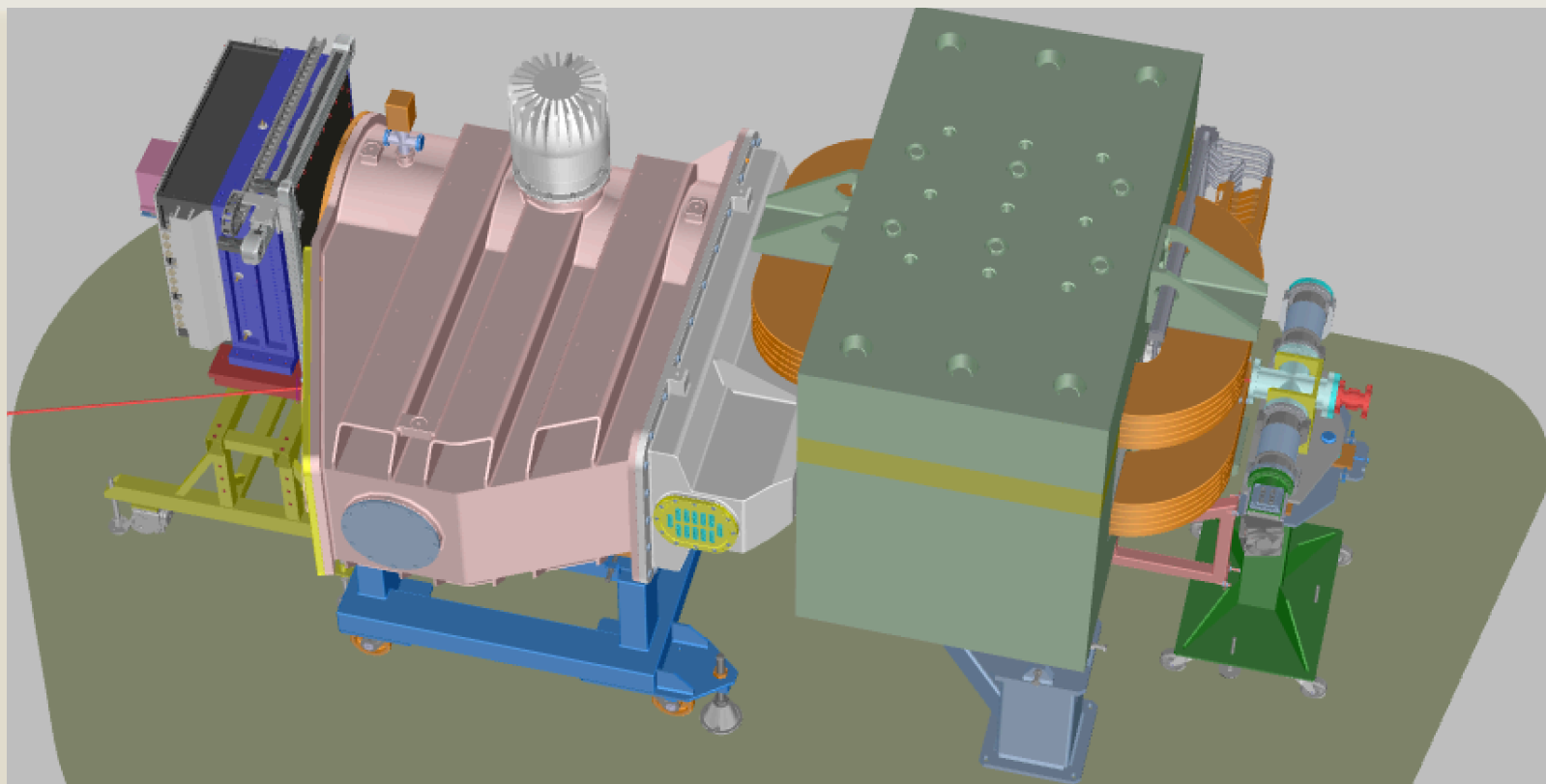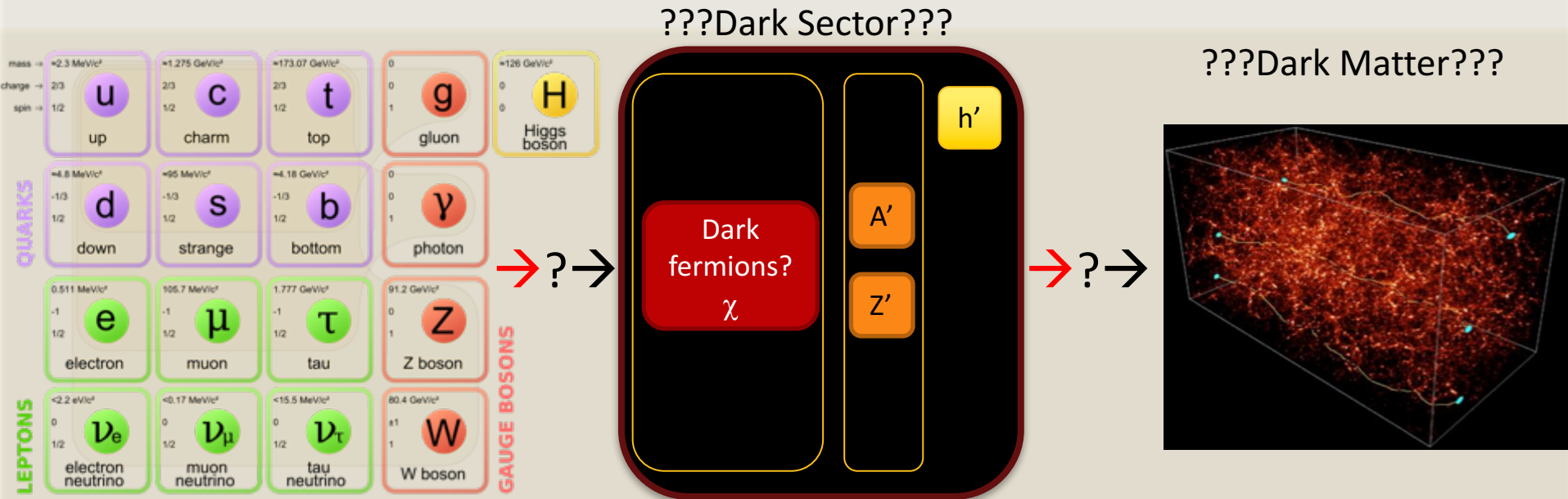# The PADME experiment

Dr. M. Raggi

Sapienza University of Rome & INFN Roma1
on behalf of the PADME collaboration

Vulcano Workshop 2018 –
Frontier Objects in Astrophysics and Particle Physics

What is the universe made of?

???Dark Sector???

???Dark Matter???

- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interact gravitationally
- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector particles spectrum?
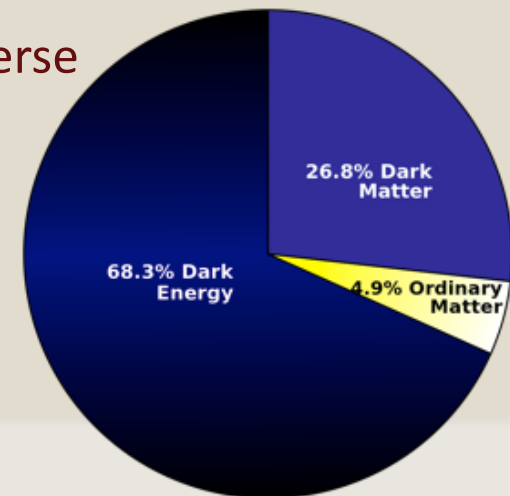
DM, dark sectors and portals

Wimp

Dark Sector

mediator

€

Dark
Sector

Standard
Model

Standard
Model

DM

DM
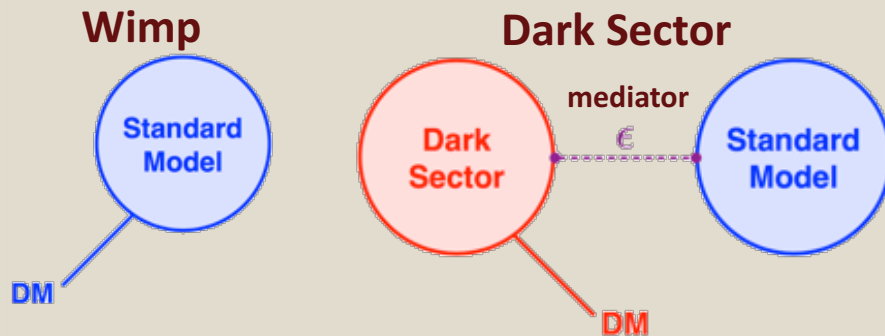
Dark (or hidden) sector:
DM particles **completely neutral** under SM forces, with **new interactions**

Mediator:
A **mediator particle** of the **new interaction**, interacting **very weekly** with SM particles

Portal interaction:
New interaction connecting dark mediator and SM particles

- The mediator can be scalar, fermion, **vector**, axion…
- The relic dark matter (DM) can be **either** the mediator particle **or** just coupled to SM via a hidden interaction
- Different portals can **co-exist:** e.g. dark photon and Higgs, or dark photon and axion
- Dark sectors invoked not only for the DM problem, but also for solving other puzzles:
  - **Muon $g-2$ anomaly**, proton radius, inflation, ^{8}**Be anomaly**, …
- The **vector portal is the simplest** both from the theory [additional U(1) gauge symmetry] and experiment point of view [just replace an ordinary γ with a dark one in any QED processes]
- **Wide mass and coupling ranges allowed**

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Where to search for a new mediator?

Dark Sector Candidates, Anomalies, and Search Techniques
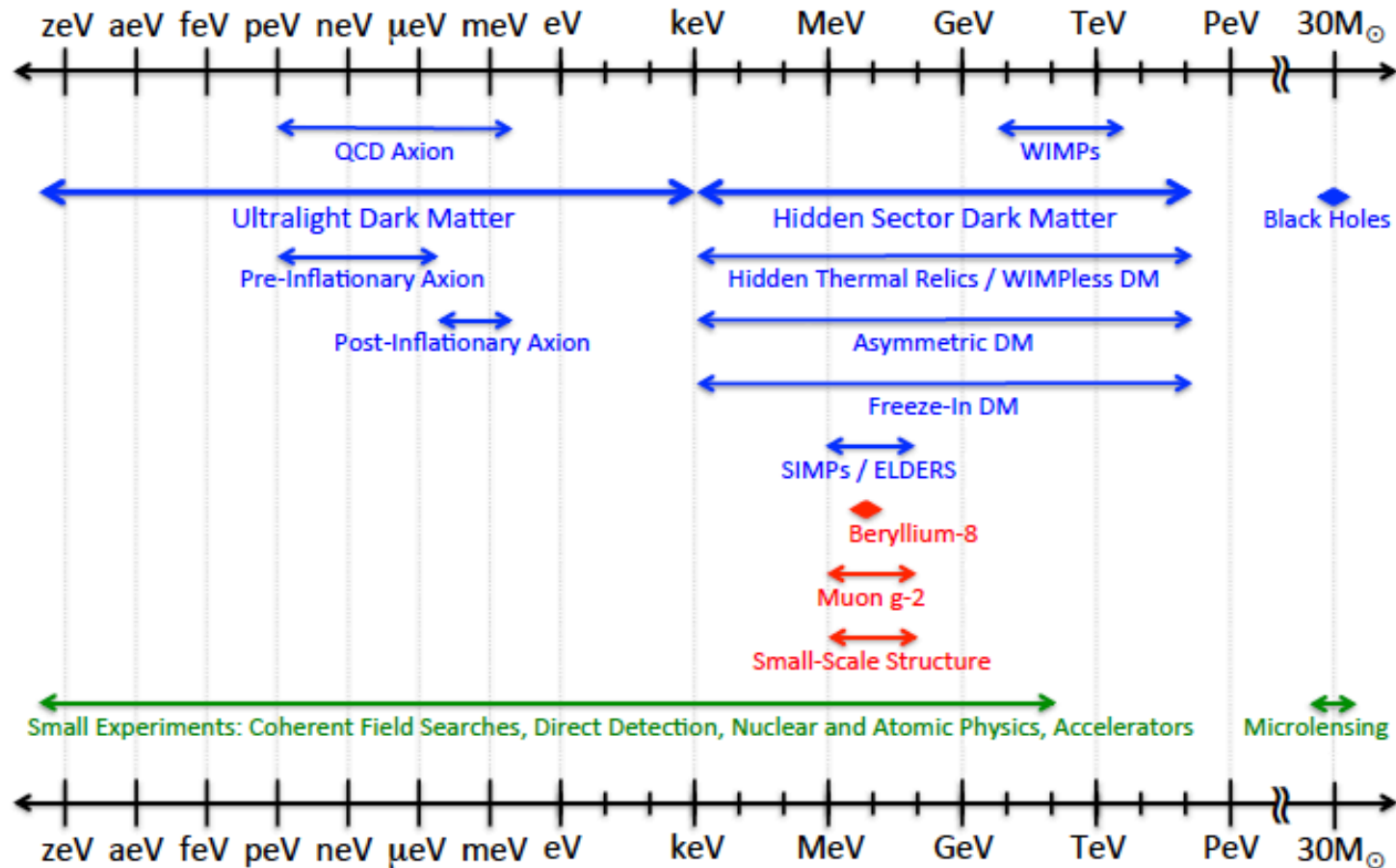
A' production and decays

- **A' can be produced in e+ collision on target by:**
  - Bremsstrahlung: e+N →e+NA'
  - Annihilation: e+e- → gA'
  - Meson decays

- **If no dark matter candidate lighter than the A' boson exists:**
  - A'→e⁺e⁻, $\mu^+\mu^-$, hadrons, "visible" decays
  - For $M_{A'}$<210 MeV A' only decays to e⁺e⁻ with BR(e⁺e⁻)=1

- **If any dark matter particle χ with $2M_\chi < M_{A'}$ exists**
  - A' will dominantly decay into pure DM
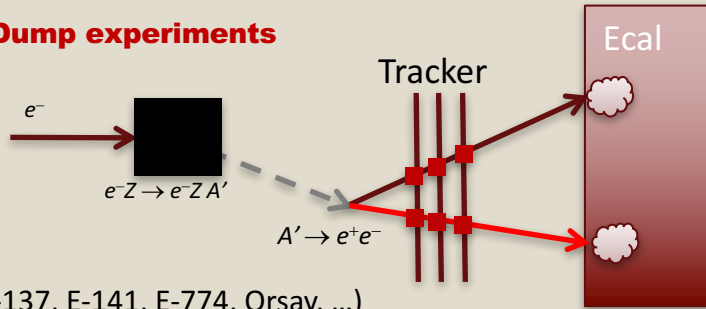 - BR($\ell^+\ell^-$) suppressed by factor ε^2
  - A'→ $\chi\chi$ ~ 1. These are the so called decays to "invisible"

Bremsstrahlung   Annihilation

Meson decays
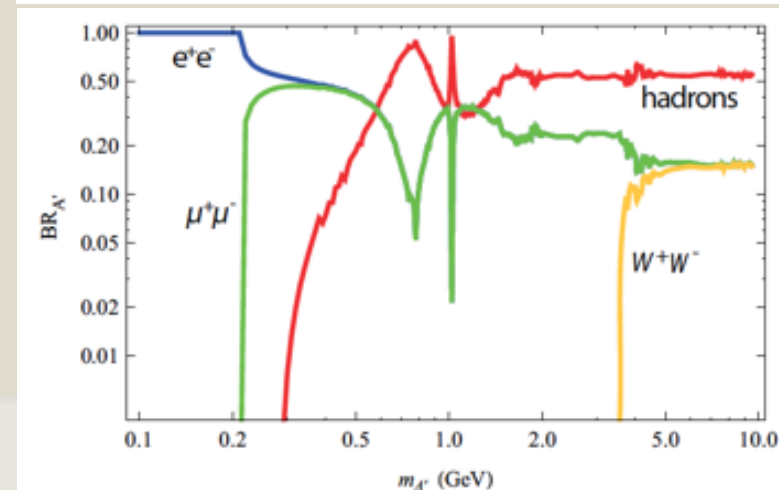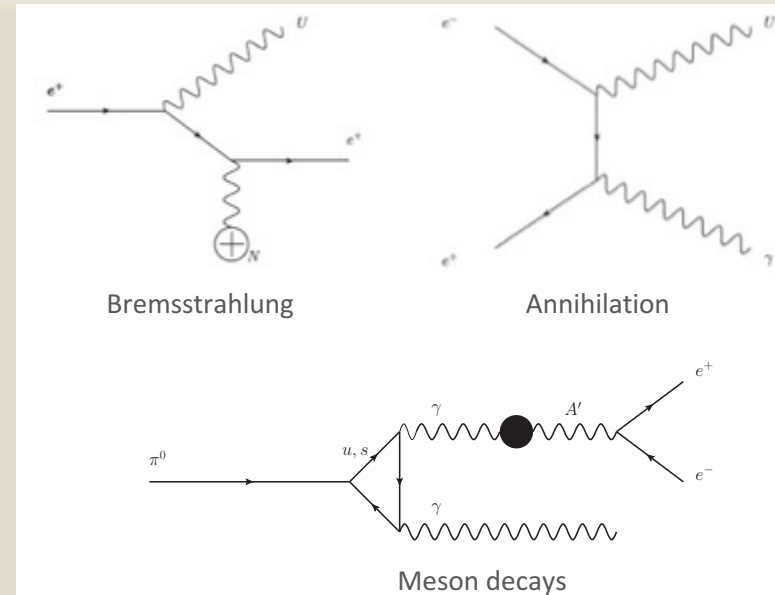
A' experiments at accelerators

visible decays (A'→ℓ⁺ℓ⁻)

Dump experiments

e^-

$e^- Z \to e^- Z\, A'$

$A' \to e^+ e^-$

Tracker

Ecal

(E-137, E-141, E-774, Orsay, ...)

