Searching for the X17 with the PADME experiment

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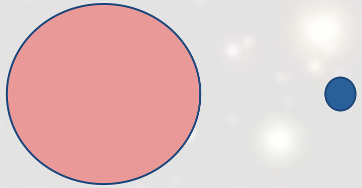
Outline

- PADME @ LNF
- Present status
- Prospects
- Conclusions

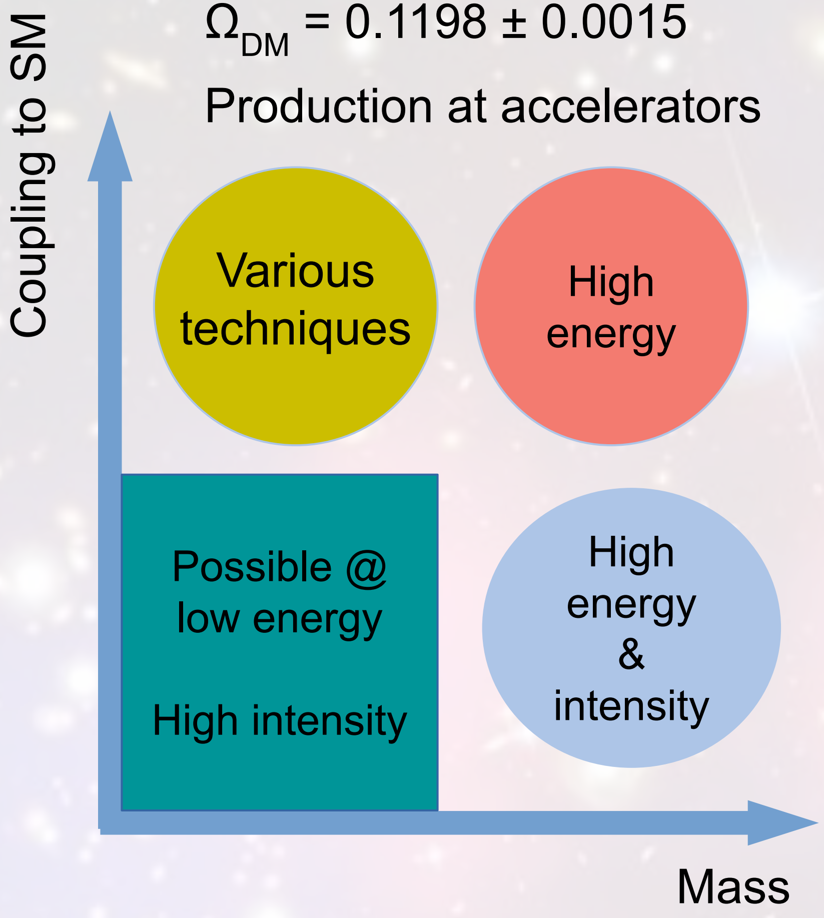
DARK MATTER

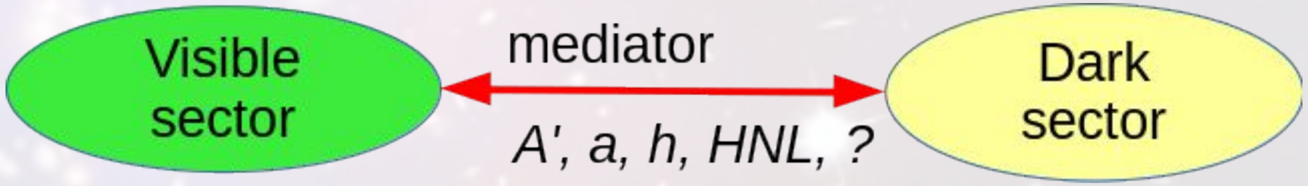


WIMP vs WISP

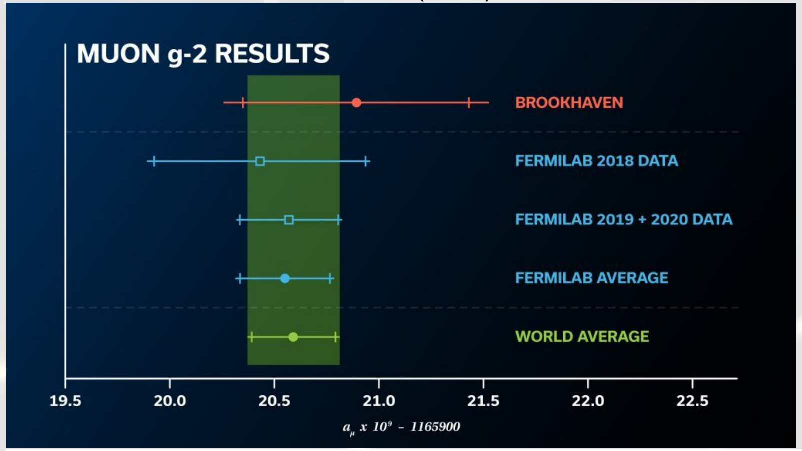
Ω_{DM} = 0.1198 ± 0.0015

Production at accelerators

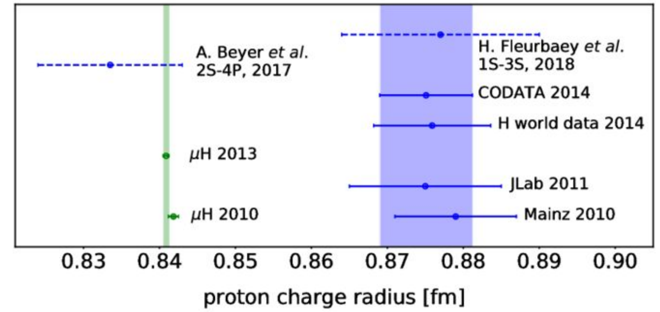


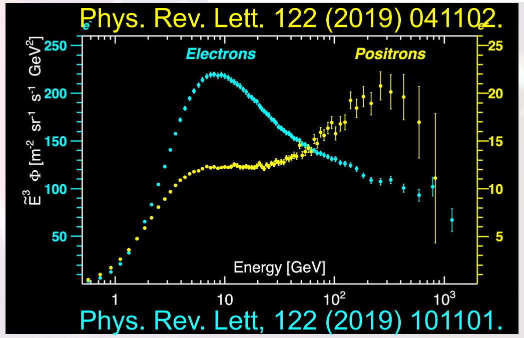


PRL 126 (2021) 14, 141801

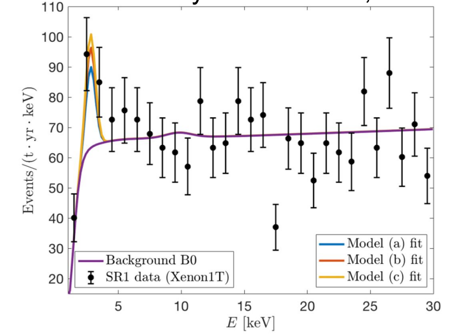


arXiv:1011.3519 [hep-ph]

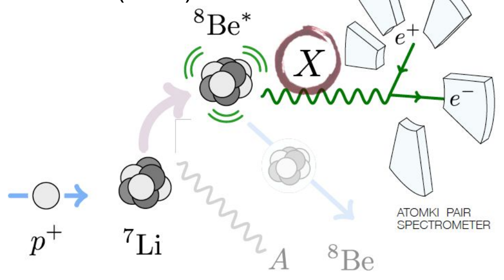




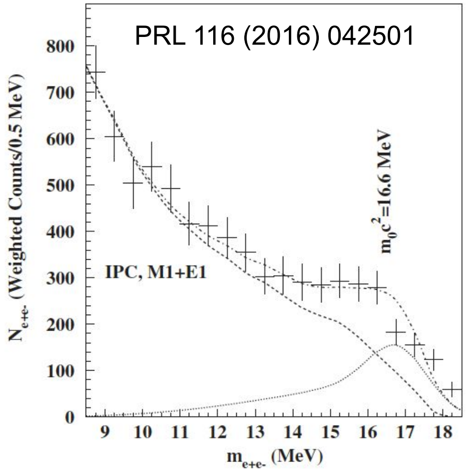
Phys. Rev. D 102, 072004



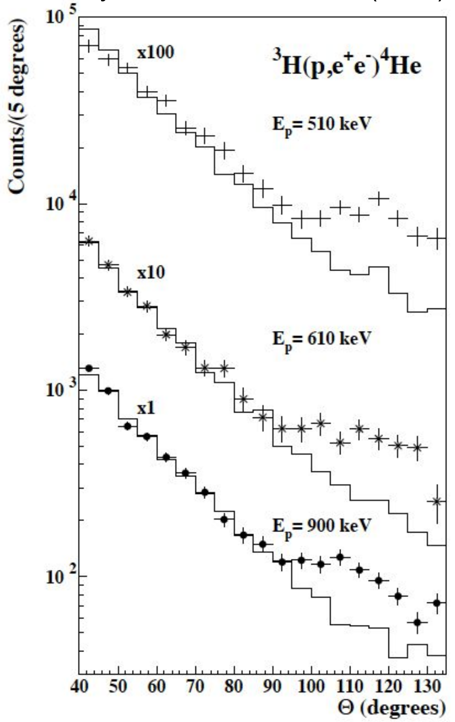
PRL 116 (2016) 042501



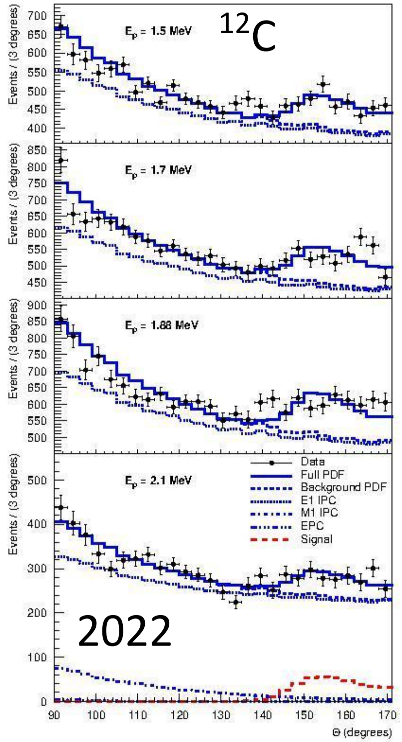
X17 anomaly

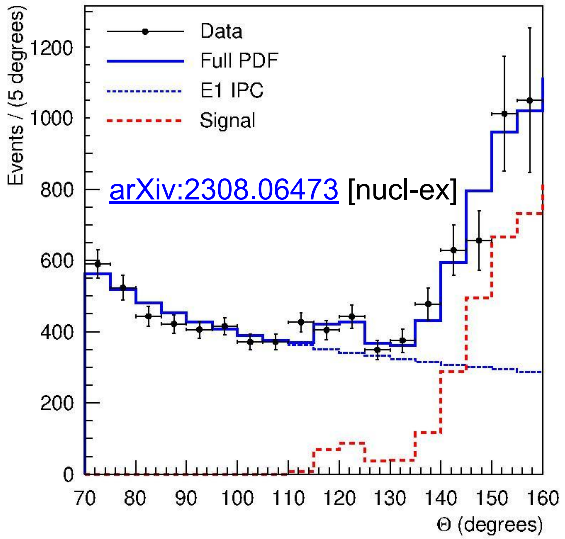


Phys.Rev.C 104, 044003 (2021)

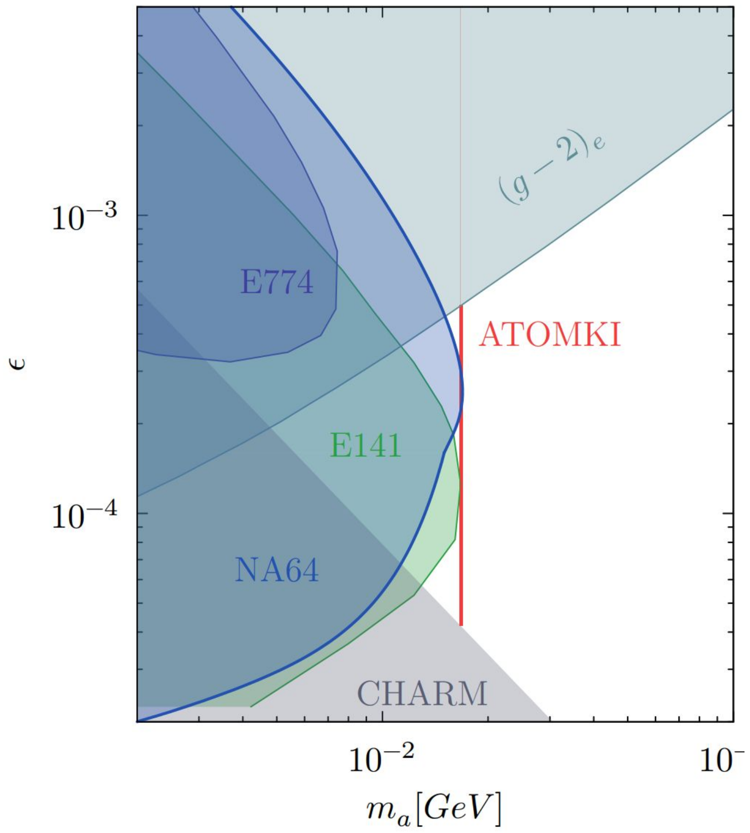


Phys. Rev. C 106, L061601 (2022)

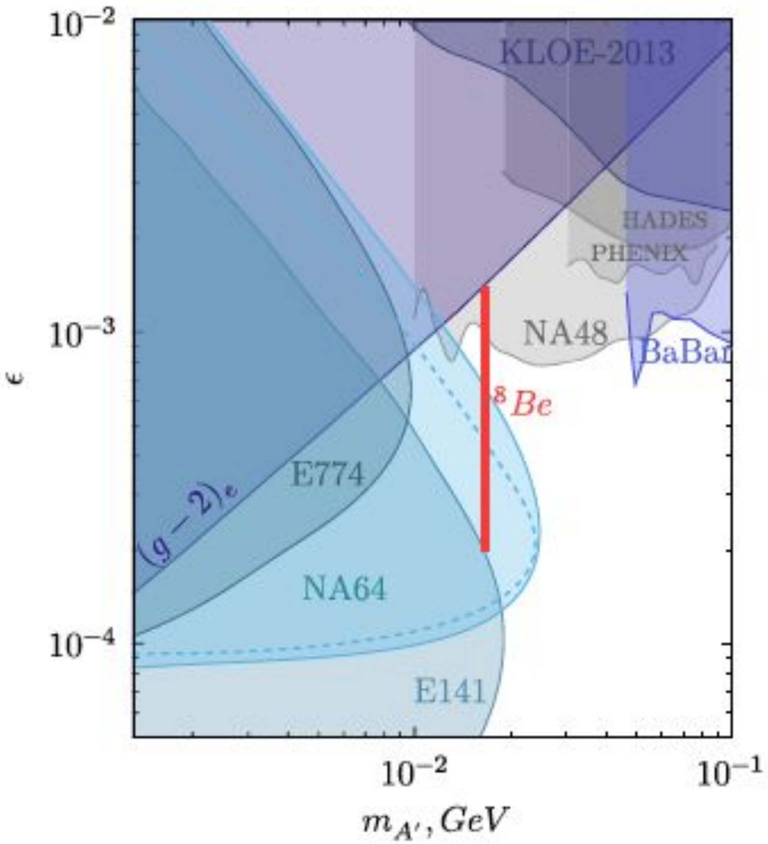




Phys. Rev. D 101, 071101(R)

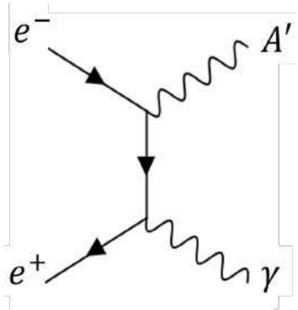


arXiv:2104.13342 [hep-ex]



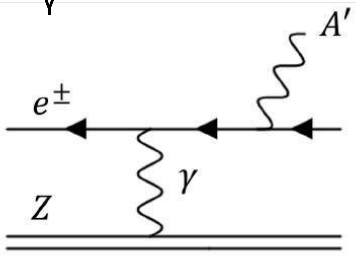
- Similar physics observables as in the ^{8}Be, ^{4}He and ^{12}C experiments
  - 2 leptons in the final state
  - Kinematics properties determined by the mass of the X particle (2 body decays)
  - M_{X17} = 16.85 ± 0.04 MeV (Phys. Rev. D 108, 015009)

New light particles in e^+ on target annihilation

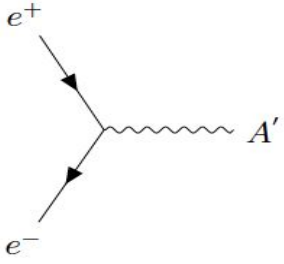


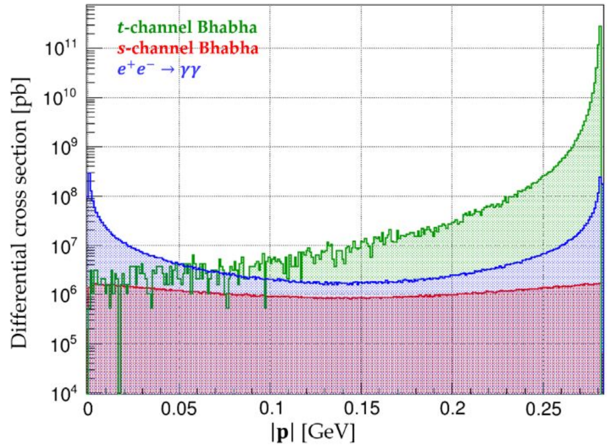
<u>Accelerated e^+ impinging on a thin target</u>

- **Associate production: $e^+ + e^- \to \gamma + X$**
  - Measurement of the recoil photon in the calorimeter
  - Suppress all the background with at least 1 photon in the final state
  - Search for bumps in $M^2_{miss} = (P_{e+} + P_{e-} - P_{\gamma})^2$ distribution



- **Bremsstrahlung: $e^+ + Z \to e^+ + Z + X$**
- **Resonant production: $e^+ + e^- \to X$**
  - $M^2_{inv} = s \sim 2\, E_{beam}\, m_e$
  - No additional particle in the final state - without tagged primary positrons X should decay to provide a visible signature: $X \to e^+e^-$
  - Scan the excess of e^+e^- final states as function of E_{beam} (i.e. M_{inv} or $\sqrt{s}$)

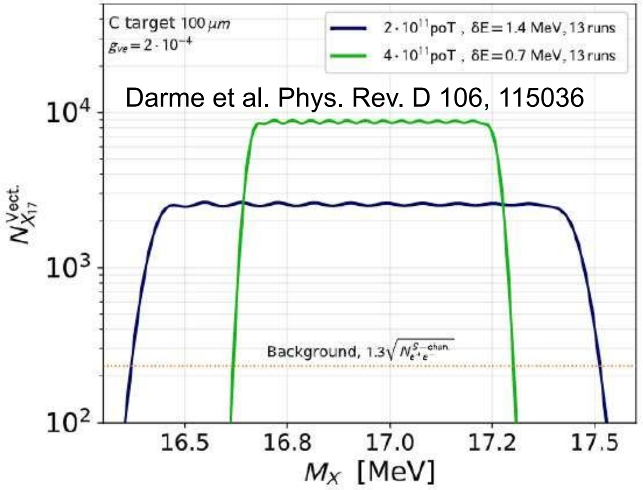




$$\mathcal{N}^{\text{Vect.}}_{X_{17}} \simeq 1.8 \cdot 10^{-7} \times \left(\frac{g_{ve}}{2 \cdot 10^{-4}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$

