New projects on dark photon search

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Overview

- Motivation
- Dark photon basics
- Searches in detectable final states
- Looking for the invisible
- Conclusions

Motivation: New Physics

- **Standard Model is complete: 2012 LHC - Higgs boson**
- Unknowns:
  - Matter-antimatter asymmetry
  - Dark matter
  - Dark Energy
- The Standard Model is a low energy approximation of a more fundamental theory.

But which theory?

- Despite the highest energy reach LHC did not provide any convincing evidence for new degrees of freedom … yet?

Where to look? How to proceed?

Most of those discrepancies originate from Astrophysics and/or Cosmology!

The smoking guns

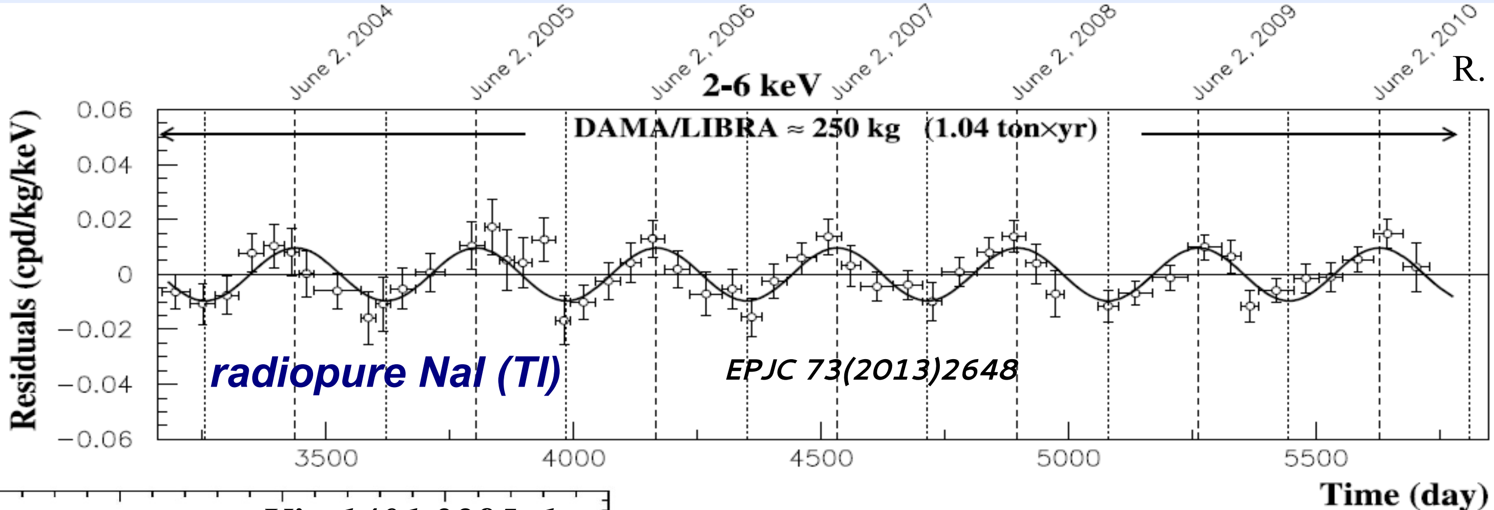
Relatively calm and stable picture of the world

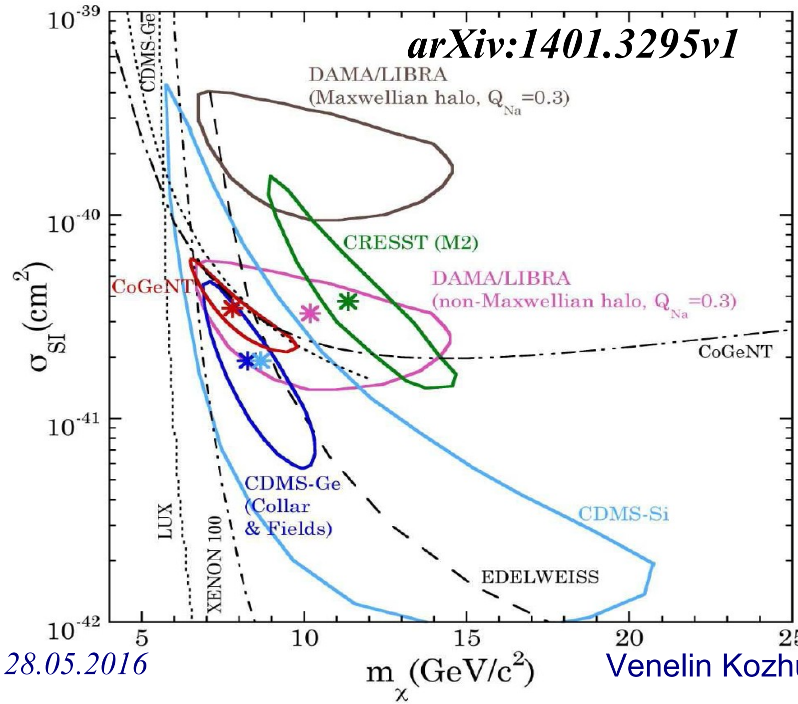
Recognize the dinamics only by looking at particular spots

portals to the inside

Direct search experiment

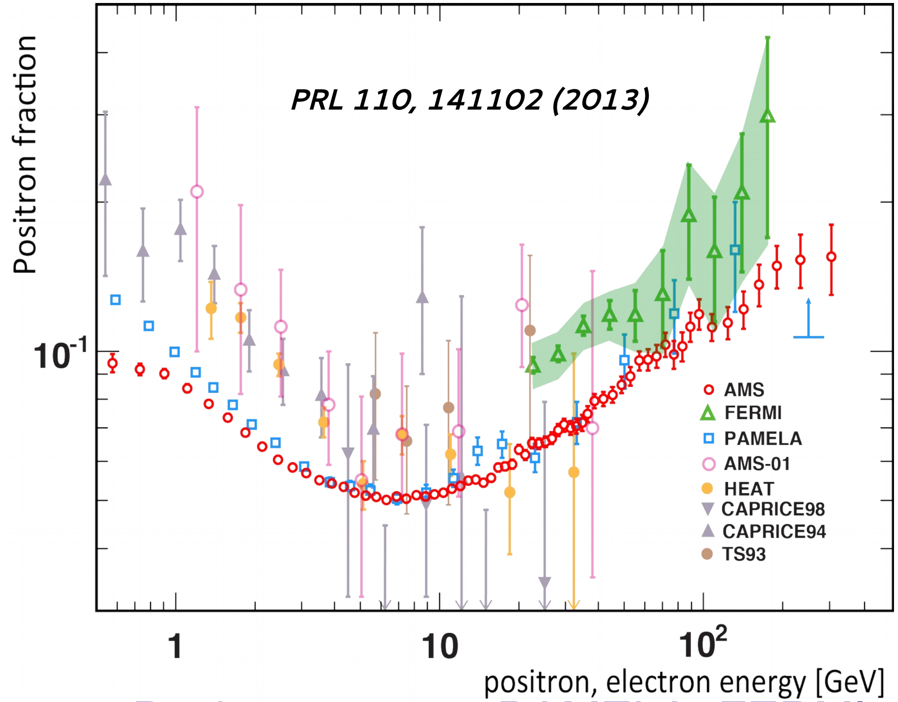
R. Bernabei talk

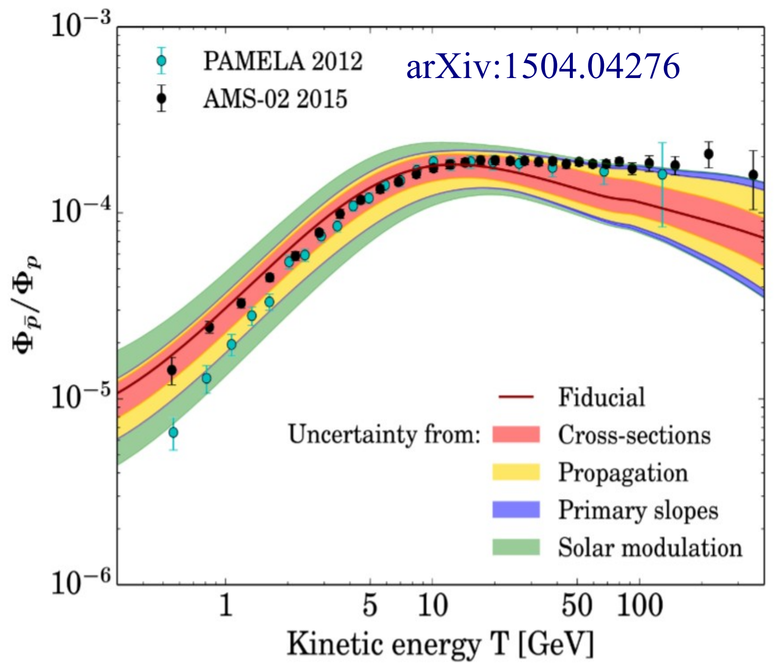




- DAMA/LIBRA results unexplained: 9.2 σ
- Possible indication by other CoGeNT
- Is it possible to build a consistent picture?
- If the explanation is Dark Matter, it could be relative light: ~10 GeV
- Interaction with the nuclei through a mediator. Mass in the MeV range is OK

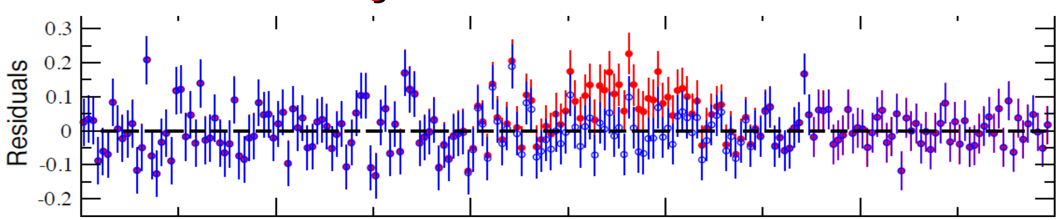
Astrophysics ...





- Positron excess: PAMELA, FERMI, AMS02
- Antiproton excess: AMS02

... and astronomy



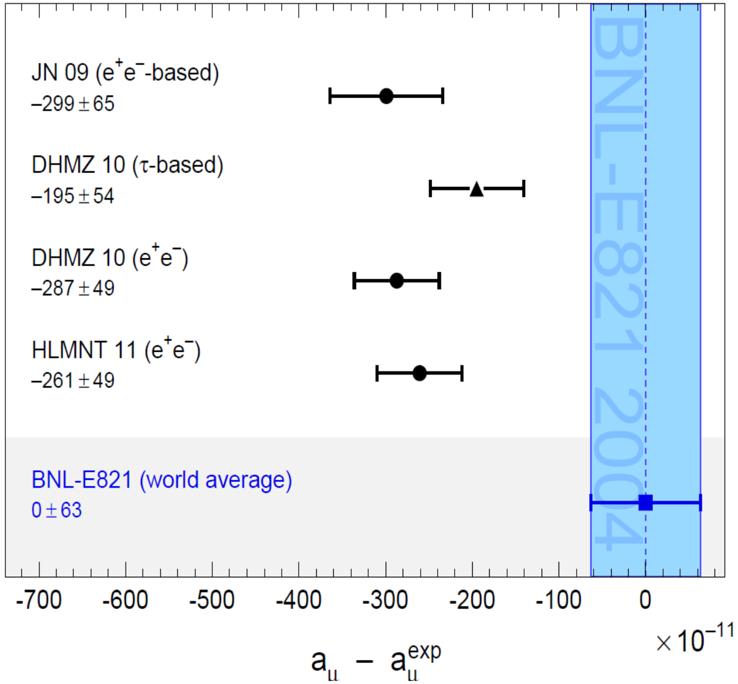
Observation of 3.5keV line?

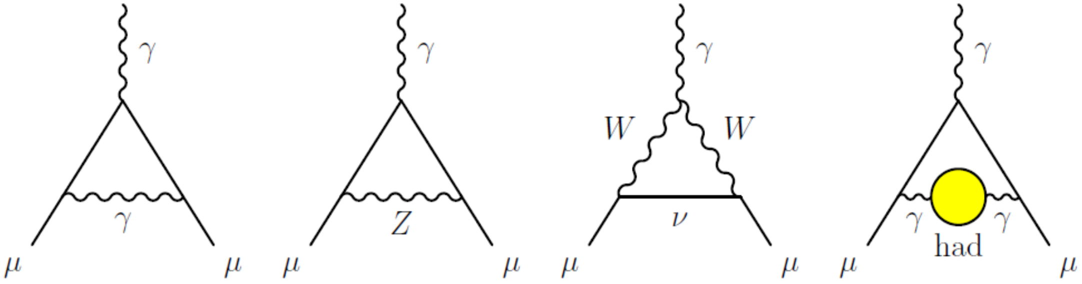
arXiv:1402.2301

arXiv:1402.4119

Possible interpretation: arXiv:1404.2220

g-2



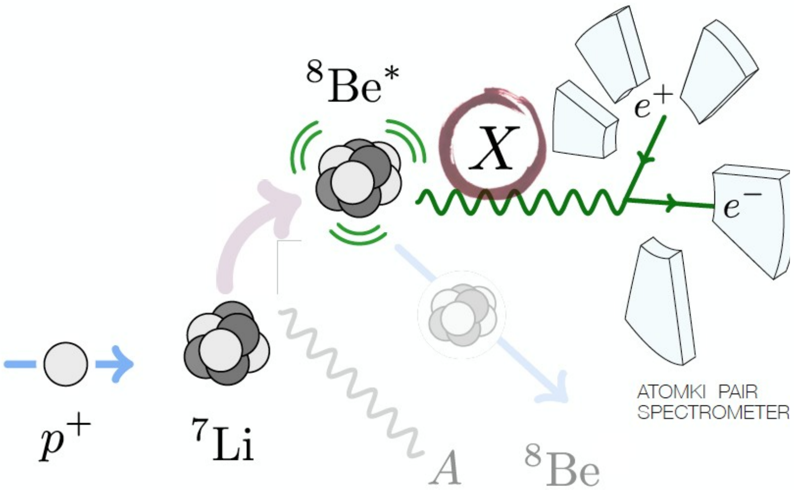


- About 3 σ discrepancy between theory and experiment (3.6 σ, if taking into account only $e^+e^- \to$ hadrons)

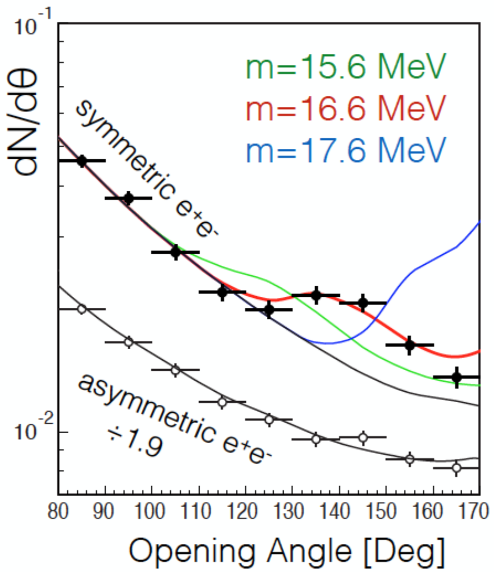
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

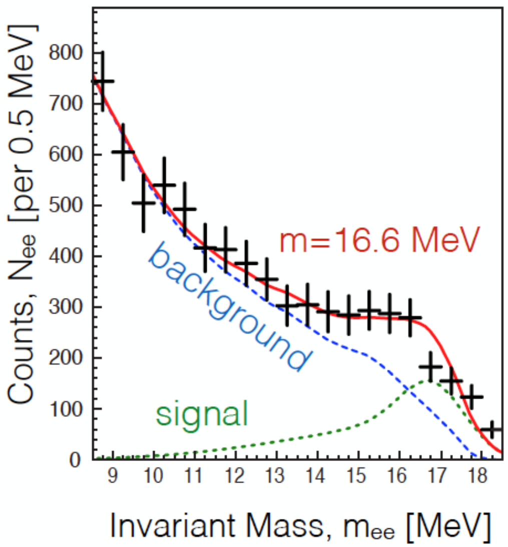
where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1$–$2\cdot 10^{-3}$ and $m_V \sim 10$–100 MeV, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

Anomalies in nuclear transitions



PRL 116, 042501 (2016)

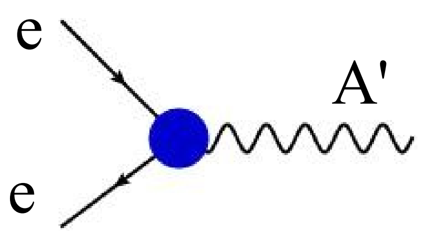


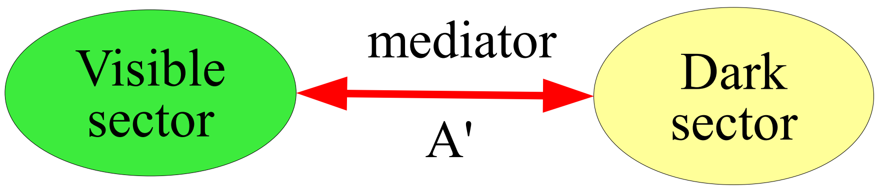


- Anomalous angular and invariant mass distribions in the IPC process
- Several indications in the last few decades
- New experiment at ATOMKI
- E-ΔE plastic scintillator detector, in the plane transversal to the beam
- The anomaly observed at ~17 MeV – cannot be interpreted within nuclear physics so far...

