PADME project at DAΦNE **BTF**

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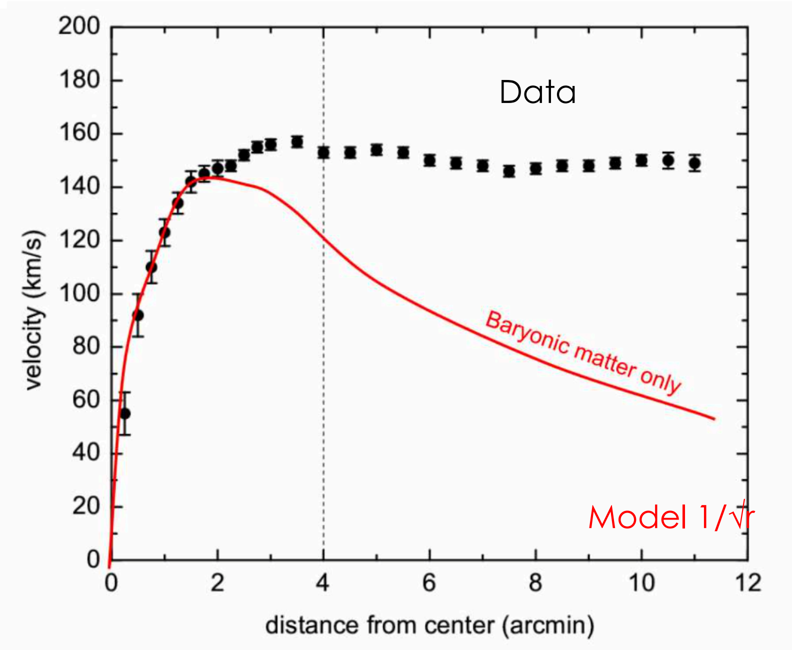
PADME website
http://www.lnf.infn.it/acceleratori/padme/index.html

Outline

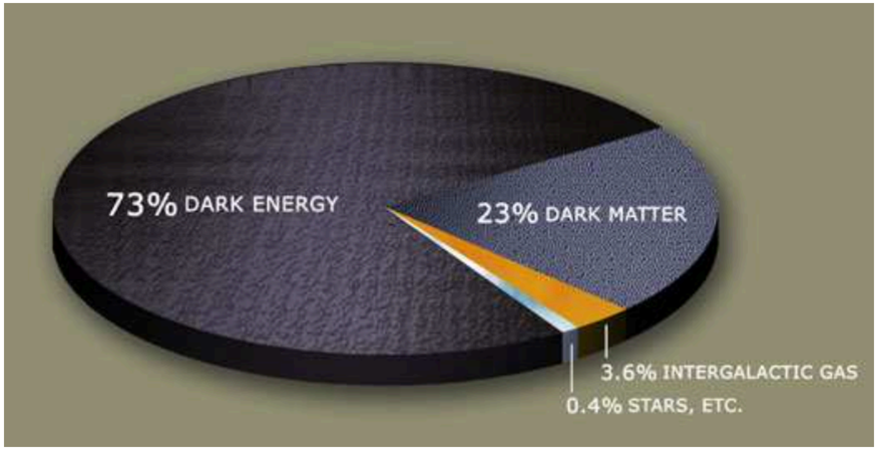
- The dark sector basic model
- Motivation for dark photon searches
- Recent results on the Dark Photon searches
- **P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment **PADME** proposal
  - Beam conditions and the Target
  - The electromagnetic calorimeter
  - The dipole magnet
  - The spectrometer
  - The Vacuum chamber
- Analysis technique for annihilation production
  - Signal selection criteria
  - Positron flux measurement
  - Limit evaluation
- Experimental technique for bremsstrahlung production
  - Decay in e+e- pair in thin target experiment
  - The dump experiments
- Conclusion and prospects

SM and the dark matter

Galaxy rotation curve



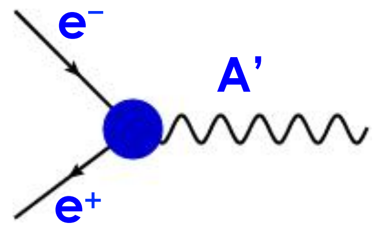
Gravitational lensing



The simplest dark sector model

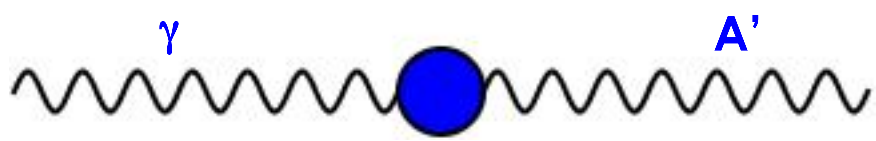
- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or U boson.
  - Two type of interactions with SM particles should be considered
- As in QED, this will generate new interactions of the type:

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



  - 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

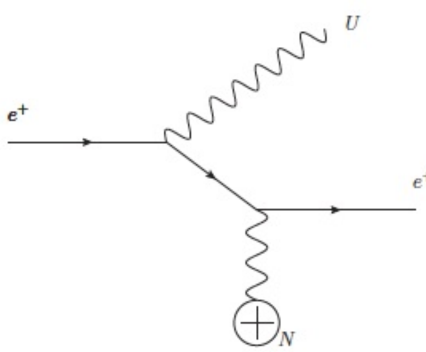
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$



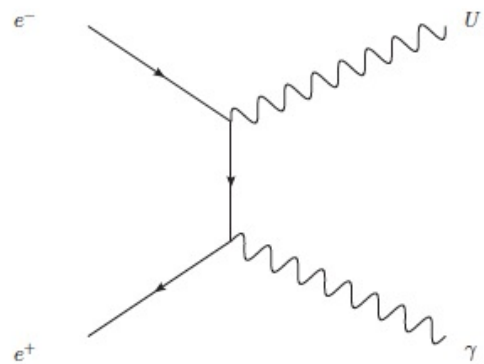
  - In this case q_f is just proportional to electric charge and it is equal for both quarks and leptons.

A' production and decays

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

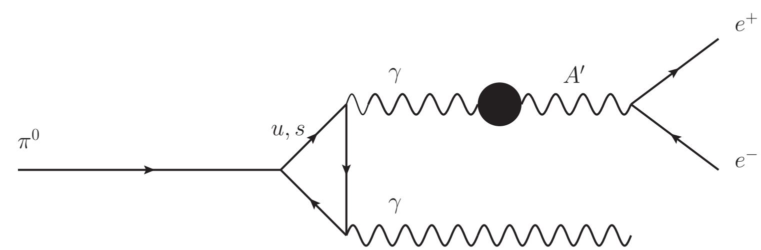


Bremsstrahlung

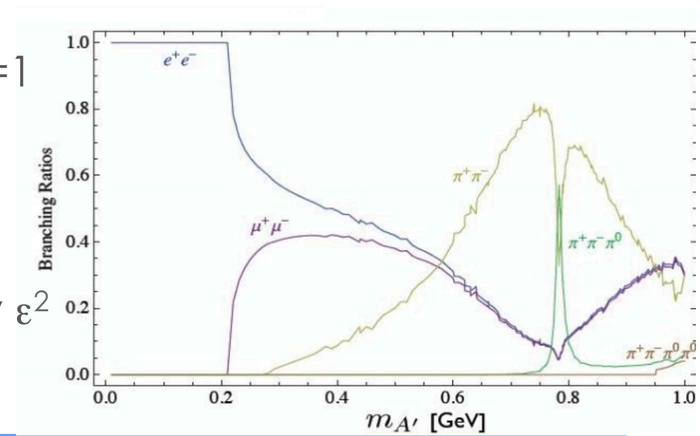


Annihilation

  - Meson decays

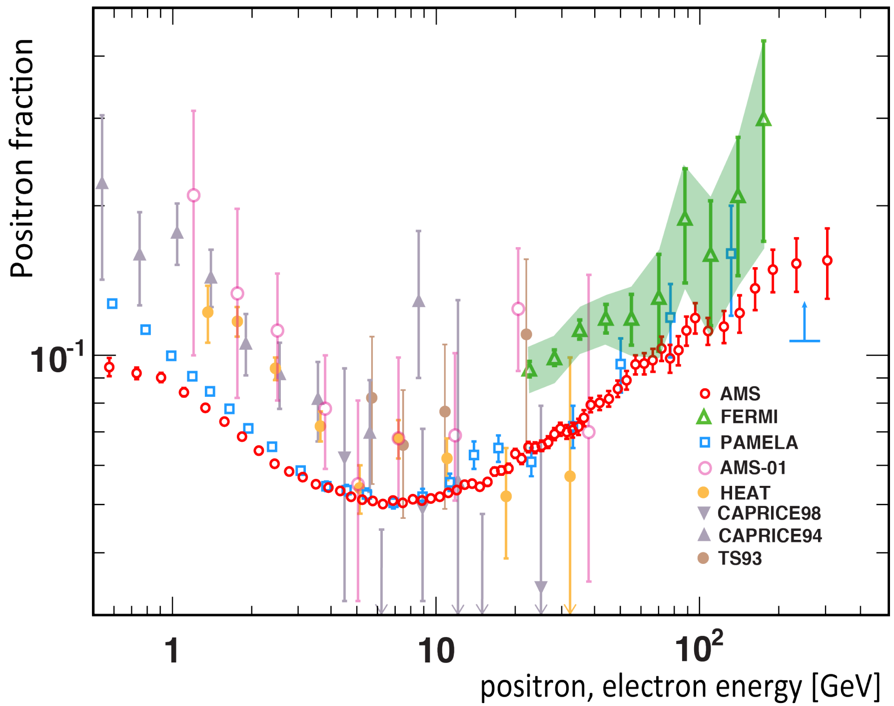


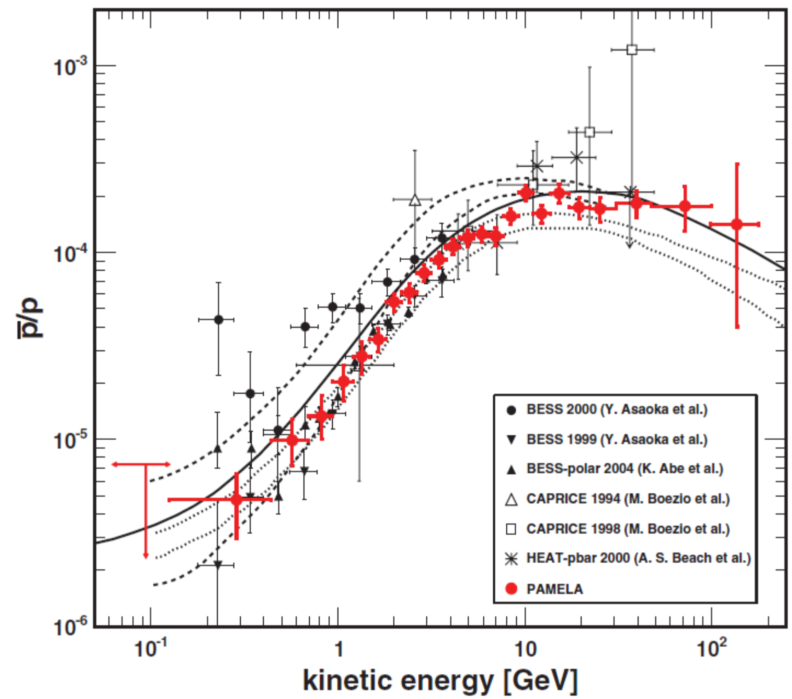
- If no dark matter candidate lighter than the A' boson exist:
  - $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ the so called "Visible" decays
  - For $M_{A'}$<210 MeV A' only decay to e^+e^- BR(e+e-)=1



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

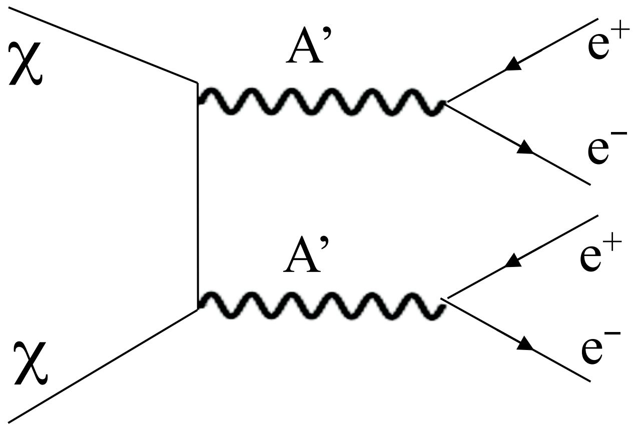
Positron excess in cosmic rays

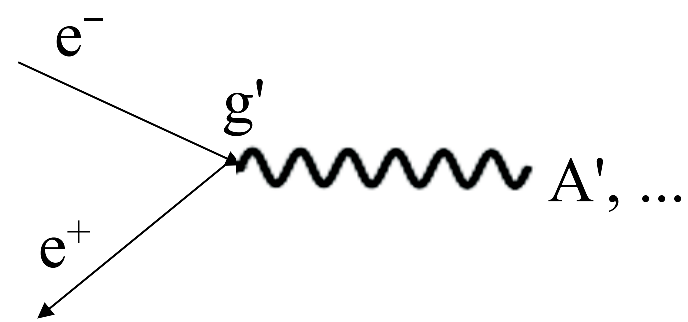




- Positron excess: PAMELA, FERMI, AMS02
- No significant excess in antiprotons
  - Consistent with pure secondary production
- Leptofilic low mass dark matter annihilation?

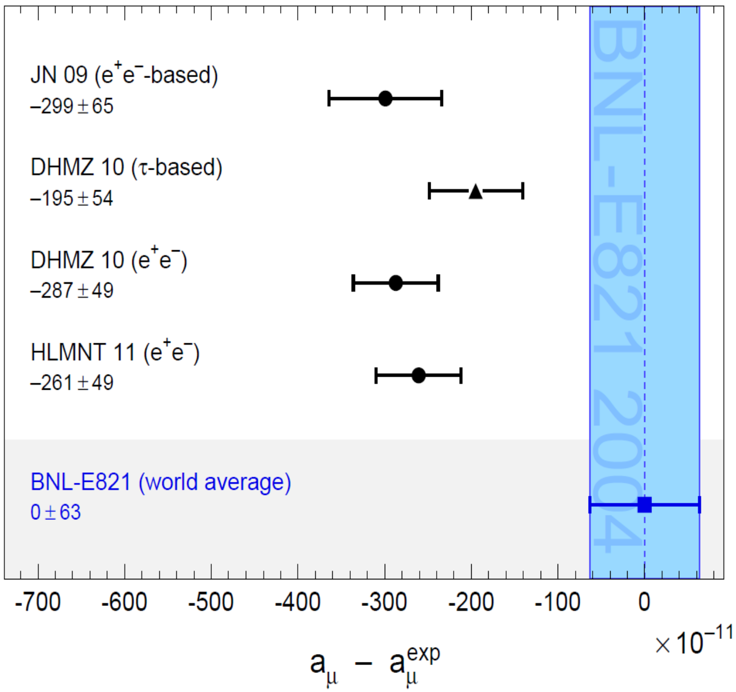
Hints for dark matter annihilation?

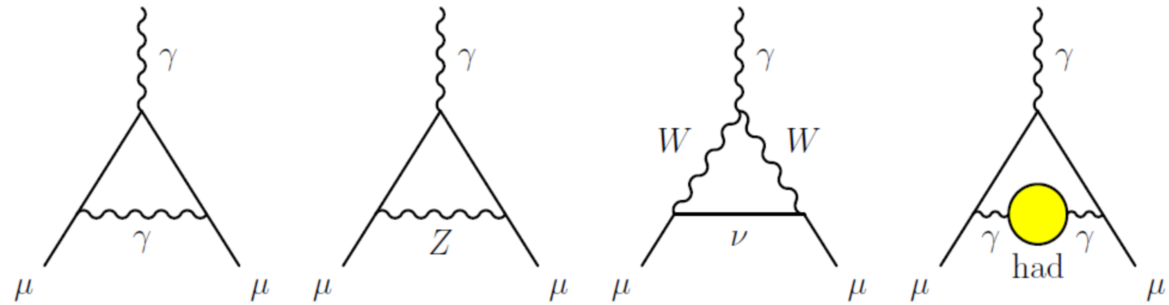




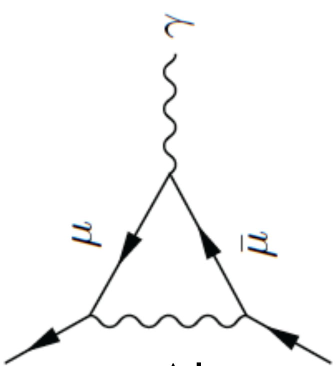
- If Dark Matter is the explanation to the positron excess, then the mediator should be light (< 2*M_{proton})
- Coupling constant to DM could be arbitrary (even O(1))
- The Lagrangian term can arise through
  - Fermions being charged (mili) under this new gauge symmetry ($q_f \rightarrow 0$ for some 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)

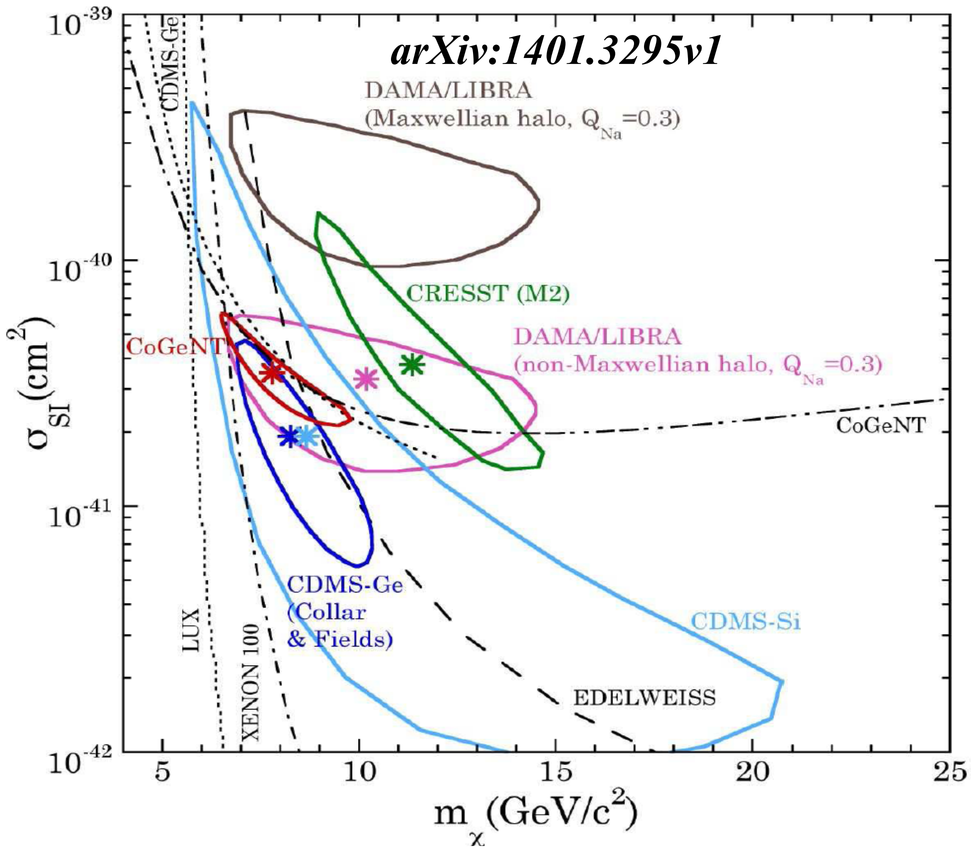


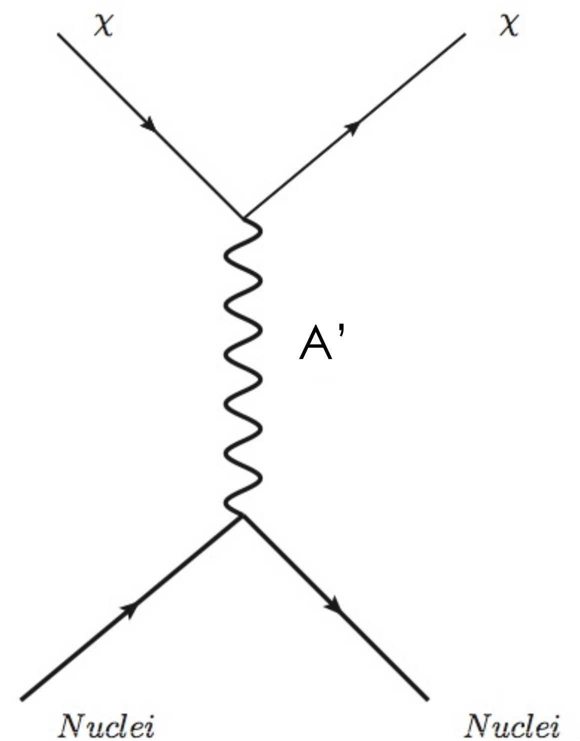
Contribution to g-2 from dark photon

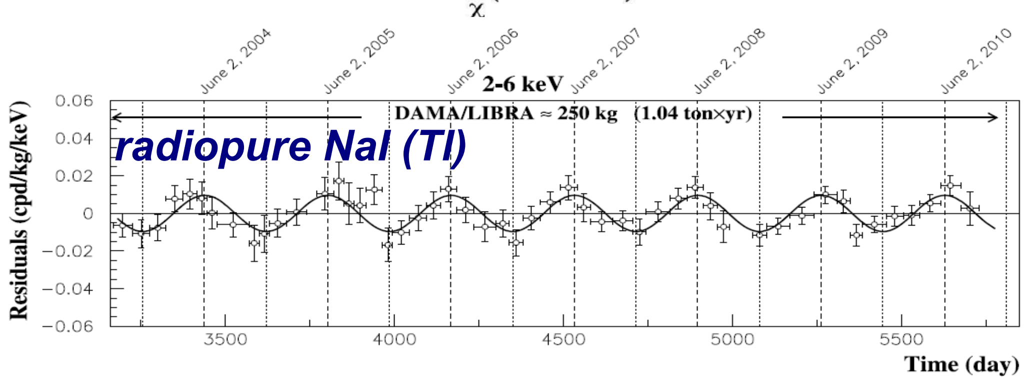
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1$–$2 \cdot 10^{-3}$ 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

The DAMA-Libra effect

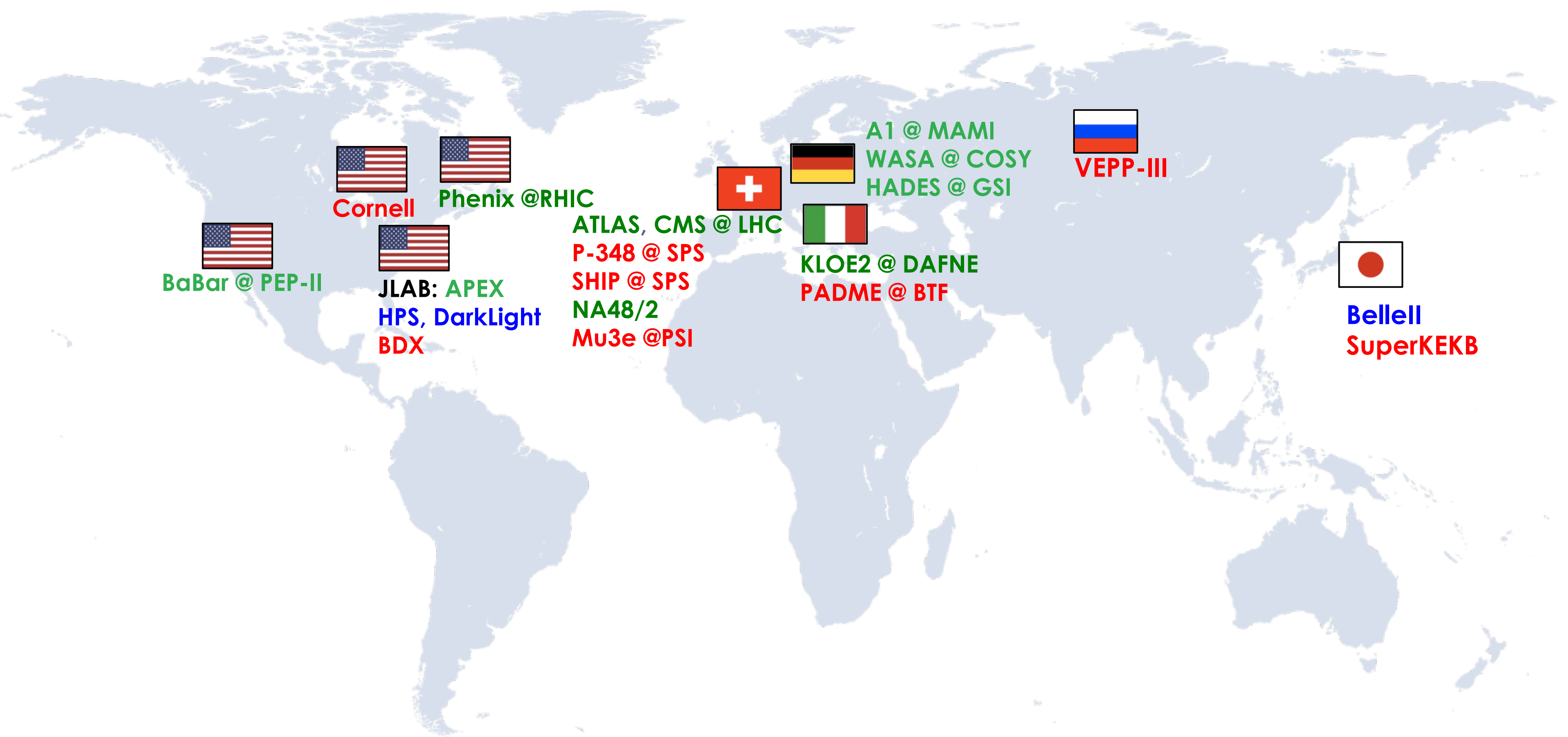






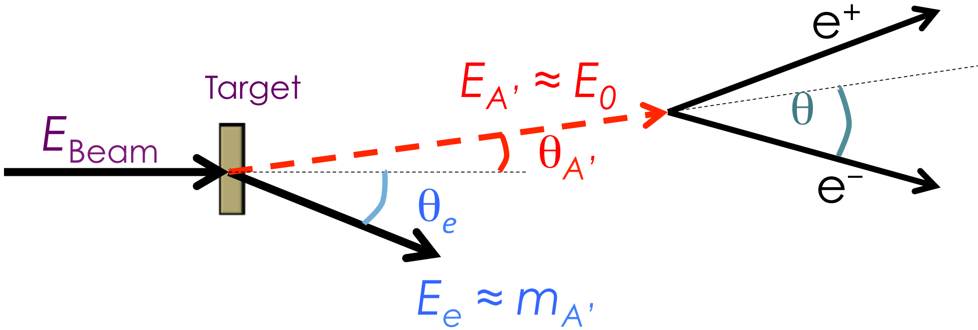
- Nuclear recoil by the exchange of a dark photon
- Independent of χ mass value