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

See Giovanni Grilli di Cortona talk



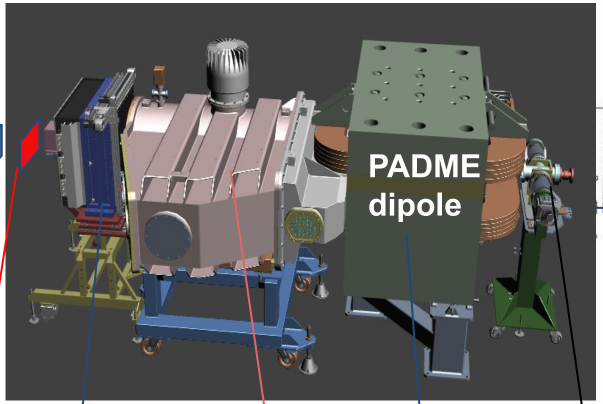
Measurement of e^+e^- final states at different $\sqrt{s}$

$$\frac{N(e^+e^-)}{N_{PoT}}, \quad \frac{N(e^+e^- + \gamma\gamma)}{N_{PoT}}, \quad \frac{N(e^+e^-)}{N(\gamma\gamma)}$$

Different strategies

Different systematics

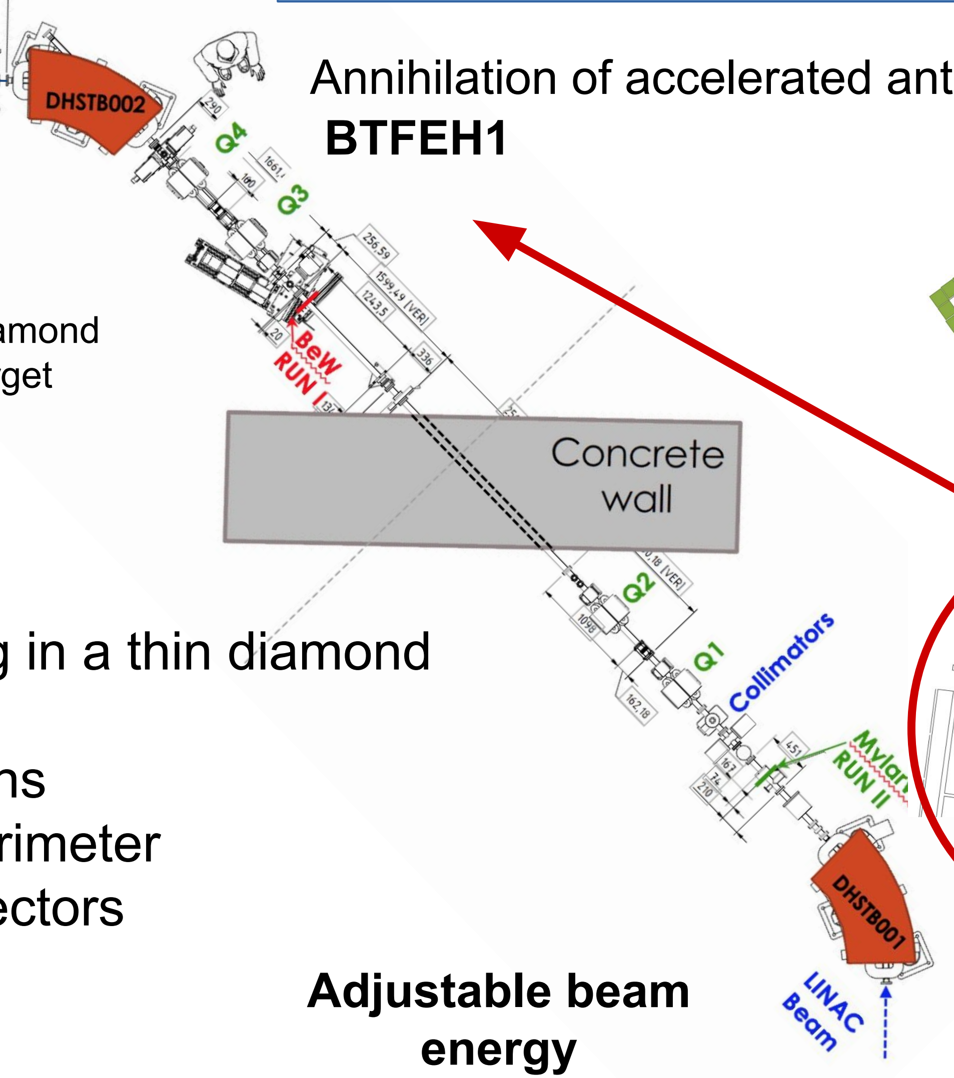
PADME: Positron on target annihilation

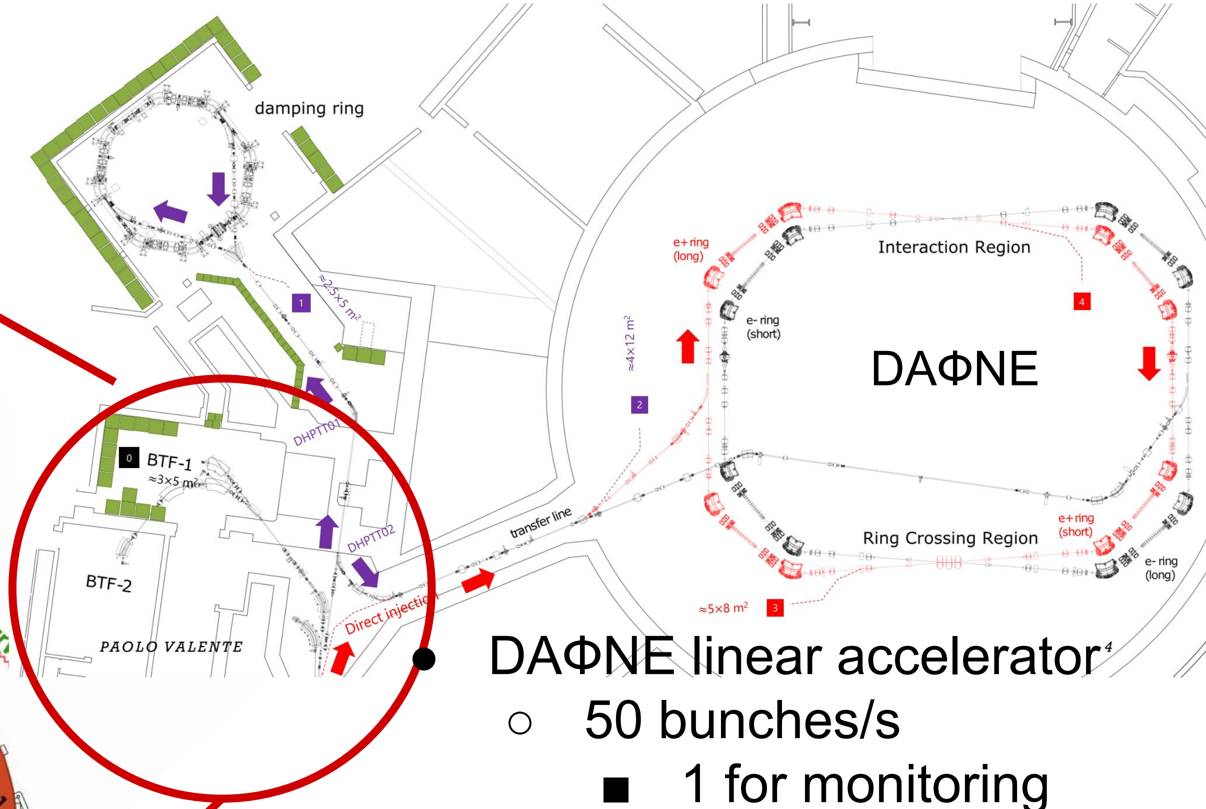


Combination of fixed target and collider techniques

Annihilation of accelerated antiparticles with matter

BTFEH1





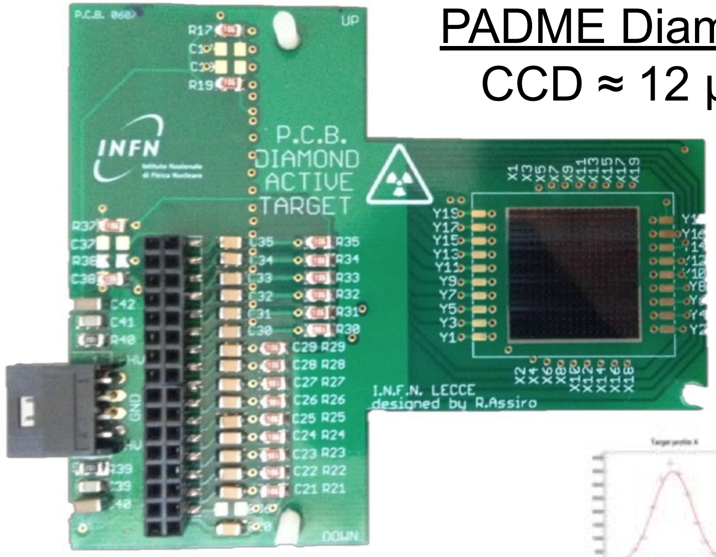
- Accelerated e^+ interacting in a thin diamond active target
- Final states: e^+, e^-, photons
  - Electromagnetic calorimeter
  - Charged particle detectors
- Beam measurement
  - Timepix
  - Leadglass

Adjustable beam energy
100 MeV - 500 MeV

- DAΦNE linear accelerator
  - 50 bunches/s
    - 1 for monitoring
  - e+/e-
  - O(300) ns bunch duration
- BTF hall beam spot: 1 mm
- Beam divergence: 1-1.5 mrad

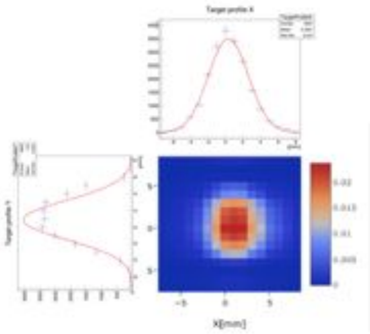
Active target

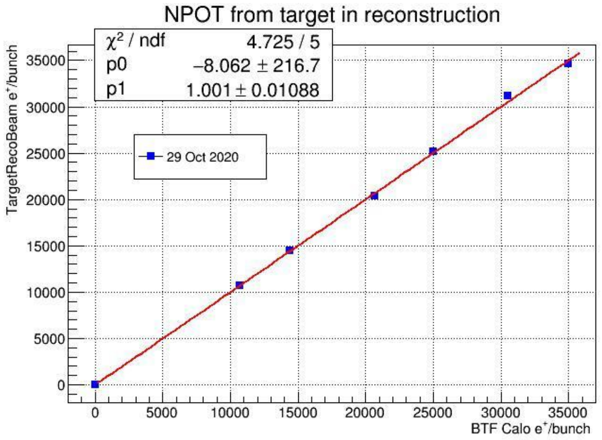
Charged particle detectors



PADME Diamond
CCD ≈ 12 µm

JINST 12 (2017) 02, C02036



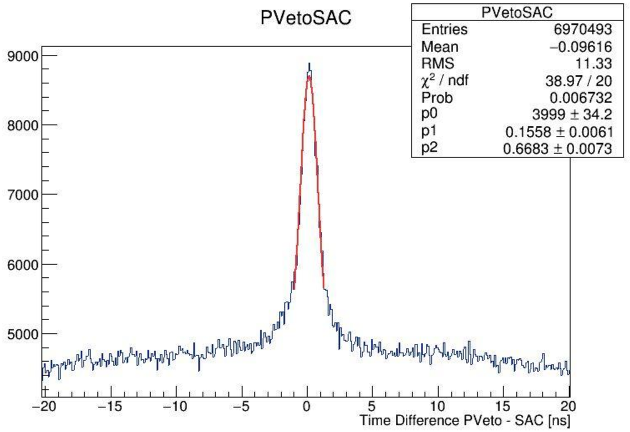


Polycrystalline diamonds

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

Extruded plastic scintillators with WLS fibers

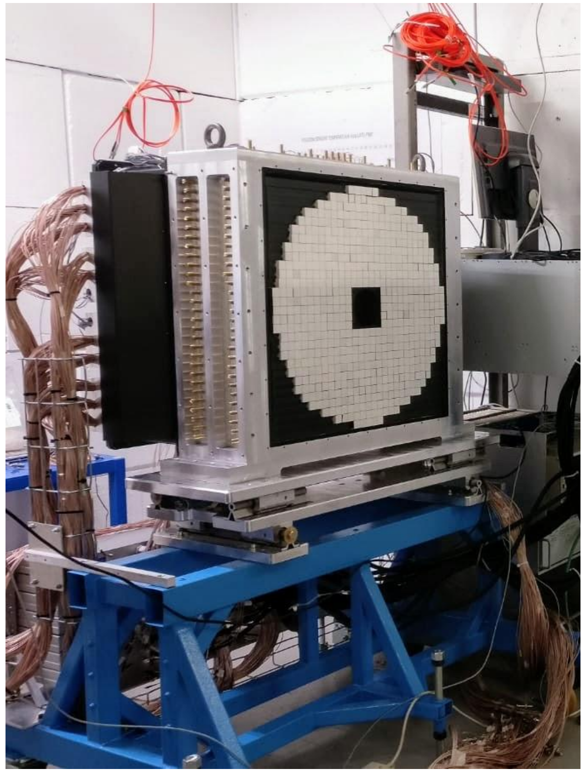
- Three sets of detectors detect the charged particles from the PADME target (at E_{beam} = 550 MeV):
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2) scintillator-WLS-SiPM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

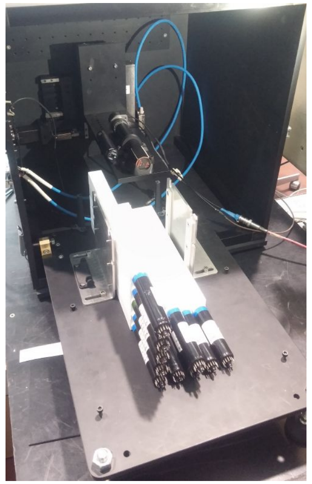


JINST 19 (2024) 01, C01051

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

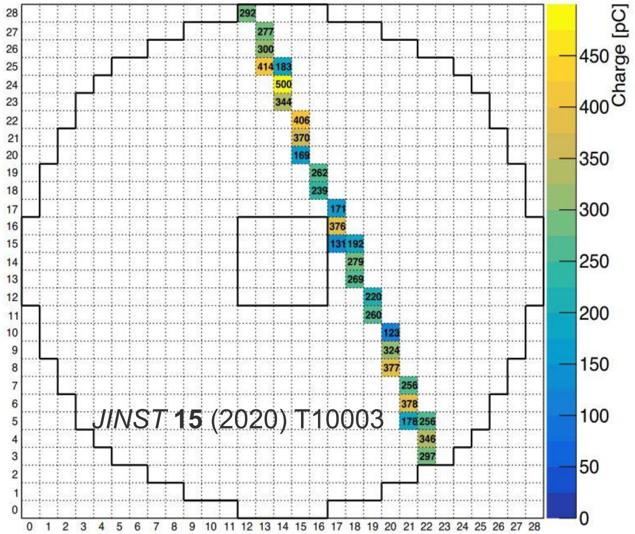
Calorimeters





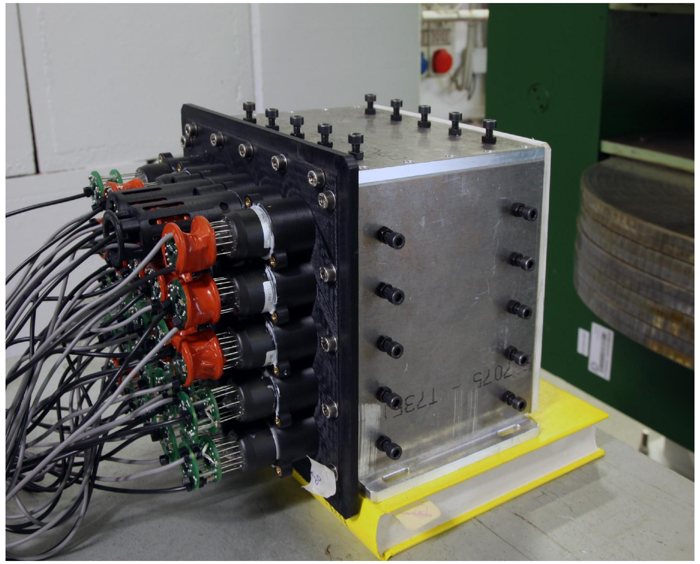
ECAL: The heart of PADME

- 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



JINST 15 (2020) 10, T10003

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

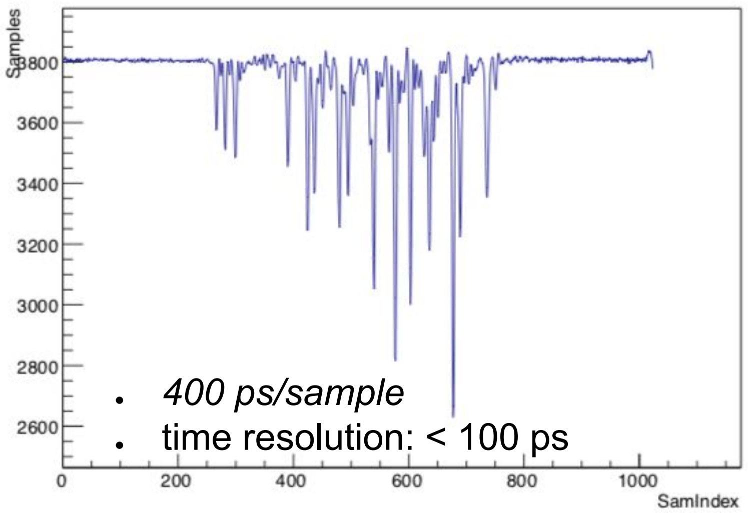


Small Angle Calorimeter (SAC)

- 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

Nucl.Instrum.Meth.A 919 (2019) 89-97

Recorded bunch



- *400 ps/sample*
- time resolution: < 100 ps

PADME RUN I and II

Run I and PADME commissioning

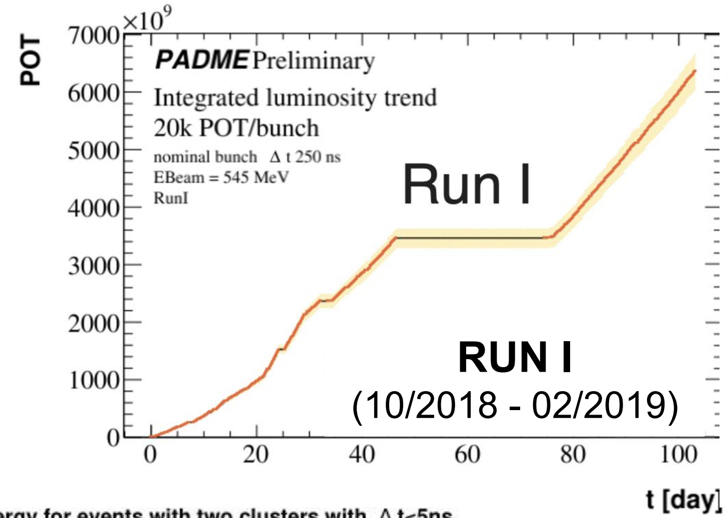
- started in Autumn 2018 and ended on February 25th
  - ~7 x 10^{12} PoT recorded with secondary beam
  - PADME DAQ, Detector, beam, collaboration commissioning
  - Data quality and detector calibration
- PADME test beam data
  - July 2019, few days of valuable data
    - Certification of the primary beam
  - Detector performance/calibration checks
  - Primary beam with E_{beam} = 490 MeV

