PADME at DAΦNE Linac

Venelin Kozhuharov

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

11 November 2014

What next LNF: Perspectives of fundamental physics at the Frascati Laboratory

LNF-INFN

B. Buonomo, G. Chiodini, L. Foggetta, V. Kozhuharov, E. Leonardi, G. Organtini, M. Raggi, S. Spagnolo, P. Valente

Overview

- Possible hints for new physics
- Dark photon in positron annihilation
- PADME experiment
- Physics reach
- Present status and activities
- Conclusions

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.

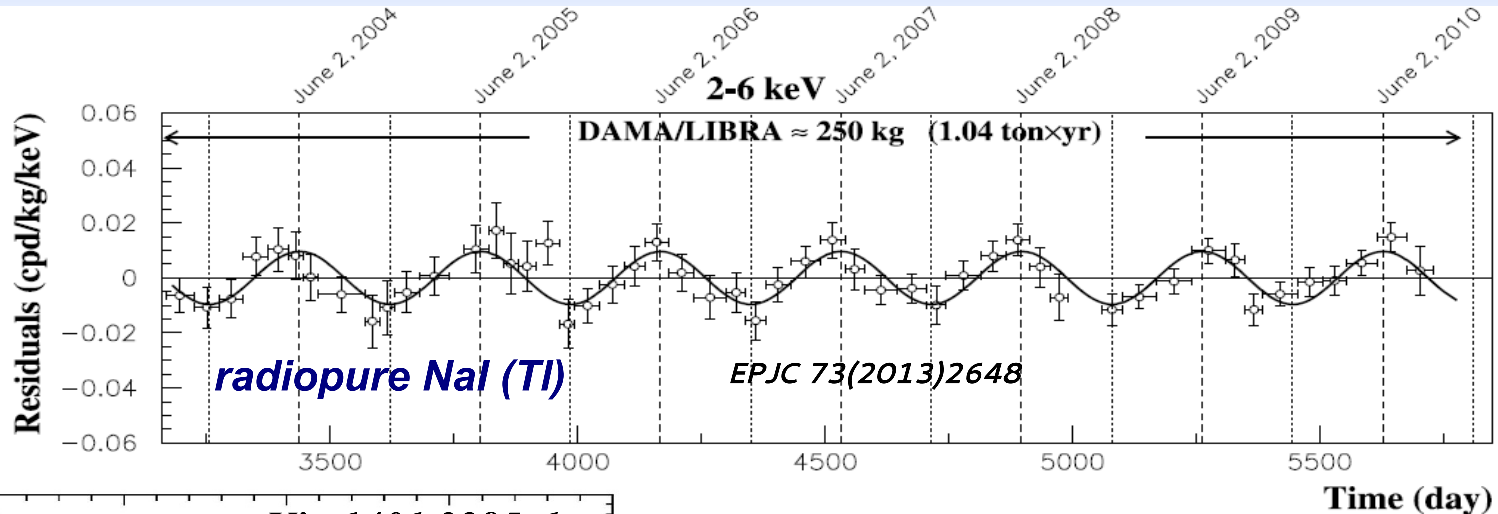
But which theory?

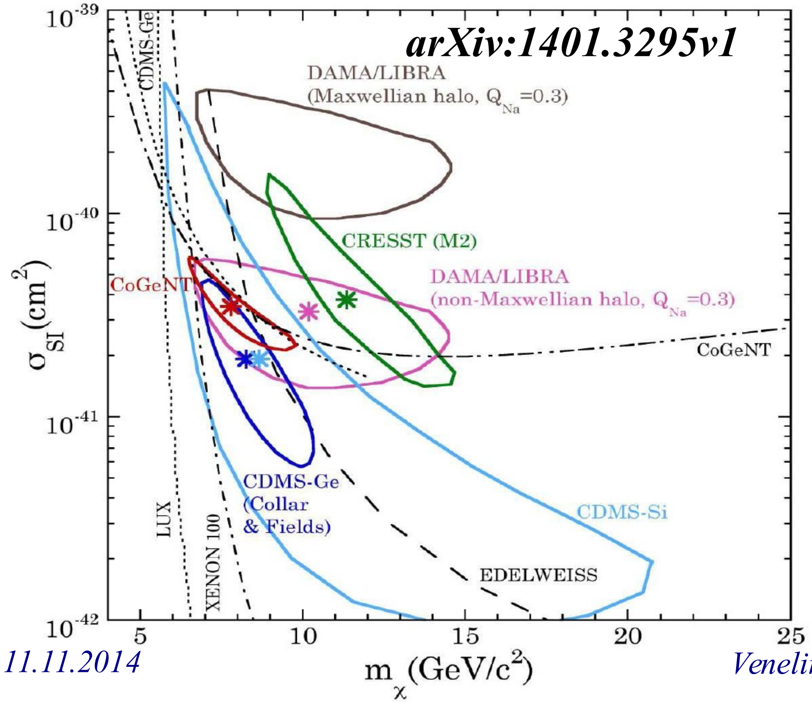
- Despite the highest energy reach LHC did not provide any evidence for new degrees of freedom

Where to look? How to proceed?

Energy frontier vs **Intensity frontier**

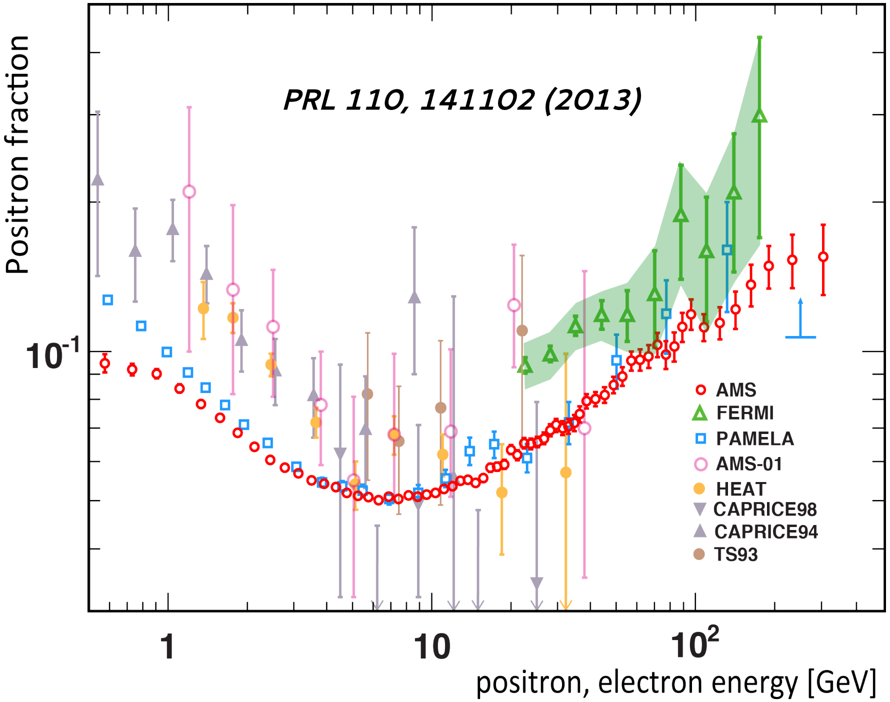
Direct search experiment

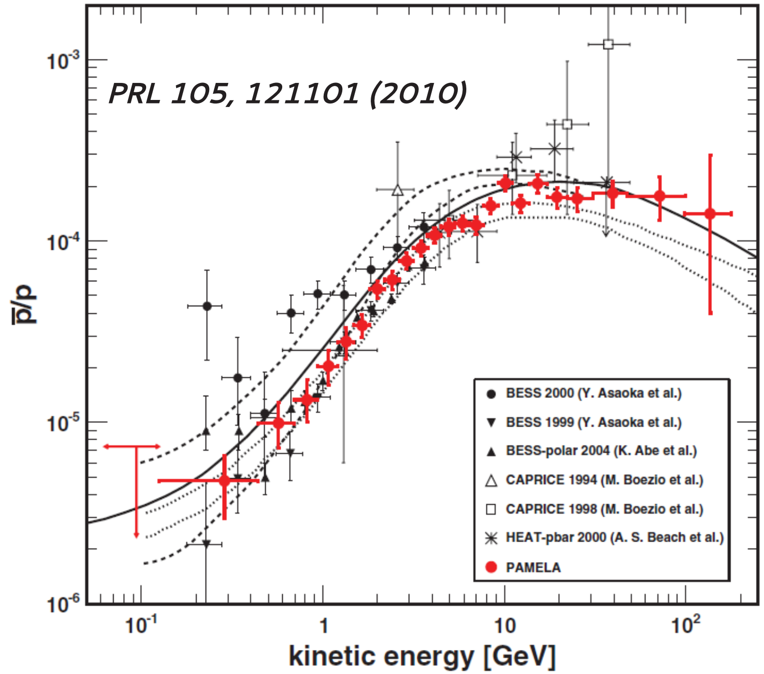




- DAMA/LIBRA results unexplained: 9.2 σ
- Used to be alone, now few other indications emerged
- Seem to be possible to build a consistent picture
- If the explanation is Dark Matter, it should be relative light: ~10 GeV
- Interaction with the nuclei through a mediator. Mass in the MeV range is OK

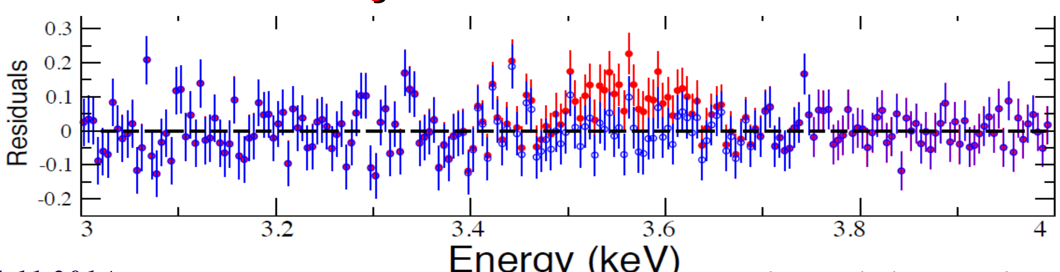
Astrophysics ...





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

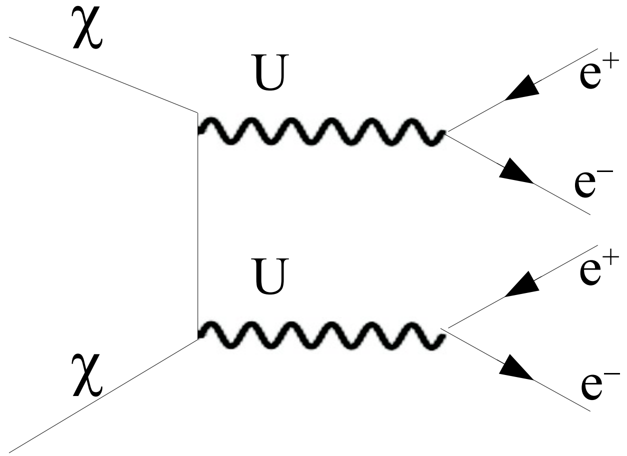
... and astronomy

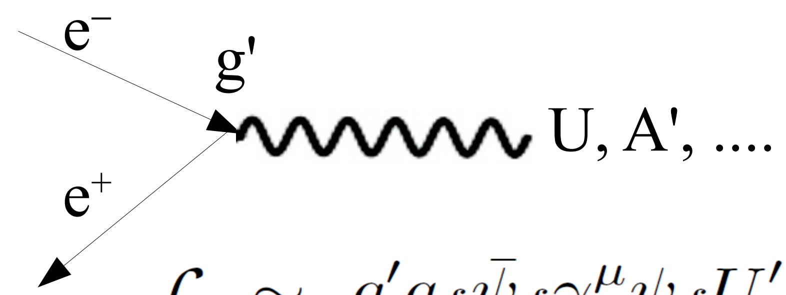


Observation of 3.5keV line?
arXiv:1402.2301
arXiv:1402.4119
Possible interpretation: arXiv:1404.2220

Hint for dark matter?

