Search for dark photon in positron annihilations at Frascati: the PADME experiment

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For the PADME experiment

SU "St. Kl. Ohridski" and LNF-INFN

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SHiP open session

CERN

INFN

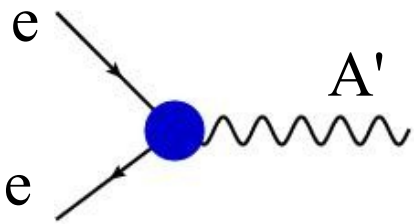
PADME

Overview

- Dark photon basics
- PADME experiment
- Physics reach
- Present status and activities
- Conclusions

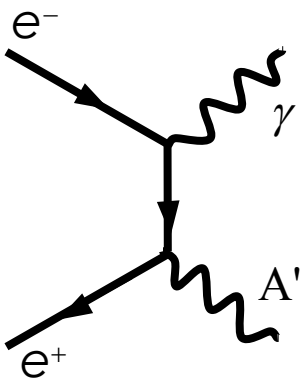
New gauge bosons

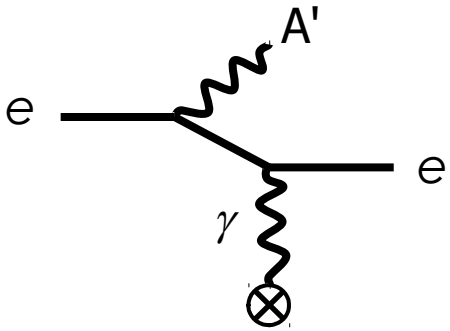
- The effective interaction that can be studied is



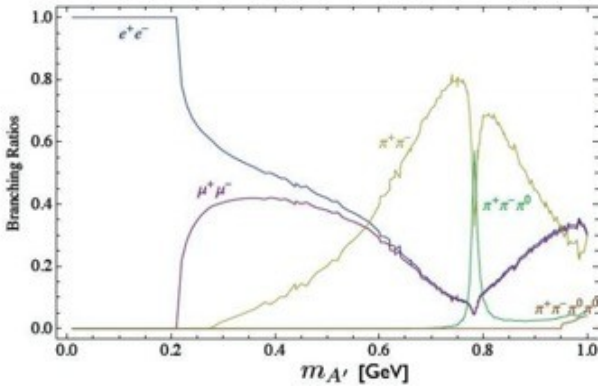
$$\mathcal{L} \sim g' \overline{\Psi} (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'^\mu, \quad usually\ \alpha'_a = 0$$

- Production mechanisms

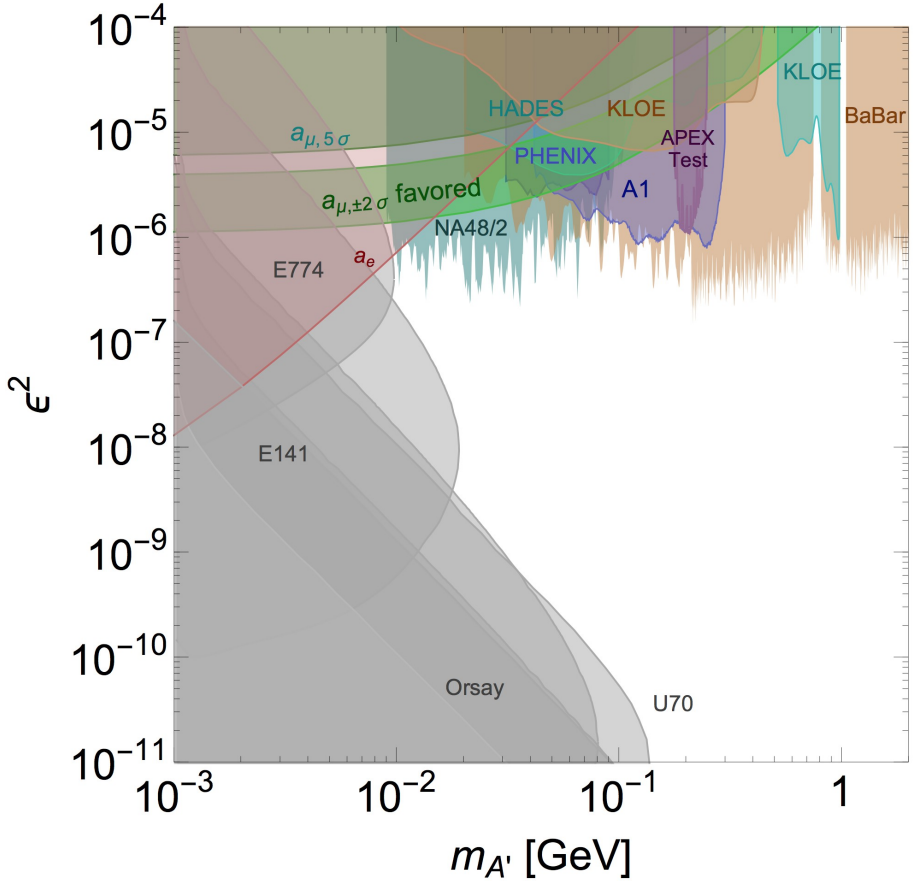


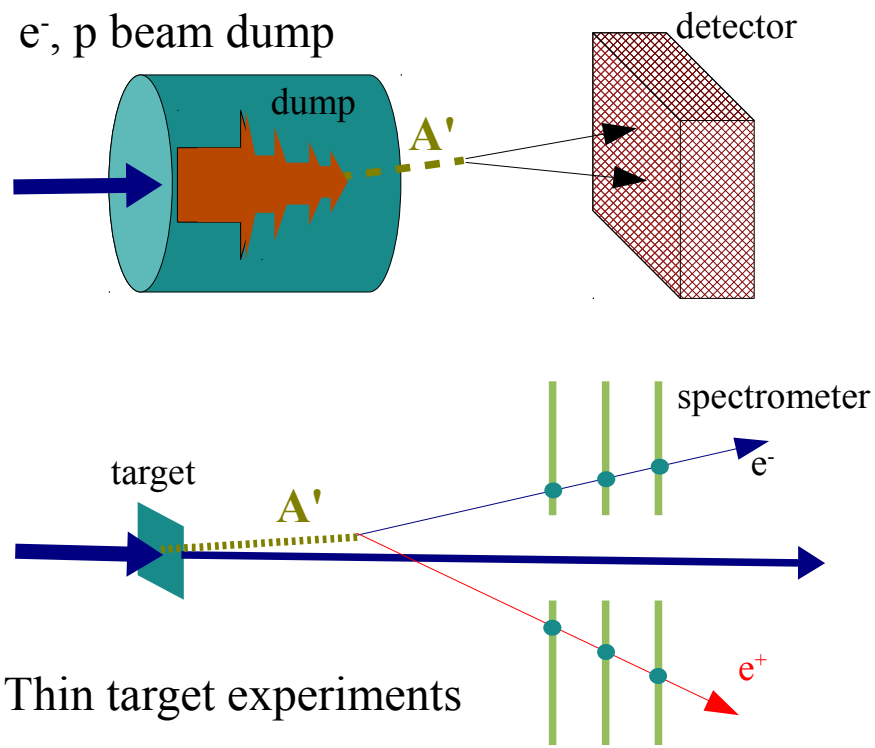


- Such textbook scenario could address the (g_μ-2) discrepancy, abundance of antimatter in cosmic rays, signals for DM scattering
  - General U'(1) and kinetic mixing with B (A', Z')
    - Universal coupling proportional to the q_{em}
    - Just single additional parameter – ε
  - Leptophilic/leptophobic dark photon
- Rich dark sector, contributing to DM explanation



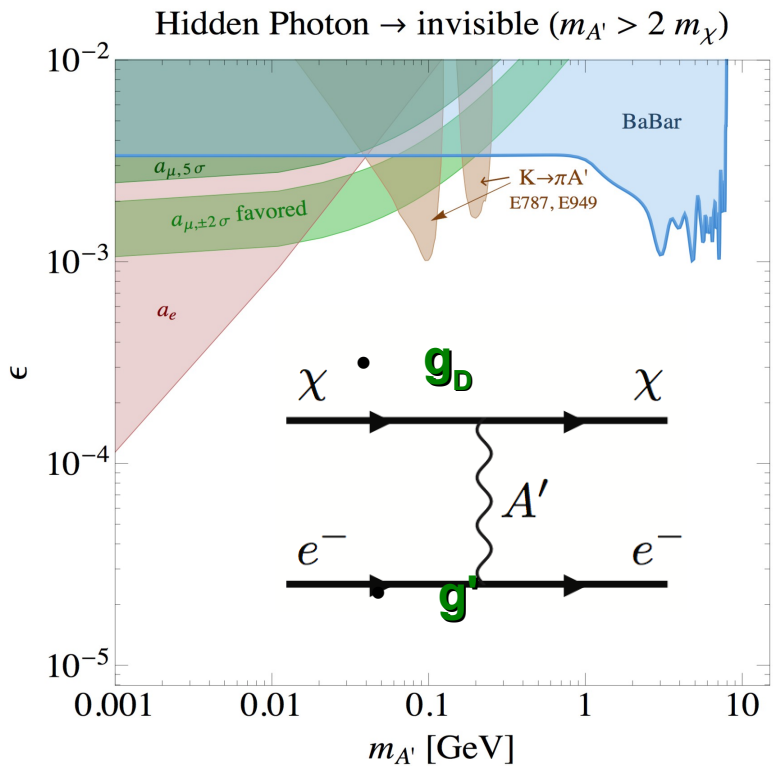
Heavy/Dark photon/boson searches

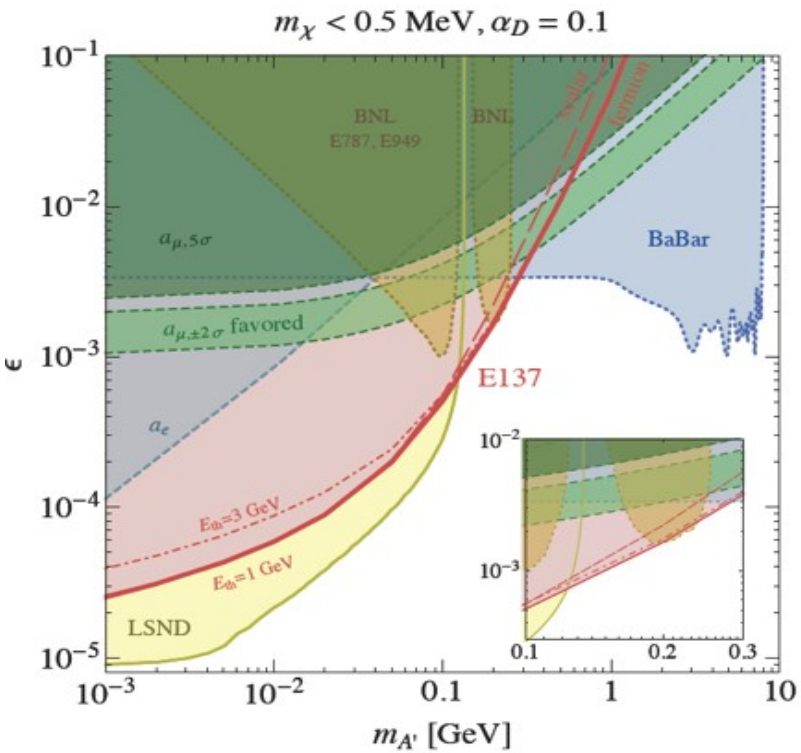




- Beam dump experiments: A'-strahlung production
- Fixed target: peaks in the e^+e^- invariant mass spectrum
- Meson decays: Peaks in M_{e+e-} or $M_{\mu+\mu-}$

Invisible A' searches





- Really model independent addressing of the dark gauge boson parameters is difficult
- Four parameter space to be studied: **$M_{A'}$, g', g_D, M_χ**
  - **g'** could also be flavour dependent

How to improve?