New gauge bosons

- The effective interaction that can be studied is





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

  - $q_f \rightarrow 0$ for some flavours

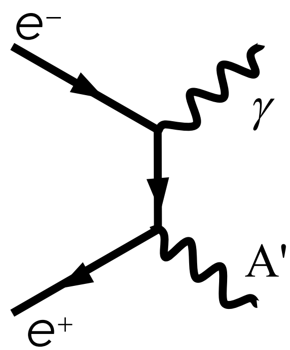
- Such textbook scenario could address the (g_μ-2) discrepancy, abundance of antimatter in cosmic rays, signals for DM scattering
  - General U'(1) and kinetic mixing with B (A', Z')
    - Universal coupling proportional to the q_{em}
    - Just single additional parameter – ε

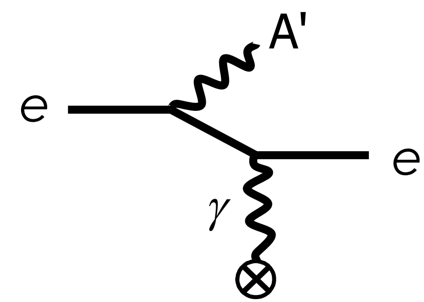
$$L_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

  - Leptophilic/leptophobic dark photon
- Other messenger types possible (neutrino, higgs, ALP, see T. Spadaro talk)
- **Rich dark sector?**

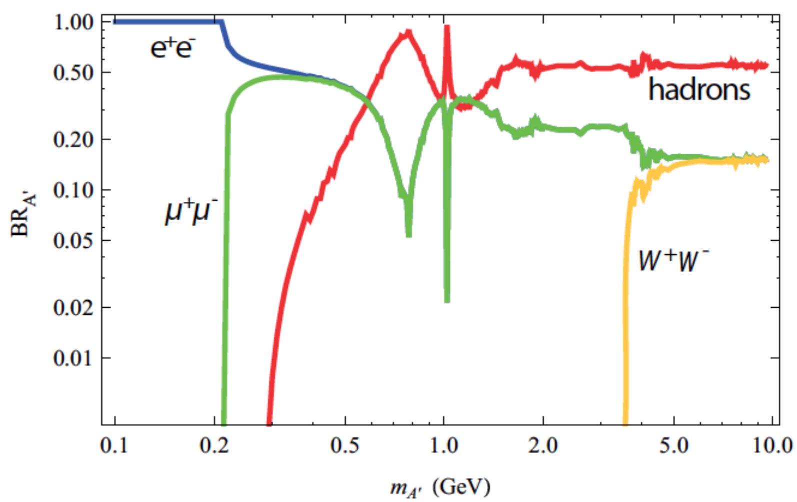
Dark photon phenomenology

- Production mechanisms
  - Meson decays
  - Bremsstrahlung
  - Annihilation



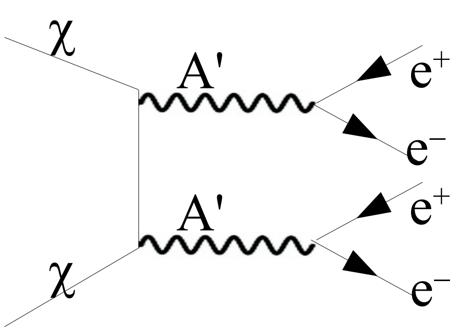


- Decays
  - To SM model particles if nothing in the DS lighter than A'



  - $A' \rightarrow \gamma\gamma\gamma$, if $M(A') < 2m_e$, small width, A' quasi stable
  - To DS particles with $Br(A' \rightarrow \chi\chi) = 1$,

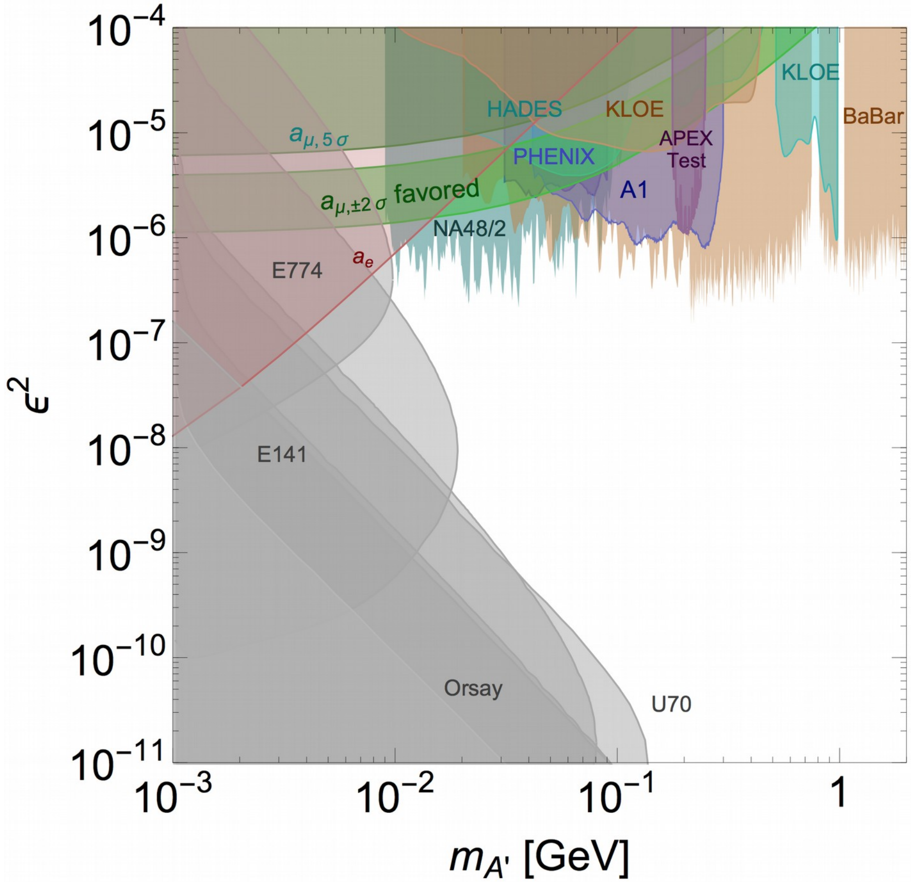
Dark matter annihilation

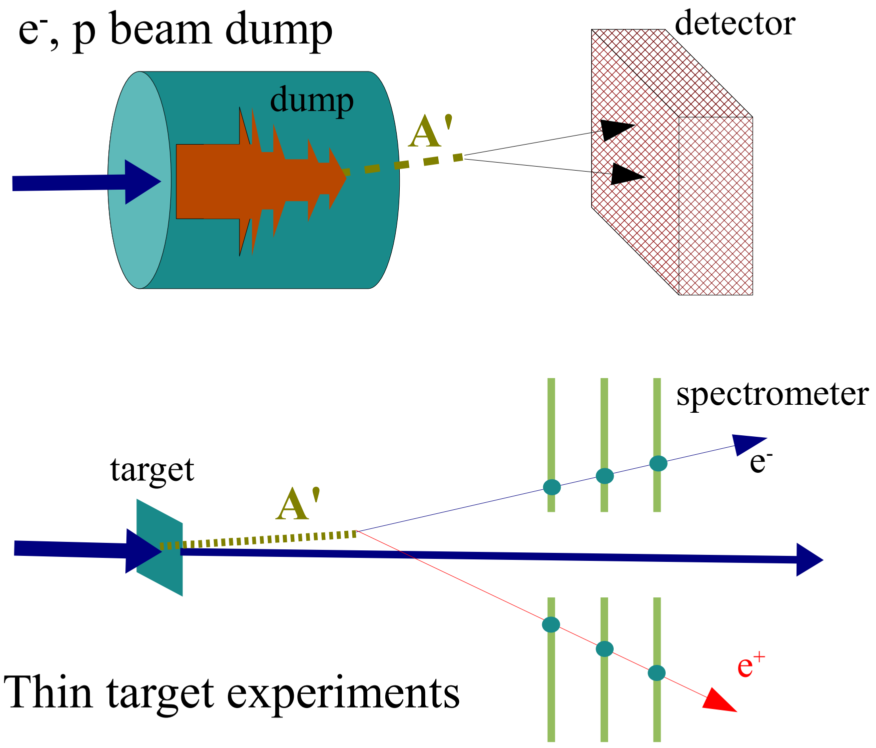


Dark photons worldwide

The physics case attracted a large attention recently

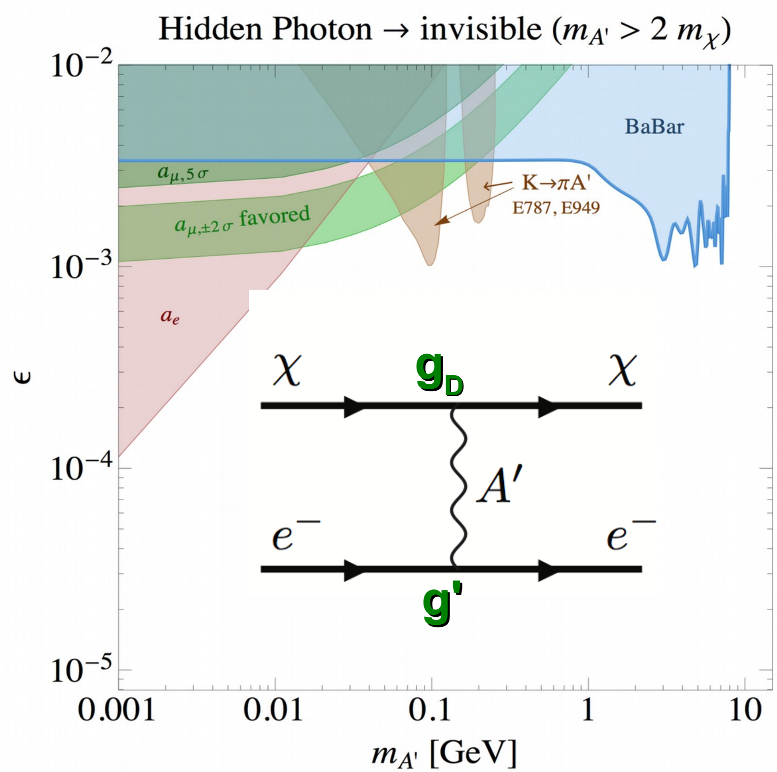
Visible DP searches in BoT

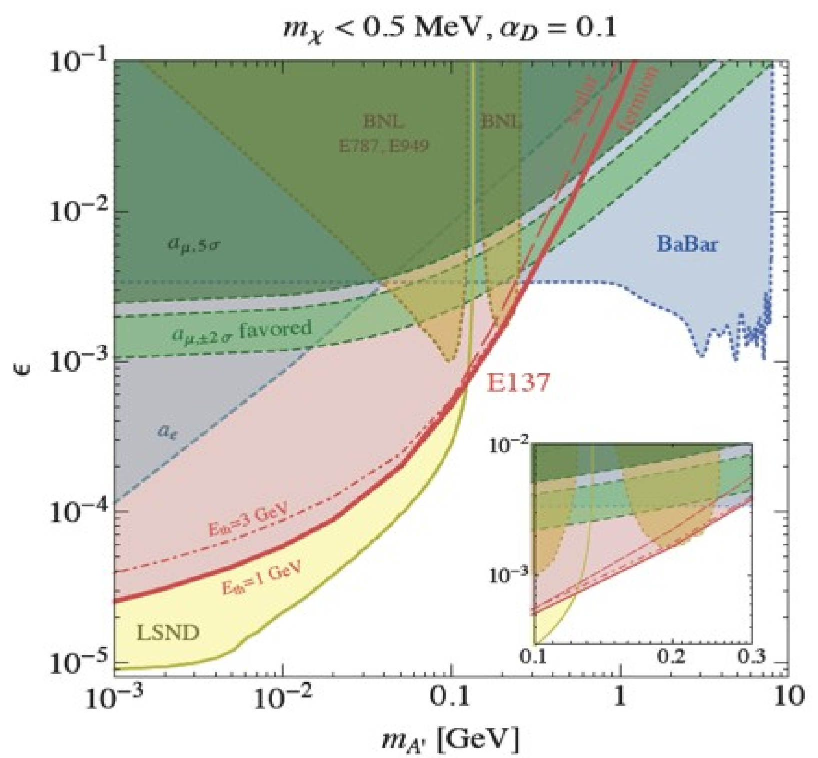




- Beam dump experiments: A'-strahlung production
- Fixed target: peaks in the e^+e^- invariant mass spectrum
- Meson decays: Peaks in M_{e+e-} or $M_{\mu+\mu-}$

