PADME project at DAFNE BTF

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First BTF User Workshop

7 May 2014

Outline

- Motivation
- Present status
- PADME experiment
- Expected sensitivity
- Dark photon searches at BTF
- Conclusion

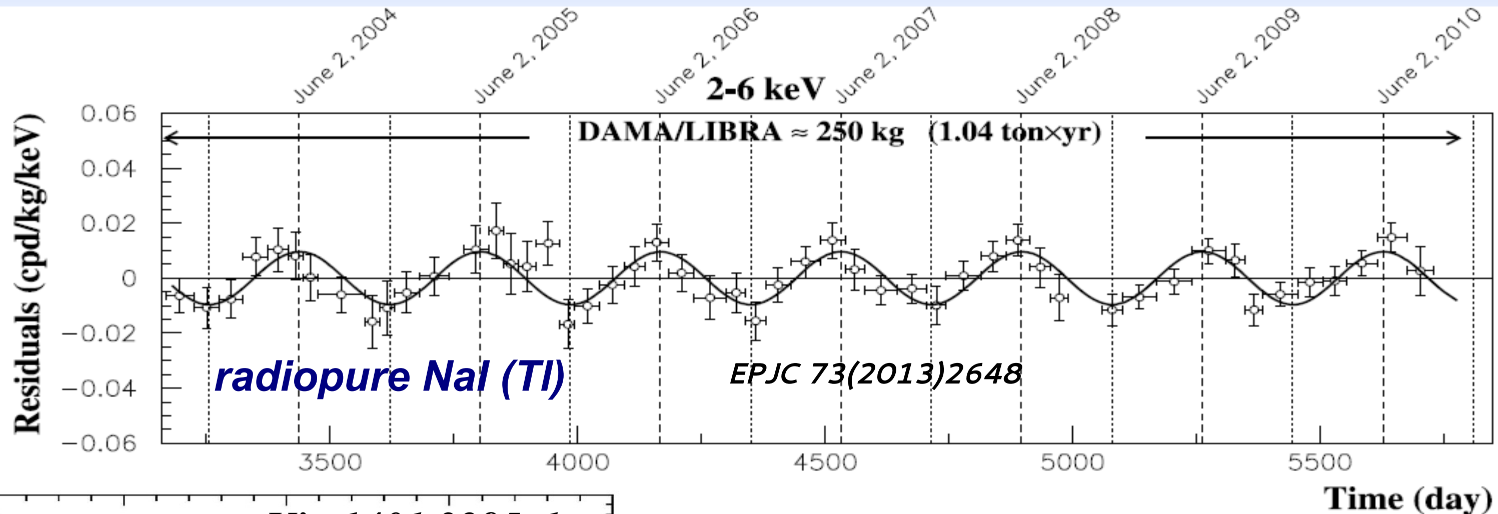
Motivation: New Physics

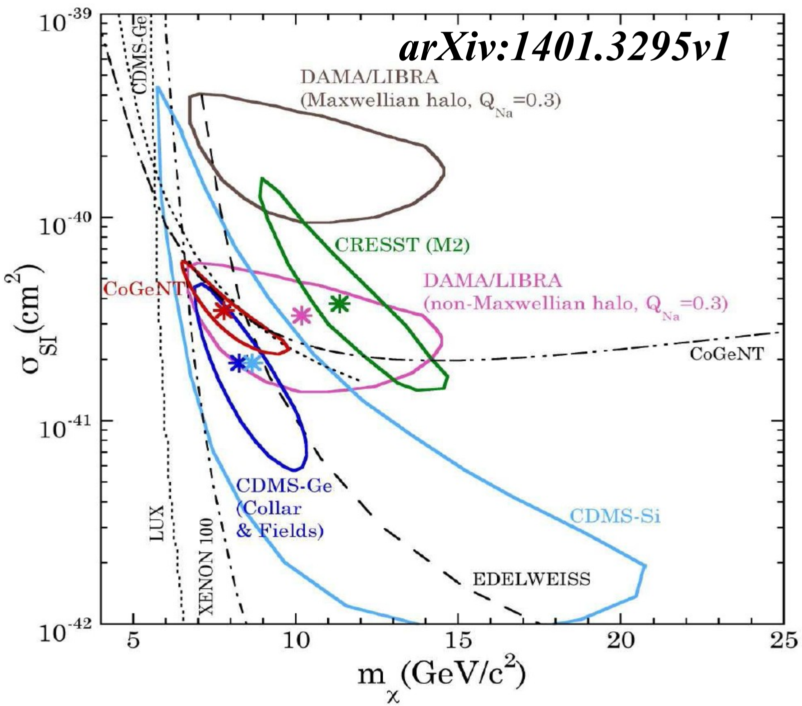
- Standard Model is complete: 2012 LHC - Higgs boson
- Unknowns:
  - Matter-antimatter asymmetry
  - Dark matter
  - Dark Energy
- Still some places of discrepancies between theory and experiment

- The Standard Model is a low energy approximation of a more fundamental theory.

But which theory?