- Searching a dark photon in a kinematically constraint event and using full reconstruction
- Basic process: positron on a fixed target

$$e^+ + e^- \rightarrow \gamma + U \begin{cases} \gamma + E_{miss} & \text{(invisible channel, } A' \rightarrow \chi\chi) \\ \gamma + e^+e^- & \text{(visible channel, } A' \rightarrow e^+e^-) \end{cases}$$

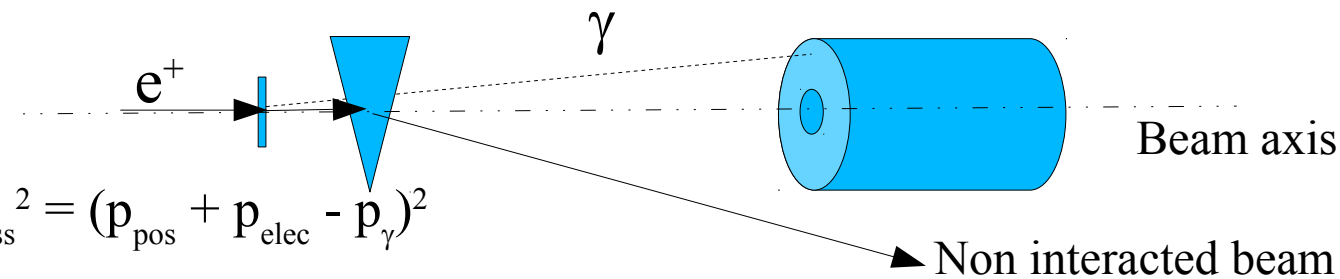
- Normalizing to the concurrent process - **annihilation**

$$\frac{\sigma(e^+e^- \rightarrow \gamma A')}{\sigma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(\gamma A')}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(\gamma A')} = \varepsilon^2 * \delta$$

  - $N(\gamma A')$, $N(\gamma\gamma)$ - number of registered events
  - $Acc(\gamma A')$, $Acc(\gamma\gamma)$ - detection efficiency
  - $\delta = \sigma(e^+e^- \rightarrow \gamma A')/\sigma(e^+e^- \rightarrow \gamma\gamma)$ at $\varepsilon = 1$ – cross section enhancement factor

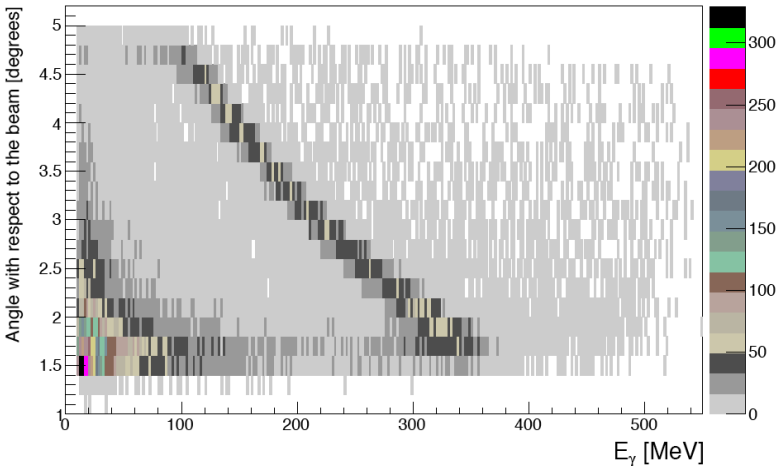
Basic ideas

Study only the recoil photon



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

- Electron is at rest
- Positron momentum is determined by the accelerator characteristics
- Basic contribution to the missing mass resolution – reconstruction of the photon 4-momentum
  - Interaction point inside the target
  - Cluster position in the calorimeter
  - Energy resolution of the calorimeter
- Background suppression
  - Veto on extra particles



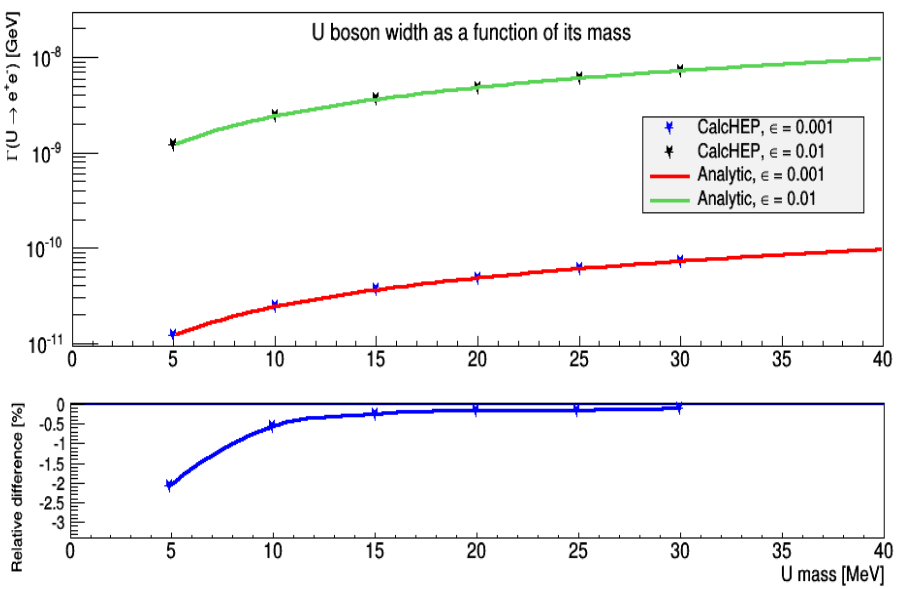
DP model

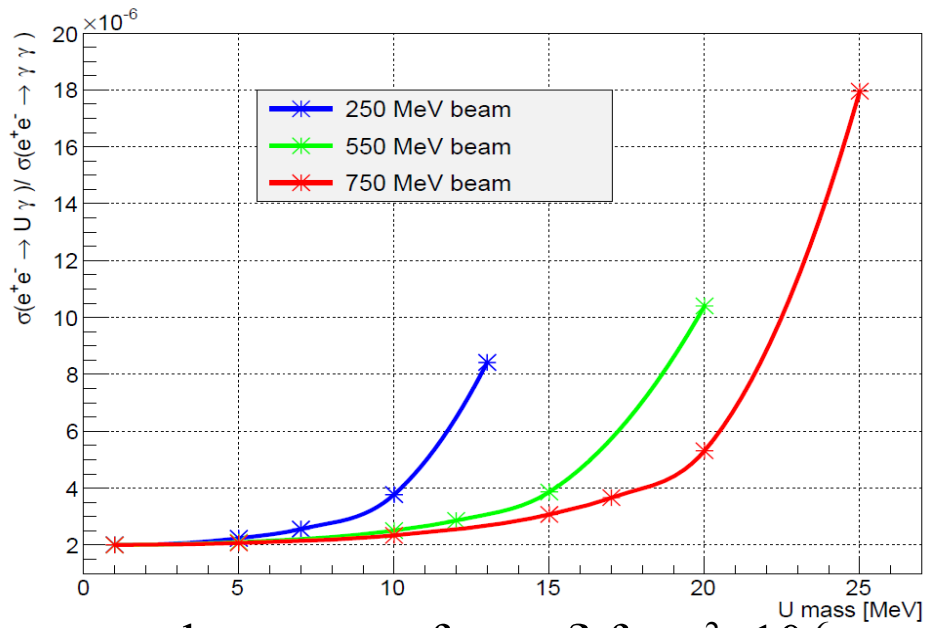
- Simple model implemented in CalcHEP, used for the further studies

$$\mathcal{L} \sim \varepsilon \bar{e} \gamma_\mu e A'^\mu, \text{only for } e^\pm$$

- Validate with A' decay rate into e^+e^-

$$\Gamma_U = \Gamma_{U\to e+e-} = \frac{1}{3}\alpha\epsilon^2 M_U \sqrt{1-\frac{4me^2}{M_U^2}}\left(1+\frac{2me^2}{M_U^2}\right)$$



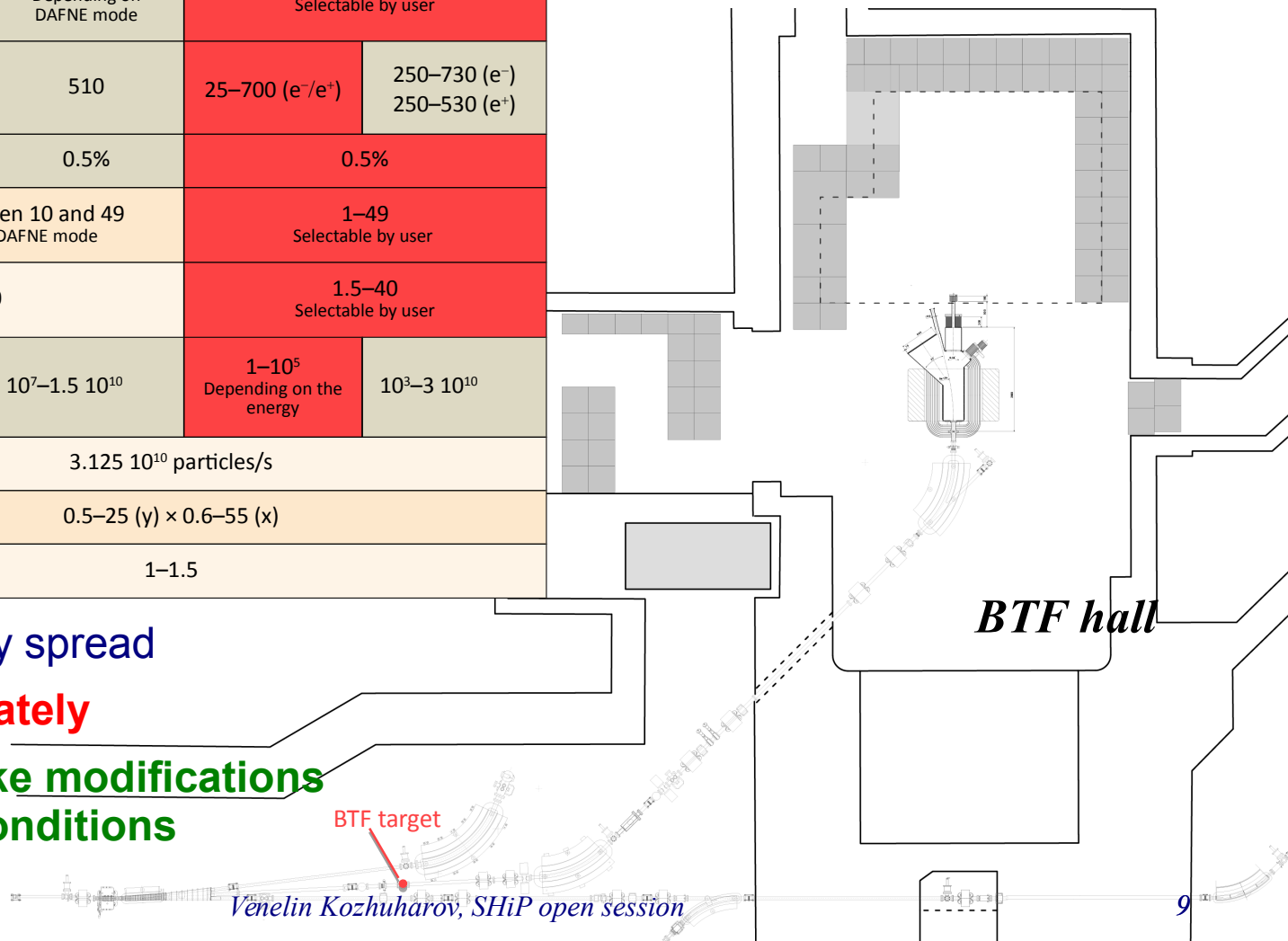


enhancement factor δ for $\varepsilon^2=10^{-6}$

For $\sqrt{s} >> M_A$, $\sigma(e^+e^-\to\gamma A') = 2 * \varepsilon^2 * \sigma(e^+e^-\to\gamma\gamma)$

BTF @ LNF

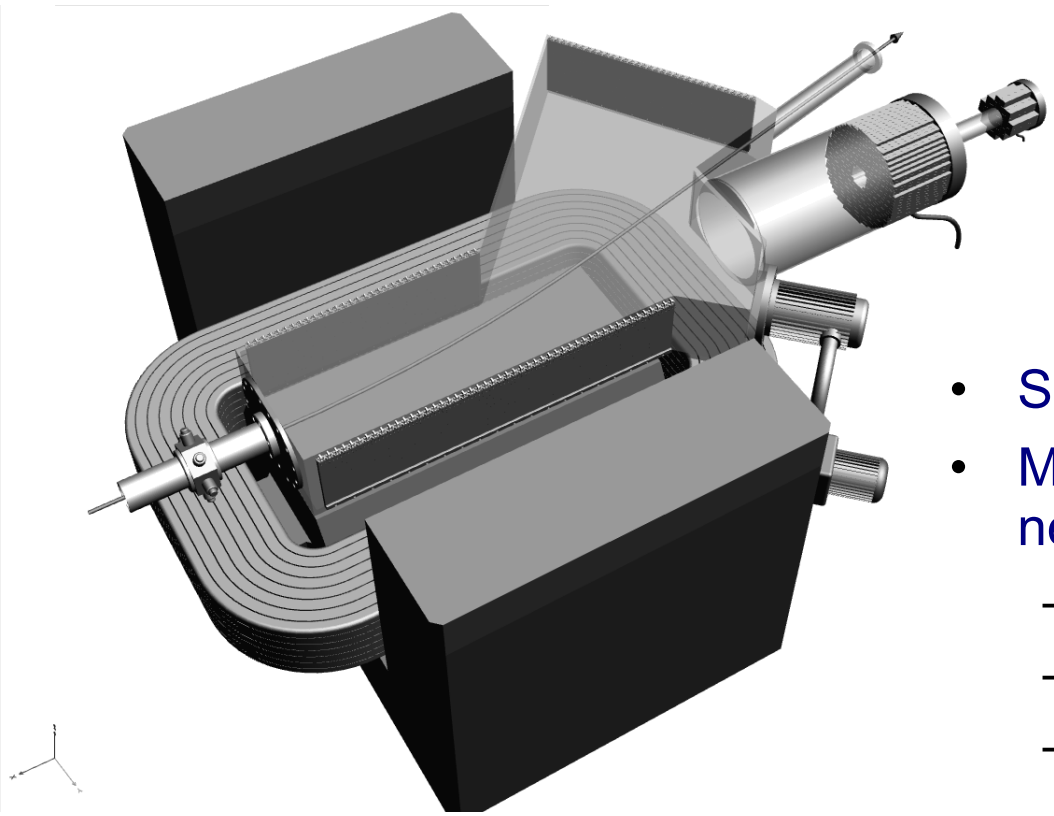
Parameter	Parasitic mode		Dedicated mode	
	With target	Without target	With target	Without target
Particle species	e^+ or e^- Selectable by user	e^+ or e^- Depending on DAFNE mode	e^+ or e^- Selectable by user	
Energy (MeV)	25–500	510	25–700 (e^-/e^+)	250–730 (e^-) 250–530 (e^+)
Energy spread	1% at 500 MeV	0.5%	0.5%	
Rep. rate (Hz)	Variable between 10 and 49 Depending on DAFNE mode		1–49 Selectable by user	
Pulse duration (ns)	10		1.5–40 Selectable by user	
Intensity (particles/bunch)	$1–10^5$ Depending on the energy	$10^7–1.5\ 10^{10}$	$1–10^5$ Depending on the energy	$10^3–3\ 10^{10}$
Max. average flux	$3.125\ 10^{10}$ particles/s			
Spot size (mm)	0.5–25 (y) × 0.6–55 (x)			
Divergence (mrad)	1–1.5			