Dark matter annihilation through

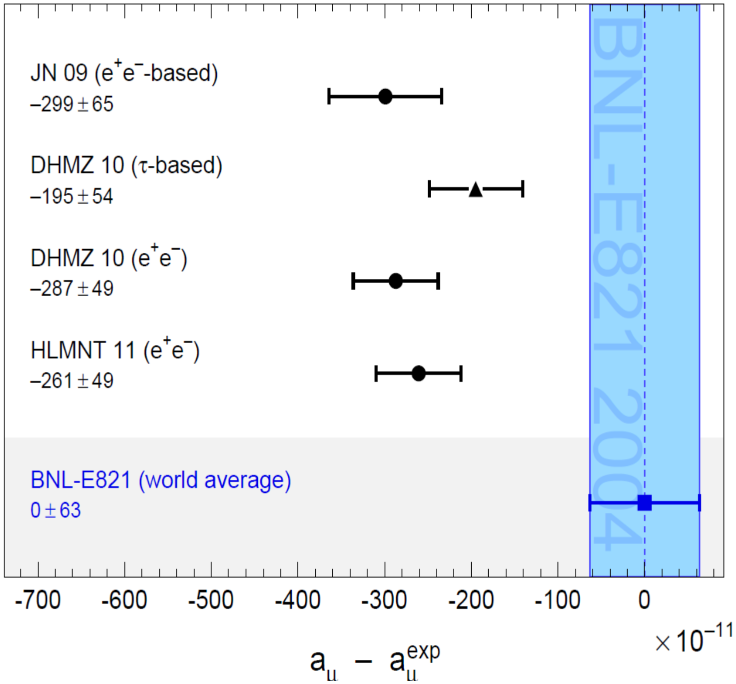


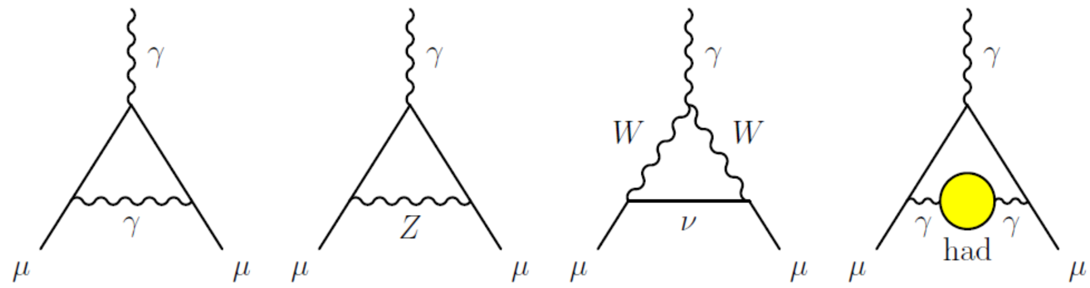


$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- 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 ($q_f \to 0$ 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





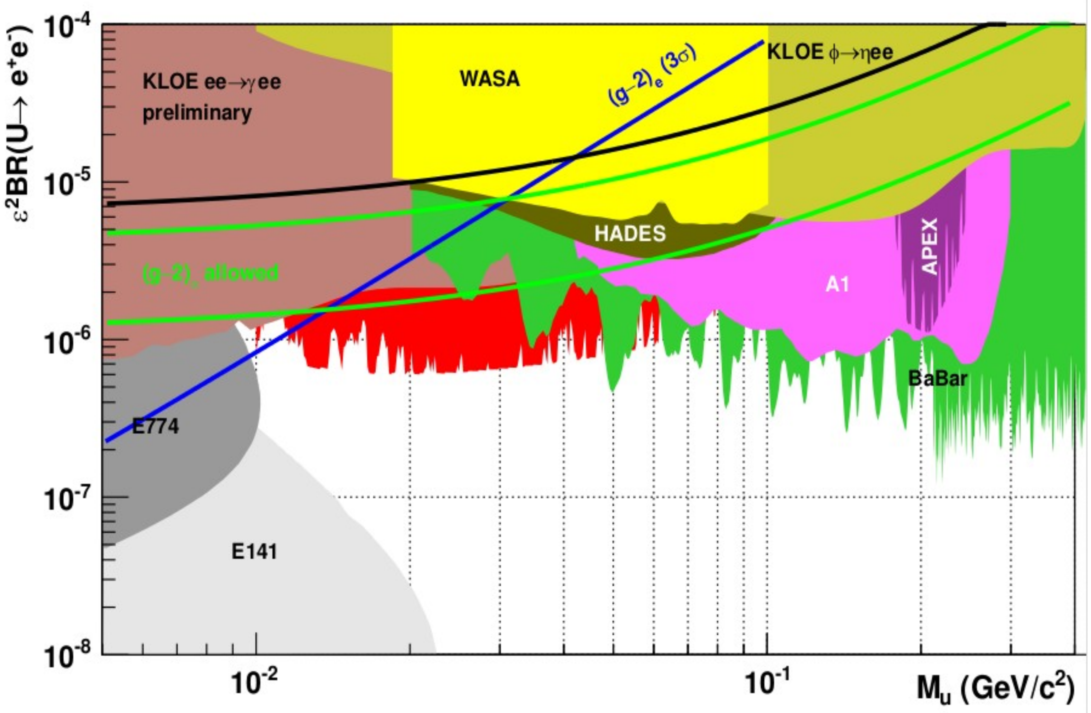
- About 3 σ discrepancy between theory and experiment (3.6 σ, if taking into account only $e^+e^- \to$ hadrons)

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

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

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 $M_{\mu+\mu-}$

see M. Battaglieri's talk

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**

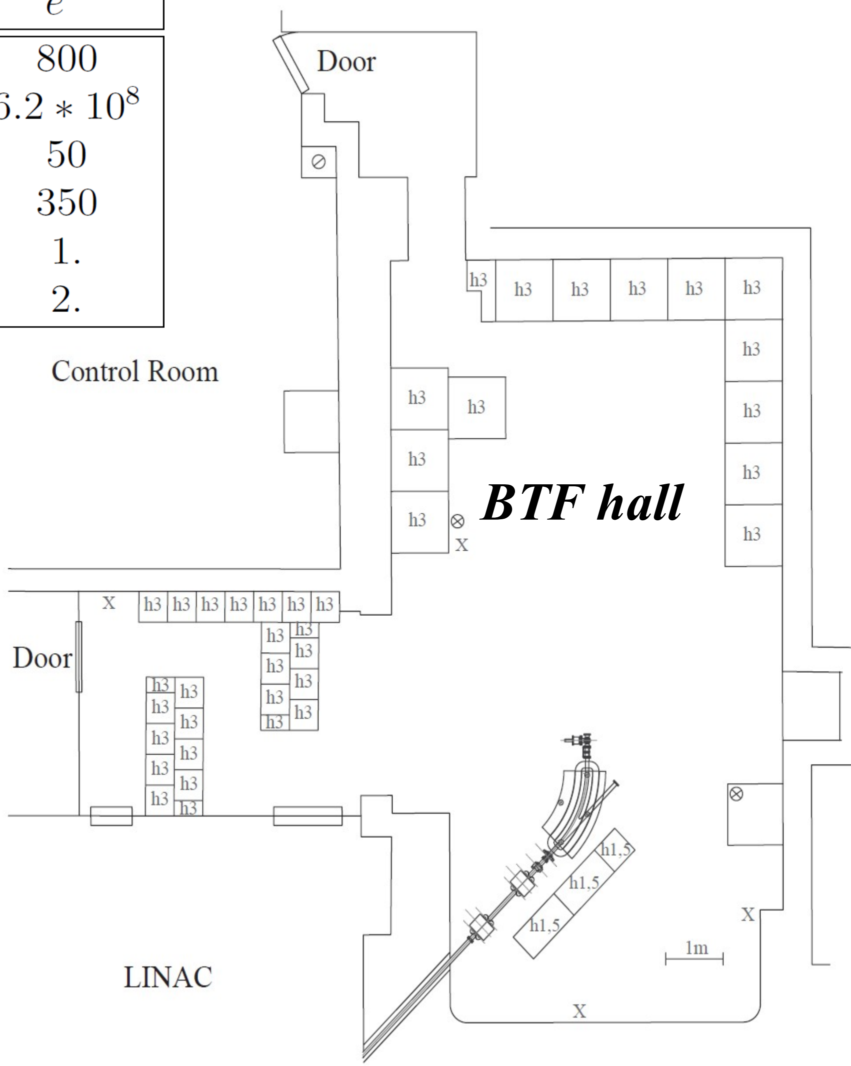
$$\frac{\sigma(e^+e^- \rightarrow \gamma U)}{\sigma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(\gamma U)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(\gamma U)} = \varepsilon^2 * \delta$$

  - $N(\gamma U)$, $N(\gamma\gamma)$ - 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

BTF @ LNF

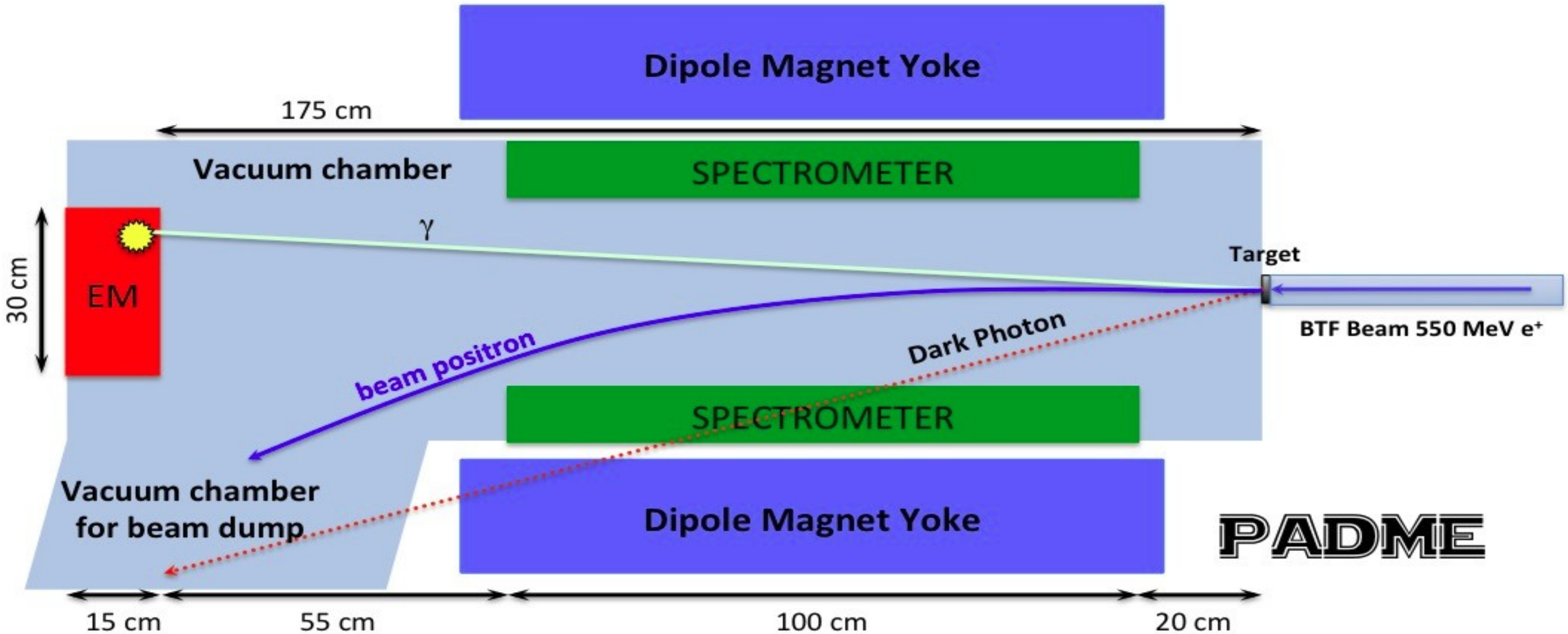
	e^+	e^-
Maximal beam energy [MeV]	550	800
Beam rate [particles/burst]	$6.2 * 10^8$	$6.2 * 10^8$
Number of bursts per second	50	50
Max. averaged current during a burst [mA]	85	350
Typical emittance (mm mrad)	1.5	1.
Beam spot size (σ in mm)	2.	2.