Thin target experiments

invisible decays (A' → χχ)

Dump+recoil

e^-

$e^- Z \to e^- Z\, A'$

$A' \to \chi\chi$

massive Ecal

recoil

Additional parameters: α_D and m_χ
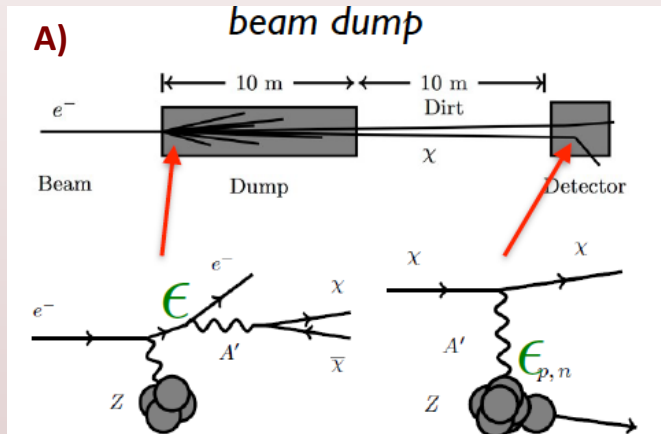
(E-137 , BDX)
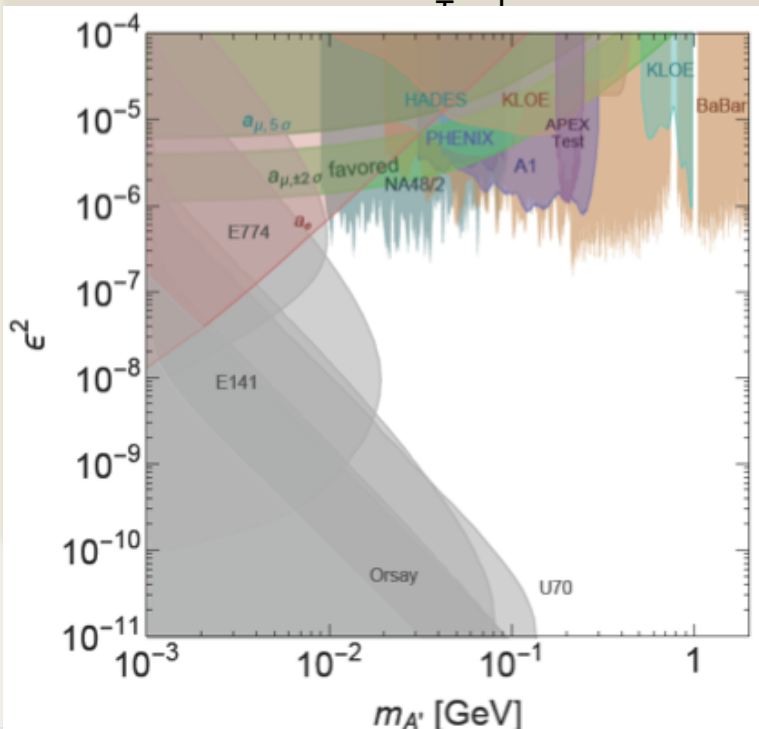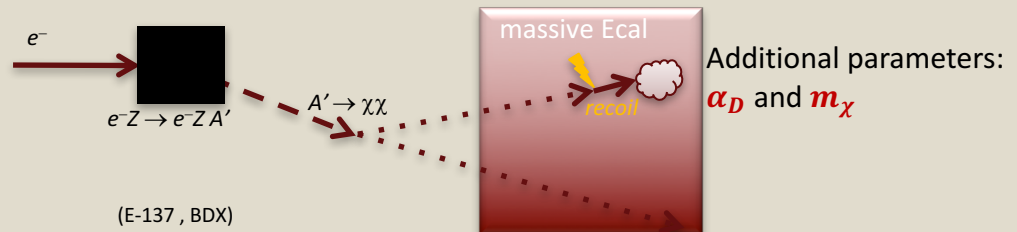
Missing energy ($E_D \ll E_{beam}$)   **Missing momentum ($p_2 \ll p_{beam}$)**
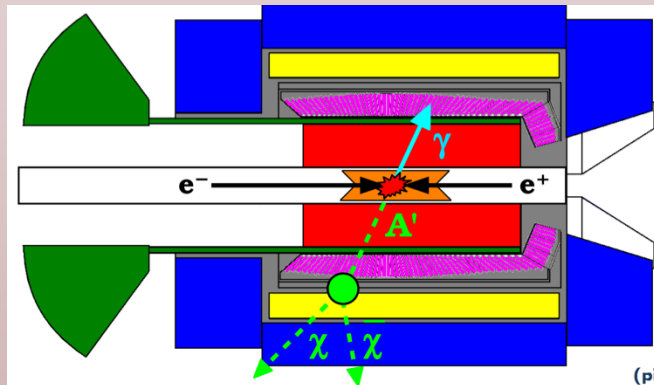

M. Ra
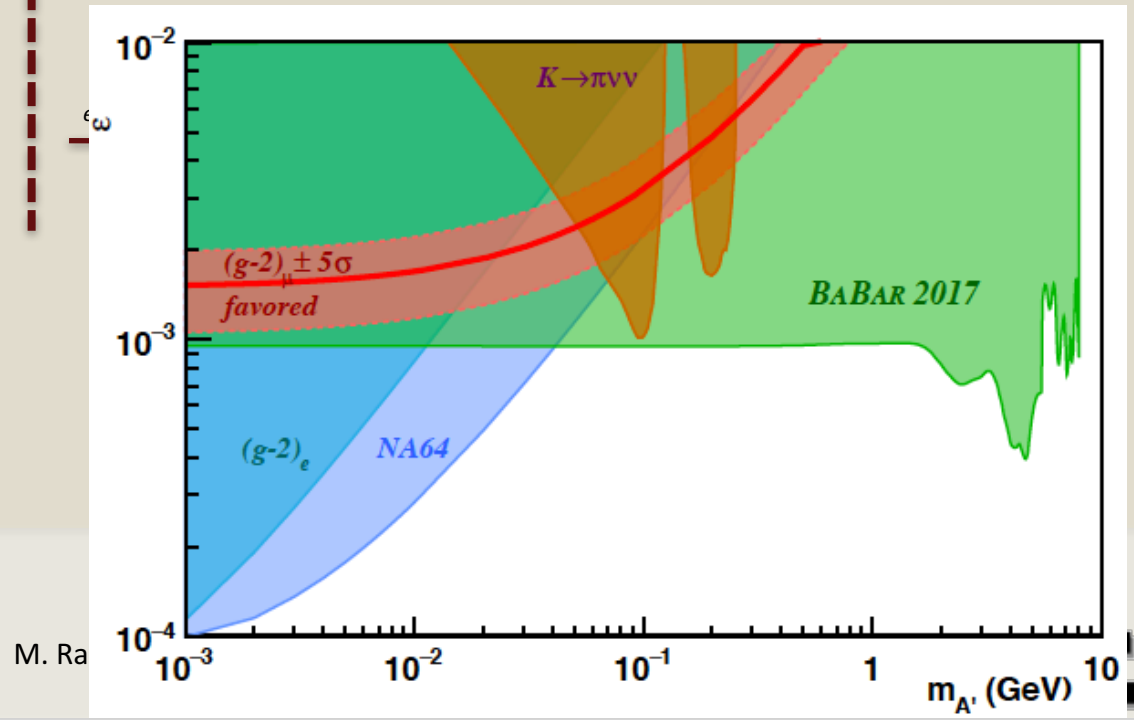
How to search for invisible decays?

Positive evidence

A)

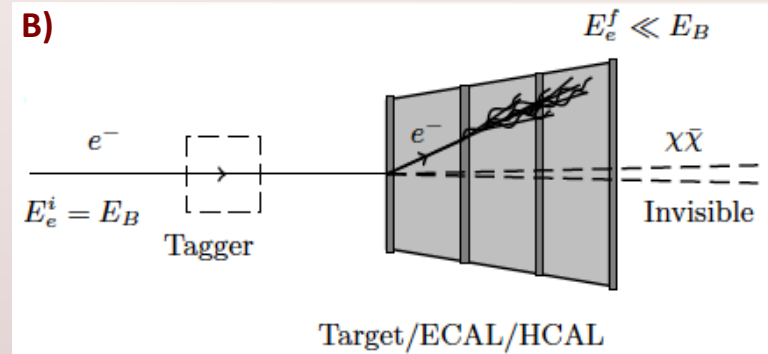$$N \propto \varepsilon^4 \sim 10^{20} \text{ EOT } (\alpha_D \text{ and } \varepsilon^2)$$

C) Missing Mass

$$N \propto \varepsilon^2 \text{ sensitive to } (\varepsilon, A') \text{ mass}$$
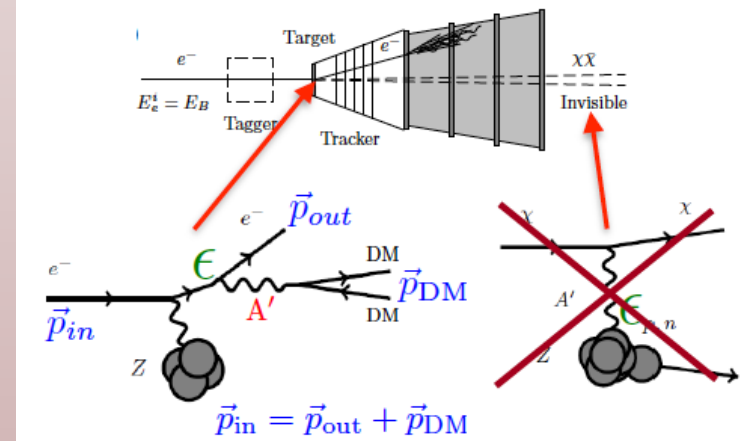**Limited by** $M_{A'} < \sqrt{2m_e \cdot E_B}$

Negative evidence
Missing energy

B)

$$N \propto \varepsilon^2 \, (\varepsilon^2 \text{ only})$$

D) *missing momentum*

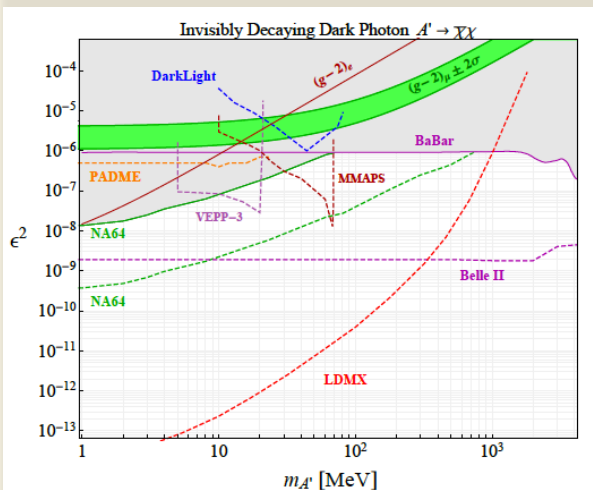$$N \propto \varepsilon^2 \text{ contains } E_{miss} \text{ exp.}$$

The PADME physics case(s)

PADME is a multipurpose dark sector search experiment with positrons on fixed target able to detect photons and charged particles:
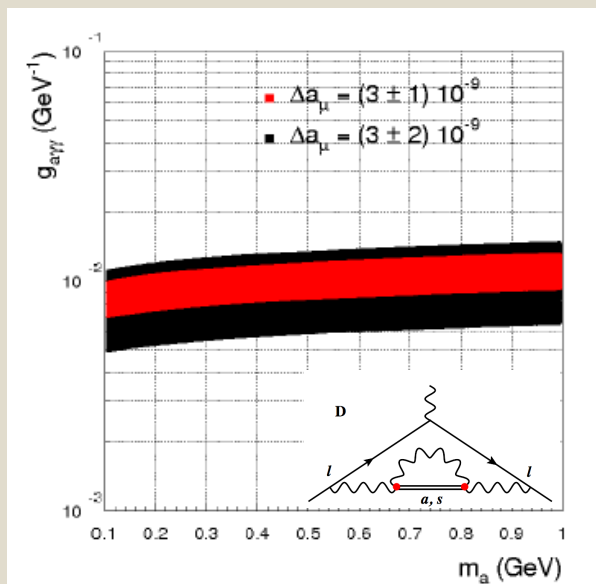
Main goal: **Invisible dark photon decays A → χχ**

Aims to use annihilation production and missing mass searches. Several physics case under analysis

Dark Photon arXiv:1707.04591v1

ALPs and g-2 PRD 94, 115033,2016
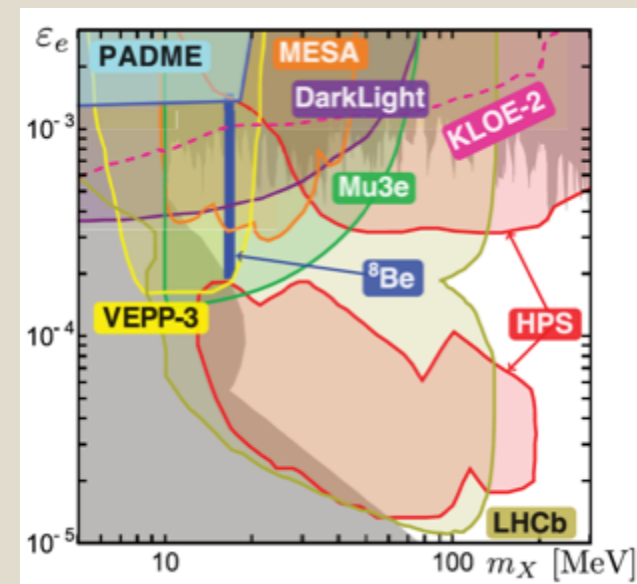

Fifth force PRL 117, 071803 (2016)

Invisible final state $A' \to \chi\chi$
(γ+missing mass)

ALPs final state $a \to \gamma\gamma$
($\gamma\gamma\gamma$ or $e\gamma\gamma$)

Final state $X \to e^+e^-$

Why missing mass technique?

