Annual Meeting 2024

TA3: Transnational Access to LNF

Catalina Curceanu, INFN-LNF, Italy

TA3 – Transnational Access to LNF

The DAΦNE Complex including LINAC, BTF and the electron-positron collider

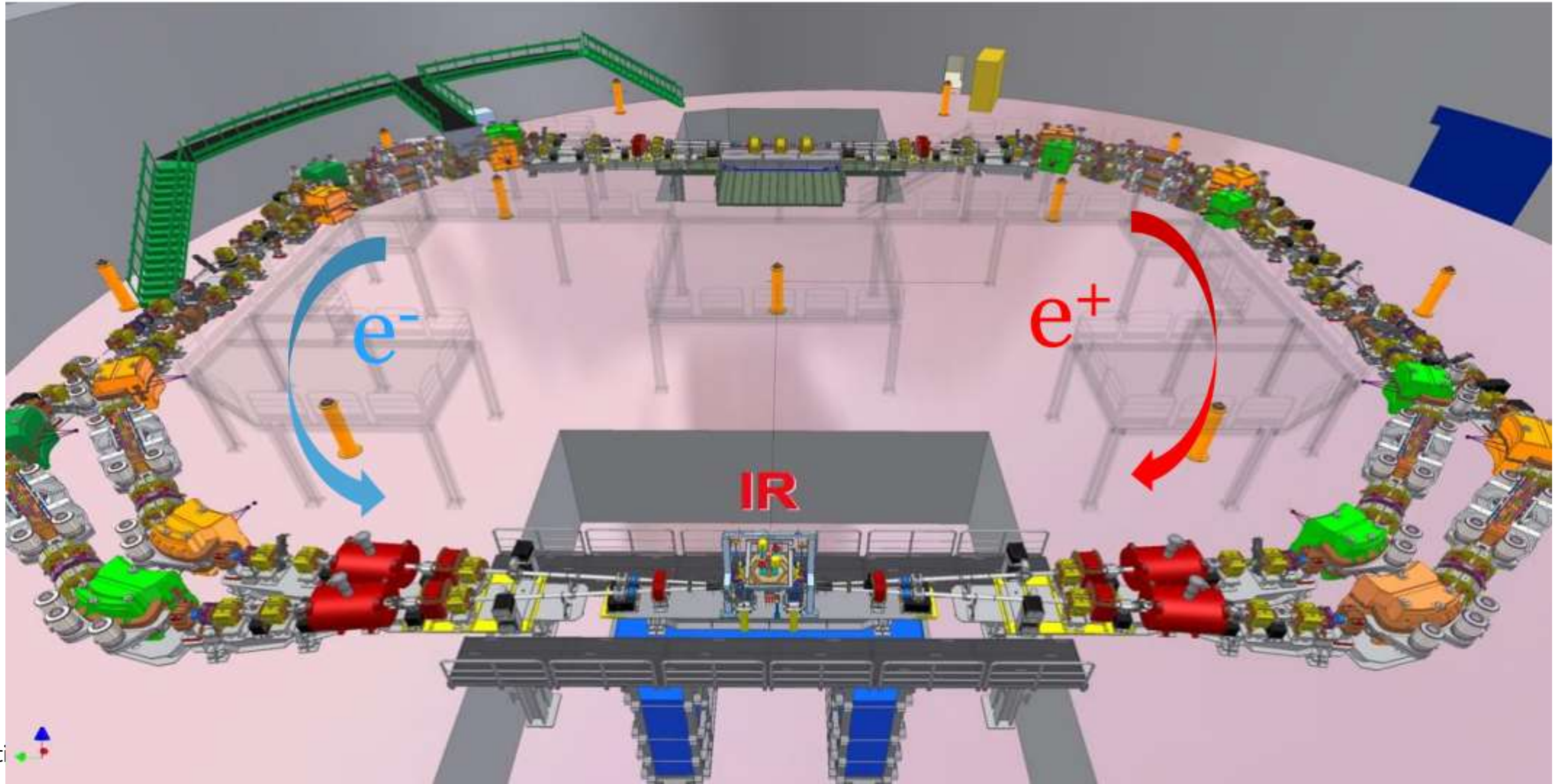
60 mt
LINAC
GUN e-
e-
SEPARATOR
e+
BTF-2
PADME
BTF-1
DAMPING
RING
TRANSFER LINE
KLYSTRON POWER SUPPLY AREA
LINAC LABORATORIES
COOLING SYSTEM MAINTENANCE AREA
COOLING SYSTEM AREA
DAFNE MAIN RINGS
e-
e+
SIDDHARTA-2
e+
e-
MAGNET POWER SUPPLY AREA
entrance
DAFNE CONTROL ROOM
INSTRUMENTATION ROOM
DAFNE LIGHT LAB
DAFNE Accelerators Layout
by LNF - SIM 2016 / v3_2023 by Sara Reda

Experiments supported with TA on the DAΦNE complex and progress during reporting period

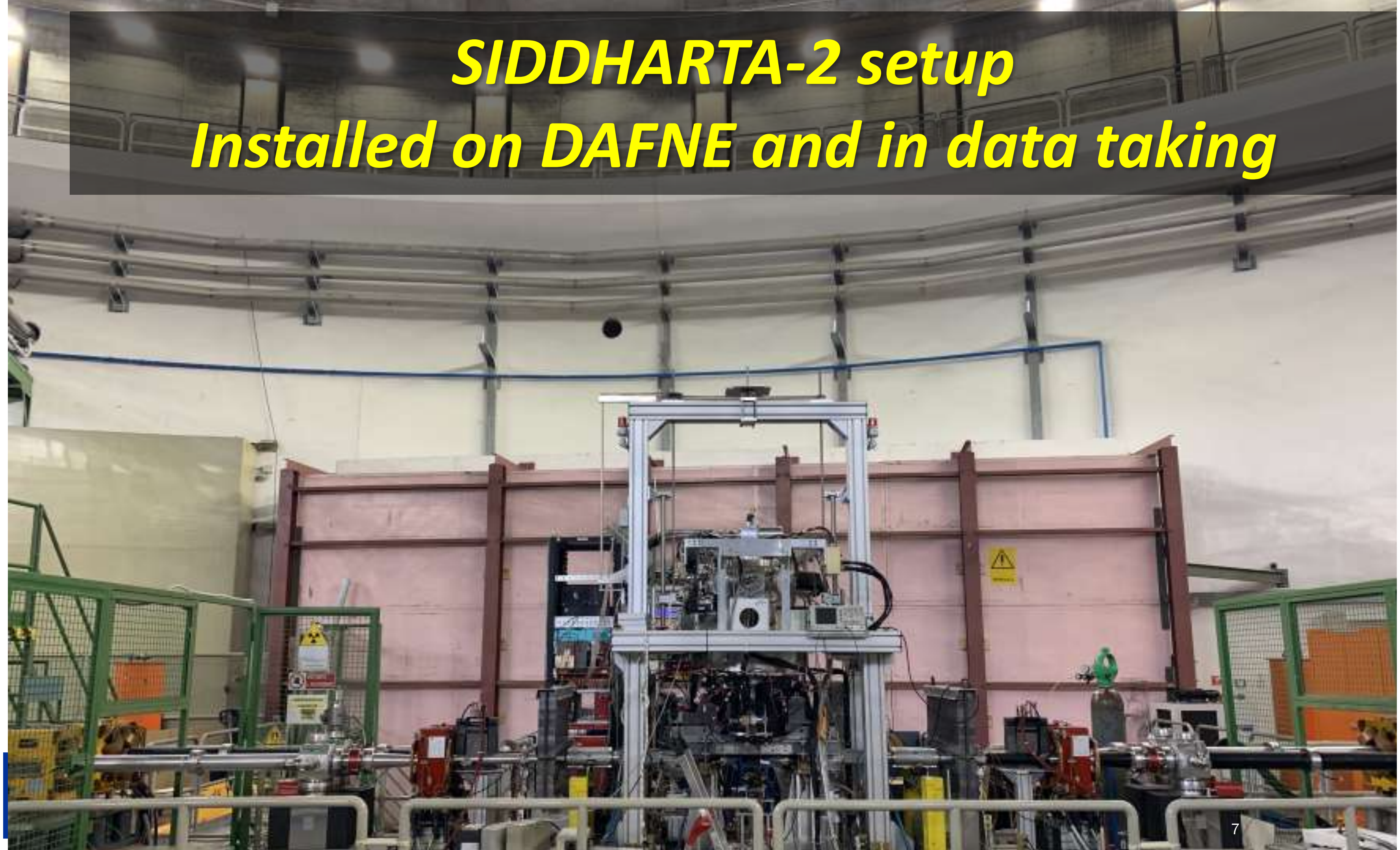
- **SIDDHARTA-2: kaonic atoms**
- **PADME: searches for Dark Matter**

Laboratori Nazionali di Frascati (LNF-INFN)

- $\Phi \rightarrow K^- K^+$ (49.1%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)