- 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



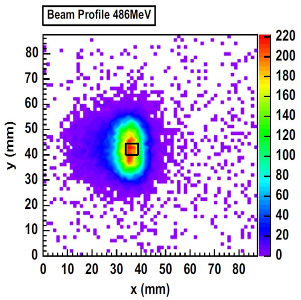
PADME experiment

Positron Annihilation into Dark Matter Experiment

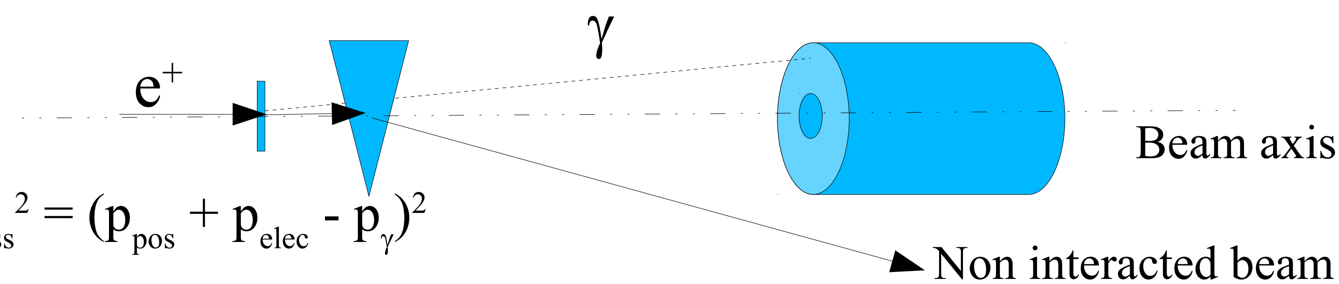


- Small scale fixed target experiment
- Measuring both charged and neutral particles:
  - Spectrometer
  - Calorimeter
  - Beam profile

Basic ideas

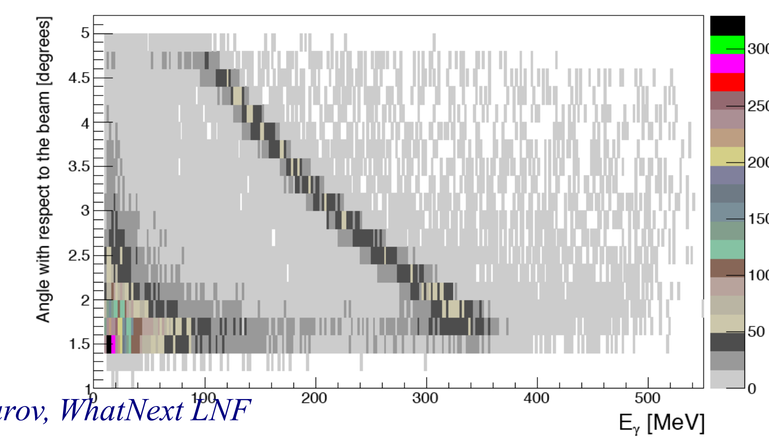


Focusing on the invisible channel



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

- 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

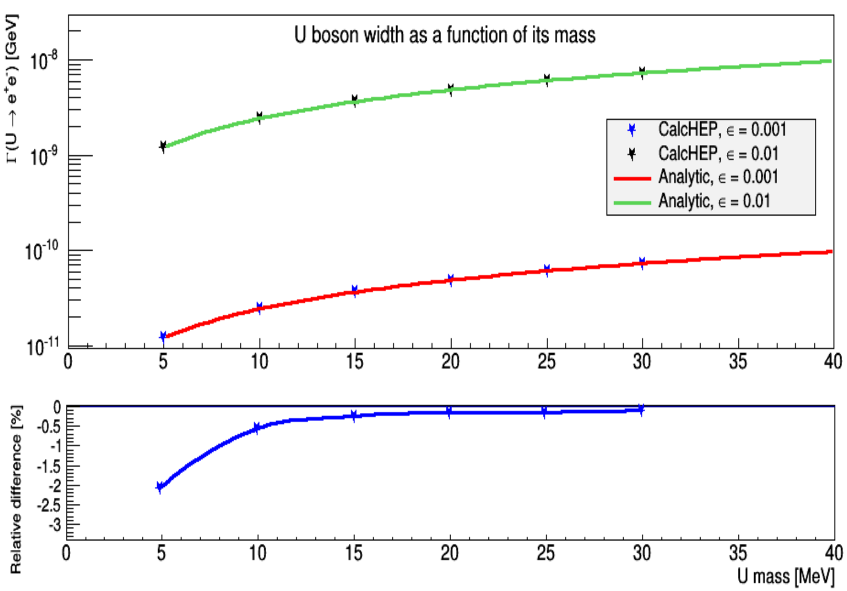


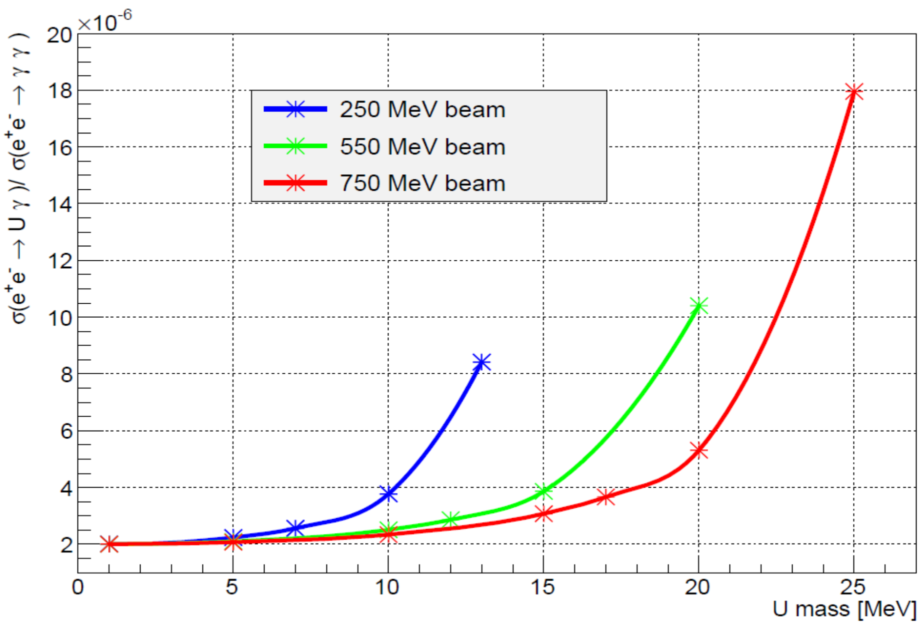
Heavy/Dark photon/boson

- After production, U boson may decay into e^+e^-

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

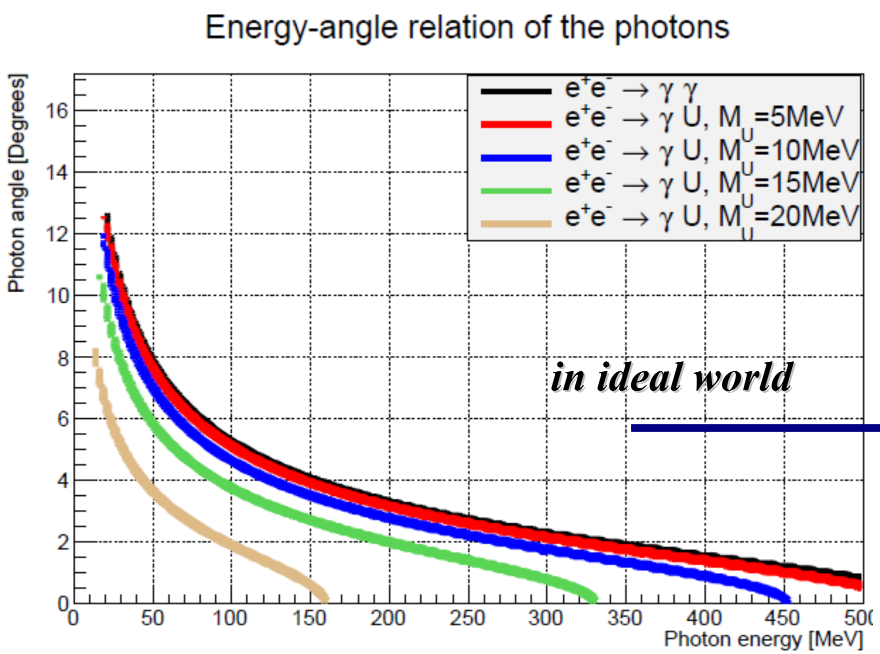
Simple model implemented in CalcHEP, used for the further studies

