# 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***

**8 October 2015**

***SHiP open session***

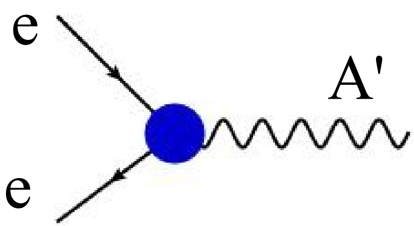
***CERN***

# Overview

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

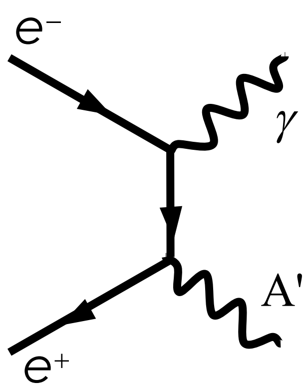
# New gauge bosons

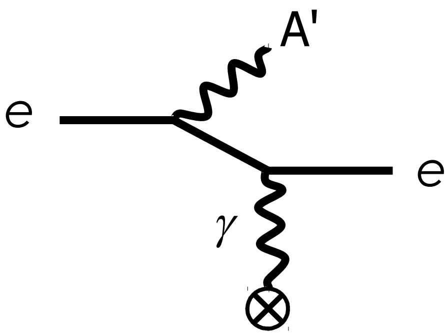
- The effective interaction that can be studied is



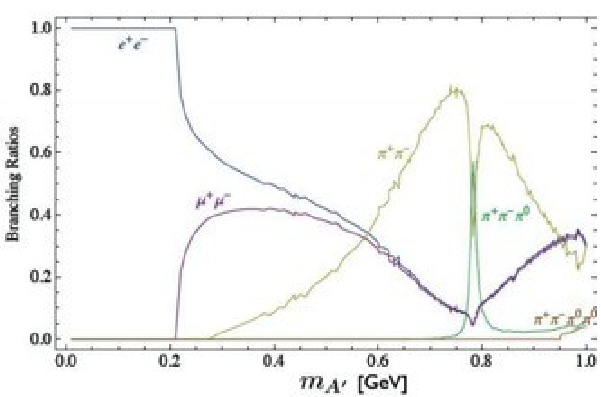

$$\mathscr{L} \sim g' \overline{\Psi} (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'^\mu, \;\; \textit{usually } \alpha'_a = 0$$

- Production mechanisms

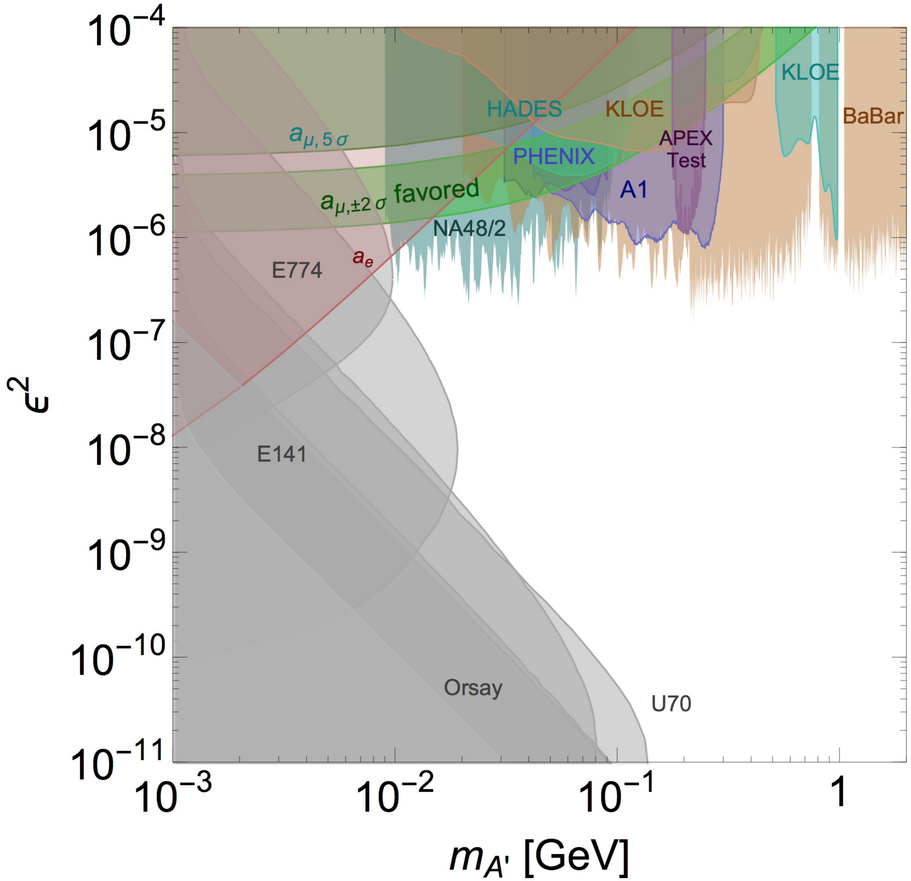


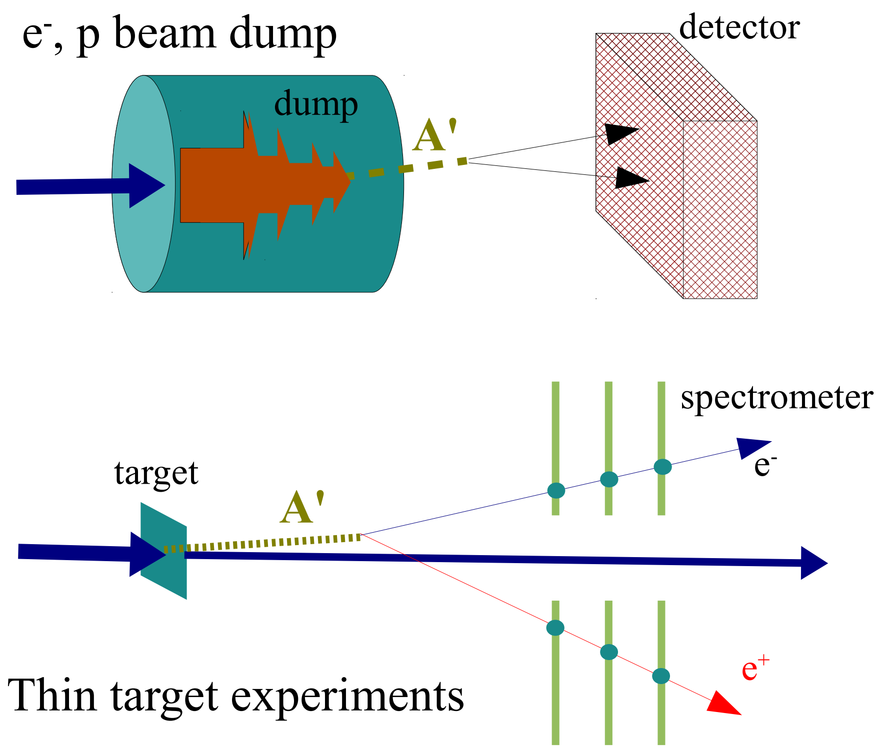




- Such textbook scenario could address the $(g_\mu$-2) discrepancy, abundance of antimatter in cosmic rays, signals for DM scattering
  - General U'(1) and kinetic mixing with B (A', Z')
    - Universal coupling proportional to the $q_{em}$
    - Just single additional parameter – $\varepsilon$
  - Leptophilic/leptophobic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



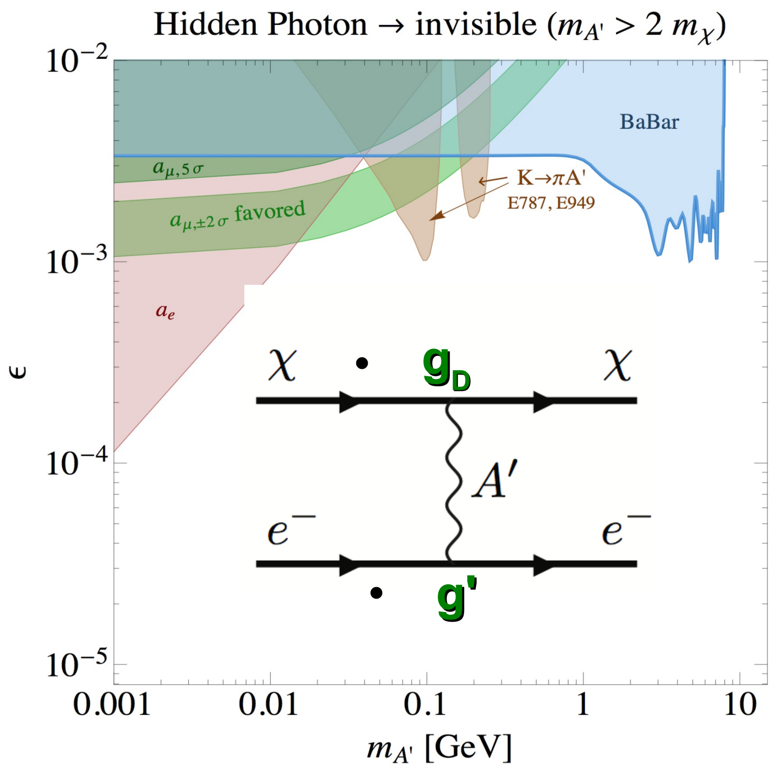
# Heavy/Dark photon/boson searches

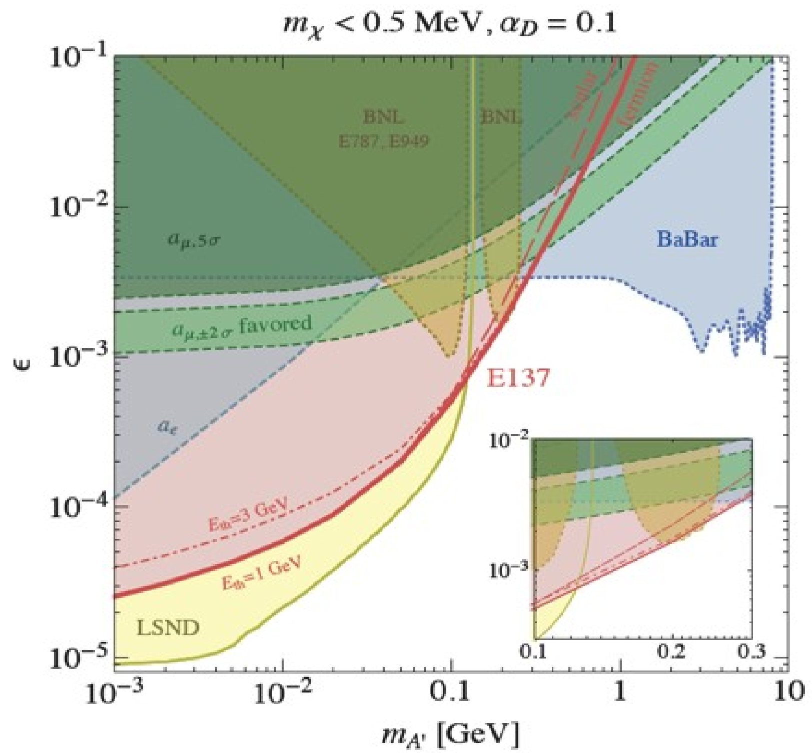



- Beam dump experiments: A'-strahlung production
- Fixed target: peaks in the $e^+e^-$ invariant mass spectrum
- Meson decays: Peaks in $M_{e+e-}$ or $M_{\mu+\mu-}$

# Invisible A' searches




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

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

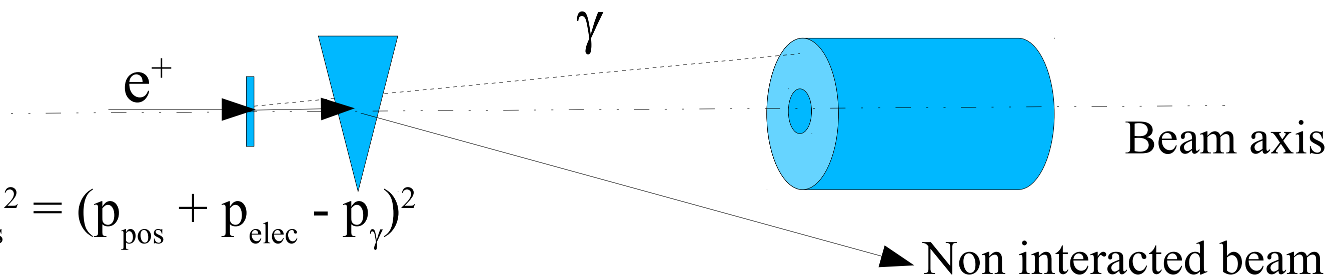
- Normalizing to the concurrent process - **annihilation**