SIDDHARTA-2 setup
Installed on DAFNE and in data taking



The Kaonic Deuterium Measurement - Timeline

- **First Kd run** May - July 2023: 164 pb^{-1} integrated luminosity;
- **Second Kd run** October - December 2023: 276 pb^{-1} integrated luminosity;
- **Third Kd run** February - April 2024: 375 pb^{-1} integrated luminosity;

2023, Nov
Annual meeting

2023, Oct - Dec
Kaonic deuterium Run2
HPGe and CdZnTe data taking

2023, Dec
Winter stop
Ordinary maintenance of the setup

2024, Feb - April
Kaonic deuterium Run3
HPGe and CdZnTe data taking

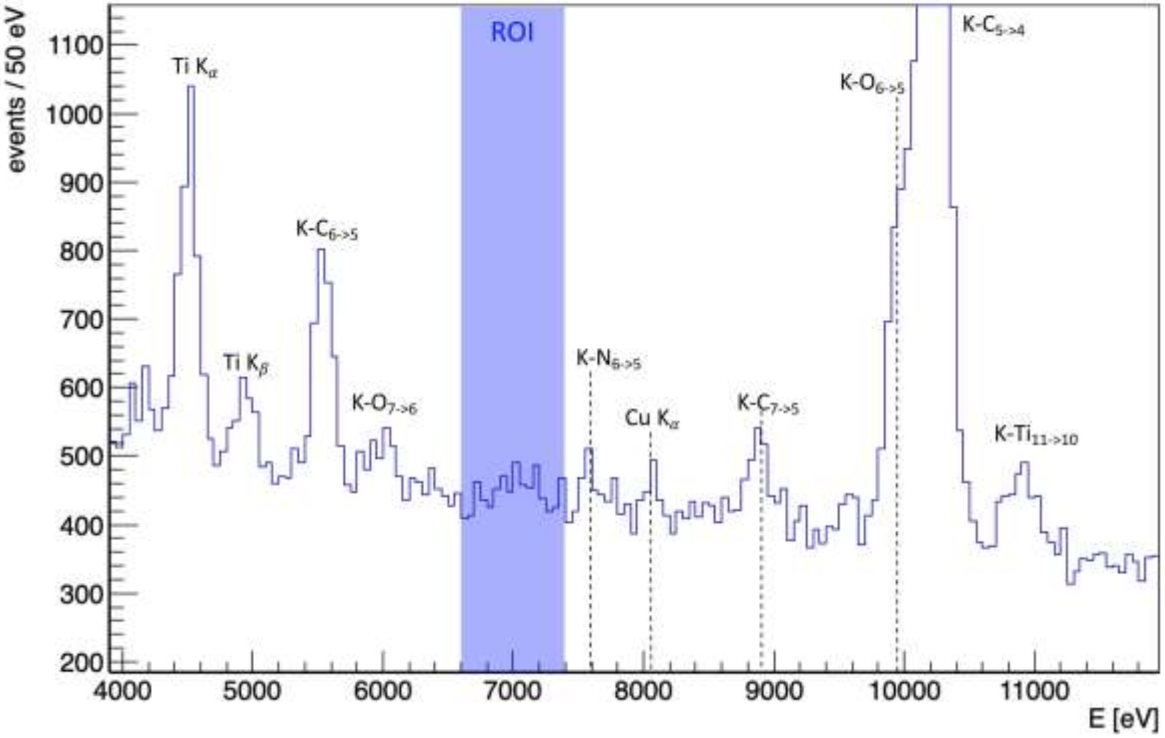
2024, May - ongoing
Kaonic deuterium Run4 – lower density
HPGe and CdZnTe data taking

...with the aim of collecting 800-900 pb-1 in total – goal achieved! Thanks to excellent DAΦNE working conditions.

	Luminosity delivered [pb^{-1}]
Run1	196
Run2	344
Run3	435
Total	**975**

Kaonic Deuterium Run1: data analysis

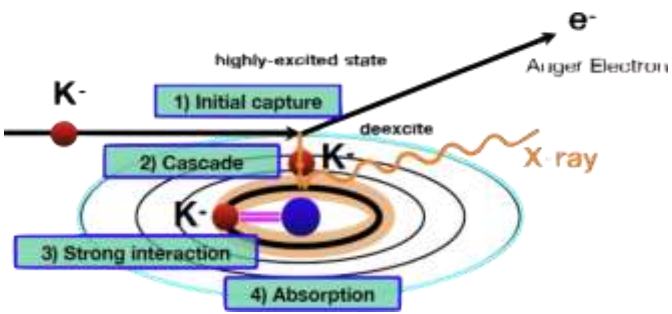
Preliminary energy spectrum after asynchronous (electromagnetic) background rejection

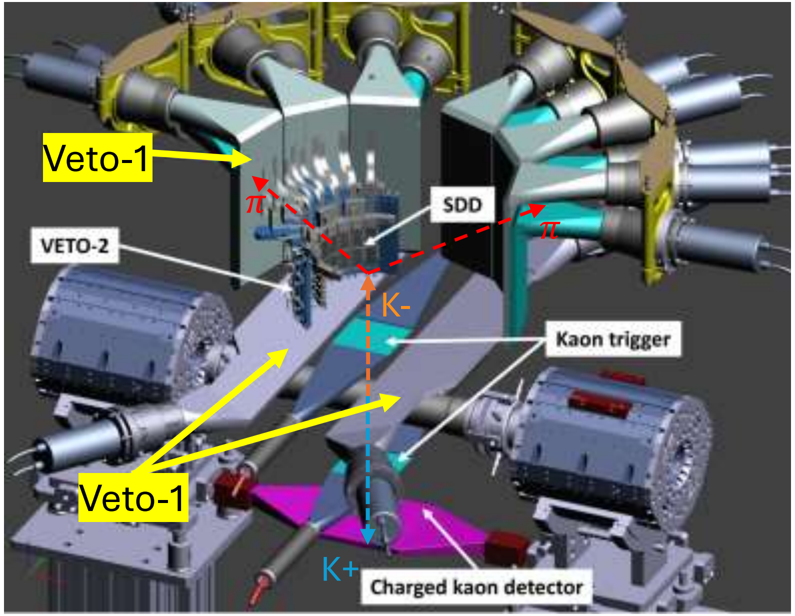


- ✓ Refined calibration
- ✓ Analysis of all veto systems data
  - ➢ Veto-1 system
  - ➢ Veto-2 system
  - ➢ Charged kaon system
- ✓ Hadronic background rejection
- ✓ Preliminary fit of the energy spectrum

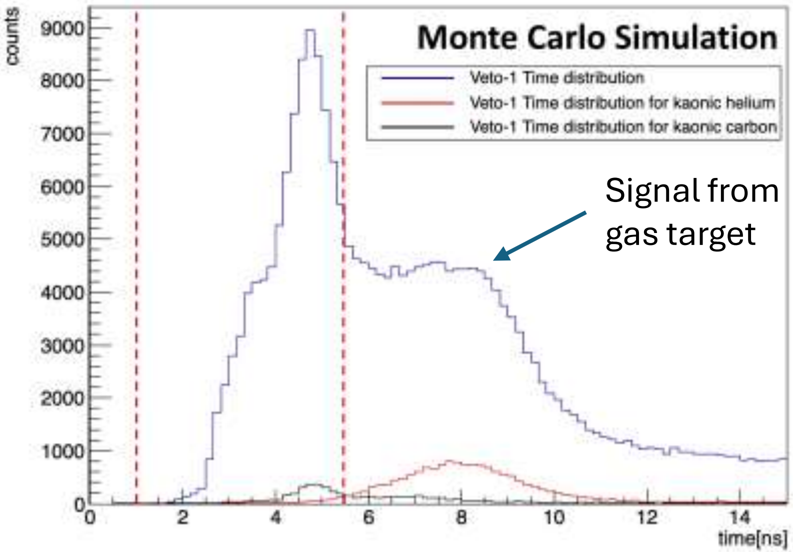
Kaonic Deuterium Run1: veto-1 system analysis

Veto-1 for synchronous background reduction:
measure the arrival time of the charged particles emitted by the kaon-nucleus absorption



