Searching for new light particles with PADME

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ФОНД
НАУЧНИ
ИЗСЛЕДВАНИЯ
МИНИСТЕРСТВО НА ОБРАЗОВАНИЕТО И НАУКАТА

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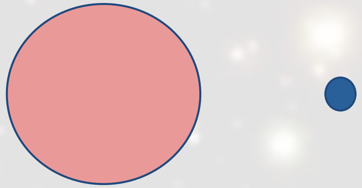
Outline

- PADME @ LNF
- Present status
- Prospects
- Conclusions

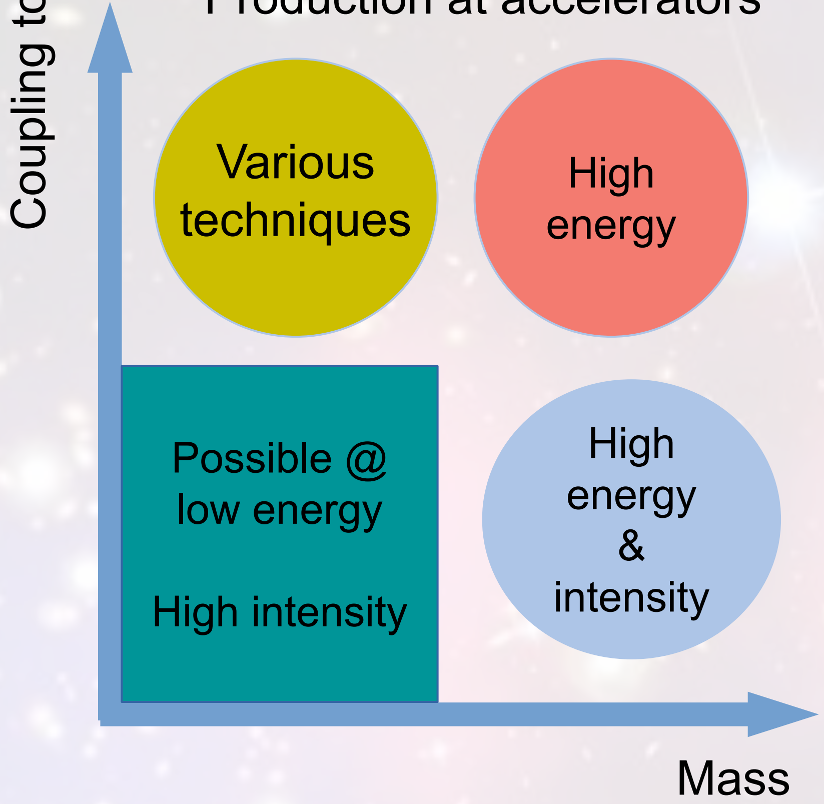
DARK MATTER

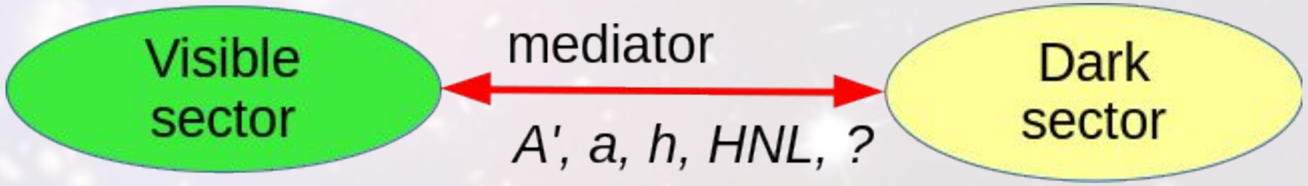


WIMP vs WISP

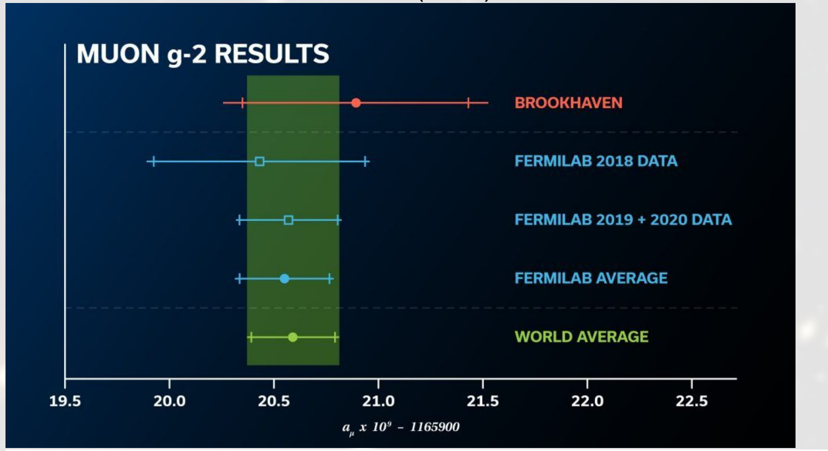
$\Omega_{DM} = 0.1198 \pm 0.0015$

Production at accelerators

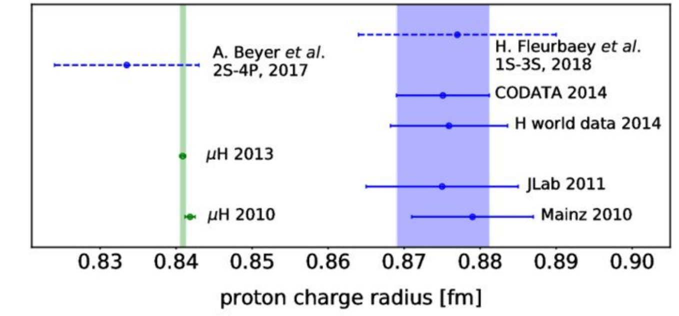




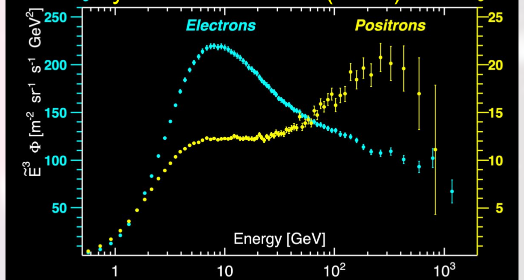
PRL 126 (2021) 14, 141801



arXiv:1011.3519 [hep-ph]

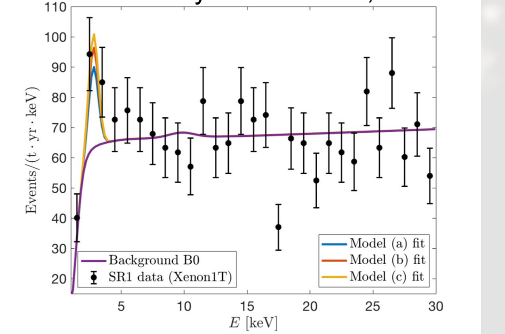


Phys. Rev. Lett. 122 (2019) 041102.

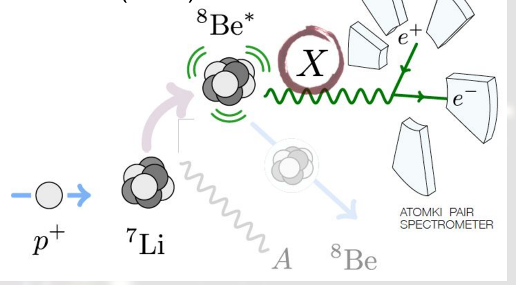


Phys. Rev. Lett, 122 (2019) 101101.

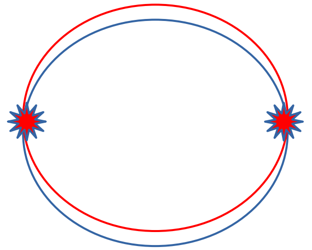
Phys. Rev. D 102, 072004



PRL 116 (2016) 042501

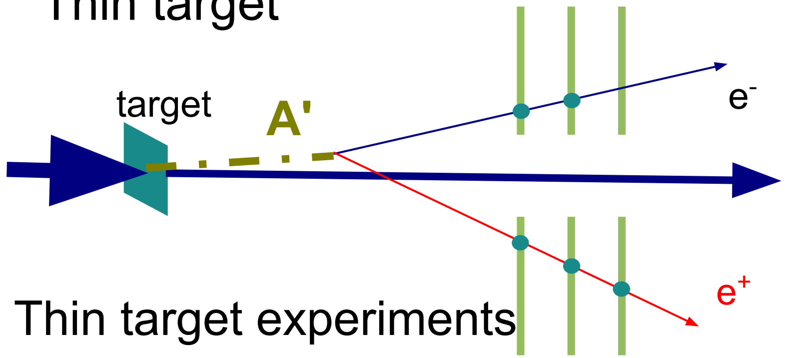


Techniques @ accelerators



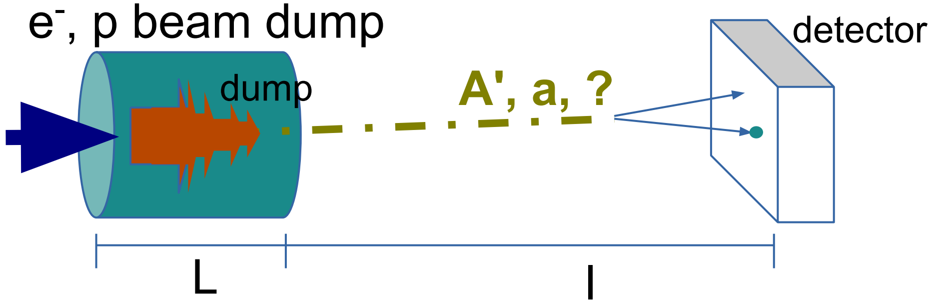
Fixed target

- Thin target

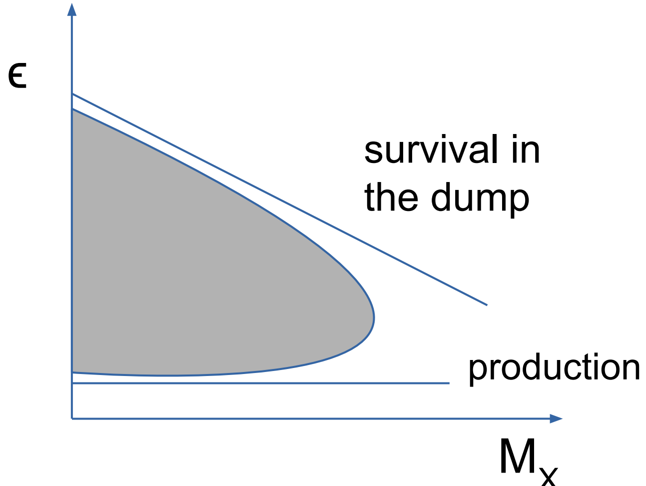


  - Direct production (usually X-strahlung)
  - Search for decays through event reconstruction (tracking)
- Production of secondary beam
  - Usually in a thick target
  - Searching for new particles in meson decays
  - M_X limited by the meson mass, coupling sensitivity – by statistics

Beam dump

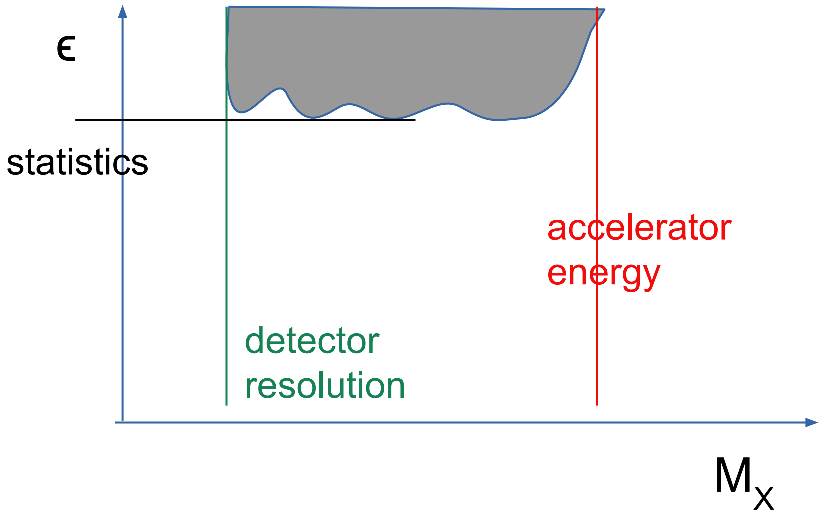


- Production: A'/a/h/?-strahlung, shower, absorption of secondaries
- Detection: everything is signal vs kinematics of the final state
  - The new particle has to survive the passage through the dump



e^+e^- colliders

- Associate production of new states
- Sensitivity depends on the resolution on invariant/missing mass of the final state

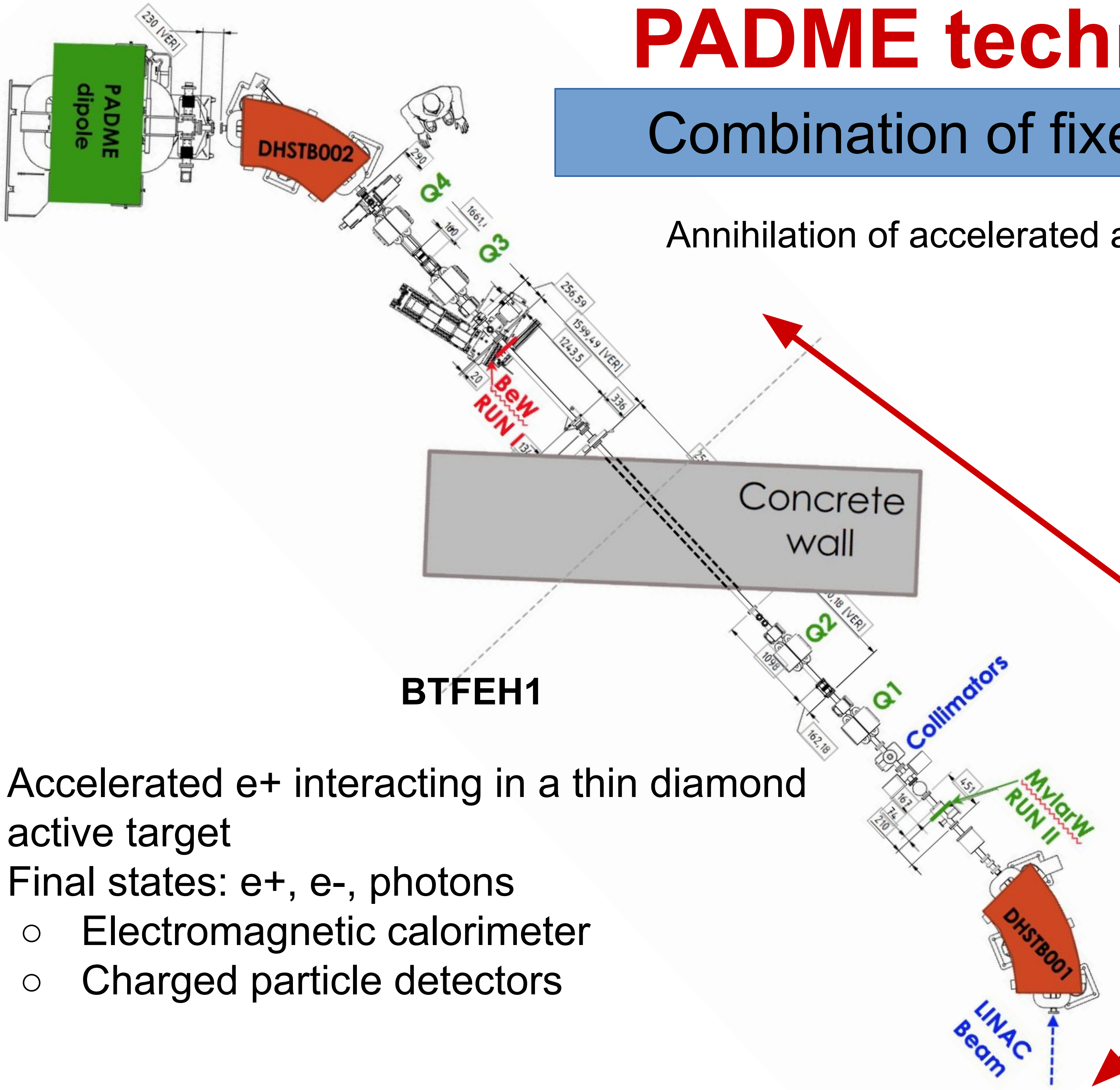


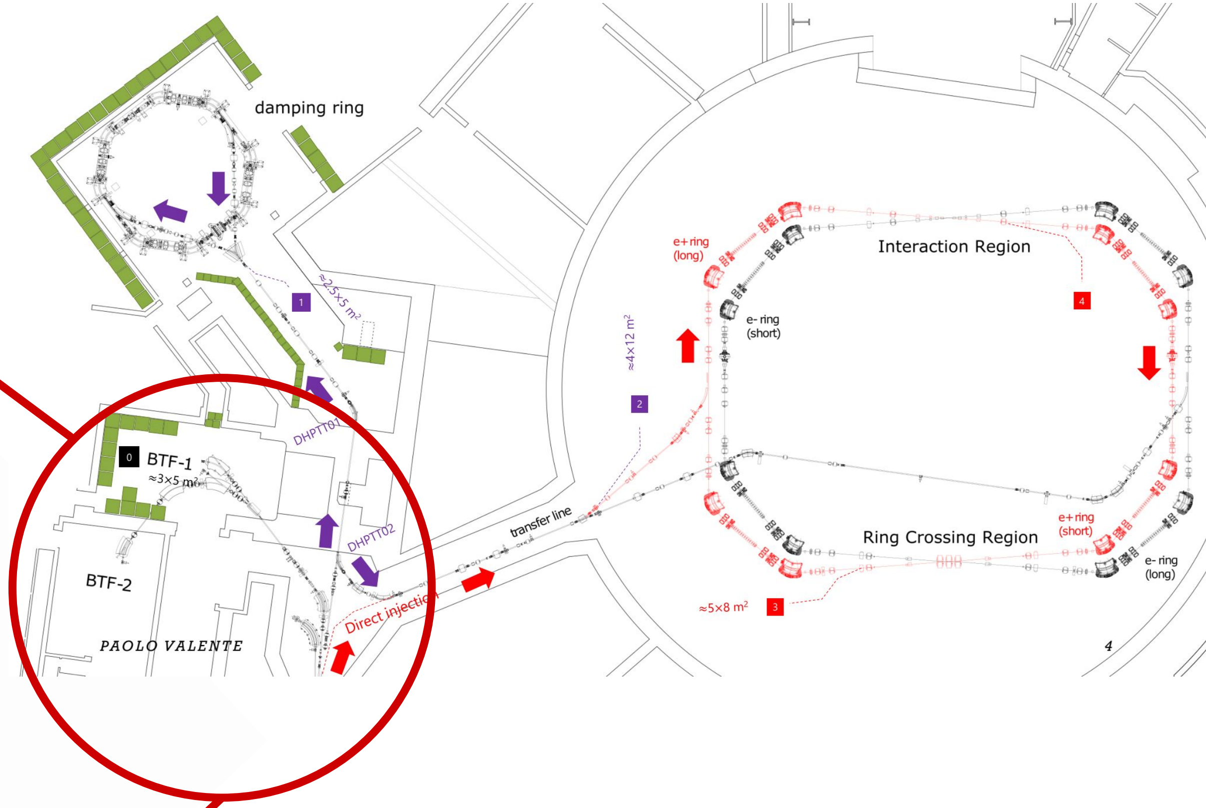
- Also searches through meson production and constrained initial state

PADME technique

Combination of fixed target and collider techniques

Annihilation of accelerated antiparticles with matter

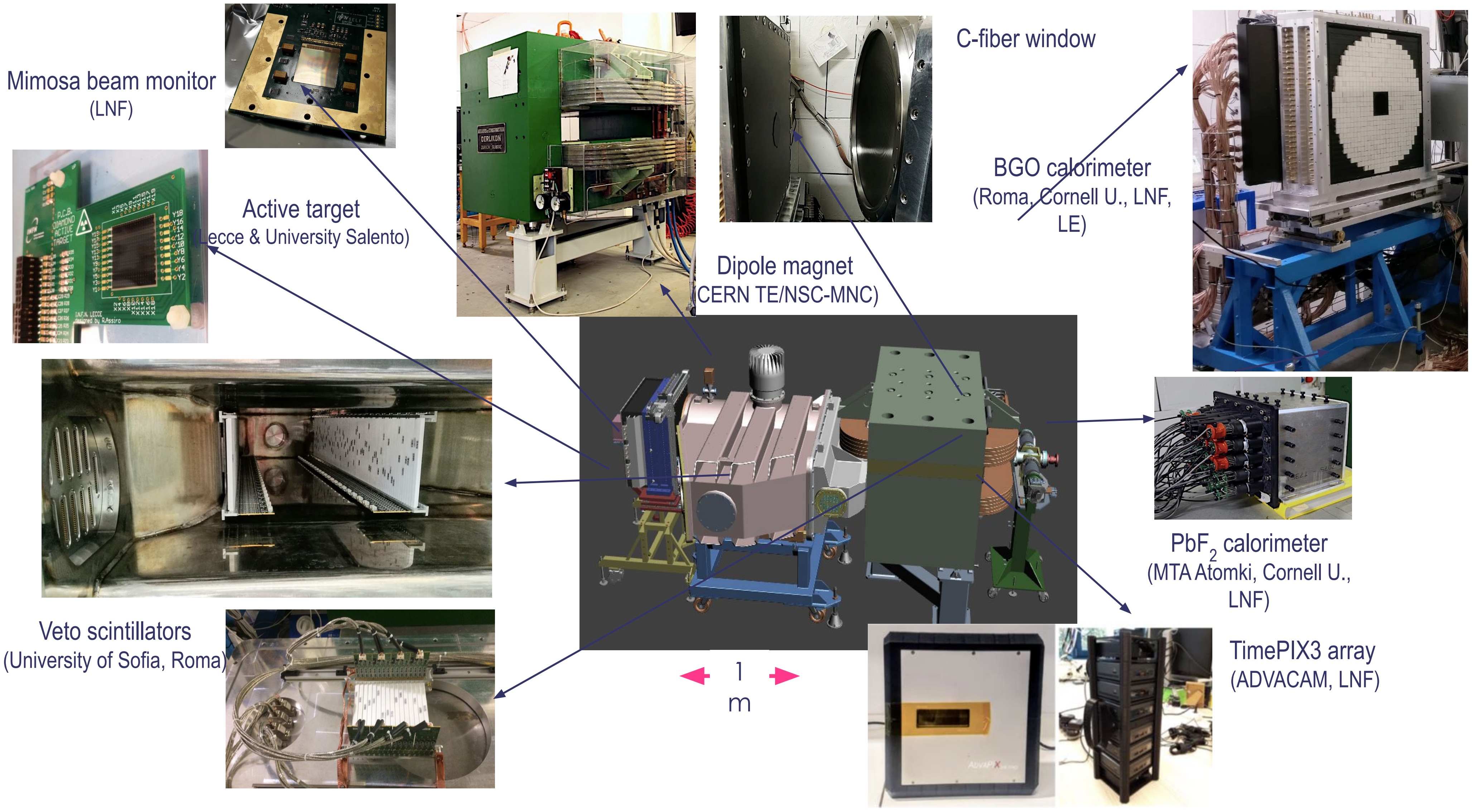




- Accelerated e+ interacting in a thin diamond active target
- Final states: e+, e-, photons
  - Electromagnetic calorimeter
  - Charged particle detectors