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

  - $N(\gamma A')$, $N(\gamma\gamma)$ - 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

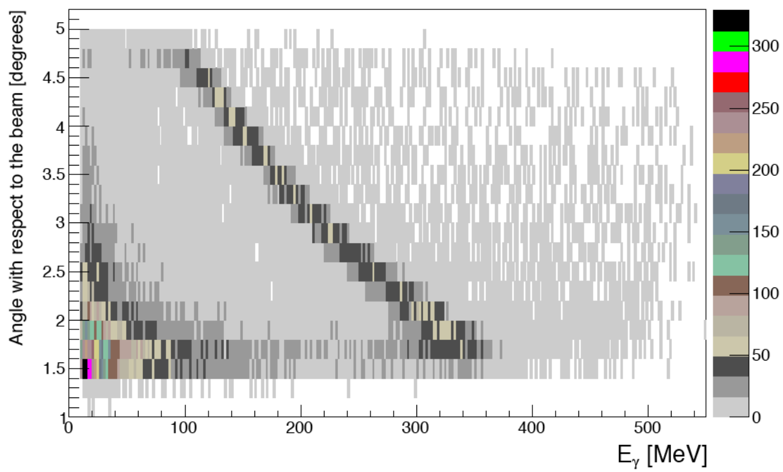
# Basic ideas

**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



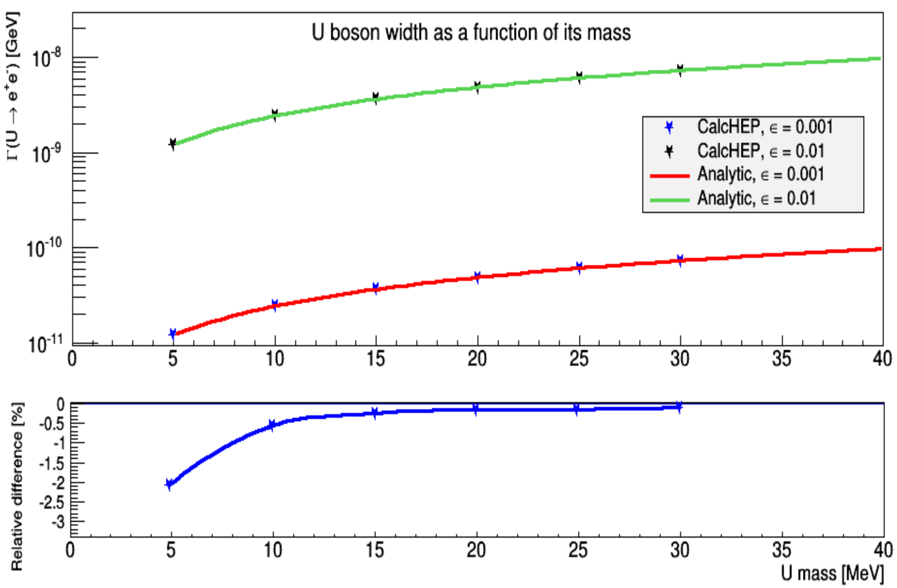
# DP model

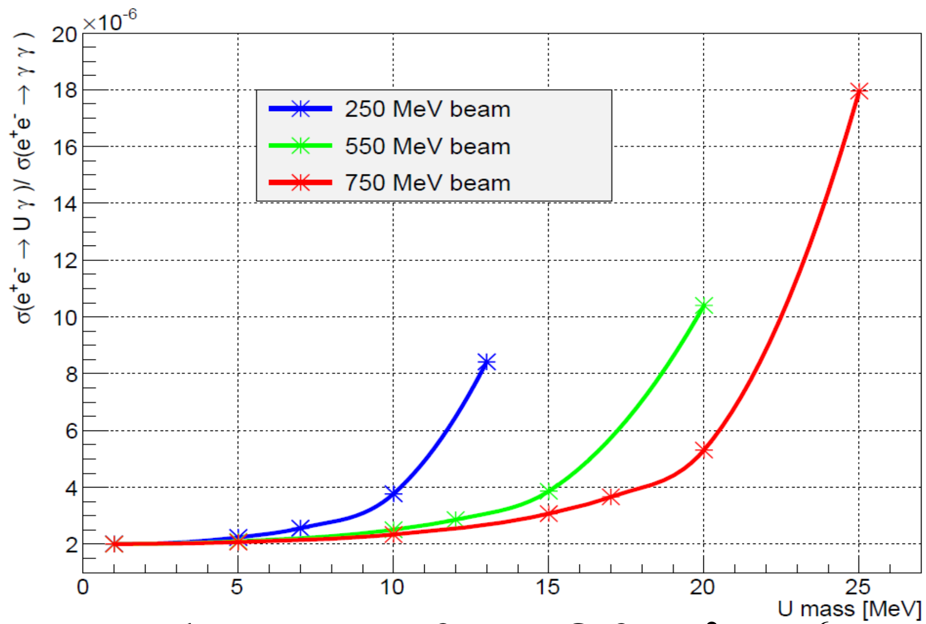
- Simple model implemented in CalcHEP, used for the further studies

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

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

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



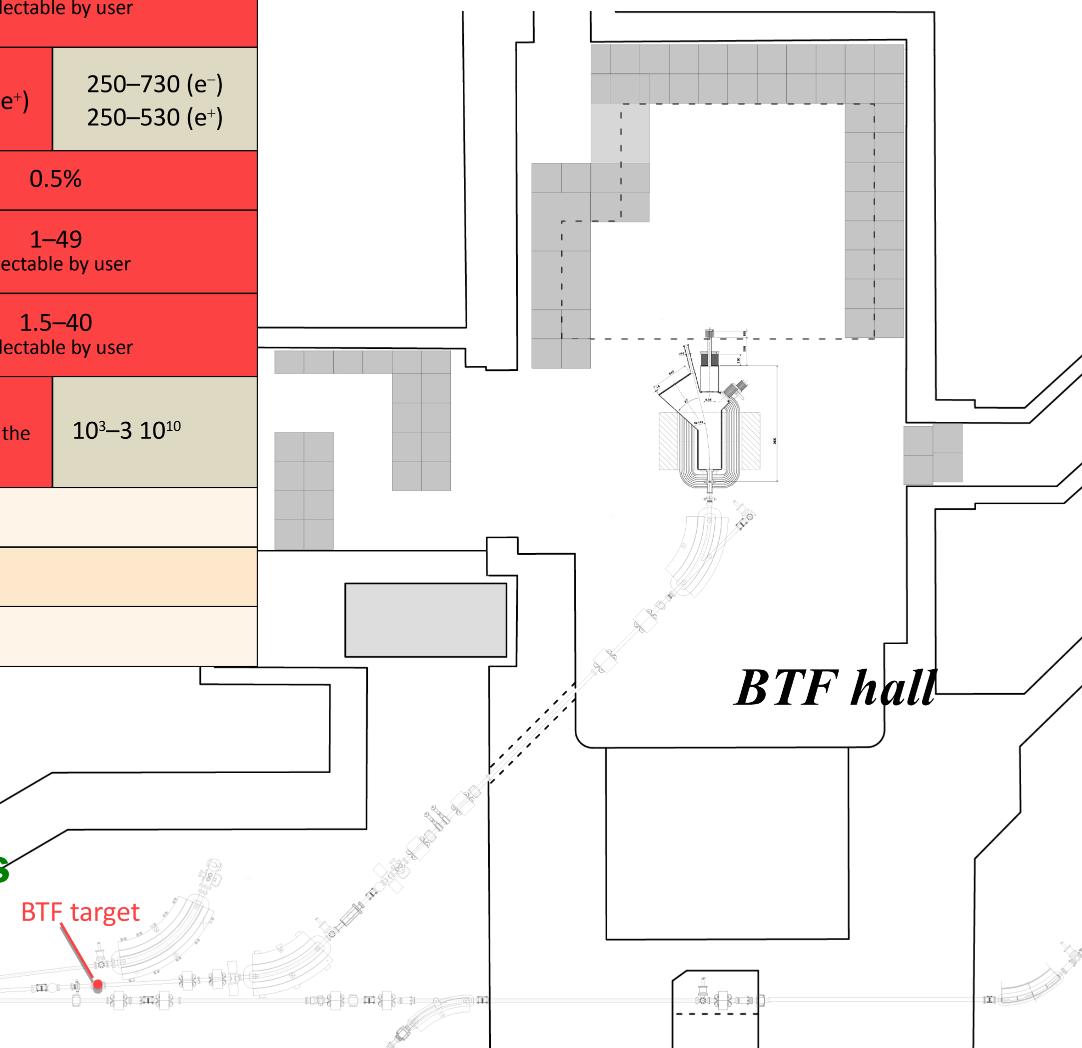

enhancement factor δ for $\varepsilon^2=10^{-6}$

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

# BTF @ LNF

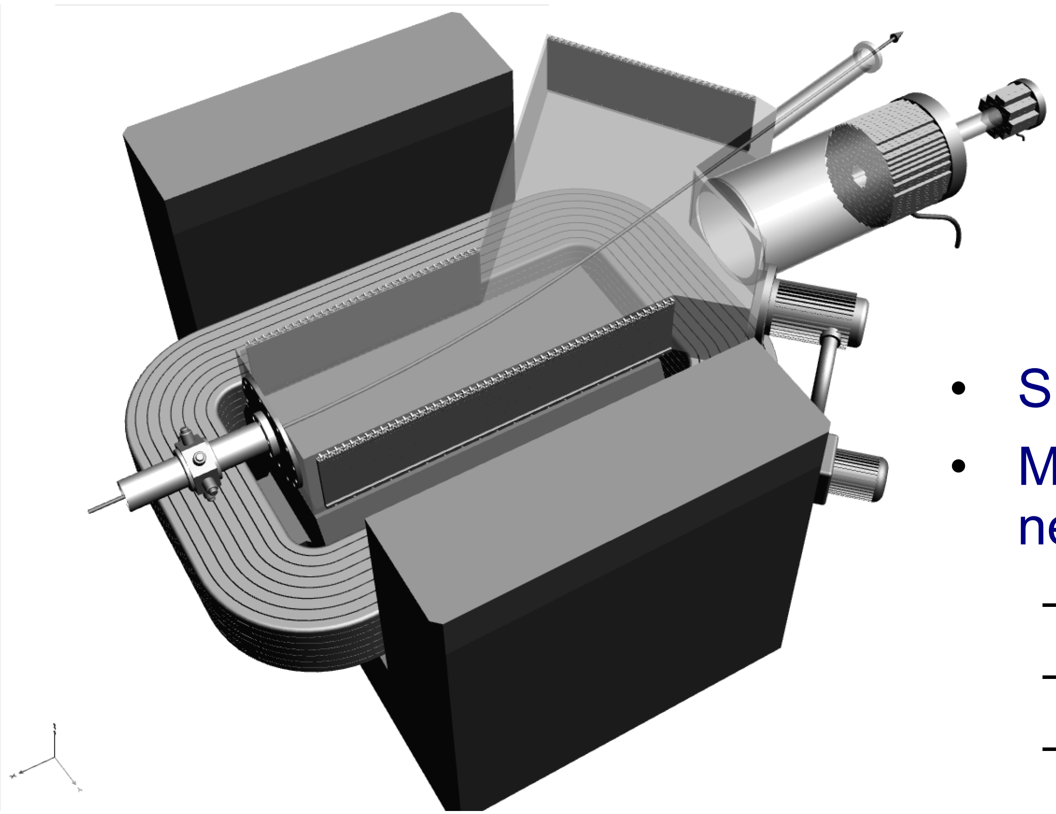
| Parameter | Parasitic mode | | Dedicated mode | |
|---|---|---|---|---|
| | With target | Without target | With target | Without target |
| **Particle species** | $e^+$ or $e^-$ Selectable by user | $e^+$ or $e^-$ Depending on DAFNE mode | $e^+$ or $e^-$ Selectable by user | |
| **Energy (MeV)** | 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

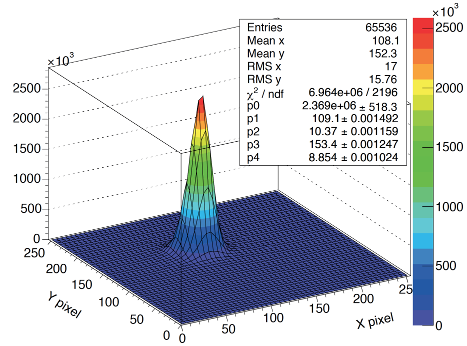
**Positron Annihilation into Dark Matter Experiment**