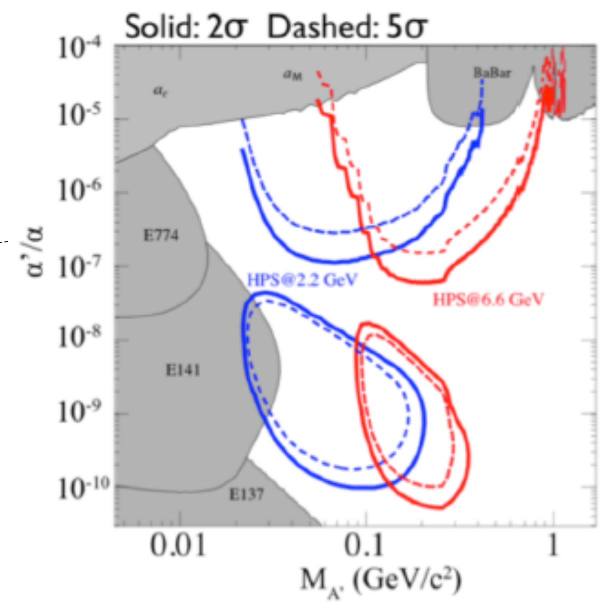
Dark photon searches in the world



Status: publishing, approved, proposals

Dark photon with thin targets

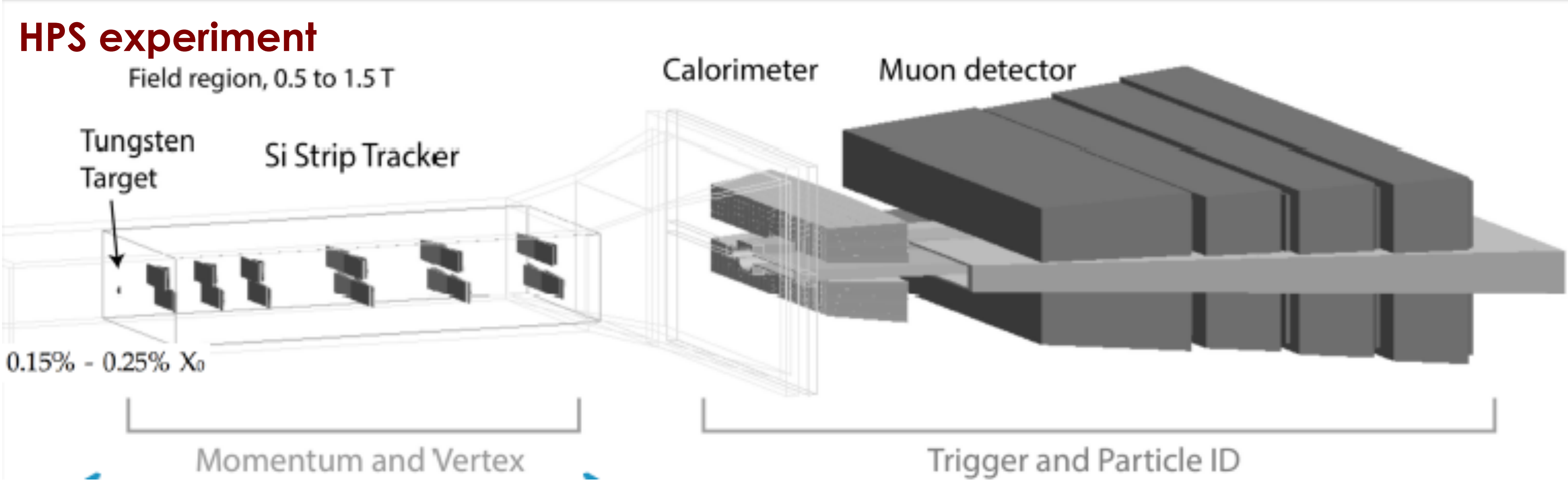




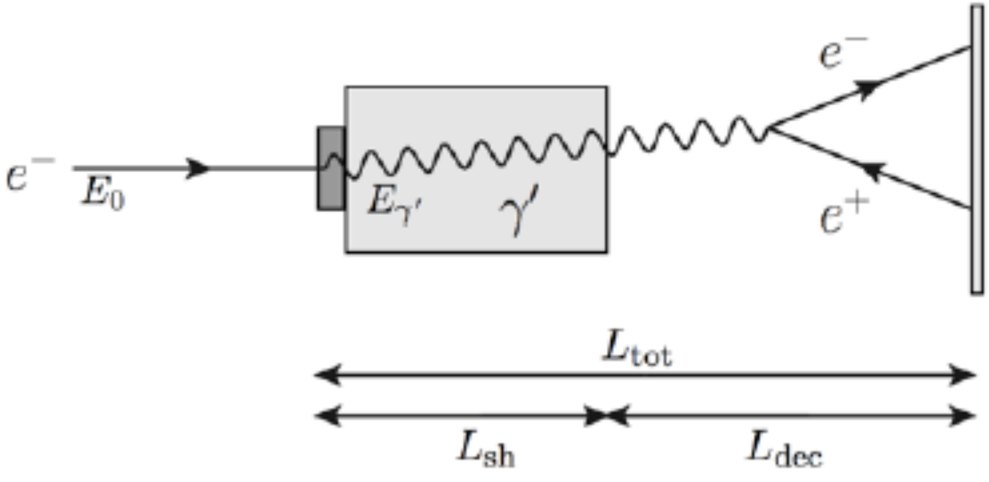
Blue:
Beam = 2.2 GeV@200 nA
Target = 0.125%

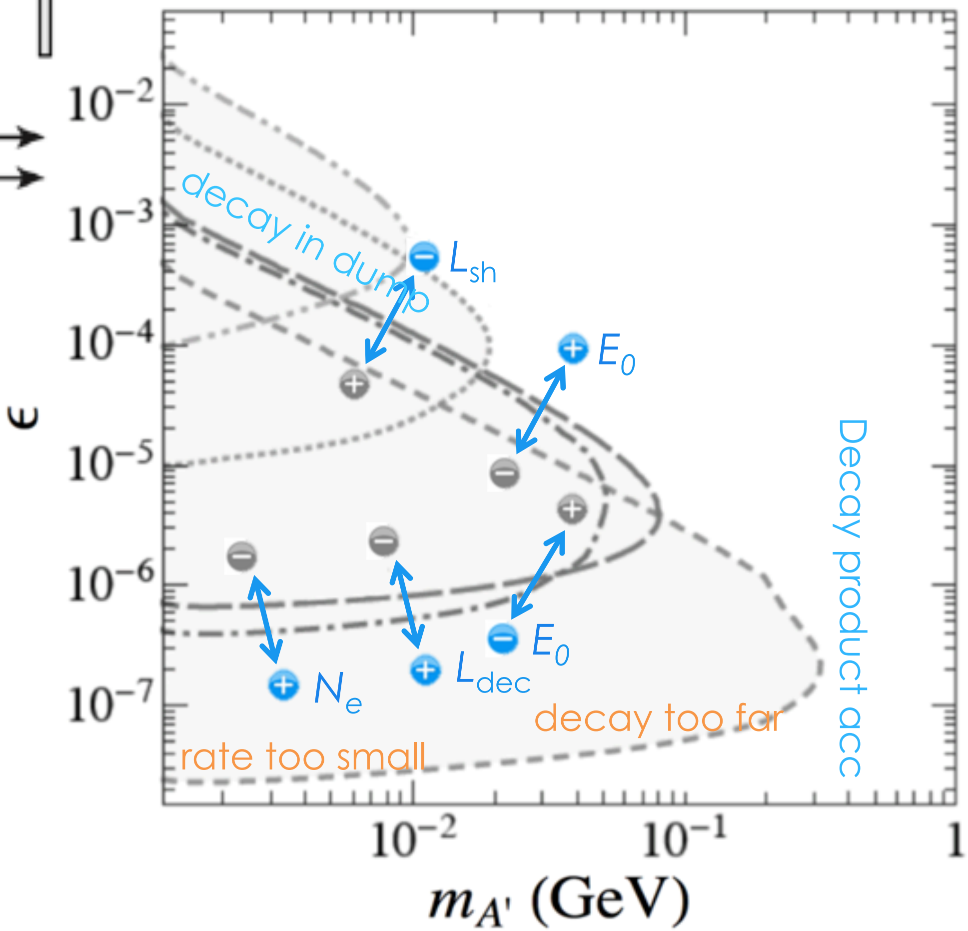
Red:
Beam = 6.6 GeV@450 nA
Target = 0.25%

3 months of running each energy = 180 days



Dark photon in dump experiments





Dump in a nutshell

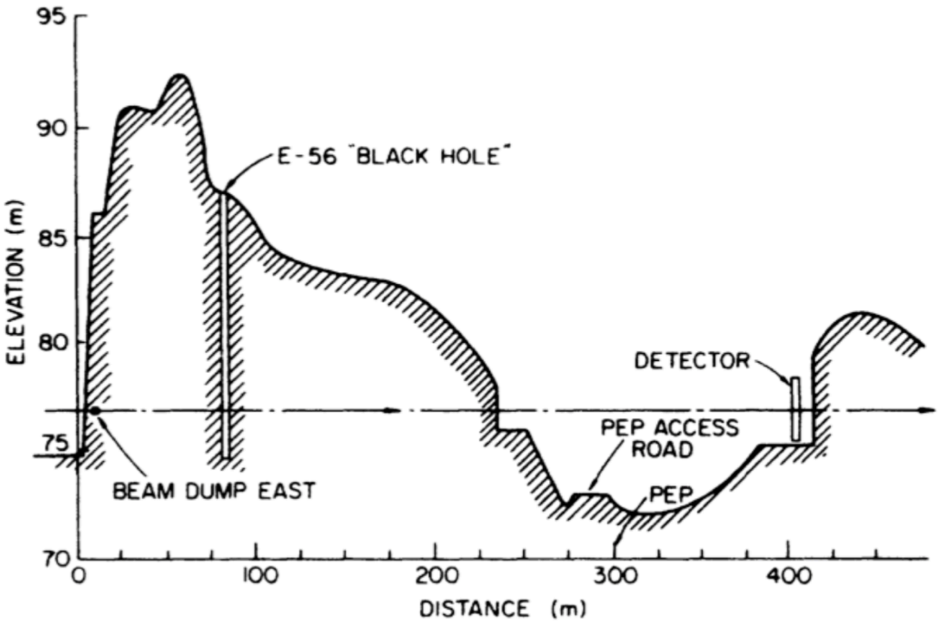
$$\sigma_{\gamma'}^{ft} \sim \frac{\alpha^3 Z^2 \chi^2}{m_{\gamma'}^2} \qquad \sigma_{\gamma'}^{coll} \sim \frac{\alpha^2 \chi^2}{E^2}$$

$$\ell^{ft} = \sigma_{\gamma'} N_e \frac{N_0 \rho_{sh} l_{sh}}{A} \qquad \mathcal{L}^{coll} \simeq \frac{N_e^2}{\mathcal{A}_b}$$

$N_e \sim 10^{20}$/year

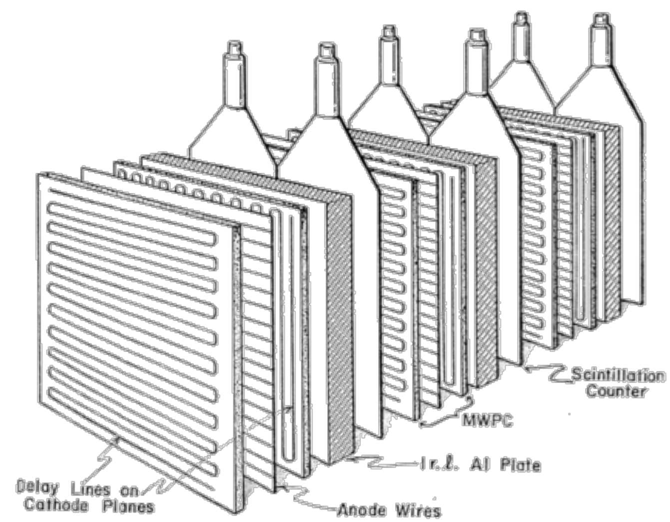
$N_0 \sim 6\text{x}10^{23}$

E137 at SLAC (1980-1982)



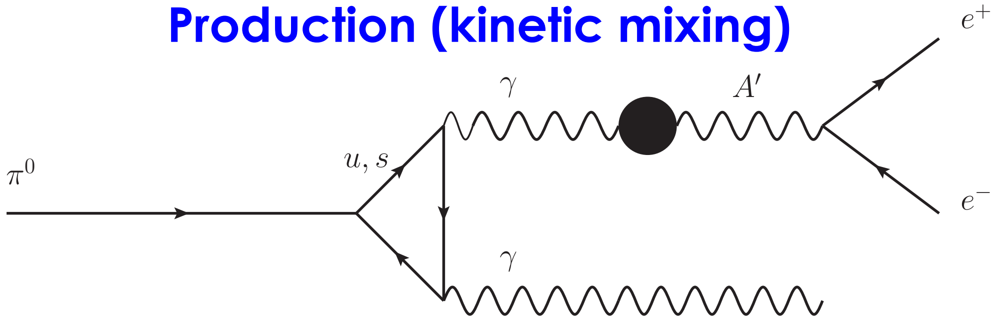
Al target
~2×10^{20} 20 GeV e^- on target
L_{shield} =179 m
L_{decay} = 204m
N_{obs} = 0

Experiment reinterpreted by S. Andeas

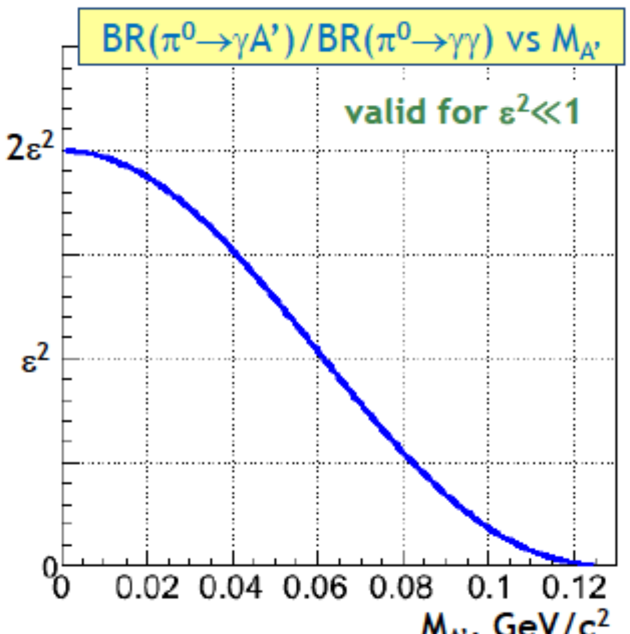


Dark photons in meson decays

Production (kinetic mixing)



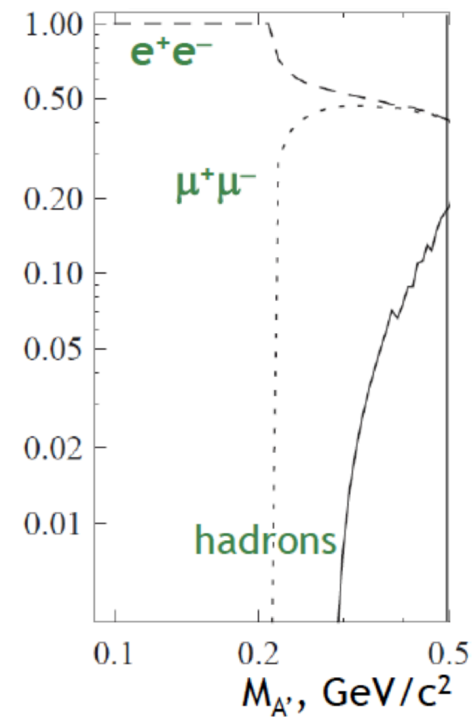
$$\frac{BR(\pi^0 \to \gamma A')}{BR(\pi^0 \to \gamma\gamma)} \approx 2\varepsilon^2 \,|\, F(M_{A'}^2)\,|^2 \left(1 - \frac{M_{A'}^2}{M_\pi^2}\right)^3$$



Batell, Pospelov and Ritz
PHYS. REV. D 80, 095024 (2009)

Decay (No light dark sector)

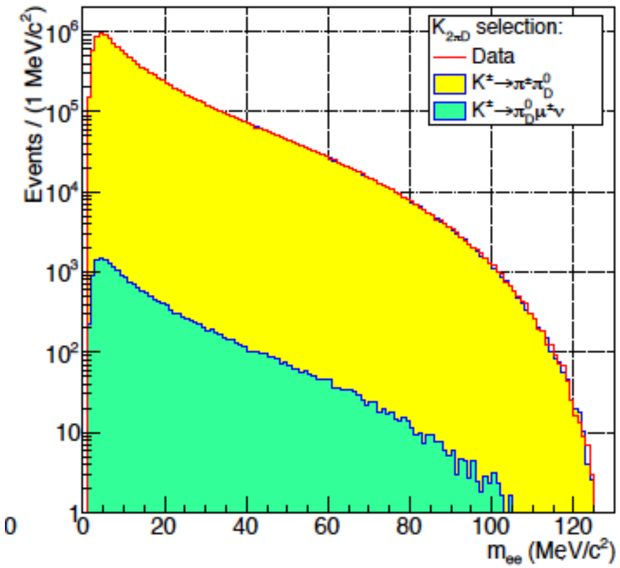
$$\Gamma(A' \to e^+e^-)\frac{\alpha}{3}\varepsilon^2 M_{A'}\sqrt{1 - \frac{4m_e^2}{M_{A'}^2}}\left(1 + \frac{2m_e^2}{M_{A'}^2}\right)$$

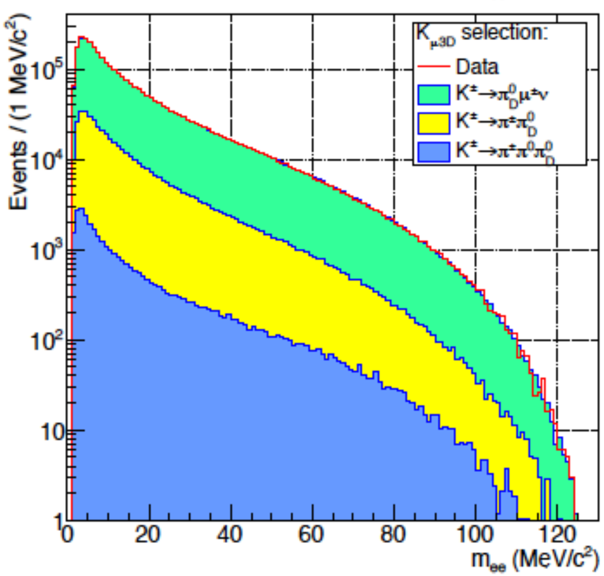


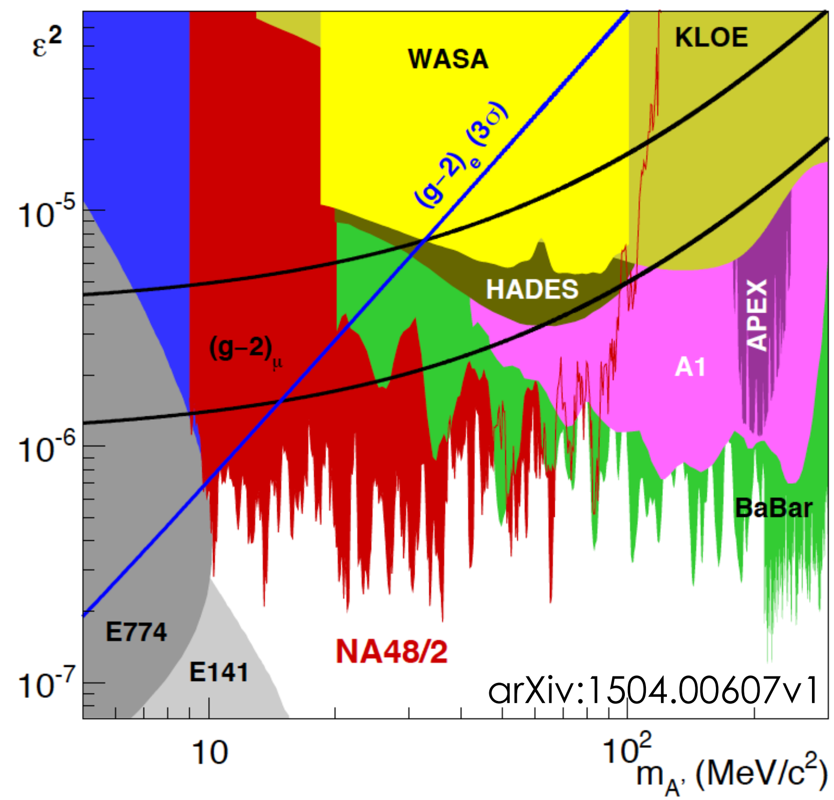
$M_{A'} < M_{\pi 0}$ and no lighter wrt A' dark sector particles exist $BR(A' \to e^+e^-) = 1$

NA48/2 dark photon limit

- Select $\pi^{\pm}\pi^{0}_{D}$ and $\pi^{0}_{D}\mu^{\pm}\nu$ decay
- Compare data and montecarlo
- Search for unexpected peak in the M_{ee}
- No excess observed → set a limit in ε^2

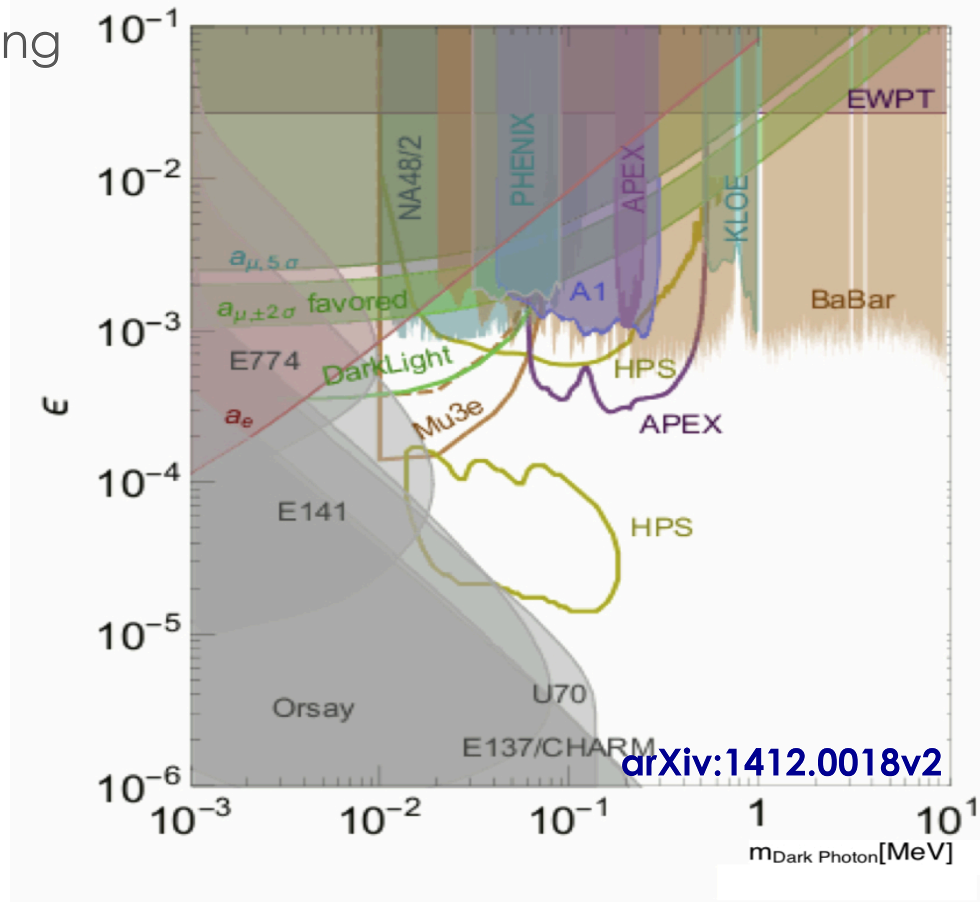






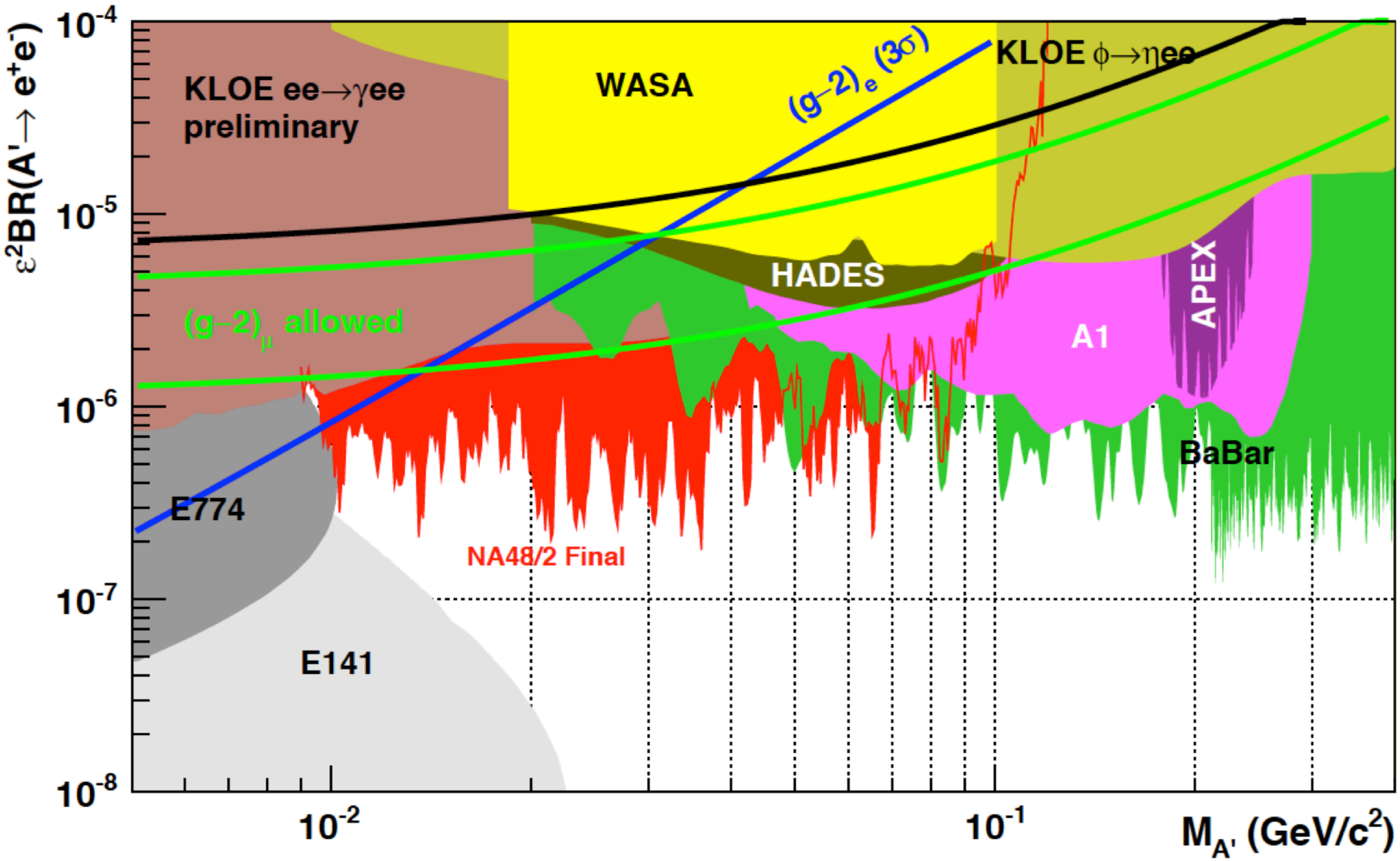
Dark photon searches status

- Favored parameters values explaining g-2 (green band)
  - A'-boson light 10-100 MeV
- Status of dark photon searches
  - Beam dump experiments (grey)
    - e^+e^- appearance after a dump
  - Fixed target
    - Peak search over QED BG
  - Mesons decays
    - Peaks in $M(e^+e^-)$ or $M(\mu^+\mu^-)$
- Indirect exclusion from g_e-2 g_μ-2
  - Recent tight limit in red filled area