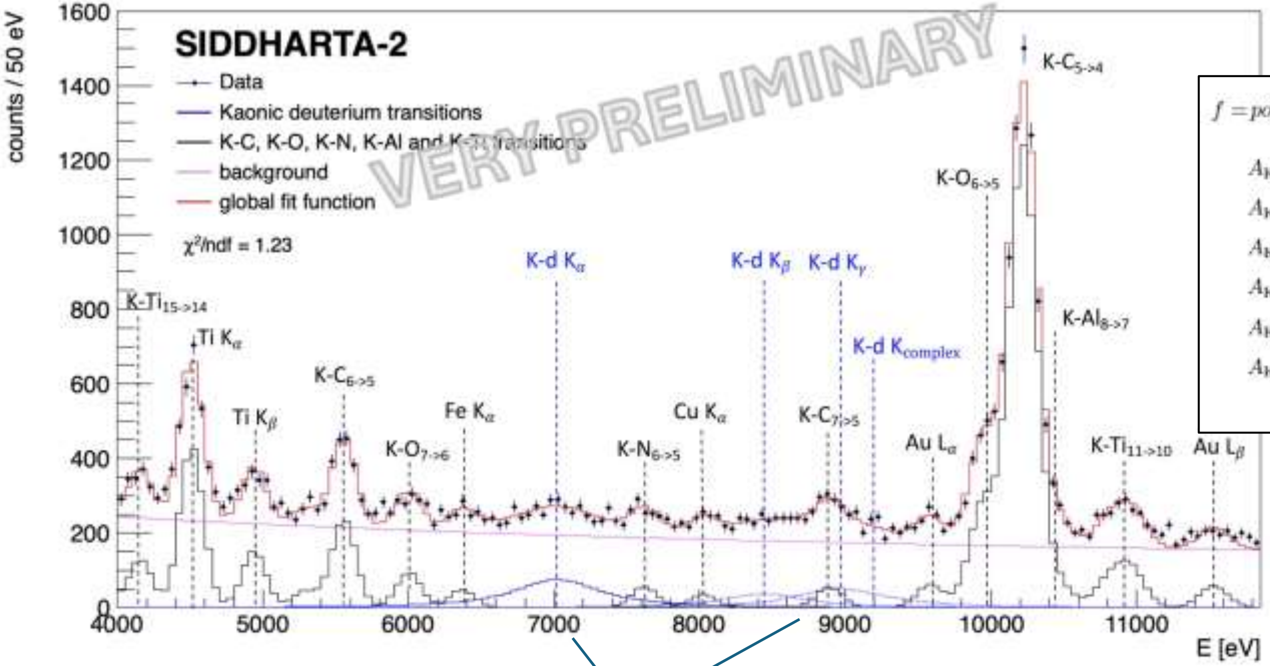


Veto-1: 14 plastic scintillators placed around and below the vacuum chamber



Kaonic Deuterium Run1: preliminary result (F. Sgaramella Ph.D. thesis)

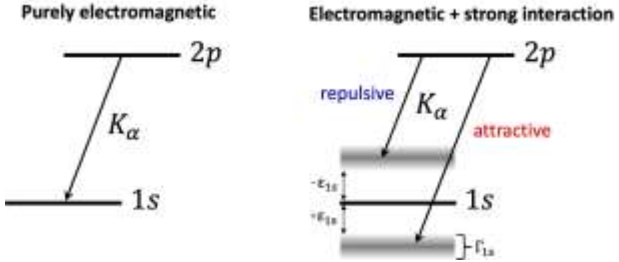
Preliminary fit of the kaonic deuterium energy spectrum



$$
\begin{aligned}
f = & \, pol_1(E) + \exp(E) + \sum_i \mathrm{Gauss}(A_{Gi}, E_i, \sigma) + \mathrm{Tail}(A_{Ti}, E_i, \beta, \sigma) + \\
& A_{\mathrm{Kd}_{2\to1}} \cdot \mathrm{Voigt}(E_{2\to1}, \sigma, \Gamma_{1s}) + \\
& A_{\mathrm{Kd}_{4\to1}} \cdot A_{\mathrm{rel}_{3\to1}} \cdot \mathrm{Voigt}(E^{\mathrm{e.m.}}_{3\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) + \\
& A_{\mathrm{Kd}_{4\to1}} \cdot \mathrm{Voigt}(E^{\mathrm{e.m.}}_{4\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) + \\
& A_{\mathrm{Kd}_{4\to1}} \cdot A_{\mathrm{rel}_{5\to1}} \cdot \mathrm{Voigt}(E^{\mathrm{e.m.}}_{5\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) + \\
& A_{\mathrm{Kd}_{4\to1}} \cdot A_{\mathrm{rel}_{6\to1}} \cdot \mathrm{Voigt}(E^{\mathrm{e.m.}}_{6\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) + \\
& A_{\mathrm{Kd}_{4\to1}} \cdot A_{\mathrm{rel}_{7\to1}} \cdot \mathrm{Voigt}(E^{\mathrm{e.m.}}_{7\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s})
\end{aligned}
$$

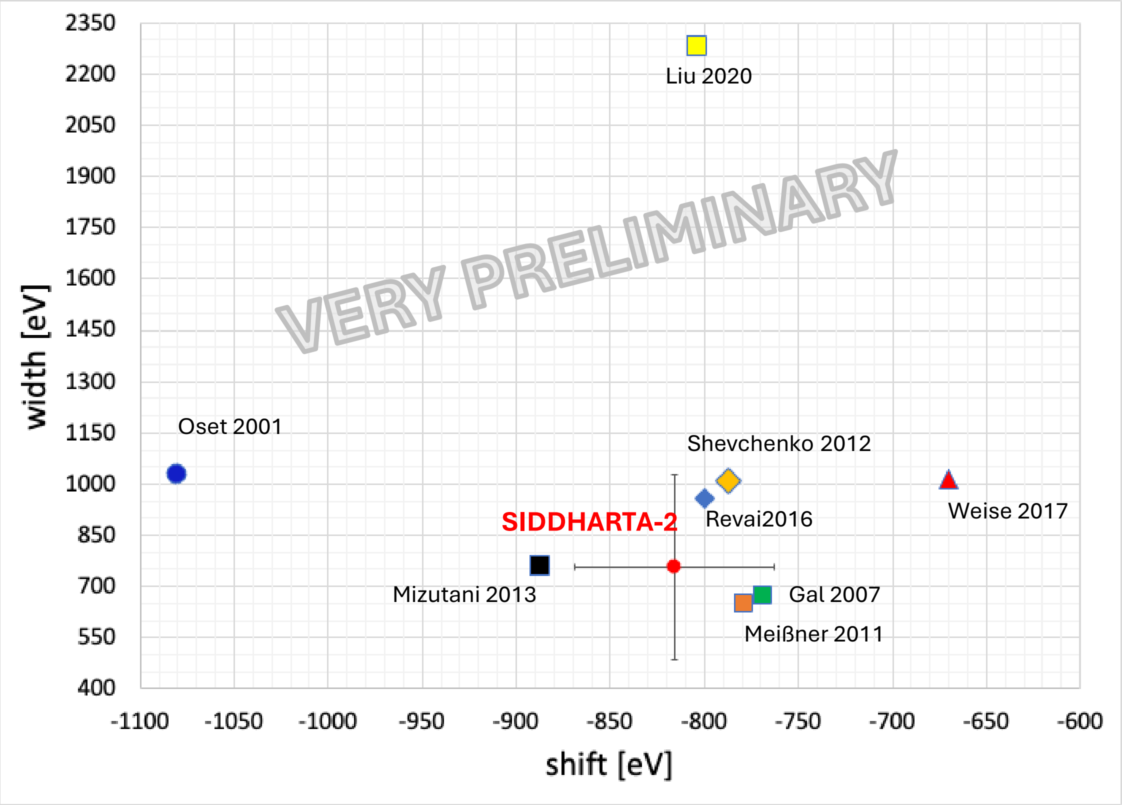
$$\varepsilon_{1s} = -816 \pm 53 \text{ (stat)} \pm 2 \text{ (syst) eV}$$

$$\Gamma_{1s} = 756 \pm 271 \text{ (stat) eV}$$



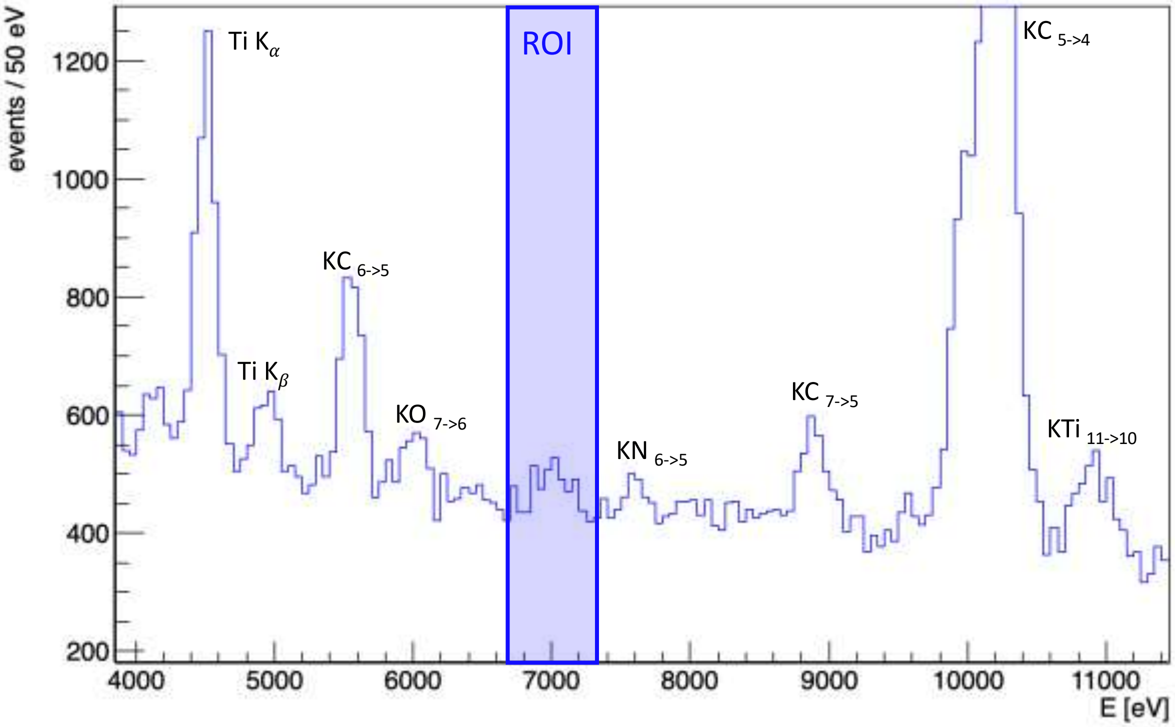
Kaonic Deuterium Run1: preliminary result