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

# Beam

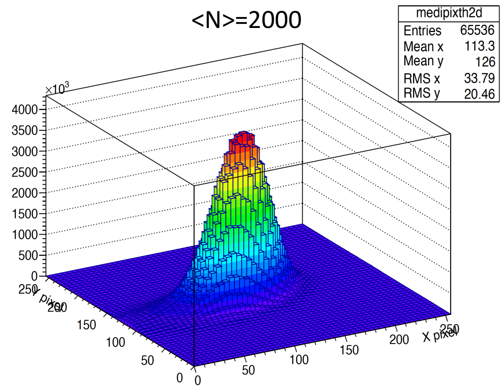
“single” particle




$RMS_x = 0.9$ mm

$RMS_y = 0.9$ mm

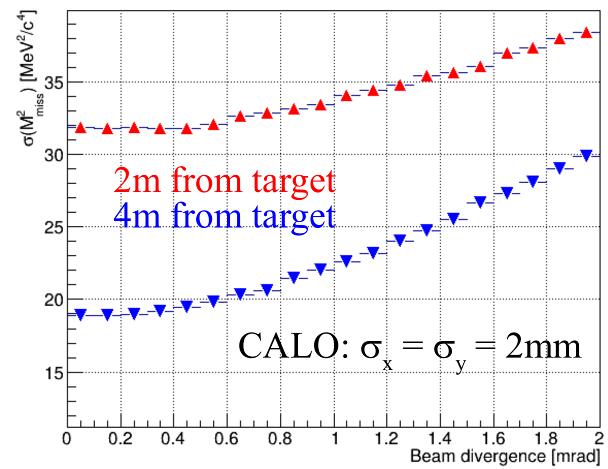
<N>=2000

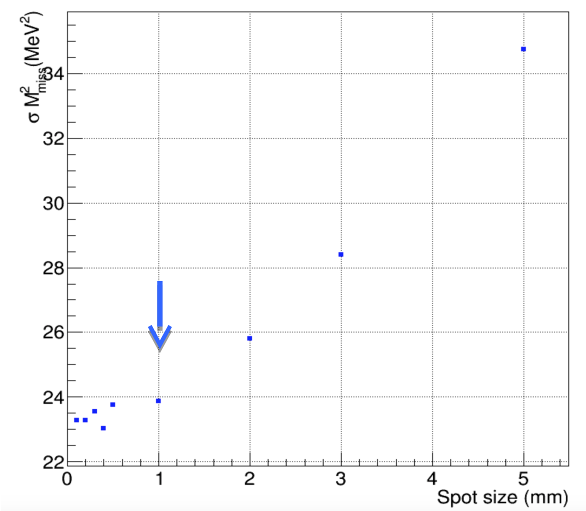


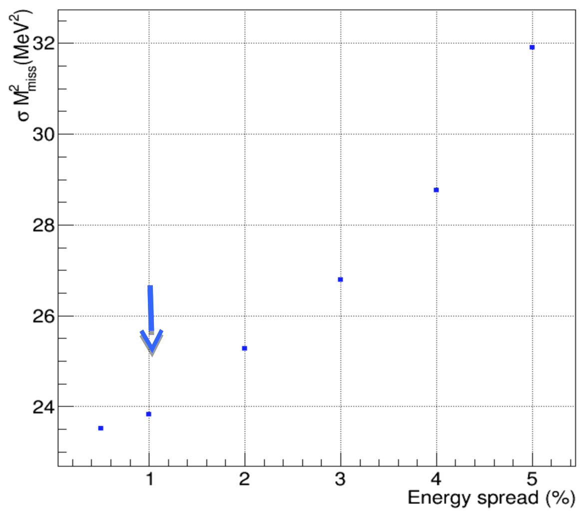

$RMS_x = 1.9$ mm

$RMS_y = 1.1$ mm

$M_{A'} = 5$ MeV



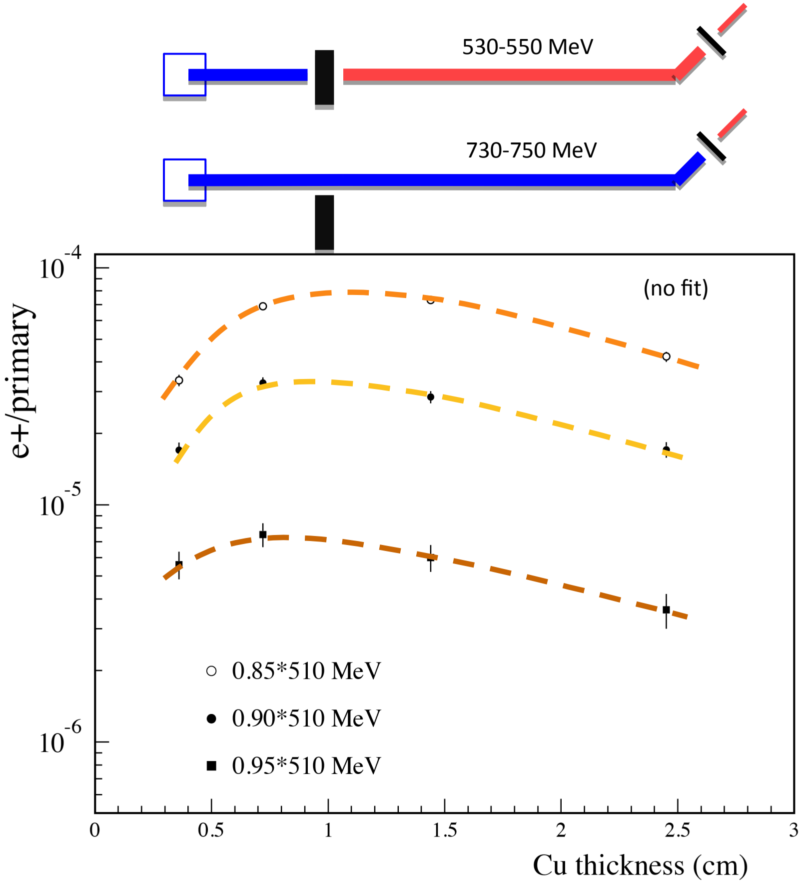



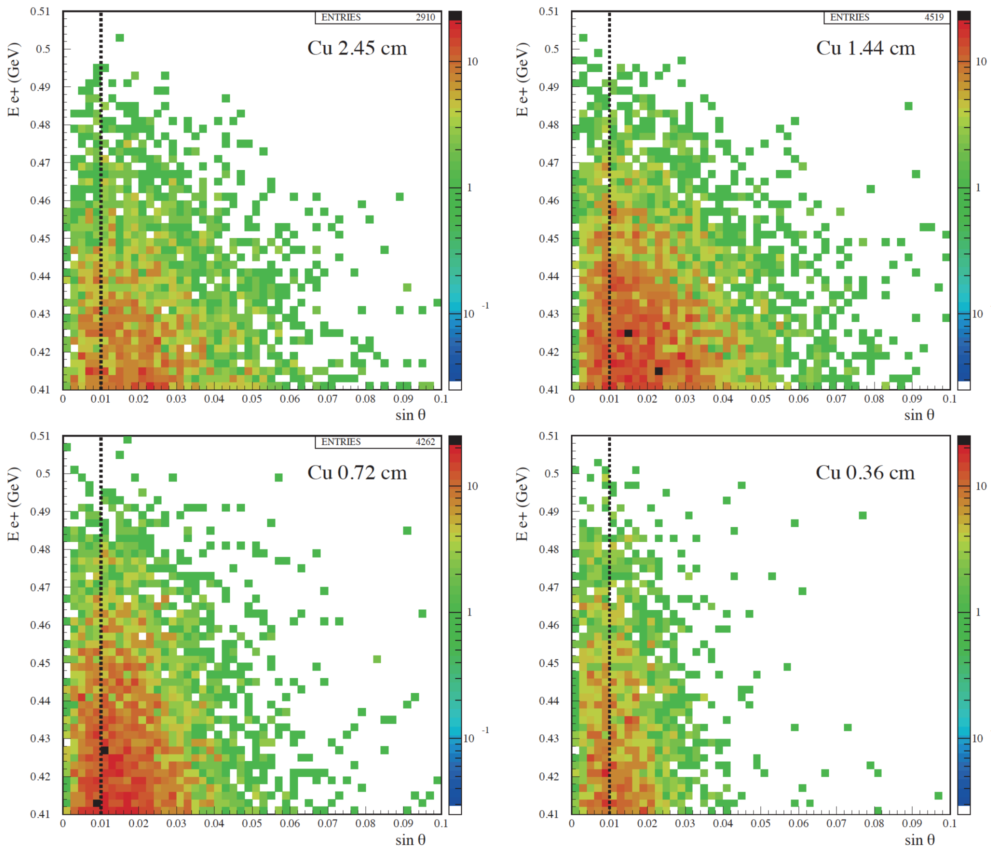

- $10^3 - 10^4$ $e^+$/bunch can be achieved by adjusting the collimators
  - Divergence
  - Energy spread

**Optimization**

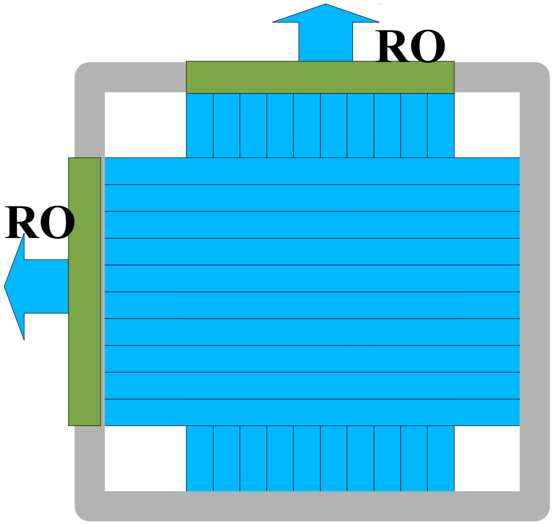
# Positron Beam optimization

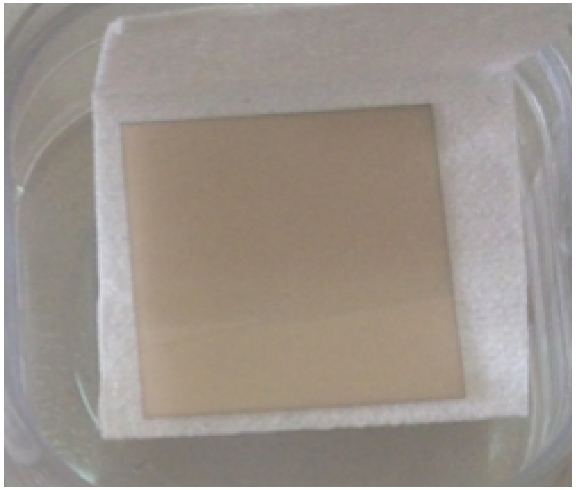
- The nominal positron convertor is after the first section of the Linac, limiting the maximum e$^+$ energy up to 550 MeV
- $10^{10}$ primary electrons/bunch, $10^4$ e+ necessary for PADME
  - **Possible to use the BTF target to produce positrons**

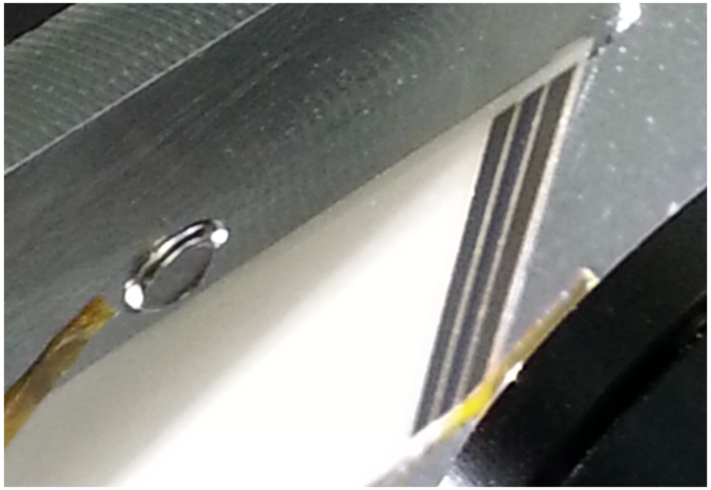


# Active target

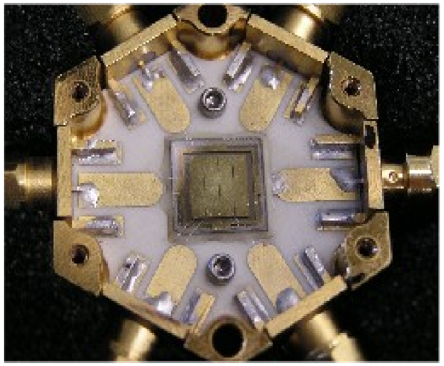


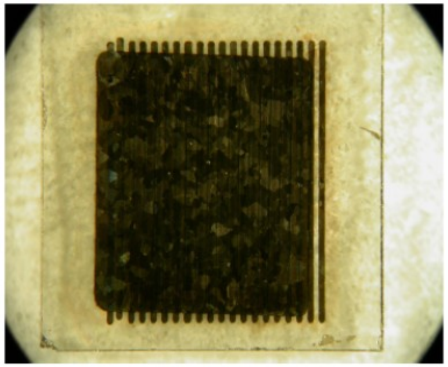


- Graphitized diamond – strips of 1mm width
  - All carbon target
- The production of 50 μm detector is state-of-the-art
  - 2 cm x 2 cm
  - Samples produced, 2x 50 μm thickness, 1 x 100μm thickness
- To be tested at BTF in November

