The PADME calorimeters for missing mass dark photon searches

F. Ferrarotto

INFN Sezione Roma 1

on behalf of the PADME Collaboration

INFN Roma, INFN Frascati, INFN Lecce, MTA Atomki Debrecen, University of Sofia, Cornell University, US William and Mary College

CHEF 2017 – 2-6/10/2017

Lyone

Why the PADME experiment ?

Long standing problem : large cosmological evidence for existence of dark matter (DM), but no clear experimental observation.

Without modifying the SM structure $U(1)_Y+SU(2)_L+SU(3)_C$ DM **can't be** strong interacting (scattering cross section too high) or electrically charged

- can be weakly interacting and massive (WIMPs)

BUT ... no observation up to now

strong constraints from **LHC** and **direct searches** at masses up to TeV

Introduce a new "hidden" sector ?

- Need new mediator particle, very weekly interacting with SM particles, connecting to DM sector
- can be light (where direct detection gets into trouble)
- can explain anomalies in muon magnetic moment, results from scattering experiments searches for DM and antimatter excess in cosmic rays.

End of 2015 : INFN approved a new experiment at the DAΦNE Linac Beam Test Facility (BTF) at Frascati National Laboratories (LNF) :

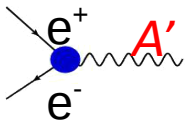
PADME (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment)

The dark photon

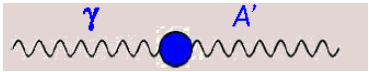
Simplest hidden sector model : one extra U(1) gauge symmetry and a new gauge boson: "dark photon" or U boson or heavy photon (γ' or A')

Two types of interactions with SM particles to be considered:

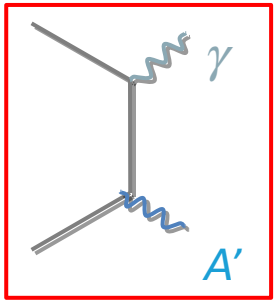
1. QED-like : interactions of the type $\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$
   - Not all SM particles need to be charged under this new symmetry
   - In most general case q_f may be different between leptons and quarks



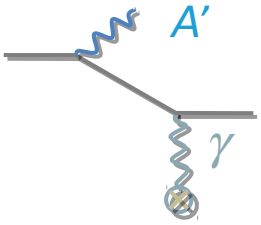
2. Coupling to SM hypercharge through kinetic mixing operator, acquiring a (small) SM charge
   - $\frac{1}{2}\,\varepsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$; $F'^{\mu\nu} = \partial_\mu A'_\nu$
   - $A_\mu \rightarrow A_\mu + \varepsilon a_\mu$; $\alpha' = \varepsilon^2 \alpha$



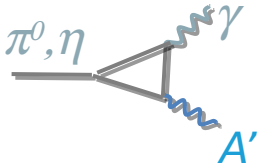
A' production



Annihilation



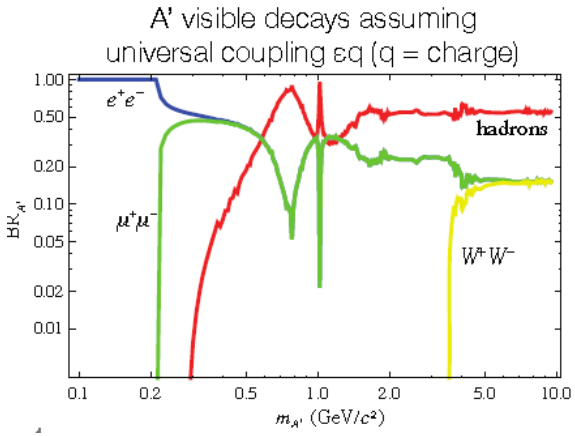
Bremsstrahlung



Meson decay

If **no** DM particles with $m_{DM} < m_{A'}/2$ exist:

- $A' \rightarrow$ SM **visible decays** BR depends on $m_{A'}$
- A' lifetime proportional to $1/(\alpha\varepsilon^2 m_{A'})$

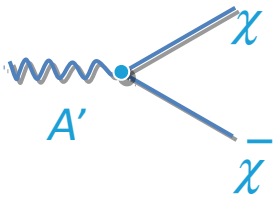


If DM particles with $m_{DM} < m_{A'}/2$ exist:

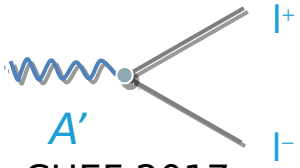
- $A' \rightarrow$ DM **invisible decays** with (likely) BR ≃ 1
- SM decays suppressed by a factor ε^2
- A' lifetime ≈ $1/(\alpha_D m_{A'})$ [α_D: A' coupling constant to the Dark Sector]

A' decay

invisible

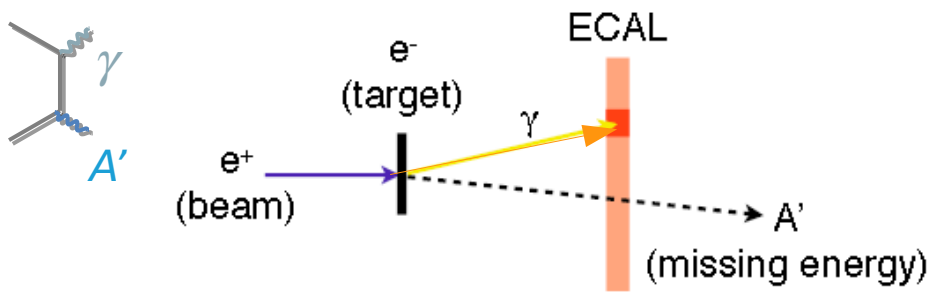


visible



The PADME approach

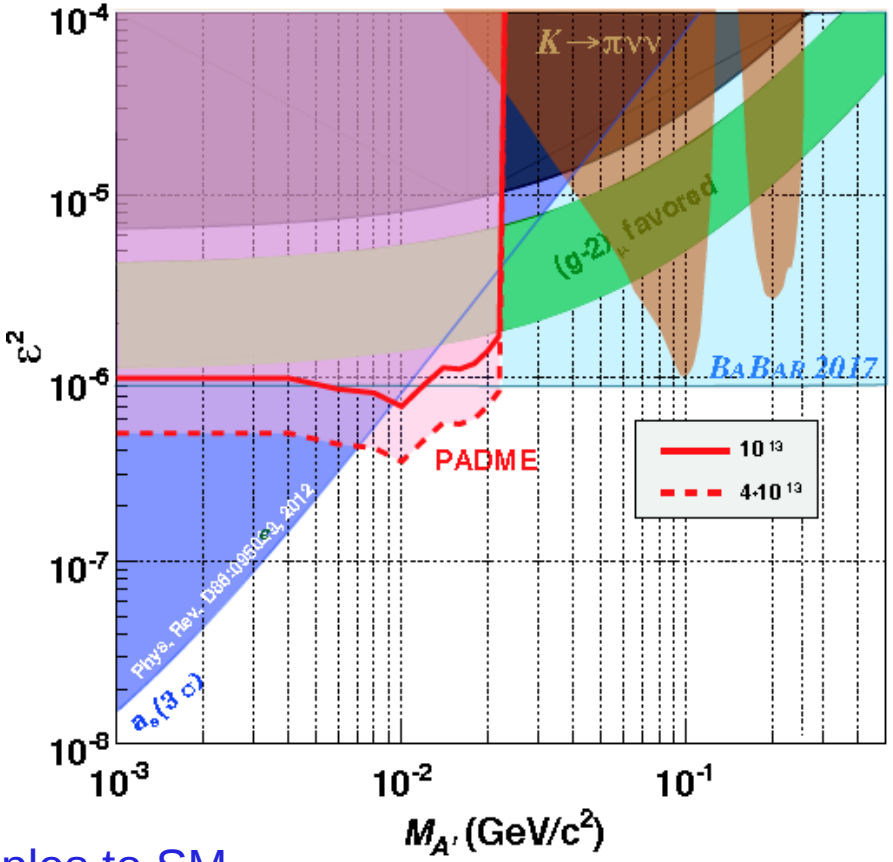
PADME proposes a new tecnique : **annihilation** of a **positron** beam on a (thin, low Z) target, search for a peak in missing mass at $M^2_{miss} \neq 0$ (invisible decay) calculated from final state γ 4-momentum in kinematically constrained condition.