PADME

Positron Annihilation into Dark Matter Experiment



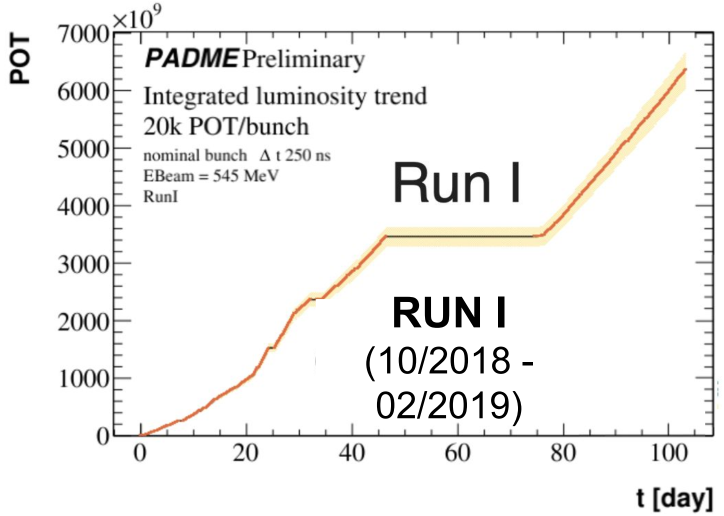
Data taking

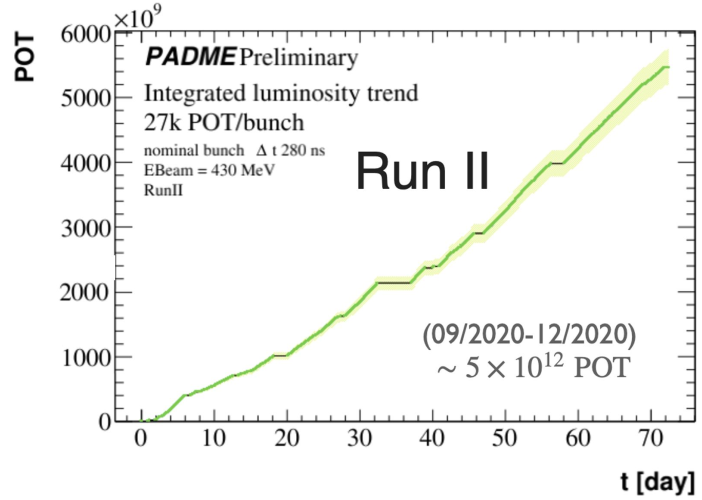
- PADME commissioning and **Run I** started in Autumn 2018 and ended on February 25th
  - ~7 x 10^{12} positrons on target recorded with secondary beam
  - PADME DAQ, Detector, beam, collaboration commissioning
  - Data quality and detector calibration

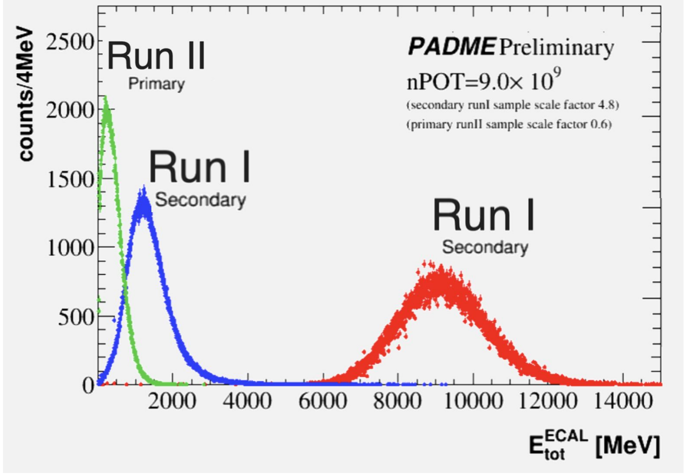
- PADME test beam data
  - July 2019, few days of valuable data
    - Certification of the primary beam
  - Detector performance/calibration checks
  - Primary beam with E_{beam} = 490 MeV

2020 era – RUN II: primary beam

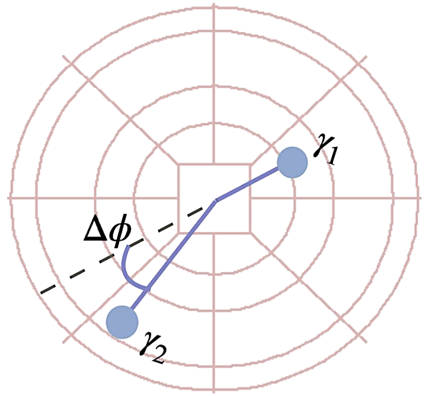
- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^+ on target
  - E_{beam} = 430 MeV

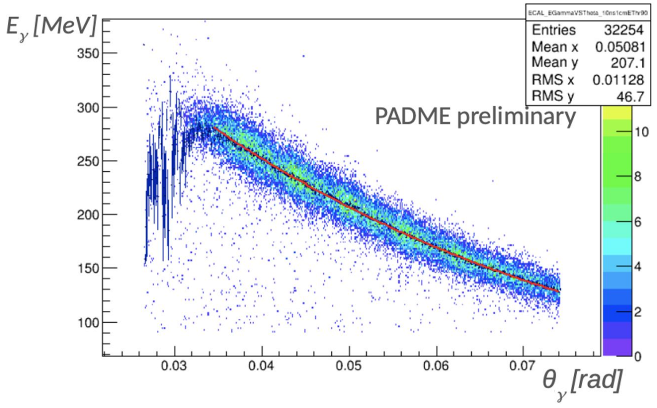


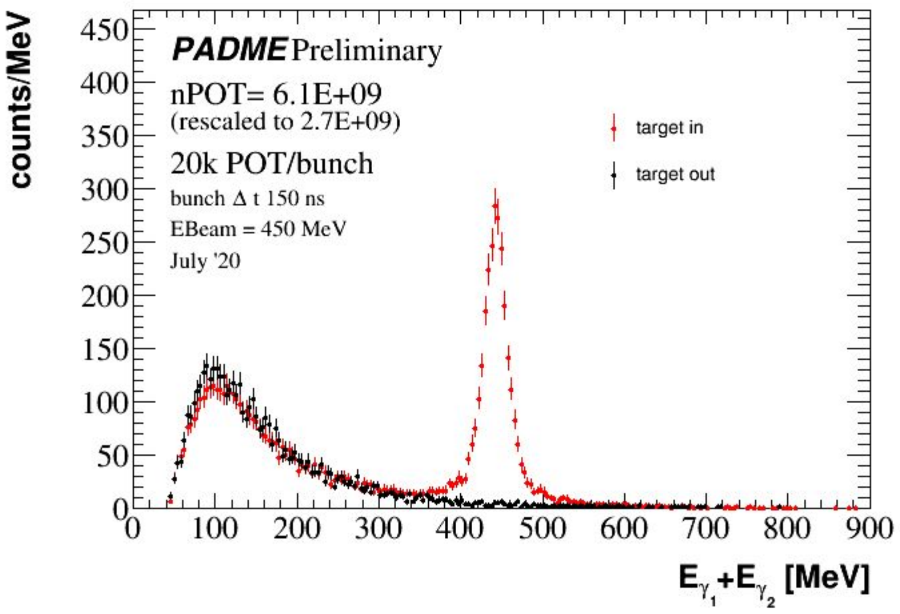




SM: Two photon events



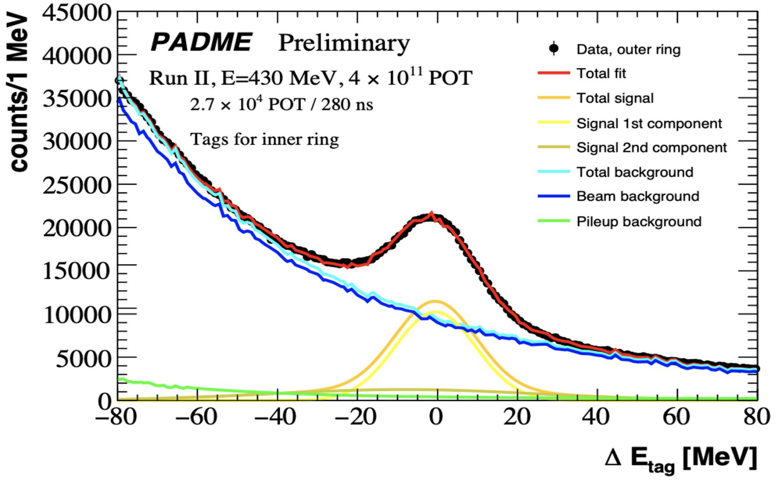




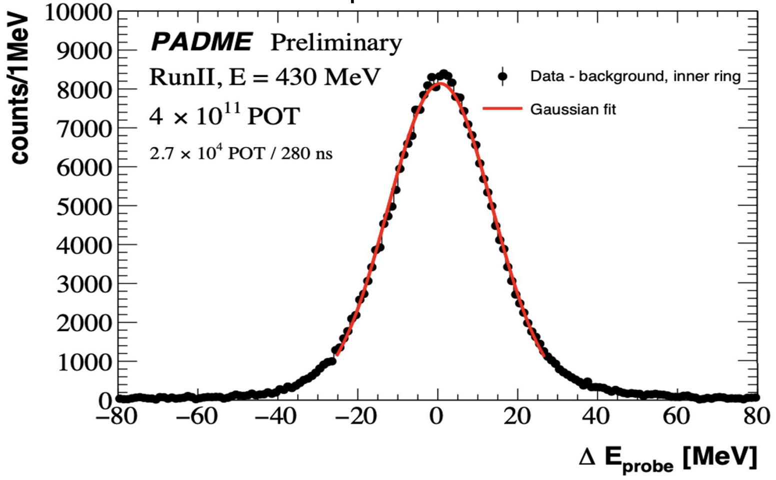
$e^+e^- \to \gamma\gamma$ cross section

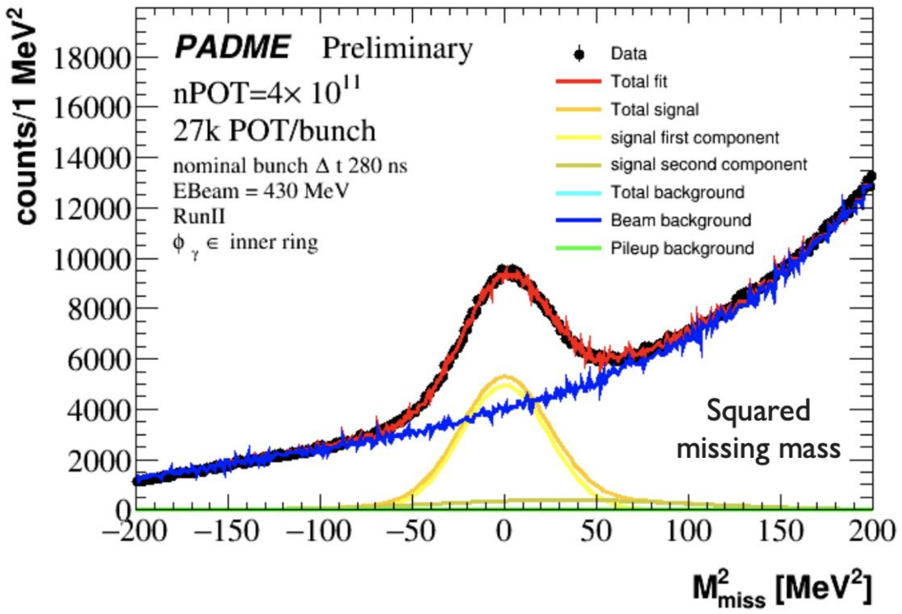
- Below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics (e.g. ALP's)
- Using 10% of Run II sample
- Tag-and-probe method on two back-to-back clusters
- Exploit energy-angle correlation

Tag photons selection

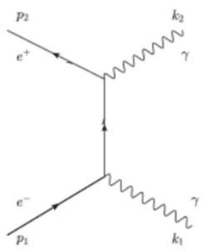


Probe photons

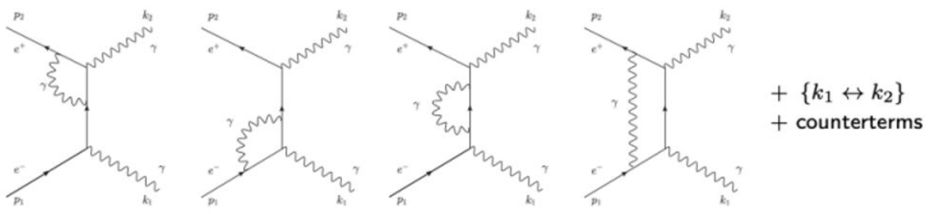




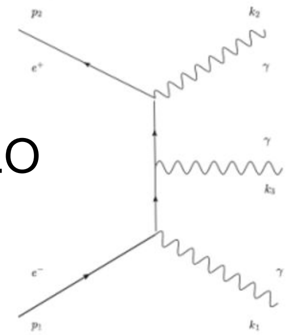
SM: $e^+e^- \to \gamma\gamma$ cross section



LO



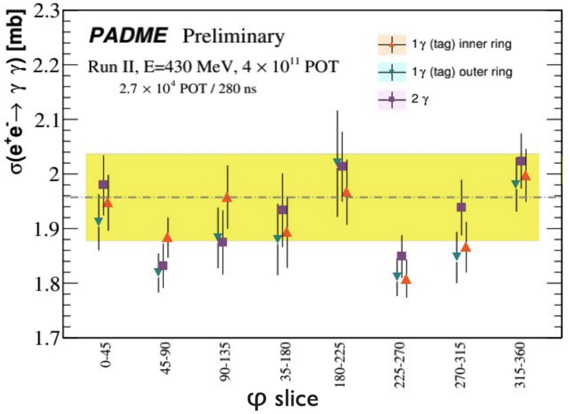
NLO

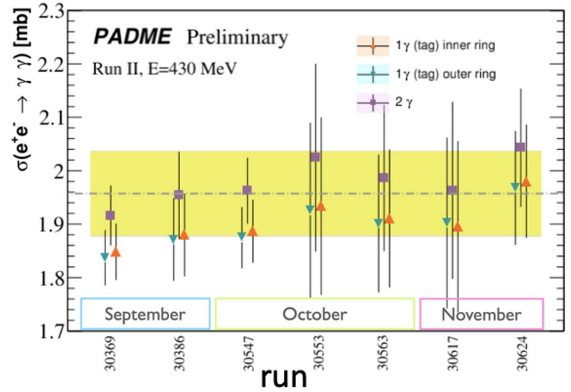


$+ \ \wp[k_1, k_2, k_3]$

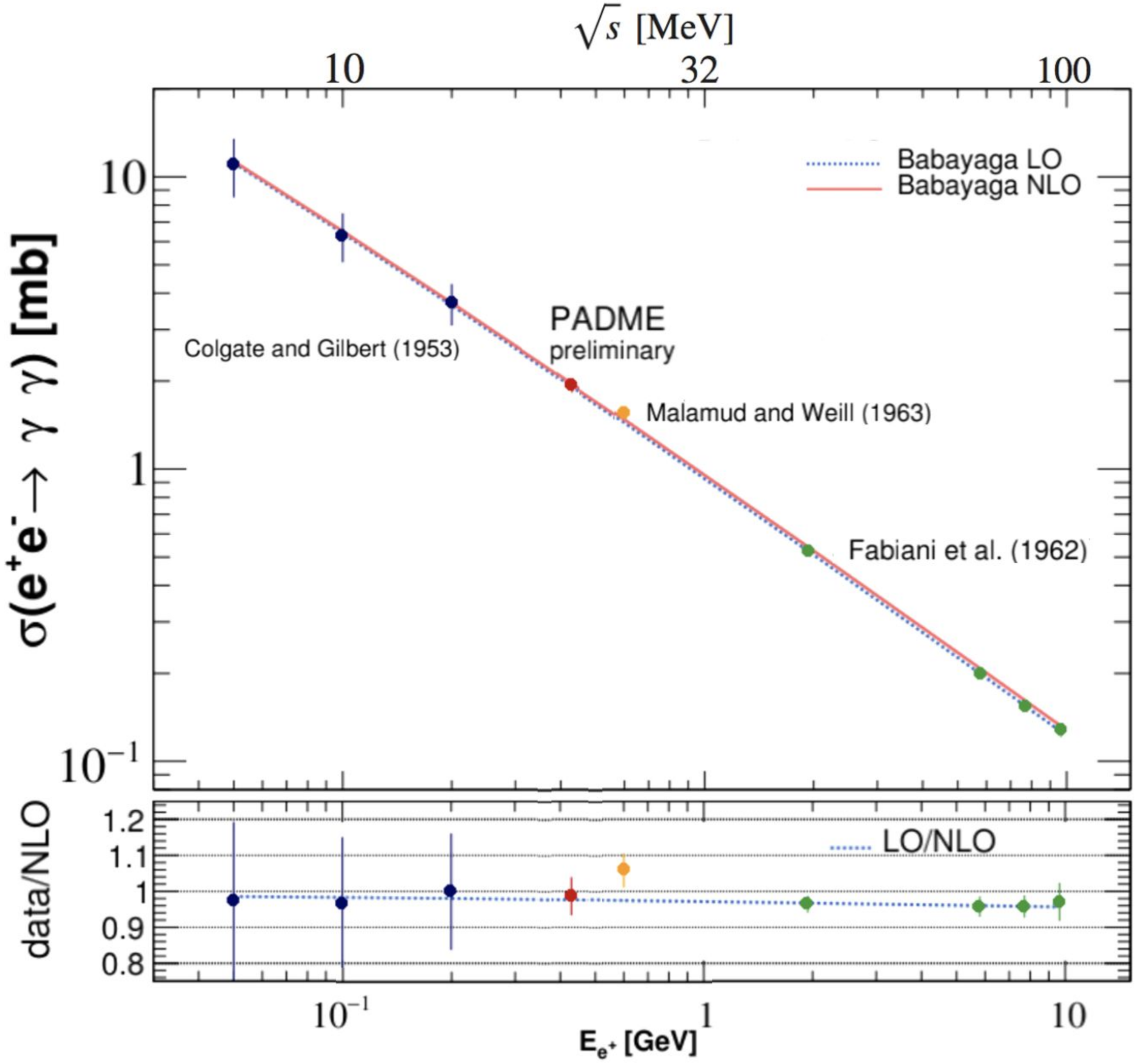
+ extra due to NP

Provides control of the e^+ flux





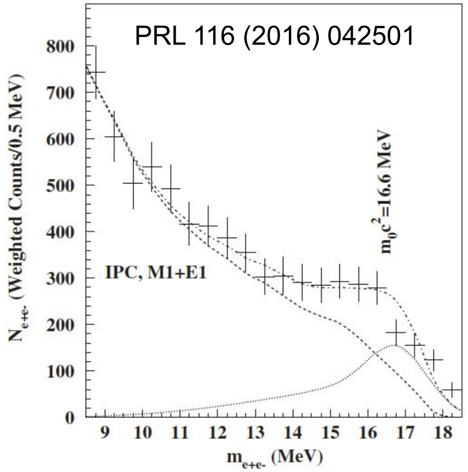
Systematic effect	Contribution δ [mb]
Detector response uniformity	0.020
Background modelling	0.047
Acceptance	0.025
n POT: target calibration	0.079
Electron density (target thickness)	0.020



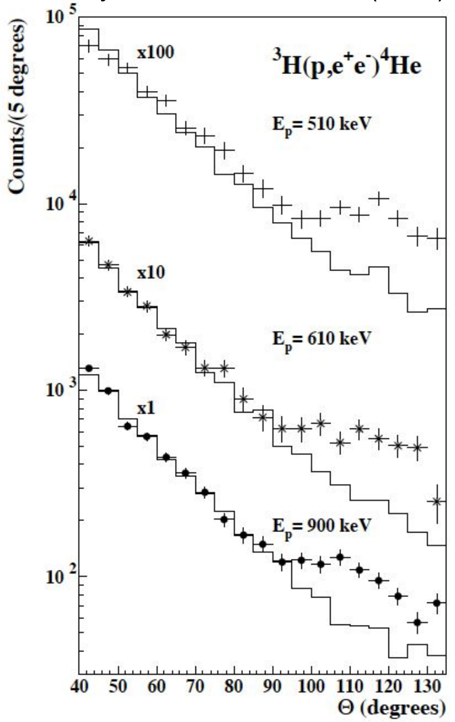
$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst})\ \text{mb}$$

PADME RUN III

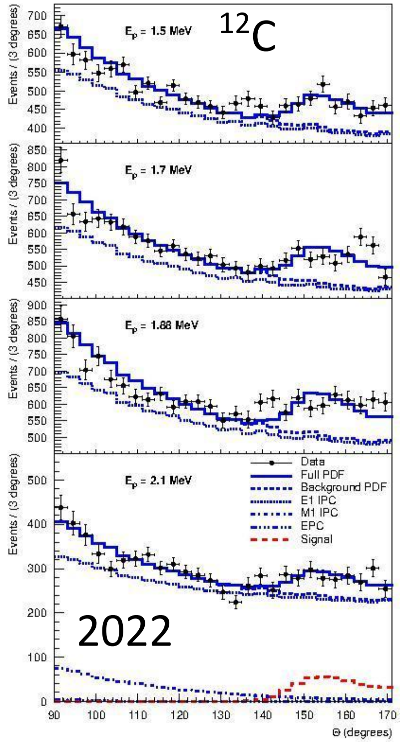
Probing X17

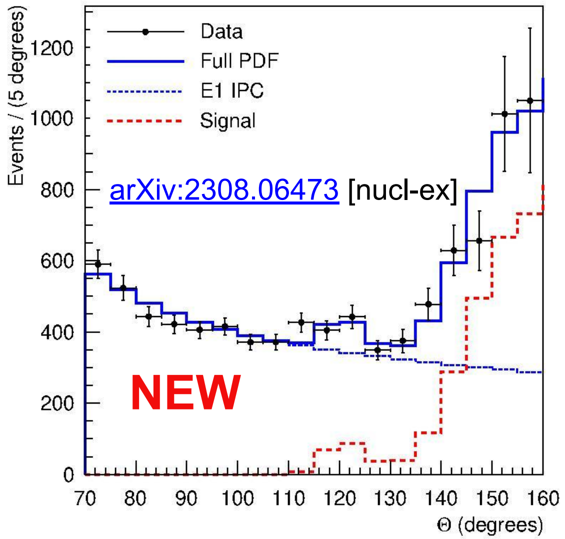


Phys.Rev.C 104, 044003 (2021)