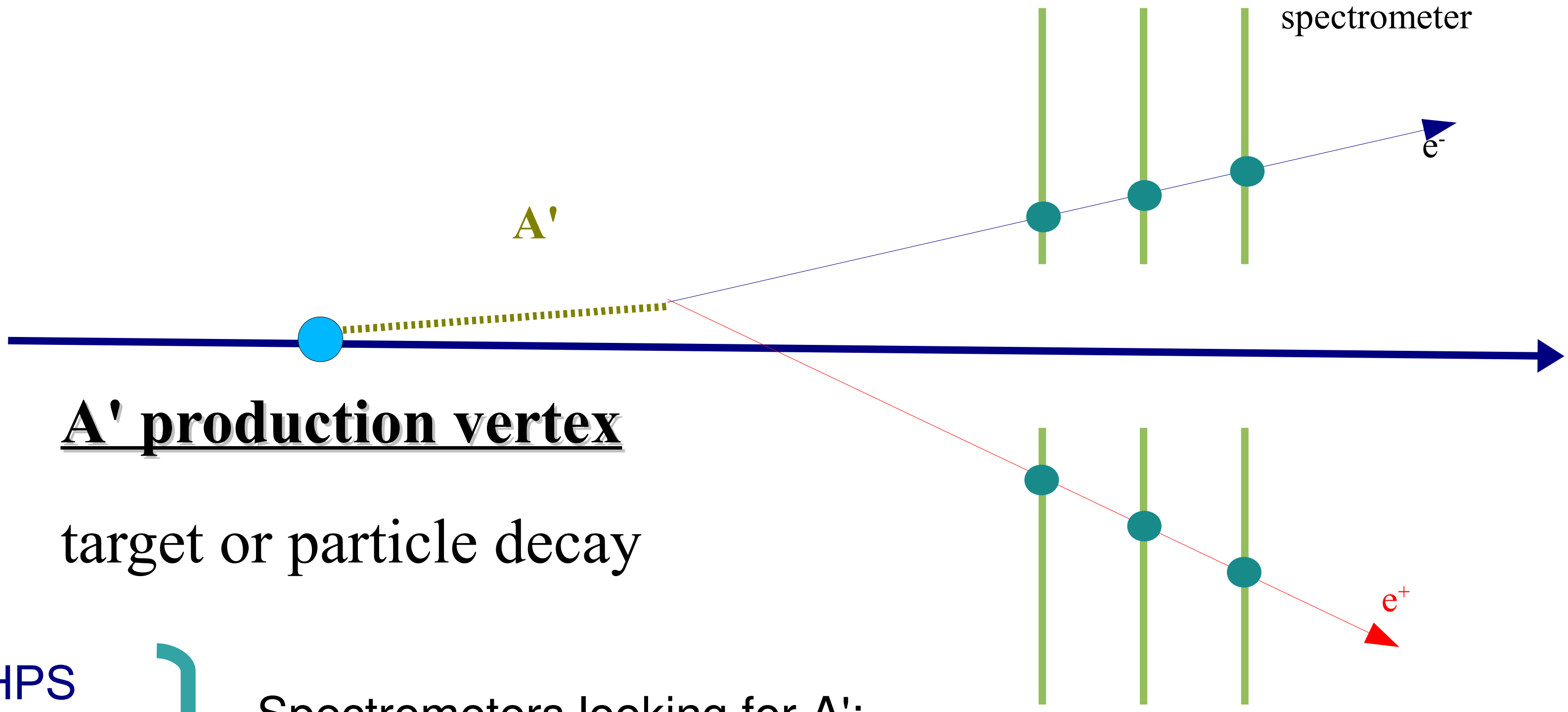
Invisible A' searches





- 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

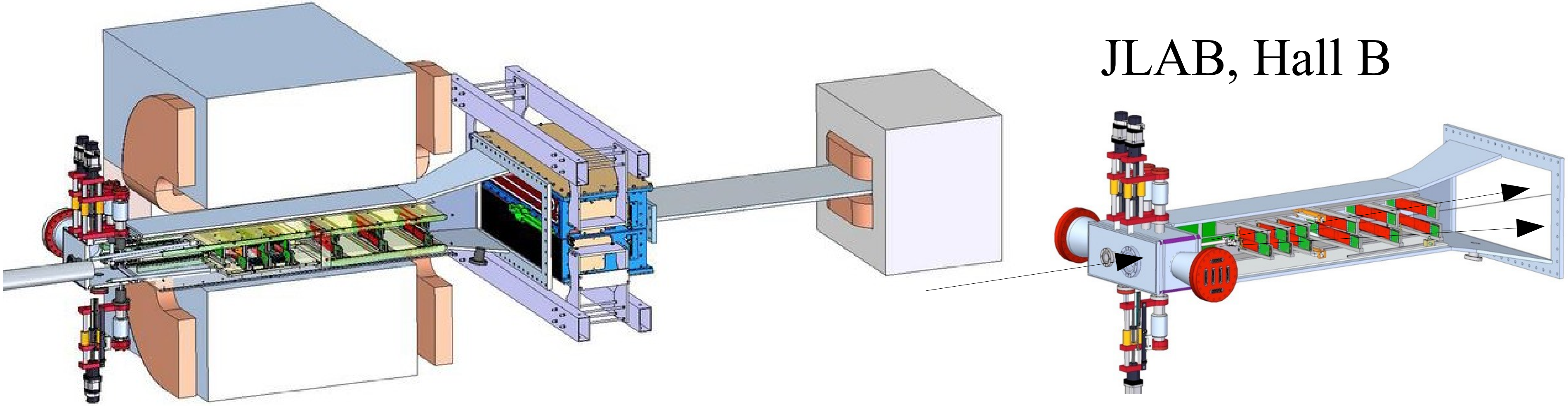
Visible dark photons



- HPS
- MESA

Spectrometers looking for A':
- produced in a thin target
- decaying to leptons

HPS experiment



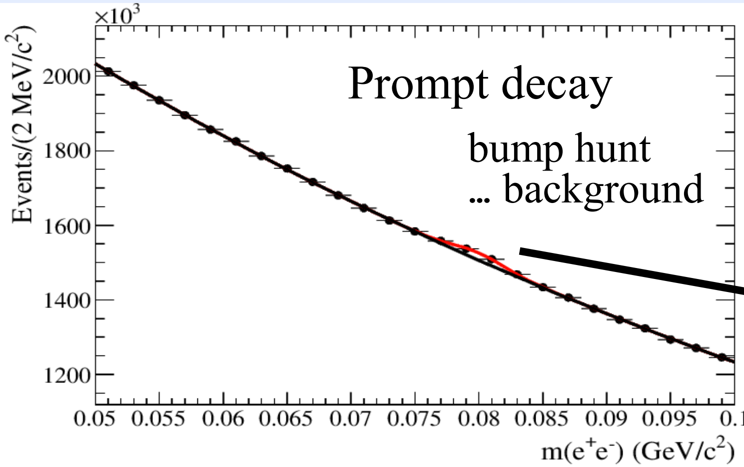
JLAB, Hall B

- Electron beam (2.2 and 6.6 GeV, up to 500 nA) on a thin tungsten target (0.25% X_0)
- A'-strahlung production
- Decay channel – A' → e^+e^-
- Silicon vertex tracker (1 m long) inside dipole magnet, 6 layers (dual sensor)
  - Particle momenta, Vertices
  - 6.4 μm hit resolution, σ(t) = 2.5 ns
- Lead tungstate electromagnetic calorimeter

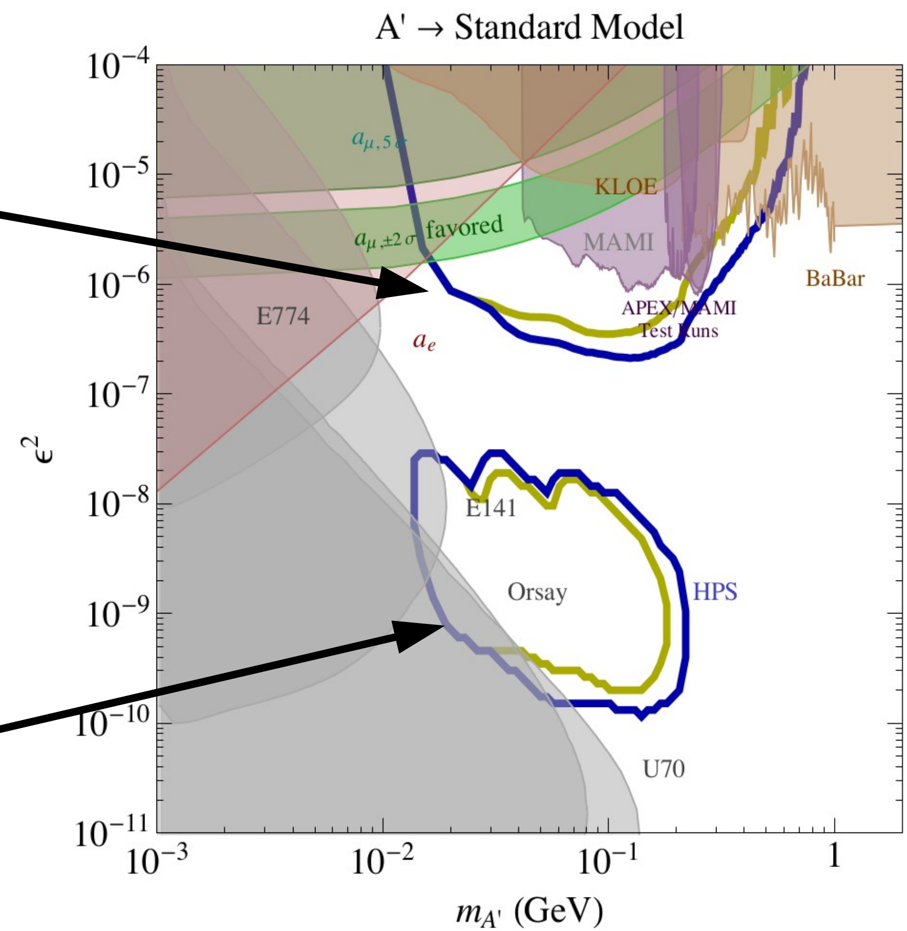
Fast energy measurement

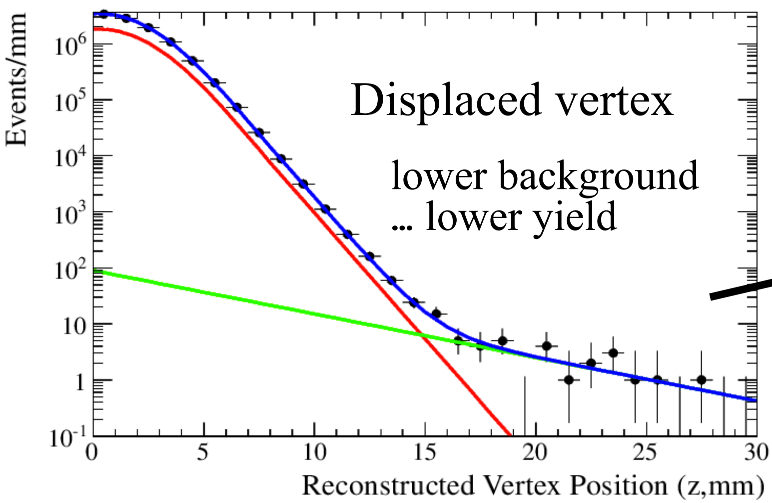
Trigger definition

HPS sensitivity



Timothy Nelson, Dark Sectors Workshop, 28-30 Apr., SLAC

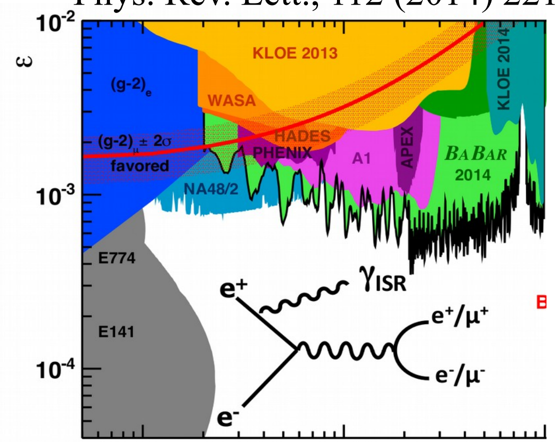




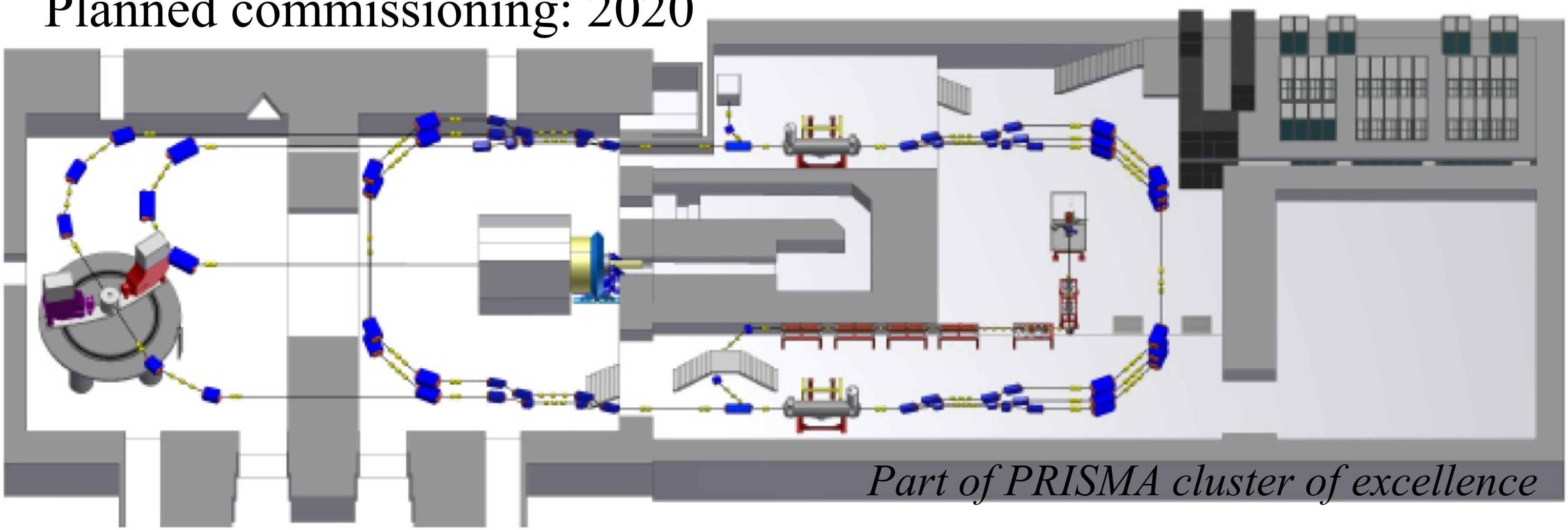
Dark photon @ Mainz

- Tradition in dark photon physics - A1 @ MAMI
- New accelerator: MESA (Mainz Energy-recovering Superconducting Accelerator)
  - Energy up to 155 MeV
  - Current > 1 mA

Phys. Rev. Lett., 112 (2014) 221802



Planned commissioning: 2020

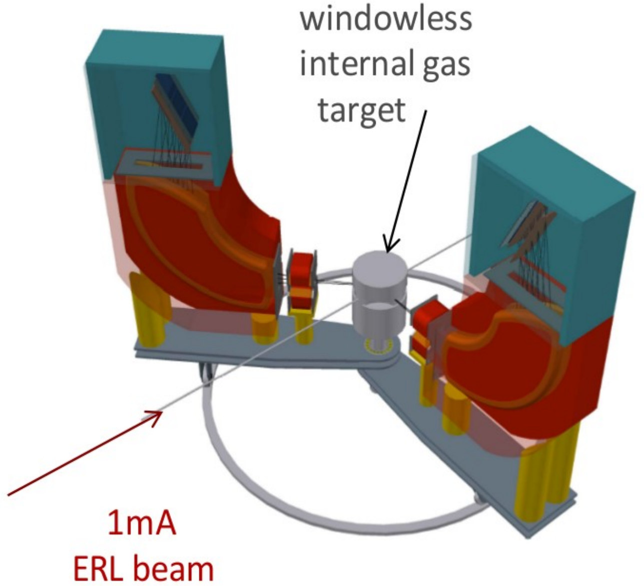


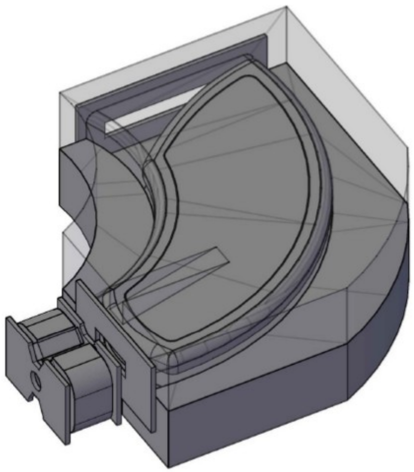
Part of PRISMA cluster of excellence

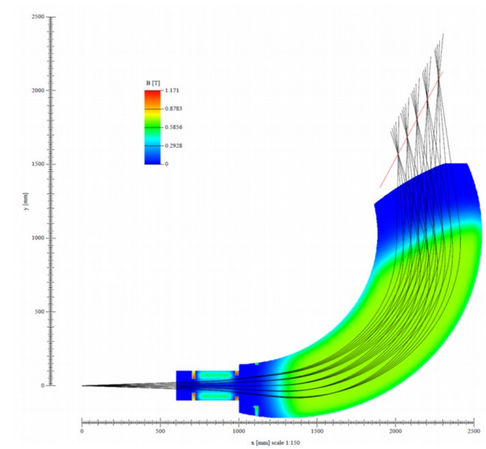
MAGIX @ MESA

The MAinz Gas Internal EXperiment

Achim Denig, Dark Sectors Workshop, 28-30 Apr., SLAC



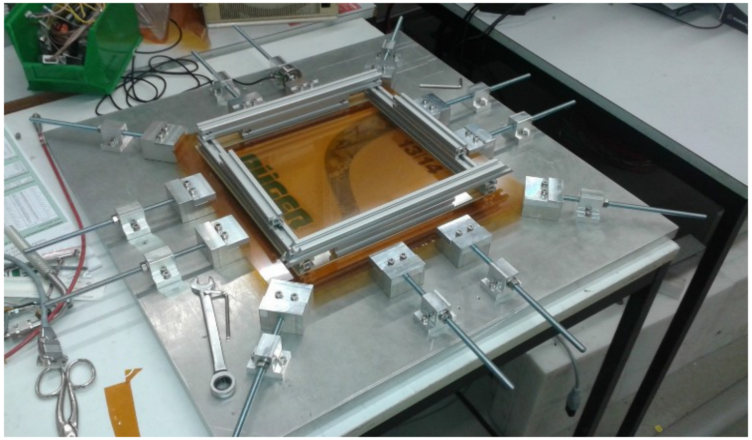


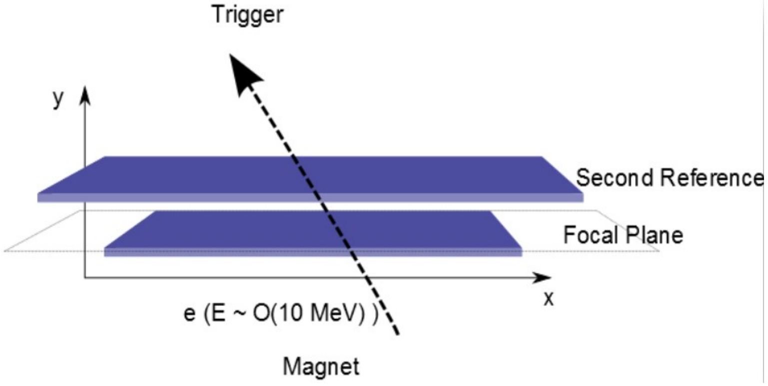


- Double arm high resolution spectrometers
  - Aim for $\Delta p/p \sim 10^{-4}$
  - Acceptance +- 50 mrad

