The PADME experiment at LNF

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For the PADME collaboration

SU “St. Kl. Ohridski”* and LNF-INFN

Light Dark Matter search at Accelerators - 2017

24-28 March 2017

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Overview

- Dark photon primer
- PADME approach
- Present status and activities
- Conclusions

Dark matter

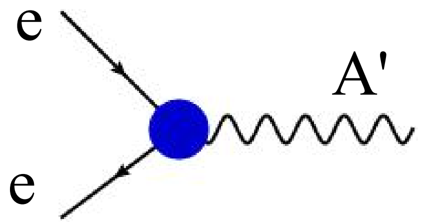
- WIMP miracle – particle with 100 GeV satisfies the requirement for a dark matter candidate
  - Weakly interacting
  - Correct density
- However …
  - No particle with such characteristics discovered so far…

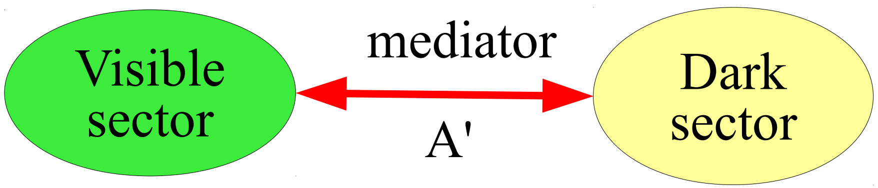
The childhood of DM is over and it is time to stop believing in miracles
(even if Santa Claus may bring presents …)

- Rich dark sector
  - Multiparticle structure of the Standard Model
    - Why the DM should be composed of a single particle?
  - The picture should be simple, but not simpler than necessary

New gauge bosons

- The effective interaction that can be studied is





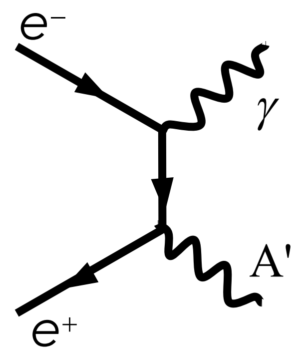
$$\mathcal{L} \sim g' q' \overline{\Psi} (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'^\mu, \ \textit{usually } \alpha'_a = 0$$

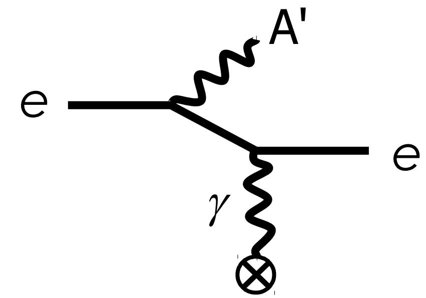
  - $q_f \rightarrow 0$ for some flavours

- Such textbook scenario could address the $(g_\mu$-2) discrepancy, abundance of antimatter in cosmic rays, signals for DM scattering
  - General U'(1) and kinetic mixing with B (A', Z')
    - Universal coupling proportional to the q_{em} $\quad L_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$
    - Just single additional parameter – ε
  - Leptophilic/leptophobic dark photon
- Other messenger types possible (neutrino, higgs, ALP)
- **Rich dark sector?**

Dark photon phenomenology

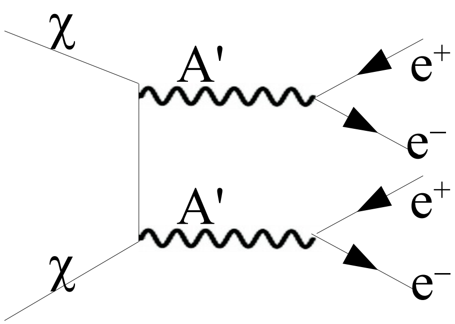
- Production mechanisms
  - Meson decays
  - Bremsstrahlung
  - Annihilation

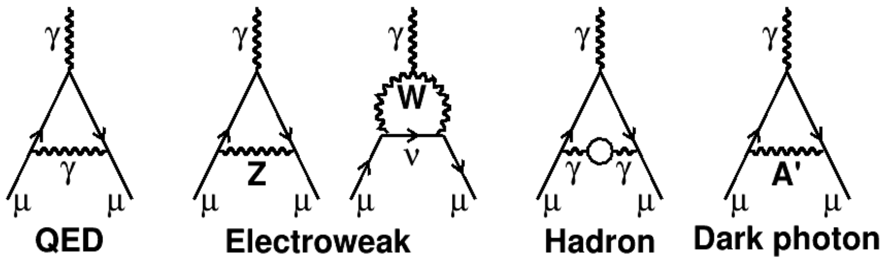


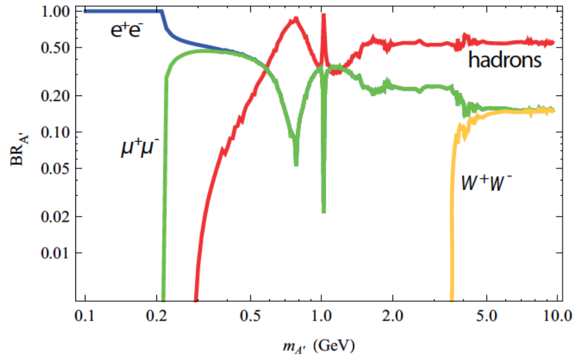


- Decays
  - To SM model particles if nothing in the DS lighter than A'
  - $A' \rightarrow \gamma\gamma\gamma$, if $M(A') < 2m_e$, small width, A' quasi stable
  - To DS particles with $Br(A' \rightarrow \chi\chi) = 1$
- Contribution to g-2:
  - About 3 σ discrepancy theory vs experiment