Preliminary comparison between SIDDHARTA-2 Run1 result and the theoretical model



Kaonic Deuterium Run2 and Run3: analysis ongoing

Preliminary energy spectrum from run2 + run3 (partial statistics ~300 pb^{-1})



Next Step of the analysis:

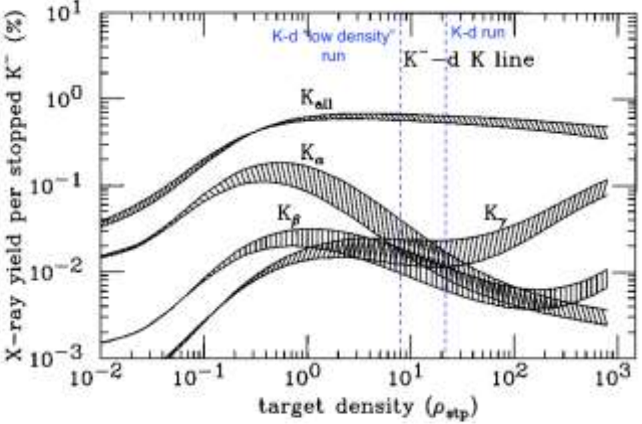
- Refined calibration of Run3 data (ongoing)
- Veto-1 analysis (similar to run1 data)
- Define a proper fit function
- Fit of the energy spectrum (full dataset)

The analysis of the full dataset can potentially improve the statistical accuracy by a factor 2

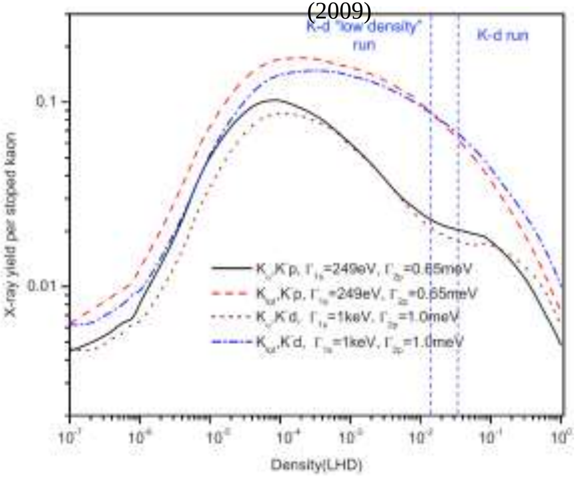
(precision similar to kaonic hydrogen measurement)

Kaonic Deuterium yield puzzle– low density run

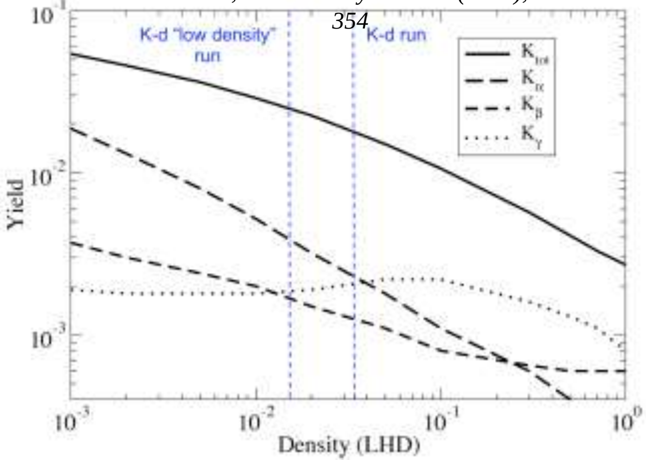
T. Koike, T. Harada, Y. Akaishi, Phys.Rev.C 53 (1996), 79-87



M Raeisi, S. Z. Kalantari, Phys.Rev.A 79, 012510 (2009)



T.S. Jensen, Frascati Phys.Ser. 36 (2004), 349-354



Several cascade model predict **completely different kaonic deuterium X-ray yields** (absolute and relative) and different trends as function of the density

Low density kaonic deuterium measurement

(60% lower compared to the previous run)

Providing unique data to investigate the de-excitation mechanism in kaonic atoms (cascade model)

The combined analysis of the kaonic deuterium measurement performed at 1.4% LDD and the ongoing measurement at 0.8% LDD **can help to disentangle between the various theoretical cascade models**

SIDDHARTA-2 Kd run – Future plan

- **First Kd run** May - July 2023**:** 164 pb^{-1} integrated luminosity;
- **Second Kd run** October **-** December 2023: 276 pb^{-1} integrated luminosity;
- **Third Kd run** February - April 2024: 375 pb^{-1} integrated luminosity;
- **Calibration run** with hydrogen 150 pb^{-1};
- **Kd low density run** – goal 200 pb^{-1}

We aim to collect 200 pb^{-1} (similar statistics to Kd run1)

12th April 2024

End of Kaonic deuterium Run3

15th Apr – 6th May (3 weeks)

Calibration run with kaonic hydrogen

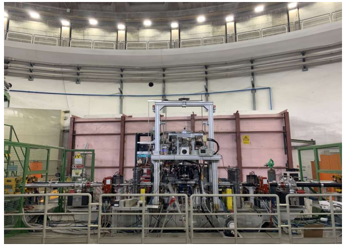
6th -12th May

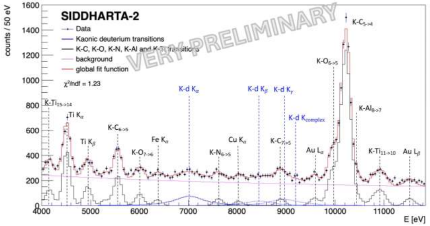
DAΦNE maintenance: refill of the target cell with deuterium (low density)

24th May – End of June - first week of July

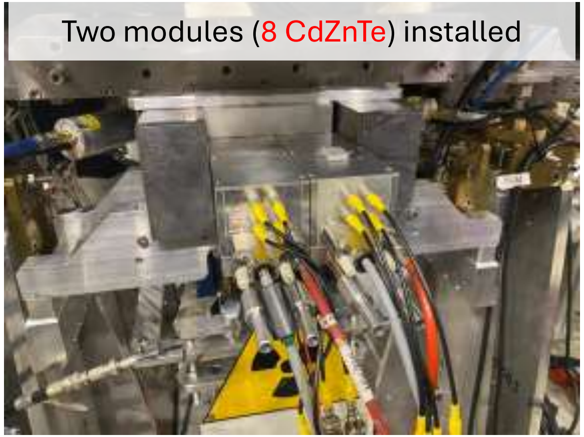
Kaonic deuterium "low density" run

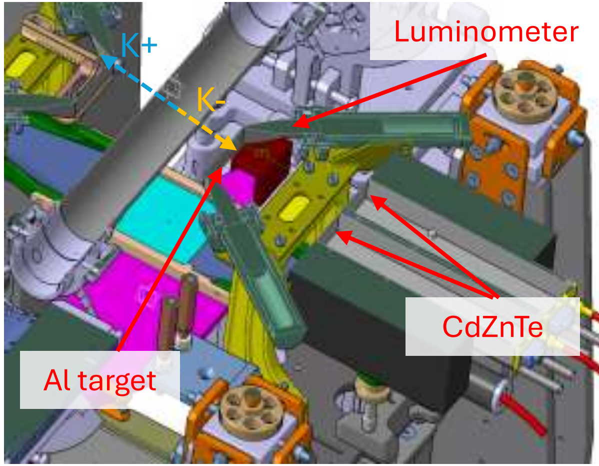
DEAR **SIDDHARTA** **SIDDHARTA-2** **First measurement ever of Kd**