- The missing mass technique represents a unique opportunity:
  - Independent of the A' decays and dark sector structure (α_D, $M\chi$) just ϵ^2 and $M_{A'}$ parameter explored!
  - Very clean signature for positive evidence (mass peak!)
  - Measure mass and coupling at the same time!
  - Theoretically clean (no dependence on missing energy and shower modelling)
  - Cross section enhanced for $m_{A'} \sim \sqrt{s}$
    (complementary to bremsstrahlung production decreasing for high $m_{A'}$)
  - Searching for positive evidence is a great opportunity for PADME (ALPs, Dark Higgs)
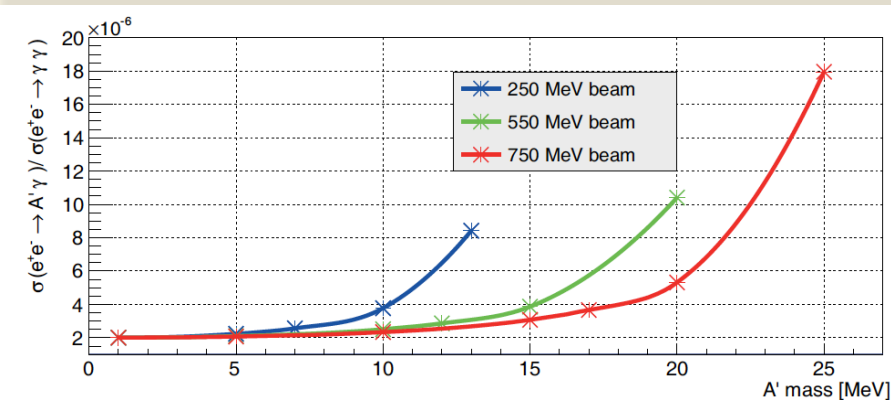
$$M_{A'} \rightarrow 0$$

$$\sigma(e^+e^- \rightarrow \gamma A') = 2\epsilon^2 \sigma(e^+e^- \rightarrow \gamma\gamma).$$

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

$$\frac{d\sigma(e^+e^- \rightarrow \gamma A')}{d\cos\theta} = \frac{\alpha\epsilon^2}{2s^2(s-m_{A'}^2)} \left(\frac{s^2 + m_{A'}^4}{\sin\theta^2} - \frac{(s-m_{A'}^2)^2}{2} \right)$$
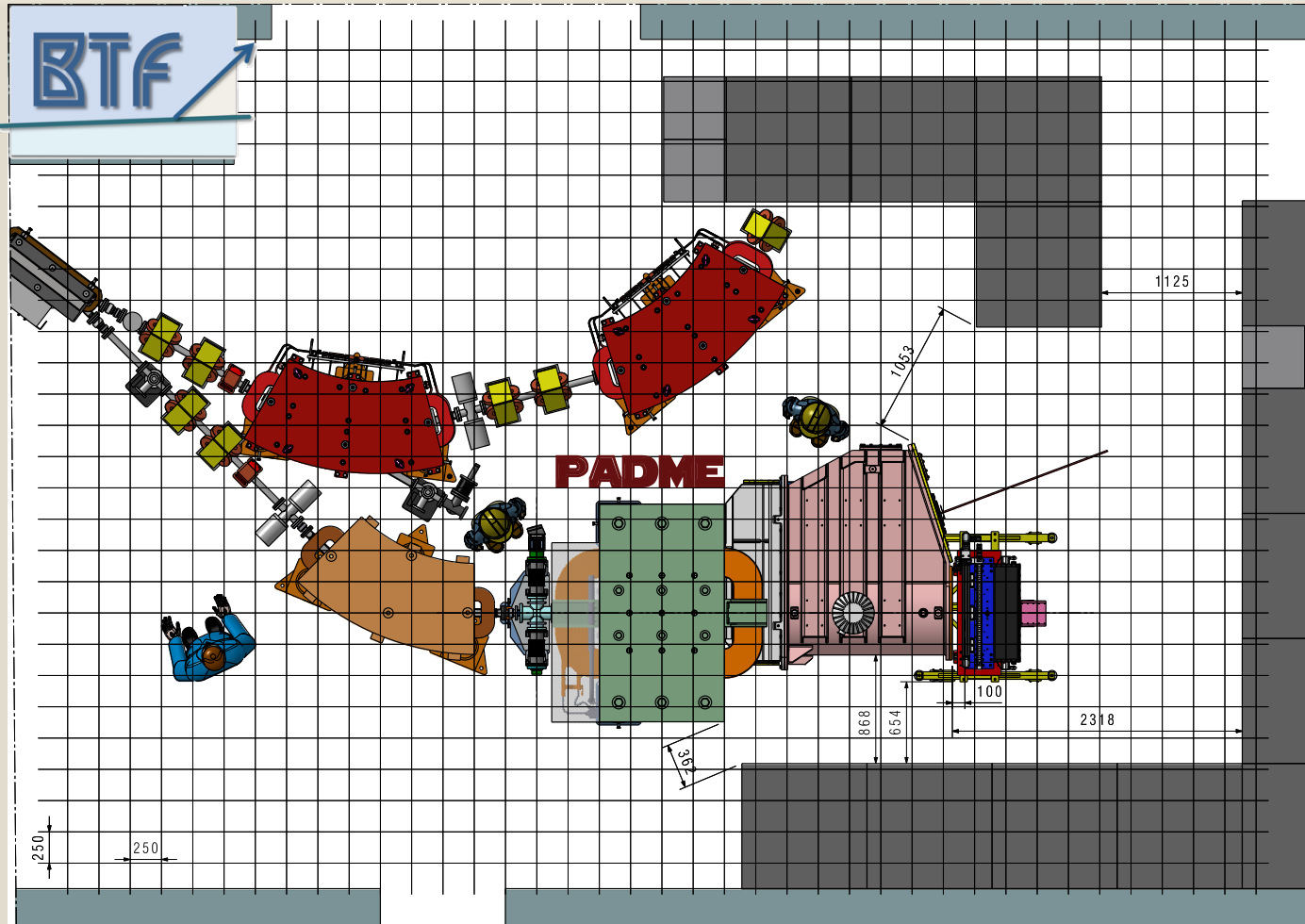
The DAΦNE Beam Test Facility (BTF)

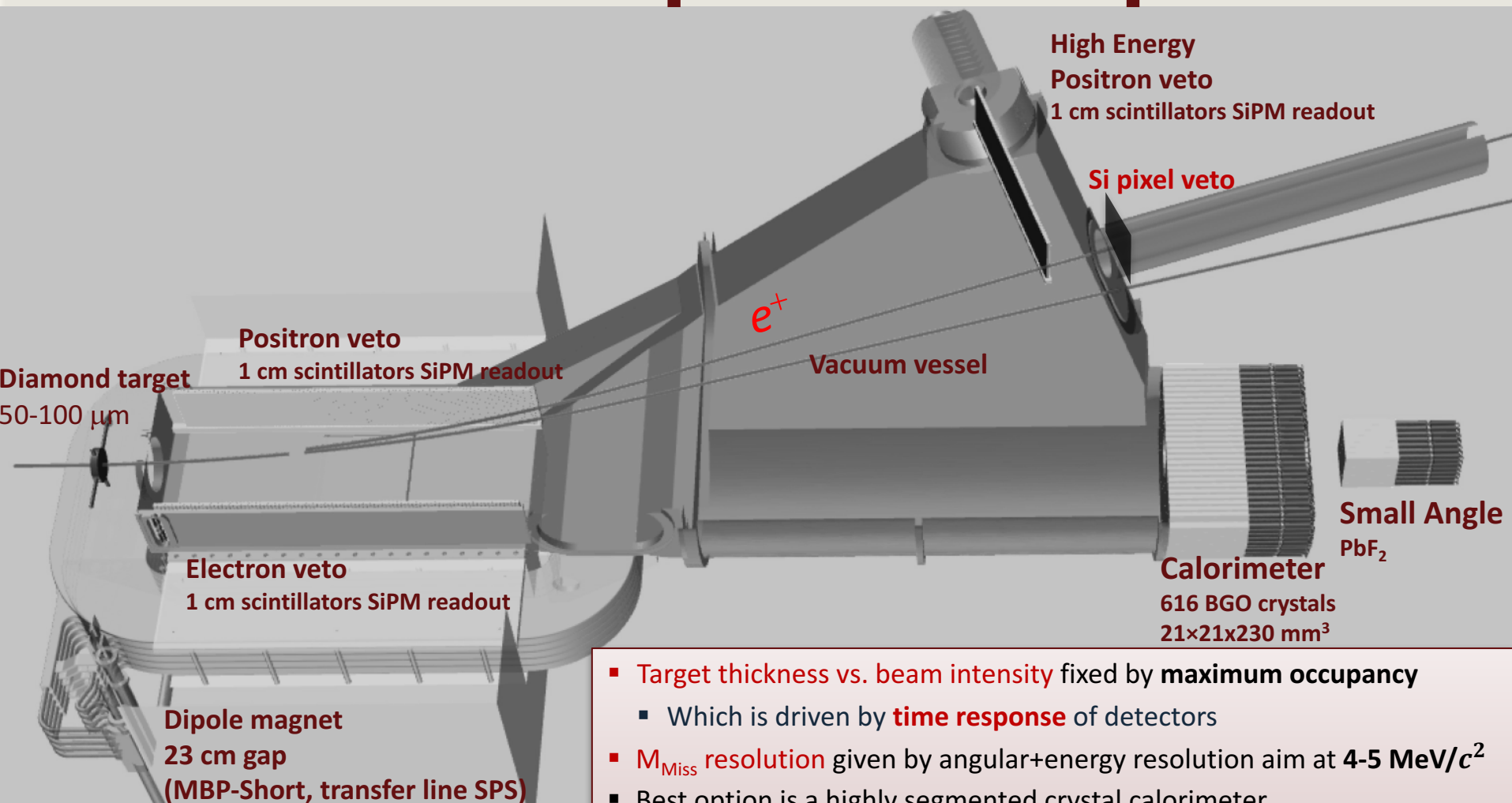|	Electrons	Positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [Dp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 – 40 (can reach 200 in 2016)	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot s [mm]	<1 mm	
Beam divergence	1-1.5 mrad	

NIM A 515 (2003) 524–542

- Able to deliver both electrons and positrons of tuneable E
  - Duty cycle 50 bunch x 40-200 ns = 2×10^{-6}-1×10^{-5} s
  - Precise energy tuning down to 100 MeV
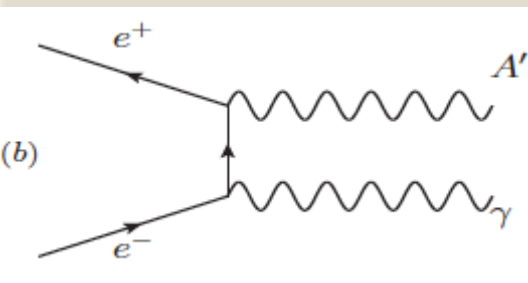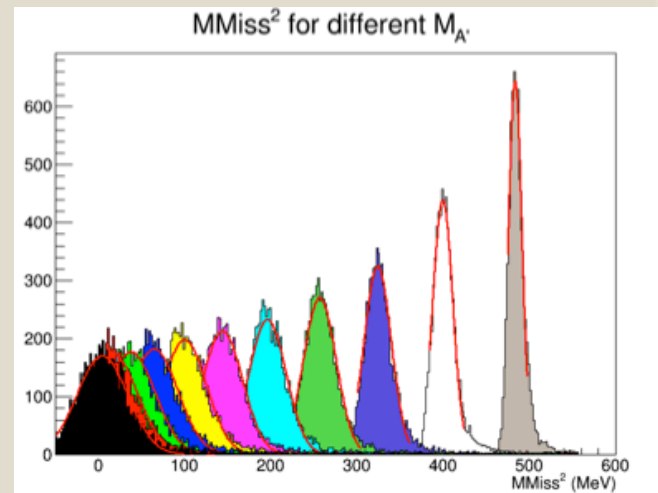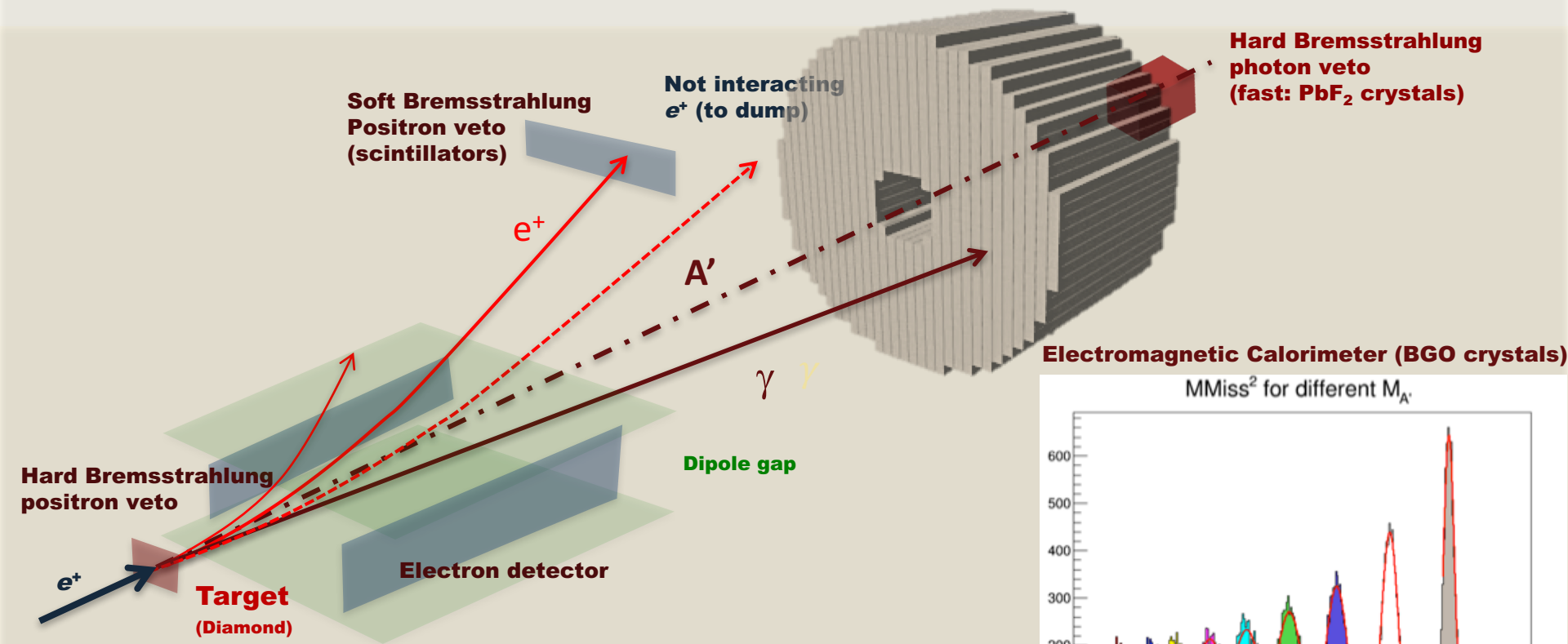 - Low emittance beam

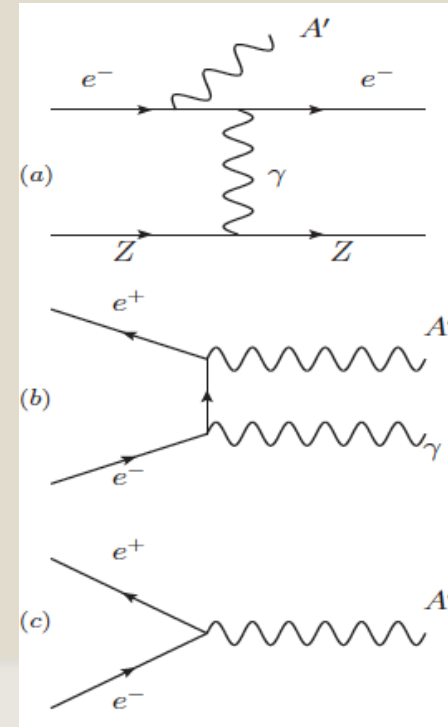# The PADME experiment at the BTF

PADME experiment setup

High Energy Positron veto
1 cm scintillators SiPM readout

Si pixel veto

e^+

Vacuum vessel

Positron veto
1 cm scintillators SiPM readout

Diamond target
50-100 μm

Electron veto
1 cm scintillators SiPM readout

Dipole magnet
23 cm gap
(MBP-Short, transfer line SPS)