- well known beam energy and position
- measure photon energy and position

$$m^2_{Miss} = (P_{beam} + P_{e-} - P_{\gamma})^2$$

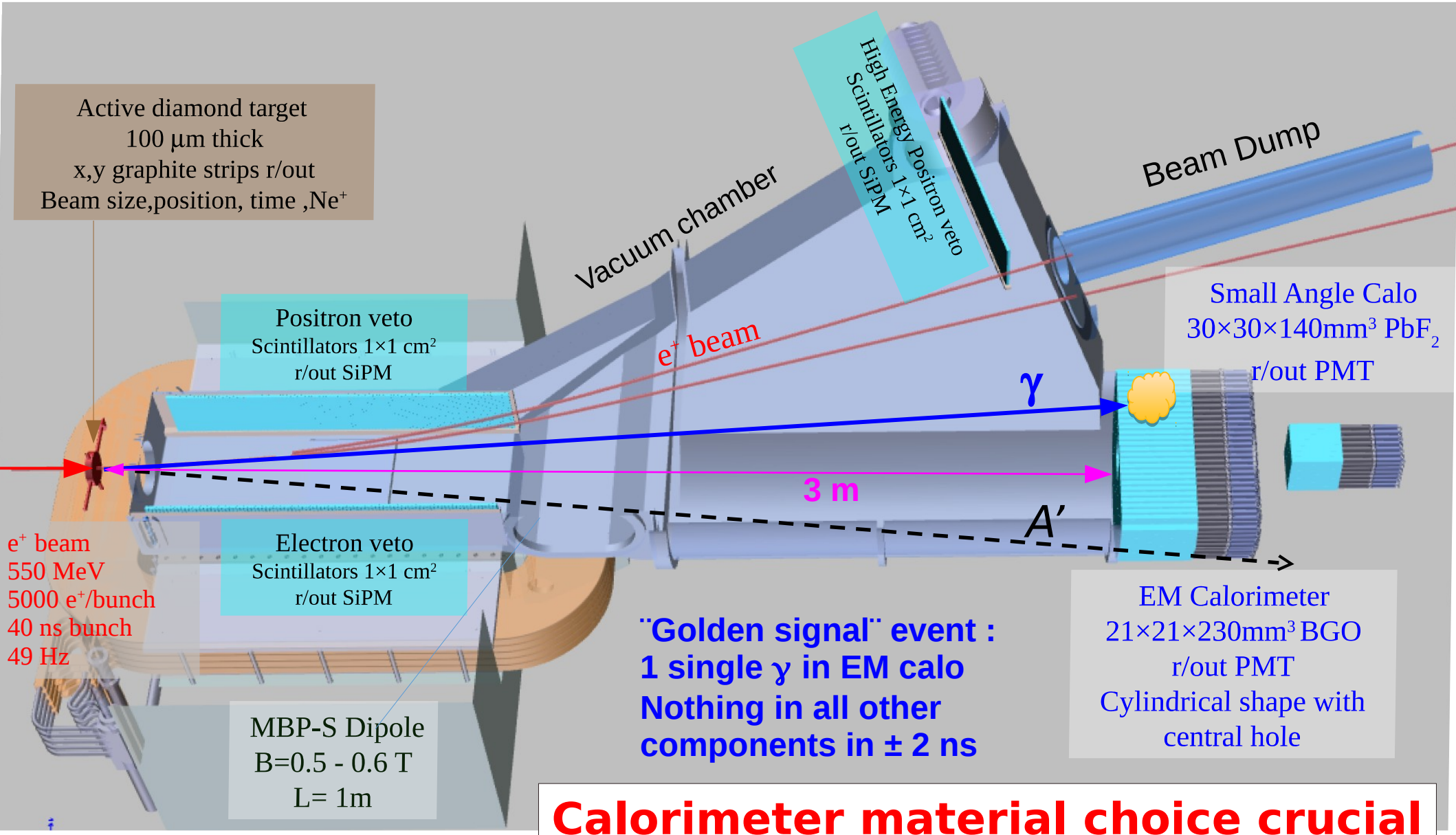
PADME can explore in a model independent way the region down to $\varepsilon \approx 10^{-3}$
$m_{A'} < 23.7$ MeV ($E_{beam} = 550$ MeV)



- minimal model dependent assumptions: A' couples to SM
- coupling of any new light particle produced in e^+e^- annihilation can be limited:
  Dark Photon, Axion Like Particles, Dark Higgs, new proto-phobic vector boson*, ...

* PRL 116, 042501 (2016), PRL 117, 071803 (2016)

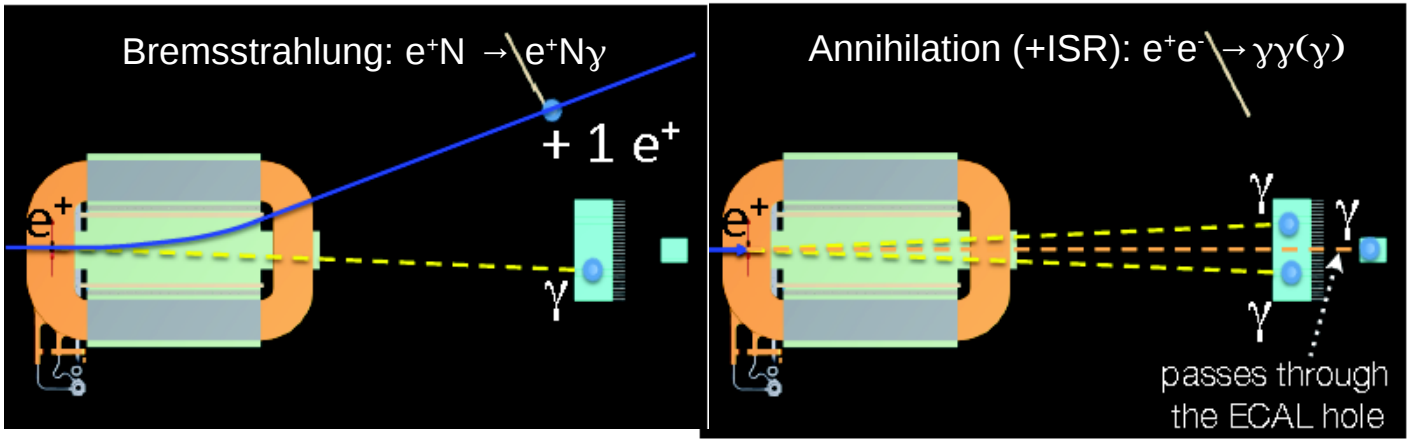
The detector layout (3D view)