CdZnTe detectors: test run with 8 detectors

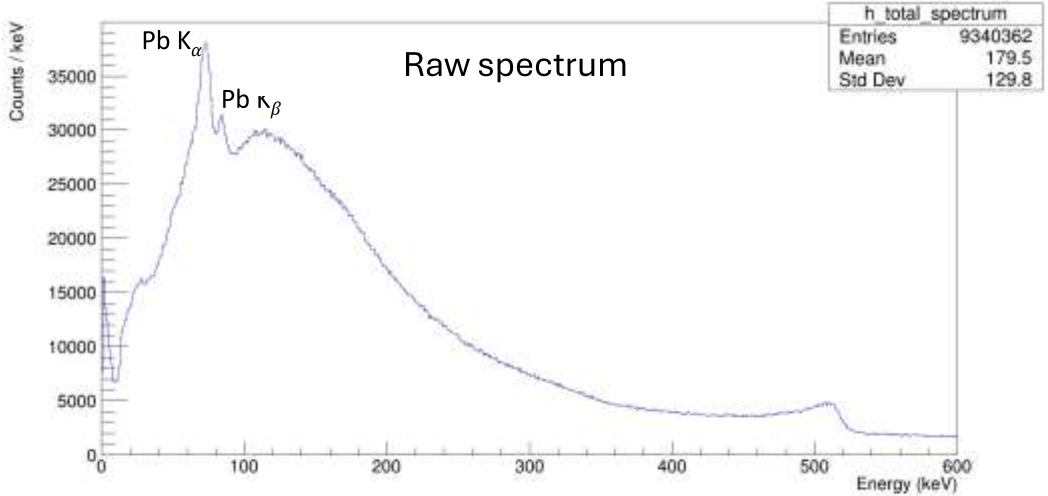




8 cm^2 CdZnTe detectors to perform X-ray spectroscopy of kaonic aluminium in parallel with SIDDHARTA-2 kaonic deuterium run (L. Abbene, A. Buttacavoli, F. Principato, A. Scordo)

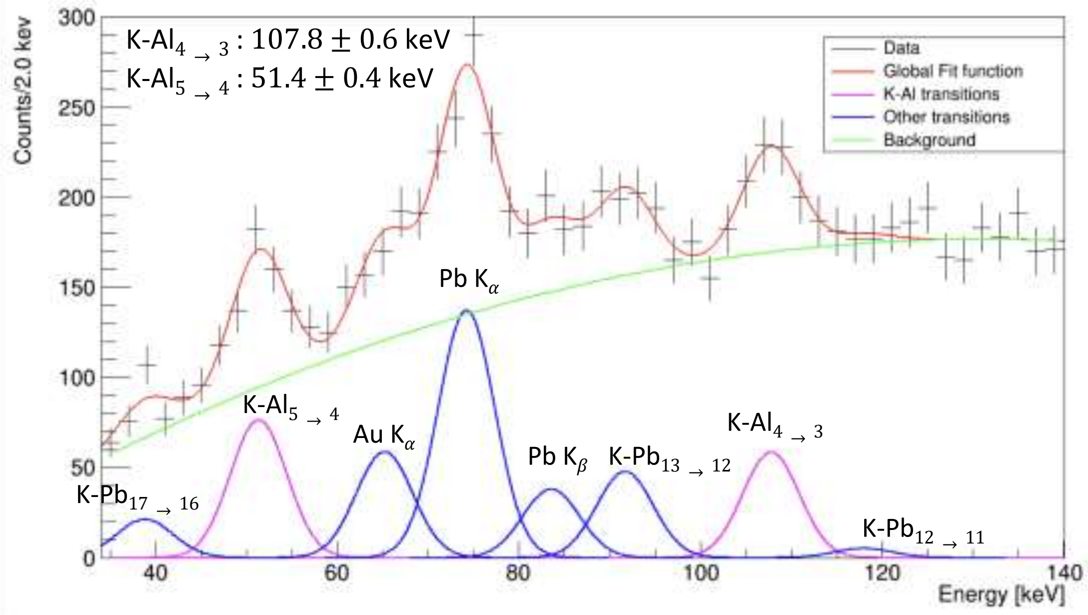
Advanced ultra-fast solid STate detectors for high precision RAdiation spectroscopy : ASTRA

~ 60 pb^{-1} of data with a 2,2 mm Al target



CdZnTe detectors: test run with 8 detectors

Preliminary result from the kaonic aluminium analysis (~60 pb^{-1})



An article is in preparation

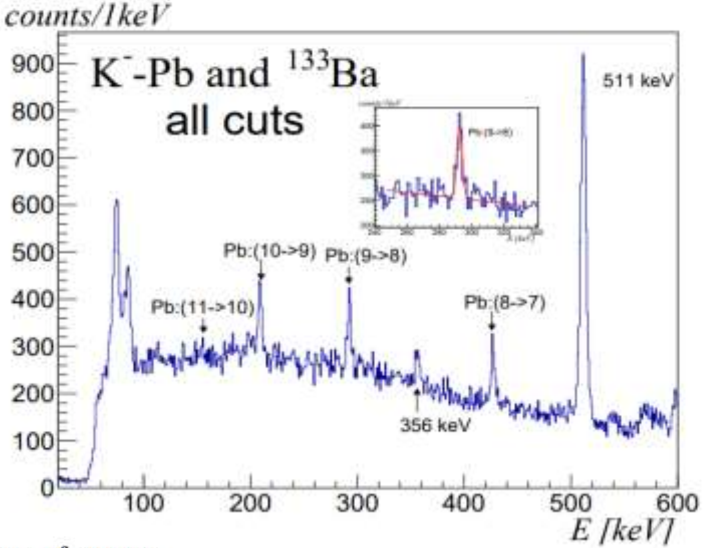
- First kaonic atoms' spectrum measured with CZT detectors
- CZT proved to be the **perfect technology for intermediate mass kaonic atoms**, with very good "in-beam" performances during preliminary tests
- CdZnTe detectors can be easily used in parallel with already existing experiments, requiring very small space and not invasive electronics.

Kaonic Lead Measurement at DAΦNE with HPGe

(Zagreb Uni; Krakow, Jagiellonian Uni – Lumi)

Installed in the antiboost side of the IP to perform the kaonic lead measurement in parallel with the SIDDHARTA-2 kaonic deuterium measurement

Integrated luminosity: 109.38 pb^{-1}: subset of 40 pb^{-1} already analysed



K^{-}-Pb transition	Peak position (keV)	Resolution (FWHM) (keV)	Number of events
$10 \rightarrow 9$	208.92 ± 0.17	3.68 ± 0.42	584 ± 30
$9 \rightarrow 8$	292.47 ± 0.17	3.97 ± 0.49	770 ± 65
$8 \rightarrow 7$	427.07 ± 0.24	4.37 ± 0.54	457 ± 45

Article submitted to Nuclear Instruments and Methods A preprint: arXiv:2405.12942

Publications since November 2023

1) *F. Sgaramella et al.*, **First measurement of kaonic helium-4 M-series transitions**, 2024 **J. Phys. G: Nucl. Part. Phys**. 51 055103

2) *A. Scordo et al.*, **CdZnTe detectors tested at the DAFNE collider for future kaonic atoms measurements. Nuclear Instruments and Methods in Physics Research Section A**, Volume 1060, 2024, 169060.

3) *F. Sgaramella et al.*, **Kaonic helium-4 L-series yield measurement at 2.23 g/l density by SIDDHARTA-2 at DAΦNE**, **Acta Phys. Pol. B** 17, 1-A8 (2024)

4) *F. Clozza et al.*, **Characterization of the SIDDHARTA-2 Setup via the Kaonic Helium Measurement**, ***Condensed Matter***. 2024; 9(1):16.

5) *F. Artibani, F. Clozza et al.*, **The Odyssey of Kaonic Atoms Studies at the DAFNE collider: from DEAR to SIDDHARTA-2. Acta Phys. Pol. B** 55, 5-A2 (2024)

Publications since last SciCom – November 2023

6) *Wycech, S.; Piscicchia, K.* **On the Importance of Future, Precise, X-ray Measurements in Kaonic Atoms.**, **Condens. Matter** 2024, 9, 4.

7) *L. De Paolis et al.,* **The measurements of E2 nuclear resonance effects in kaonic atoms at DAΦNE: the KAMEO proposal, EPJ Web Conf**., 291 05003 (2024)

8) *F. Sirghi et al.,* **Kaonic atoms with SIDDHARTA-2 at the DAΦNE Collider, EPJ Web Conf.,** 291 (2024) 01008

9) *F. Sgaramella et al.,* **The SIDDHARTA-2 experiment for high precision kaonic atoms X-ray spectroscopy at DAΦNE**, accepted for publication on **Nuovo Cimento C-** Colloquia and Communications in Physics.