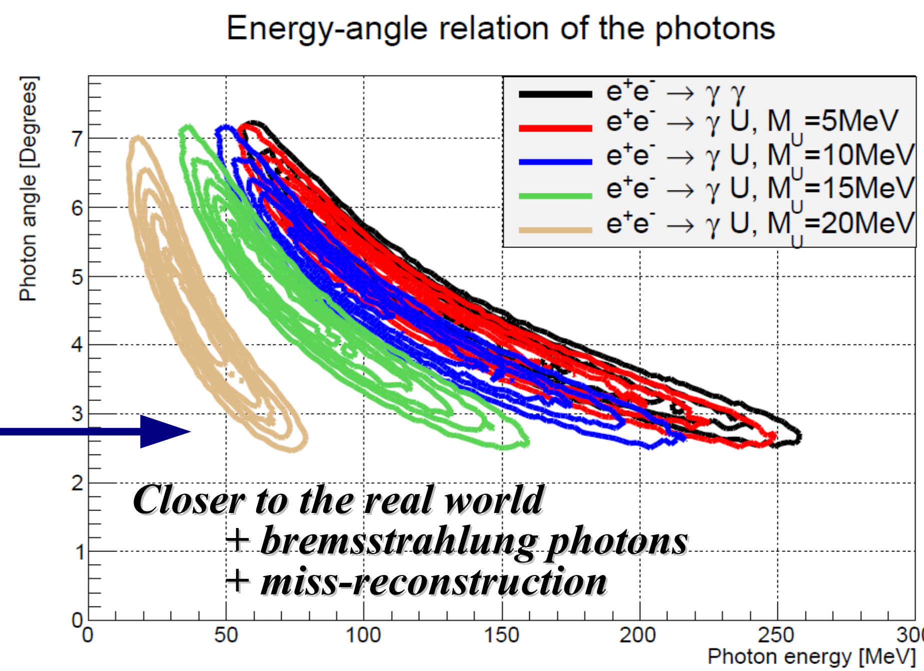




enhancement factor δ for $\varepsilon^2=10^{-6}$

Event reconstruction



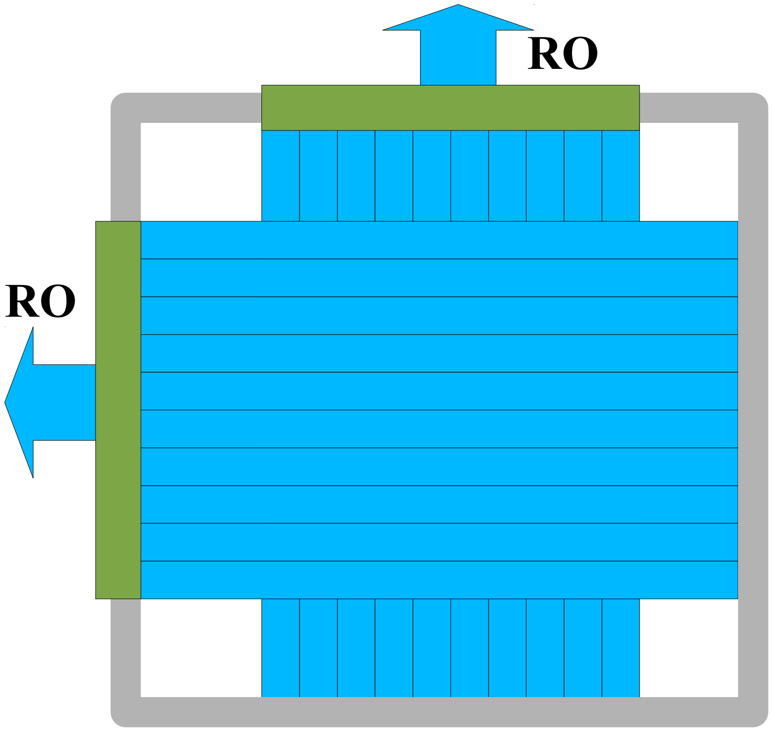


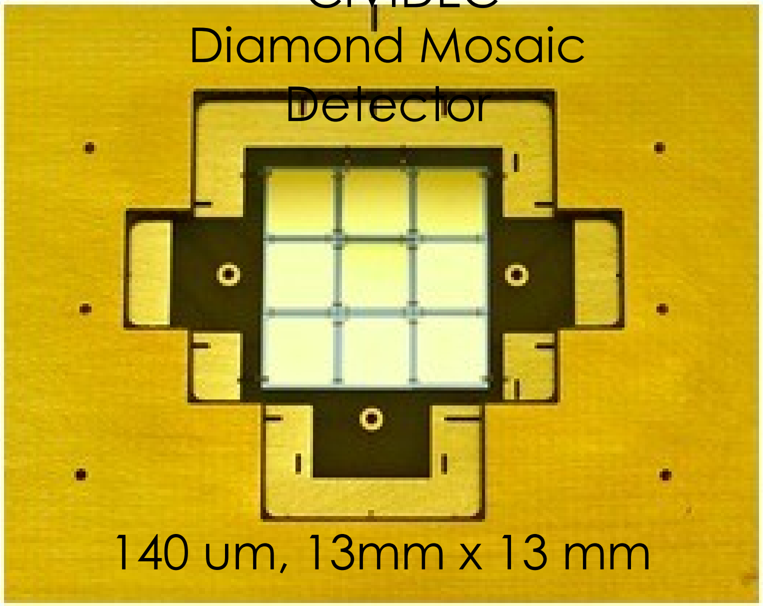
- Clear 2 body correlation

MeV^2/c^4

- Background minimization
  - Best possible resolution on energy/angle measurement
  - **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Photons vetoing
  - Minimize the interaction remnants + vetoing

Target

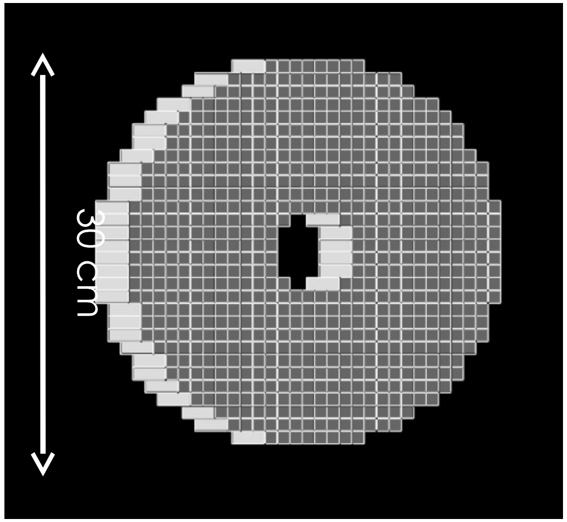


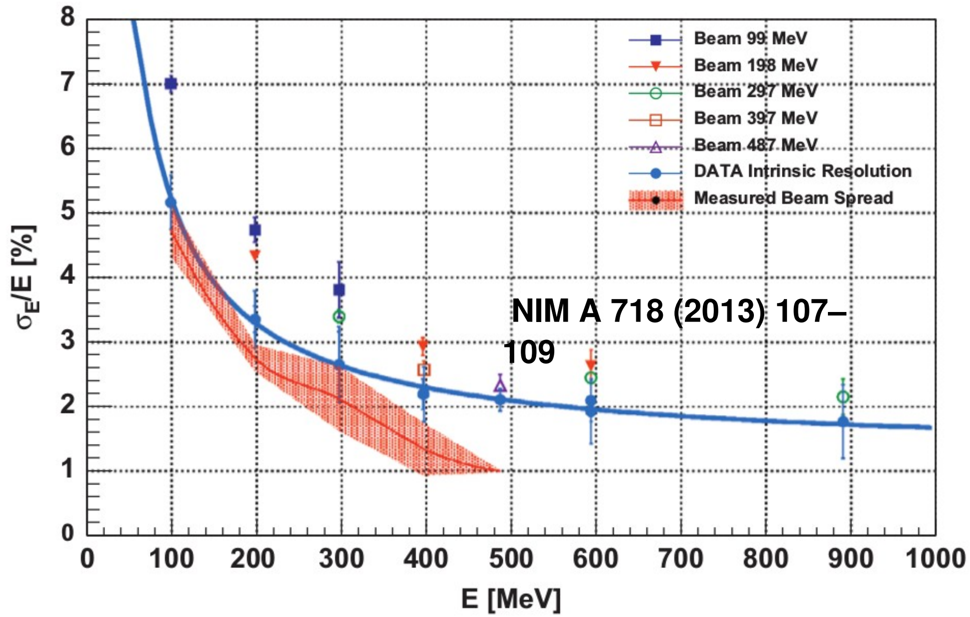


- U boson may also be produced in a higher cross section U-strahlung process: $e^+ + N \rightarrow e^+ + N + U$
- Accessible if the experiment is sensitive to $U \rightarrow e^+e^-$

- Assumed 10 diamond strips of 2 mm x 50 mm with 25um thickness
  - Horizontal and vertical mounted on a vacuum flange
- Information for beam position and intensity (normalization crosscheck)
- Sensitivity: from single particle to 10^9 particles/bunch

Calorimeter



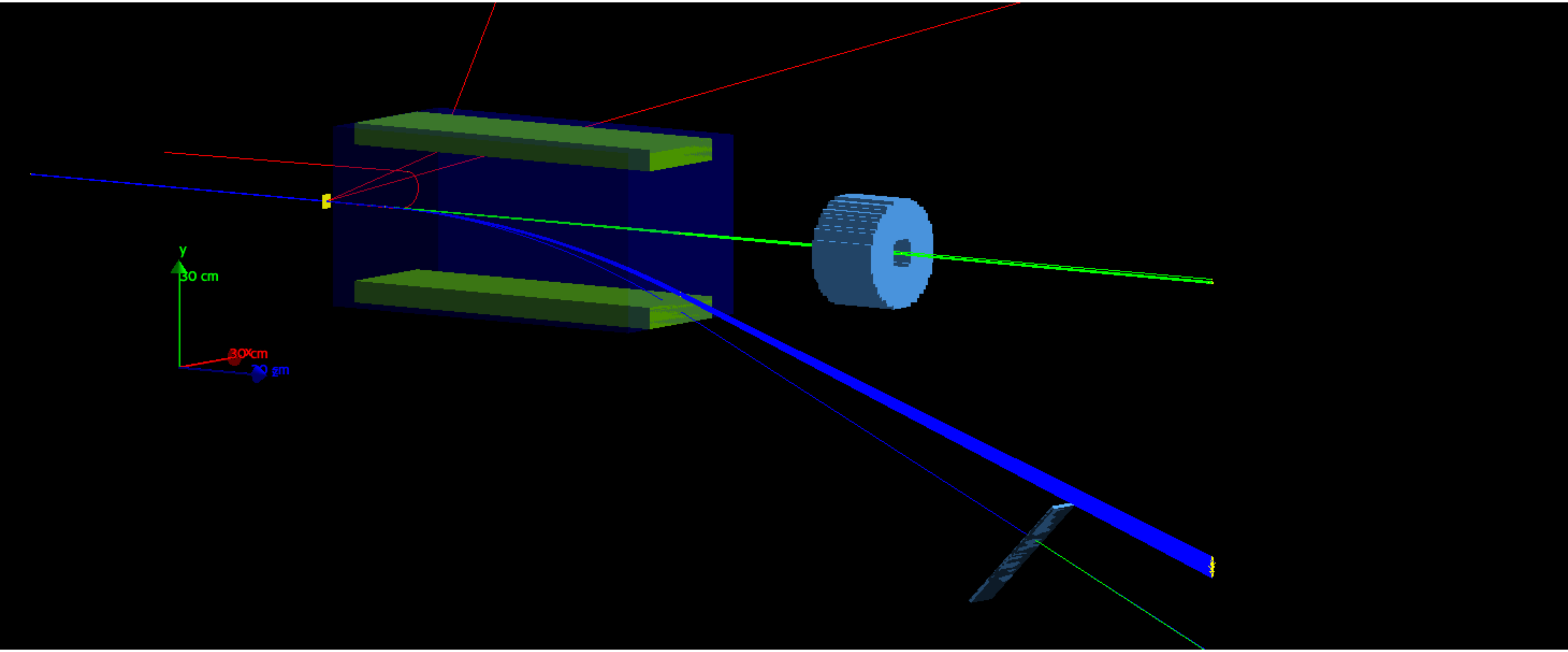


- Cylindrical shape
- 656 LYSO crystals, 1x 1 x 15 cm^3
- Energy resolution:

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

- Possible substitutions: BGO?
  - LYSO is the best solution, but may be something already available could be appropriate

PADME setup

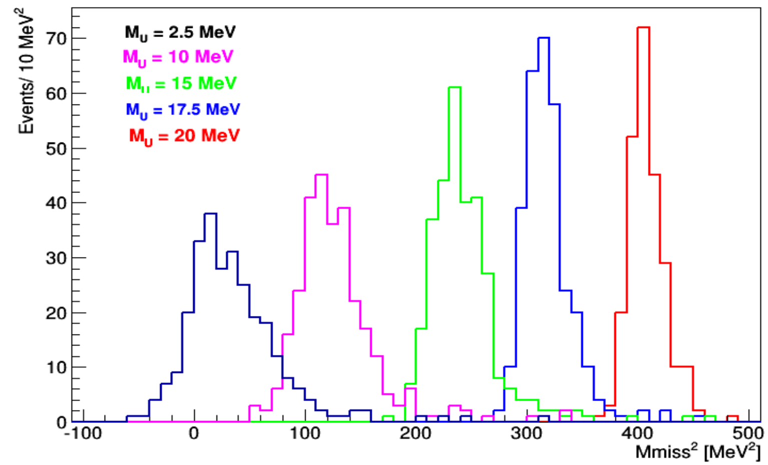


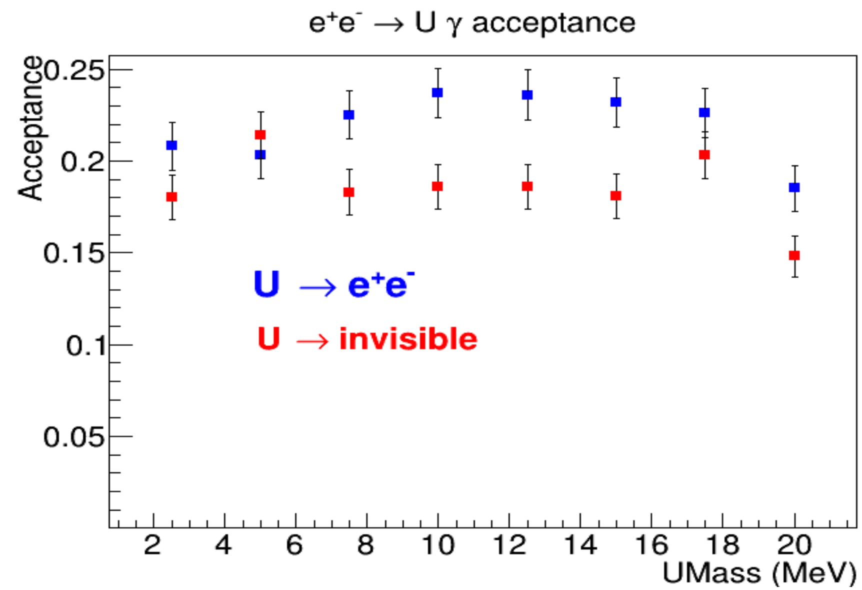
- Spectrometer design under discussion
- Additional elements could be added in case of necessity (or profit)