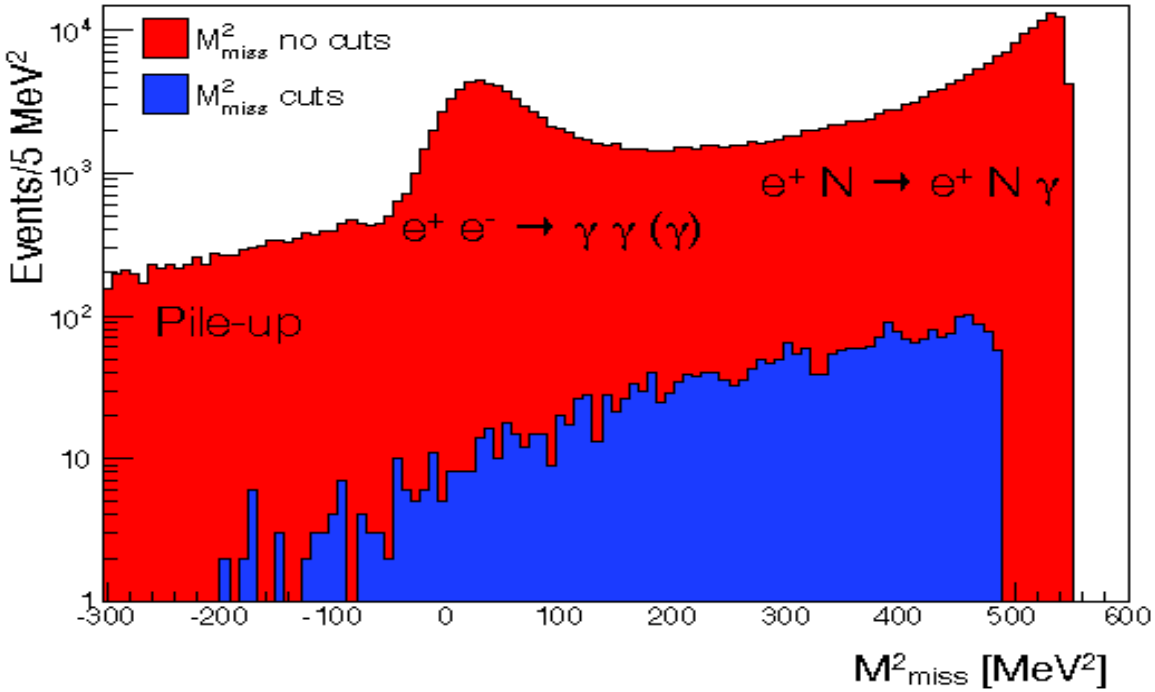


Calorimeter material choice crucial

Backgrounds

e/p/HEP Vetos and SAC essential to veto backgrounds





Signal selection cuts:

- 1 cluster in ECAL fiducial volume
- no hits in e/p/HEP vetoes in ± 2 ns
- no γ in the SAC E_γ > 50 MeV in ± 2 ns
- Cut 20-150 MeV < E_γ < 120-350 MeV (depending on $m_{A'}$)

EM Calorimeter choice

3 basic requirements for the calorimeter:

1. Measure E_γ , θ_γ

- Good energy resolution: 1-2%/√E [GeV]
- High Photo-statistics
- Good containment
- Good angular resolution: ≈1 mrad

2. Fight pile-up and backgrounds

- Sub-ns timing resolution

Material → Moliére radius → granularity
Material → radiation length → volume → cost
Material → light yield → energy and time resolution
(+ photo-sensor)

Choice limited to:

- LYSO (R_M = 2.07 cm) Best choice - expensive
- BGO (R_M = 2.23 cm) 2. best

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

Obtained for free from the L3 calorimeter part of the EC BGO crystals thanks to an agreement between INFN, the L3 Coll. and Prof. Ting

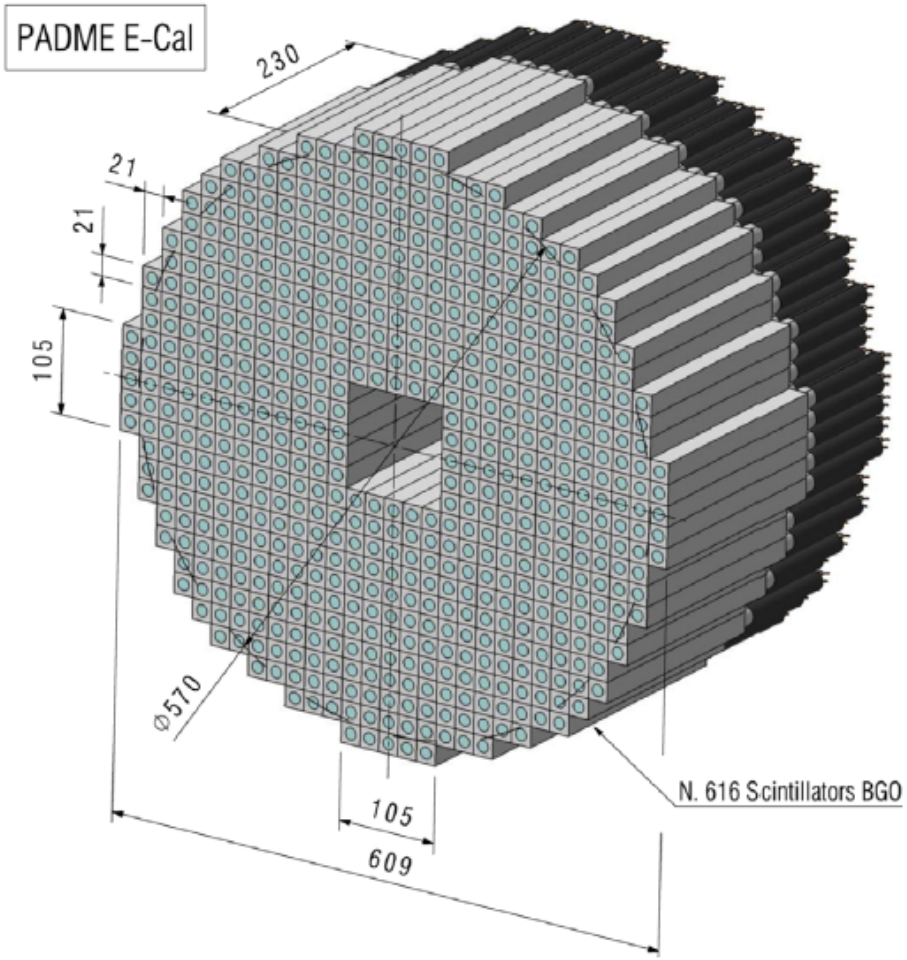
Crystals dismounted and annealed at CERN
Reworked to get usable size and shape for PADME

Crystal cost :
50 k€ (BGO) vs 2 M€ (LYSO) (!)