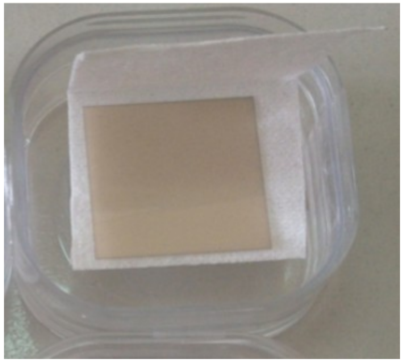
# BTF test run in October, 2014



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

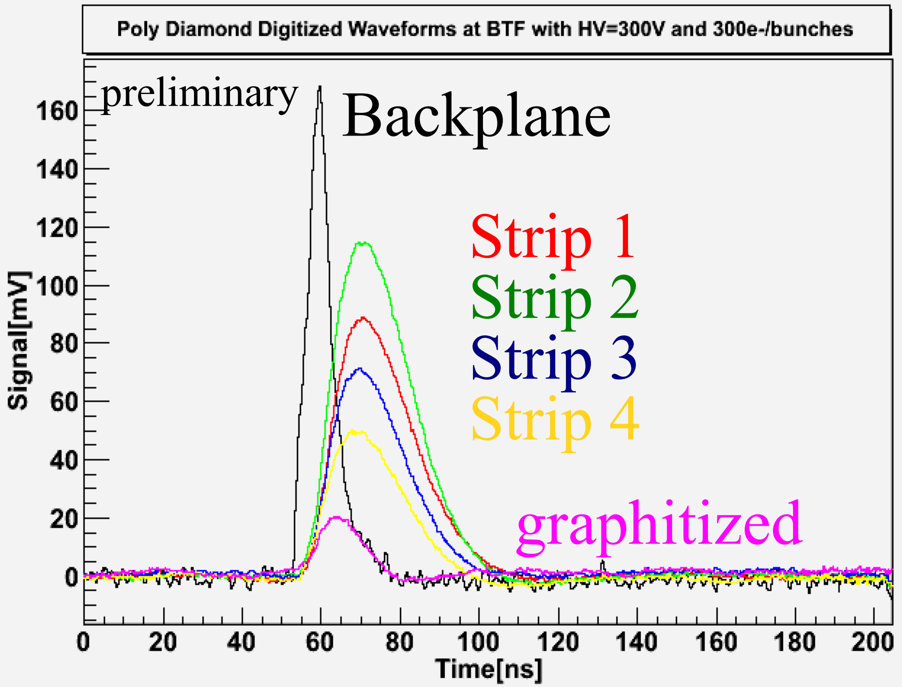


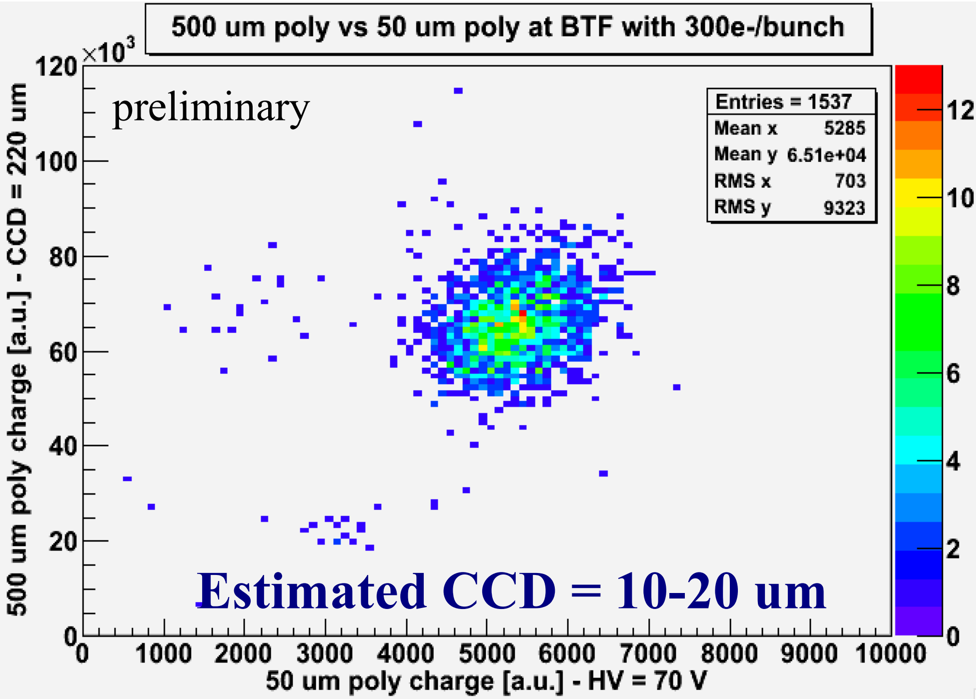
300 um, graphitized strips
3mm long, 100 um width



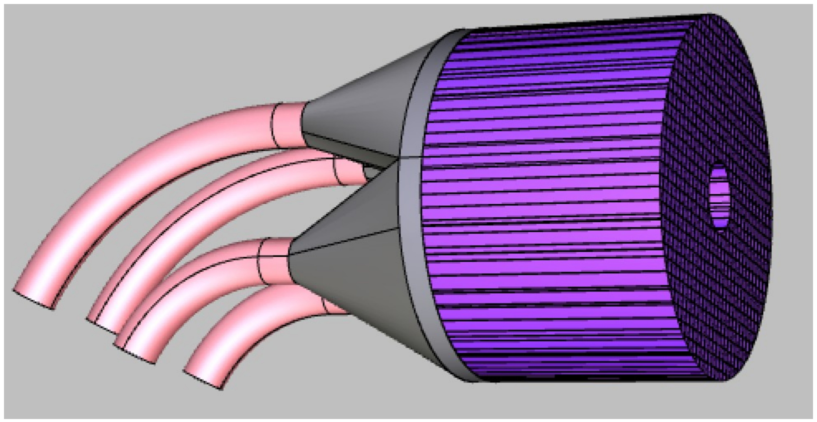
50 um, 2cm x 2 cm
first sample for PADME

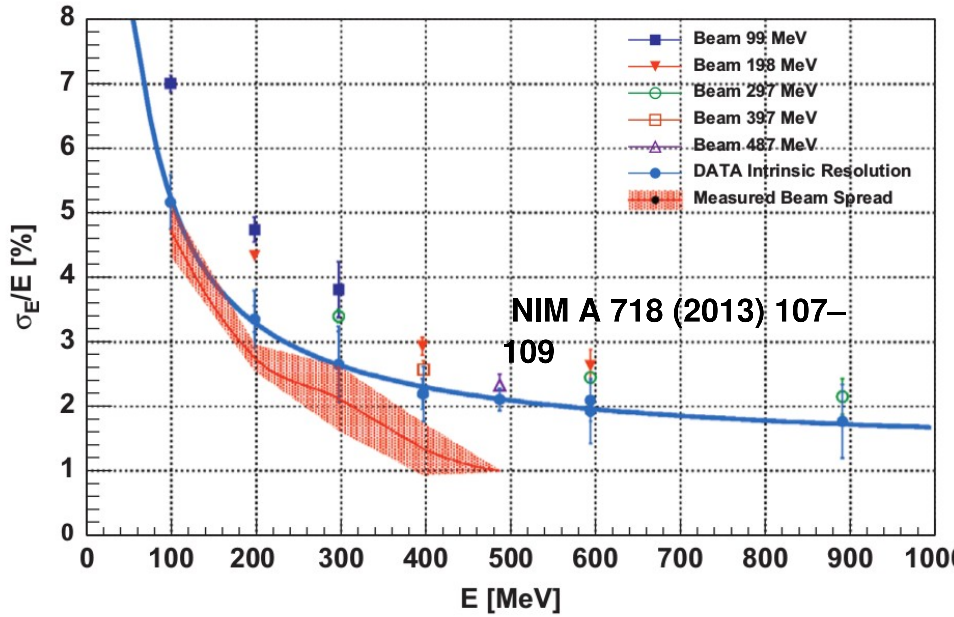
50 um, silver paint
5 mm x 5 mm



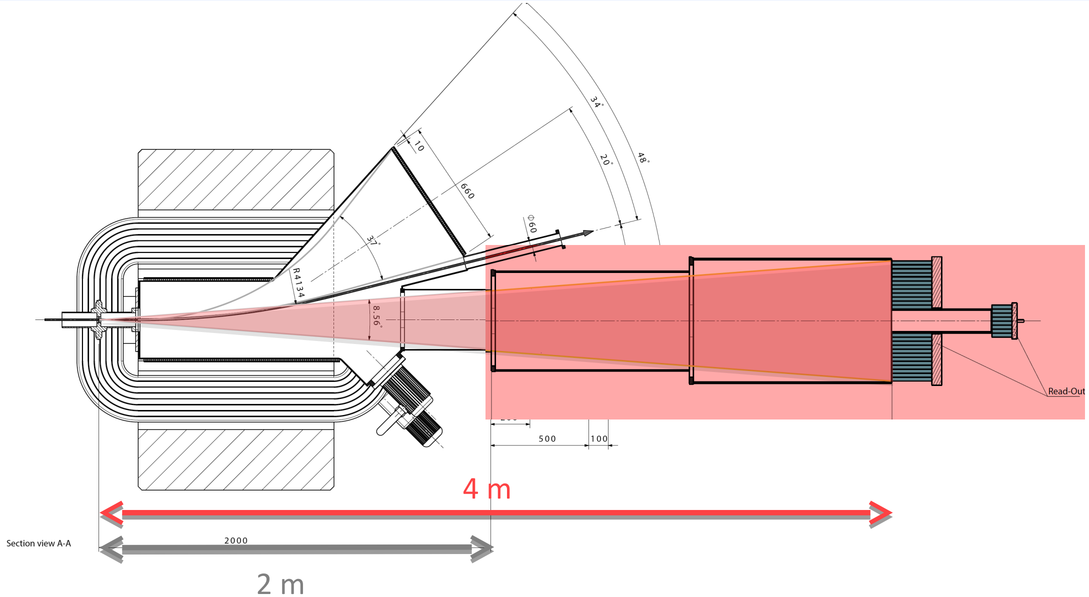
# Calorimeter

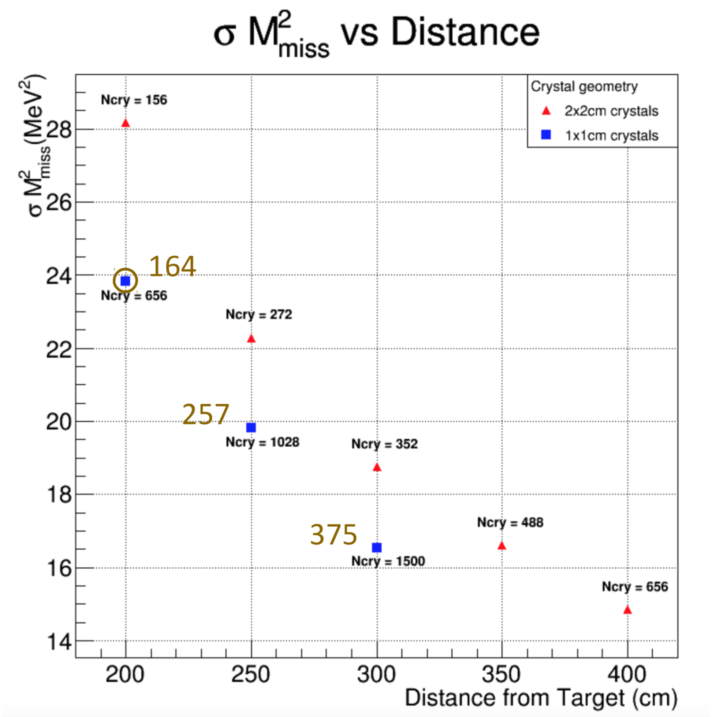





- Cylindrical shape
- LYSO was assumed to be the best solution and was used as a baseline for estimating the sensitivity
  - Located 2m downstream the target
  - 656 LYSO crystals. 1x 1 x 15 cm$^3$
- Energy resolution: $\sigma E/E = \frac{1.1\%}{\sqrt{E}} \oplus \frac{0.4\%}{E} \oplus 1.2\%$
- Possible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