Small Angle PbF_2
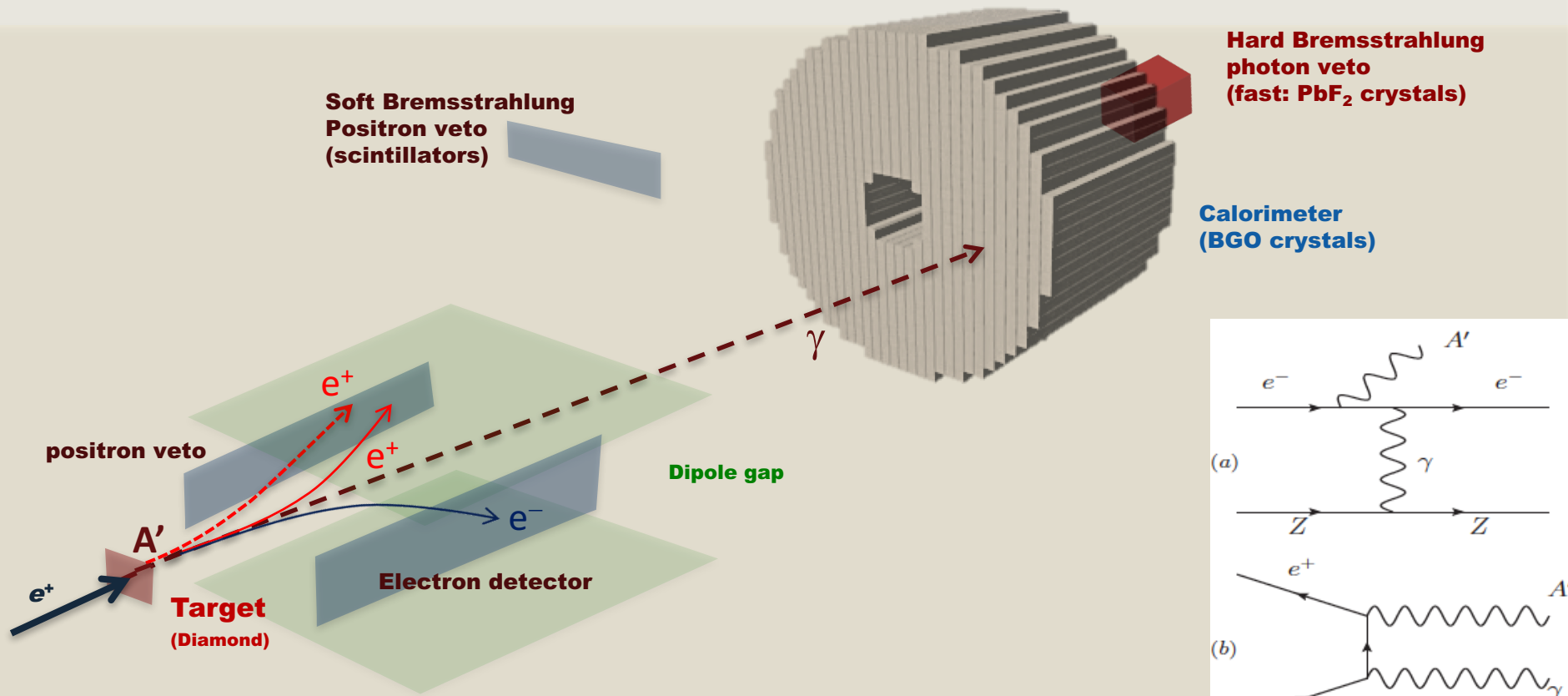
Calorimeter
616 BGO crystals
21×21x230 mm³

- Target thickness vs. beam intensity fixed by **maximum occupancy**
  - Which is driven by **time response** of detectors
- M_{Miss} resolution given by angular+energy resolution aim at **4-5 MeV/c^2**
- Best option is a highly segmented crystal calorimeter
  - Crystal size 21x21x230mm³ fixed by Moliére radius
  - Calorimeter size fixes the number of crystals
  - Distance + dipole gap fixes the **acceptance**
  - Hole in BGO calorimeter + small angle fast detector to cope with rate
- Everything in **vacuum to avoid e+ interaction outside the target**

PADME invisible technique: A→χχ

**Soft Bremsstrahlung Positron veto (scintillators)**

Not interacting e^+ (to dump)

Hard Bremsstrahlung photon veto (fast: PbF$_2$ crystals)

e^+

A'

γ γ

Hard Bremsstrahlung positron veto

Dipole gap

Electron detector

e^+

Target (Diamond)

Electromagnetic Calorimeter (BGO crystals)

MMiss² for different M$_{A'}$

PADME visible technique: A' → e⁺e⁻

Soft Bremsstrahlung
Positron veto
(scintillators)

Hard Bremsstrahlung
photon veto
(fast: PbF₂ crystals)

Calorimeter
(BGO crystals)

positron veto

e⁺

e⁺

e⁻

γ
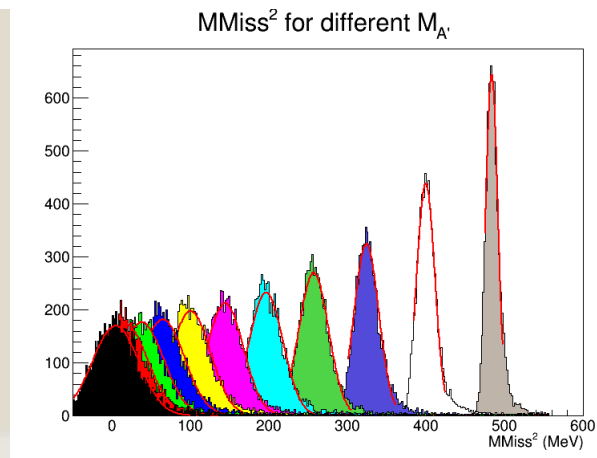
Dipole gap

A'

e⁺

Target
(Diamond)

Electron detector
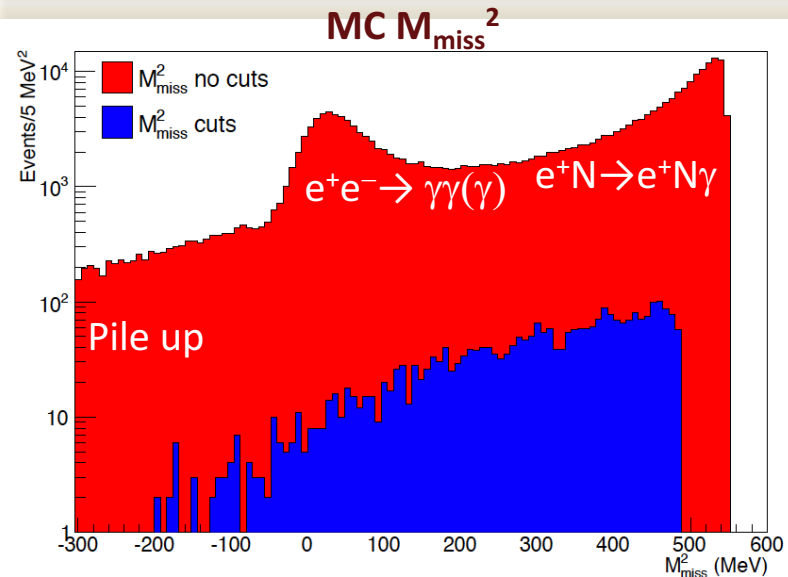
- Three different final states can be explored using 3 different production
  a) Final state A'-strahlung: e⁺e⁻e⁺
  b) Annihilation in 2γ final state: e⁺e⁻γ
  c) Final state: e⁺e⁻   (only for defined A' mass sqrt(2meE_B))

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14

PADME GEANT4 Monte Carlo
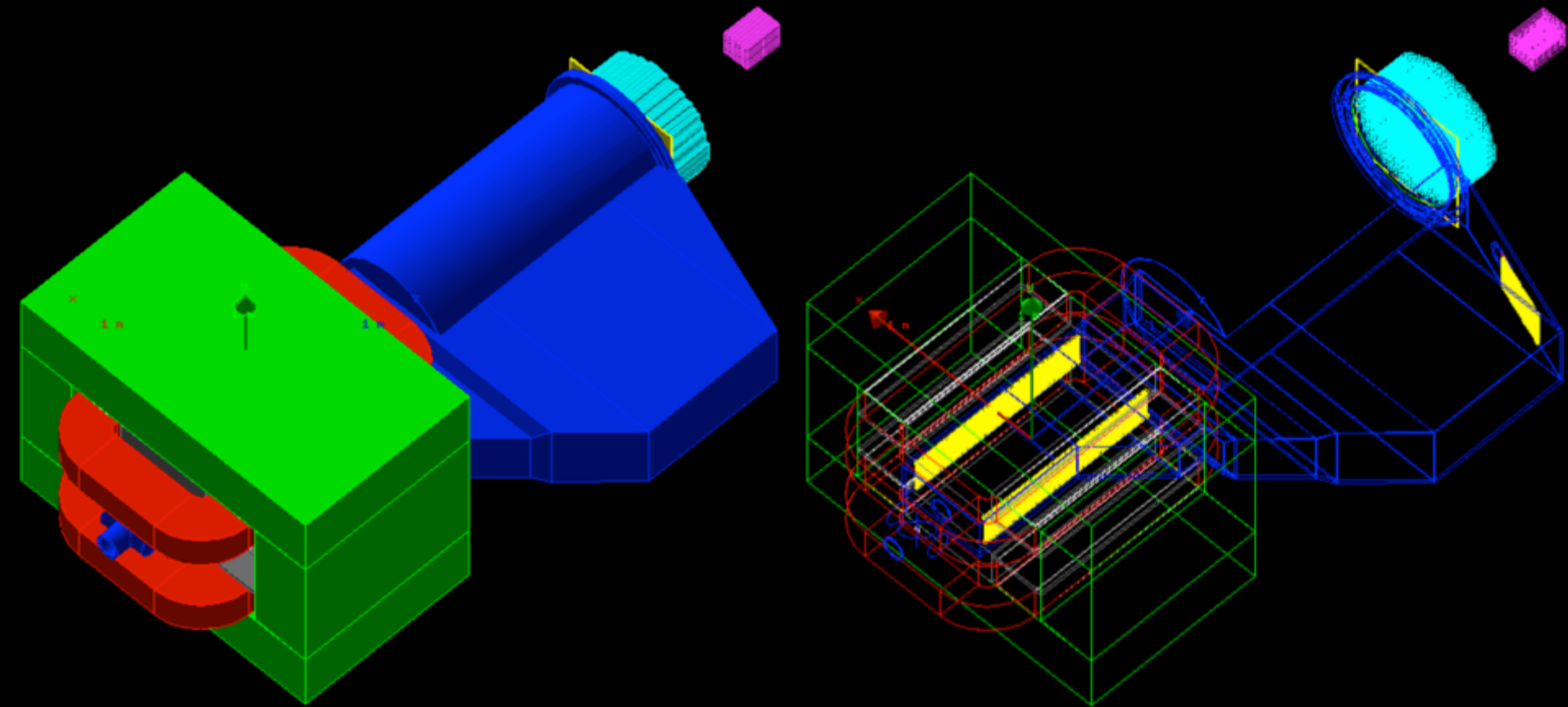
- Full description of the detector achieved including passive materials
- **New sensitivity estimate ongoing**
- **Need theoretical guidance to study sensitivity non dark photon scenario:**
  - **ALPs generators**
 - **X-Bosons optimization under study**

A' to invisible sensitivity analysis

MC M_{miss}^2

Events/5 MeV²

M_{miss}^2 no cuts
M_{miss}^2 cuts

$e^+e^- \rightarrow \gamma\gamma(\gamma)$ $e^+N \rightarrow e^+N\gamma$

Pile up

M_{miss}^2 (MeV)

MMiss² for different $M_{A'}$

MMiss² (MeV)

Candidate Signal selection

- Just one photon cluster in the ECal
- 30 mrad < θ_{Cl} < 65 mrad
- No tracks in the charged veto in within ±2 ns
- No photons with E_γ > 50 MeV in within ±2ns in the SAC
- Cluster Energy: $E_{min}(M_{A'})$ < E_{Cl} < $E_{max}(M_{A'})$ MeV
- Missing mass in the region: $M_{A'}^2 \pm \sigma(M_{miss2})$

Search technique

- Count the number of BG events in each mass region from the blue distribution
- Consider them as A' candidate

PADME-invisible decay sensitivity
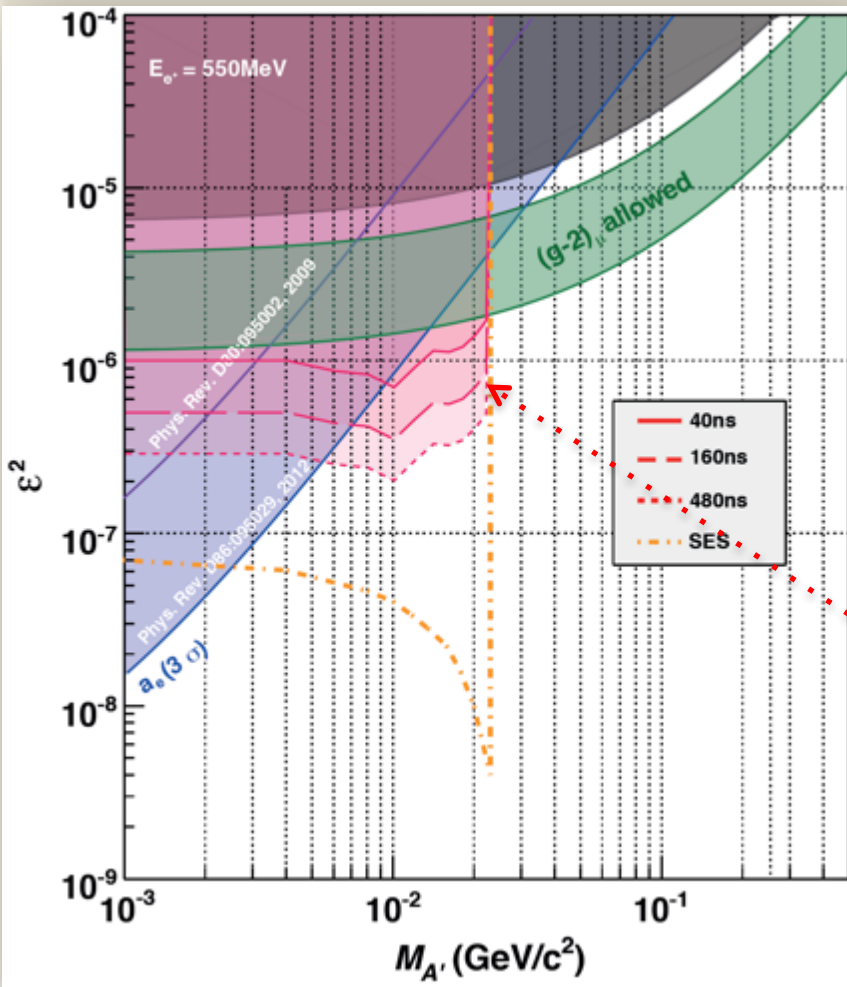
- Based on 2.5×10^{10} fully GEANT4 simulated 550MeV e+ on target events
  - Number of BG events is extrapolated to 1×10^{13} electrons on target

- Using $N(A'\gamma) = \sigma(N_{BG})$

- δ enhancement factor $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon = 1$ due to A' mass

$$\frac{\Gamma(e^+e^- \rightarrow A'\gamma)}{\Gamma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)} \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon \cdot \delta$$

PADME 2 years of data taking at 60% efficiency with bunch length of 200 ns
4×10^{13} EOT = **20000 e$^+$/bunch** × 2 × **$3.1 \cdot 10^7$ s** × 0.6 · **49 Hz**

PADME single event sensitivity far to be reached improvement on the limits still possible.