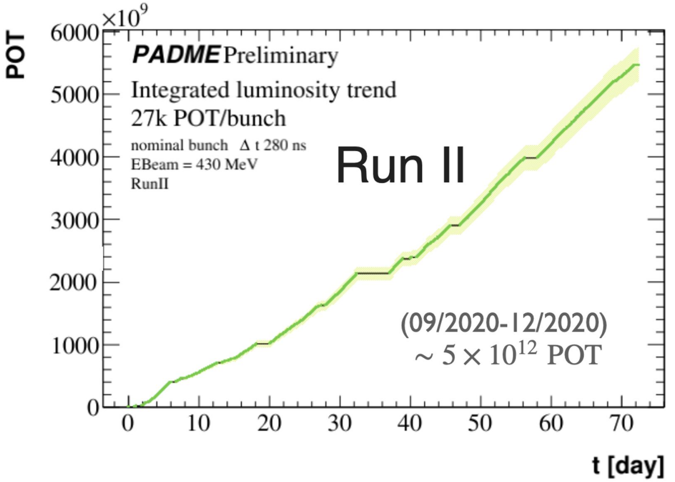
RUN II: primary beam

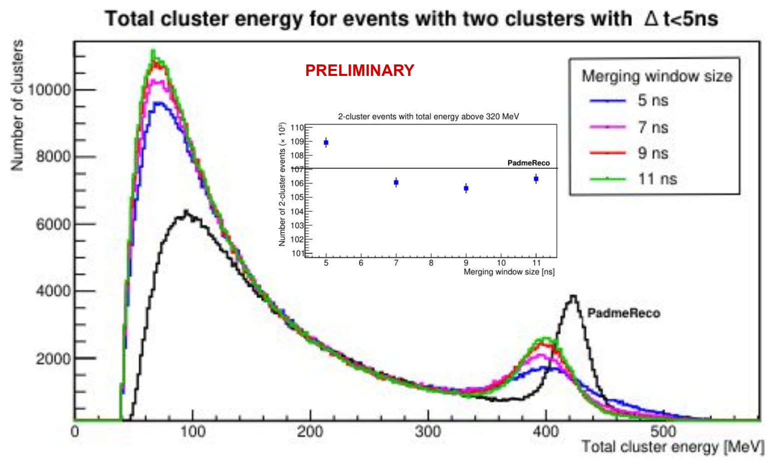
- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^+ on target
  - E_{beam} = 430 MeV

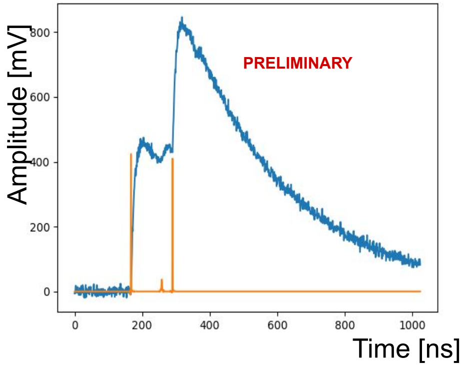
20 000 - 30 000 e^+ per bunch → pileup in the downstream detectors →new reconstruction techniques

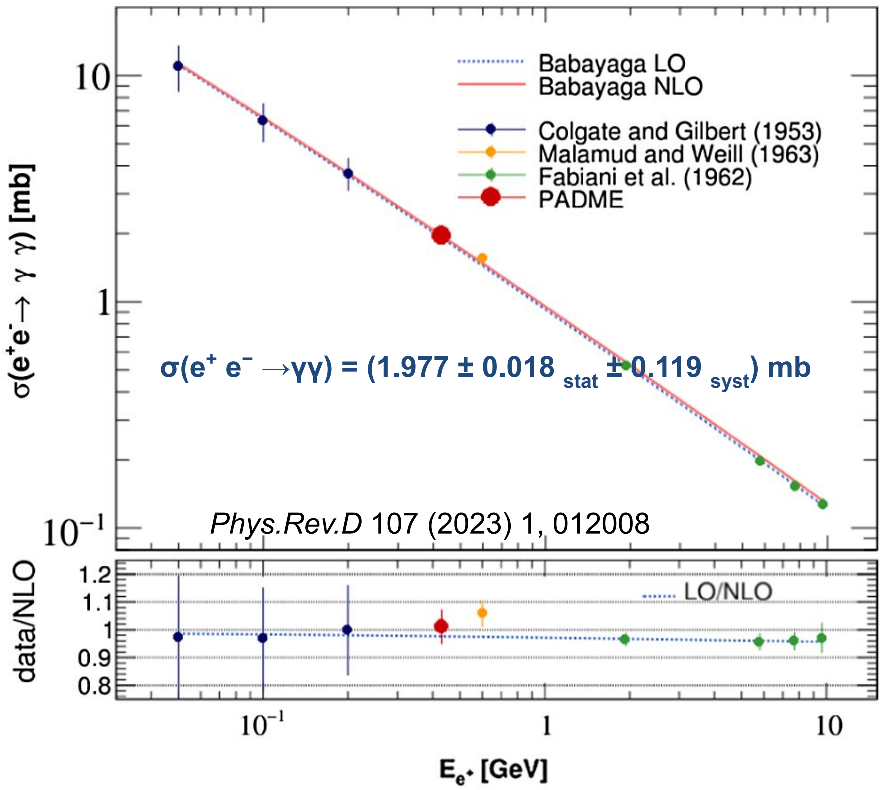
JINST 17 (2022) 08, P08032



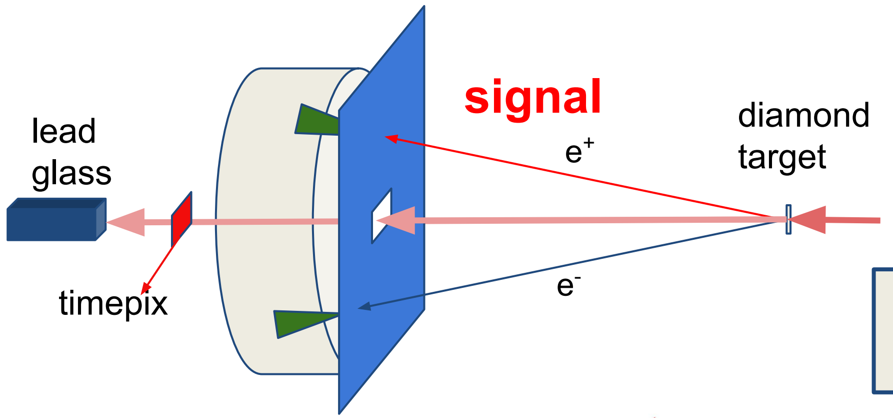






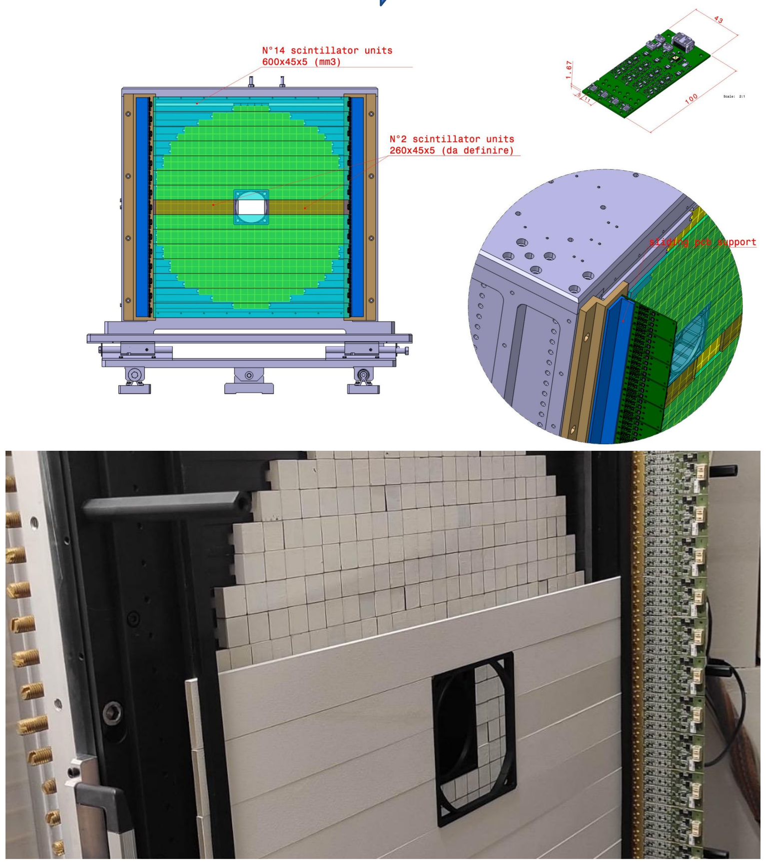


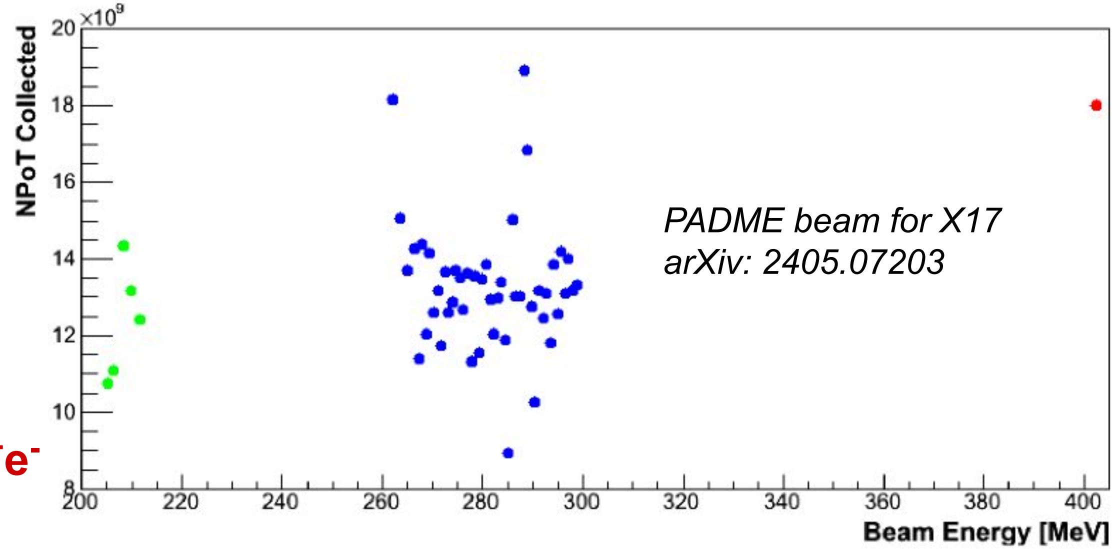
PADME RUN III: Resonant X17 production



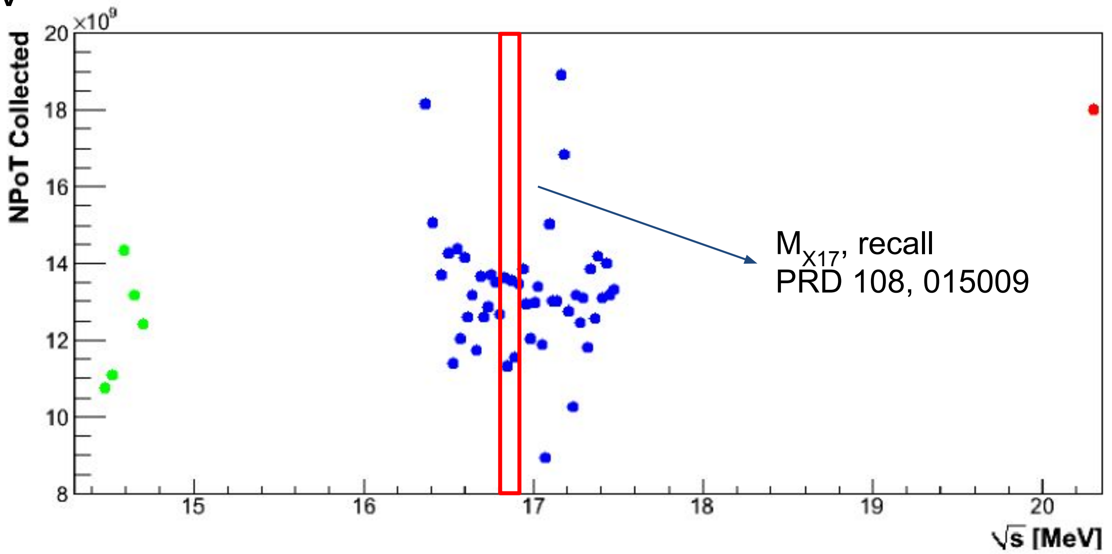
Running with no magnetic field in PADME dipole

$e^+e^- \rightarrow X17 \rightarrow e^+e^-$



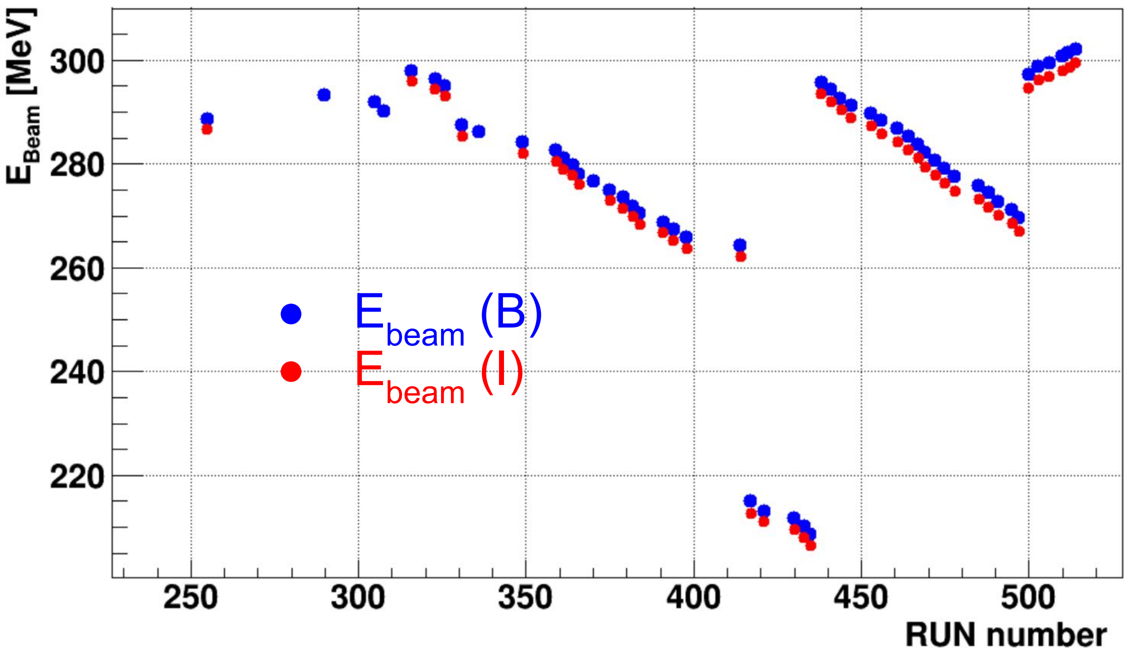


- On-shell production of X17
- Scan and search for a change in **$\sigma(e^+e^- \rightarrow e^+e^-)$ as function of $\sqrt{s}$**
- 47 points, 263 MeV < E_{beam} < 299 MeV
  - 16.4 MeV < M_{X17} < 17.5 MeV
  - Energy step: 0.7 MeV
  - Mass step: ~ 20 keV
- 5 points below resonance
  - 205 MeV < E_{beam} < 211 MeV
- 1 point with E_{beam} = 402 MeV
- Low (compared to RUN I & II) beam multiplicity - O(3000) e^+ / bunch



Collected ~ 6 x 10^{11} PoT, > 10^{10} PoT per scan point

Probing X17 in resonant production



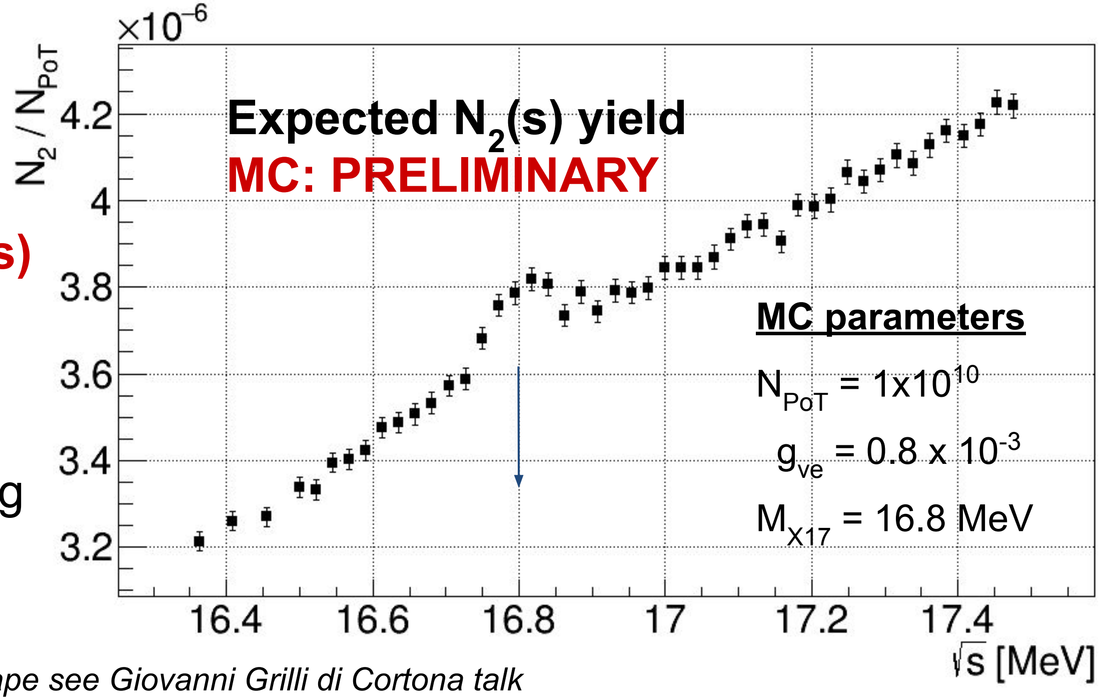
- Beam energy monitoring
  - Hall probe of DHSTB001 (dipole to BTFEH1)
    - P_{beam} [MeV] ~ 0.0551 x B [G]
  - Current of DHSTB001 coils
    - Residual magnetization, variable during data taking
- Beam energy known to 1 % ⇒ systematics δM_{X17} ~ 30 keV
- Beam energy spread - defined by collimators and measured with no-target runs (no Coulomb scattering)
  - BES ~ 0.25 %

- PADME RUN III strategy: measure all two cluster events $N_2(s)$ and normalize to number of positrons on target, i.e discriminate

$$N_2(s) = N_{PoT}(s) \times [\, B(s) + S(s; M_{X17}, g)\ \varepsilon_S(s)\,] \text{ vs } N_2(s) = N_{PoT}(s) \times B(s)$$