Event selection

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

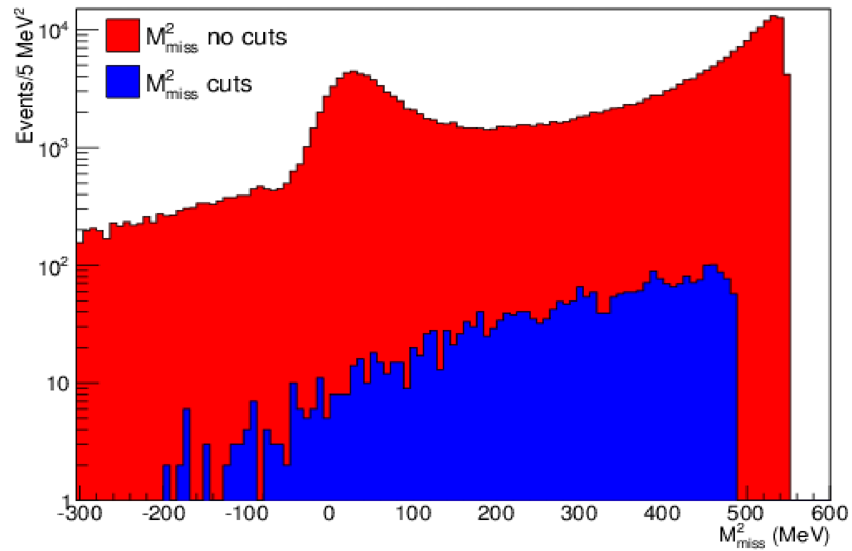
- Single cluster in the Calo
- 5 cm < Rcl < 13 cm
- Cluster energy:
  $E^{CL}_{min}(M_U)$ in 50 – 150 MeV
  $E^{CL}_{max}(M_U)$ in 120 – 350 MeV
- Kinematics
  - ± 1σ cut on the missing mass
- Veto on positrons in the spectrometer:
  - If E_{e+} < 500 MeV, then $E_{e+} + E\gamma$ < 500 MeV

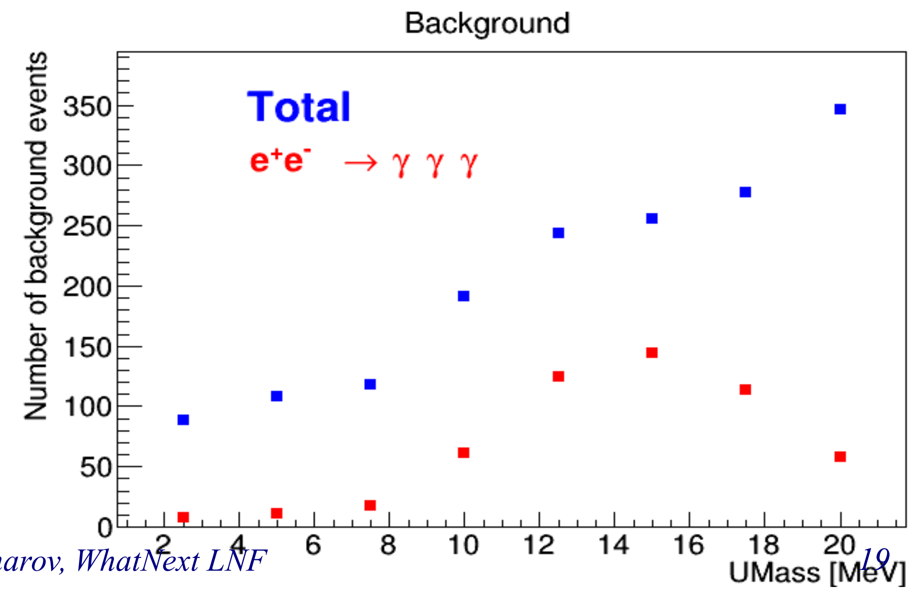




Background

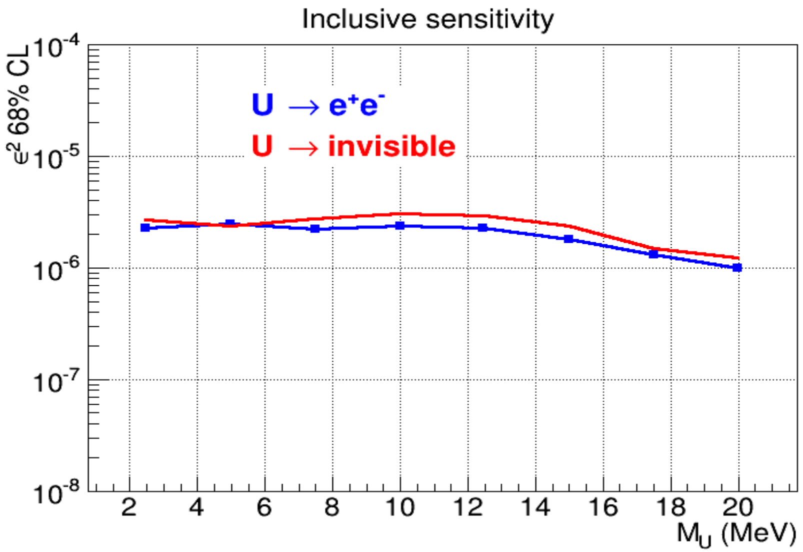
- Two γ background is suppressed by the geometry
  - If one of the clusters is detected in the CALO the other is also registered
- An irreducible 3γ background due to the hole in the center
  - ISR events
  - Only an estimation is possible
- Bremsstrahlung rejected by the spectrometer
- Residual background due to pile up, 3γ
- Seem under control and measurable

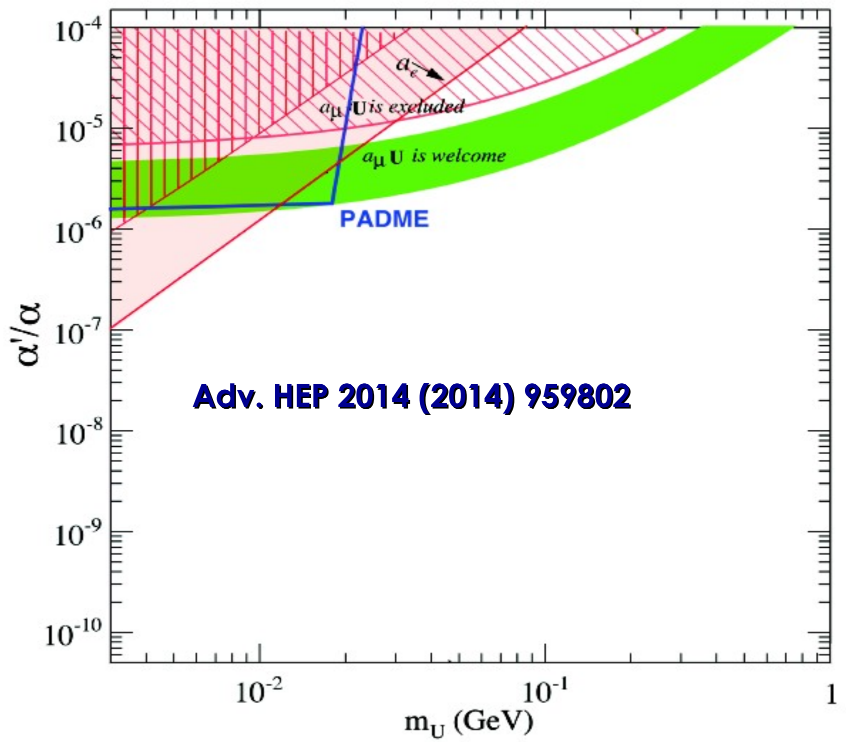




Expected sensitivity

GEANT4 based simulation to assess the possible reach

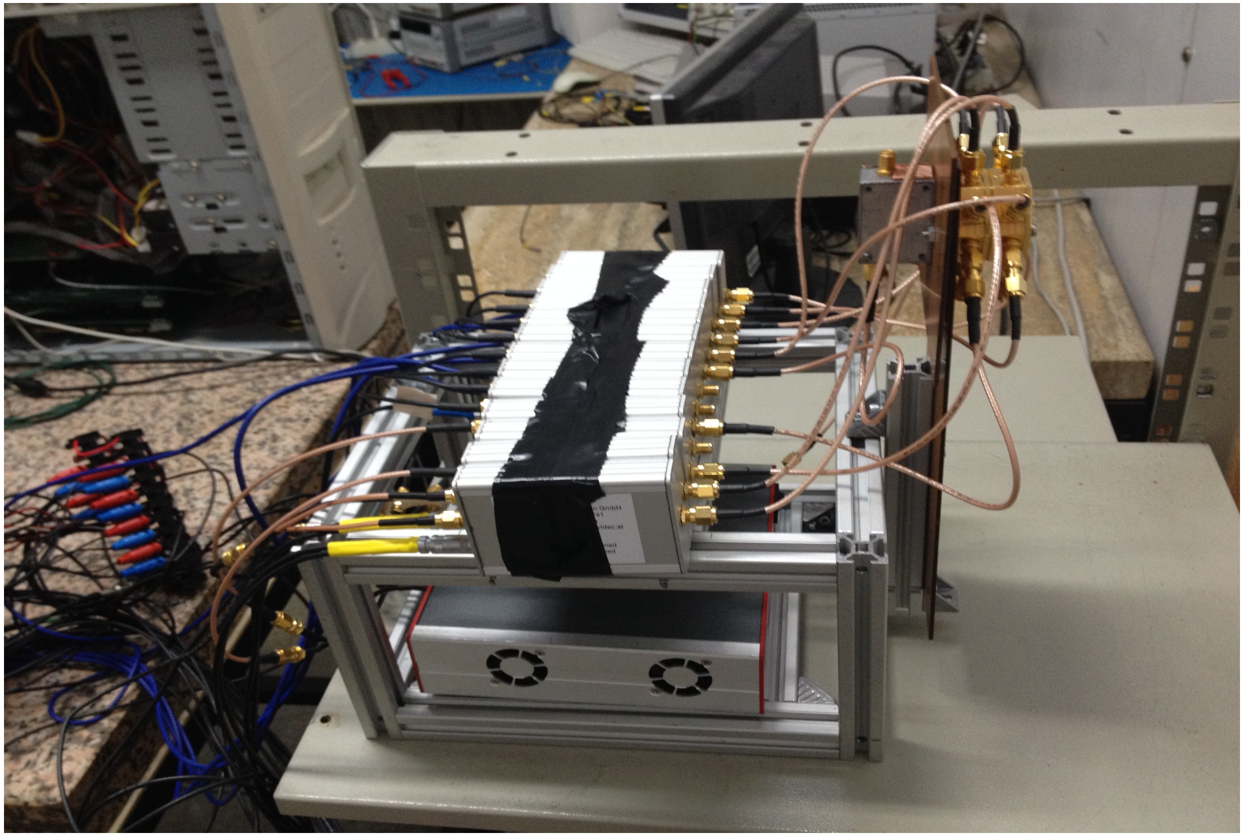




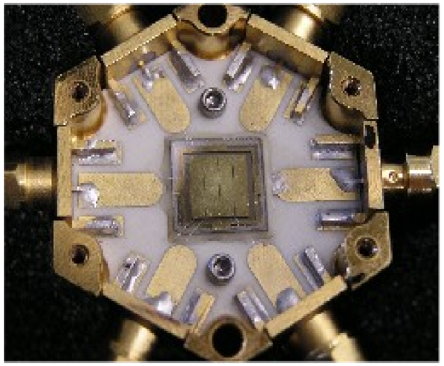
- Generated $1{*}10^{11}$ positrons on target, background extrapolated to $1{*}10^{13}$ pot
  - 1 year of continuous running
  - 60% efficiency (data taking)
  - 50 bursts/s
  - 10^4 positrons/burst
- Considering the statistical uncertainty of the expected background to set the limits