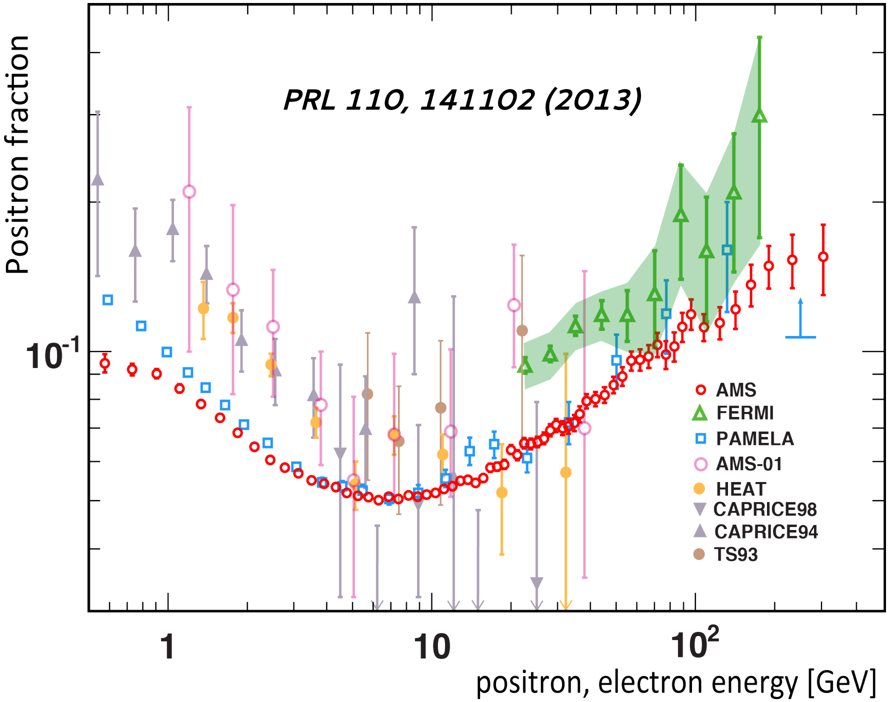
Direct search experiment

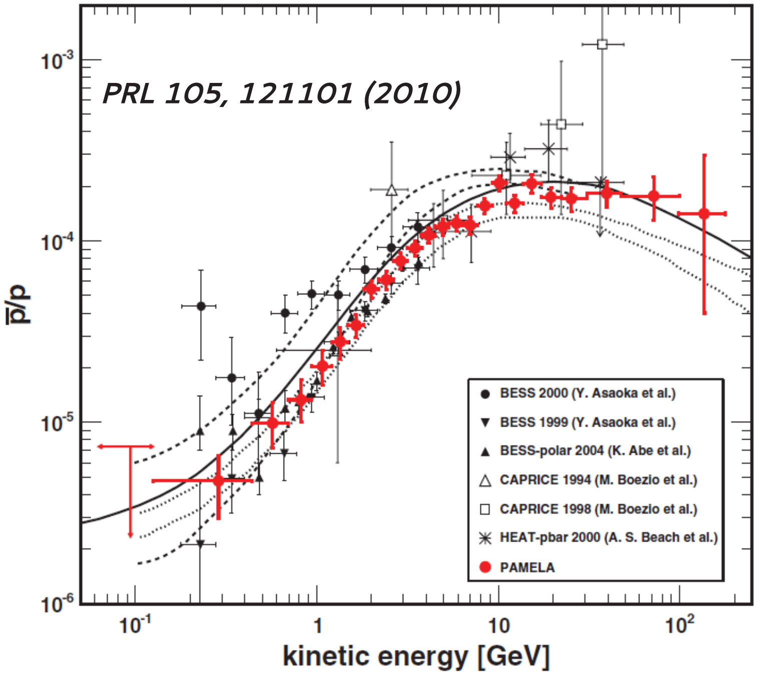




- DAMA/LIBRA results unexplained: 9.2 σ
- Used to be alone, now few other indications emerged
- Seem to be possible to build a consistent picture
- If the explanation is Dark Matter, it should be relative light: ~10 GeV
- Interaction with the nuclei through a mediator. Mass in the MeV range is OK

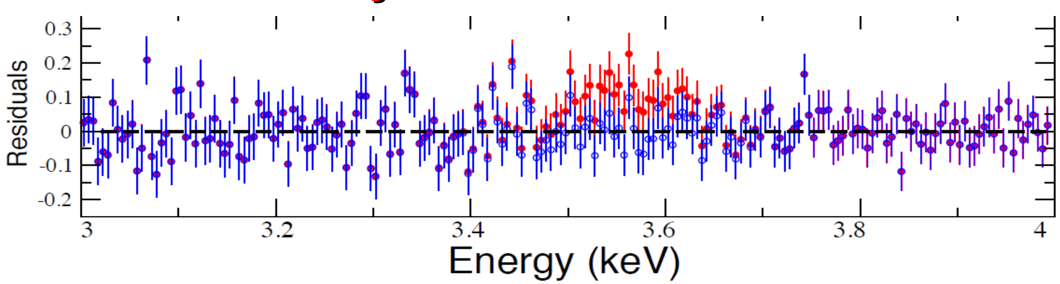
Astrophysics ...





- Positron excess: PAMELA, FERMI, AMS02
- No significant excess in antiprotons: pure secondary production

... and astronomy



Observation of 3.5keV line?

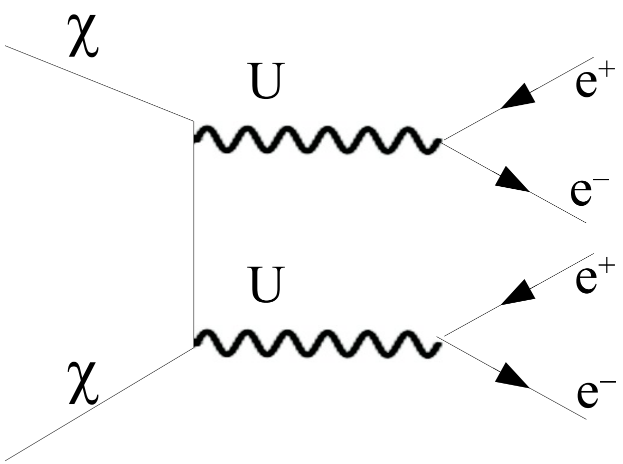
arXiv:1402.2301

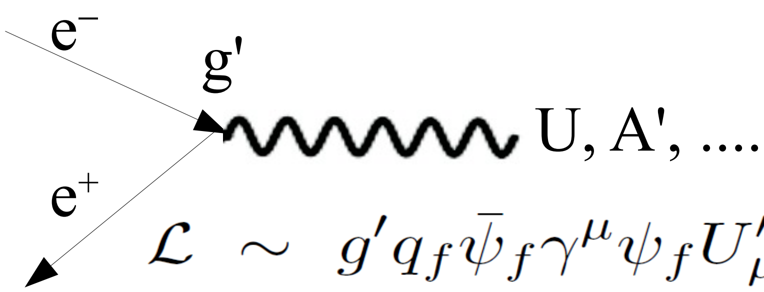
arXiv:1402.4119

Possible interpretation: arXiv:1404.2220

Hint for dark matter?

Dark matter annihilation through

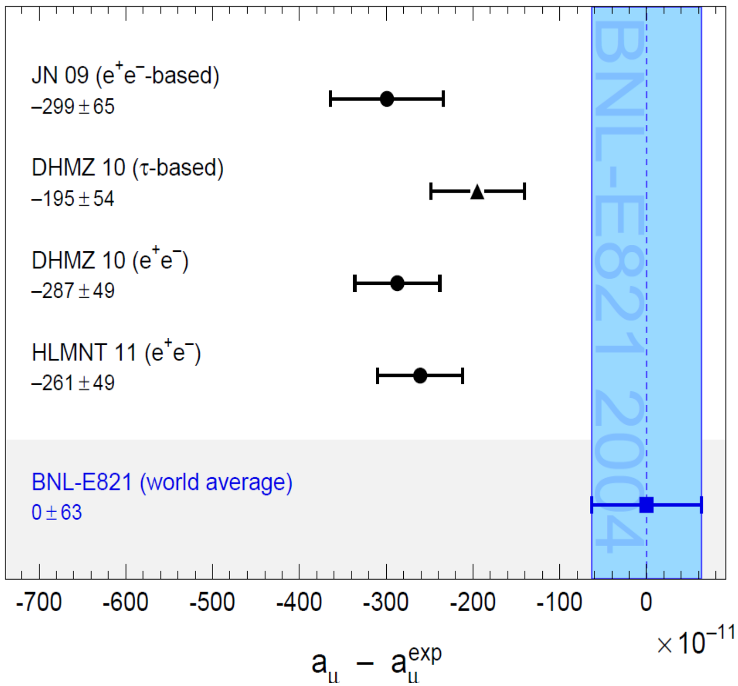


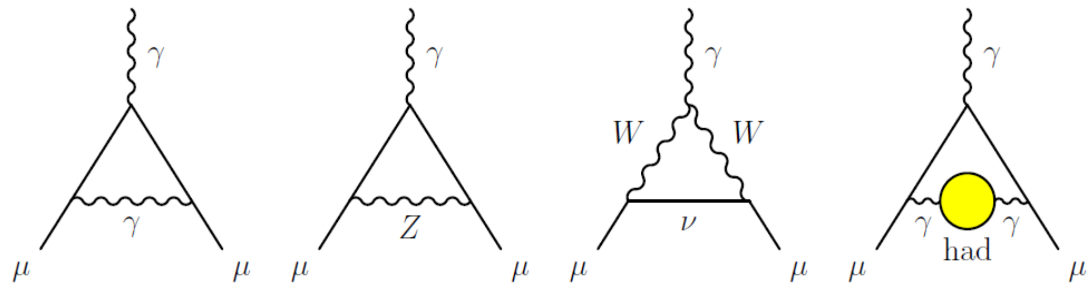


$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- 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