Dark matter annihilation

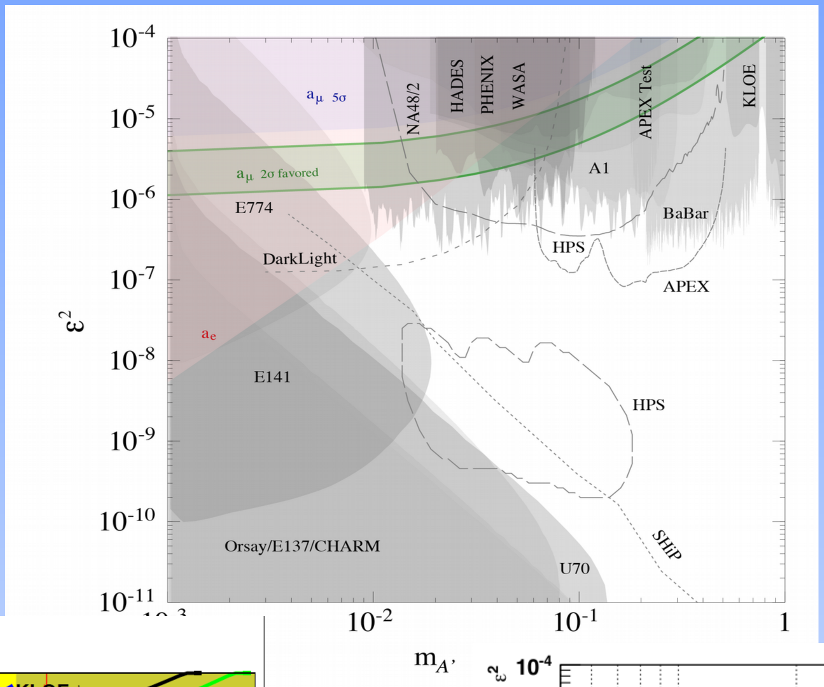


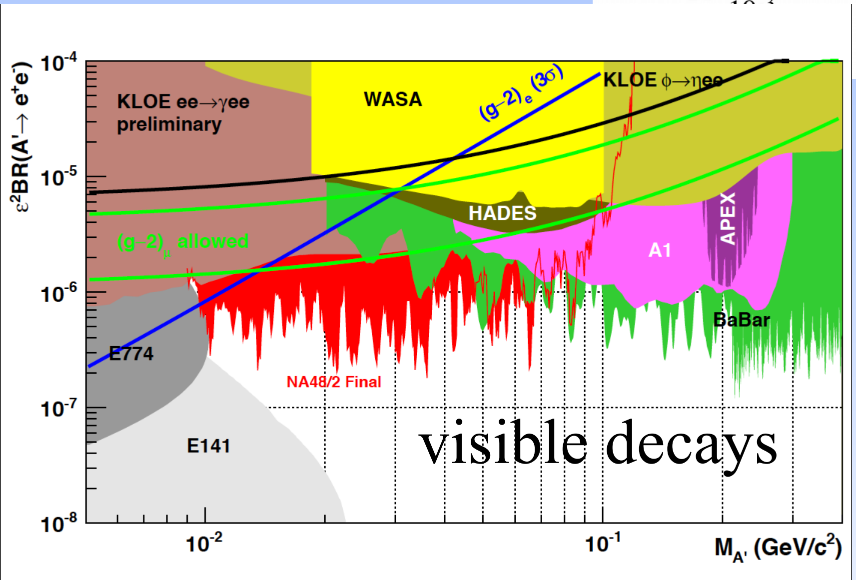




Dark photons

Dark photon
Secluded photon
Paraphoton
A'
U
...





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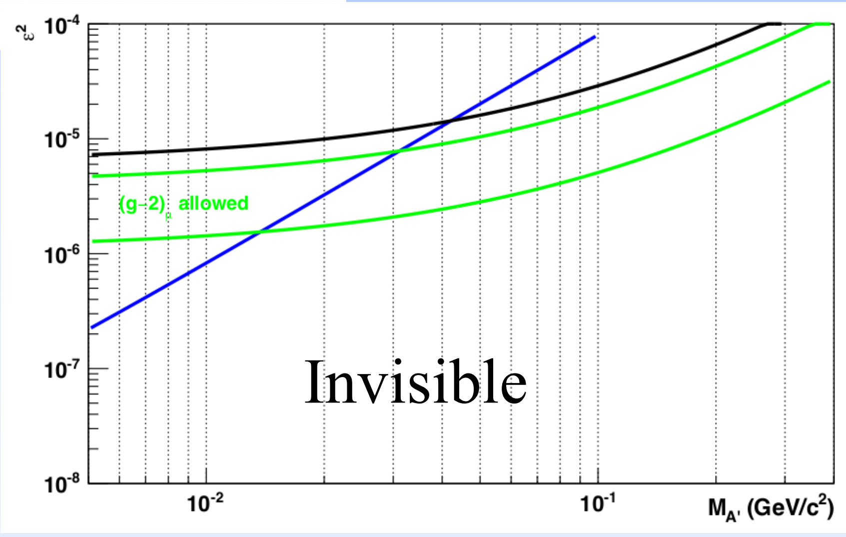
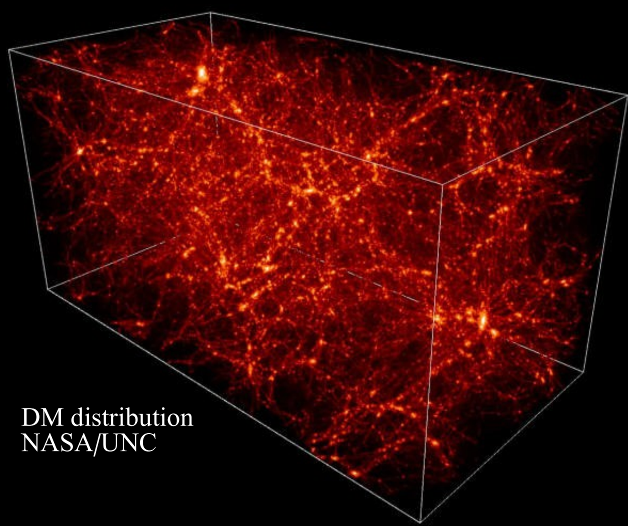
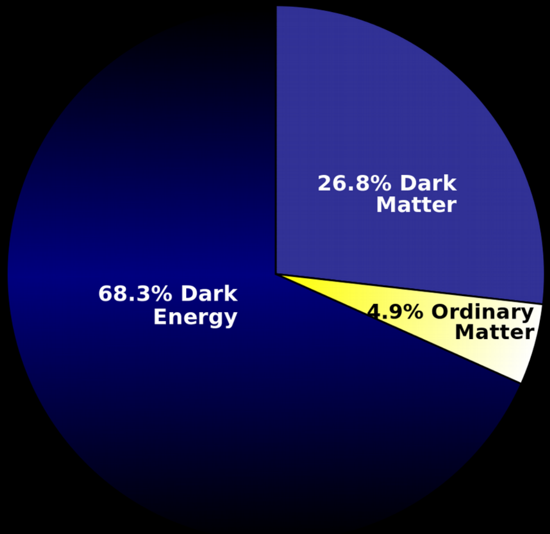