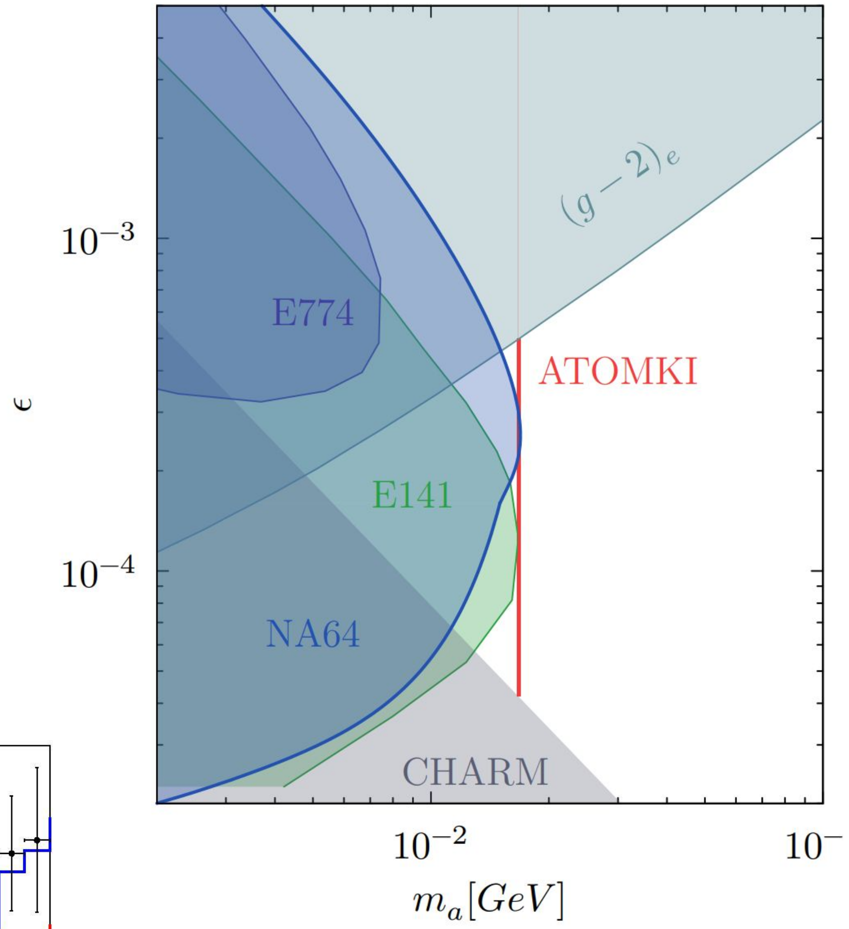


Phys. Rev. C 106, L061601 (2022)

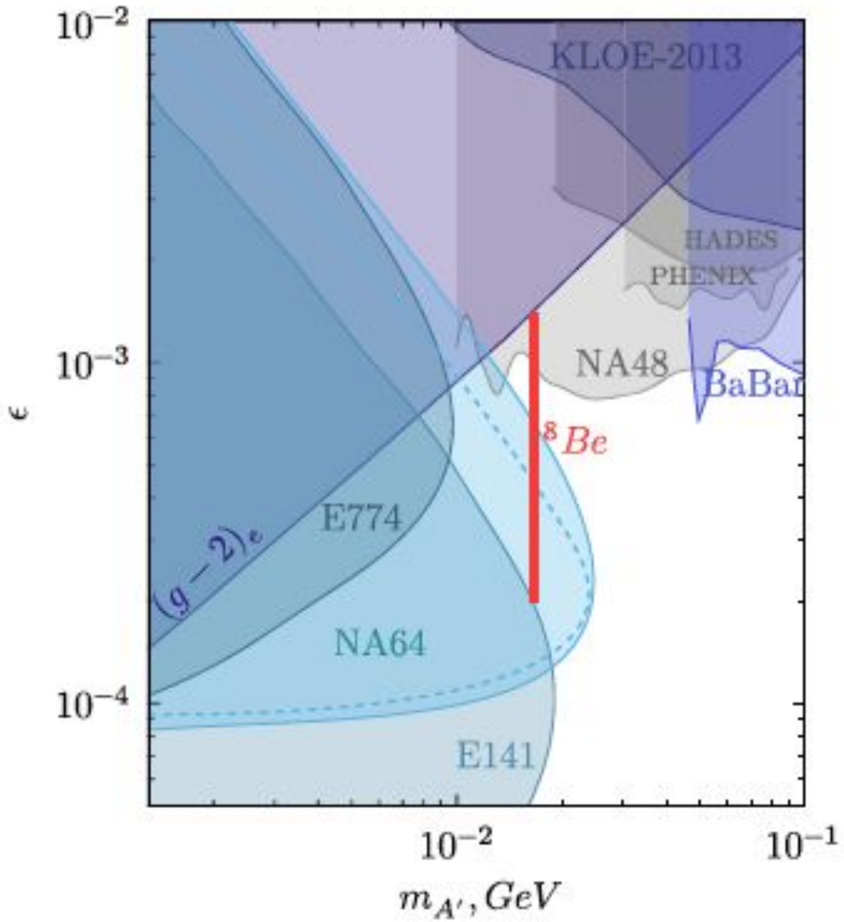




Phys. Rev. D 101, 071101(R)



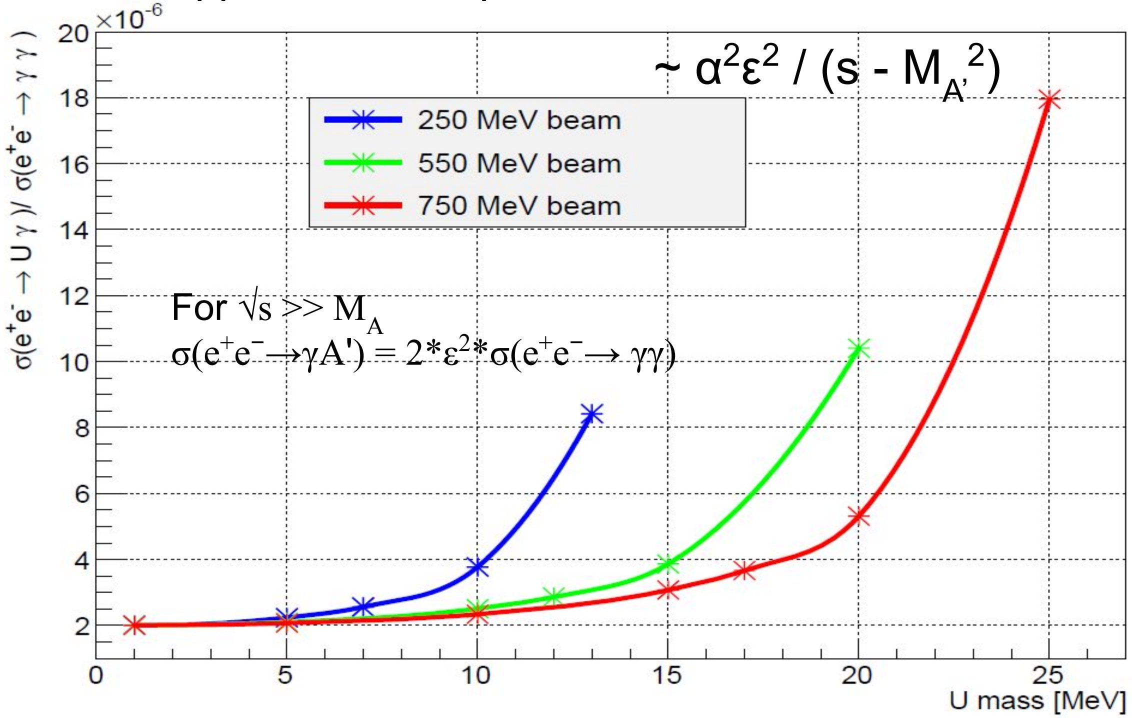
arXiv:2104.13342 [hep-ex]



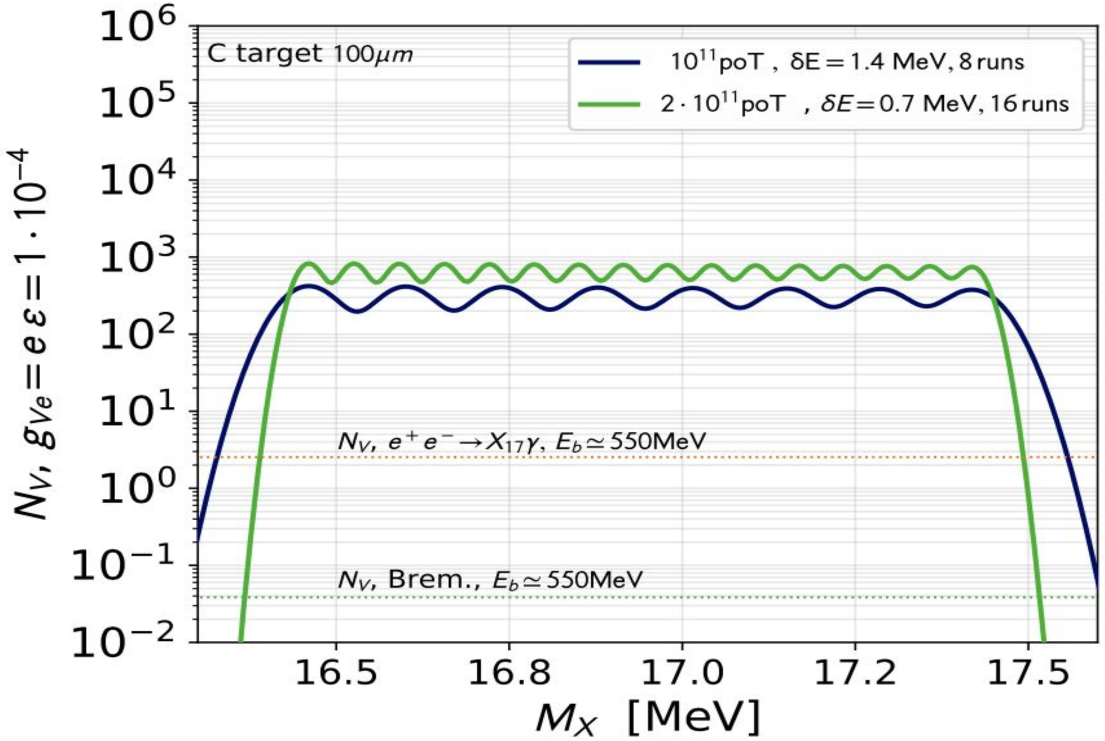
- Similar physics observables as in the ^{8}Be, ^{4}He and ^{12}C experiments
  - 2 leptons in the final state
  - Kinematics properties determined by the mass of the X particle (2 body decays)

X17 @ PADME strategy

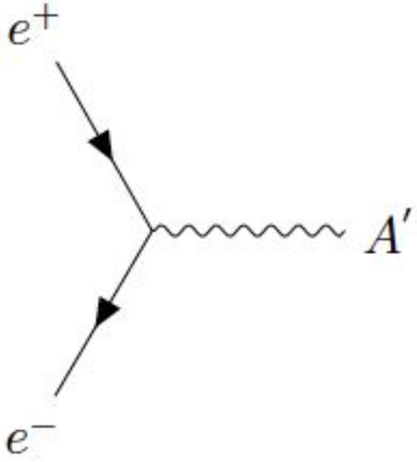
Cross section enhancement with the approach of the production threshold



L. Darmé et. al.,



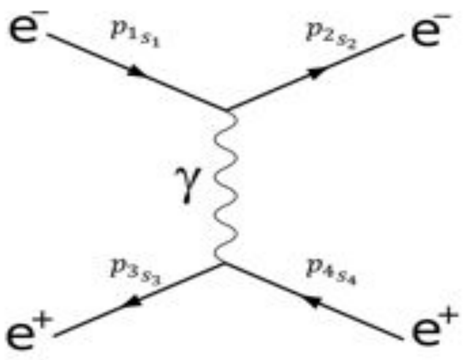
- Resonant production of X17
- energy at resonance: ~283 MeV: scan
- Need to measure the final state to reconstruct the invariant mass
  - Or change in cross section

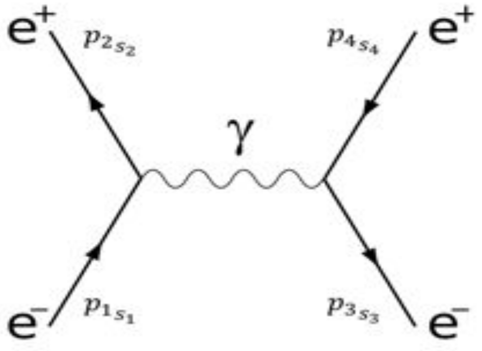


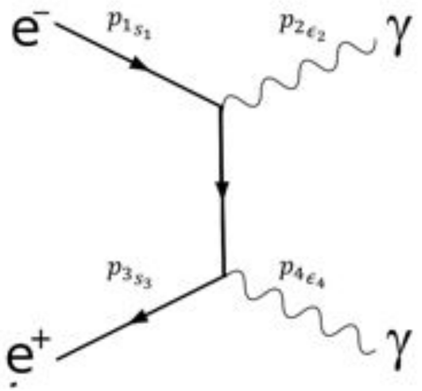
$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4}$$

$$\sigma_{\rm peak} = 12\pi/m_{A'}^2 \qquad \Gamma_{A'} = \frac{1}{3} m_{A'} \varepsilon^2 \alpha$$

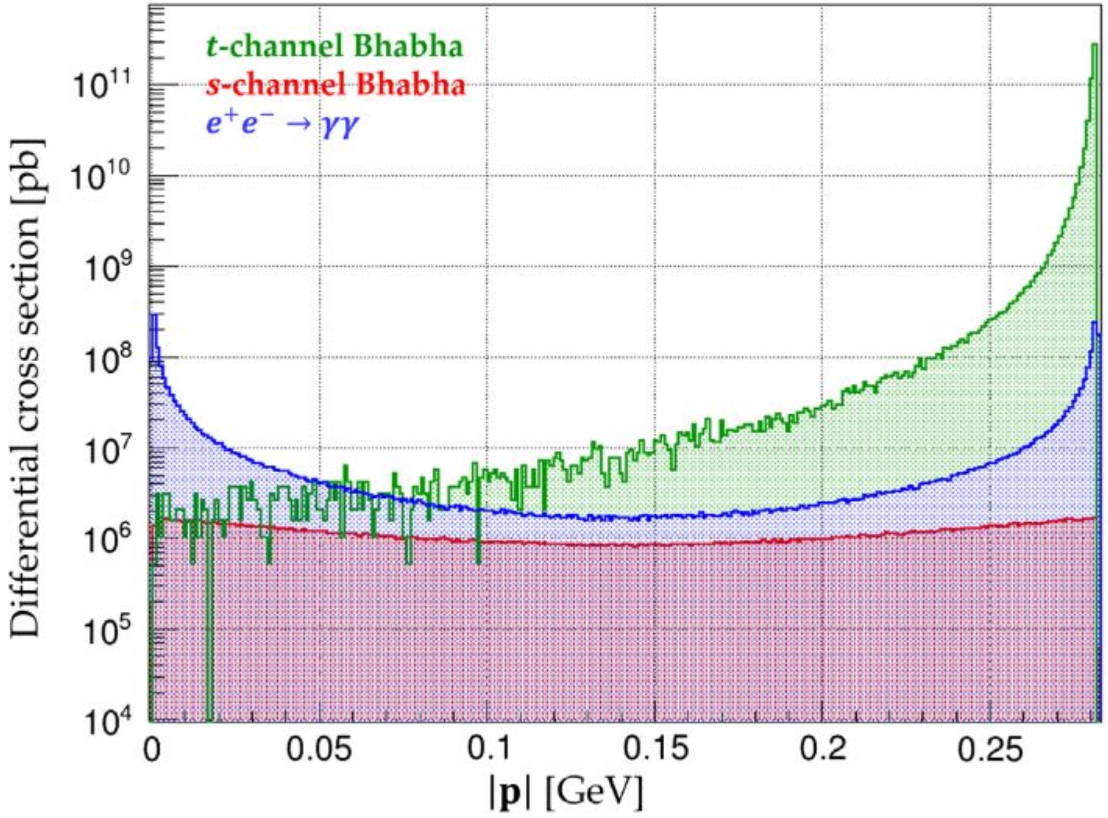
PADME strategy: $e^+e^- \to X17 \to e^+e^-$







Bhabha scattering dominates the event rate in the background contribution for high P_{e+}



- Resonant cross section significant → X17 event yield

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

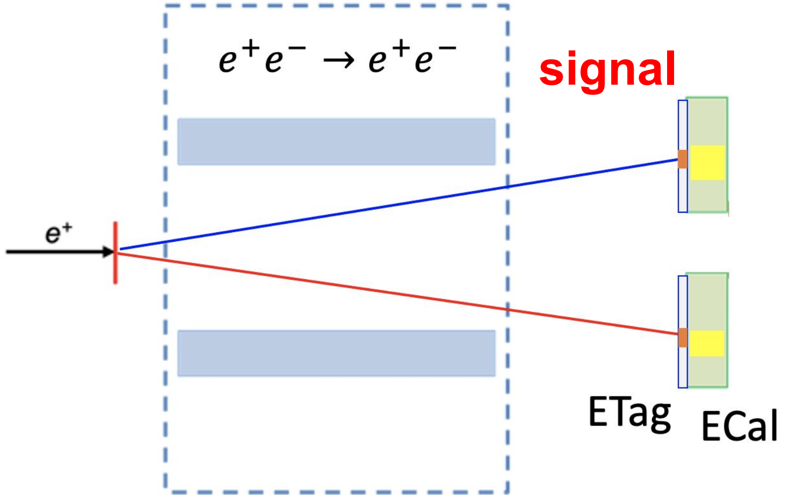
$$\mathcal{N}_{X_{17}}^{\text{ALP}} \simeq 5.8 \cdot 10^{-7} \times \left(\frac{g_{ae}}{\text{GeV}^{-1}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$

σ_E - beam energy spread

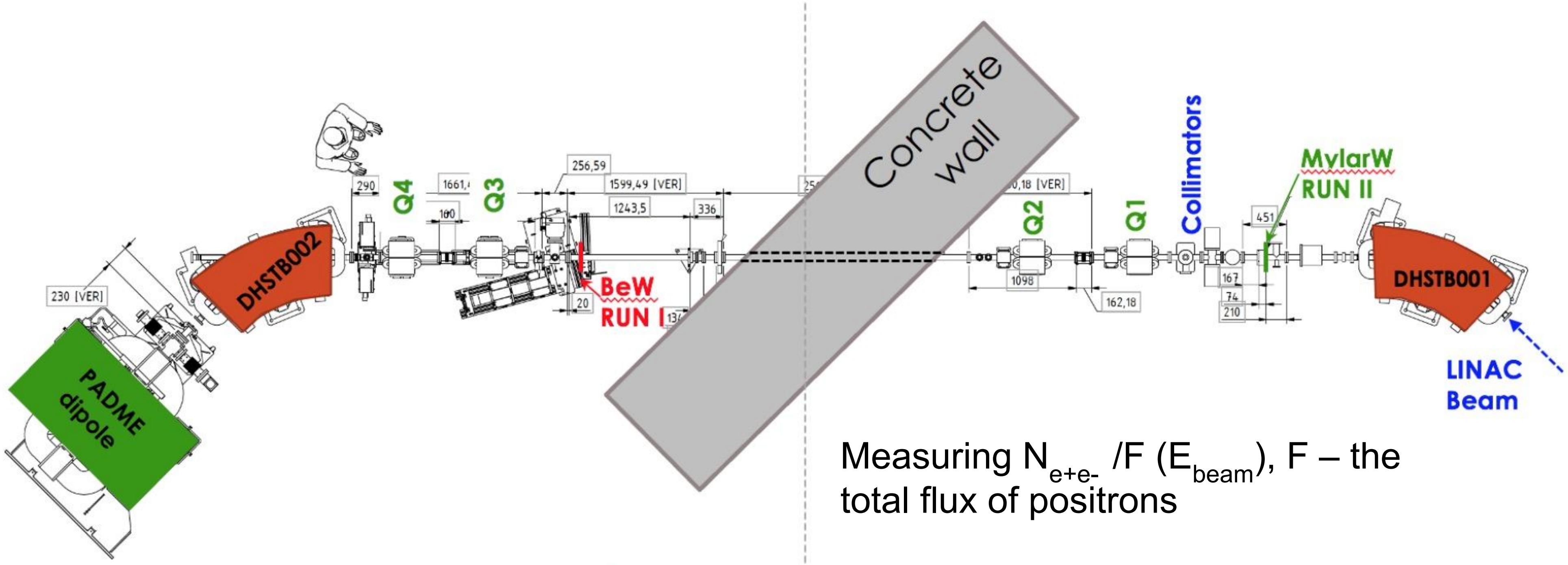
Production of $O(10^3)$ X17 events with 10^{10} positrons on target