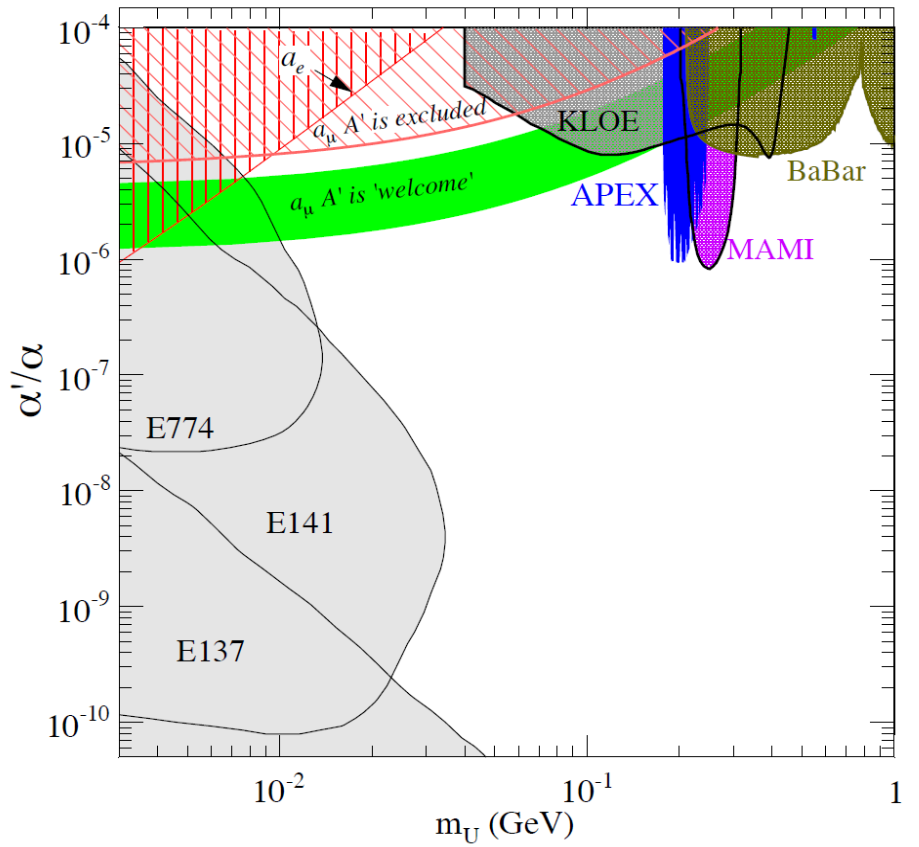
- About 3 σ discrepancy between theory and experiment (3.6 σ, if taking into account only $e^+e^- \to$ hadrons)

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

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

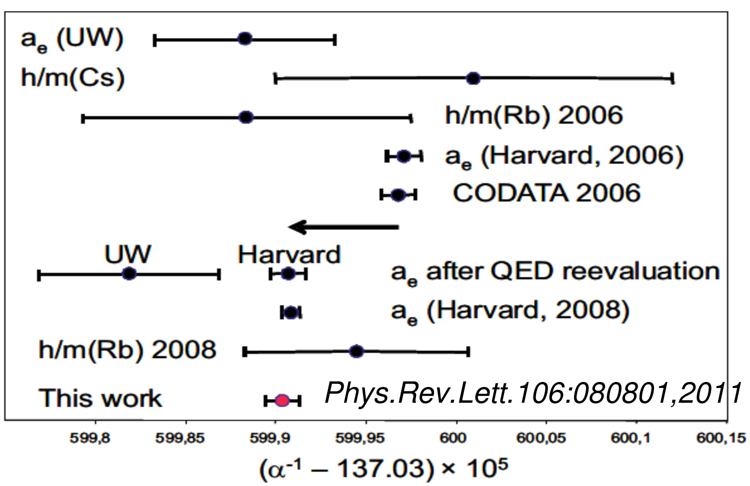
Heavy/Dark photon/boson

- The most attractive explanation of the phenomena is the simplest one – with a single object
- If this is the U-boson, it should be sufficiently light – 10-100MeV
- Searches
  - Beam dump experiments
    - A'-strahlung production
    - Every observed event is signal
  - Fixed target
    - peaks in the e^+e^- invariant mass spectrum
  - Meson decays
    - Peaks in M_{e+e-} or $M_{\mu+\mu-}$



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}



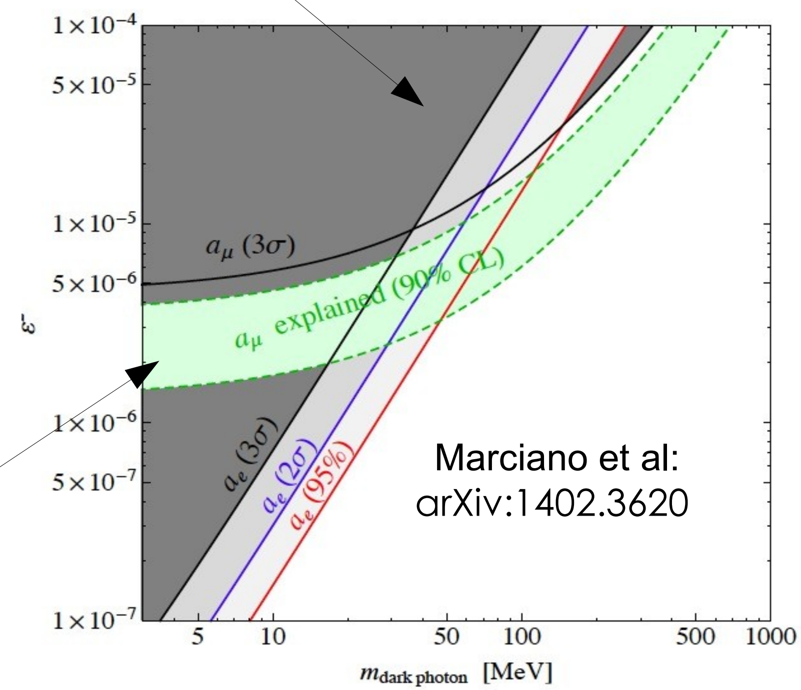
α^{-1} = 137 .035 999 037 (91)

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

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

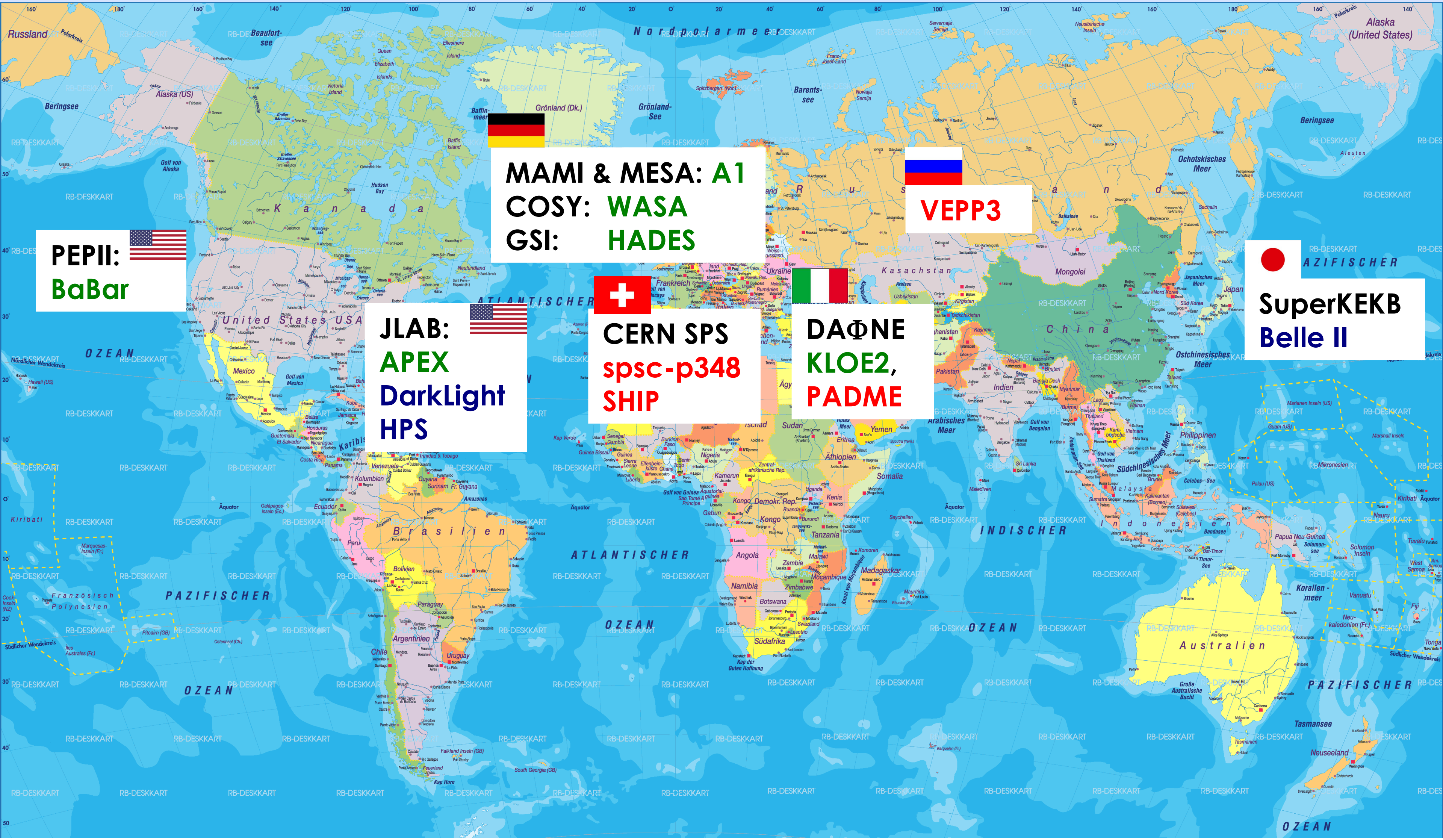
$$\delta a = \frac{\alpha_{EM}\,\epsilon^2}{2\pi} * f,\ f = \begin{cases} 1, \text{ for } m_l >> M_U \\ 2m_l^2/(3M_U^2), \text{ for } m_l << M_U \end{cases}$$