BTF run in October

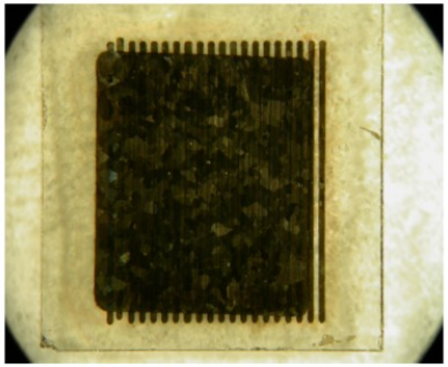
- Test the diamond beam monitor – different samples (5Gs/s ADC RO)
- Check for a first time of a 50um diamond detector
  - achievement useful not only for PADME!
- Check the possibility of graphitization of the samples



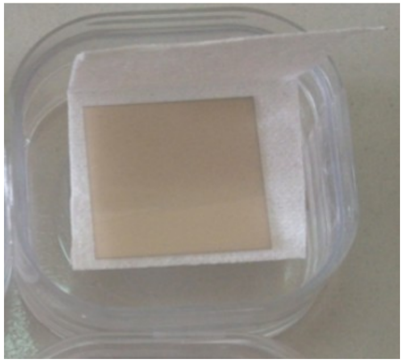
BTF run in October



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

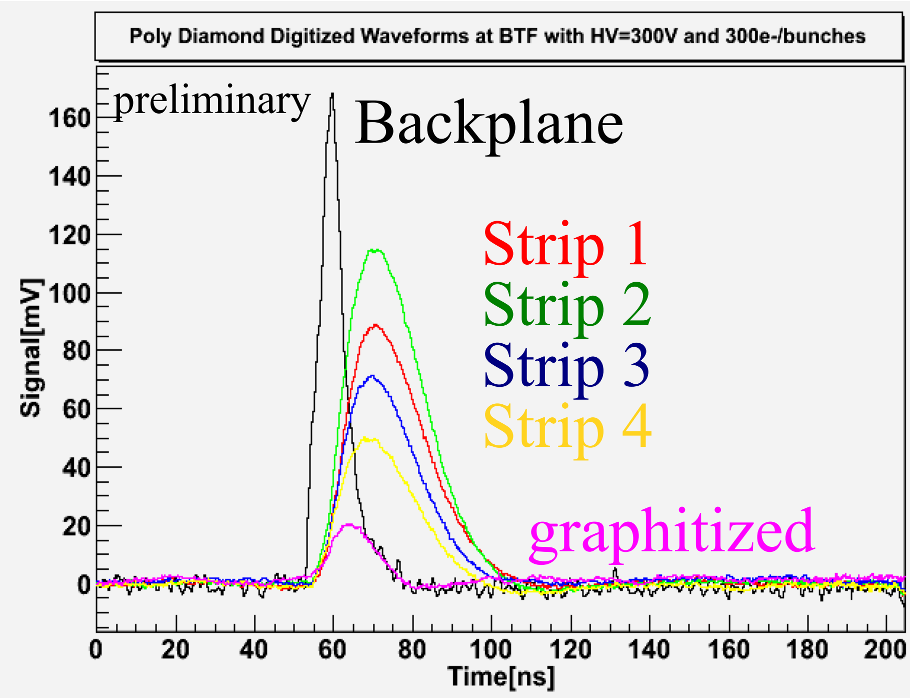


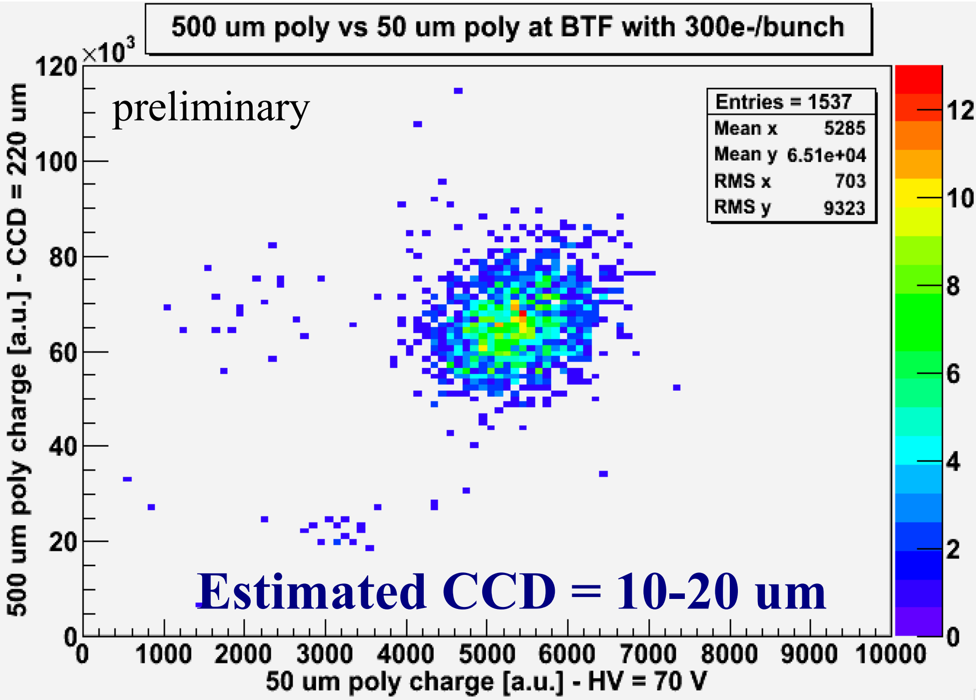
300 um, graphitized strips
3mm long, 100 um width



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

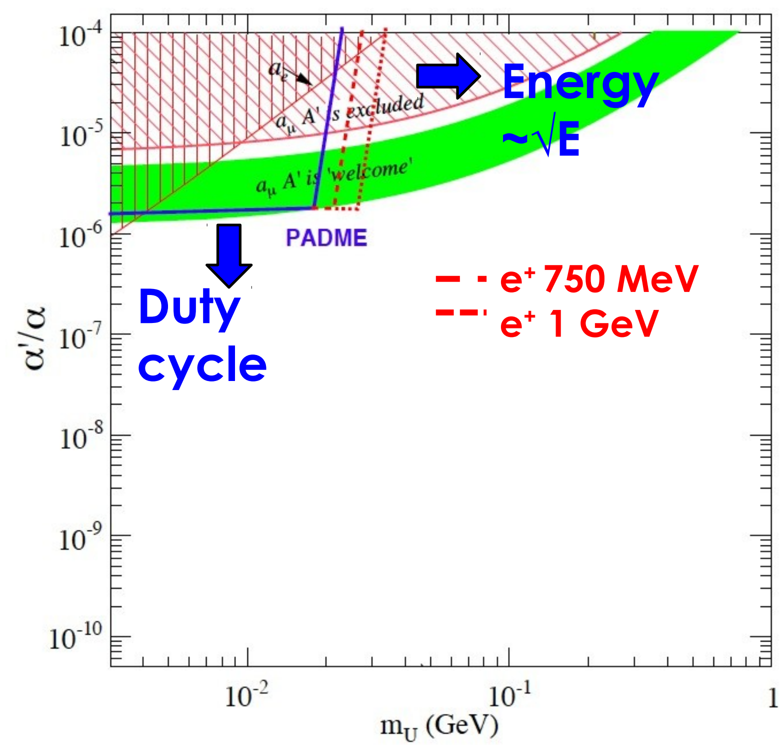
50 um, silver paint
5 mm x 5 mm





Possible improvements

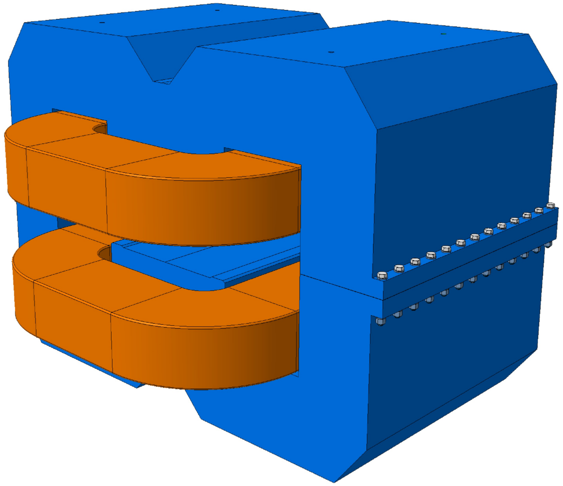
- Duty cycle upgrade:
  - Present: 50Hz * 10ns = $0.5 \cdot 10^{-6}$
  - At 10 ns all the particles in the bunch are treated as belonging to the same event
  - At 40ns the time resolution of LYSO & the spectrometer improves the veto
  - **Seems possible to achieve 160ns bunch length → factor of 2 in the sensitivity!**
- Energy upgrade
  - Extend the access to M_U ~27 MeV
  - Improve the results in the range 20 – 23 MeV

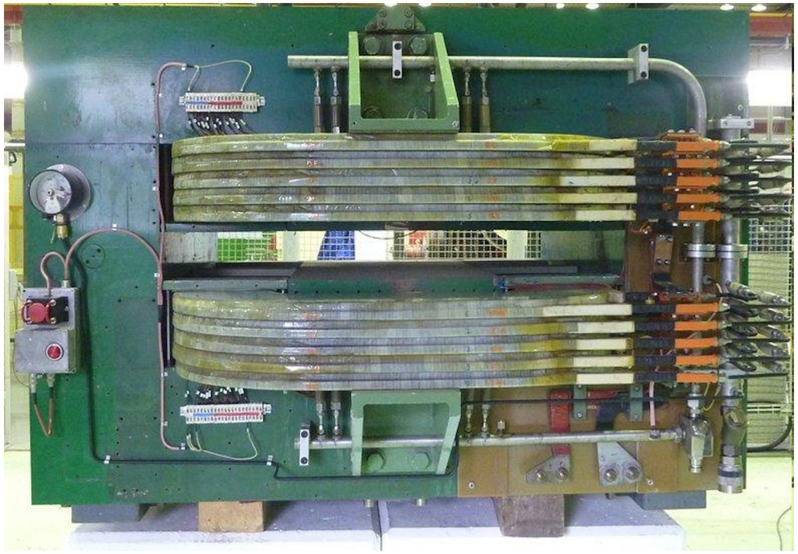


- Beam related background (i.e. accompanying spurious particles)
  - Difficult to access in the simulation, desired to be as minimal as possible
  - Should be estimated from data and verified in test runs

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 status and future steps

- Interested parties:
  - INFN – LNF: M. Raggi, V. Kozhuharov, B. Buonomo, L. Foggetta
  - INFN – ROMA1: P. Valente, E. Leonardi, G. Organtini;
  - INFN – Lecce: G. Chiodini, S. Spagnolo
  - Sofia, Bulgaria: V. Kozhuharov + *G. Georgiev, R. Kirina (EoI)*
- Planned activities:
  - Test run @BTF: 24.11 – 4.12 . 2014
    - Study the possibility to use BGO
    - Monte Carlo validation
    - Background study at low statistics
    - Diamond beam monitor/target test
    - Positron emittance to be re-measured
  - Bunch structure tests
  - Maximal BTF instantaneous current test