- Small beam energy spread
- **Available immediately**
- **Possibility to make modifications to optimize the conditions**

PADME experiment

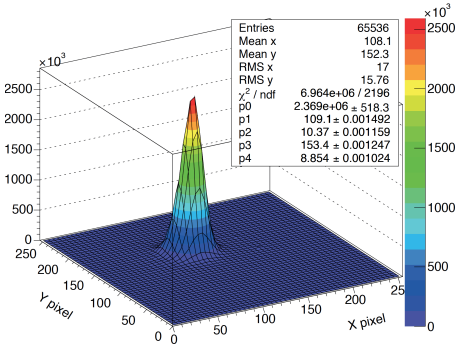
Positron Annihilation into Dark Matter Experiment



- Small scale fixed target experiment
- Measuring both charged and neutral particles:
  - Charged particles detector
  - Calorimeter
  - Beam profile

Beam

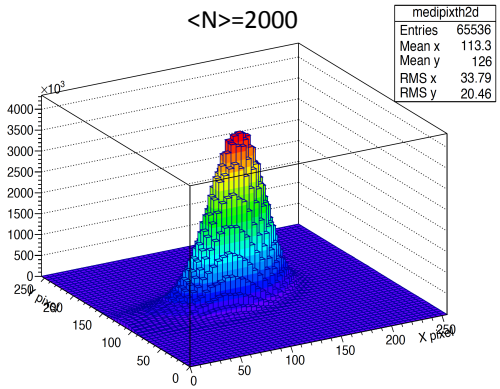
"single" particle



$RMS_x = 0.9$ mm

$RMS_y = 0.9$ mm

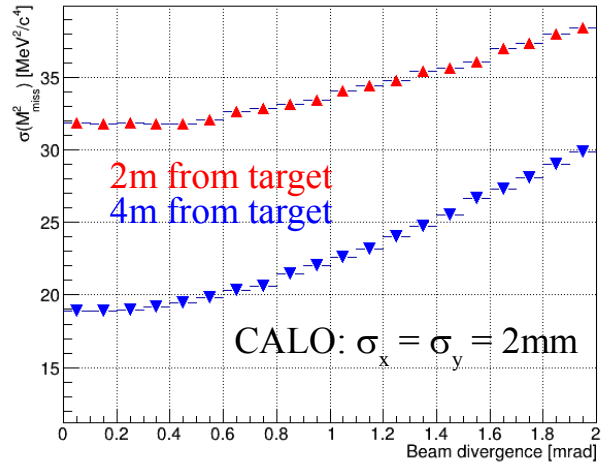
<N>=2000

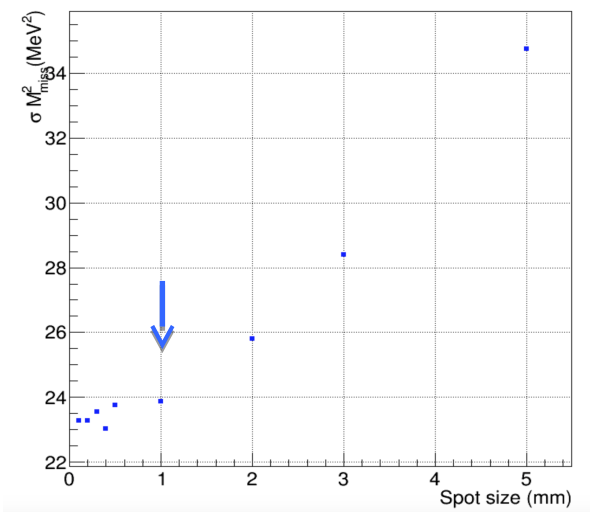


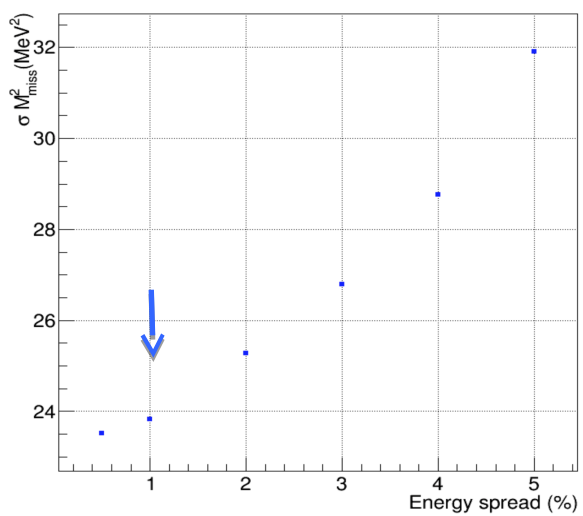
$RMS_x = 1.9$ mm

$RMS_y = 1.1$ mm

$M_{A'} = 5$ MeV





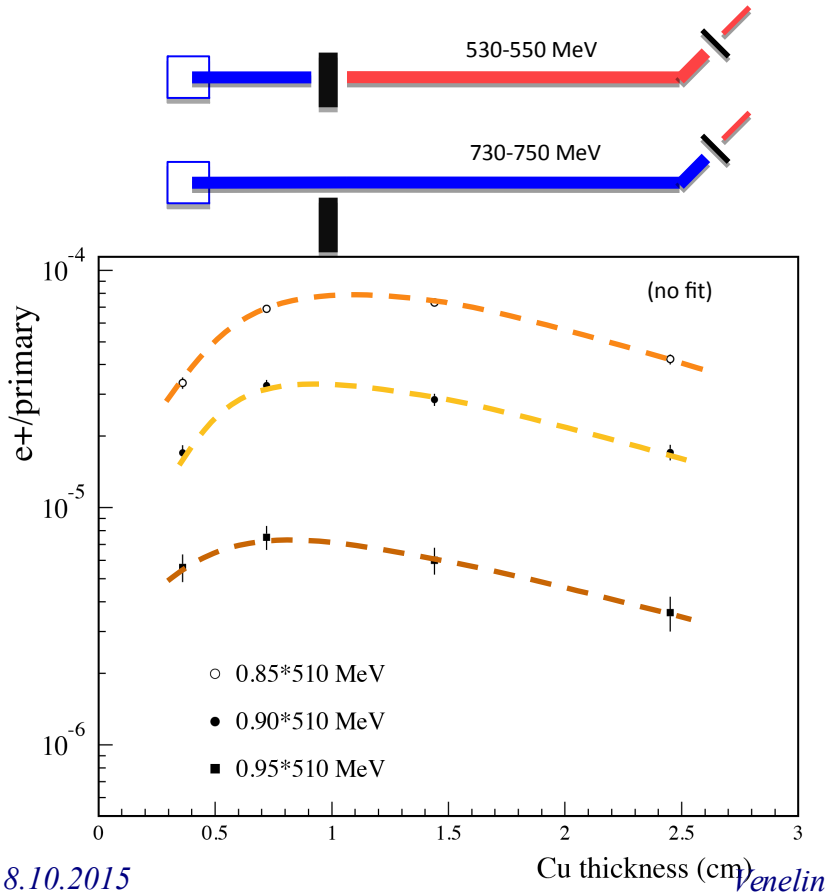


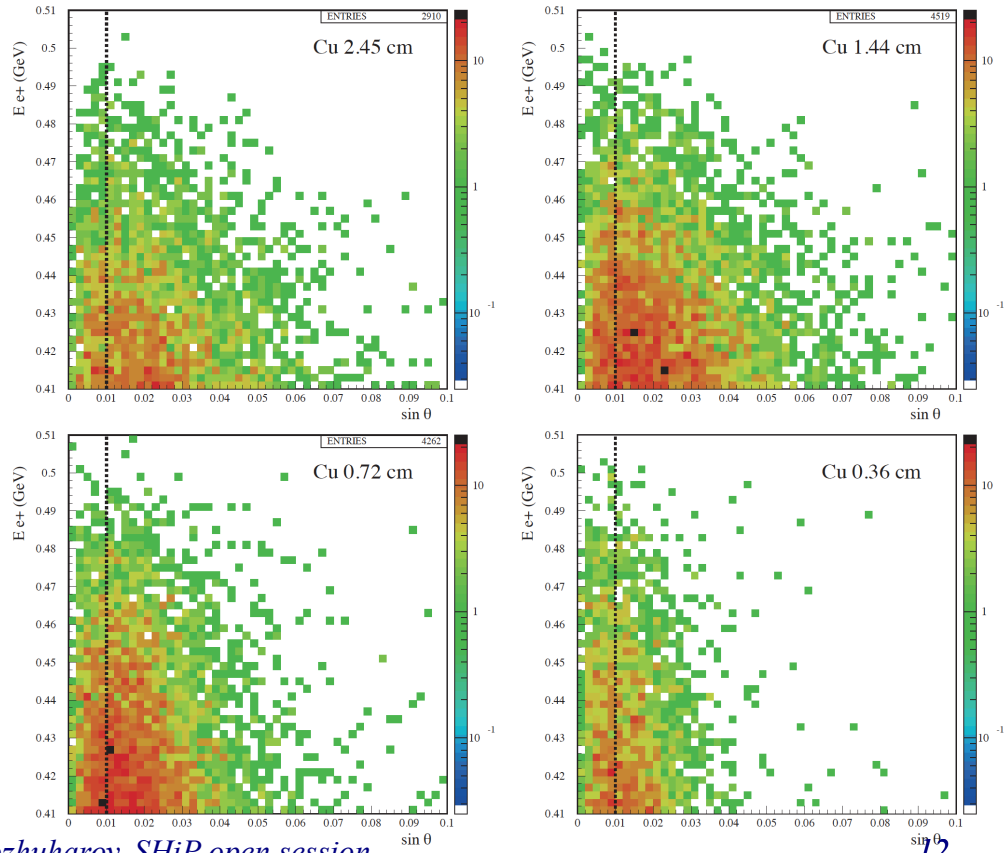
- 10^3 – 10^4 e^+/bunch can be achieved by adjusting the collimators
  - Divergence
  - Energy spread

Optimization

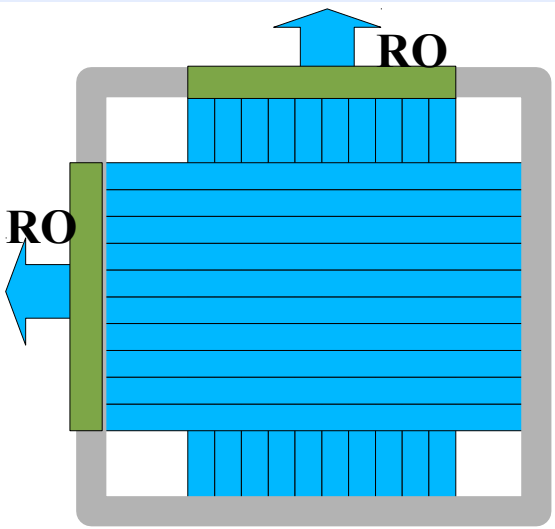
Positron Beam optimization

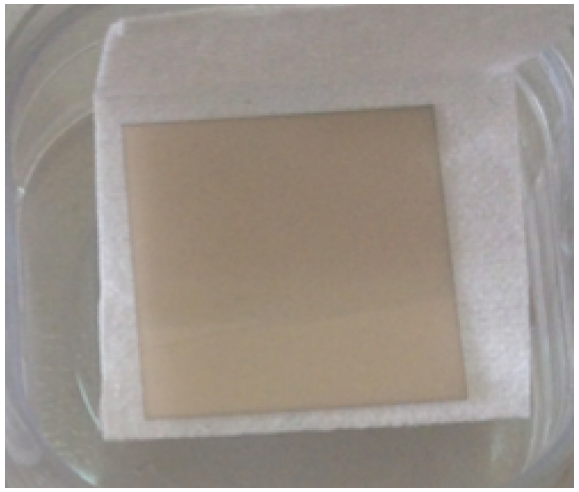
- The nominal positron convertor is after the first section of the Linac, limiting the maximum e^+ energy up to 550 MeV
- 10^{10} primary electrons/bunch, 10^4 e+ necessary for PADME
  - **Possible to use the BTF target to produce positrons**