Change in $\sigma_{tot}(e^+e^- \to e^+e^-)$

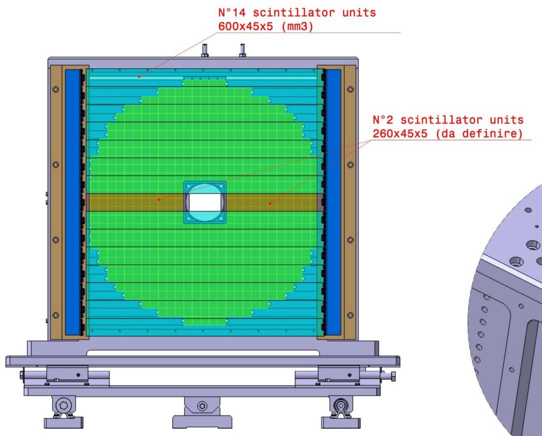
PADME RUN III

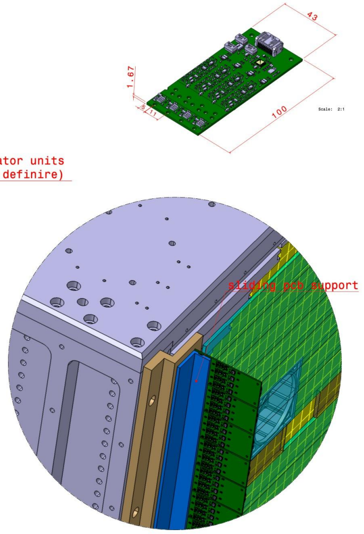


Running with no magnetic field in PADME dipole



Measuring N_{e+e-} /F (E_{beam}), F – the total flux of positrons

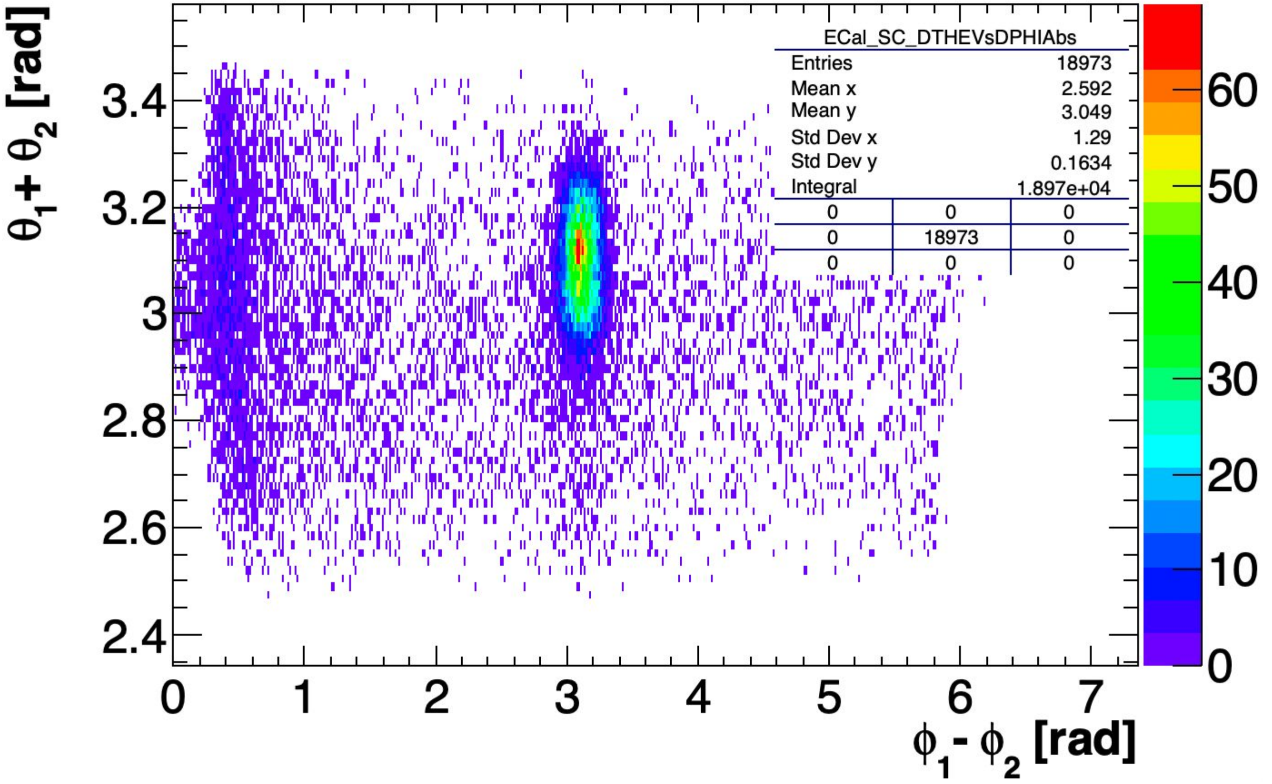


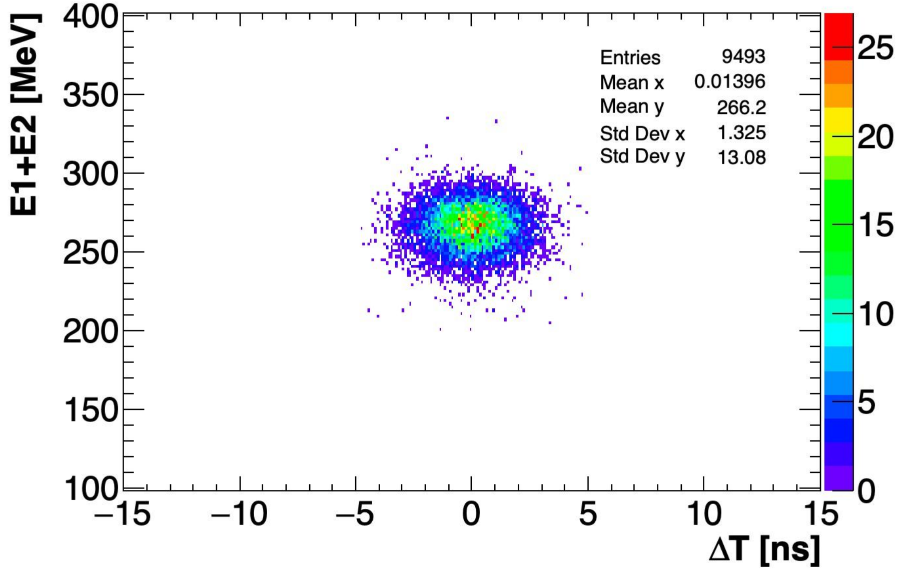


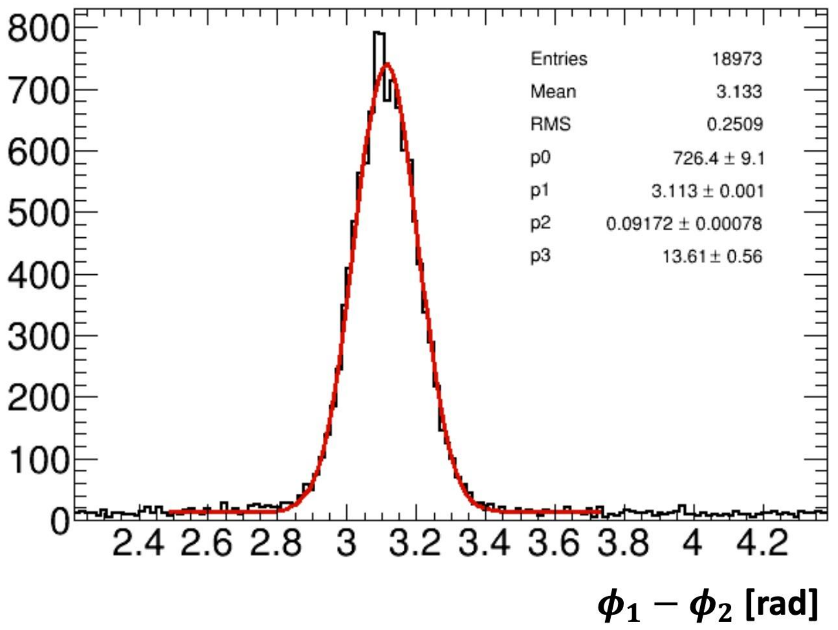
Components in the analysis:

- **Signal selection & events identification**
  - Background contribution
- **Determination of the normalization**
  - PADME beam measurement
- **Expected signal yield**
  - “Theory” input: X17 line shape

Signal selection: $N_{2cl} = N_{e+e-} + N_{\gamma\gamma}$



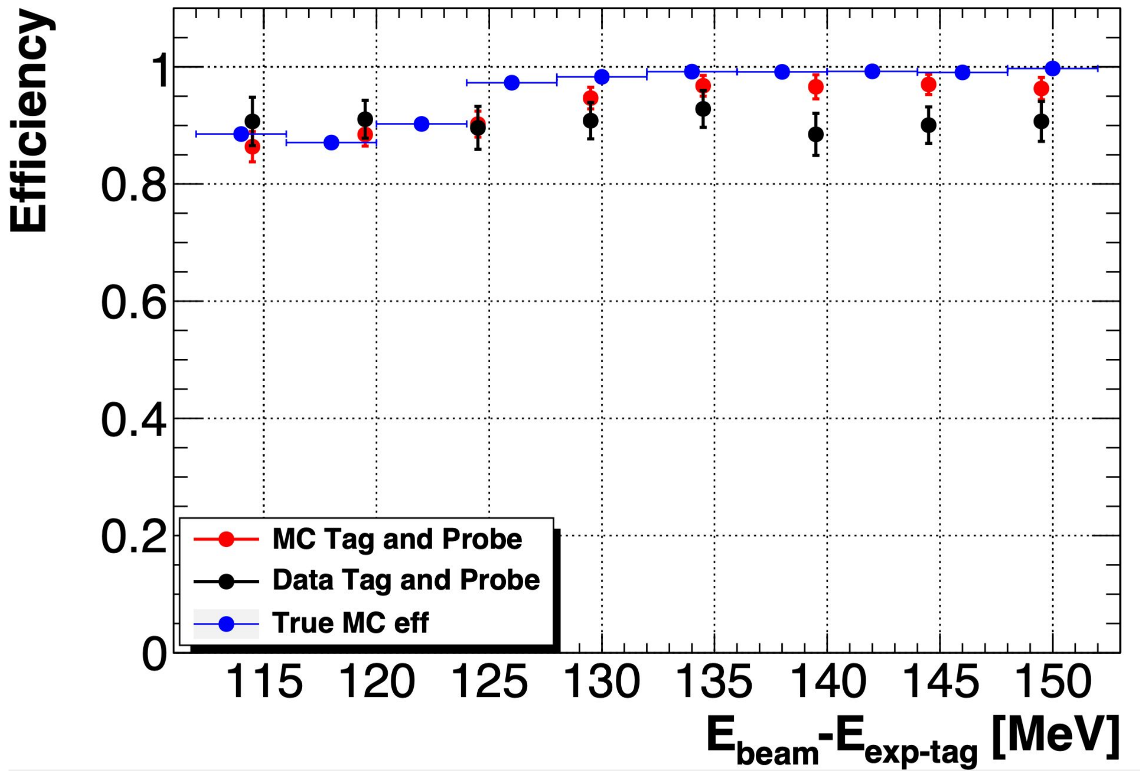




- ECal based: two in-time clusters with two body kinematics
- Background estimation: ~ 4 %
- The measurement is N_{2cl}/Flux (E_{beam})
  - Flux = PoT

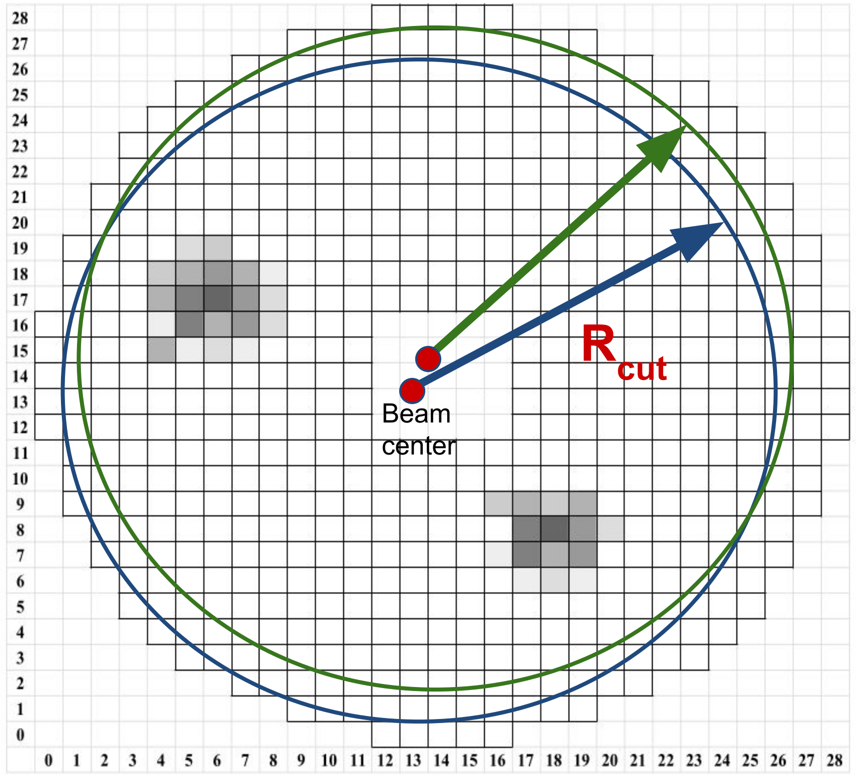
Signal selection: selection efficiency

Cluster reconstruction efficiency:
TAG & PROBE with DATA



- Single hit identification threshold of 15 MeV
- Cluster reconstruction efficiency is stable over time
  - With the bad crystals excluded from the reconstruction

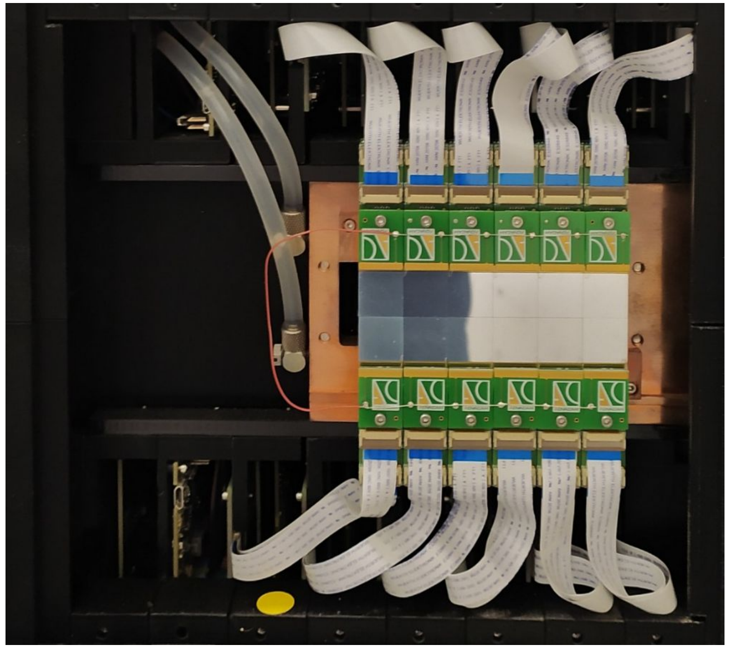
Geometrical efficiency (acceptance)

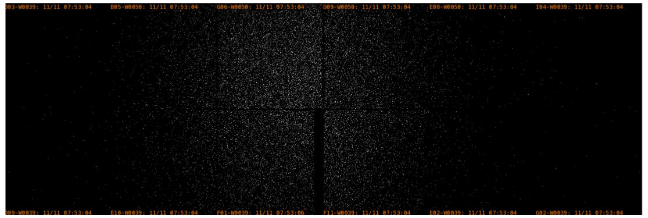


- Dominated by the cut on the outer radius of a cluster in the calorimeter
- Beam center drift limits the maximal R_{cut}

Beam position monitoring

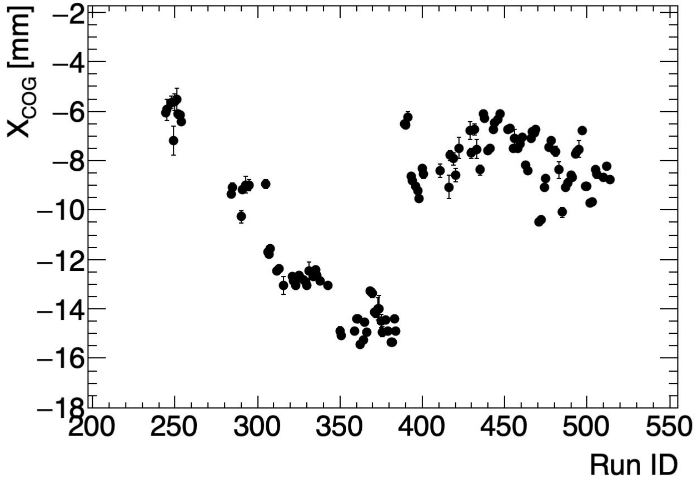
Timepix 3 array

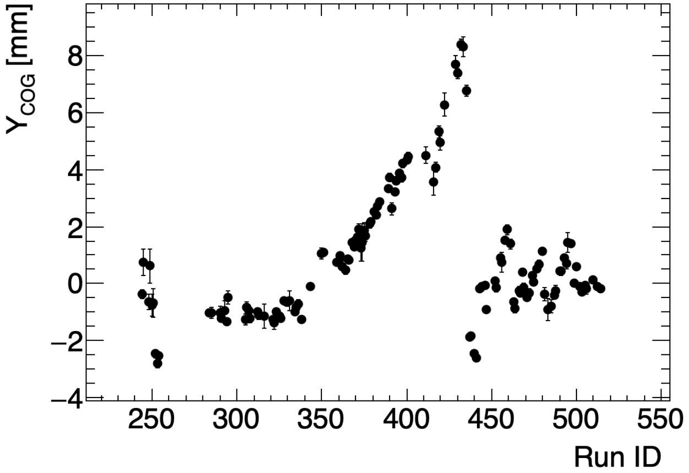




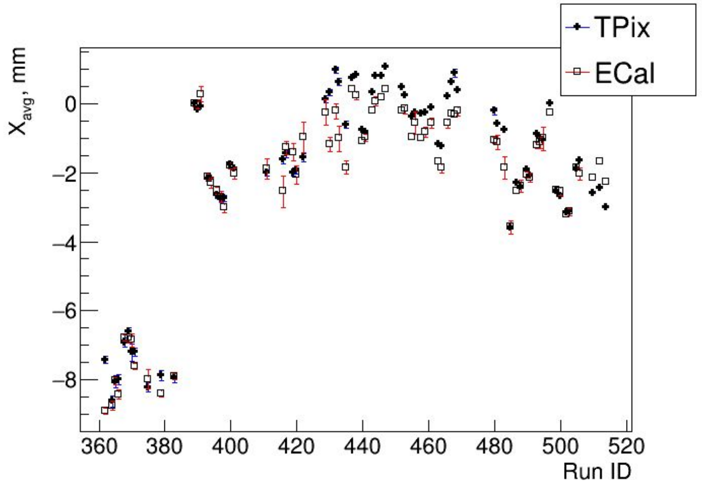
- Matrix of 2 x 6 Timepix3 detectors
  - each 256x256 pixels
- Operated in 2 modes:
  - image mode, integrating
  - streaming mode, feeding ToT and ToA for each fired pixel

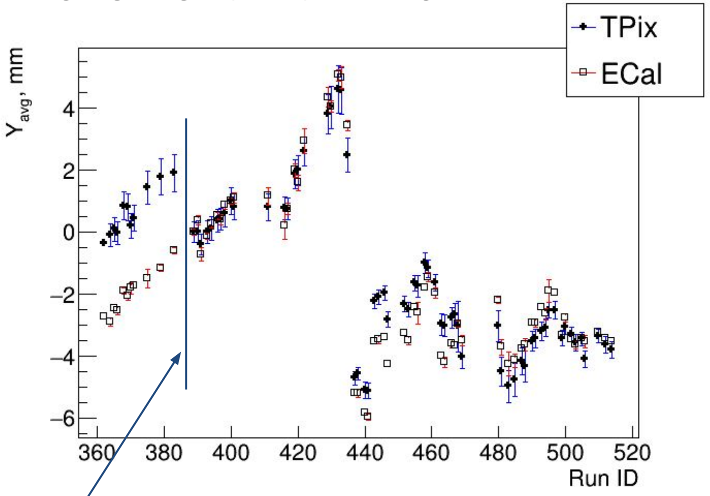
COG at the ECal front face from 2 cluster events





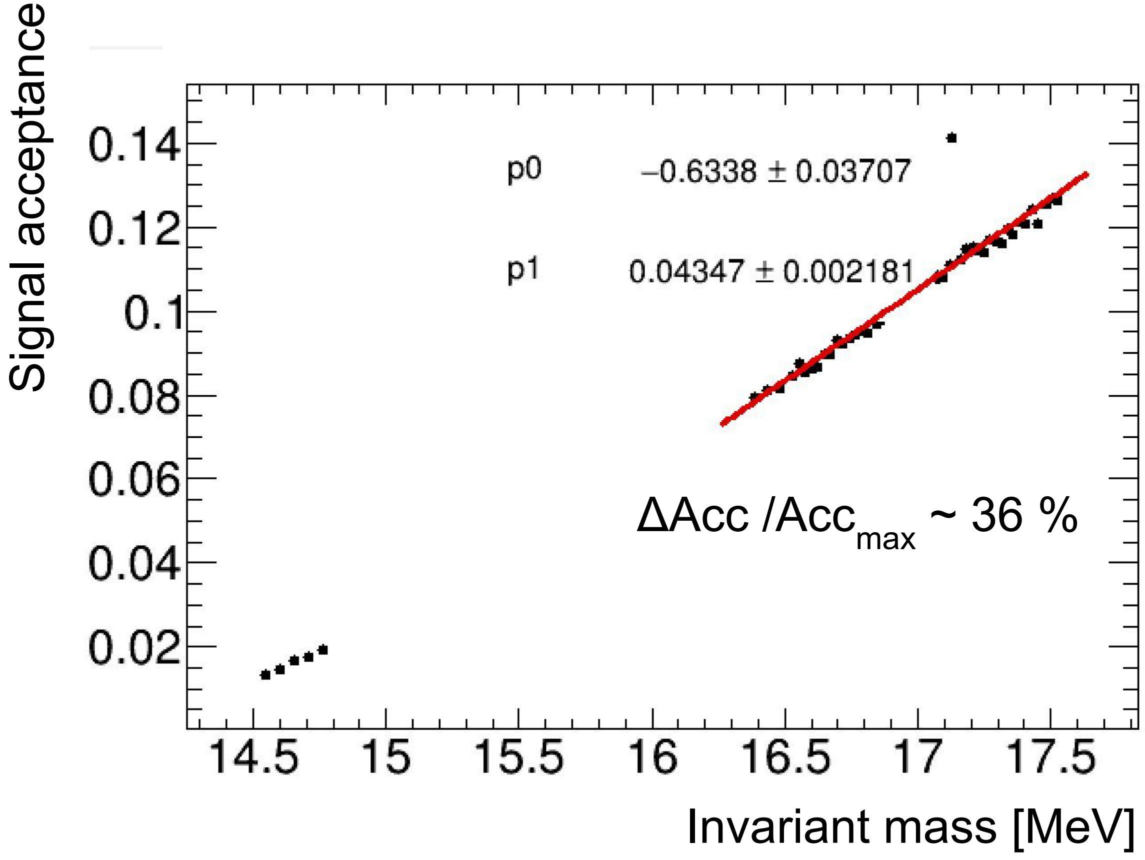
Movement within 10 mm

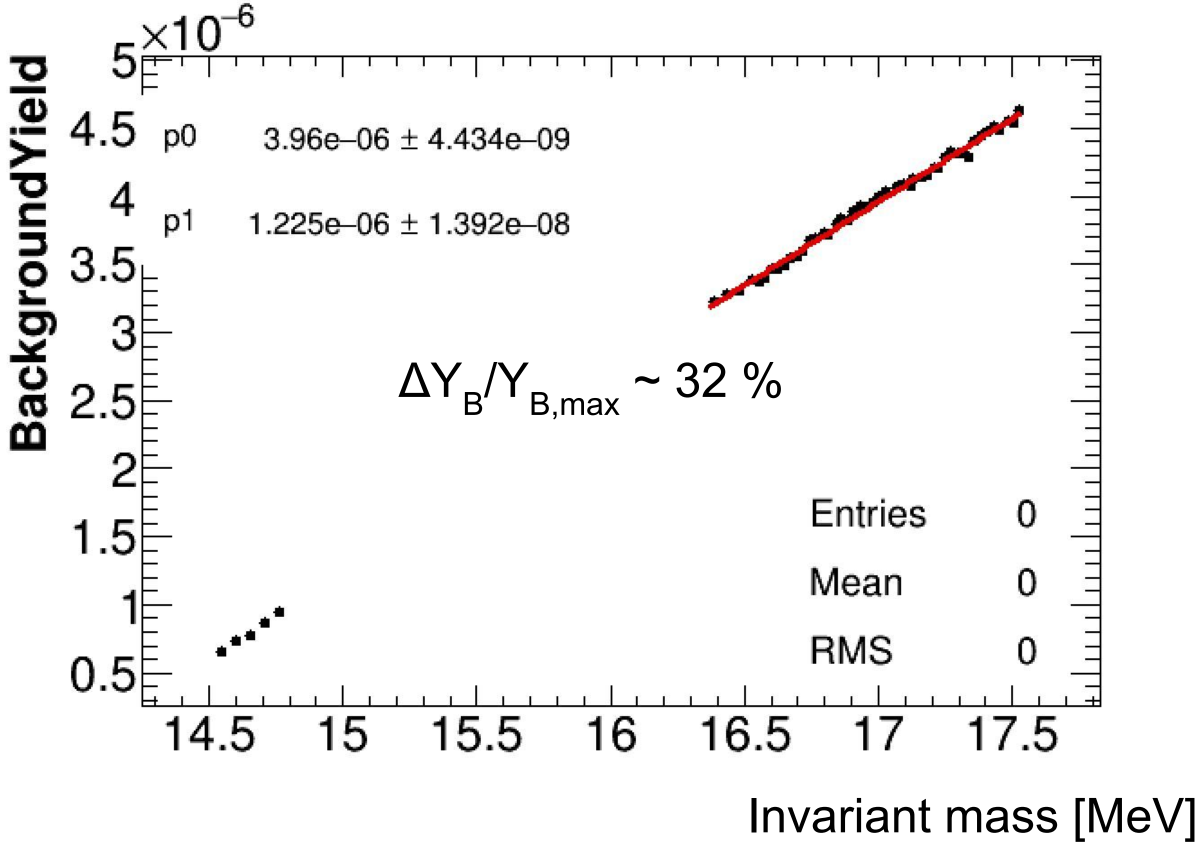




Timepix was moved by 1.8 mm
Recovered

Signal and background: MC study

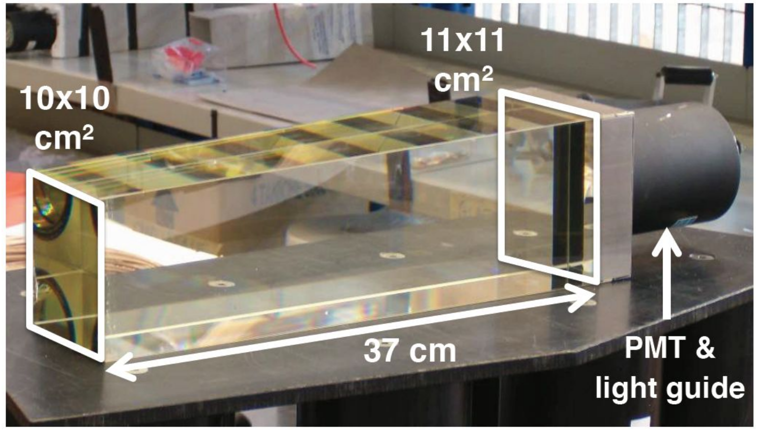




- Signal acceptance of the level of O(10%)
  - Outer radius cut with respect to the beam CoG at ECal
- Background contribution of the order of 40000 events per invariant mass point
- Both are dependent on the e^+e^- invariant mass
  - Accidental cancellation in the S/B ratio, for a fixed g_{ve}
- The total uncertainty is of O(1%)