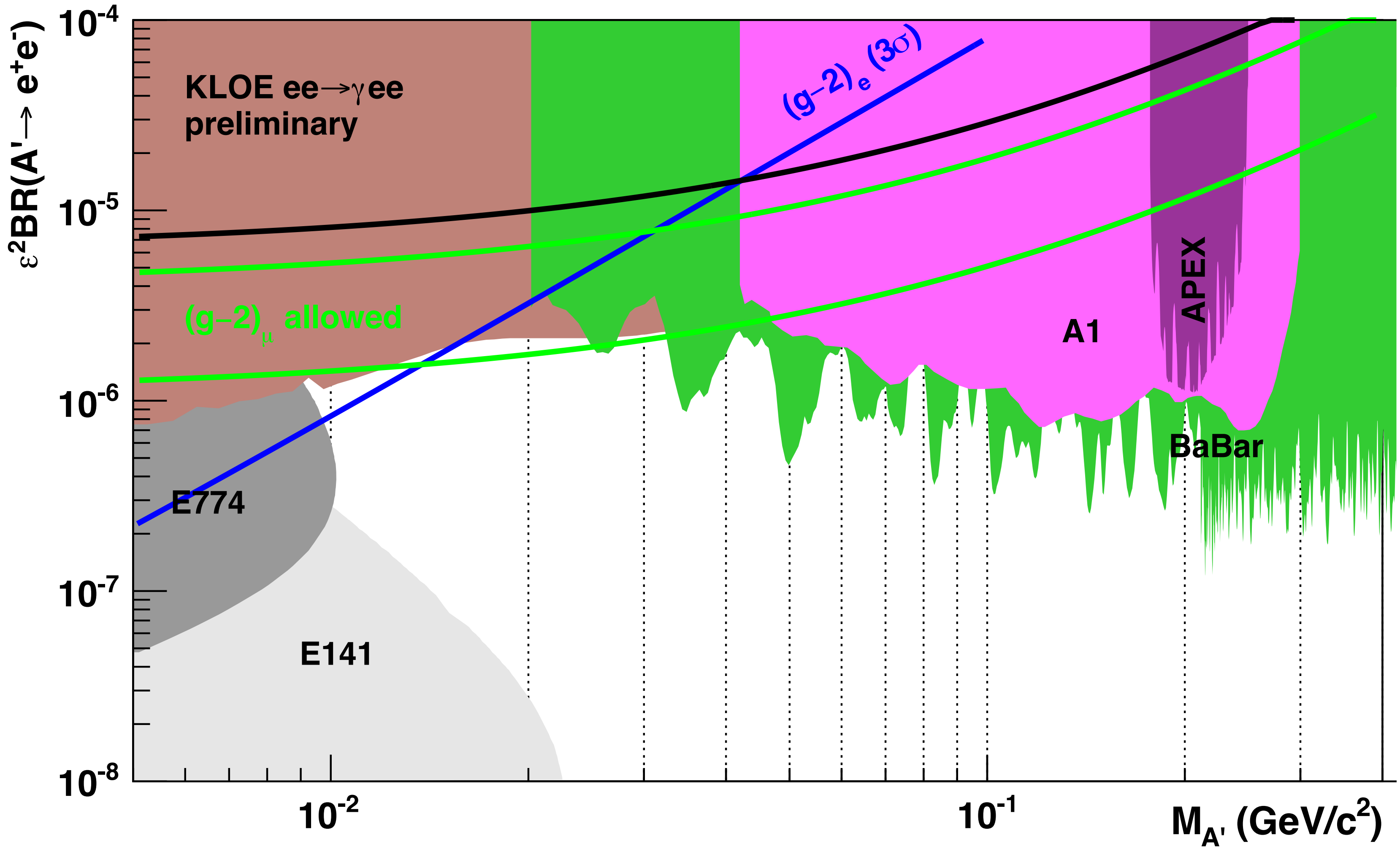
- Many different techniques, assumptions on dark photon interaction models
  - Kinetic mixing, decay to electrons, no dark sector particles

Status $\varepsilon_q \neq 0$ and $A' \to e^+e^-$



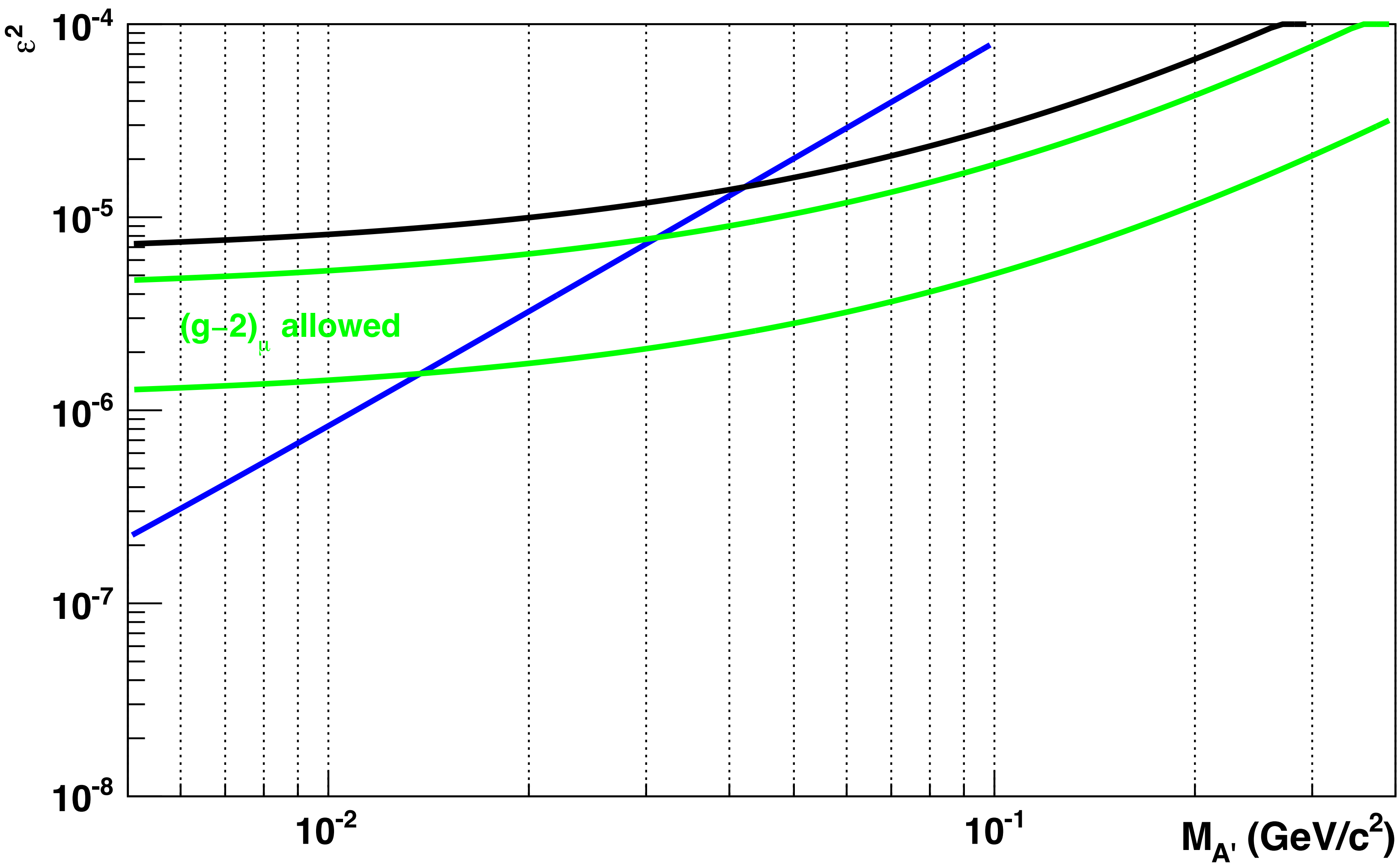
g-2 muon band excluded by recent NA48/2 measurement

Status ε_q=0 and A'→e^+e^-



Meson decays not included the (g-2)μ band is not covered any more

Status ε_q=0 and $A'\to\chi\chi$ decays



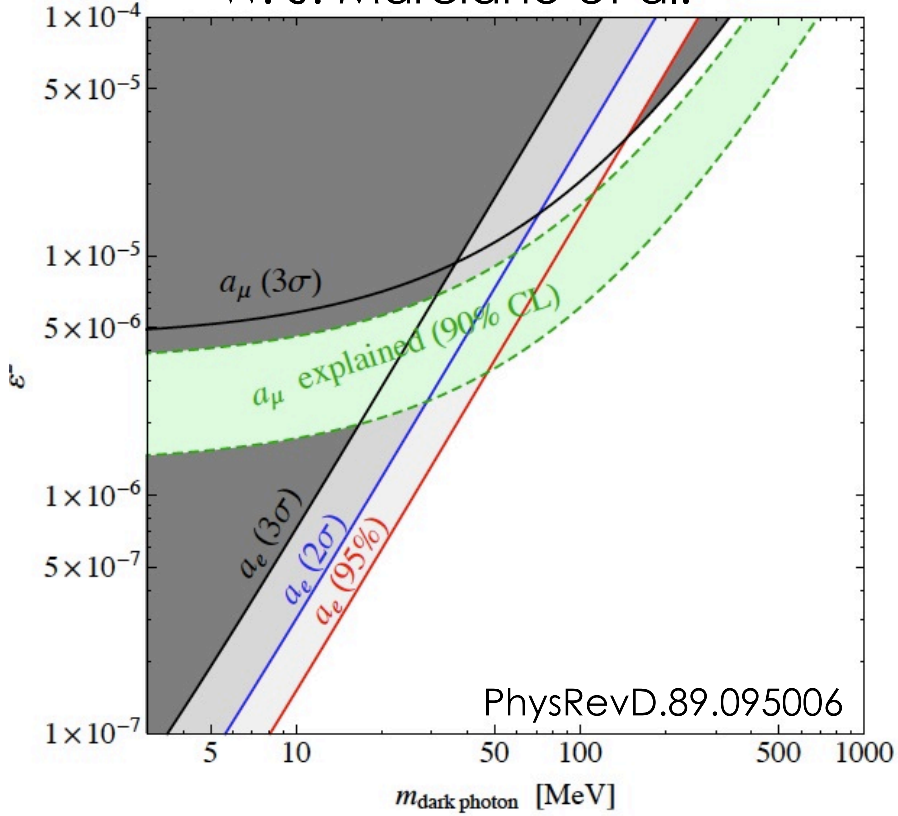
Removing the assumption $BR(A'\to e^+e^-=1)$ and introducing light dark matter

Why dark photon invisible decays?

- The invisible search technique remove any assumption except coupling to leptons
- A' increase its capability of having escaped detection so far
- No data in the minimal assumptions

"If, instead, the A' decays primarily into invisible light particles (e.g. a pair of dark matter particles with mass < $m_{A'}/2$), that change would essentially negate all the bounds except those coming from anomalous magnetic moments" W. J. Marciano et al. arXiv:1402.3620v2

W. J. Marciano et al.



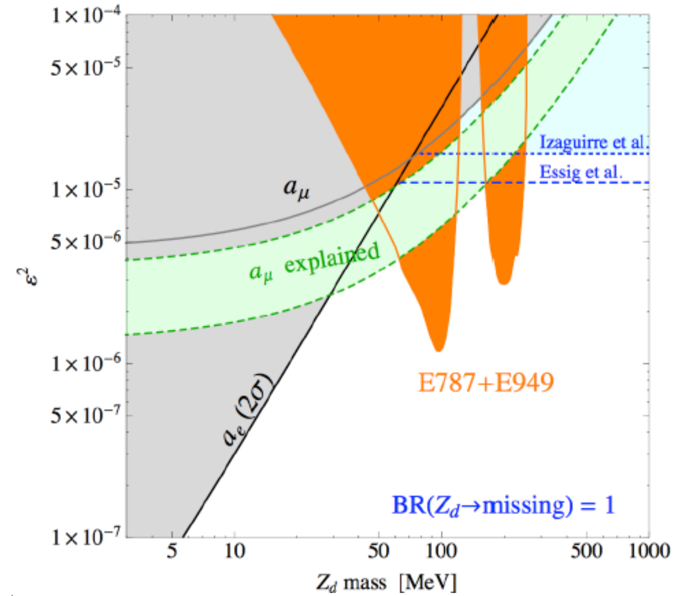
- At present there are no MI experimental limit for the A'→invisible decay
  - Just a never published ArXiv 0808.0017 by Babar '08 with very limited sensitivity on ε^2 ($\Upsilon_{3S}\to\gamma U$ assumes coupling to quarks!)
  - Indirect limit from $K^+\to\pi^+\nu\nu$ (assumes coupling to quarks!) arXiv:1309.5084v1

Invisible dark photon and kaons

In models assuming that the dark photon couples to SM through kinetic mixing $\varepsilon_q \neq 0$ $K^\pm \to \pi^\pm \nu\nu$ can be used to constrain $K^\pm \to \pi^\pm A'$

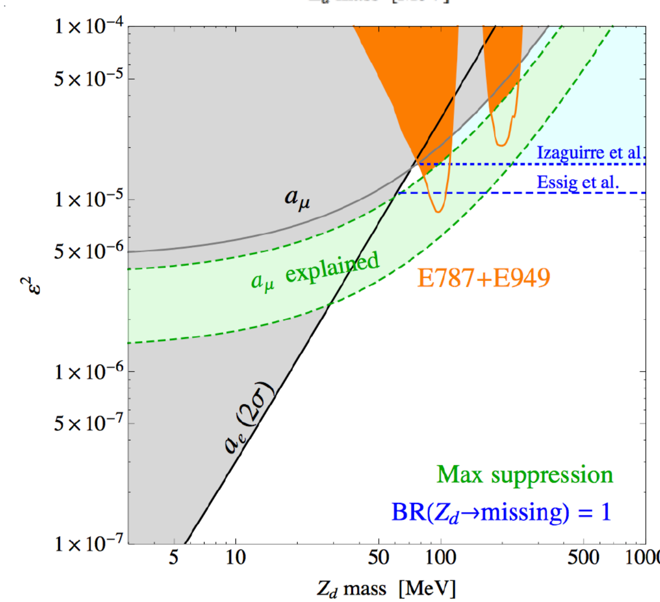
$$\Gamma(K^\pm \to \pi^\pm Z_d)|_\varepsilon = \frac{\varepsilon^2 \alpha W^2 m_{Z_d}^2}{2^{10}\pi^4} \frac{}{m_K^7} \sqrt{\lambda(m_K^2, m_\pi^2, m_{Z_d}^2)} \times [(m_K^2 - m_\pi^2)^2 - m_{Z_d}^2 (2m_K^2 + 2m_\pi^2 - m_{Z_d}^2)],$$

Z_d=A' for Marciano!



Depending on how the model is build the limit can change significantly for example allowing the presence of dark Z.

PhysRevD.89.095006



The PADME approach

- At present all experimental results rely on at least one of the following model dependent assumptions:
  - A' decays to e^+e^- (visible decay assumption $BR(A'\rightarrow e^+e^- = 1)$
  - A' couples with the same strength to all fermions ($\varepsilon_q = \varepsilon_l$) (kinetic mixing)

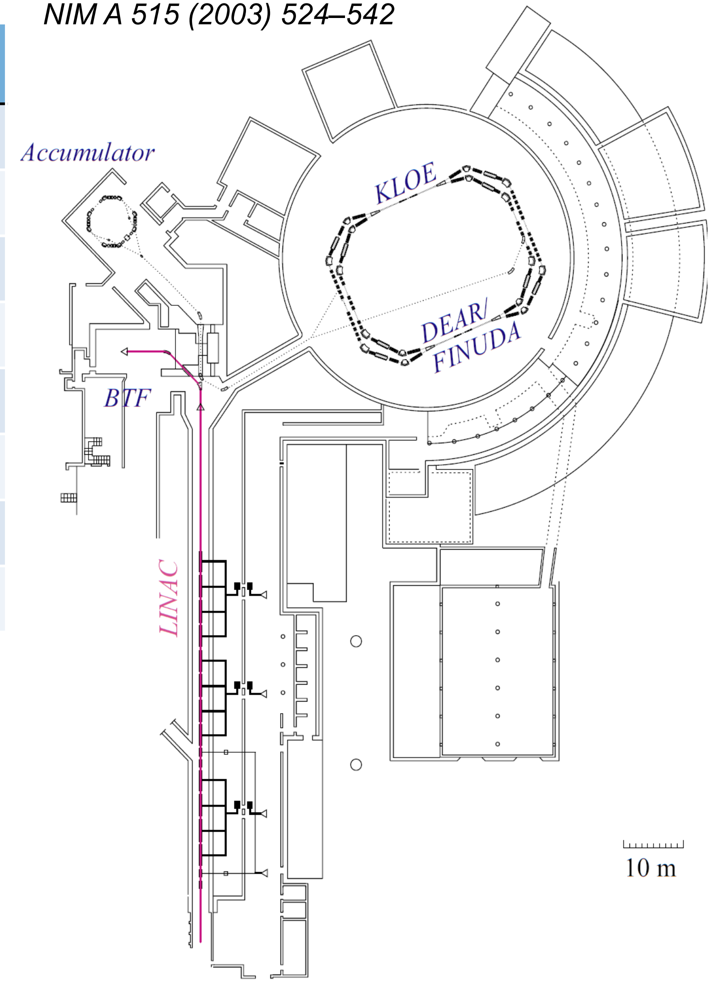
- In the most general scenario (PADME)
  - A' can decay to dark sector particles lighter than the A' $BR(A'\rightarrow e^+e^- << 1)$
    - Dump and meson decay experiment only limit $\varepsilon^2 BR(A'\rightarrow e^+e^- << 1)$
  - A' can couple to quark with a coupling constant smaller ε_l or even 0
    - Suppressed or no production at hadronic machines and in mesons decays

- **PADME aims to detect A' produced in e^+e^- annihilation and decaying into invisible by searching for missing mass in $e^+e^-\rightarrow\gamma A'$ $A'\rightarrow\chi\chi$**
  - No assumption on the A' decays products and coupling to quarks
  - Only minimal assumption: A' bosons couples to leptons
  - PAMDE will limits the coupling of any new light particle produced in e^+e^- collision (scalars (H_d), vectors (A' and Z_d))

DAΦNE Beam Test Facility (BTF)

	electrons	positrons
Maximum energy [MeV]	750 (1050) MeV	550 (800) MeV
Linac energy spread	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 - 40	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~10
Beam spot σ [mm]	1 mm	
Beam divergence	1-1.5 mrad	

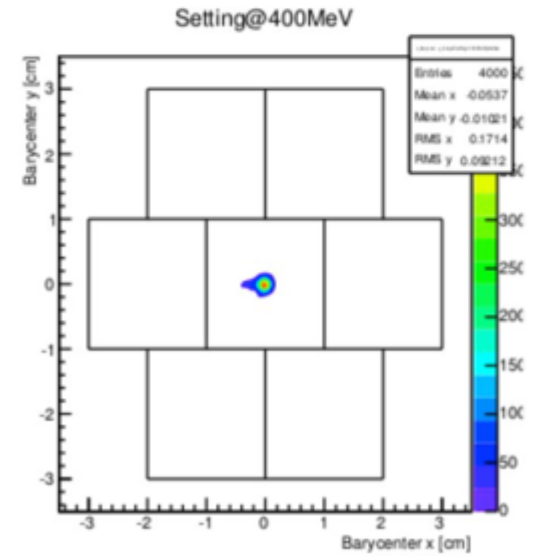
NIM A 515 (2003) 524–542



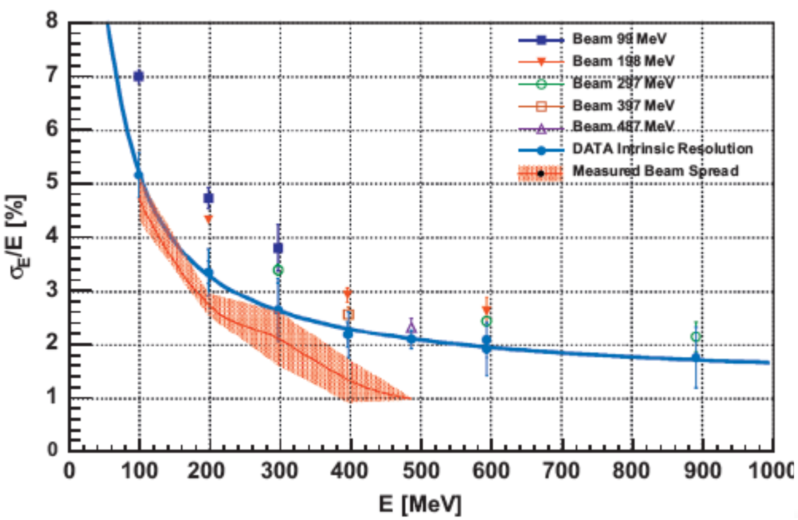
- Longer Duty Cycle
  - Standard BTF duty cycle = 50*10 ns = 5×10^{-7} s
  - Already obtained upgrade 50*40ns= 20×10^{-7} s work in progress to exceed 100 ns
  - Energy upgrade possible in 2017.
- The accessible $M_{A'}$ region is limited by beam energy
  - Region from 0-22 MeV can be explored with 550 MeV e^+ beam

BTF beam summary

- Energy spread **Δp/p ~1%**
- Beam spot: **1 – 2 mm RMS**
- Divergence: **1 – 1.5 mrad**
  - Effect of **multiple scattering and Bremsstrahlung** on the Beryllium exit window and in air has to be considered
  - Both size and divergence depend on the **optics**
- Beam position: **0.25 mm RMS**
- Pulse duration: **1.5 – 40 ns**
  - 10 ns during collider operations

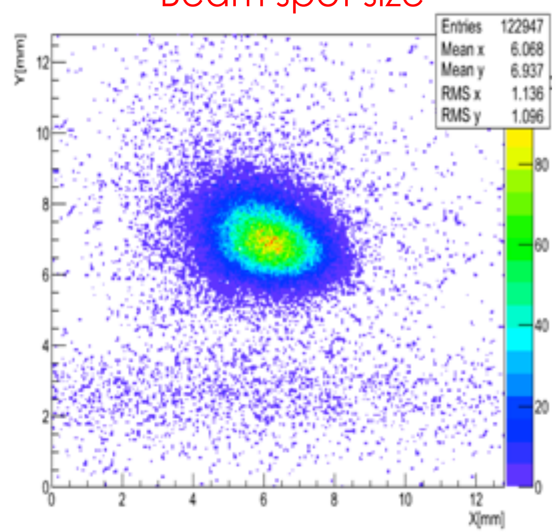


Measurement of the beam *E* spread

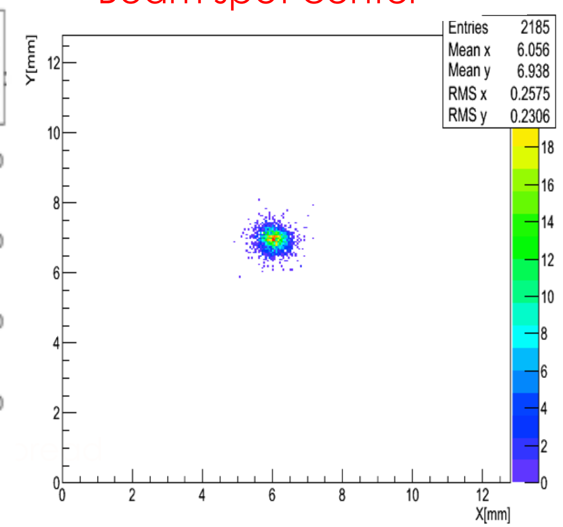


Nucl. Instrum. Meth. **A718** (2013) 107–109

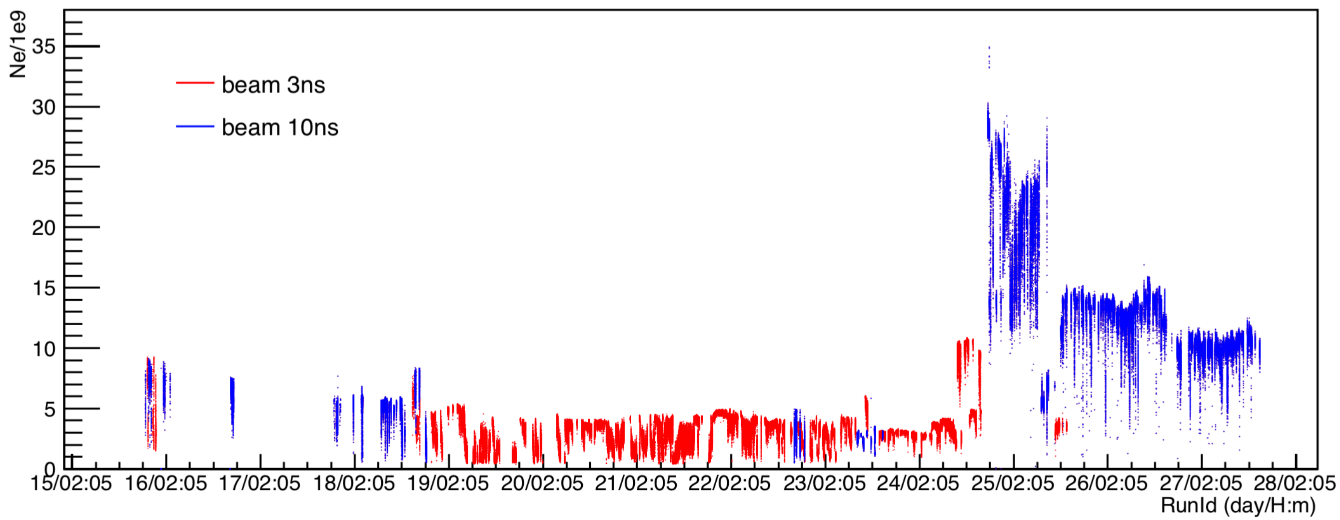
Beam spot size

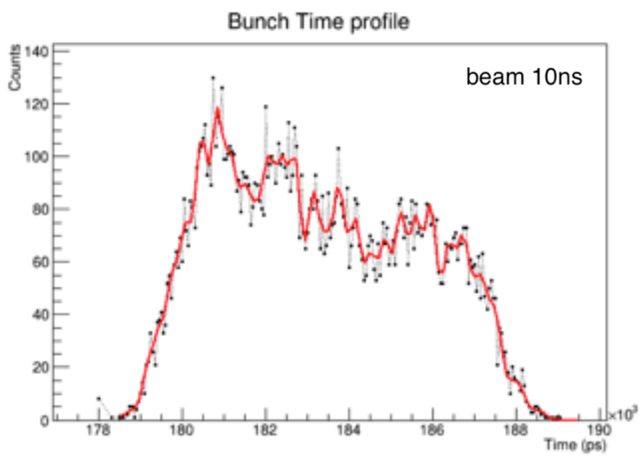


Beam spot center



High intensity

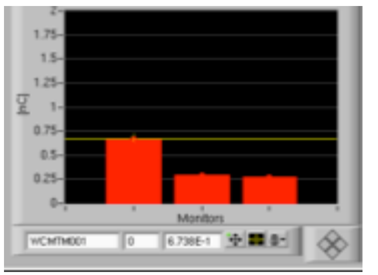




Radioprotection limit:
<n> = **3.125×10^{10} particles/s**

Typical charge to damping ring:

- **>1 nC/pulse** for **e⁻**
- **0.7-0.8 nC/pulse** for **e⁺**



But…

- Much higher charge on positron converter
- 8 A (12 A) from gun cathode

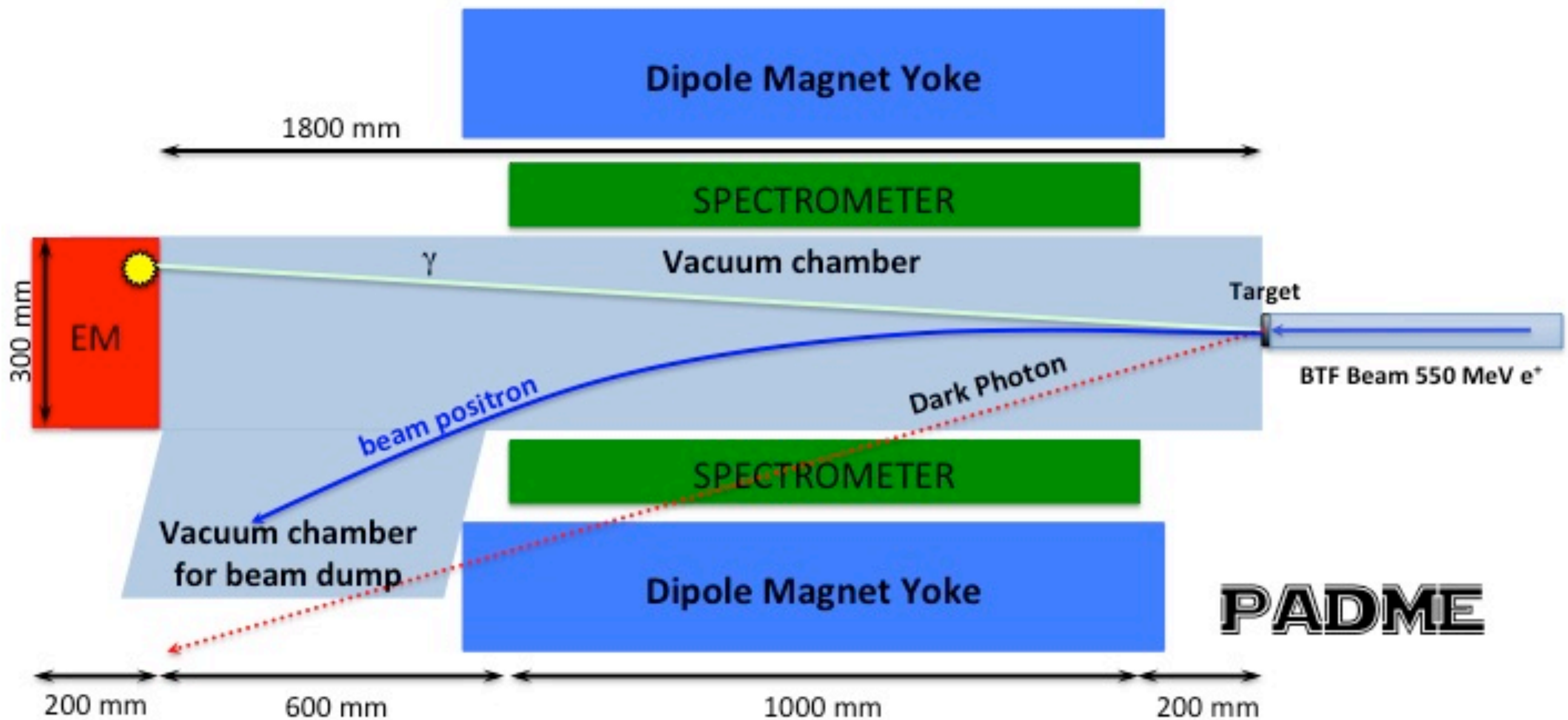
A few measurements on the maximum LINAC charge, driven by beam-dump experiments requirements

How many electrons on target?