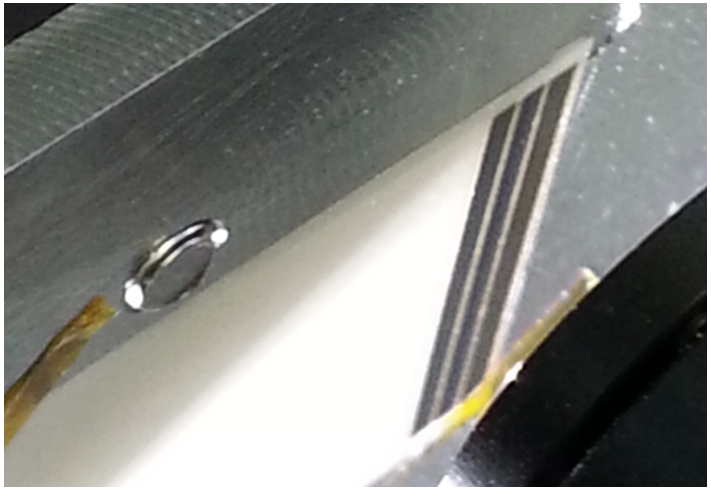




Active target

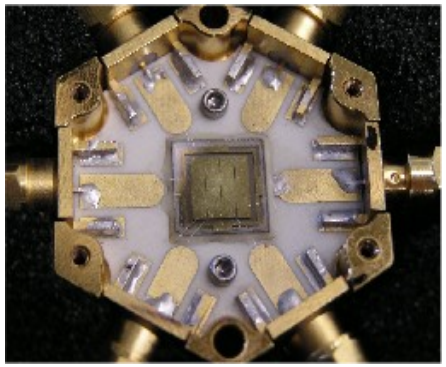




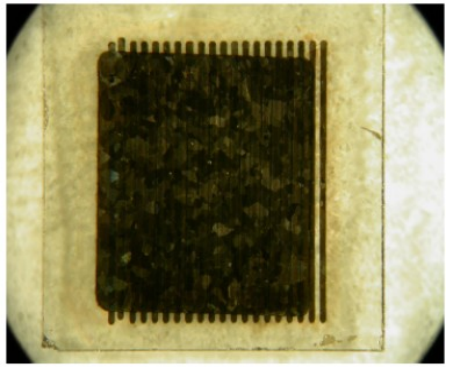


- Graphitized diamond – strips of 1mm width
  - All carbon target
- The production of 50 μm detector is state-of-the-art
  - 2 cm x 2 cm
  - Samples produced, 2x 50 μm thickness, 1 x 100μm thickness
- To be tested at BTF in November

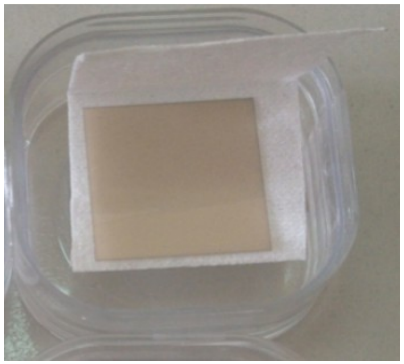
BTF test run in October, 2014



500 um, metal strips
6.5 mm long, 1.5 mm pitch

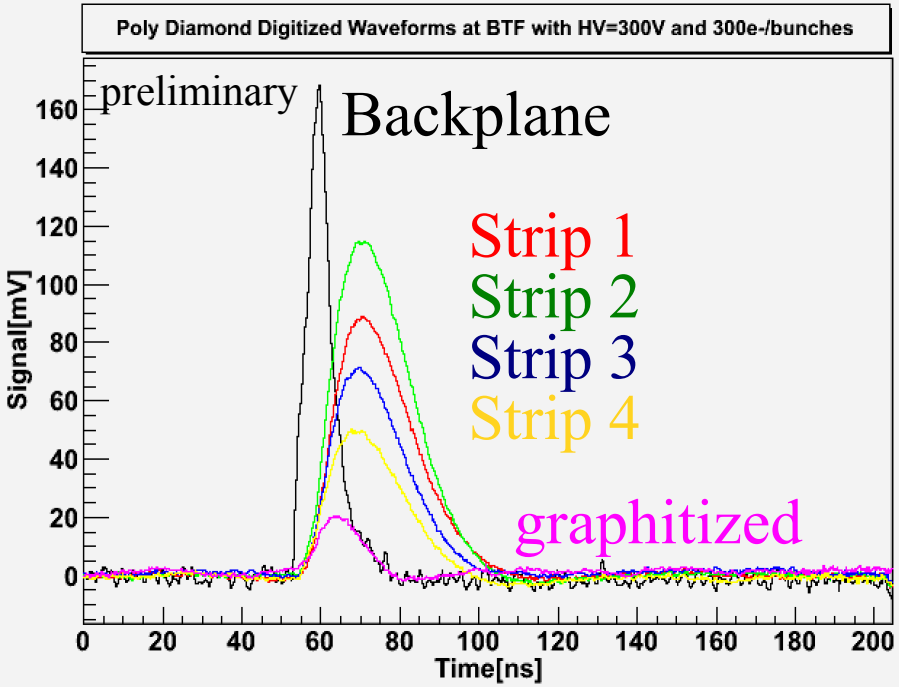


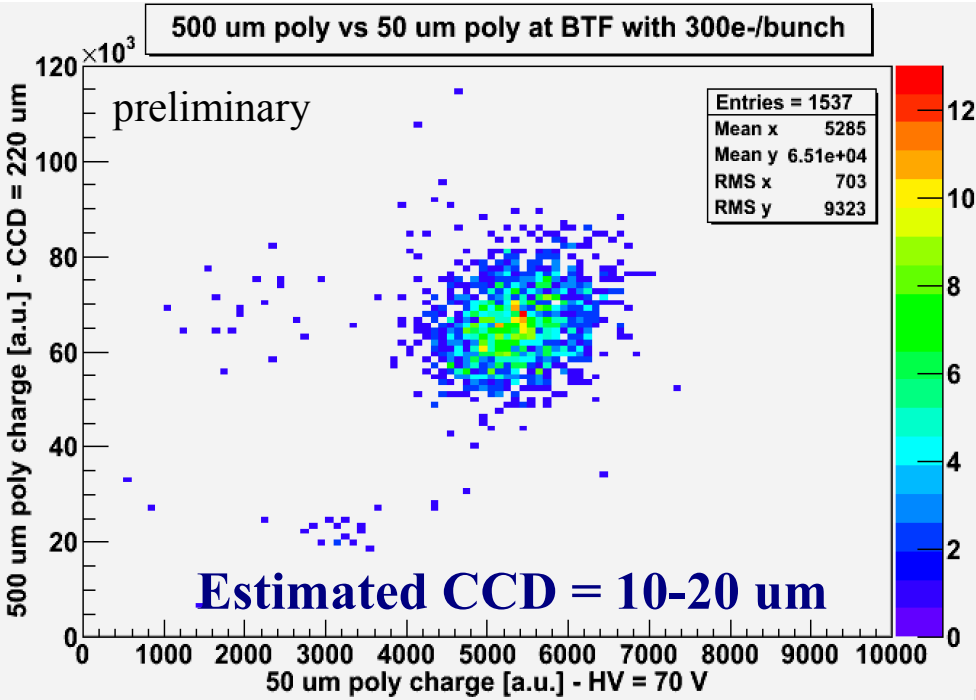
300 um, graphitized strips
3mm long, 100 um width



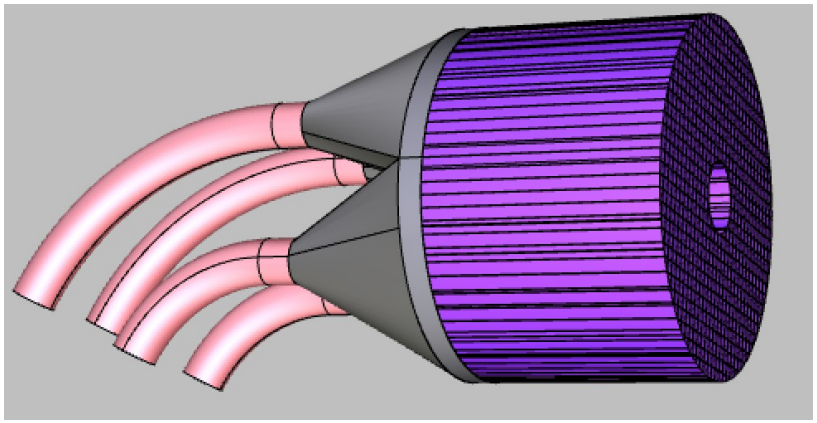
50 um, 2cm x 2 cm
first sample for PADME

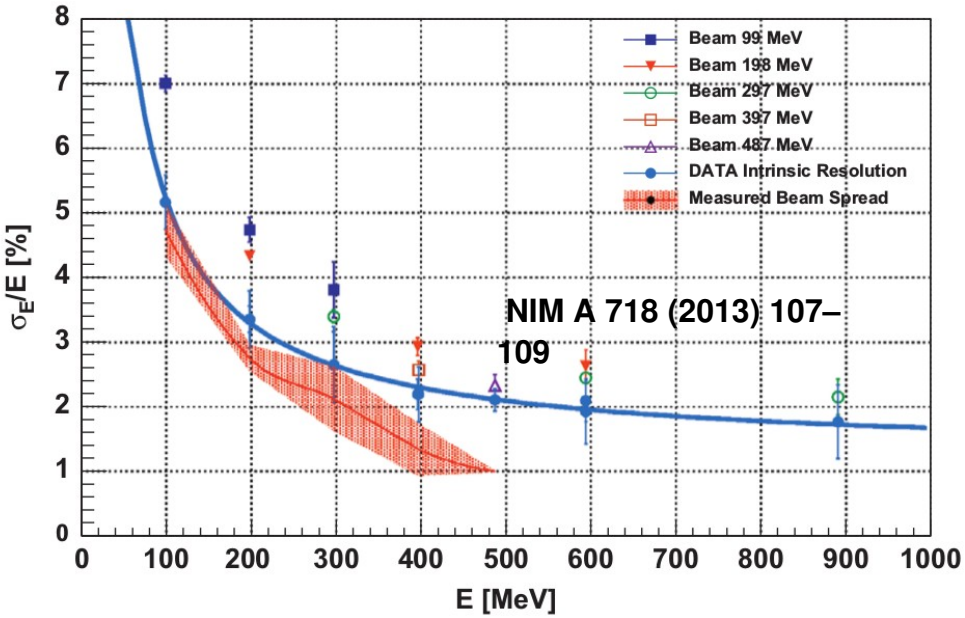
50 um, silver paint
5 mm x 5 mm





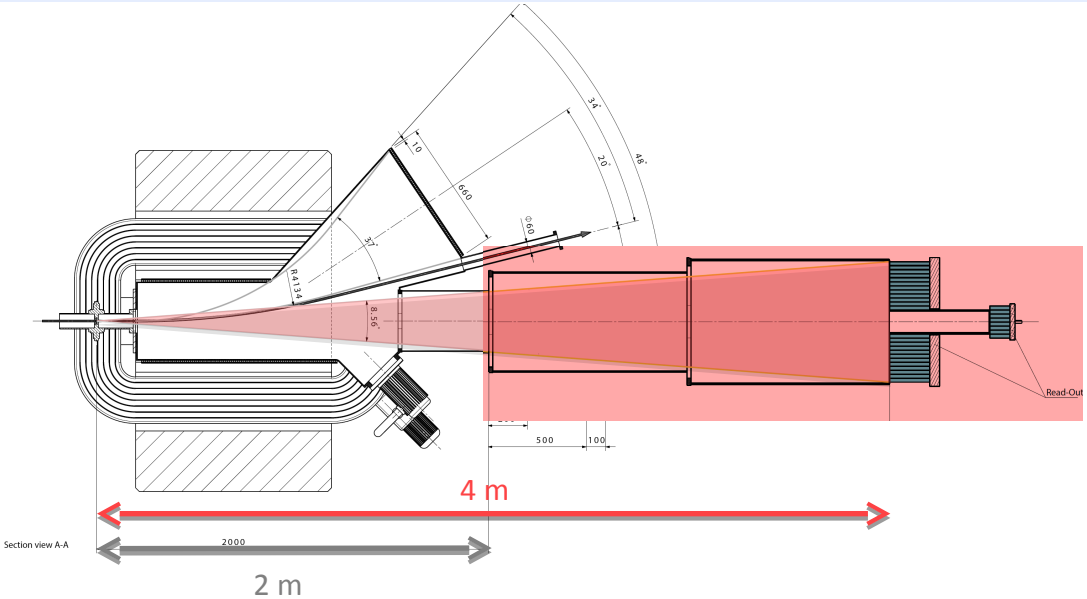
Calorimeter

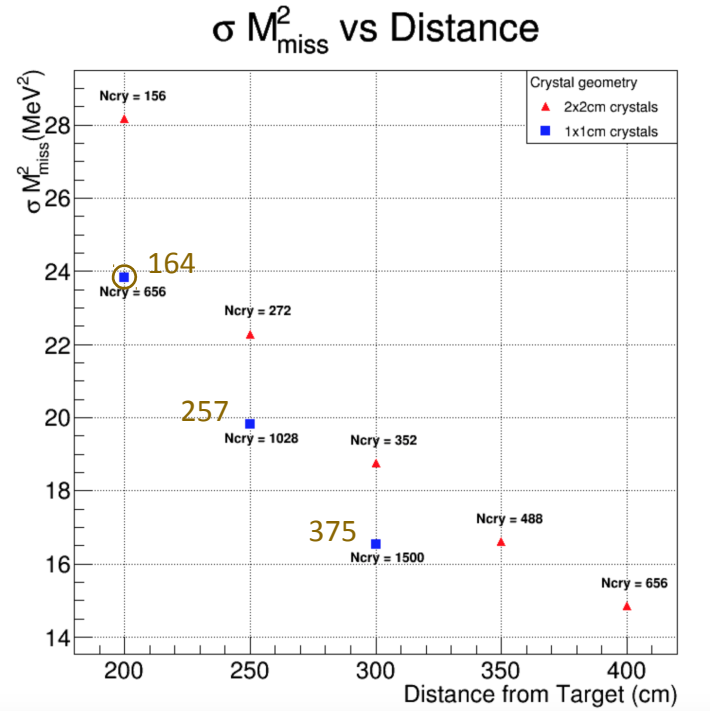




- Cylindrical shape
- LYSO was assumed to be the best solution and was used as a baseline for estimating the sensitivity
  - Located 2m downstream the target
  - 656 LYSO crystals. 1x 1 x 15 cm^3
- Energy resolution: $\sigma E/E = \frac{1.1\%}{\sqrt{E}} \oplus \frac{0.4\%}{E} \oplus 1.2\%$
- Possible substitutions under investigation: BGO