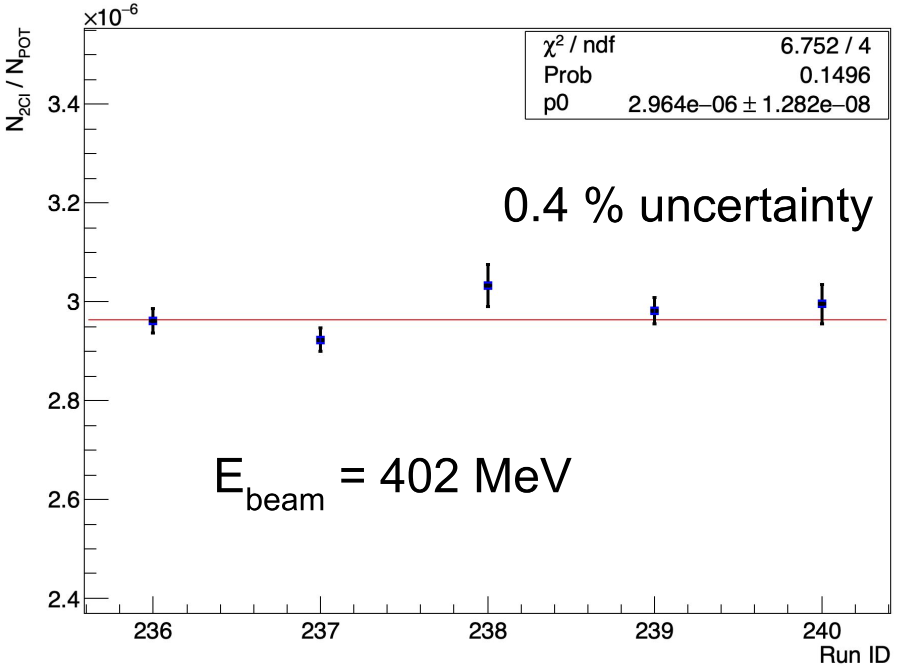
Positron flux measurement

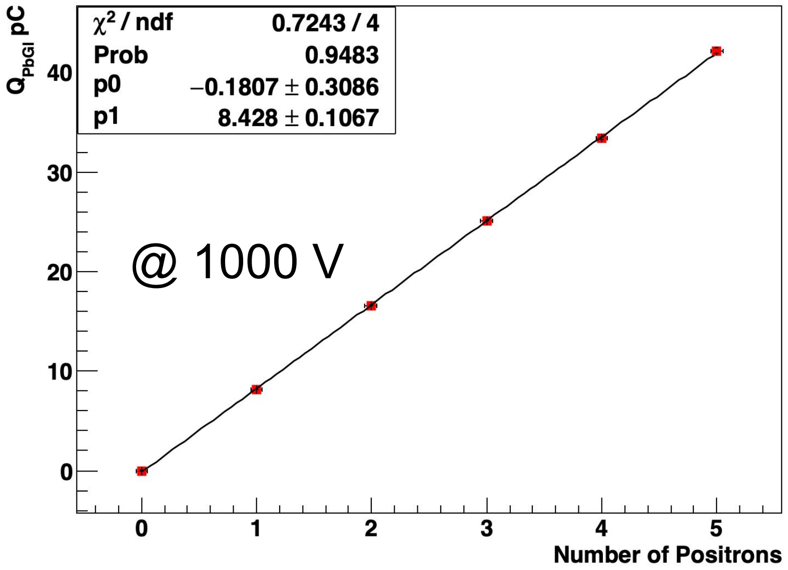
arXiv:2405.07203 [hep-ex]



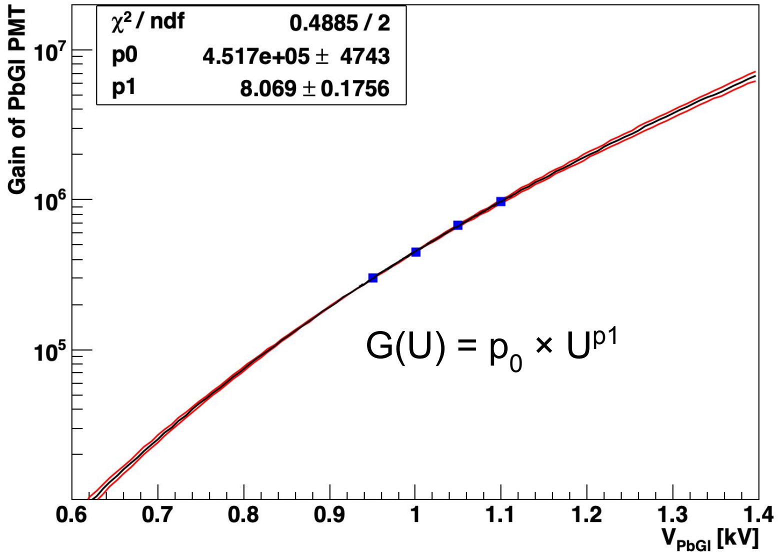
- PoT is primarily measured by an OPAL lead glass block downstream of the setup
- Additional detectors to control the PoT systematics
  - and to derive correction factors
- Several testing campaigns
  - A few positrons -> clear 1e, 2e, etc. peak identification
  - O(2000) PoT - cross-calibration with the FitPix

- Higher energy runs
  - control of the NPoT systematics
  - 2 clusters selection stability





$Q_{1e} = (8.24 \pm 0.021_{Stat} \pm 0.12_{Syst})$ pC

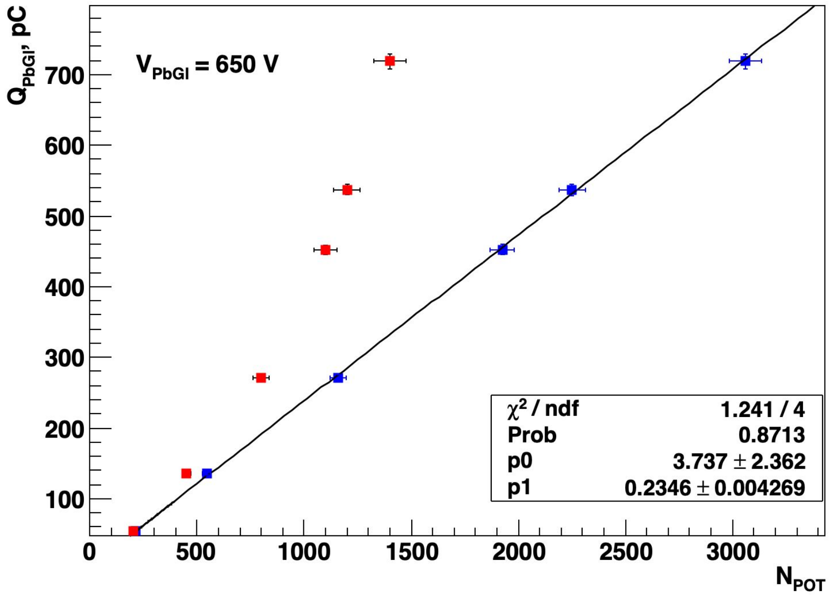


G (650V) = (14001 ± 1121)

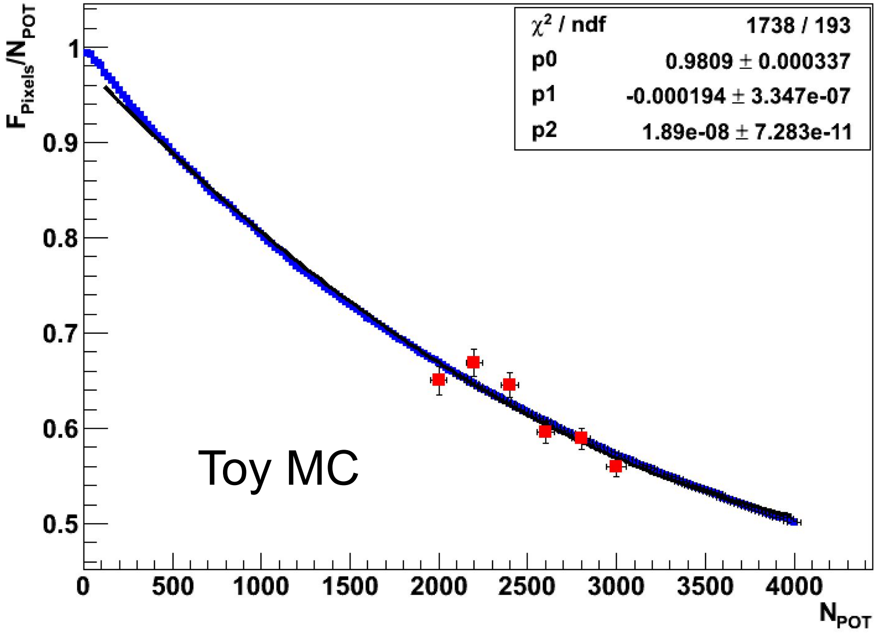
8 % uncertainty on NPoT

NOTE: consider more points for gain curve determination

Absolute positron flux measurement



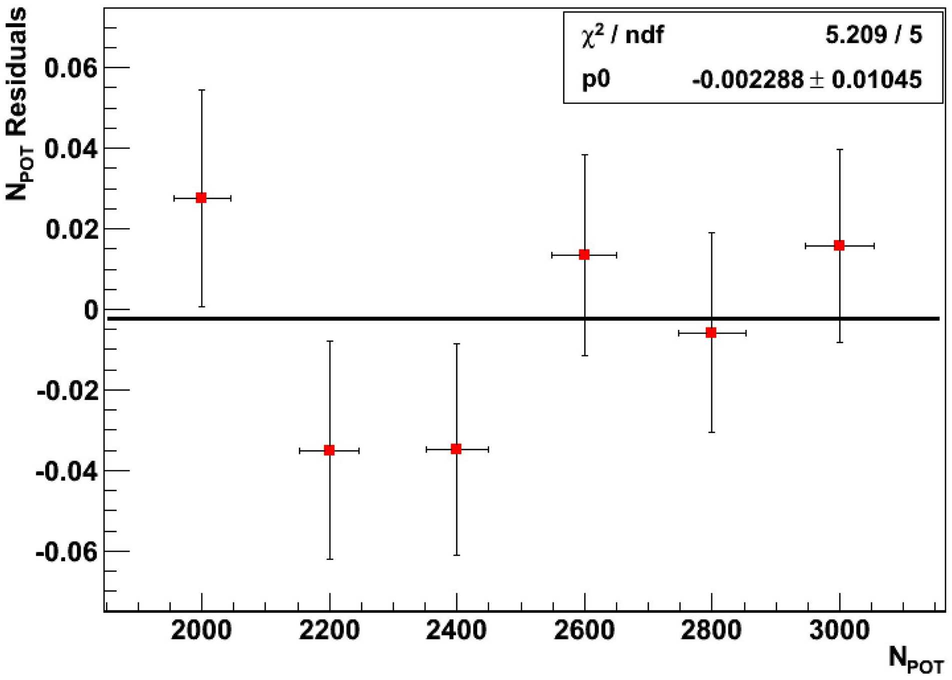
- Calibration of the lead glass @ 650 V with respect to the BTF FitPix
- Correction applied to the FitPix data to account for the high positron density



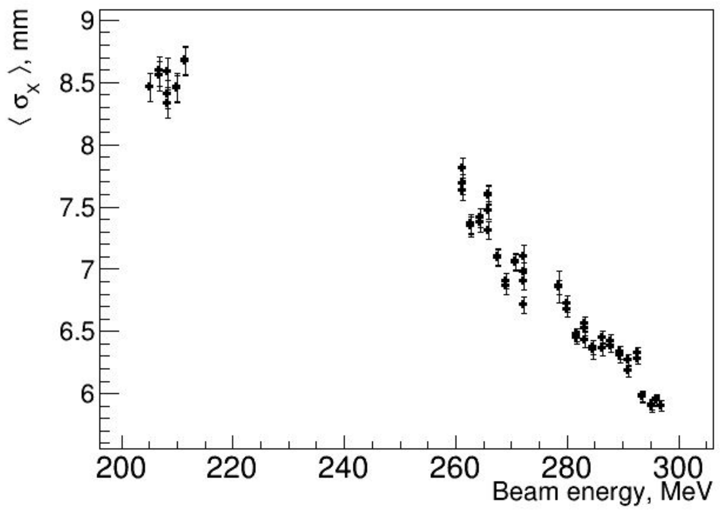
- Validation of the toy MC (and F_{pixel} correction factor) with an independent measurement from BTF luminometer
- Correction uncertainty - of the order of 1 %
  - Common to all the measurements

Q_{1e} = (0.235 ± 0.0043) pC

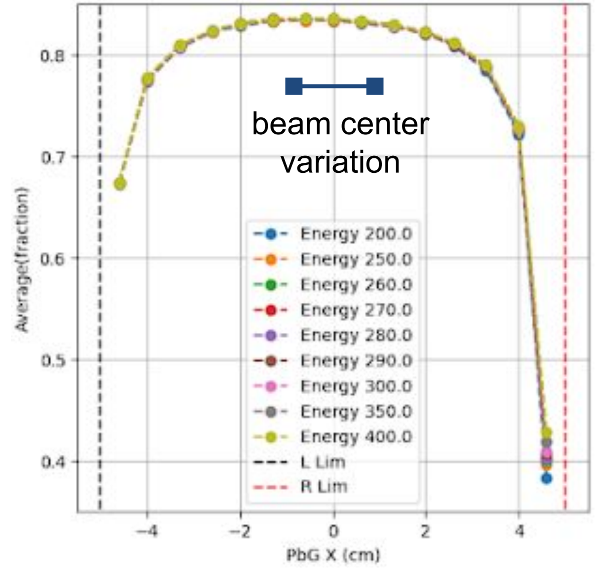
- Uncertainty on Q_{1e}: < 2%

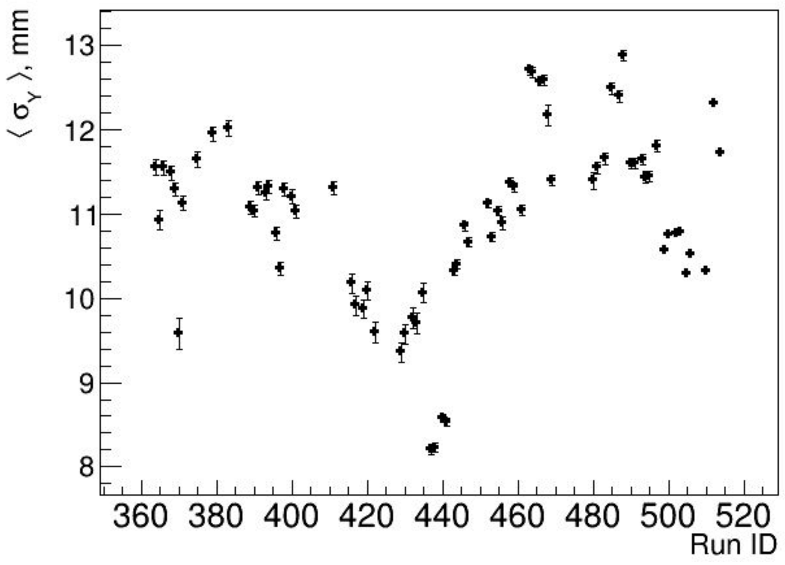


Positron flux measurement

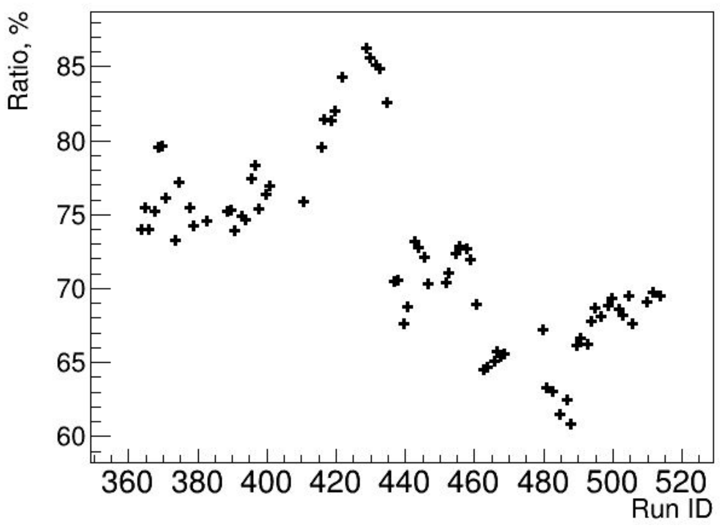


- The beam spread in Y direction varies within ~2 mm during the data taking
- The beam spread in X is energy dependent
  - However in X the containment is largely ensured

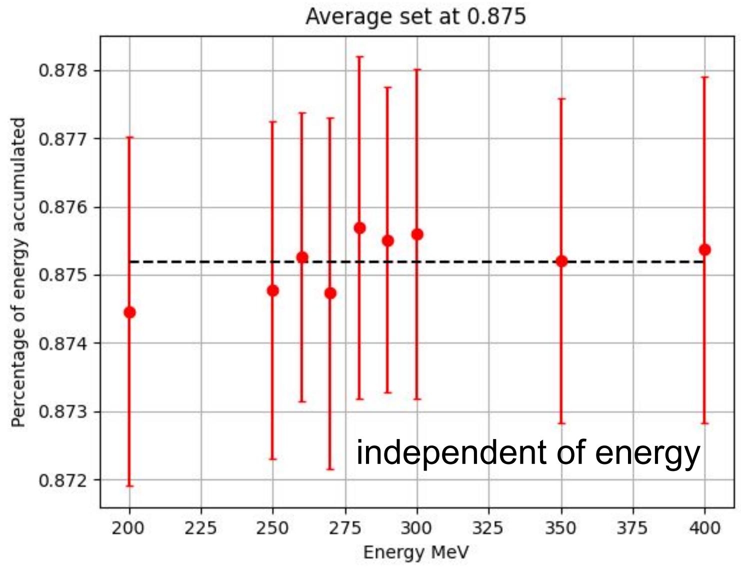




Particles impacting inside the TPix sensitive area

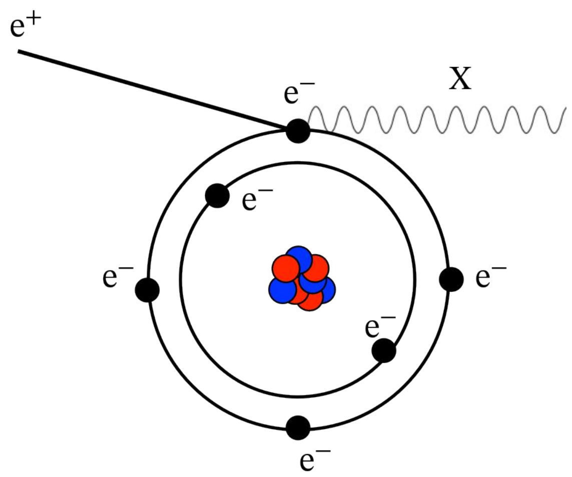


Correction due to the beam movement (convolution of TimePix & LeadGlass) results in systematics contribution < 1 %