- Let's compute how many **eot/y*** for **10 nC/pulse** so we can scale easily with the charge available from the LINAC
  - **10 nC** = $10^{-8}/1.6\times10^{-19}$ = **6.25×10^{10}**
  - At 49 Hz (1 pulse to spectrometer line) = 3×10^{12} e/s
    - 2 orders of magnitude more than present BTF authorization
    - Standard year = 1 y*= 120 days at 100% efficiency (10^7 s)
    - **3.175×10^{19} eot/y***
- **25 nC** translates in **0.8×10^{20} eot/y***
  - Considering measurements at 725 MeV, 40 ns, in the **present LINAC configuration** and quite conservative assumptions
  - Further extension of the pulse to 150 ns seems feasible with the present RF configuration, and should bring us to ≈100 nC, i.e. **3×10^{20} eot/y***

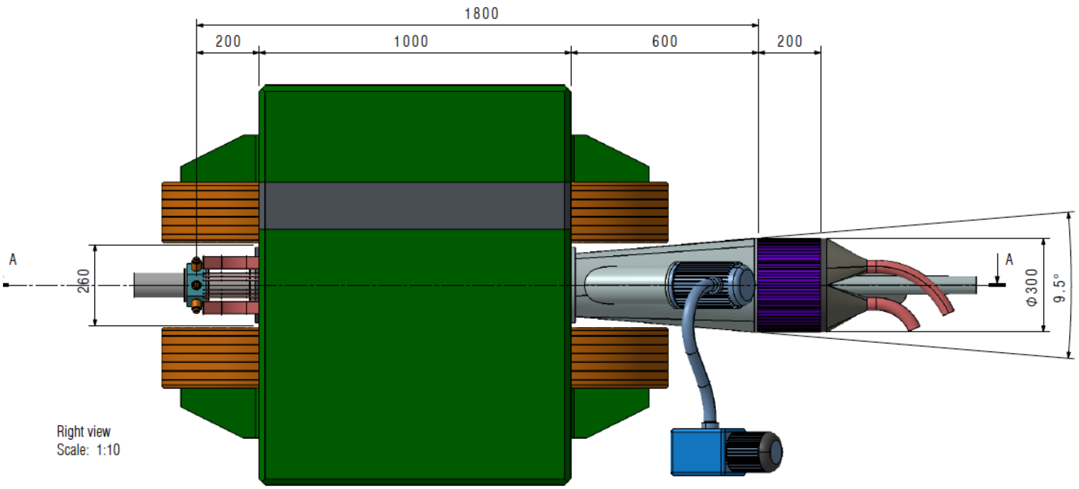
Where can we dump 3×10^{12} to 3×10^{13} e/s ?

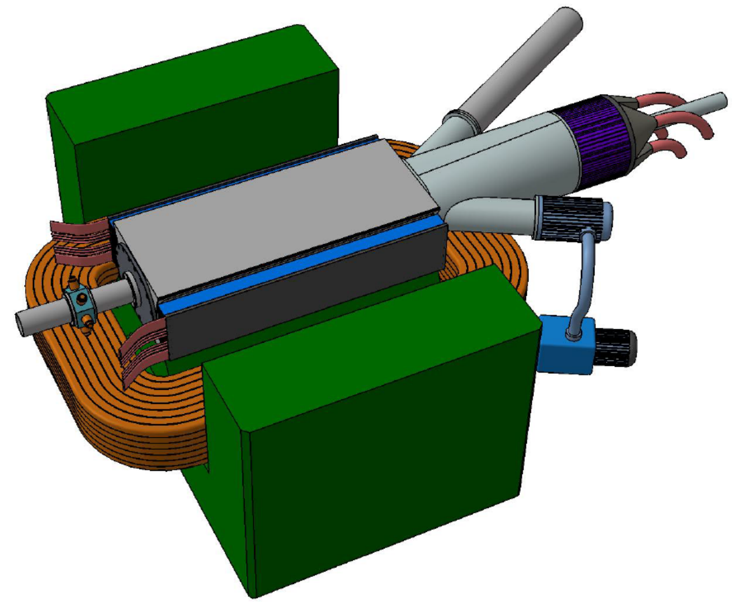
The PADME experiment

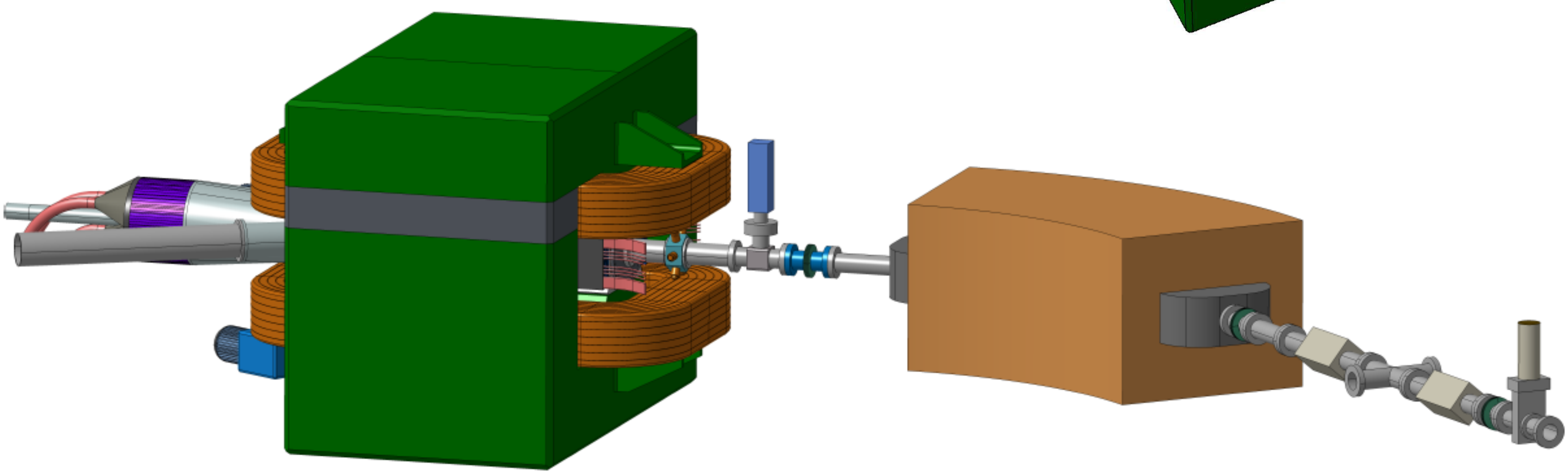


- 10^3-10^4 e^+ on target per bunch at 50 bunch/s (10^{13}-10^{14} e^+/year)
- Basic detector components:
  - Active 50μm diamond target
  - GEM based magnetic spectrometer ~1m length
  - Conventional 0.6T magnet
  - 15 cm radius cylindrical crystal calorimeter with 1x1x20 cm^3 crystals

The PADME experiment



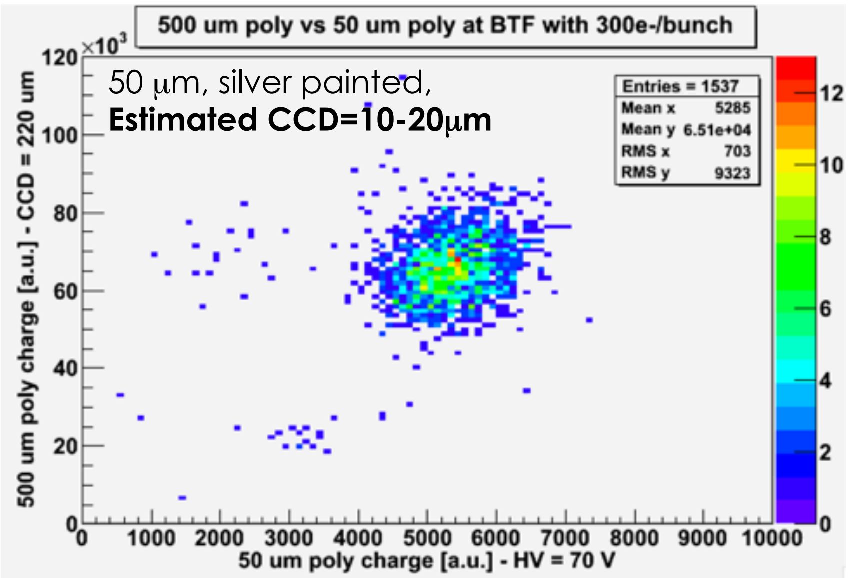




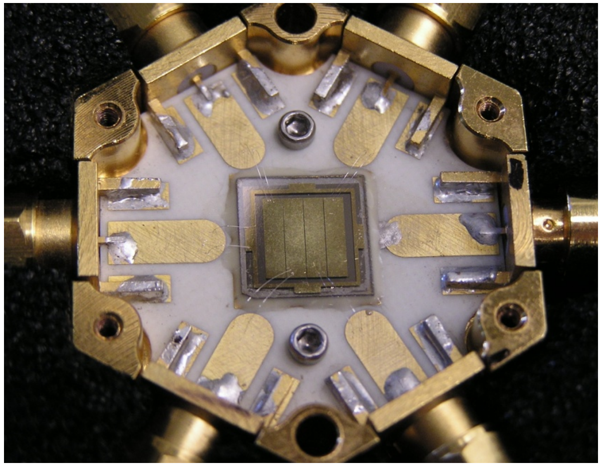
By C. Capoccia LNF SPAS

The PADME diamond target

- First BTF test-beam with polycrystalline diamonds:
  1. Two 500 μm thick and 4 **metal** strips: 6.5 mm long and 1.5 mm pitch
  2. 300 μm thick 40 **graphitized** strips 3 mm long, 100 μm width, and 170 μm pitch
  3. 50 μm thick, 2×2cm^2 sample for first PADME prototype
  4. 50 μm thick 5×5mm^2 sample for BTF beam diagnostics with Silver Paint

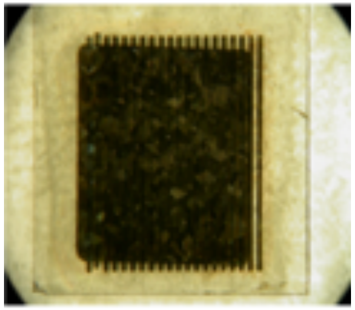


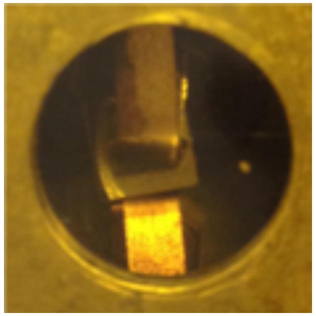
Main result of feasibility of 50 μm sensors already established



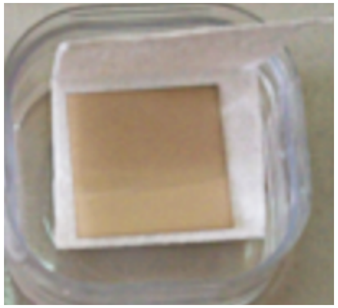
1.

2.



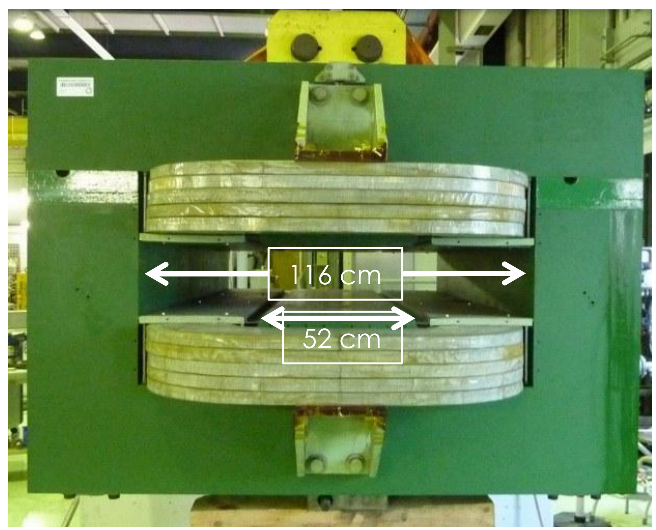


3.



4.

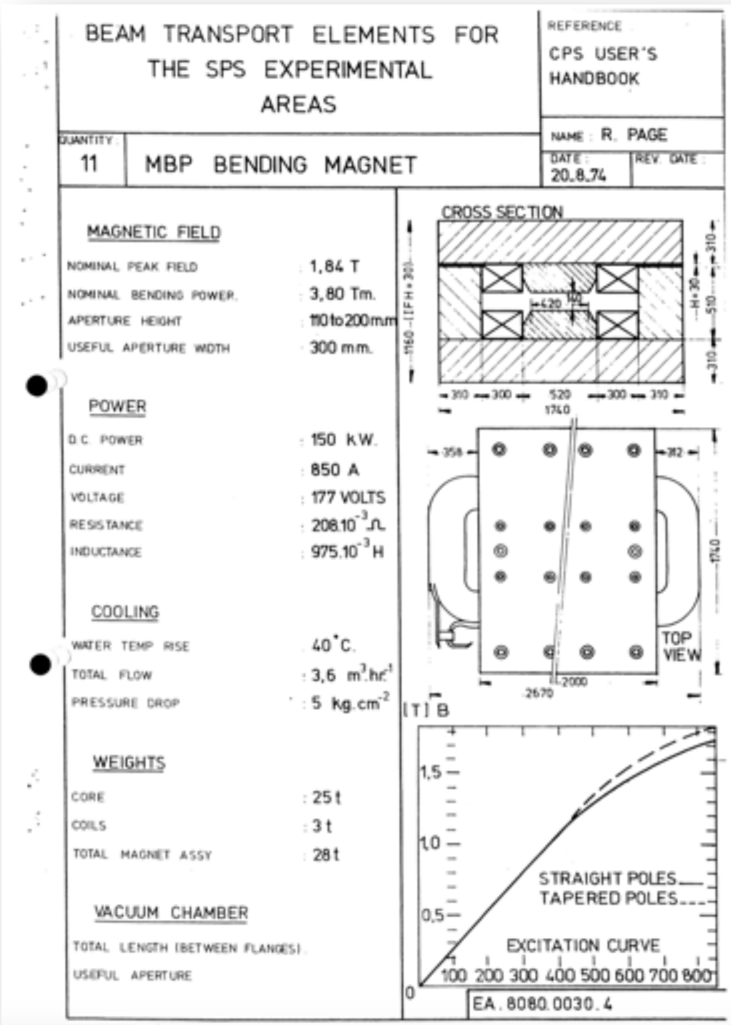
A possible analyzing magnet for PADME



11 to 20 cm gap

Available at CERN magnet division

A possible analyzing magnet for PADME



BEAM TRANSPORT ELEMENTS FOR THE SPS EXPERIMENTAL AREAS

REFERENCE: CPS USER'S HANDBOOK

QUANTITY: 11 — MBP BENDING MAGNET

NAME: R. PAGE — DATE: 20.8.74 — REV. DATE:

MAGNETIC FIELD

NOMINAL PEAK FIELD	1,84 T
NOMINAL BENDING POWER	3,80 Tm
APERTURE HEIGHT	110 to 200 mm
USEFUL APERTURE WIDTH	300 mm

POWER

D.C. POWER	150 kW
CURRENT	850 A
VOLTAGE	177 VOLTS
RESISTANCE	$208.10^{-3}\,\Omega$
INDUCTANCE	975.10^{-3} H

COOLING

WATER TEMP RISE	40°C
TOTAL FLOW	$3,6\ m^3 h^{-1}$
PRESSURE DROP	$5\ kg.cm^{-2}$

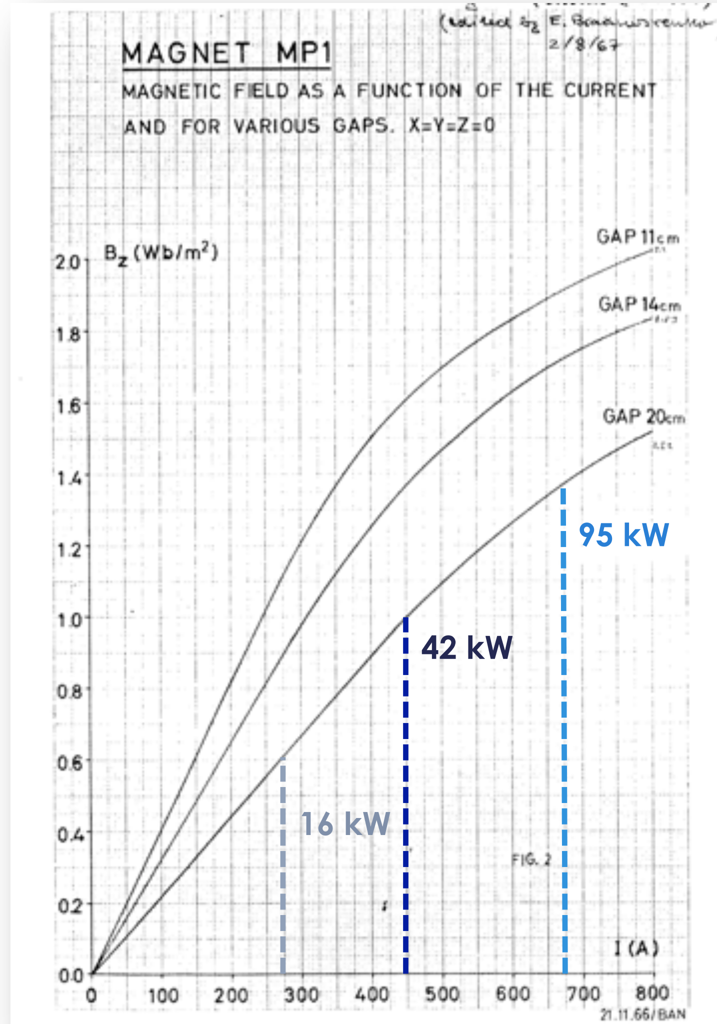
WEIGHTS

CORE	25 t
COILS	3 t
TOTAL MAGNET ASSY	28 t

VACUUM CHAMBER

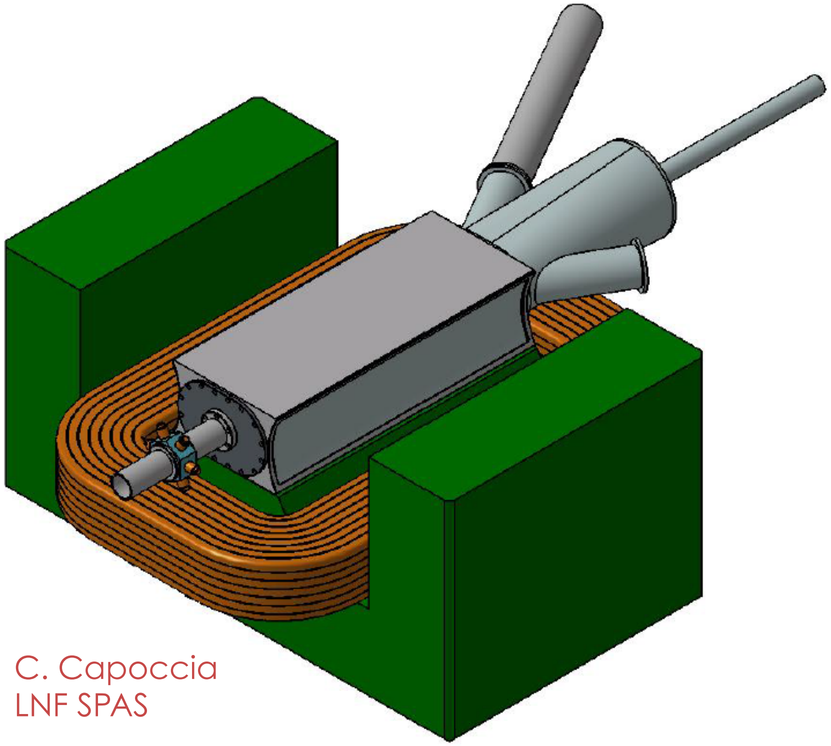
TOTAL LENGTH (BETWEEN FLANGES)

USEFUL APERTURE



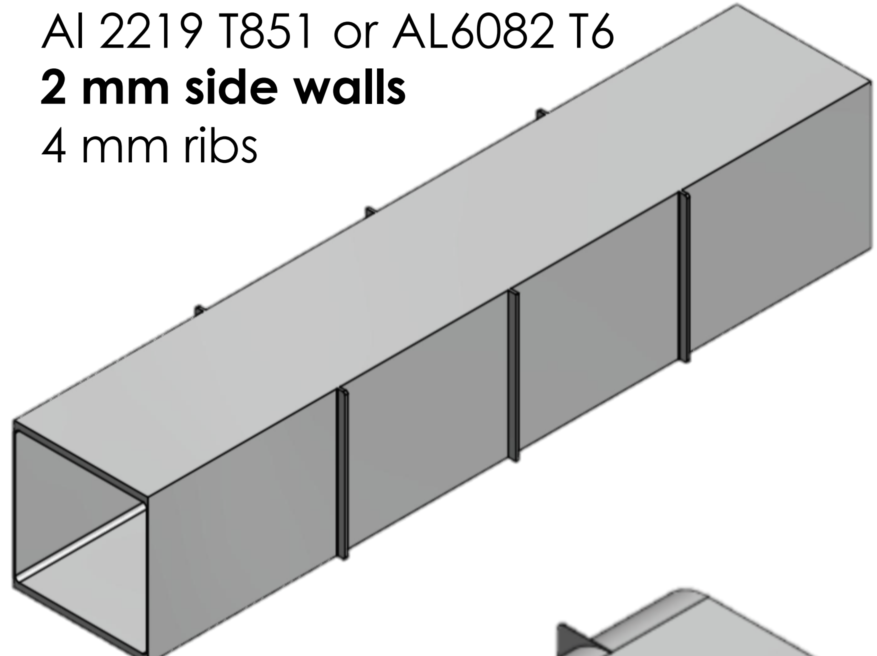
Tapered poles

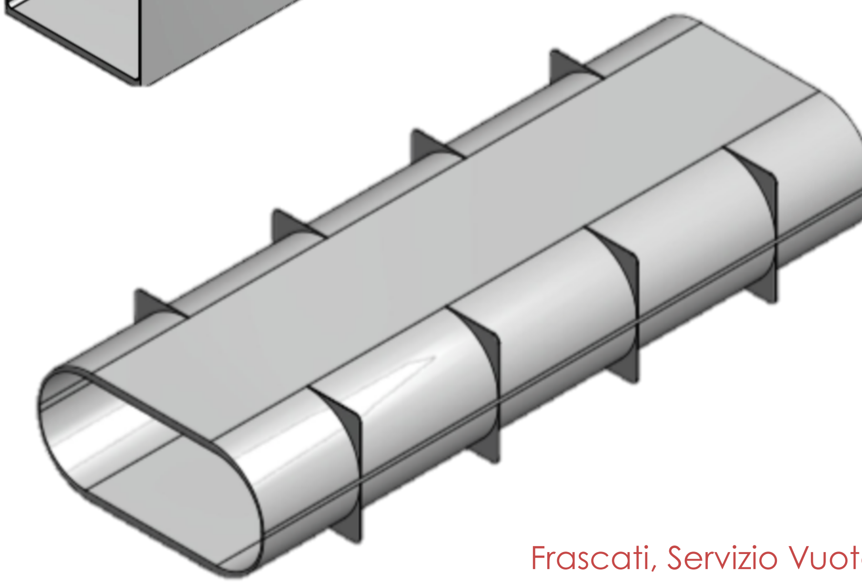
PADME vacuum vessel study



C. Capoccia
LNF SPAS

Al 2219 T851 or AL6082 T6
2 mm side walls
4 mm ribs



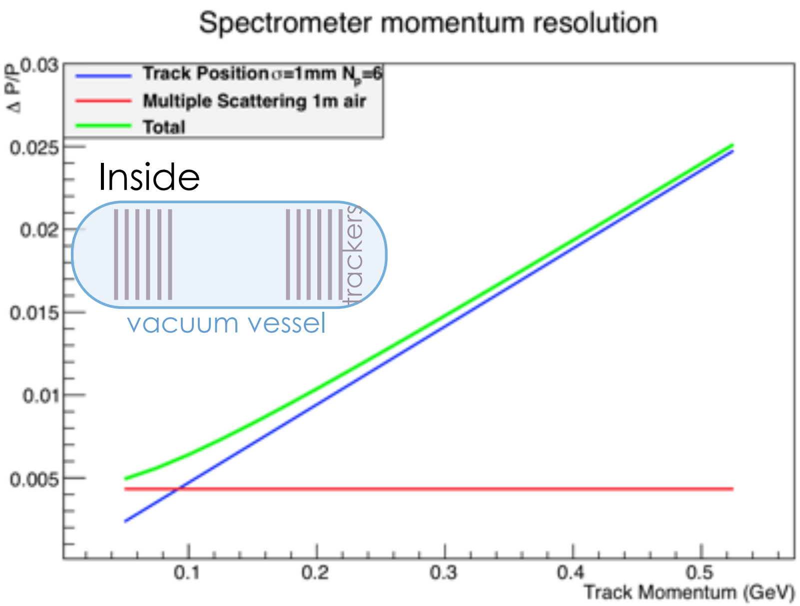


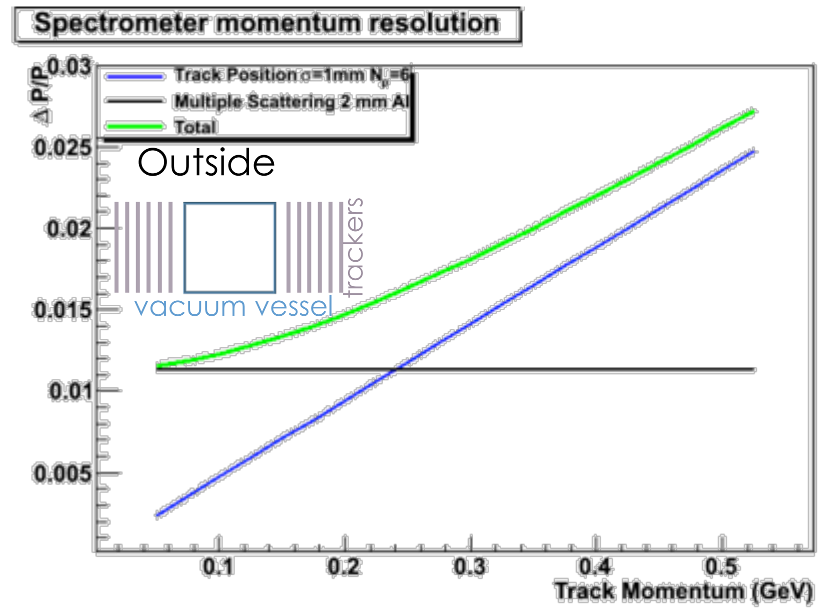
Frascati, Servizio Vuoto
V. Lollo, S. Bini

Different possibilities under study to minimize the material thickness

Different possibilities under study to minimize the material thickness

PAMDE spectrometer



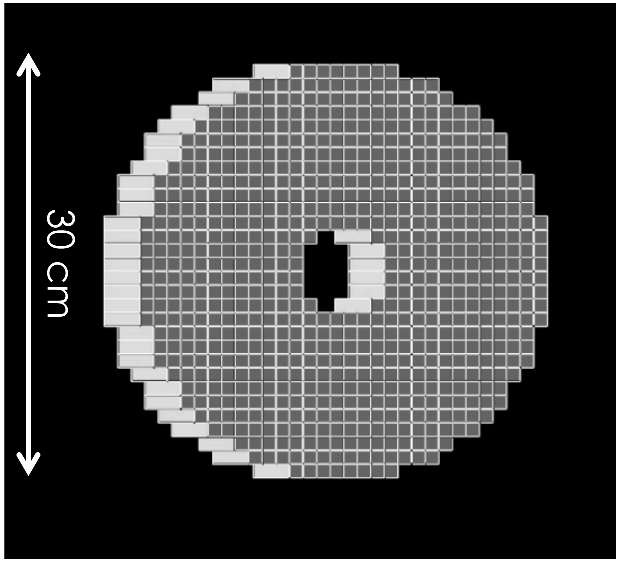


$$\left.\frac{\sigma(p)}{p}\right|^{\text{track error}} = \frac{\sigma(x)\ [\mathrm{m}]}{0.3\,B\ [\mathrm{T}]\ (L\ [\mathrm{m}])^2}\sqrt{720/(N+4)}\cdot p\ [\mathrm{GeV}/c]$$

$$\left.\frac{\sigma(p)}{p}\right|^{\mathrm{MS}} = \frac{\Delta p_x^{\mathrm{MS}}}{\Delta p_x^{\mathrm{magn}}} = \frac{13.6\,\sqrt{L/X_0}\ \mathrm{MeV}/c}{e\int_0^L B_y(l)\,\mathrm{d}l}$$

There is the possibility of having a spectrometer outside the vacuum: Impact on the PADME-visible experiment to be understood

The electromagnetic calorimeter

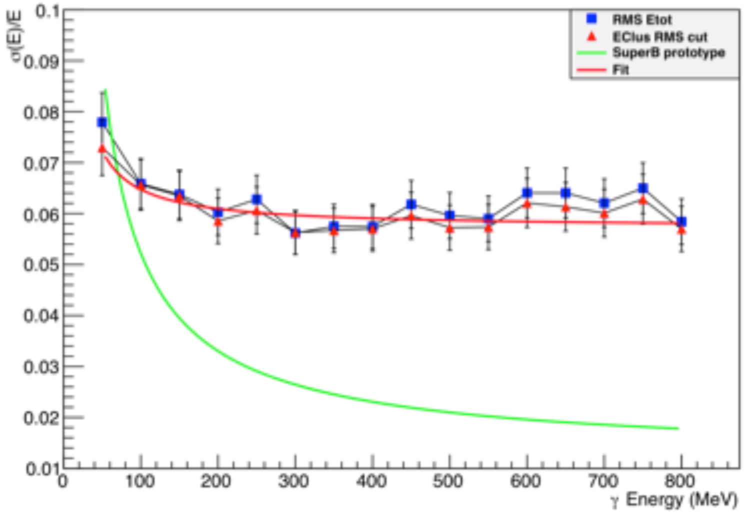


Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	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

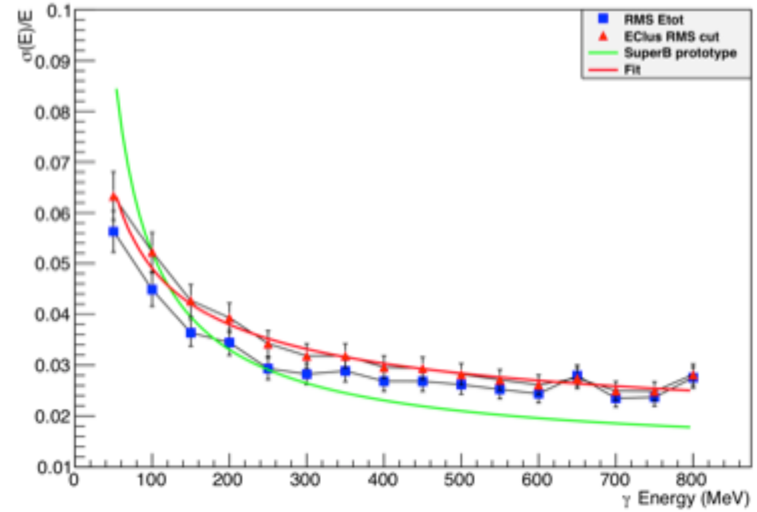
- Cylindrical shape: radius 150 mm, depth of 200 mm
  - Inner hole 4 cm radius
  - Active volume 13120 cm^3 total of 656 crystals 10x10x200 cm^3
- Material LSO(Ce): high LY, high ρ, small X_0 and R_M, short τ_{decay}
- Material BGO: high LY, high ρ, small X_0 and R_M, long τ_{decay}, (free form L3?)
- 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

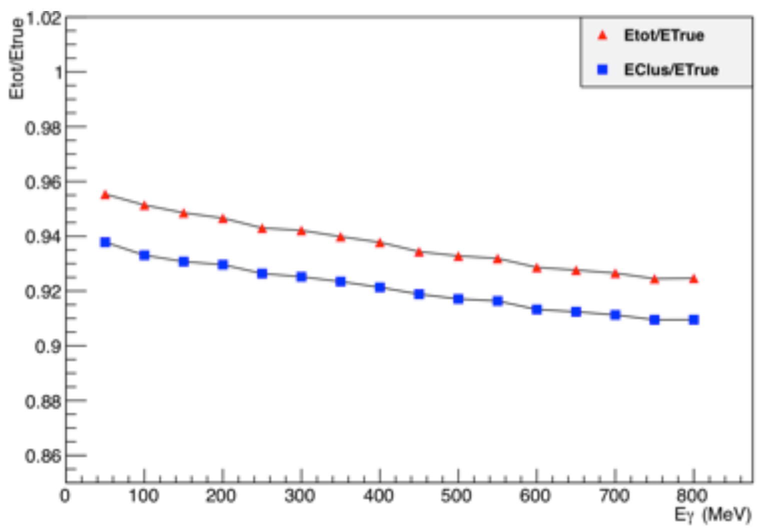
PADME calorimeter simulation

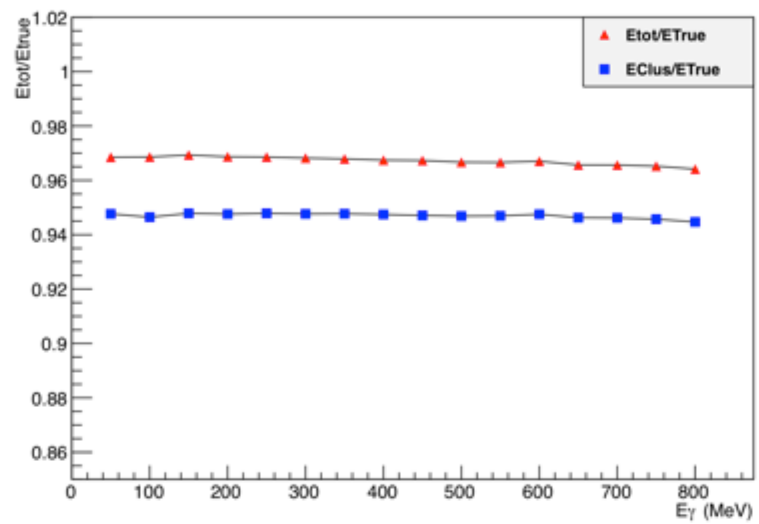
15 cm long LYSO crystals



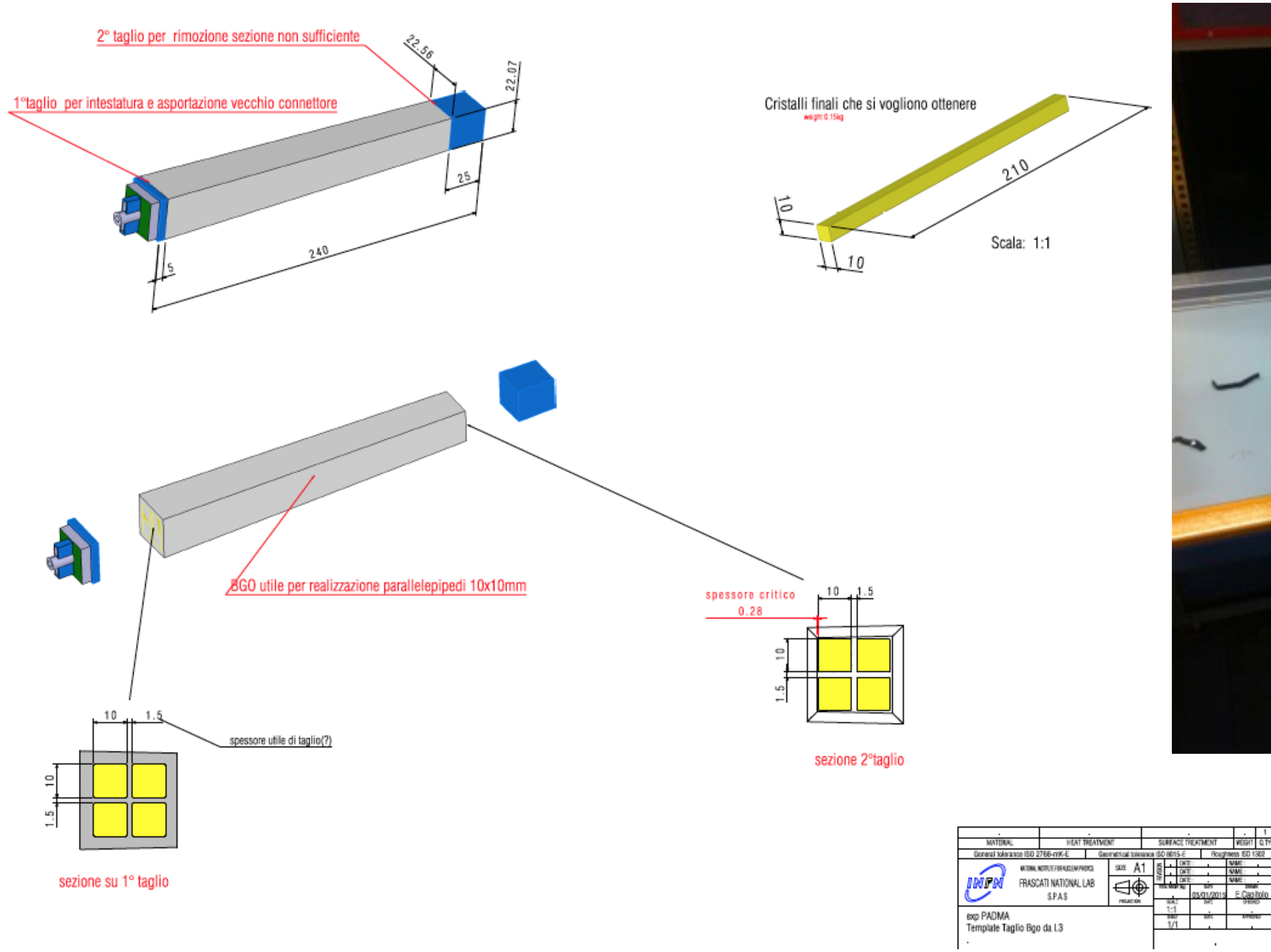
20 cm long LYSO crystals

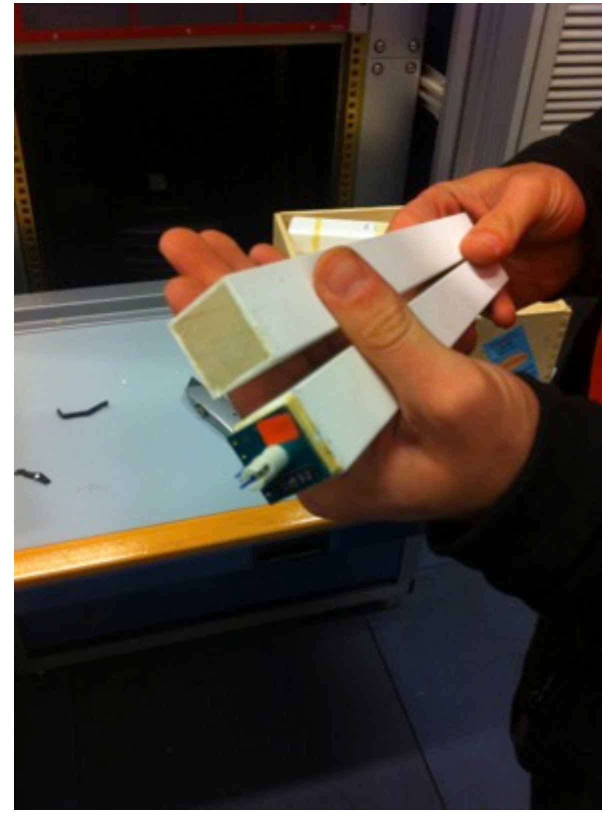






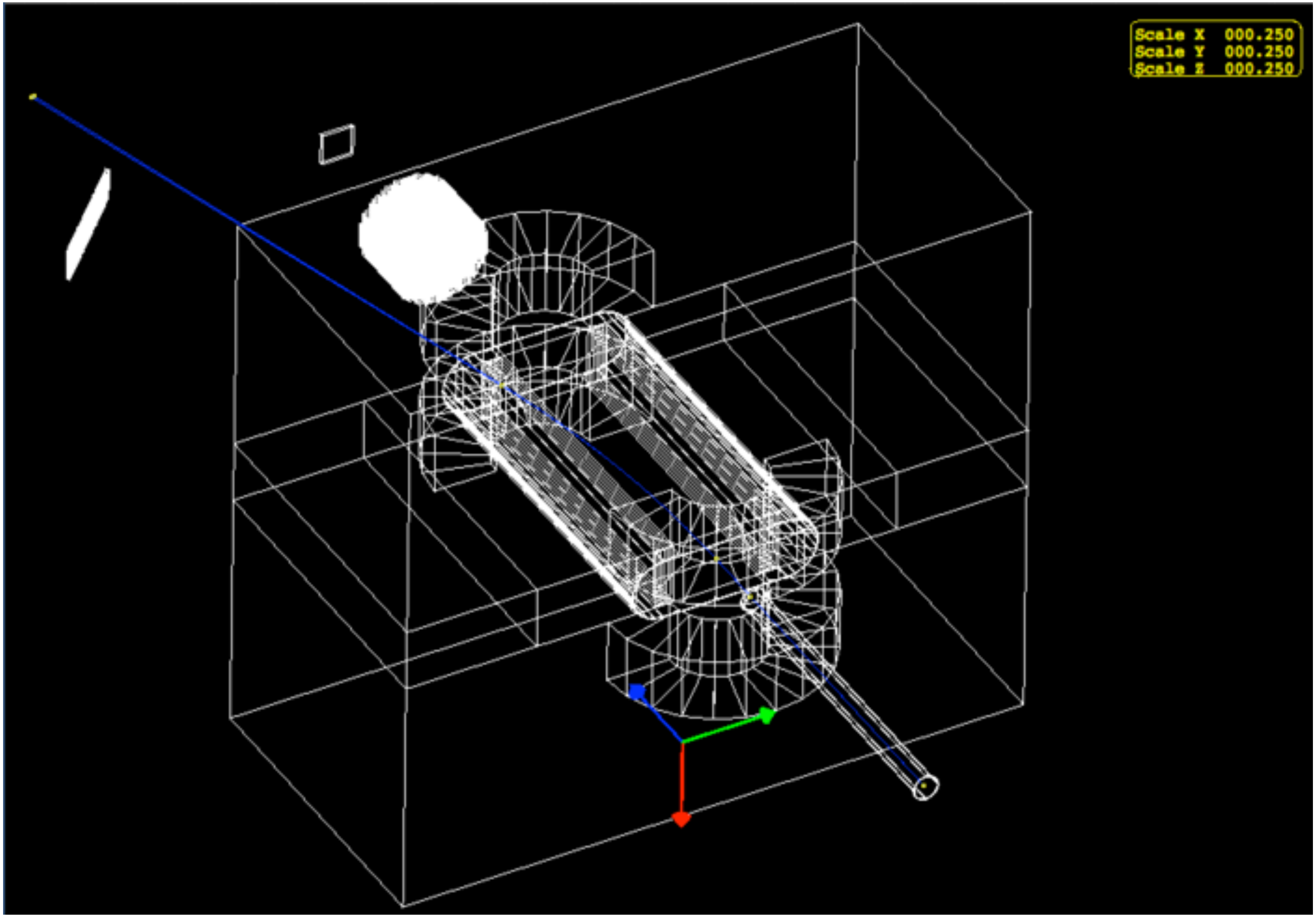
PADME ecal using L3 BGO crystals



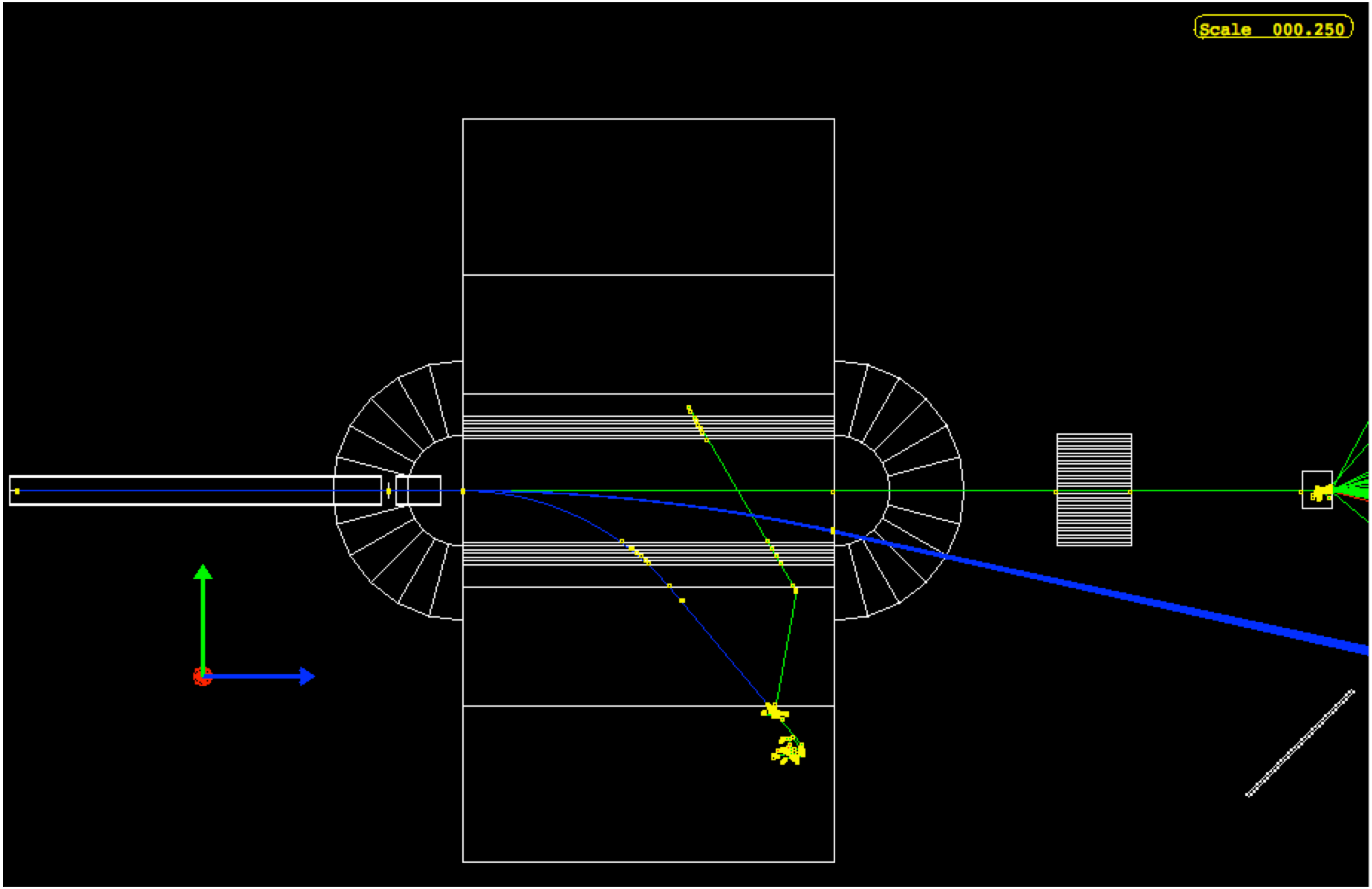


We collected ~80 BGO crystal from L3 calorimeter. We plan to cut them in 4 pieces of $10x10x210\ mm^3$ (up to 240 ecal cells already in our hands!)
Plan to test performance with 3x3mm APD and SiPM of 64 ch matrix in 2015

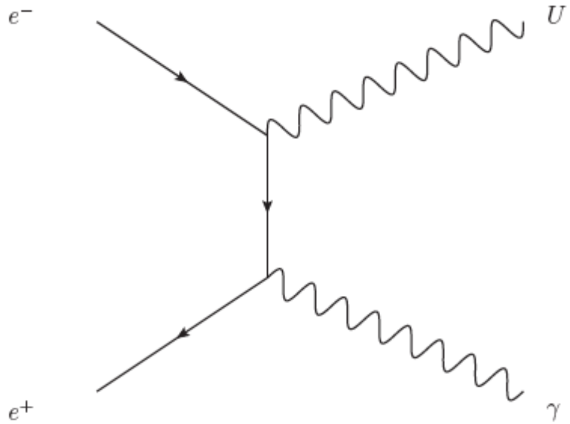
PADME geant4 simulation



A PADME BG event (2000 e^+)

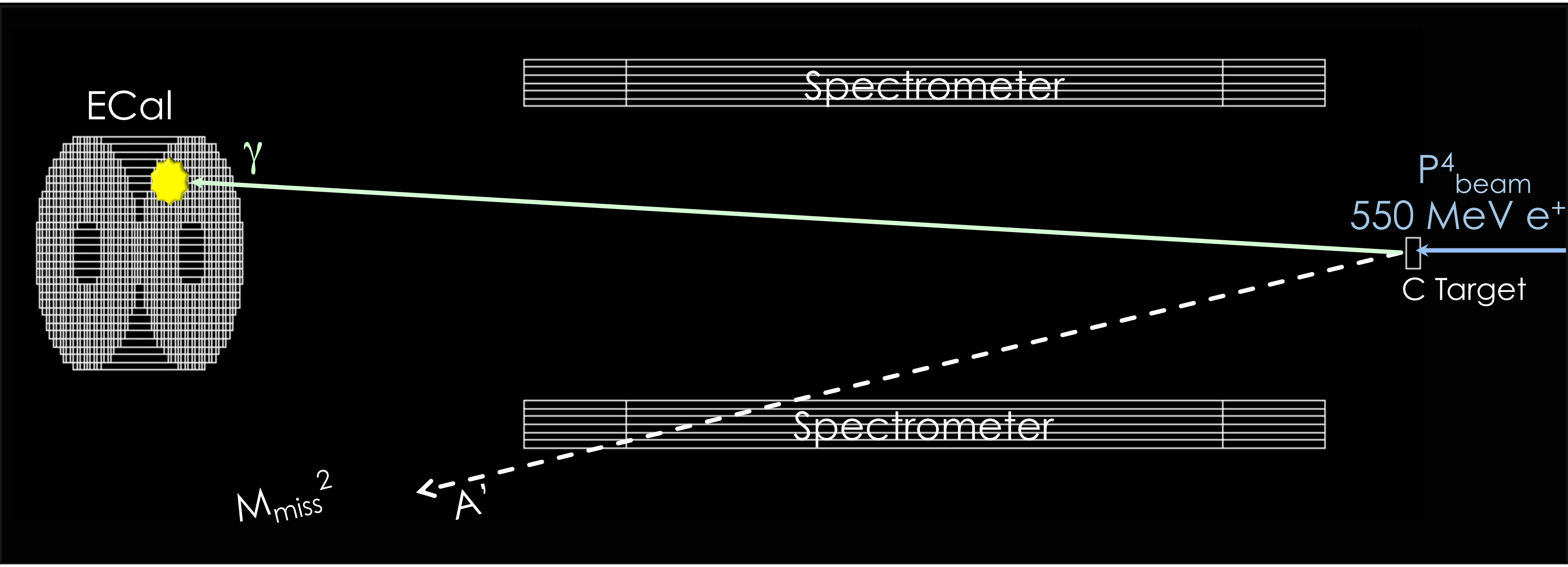


Search in annihilation production



Annihilation

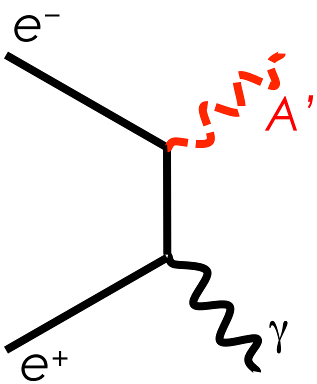
Experimental technique



- Search for the process: $e^+e^- \rightarrow \gamma A'$ on target e^- at rest electrons
- (10^4 550 MeV e^+)/bunch beam on a 50 μm diamond target with 50 bunch/s
  - Collect 4×10^{13} e+ on target in each year of data taking period at BTF (60% eff.)
- Measure in the ECal the E_γ and θ_γ angle wrt to beam direction
- Compute the $M_{miss}^2 = (P^4_{e-} + P^4_{beam} - P^4_{\gamma})^2$
  - $P^4_{e-} = (0,0,0,m_e)$ and $P^4_{beam} = (0,0,550,\mathrm{sqrt}(550^2 + m_e^2))$

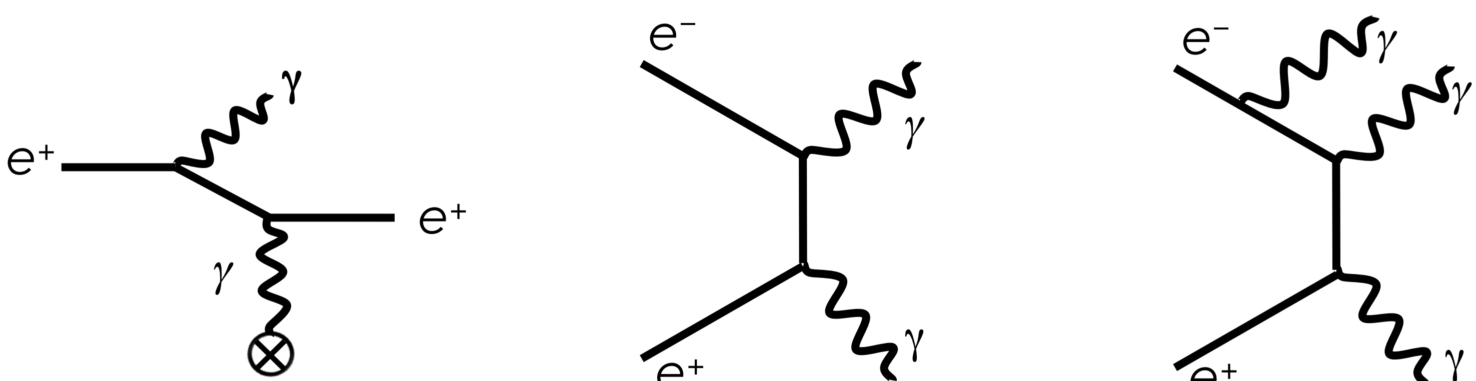
Main background sources

- Geant4 simulation accounts for:
  - Bremsstrahlung, 2 photon annihilation, Ionization processes, Bhabha and Moller scattering, and production of δ -rays.
  - Custom treatment of $e^+e^-\rightarrow\gamma\gamma(\gamma)$ using CalcHep generator.



Signal: $e^+e^- \rightarrow \gamma$ +missing mass (A')

Backgrounds



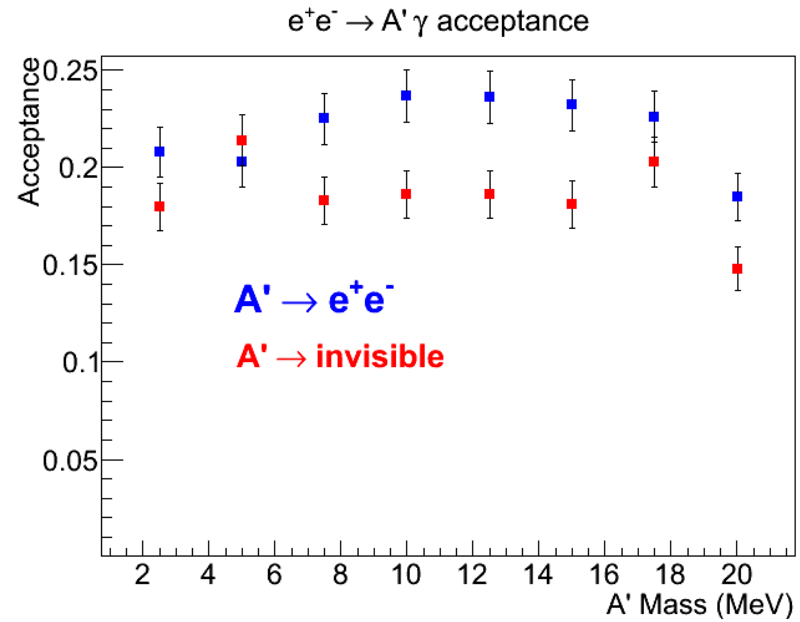
+1 electron

+1 γ

+2 γ

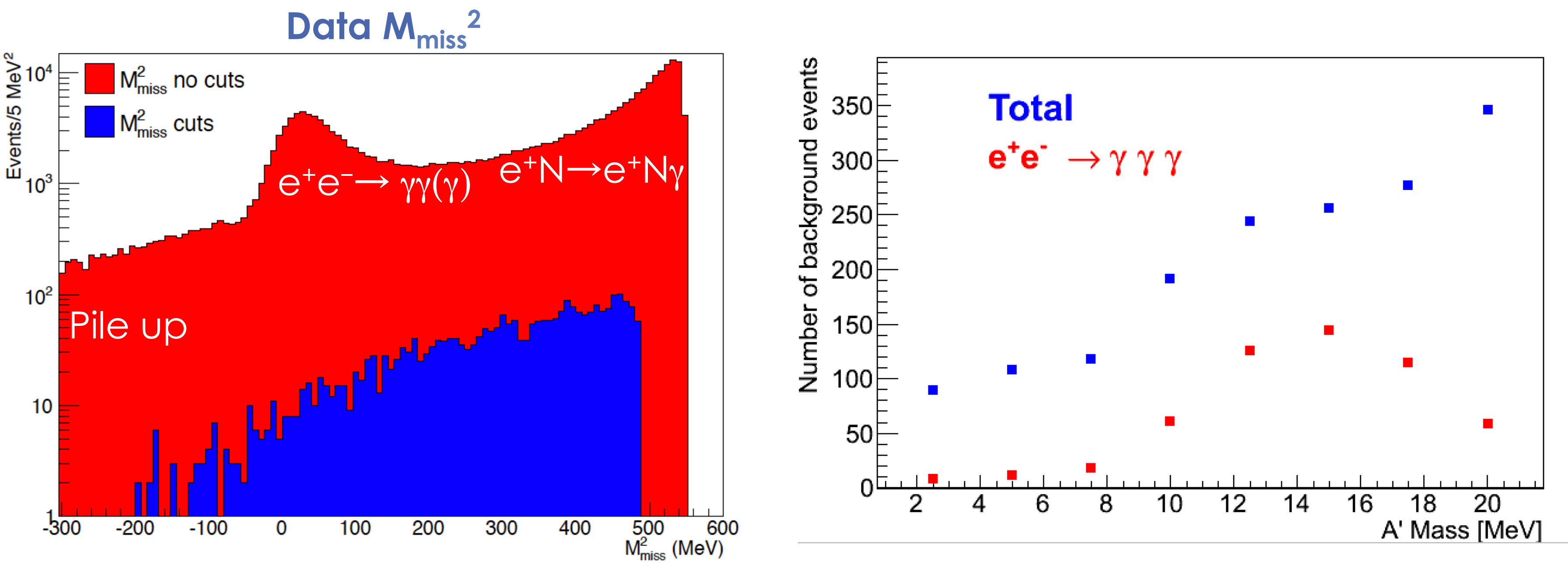
Inclusive signal selection

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: $E_{min}(M_{A'}) < E_{Cl} < 400$ MeV
  - Removes low energy bremsstrahlung photons and piled up clusters
- Positron veto using 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: $M_{miss}{}^2{}_{A'} \pm \sigma Mmiss^2{}_{A'}$

Background estimates

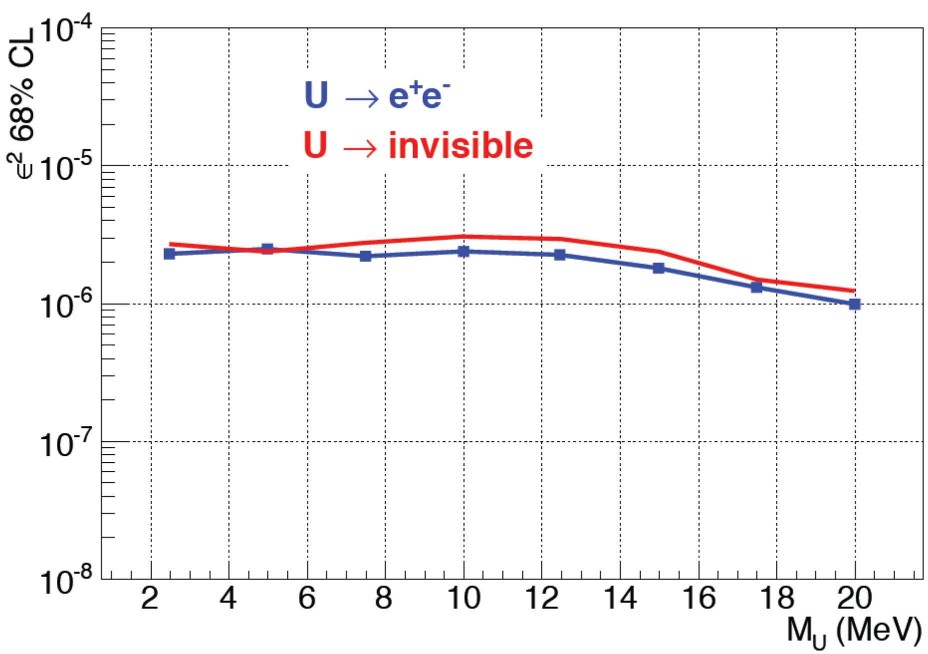


- BG sources are: $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma\gamma$, $e^+N \to e^+N\gamma$, Pile up
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{Miss}^2.
- Veto inefficiency at high missing mass ($E(e^+) \simeq E(e^+)_{beam}$)
  - New Veto detector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

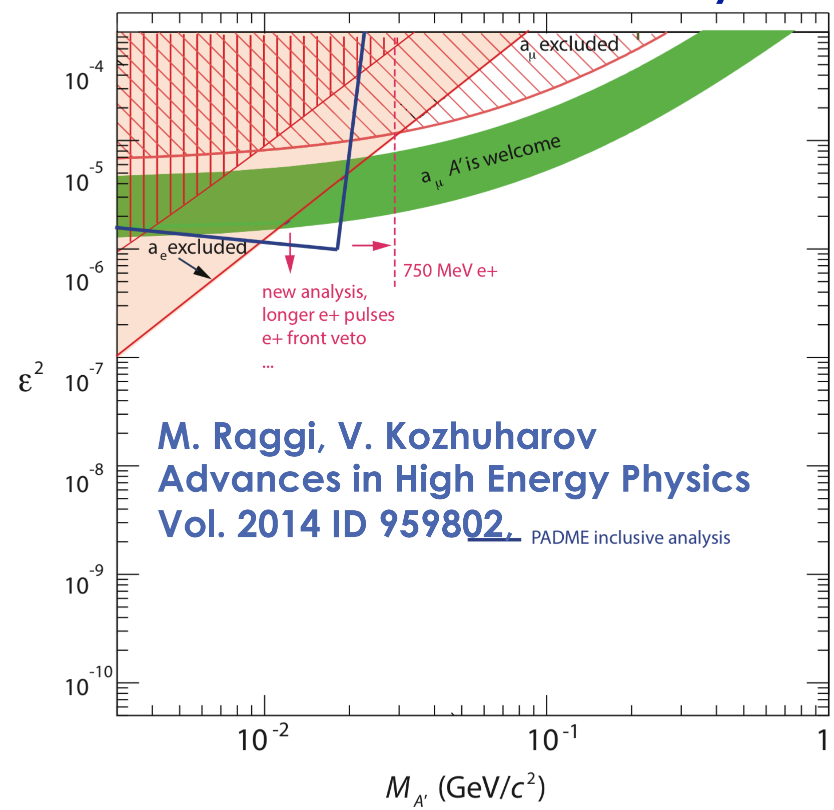
PADME invisible sensitivity estimate

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

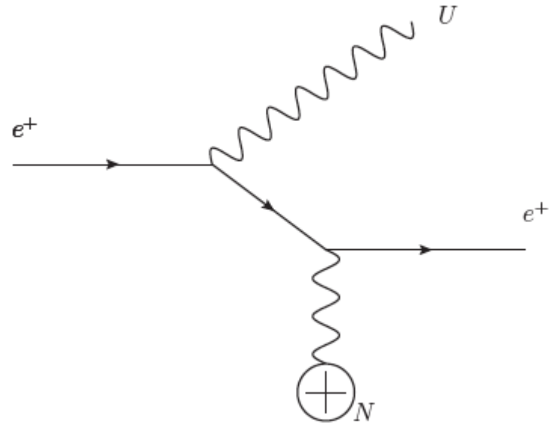
$$\frac{\Gamma(e^+e^- \to U\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta$$



PADME invisible sensitivity

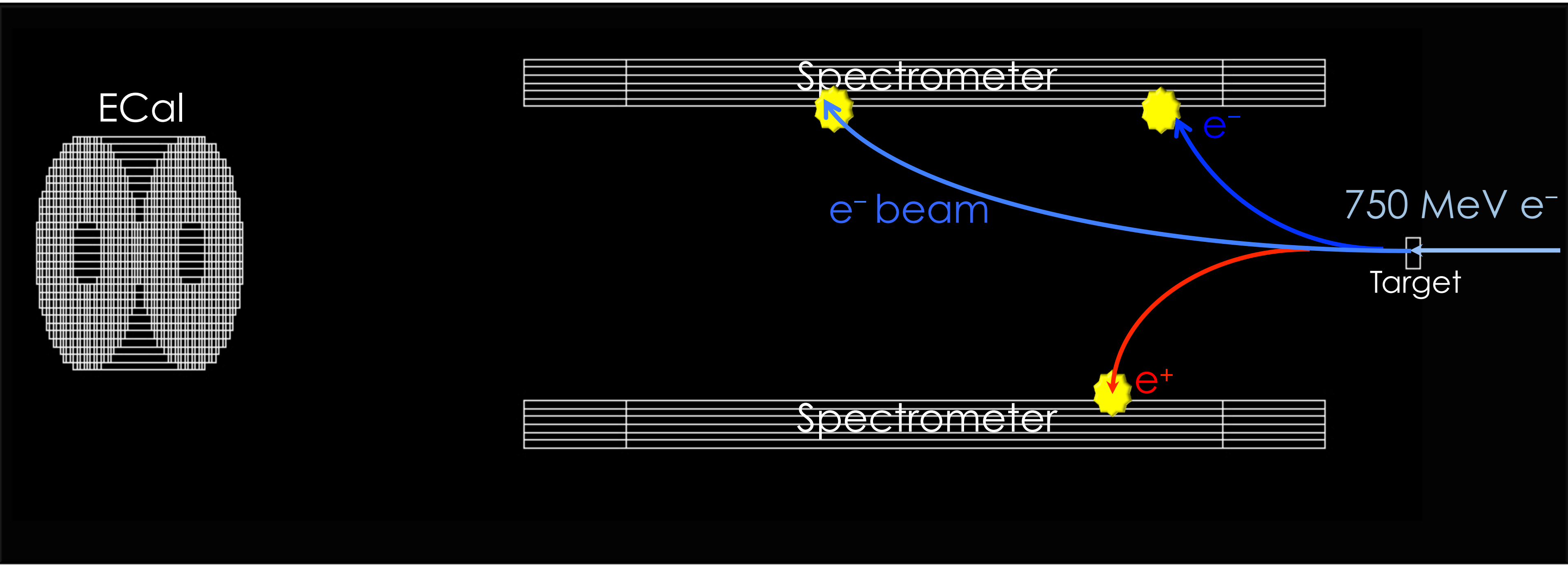


Search in bremsstrahlung production



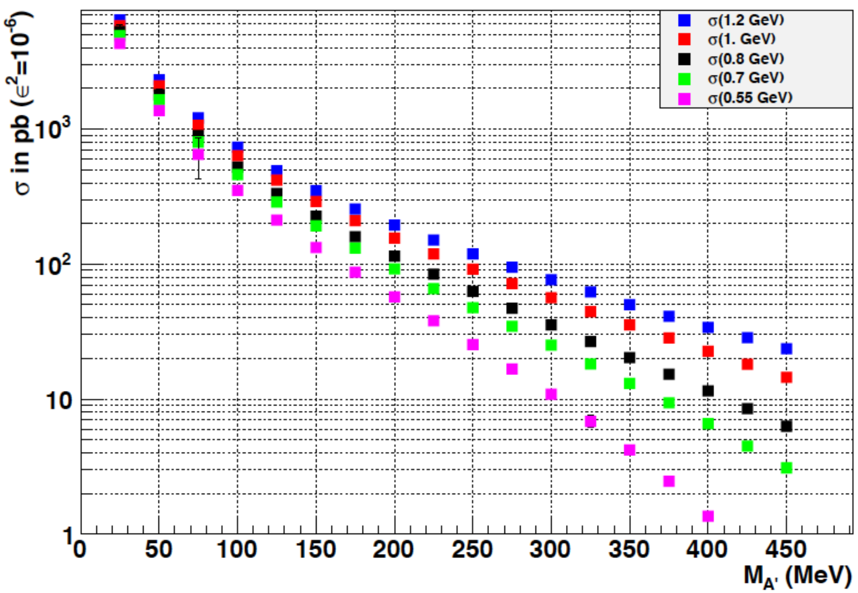
$Bremsstrahlung$

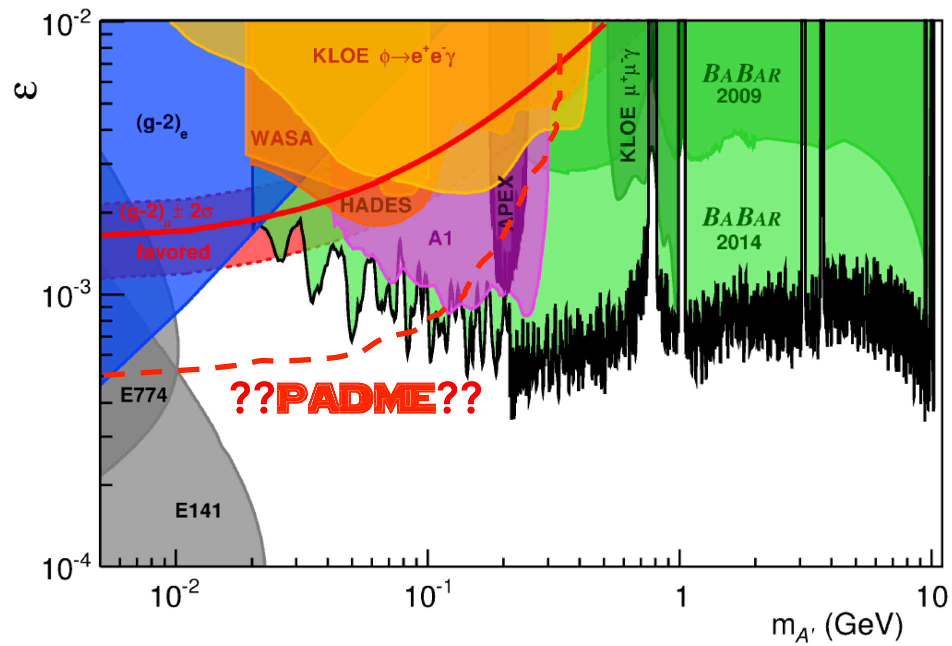
Visible search experiment



- Search for the process: **$e^-N \rightarrow Ne^-A' \rightarrow Ne^-e^-e^+$**
- 750 MeV electron beam on a ~0.5 mm tungsten target
- Measure in the spectrometer only the P^4_{e-} P^4_{e+}
- Compute the $M_{A'}^2 = (P^4_{e-} + P^4_{e+})^2$ and decay vertex position
  - Search for peaks in the e^+e^- invariant mass

Indication on visible decay sensitivity

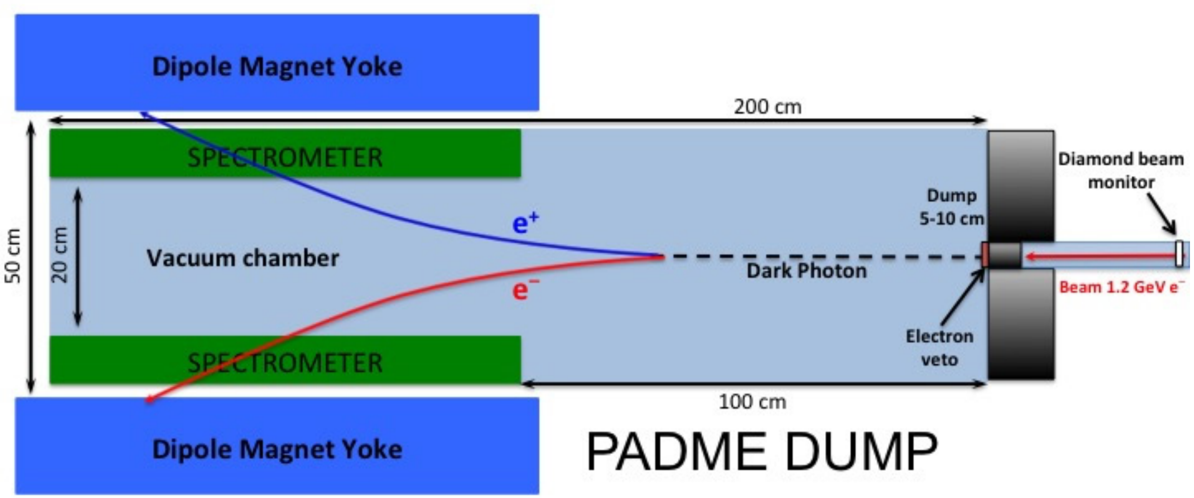


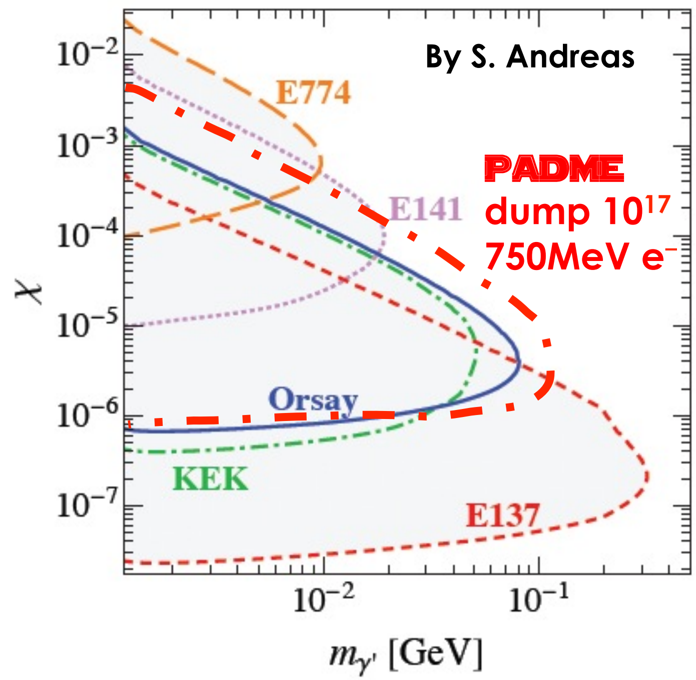


- Production cross section calculated with MADGraph code
- Final state is more constrained by invariant mass of the e^+e^- pair
- Indication of a limit down to $\varepsilon^2 \sim 10^{-7}$ is expected at low masses
  - Density of tracks in the spectrometer is the crucial point to be clarified
  - Design of the spectrometer not yet finalized

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**	**1.2**	**$2\cdot10^{20}$**	**~30 C**	**~0.1**	**1**		





PADME dump toymc

- Try to evaluate driving design parameters for the PADME dump
- Toymc includes:
  - Production cross section calculated by MADgraph (thanks to A. Celentano)

$$\frac{d\sigma_{\gamma'}}{dx_e\, d\cos\theta_{\gamma'}} = 8\alpha^3\chi^2 E_e^2 x_e\, \xi(E_e, m_{\gamma'}, Z, A)\sqrt{1-\frac{m_{\gamma'}^2}{E_e^2}} \left[\frac{1-x_e+\frac{x_e^2}{2}}{U^2} + \frac{(1-x_e)^2 m_{\gamma'}^4}{U^4} - \frac{(1-x_e)x_e m_{\gamma'}^2}{U^3}\right],$$

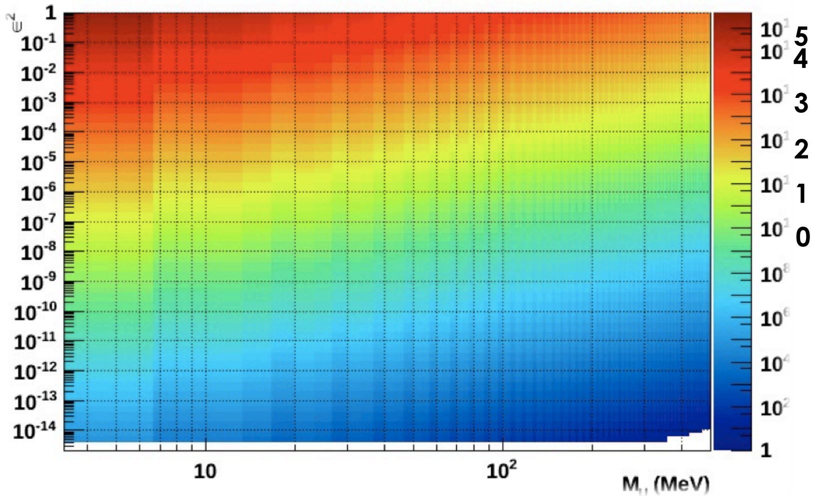
  - Evaluate the produced number of dark photons

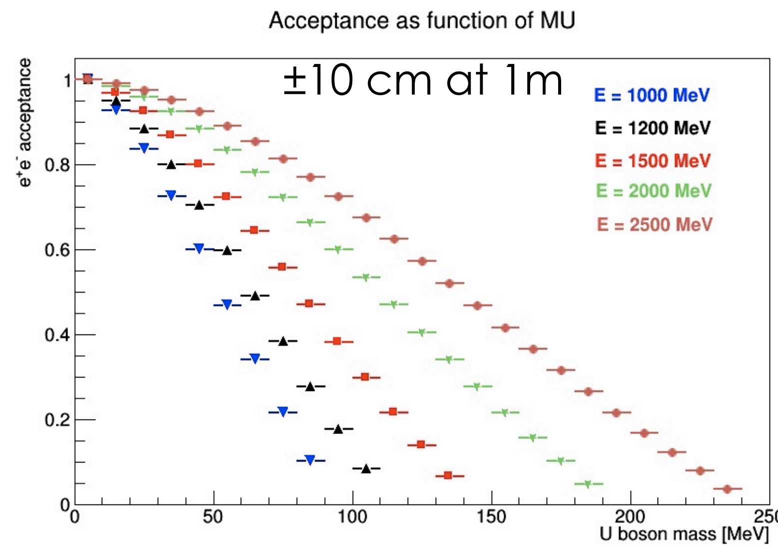
$$N_{\gamma'} = \sigma_{\gamma'} N_e\, n_{sh}\, L_{sh} = \sigma_{\gamma'} N_e \frac{N_0}{A} \rho_{sh} L_{sh},$$

  - Scale by decay length acceptance $\frac{dP(l)}{dl} = \frac{1}{l_{\gamma'}} e^{-l/l_{\gamma'}}$
  - Scale by electron acceptance in the detector using kinematical distribution from a toy
    - Distribution have been compared with MADGraph for several M_U
  - Not yet implemented final in depth production of the A'
    - Reduce # electron of 1/e each X_0 (pessimistic!)
    - Next plot not to be considered exclusions still

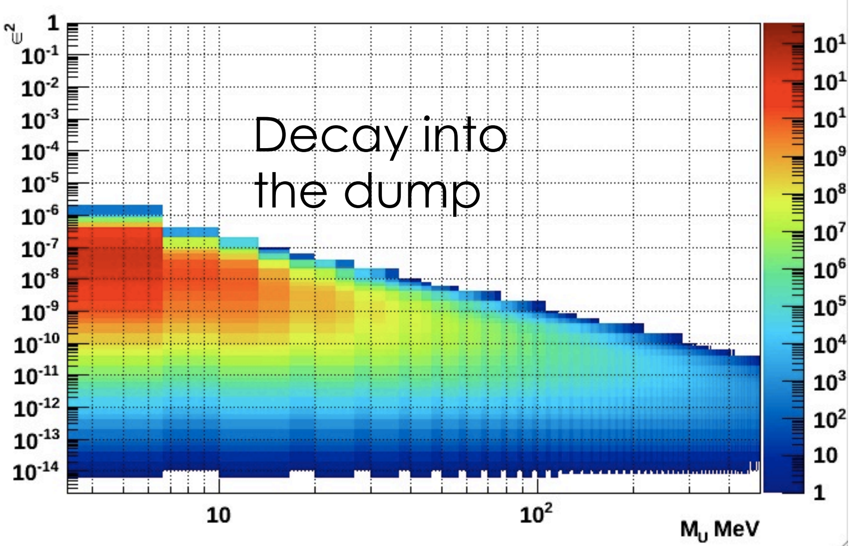
PADME dump main parameters

Dark photon production

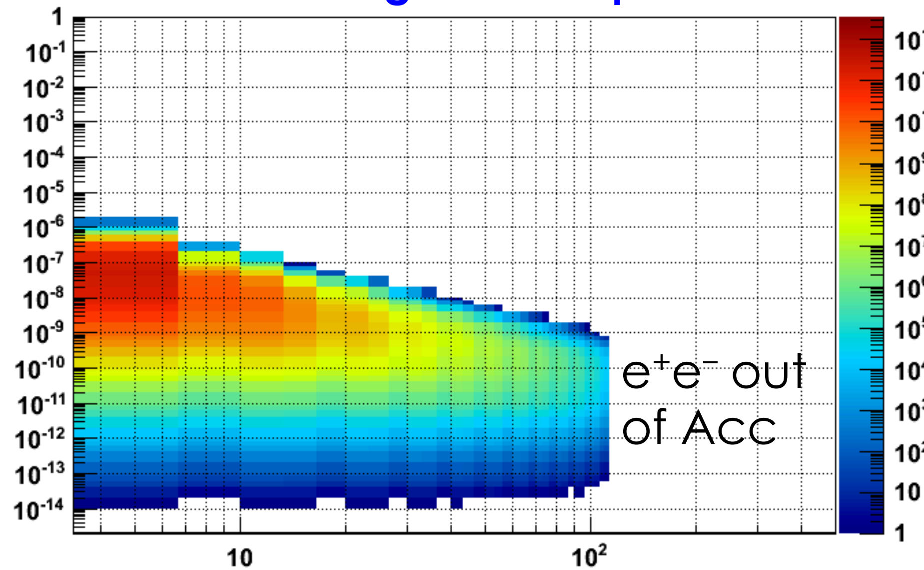




Decay length acceptance applied

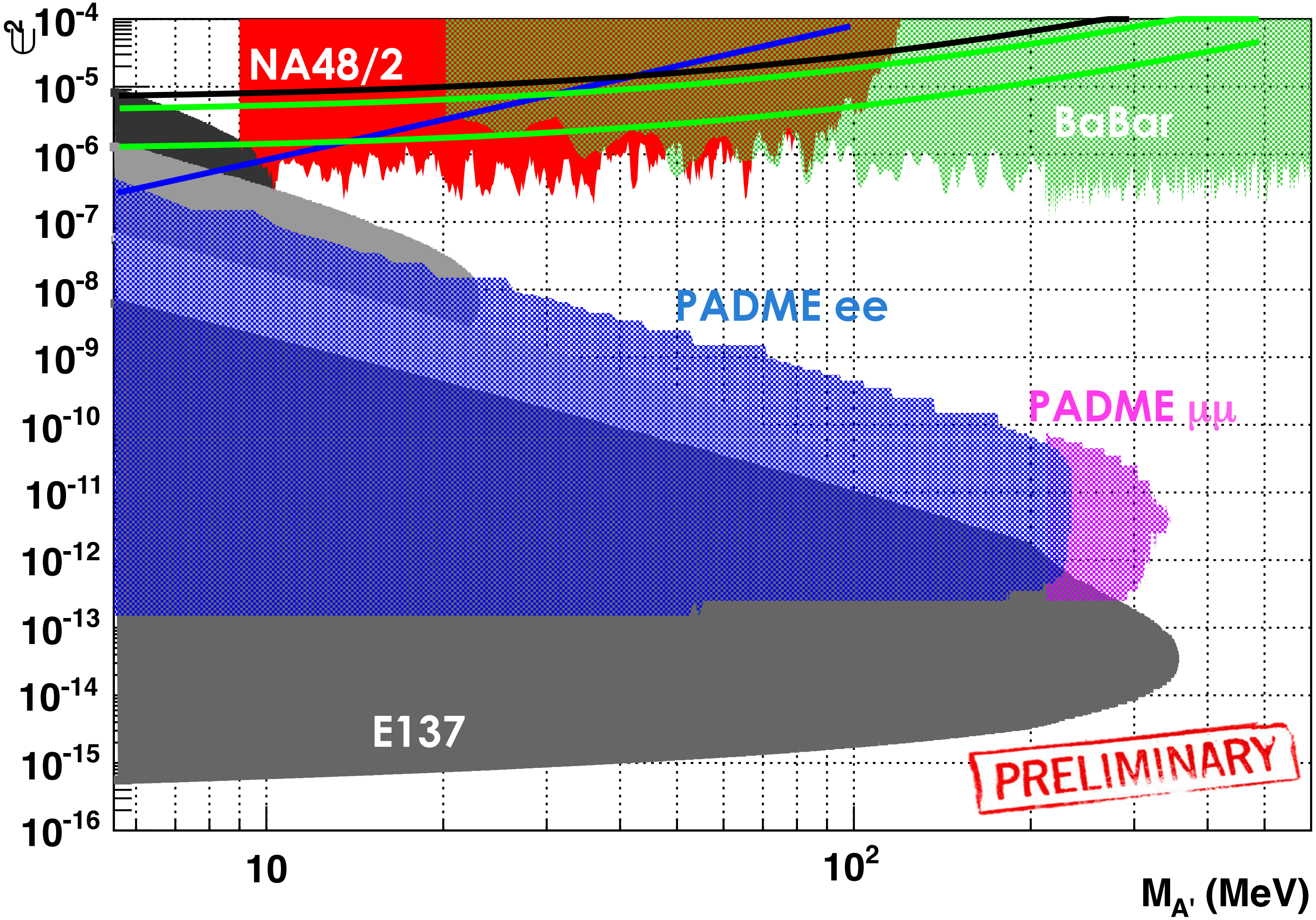


Electron angular acceptance



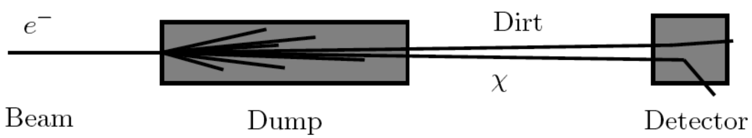
Dump comparison

Zero BG hypothesis, in depth production to be refined, not yet a sensitivity plot



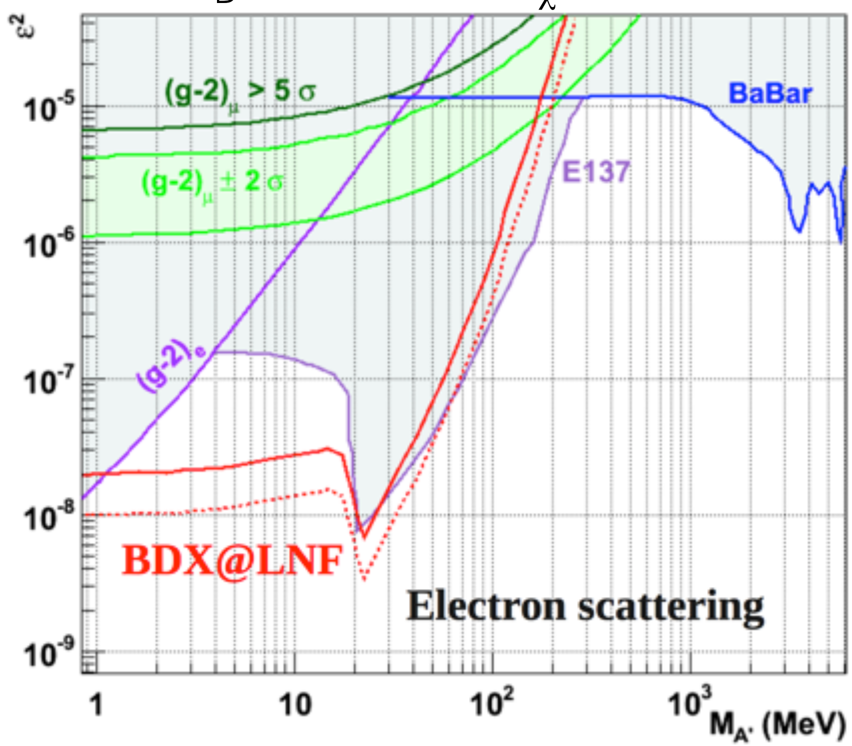
$1 \cdot 10^{20}$, 1.2 GeV electrons; 20 cm aperture at 50 cm from 10 cm W dump

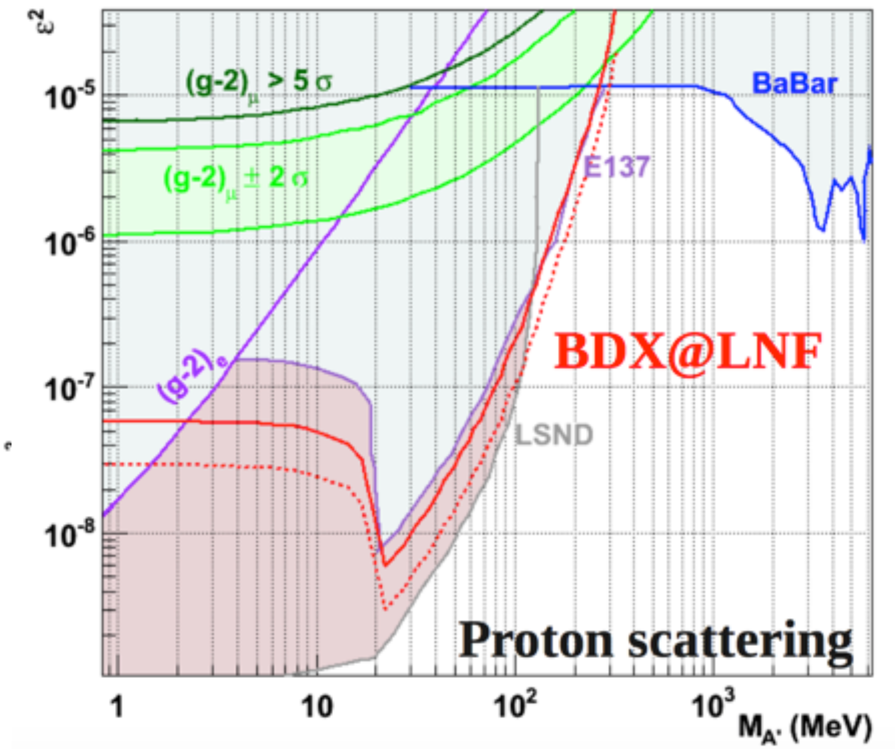
BDX @ LNF



A. Celentano, talk at " What Next LNF"
Same acceptance limit at 100 MeV coming from low beam energy

α_D=0.1 m_χ=10 MeV





Beam energy **1.2 GeV** (e^-)
CsI detector 60×60×225 cm^3 built with crystals from dismounted BaBar ECal?

PADME project plans

- Project has been presented as a “What Next” Project in INFN CSN1
  - The project has received positive comments form CSN1 referees
  - Proposal for R&D financing will be discussed in the next CSN1 meeting
- Proto collaboration formed including
  - LNF, Rome1, Lecce and Sofia university
- **6 weeks** test beam time asked at **DAΦNE BTF in 2015**
  - Study the prototype of BGO calorimeter solution (L3 crystals)
  - Test diamond target prototypes
  - Study the maximum beam current per bunch and beam spot size
  - Optimize beam characteristics for PADME operation bunch length, number of particle per bunch, background, beam positioning stability
- Interesting synergy with BDX project identified (BDX at LNF?)
- Many item still to be covered! Search for more collaborators started

PADME kick-off meeting

PADME kickoff meeting

20-21 April 2015 *Laboratori Nazionali di Frascati*
Europe/Rome timezone

- **Overview**
- Scientific Programme
- Timetable
- Contribution List
- Author index

Massive photon-like particles are predicted in many extensions of the Standard Model. They have interactions similar to the photon, are vector bosons, and can be produced together with photons.
The **PADME** experiment proposes a search for the dark photon (U) in the $e^+e^- \rightarrow \gamma U$ process in a positron-on-target experiment, exploiting the positron beam of the DAΦNE BTF, produced by the linac at the Laboratori Nazionali di Frascati, INFN.
In one year of running a sensitivity in the relative interaction strength down to 10^{-6} is achievable, in the mass region from 2.5 MeV < M_U< 22.5 MeV. To exploit the production of dark photons in Bremsstrahlung processes and their subsequent decay into pairs of leptons $U \rightarrow e^+e^-$ the experiment employs a magnetic spectrometer, which allows to probe and improve the current exclusions limits by extracting the linac electron beam at maximum intensity (~ 10^{20} EOT/year) on a dump.
This meeting aims at identifying the necessary research and development, design and simulation issues that will lead to the preparation of a draft of a Technical Proposal before the summer. The event will also further strengthen the **PADME** collaboration by bringing together a large community of colleagues who are interested in this kind of physics.

PADME website
http://www.lnf.infn.it/acceleratori/padme/index.html

Conclusions and plans

- An experiment running at DAΦNE BTF sensitive to both A'→invisible and A'→e^+e^- decays has been proposed to INFN CSN1
- Exclusion limit in ε^2 down to $1\text{-}2\cdot10^{-6}$ can be achieved in invisible decays with the present BTF beam parameters in the region $M_{A'}$ 2-22 MeV (28 with e^+ energy 750 MeV)
  - **M. Raggi and V. Kozhuharov, Advances in High Energy Physics Vol. 2014 ID 959802,**
- Possible accessible regions for a bremsstrahlung produced A'→e^+e^- were identified to reach ~100MeV
  - Detailed study of the sensitivity in this channel are ongoing
- Beam dump experiment searching for both visible and invisible Dark photon decays are also possible.
- In all the cases an energy upgrade of the Linac will be desirable

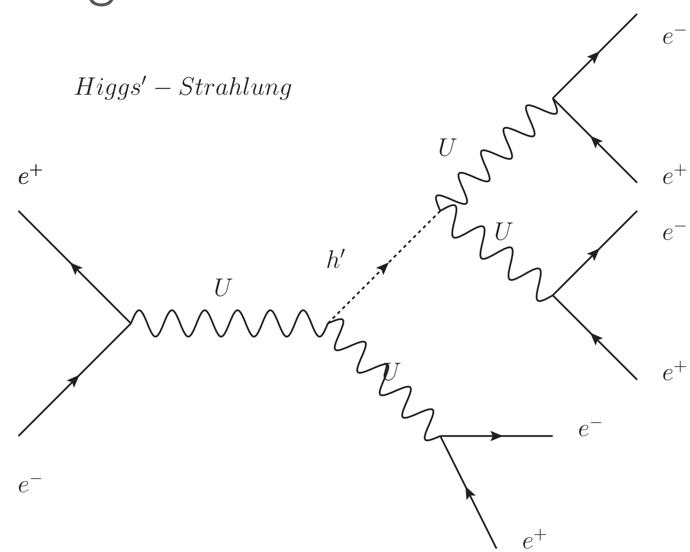
SPARE SLIDES

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)

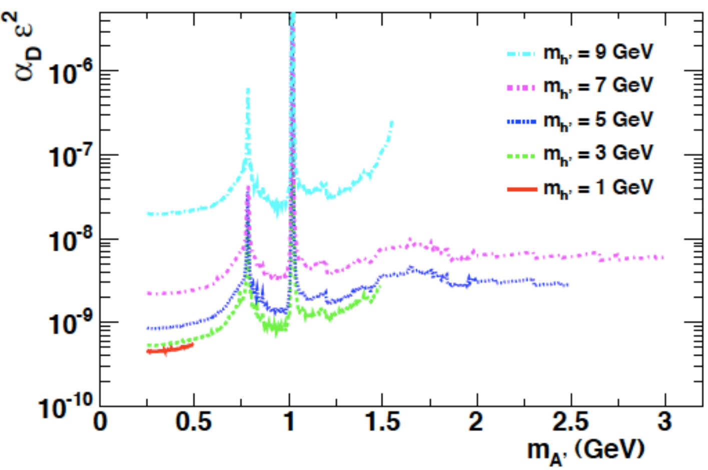
- U boson can be produced together with a dark Higgs h' through a Higgs-strahlung $e^+e^- \rightarrow Uh'$
  - Cross section =20fb x $(\alpha/\alpha_D)(\varepsilon^2/10^{-4})(10\text{GeV})^2/s$
  - For light h' and U ($M_{U,h'}<2M\mu$) final state with 3(e+e- pair) are predicted
  - Background events 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

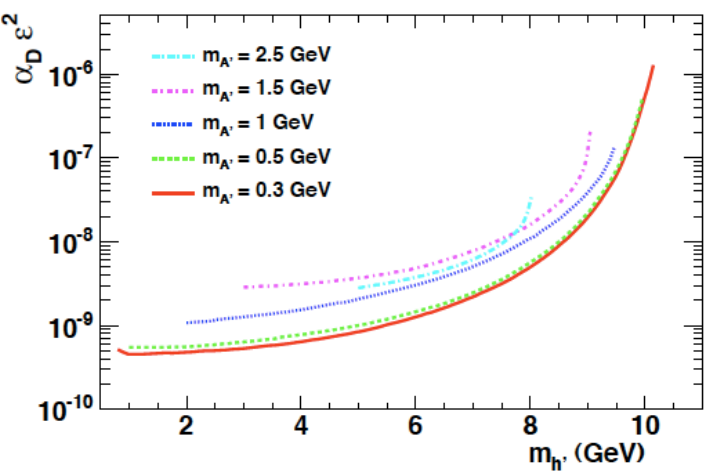
- Experimental search by BaBar and KLOE for U masses above 200 MeV



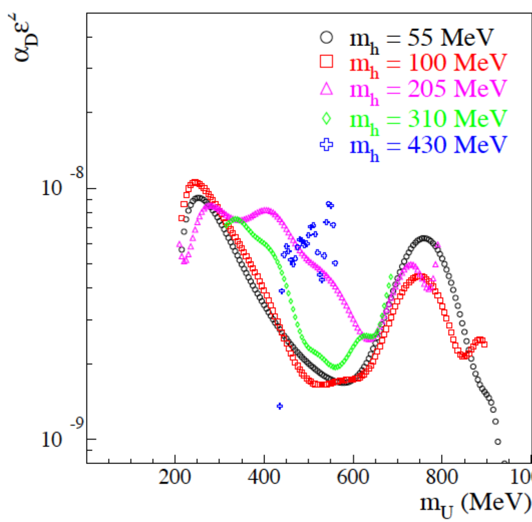
Experimental status U(1) + dark higgs

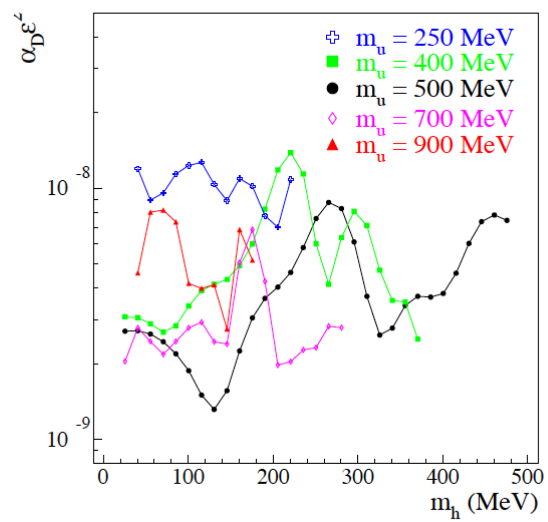
BaBar Phys. Rev. Lett. 108, 211801 (2012)





KLOE-2 arXiv:1501.06795

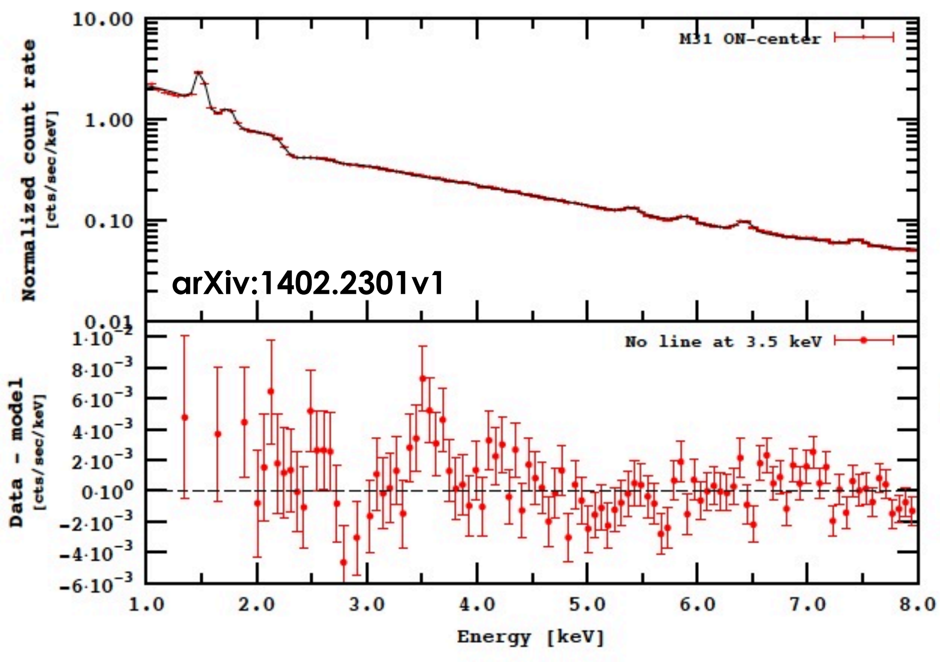


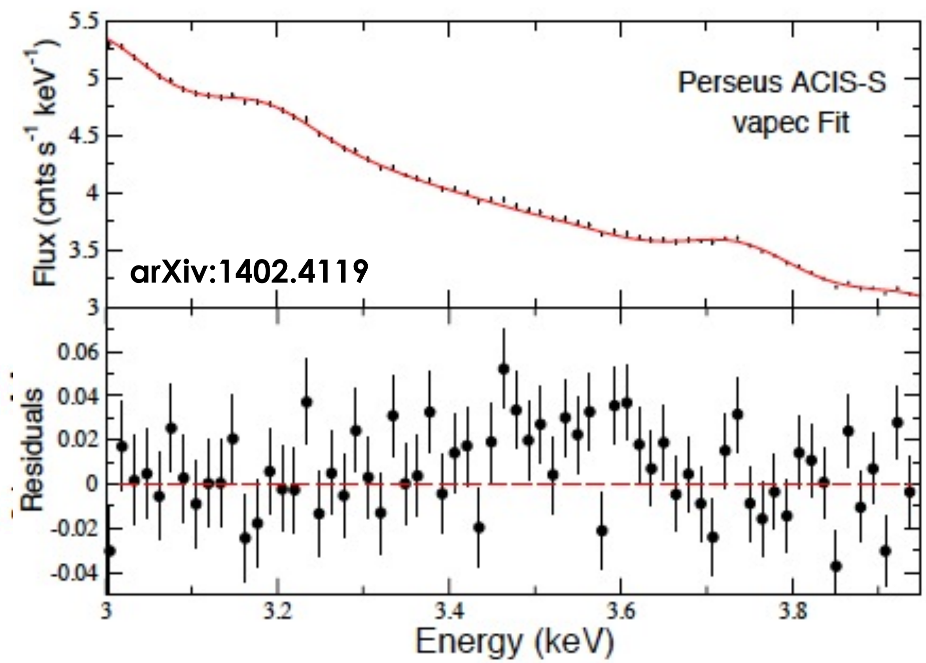


- Production mechanism being bremsstrahlung allows PADME to reach >100MeV A' masses
- No data available below 200 MeV in $M_{A'}$
- PADME can provide sensitivity in unexplored parameter region.

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**

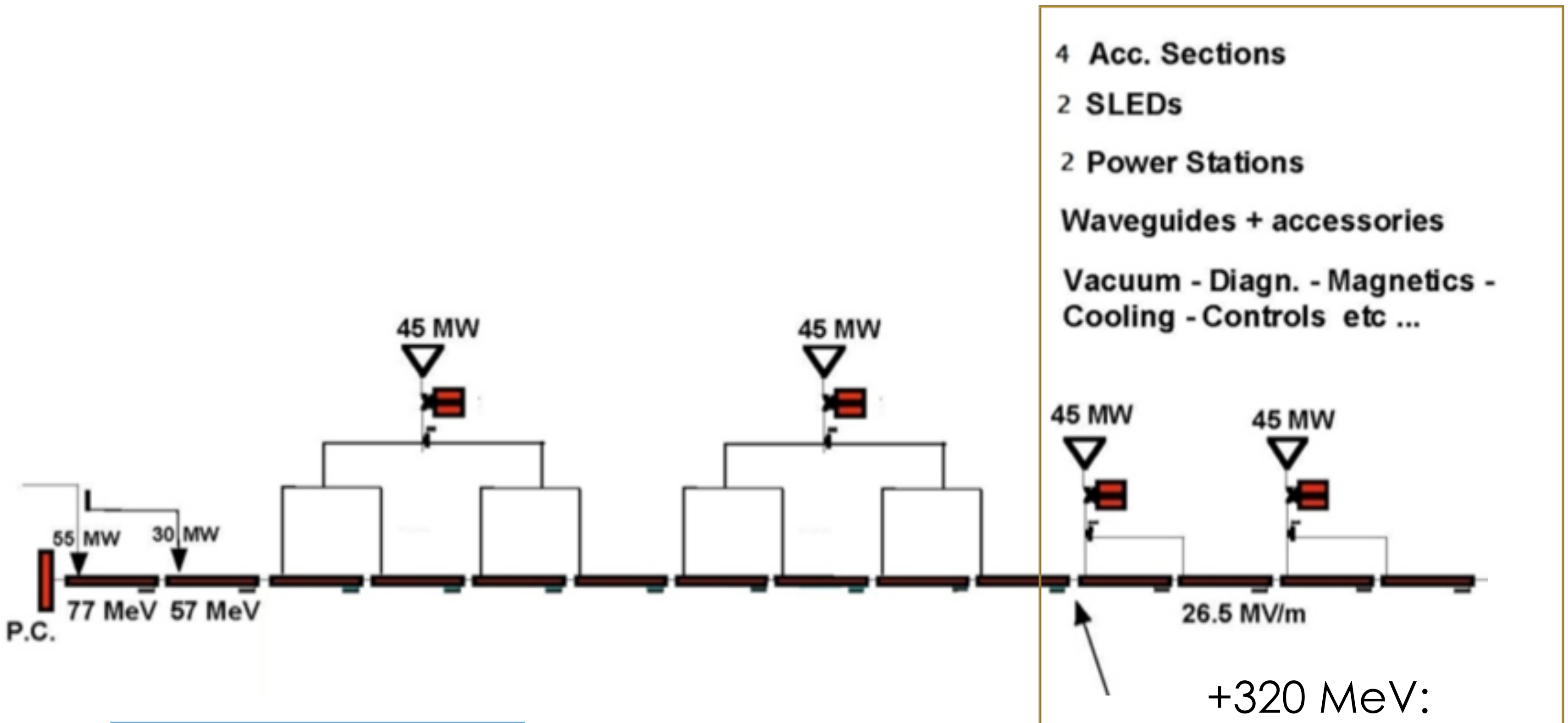




U(1) symmetry explanation

- 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 A' 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 A' boson becomes massive
  - Due to constraints coming from the relic abundance a mass interval has been identified by authors for the A' boson mass
    - $7KeV<M_{A'}<10MeV$

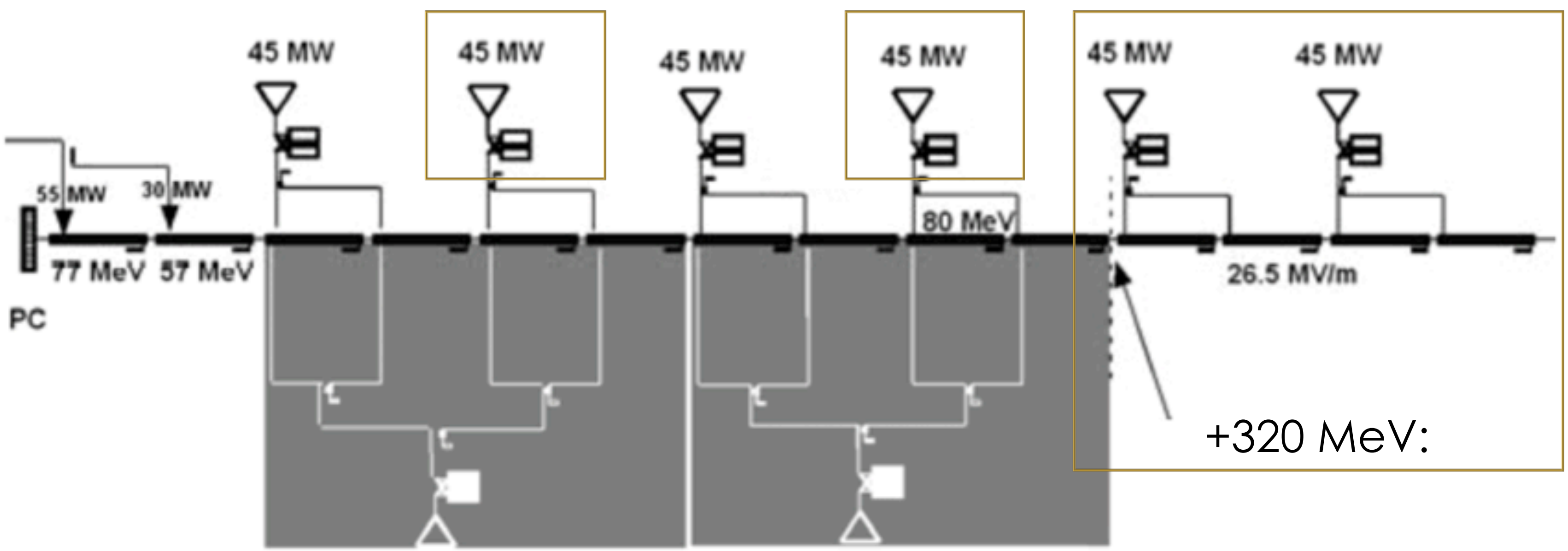
Add 4 sections + 2 SLED-ed klystrons



Reach:
1070 MeV electrons

Add 4 sections + 4 SLED-ed klystrons

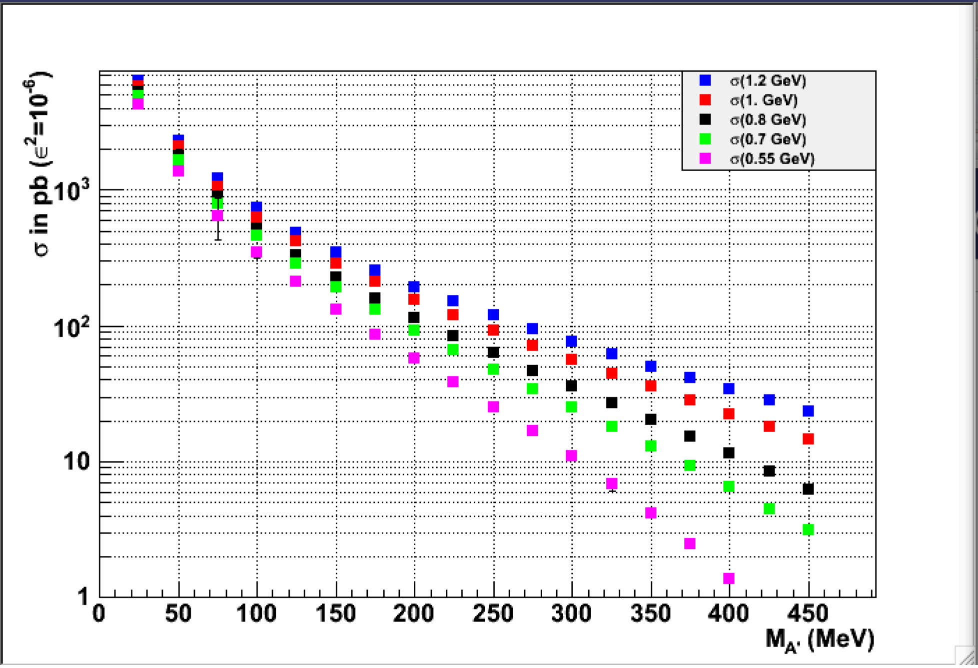
+180 MeV:

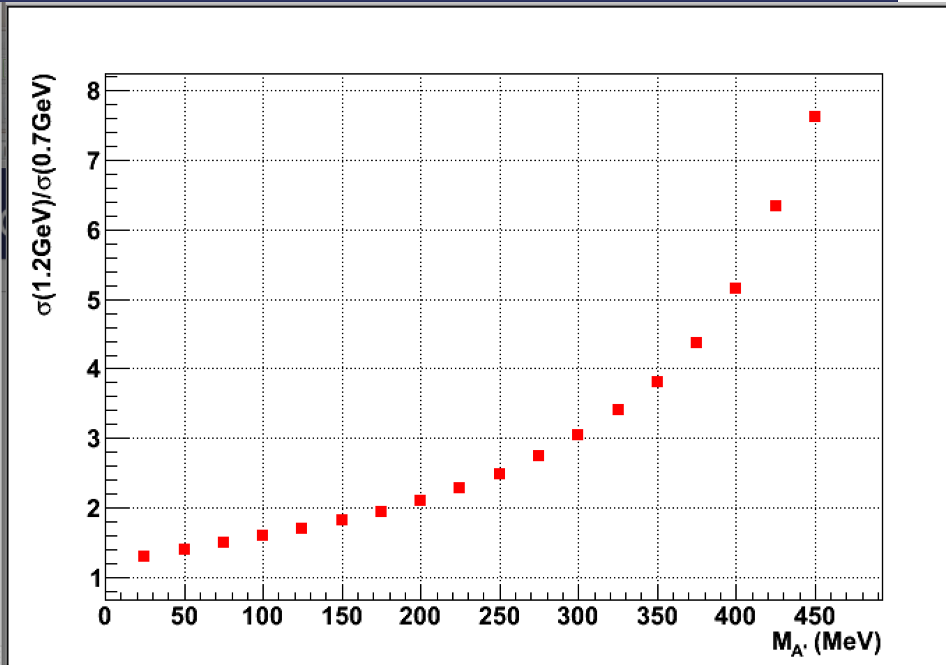


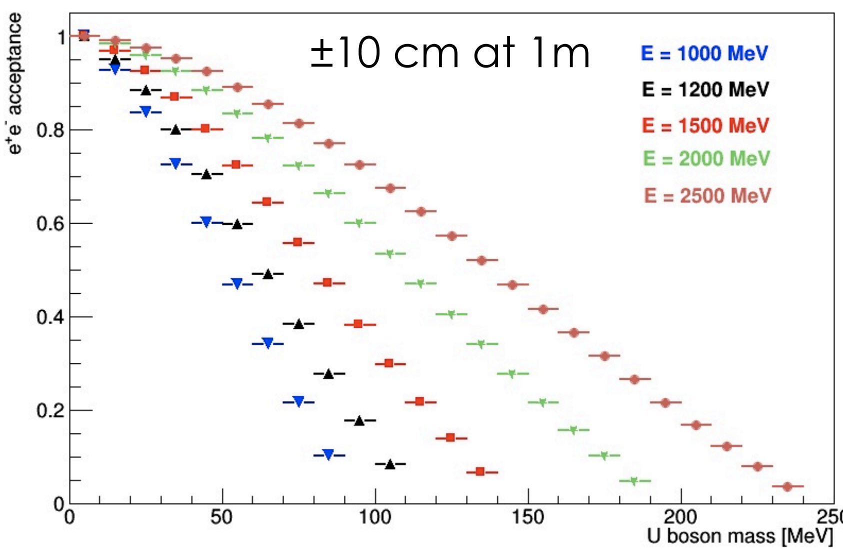
Reach:
1250 MeV electrons

Add **two more SLED-ed klystrons** and split power only in two sections instead of four

BTF Energy upgrade

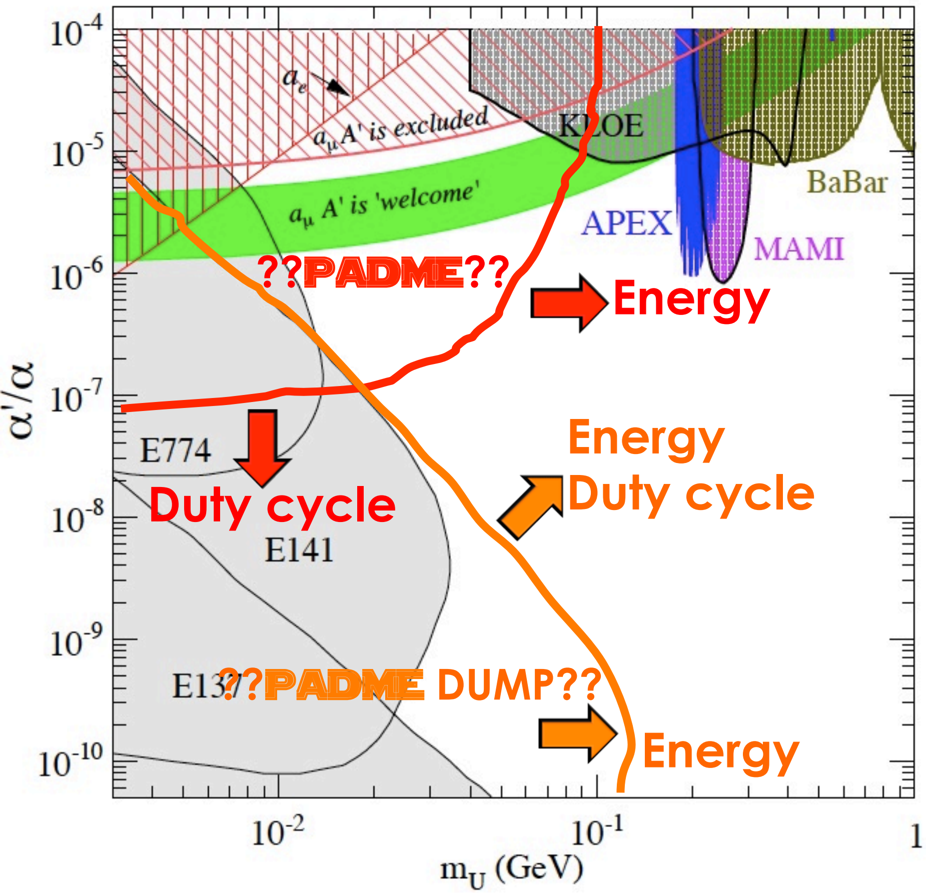




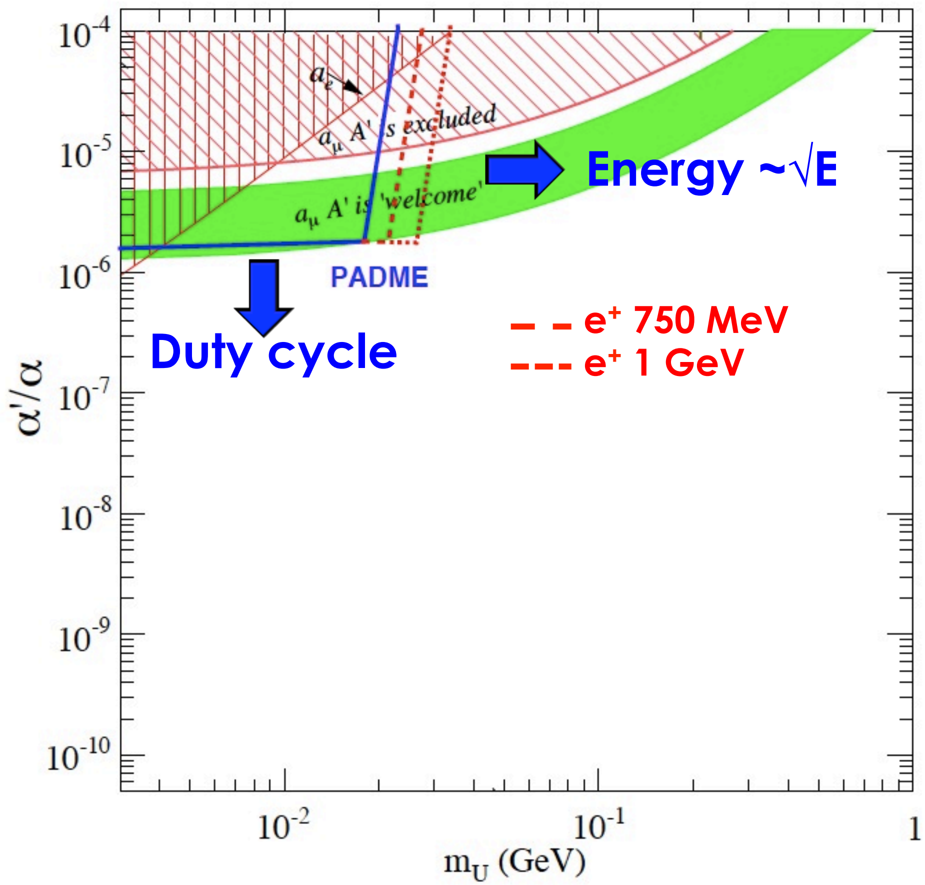


Improvement in case of BTF upgrades

Decays to lepton pairs

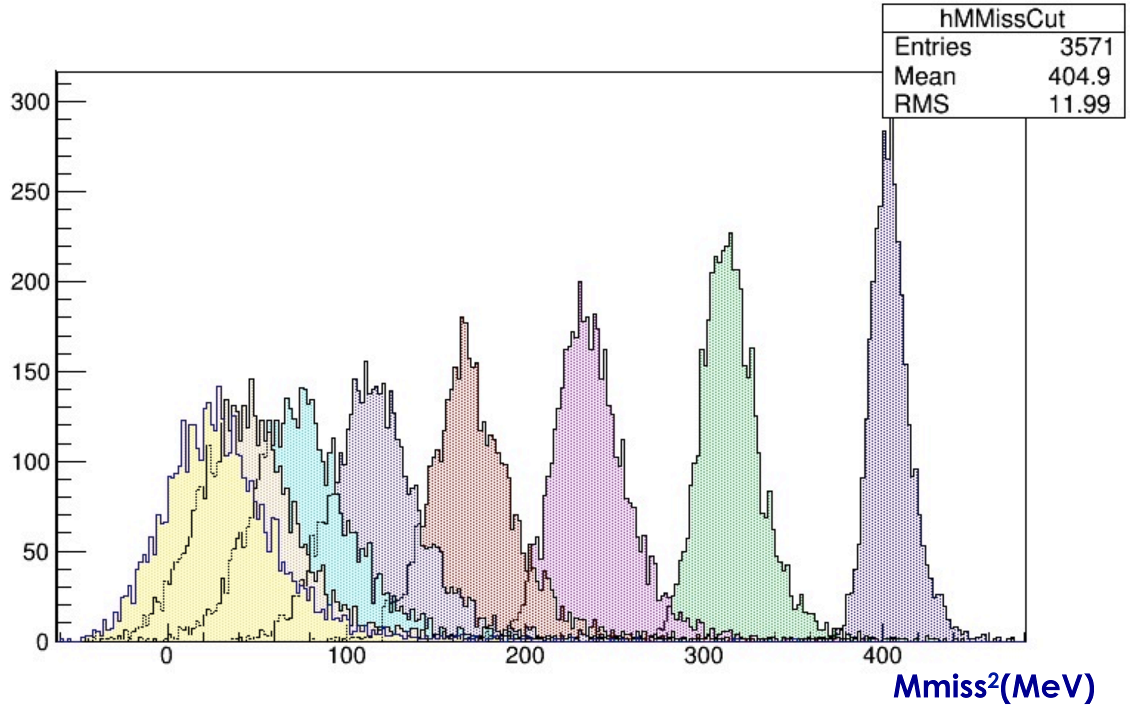


Decays to invisible



- 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

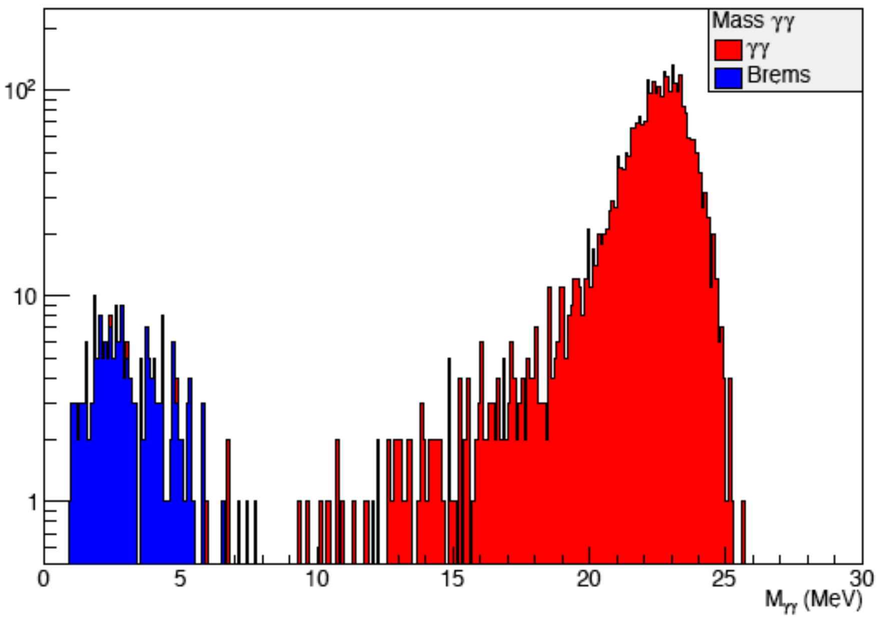
MC calorimeter performance



- 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

The γγ normalization selection

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



- Number of calorimeter clusters = 2
- Cluster energy: $100 MeV < E_{Cl} < 400 MeV$
- 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

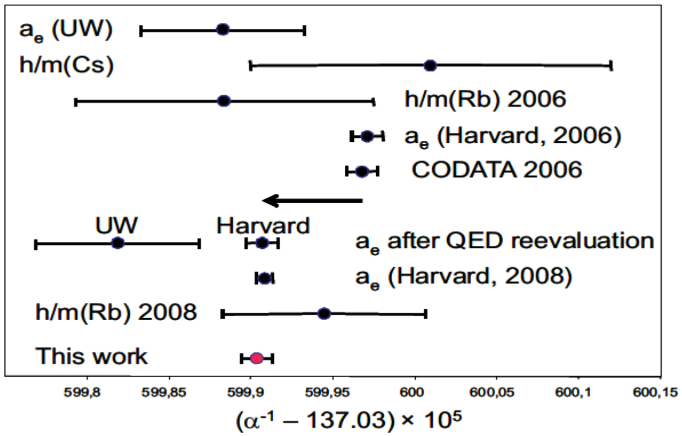
- Collimation system
  - Assure better beam definition for positrons beam

- Maximum current in BTF hall
  - Limited by radio protection to 6.2×10^{8} per bunch for long term operation
  - Can reach $>3 \times 10^{10}$ particle per bunch after proper screening

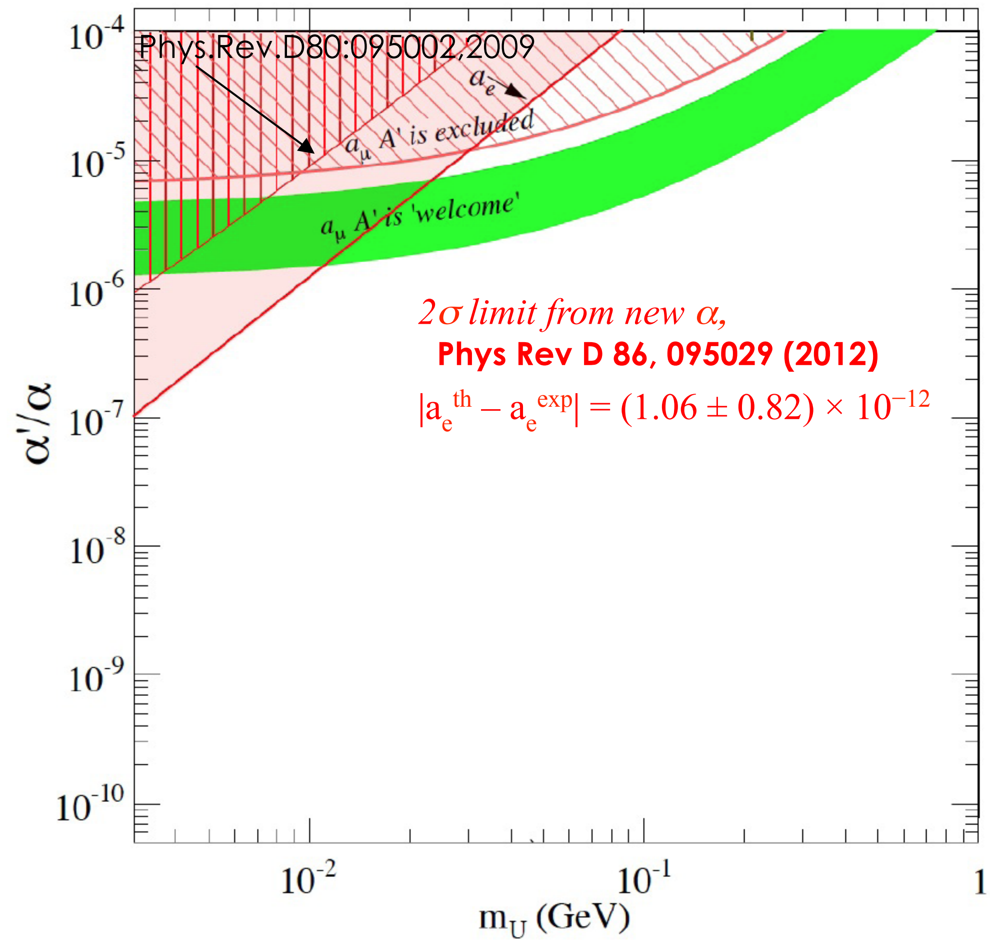
See recent BTF user workshop for details at:
https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=7359

Indirect limits

Phys.Rev.Lett.106:080801,2011



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

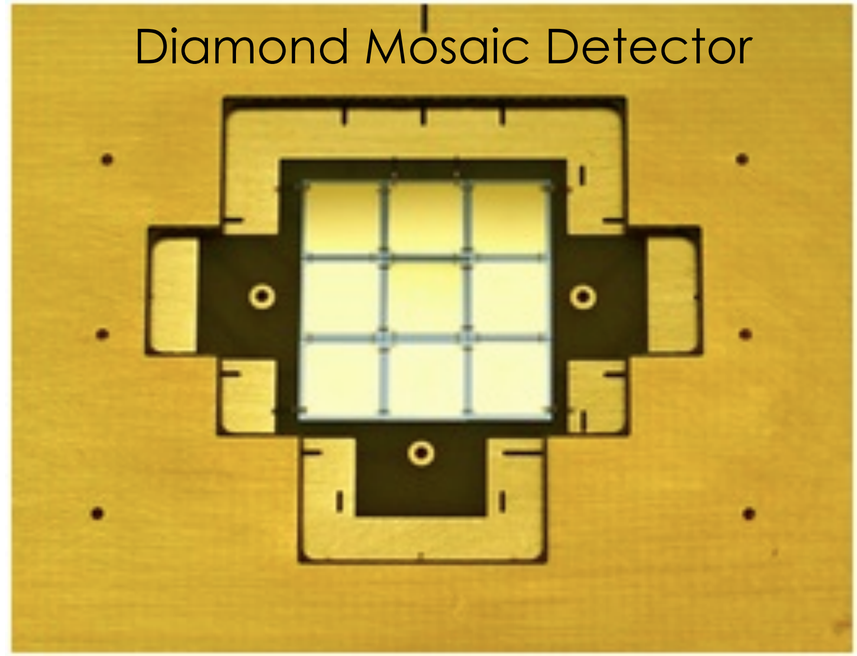


However this is based on a single measurement with drastically improved precision

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

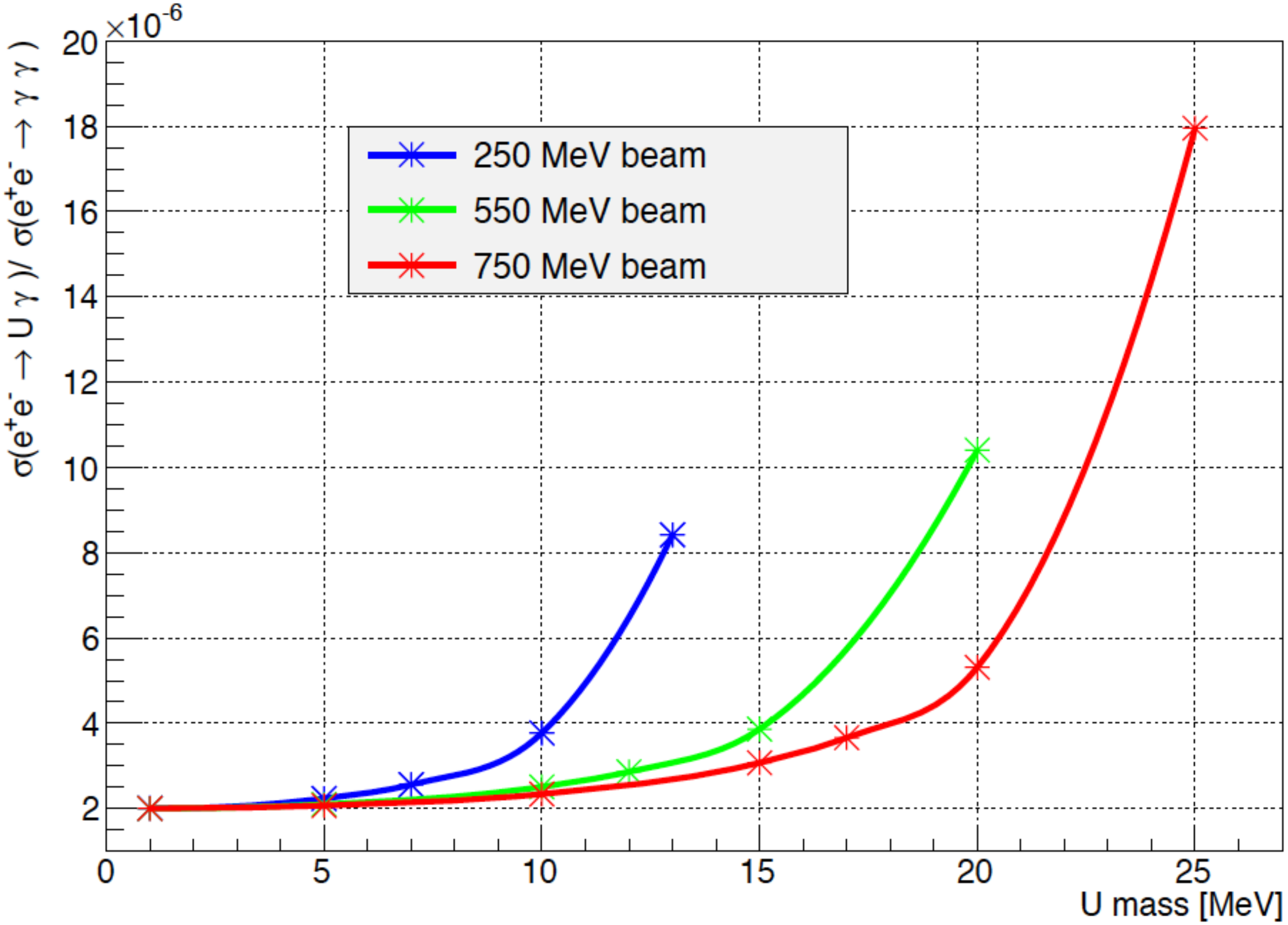


Features:	
Active area:	13 mm x 13 mm
Energy resolution:	35 keV FWHM
Particle rate:	1 MHz

NEW

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

Cross section enhancement



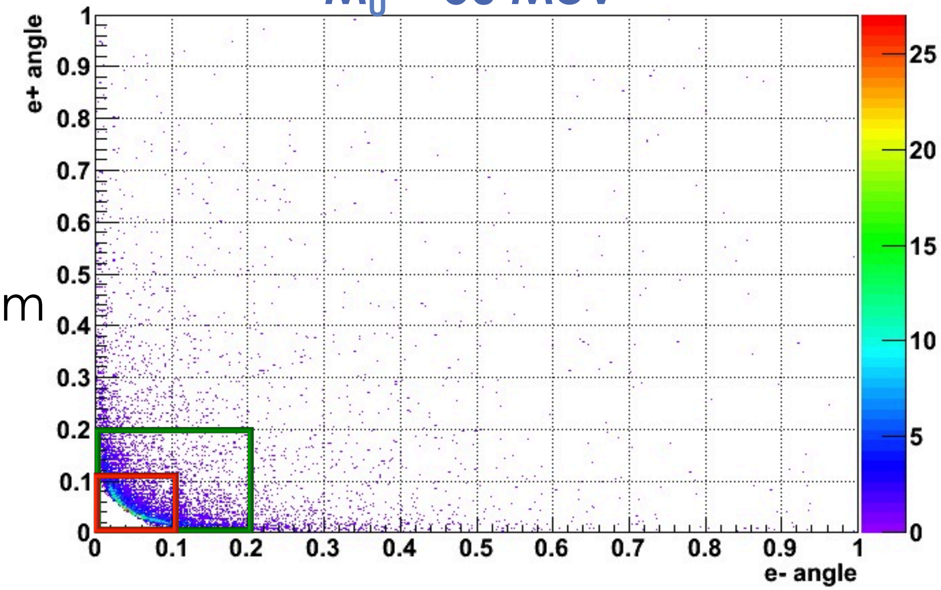
Detector acceptance E_b=1.2 GeV

e^+e^- acceptance

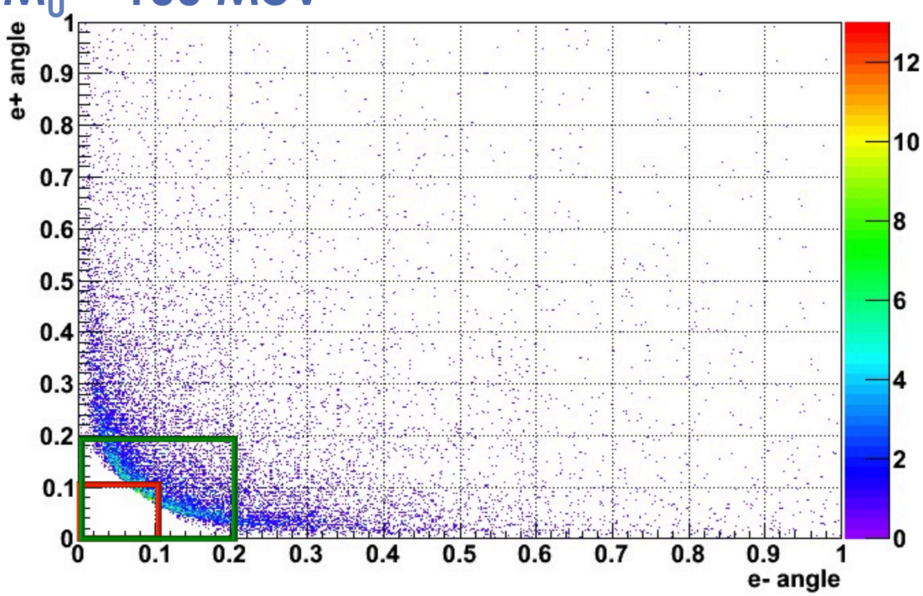
(red box) ±10 cm at 1m

(green box) ±10 cm at 0.5 m

M_U = 50 MeV



M_U = 100 MeV



M_U = 300 MeV