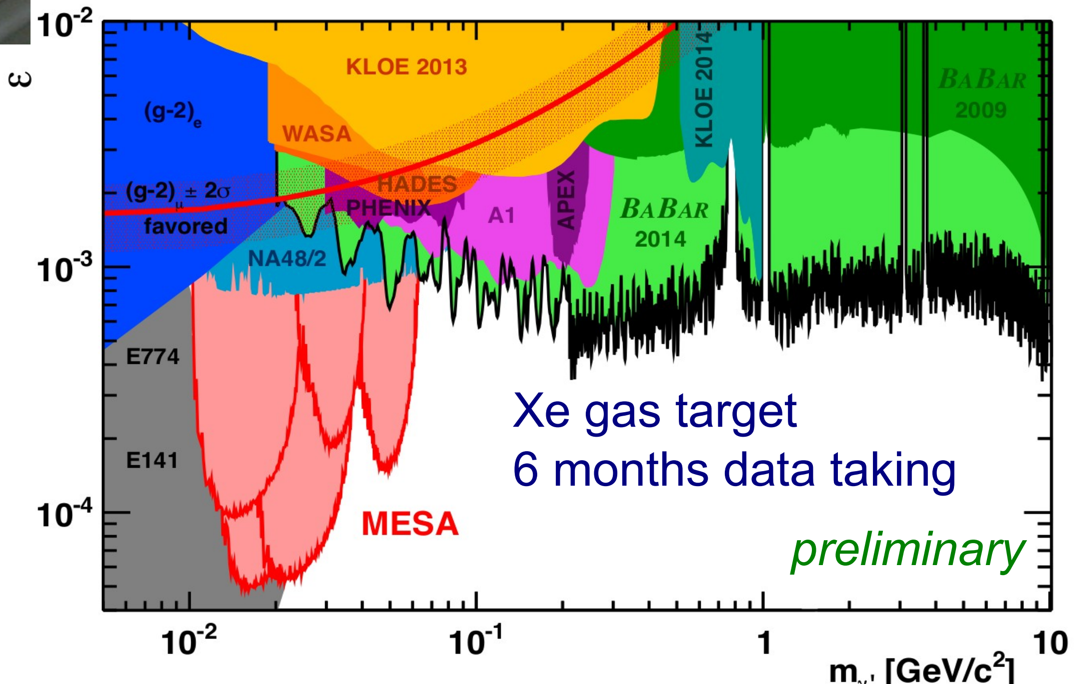
- Gas jet target
  - Supersonic gas /cluster jet
  - High gas density ($10^{19}/cm^2$)
  - O(mm) target length
  - Windowless
  - **Ready in 2016**

MAGIX @ MESA





- Two position detectors
  - Focal plane
  - Direction measurement
- GEM detectors considered
  - 0.7% X0
  - High rate capability
  - 2D strip readout
    - Should aim for 50μm coordinate resolution



Visible dark photons status

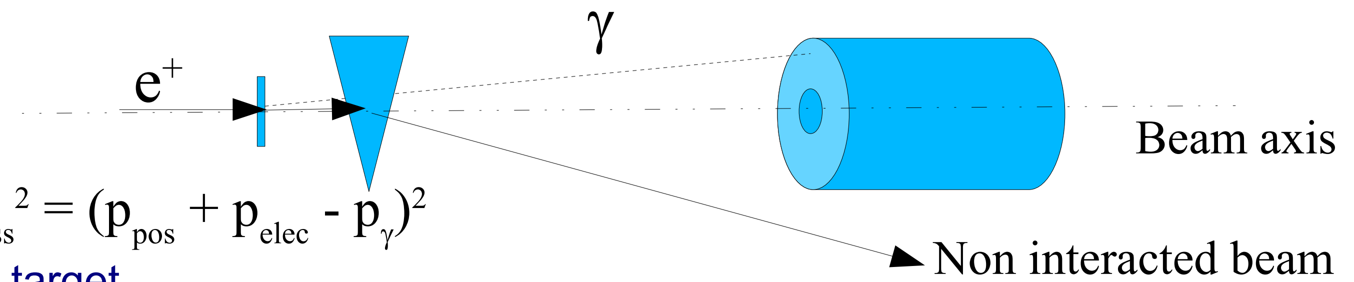
- HPS
  - 2015 – engineering run @1.06 GeV
    - Results in the next few months
  - 2016 – physics data quality @ 2.3 GeV
    - Results expected in ~1 year
- MAGIX
  - Accelerator commissioning – 2020
- Address short and medium living DP
- Many other proposals and techniques are being tested
  - See T. Spadaro talk

Invisible dark photons

- Addressing the missing mass
  - PADME@Frascati, VEPP3@Novisibirsk, MMAPS@Cornell
  - Positron beam on a thin target
  - Annihilation production of dark photons
- Missing energy
  - NA64: leakage of energy to the dark sector in high energy shower development
- Dark matter scattering
  - BDX

Missing mass technique

Study only the recoil photon

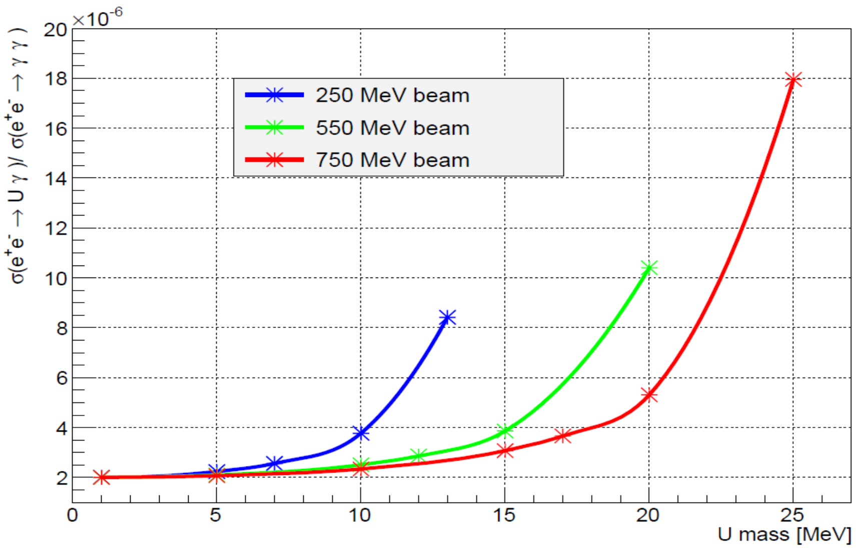


$$M_{miss}^2 = (p_{pos} + p_{elec} - p_{\gamma})^2$$

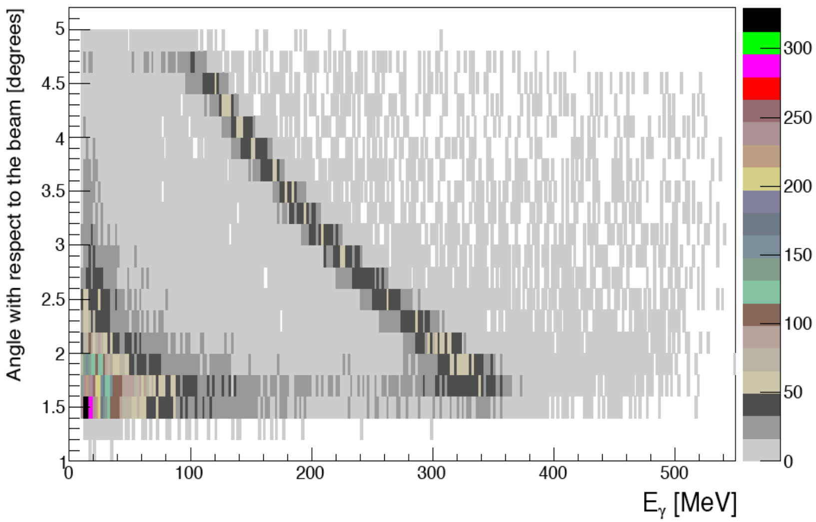
- Positron beam on a thin target
- Positron momentum is determined by the accelerator characteristics
- Missing mass resolution: annihilation point, E_{γ}, φ_{γ}

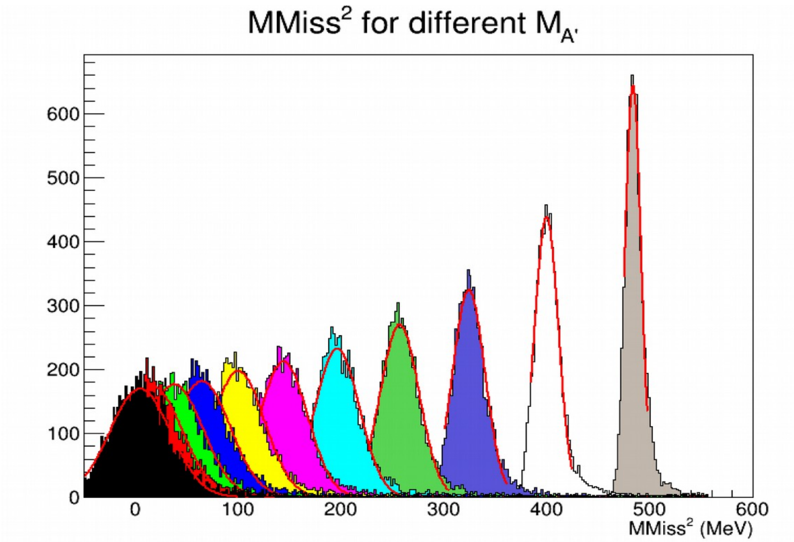
$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta,$$