Phys.Rev.D80:095002,2009



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

Present status



PEPII: BaBar

MAMI & MESA: A1
COSY: WASA
GSI: HADES

VEPP3

SuperKEKB
Belle II

JLAB:
APEX
DarkLight
HPS

CERN SPS
spsc-p348
SHIP

DAΦNE
KLOE2,
PADME

Status: ongoing, planned, proposals

How to improve?

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

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

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

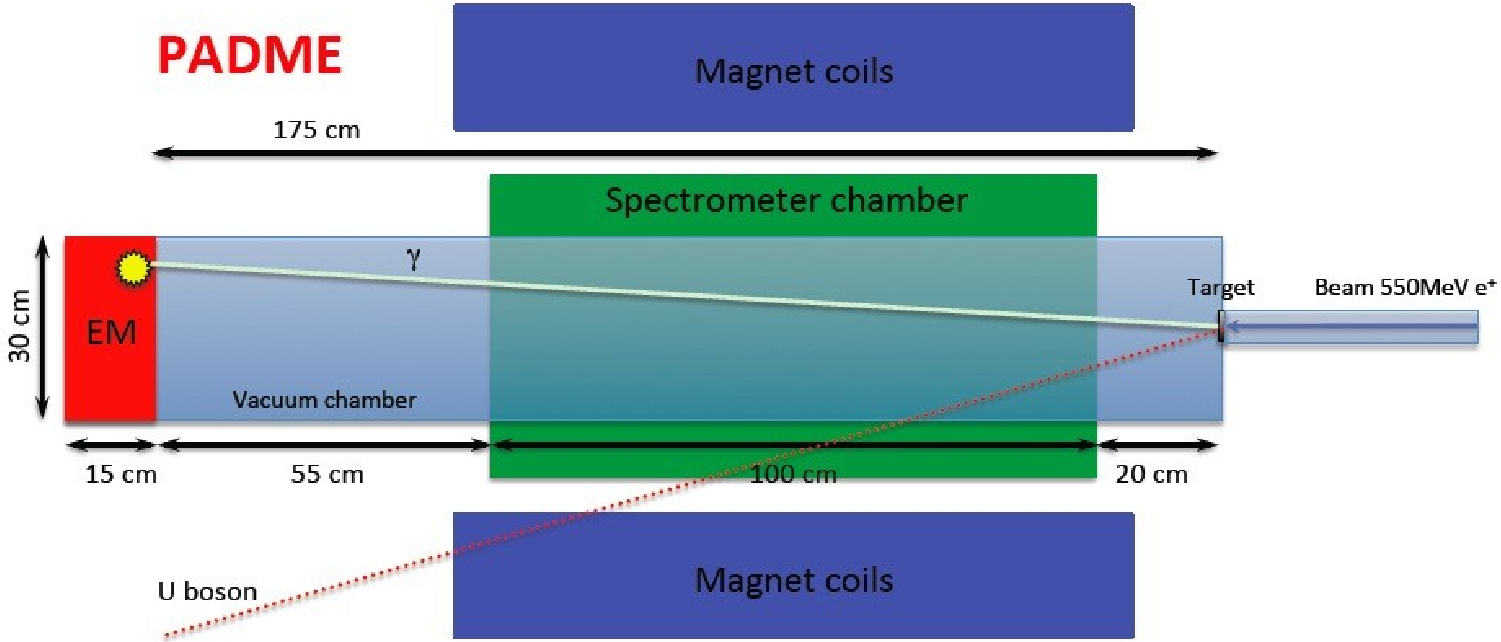
$$\frac{\sigma(e^+e^- \rightarrow \gamma U)}{\sigma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(\gamma U)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(\gamma U)} = \varepsilon^2 * \delta$$

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

Is it possible such a search to be conducted at BTF?

PADME experiment

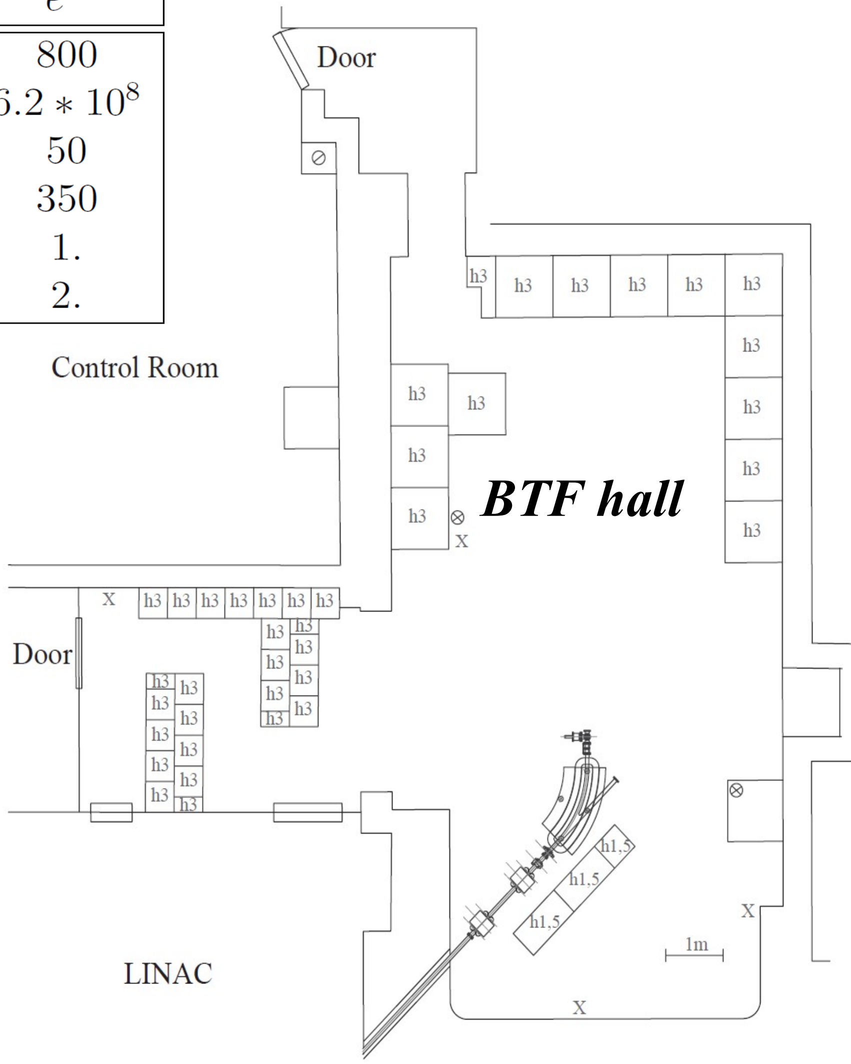
Positron Annihilation into Dark Matter Experiment