The EM Calorimeter

BGO - high LY, high ρ, small X_0 and R_M, long τ_{decay}

- **616 crystals each 21x21x230 mm³**
  crystal depth = 20.5 X_0
- Shape ~ cylinder R ~ 285 mm
  front face at 3 m from active target
- Magnet dipole gap limits angular coverage: [20,93]
- Fiducial volume angular acceptance: [26,83] mrad
- Inner hole ~ 105x105 mm^2 wide square for vetoing backgrounds (faster SAC calorimeter)
- readout by HZC XP1911 PMT
  19 mm ∅ good coverage of crystal

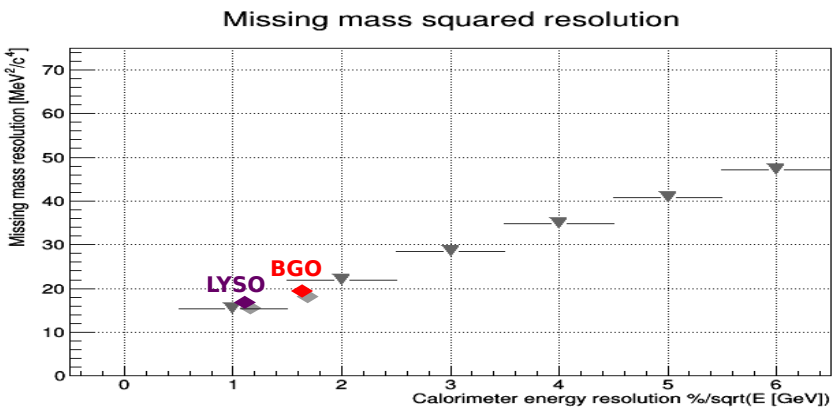


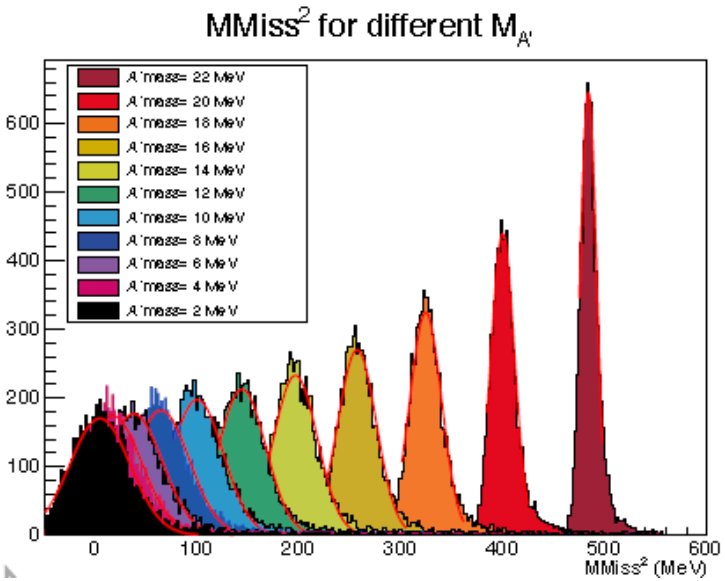
HZC XP1911 19 mm PMT

EM Calorimeter performances

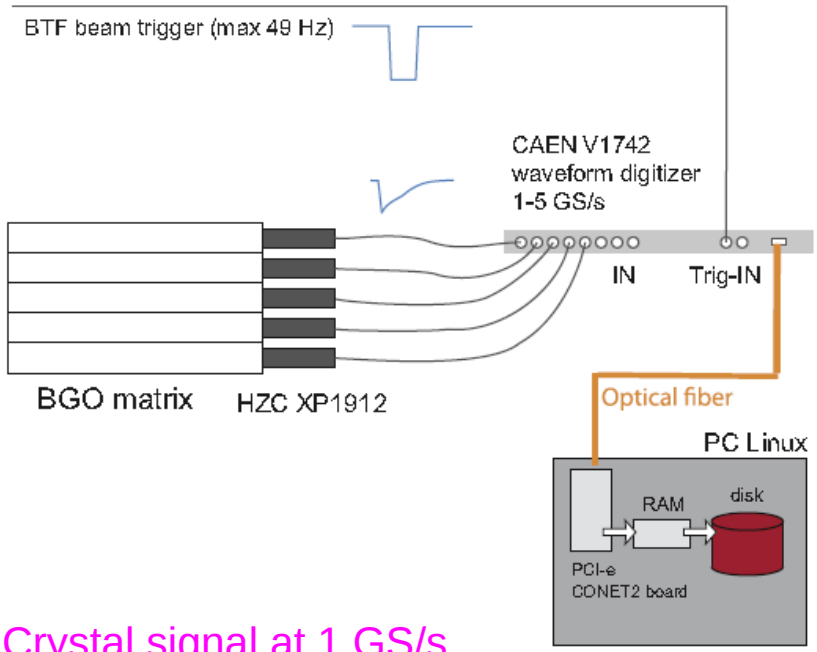
Expected Performances :

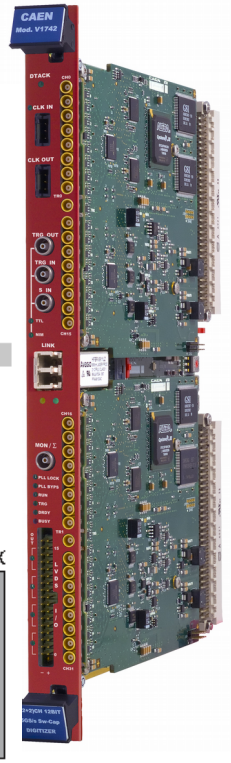
- $\sigma(E)/E \sim 1\text{-}2\ \%/\sqrt{E}$
- $\sigma(\theta) < 1$ mrad
- Timing : < 1 ns from signal shape fit