E_{e+}=550 MeV: $M_{A'} < 23.7$ MeV/c^2

E_{e+}=750 MeV: $M_{A'} < 27.7$ MeV/c^2

E_{e+}=1 GeV: $M_{A'} < 32$ MeV/c^2

PADME detector status

Very fast PbF2 Cherenkov calorimeter for rejecting 2 and 3 photon background events and withstand Bremsstrahlung rate fast PMT readout
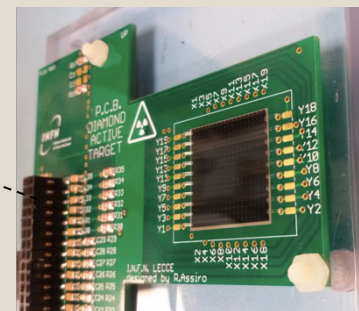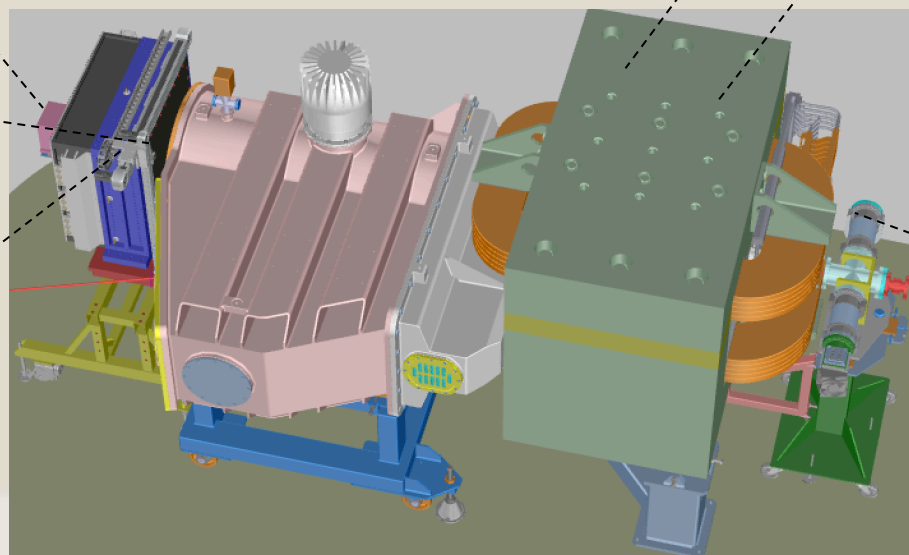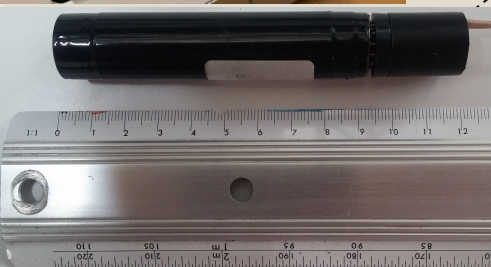
Spare dipole from CERN SPS (23 cm gap, 1 m long)

Scintillating bars with SiPM readout for rejecting Brems. background events (tagging positrons) Inside vacuum vessel

EM calorimeter BGO L3 crystals

Diamond with graphite strips: All-Carbon active target, beam position & size and luminosity monitor.
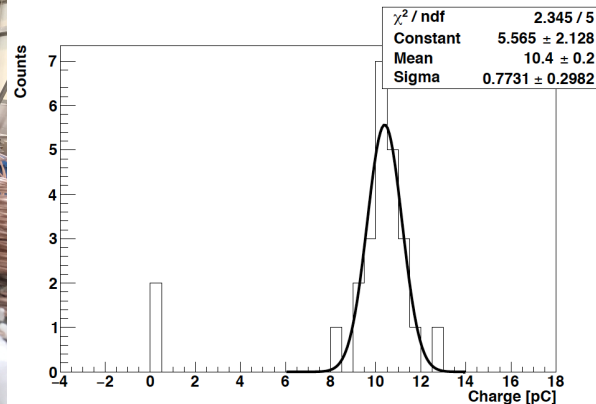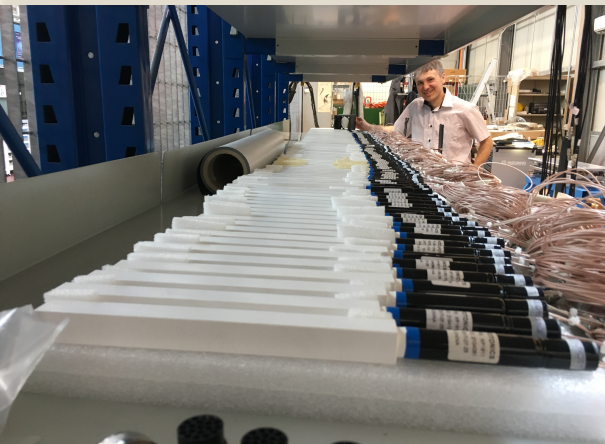
The PADME Ecal Status

Test each single crystal with a ^{22}Na source and 10 different PMT HV value to measure the crystals response curve. Compute the equalisation voltage.
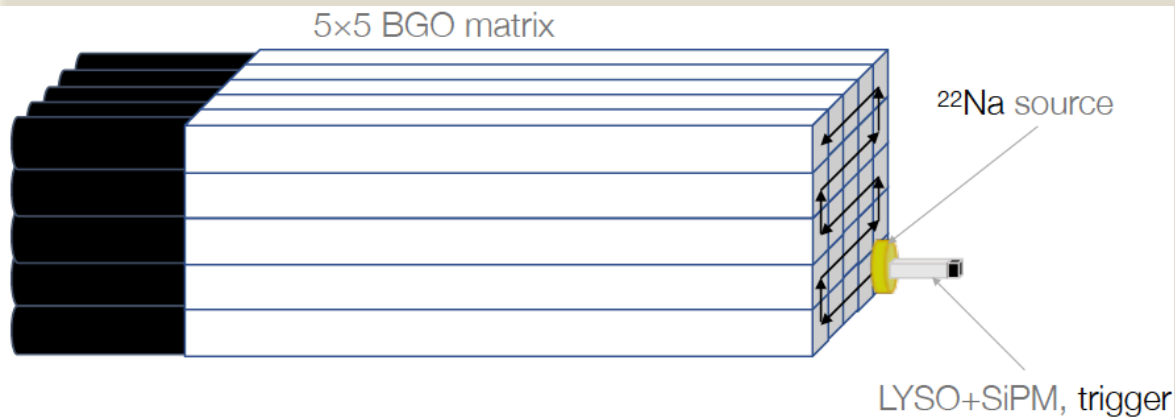
Ecal mechanics ready for assembly (moving at BTF next week)

5×5 BGO matrix

^{22}Na source

LYSO+SiPM, trigger

More than 300 crystals already ~50% tested and ready to be assembled

χ^2 / ndf	2.345 / 5
Constant	5.565 ± 2.128
Mean	10.4 ± 0.2
Sigma	0.7731 ± 0.2982

Charge [pC]

INFN ROMA

PADME

The PADME vacuum chamber

Inner chamber assembly at Fantini S.P.A

commissioning and running plans

2018

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PADME Construction					Commissioning			PADME Run I			

Now

2019

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beam time for PADME to be negotiated with INFN and LNF management											

2018: commissioning and running

- PADME aims at collecting **1×10^{13}** positrons on target **by the end of 2018**
- **Start of data taking for physics during July 2018**
- **Data 2018 collection**
  - Assuming a 65% eff. with 200 ns pulse length: 1.5E7s*49pulses/s*2E4e+/pulse*0.65 = **10^{13} e+ on target**
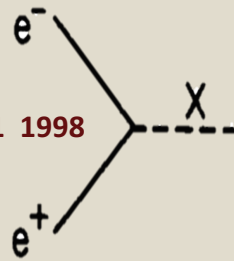
ALPs physics at PADME

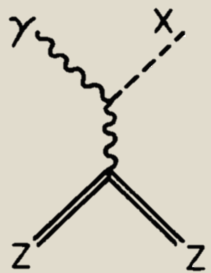PADME can search for ALP having electron or photon couplings exploring different production mechanisms.
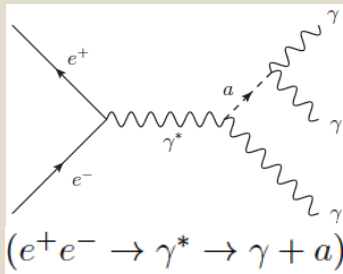
Bremsstrahlung

Phys rev D 38 11 1998
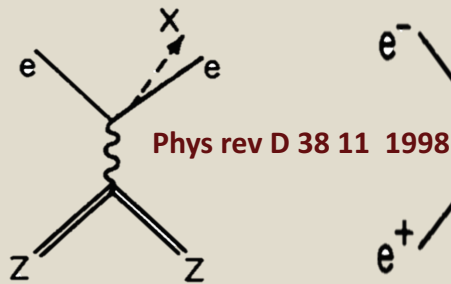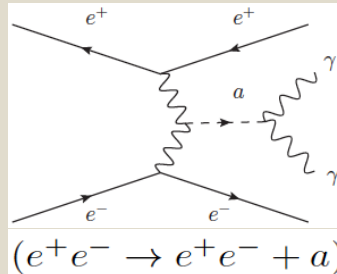
Annihilation

Primakoff

aγ Ann.

$$(e^+ e^- \rightarrow \gamma^* \rightarrow \gamma + a)$$
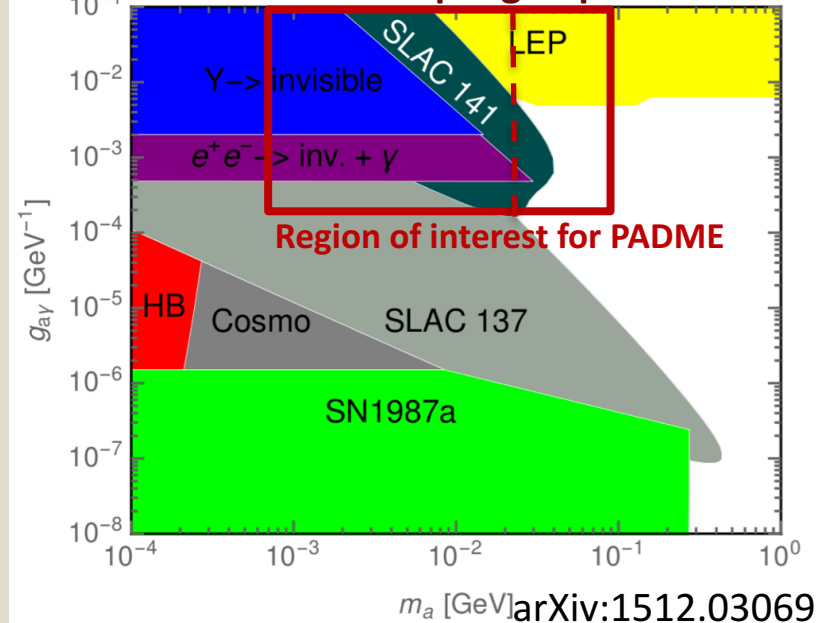
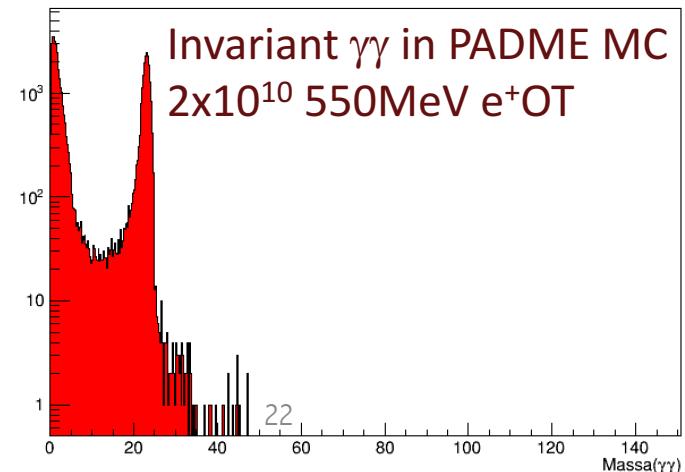### Photon fusion

$$(e^+ e^- \rightarrow e^+ e^- + a)$$

The observables at PADME might be:

Visible ALPs: $e^+\gamma\gamma$, $\gamma\gamma\gamma$, $e^+e^-\gamma\gamma$

Invisible ALPs: $\gamma + M_{miss}$, $e^+e^- + M_{miss}$

Limits on ALPs coupling to photons

SLAC 141
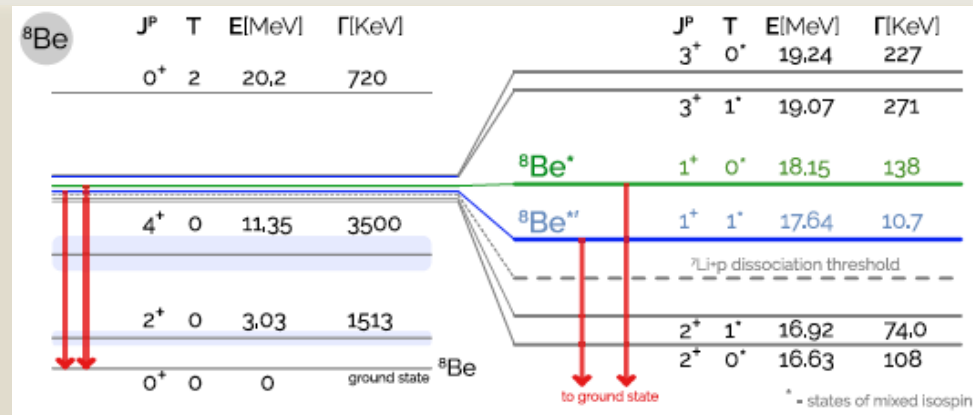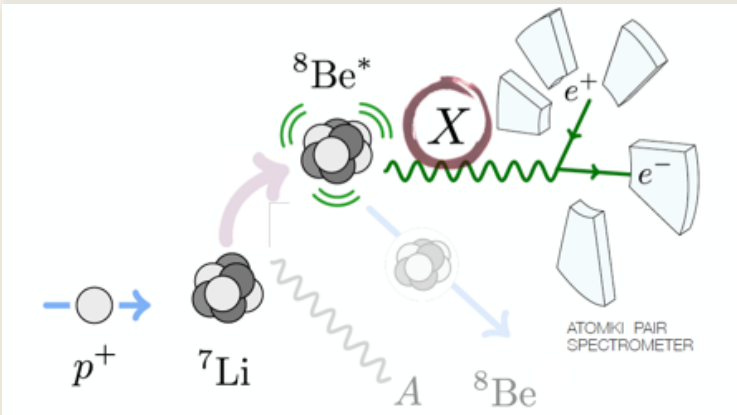Υ-> invisible
LEP
$e^+e^- \rightarrow$ inv. + γ
Region of interest for PADME
HB
Cosmo
SLAC 137
SN1987a
$g_{a\gamma}$ [GeV^{-1}]
m_a [GeV]
arXiv:1512.03069

Invariant γγ in PADME MC
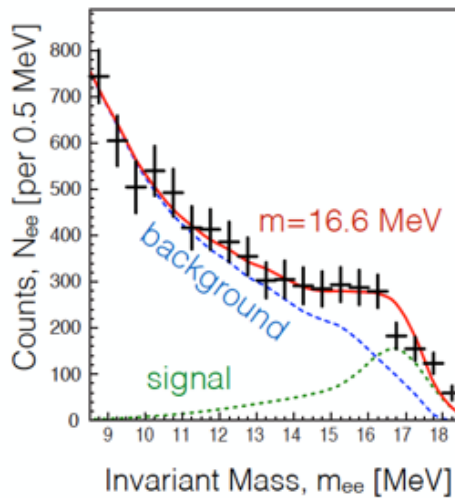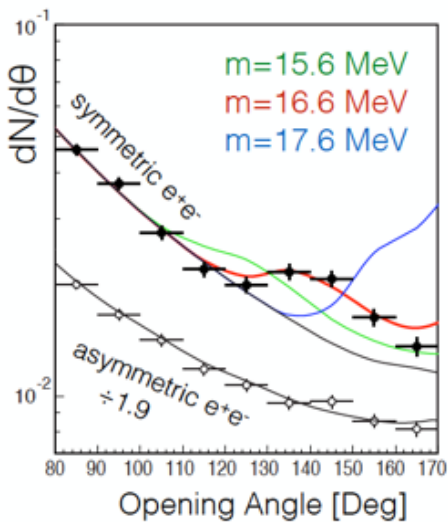2×10^{10} 550MeV e^+OT

Massa(γγ)

The ^{8}Be anomaly

Is this an evidence of a new light dark photon?

$$m_X = 16.7 \pm 0.35(\text{stat}) \pm 0.5(\text{sys}) \text{ MeV}$$

- **Sanity checks performed**
  - Excess disappears as one scans through the proton beam resonance kinetic energy of 1.03 MeV
  - excess becomes more pronounced when restricting to the subset of events with E > 18 MeV and is absent for lower energy events
  - Excess only appears for events with symmetric E_{e+} and E_{e-}

Can only explain the anomaly observed in the internal pair production in the Beryllium-8 nucleus?