The energy containment correction uncertainty well below 1 %

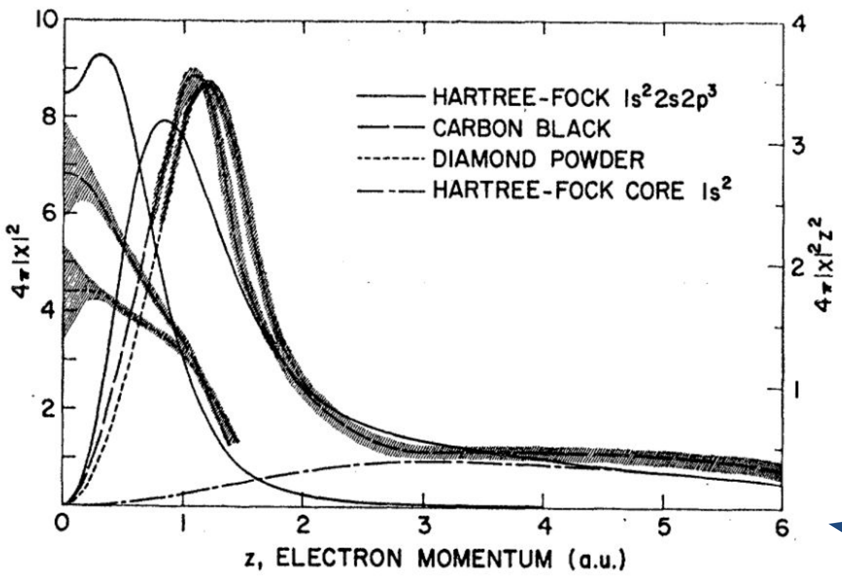
Signal yield: theoretical input



arXiv:2403.15387 [hep-ph] ,Accepted in PRL, Thanks to
Fernando Arias-Aragón, Luc Darmé, Giovanni Grilli di Cortona, Enrico Nardi

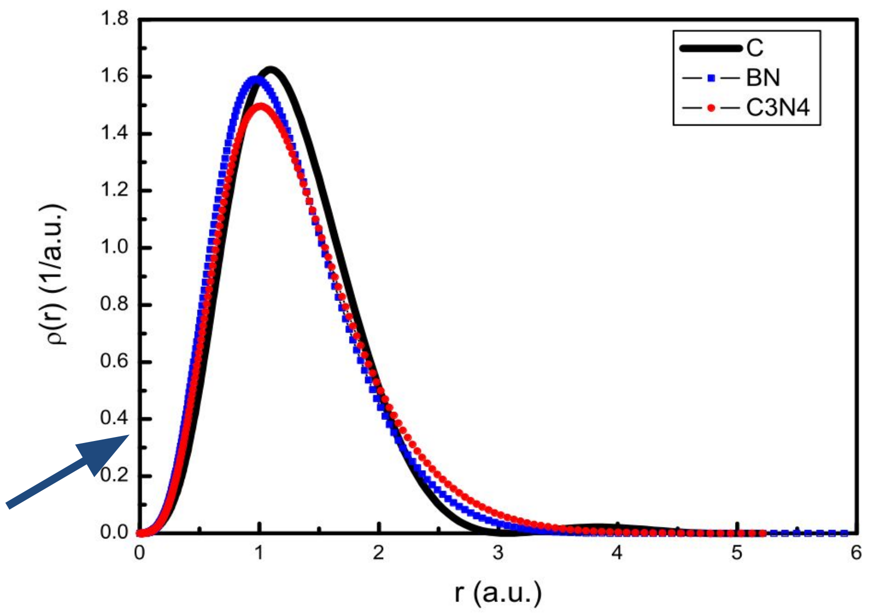
$$d\sigma = \frac{d^3p_X}{(2\pi)^3}\int \frac{d^3k_A}{(2\pi)^3}\frac{(2\pi)^4}{8E_XE_AE_B|v_A - v_B|} n\left(\vec{k}_A\right) |\mathscr{M}|^2 \delta^{(4)}(k_A + p_B - p_X)$$

- Line shape modification due to electron motion
  - Bound e⁻ momentum changes the e+e- invariant mass
- Peak height decreases, width increases, S/B decreases
- **n(k$_A$)** - electron momentum density function
  - Theory: calculate it using Hartree-Fock
  - Experiment: X-ray determination of electron momentum density



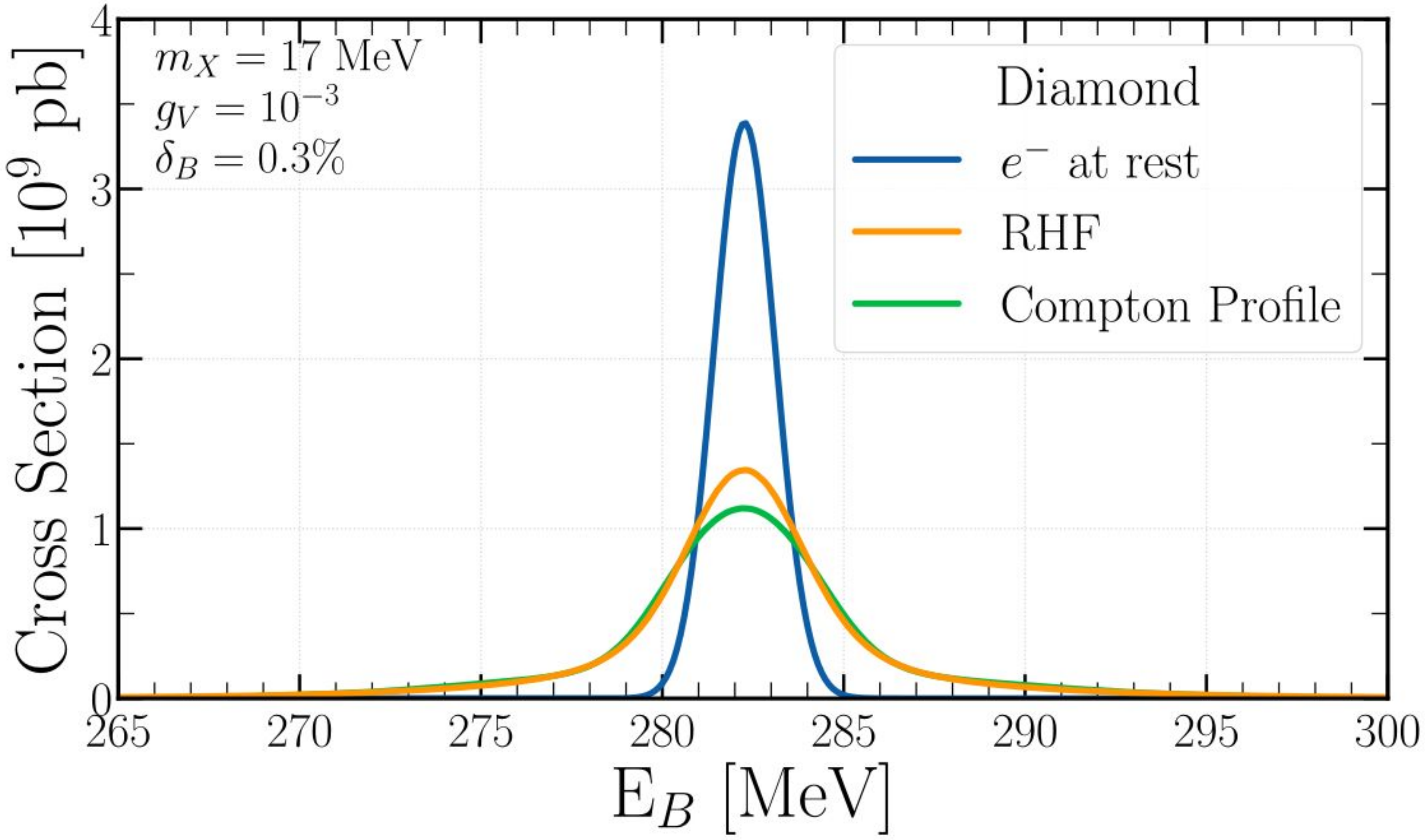
[Phys. Rev. 176 (1968) 900]

Physica B 521 (2017) 361–364



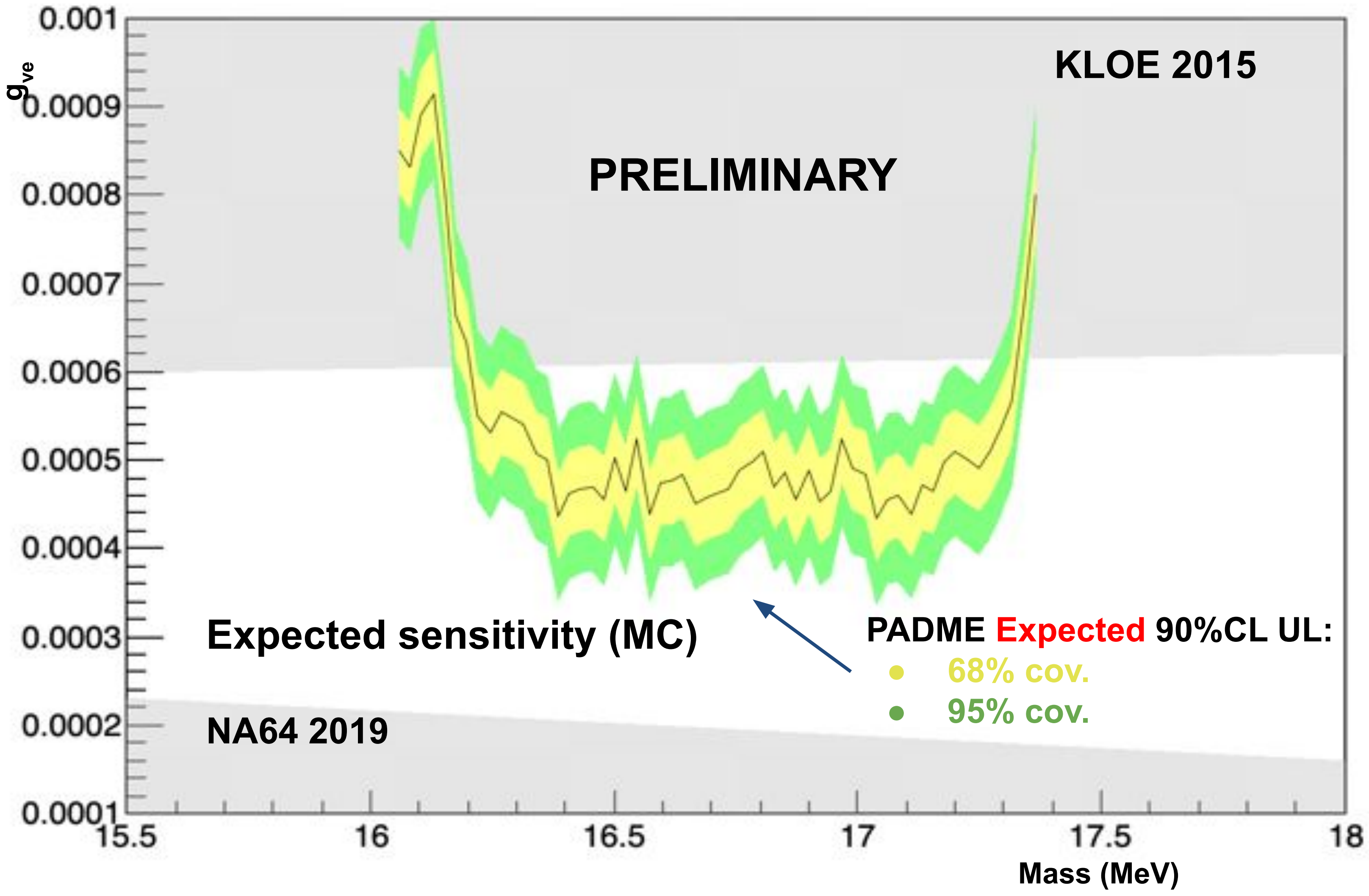
Sensitivity estimation

- Sensitivity depends on S/B and the uncertainty on the background determination
  - Statistical (N_B), 47 points with $O(10^{10})$ PoT, $\Delta E = 0.75$ MeV
  - Systematics (e.g. N_{poT})
  - Background: N_B ~ 45000 events per point
  - Signal acceptance



- **Sources of systematics**
  - Relative PoT estimation O(0.5%)
  - Acceptance 0.75%
  - Beam energy spread 0.05 %
  - Signal shape uncertainty
  - Beam
  - Time dependent ECal efficiency
  - Beam energy uncertainty - controlled by Hall probes $< 10^{-3}$
  - ECal calibration
- **Normalization systematics**
  - absolute PoT - 5 %

PADME MC sensitivity estimate for RUN III



- Expected 90% CL upper limits are obtained with the CLs method
  - modified frequentist approach, LEP-style test statistic
- Likelihood fits performed for the separate assumptions of signal + background vs background only

$$Q_{statistics} = -2\, ln\, (L_{s+b} / L_b)$$

- Pseudo data (SM background) is generated accounting for the expected uncertainties of nuisance parameters + statistical fluctuations
- 150 Nuisance parameters:
  - POT of each scan point
  - Common error on POT (scale error)
  - Signal efficiency for each scan point
  - Background yield for each scan point
  - Signal shape parameters: signal yield @ a given X17 mass and g_{ve}
  - Signal shape parameter: beam-energy spread

How to improve:

Towards PADME RUN IV

Strategy: $N_{e+e-}/N_{\gamma\gamma}$

- The results from PADME RUN III will be dominated by PoT systematics, two clusters acceptance acceptance systematics

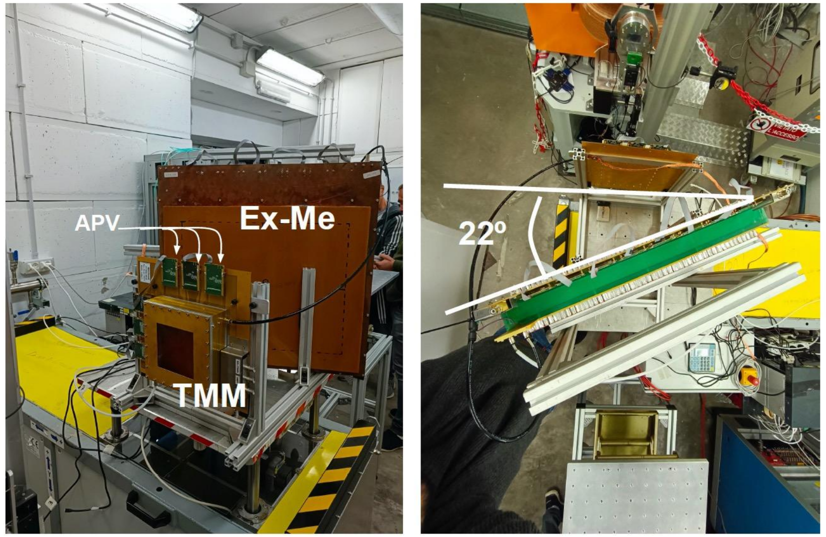
  → Exploit a different normalization channel which could possibly cancel part of the systematic effects
- Natural candidate: $e^+e^- \to \gamma\gamma$
  - Same 2 body kinematics: similar ECal illumination, systematics due to bad ECal crystals largely cancels

- Back on the envelope estimation: need knowledge of $N_{\gamma\gamma}$ at 0.5 % for each scanning point
  - $\sigma(e^+e^- \to \gamma\gamma)_{E=300\ MeV}$ ~ 2 mb, Acc ($e^+e^- \to \gamma\gamma$) ~ 10 % ⇒ O(10k) $\gamma\gamma$ events per 10^{10} PoT
    - Need 4 times higher statistics per scan point
  - Less scan points due to the widening of X17 lineshape because of the electronic motion
  - Higher intensity – by a factor of 2
- Need good separation between charged and neutral final states

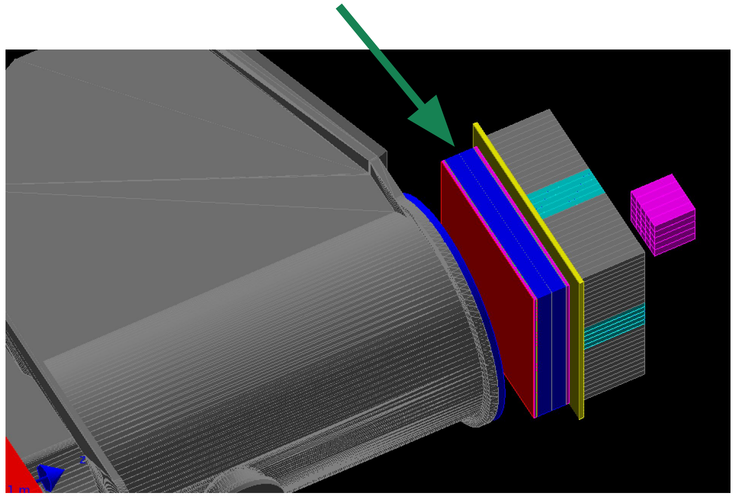
Strategy: $N_{e+e-}/N_{\gamma\gamma}$

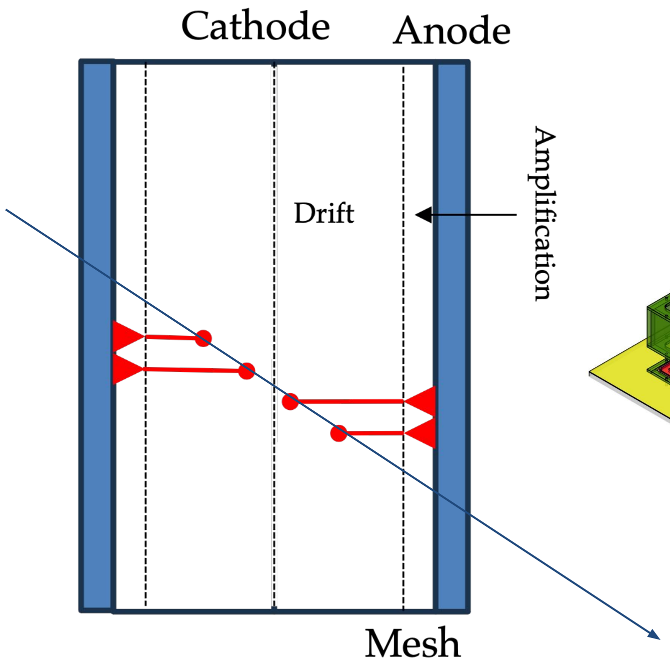
- e^+e^- tagging with high efficiency
  - And well controlled mis-tagging probability
- Micromegas tagger – double sided readout gas chamber with X/Y readout

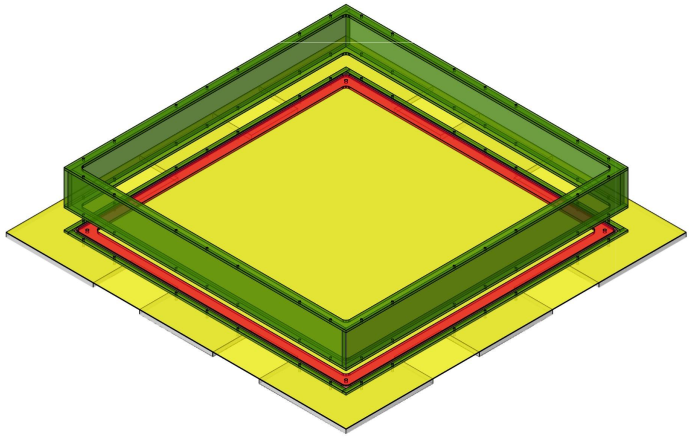
Testbeam results, tracking at 22 degrees

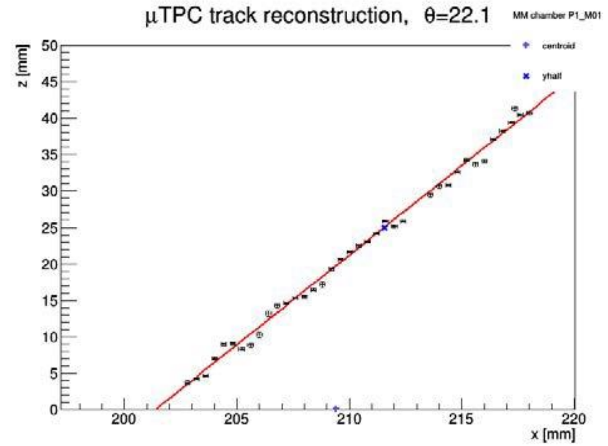


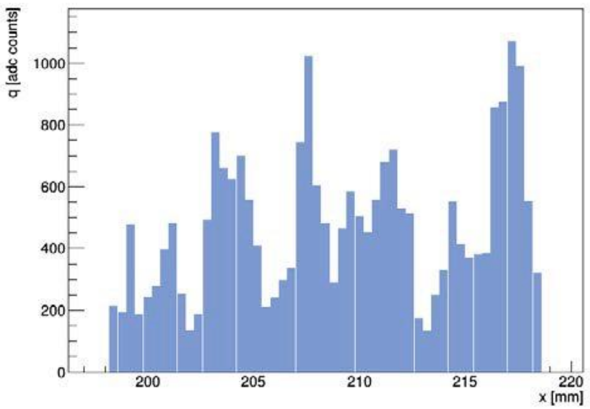
e-/e+ identification







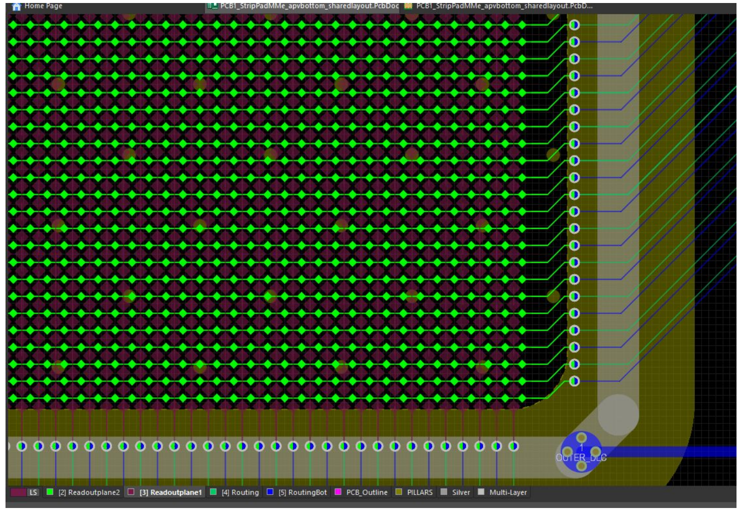


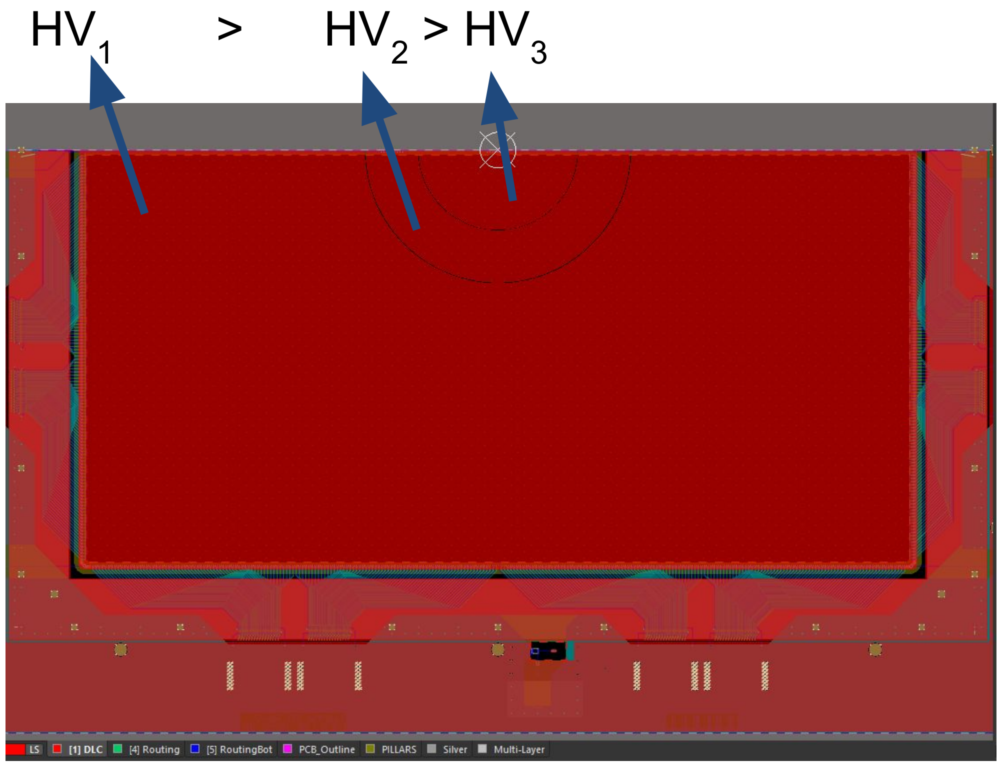


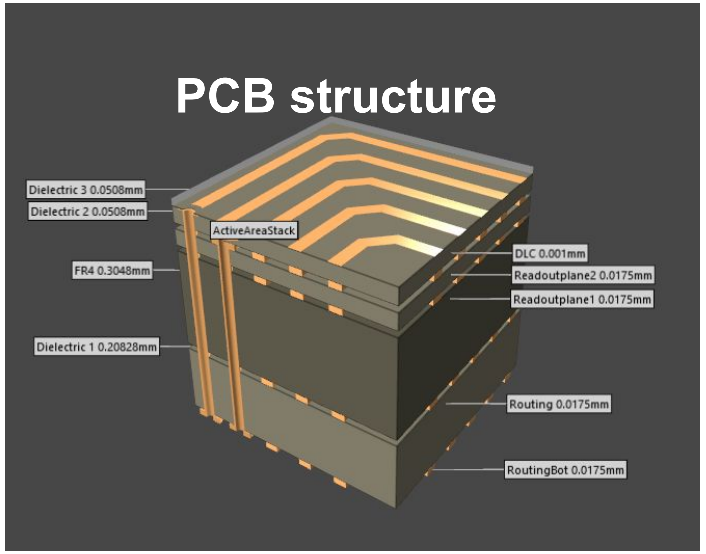
- Installing a new detector in the PADME setup due to rate limitations of the present tagger
- A completely new detector technology to be used in PADME
  - Gaining expertise and manpower from LNF ATLAS group