10) *D. Bosnar et al.,* **Kaonic lead feasibility measurement at DAΦNE to solve the charged kaon mass discrepancy,** submitted to **Nuclear Instruments and Methods A** (arXiv:2405.12942)

11) *F. Artibani, F. Clozza et al*., **Intermediate Mass Kaonic Atoms at DAΦNE. Submitted to Acta Phys. Pol.**

the PADME experiment @ LNF

Dark photon production

A Dark Photon (*A’*) can be produced using e^+ via:

- Bremsstrahlung: $e^+N \rightarrow e^+NA'$
- Annihilation associate production: $e^+e^- \rightarrow \gamma A'$
- Annihilation direct production: $e^+e^- \rightarrow A'$

For the *A’* decay two options are possible:

- No dark matter particles lighter than the *A’*:
  - $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, hadrons, **“visible”** decays
  - For $M_{A'}<210$ MeV *A’* only decays to e^+e^- with $BR(e^+e^-)=1$
- Dark matter particles χ with $2M_\chi<M_{A'}$
  - *A’* will dominantly decay into pure DM
  - $BR(l^+l^-)$ suppressed by factor ε^2
  - $A' \rightarrow \chi\chi \sim 1$. These are the so called **“invisible”** decays

PADME aims to produce *A’* via the reaction:

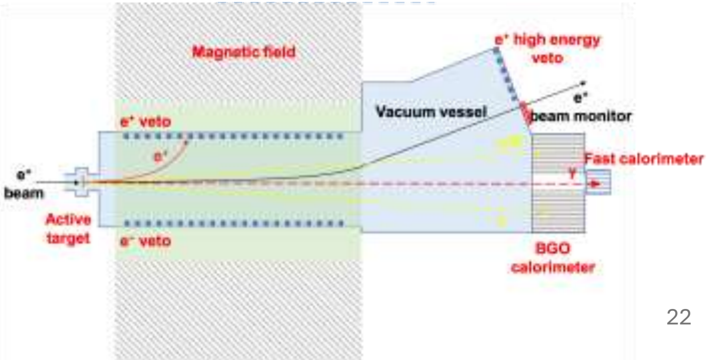
$$e^+e^- \rightarrow A'\gamma$$

This technique allows to identify the *A’* even if it is stable or decays into dark sector particles $\chi\bar{\chi}$.

Know e^+ beam **momentum and position,** measuring the recoil photon **position** and **energy**

$$M^2{}_{miss} = (\bar{P}_{e^+} + \bar{P}_{e^-} - \bar{P}_\gamma)^2$$

Only a minimal assumption: *A’* couples to leptons



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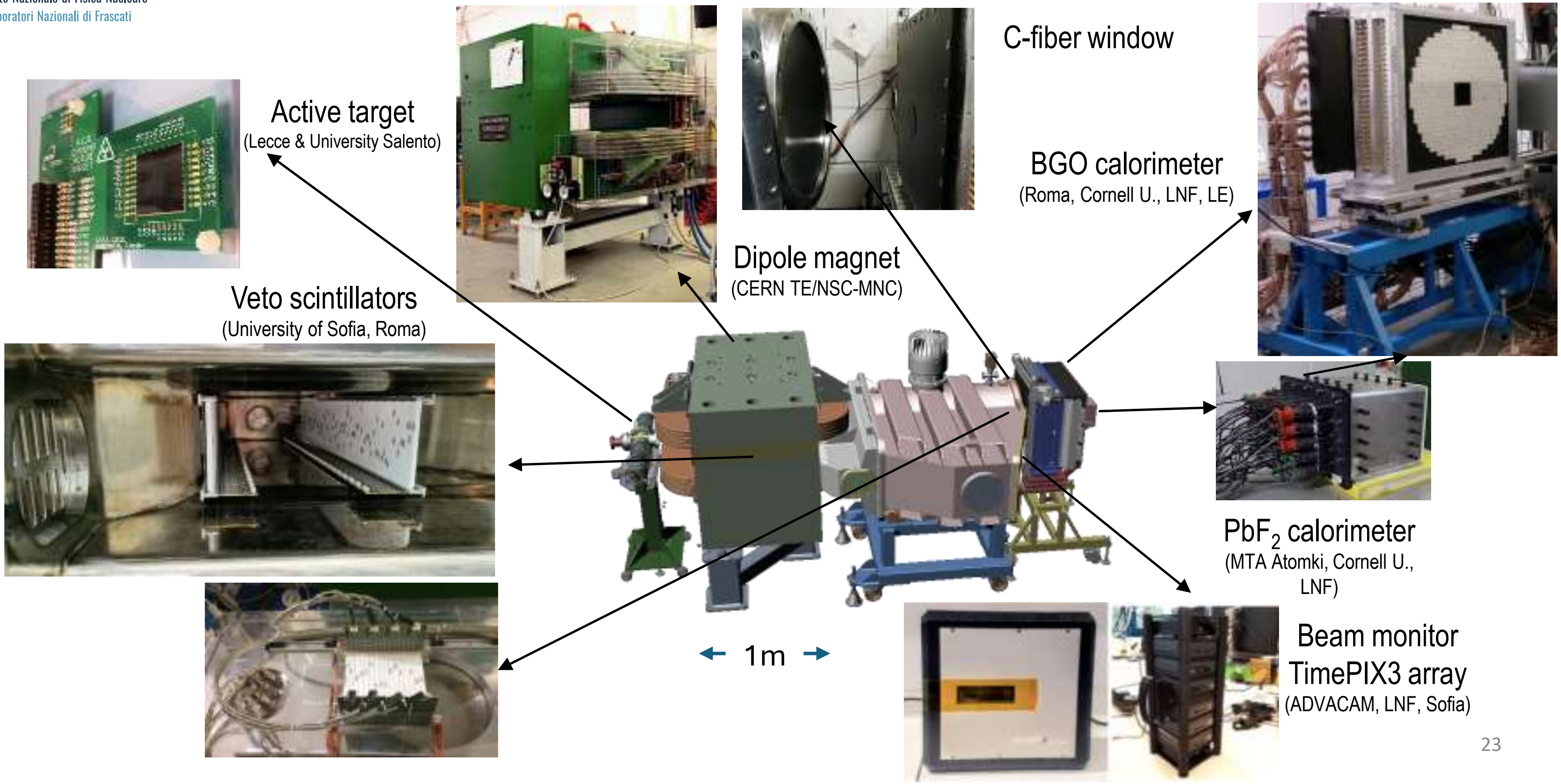
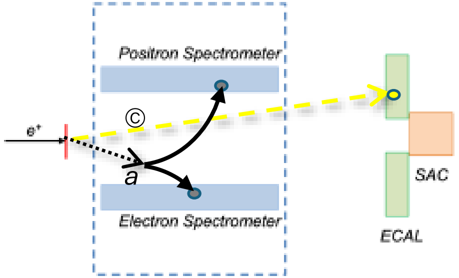
The PADME detector in a nutshell

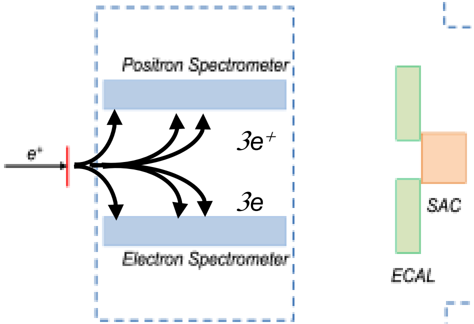


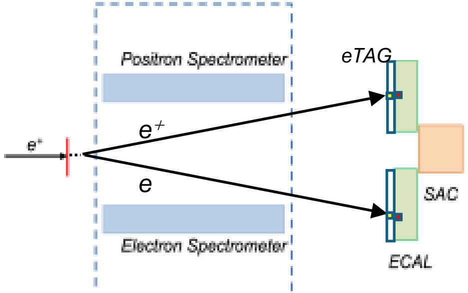
Dark sector studies at PADME

The PADME approach can explore the existence of any new particle produced in e⁺e⁻ annihilations:

- Axion Like Partiles $e^+e^- \rightarrow \gamma a$
  - visible decays: $a \rightarrow \gamma\gamma, ee$
  - invisible decay: $a \rightarrow \chi\bar{\chi}$
- Dark Higgs $e^+e^- \rightarrow h'A'; h' \rightarrow A'A'$
  - final state: $A'A'A' \rightarrow e^+e^-e^+e^-e^+e^-$
- $X17$ Boson $e^+e^- \rightarrow X_{17};\ X_{17} \rightarrow e^+e^-$
  - tuning beam energy and slightly modifying the detector







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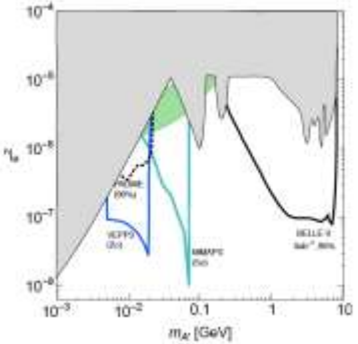
Dark sector studies at PADME

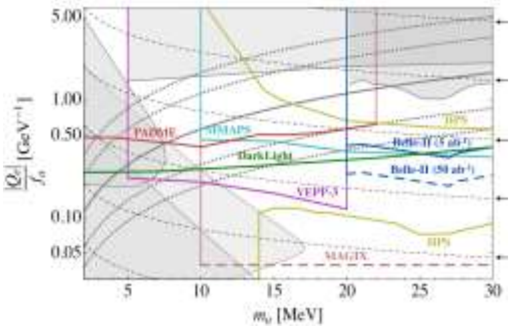
Other DM approaches can be addressed by PADME

Dark Photon A’
arXiv:1608.08632v1



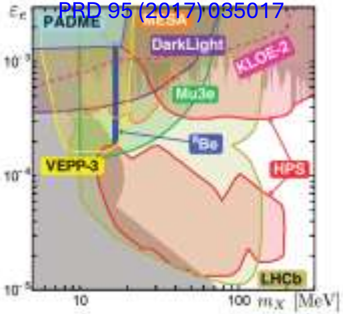
$e^+e^- \to \gamma A'$
Visible, invisible decays:
$A' \to \chi\bar{\chi}, e^+e^-$