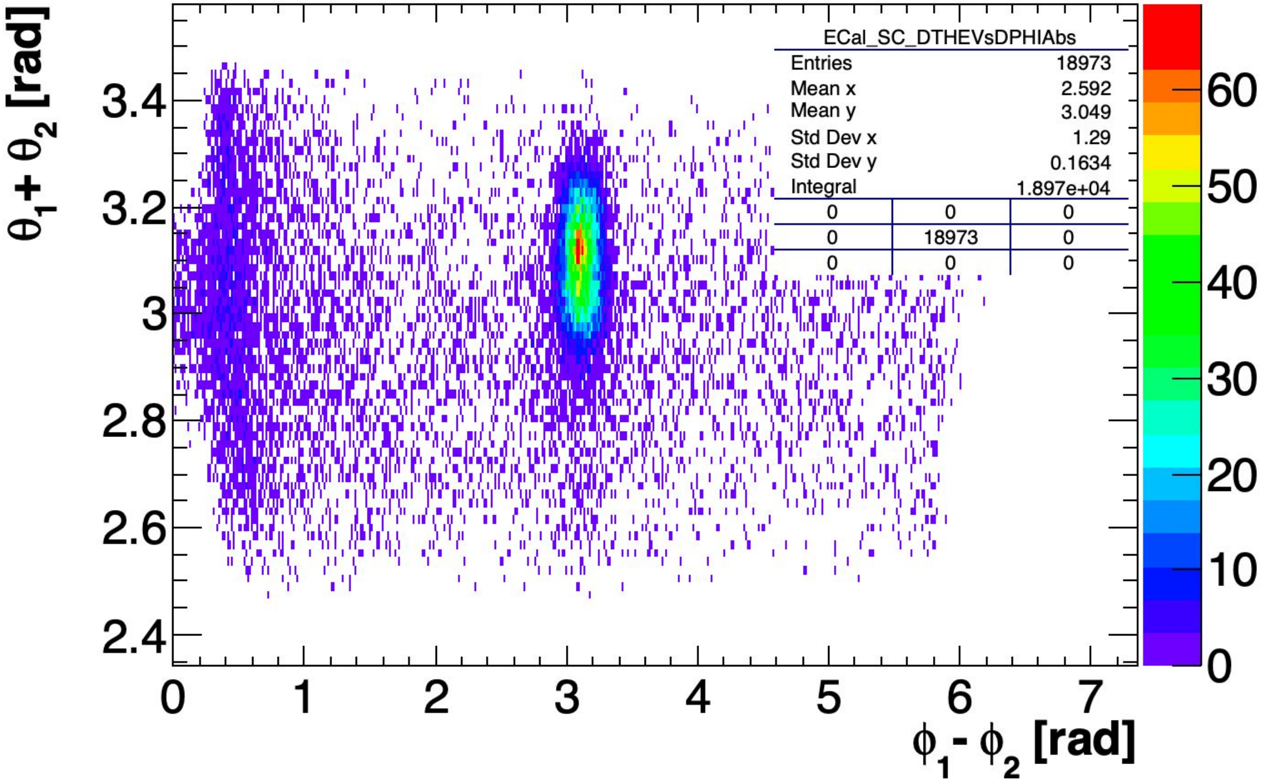
- **N_{PoT}** - positrons on target
- **B(s)** - background yield per PoT
- **$S(s, M_{X17}, g)$** - signal production as a function of mass and coupling
- **$\varepsilon_S(s)$** - signal selection efficiency
- **√s** - measured from E_{beam} run by run

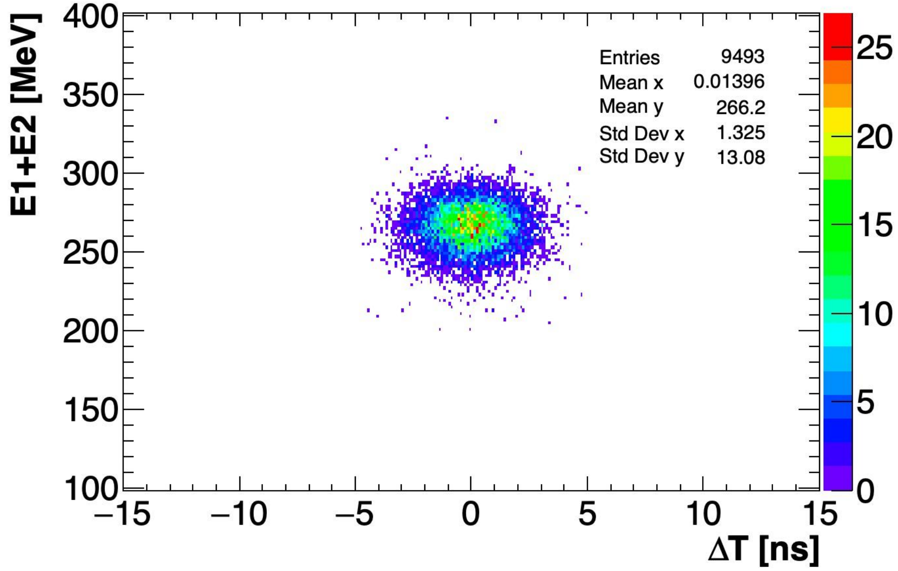
$N_2(s)$ is kept blind throughout the analysis!

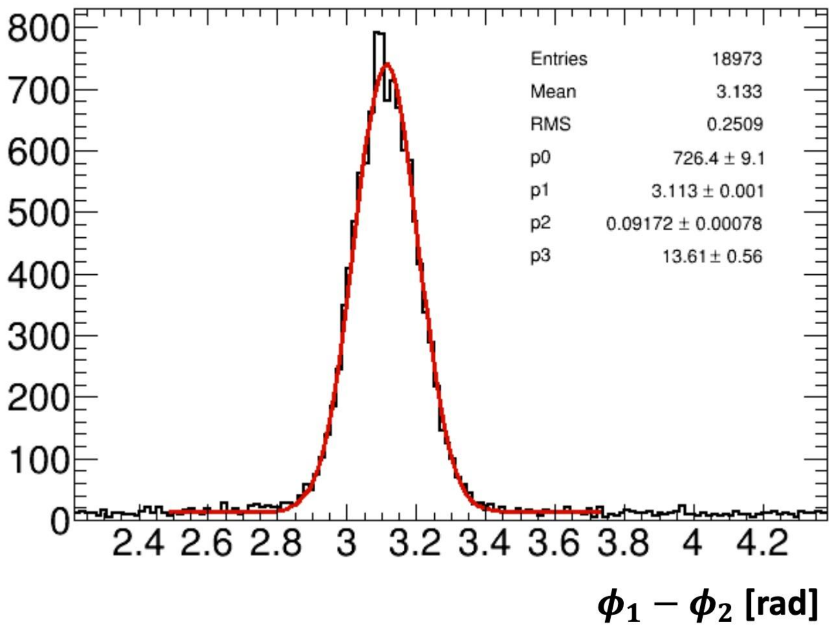


For line shape see Giovanni Grilli di Cortona talk

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



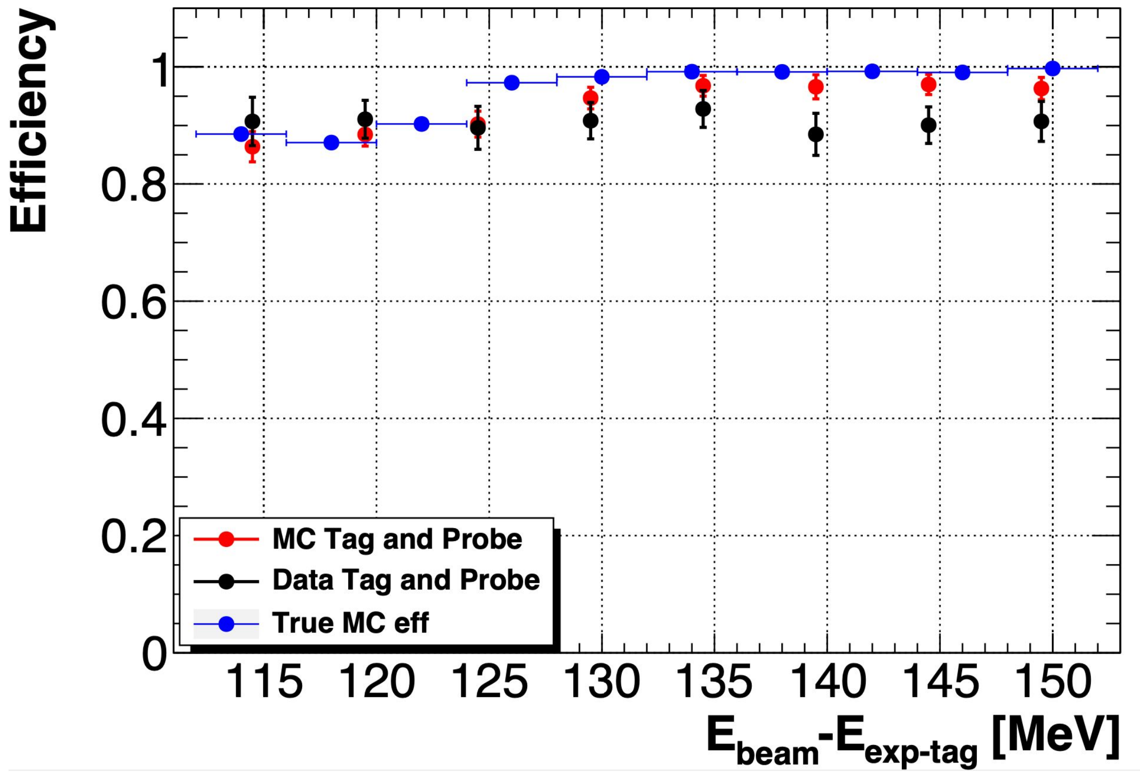




- ECal based:
  - two in-time ($\Delta t < 5$ ns) clusters with two body kinematics
  - E_{cut}, R_{cut}, with respect to CoG
- Background estimation: ~ 4 %
- The measurement is N_{2cl}/Flux (E_{beam})
  - Flux = PoT

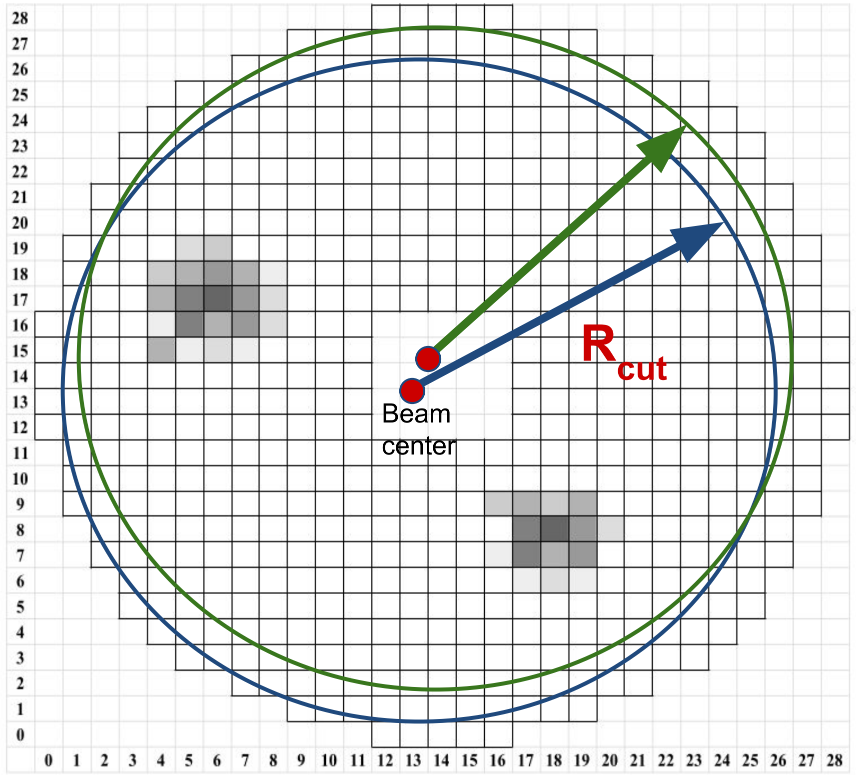
Signal selection: selection efficiency

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)

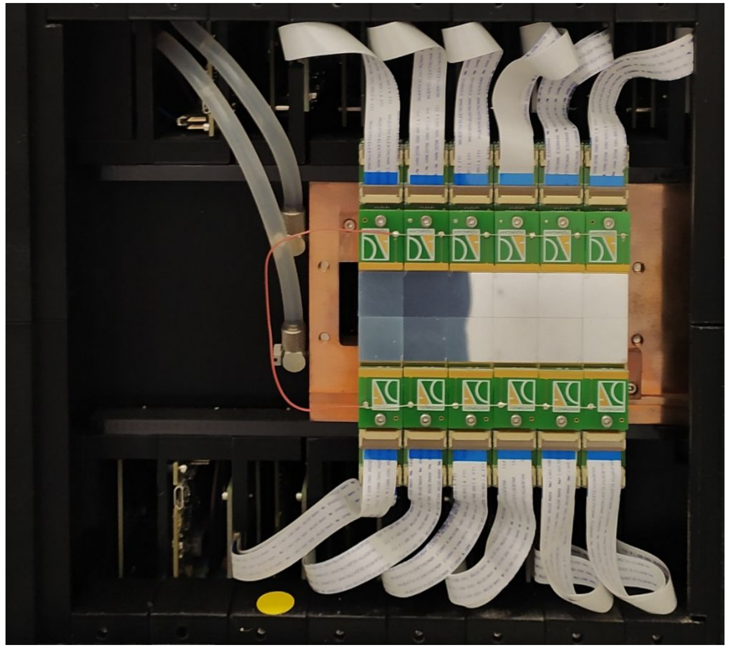


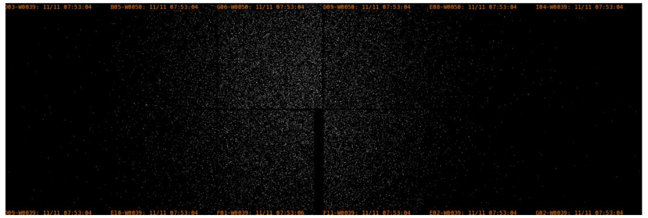
- Dominated by the cut on the outer radius of a cluster in the calorimeter
- Beam center drift limits the maximal R_{cut}

Event selection

JINST 19 (2024) 01, C01016

Timepix 3 array

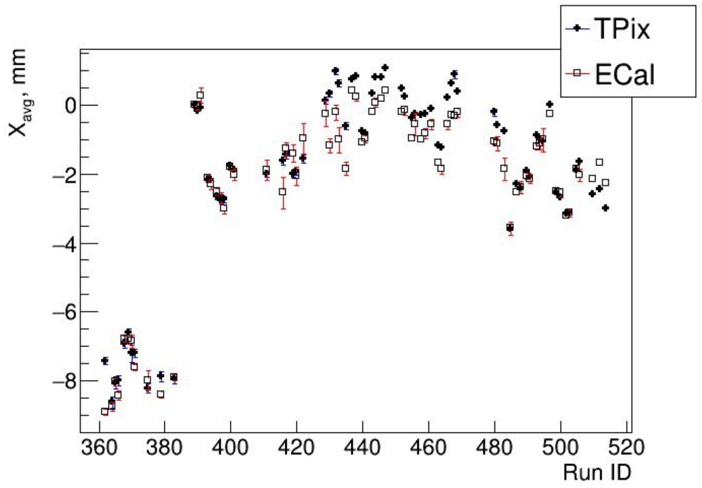


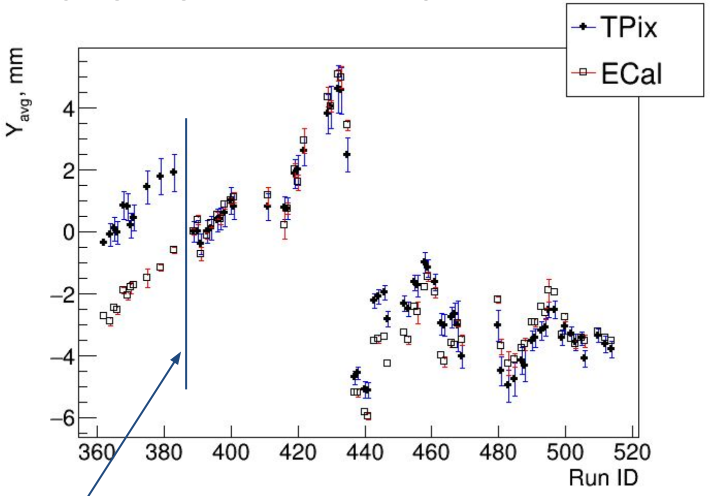


- Matrix of 2 x 6 Timepix3 detectors
  - each 256x256 pixels
- Operated in 2 modes:
  - image mode, integrating
  - streaming mode, feeding ToT and ToA for each fired pixel

COG at the ECal front face from 2 cluster events

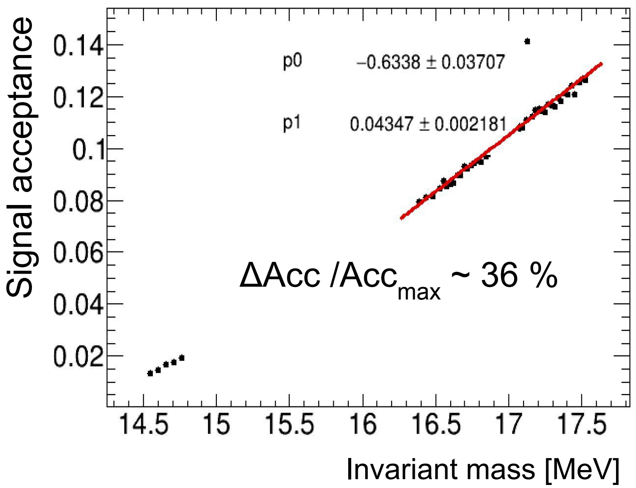
Movement within 10 mm

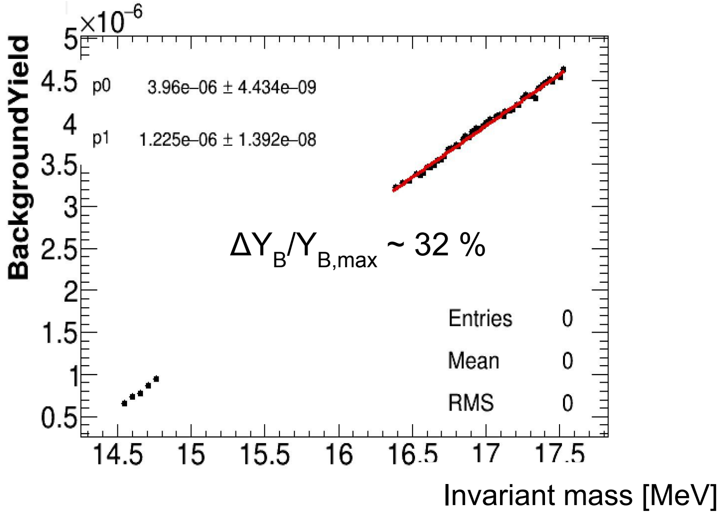




Timepix was moved by 1.8 mm

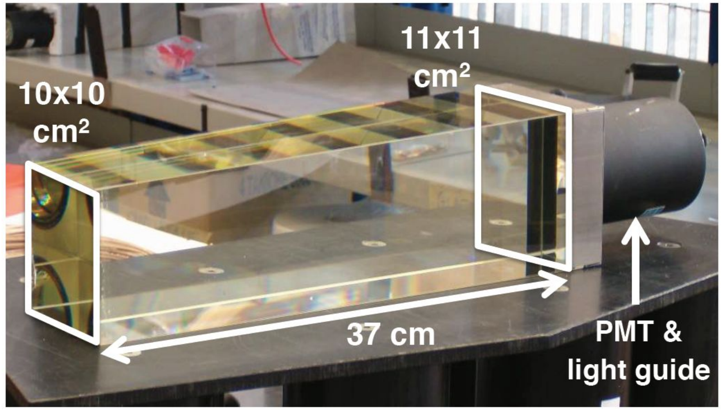
arXiv:2405.07203 [hep-ex]