Xilin Zhang[1,*] and Gerald A. Miller[1,†]

[1]Department of Physics, University of Washington, Seattle, WA 98195, USA
(Dated: March 16, 2017)

Can only mitigate the anomaly by 1σ by improving nuclear treatment. j.physletb.2017.08.013

The ^{8}Be anomaly interpretation

## Protophobic Fifth-Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions

Jonathan L. Feng,[1] Bartosz Fornal,[1] Iftah Galon,[1] Susan Gardner,[1,2] Jordan Smolinsky,[1] Tim M. P. Tait,[1] and Philip Tanedo[1]

Protophobia

Equations (5) and (8) may be satisfied with a mild ~10% cancellation, provided the charges satisfy

$$-2.3 < \frac{\varepsilon_d}{\varepsilon_u} < -1.8, \qquad -0.067 < \frac{\varepsilon_p}{\varepsilon_n} < 0.078. \quad (9)$$

Given the latter condition, we call the general class of vector models that can both explain the ^{8}Be anomaly and satisfy pion decay constraints "protophobic."
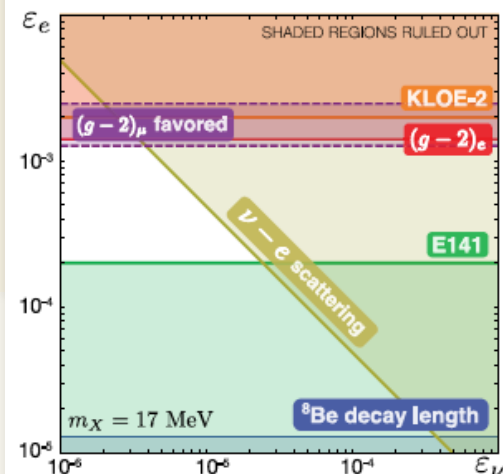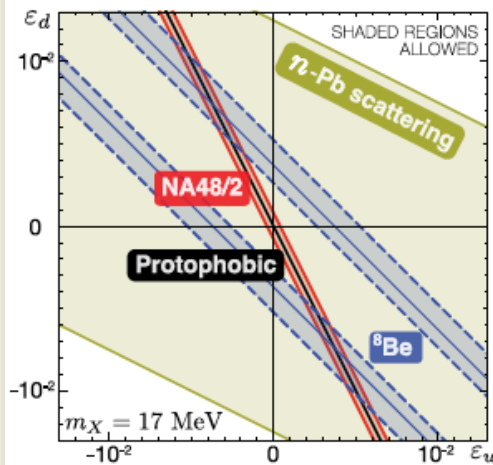
Strongest experimental limit on the electron coupling comes from KLOE data: $\varepsilon_e < 2E\text{-}3$

M. Raggi Vulcano Workshop 2018
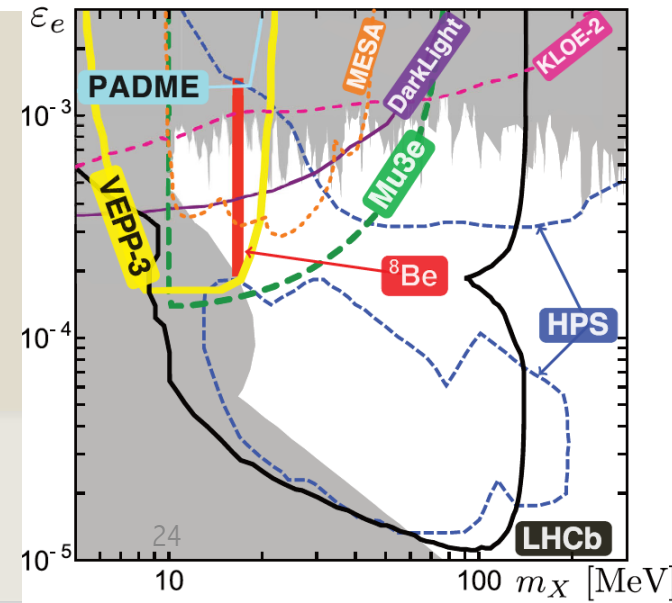
^{8}Be anomaly at PADME

Resonant production of dark photons in positron beam dump experiments

Enrico Nardi,[1,*] Cristian D. R. Carvajal,[2] Anish Ghoshal,[1,3] Davide Meloni,[3,4] and Mauro Raggi[5]

- Exploit the fact that you "know" where to search 17 MeV

- Exploit the unique possibility to have e$^+$ at 282.7MeV @LNF

- Tune E_{e+} such that E_{CM}=sqrt(2*m$_e$*E$_B$)=17MeV

  - Produce A' of 17MeV on shell through direct annihilation ee->A'

  - Parametrically enhanced ee->A' O(α) wrt ee->A'γ O(α^2)

- Use threshold effect to have solid evidence if any

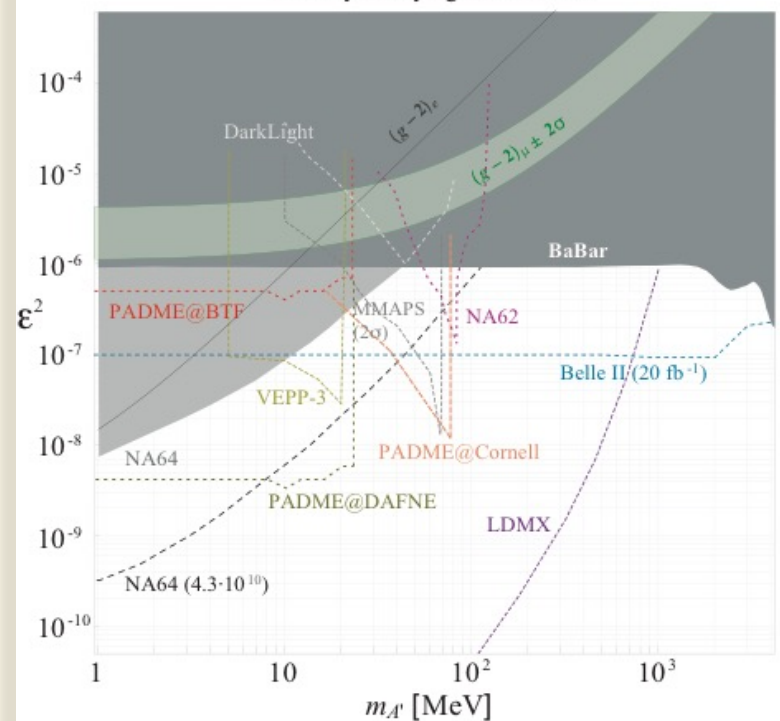- Absorb any SM BG in W dump

- Work ongoing on thin target reaches

Dump mode:
1E18 POT
~282.6 MeV
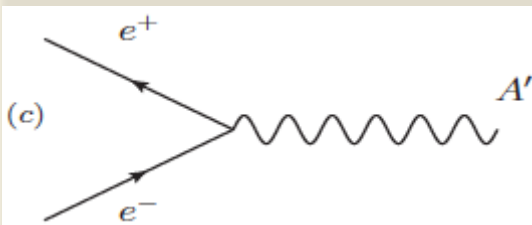
$\epsilon / N_{A'}^{\mathrm{prod}}$	E_{res} ($v_e = 0$)	E_{res}	$E_{\mathrm{res}} + 2\sigma_b$
1.0×10^{-3}	7.69×10^{11}	1.51×10^{11}	4.72×10^{11}
5.0×10^{-4}	1.81×10^{11}	3.79×10^{10}	1.17×10^{11}
1.0×10^{-4}	7.25×10^{9}	1.49×10^{9}	4.73×10^{9}
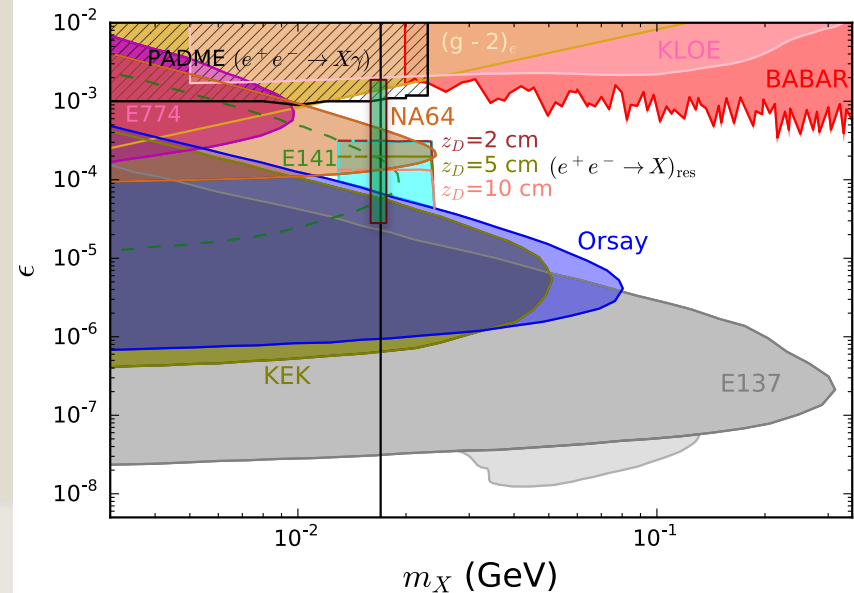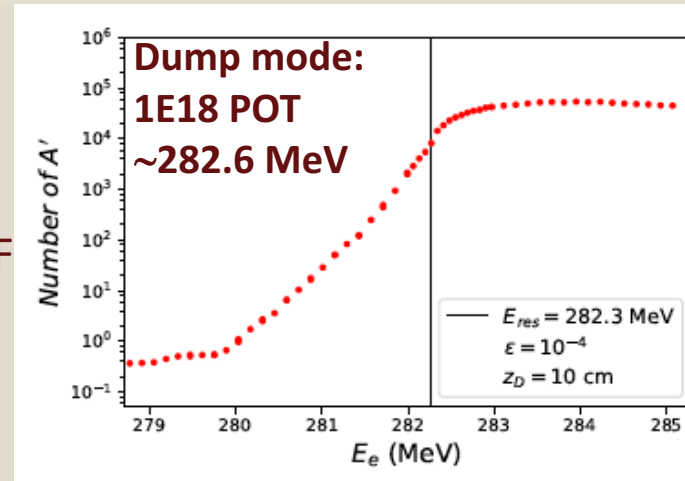
Possible future for PADME in the USA?

Invisibly Decaying Dark Photon

- Main limitation on PADME sensitivity comes from the very small duty cycle of DAFNE Linac (2E-6 – 1E-5)
  - **50Hz x (40-250) ns/bunches**
- Beam energy limits PADME mass reach
  - 550MeV limits $M_{A'}$ < 23.7MeV
- **PADME moved to CESR @ Cornell can profit of:**
  - x10000 higher luminosity
  - x12 Higher energy (6 GeV) $M_{A'}$ < 78 MeV
- **PADME can offer to Cornell:**
  - High spatial and energy resolution BGO crystal Ecal
  - Faster crystals wrt to CLEO CSI(TL)
  - Spectrometer magnet and veto detectors

- Moving PADME to Cornell will be a 1-2M$ scale project (detector ready by summer of 2018!)
- MRI for the extraction of a positron beam from CESR submitted (Feb 2018)
  - Expecting final decision by October 2018.
- PADME might be able to run @CESR in just few years end of 2021-2022?
- A very interesting physics potential: including visible and invisible A', ALPs

Conclusions

- The PADME experiment construction is expected to be completed by the beginning of July
- PADME can be the first experiment to explore the process $e^+e^- \rightarrow \gamma A'$, $A \rightarrow \chi\chi$ in a low energy fixed target environment.
- With 1-2 year of running PADME can still extend the BaBar sensitivity to invisible A' decays to lower couplings.
- PADME experiment is **extending its physics case to other dark sector models**
    - Visible Dark Photons, ALPs searches, Fifth force, dark Higgs
- **Starting data-taking by first half July 2018**
- **PADME is aiming at extending its international collaboration**
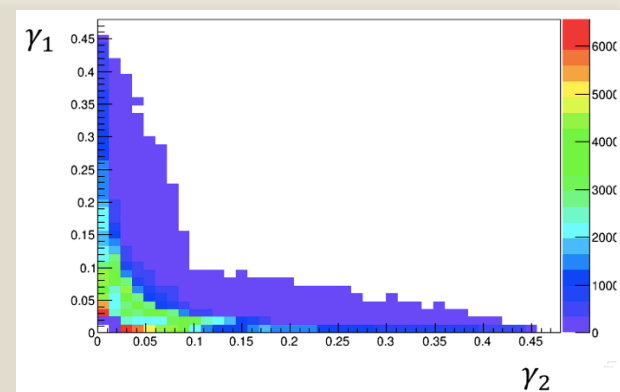   - Your are welcome to join us!