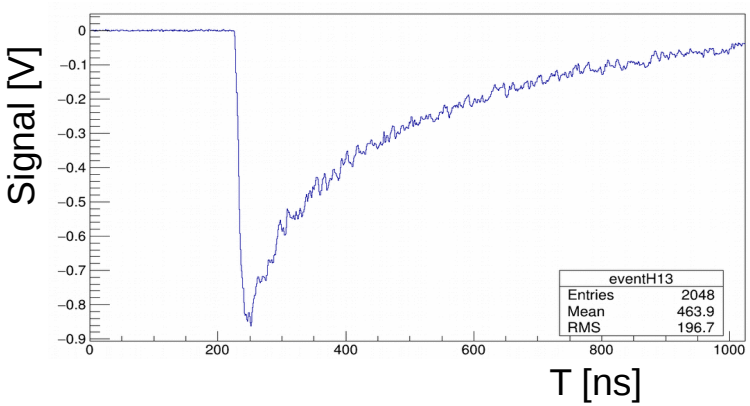


Full digitization of signals over ~1 μs (~3 τ_{BGO}) with CAEN V1742@1GS/s



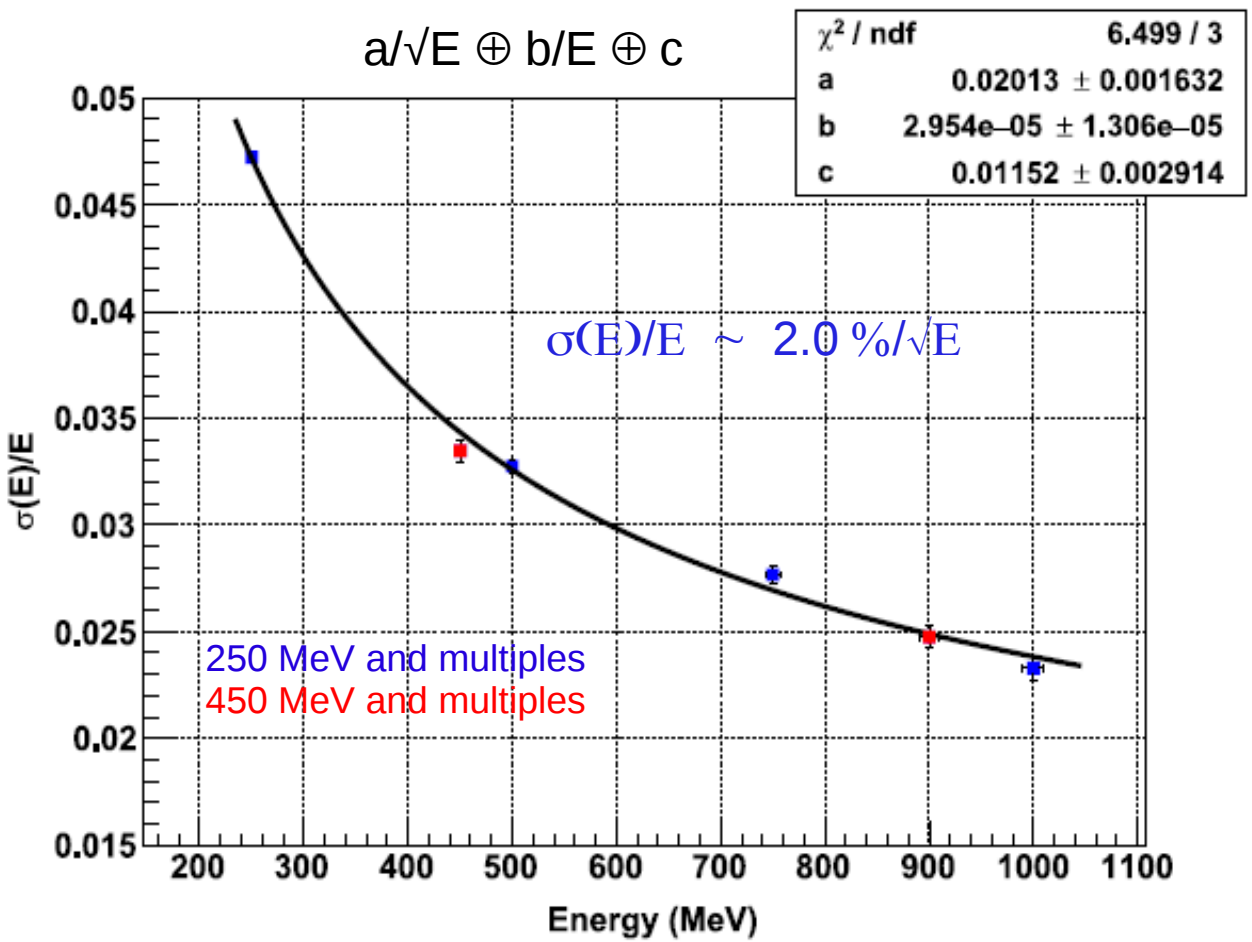


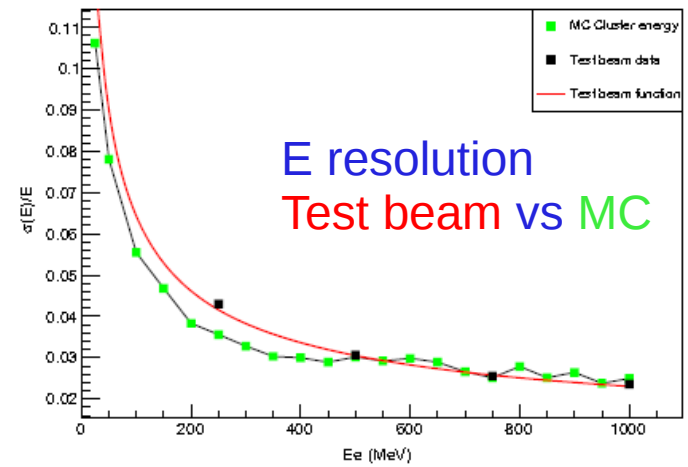
Crystal signal at 1 GS/s

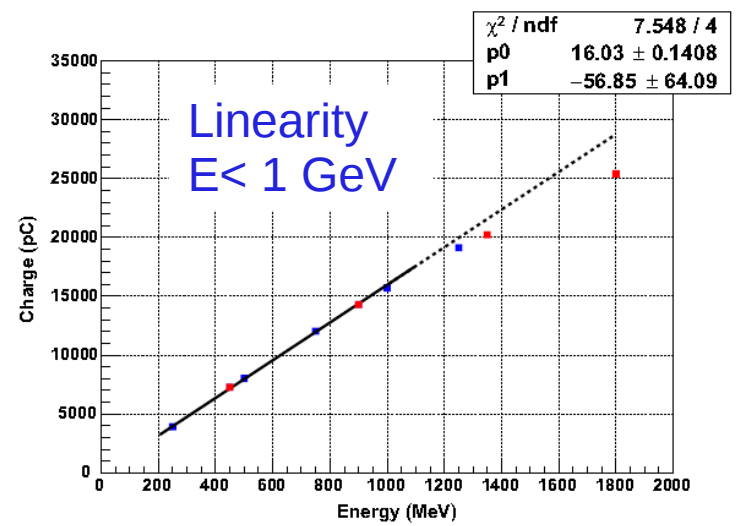


EM calo 2016 beam test

5x5 crystal prototype, HZC 1911 PMTs at LNF BTF
(Average) single particle e^+ beam mostly – 10 ns bunch@49 Hz
Crystals wrapped white Teflon tape – PMT coupled w/ opt grease
2016 test results published in **NIM. A 862 (2017) 31-35**
Crystal response ~ 16 pC/MeV







Improvements 2017

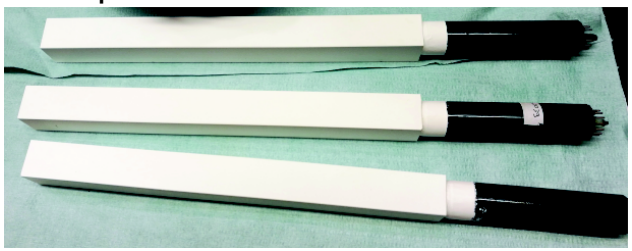
Radiation damage tests done :

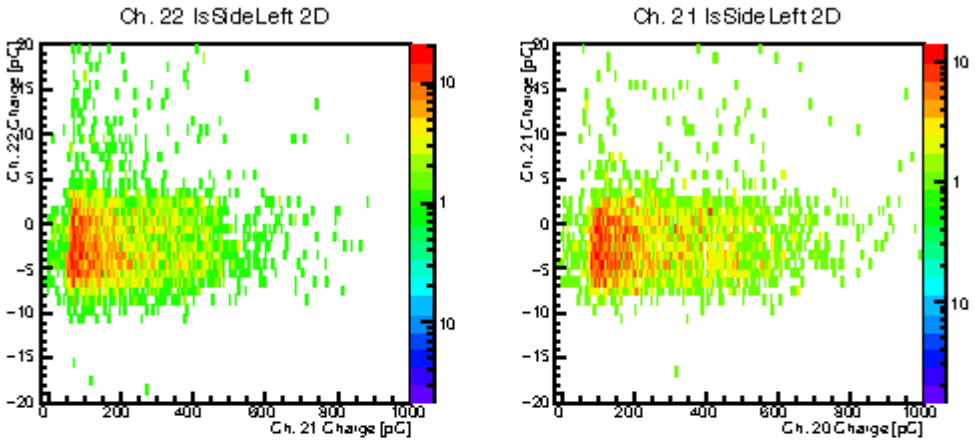
- No significant radiation damage on PMT
- Radiation damage on BGO observed at dose levels expected from literature
- Damage **recovered** by high temperature annealing

Improvements before 2017 Tests :