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

BTF @ LNF

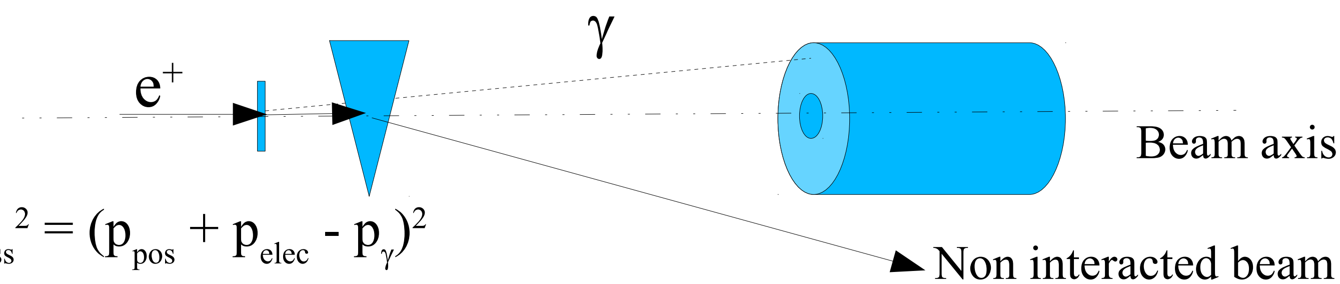
	e^+	e^-
Maximal beam energy [MeV]	550	800
Beam rate [particles/burst]	$6.2 * 10^8$	$6.2 * 10^8$
Number of bursts per second	50	50
Max. averaged current during a burst [mA]	85	350
Typical emittance (mm mrad)	1.5	1.
Beam spot size (σ in mm)	2.	2.



- Variable beam energy
  - from ~250 MeV to E_{MAX}
- Variable beam intensity
- Possibility for single particle beam
  - However we need statistics...
- Both positron and electron beams
- Small beam energy spread
- Available immediately
- The accessible region is limited by the maximal beam energy
  - **Around 23 MeV for 550 MeV e^+ beam**

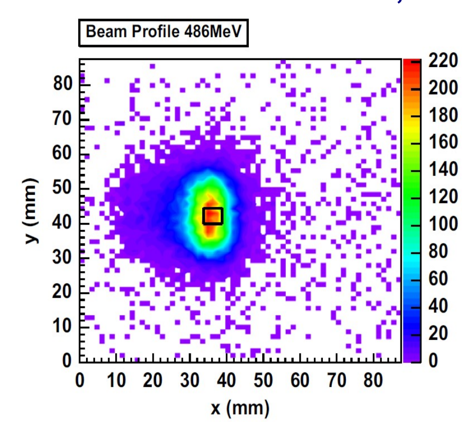
Basic ideas

Focusing on the invisible channel

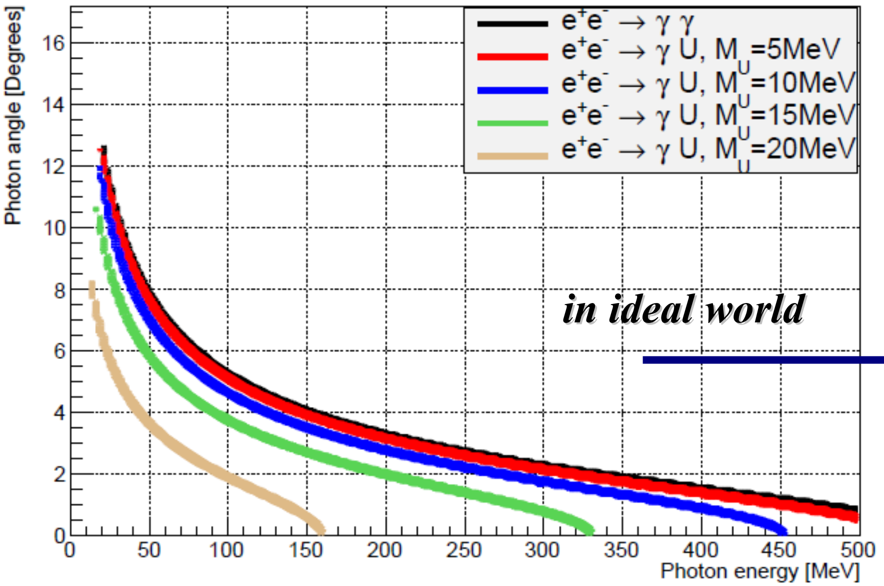


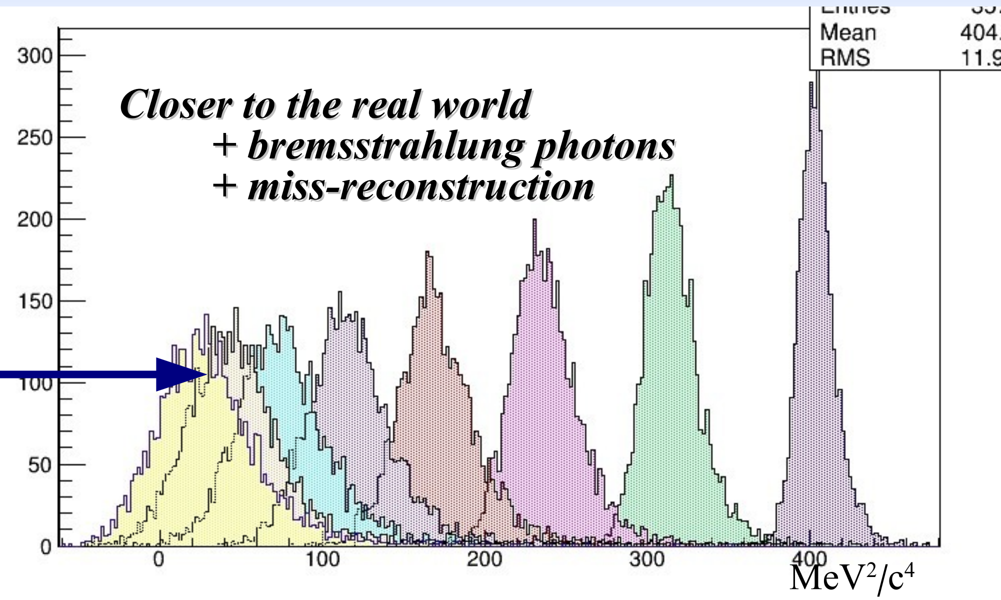
$$M_{miss}^{2} = (p_{pos} + p_{elec} - p_{\gamma})^{2}$$

- Electron is at rest
- Positron momentum is determined by the accelerator characteristics – 1% resolution
- Basic contribution to the missing mass resolution – reconstruction of the photon 4-momentum
  - Interaction point inside the target – beam transverse size is small, but the time stability is not sufficient
  - Cluster position in the calorimeter
  - Energy resolution of the calorimeter