PADME tagger

- A novel micromegas readout plane suggested
  - Rhomboidal pads for X and Y direction, decrease the mutual capacitance
- Variable HV depending on the distance from the beam center
  - Low HV in the center, measure the beam multiplicity
    - Additional control on the PoT
  - Higher HV in periphery to ensure close to 100 % efficiency







- Gas mixture: $Ar:CF_4:i\text{-}C_4H_{10} = 88:10:2$
- Readout - SRS system with APV ASIC hybrid
  - An adapter card in preparation to allow APV25 to accept/record trigger signal
  - Timing and event matching

Status

- PCBs under preparation, to be ready for assembly in July
- Readout exists, integration with PADME DAQ ongoing (online vs offline)
- Gas supplies - premixed gas (7-10 days) vs gas mixer in BTFEH1

PADME RUN IV schedule

Requested period	Hall	Beam	Objective	Prerequisites
30 September - 6 October **Week 40**	BTFEH2	Electron beam (secondary)	- Timepix wrt Leadglass efficiency measurement - Timepix calibration - Leadglass calibration: response dependence wrt to HV (scan) and beam multiplicity	- Timepix transport to BTFEH2
4 - 17 November **Week 45**	BTFEH1	No beam	- Connection of PADME chamber to the the BTF line - Timepix and LeadGlass installation in place - Installation of Micromegas tracker with the gas infrastructure	- Green light from PADME Calorimeter crystals resurrection - Operational Micromegas, validated with cosmic in LAB - Green light from beam group
Week 46		Positron beam (secondary)	- Switch ON the detectors in the setup (warm up) - Common DAQ with event synchronization test - Micromegas first test with beam	- Installed Micromegas together with the gas (consumables) infrastructure - Installed Timepix and precise position survey
9 - 16 December **Week 50**	BTFEH1	Positron beam (primary, if possible)	- Full PADME operation - Detectors commissioning for RUN IV (efficiency, LeadGlass calibration, etc.) - Test and validate the new PADME Micromegas tracker	- LeadGlass positioning wrt Timepix - Operational Micromegas attached to the PADME ECal
20 - 31 January	BTFEH1	Primary positron beam	- Beam commissioning - Focusing at ECal / Timepix3 plane	- Operational PADME experiment - Operational Timepix/ECal
February - July	**BTFEH1**	**Primary positron beam**	**COLLECT GOOD DATA**	

Conclusions

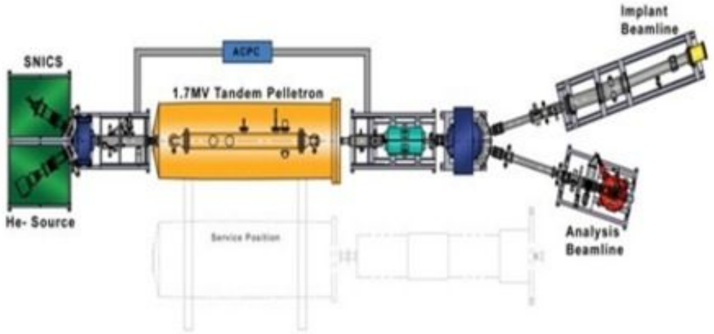
- PADME technique is extremely powerful for electro
- Dark photon analysis in RUN I/II data pushed forward thanks to application of ML methods for hit reconstructions in high rate environment
  - Good time resolution at the price of slightly degraded energy resolution
  - Allows to **keep background under control** at O(30000) PoT per bunch
- X17 analysis advances
  - Beam flux and beam geometry understanding, paper submitted to JHEP
  - X17 line shape extracted from theory and validated with compton profile - PRL
  - Common theory-experimental strategy paper in preparation
  - Signal acceptance and background estimation under control with systematics O(1%)

Aiming to open the box for the summer conferences

- An example for a very successful cooperation between theory and experiment
  - **Pushing the theory and an advancement of the field in general**
- A major improvement to PADME setup before RUN IV
  - Precise e^+e^- / $\gamma\gamma$ discrimination with a Micromegas tracker
  - **Allow probing the full unexplored region for the X17 allowed parameter space**

PADME: **P**recision **A**nd **D**ouble **M**onitoring of **E**verything

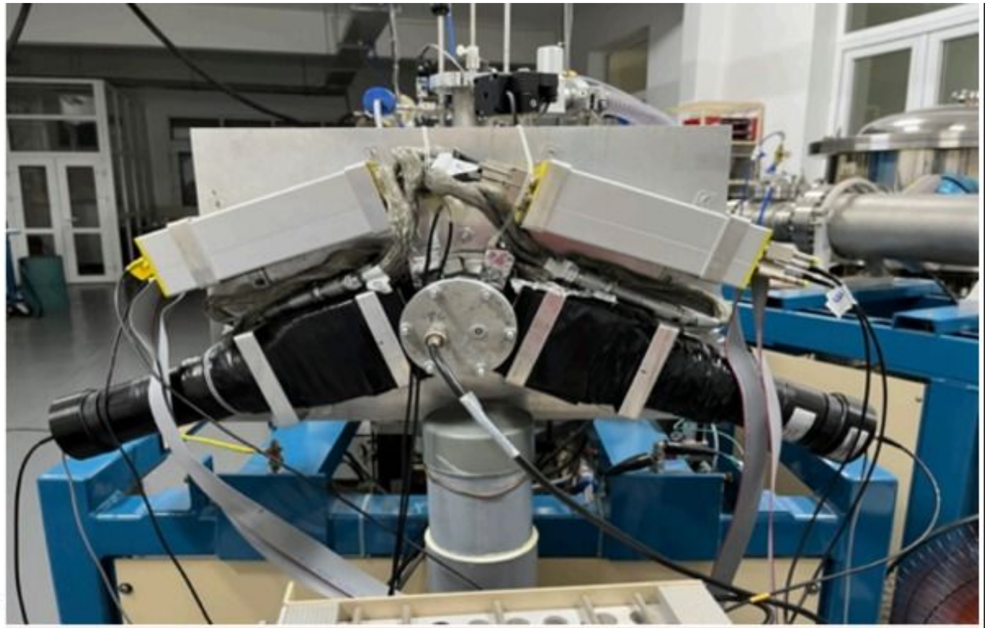
SPARE



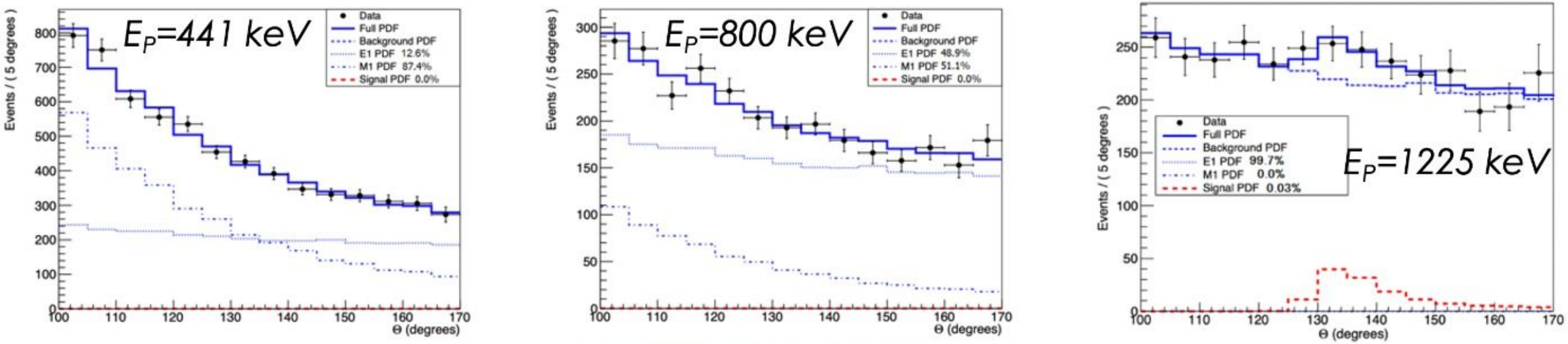
Pelletron Beamline, analysis beamline
Terminal Voltage: 1.7 MV
Ion: H^+, He^+, C^+, Si^+, Cu^+, Au^+...
Beam Current: 1nA – 2microA

Main tasks:
RBS
PIXE
Ion implantaion
Astro nuclear reactions

ISMD2023



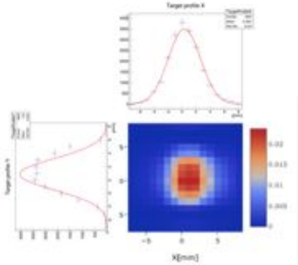
2 arm spectrometer (ATOMKI like)
ATOMKI group participants
^{7}Li and ^{11}B target used.

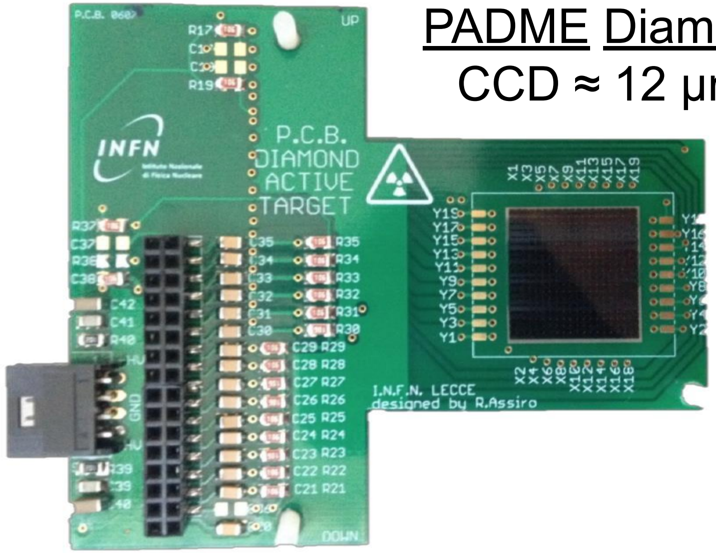


Universe **2024**, *10*(4), 168;

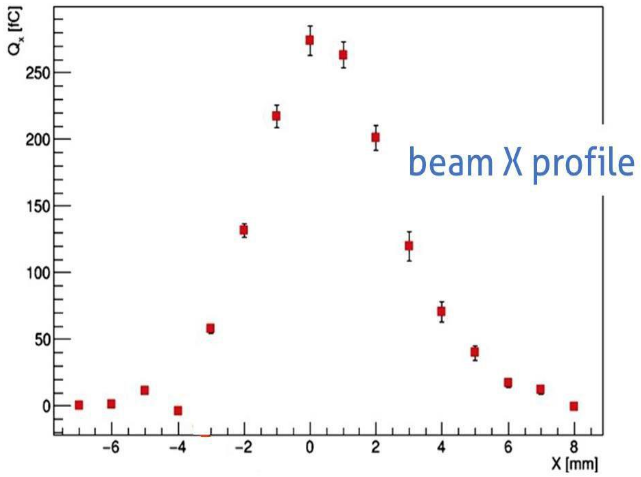
Anomaly confirmed at 1225 KeV E_p. Not observed for lower bombarding energies.

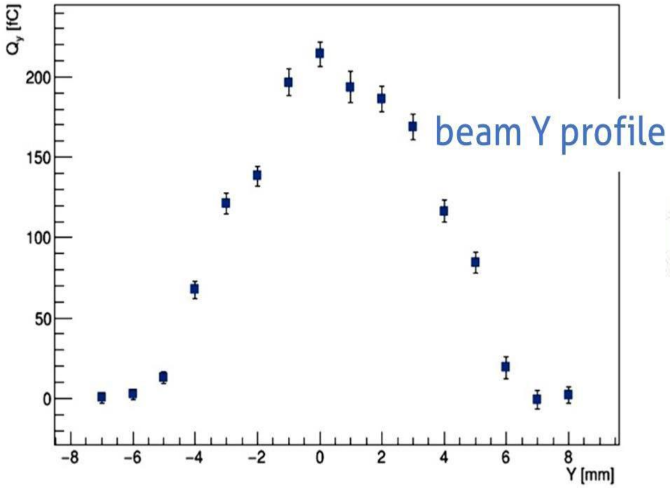
Active target

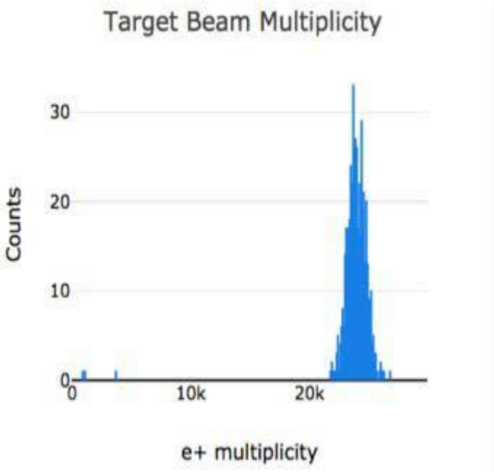


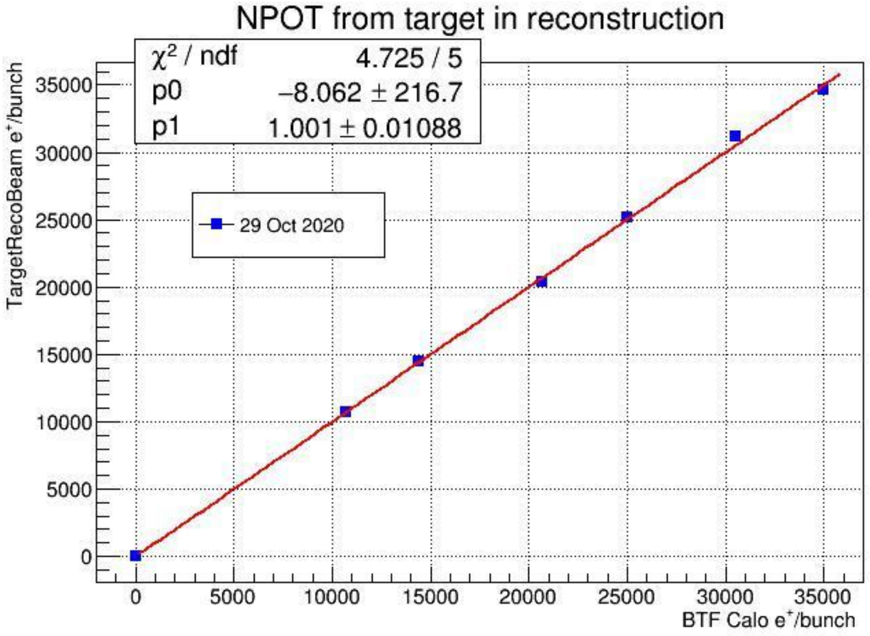


PADME Diamond
CCD ≈ 12 μm



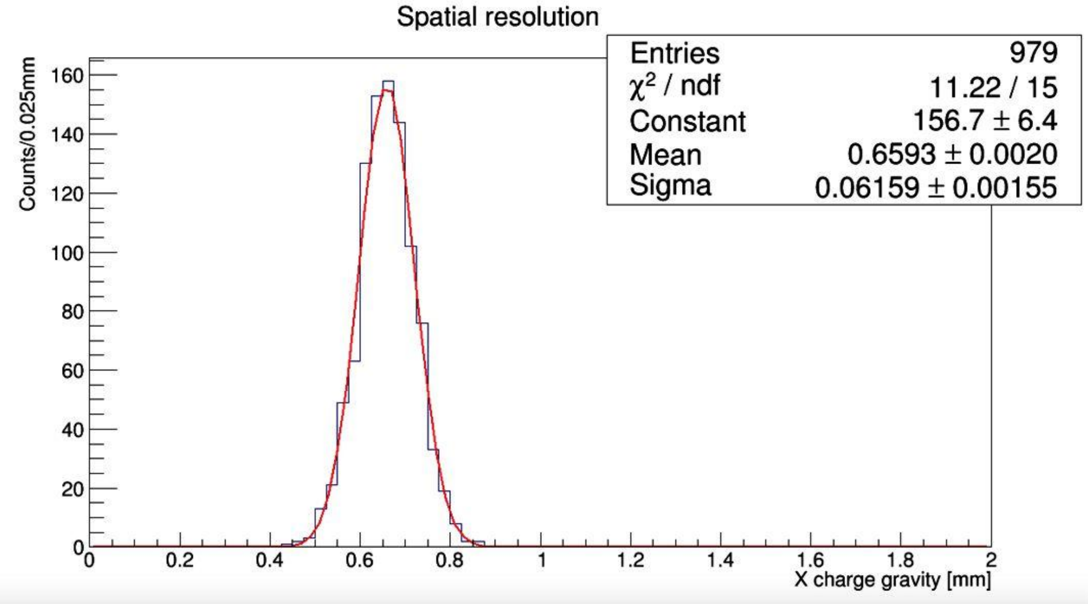




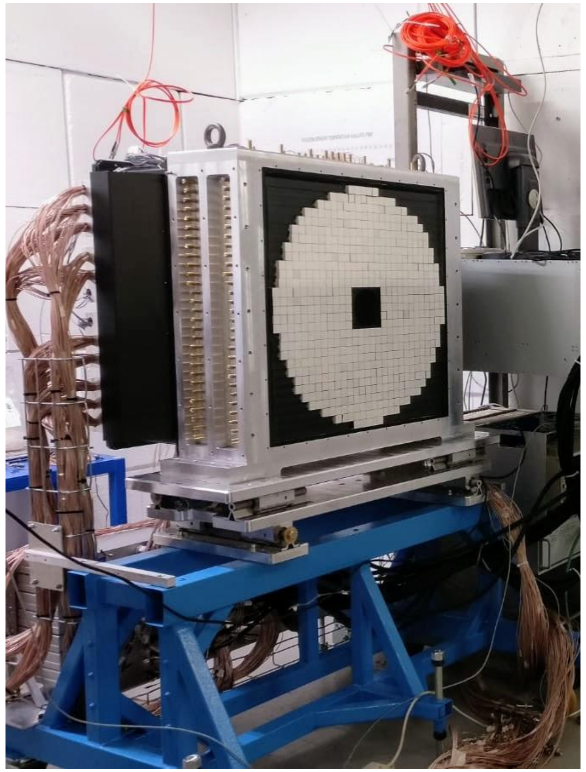


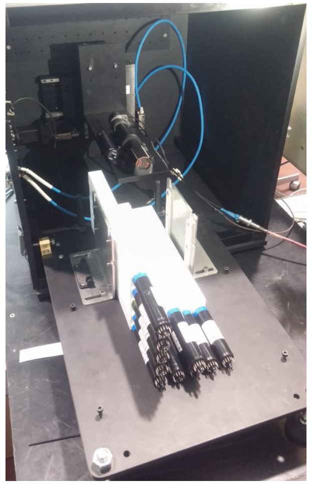
Polycrystalline diamonds

- 100 μm thickness:
- 16 × 1 mm strip and X-Y readout in a single detector
- Graphite electrodes using excimer laser



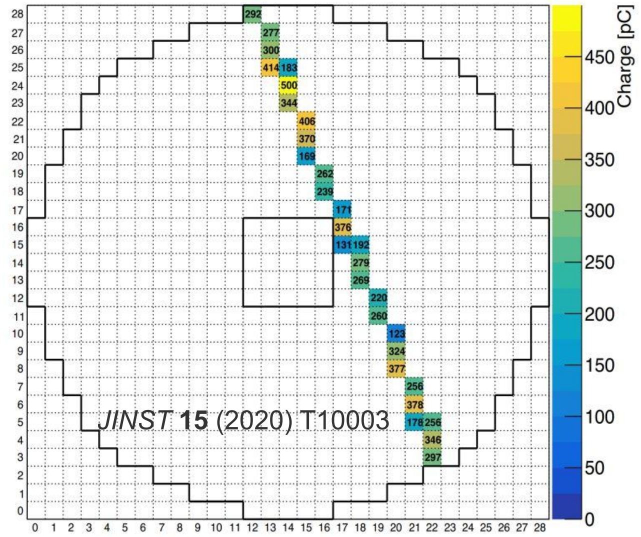
Calorimeters



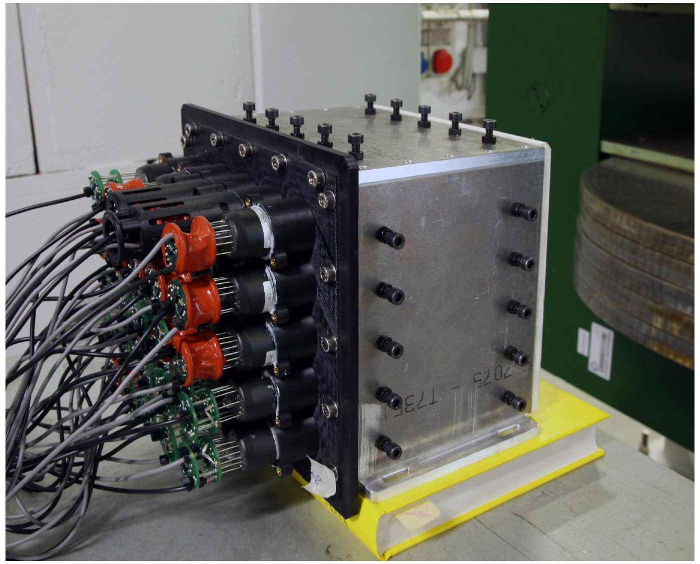


ECAL: The heart of PADME

- 616 BGO crystals, 2.1 x 2.1 x 23 cm^3
- BGO covered with diffuse reflective TiO_2 paint
  - additional optical isolation: 50 – 100 μm black tedlar foils