**Join the dark side!**

A' to invisible backgrounds
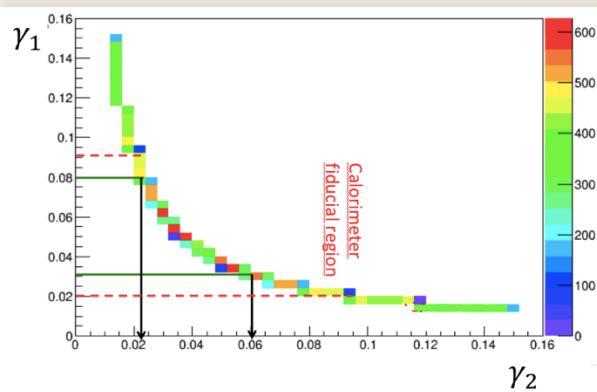
For $\gamma\gamma$ **events**, given one photon in fiducial region, also the second is in the **calorimeter easy to control**
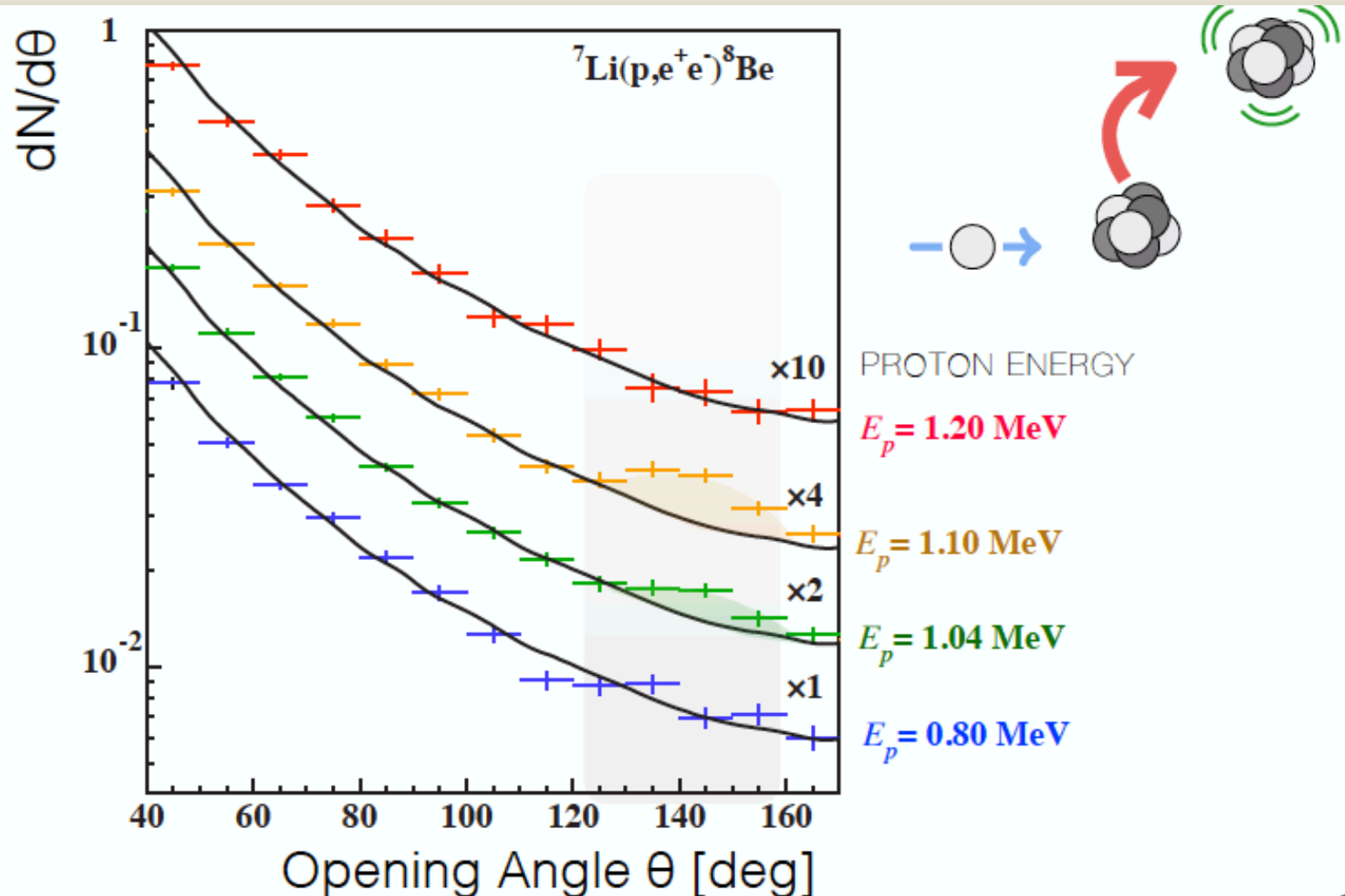

For $\gamma\gamma(\gamma)$ **events**, given one photon in fiducial region, the **small angle calorimeter** is crucial to recover full efficiency on second photon

Residual background dominated by Bremsstrahlung with e^+ missed by the scintillating bars veto
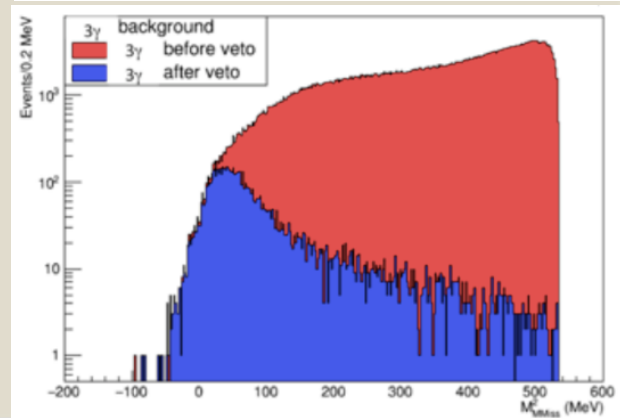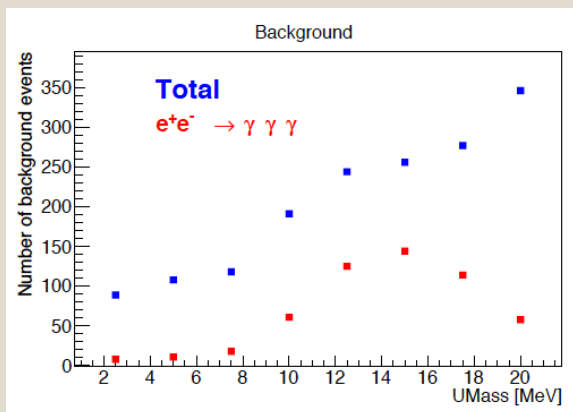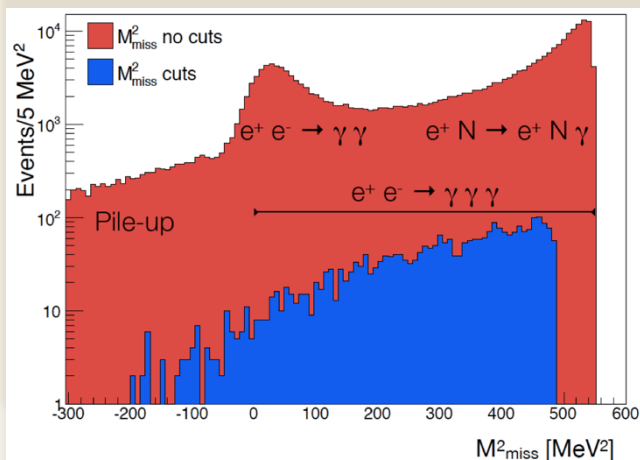
Excitation energy checks

$^7Li(p,e^+e^-)^8Be$

PROTON ENERGY

$E_p = 1.20$ MeV

$E_p = 1.10$ MeV

$E_p = 1.04$ MeV

$E_p = 0.80$ MeV

The PADME collaboration

Istituto Nazionale di Fisica Nucleare ITALY
- Hosting the experiment at Laboratory Nazionali di Frascati
- Participating institutions: LNF, Roma1, Roma3, and Lecce
- 32 researchers working on the project part of their time

University of Sofia, prof. Venelin Kozhuharov and collaborators
- Responsibility of scintillator veto detectors
- Grant obtained to participate into PADME in the next 3 years!

MTA Atomki, Debrecen (Hungary), prof. Attila Krasznahorkay and collaborators

Cornell University, CLASSE laboratory, prof. J. Alexander and collaborators
- MRI submitted for positron extraction line at Cornell to run PADME.

College William and Mary, Prof. B. Wojtsekhowski

The University of Iowa, Adj. Prof. Burak Bilki
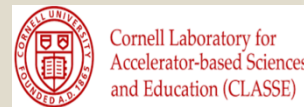
The PADME approach to A' searches

The goal

- Develop a dark sector search which is as much as possible **model independent**
    - Explore several models at the same time (Vectors, pseudo-scalars)
- Minimize the number of interactions and parameters in the data interpretation
    - Need only to describe production mechanism
    - Needs only coupling to electrons
- Provide a **strong and unquestionable experimental evidence for A'**
    - Measure mass and coupling simultaneously can use data driven background estimate!

The way

- Search for the process **e$^+$e$^-$ ->γA'**   A'->Inv. by **measuring the final state missing mass**
    - Independent from the A' decay mechanism, A' lifetime, nature and mass of the dark matter χ
- **Measure ε^2 from rate and M$_{A'}$** from the missing mass
    - Completely constrain the minimal A' model
- Measure ε^2 with minimal theoretical uncertainties
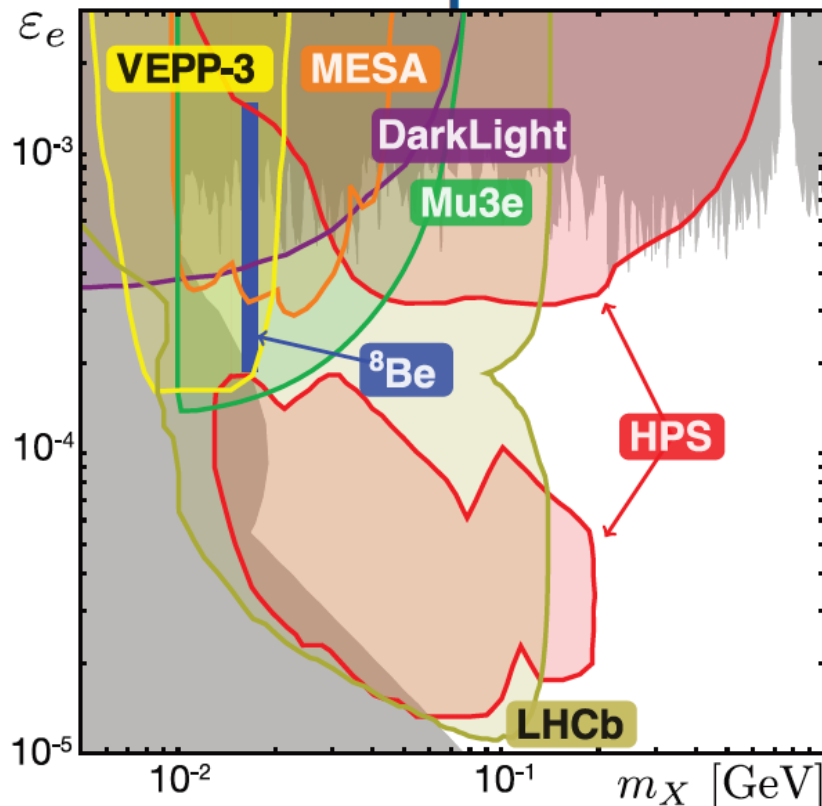   - Just the delta cross section enhancement factor.

⁸Be anomaly at PADME?
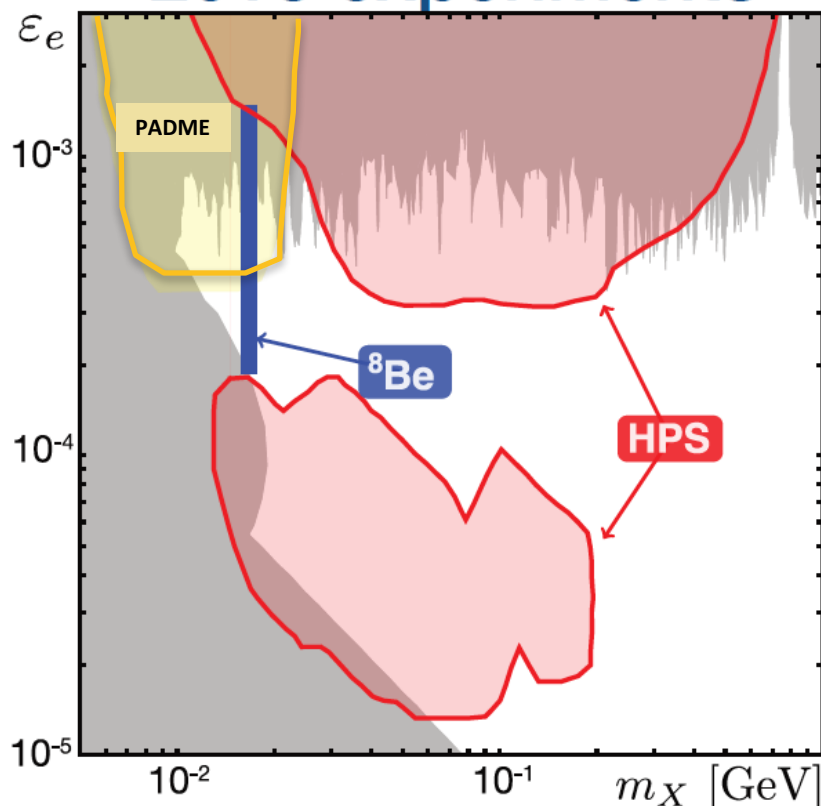
- PADME has the unique chance of producing X in resonant mode BTF a 282 MeV
- Measurement limited from the radiative babbah scattering ee-> eeγ
  - Thin or thick target? Get rid of radiative babbah!
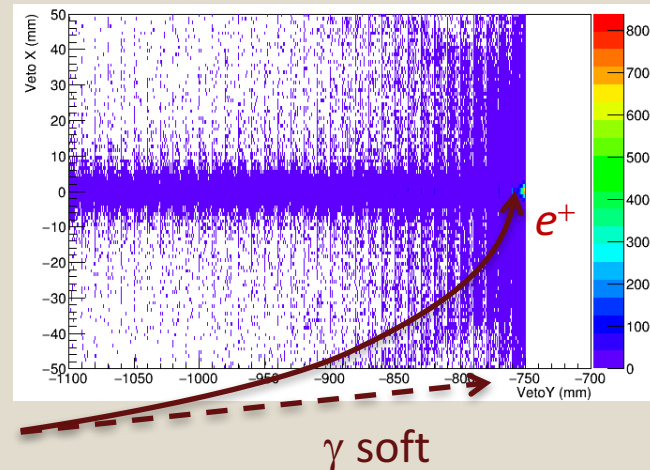- Need a computation of X production cross section at 550 MeV to assess PADME sensitivity

Residual background

Bremsstrahlung
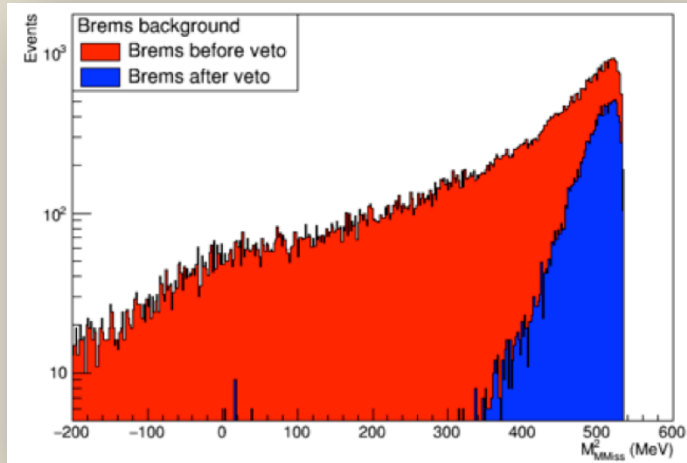
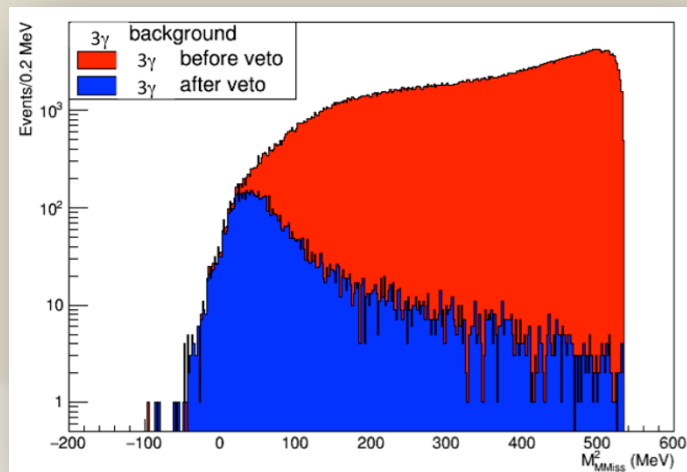
Difficult to veto positron with Ee+≈Ebeam events

e^+

γ soft

3 photons decay

Difficult to veto low energy photons due to high bremsstrahlung rate in the SAC

Design optimization ongoing to reduce residual background new sensitivity expected by summer