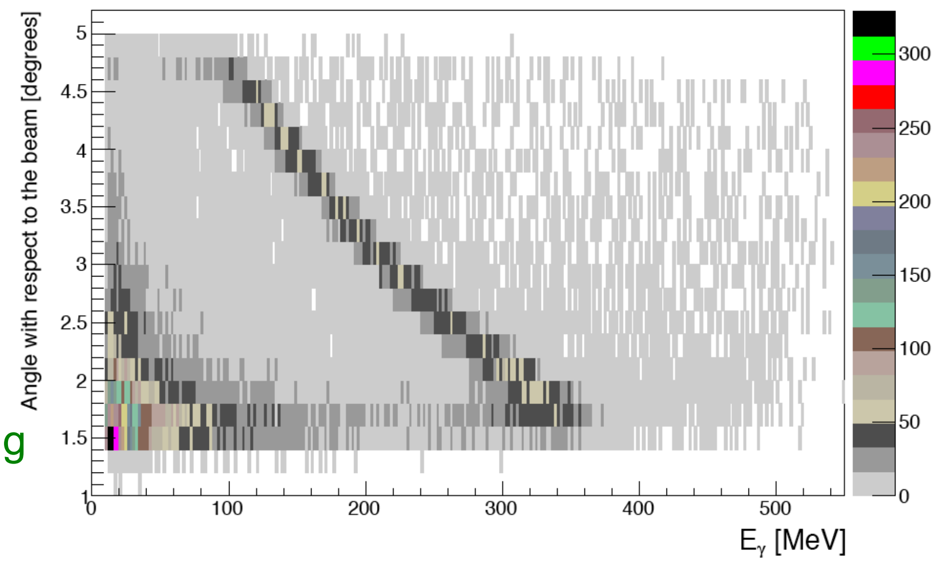


Event reconstruction

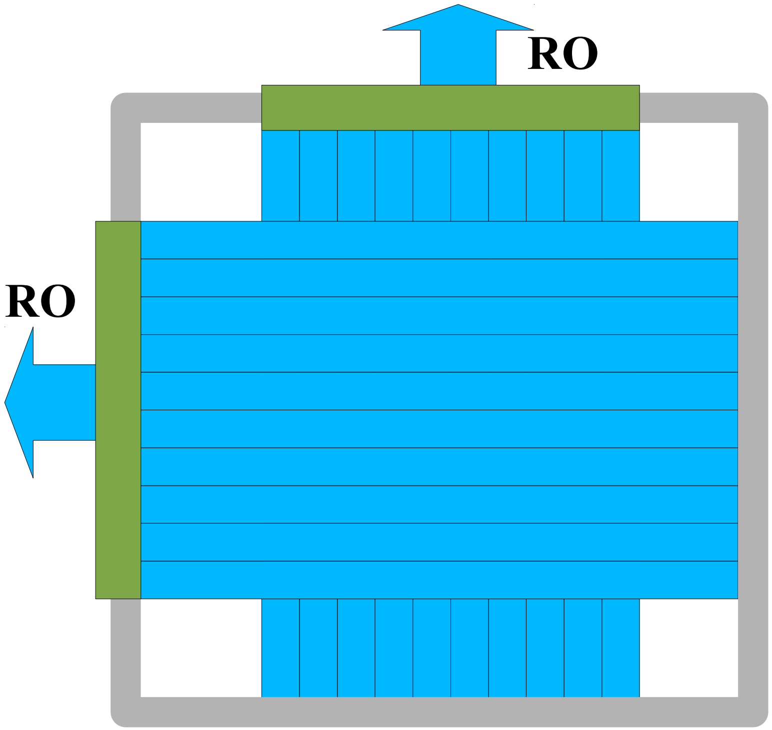


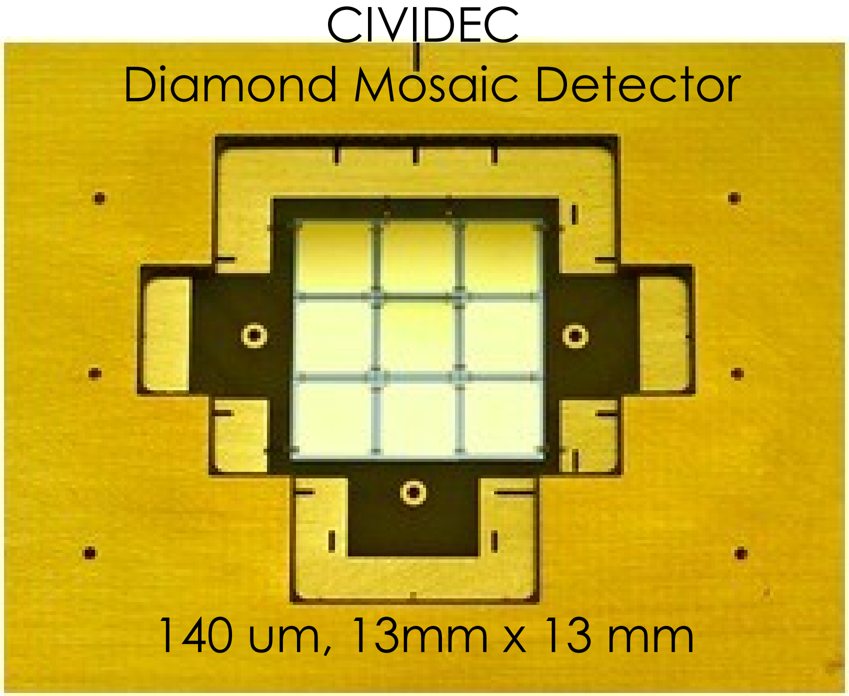


- Clear 2 body correlation
- **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Best possible resolution on energy/angle measurement
  - Photon vetoing
  - Minimize the interaction remnants + vetoing