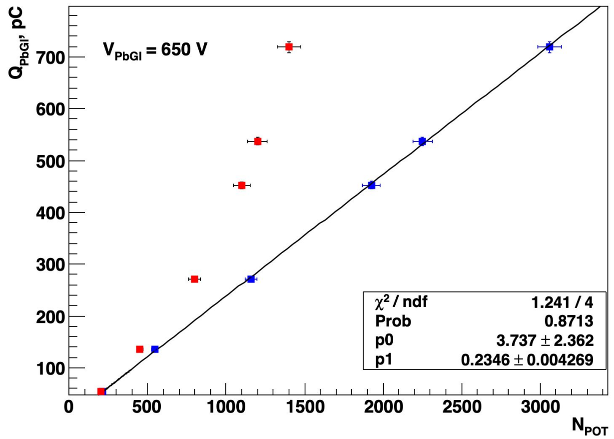
Positron flux measurement

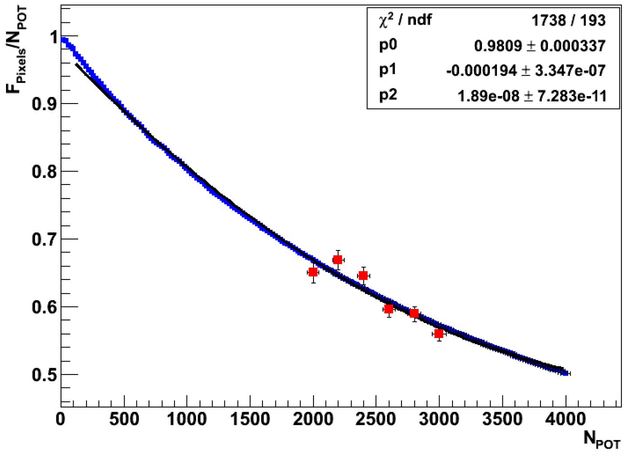
arXiv:2405.07203 [hep-ex]

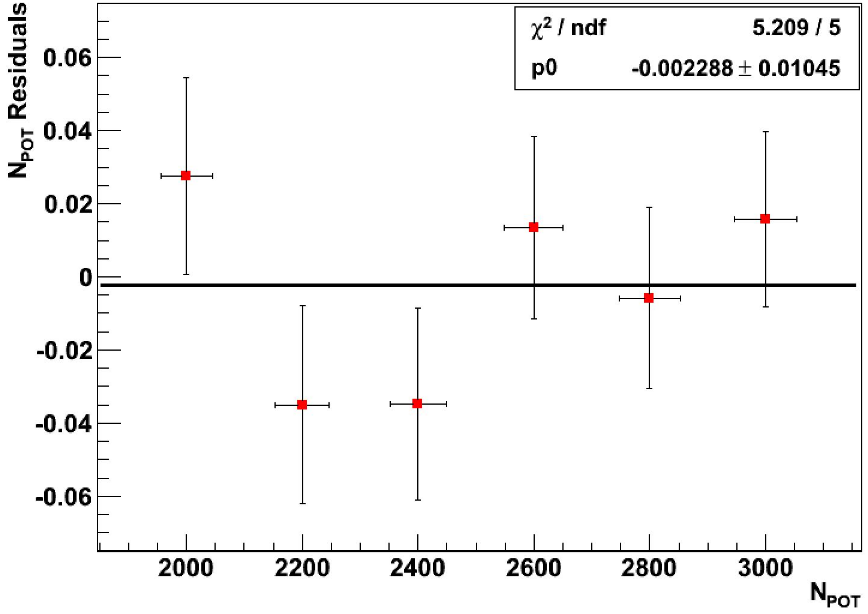


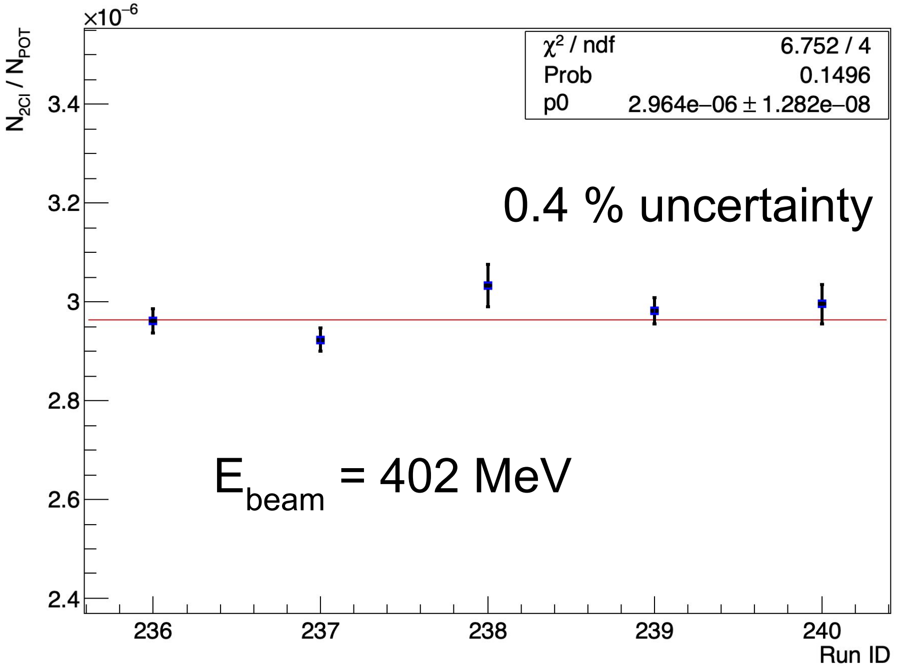
- PoT is primarily measured by an OPAL lead glass block downstream of the setup
- Additional detectors to control the PoT systematics
  - and to derive correction factors
- Several testing campaigns
  - A few positrons -> clear 1e, 2e, etc. peak identification
  - O(2000) PoT - cross-calibration with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

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



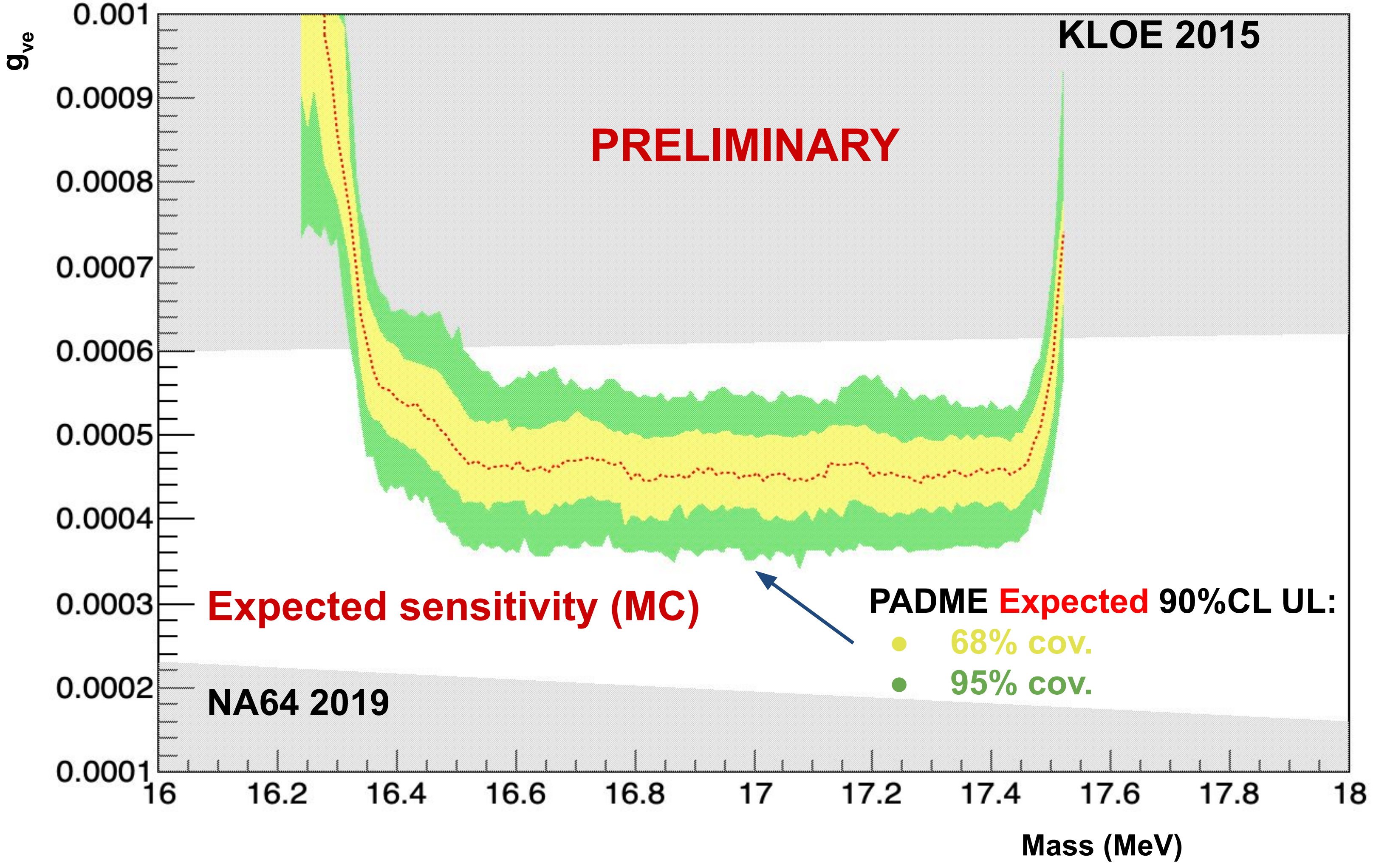






- Validation of the toy MC (and F_{pixel} correction factor) with an independent measurement from BTF luminometer
- Correction uncertainty - of the order of 1 %
  - Common to all the measurements

PADME MC sensitivity estimate for RUN III



- Expected 90% CL upper limits are obtained with the CLs method
  - ATL-PHYS-PUB-2011-11/CMS NOTE-2011/005
- 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
- 147 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

Strategy for unblinding prepared and being tested
"Open the box" in two steps: data self-consistency and looking for X17

PADME RUN IV: $N_{e+e-}/N_{\gamma\gamma}$

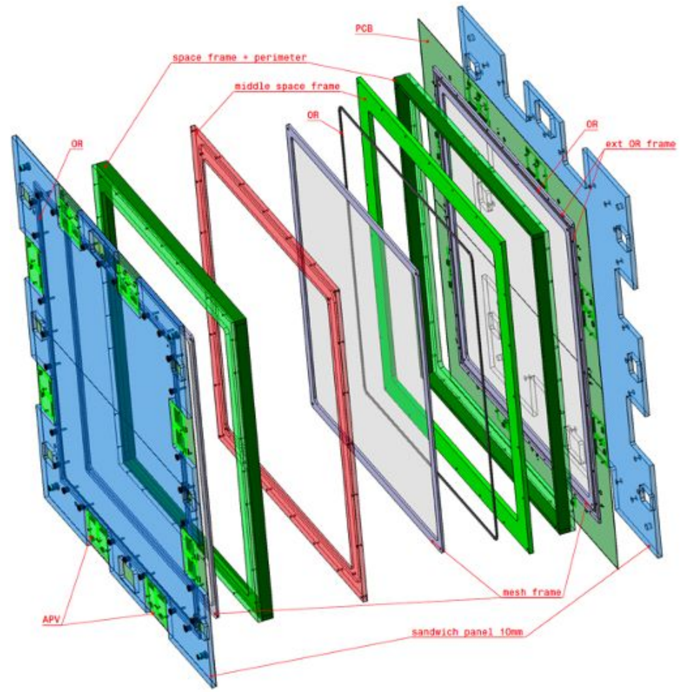
- The results from PADME RUN III will be dominated by PoT systematics, two clusters acceptance acceptance systematics

  → Exploit a different normalization channel which could possibly cancel part of the systematic effects

- Natural candidate: $e^+e^- \rightarrow \gamma\gamma$
  - Same 2 body kinematics: similar ECal illumination, systematics due to bad ECal crystals largely cancels

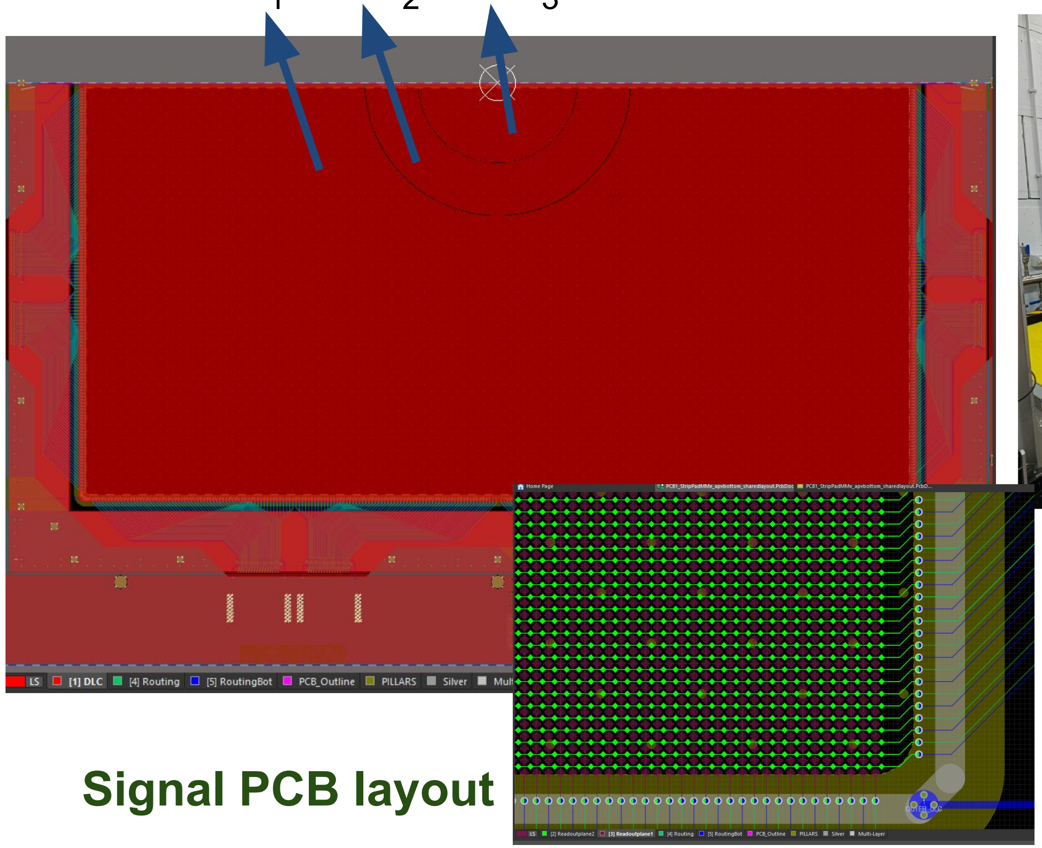
- Back on the envelope estimation: need knowledge of $N_{\gamma\gamma}$ at 0.5 % for each scanning point
  - $\sigma(e^+e^- \rightarrow \gamma\gamma)_{E=300\ \mathrm{MeV}}$ ~ 2 mb, Acc ($e^+e^- \rightarrow \gamma\gamma$) ~ 10 % ⇒ O(10k) γγ events per 10^{10} PoT
    - Need 4 times higher statistics per 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

PADME tagger

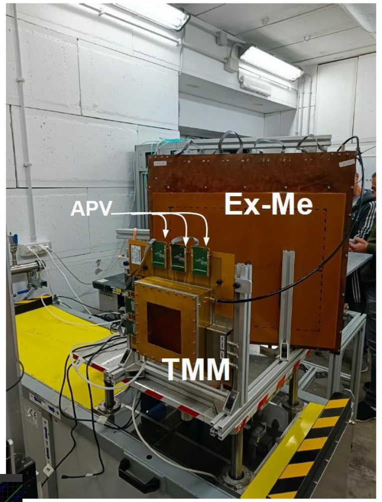


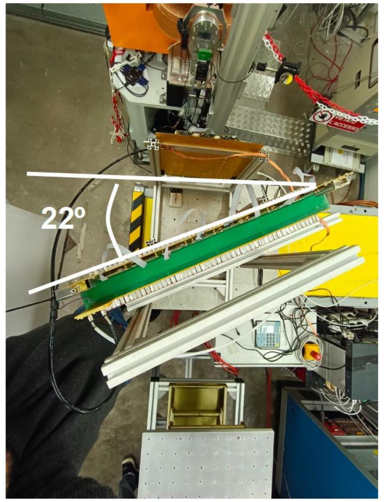
- A novel micromegas readout plane suggested
  - Rhomboidal pads for X and Y direction, decrease the mutual capacitance
- Variable HV depending on the distance from the beam center
  - Low HV in the center, measure the beam multiplicity
    - Additional control on the PoT
  - Higher HV in periphery to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

$HV_1 > HV_2 > HV_3$



Signal PCB layout





- 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)

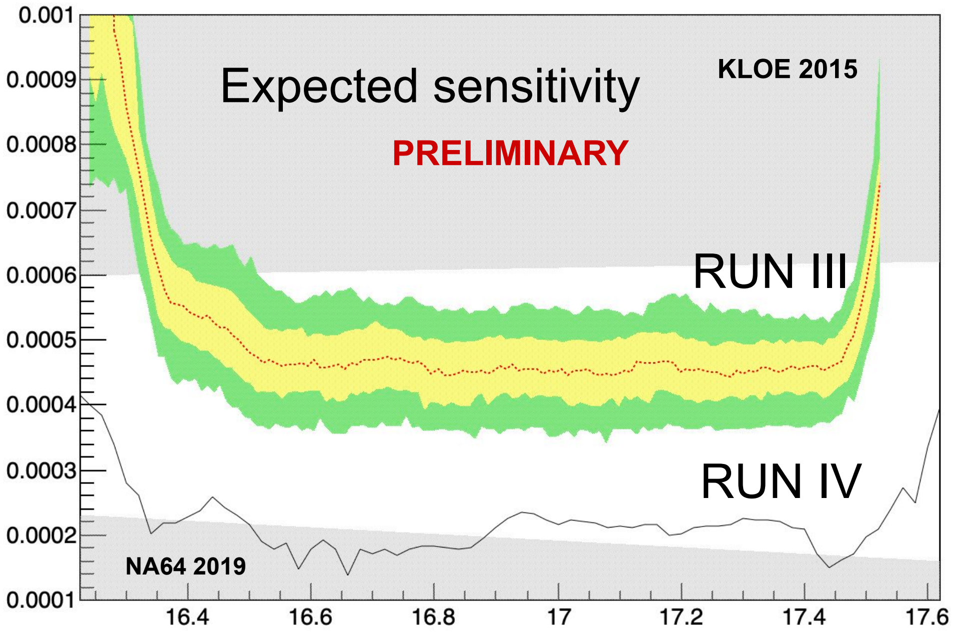
Conclusions

- RUN III X17 analysis is in its final track
  - PoT determined with various cross-calibration procedures with uncertainty down to < 1 %
  - Signal acceptance and background estimation under control with systematics O(1%)
  - Methodology for “box opening” developed and being extensively tested