Cross section enhancement with the approach of the production threshold



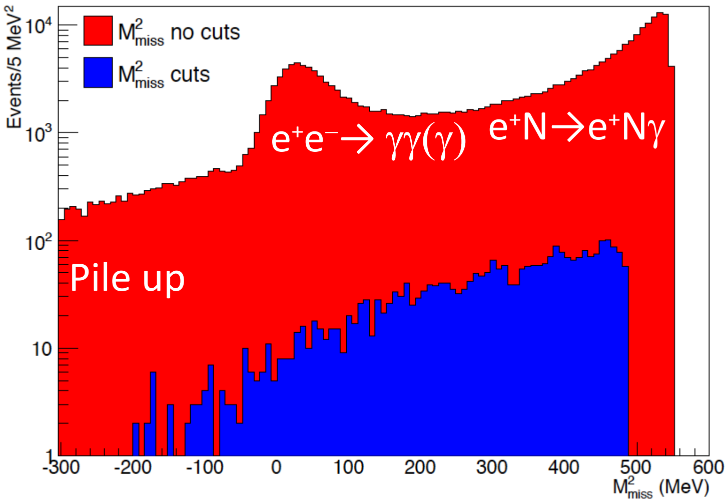
Measurement strategy



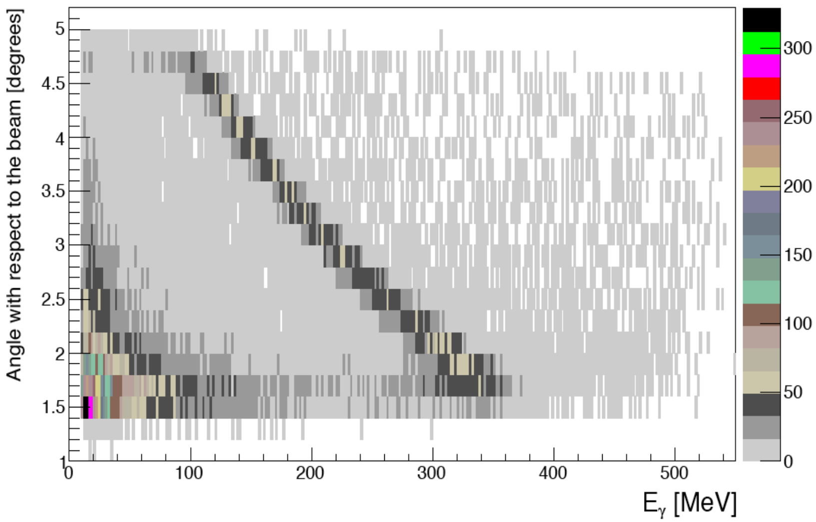


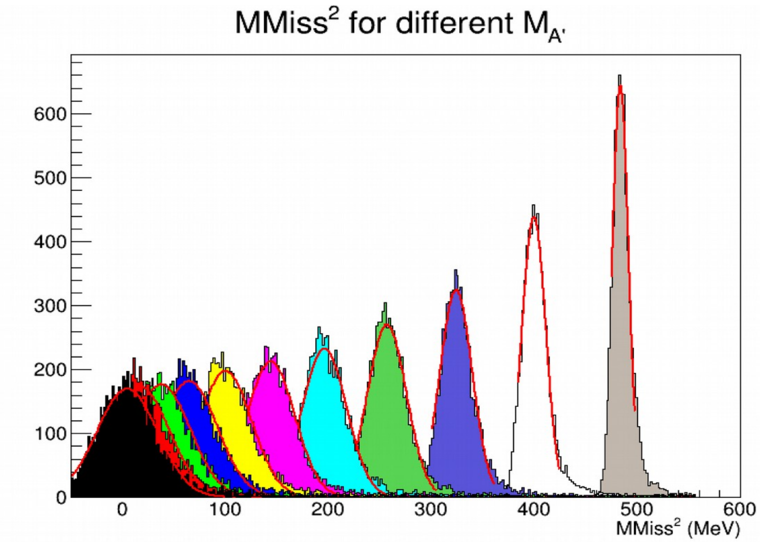
- Background suppression

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



Measurement strategy





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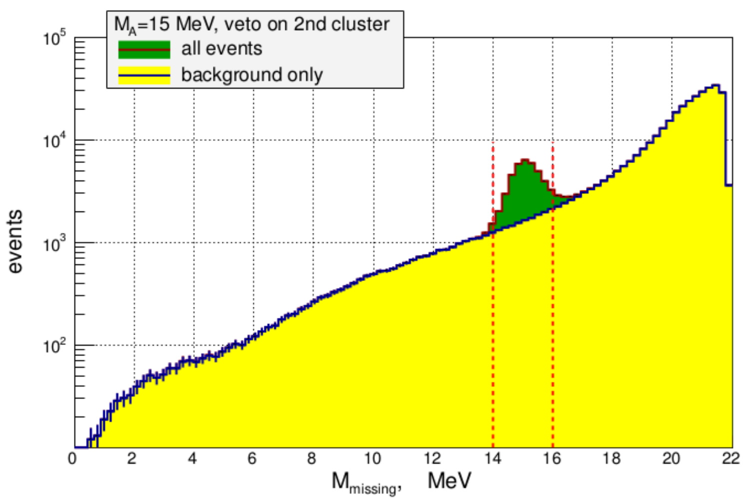
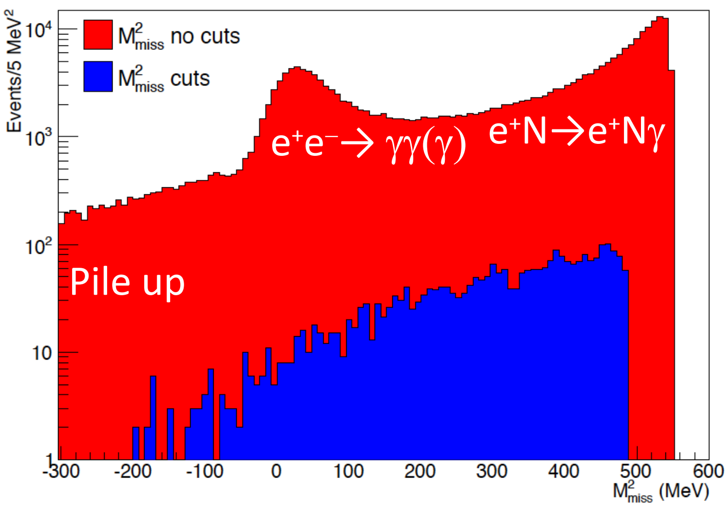
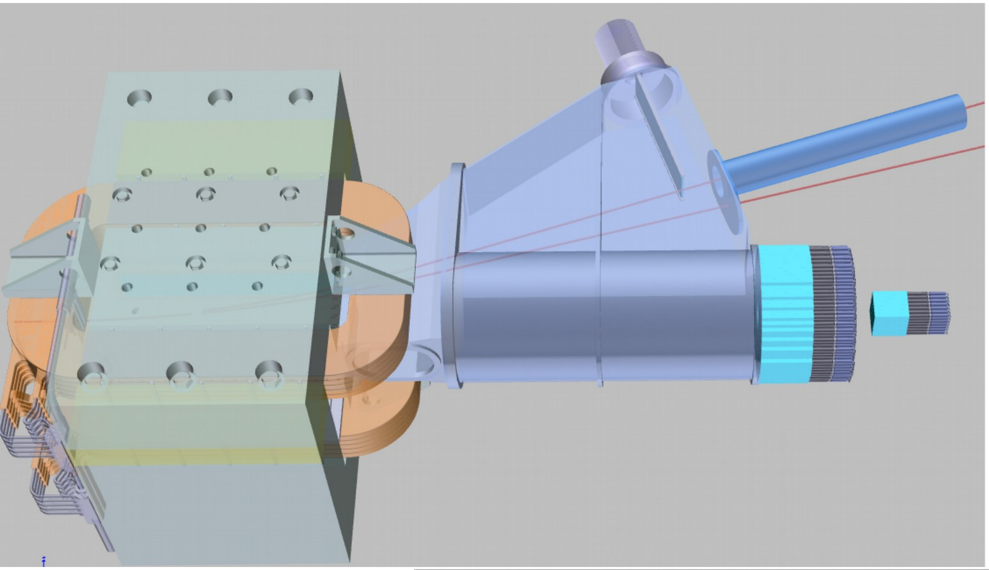


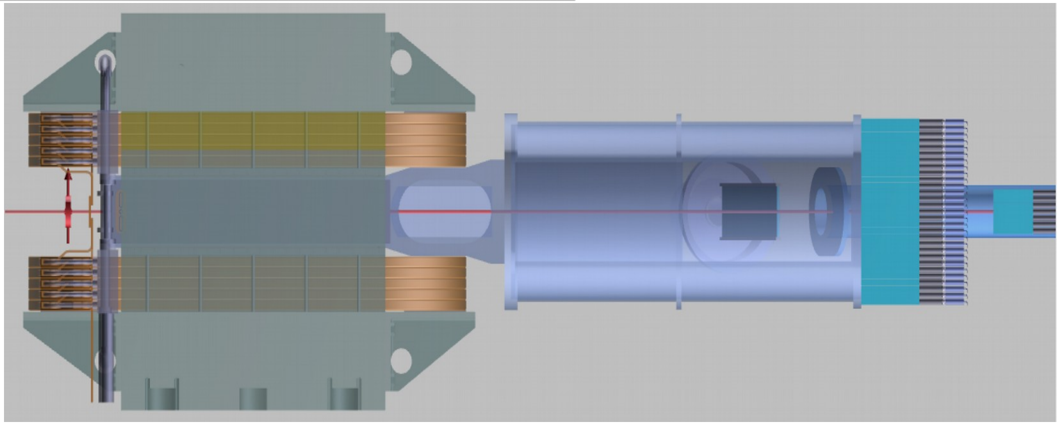


PADME experiment

Positron Annihilation into Dark Matter Experiment

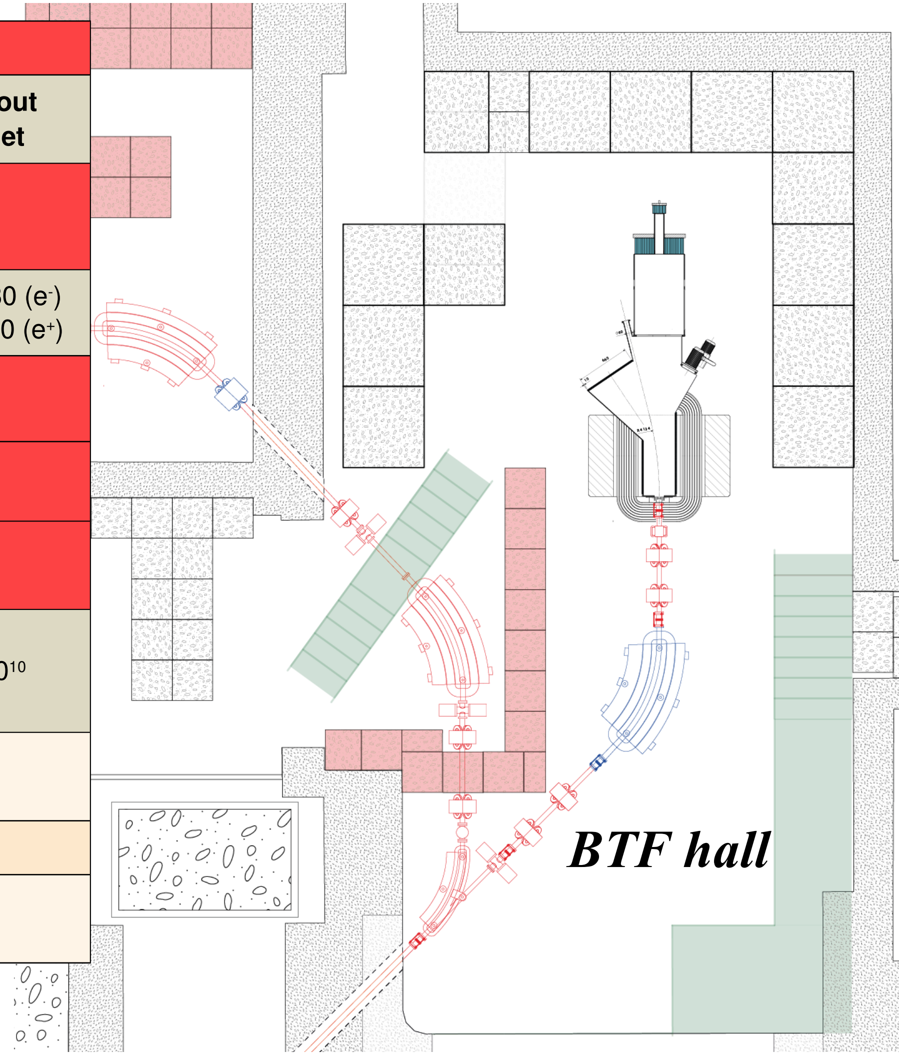


- Small scale fixed target experiment
- Measuring both charged and neutral particles:
  - Charged particles detector
  - Calorimeter
  - Beam profile

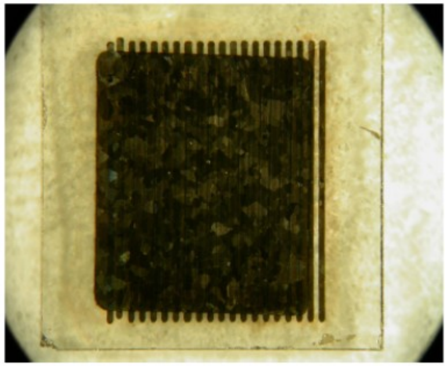


BTF @ LNF

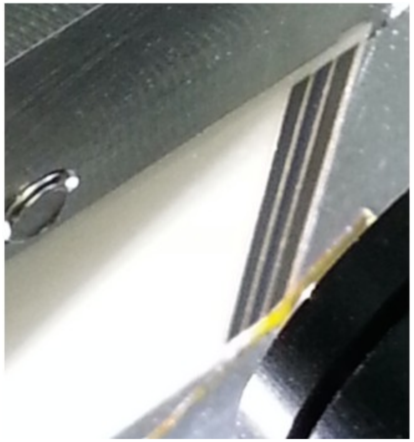
Parameter	Parasitic mode		Dedicated mode	
	With target	Without target	With target	Without target
Particle species	e^+ or e^- Selectable by user	e^+ or e^- Depending on DAFNE mode	e^+ or e^- Selectable by user	
Energy (MeV)	25–500	510	25–700 (e^-/e^+)	250–730 (e^-) 250–530 (e^+)
Energy spread	1% at 500 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			

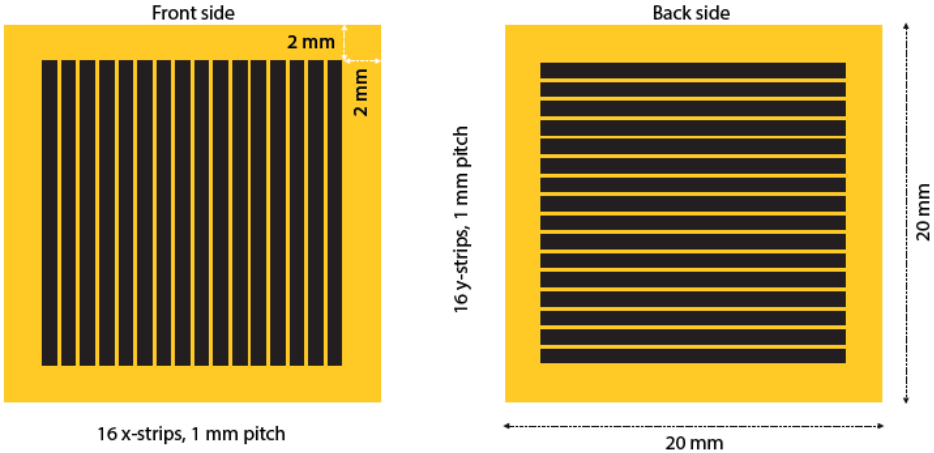


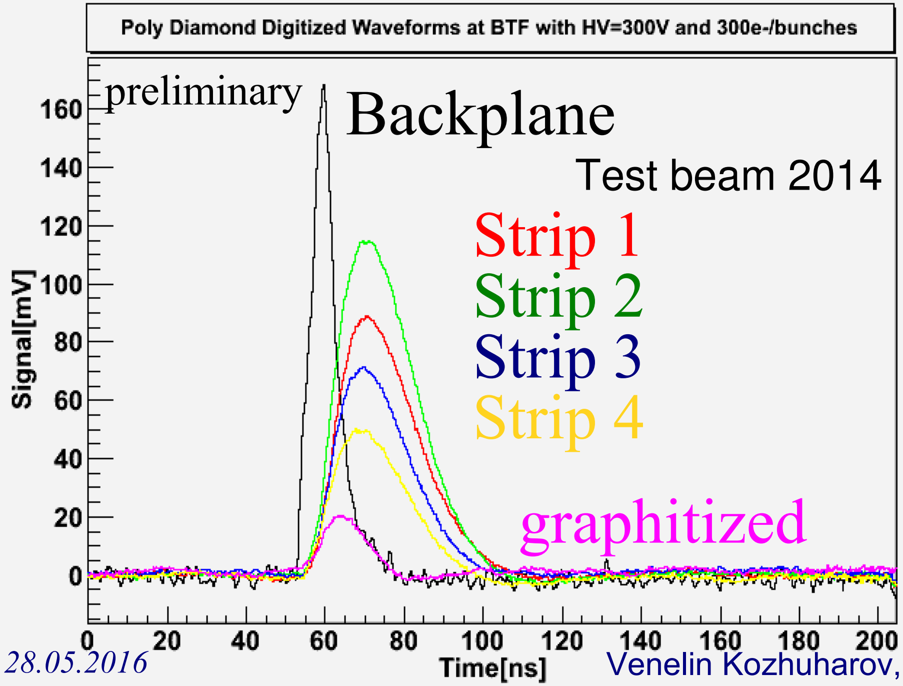
Diamond target



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



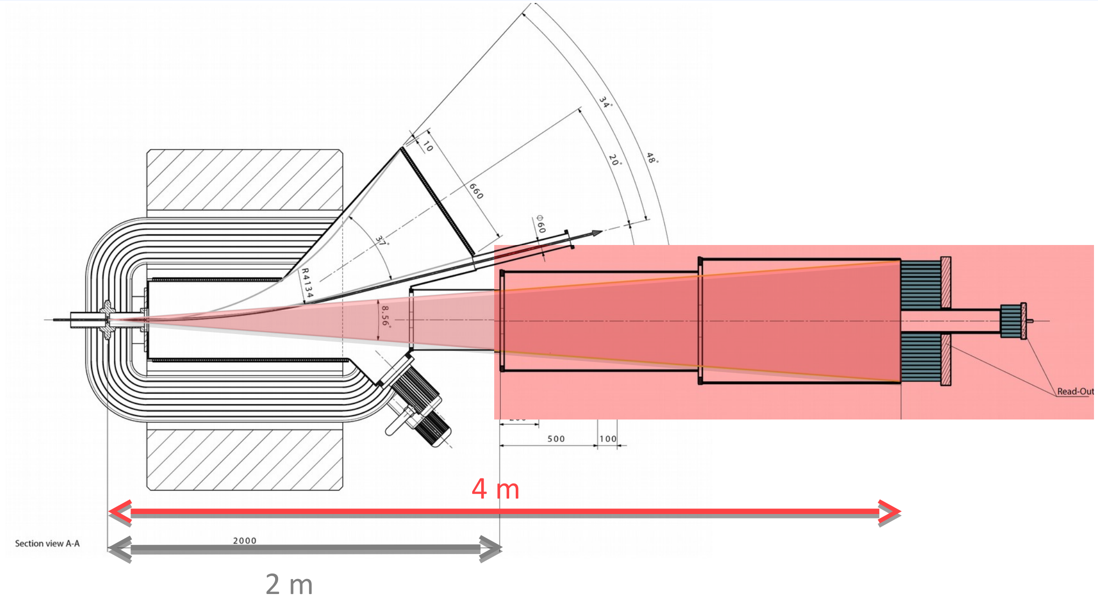


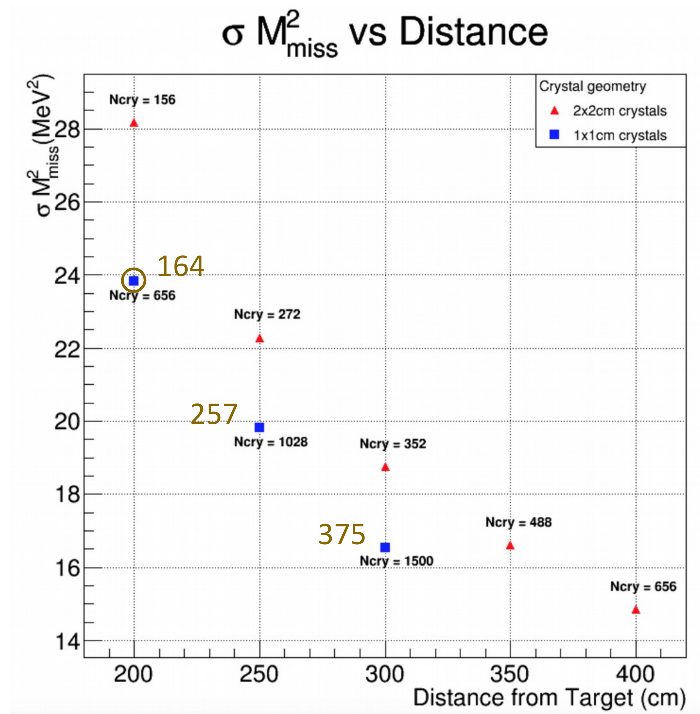


Polycrystalline diamonds

- 100 mm thickness:
- 16x1mm^2 strip and X-Y readout in a single detector
- Readout strips are graphitized by using a laser to avoid metallization
- PADME prototype 20×20mm^2 produced and tested in October 2015