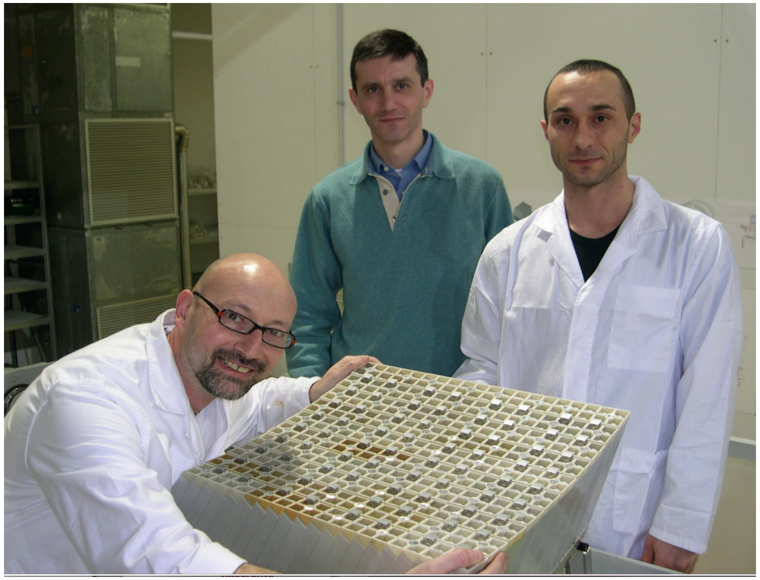
# Calorimeter design

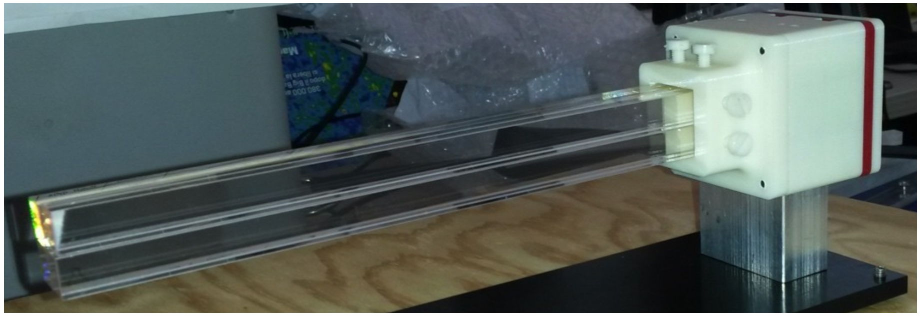



- BGO crystals available from L3 experiment
- Crystal geometry is close to 2 x 2 cm front face
  - Cut the crystals in 1 x 1 cm and place them at 2 m
    - Requires cutting of the existing crystals, but the quantity is identified and available
  - Place the calorimeter at 4 m distance and keep the dimensions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

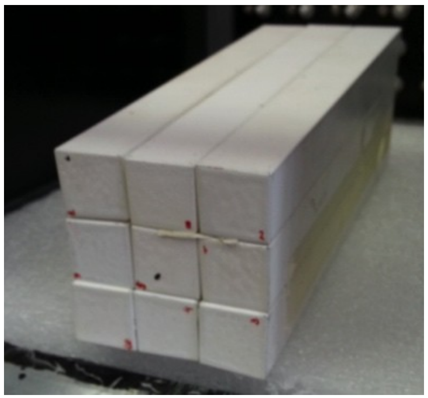
# BGO crystals

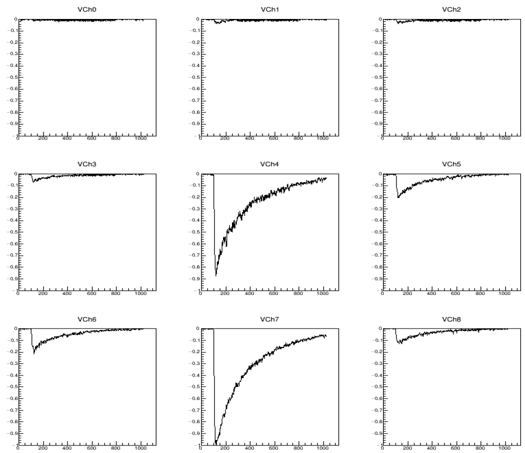


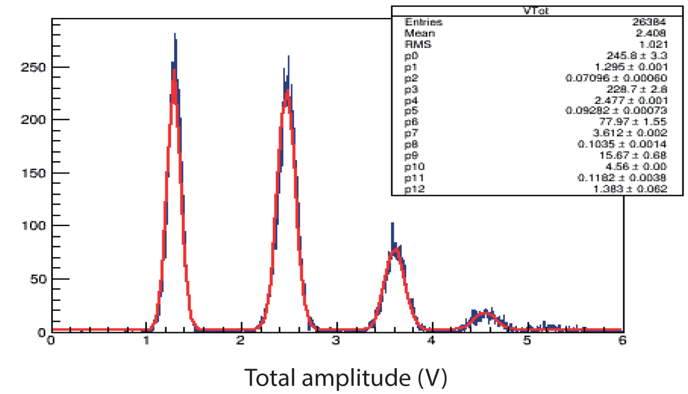


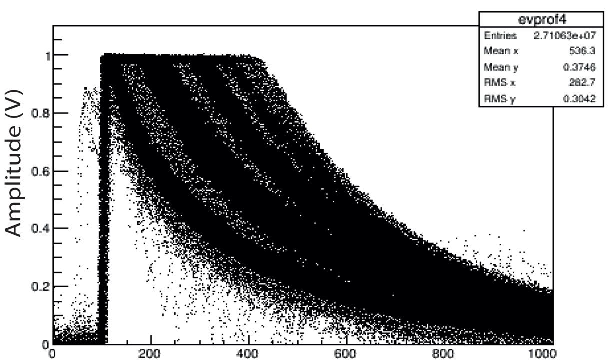
- Single L3 crystal cut into 4 1cm x 1cm crystals
- Primary solution for the calorimeter
  - Only 164 BGO crystals required
- If more crystals available -> bigger calorimeter

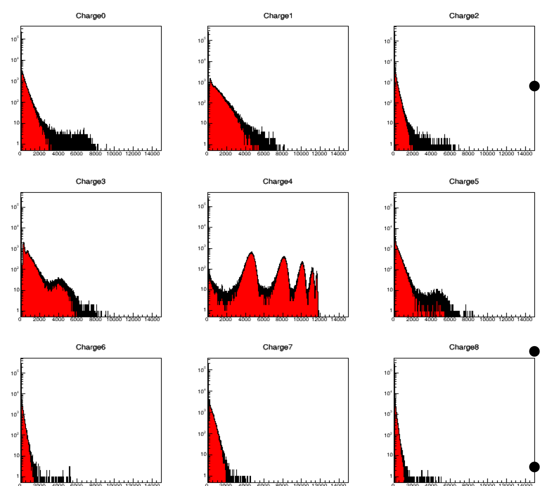
# Test run at BTF





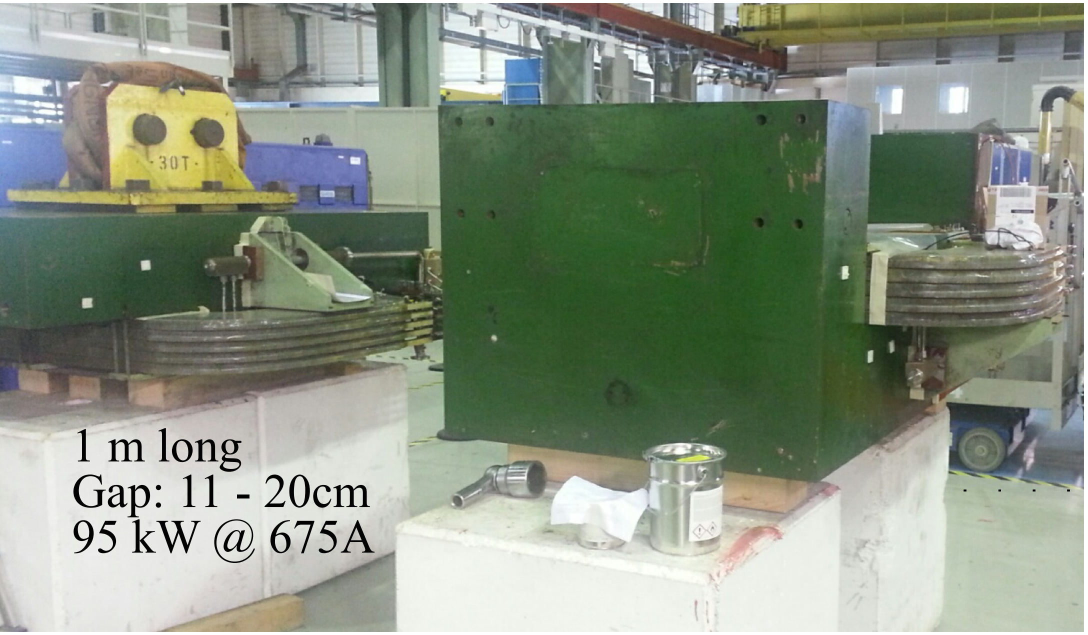


- 3x3 matrix tested at BTF in May
  - PMT R6427
- RO: CAEN V1742 digitizer @ 1GS/s
  - Study the signal shape
  - Reconstruct pulses
  - Address saturation
- A fit on the signal leads to proper energy deposit determination
- Test with APD and SiPM foreseen

# Magnet



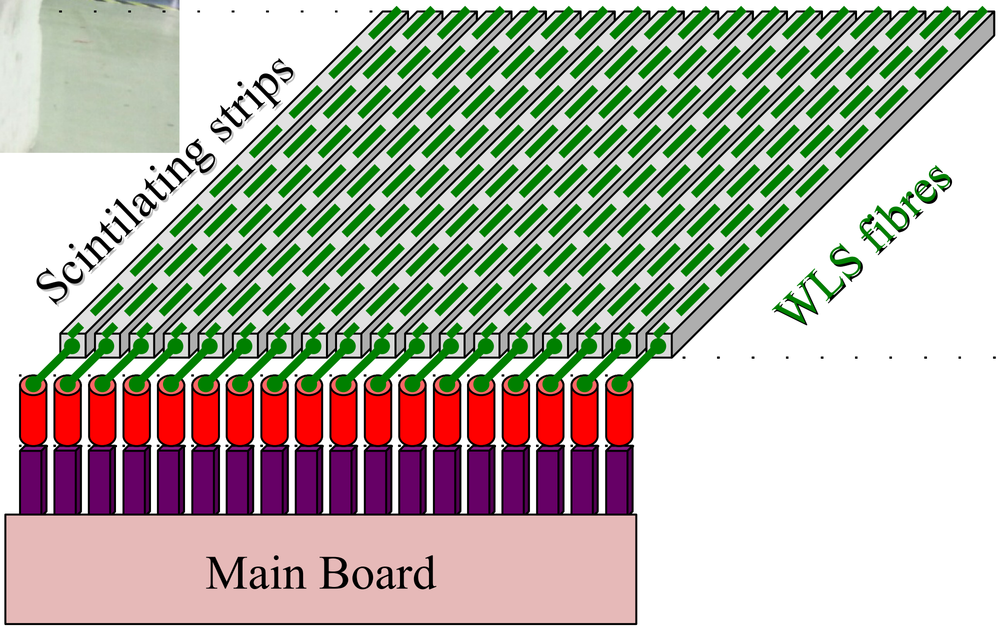

- CERN spare magnet: MBP-S
- To be refurbished from CERN and transported to LNF
- Usage of the DAΦNE PS: 400A