- 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 X17**

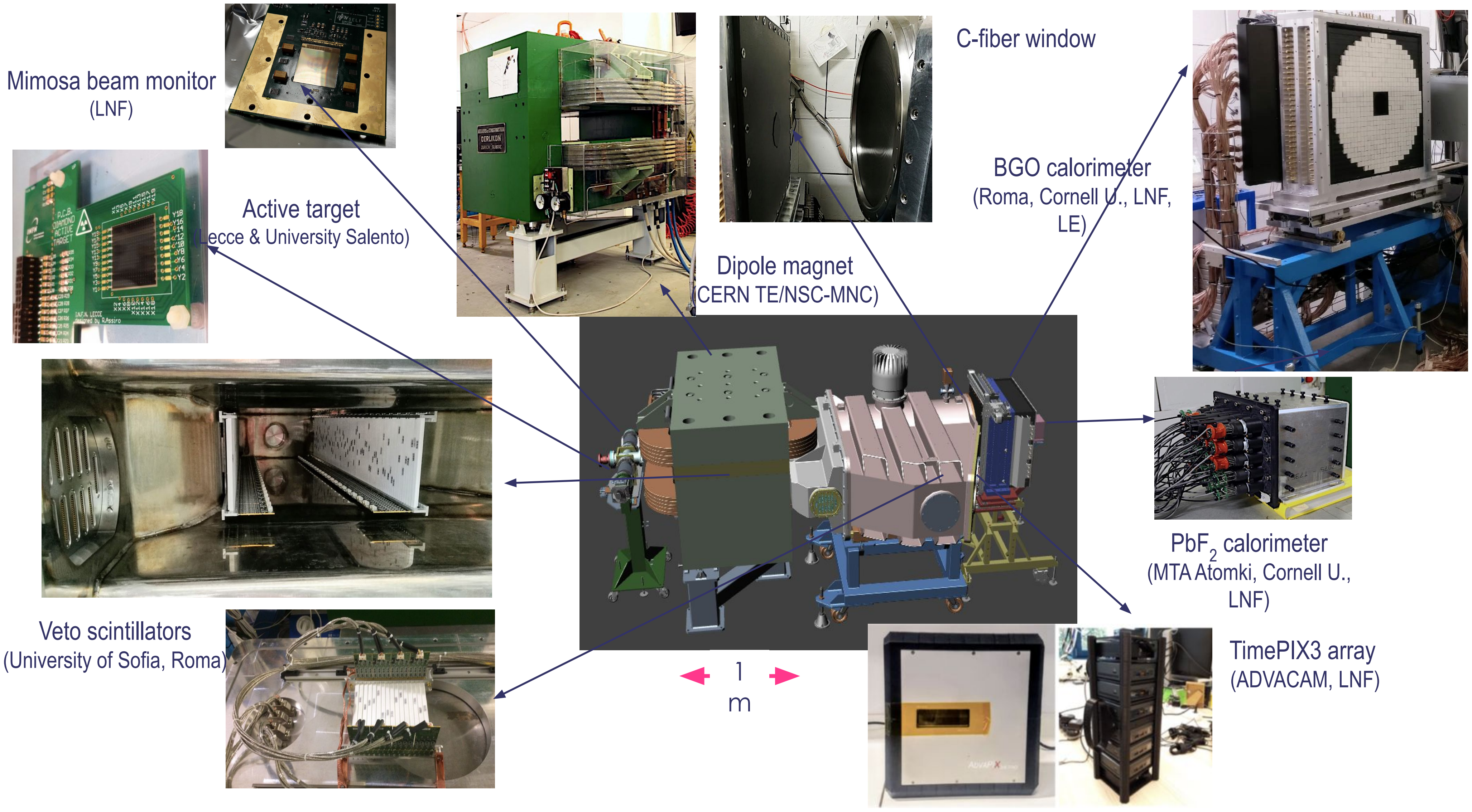
Stay tuned for PADME RUN III unblinding



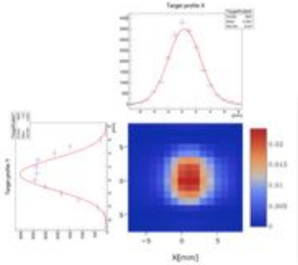
EXTRA MATERIAL

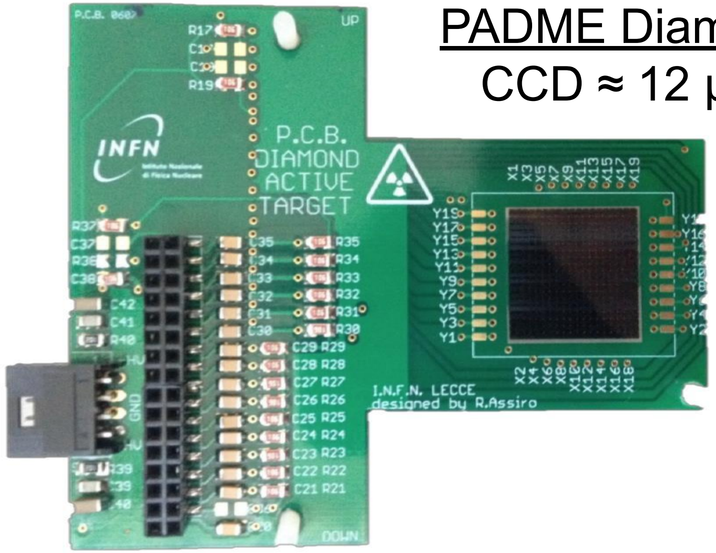
PADME

Positron Annihilation into Dark Matter Experiment



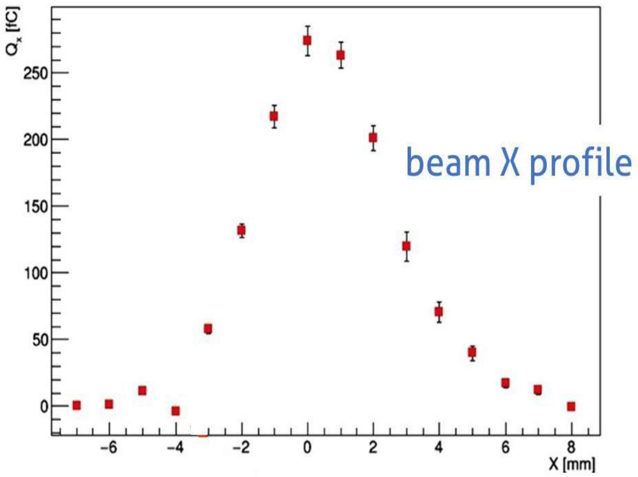
Active target

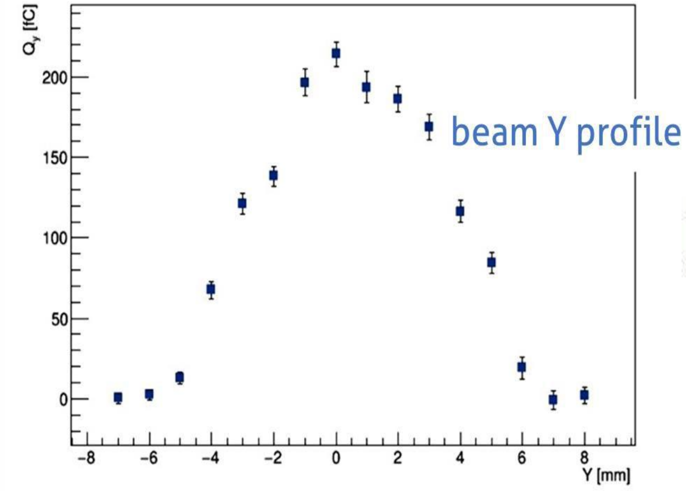


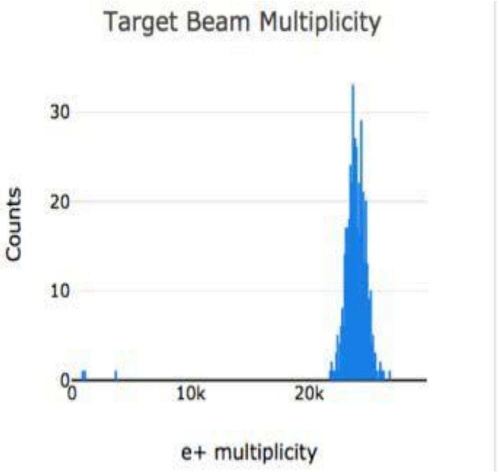


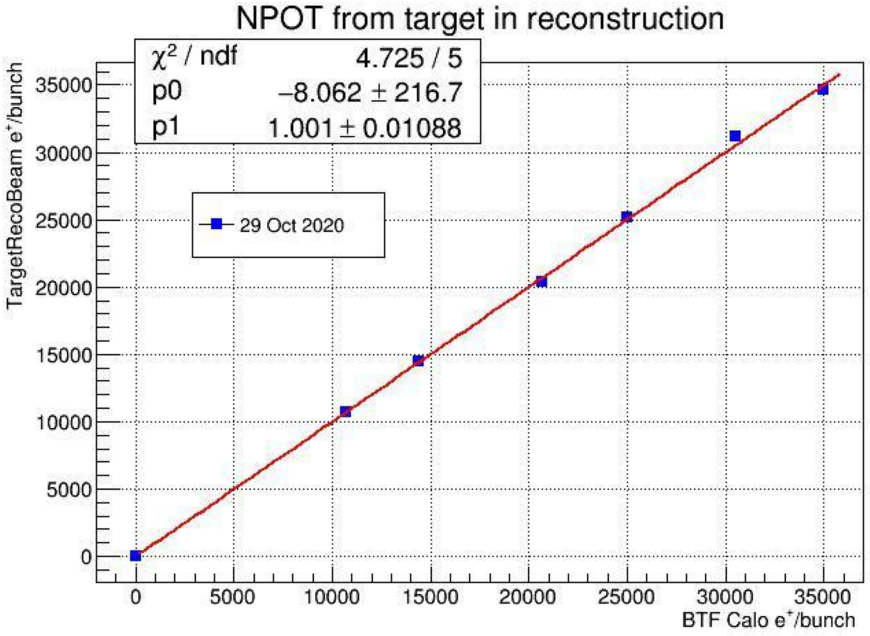
PADME Diamond

CCD ≈ 12 μm



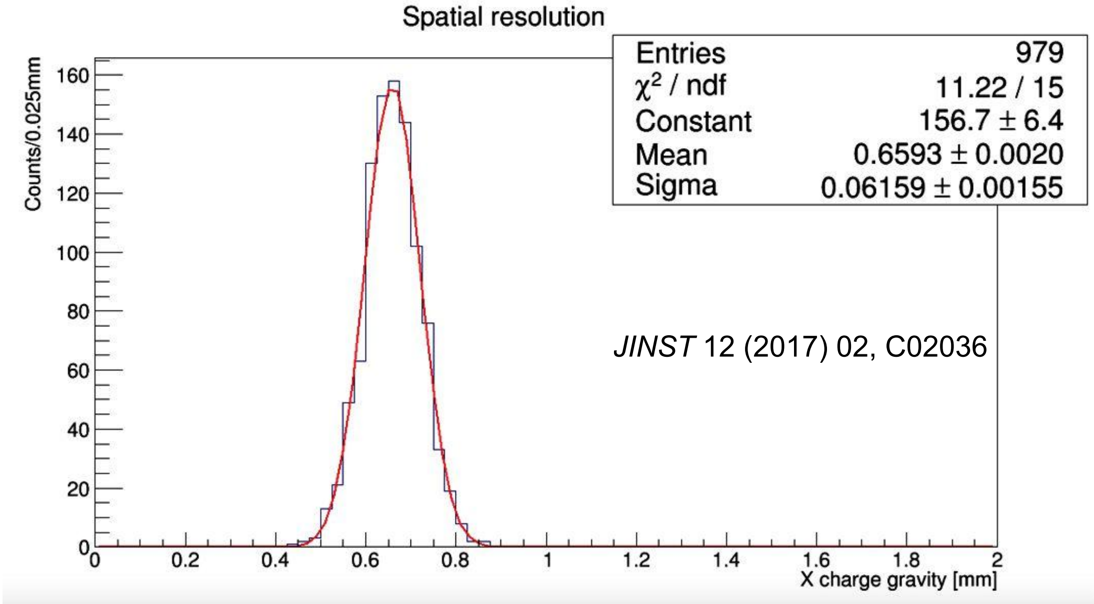






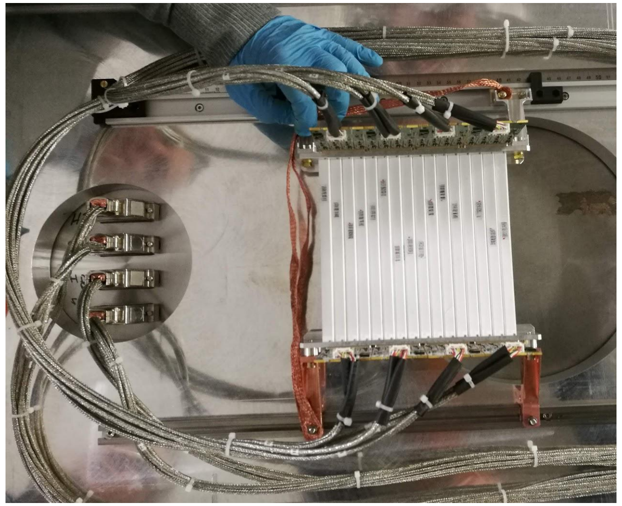
Polycrystalline diamonds

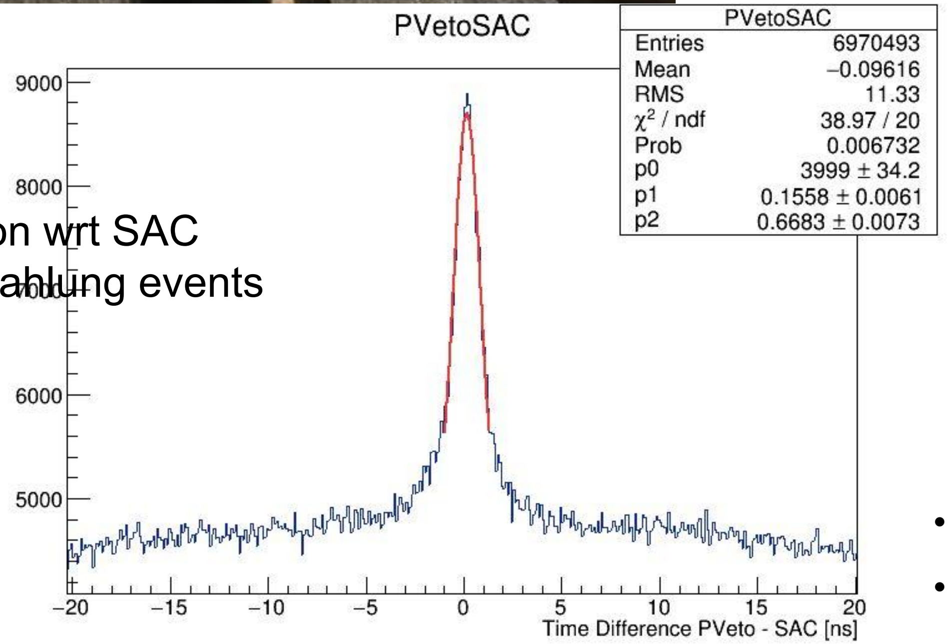
- 100 μm thickness:
- 16 × 1 mm strip and X-Y readout in a single detector
- Graphite electrodes using excimer laser



Charged particle detectors

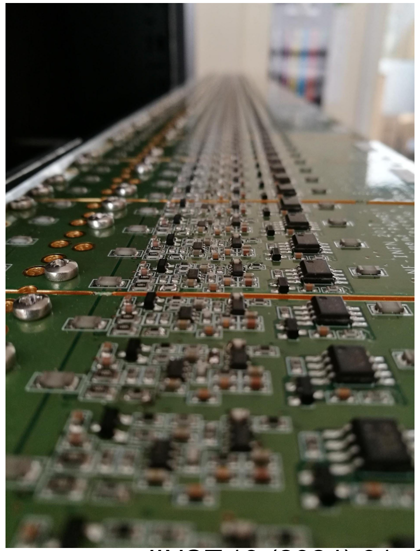
- Three sets of detectors detect the charged particles from the PADME target (at E_{beam} = 550 MeV):
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2) scintillator-WLS-SiPM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



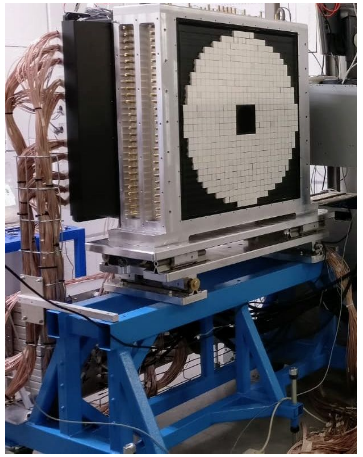
JINST 19 (2024) 01, C01051

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

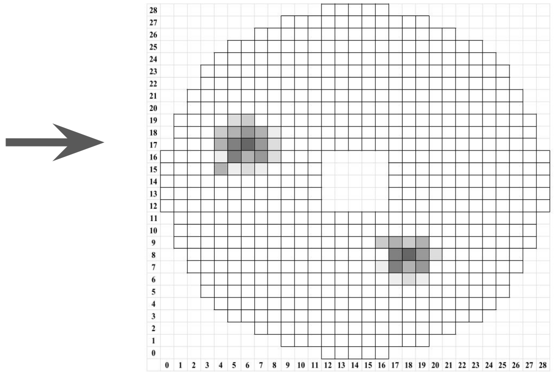
ML for double particle separation in ECal

