PADME project at DAΦNE BTF

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Dark Matter, Hadron Physics and Fusion Physics

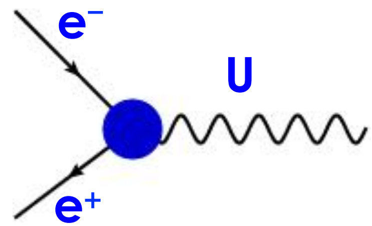
Messina (Italy) - September 24th-26th, 2014

Positron Annihilation into Dark Matter Experiment
http://www.lnf.infn.it/acceleratori/padme/

The simplest dark sector model

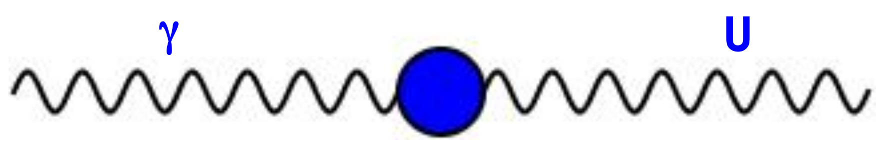
- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or U boson.
  - Two type of interactions with SM particles should be considered
- As in QED, this will generate new interactions of the type:

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



  - Not all the SM particles need to be charged under this new symmetry
  - In the most general case q_f is different in between leptons and quarks and can even be 0 for quarks. (P. Fayet, Phys. Lett. B 675, 267 (2009).)
- The coupling constant and the charges can be generated effectively through the kinetic mixing between the QED and the new U(1) gauge bosons

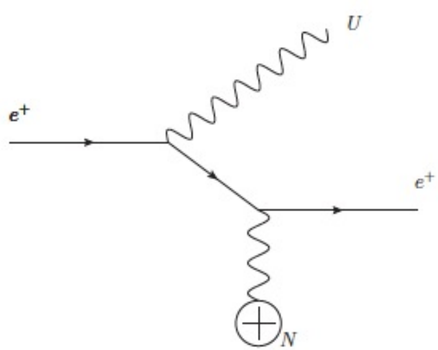
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$



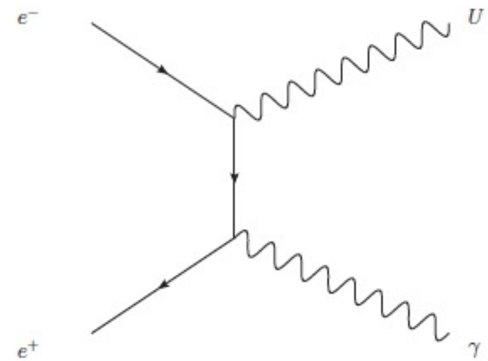
  - In this case q_f is just proportional to electric charge and it is equal for both quarks and leptons.

U boson production and decays

- U boson can be produced in e^+ collision on target by:
  - Bremsstrahlung: $e^+A \rightarrow e^+AU$
  - Annihilation : $e^+e^- \rightarrow \gamma U$

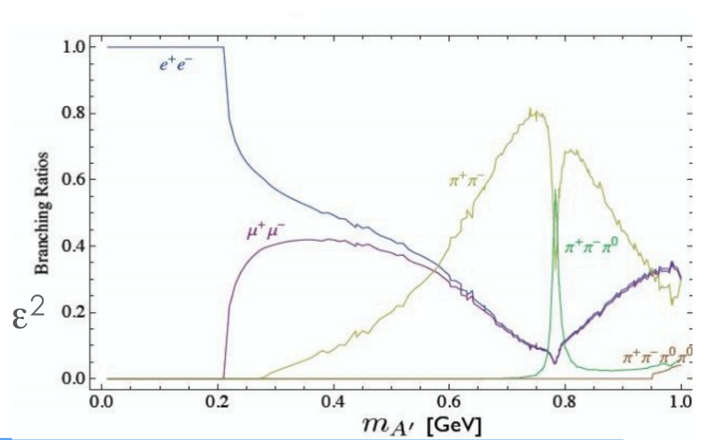


Bremsstrahlung



Annihilation

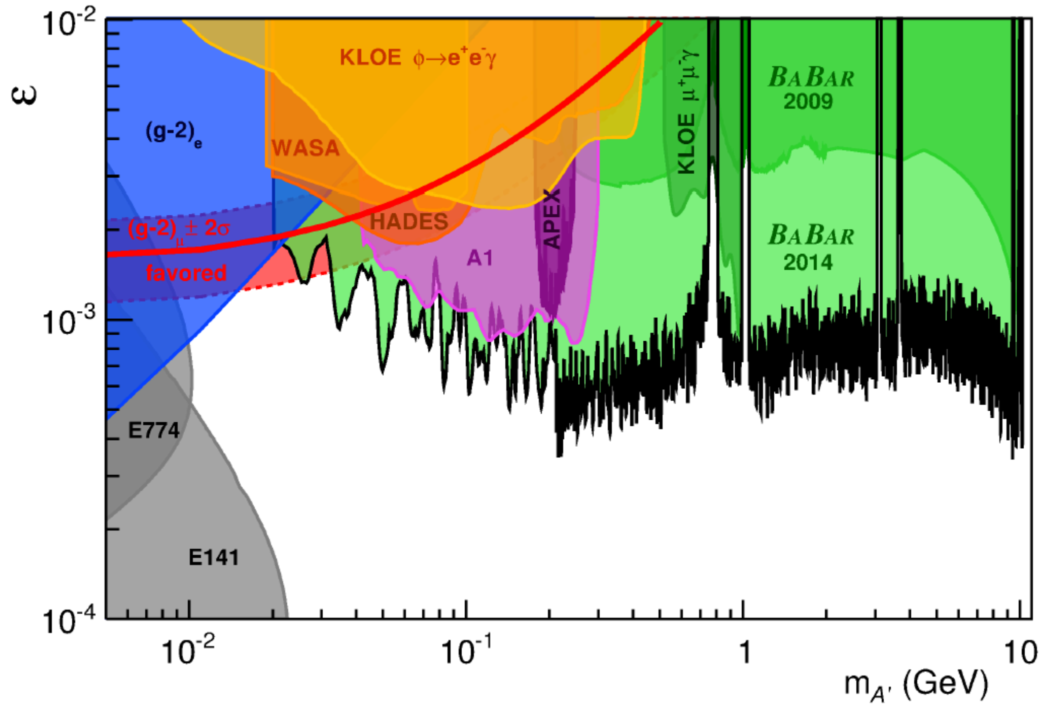
- If no dark matter candidate lighter than the U boson exist:
  - $U \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ the so called "Visible" decays
  - For M_U<210 MeV U only decay to e^+e^- BR(e+e-)=1



- If any dark matter χ with $2M_\chi < M_U$ exist
  - U will dominantly decay into pure dark matter and BR(l+l-) becomes small suppressed by ε^2
  - $U \rightarrow \chi\chi \sim 1$ so called "Invisible" decays"

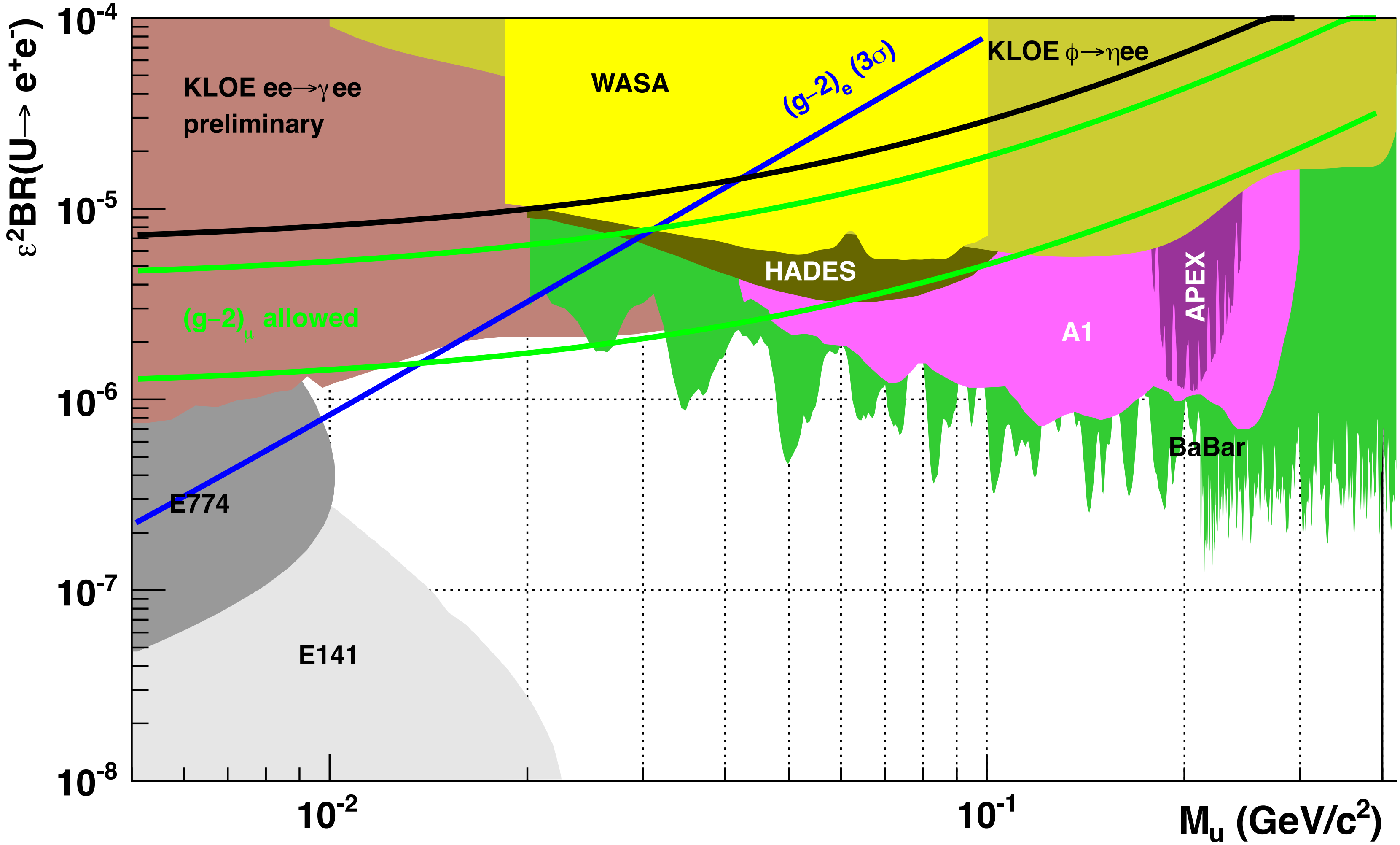
Dark photon searches status

- Favored parameters values explaining g-2 (red band)
  - U-boson light 10-100 MeV
- Status of dark photon searches
  - Beam dump experiments (grey)
  - Fixed target
    - Peak search in BG
  - Mesons decays
    - Peaks in M(e+e-) or M(μ+μ−)
- Indirect exclusion from g_e-2 g_μ-2
  - Recent tight limit in blue filled area



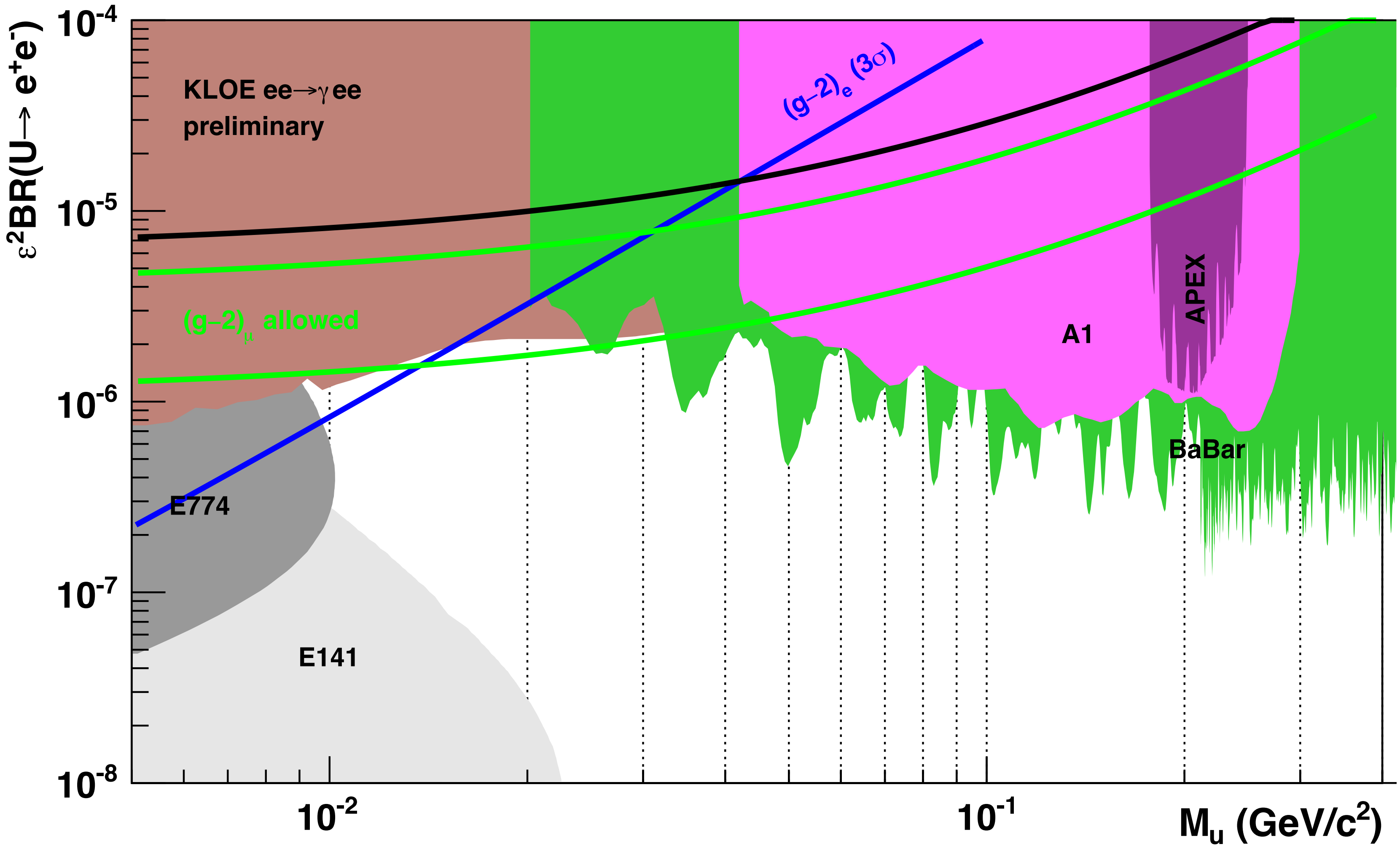
- Many different techniques, assumptions on dark photon interaction models