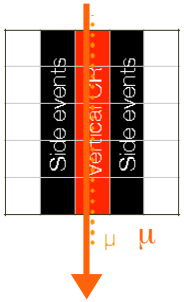
- PMT glued (optical glue) on crystals before painting
- 100 µm paint OK for light tightness at few % level
- Studies with cosmics : need to add TEDLAR foils (50 µm) to drop optical cross-talk to zero
- Calibration using Co and Na_{22} sources

Final element crystal+PMT painted and mounted





Verticality : 5 largest signals in column

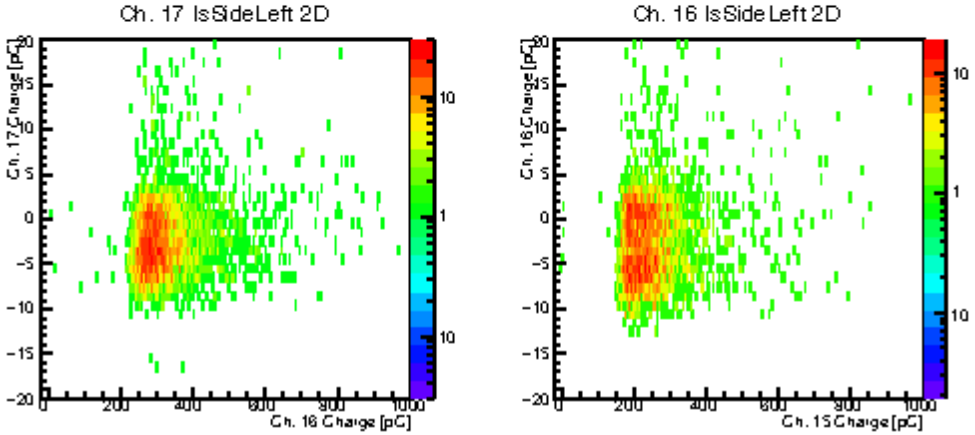


Cosmics run with Tedlar

Crystal Q with vertical passing track vs left crystal Q

Shown only 4/25 crystals

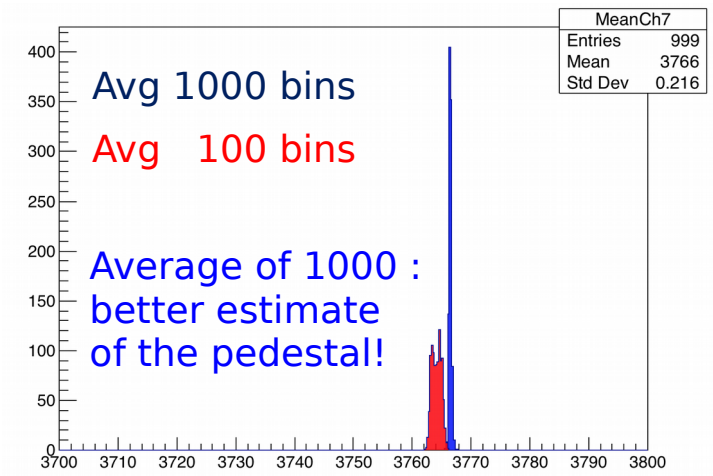
No slope (expected by optical xtalk)

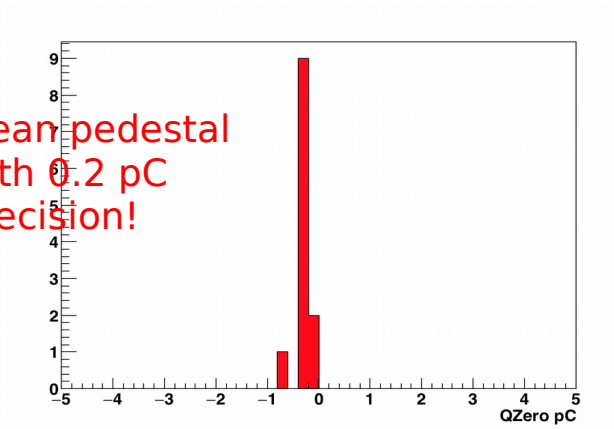


Improvements 2017

Improving pedestal calculation precision essential for zero suppression and better resolution at lower energies

Foreseen random trigger for pedestals between 49 Hz events (not yet in BTF tests)