Charged particle detector

- Plastic scintillator detector

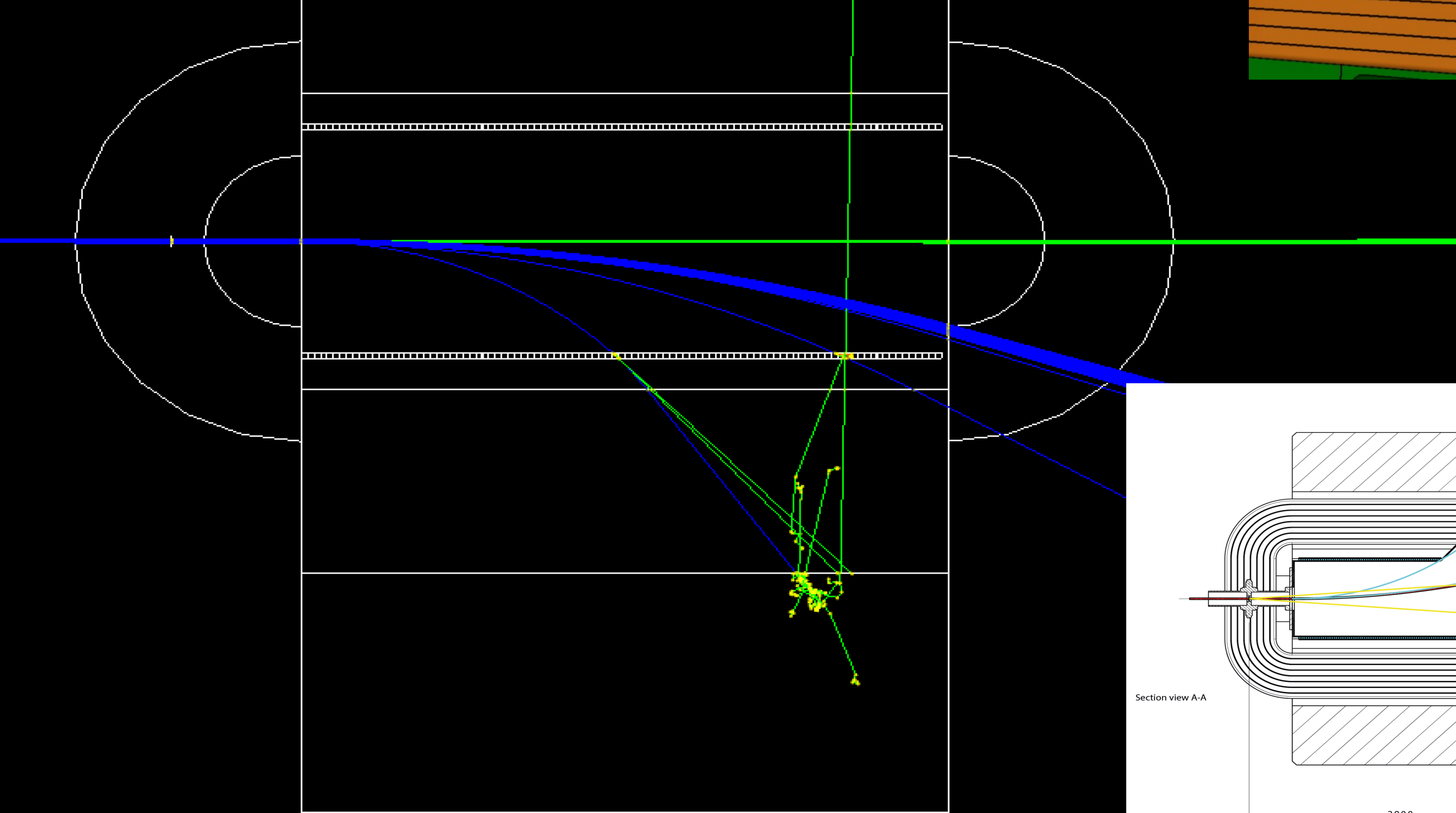
SiPM based readout

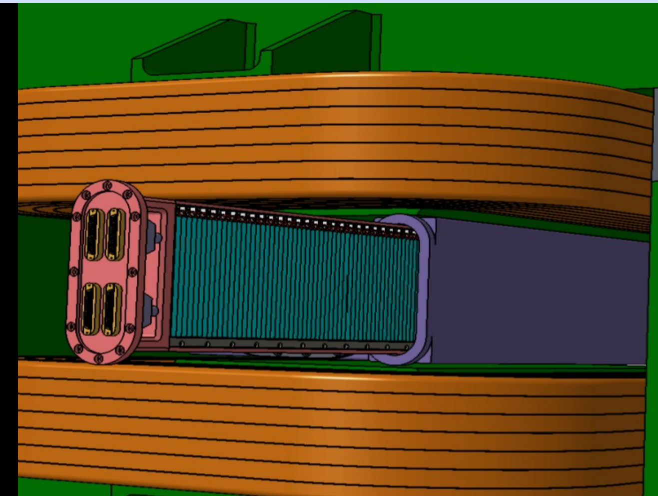
FEE electronics & power supply

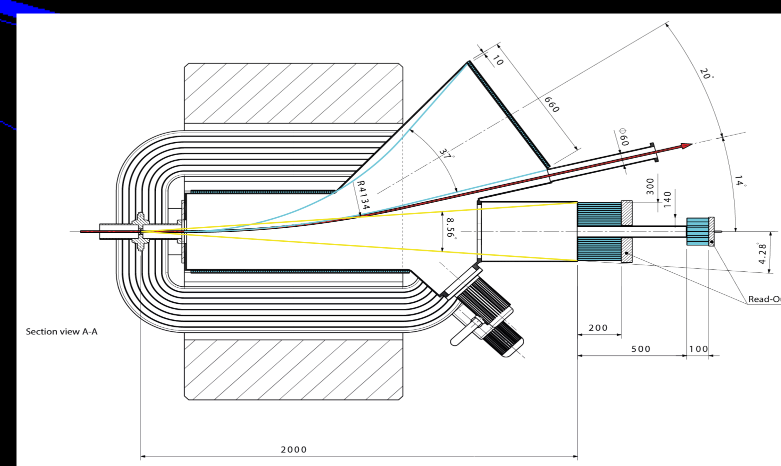


# Sensitivity

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





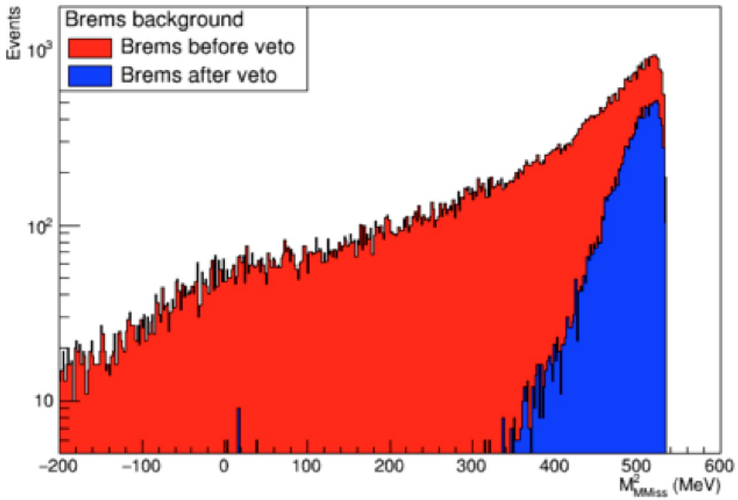


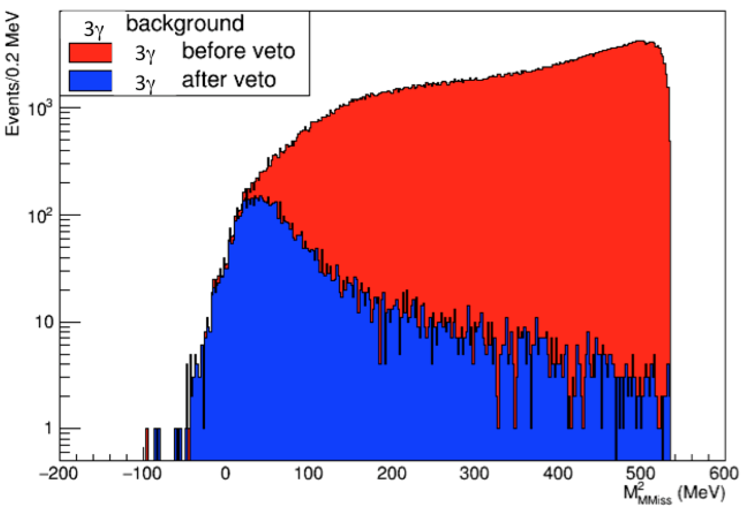
# Background

## Selection

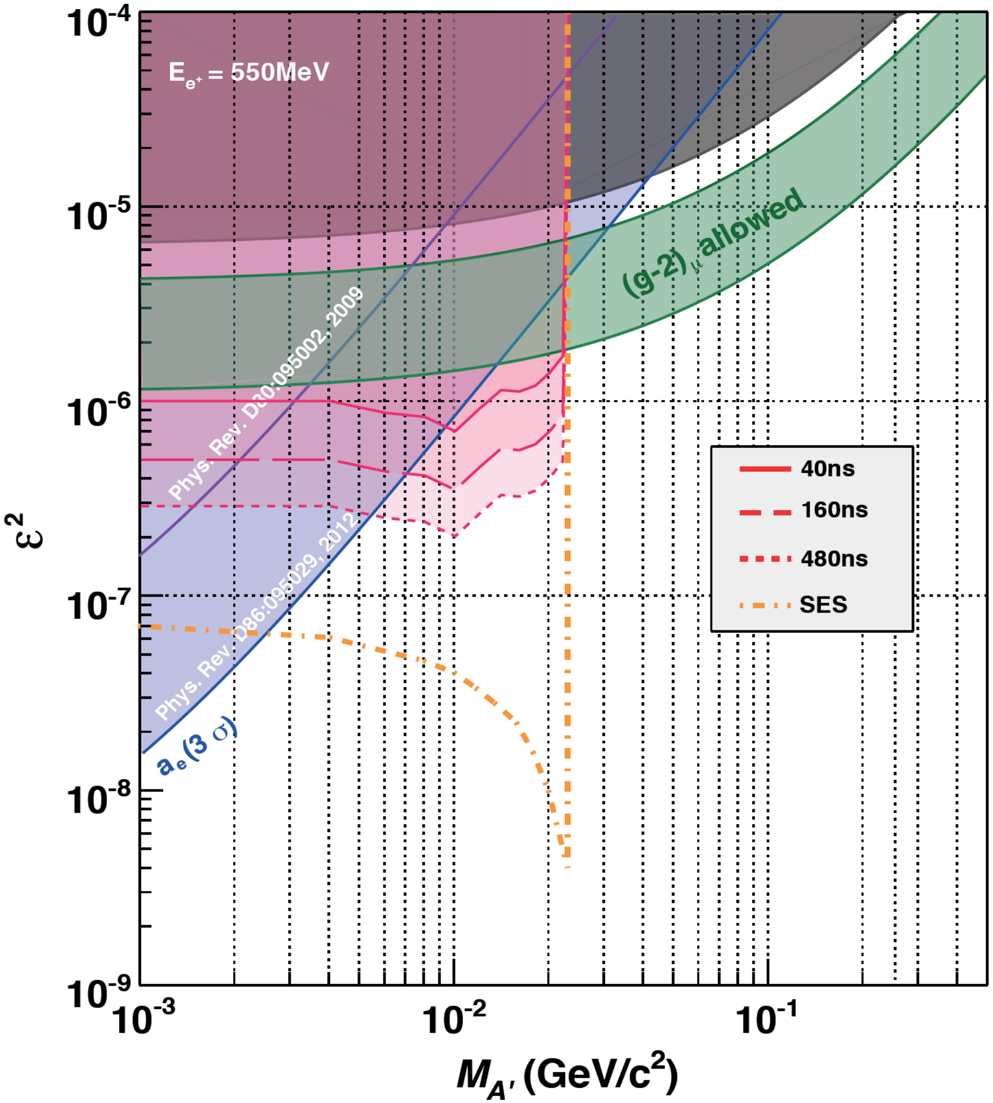
- Kept as simple as possible
- Attempt for a common selection of visible/invisible scenarios

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

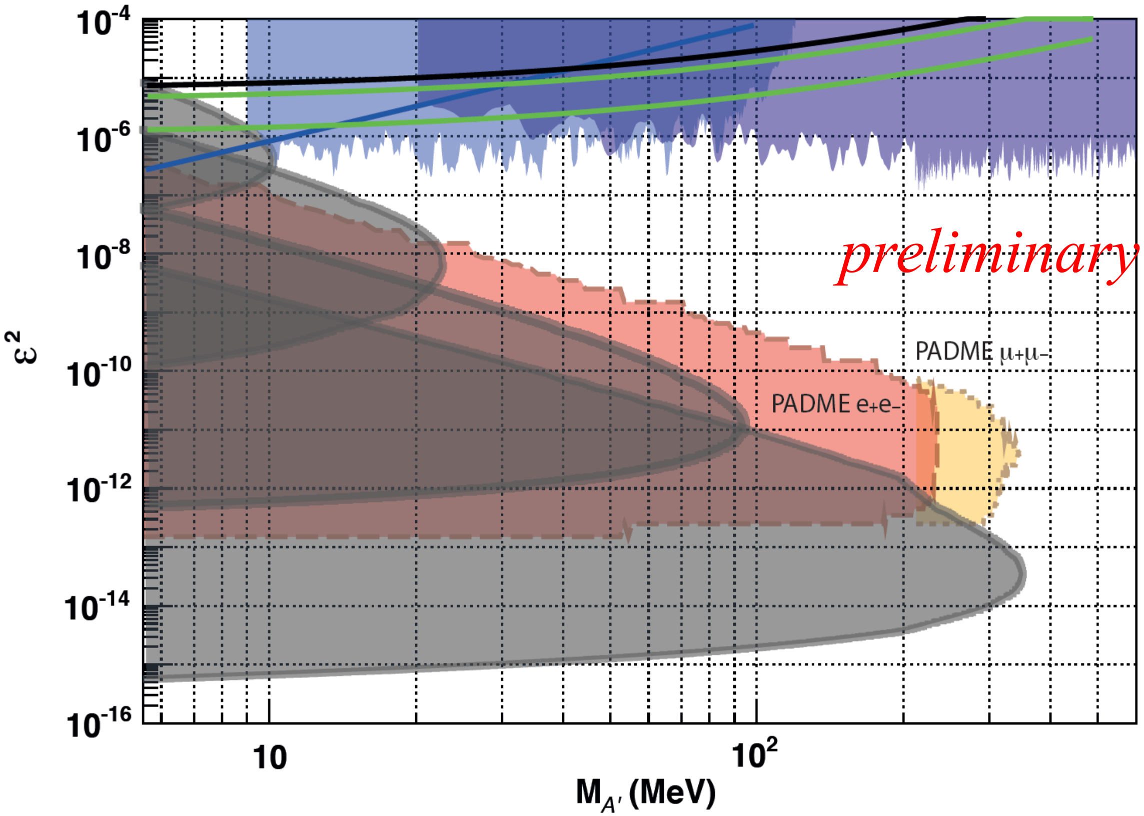
- ~High acceptance (high boost of the produced A' and deflection in the magnet)
  - ~2 times more sensitivity
- Better invariant mass resolution
- Missing mass of $\gamma$ constraint
- Sensitivity: $\varepsilon \sim 10^{-7}$
- The first channel to look at if excess of events is observed