WEB: http://www.lnf.infn.it/acceleratori/padme/

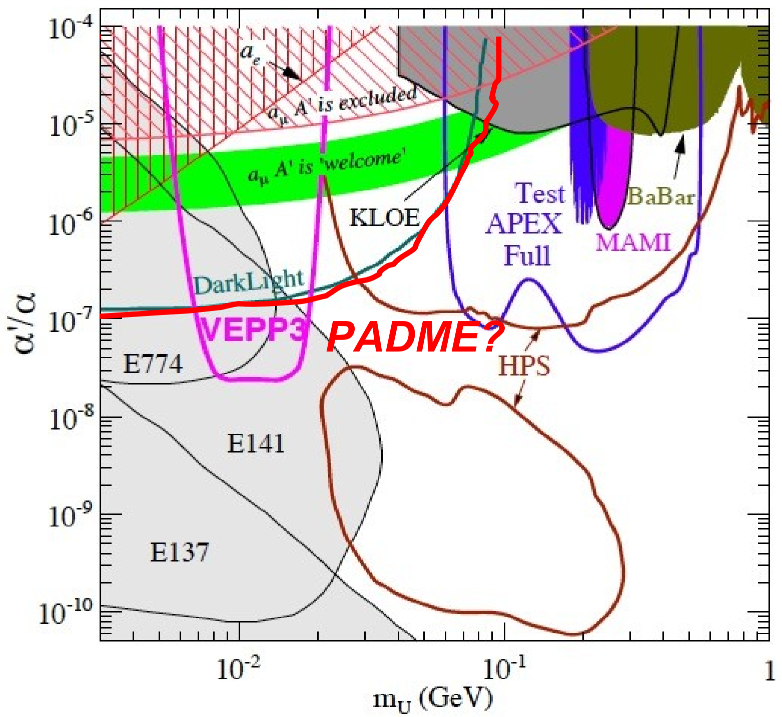
MAIL: https://lists.infn.it/sympa/subscribe/padme-general

PADME visible decays

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 $M_{e^+e^-}$



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

See M. Raggi's talk

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

- ~100 % acceptance (high boost of the produced U-boson 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

Extend M_U sensitivity, but model dependent

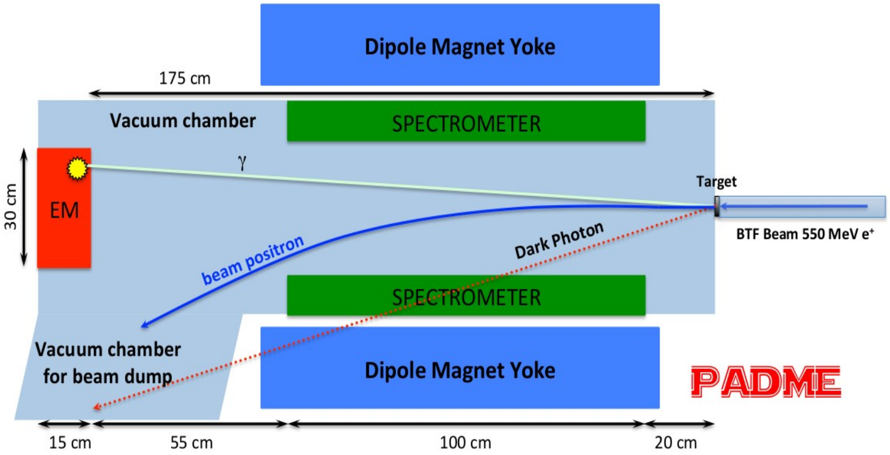
Conclusions

- 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 INFN referees
- Aim is to devote only 2 years to construction and to be ready for data taking in 2017