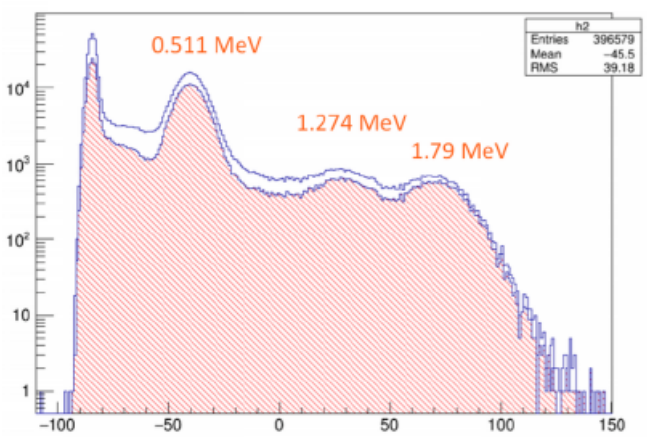


Gaussian pedestal average σ=1.3 pC

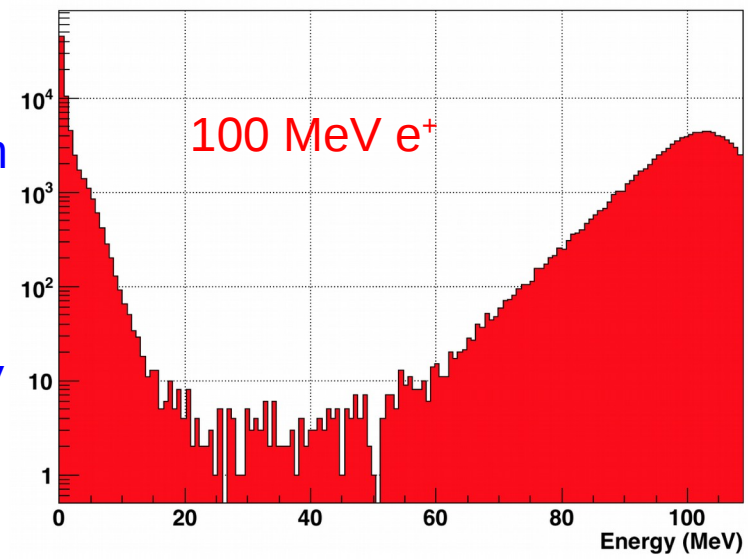
With 16 pC/MeV crystal response

E_{thr} ~ 0.35 MeV

Na_{22} calibration w/ new pedestal

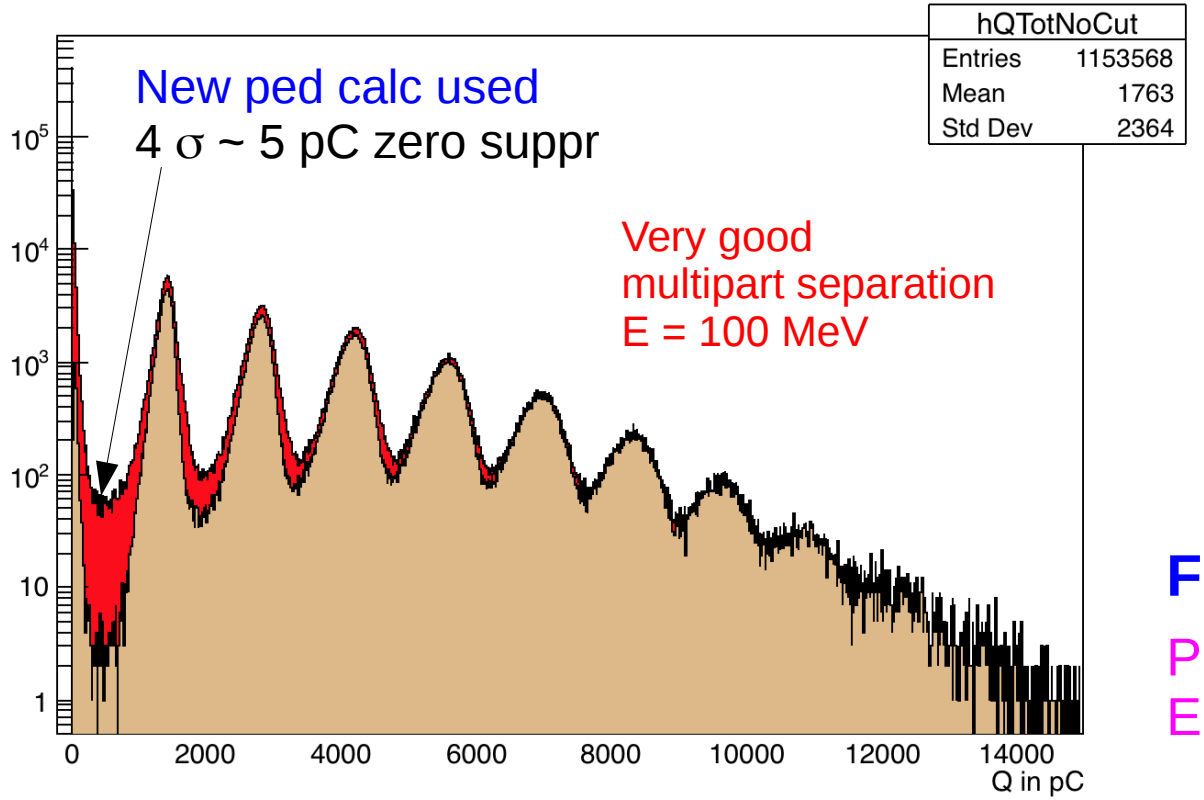


Very good spectrum for low energy γ with reasonable energy scaling.
End point ~ 20 MeV



EM calo 2017 beam test *preliminary*

4x3 and 5x5 crystal prototypes tested, HZC 1911 PMTs at LNF BTF
(Average) single particle e^+ beam mostly – 10 ns bunch@49 Hz
Energy scan 100-400 MeV in 50 MeV bins

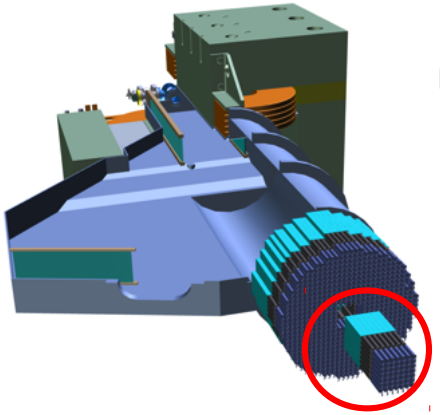


Painted and glued crystal + PMT
Tedlar foils between crystals

Final analysis in progress

Preliminary :
Energy resolution at 100 MeV ~ 7%

The SAC calorimeter



Basic requirements : **FAST**, **compact** calorimeter

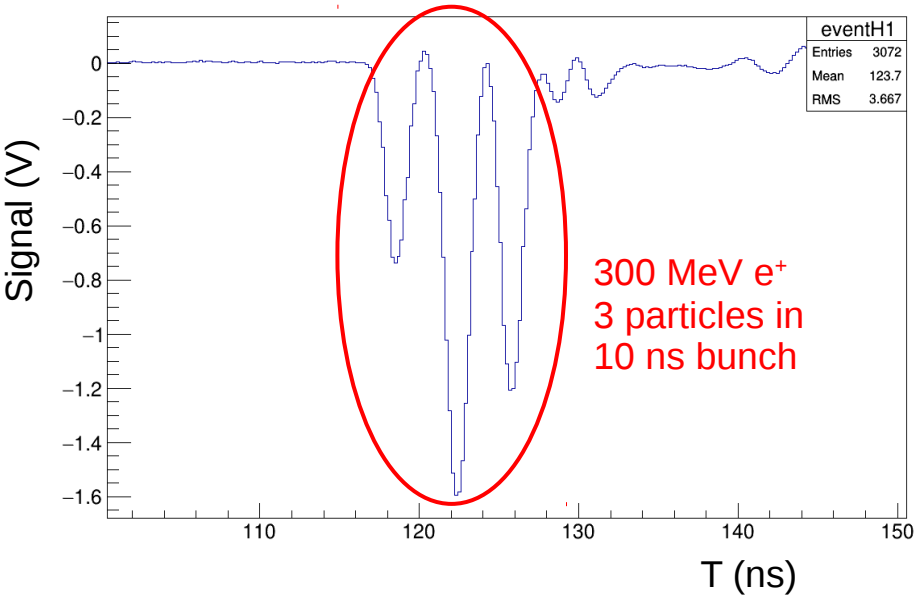
- measure Eγ from ~ 50 MeV at very high rates : several*10 γ in 200 ns
- avoid scintillation mechanism (τ too long) → Cherenkov light
- good time resolution needed O(≤ 200) ps → very fast photosensors
- no need for high light yield material: 0.5 - 2 p.e./MeV is OK
- radiation tolerant (order 1 Gy per 10^{13} e^+ on target)
- moderate energy resolution O(5-10 %) /√E
- transparency at shorter wavelenghts (higher Cherenkov yield)

Choice : 5x5 matrix of 30x30x140mm^3 **PbF_2** crystals

Readout : Hamamatsu R13478 PMT (BA) : fast (< 1 ns risetime) - 2.54 mm Ø (**56% coverage**)
Scale of 1-2 p.e./MeV expected
Black wrapping of crystal to avoid reflections inside

2017 BTF beam test
Black wrapped single PbF_2 crystal
Signal digitization at 5 GS/s by CAEN V1742
with improved dynamic range : 0-2 V

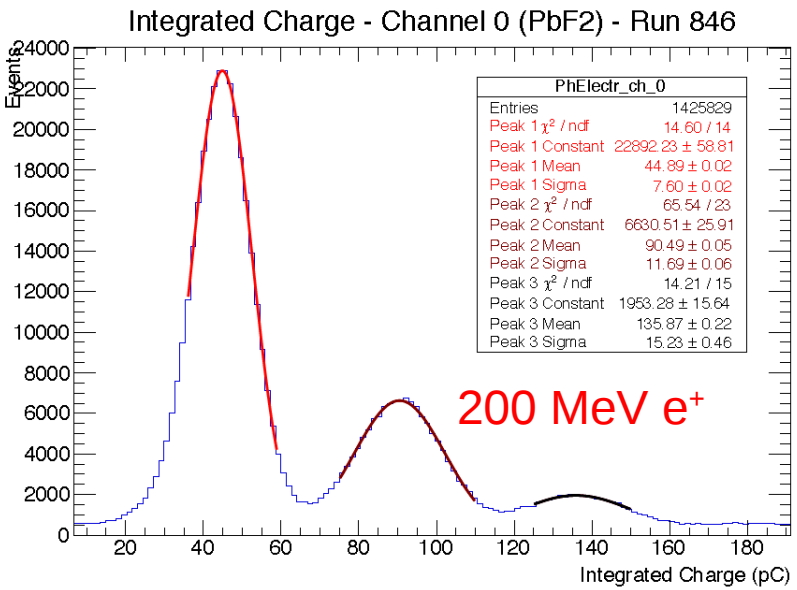
Very good particle separation with ~ 2 ns spacing



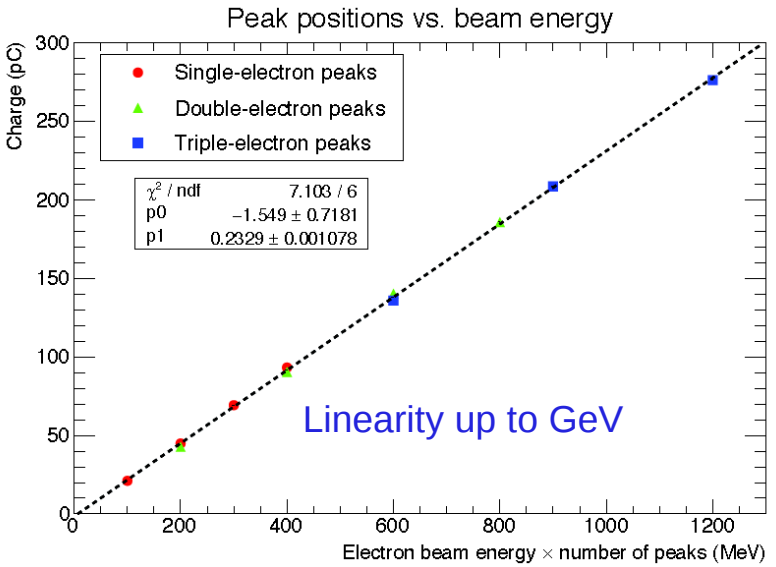
SAC performances - *preliminary*

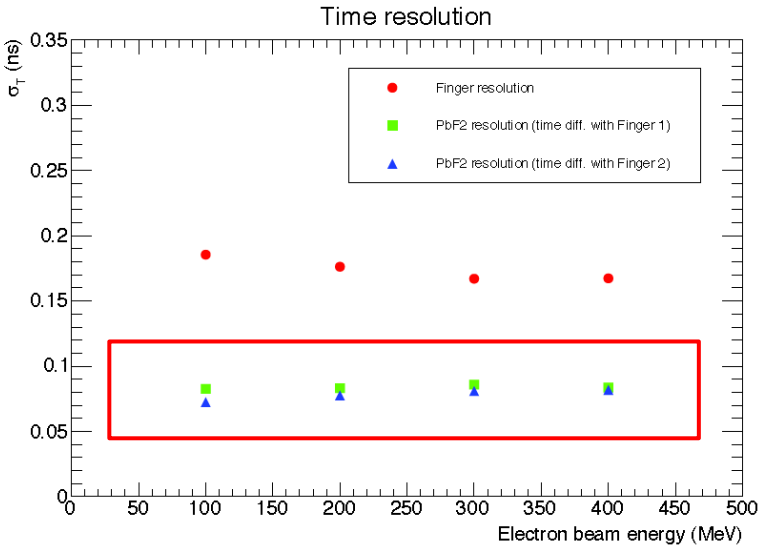
Test beams performed an LNF BTF in 2017 – 100-400 MeV e^+ - **single PbF_2 crystal**

Measured light yeld ~ 1.5 p.e. /MeV **OK for us**



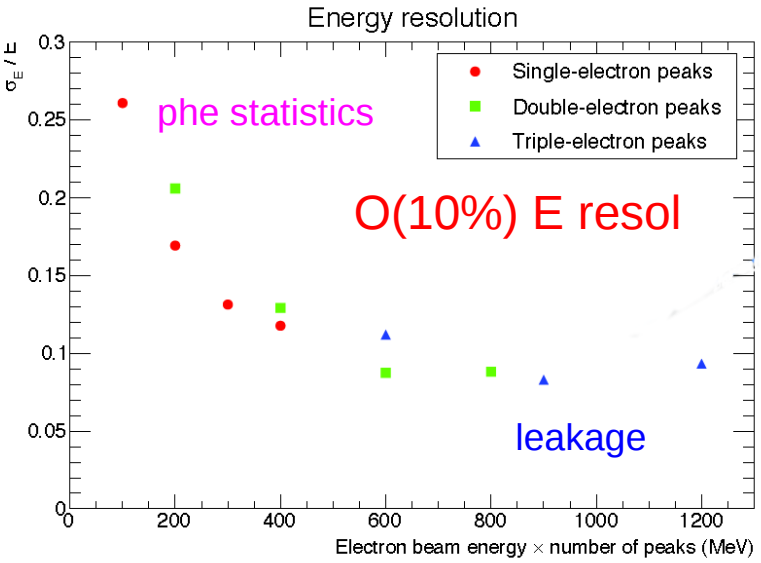
Very good multipart peak separation





Single part only

Very good time resolution < 100 ps at all energies



Running program

Expect to finish installation by end of 2017

Commissioning during first 3 months of 2018

Expect to have ~ 6 months of physics runs in 2018 to get 10^{13} POT (possibly using 200 ns bunch)

6 months data taking with 50% efficiency - bunch length 200 ns – $2{,}5*10^3$ e^+/bunch

10^{13} POT ~ 25000 e^+/bunch × $7.8*10^6$s × 49 Hz

Possible extension of data taking in 2019

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Procurement					Construction					Installation	

2017

Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec
Commissioning			PADME run 1				DAΦNE			run 1	

2018

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hand-shaking with DAΦNE collisions											

2019

Conclusions

- Dark Photon (DP) is predicted in new class of general new physics models with a “hidden“ sector.
- PADME will search for an “invisible” DM decaying DP at the new dedicated BTF line at the Linac of Laboratori Nazionali di Frascati.
- We have made beam tests at LNF BTF in 2016 and 2017 for all the main detector components : all behave as expected from design. We are starting the construction phase.
- Schedule: building within end of 2017 and 6 month data taking on new dedicated BTF line at LNF in 2018 (possibly also 2019).
- Results will apply also to other hypothetical light particles like Axion Like Particles, Dark Higgs, new proto-phobic vector boson.

A very exciting time awaits us all !
You are welcome to join “the dark side“ !

References

Dark Photon

- P. Galison and A. Manohar, Phys. Lett. B 136, 279 (1984)
- B. Holdom, Phys. Lett. B 166, 196 (1986)

Dark Photon and $(g-2)_\mu$ anomaly

- M. Pospelov, Phys. Rev. D 80, 095002 (2009)
- J. P. Lees et al., arXiv:1702.03327 (2017)

Dark Photon research status and perspectives

- M. Raggi and V. Kozhuharov, Riv. Nuovo Cim. 38 , 449 (2015)
- J. Alexander et al., arXiv:1608.08632 (2017)
- M. Battaglieri at al., arXiv:1707.04591v1

ALPs and $(g-2)_\mu$

- W. J. Marciano et al., Phys. Rev. D 94, 115033 (2016)

Be anomaly - Fifth force

- A. J. Krasznahorkay et al., PRL 116, 042501 (2016)
- Jonathan L. Feng et al., PRL 117, 071803 (2016)
- Jonathan L. Feng et al., Phys. Rev. D 95, 035017 (2017)

PADME

- M. Raggi and V. Kozhuharov, AdHEP 2014 , 959802 (2014)
- M. Raggi, V. Kozhuharov and P. Valente, EPJ Web Conf. 96 , 01025 (2015)
- M. Raggi et al., NIM. A 862 (2017) 31-35