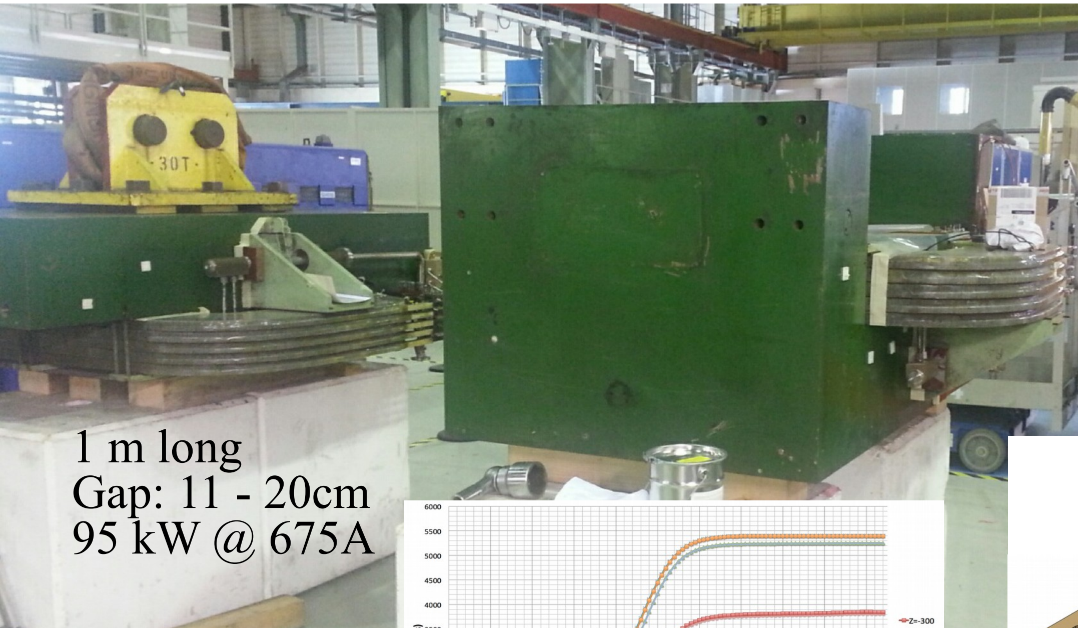
Calorimeter design



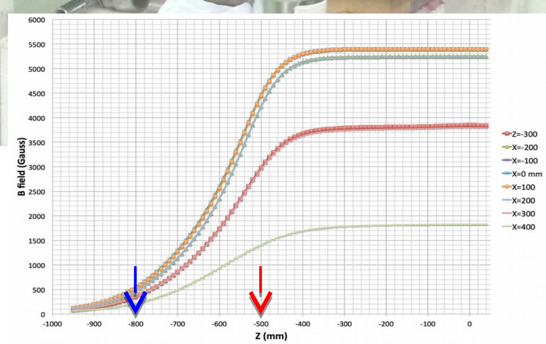


- BGO crystals available from L3 experiment
- Crystal geometry is close to 2 x 2 cm front face
  - Cut the crystals in 1 x 1 cm and place them at 2 m
    - Requires cutting of the existing crystals, but the quantity is identified and available
  - Place the calorimeter at 3 m distance and keep the dimensions 2x2 cm
    - Agreement on the usage of extra crystals

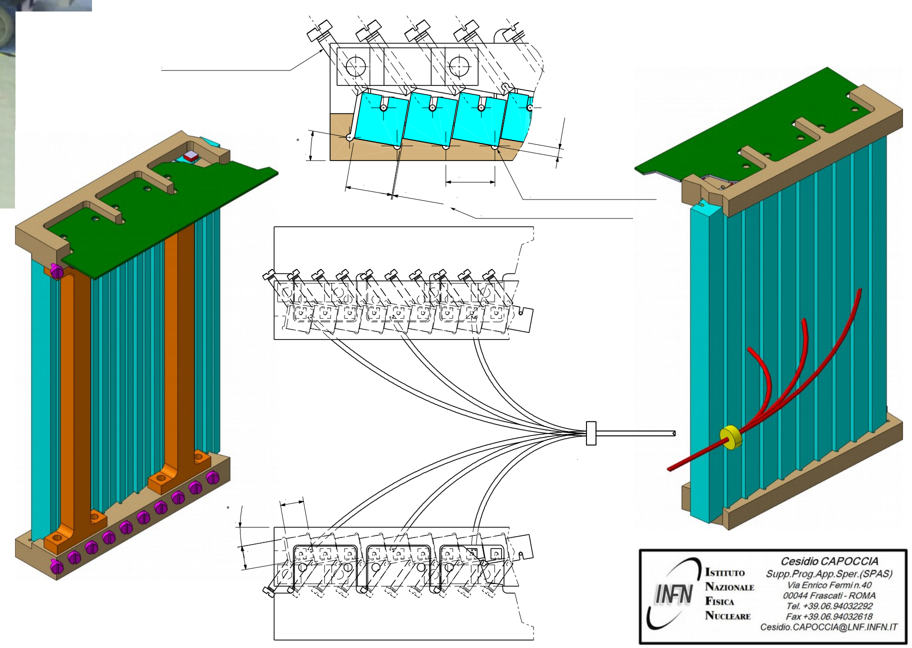
Magnet



1 m long
Gap: 11 - 20cm
95 kW @ 675A



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

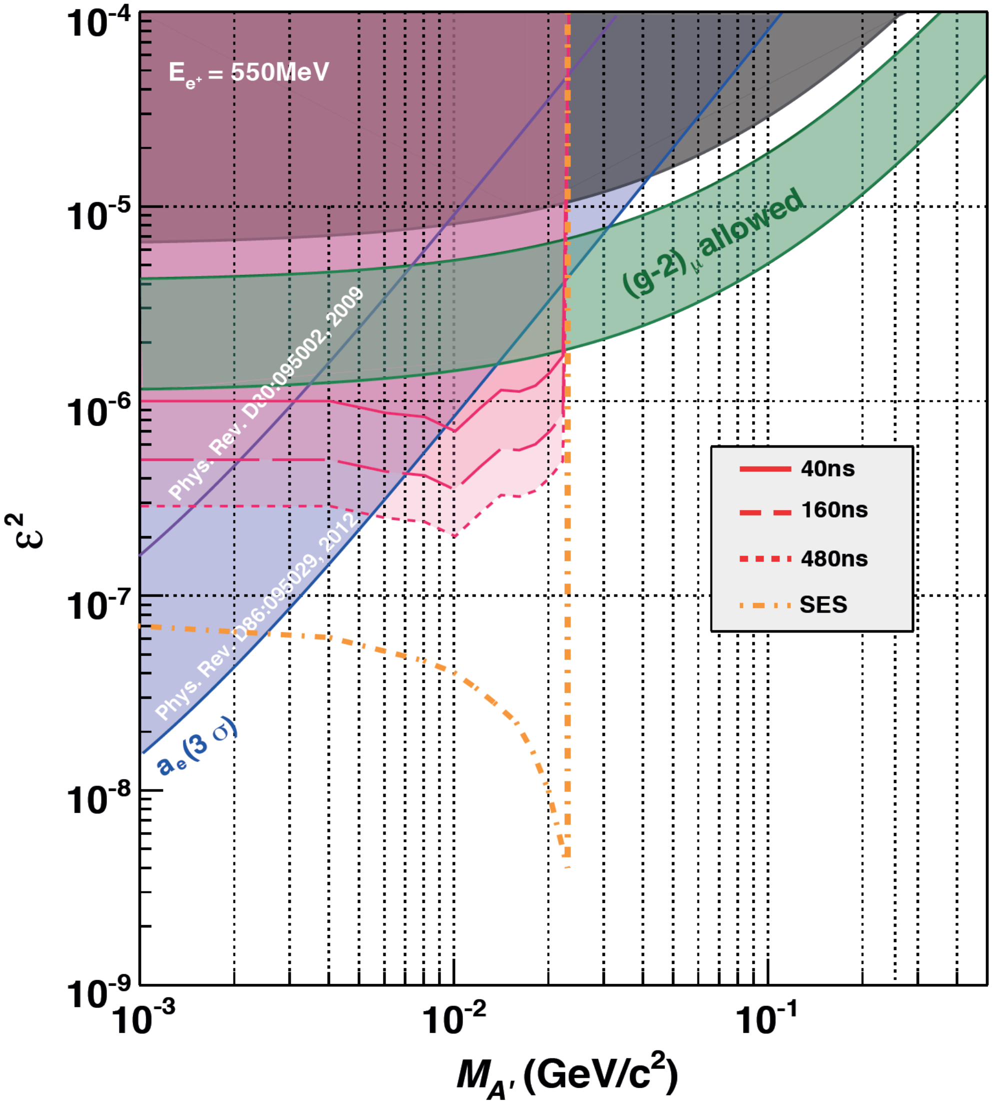


Charged particle detector

- Plastic scintillator detector

SiPM based readout

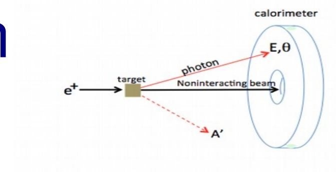
Sensitivity estimation

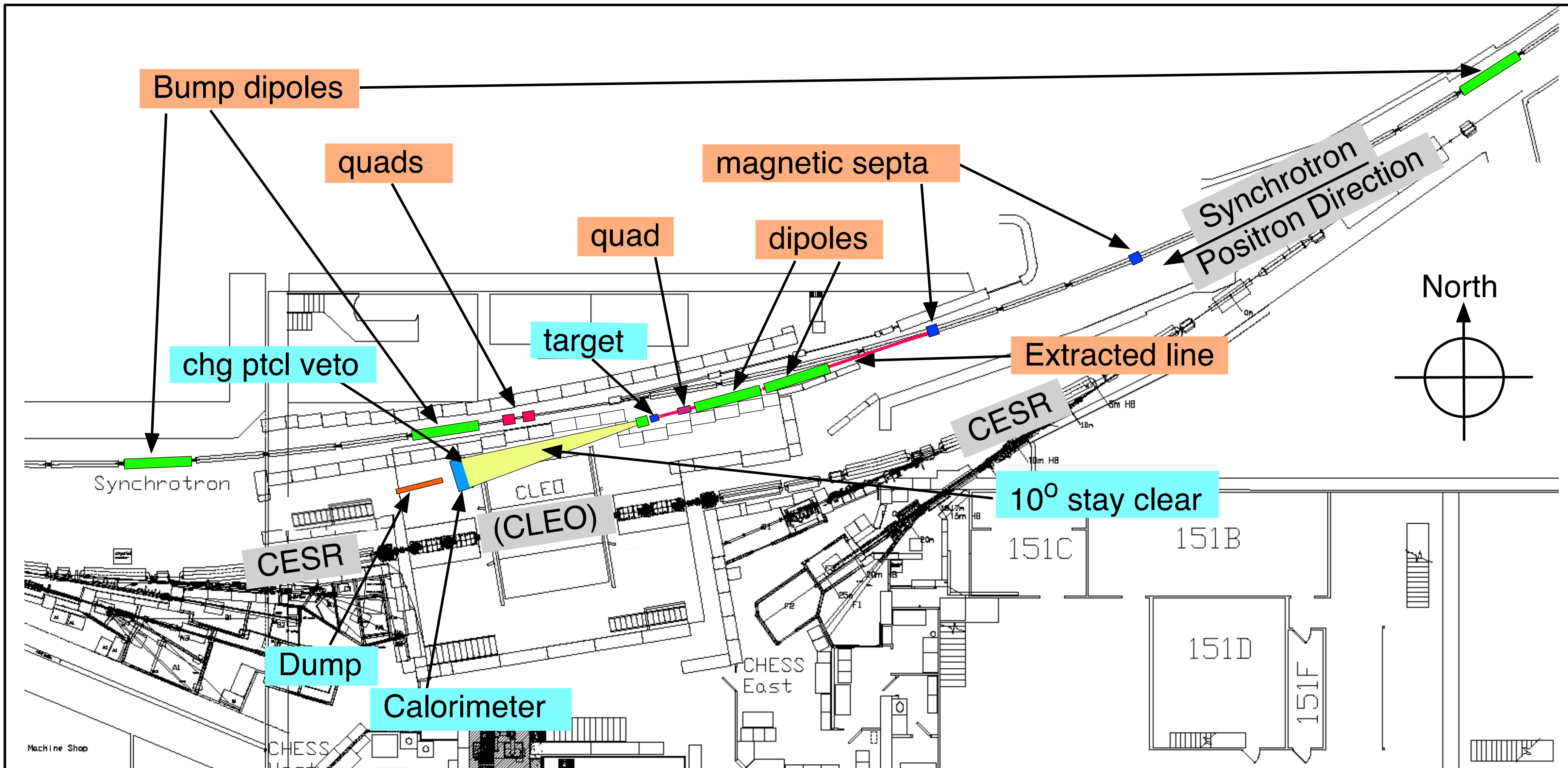


- Assumptions:
  - 40 ns bunch length
  - 49 Hz repetition
  - 6000 e^+/bunch
- Accessible regions:
  - E=550MeV: $M_{A'}$ < 23.7 MeV
- Improvements possible
  - Increase beam energy
  - Extend the bunch length

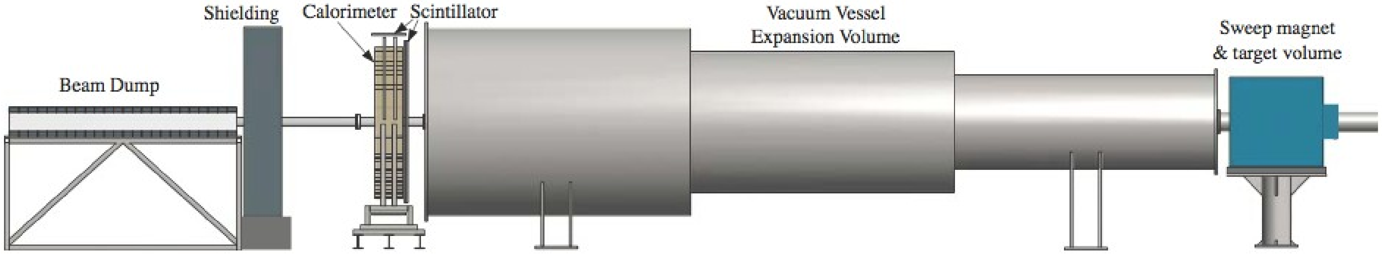
MMAPS

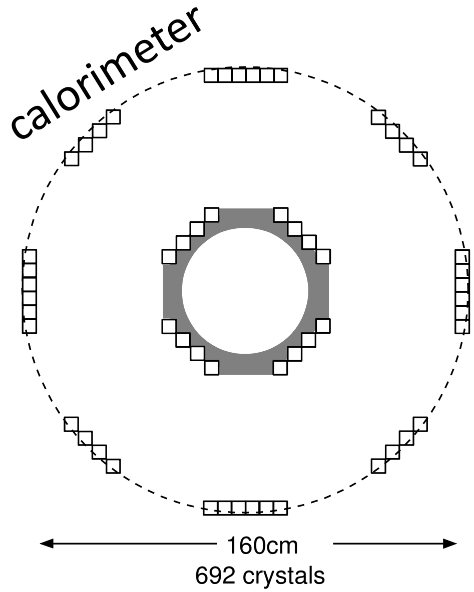
- Approach similar to PADME: Missing Mass A-Prime Search
  - E_{beam} = 1.8 -- 5.3 GeV, I_{beam} ~ 2.3 nA at target,
  - ~millisecond spills @ 60Hz
  - pulse structure: 168ns