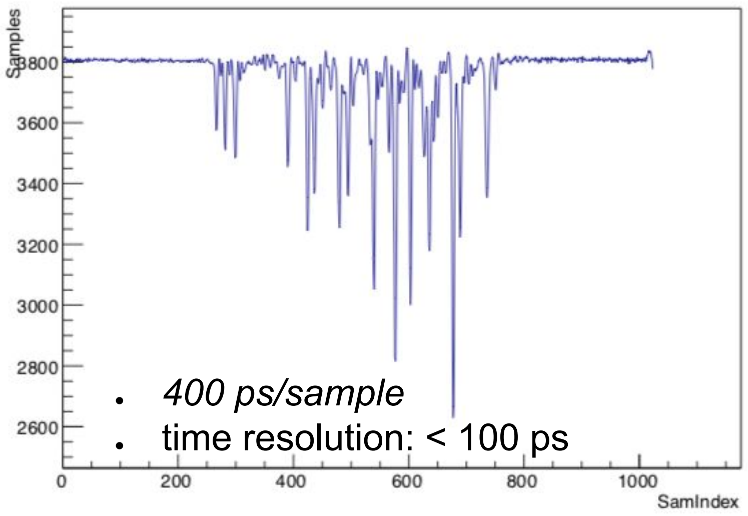
- Calibration at several stages:
  - BGO + PMT equalization with ^{22}Na source before construction
  - Cosmic rays calibration using the MPV of the spectrum
  - Temperature monitoring



Small Angle Calorimeter (SAC)

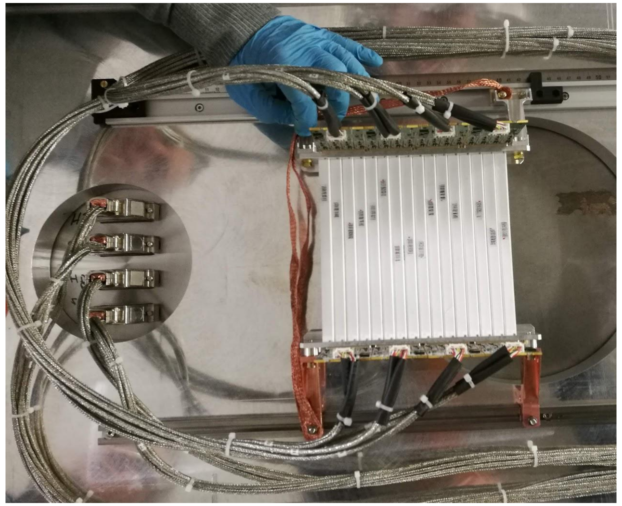
- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Dimensions of each crystal: 3 × 3 × 14 cm^3
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV with custom dividers
- Angular acceptance: [0,19] mrad

Recorded bunch

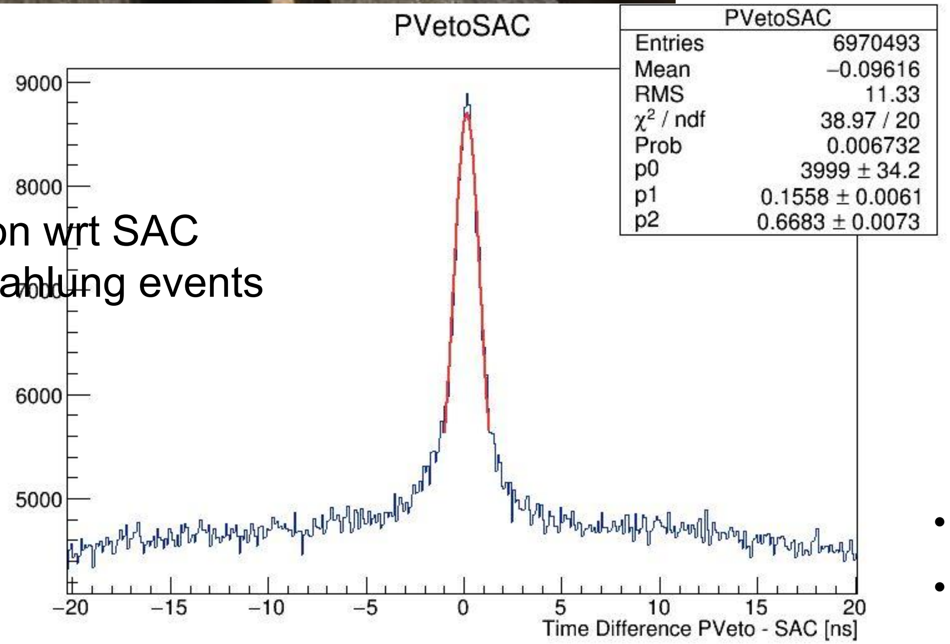


Charged particle detectors

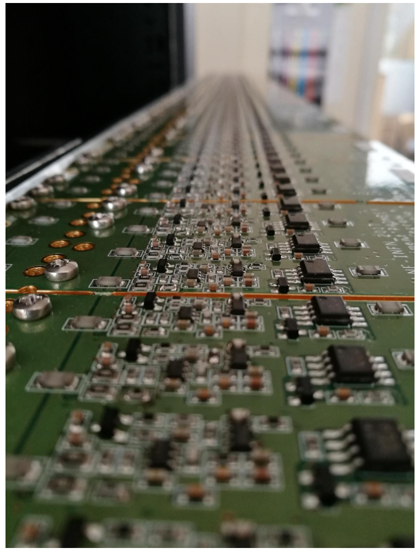
- Three sets of detectors detect the charged particles from the PADME target (at E_{beam} = 550 MeV):
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2) scintillator-WLS-SiPM RO channels
- Segmentation provides momentum measurement down to ~ 5 MeV resolution



Time calibration wrt SAC
Bremsstrahlung events



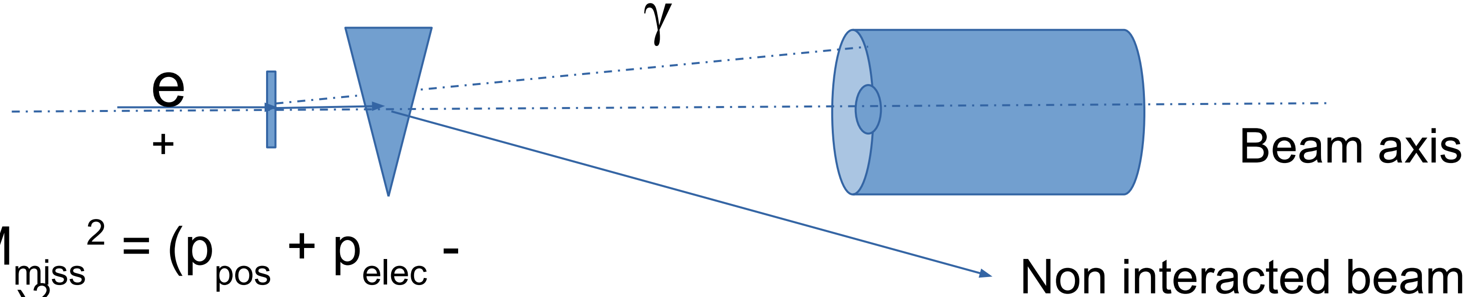
- Custom SiPM electronics, Hamamatsu S13360 3 mm, 25μm pixel SiPM
- Differential signals to the controllers, HV, thermal and current monitoring



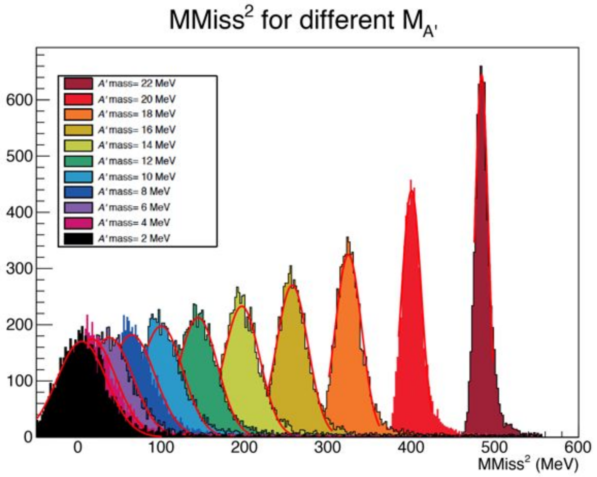
- Online time resolution: ~ 2 ns
- Offline time resolution after fine T_0 calculation – better than 1 ns

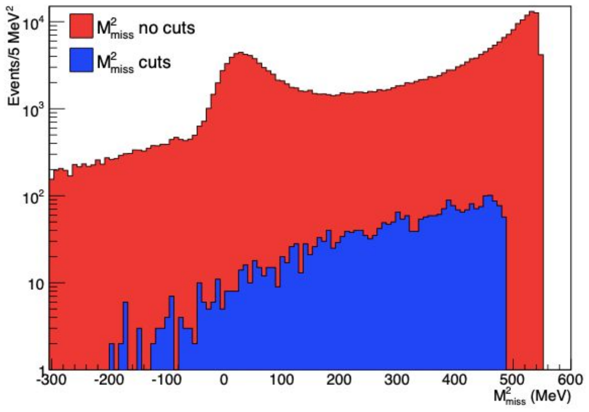
Physics case of PADME

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



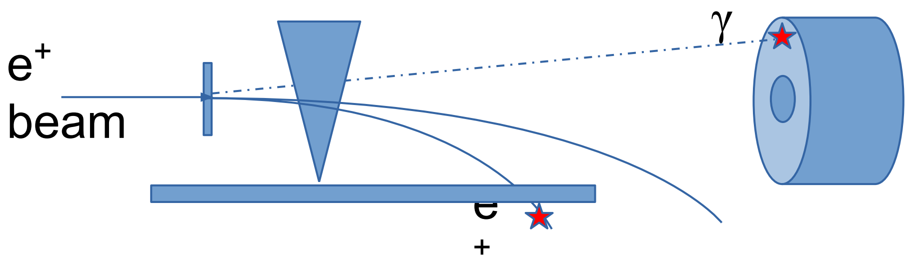
$M_{miss}^2 = (p_{pos} + p_{elec} - p)^2$

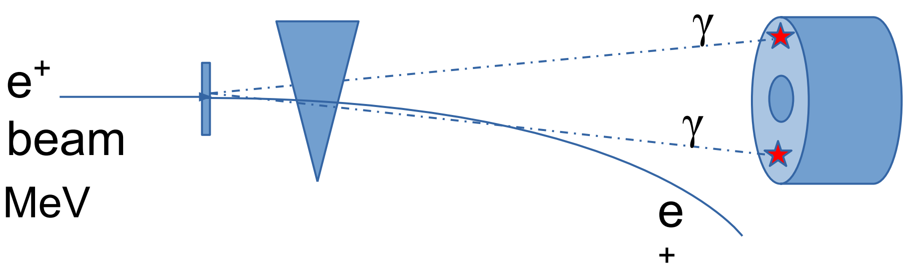


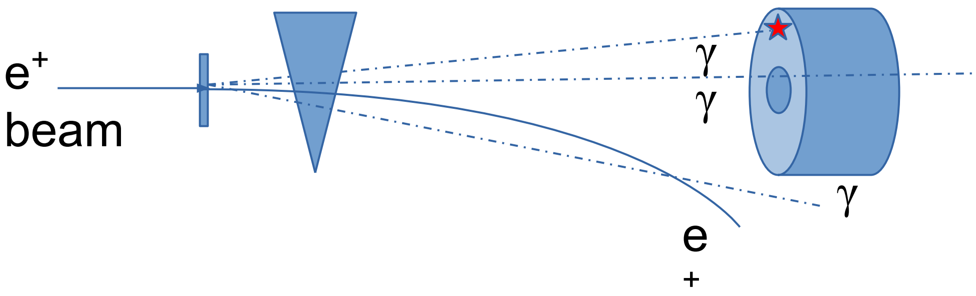


Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb	
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb	E_γ > 1MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, E_γ > 1MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP, E_γ > 1MeV

- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection
- 2 photon annihilation
  - Peaks at $M_{miss} = 0$
  - Quasi symmetric in gamma angles for E_γ > 50 MeV
- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
- Radiative Bhabha scattering
  - Topology close to bremsstrahlung



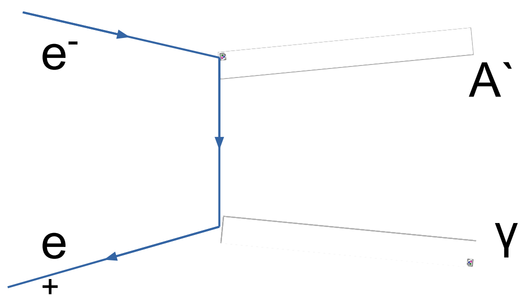


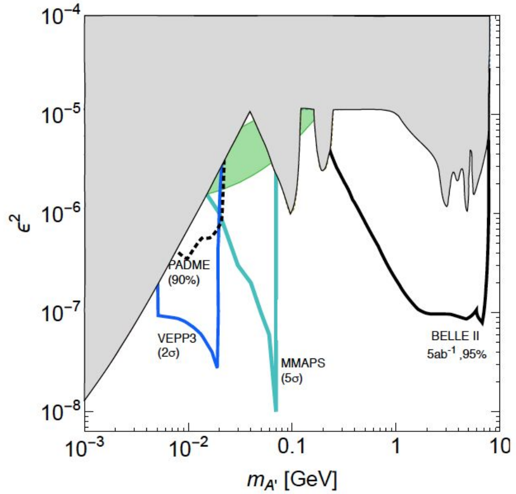


Summary: NP @ PADME

Dark Photon A’

arXiv:1608.08632v1





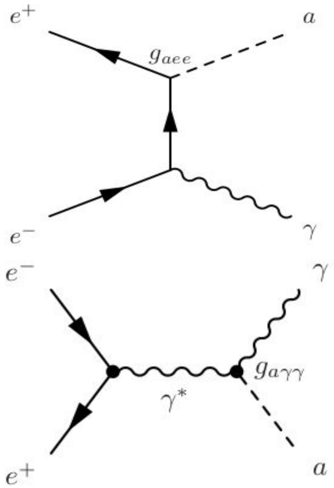
$e^+e^- \to \gamma A'$

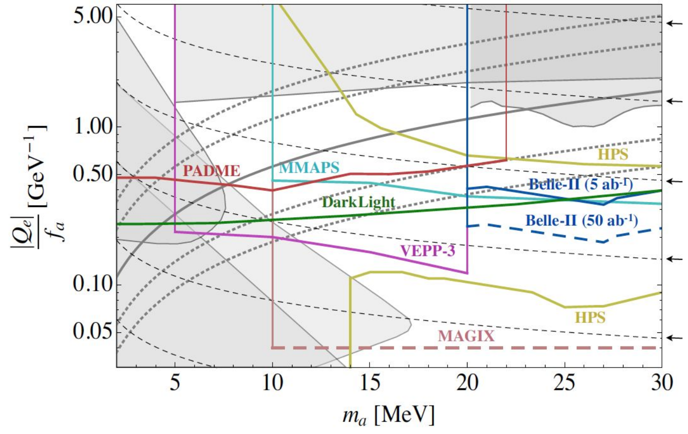
Visible, invisible decays:

$A' \to \chi\bar{\chi}, e^+e^-$

Axion Like Particles

JHEP 07 (2018) 092





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

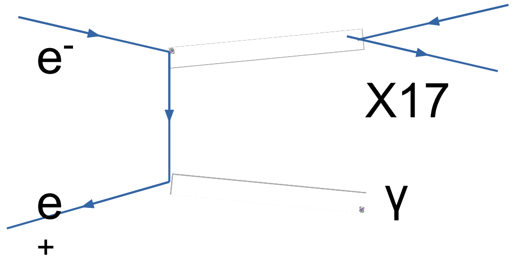
ALPs final states:

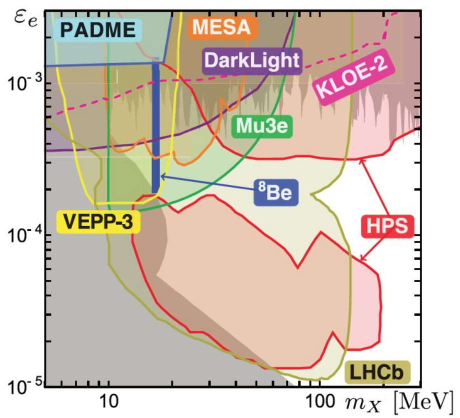
$a \to \chi\bar{\chi}, e^+e^-, \gamma\gamma$

arXiv:2012.07894

BE anomaly - X boson

PRD 95 (2017) 035017



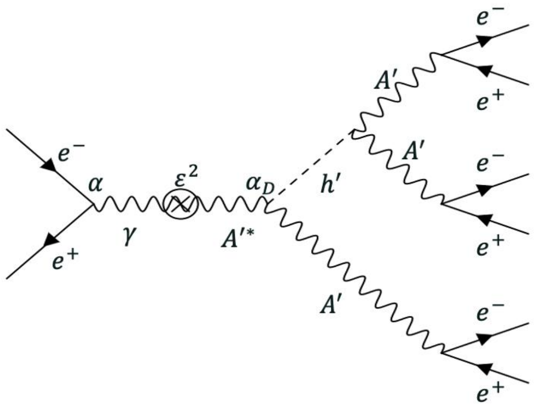


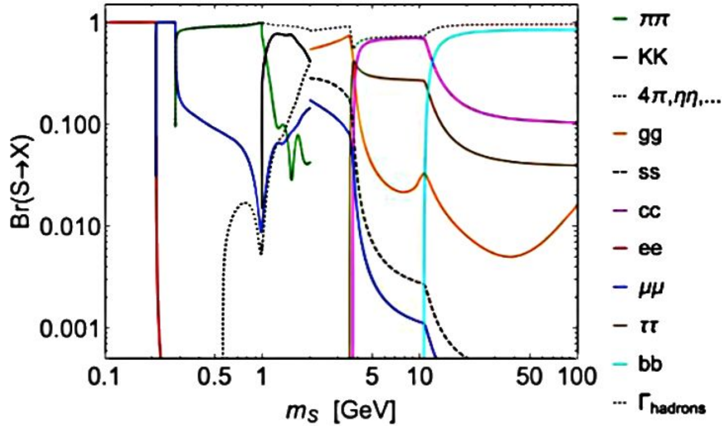
$e^+e^- \to \gamma X_{17}$

Final state X17→ee

Dark higgs

arXiv:2102.12143v1





dark higgs decay: $h' \to$

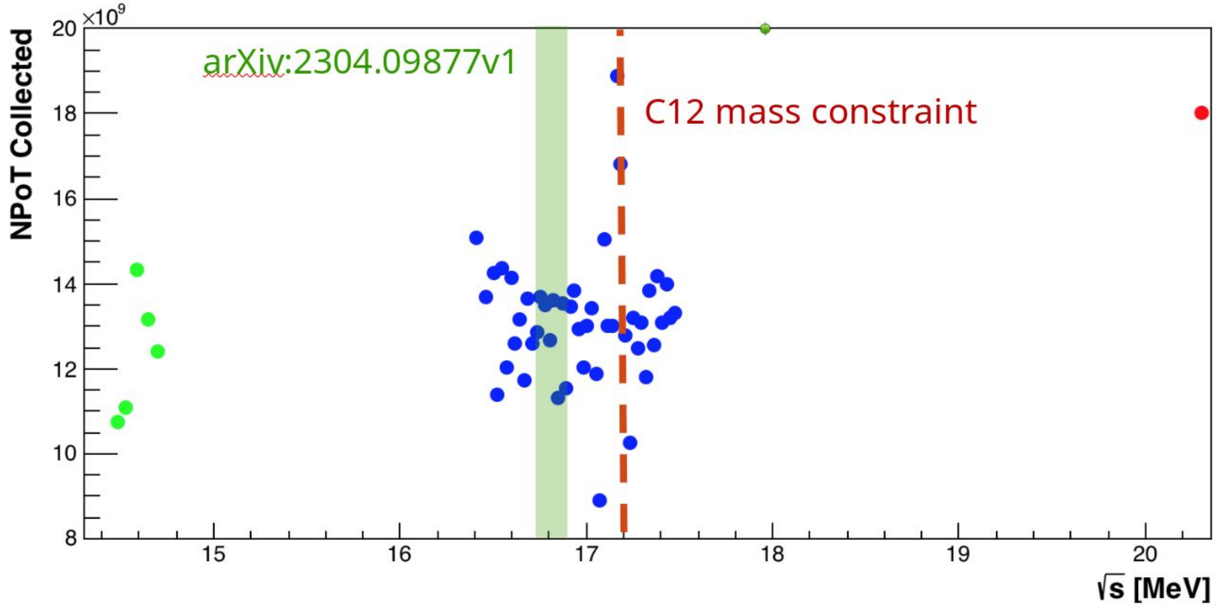
$A'A', A' \to e^+e^-, \chi\bar{\chi}$

Final state: $A'A'A' \to e^+e^- \; e^+e^- \; e^+e^-$

arXiv:2012.04754

Data taking

- Resonance scanning
  - 47 points in the range 263 MeV – 299 MeV
  - Spacing between the points: $\Delta E = 0.75$ MeV
  - Naive precision on M_{X17} ~ 20 KeV
- Off resonance data sets:
  - Above Resonance: 402 MeV: ~ 1.2E10 POT
  - Below Resonance: 205-211 MeV, 5 different energies, ~ 5E10 POT
- First selection aimed at $N(2cl)/N_{PoT}$ studies:
  - Provides information about the stability of the detector operation and acceptance during the data taking
  - 2 in time clusters in the $\Delta t < 5$ns in ECal
  - Energy and radius cuts, CoG consistency
  - Cluster energy vs angle correlation compatible with a 2 body final state.



- $E_{beam} = 402$ MeV