DM distribution
NASA/UNC



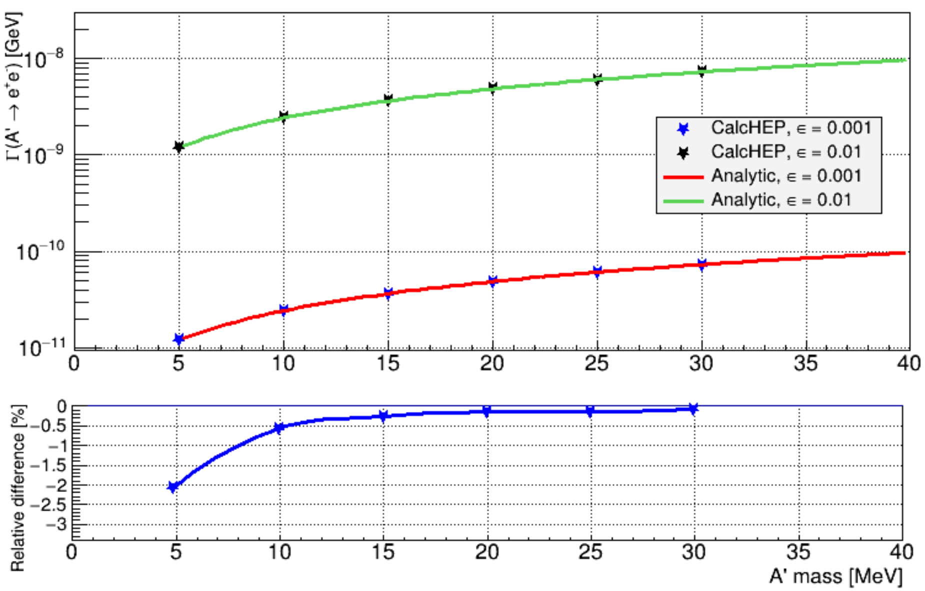
Dark photon

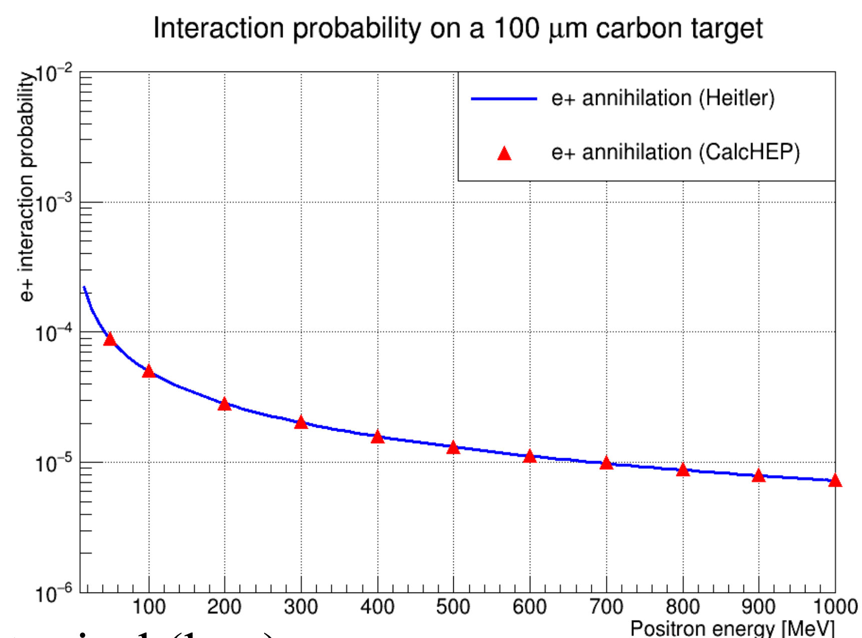
Simple effective model implemented in CalcHEP, used for further studies

$$\mathcal{L} \sim \varepsilon\, e\, \overline{\Psi} \gamma_\mu \Psi A'^{\mu}$$

Dark photon decay width into e^+e^- used for validation of the calculations

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

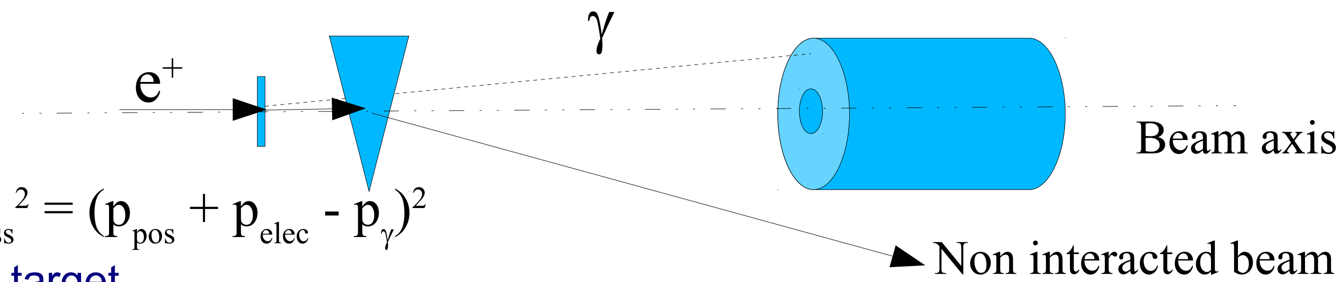




CalcHEP @ non-typical (low) energy

Missing mass technique

Study only the recoil photon



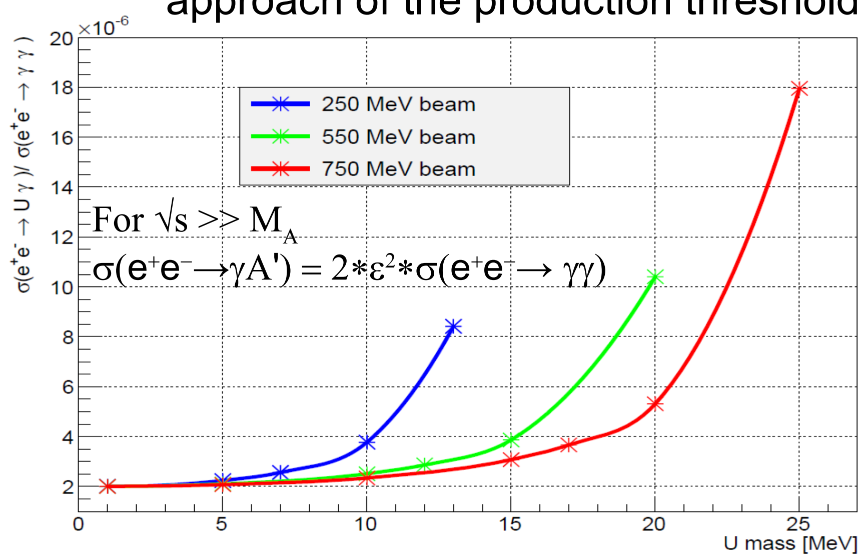
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

- Positron beam on a thin target
- Positron momentum is determined by the accelerator characteristics
- Missing mass resolution: annihilation point, E_γ, φ_γ