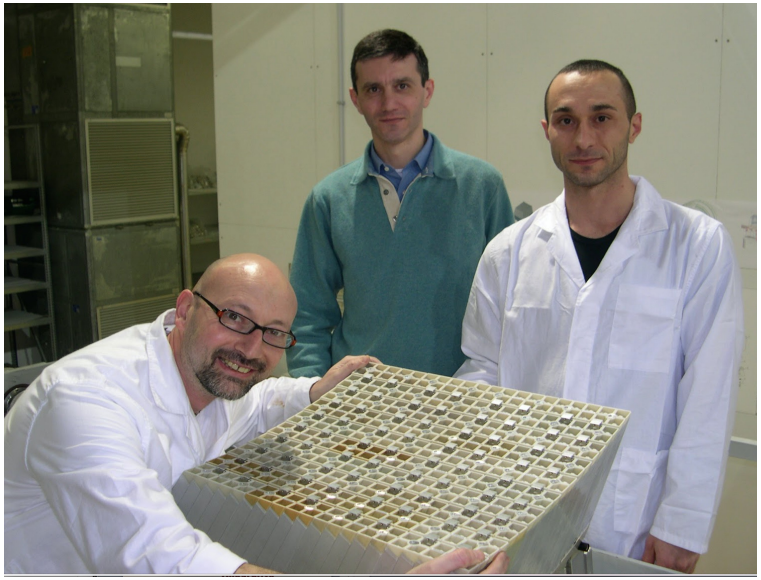
Calorimeter design





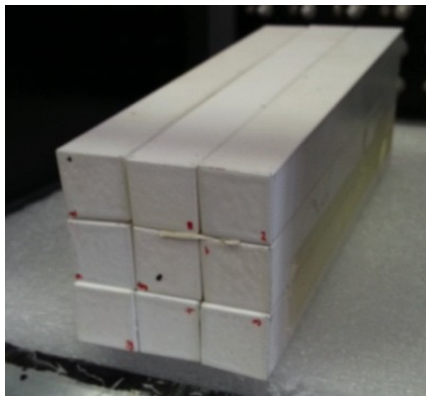
- BGO crystals available from L3 experiment
- Crystal geometry is close to 2 x 2 cm front face
  - Cut the crystals in 1 x 1 cm and place them at 2 m
    - Requires cutting of the existing crystals, but the quantity is identified and available
  - Place the calorimeter at 4 m distance and keep the dimensions 2x2 cm
    - Agreement on the usage of extra crystals

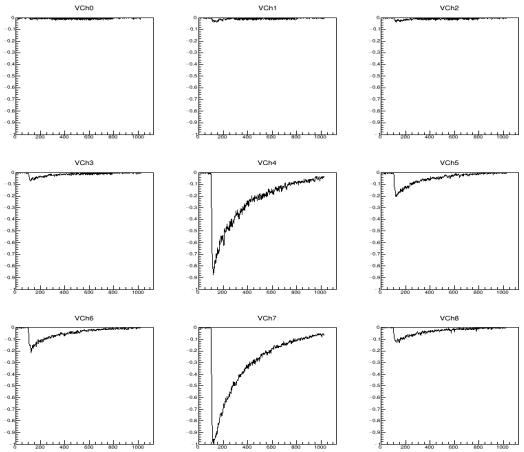
BGO crystals

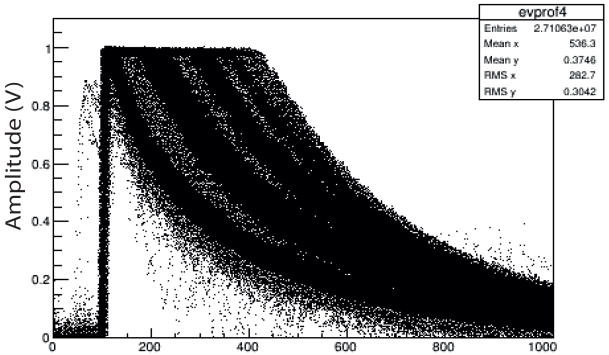


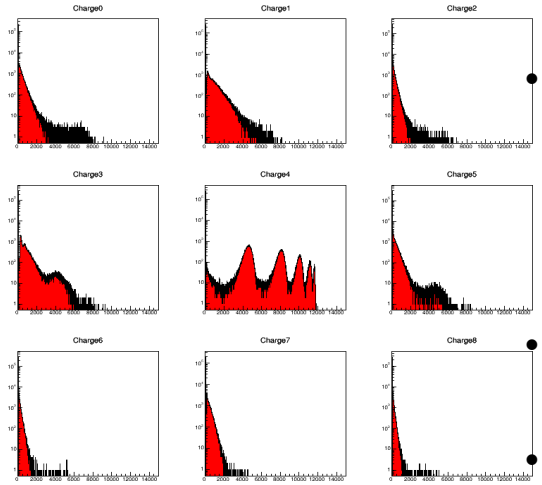
- Single L3 crystal cut into 4 1cm x 1cm crystals
- Primary solution for the calorimeter
  - Only 164 BGO crystals required
- If more crystals available -> bigger calorimeter

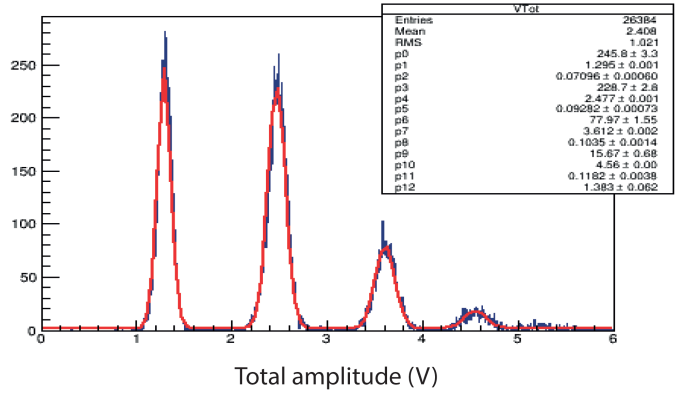
Test run at BTF





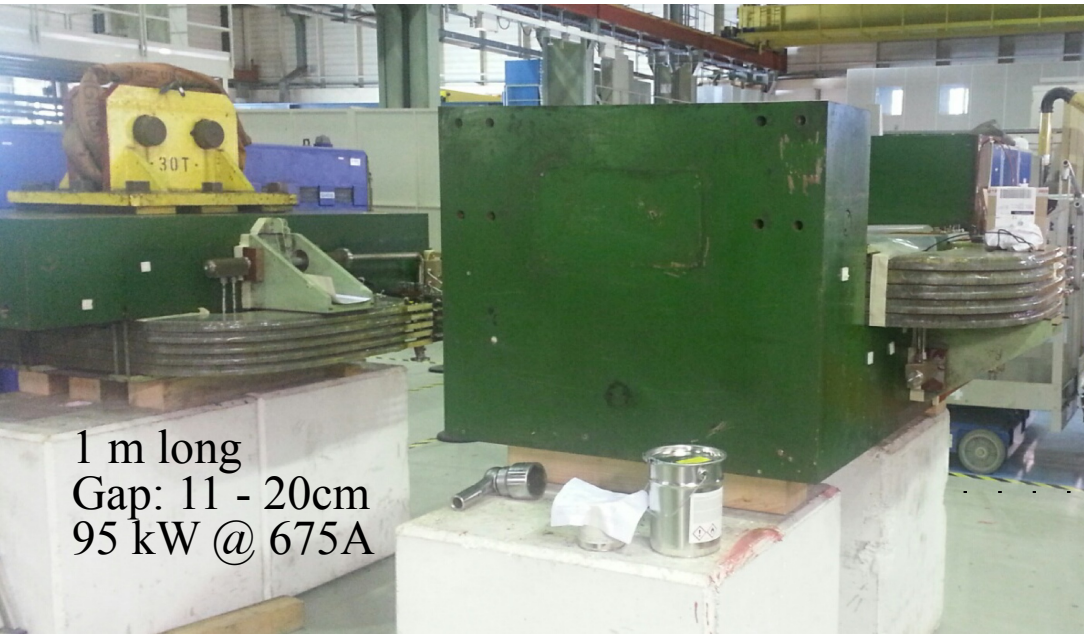






- 3x3 matrix tested at BTF in May
  - PMT R6427
- RO: CAEN V1742 digitizer @ 1GS/s
  - Study the signal shape
  - Reconstruct pulses
  - Address saturation
- A fit on the signal leads to proper energy deposit determination
- Test with APD and SiPM foreseen

Magnet



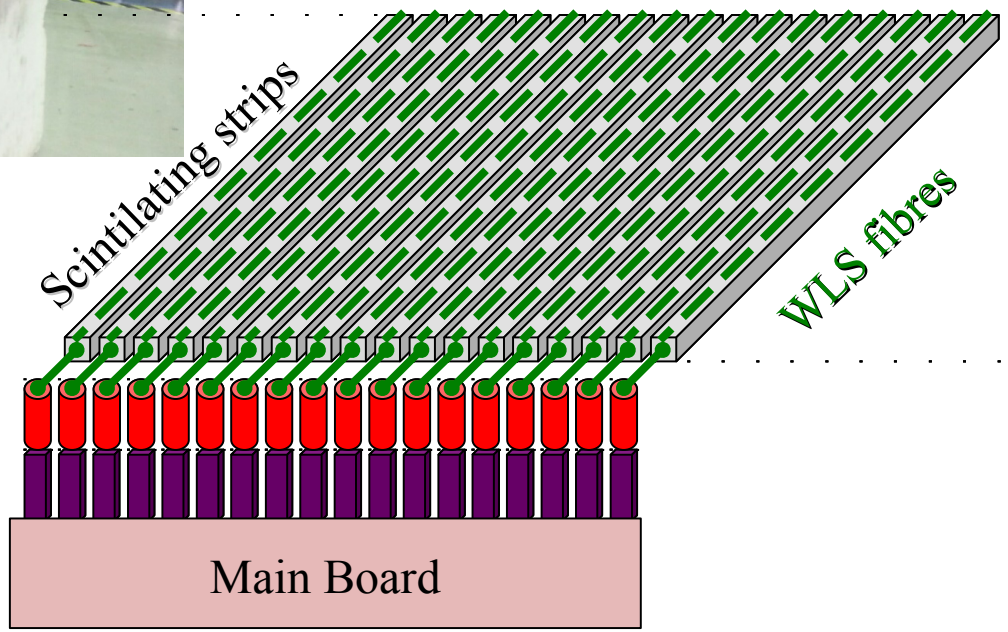
- CERN spare magnet: MBP-S
- To be refurbished from CERN and transported to LNF
- Usage of the DAΦNE PS: 400A