Axion Like Particles
JHEP 07 (2018) 092



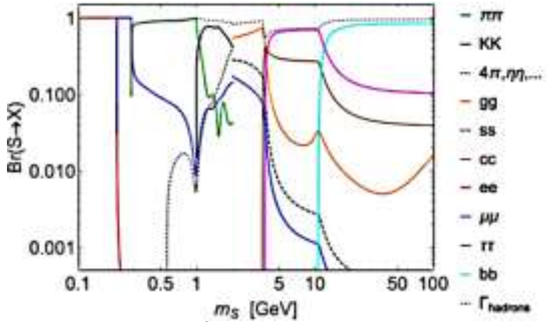
$e^+e^- \to \gamma a$
ALPs final states:
$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

Be anomaly - X boson
PRD 95 (2017) 035017



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

Dark Higgs
arXiv:2102.12143v1



$e^+e^- \to h'A'$
dark higgs decay: $h' \to A'A', A' \to e^+e^-, \chi\bar{\chi}$
Final state: $A'A'A' \to e^+e^-\ e^+e^-\ e^+e^-$

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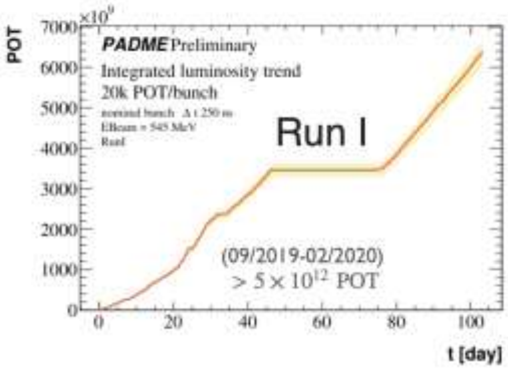
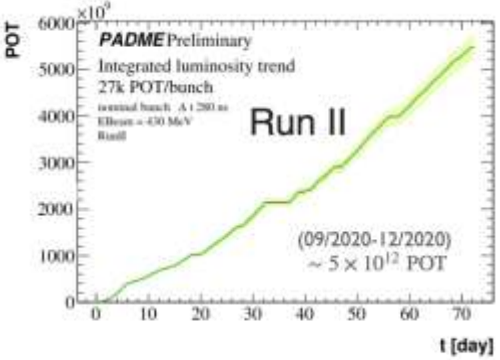
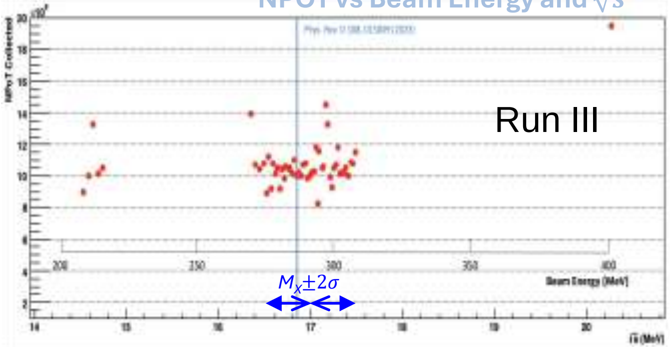
PADME Data Sets



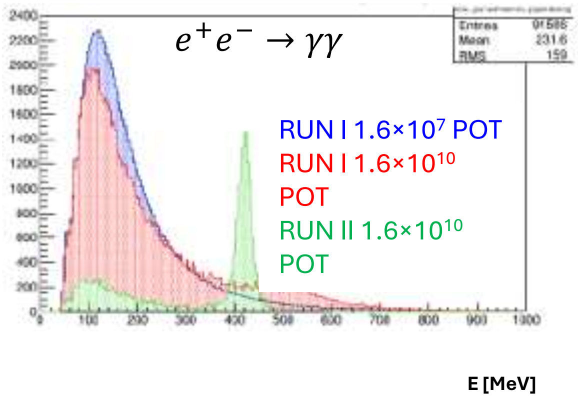


NPOT vs Beam Energy and $\sqrt{s}$



Dots energy values explored by PADME **Blue** Combined Be, He, C Atomki mass ranges
Cyan mass range fit results in *PRD 108, 015009 (2023)*

- Run II wrt Run I
  - Similar statistics, approximately 1/2 of minimal goal (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 (thinner Mylar window upstream)
  - Less beam-induced background with primary wrt secondary beam
- Run III
  - 47 different energy values plus off-resonance calibration points
  - **Observables:**



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Activity 2021 – 2024

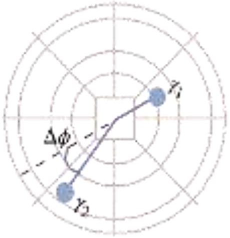
PADME Run III: Oct. – Dec. 2022 2022 devoted to the search of the hypothetic X_{17} boson

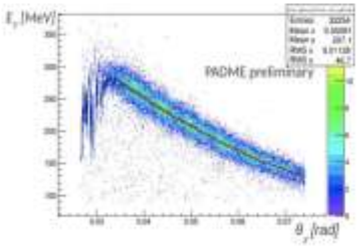
- with resonant production at $\sqrt{s} \cong 17$ MeV/c^2
- In the **visible decay** $e^+e^- \to X_{17} \to e^+e^-$
  - Studies performed on event collected in 2020 and MC simulations
  - **Detector upgraded** (eTagger - of plastic scintillators - in front of ECAL)
- Analysis of data sets
  - Data processing and detectors calibration (RUN I and Run II)
  - Considering different beam **energy** (550, 490, 430 MeV), bunch **length** (150, 280 ns) and **beam profile**
  - Published commissioning paper, and MC beam line paper [JINST 17 (2022) 08, P08032, JHEP 09 (2022) 233]
  - Published $e^+e^- \to \gamma\gamma$ cross-section measurement [Phys. Rev. D 107 (2023) 012008]
  - Preliminary selection of $e^+e^- \to \gamma +$ invisible [a paper will be published upon full statistic collection]
  - Blind analysis of Run III data. Precise evaluation of beam energy spread [arXiv:2405.07203 to be pub. JHEP]

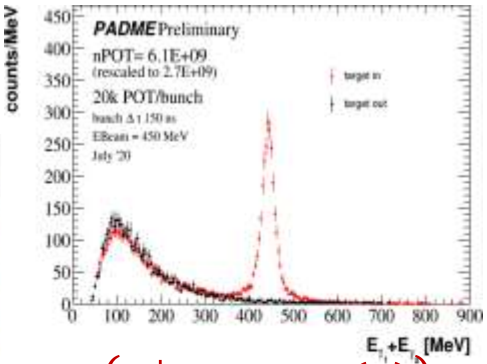
$e^+e^- \to \gamma\gamma$ cross section

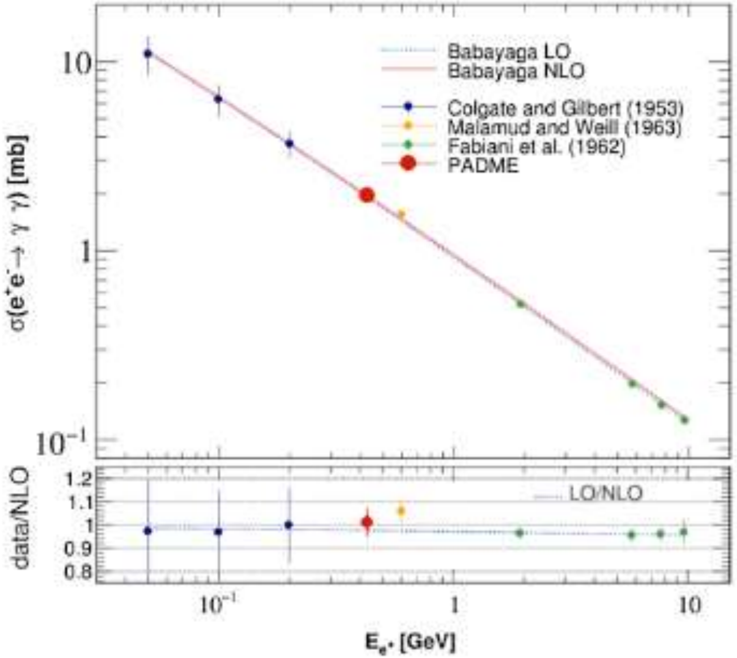
$e^+e^- \to \gamma\gamma$ cross section

- Below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics since available measurement $e^+e^- \to non - charged\ particles$
- Used 10% of Run II sample
- Tag-and-probe method on two back-to- back clusters. Exploit energy-angle correlation.