Status $\varepsilon_q \neq 0$ and $U \rightarrow e^+e^-$



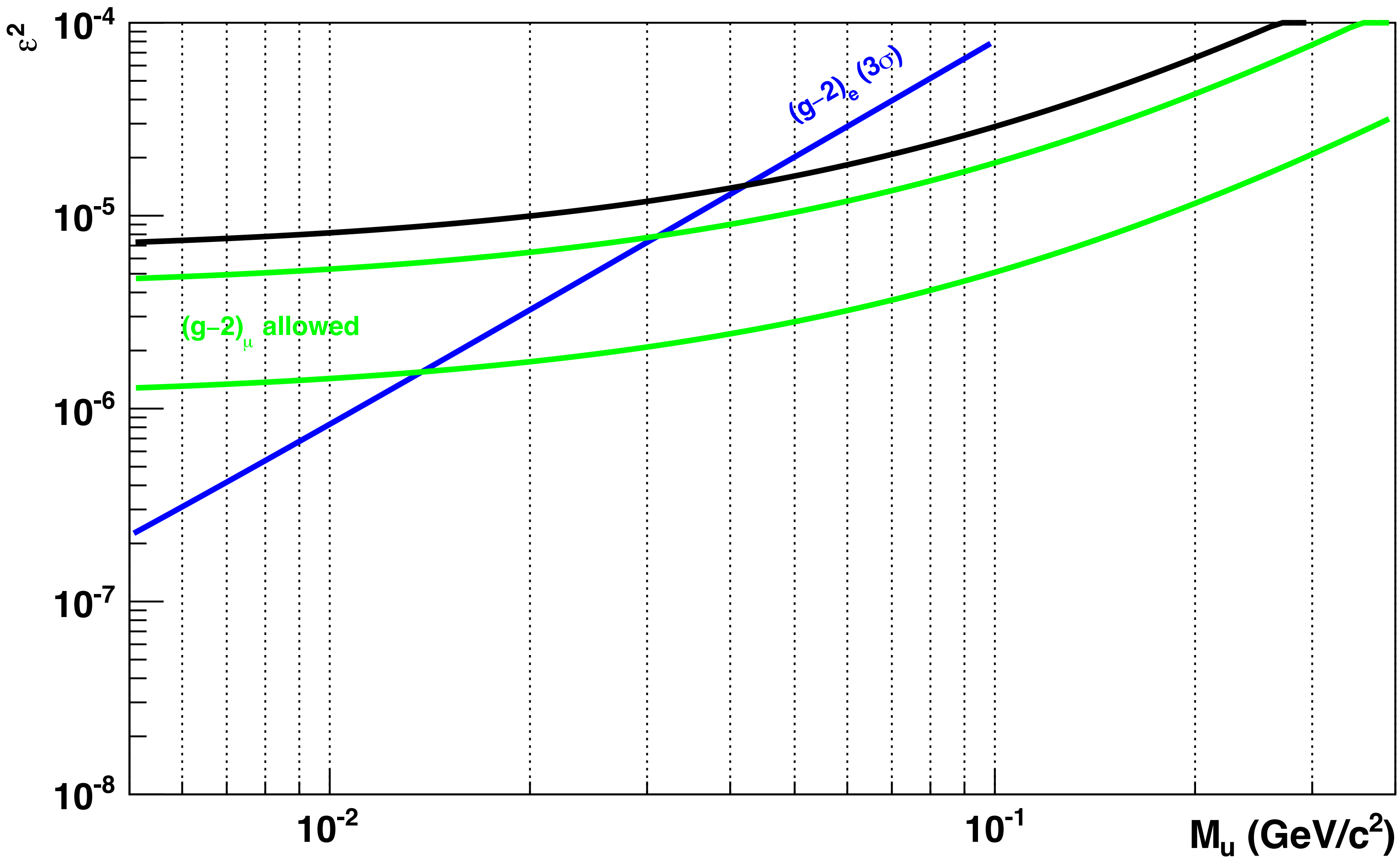
Valid for the next 1.30 hours see E. Goudzovski talk

Status ε_q=0 and $U \to e^+e^-$



Identical exclusion in case of ε_q=0 (still for 1.30 hours)

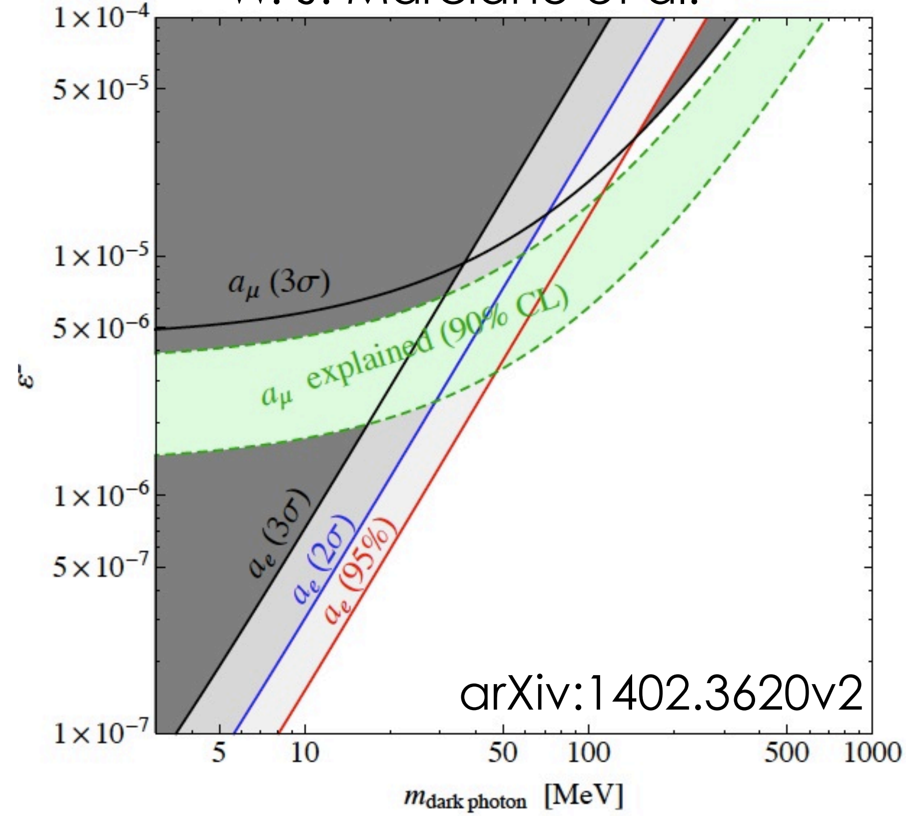
Status regardless ε_q and U decays



Why dark photon invisible decays?

- In this scenario U boson keeps all the necessary characteristics to explain positron excess, g-2
- The invisible search technique remove any assumption except coupling to leptons
- U boson increase its capability of having escaped detection so far
- No data in the minimal assumptions

W. J. Marciano et al.



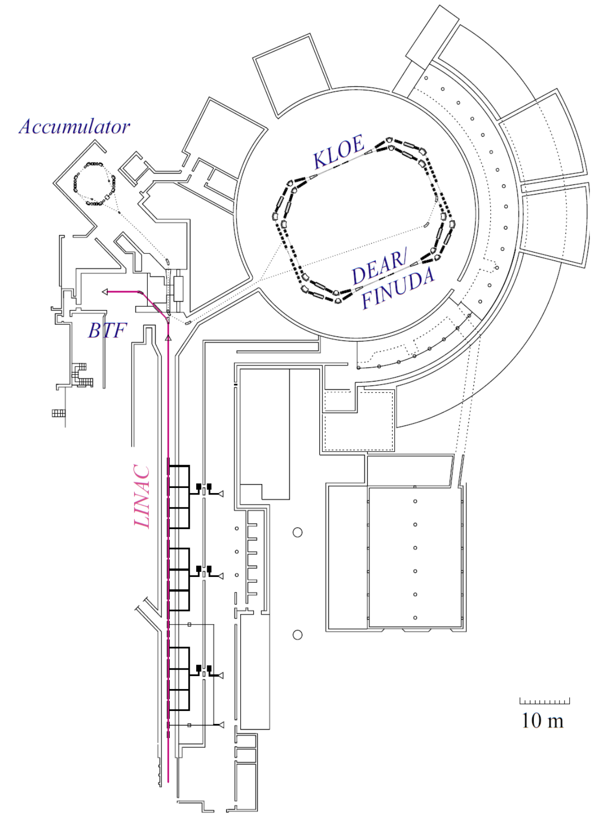
arXiv:1402.3620v2

- At present there are no experimental limit for the U→invisible decay
  - Just a never published ArXiv 0808.0017 by Babar '08 with very limited sensitivity on ε^2 ($\Upsilon_{3S}\rightarrow\gamma U$ assumes coupling to quarks!)
  - Indirect limit from $K^+\rightarrow\pi^+\nu\nu$ (assumes coupling to quarks!) arXiv:1309.5084v1
- New approach by BDX with direct detection of dark matter (arXiv:1406.3028v1)

DAΦNE Beam Test Facility (BTF)

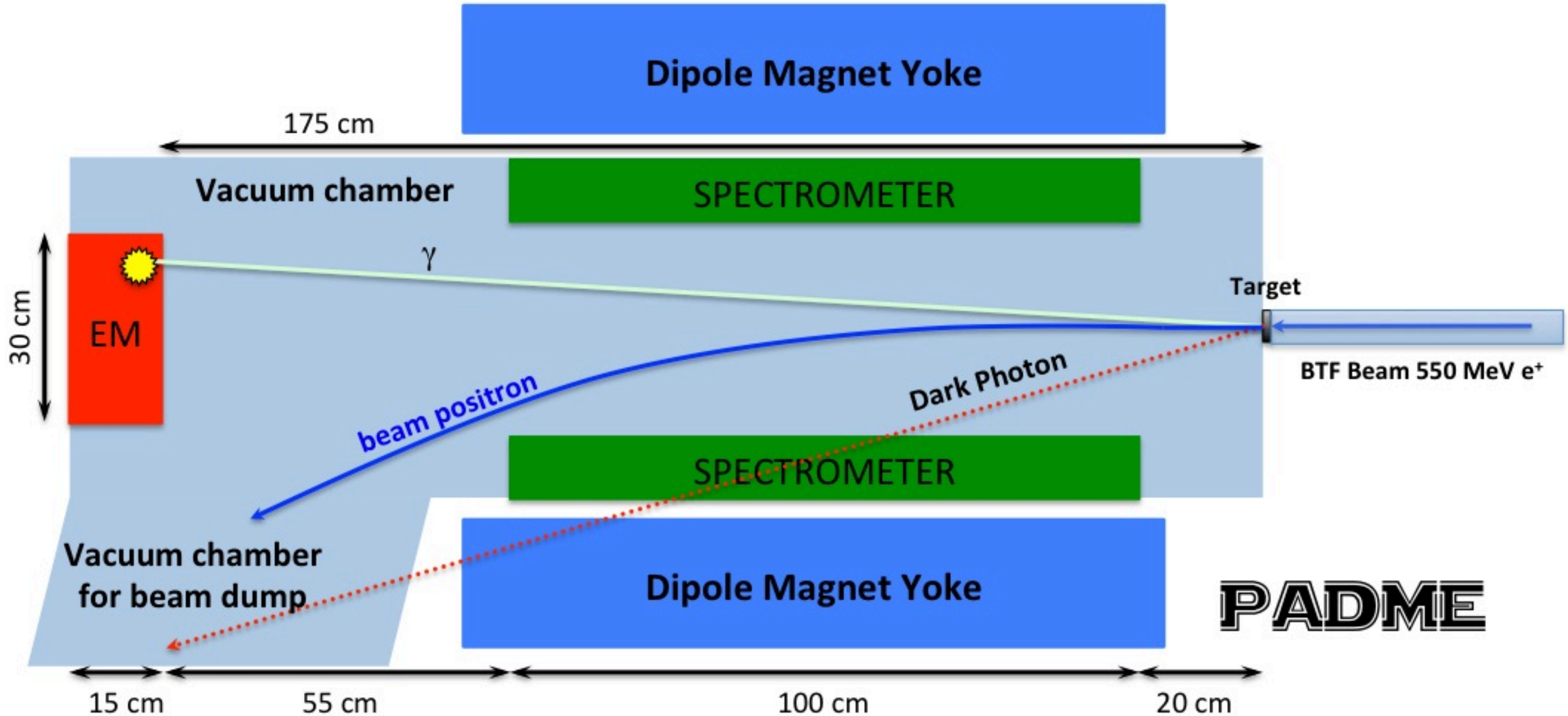
	electrons	positrons
Maximum energy [MeV]	750 MeV	550 MeV
Charge [nC]	5 nC	0.85 nC
Bunch length [ns]	1.5 - 40	
Repetition rate	25/50 Hz	25/50 Hz
Typical emittance [mm mrad]	1	1.5
Beam spot σ [mm]	2	2

NIM A 515 (2003) 524–542



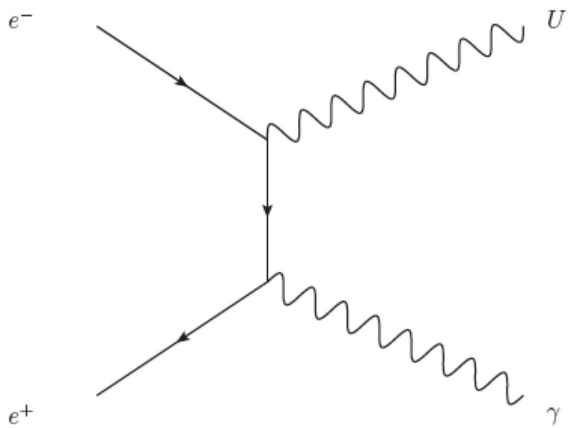
- Longer Duty Cycle
  - Standard BTF duty cycle = 50*10 ns = 5×10^{-7} s
  - Already obtained upgrade 50*40ns= 20×10^{-7} s (Thanks to BTF team)
  - Any increase of duty cycle increase linearly experiment statistics
- Possibility for single particle beam to 10^{10}
  - Packed in 50 bunch of ~10ns
- The accessible M_U region is limited by beam energy
  - Region from 0-22 MeV can be explored with 550 MeV e^+ beam