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

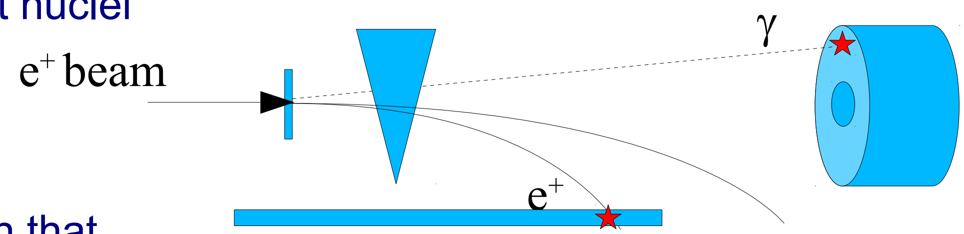
- Clear 2 body correlation
- Background minimization
  - Best possible resolution on energy/angle measurement
  - **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Photons vetoing
  - Minimize the interaction remnants + vetoing

Cross section enhancement with the approach of the production threshold

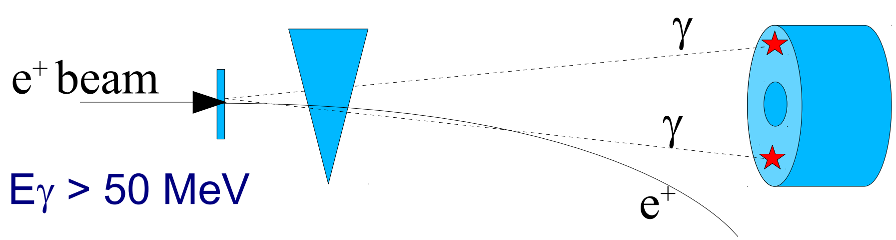


Backgrounds

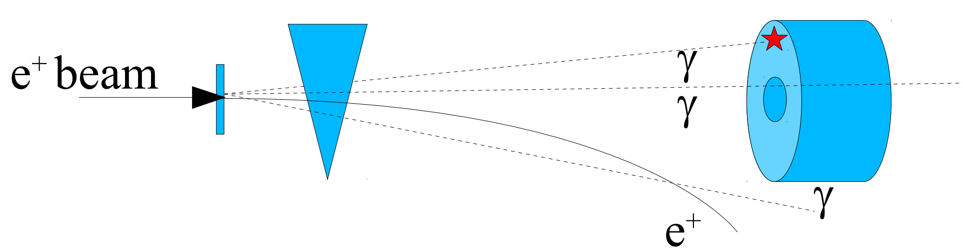
- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection



- 2 photon annihilation
  - Peaks at M_{miss} = 0
  - Quasi symmetric in gamma angles for Eγ > 50 MeV

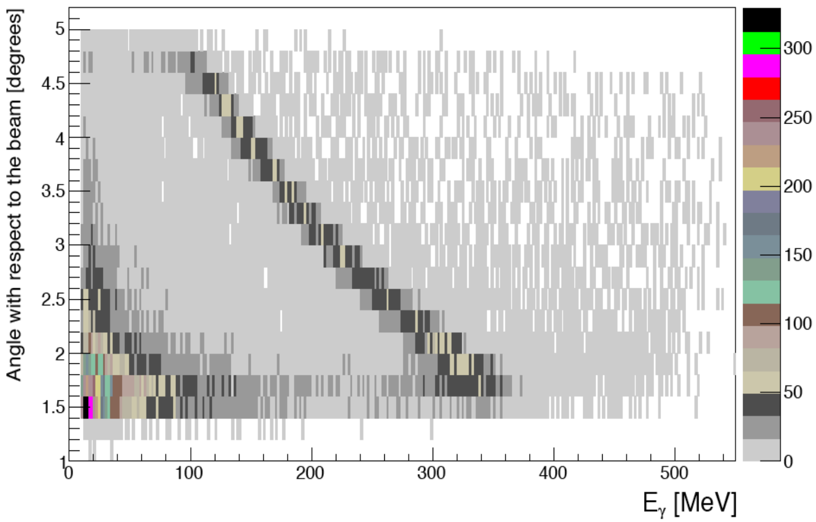


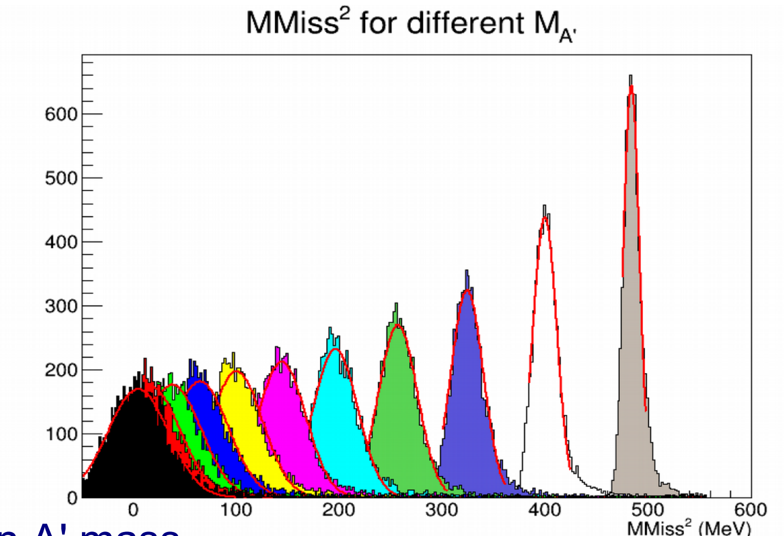
- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
  - Does not peak