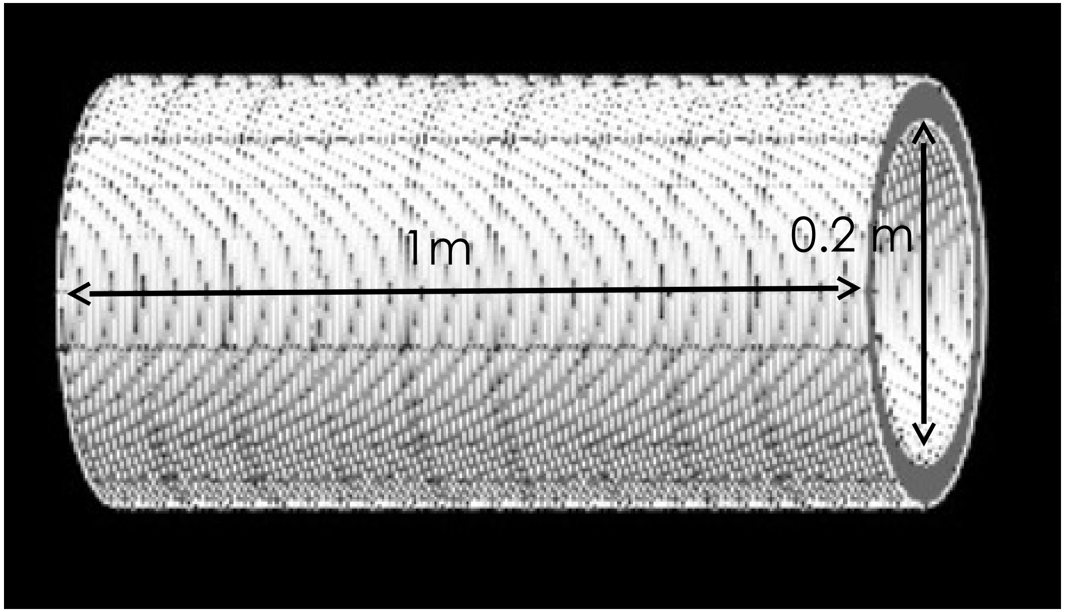
Target





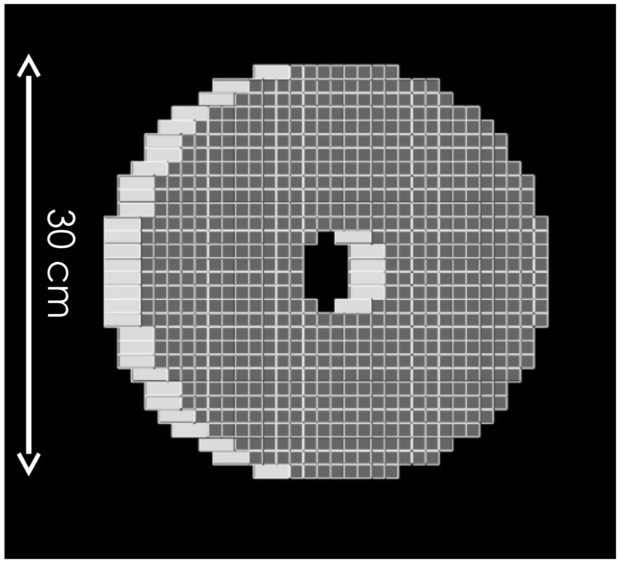
- 10 diamond strips of 2 mm x 50 mm with 25um thickness
- Time resolution: below 1ns
- Sensitivity: from few to 10^9 particles
- QDC readout and bunch-by-bunch beam spot determination

Magnetic spectrometer



- 0.6 T magnetic field, conventional dipole magnet
- Gaseous detector with 1m length, 20cm radius (10cm from the beam direction)
  - 5 layer of triple GEMs
  - Planar or cylindrical
  - Position and momentum measurements of the charged tracks (vetoing)
  - Track time resolution: ~1ns
- Readout based on custom ASIC (possibly GASTONE?)

Calorimeter

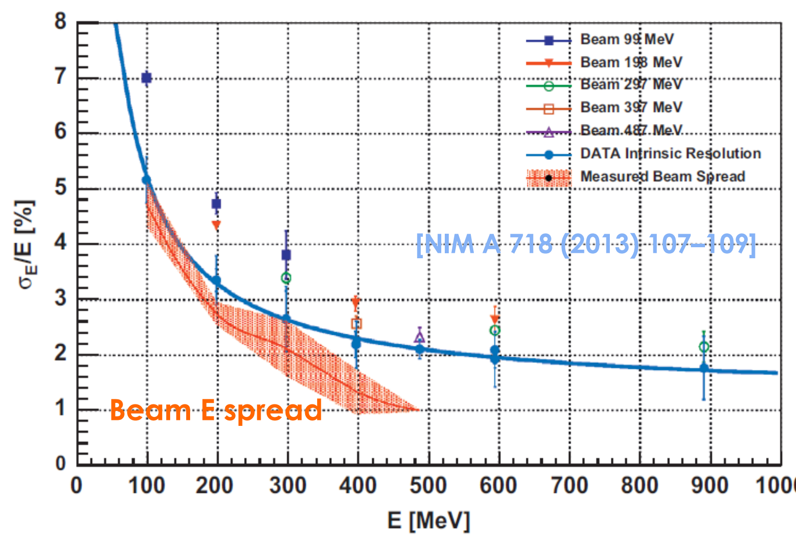


Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	420^s	1.95	3.6^s	slight	−1.4
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

- Cylindrical shape, Rin = 4cm, Rout = 15cm
- 656 LYSO crystals, 1 cm x 1cm x 15-20 cm
- Energy resolution:

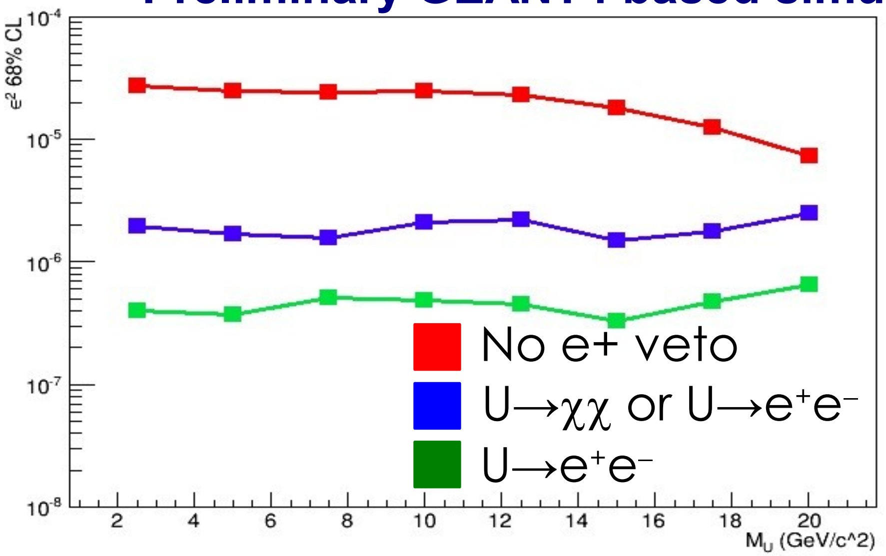
$$\sigma E/E = \frac{1.1\%}{\sqrt{E}} \oplus \frac{0.4\%}{E} \oplus 1.2\%$$

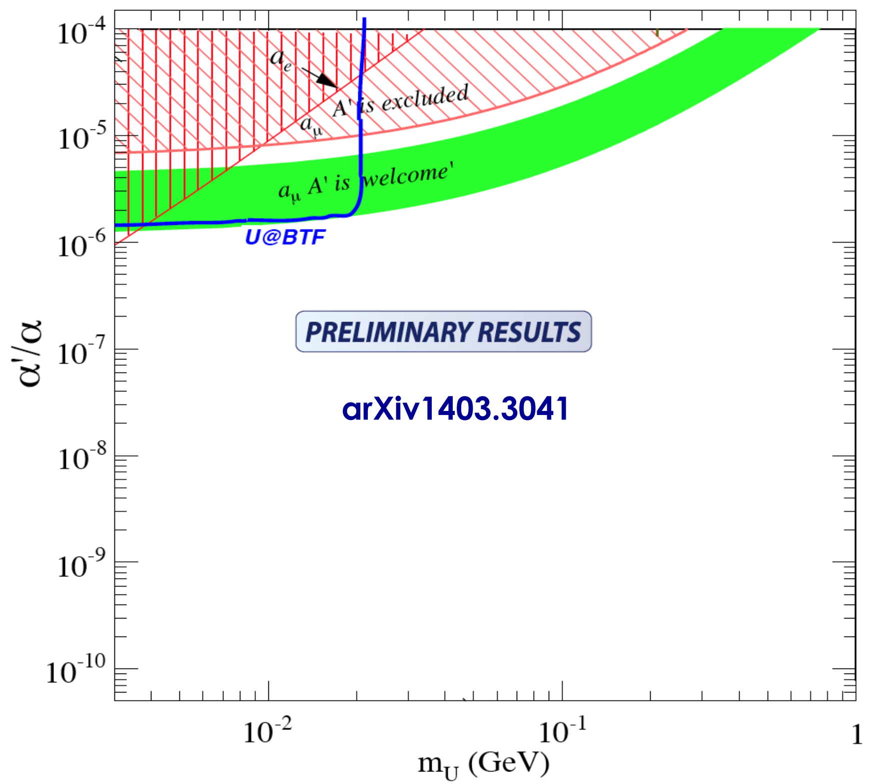
- Angular acceptance: 1.5 – 5 degrees
  - resolution < 2mrad
- Digitizer readout