The PADME experiment proposal



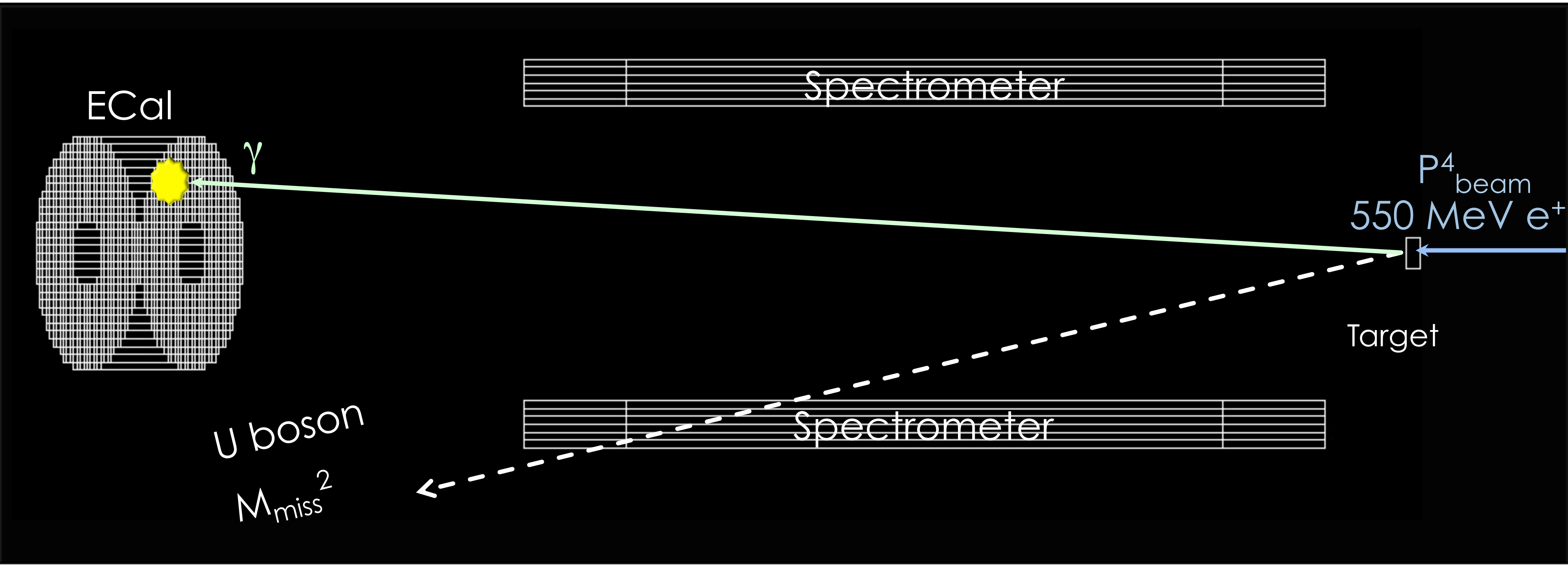
- Basic detector components
  - Active 50μm diamond target
  - 10^3-10^4 e^+ on target per bunch at 50 bunch/s (10^{13}-10^{14} e^+/year)
  - GEM based magnetic spectrometer ~1m length
  - Conventional 0.6T magnet
  - 15 cm radius cylindrical LYSO calorimeter with 1x1x15 cm^3 crystals

Search in annihilation production



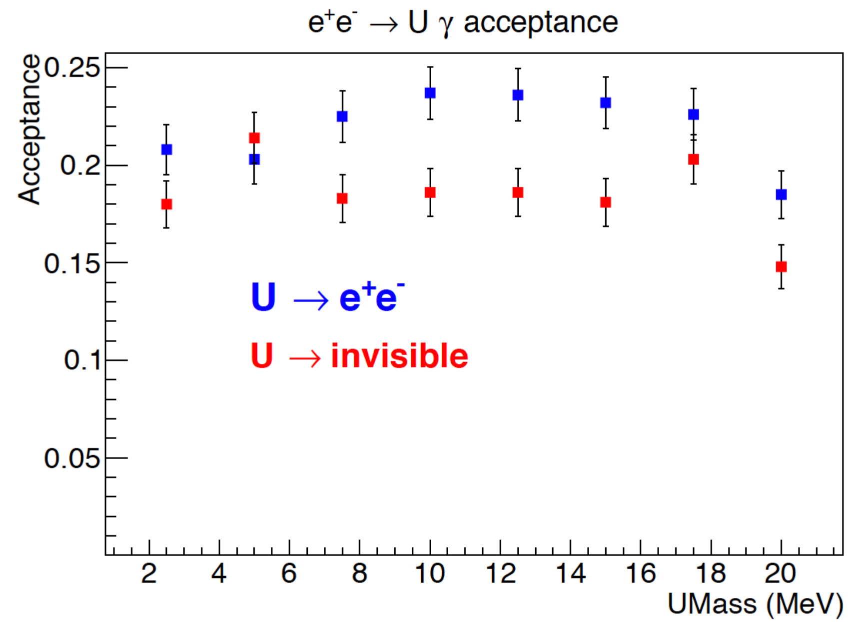
Annihilation

Experimental technique



- Search for the process: $e^+e^- \rightarrow \gamma U$ on target e^- at rest electrons
- 550 MeV positron beam on a 50 μm diamond target
- Measure in the ECal the $E\gamma$ and $\theta\gamma$ angle wrt to beam direction
- Compute the $M_{miss}^2 = (P4_{e-} + P4_{beam} - P4_{\gamma})^2$
  - $P4_{e-} = (0,0,0,m_e)$ and $P4_{beam} = (0,0,550,\mathrm{sqrt}(550^2 + m_e^2))$

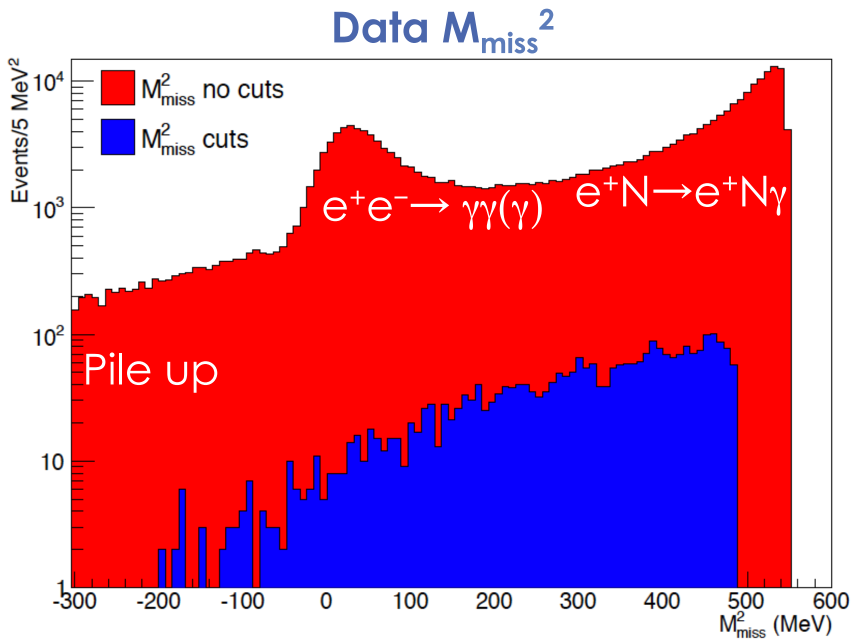
Signal selection

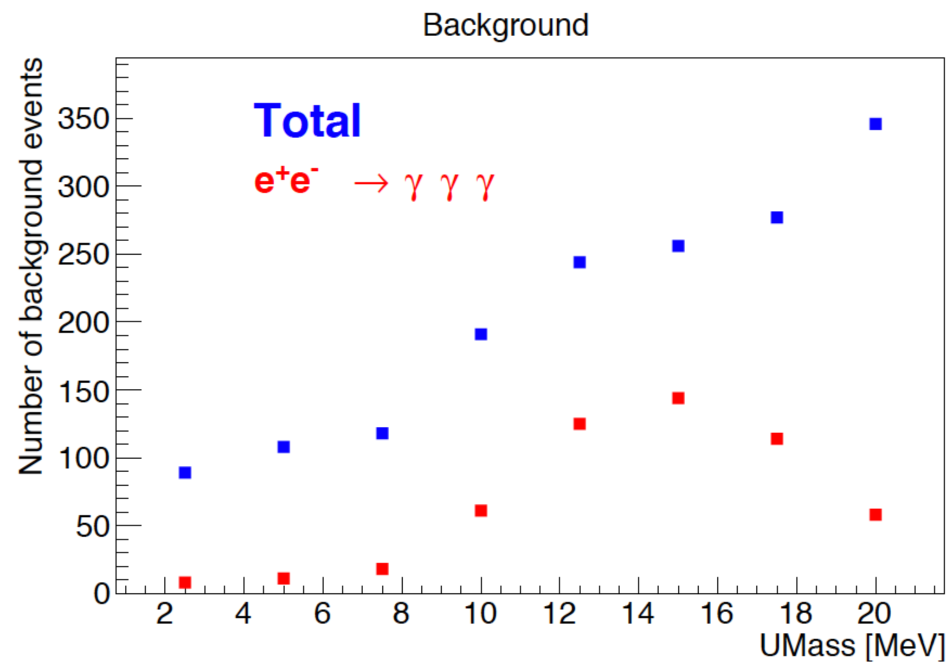


Selection cuts (all decay modes)

- Only one cluster in EM calo
  - Rejects $e^+e^- \to \gamma\gamma$ final state
- $5\ cm < R_{Cl} < 13\ cm$
  - Improve shower containment
- Cluster energy within: $E_{min}(M_U) < E_{Cl} < 400$ MeV
  - Removes low energy bremsstrahlung photons and pile up clusters
- Positron veto in the spectrometer
  - $E_{e+} < 500$ MeV then $(E_{beam} - E_{e+} - E_{cl}) > 50$ MeV
  - Reject BG from bremsstrahlung identifying primary positrons
- Missing mass in the region: $M_{miss}{}^2{}_U \pm \sigma Mmiss^2{}_U$

Background estimates



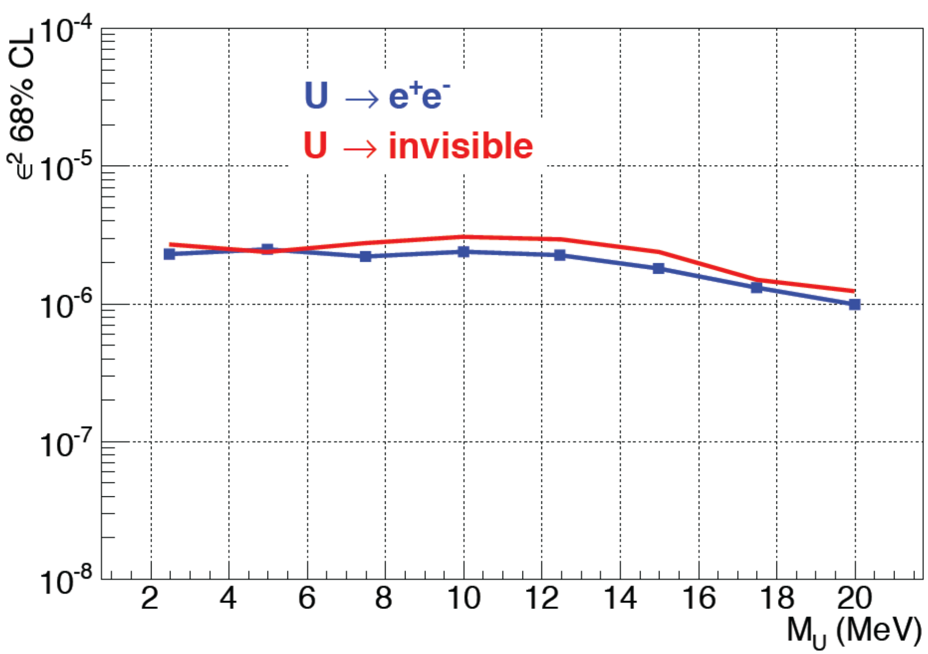


- BG sources are: $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma\gamma$, $e^+N \rightarrow e^+N\gamma$, Pile up
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{Miss}^2.
- Veto inefficiency at high missing mass ($E(e^+) \simeq E(e^+)_{beam}$)
  - New Veto detector introduced to reject residual BG
  - New sensitivity estimate ongoing

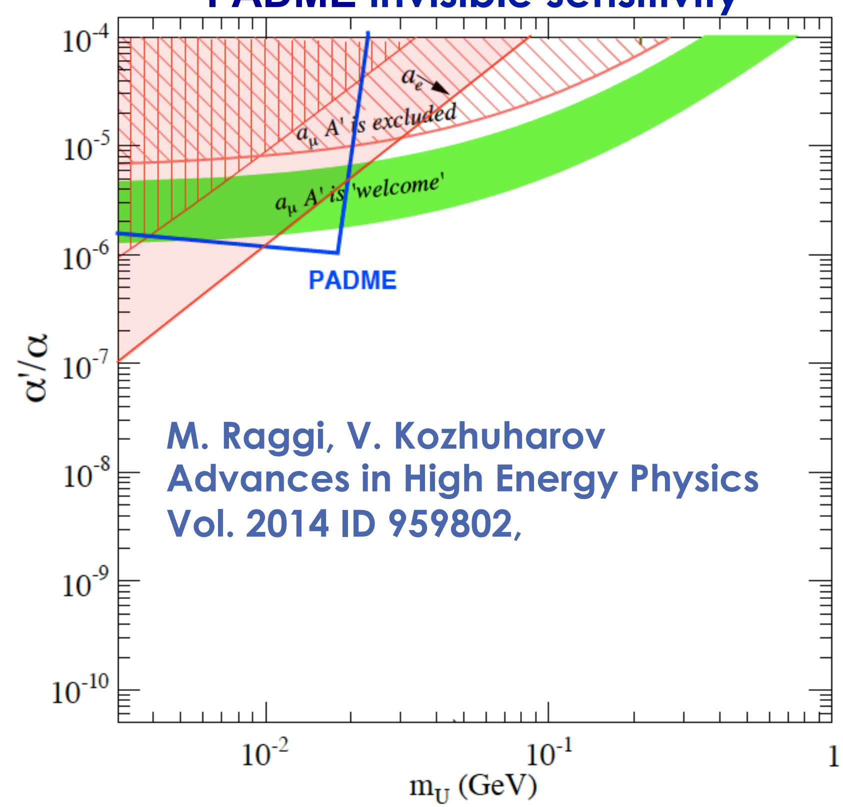
PADME sensitivity estimate

- Based on $1\text{x}10^{11}$ fully GEANT4 simulated e^+ on target events
- Number of BG events is extrapolated to $4\text{x}10^{13}$
  - Using $N(U\gamma)=\sigma(N_{BG})$
  - δ enhancement factor $\delta(M_U) = \sigma(U\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$

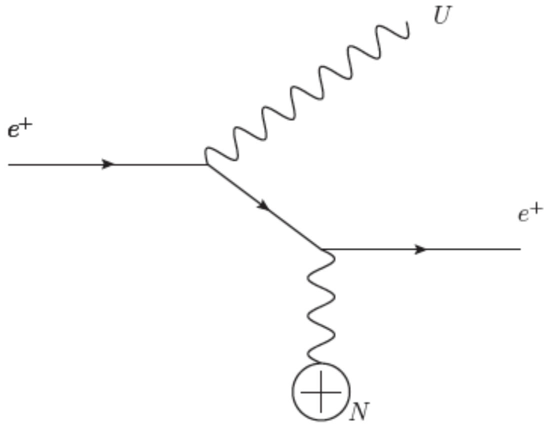
$$\frac{\Gamma(e^+e^- \to U\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta$$