- Radiative bhabha scattering
  - Topology close to bremsstrahlung

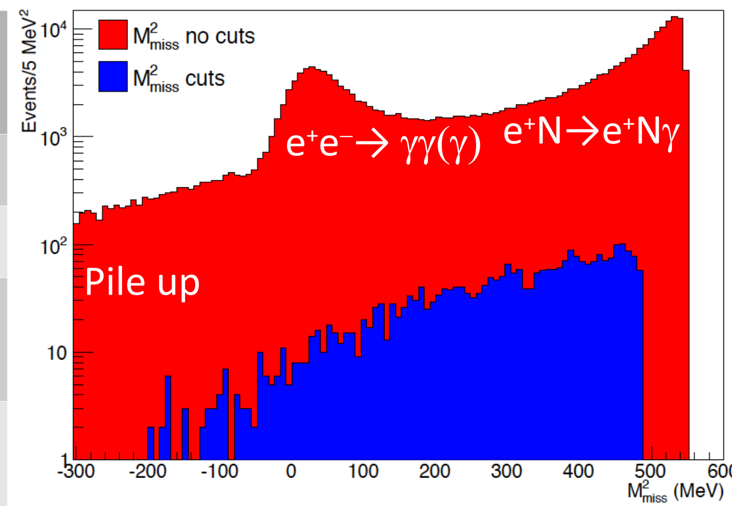
Measurement strategy





- O(10^4 – 10^5) foreseen background events for a given A' mass

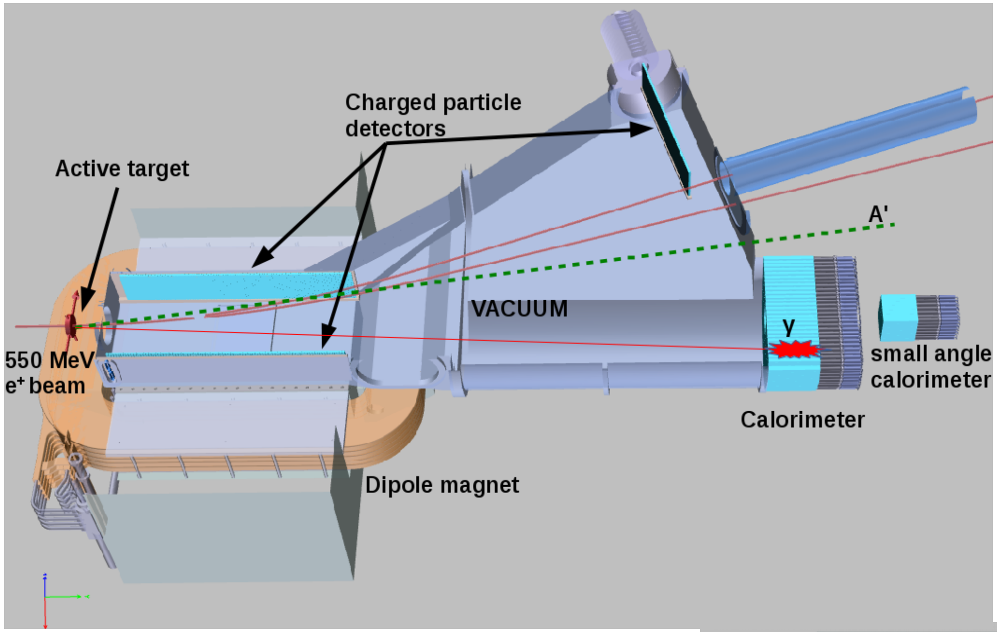
Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+ + N \to e^+ N \gamma$	4000 mb	$E\gamma$ > 1MeV
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma$ > 1MeV
$e^+e^- \to e^+e^-\gamma$	180 mb	CalcHEP, $E\gamma$ > 1MeV



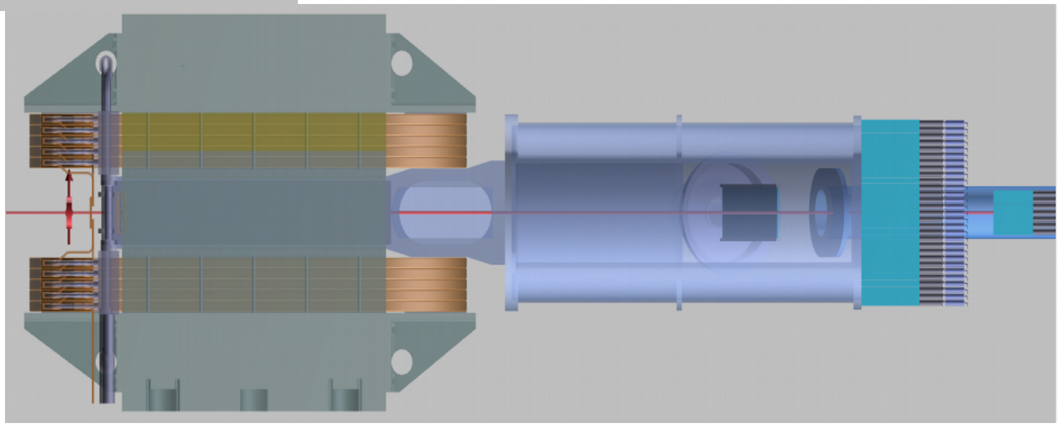
PADME experiment

Positron Annihilation into Dark Matter Experiment

Adv. HEP 2014 (2014) 959802

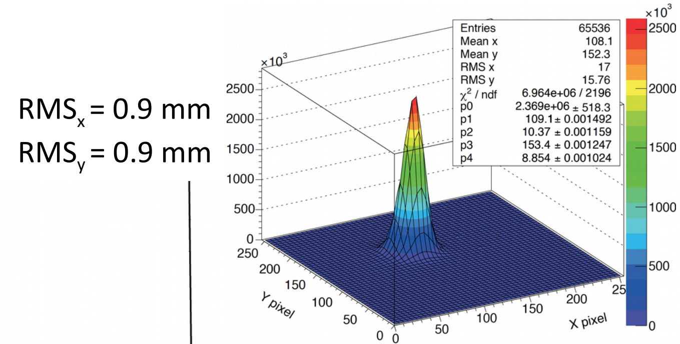


- Small scale fixed target experiment
- M. Raggi, V. Kozhuharov and P. Valente:
  - e^+ @ Frascati Beam test facility
  - Solid state target
  - Charged particles detectors
  - Calorimeter

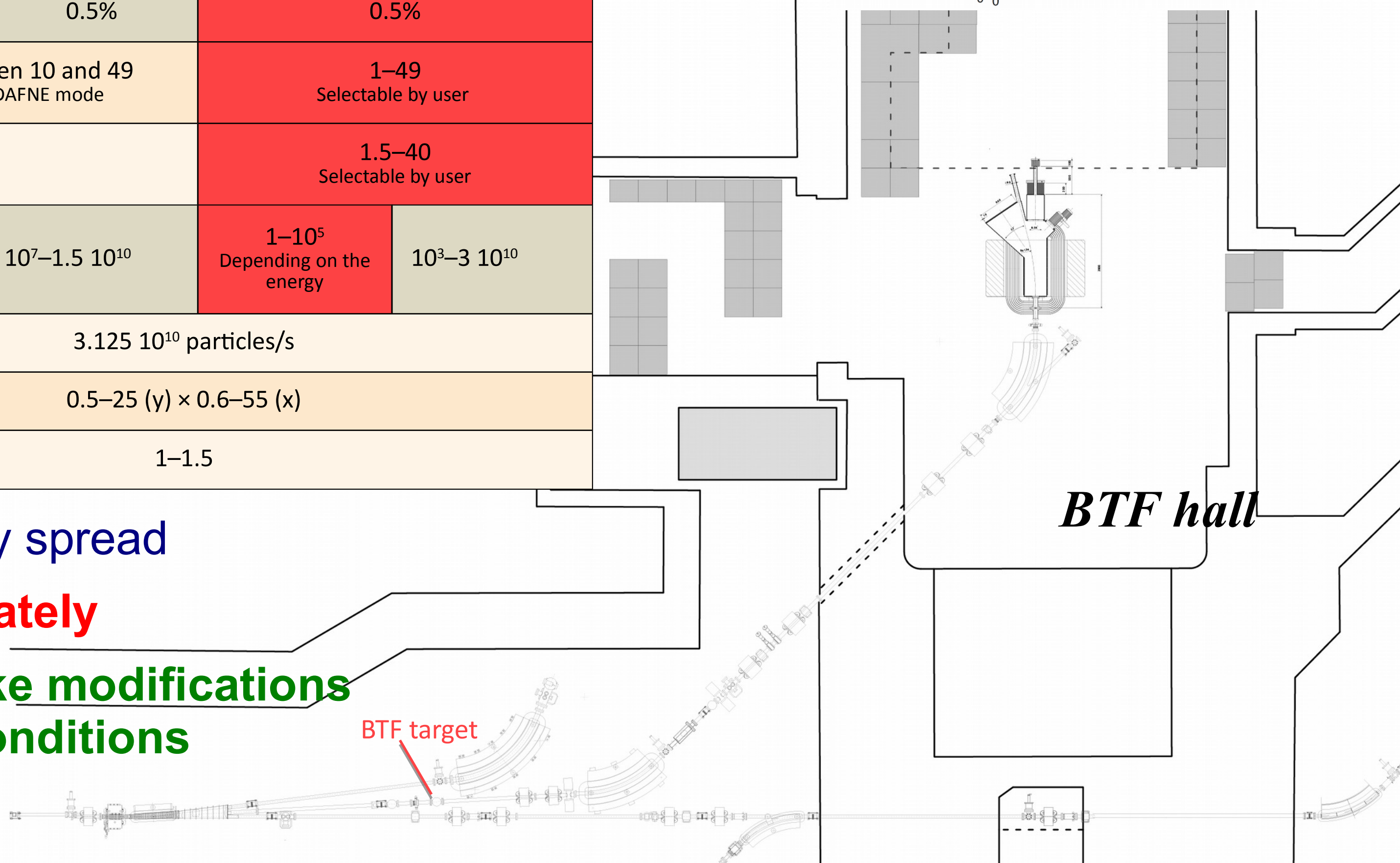


BTF @ LNF

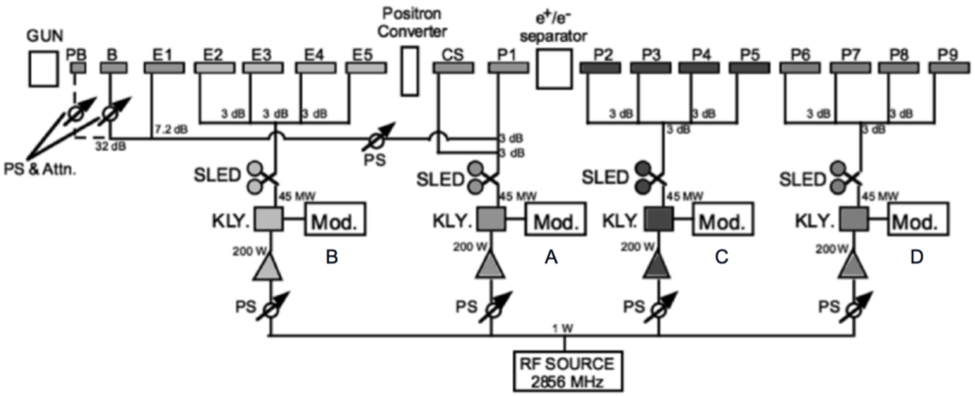
Parameter	Parasitic mode		Dedicated mode	
	With target	Without target	With target	Without target
Particle species	e^+ or e^- Selectable by user	e^+ or e^- Depending on DAFNE mode	e^+ or e^- Selectable by user	
Energy (MeV)	25–500	510	25–700 (e^-/e^+)	250–730 (e^-) 250–530 (e^+)
Energy spread	1% at 500 MeV	0.5%	0.5%	
Rep. rate (Hz)	Variable between 10 and 49 Depending on DAFNE mode		1–49 Selectable by user	
Pulse duration (ns)	10		1.5–40 Selectable by user	
Intensity (particles/bunch)	1–10^5 Depending on the energy	10^7–1.5 10^{10}	1–10^5 Depending on the energy	10^3–3 10^{10}
Max. average flux	3.125 10^{10} particles/s			
Spot size (mm)	0.5–25 (y) × 0.6–55 (x)			
Divergence (mrad)	1–1.5			



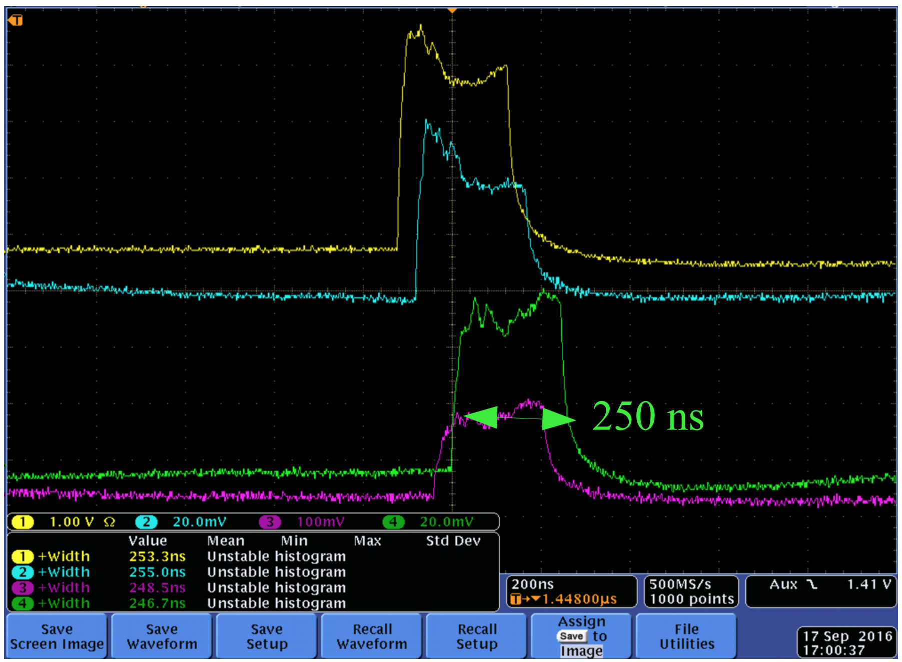
- Small beam energy spread
- **Available immediately**
- **Possibility to make modifications to optimize the conditions**



BTF @ LNF

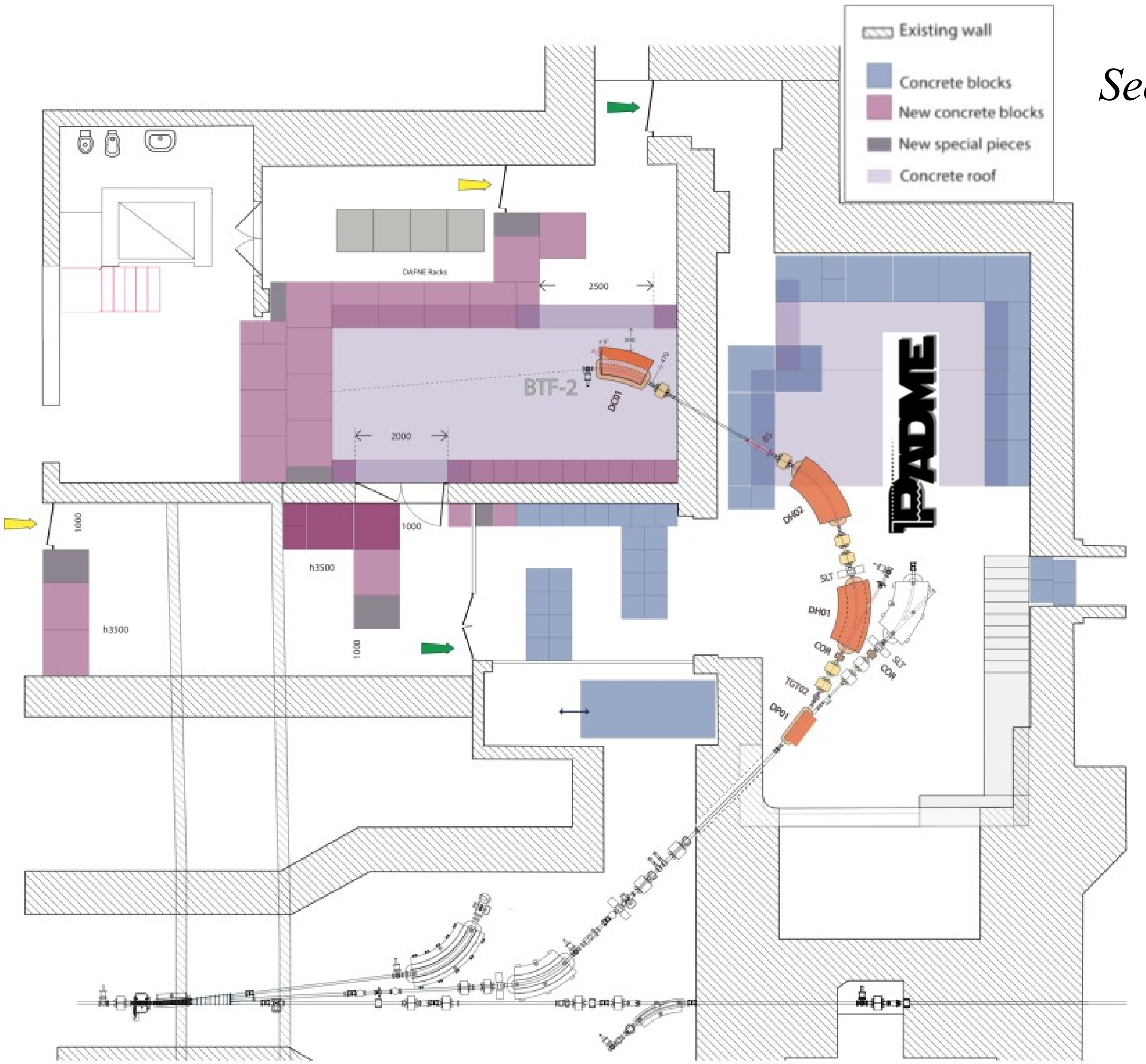


The linac achieved 250 ns bunch length



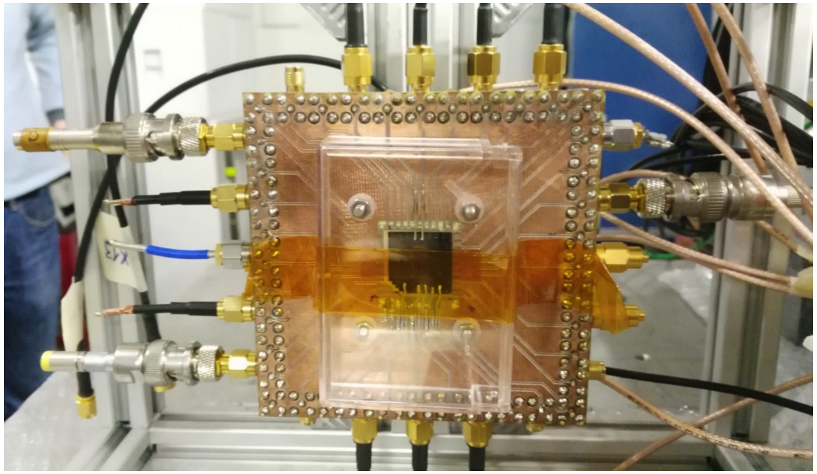
- PADME requirement: > 10^{13} positrons on target
- Repetition rate: 49 Hz
  - 5000 e^+, 40 ns bunch length
- Positron production:
  - Positron converter
  - BTF target
- Bunch length limited by the RF compression at SLED
  - A longer pulse allows increasing the number of positrons/pulse
  - RF power flat over 4.5 μs at KLY
- Optimization ongoing
  - Expected to run at 160 ns in 2018