Charged particle detector

- Plastic scintillator detector

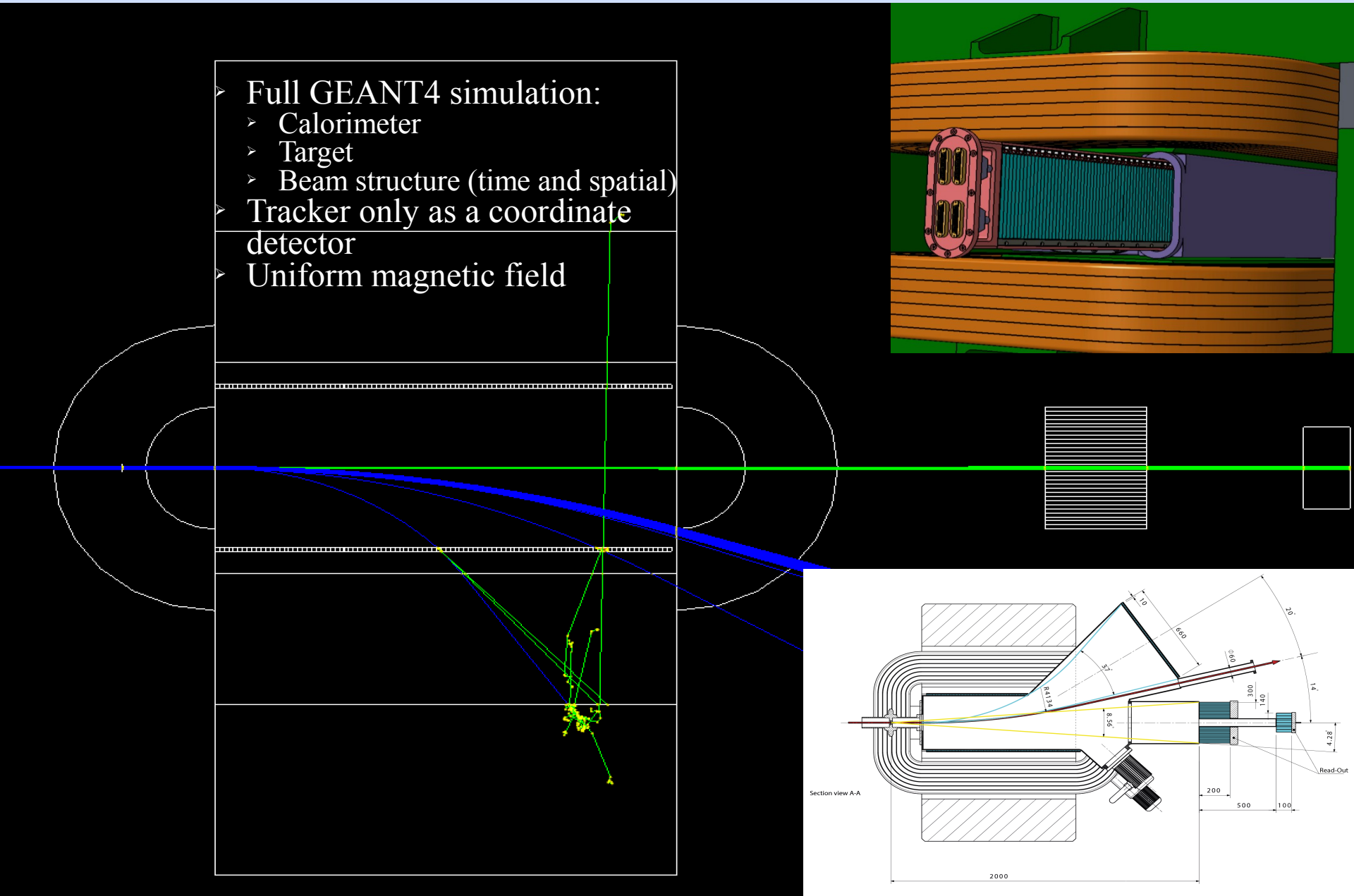
SiPM based readout

FEE electronics & power supply



Sensitivity

- Full GEANT4 simulation:
  - Calorimeter
  - Target
  - Beam structure (time and spatial)
- Tracker only as a coordinate detector
- Uniform magnetic field

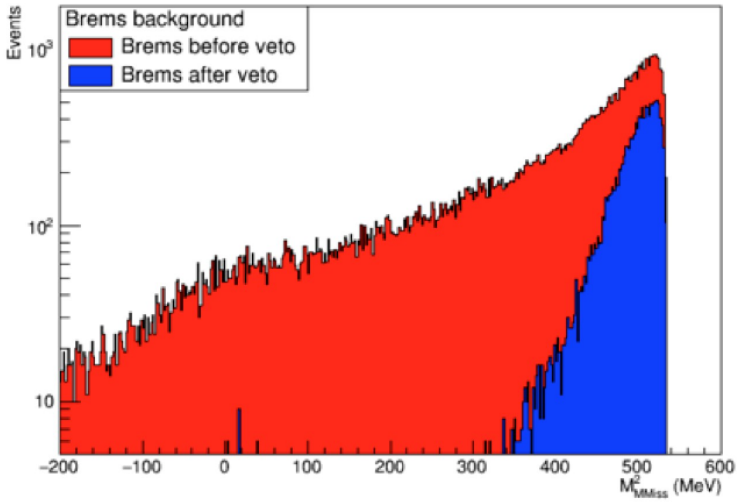


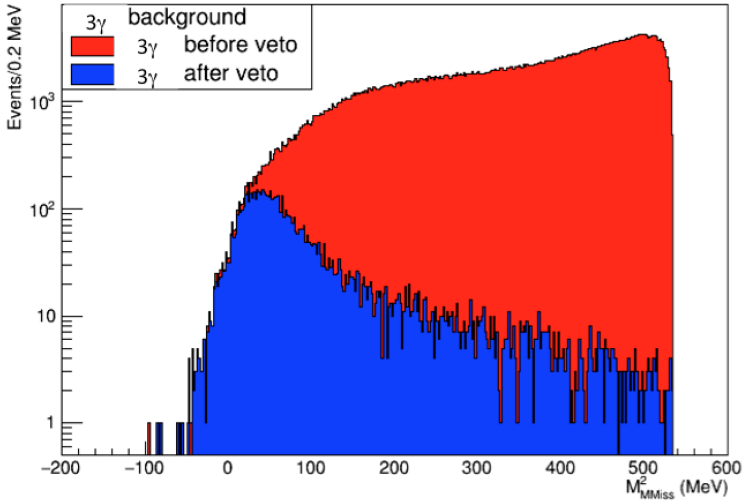
Background

Selection

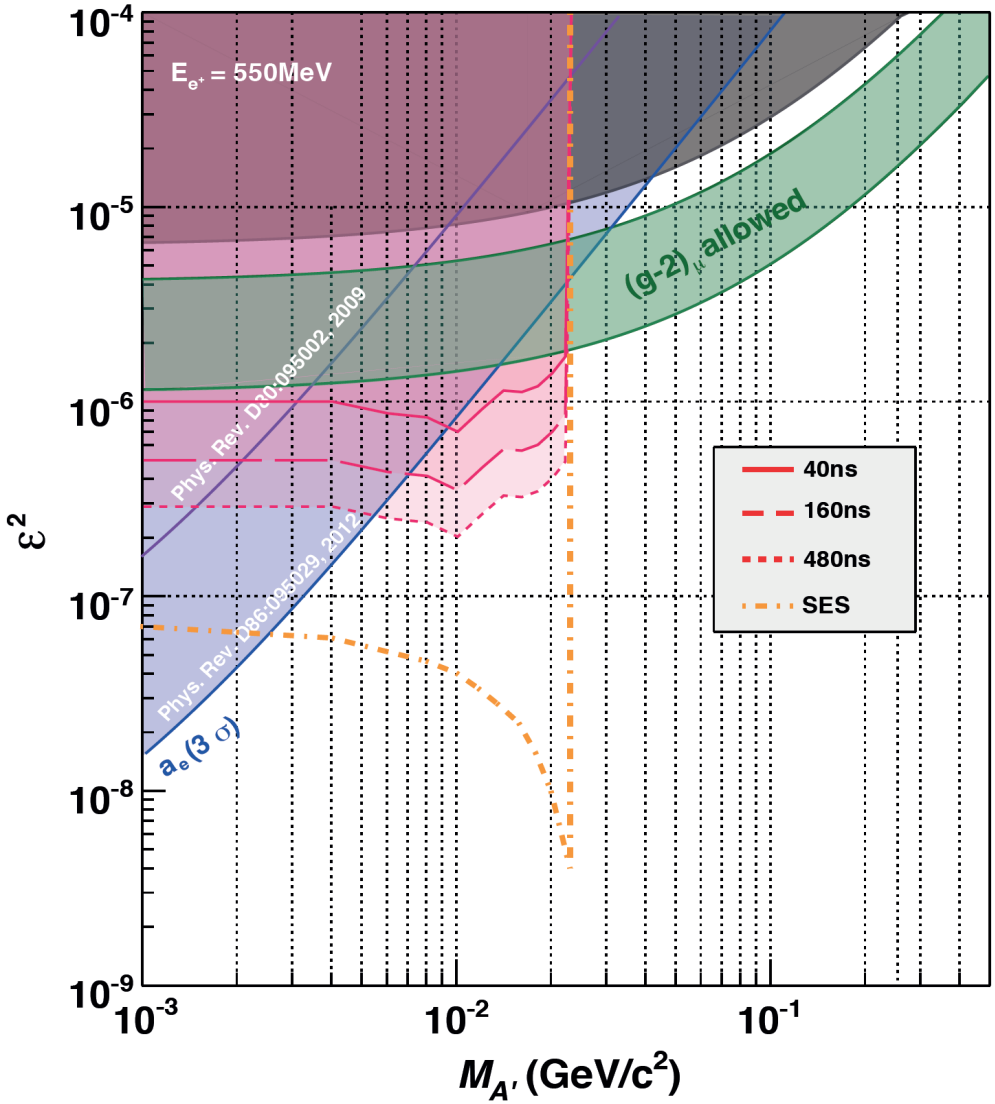
- Kept as simple as possible
- Attempt for a common selection of visible/invisible scenarios

- Single cluster in the Calo
- 5 cm < Rcl < 13 cm
- Cluster energy:
  $E^{CL}_{min}(M_{A;})$ in 50 – 150 MeV
  $E^{CL}_{max}(M_{A'})$ in 120 – 350 MeV
- Kinematics
  - ± 1σ cut on the missing mass
- Veto on positrons
- **Background: 2γ, 3γ, bremsstrahlung**





Sensitivity estimation



- Assumptions:
  - 40 ns bunch length
  - 49 Hz repetition
  - 6000 e^+/bunch
- Accessible regions:
  - E=550MeV: $M_{A'}$ < 23.7 MeV
- Improvements possible
  - Increase beam energy
  - Extend the bunch length

PADME extended programme

conventional electron beam and A'-strahlung: $e^- Z \rightarrow e^- Z A'$

$A' \rightarrow l^+l^-$ visible decay search

Beam dump experiment

- Measuring l^+l^- momentum with a spectrometer
- Selection based on M_{l+l-}

Visible decays in $e^+ + e^- \rightarrow \gamma + A' \rightarrow \gamma + e^+ + e^-$

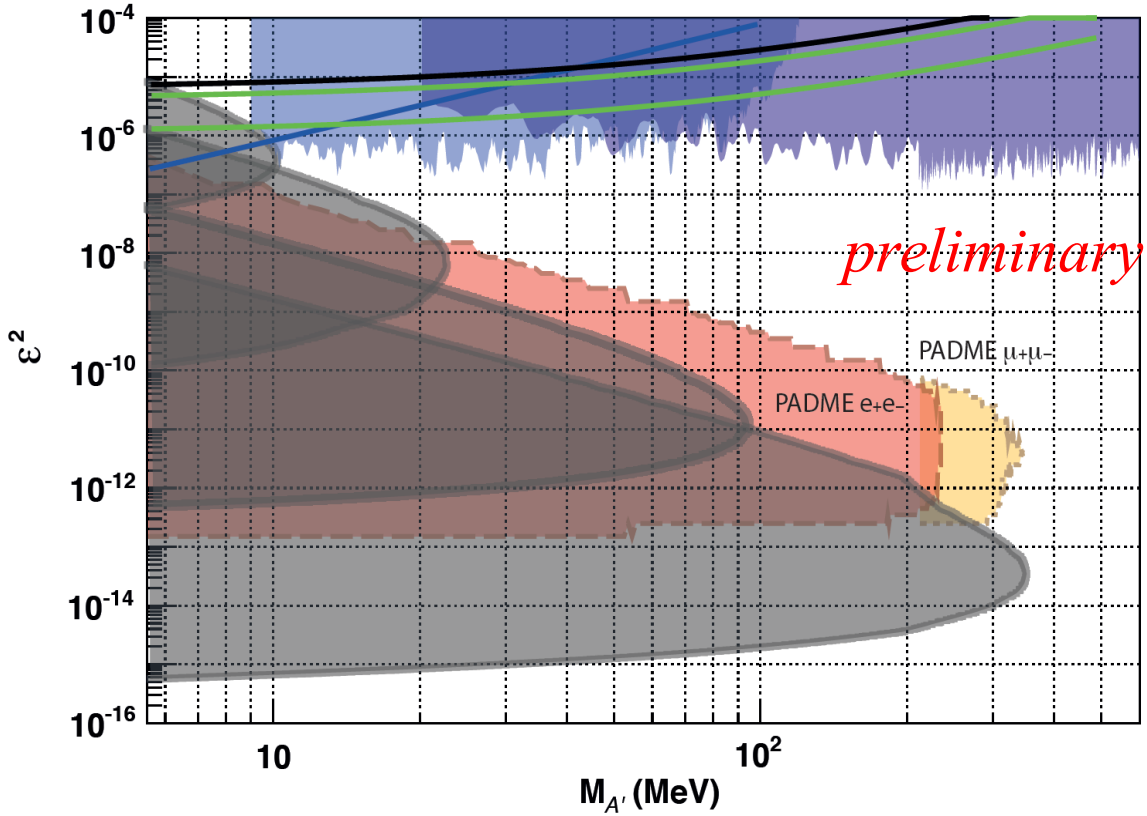
- ~High acceptance (high boost of the produced A' and deflection in the magnet)
  - ~2 times more sensitivity
- Better invariant mass resolution
- Missing mass of γ constraint
- Sensitivity: $\varepsilon \sim 10^{-7}$
- The first channel to look at if excess of events is observed