PADME invisible sensitivity

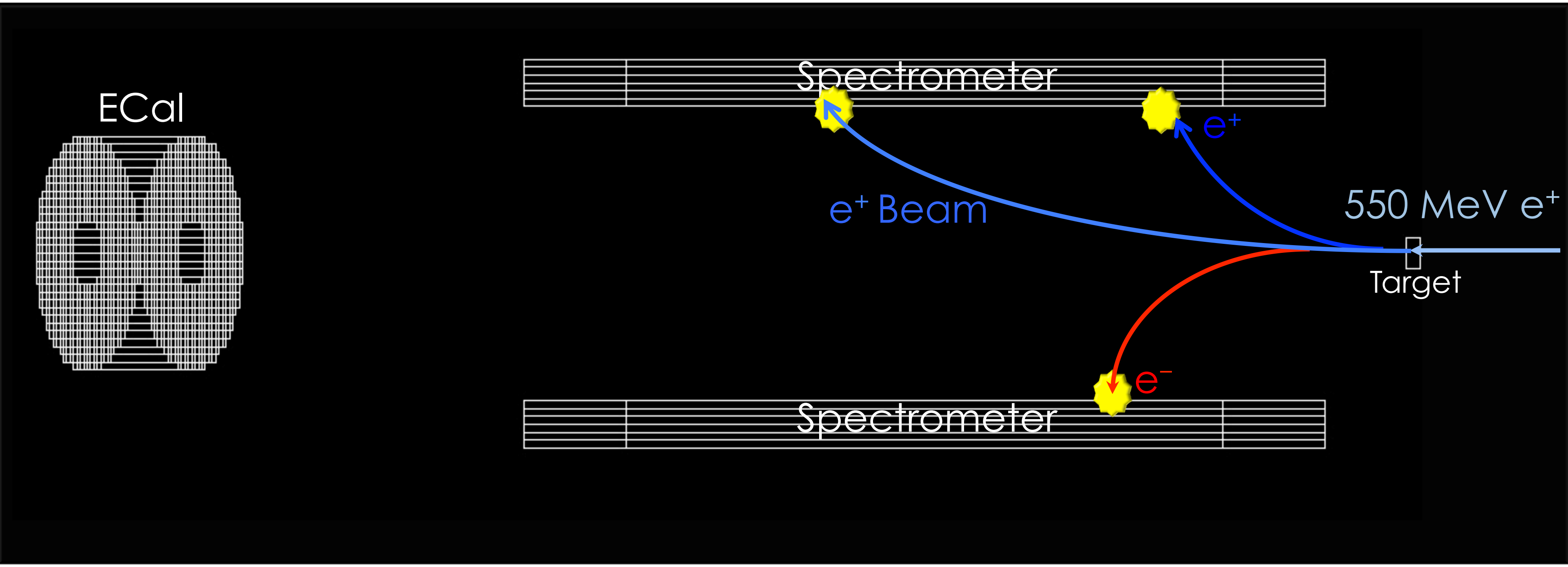


Search in bremsstrahlung production



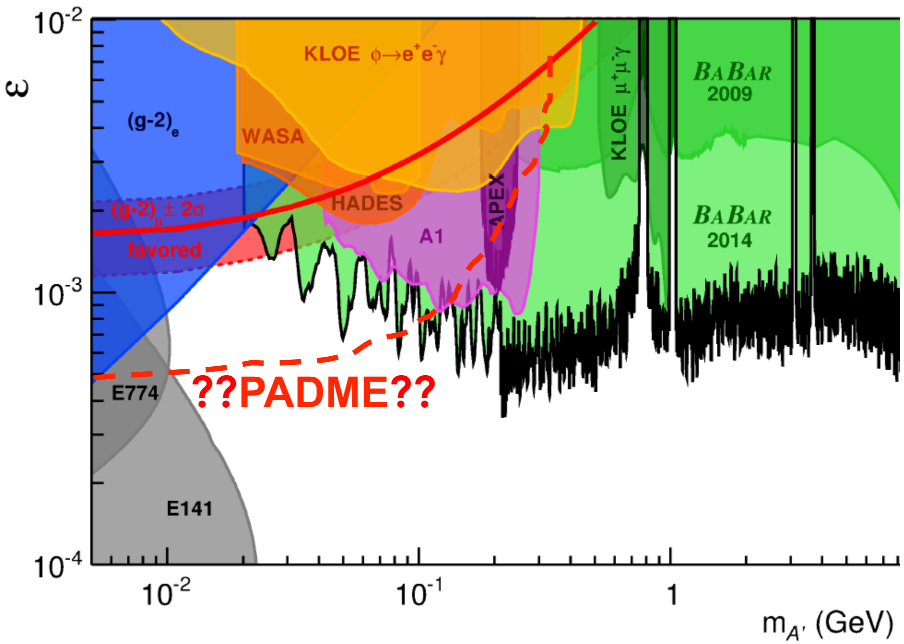
Bremsstrahlung

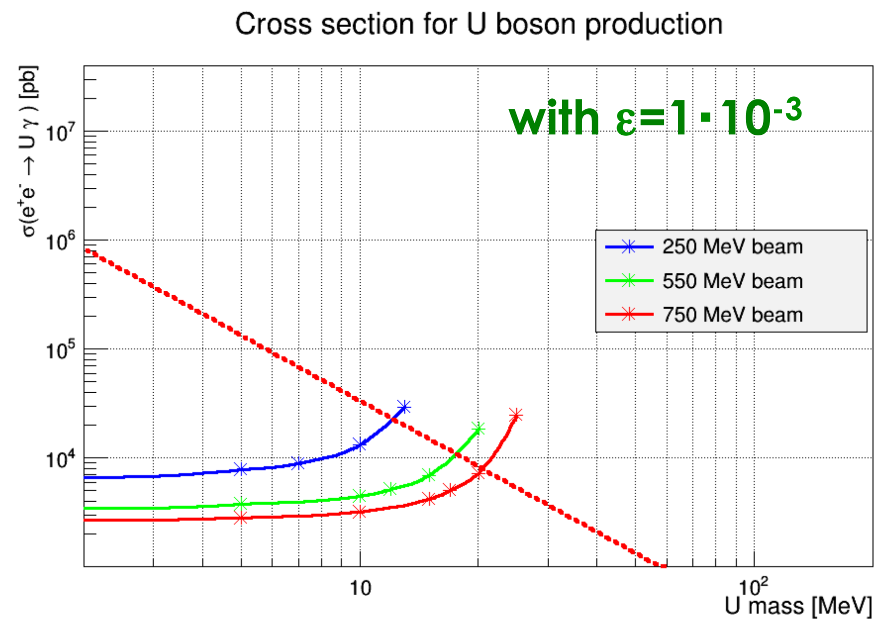
Visible analysis strategy



- Search for the process: **$e^+N \rightarrow Ne^+U \rightarrow Ne^+e^+e^-$**
- 550 MeV positron beam on a 50 μm diamond target
- Measure in the spectrometer only the P^4_{e-} P^4_{e+}
- Compute the $M_U^2 = (P^4_{e-} + P^4_{e+})^2$

Indication on visible decay sensitivity



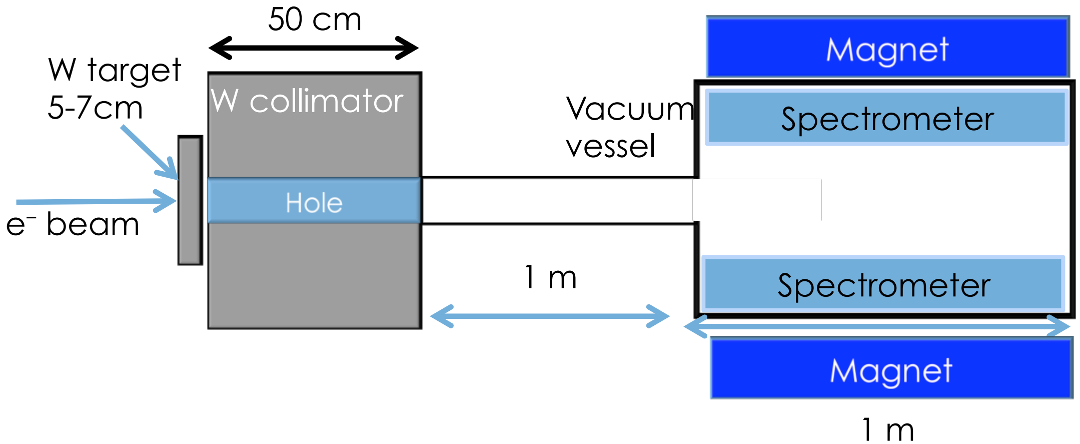


- Ratio of bremsstrahlung wrt to annihilation at 1MeV ~ 400
- Scaling low of the U-strahlung is $1/M_U^2$
- Final state is more constrained by invariant mass of the e^+e^- pair
- Naively a limit down to $\sim\varepsilon<4\text{x}10^{-4}$ is expected at low masses
  - Only an indication no real simulation so far!

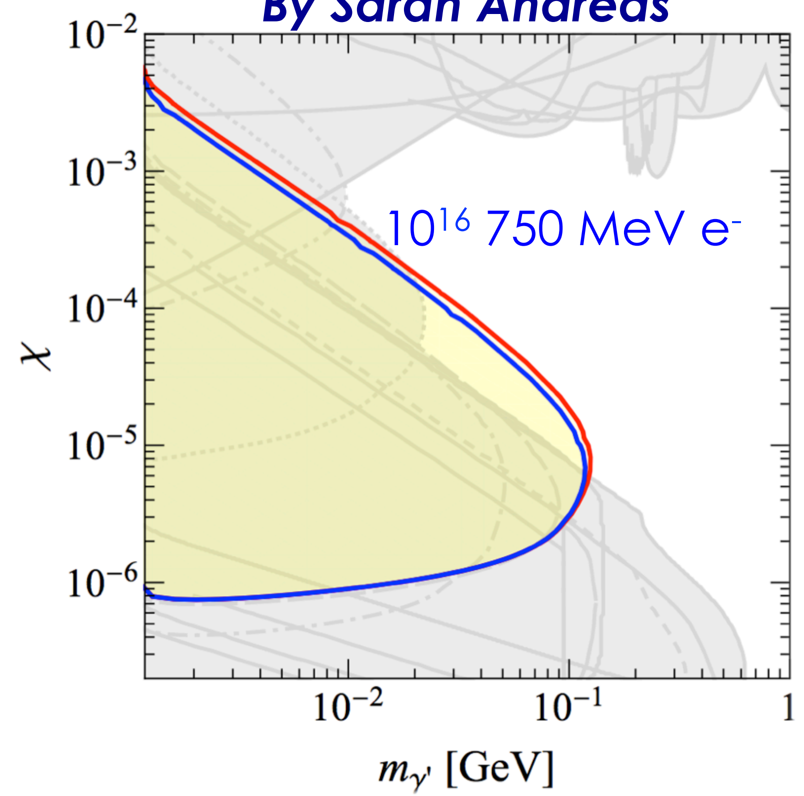
PADME dump experiment

- Uses the same detector
  - Change the target with 5-7.5 cm W one
  - Build a W collimator

PADME dump schematic



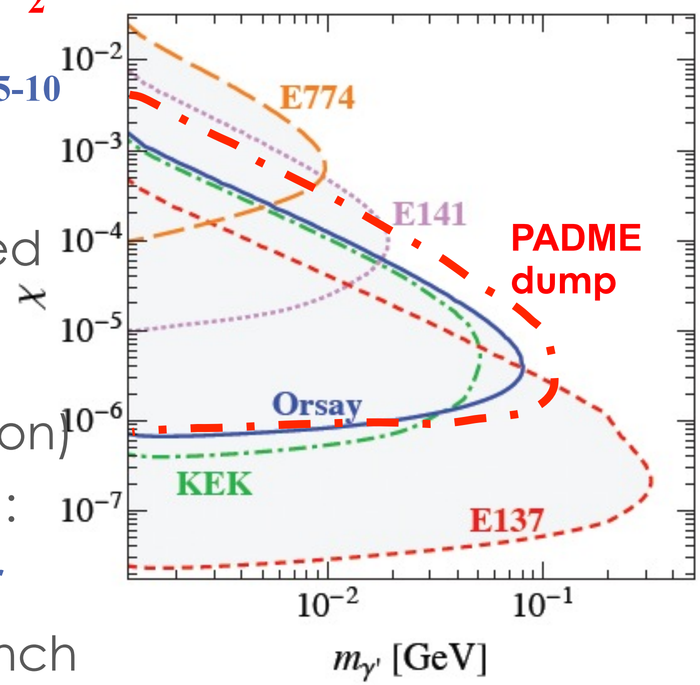
By Sarah Andreas



- Early study for a beam dump experiment @ LNF (Sarah Andreas)
  - 1E7 electrons of energy 750 MeV per bunch in 50 bunch/s over 1 year
  - Total e⁻ on target being: $50 \times 1\times10^{7} \times 3.15\times10^{7} = 1.6\times10^{16}$ (we use 1×10^{16})
  - Study based on 0 events observed after the dump. (not easy to achieve)
  - Much better sensitivity can be achieved using a total 10^{20} e⁻ on target
    - Further improvement by using longer decay region

Electron dumps experiments

Experiment	target	E_0 [GeV]	N_{el} electrons	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
PADME dump	**W**	**0.8**	**$1\cdot10^{16}$**	**~1.6mC**	**0.1**	**2**		
PADME dump+	**W**	**1.2**	**$2\cdot10^{20}$**	**~30 C**	**0.1-2**	**5-10**		



- Due to authorization of LNF site we cannot exceed
  - Total limit on Year at BTF = **9.8×10^{17} e⁻/Year**
- PADME dump+ (E upgrade, improved authorization)
  - BTF maximum current 1.2×10^{11} e-/bunch (40ns):
  - e⁻/Year=$1.2\times10^{11}\times50\times3.15\times10^{7}$=**$1.9\times10^{20}$ e⁻/Year**
  - We can get **4.5×10^{17}** in **3 days** at 3×10^{10} e⁻/bunch

Project status

- Project has been presented as a What Next Project in INFN CSN1
  - The project has received referees and its under study
  - Proposal for R&D financing will be discussed in the next CSN1 meeting
- Proto collaboration formed including
  - LNF, Rome1, Lecce and Sofia university
- Interesting synergy with BDX project identified (BDX at LNF?)
- 2 weeks test beam time planned in December at DAΦNE LINAC
  - Asses the maximum beam current per bunch and beam spot
- Many item still to be covered! Search for more collaborators started

Conclusions

- An experiment running at DAΦNE LINAC sensitive to both $U \rightarrow$invisible and $U \rightarrow e^+e^-$ decays is proposed

- Sensitivity study for U boson produced into annihilation process $e^+e^- \rightarrow \gamma U$ was presented
  - The detection through missing mass is independent of the U decay mode and never performed so far