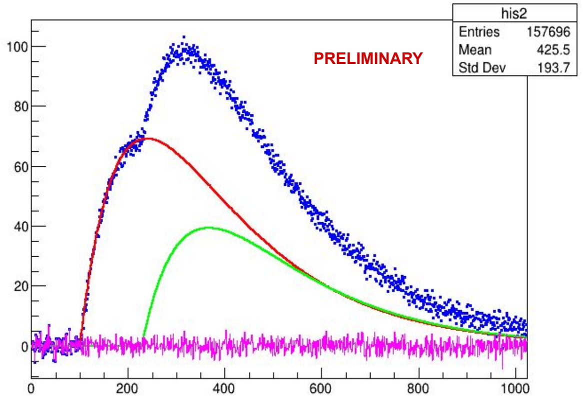
Instruments 6 (2022) 4, 46

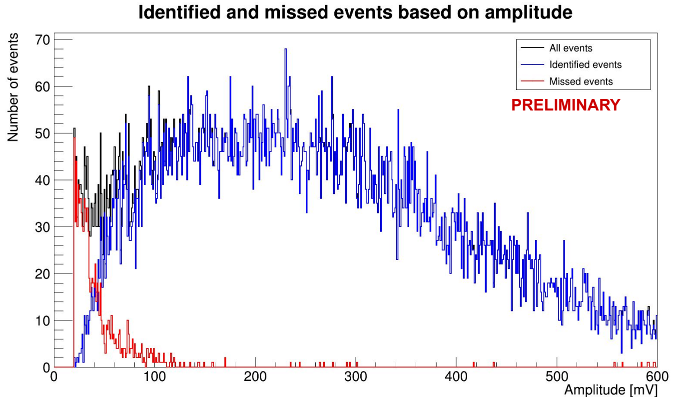
PADME ECAL

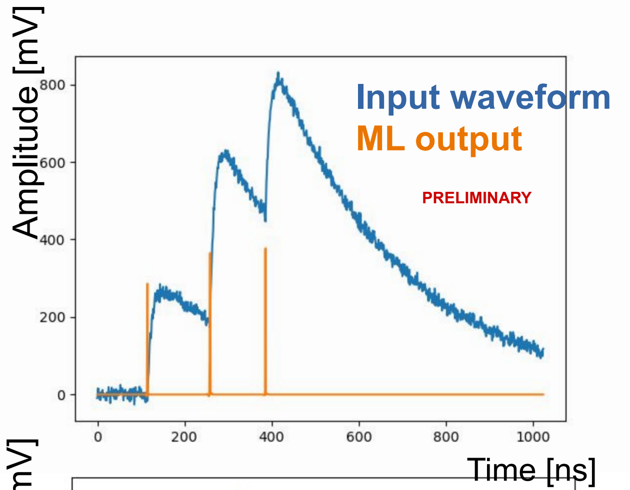


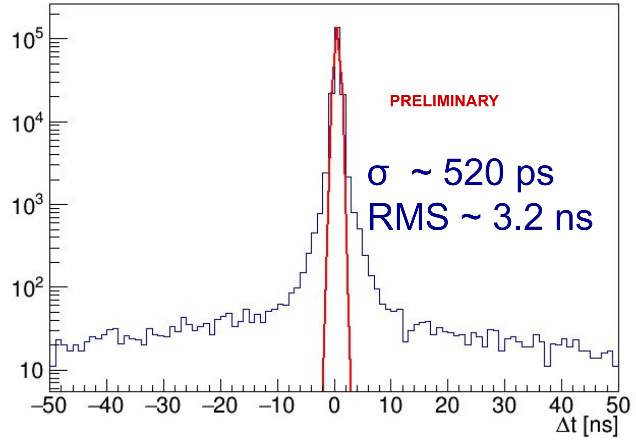
Two photon showers in the ECAL



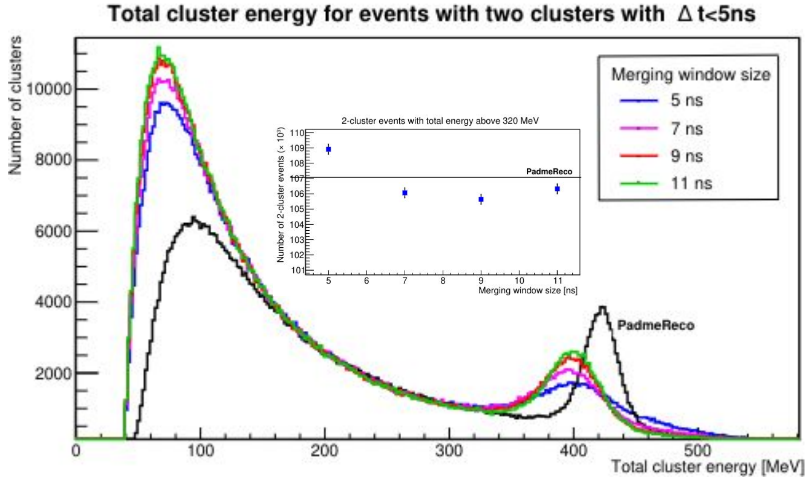


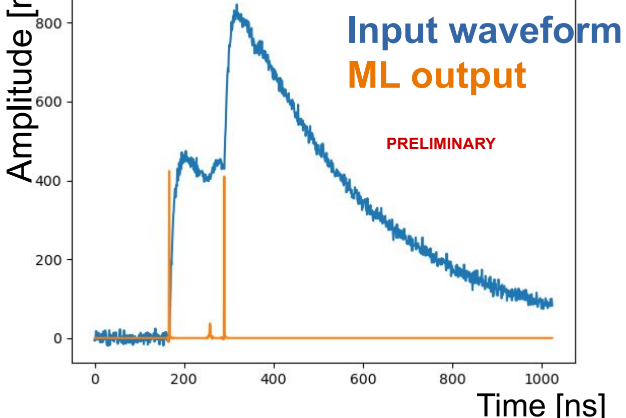


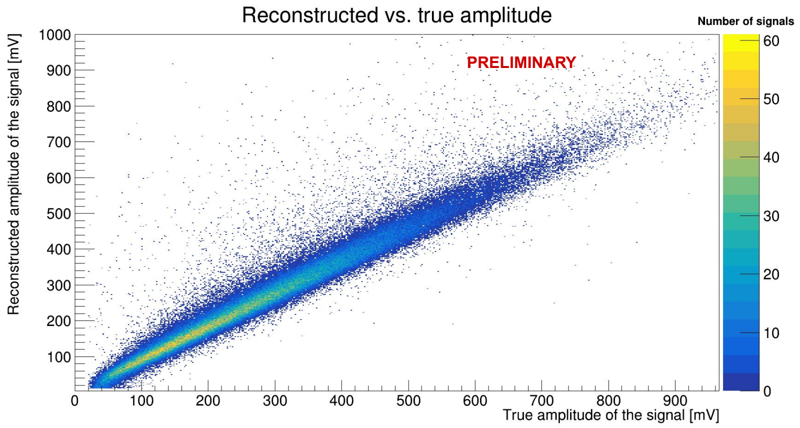




- AI to identify the number of pulses in a waveform
- Simple output – up to five pulses
- Trained on 100 000 events

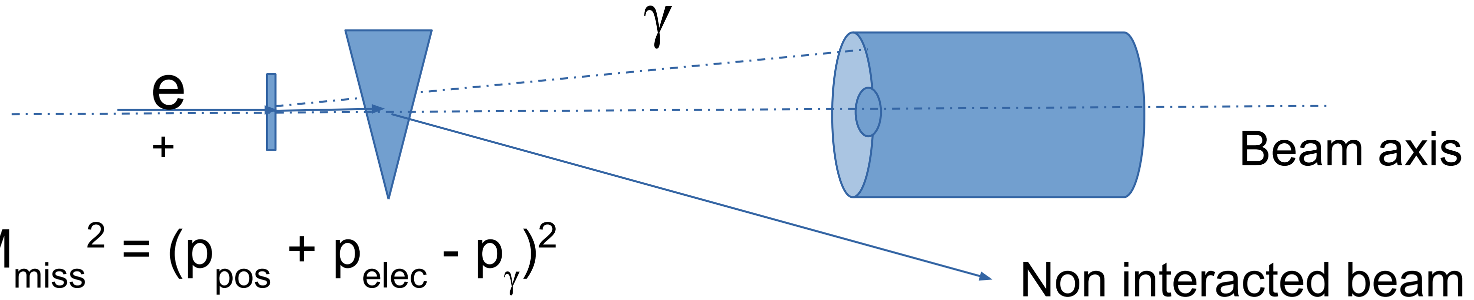




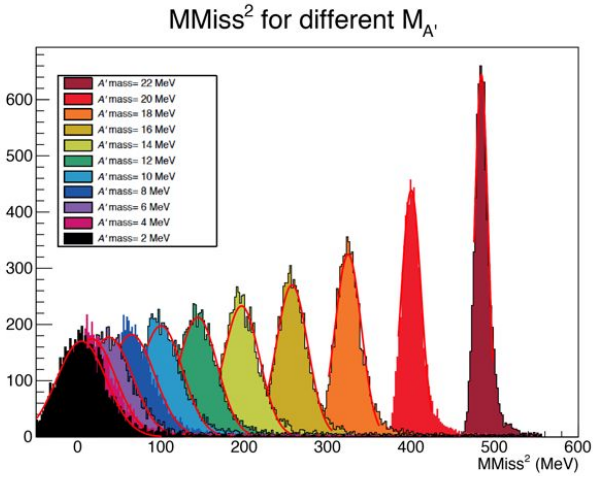


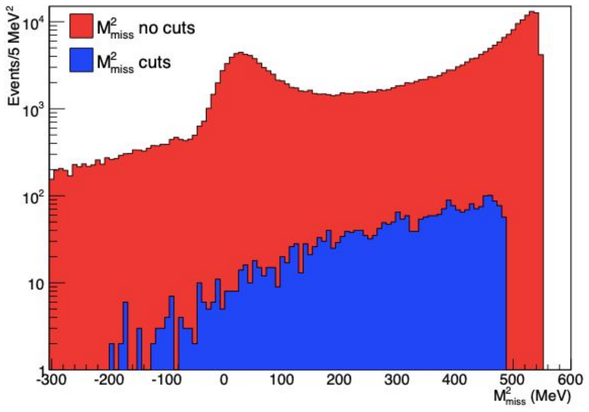
Positron annihilation into new light particles

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



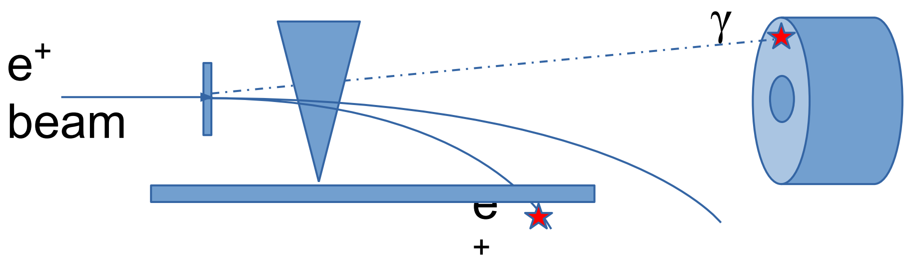
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

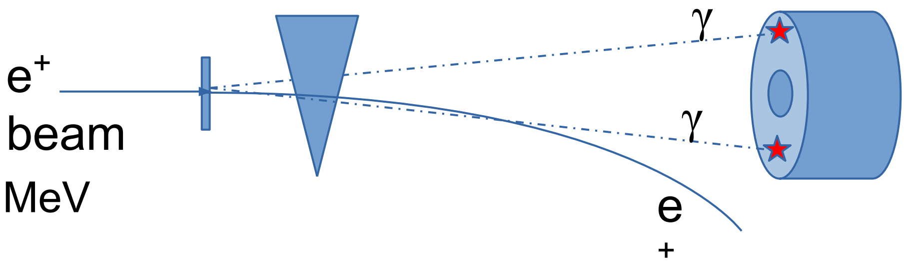


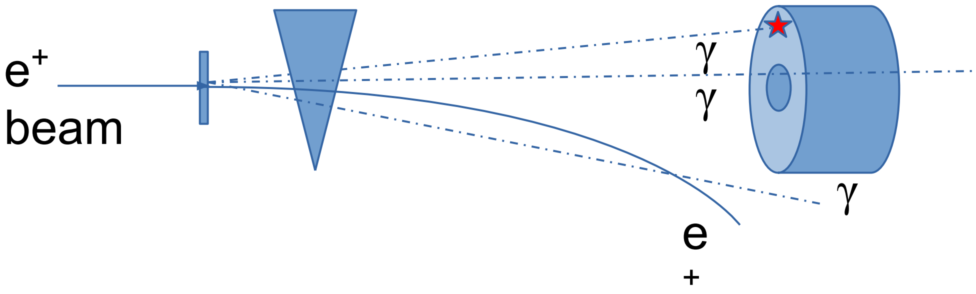


Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+ + N \to e^+ N \gamma$	4000 mb	$E\gamma > 1$MeV
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma > 1$MeV
$e^+e^- \to e^+e^-\gamma$	180 mb	CalcHEP, $E\gamma > 1$MeV

- 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 $E\gamma > 50$ MeV
- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
- Radiative Bhabha scattering
  - Topology close to bremsstrahlung

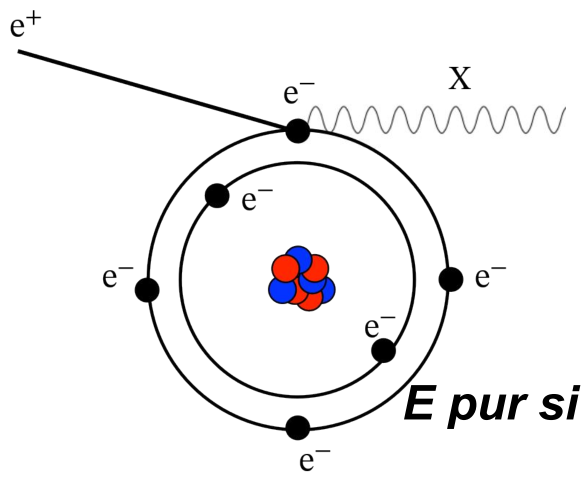






Signal yield: theoretical input

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



E pur si muove

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

- 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

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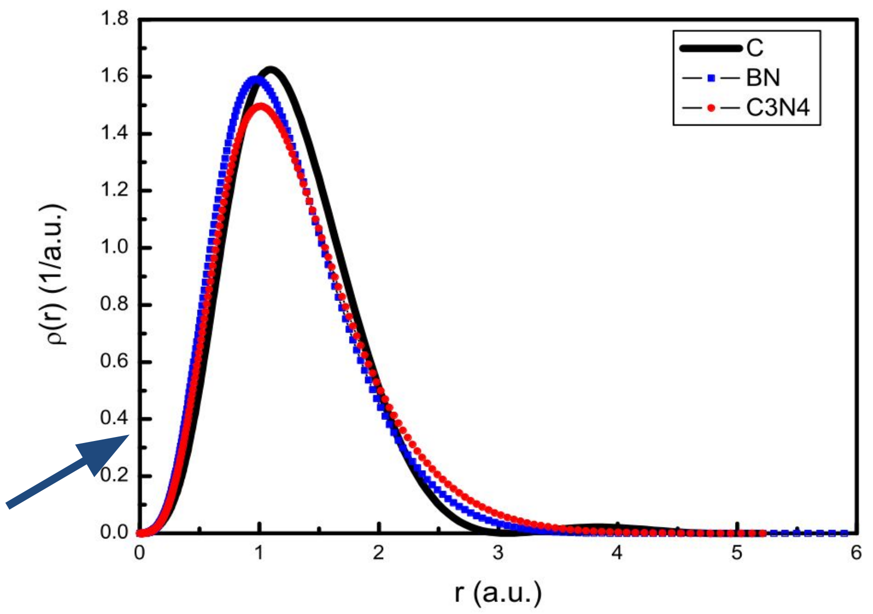
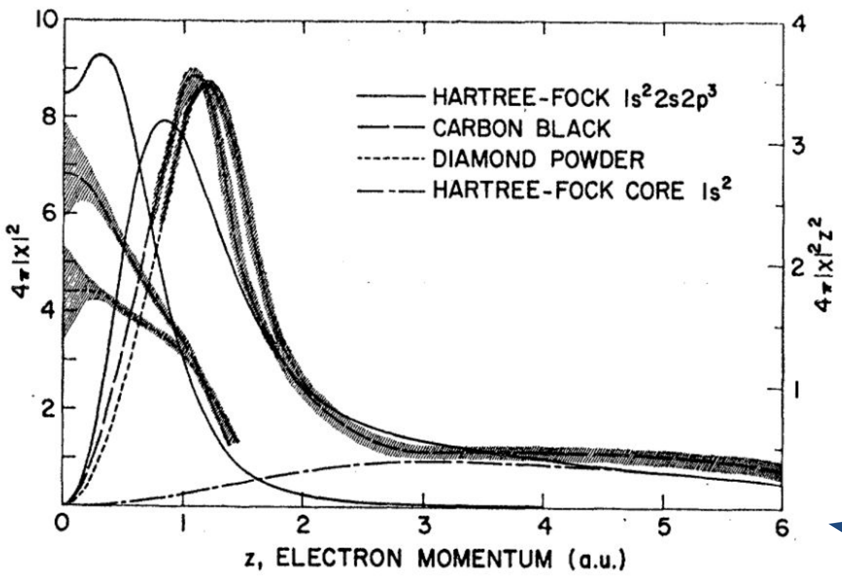
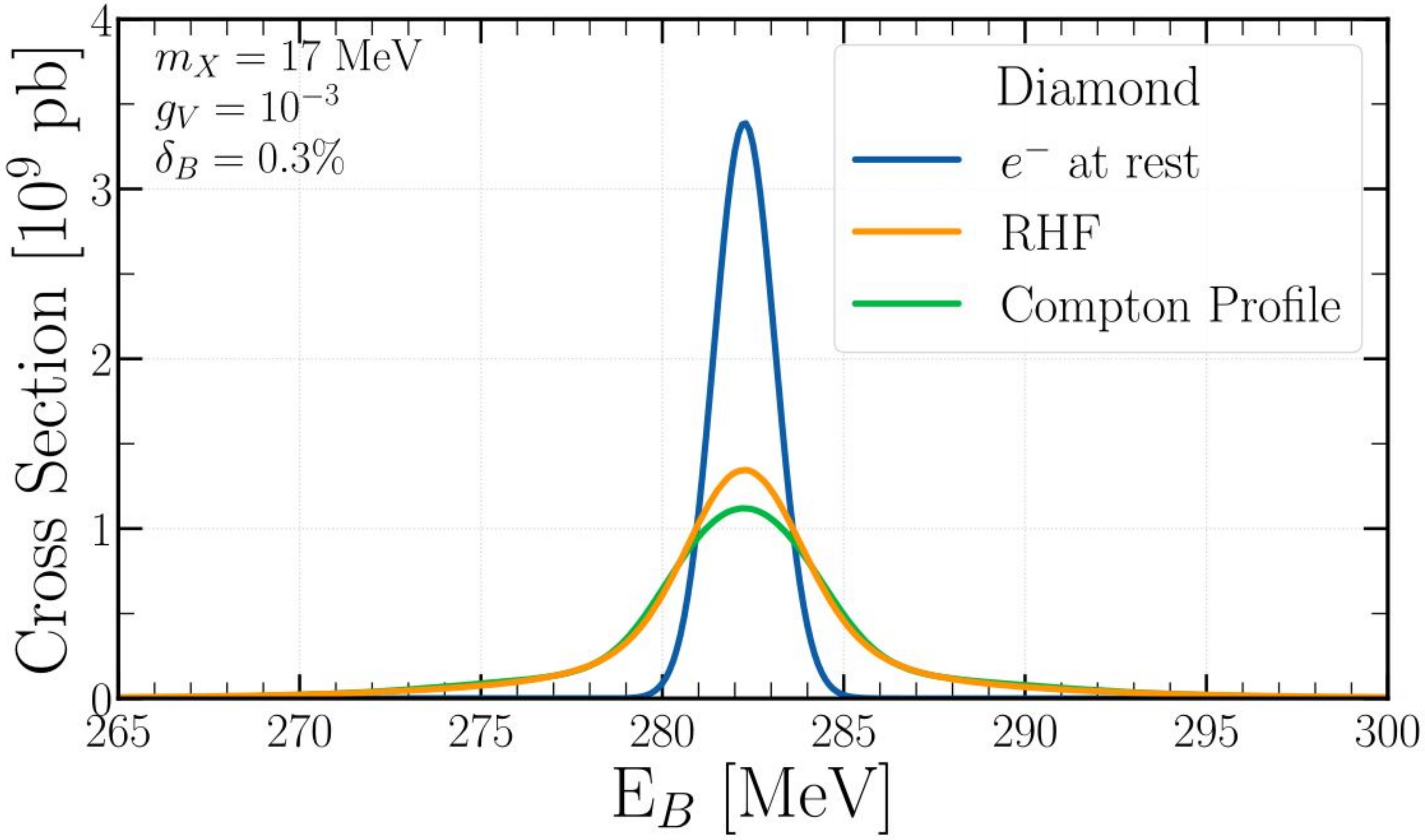




[Phys. Rev. 176 (1968) 900]

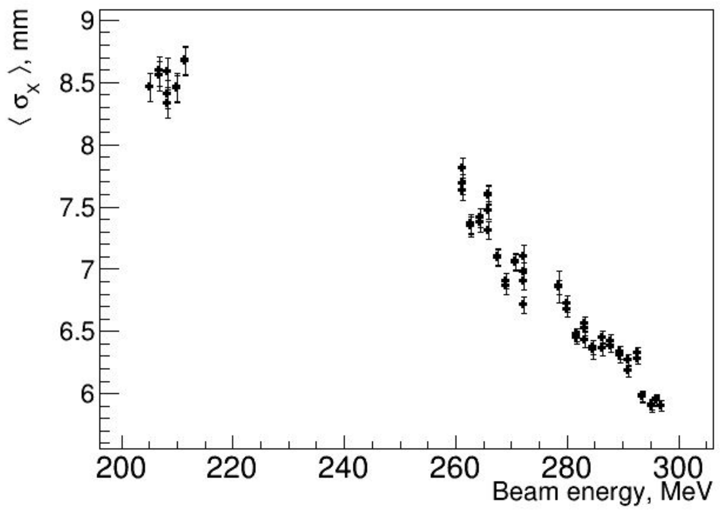
Sensitivity estimation

- 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: $N_B \sim 45000$ events per point
  - Signal acceptance