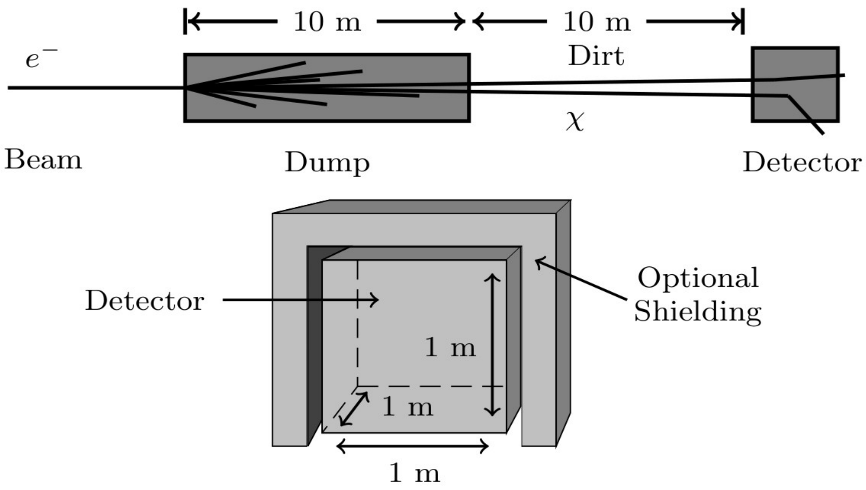
SPARE

New physics prospects at LNF

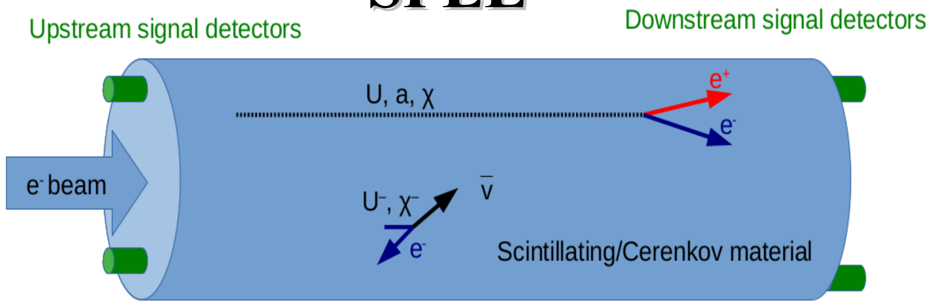
PADME



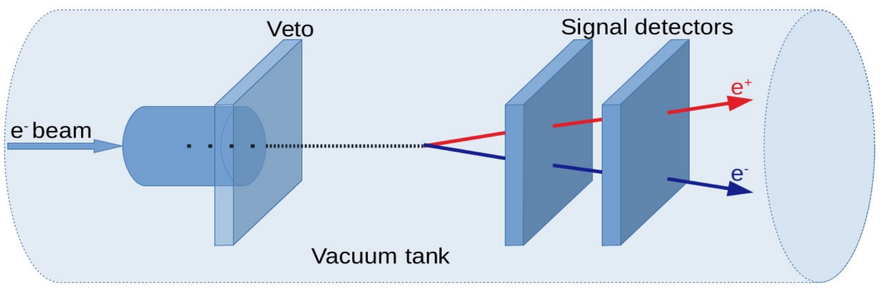
BDX



Search for Particles with Extended Lifetime
SPEL

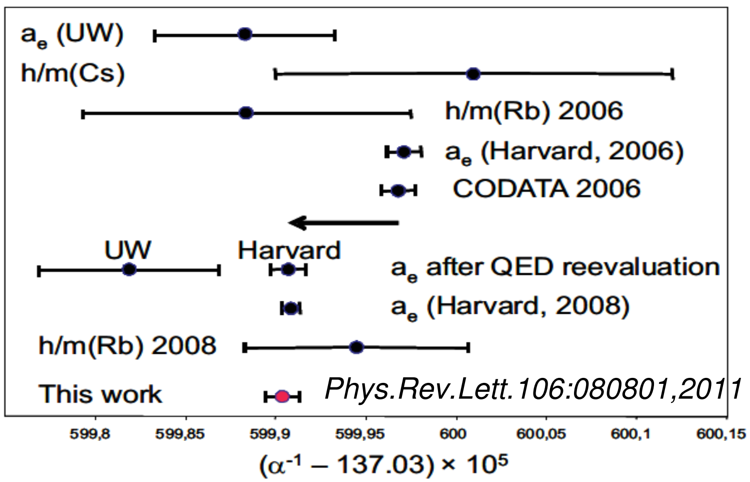


U-boson decays in vacuum



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}



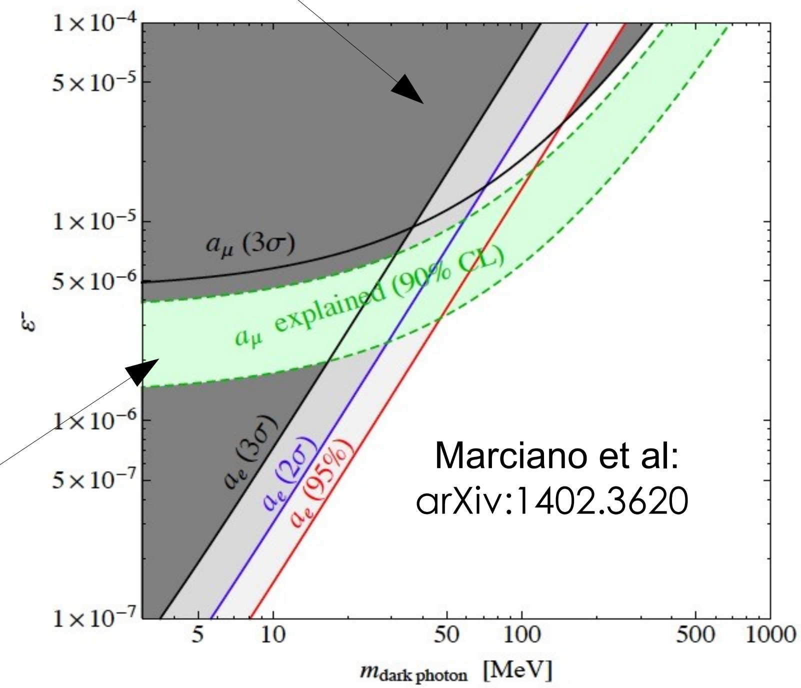
$\alpha^{-1} = 137.035\,999\,037\,(91)$

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

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

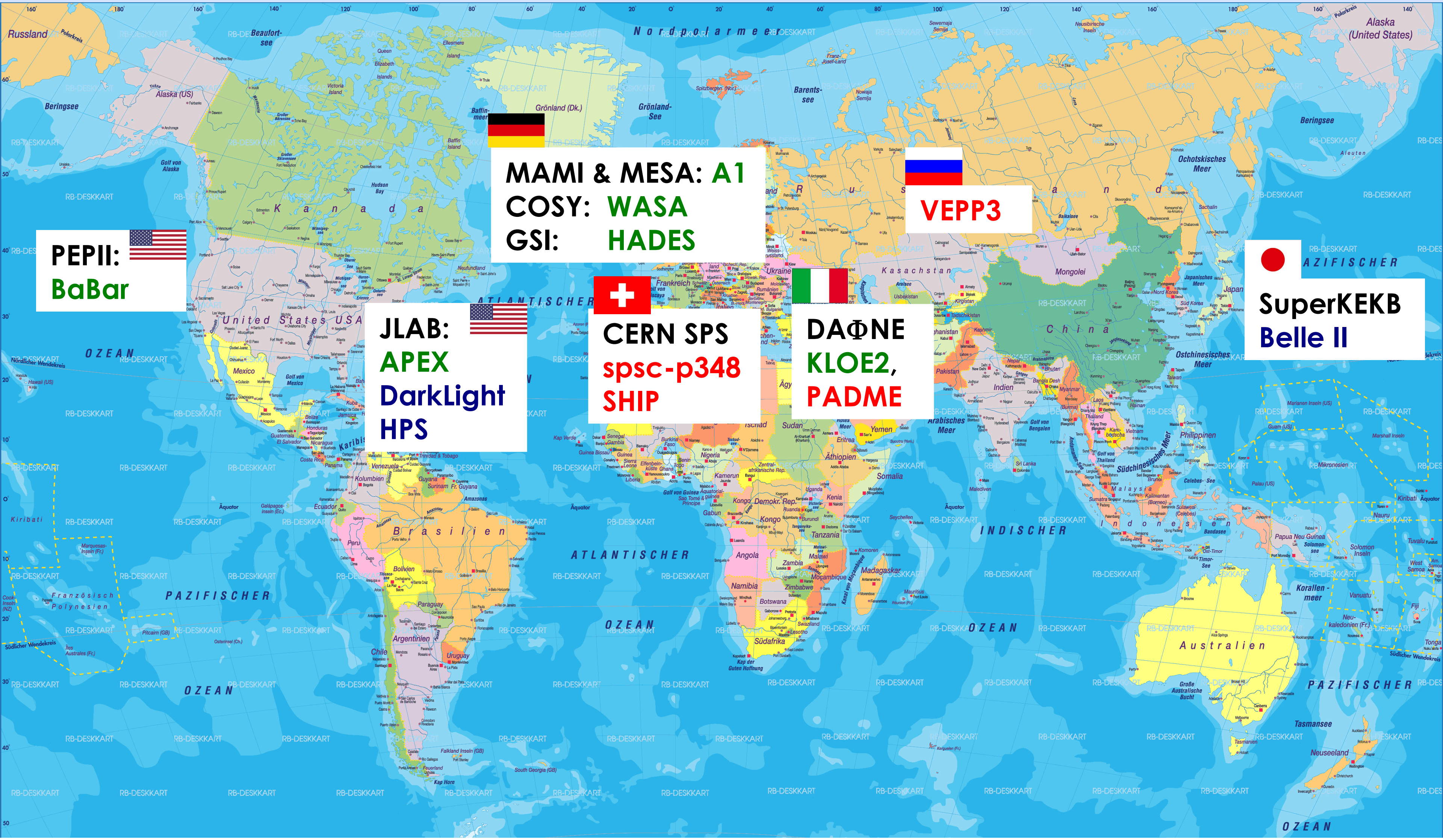
$$\delta a = \frac{\alpha_{EM}\,\epsilon^2}{2\pi} * f,\ f = \begin{cases} 1, \text{ for } m_l >> M_U \\ 2m_l^2/(3M_U^2), \text{ for } m_l << M_U \end{cases}$$

Phys.Rev.D80:095002,2009



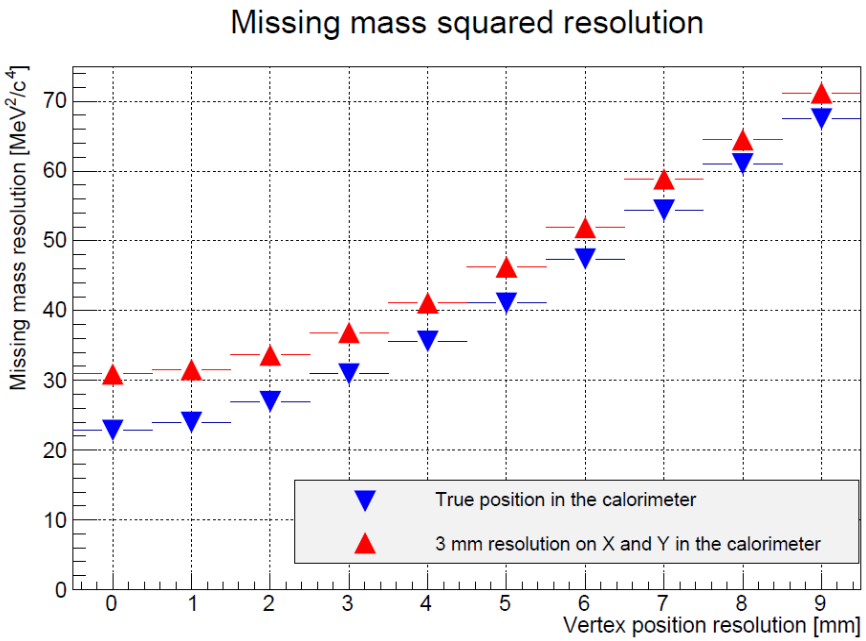
The invisible search removes any assumption apart from coupling to leptons!

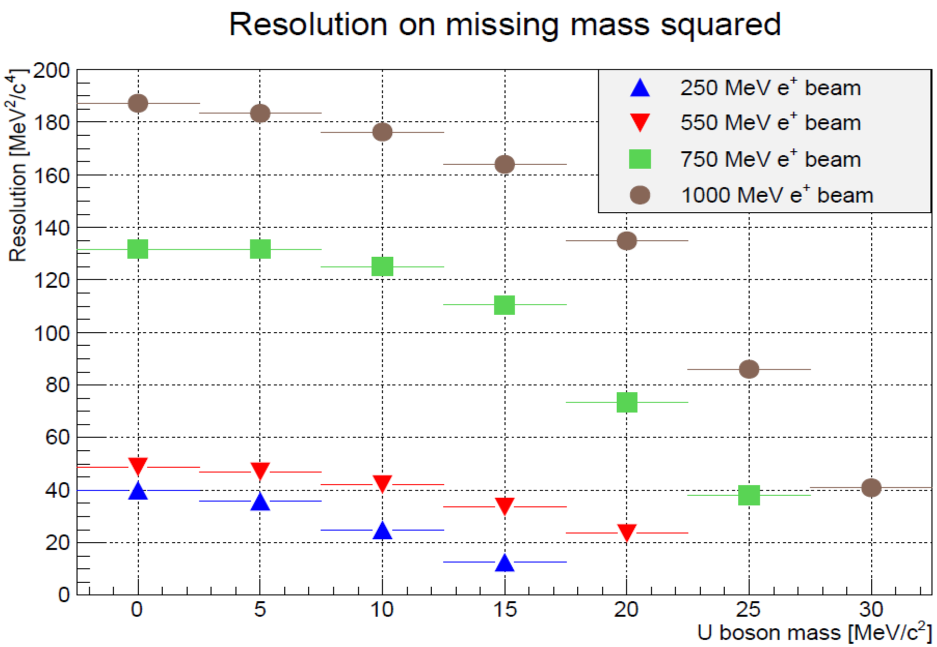
Present status



Status: ongoing, planned, proposals

Missing mass resolution: target





- Toy studies on kinematics
- Target optimization to minimize the scattering of the beam inside while keeping the annihilation probability relatively high

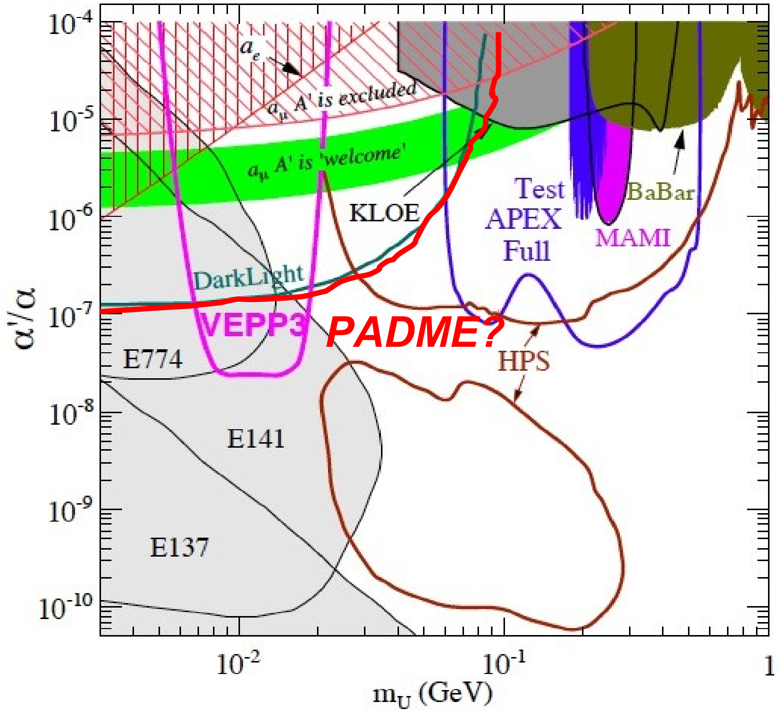
10^4 – 10^5 positrons/burst, 50um target thickness

PADME future program

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

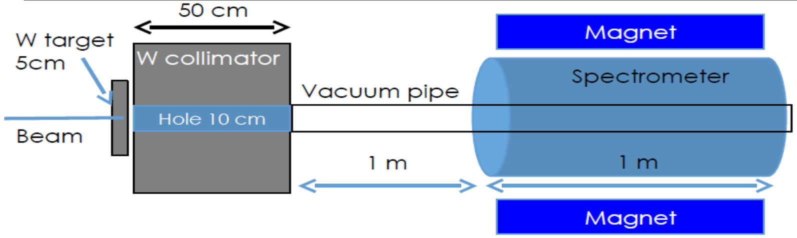
$U \rightarrow e^+e^-$ visible decay search

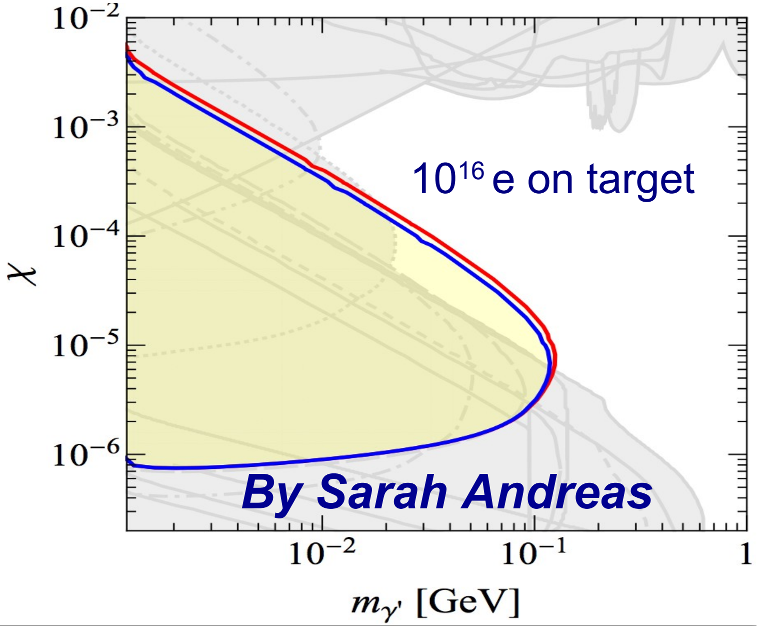
- Measuring e^+e^- momentum with the spectrometer
- Selection based on $M_{e^+e^-}$



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

Beam dump prospects

Experiment	target	E_0 [GeV]	N_{el} electrons	N_{el} Coulomb	L_{sh} [m]	L_{dec} [m]	N_{obs}	$N_{95\%up}$
E141 [47]	W	9	2×10^{15}	0.32 mC	0.12	35	1126^{+1312}_{-1126}	3419
E137 [48]	Al	20	1.87×10^{20}	30 C	179	204	0	3
E774 [49]	W	275	5.2×10^{9}	0.83 nC	0.3	2	0^{+9}_{-0}	18
KEK [39]	W	2.5	1.69×10^{17}	27 mC	2.4	2.2	0	3
Orsay [40]	W	1.6	2×10^{16}	3.2 mC	1	2	0	3

- Improvements both in number of electrons and size of the experiment
  - Present BTF limit – 10^{18} e^-/year due to plant authorization
  - **Possible flux up to 10^{21} e^-/year!**
  - **Access to unexplored regions in just 3 days of running**
- Decay length governs the access to high ε – small scale is better if background is under control
- Flux governs the access to higher masses
- A dedicated and optimized search, not a data mining technique