PADME visible decays

conventional electron beam and A'-strahlung: $e^- Z \rightarrow e^- Z A'$

$A' \rightarrow e^+e^-$ visible decay search

Beam dump experiment: $A' \rightarrow e^+e^-$ and $A' \rightarrow \mu^+\mu^-$



Extend $M_{A'}$ sensitivity, but model dependent

Status

The PADME experiment Technical Proposal

The PADME Collaboration*

Editors: Mauro Raggi[a,1], Venelin Kozhuharov[b,2], and Paolo Valente[c,3]

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PADME

September 25, 2015

INFN Istituto Nazionale di Fisica Nucleare

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Conclusions

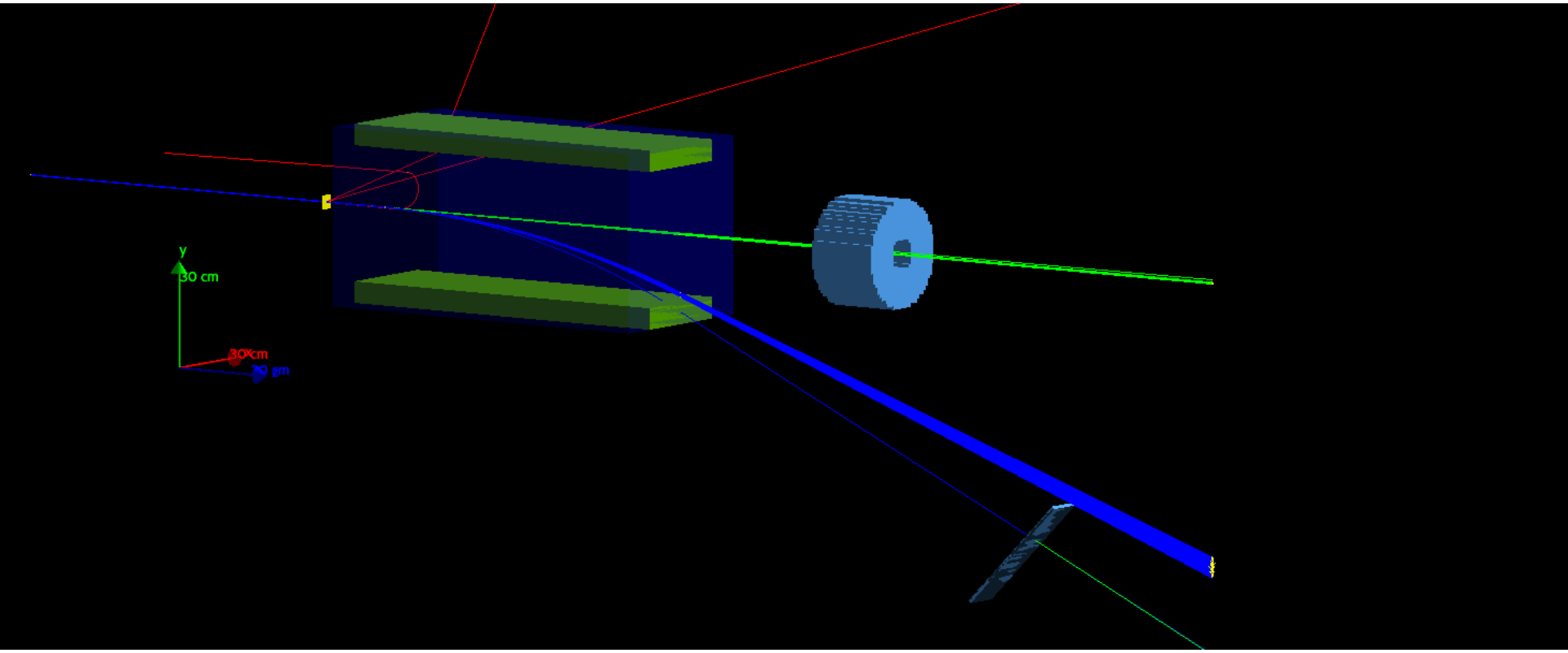
- PADME is a small scale fixed target experiment to search for dark photons in the invisible channel.
- Interesting parameter space could be covered, using 10^3 – 10^5 e^+/bunch.
- **Test beam and initial studies already ongoing**
- A portal for a complete physics program devoted to the dark photon searches is open – visible, invisible, thin target, thick target, dump, electron or positron

- **PADME was endorsed by CSN1 for full financing inside the WhatNext INFN programme**

Starting construction next year

SPARE

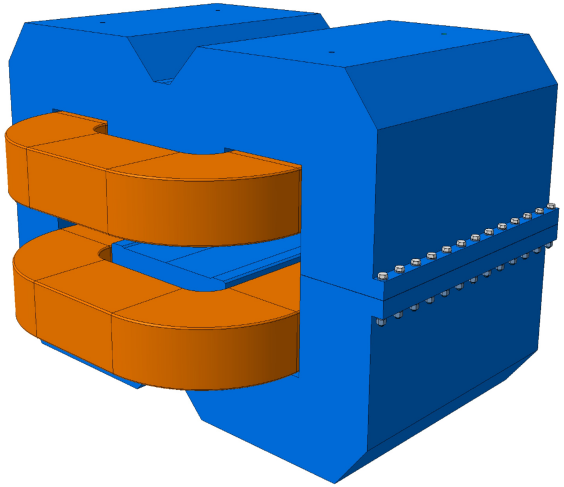
PADME schematics

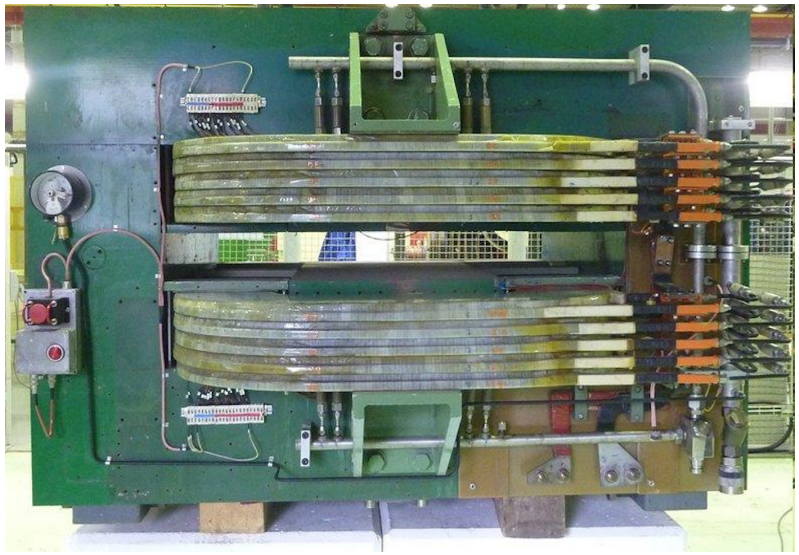


- Additional elements could be added in case of necessity (or profit)

Spectrometer technology

- CERN available magnet versus special magnet design





0.6 T.m in simulation

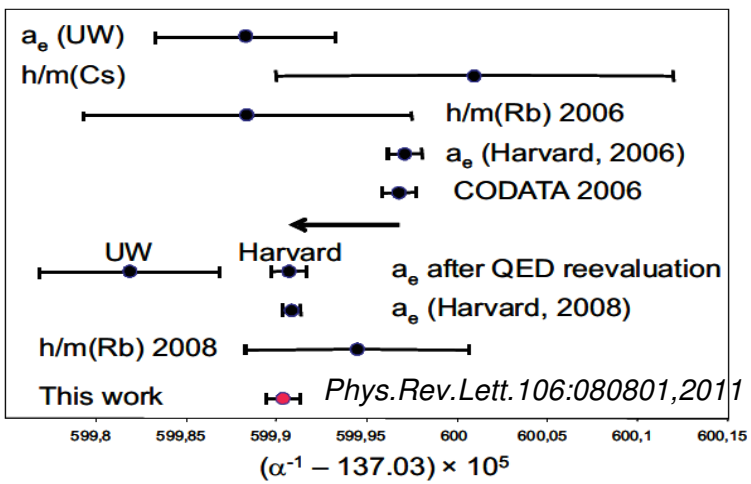
~ 0.8 T possible for aperture 20cm

Detector technology

- GEM based detector
  - 5 layers of tripple GEMs on each side or TPC with GEM readout
- Plastic scintillator detector
  - Correlation between longitudinal impact and track momentum
  - Strips versus fibers, SiPM readout vs CCD readout (50 Hz events)
- Other alternatives also in consideration

Present limits: invisible searches

- There is no published direct present limit in the U→invisible decay – from $a=\frac{g-2}{2}$
- The discrepancy is not in g_μ-2 itself, it's in the consistency of g_e & g_μ
- Alternative inputs should be used to extract information from g_e: α_{EM}



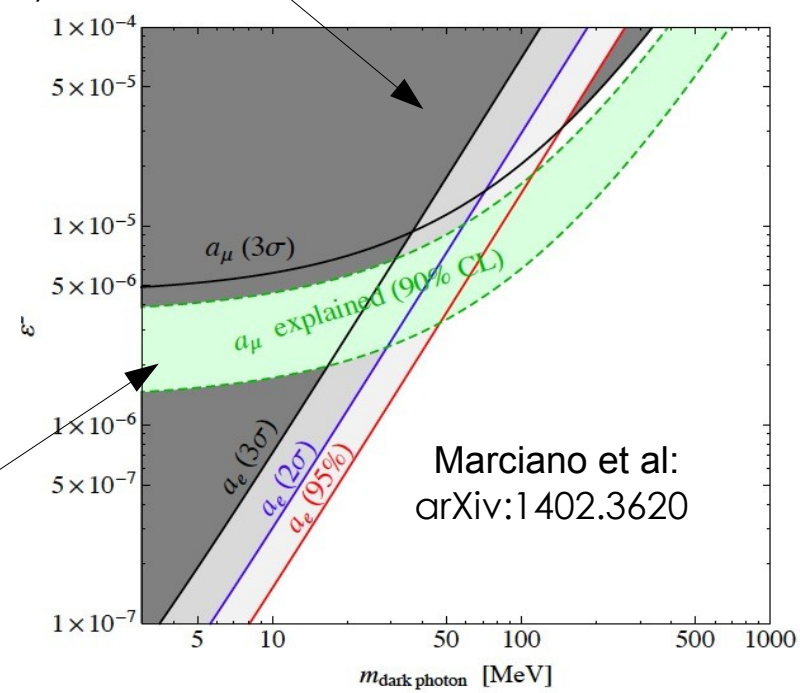
α^{-1} = 137 .035 999 037 (91)

$$|a_e^{th} - a_e^{exp}| = (1.06 \pm 0.82) \times 10^{-12}$$

- Anomalous magnetic moment limits
  - α_{EM} usually a determined from g_e-2 - ***input***
  - Used further to constrain g_μ-2
  - Dark photon contribution:

$$\delta a = \frac{\alpha_{EM}\,\epsilon^2}{2\pi} * f,\ f = \begin{cases} 1, \text{ for } m_l >> M_U \\ 2m_l^2/(3M_U^2), \text{ for } m_l << M_U \end{cases}$$