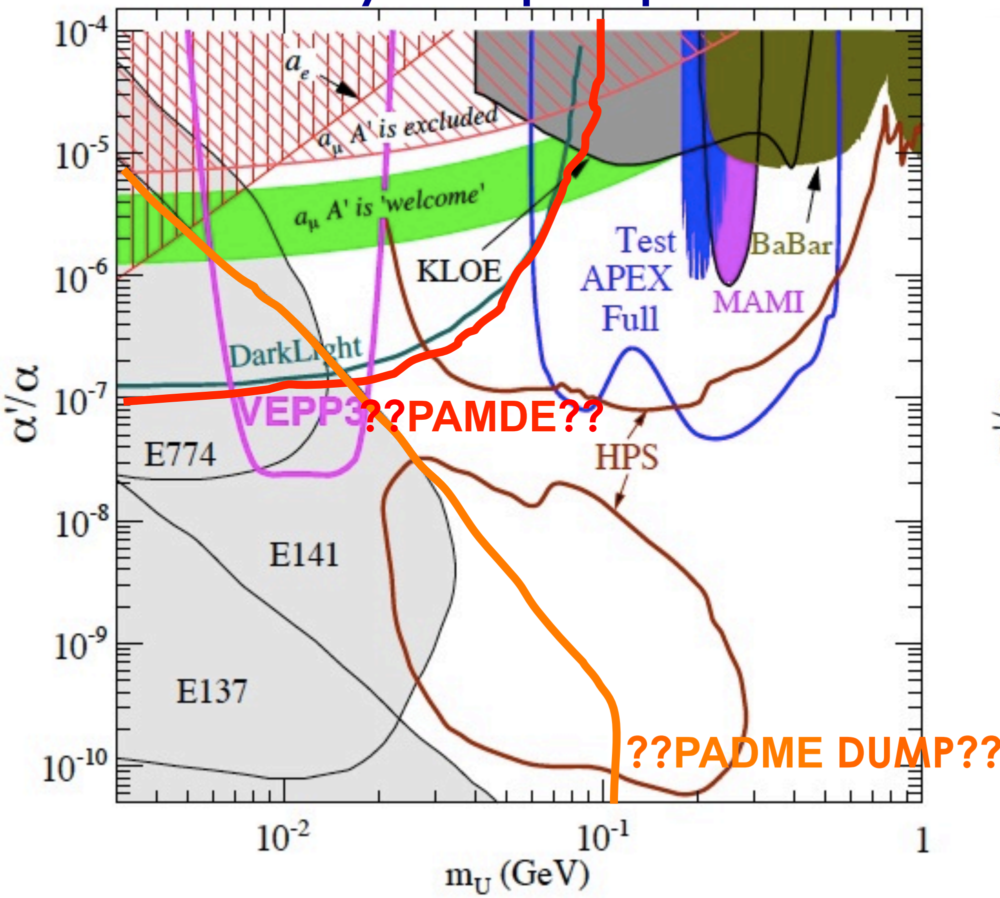
- Exclusion limit in ε^2 down to $1\text{-}2 \cdot 10^{-6}$ can be achieved in invisible decays with the present BTF beam parameters in the region M_U 2-20 MeV
  - **M. Raggi and V. Kozhuharov,
    Advances in High Energy Physics Vol. 2014 ID 959802, 14 pages**

- Possible accessible regions for a bremsstrahlung produced $U \rightarrow e^+e^-$ were identified to reach 100MeV
  - Detailed study of the sensitivity in this channel is planned
  - Need theoretical guidance to implement a bremsstrahlung generator in the PADME GEANT MC

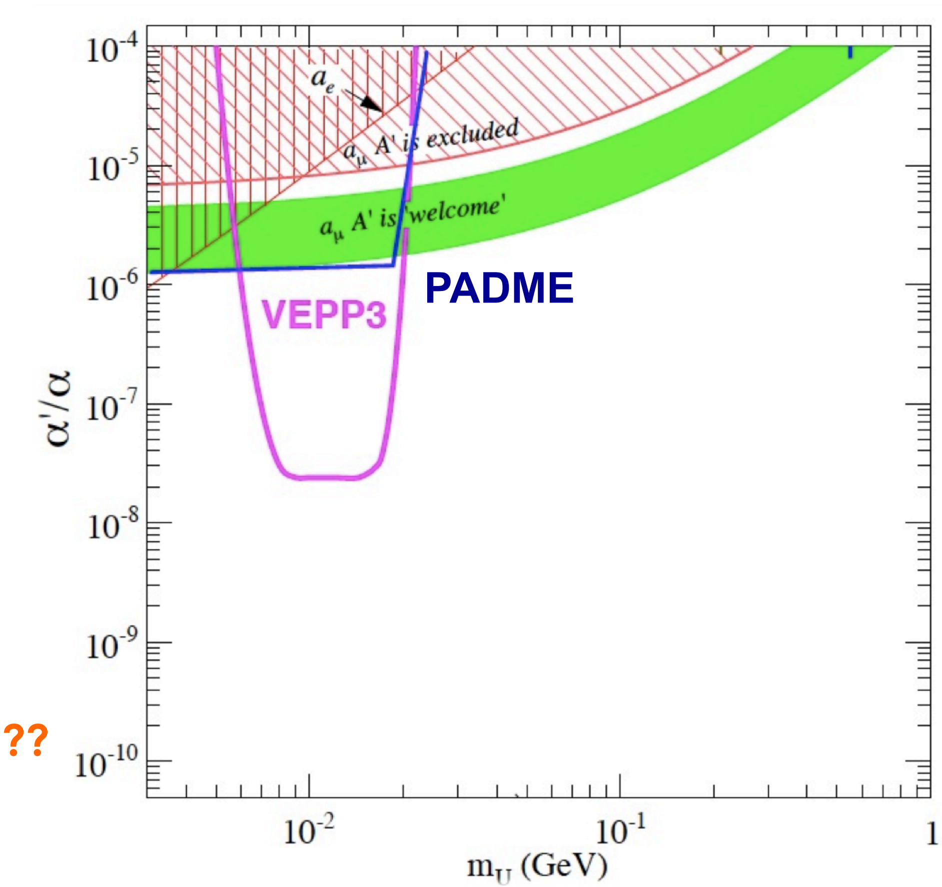
SPARE SLIDES

Competitors

Decays to lepton pairs



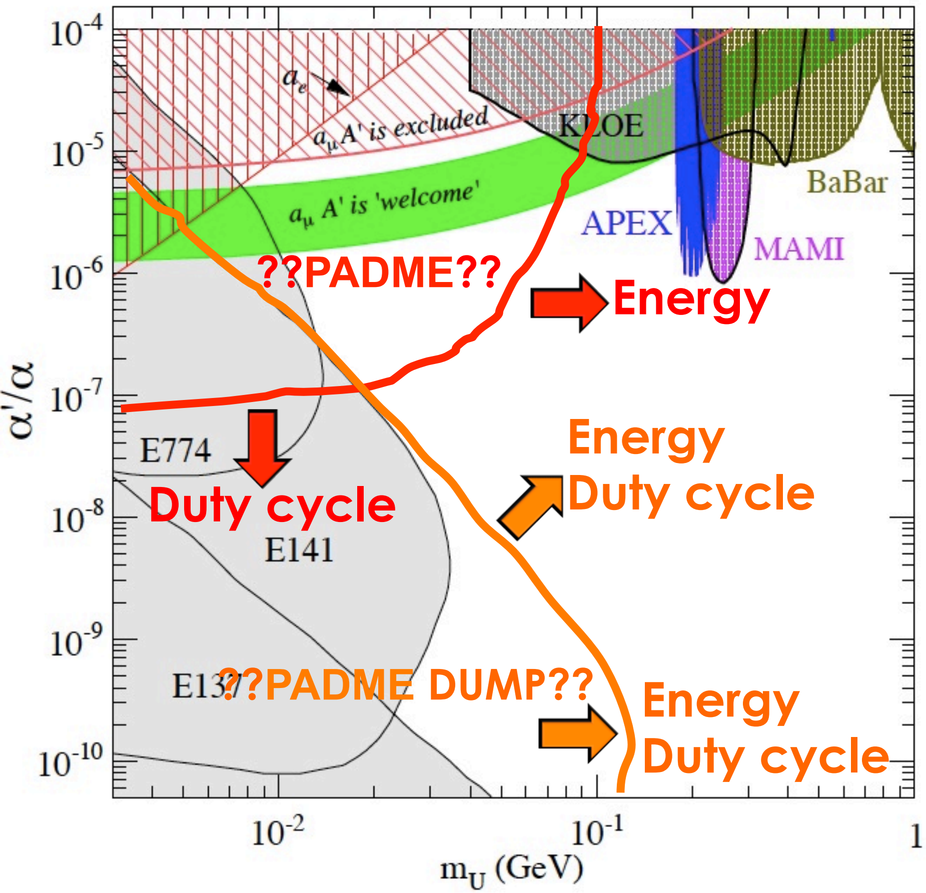
Decays to invisible



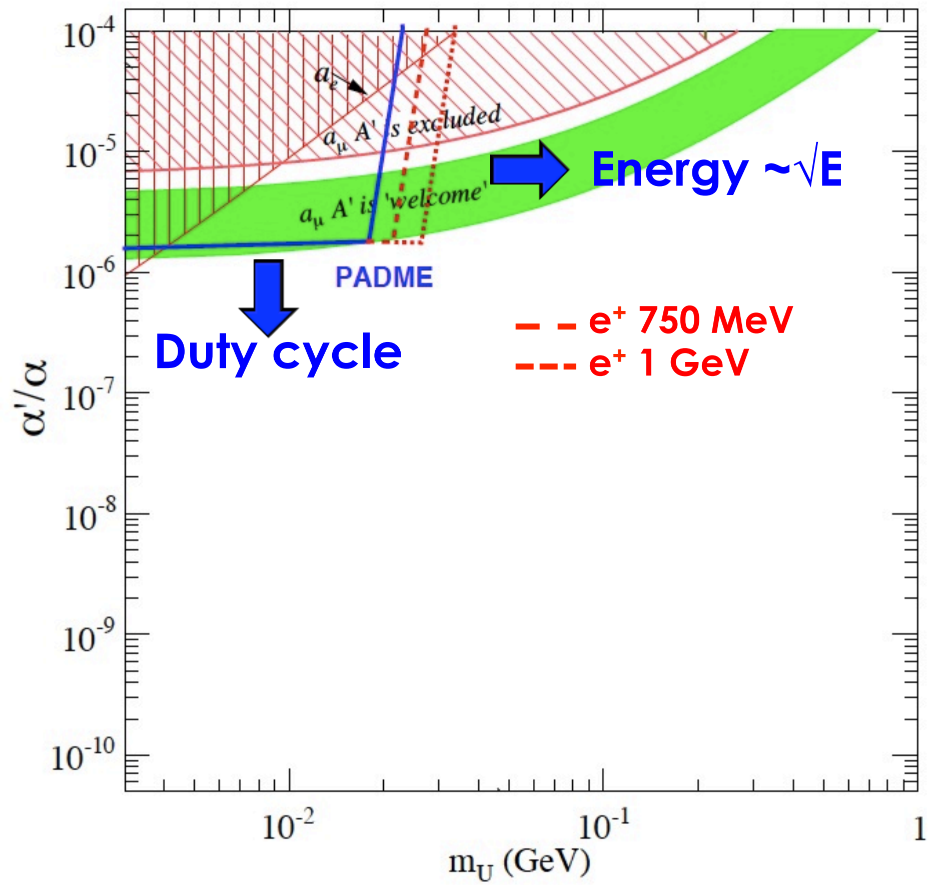
- Expected results for PADME are shown for annihilation production only
  - Accessible regions in the decays to lepton pairs are shown
- Many competitors in e^+e^- decay scenario, APEX, HPS, MAMI A1
- Only VEPP3 proposal in the invisible searches (exclusion is a naïve estimate)

Improvement in case of BTF upgrades

Decays to lepton pairs



Decays to invisible



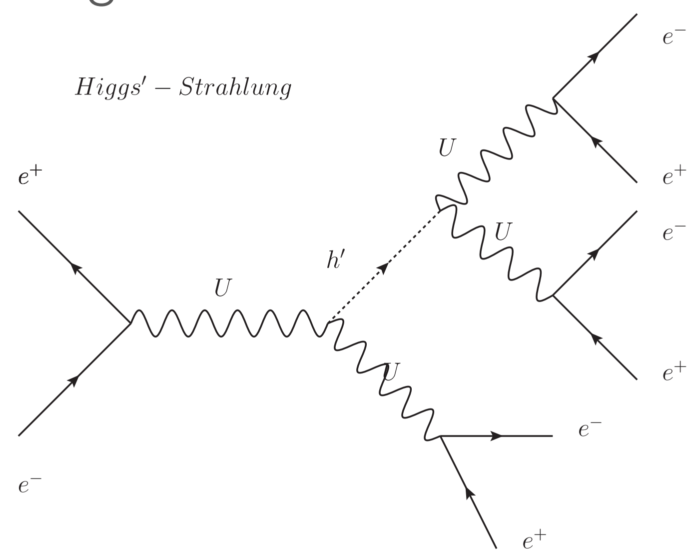
- The PADME experiments can profit of any upgrade of the BTF beam
  - Energy gives access to higher masses both in visible and invisible decays
  - Duty cycle gives access to lower ε^2
  - In case of Bremsstrahlung production duty cycle helps also in the mass ranges

Dark sector with dark Higgs

- Model assumes the existence of an elementary dark Higgs h' boson, which spontaneously breaks the U(1) symmetry.
  PRD 79, 115008 (2009)

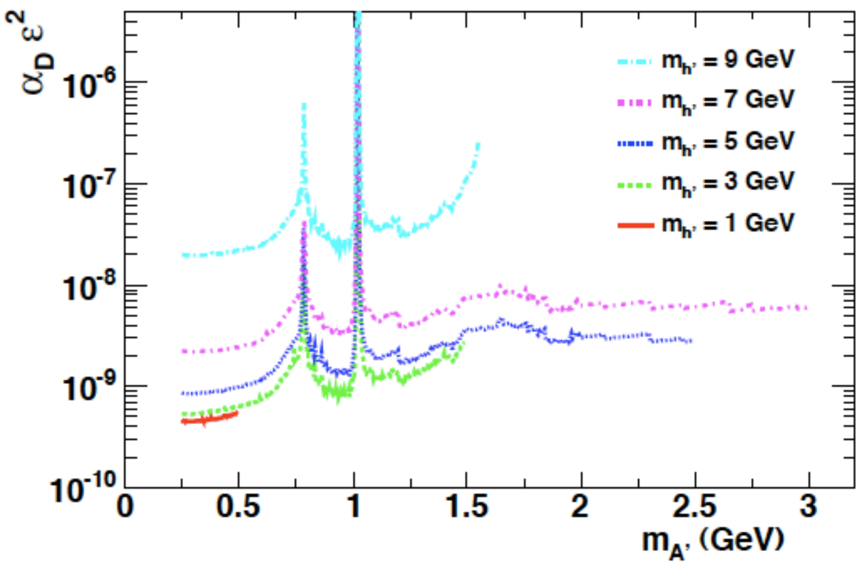
- U boson can be produced together with a dark Higgs h' through a Higgs-strahlung $e^+e^- \rightarrow Uh'$
  - Cross section =20fb x $(\alpha/\alpha_D)(\varepsilon^2/10^{-4})(10\text{GeV})^2/s$
  - For light h' and U ($M_{U,h'}<2M\mu$) final state with 3(e+e- pair) are predicted
  - Background events with 6 leptons are very rare at this low energies
  - Due to U,h'being very narrow resonances strong kinematical constraints are available on lepton pair masses