# 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*

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PADME

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INFN Istituto Nazionale di Fisica Nucleare


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# Conclusions

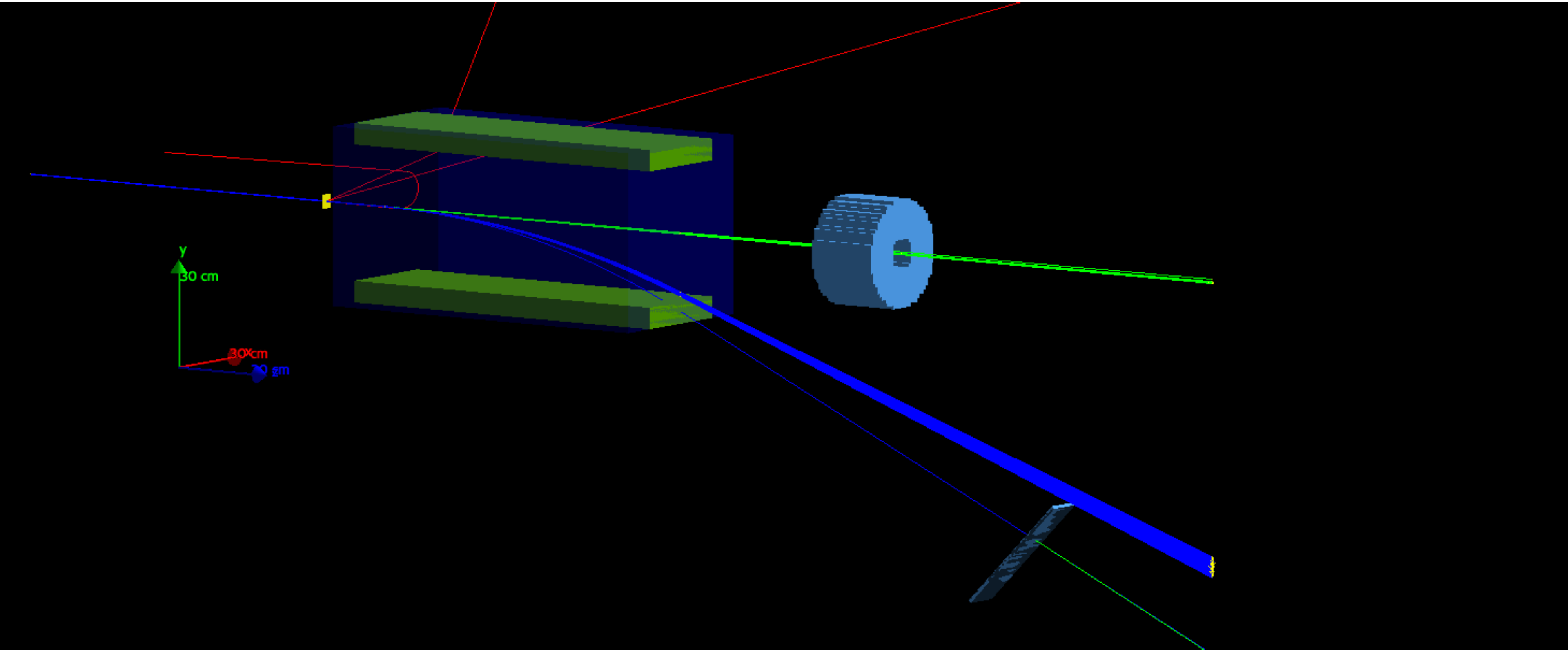
- PADME is a small scale fixed target experiment to search for dark photons in the invisible channel.
- Interesting parameter space could be covered, using $10^3 - 10^5$ $e^+$/bunch.
- **Test beam and initial studies already ongoing**
- A portal for a complete physics program devoted to the dark photon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

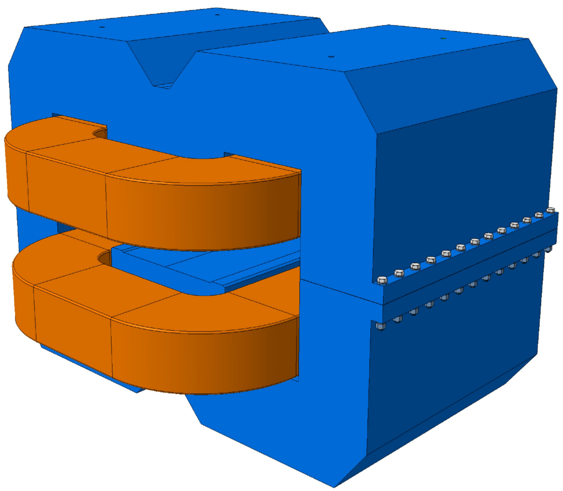
# PADME schematics

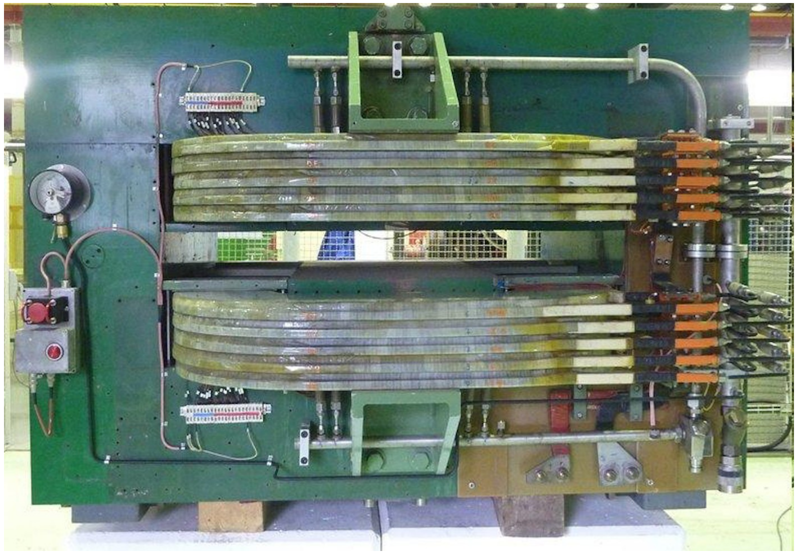



- Additional elements could be added in case of necessity (or profit)

# Spectrometer technology

- CERN available magnet versus special magnet design





0.6 T.m in simulation

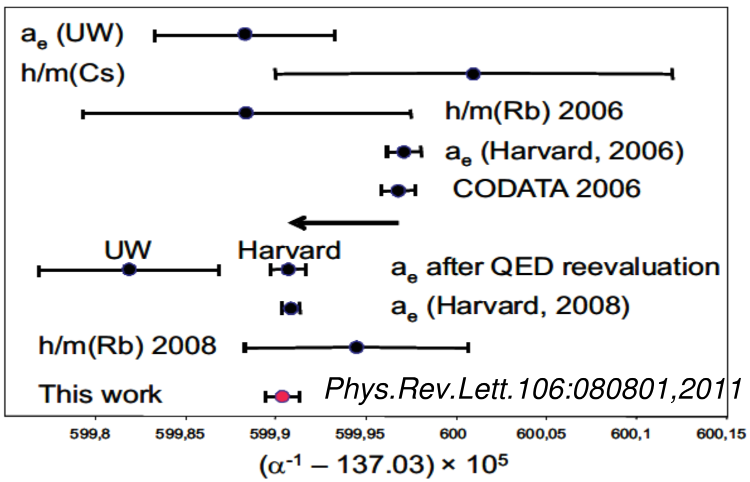
~ 0.8 T possible for aperture 20cm

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 $g_\mu$-2 itself, it's in the consistency of $g_e$ & $g_\mu$
- Alternative inputs should be used to extract information from $g_e$: $\alpha_{EM}$



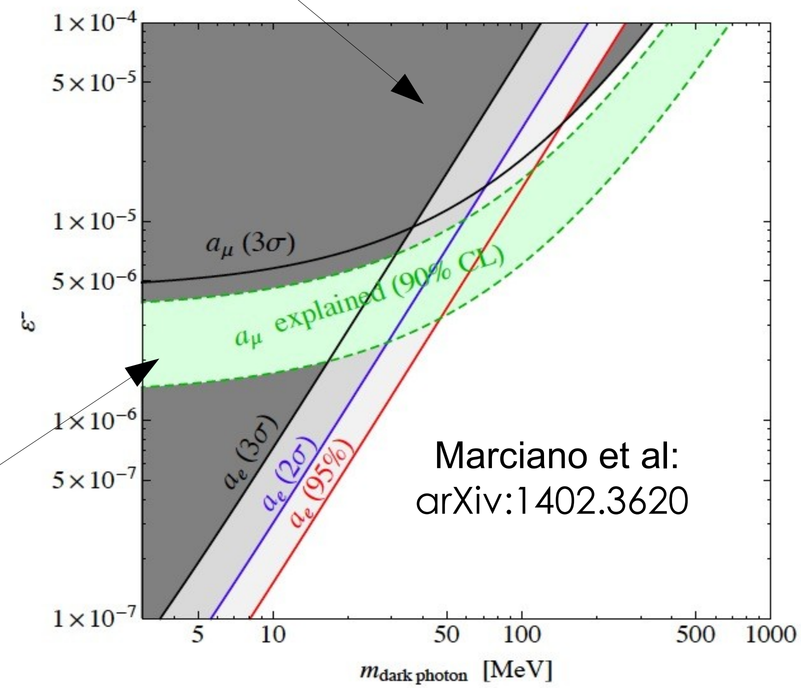

$\alpha^{-1} = 137.035\,999\,037\,(91)$

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

- Anomalous magnetic moment limits
  - $\alpha_{EM}$ usually a determined from $g_e$-2 - *input*
  - Used further to constrain $g_\mu$-2
  - Dark photon contribution:

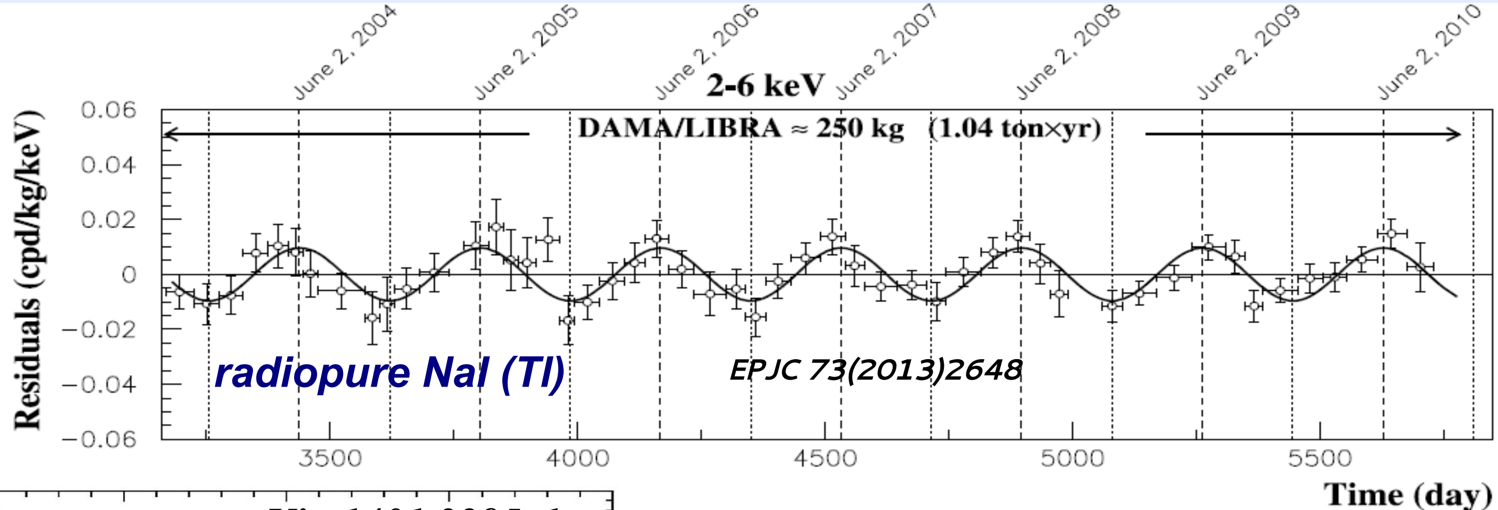
$$\delta a = \frac{\alpha_{EM}\,\epsilon^2}{2\pi} * f,\ f = \begin{cases} 1, \text{ for } m_l >> M_U \\ 2m_l^2/(3M_U^2), \text{ for } m_l << M_U \end{cases}$$

