Dark sector studies with the PADME experiment

ICHEP 2022
BOLOGNA

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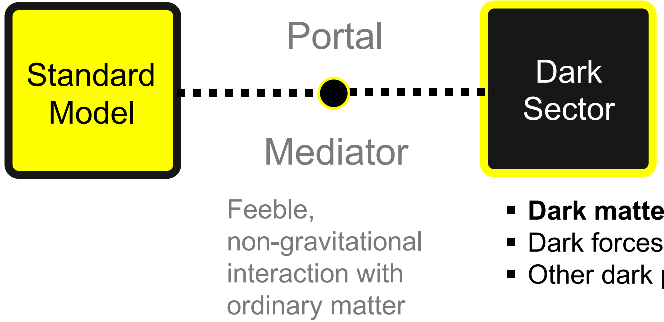
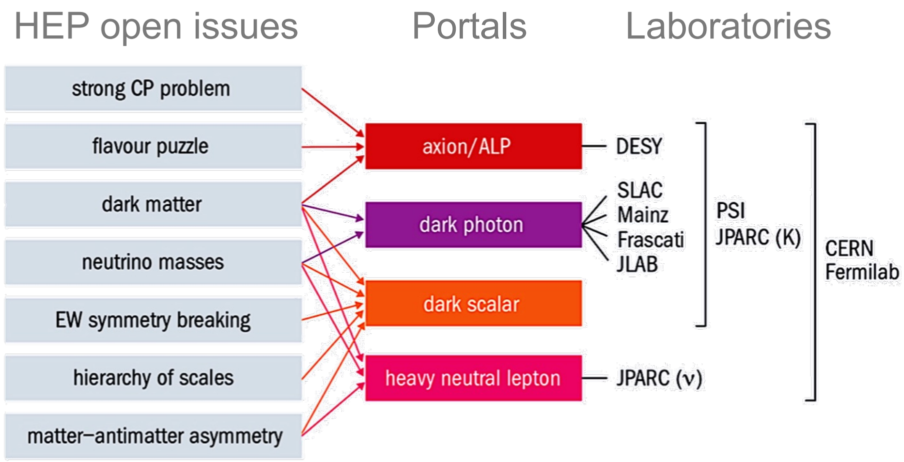
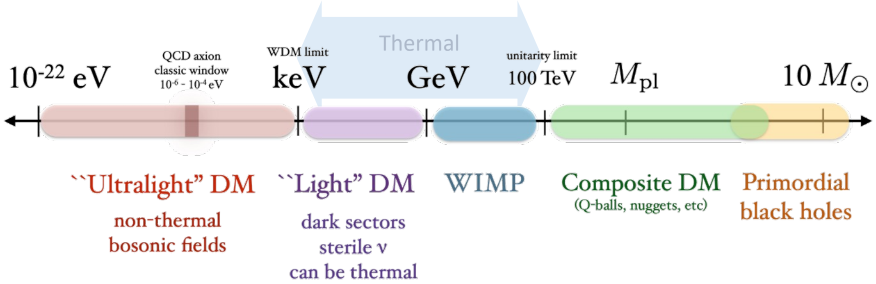
on behalf of the Collaboration

The dark sector paradigm



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





Adapted from B. Batell, G. Lanfranchi/M. Rayner, T. Lin

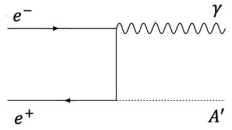
- **Experimental anomalies** can be explained in the context of dark sectors
- The mediator can have a **small mass**
- Thanks to the (feeble) coupling to SM particles, the mediator can be **produced at accelerators**
- It can **decay back to ordinary matter** with the same portal coupling: “visible” vs. “invisible” searches

Experimental approaches

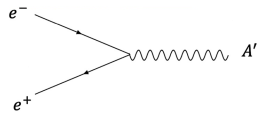
Considering the vector portal, dark photon A', production mechanisms are: **A'-strahlung**, meson **decays**, electron-positron **annihilations**

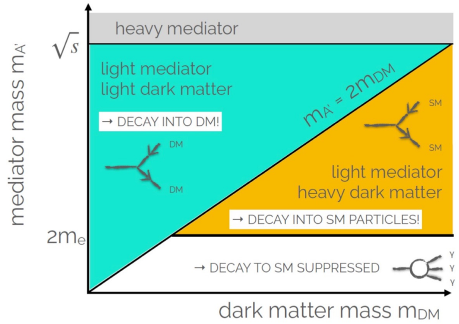
- **Visible searches**: A' detected as it decays back to a lepton pair
  - At beam-dump experiments: produced in a **thick target** where a **proton** or **electron** beam is absorbed (NA64, old dump experiments)
  - At colliders or in meson decays
- **Invisible searches:**
  - **Missing energy/momentum**: A' produced in the interaction of an electron beam with **thick/thin target** (NA64/LDMX)
  - **Missing mass**: $e^+e^- \to A'(\gamma)$ and search for invisible particle closing the kinematics (Belle II, **PADME**)