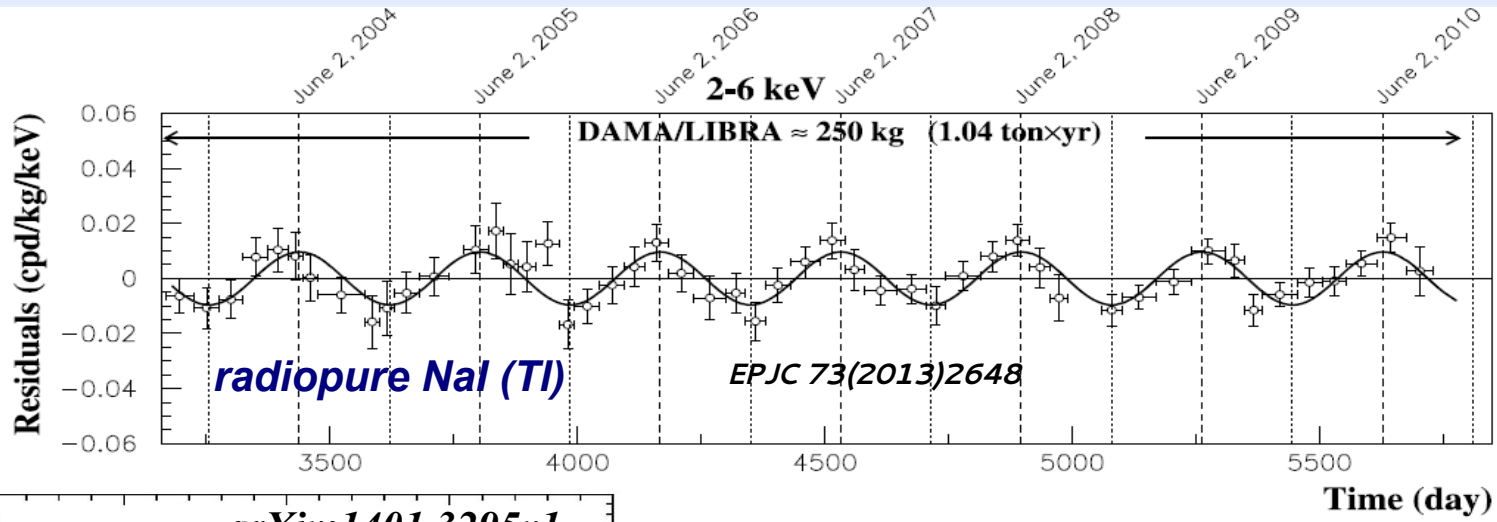
Phys.Rev.D80:095002,2009

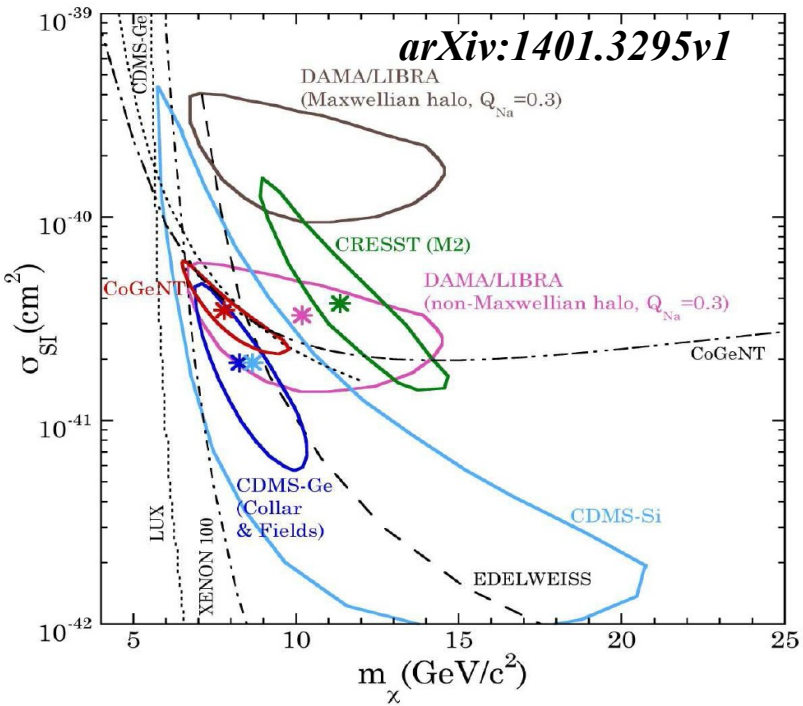


Marciano et al: arXiv:1402.3620

The invisible search removes any assumption apart from coupling to leptons!

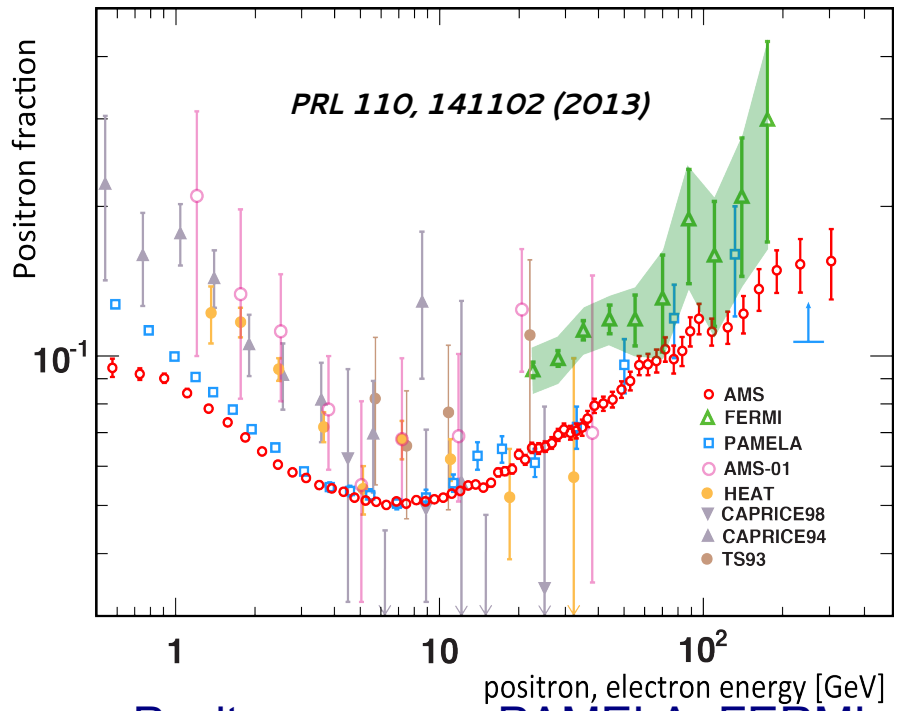
Direct search experiment

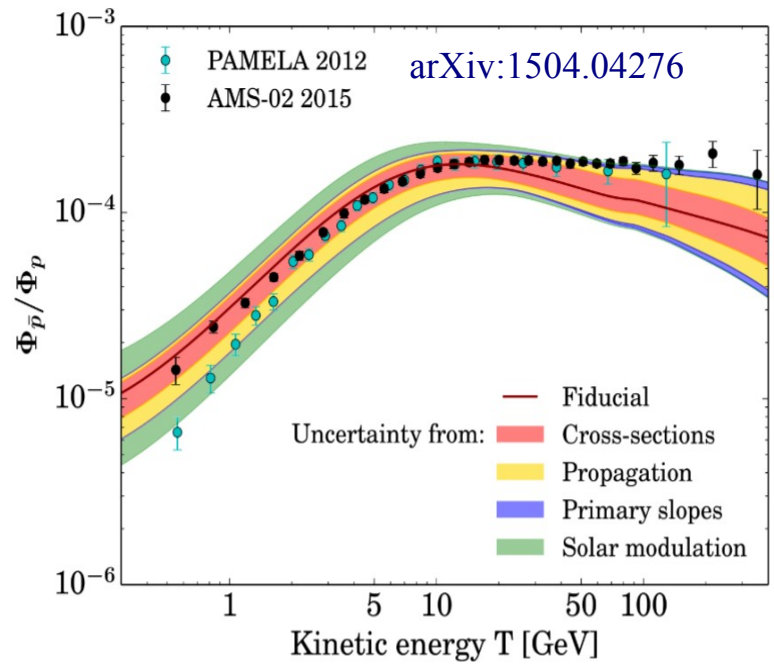




- DAMA/LIBRA results unexplained: 9.2 σ
- Used to be alone, now few other indications emerged
- Seem to be possible to build a consistent picture
- If the explanation is Dark Matter, it should be relative light: ~10 GeV
- Interaction with the nuclei through a mediator. Mass in the MeV range is OK

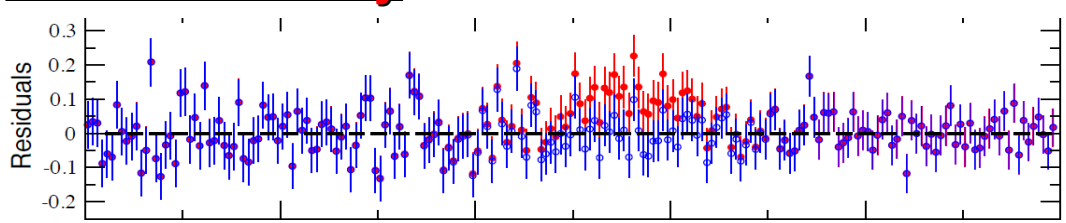
Astrophysics ...





- Positron excess: PAMELA, FERMI, AMS02
- Now also new results from AMS on the antiproton

... and astronomy



Observation of 3.5keV line?

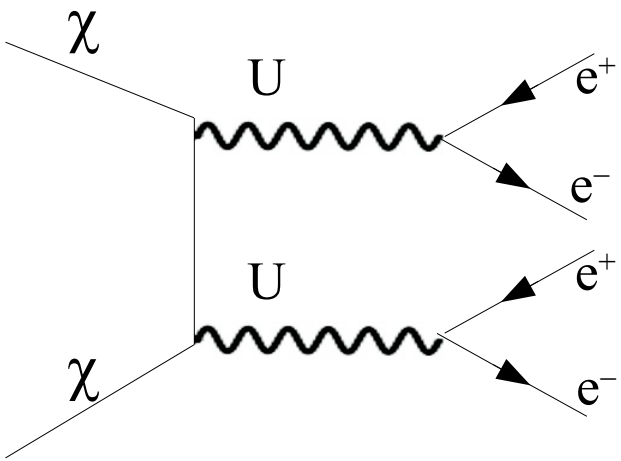
arXiv:1402.2301

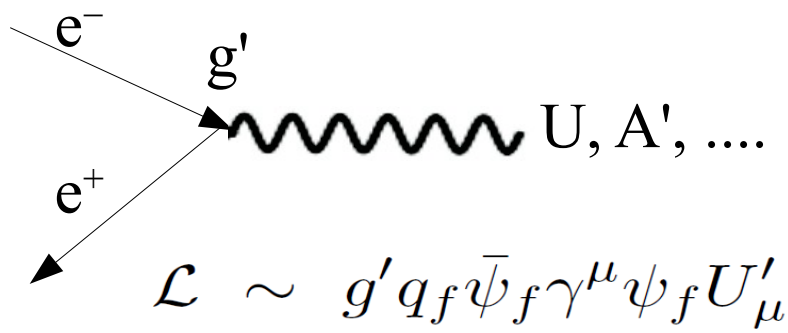
arXiv:1402.4119

Possible interpretation: arXiv:1404.2220

Hint for dark matter?

Dark matter annihilation through

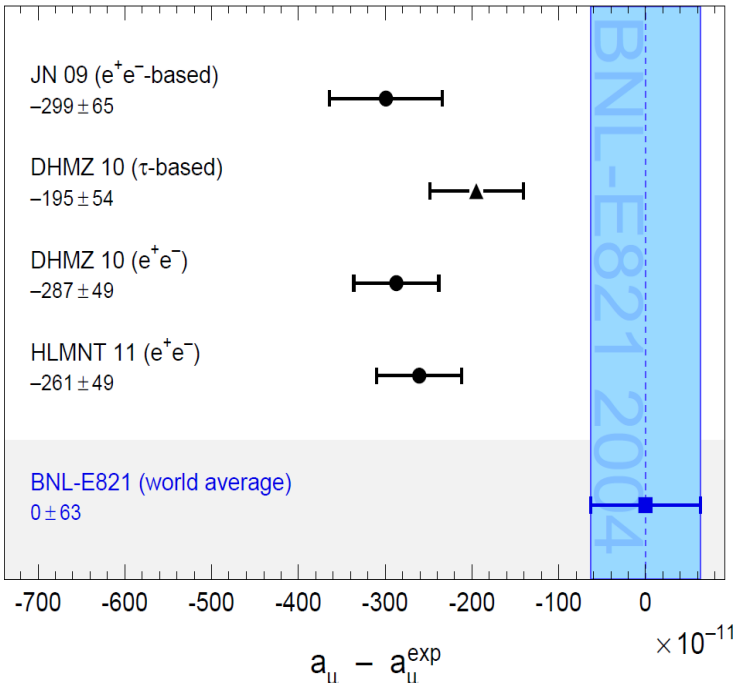


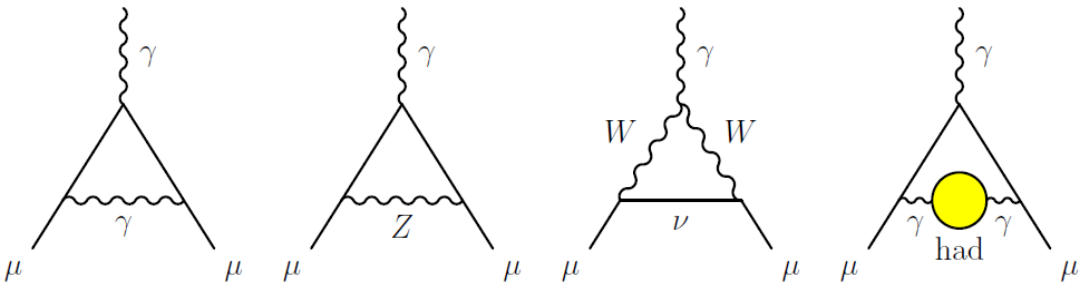


$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- If Dark Matter is the explanation to the positron excess, then the mediator should be light (< $2*M_{proton}$)
- Coupling constant to DM could be arbitrary (even O(1))
- The Lagrangian term can arise through
  - fermions being charged (mili) under this new gauge symmetry ($q_f \rightarrow 0$ for some flavours)
  - Kinetic mixing between ordinary photon and DM one: $\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$
  - **Using simply an effective description:** $g'.q'_e = \varepsilon$, $\alpha' = \alpha * \varepsilon^2$

g-2





- About 3 σ discrepancy between theory and experiment (3.6 σ, if taking into account only $e^+e^- \to$ hadrons)

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

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