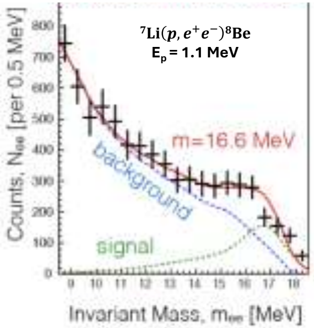
Phys. Rev. D 107 (2023) 012008

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.977 \pm 0.018(stat) \pm 0.119(syst)$$

The ^{8}Be anomaly

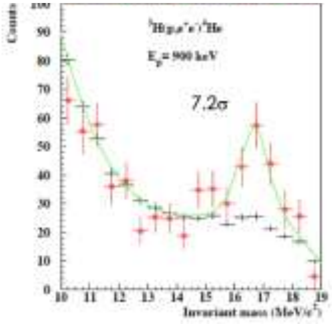
The study of de-excitation of light nuclei via IPC pointed out an anomaly in the decay of ^{8}Be, ^{4}He and ^{12}C.

$m_X = 16.7 \pm 0.35(stat) \pm 0.5(sys) MeV$



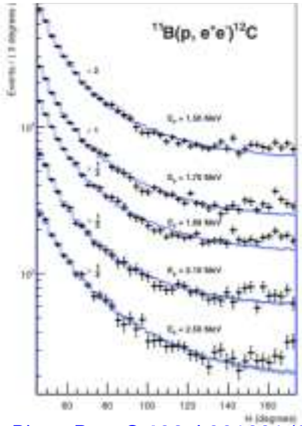
Phys. Rev. Lett. **116**, 042501 (2016)

$m_X = 16.90 \pm 0.12(stat) \pm 0.21(sys) MeV$

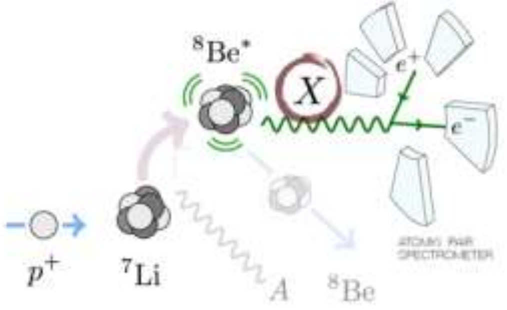


Phys. Rev. C **104**, 044003 (2021)

$m_X = 17.03 \pm 0.11(stat) \pm 0.20(sys) MeV$



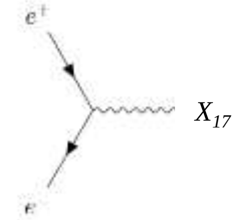
Phys. Rev. C **106**, L061601 (2022)



E. Nardi *et al.*, **"Resonant production of dark photons in positron beam dump experiments"** Phys.Rev. D**97** (2018) no.9, 095004

Setting the e$^+$ beam at ~283 MeV, PADME has the unique opportunity to product resonantly the X_{17}.
Several uncertainties:

- resonance smearing due to target e$^-$ motion;
- Bhabha scattering background;



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PADME papers 2023 – 2024

S. Bertelli et al.	Design and performance of the front-end electronics of the charged particle detectors of PADME experiment	JINST 19 (2024) 01, C01051
S. Bertelli et al.	Beam diagnostics with silicon pixel detector array at PADME experiment	JINST 19 (2024) 01, C01016
E. Long	Status and Prospects of PADME	Proceedings of the 57th Rencontres de Moriond 2023 Electroweak Interactions and Unified Theories, arXiv:2305.08684 [hep-ex]
V. Kozhuharov	The PADME experiment at LNF-INFN	PoS BPU11 (2023) 078
P. Gianotti	The study of the X17 anomaly with the PADME experiment	J.Phys.Conf.Ser. 2586 (2023) 01214
F. Bossi et al.	Cross-section measurement of two-photon in-flight annihilation of positrons at $\sqrt{s}$ = 20 MeV with the PADME detector	Phys. Rev. D 107 (2023) 012008
I. Oceano	First results from PADME experiment - getting ready for dark sector studies	Proceedings of the 56th Rencontres de Moriond 2022 Electroweak Interactions and Unified Theories, DOI: https://doi.org/10.58027/9qzt-x624
Sv. Ivanov	Profile Characterization of the PADME Experiment's Positron Beam Using a TimePix3 Sensor Array	Proceedings of the National Forum on Contemporary Space Research 2022, Sofia, 10 - 12 Nov. 2022

6 published papers, 1 submitted

Complete list https://padme.lnf.infn.it/list-of-papers/

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Plan of presentation

01 Progress achieved by the WP during the last year

02 Important highlights of the performed work (last year + full project duration)

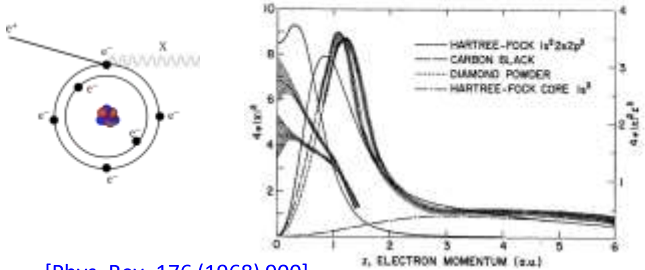
03 Tasks and achievements beyond the initial Work Program and/or tasks which could not be carried out

We kindly ask you to focus your presentations on the scientific progress of your WP (financial and administrative aspects of the implementation of the tasks to be included in the written report before 31/07/2024)

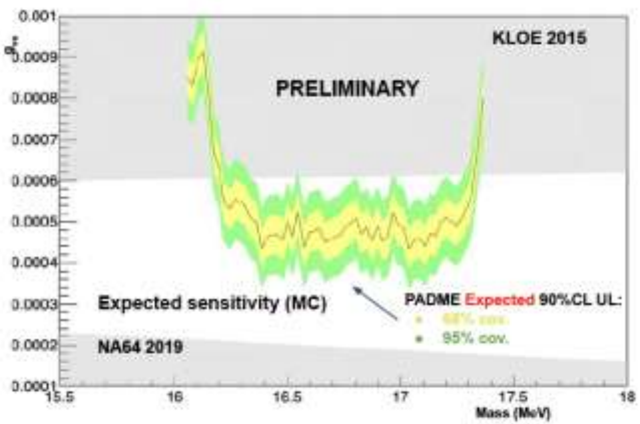
Prospects for 2025 and beyond

- According to phenomenological estimates Run III will not allow PADME to close the gap for the ***X*₁₇ vector hypothesis**
- At the end of 2023 theorists realized that e^- motion in diamond is not negligible. New estimate of PADME sensitivity

  [*arXiv:2403.15387 [hep-ph] ,Accepted in PRL, F. Arias-Aragón, L. Darmé, G. Grilli di Cortona, E. Nardi*]
- **PADME will perform a new Run first half of 2025 to improve/complete the X_{17} study.**
- **A new gaseous tracking detector is under construction to better measure X_{17} decay products.**
- To reach design sensitivity on *A′* existence, still 5×10^{12} particles-on-target must be collected.



[Phys. Rev. 176 (1968) 900]



Expected 90% CL considering RUN III statistics and target e^- motion.

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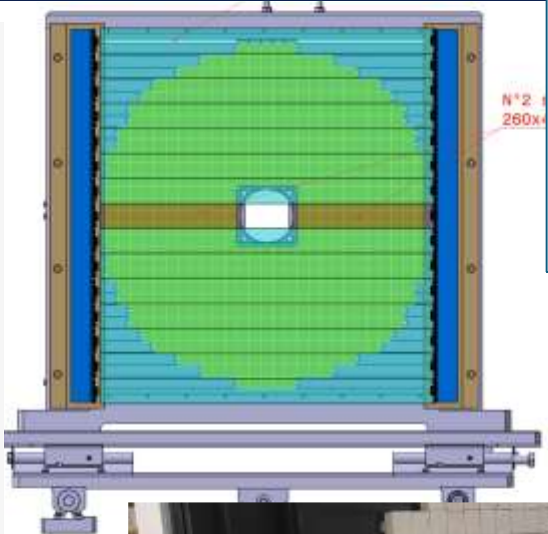
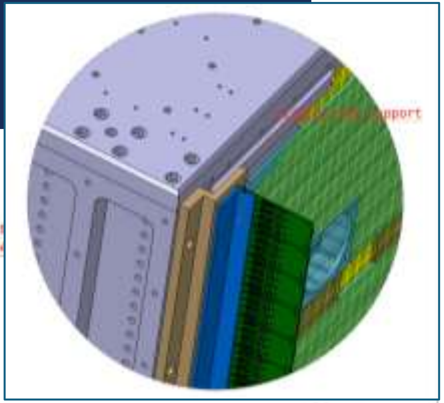
PADME new detector: eTagger

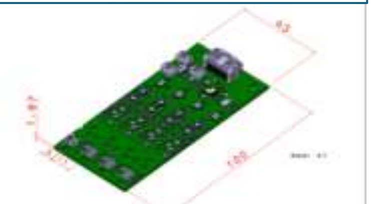
The new **eTagger** has been installed (2021-2022):

- 16 scintillators BC408 (600x45x5 mm^3);
- readout with 4 SiPMs (Hamamatsu S13360) on both sides. Same electronic cards developed for the veto detectors;
- Mechanical structure attached to the Ecal frame.

Used to separate $\gamma\gamma$ from ee clusters







LNF-SEA design