Associated production

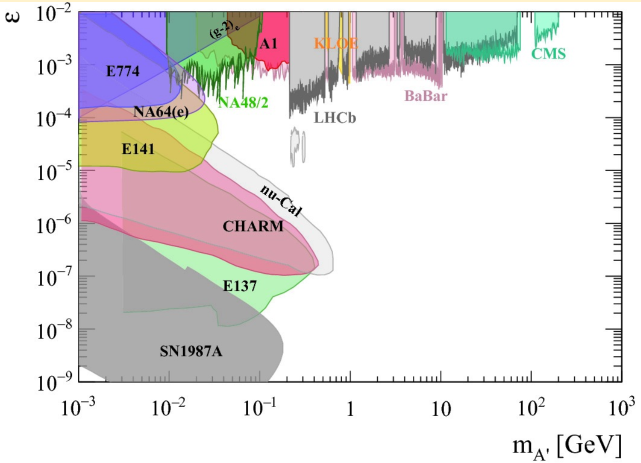


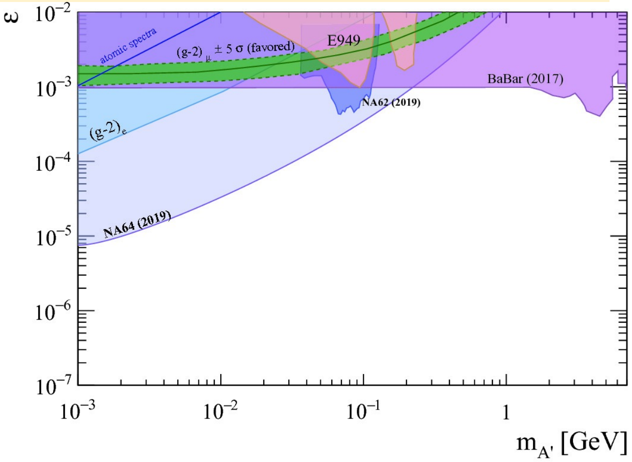
Resonant





T. Ferber

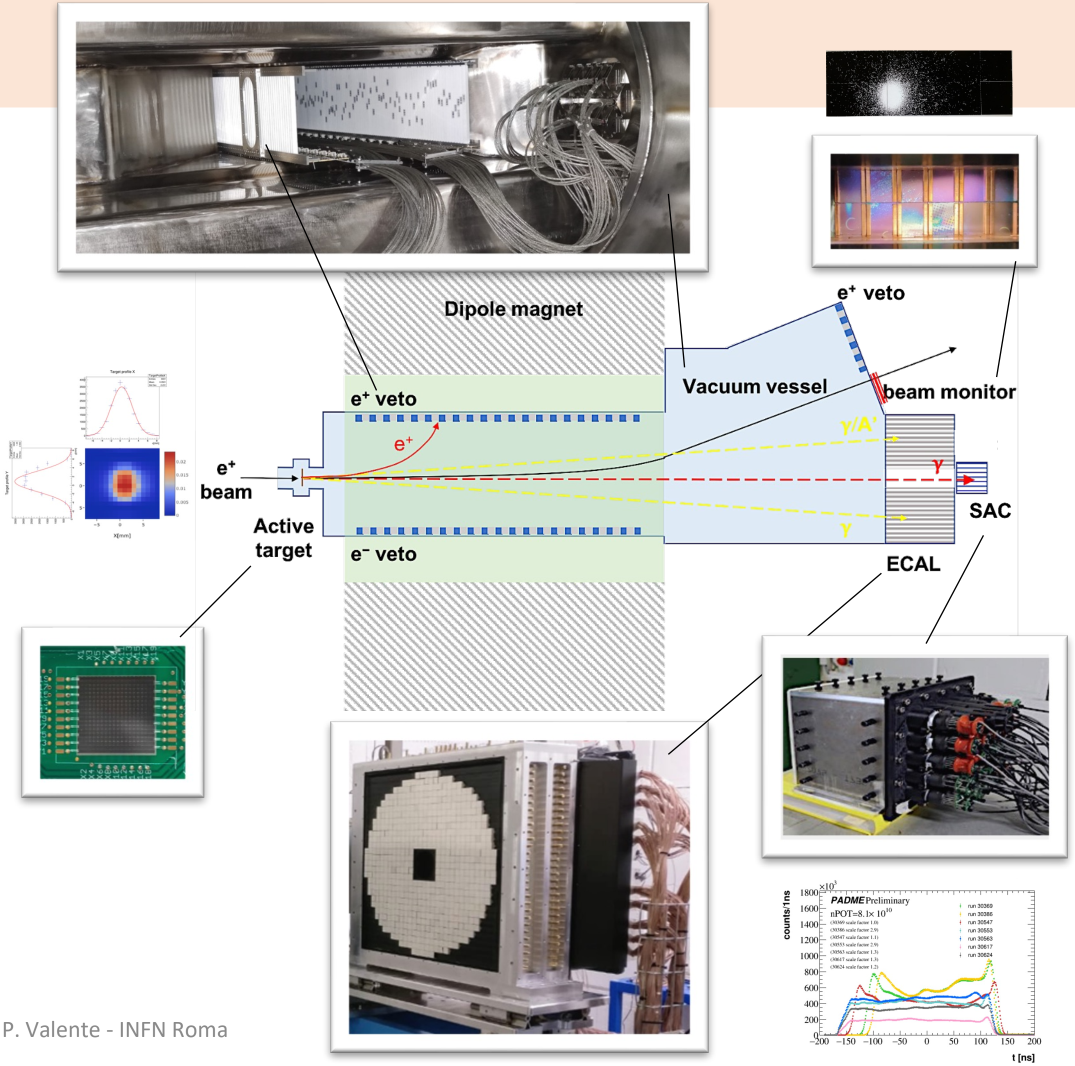




- Looking for the **scattering** of dark decay products $A' \to \chi\bar{\chi}$ has been also proposed (BDX)

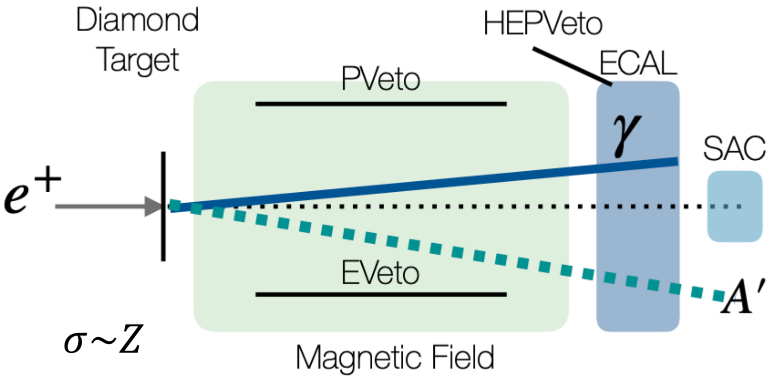
PADME setup

- Positron beam of ~**0.5 GeV/c**
  - LINAC repetition rate 50 Hz
  - Macro-bunches maximum length $\Delta t \lesssim$**300 ns**
- Active, full Carbon target, **100 μm thick**
  - CVD diamond with graphite x and y strips
  - Pulse-by-pulse beam intensity measurement
- 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) measuring beam position and size
  - Using dipole dispersion, allows to determine the momentum spread of the beam: $\boldsymbol{\delta p/p \sim 0.3\%}$
- Photon clusters measured by a **BGO calorimeter (ECAL)** …
  - 616 crystals, 2,1×2.1×23 cm³, with central square hole
- … and by a faster, **PbF₂**, small angles calorimeter **(SAC)**
  - 25 crystals 3×3 cm²
  - Precise (<1 ns) measurement of beam **time structure**