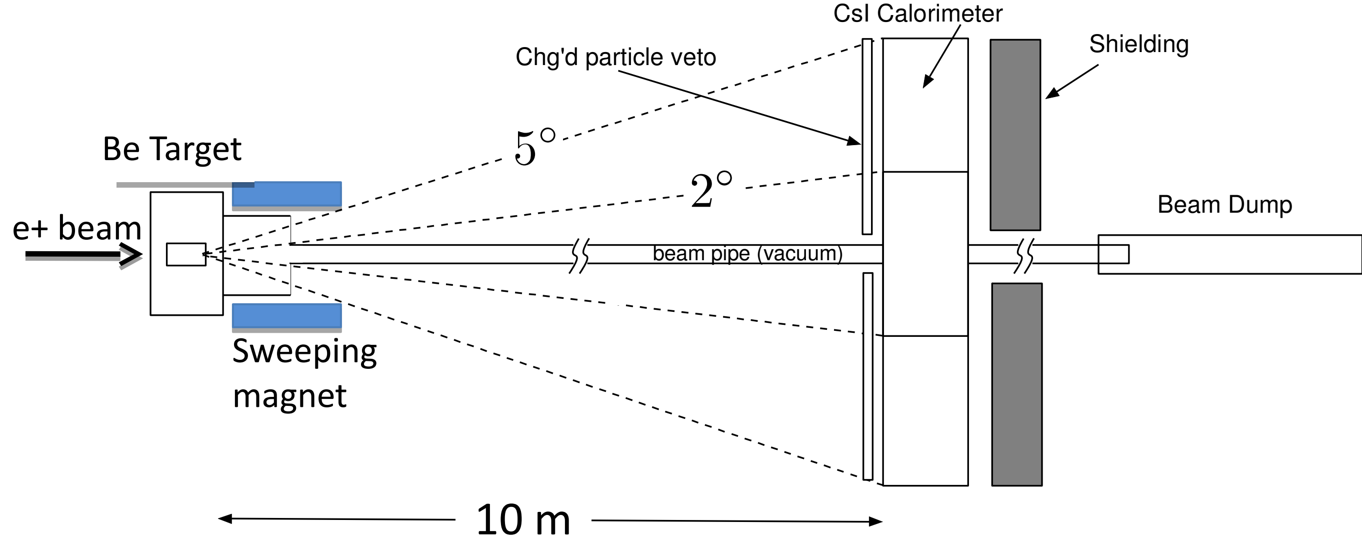




MMAPS design and sensitivity





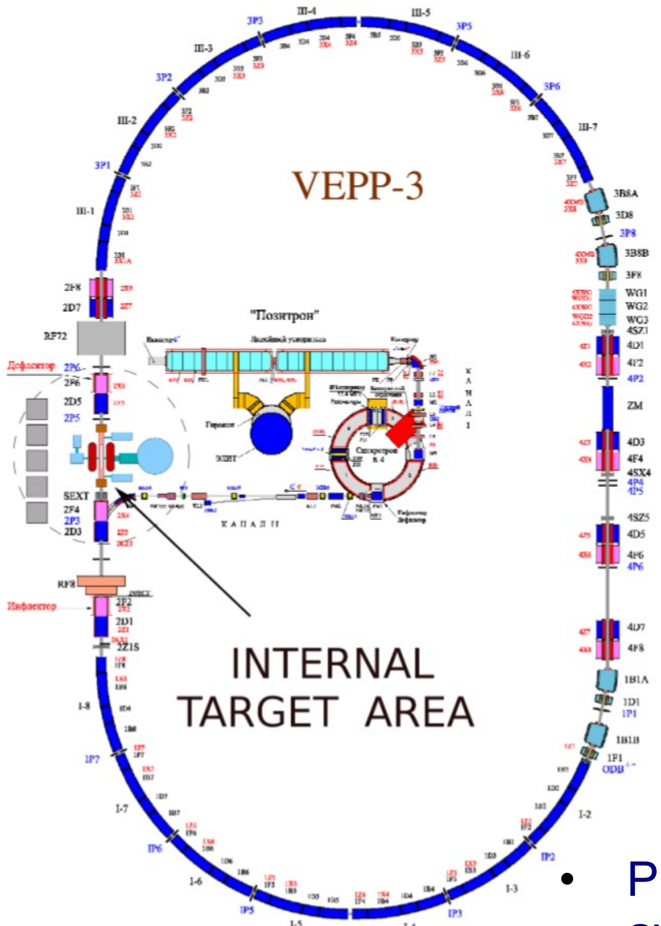


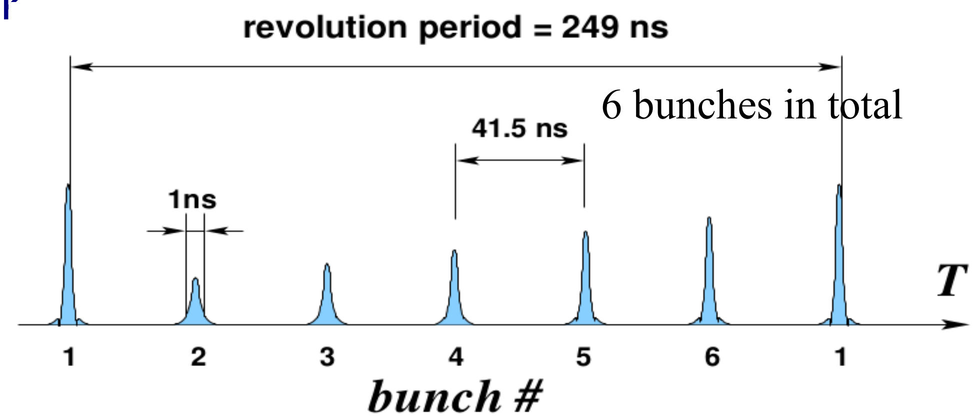
- Charged particle vetoes in front of the calorimeter
- CsI(Tl) crystal calorimeter (from CLEO), PMTs instead of photodiodes (time properties)
- Issues with **overlap @ maximal luminosity**: good double pulse separation necessary

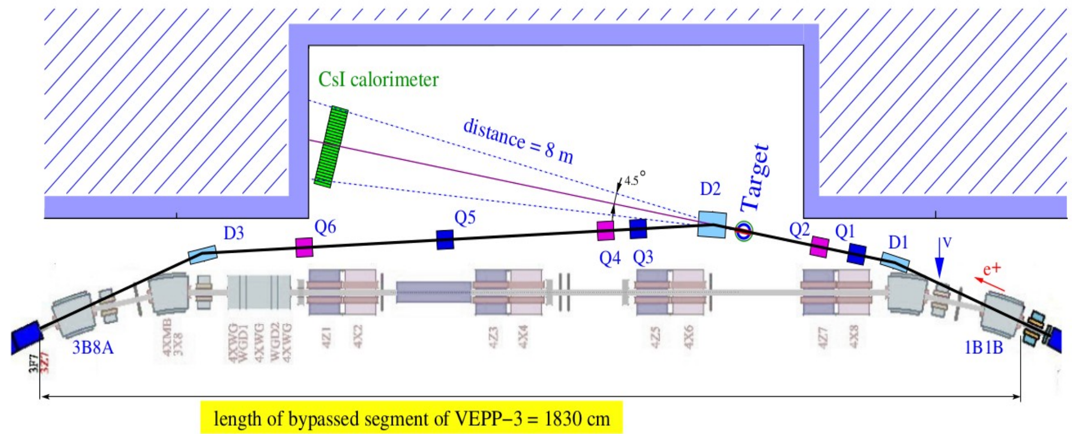
Extend the accessible region up to $M_{A'} = 74$ MeV

VEPP3

- 500 MeV storage ring @ Novosibirsk



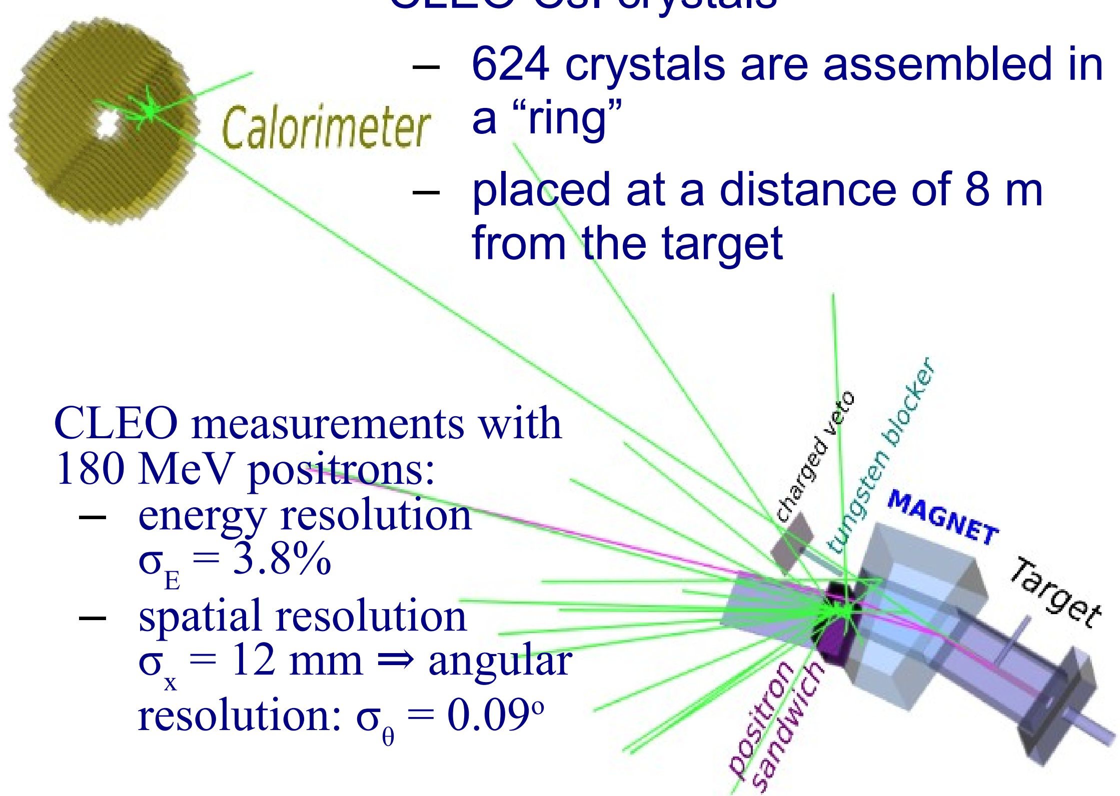




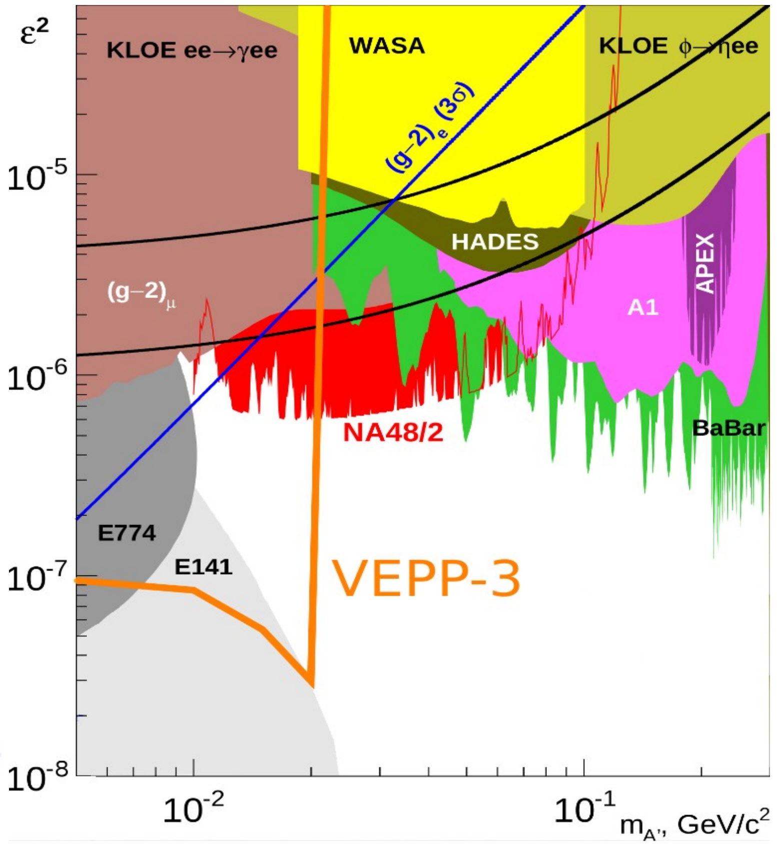
- Proposed to construct a ByPass, allowing to utilize available space for a crystal calorimeter and shielding
- Operating in paralel with the ongoing VEPP-3 activities

VEPP3

- CLEO CsI crystals
  - 624 crystals are assembled in a “ring”
  - placed at a distance of 8 m from the target



- CLEO measurements with 180 MeV positrons:
  - energy resolution $\sigma_E = 3.8\%$
  - spatial resolution $\sigma_x = 12$ mm $\Rightarrow$ angular resolution: $\sigma_\theta = 0.09^o$



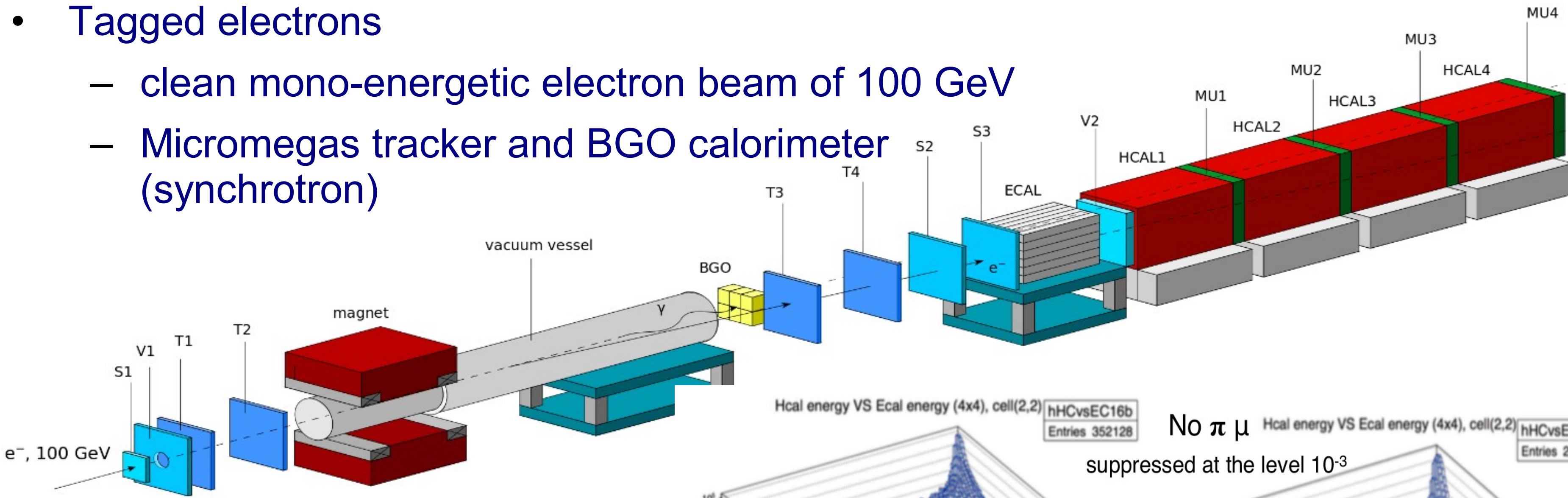
- Possible operation in 3-4 years with the by-pass beam line