Cross sections at PADME

Vladimir Ivantchenko — PADME — 24 febbraio 2017 18:38

RE: cross section measurement at PADME — Dettagli

A: Mauro Raggi, Cc: Paolo Valente e altri 1

Dear Mauro,

For these energies, in Geant4 EM usually theoretical formulas are used for majority of models. Comparison with the data allow to clarify validity of chosen models and their configurations. For EM physics, there are not much data which can be used for validation purposes. For example, known data for bremsstrahlung thin target are available for 1-2 MeV, 15-30 MeV, and 8, 25, 170, 250, 300 GeV. Of course, there are checks in each experiment for calorimeters as a whole, where EM shower is measured and all processes contribute together.
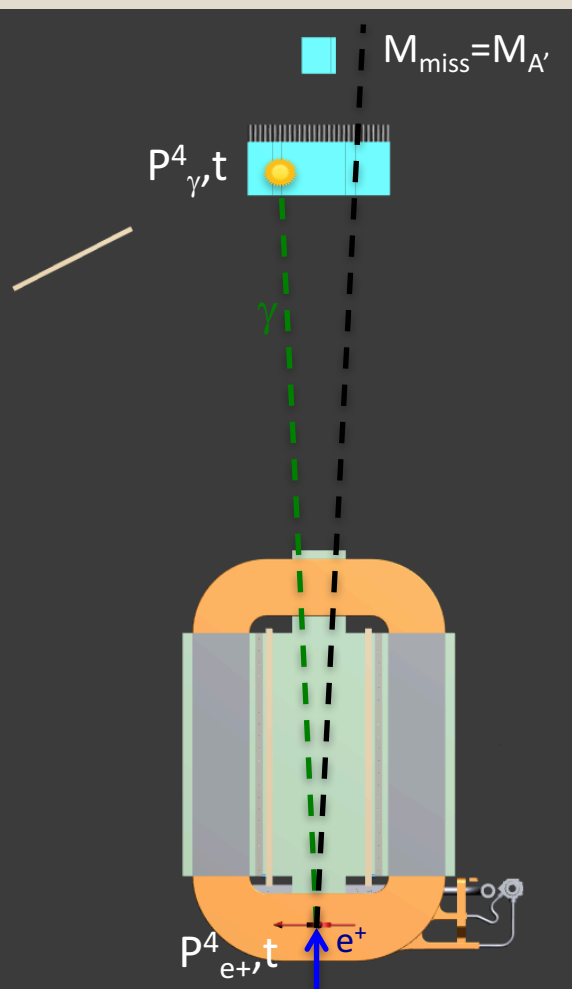
I do not know good thin target data suitable for comparisons for 100-1000 MeV energy range for bremsstrahlung. From my point of view, your measurements may be very useful.
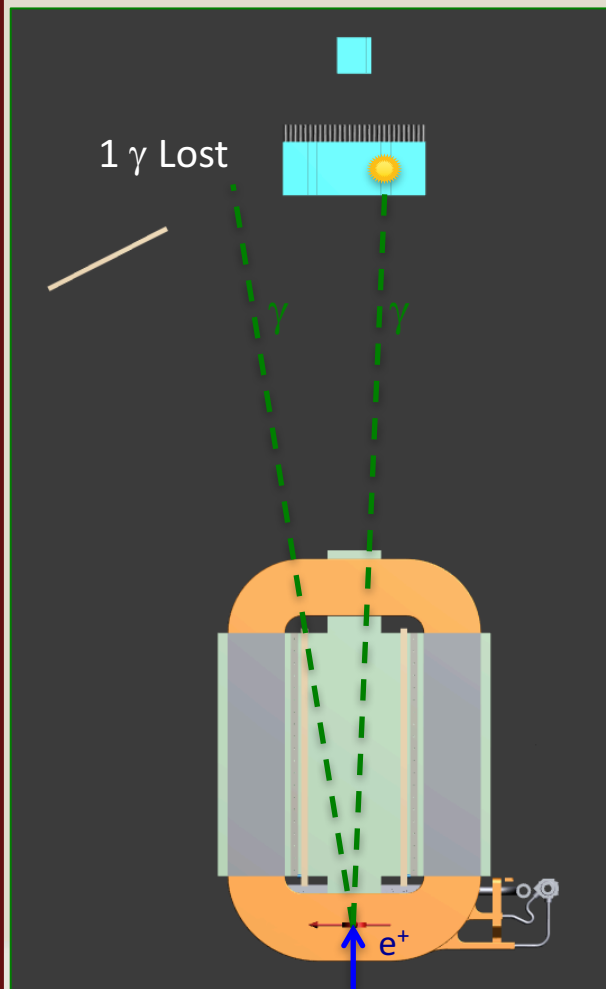
Cheers,
Vladimir

GEANT4 low energy EM libraries
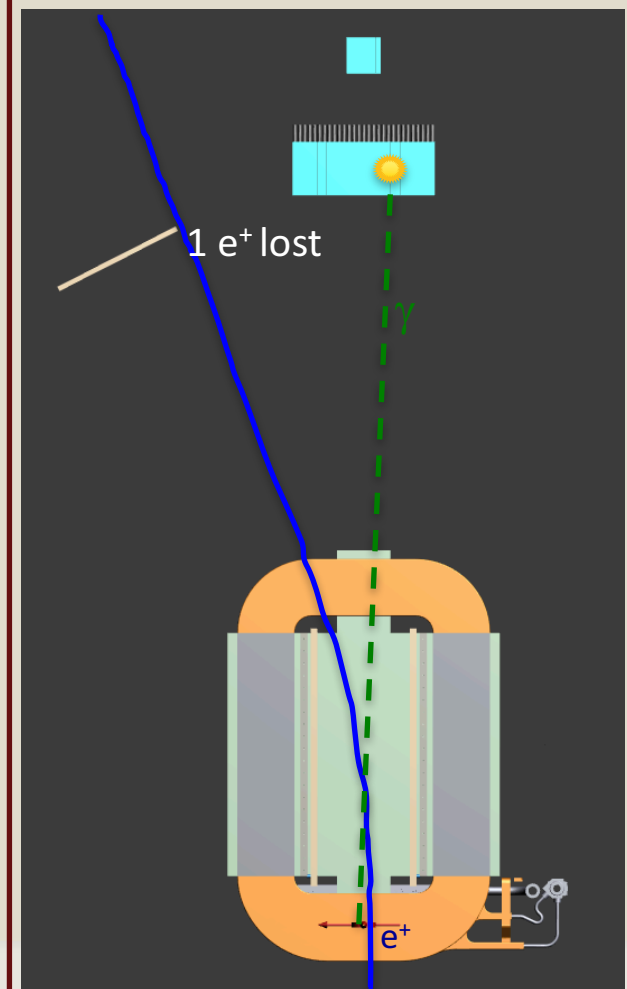
PADME A' main backgrounds

Signal e⁺e⁻->γA'

$M_{miss}=M_{A'}$

P^4_γ, t

γ

P^4_{e+}, t e⁺

BG annihilation e⁺e⁻->γγ(γ)

1 γ Lost

γ γ

e⁺

BG SM Brems.: e⁺N->e⁺Nγ

1 e⁺ lost

γ

e⁺

PADME

Why at low energy fixed target?

- Can play with the target material to get cross section enhancement (ie high Z)
- Can play with beam energy to get resonant production (if mass is known X Boson)
- Just few background sources
    - (below pion production thresholds only QED is involved)
- Can use electron and positron to isolate exotic annihilation productions.
- Small scale and relatively cheap detectors
- Moreover NO ONE ever performed an A' annihilation search experiment at fixed target!
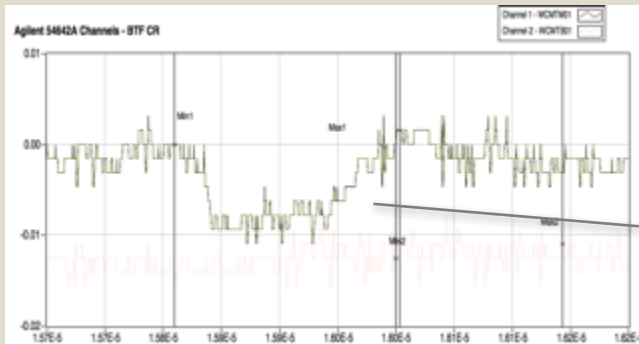
BTF long pulses

Electron gun
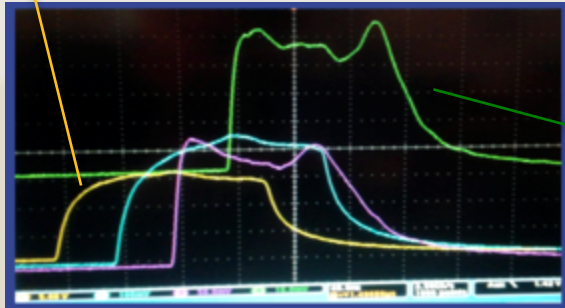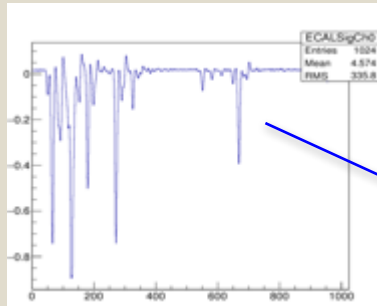

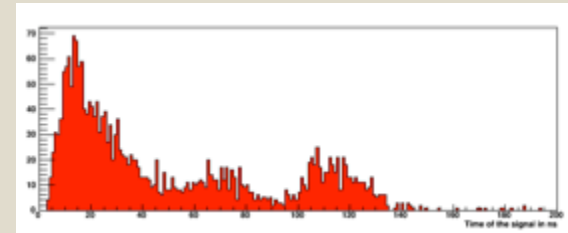Nov. 8th: Gun at 150 ns, flat pulse,
>510 MeV, 1% spread

End of LINAC

- Ancora è necessario del lavoro di ottimizzazione del LINAC allo scopo di ottenere il miglior possibile **spread** in energia e – di conseguenza – un impulso più piatto su un intervallo temporale più lungo possibile
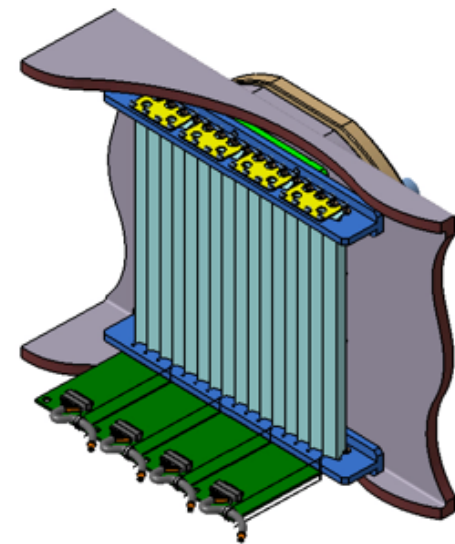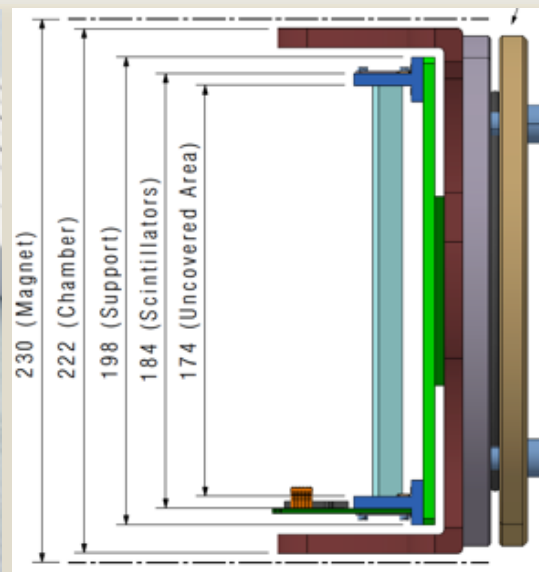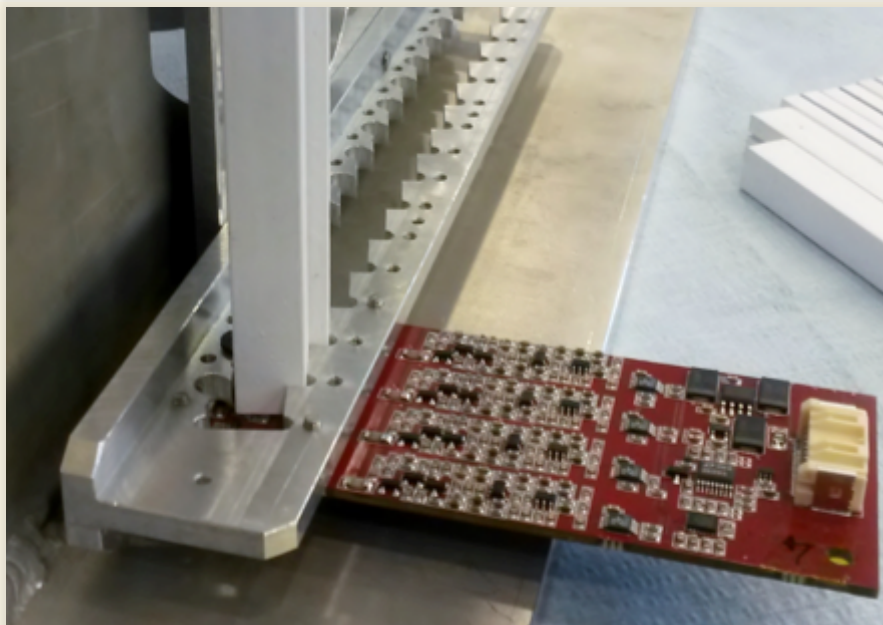

WCM at BTF target

SF57 crystal signal

SF57 crystal signals time distribution

Charged particle veto detectors

10×10x184 mm³ scintillator read out by silicon Photomultipliers

- All scintillator bars **delivered**
- Design of the mechanics **ready**
  - Prototype of the mechanical assembly **ready**
- Prototype electronics prototype **ready**
  - Test-beam in April to measure efficiency and time resolution
- Read-out by same digitizing system as calorimeter (**ready**)
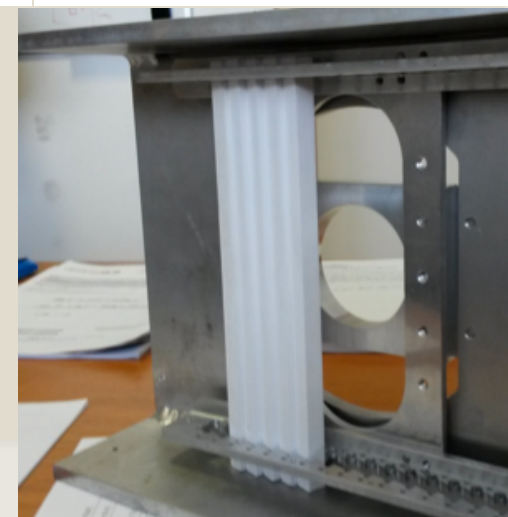
Dark sector search priorhedron©

Dark sector coupling prior

		Weak	Strong
m$_\chi$ prior	**Light**	A' invisible decays ALPs	Axions
	Heavy	B-L couplings Proto-phobic (X->ee)	WIMPs Visible universal A' decays (ee, $\mu\mu$, $\pi\pi$ …)

- Early A' searches inspired by strong priors:
  - Heavy dark matter A' the lightest dark sector state
  - A' coupling to fermions universal!
- It's now time to take a step back in the priors and explore a wider panorama
  - Any dark matter mass no prejudice on the coupling to fermions

©Neal Weiner thanks for the inspiring talk