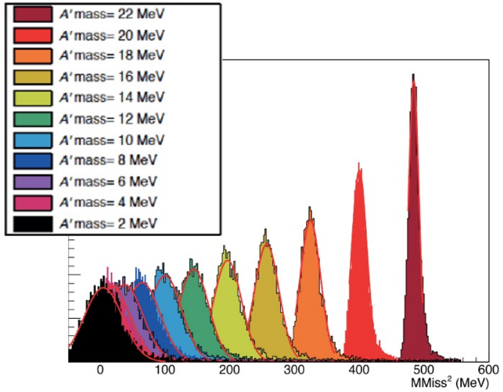
A' to invisible signature

Signal:



Knowing the beam momentum $\underline{p}_{e^+}$,

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

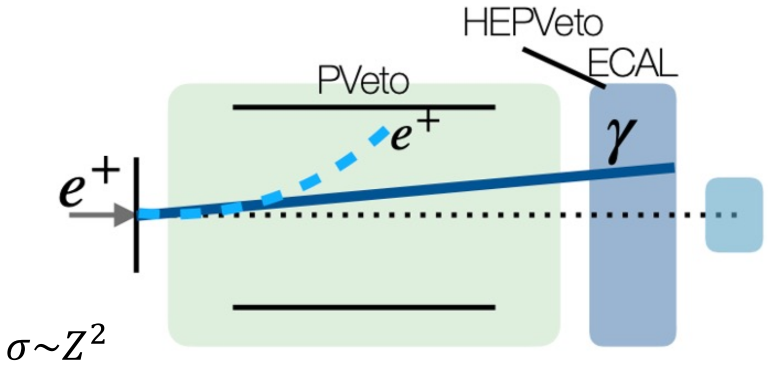


Normalize to $\gamma\gamma$ channel:

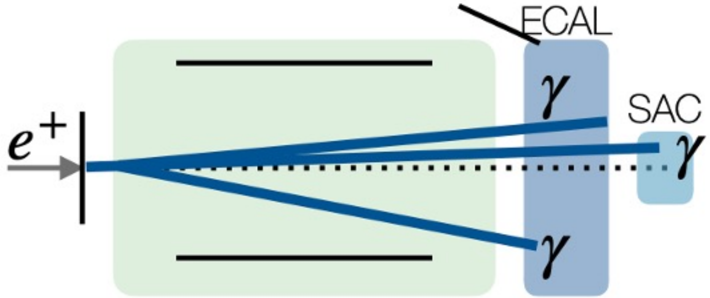
$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = $$

$$= \frac{N(A'\gamma)}{N(\gamma\gamma)} \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon\delta$$

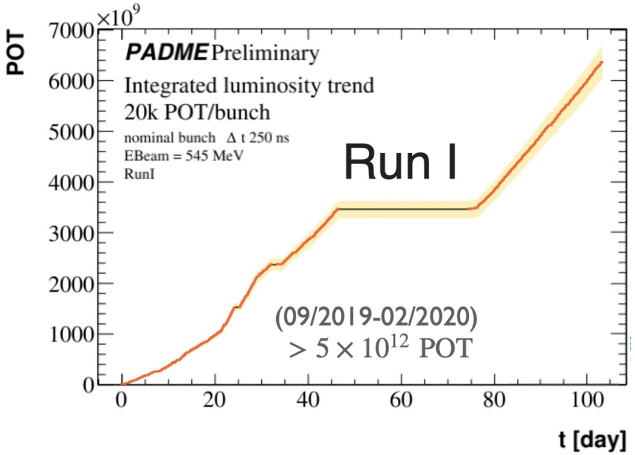
Background: Bremsstrahlung

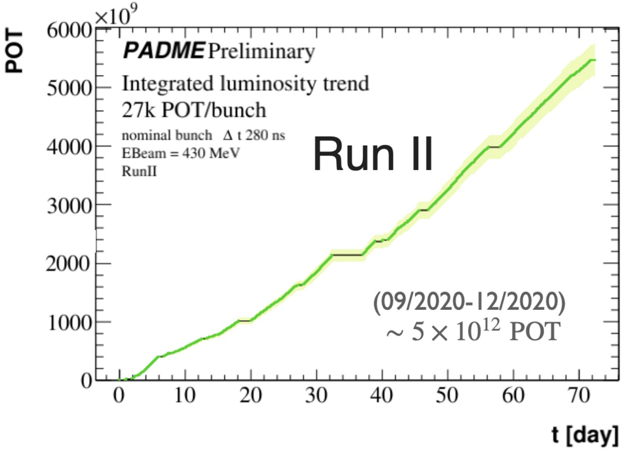


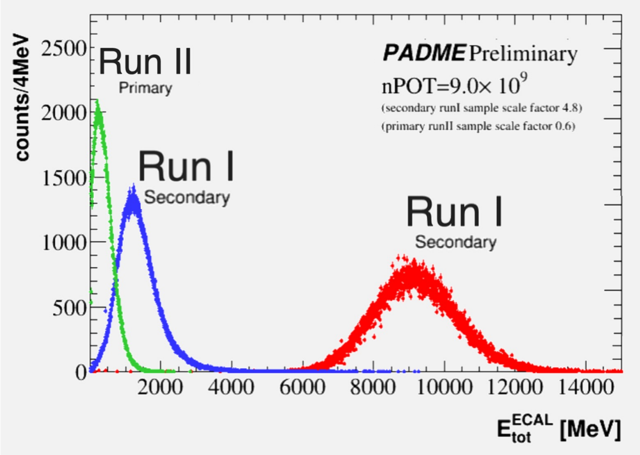
Background: $\gamma\gamma$ and $\gamma\gamma\gamma$



PADME data

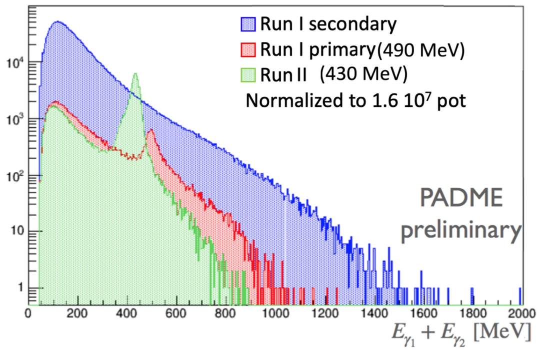


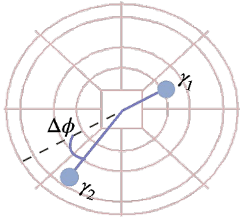




- Two physics runs in **2019** winter and **2020** winter
- Run II wrt Run I
  - Similar statistics, approximately 1/2 of minimal objective (10^{13} particles-on-target)
  - Slightly lower beam momentum in Run II, 430 MeV/c, wrt to Run I, 490 MeV/c
  - **Improved vacuum separation** between experiment and beamline
  - Less beam-induced background with primary wrt secondary beam
- Run III expected in winter 2022

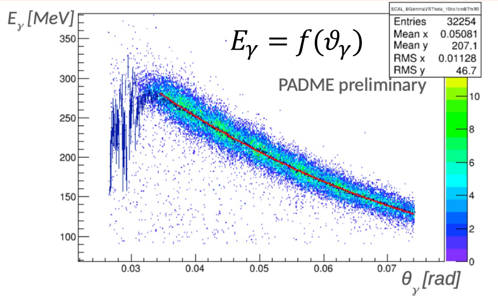
Two photons events

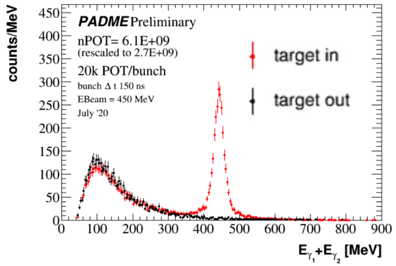




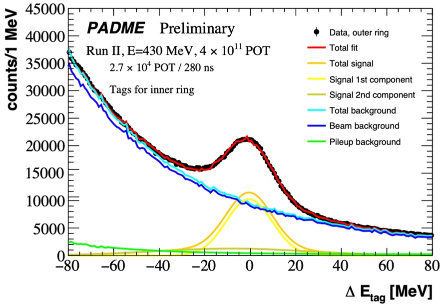
- Normalization for $A'\gamma$
- Source of photons with energy in the range of interest for the signal for efficiency measurement
- Independent determination of luminosity
- **Cross-section measurement**

- Below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics (e.g. ALP's)
- Using ~10% of Run II sample
- 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 $m^2_{miss} \sim 0$

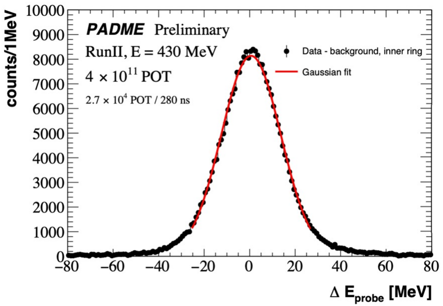




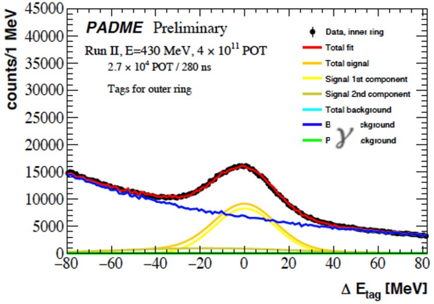
Tag photons selection

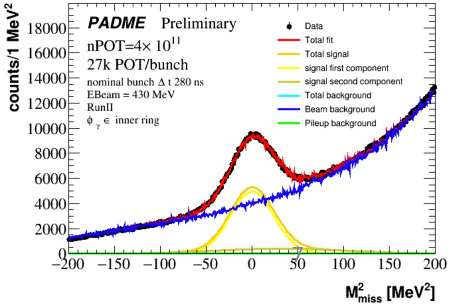


Probe photons

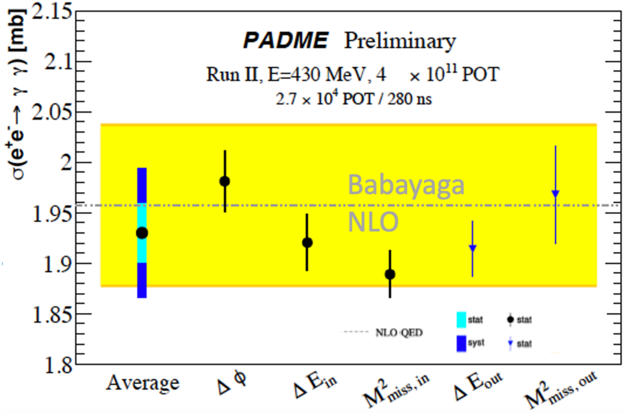


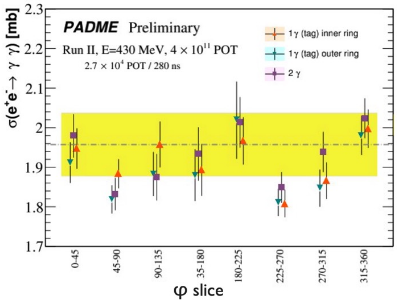
Single photon selection

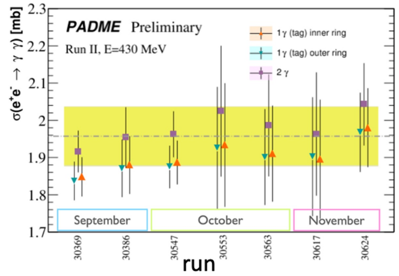


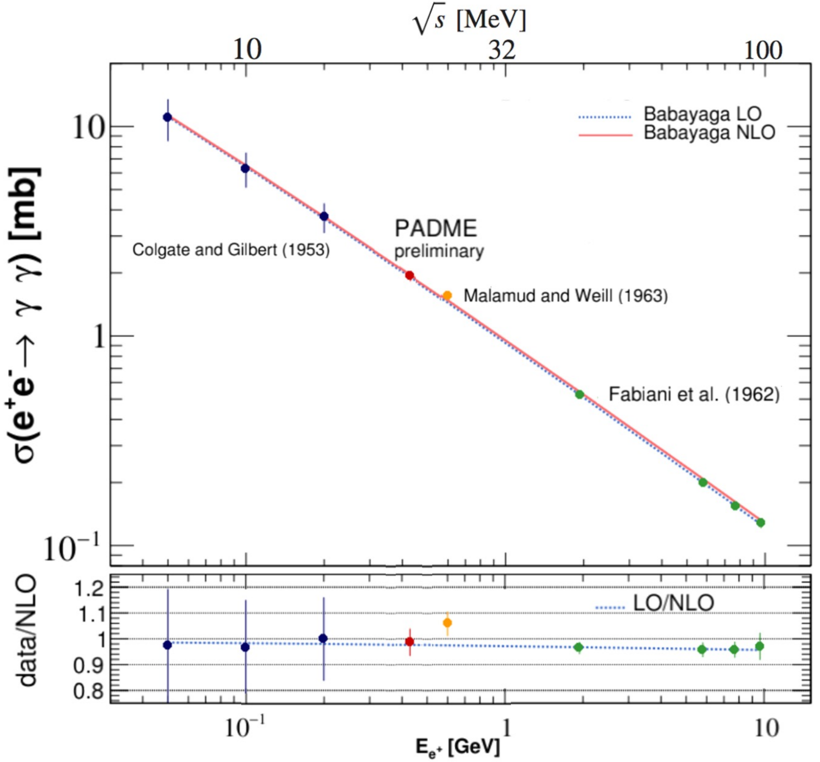


Two photons cross-section



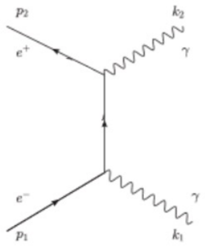




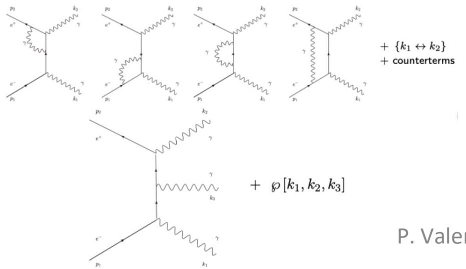


Detector response uniformity	0.020 mb
Background modelling	0.047 mb
Acceptance	0.025 mb
n POT: target calibration	0.079 mb
Electron density (target thickness)	0.020 mb

LO



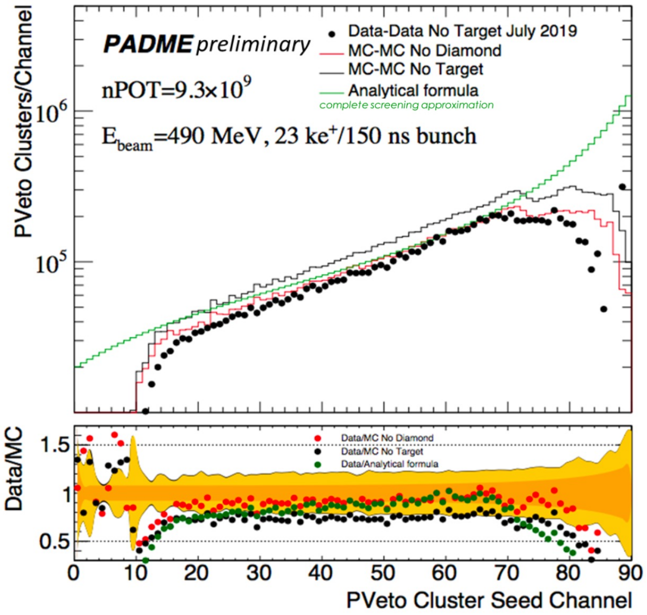
NLO



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

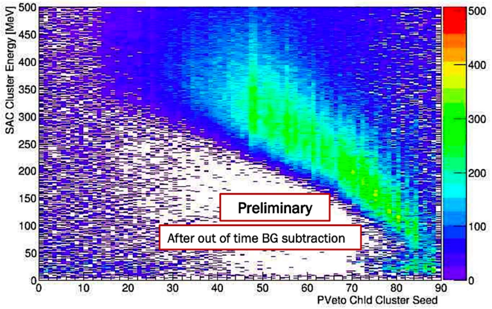
Full details, see talk by **I. Oceano** at Moriond 2022

Single photon events

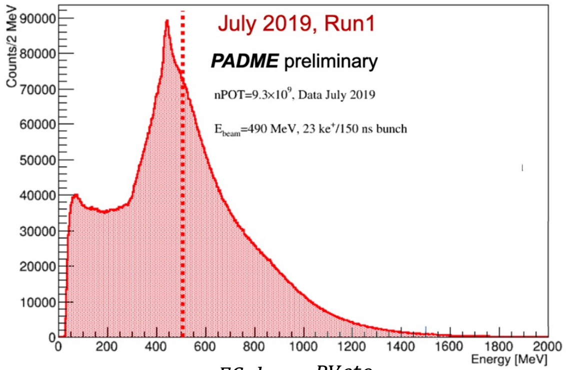


Beam background dominated by Bremsstrahlung:

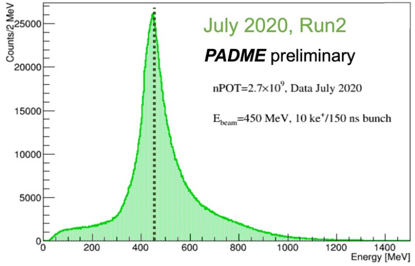
- Measured with no-target runs and subtracted
- Bremstrahlung photon distribution in agreement with **Monte Carlo simulation** and **analytical calculation**
- Main systematic uncertainties:
  - Background normalization
  - Positron momentum scale
  - n POT calibration