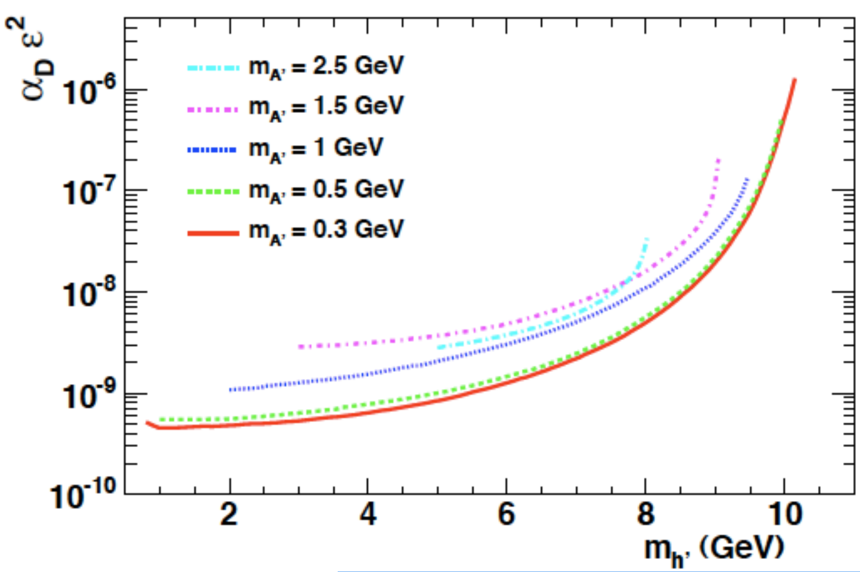
- Experimental search by BaBar and KLOE for U masses above 200 MeV

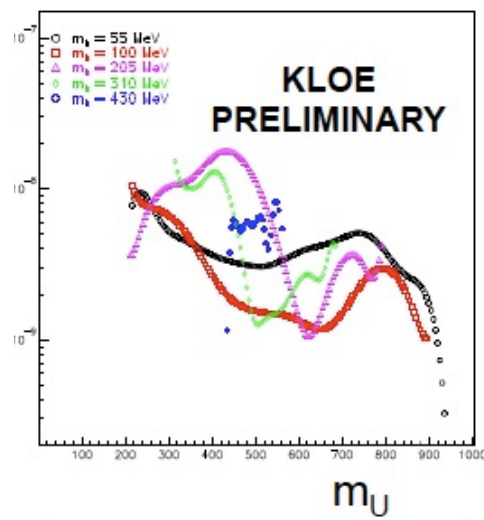


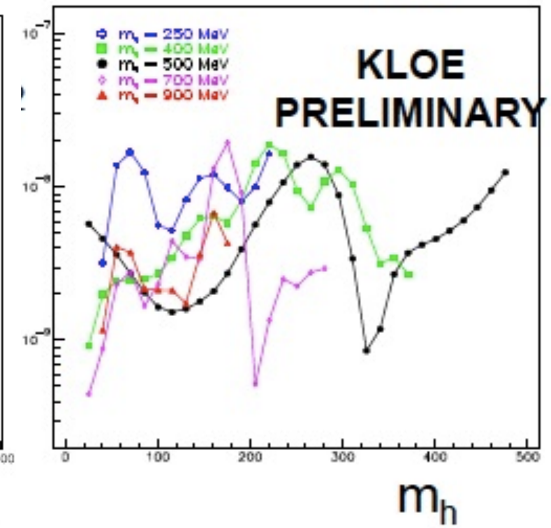
Experimental status U(1) + dark higgs

BaBar Phys. Rev. Lett. 108, 211801 (2012)





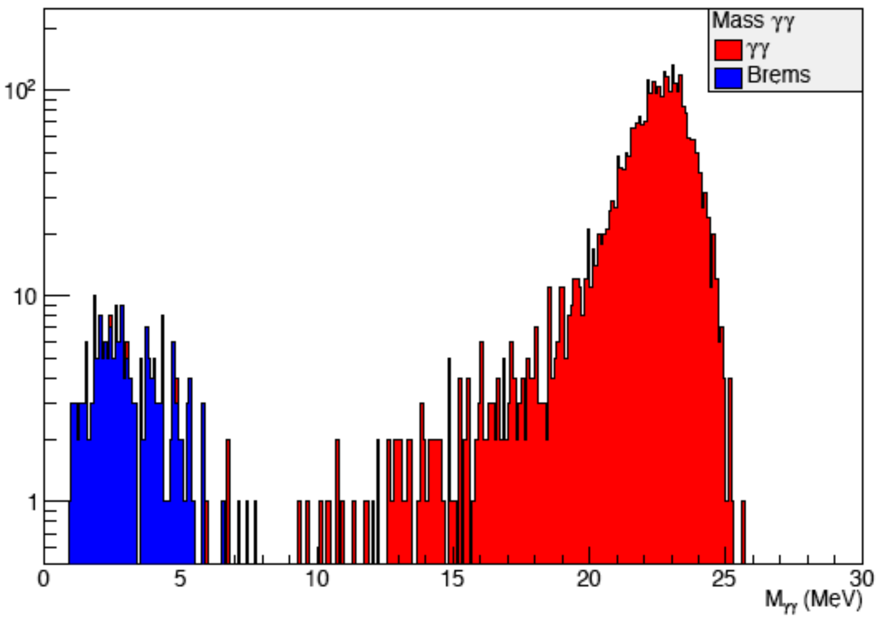




- Production mechanism being bremsstrahlung allows PADME to reach >100MeV U masses
- No data available below 200 MeV in M_U
- PADME can provide sensitivity in unexplored parameter region.

The γγ normalization selection

$$N_{\gamma\gamma}^{tot} = \frac{N_{\gamma\gamma}}{Acc_{\gamma\gamma}} = Flux(e^+) \cdot \sigma_{\gamma\gamma}$$



- Number of calorimeter clusters = 2
- Cluster energy: 100MeV<E_{Cl}<400 MeV
- Cluster radial position 5 cm <R_{Cl}< 13 cm
- γγ invariant mass 20 MeV < $M_{\gamma\gamma}$ < 26 MeV

$$M_{\gamma\gamma} = \frac{\sqrt{[(X_{\gamma 1} - X_{\gamma 2}) + (Y_{\gamma 1} - Y_{\gamma 2})] E_{\gamma 2} E_{\gamma 2}}}{Z_{EMcal} - Z_{Target}}$$

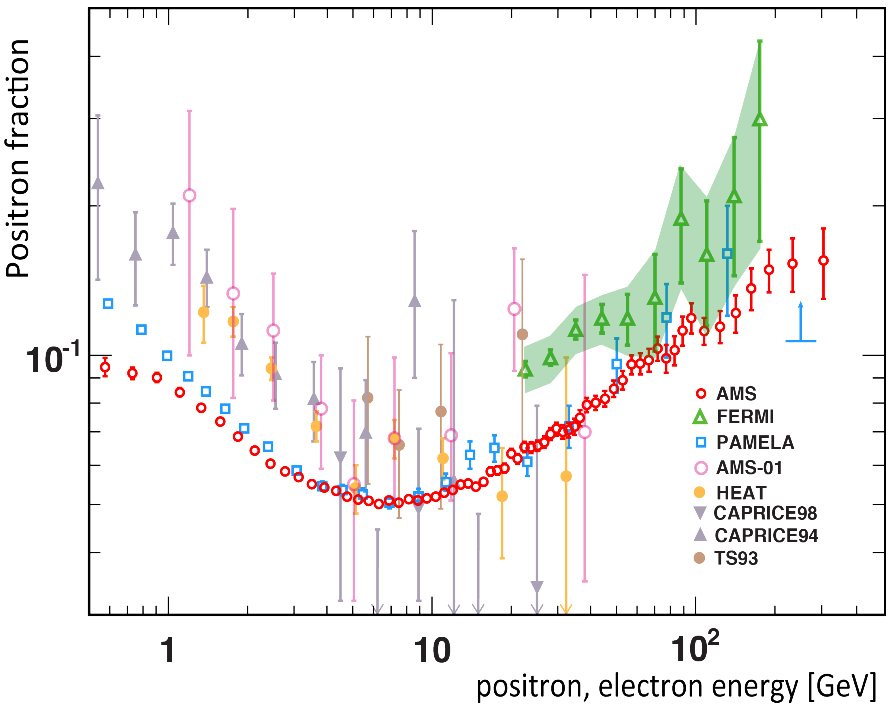
- $Acc_{\gamma\gamma}$ = 7%
- Contamination from bremsstrahlung < 1‰

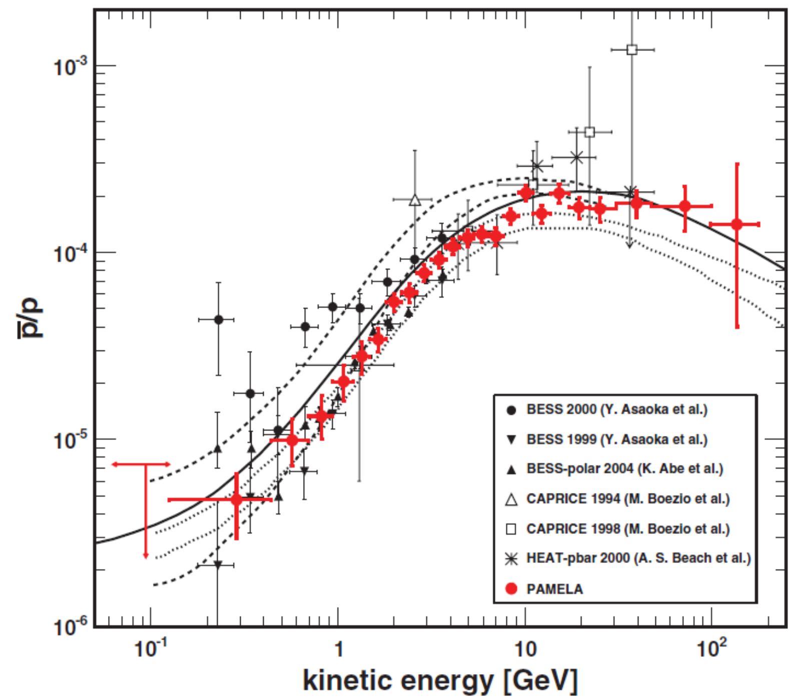
Possible BTF upgrades

- Energy upgrades up to 1.2 GeV electrons
  - Proposal to reach >800 MeV energy for positrons (see V. Buonomo BTF user workshop)
- Longer Duty Cycle
  - Standard BTF duty cycle = 50*10 ns = 5×10^{-7} s
  - Already obtained upgrade 50*40ns= 20×10^{-7} s (Thanks to BTF team)
  - Any increase of duty cycle increase linearly experiment statistics
- Collimation system
  - Assure better beam definition for positrons beam
- Maximum current in BTF hall
  - Limited by radio protection to 6.2×10^{8} per bunch for long term operation
  - Can reach $>3\times10^{10}$ particle per bunch after proper screening

See recent BTF user workshop for details at:
https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=7359

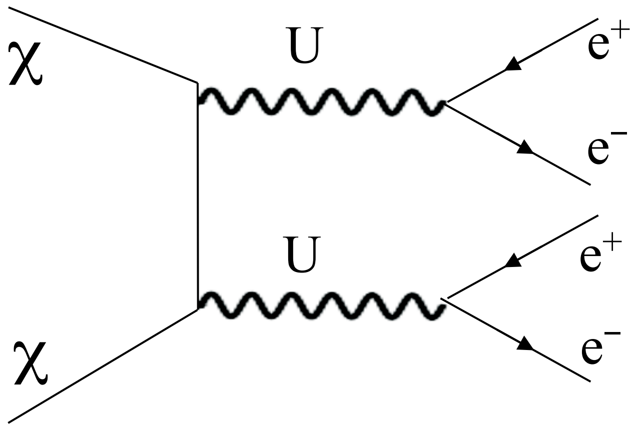
Particle astrophysics PAMELA AMS

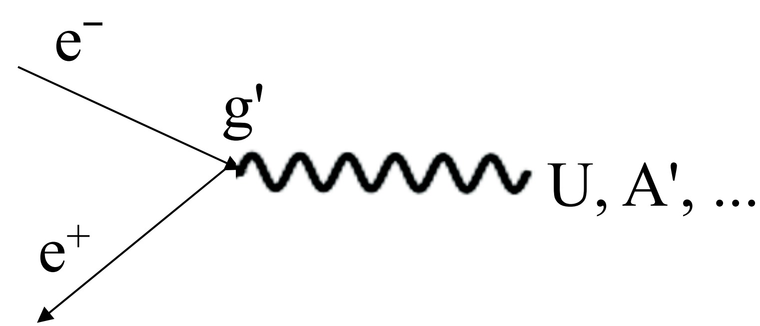




- Positron excess: PAMELA, FERMI, AMS02
- No significant excess in antiprotons
  - Consistent with pure secondary production
- Leptofilic dark matter annihilation?

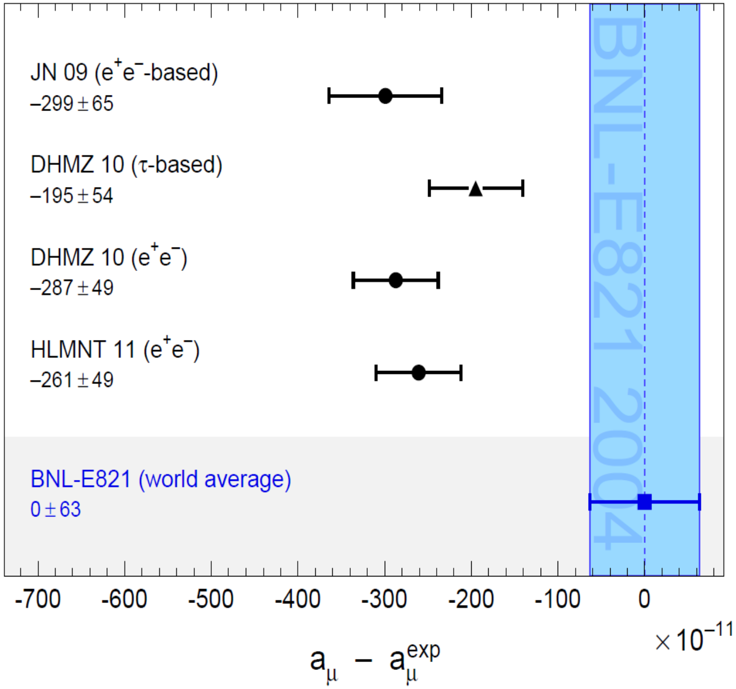
Hints for dark matter annihilation?