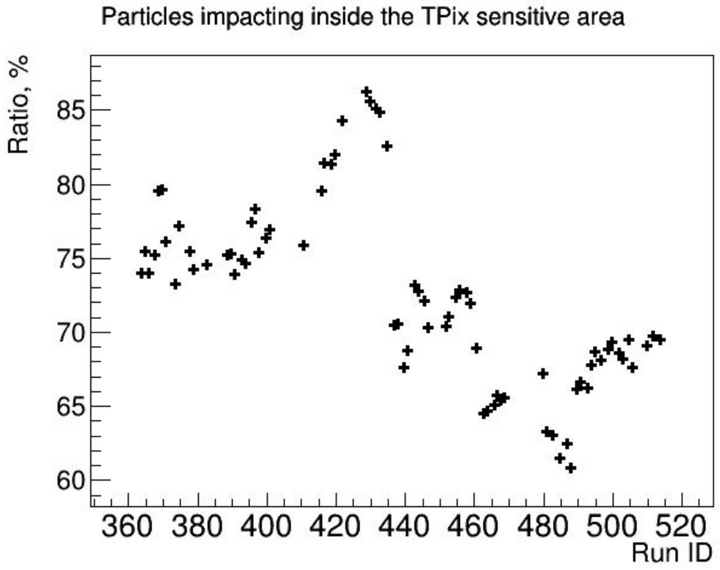


- **Sources of systematics**
  - Relative PoT estimation O(0.5%)
  - Acceptance 0.75%
  - Beam energy spread 0.05 %
  - Signal shape uncertainty
  - Beam
  - Time dependent ECal efficiency
  - Beam energy uncertainty - controlled by Hall probes < 10^{-3}
  - ECal calibration
- **Normalization systematics**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

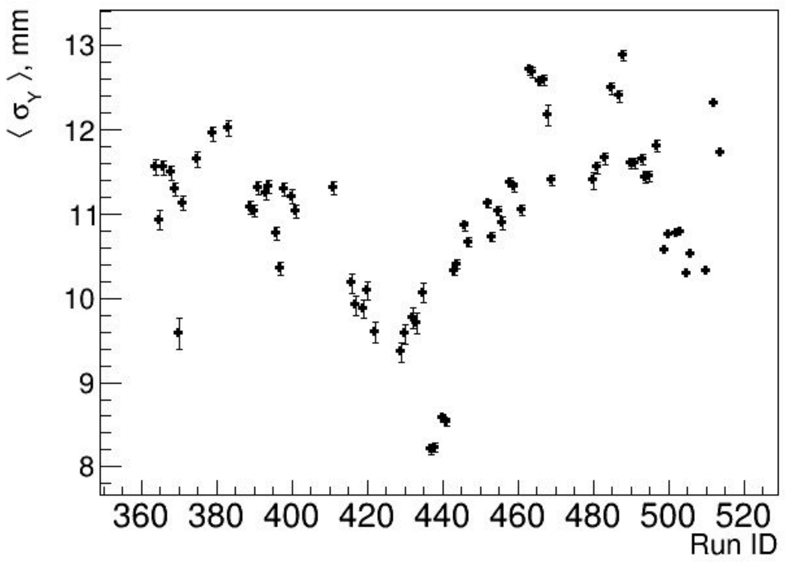
Positron flux measurement

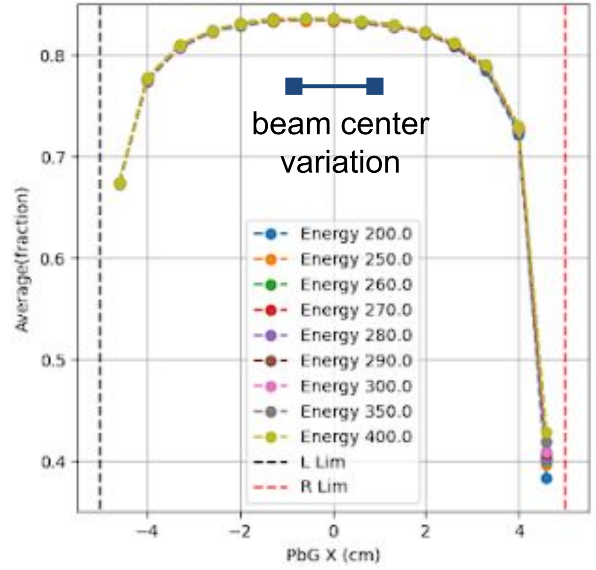


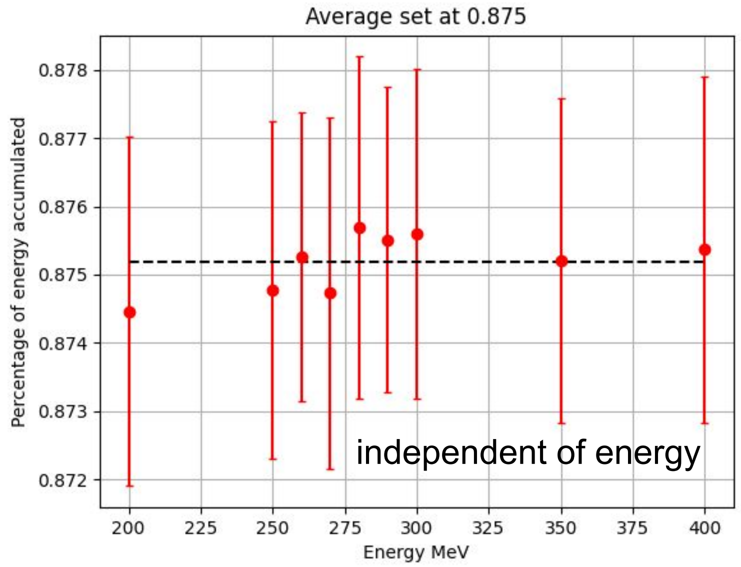
- The beam spread in Y direction varies within ~2 mm during the data taking
- The beam spread in X is energy dependent
    - However in X the containment is largely ensured



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

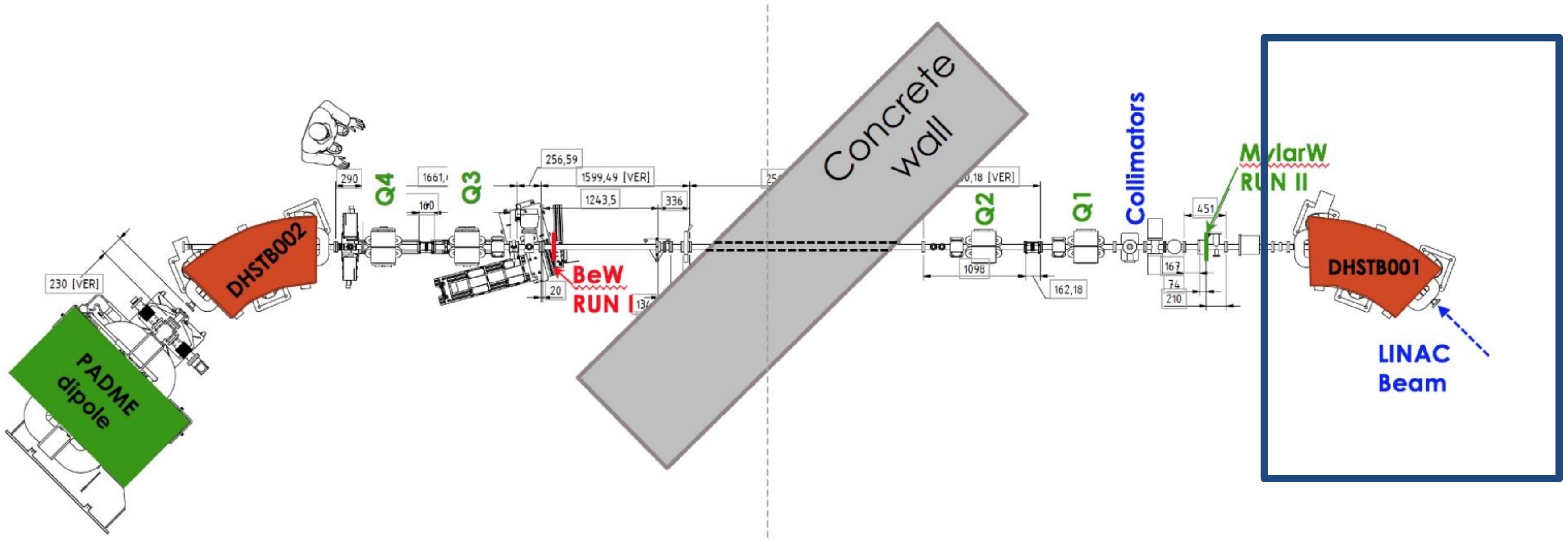




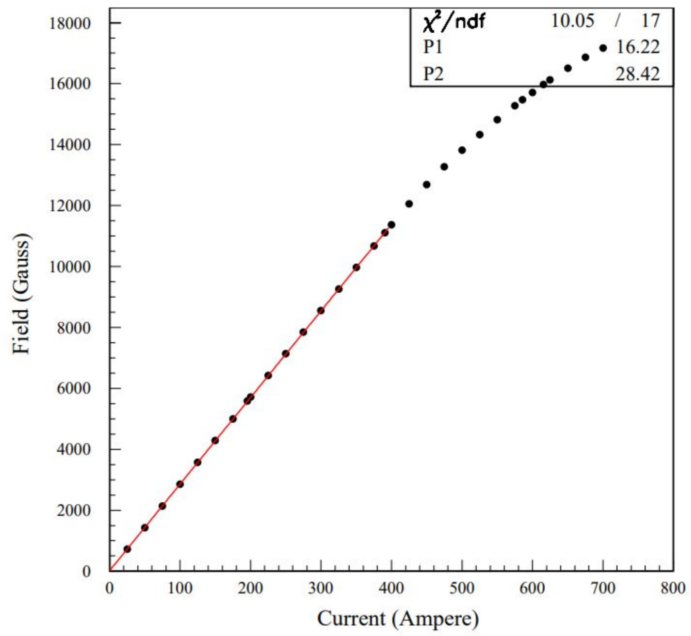


The energy containment correction uncertainty well below 1 %

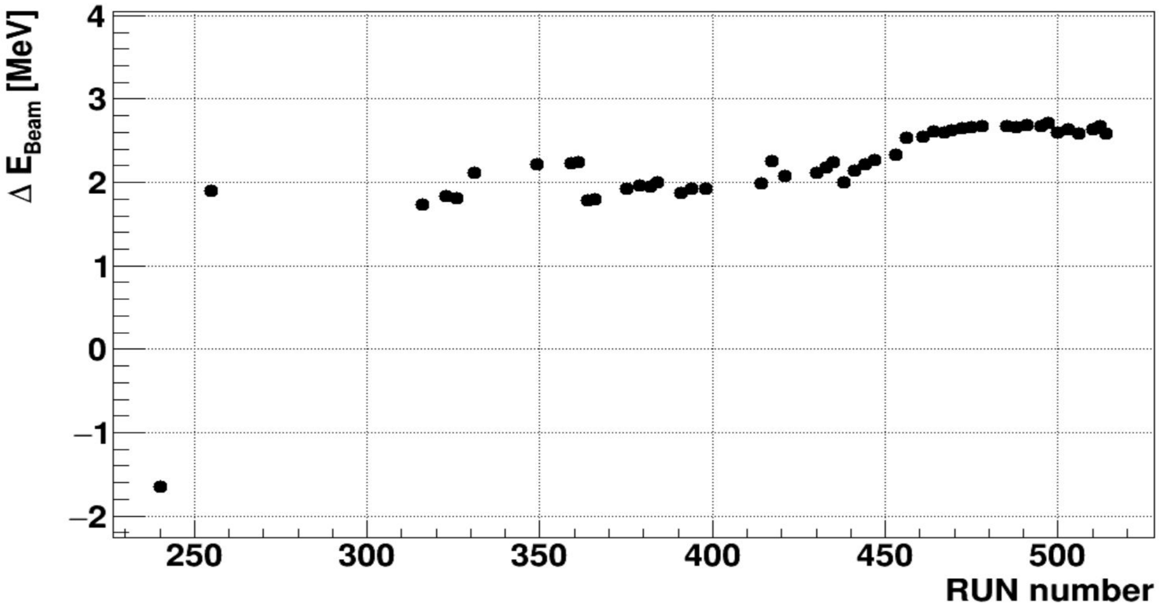
Beam energy



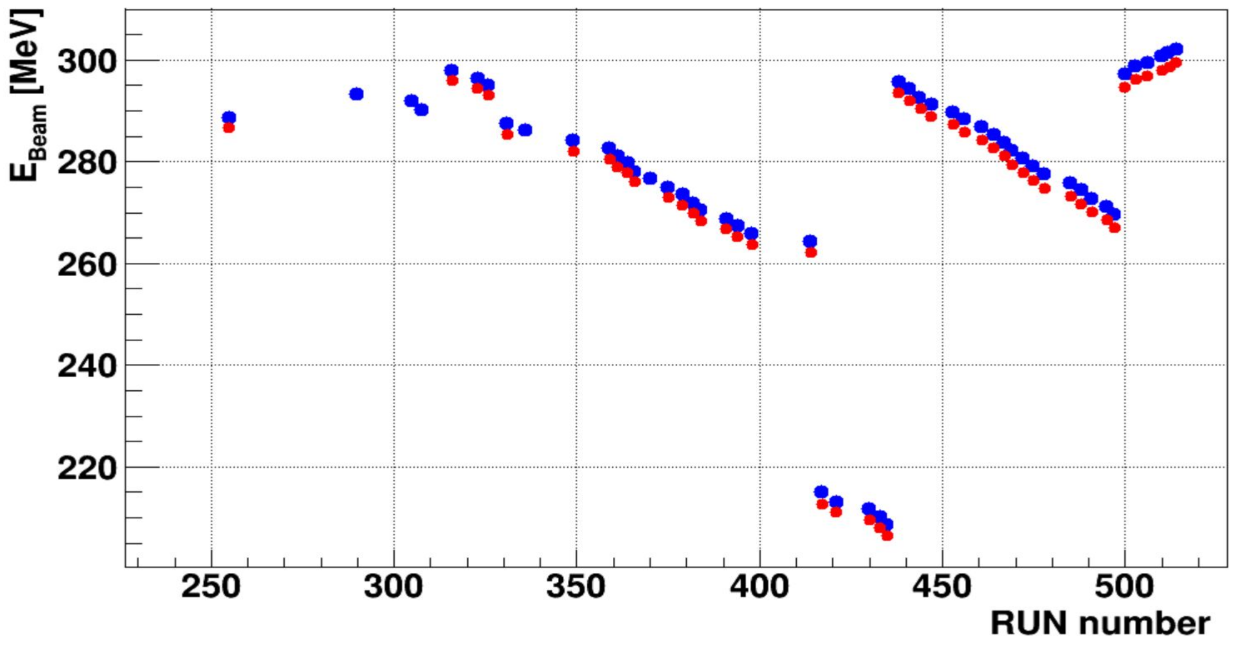
PADME dipole
DHSTB002
Q4
Q3
BeW
RUN I
Concrete wall
Q2
Q1
Collimators
MylarW
RUN II
DHSTB001
LINAC Beam



χ^2/ndf 10.05 / 17
P1 16.22
P2 28.42
Field (Gauss)
Current (Ampere)

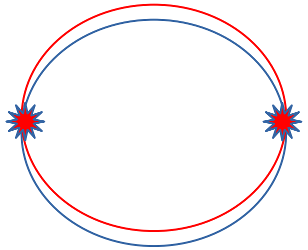


Δ E_{Beam} [MeV]
RUN number



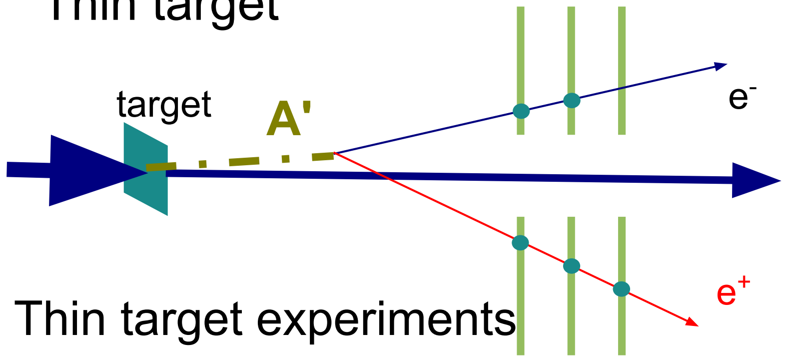
E_{Beam} [MeV]
RUN number

Techniques @ accelerators



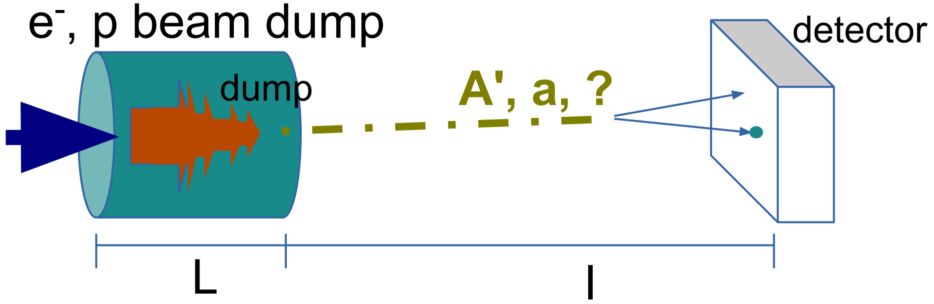
Fixed target

- Thin target

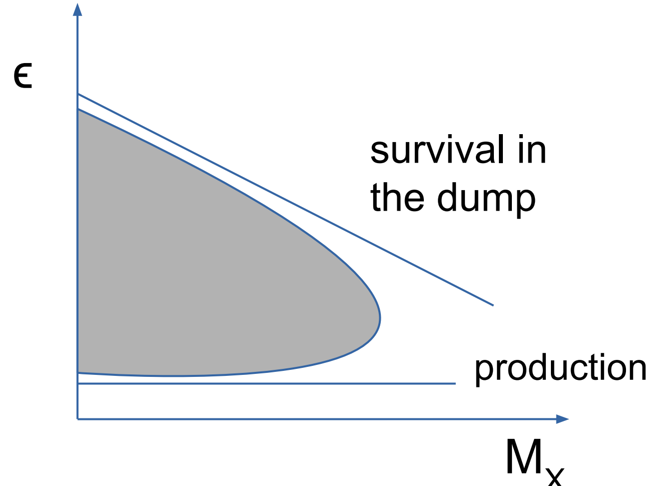


  - Direct production (usually X-strahlung)
  - Search for decays through event reconstruction (tracking)
- Production of secondary beam
  - Usually in a thick target
  - Searching for new particles in meson decays
  - M_X limited by the meson mass, coupling sensitivity – by statistics

Beam dump

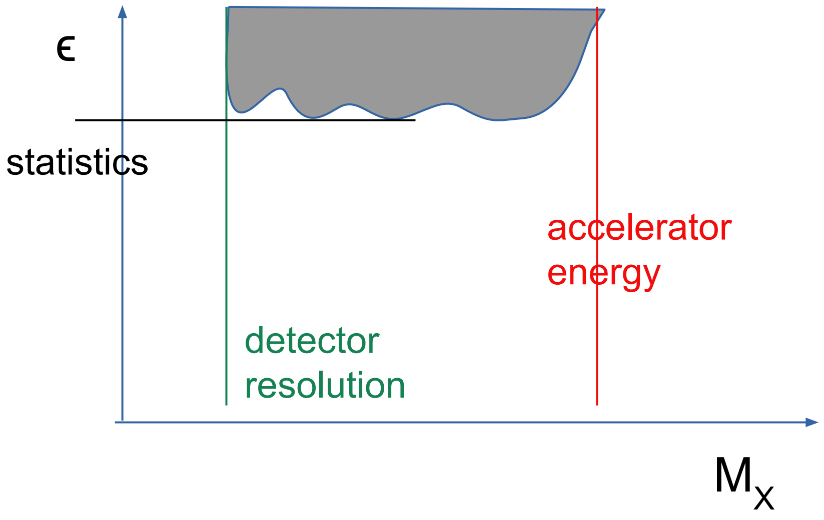


- Production: A'/a/h/?-strahlung, shower, absorption of secondaries
- Detection: everything is signal vs kinematics of the final state
  - The new particle has to survive the passage through the dump



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