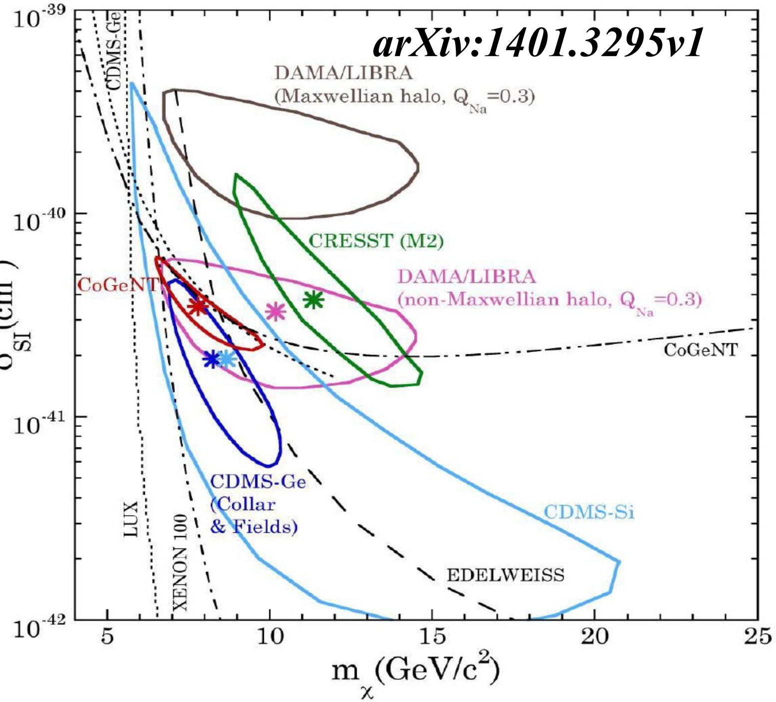
Phys.Rev.D80:095002,2009




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

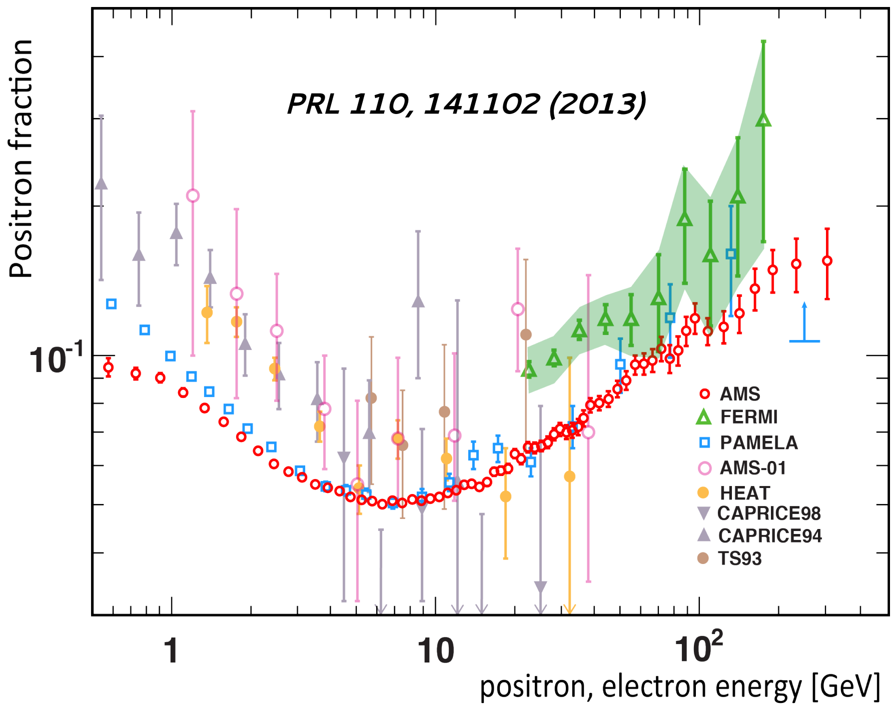
# Direct search experiment

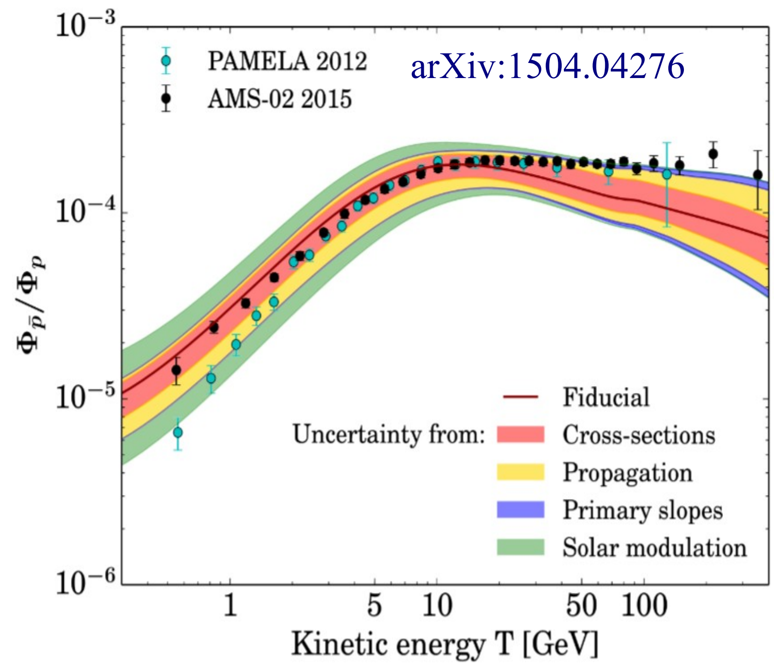



- DAMA/LIBRA results unexplained: 9.2 $\sigma$
- Used to be alone, now few other indications emerged
- Seem to be possible to build a consistent picture
- If the explanation is Dark Matter, it should be relative light: ~10 GeV
- Interaction with the nuclei through a mediator. Mass in the MeV range is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

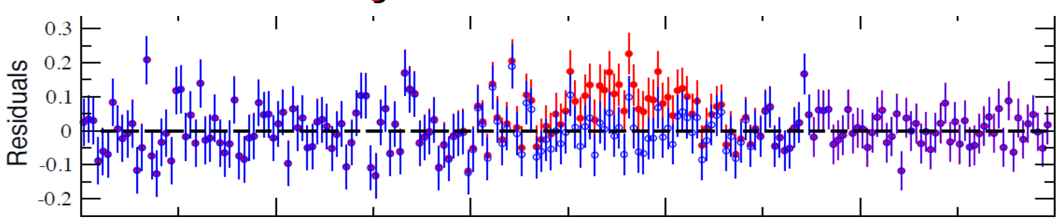
# Astrophysics ...




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

## ... and astronomy




Observation of 3.5keV line?

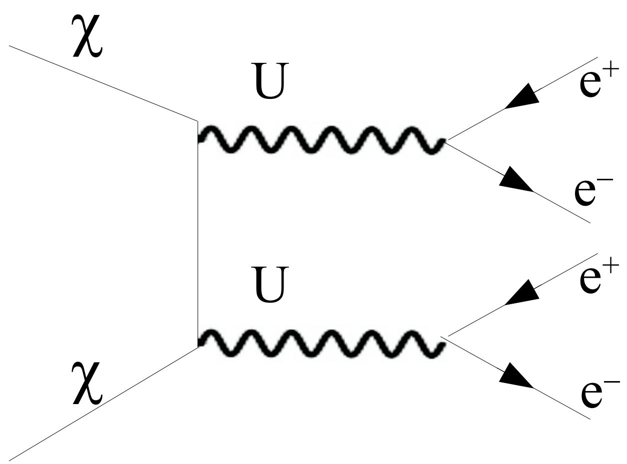
arXiv:1402.2301

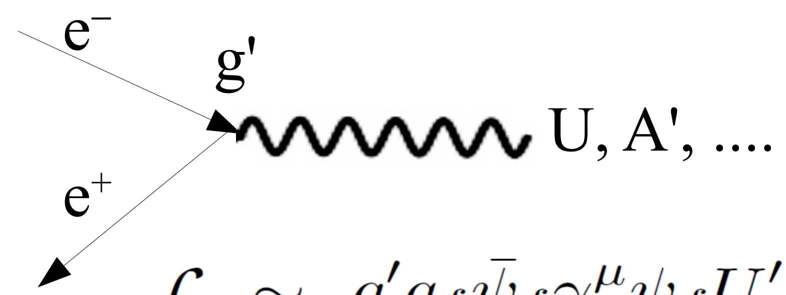
arXiv:1402.4119

Possible interpretation: arXiv:1404.2220

# Hint for dark matter?

Dark matter annihilation through

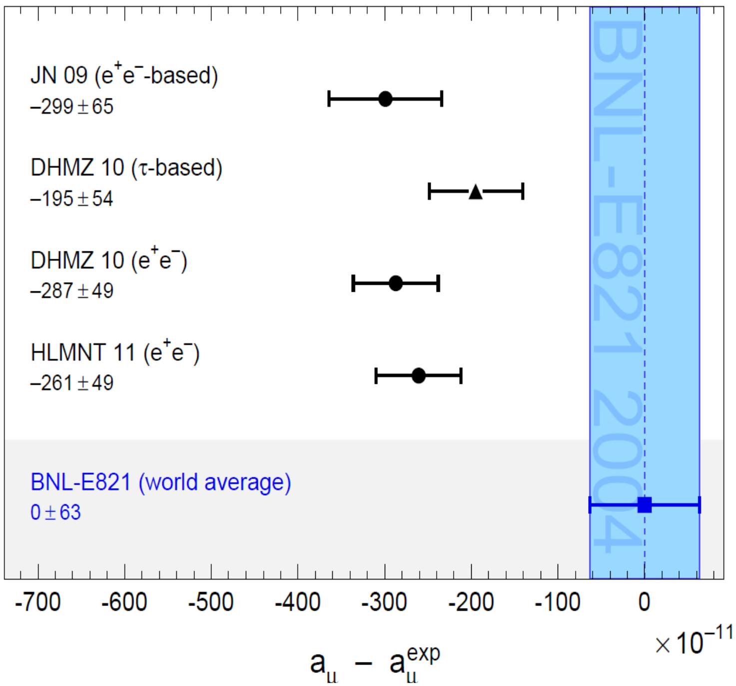


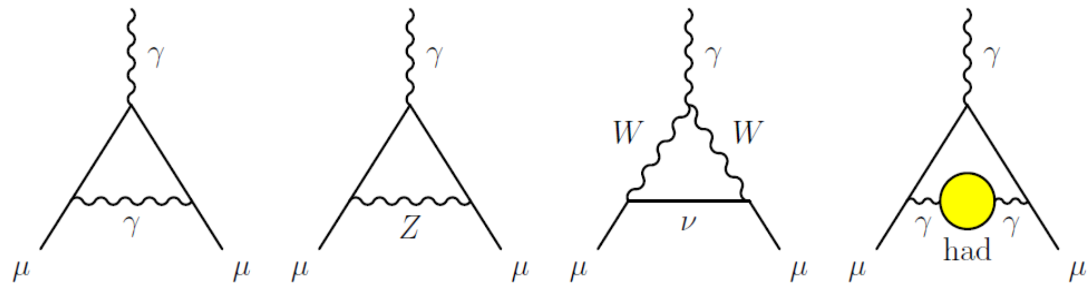




$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- 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 $\varepsilon \sim 1$–$2 \cdot 10^{-3}$ and $m_V \sim 10$–$100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark