf/2209.09261.pdf

Vector X17



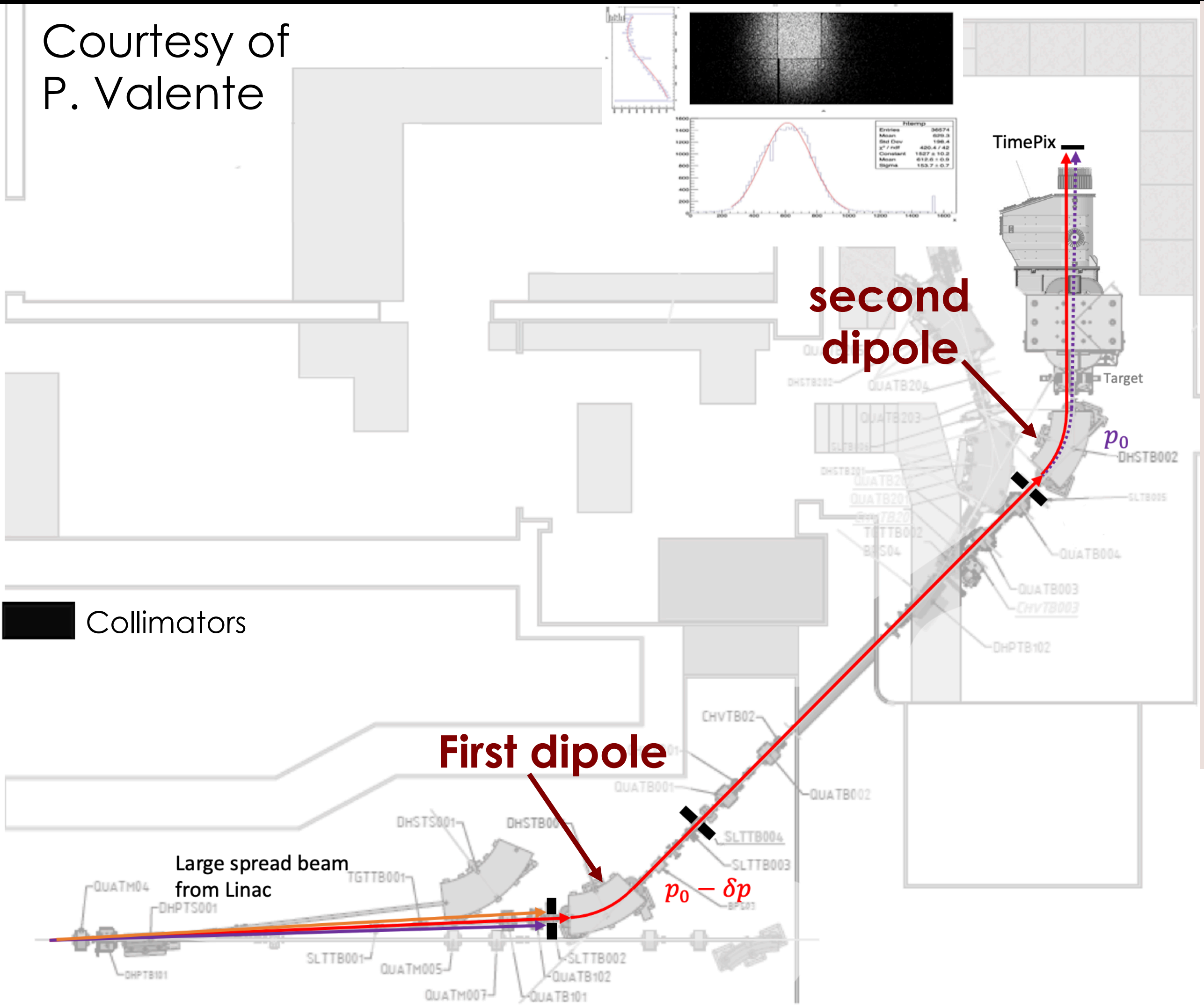
Pseudo scalar X17



- 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
- PADME maximum sensitivity in the vector case

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

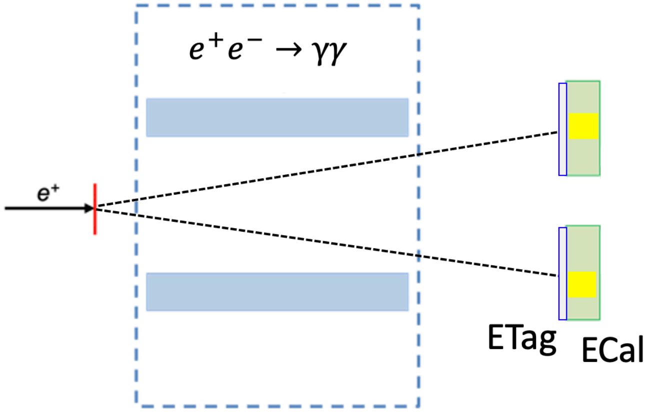
Correct the trajectory using second dipole to put the beam back on axis at PADME

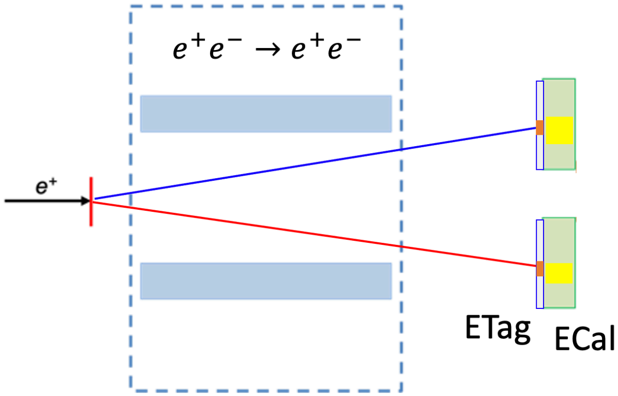
Measure the displacement at the target and timePix to measure the energy step performed

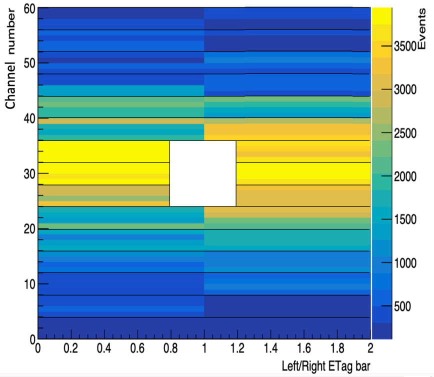
PADME Run III modified setup

- PADME veto spectrometer is hard to reconstruct $e^+ e^-$ mass having no vertex detector
- Idea: identify $e^+e^- \to e^+e^-$ using the BGO calorimeter, as for $\gamma\gamma$ events in Run II

- Switch the **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





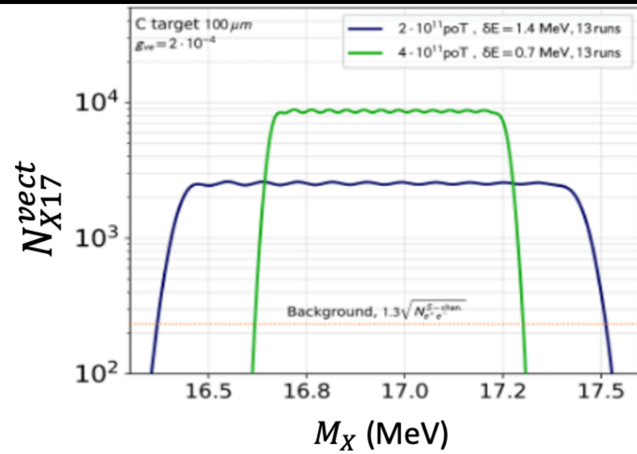


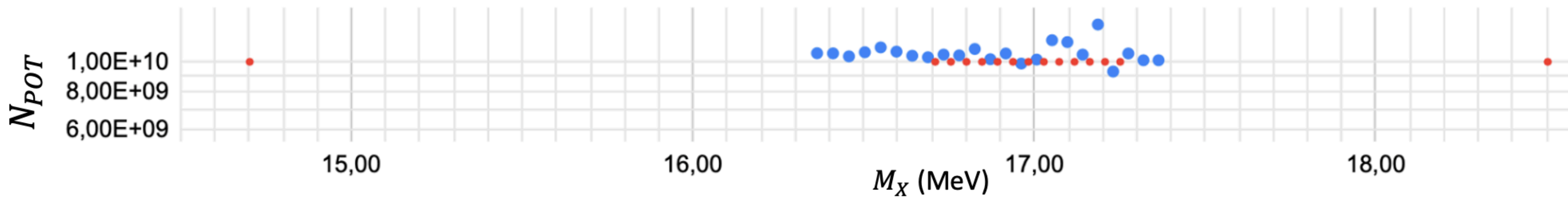
- Thanks to the enhanced production cross section can reduce N_{POT}/bunch by factor 10.
- Much lower pile-up and better energy resolution

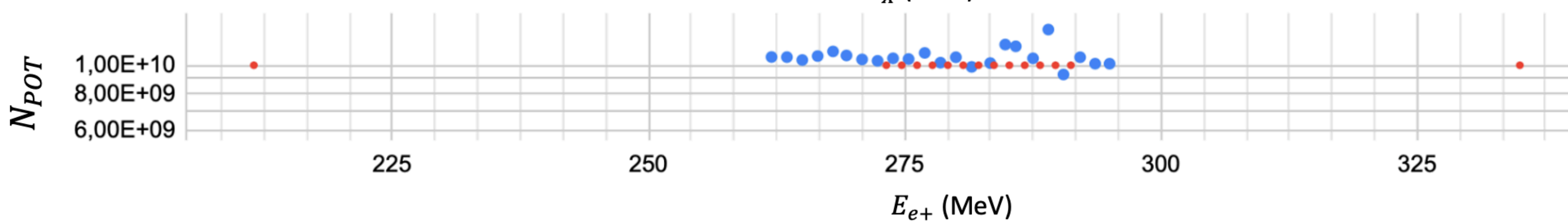
Status of the run III data taking

Try to cover the blue scan with the green granularity

Acquire points below and above the X17 mass to measure the SM $e^+e^- \to e^+e^-$ cross section







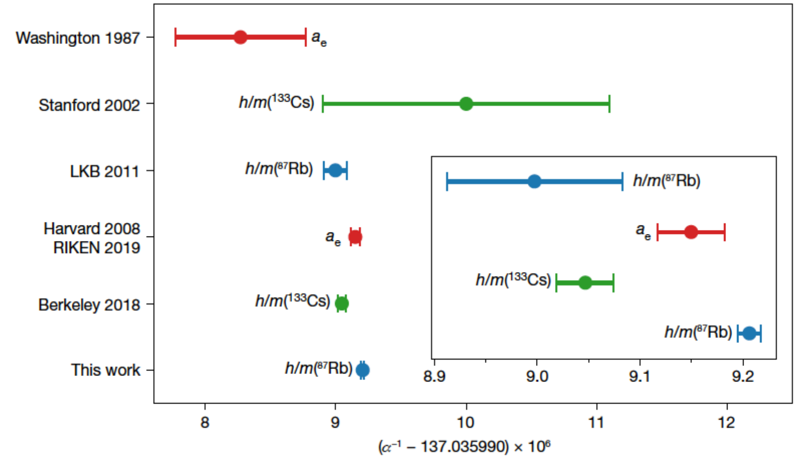
Already covered a region of ~1MeV around the X17 resonance
Now moving off resonance

Conclusions

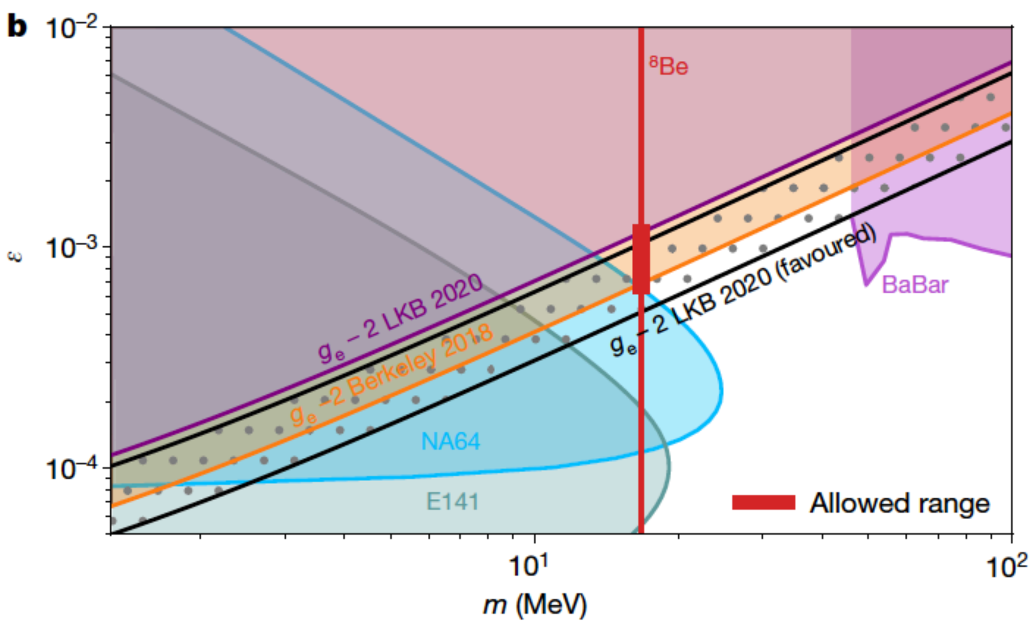
- PADME performed two physics runs, collecting ~$5{\cdot}10^{12}$ POT each
- Run II data-set, collected during the pandemics, with primary positron beam showed much better background conditions than Run I
- The detectors are performing very well, a reliable Monte Carlo simulation, including the beamline, is also available
- **PADME delivered its first physics result**
  - $\boldsymbol{\sigma(e^+e^- \to \gamma\gamma)}$**= 1.930 ± 0.029(stat) ± 0.099(syst) mb**
  - 5% precision, best measurement below 1 GeV
  - Can constrain pseudo-scalar dark sector candidates
  - A step towards the invisible dark photon analysis
- Single photon analysis under way, Bremsstrahlung and beam crash background rejection being the key issues
- **PADME Run III** is ongoing and will address **the X17 anomaly**, trying to significantly impact the vector portal scenario.

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



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

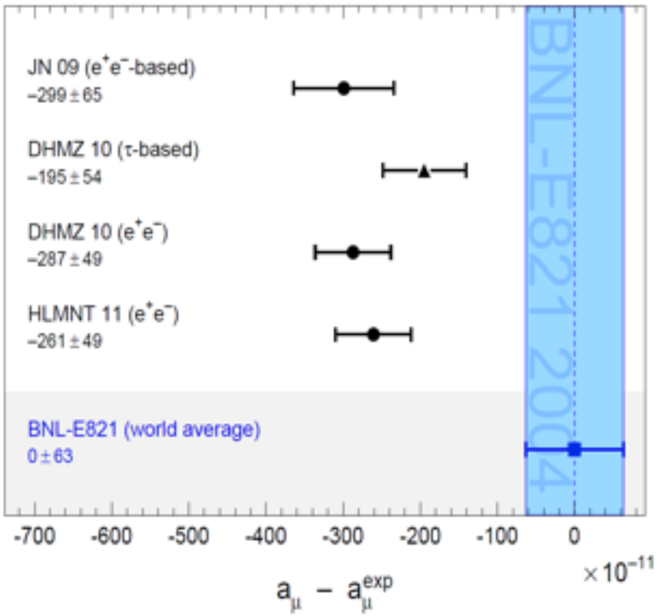


The uncertainty contribution from the ratio $h/m(^{87}Rb)$ is 2.4×10^{-11} (statistical) and 6.8×10^{-11} (systematic). Our result improves the

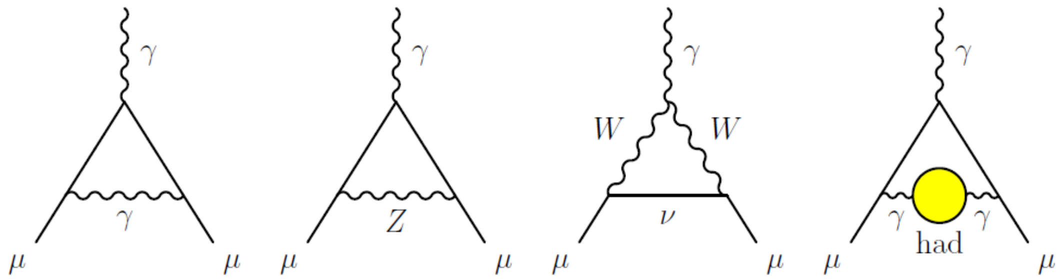
https://www.nature.com/articles/s41586-020-2964-7

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 $a_{e,exp}$.

Muon g-2 anomaly



g-2 in the standard model

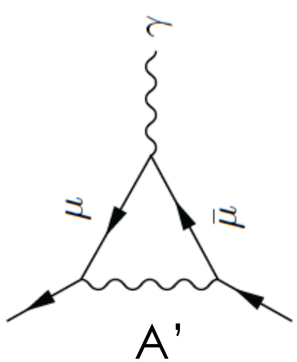


About 3σ discrepancy between theory and experiment (3.6σ, if taking into account only e+e–>hadrons)

Contribution to g-2 from dark photon

Additional diagram with dark photon exchange can fix the discrepancy (with sub GeV A' masses)

g-2 and A'



$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1$–$2 \cdot 10^{-3}$ and $m_V \sim 10$–100 MeV, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

dark sectors in the future of LNF?

- Background dominated: the limit scales as $\sqrt{\mathrm{bkg}}$ so great improvement can come from a significant background reduction
- Ideally, from a "single-particle" experiment with a continuous or quasi-continuous beam
  - Project for using DAFNE ring as pulse stretcher of the LINAC positron beam, in principle 10^{16} POT achievable in few years arXiv:1711.06877, Phys. Rev. Accel. Beams 25 (2022) 3, 033501