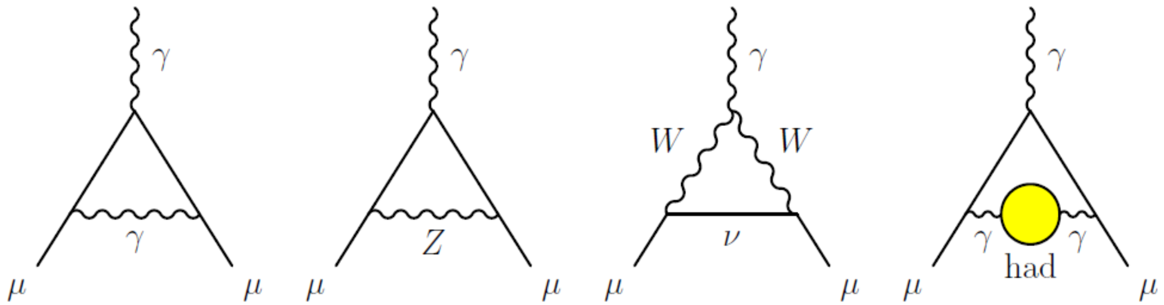




- If Dark Matter is the explanation to the positron excess, then the mediator should be light (< 2*M_{proton})
- Coupling constant to DM could be arbitrary (even O(1))
- The Lagrangian term can arise through
  - Fermions being charged (mili) under this new gauge symmetry ($q_f \to 0$ for some flavors)
  - Kinetic mixing between ordinary photon and DM one
  - Using simply an effective descriptio $\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$

Muon g-2 SM discrepancy





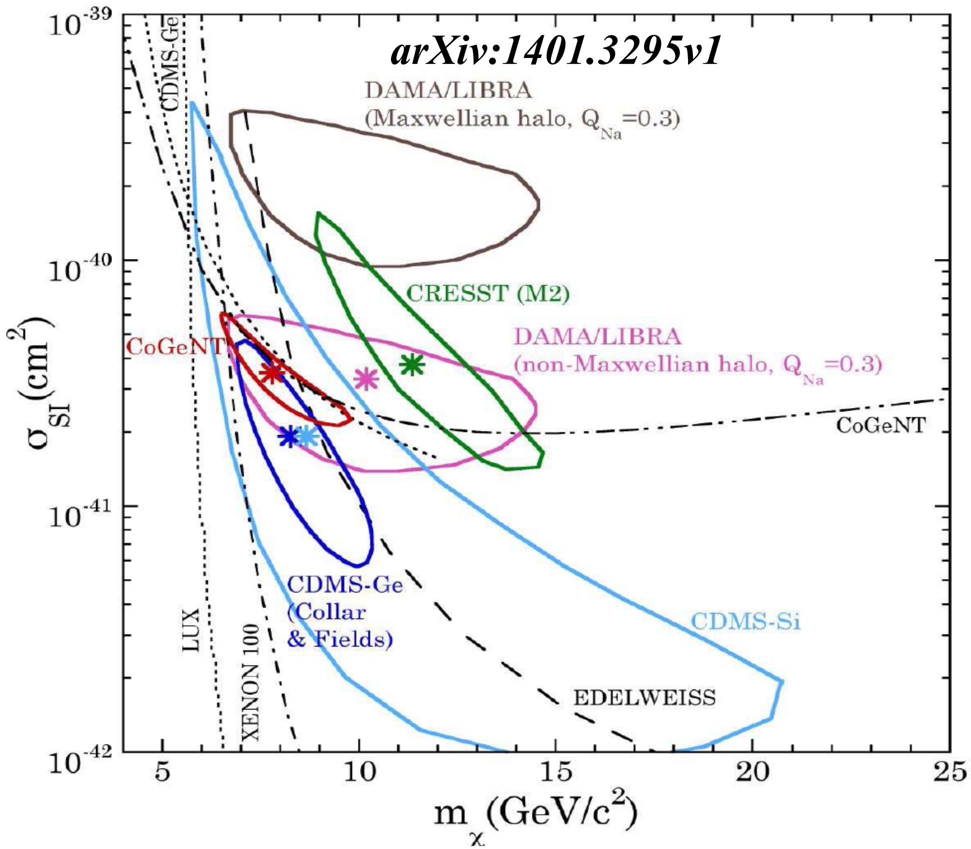
- About 3σ discrepancy between theory and experiment (3.6σ, if taking into account only $e^+e^-\to$hadrons)

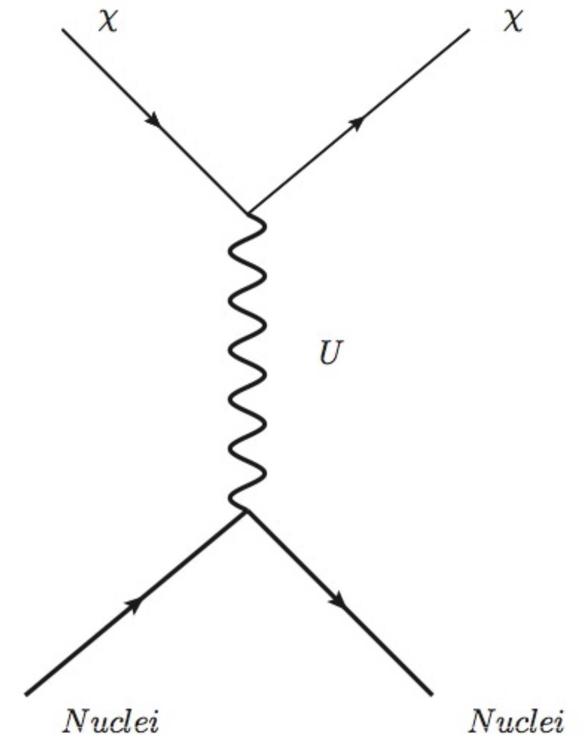
Contribution to g-2 from dark photon

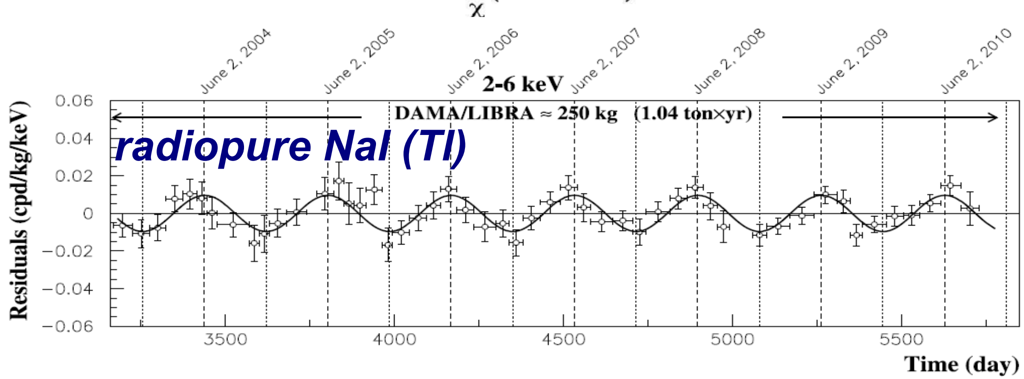
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

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

The DAMA-Libra effect





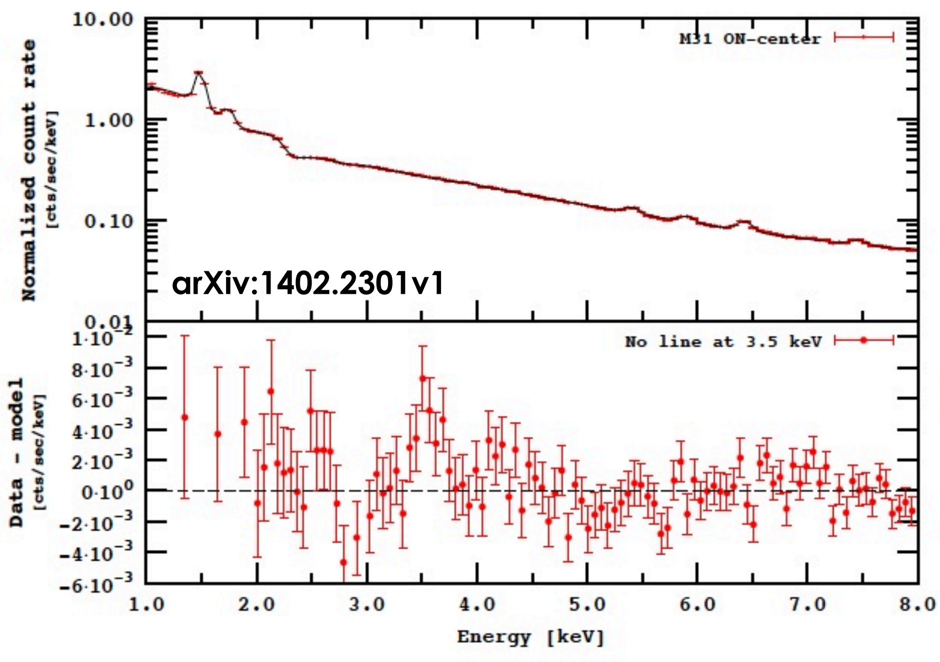


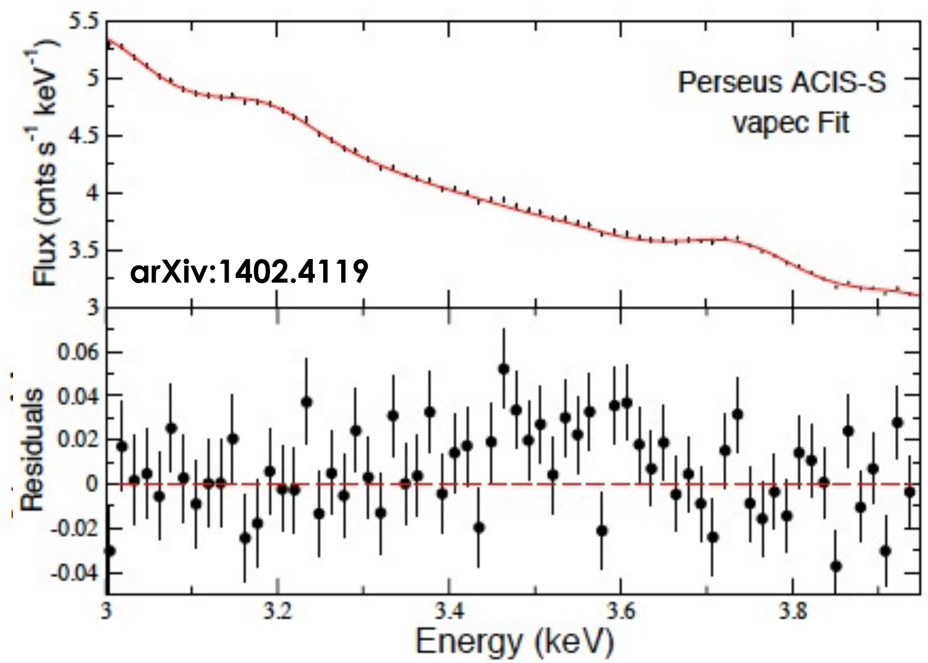
- Nuclear recoil by the exchange of a dark photon
- Independent of χ mass value

Observation of 3.5KeV X-ray line

- Recently a 3.55 KeV X-ray line (~3σ) has been reported in the stacks analysis of 73 galaxy clusters from the XMM-Newton telescope **arXiv:1402.2301v1**

- A similar analysis finds an evidence at the 4.4σ level for a 3.52 KeV line from the analysis of the X-ray spectrum of the Andromeda galaxy (M31) and the Perseus Cluster **arXiv:1402.4119**



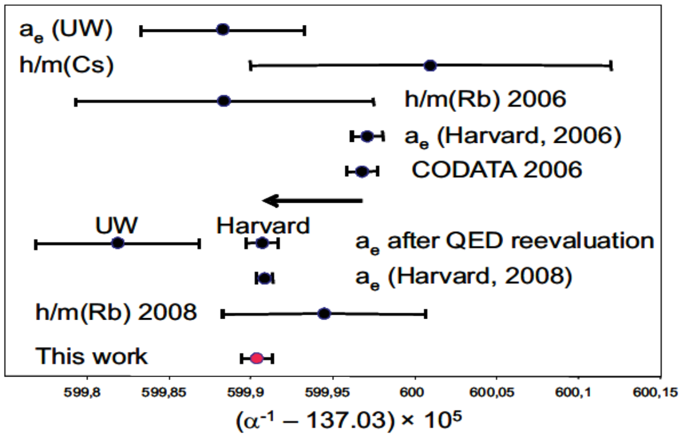


U(1) symmetry explanation

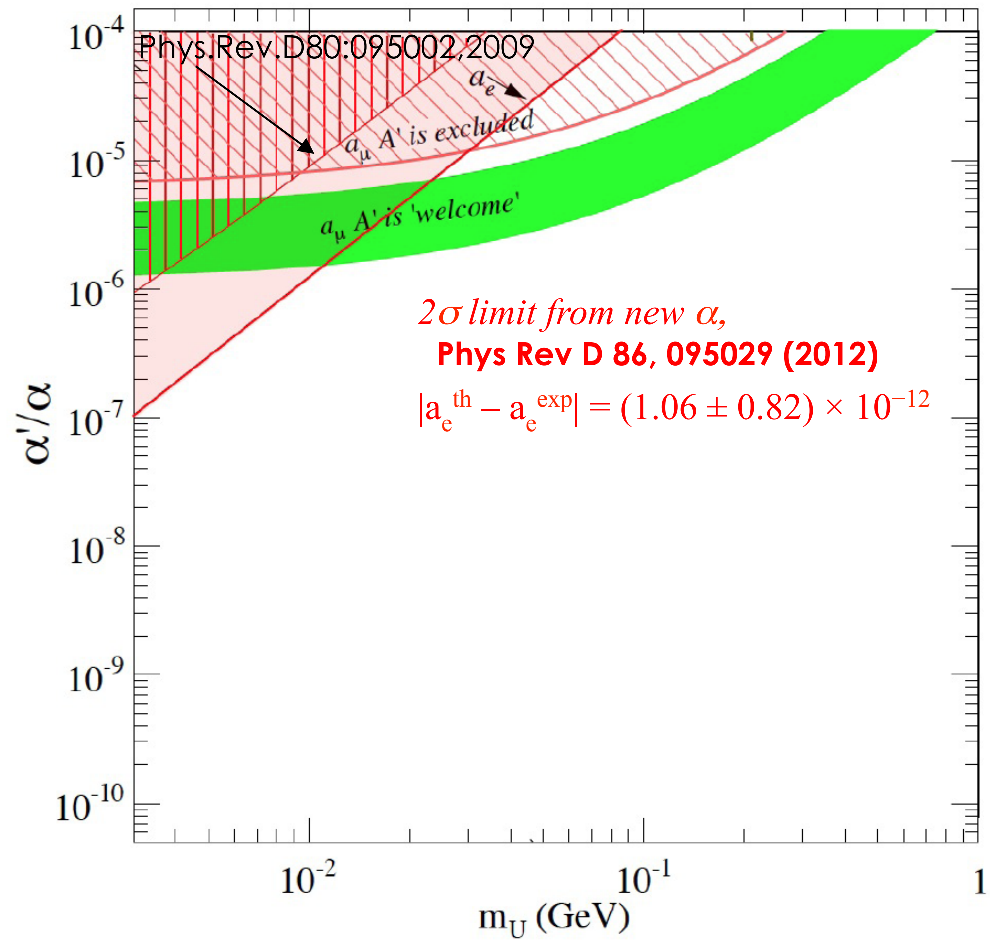
- Many models have been developed to explain such a line based on sterile neutrinos
- A possible explanation of such a line in term of the U(1) gauge theory with an Higgs mechanism is proposed in **arXiv:1404.2220v1**
  - A single new scalar dark matter field ϕ of mass 7.1 KeV is introduced
  - ϕ couples to SM Higgs through U boson
  - Due to the very small mass ϕ can only decay into $\gamma\gamma$ or $\nu\nu$ creating the Xray line at 3.5 KeV
  - After spontaneous symmetry breaking of the U(1) symmetry the U boson becomes massive
  - Due to constraints coming from the relic abundance a mass interval has been identified by authors for the U boson mass
    - $7 KeV < M_U < 10 MeV$

Indirect limits

Phys.Rev.Lett.106:080801,2011



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



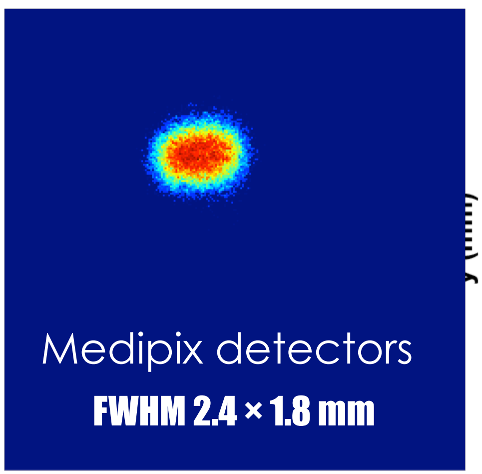
However this is based on a single measurement with drastically improved precision

Experimental status

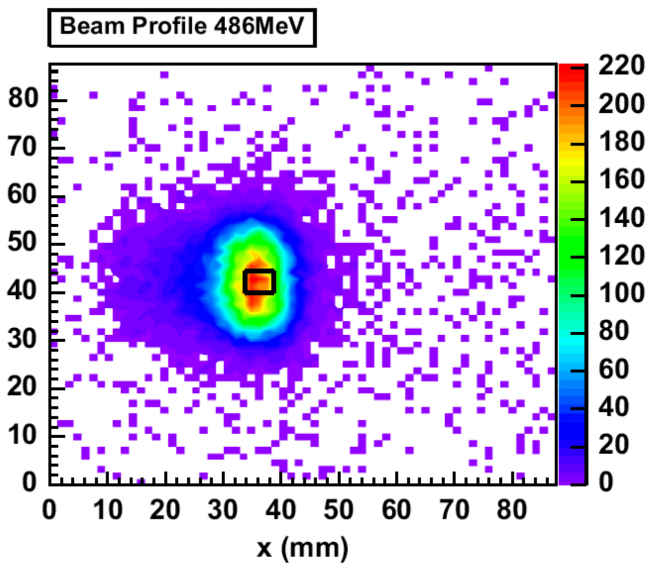
Experiment	Extra assumptions	Results	Technique	Status
KLOE2	$Q_q \neq 0$ & $U \to e^+e^-$	YES	$\phi \to \eta e^+e^-$	Running
KLOE2	$U \to \mu^+\mu^-$	Prel.	$e^+e^- \to \mu^+\mu^-\gamma$	Running
APEX	$U \to e^+e^-$	YES	e^- on target	Completed
HPS	$U \to e^+e^-$		e^- on target	Start running 2014
BABAR	$Q_q \neq 0$ & $U \to \mu^+\mu^-$	YES		Completed
A1 (MAMI)	$U \to e^+e^-$	YES	e^- on target	Completed
WASA (cosy)	$Q_q \neq 0$ & $U \to e^+e^-$	YES	$\pi^0 \to e^+e^-\gamma$	Completed
SHIP	$Q_q \neq 0$ & $U \to e^+e^-$		p on dump	Proposal (2023)
DARK LIGHT	$U \to e^+e^-$		e^- on H target	Planned (2016?)
VEPP3	NONE		e^+ on H target	Proposal (unknown)
HADES	$Q_q \neq 0$ $U \to e^+e^-$ + 5	YES	P on nuclei	Completed
SINDRUM	$Q_q \neq 0$ $U \to e^+e^-$	YES	$\pi^0 \to e^+e^-\gamma$	Completed
NA48/2	$Q_q \neq 0$ $U \to e^+e^-$	YES	$\pi^0 \to e^+e^-\gamma$	Completed
P348 (CERN)	$U \to e^+e^-$ or NONE		e^- on target	Proposal (201?)
PADME	NONE		e^+ on target	Proposal (2016?)

Beam conditions

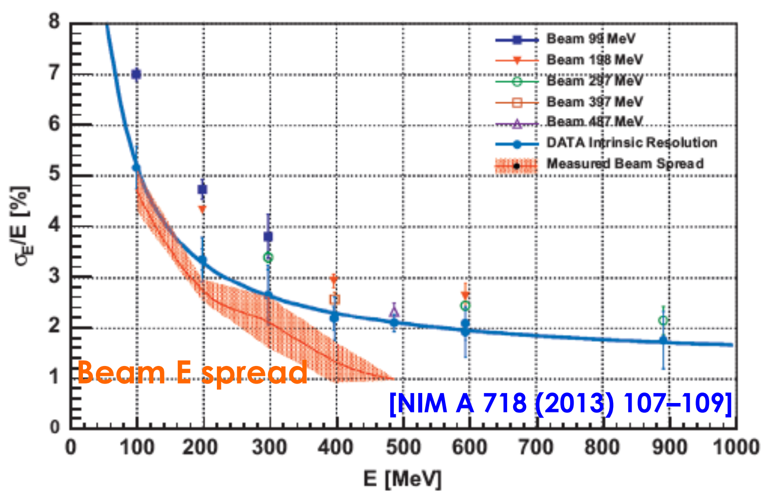
- In the present study we assume that the BTF will be able to deliver
  - 1E4 positrons of energy 550 MeV per bunch in 50 bunch/s over 1 year
  - Total e^{+} on target being: 50*1E4*3.15E7 = 1.6E13 (we use 1E13)
  - Beam energy spread ~1% (BTF can do much better)
  - RMS of beam position 2mm and emittance 1mm*mrad
  - Bunch duration 10 ns (can already go up to 40ns)



Single bunch beam spot

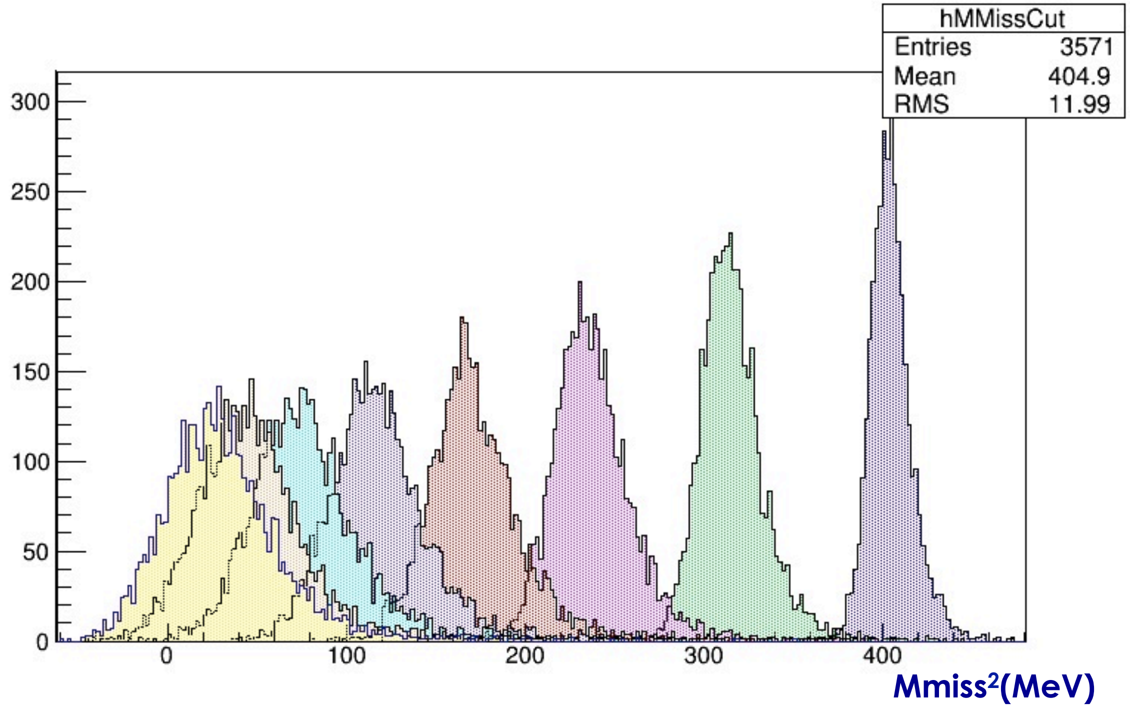


Integrated beam spot



Measurement of the beam spread

MC calorimeter performance

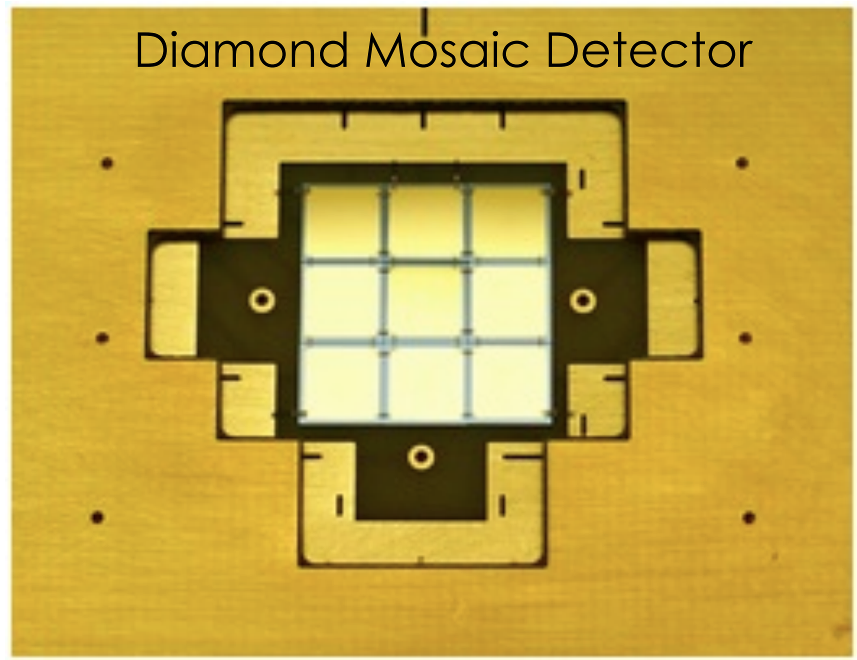


- Missing mass resolution in agreement with toy MC using
  - $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$ [NIM A 718 (2013) 107–109]
  - Differences are ~ 10%
- Resolution is the result of combination of angular resolution energy resolution and angle energy correlation due to production

PADME active target

- Diamond 50μm thick target
  - Most probably strip detector
- Active area 2x2cm^2
- Position resolution ~2mm in both X and Y
- Sensitive from few particle to 10^9 particle
- Real time beam imaging
- Time resolution below 1ns
- Readout with QDC.
- R&D can start from CIVIDEC diamond mosaic detector

CIVIDEC

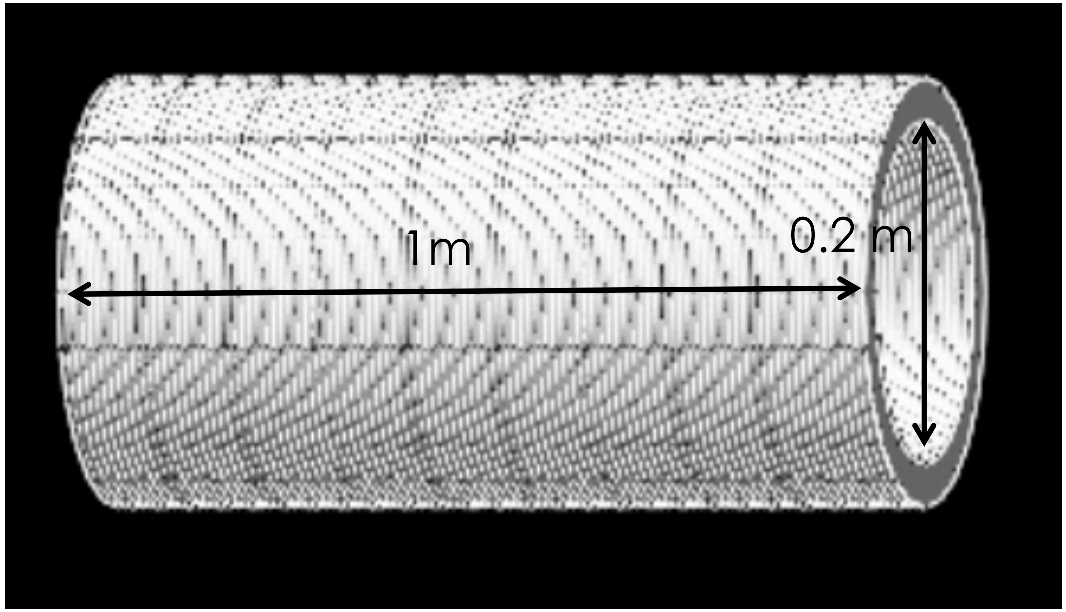


NEW

Features:	
Active area:	13 mm x 13 mm
Energy resolution:	35 keV FWHM
Particle rate:	1 MHz

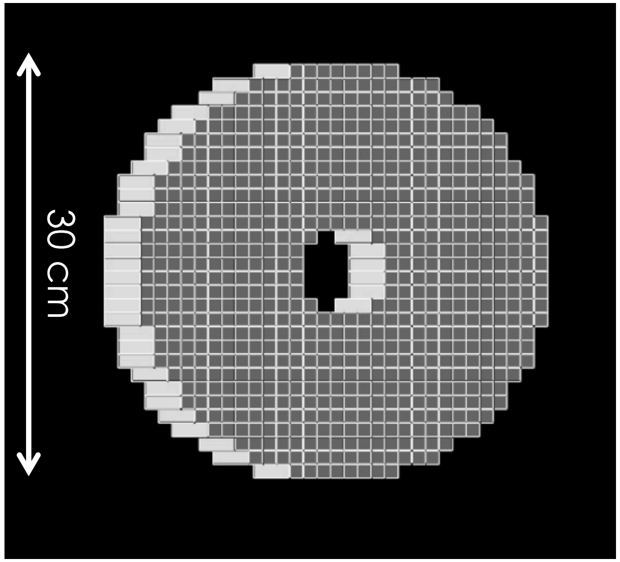
Detector:	
Type:	sCVD Diamond Mosaic-Detector
Diamond substrates:	4.5 mm x 4.5 mm
Thickness:	140 μm
Electrode structure:	3x3 mosaic structure
Metallization:	Au electrodes

PADME spectrometer & Magnet



- Conventional magnet with B=0.6 Tesla
- Generic cylindrical chamber filled with gas
  - Inner radius 20 cm outer radius 25 cm length 100 cm
  - 5 cylindrical layers of 1cm each
- Expected to measure track crossing position with 300μm resolution
- Used in the experiment to veto positron and to reconstruct mass of lepton pairs.

The electromagnetic 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: radius 15 cm, depth of 15-20 cm
  - Inner hole 4 cm radius
  - Active volume 9840 cm^3 total of 656 crystals 1x1x15-20 cm^3
- Material LSO(Ce): high LY, high ρ, small X_0 and R_M, short τ_{decay}
- Expected performance:
  - $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$ superB calorimeter test at BTF [NIM A 718 (2013) 107–109]
  - $\sigma(\theta)$ = 3 mm/1.75 m < 2 mrad
  - Angular acceptance 1.5-5 degrees