Veto momentum vs. SAC energy
490 MeV, primary beam, Δt <1 ns



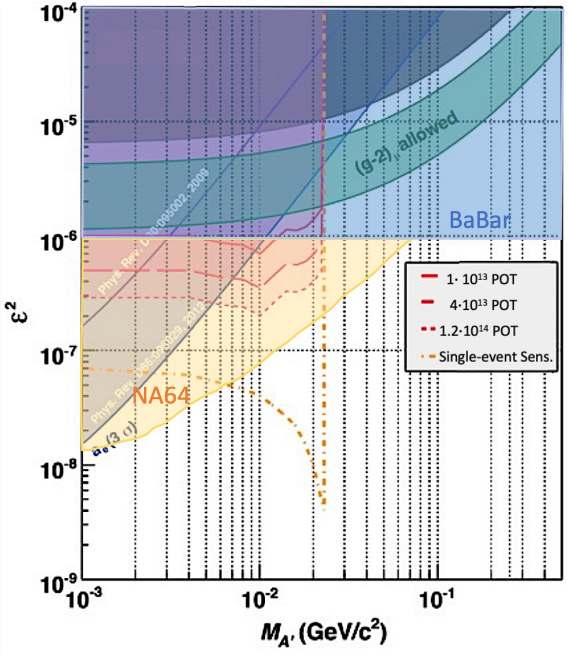
$p_\gamma^{ECal} + p_{e^+}^{PVeto}$



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

- Essential for dark photon analysis

Dark photon invisible decays sensitivity

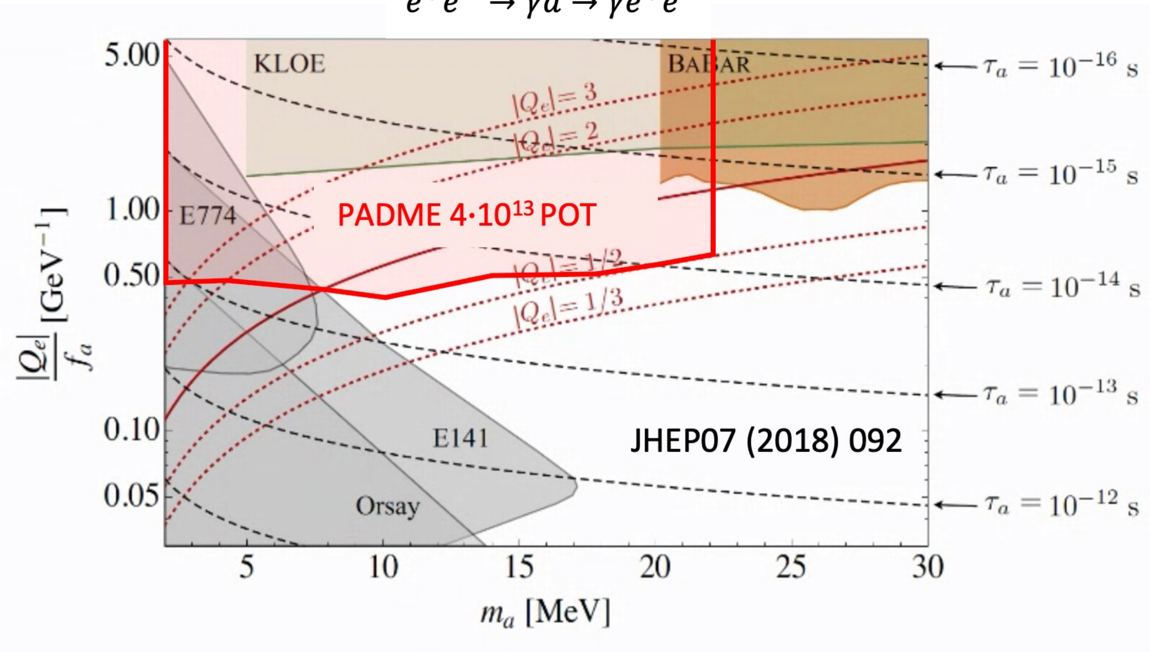


- Background dominated: the limit scales as $\sqrt{\mathrm{bkg}}$ so great improvement can come from a significant background reduction
- Ideally, from a "single-particle" experiment with a continuous or quasi-continuous beam
  - Project for using DAFNE ring as pulse stretcher of the LINAC positron beam, in principle 10^{16} POT achievable in two years

    arXiv:1711.06877,
    Phys. Rev. Accel. Beams 25 (2022) 3, 033501

ALP searches

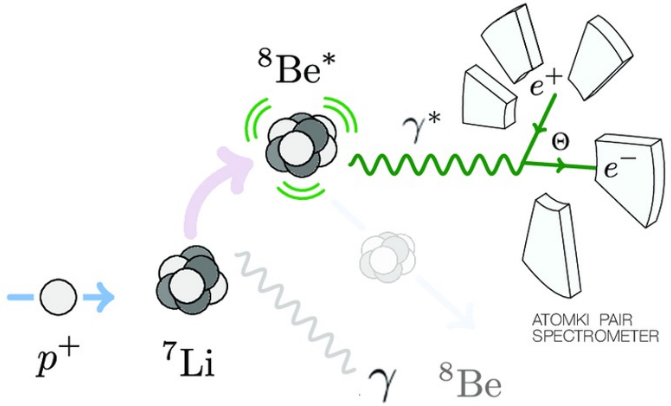
$e^+e^- \to \gamma a \to \gamma e^+e^-$

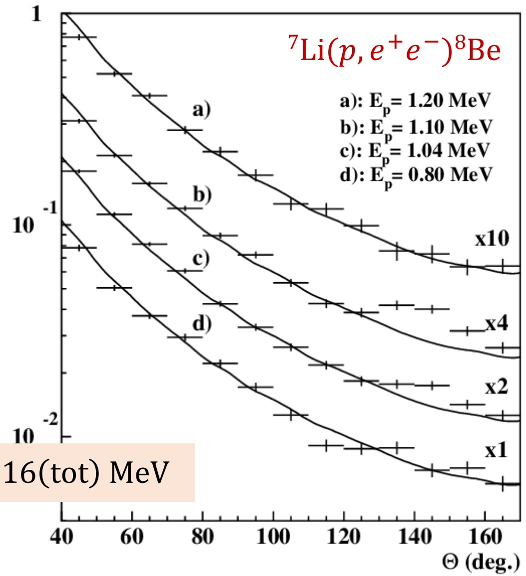


- Interesting prospects in the ALP to visible decays
- Same selection as dark photon or $X17$ to visible searches
- Proper sensitivity study, including resonant production under way

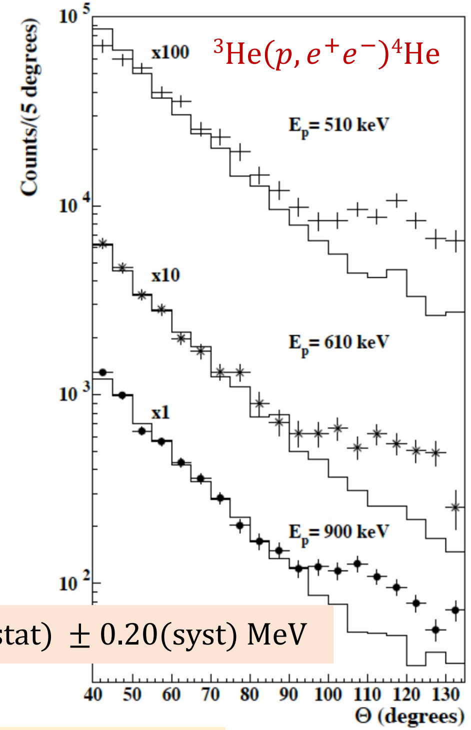
The Beryllium anomaly

PRL **116**, 042501 (2016) Phys. Rev. C **104**, 044003 (2021)





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

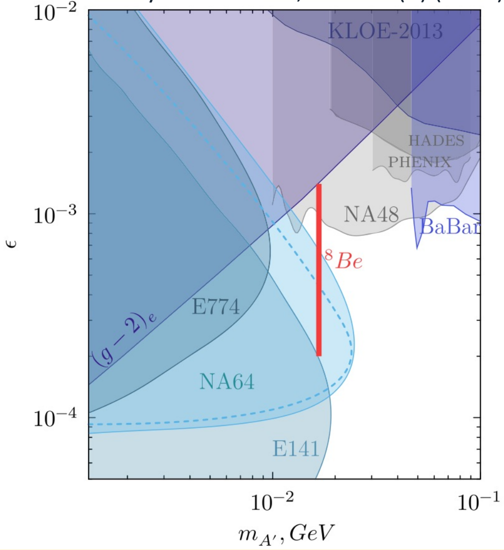


$m_X c^2 = 16.98 \pm 0.16(\mathrm{stat}) \pm 0.20(\mathrm{syst})$ MeV

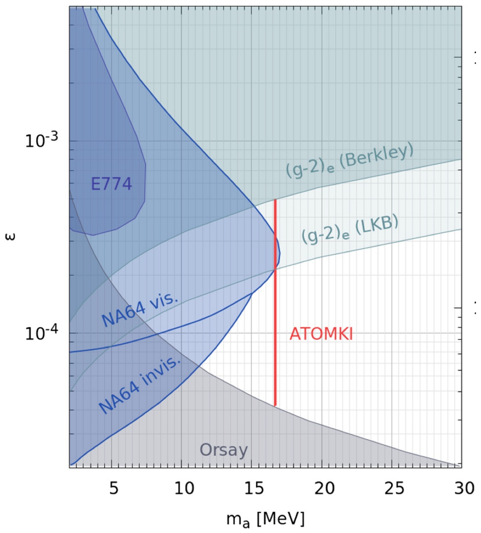
ATOMKI has recently confirmed the anomalous peak in the angular distribution of internal pair creation from two experiments in the ^{8}**Be** and one in the ^{4}**He** transitions, with different kinematics but at the **same invariant mass value**

$X17$ as vector or pseudo-scalar

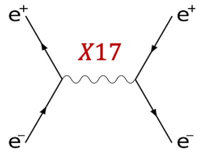
Phys. Rev. D 101, 071101 (R) (2020)



Phys. Rev. D 104, L111102 (2021)

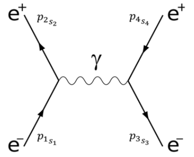


- Interpretation of the ATOMKI anomaly as **vector** or **pseudo-scalar** particle of 17 MeV/c^2 not totally excluded

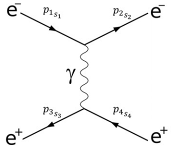


At PADME:

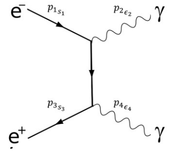
- Similar observables as in the ATOMKI experiments: 2 leptons in the final state, but with a totally different production
- Cross section enhancement from **resonant production** in e^+e^- annihilations at $\boldsymbol{E_{e^+}\sim}$**283 MeV**
- Main backgrounds:
  - **Bhabha scattering**, both from the s channel and t channel
  - Two clusters in the calorimeter of course also produced in $\gamma\gamma$ events



s channel



t channel

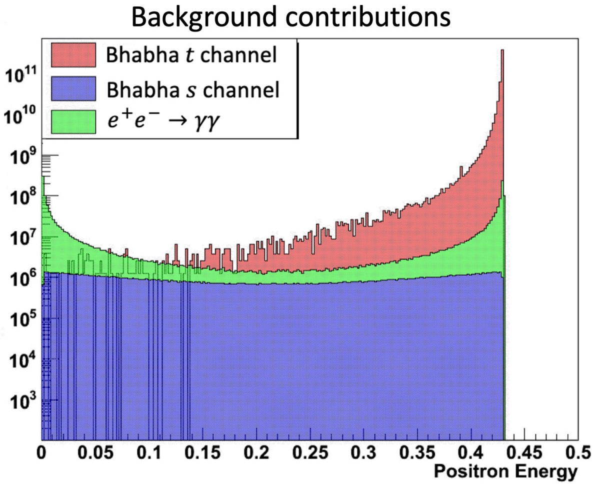


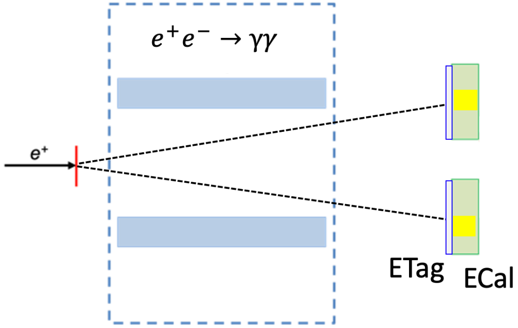
PADME Run III setup

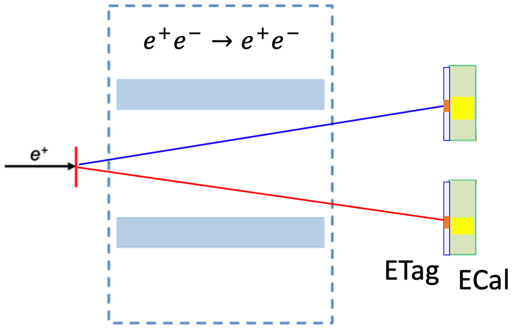
PADME veto spectrometer cannot be used to constrain e^+e^- vertices not coming from the production target