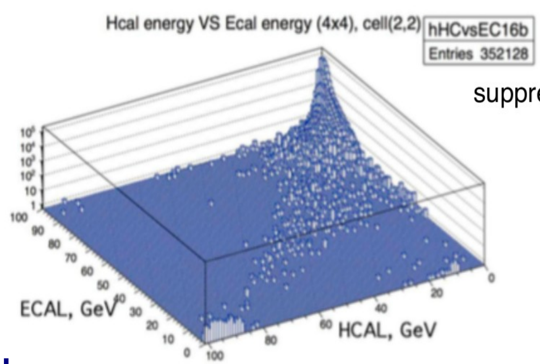
Missing mass searches status

	PADME	MMAPS	VEPP3
Place	LNF	Cornell	Novosibirsk
Beam energy	550 MeV	Up to 5.3 GeV	500 MeV
$M_{A'}$ limit	23 MeV	74 MeV	22 MeV
Target thickness	$2x10^{22}$ e^-/cm^2	$O(2x10^{23})$ e^-/cm^2	$5x10^{15}$ e^-/cm^2
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA
$e^+e^- \rightarrow \gamma\gamma$ rate [s^{-1}]	15	2.2×10^6	1.5×10^6
ε^2 limit (plateau)	**10^{-6} (*10^{-7} SES*)**	**$10^{-6} – 10^{-7}$**	**10^{-7}**
Time scale	2017 - 2018	?	2020 (ByPass)
Status	**Approved**	**Not funded by NSF**	**Proposal**

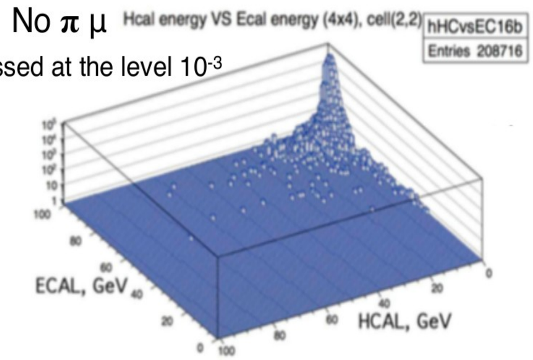
Missing energy technique: NA64

- Location: SPS (CERN)
- Tagged electrons
  - clean mono-energetic electron beam of 100 GeV
  - Micromegas tracker and BGO calorimeter (synchrotron)



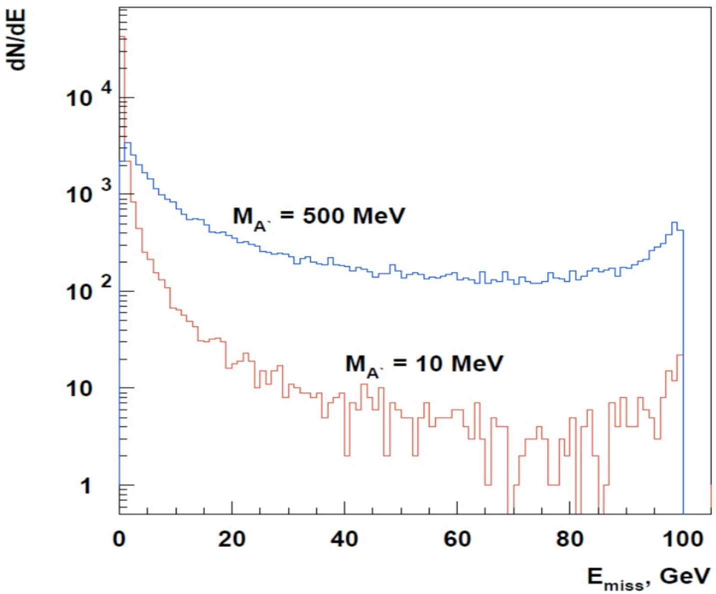


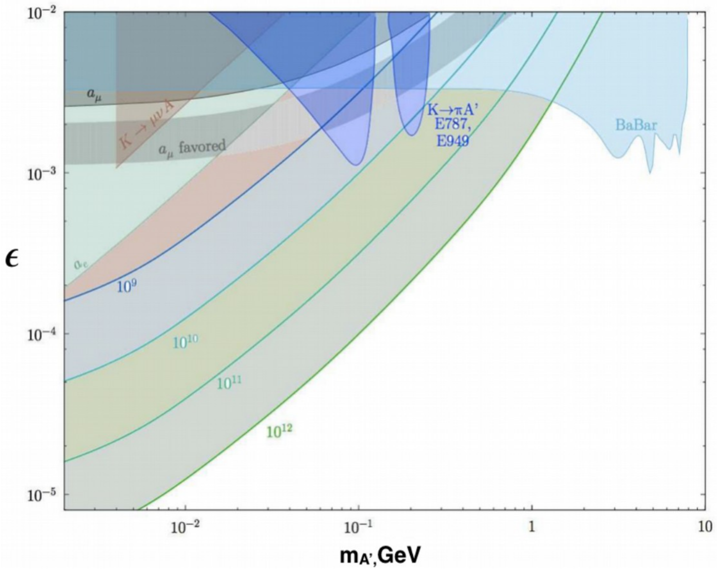
No π μ suppressed at the level 10^{-3}



- Signature:
  - 100 GeV e^- track.
  - < 50 GeV EM shower in ECAL
  - no energy in Veto + HCAL

NA64 experiment



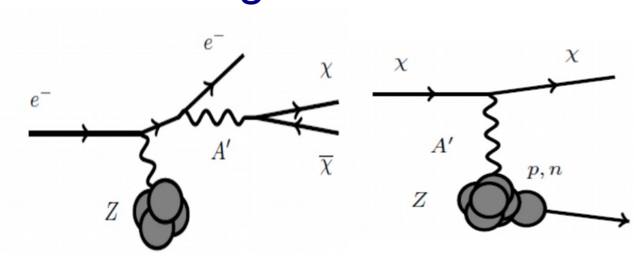


- Interesting technique
- In case of unexpected background and/or signal – not possible to disentangle
  - Can we describe particle showers in matter at 10^{-9} level?
    - NA64 Could test our understanding of the shower simulation
  - complementarity with the missing mass strategy
- Approved as an experiment at SPS in 2016
  - 2 + 4 weeks of data taking (tests, commissioning) in 2016, operation in 2017

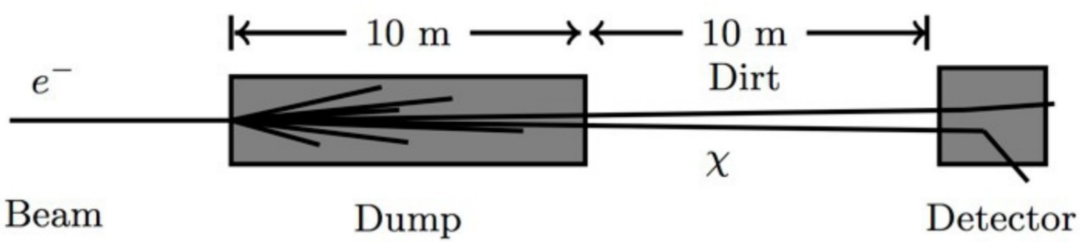
DM scattering: BDX

Beam Dump eXperiment

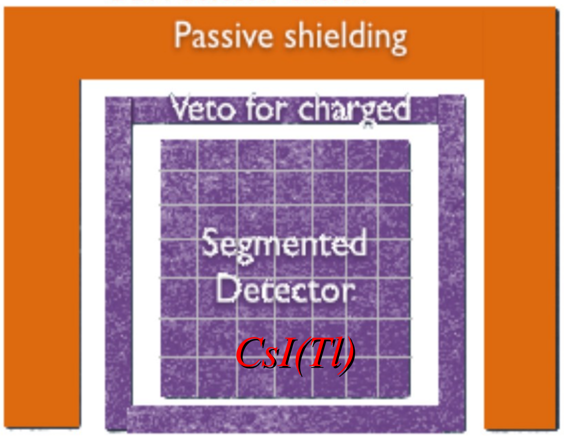
- χ production
  - High-energy, high-intensity e^- beam impinging on a dump
  - χ particles pair-produced radiatively, trough A'
- χ detection
  - Detector placed behind the dump, O(10m)
  - χ scattering trough A'
  - Different signals depending on the interaction (e^-elastic, p quasi-elastic,.)

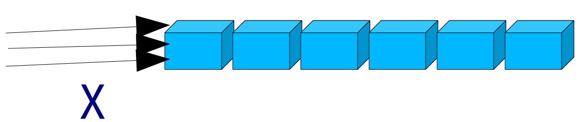


Number of events: $\frac{\alpha_D \epsilon^4}{M_A^4}$



BDX detector sketch





- LoI submitted to JLab PAC (2014) - positive feedback
- Preparation of a full Proposal ongoing
- Interesting opportunities for a phase-1 run @ other facilities

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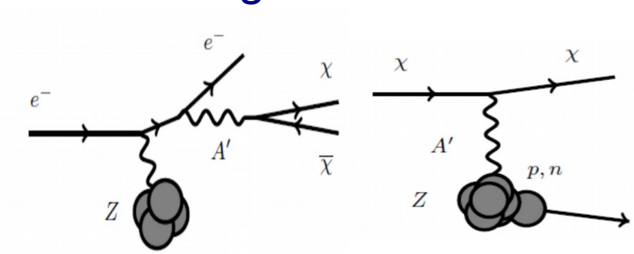

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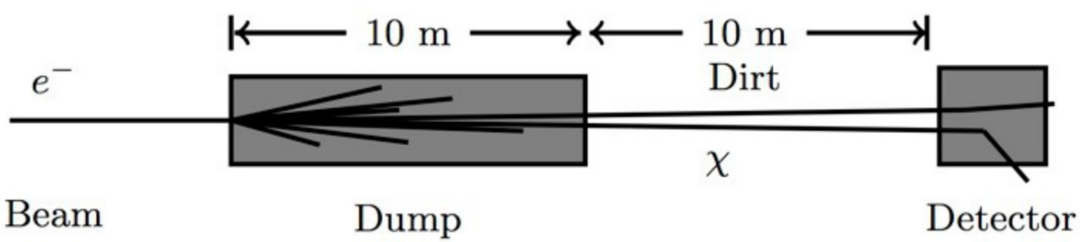

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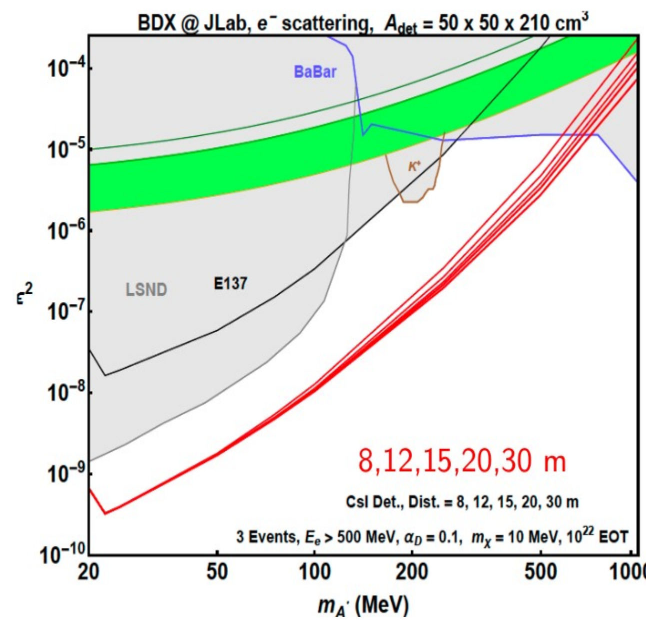

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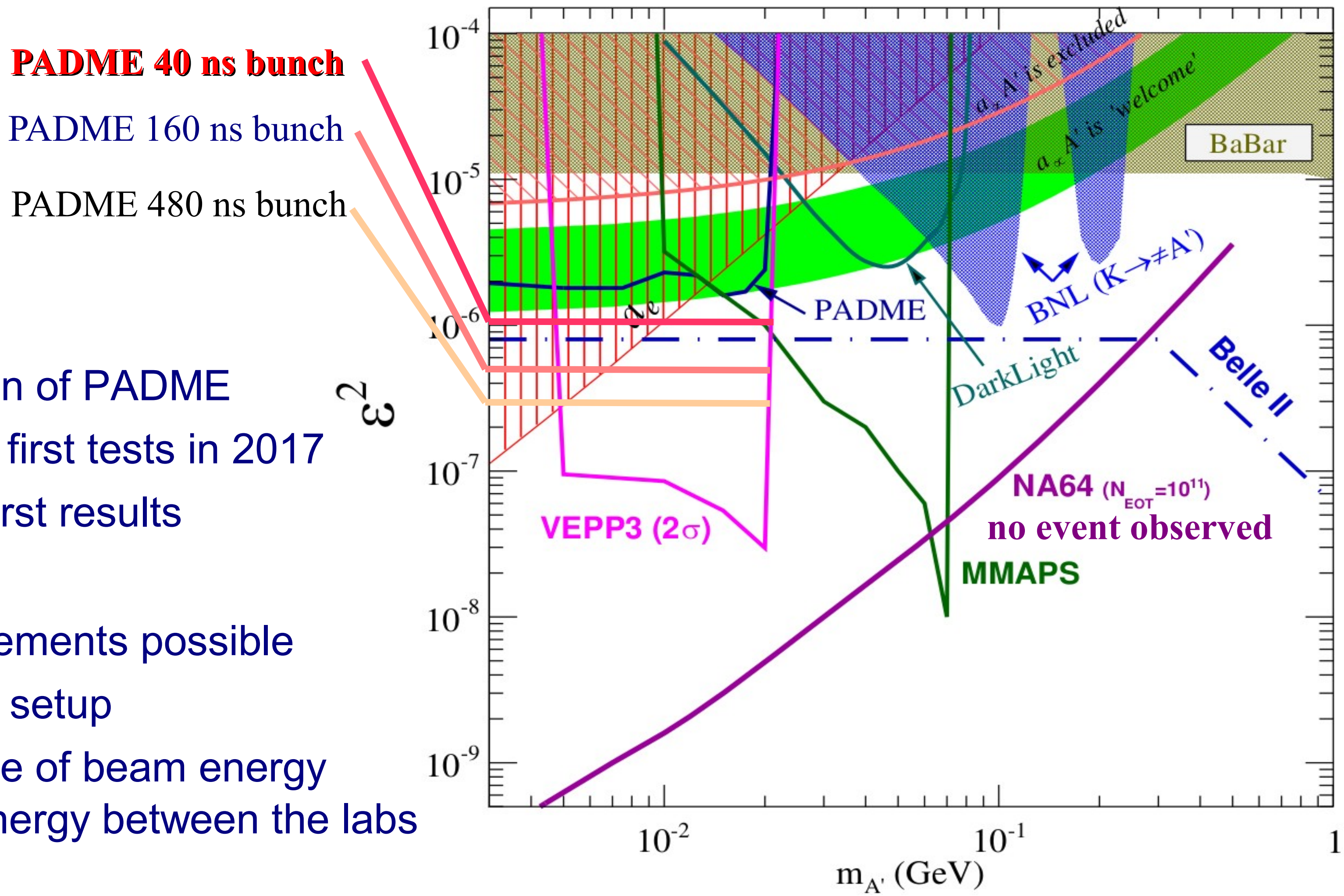
Invisible perspective



- Construction of PADME
  - Aim for first tests in 2017
  - 2018: first results
- Long term
  - Improvements possible
  - VEPP3 setup
  - Increase of beam energy
    - Synergy between the labs

Conclusions

- Increased interest recently
- Many activities undergoing and many new projects are on the scene
- Covering multi-probes for Dark Photon
  - Visible in bremsstrahlung
  - Visible in meson decays
  - Invisible: missing mass, missing energy, DM scattering
- Interesting results expected before 2020
- Stay tuned