Expected sensitivity

Preliminary GEANT4 based simulation to assess the possible reach





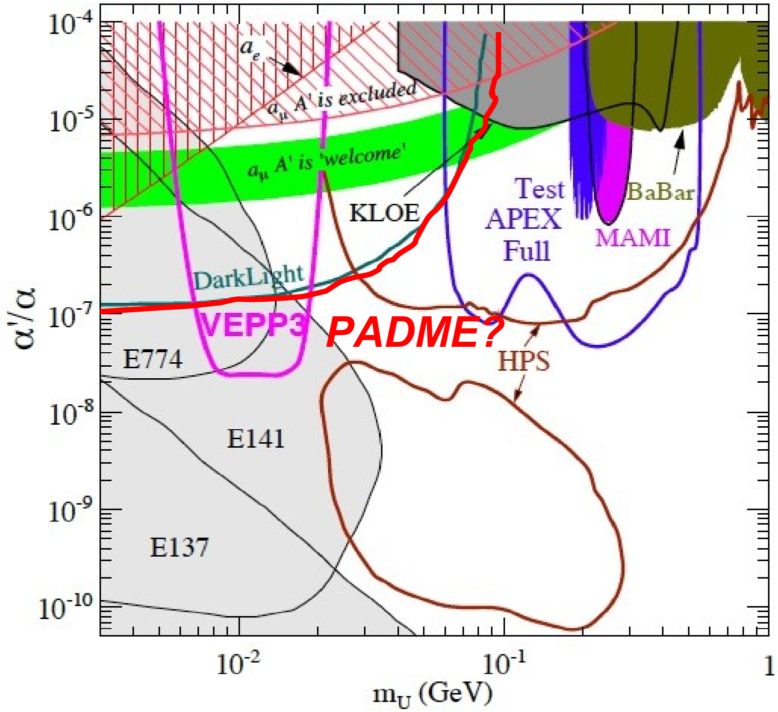
- Rough selection based on **missing mass** cut, **veto** on extra **clusters** and **positrons**
  - 1 year of continuous running
  - 60% efficiency (data taking)
  - 50 bursts/s
  - 10^4 positrons/burst
- Considering the statistical uncertainty of the expected background to set the limits

Dark photon prosects at BTF

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

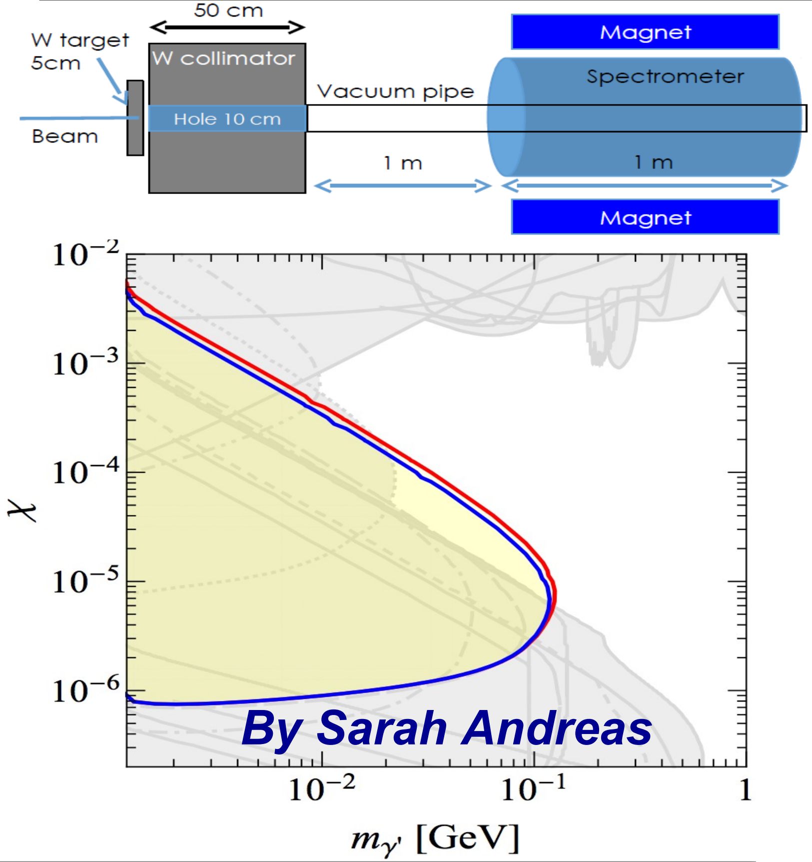
$U \rightarrow e^+e^-$ visible decay search

- Measuring e^+e^- momentum with the spectrometer
- Selection based on $M_{e^+e^-}$



Extend M_U sensitivity, but model dependent

Beam dump experiment: $U \rightarrow e^+e^-$



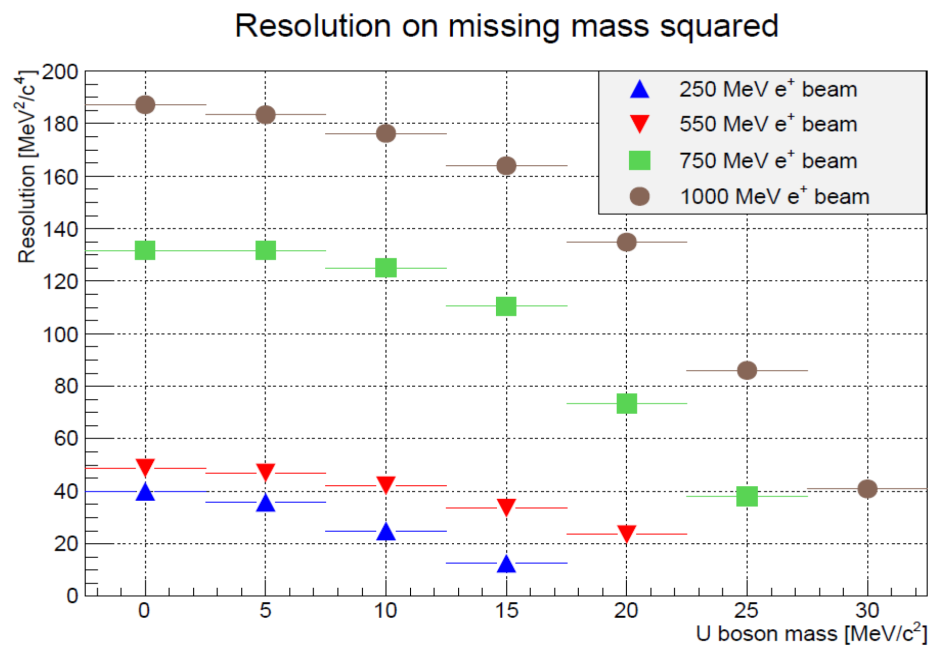
- 10^7 e^-/bunch, 50 bunch/s, 1 year
- E_{e-} = 750 MeV

Conclusions

- BTF machine provides unique opportunity to study possible dark photon production in annihilation channel
- Small fixed target experiment to search for dark photons in the invisible channel proposed.
- Interesting parameter space could be covered, using $10^3 - 10^5$ e^+/bunch.
- Preliminary studies have been initiated as a sidework activity
- Short time scale of the project
- PADME could turn BTF from a test beam facility into a fundamental physics machine
- PADME would profit from both energy and duty cycle upgrades of the BTF

Possible improvements

- Duty cycle upgrade:
  - Present: 50Hz * 10ns = $0.5 \cdot 10^{-6}$
  - At 10 ns all the particles in the bunch are treated as belonging to the same event
  - At 40ns (100 ns) time resolution of LYSO & Spectrometer improves the veto
  - Improvement on the repetition of equal profit!
- Energy upgrade
  - Extend the access to M_U ~27 MeV
  - Improve the results in the range 20 – 23 MeV



- Bremsstrahlung production and visible/dump detection
  - Extend the mass region
  - Extend the ε^2 region to lower values due to higher U-boson boost
- Beam related background (i.e. accompanying spurious particles)
  - Difficult to access in the simulation, desired to be as minimal as possible