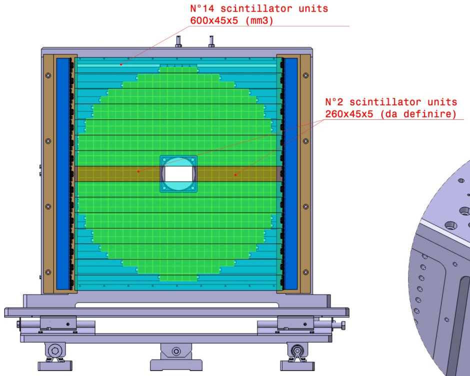
Idea: identify $e^+e^- \rightarrow e^+e^-$ using the BGO calorimeter, as for $\gamma\gamma$ events

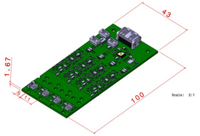
- With **magnet off** the positrons and electrons will reach the ECal
  - Can measure precisely (3%) electron-positron pair momentum and angles
  - Can reconstruct invariant mass of the pairs precisely (small pile-up)
- Requires to **identify clusters** in ECal from photons or electrons
  - New detector, plastic scintillators, similar to PADME vetos (Electron tagger, ETag) with vertical segmentation and covering the fiducial region of ECal
  - Designed and built, now ready to be installed for Run III

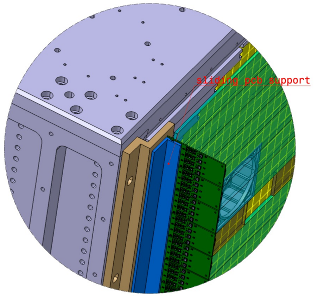




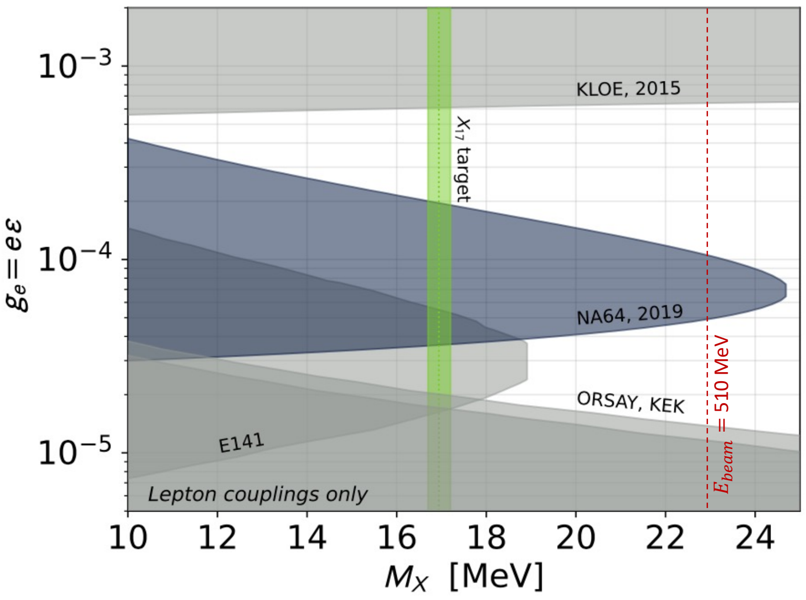


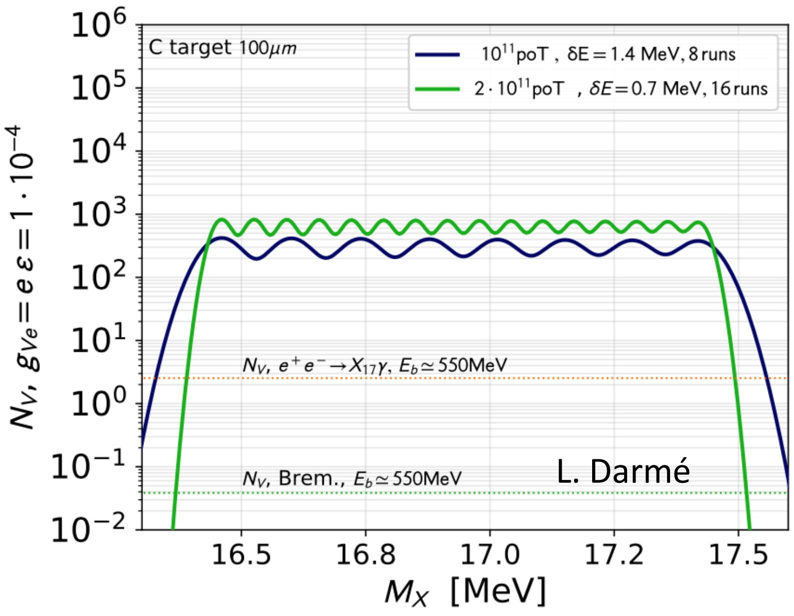






$X17$ resonant search





- There is an open window in vector $X17$ searches (2-6)×10^{-4}
- PADME can produce several thousand of $X17$ in resonant mode, even with such a small coupling
- LINAC positron beam energy up to 510 MeV → $m_X c^2$ =22.8 MeV
- Move around ~283 MeV and exploit the resonant production

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
- $\sigma(e^+e^- \to \gamma\gamma) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst})$ 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 background rejection with veto detectors being the key issue
- PADME Run III will start after summer and will address the X17 anomaly, trying to close the gap parameter space, both for the vector and pseudo-scalar models