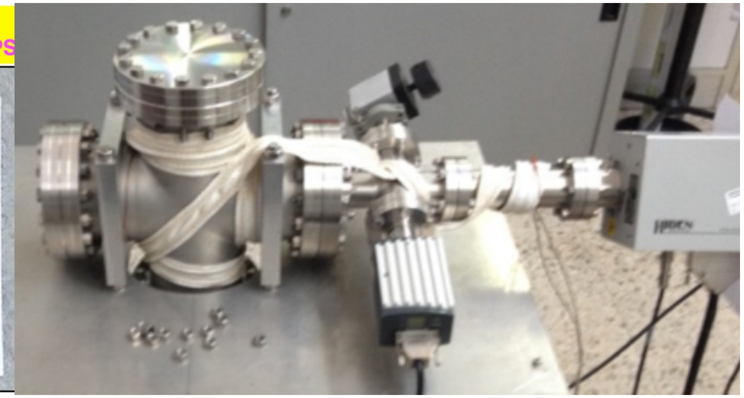
BTF infrastructure upgrade

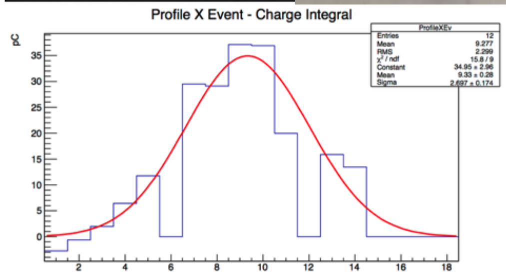


See L. Foggetta's talk

Diamond target







Motorized support structure ready: vacuum tests ongoing

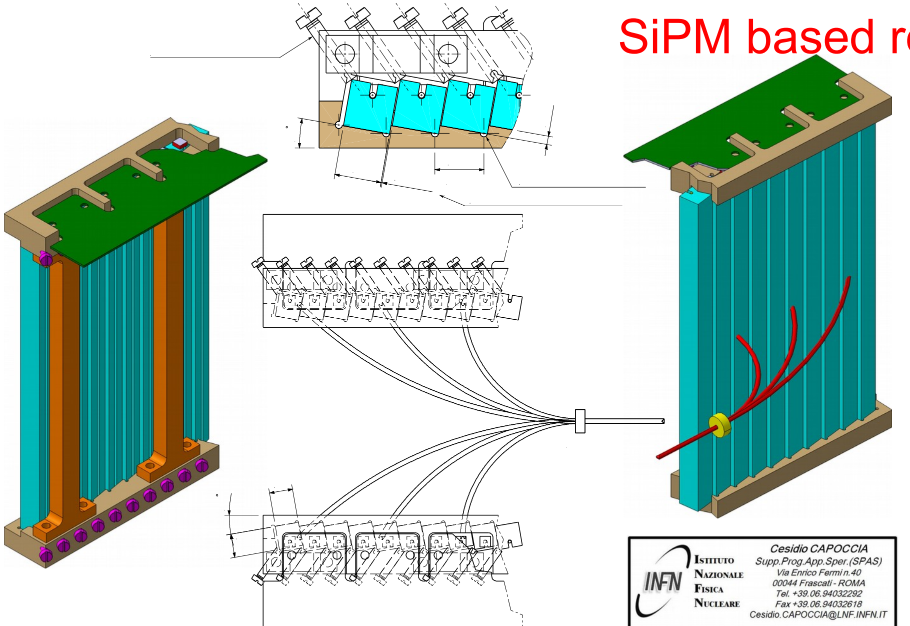
Polycrystalline diamonds

- 100 mm thickness:
- 16 × 1 mm² strip and X-Y readout in a single detector
- Samples with graphitized and metalized strips available
- PADME prototype 20 × 20 mm² produced and tested 2015
- Low noise CSA integrated in the 16 channel chip AMADEUS from IDEAS

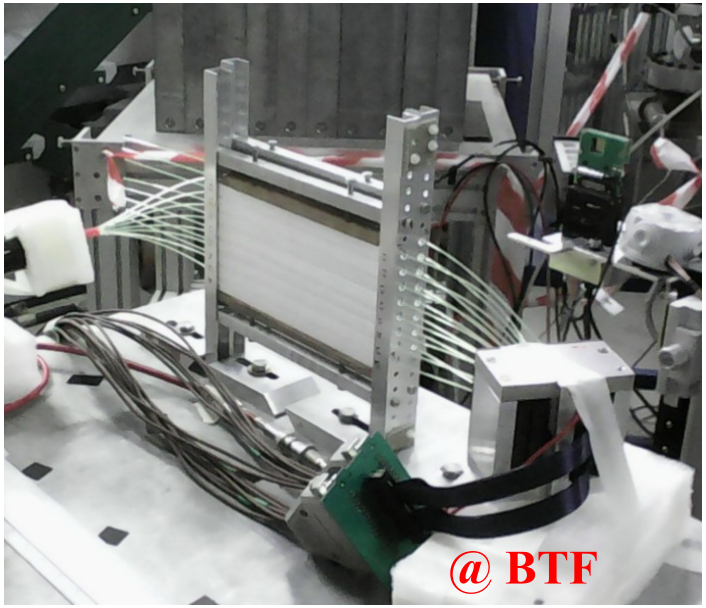
- Test beam results (~5000 e):
  - **good efficiency**
  - resolution on the position of the beam center **< 0.2 mm**
- FE electronics defined

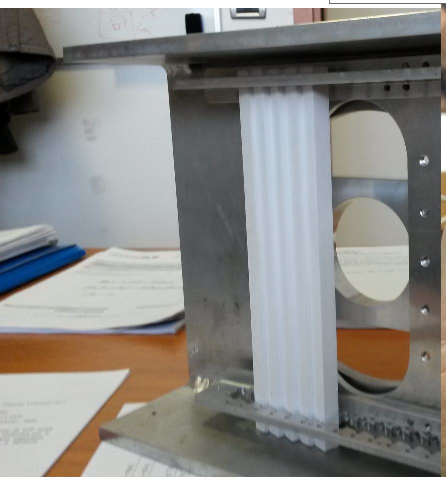
Charged particle vetoes

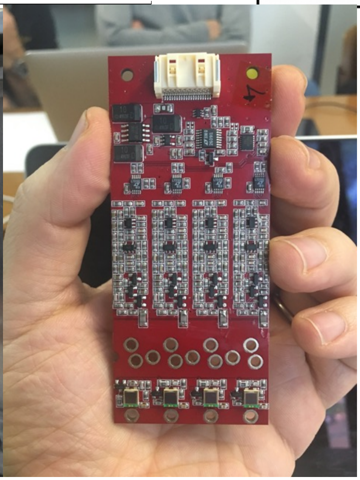
- Plastic scintillator detector



Tracker prototype for test with MAPMT

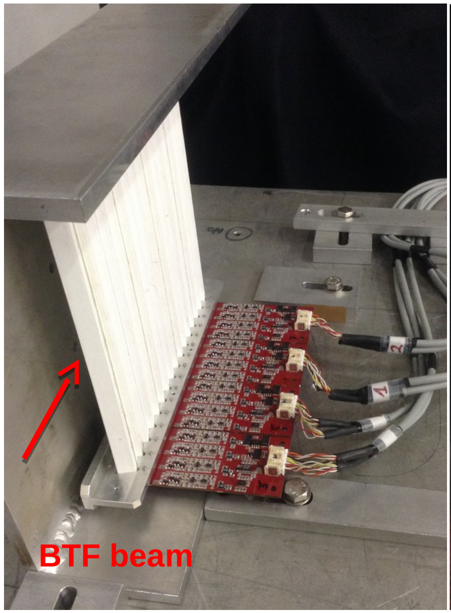


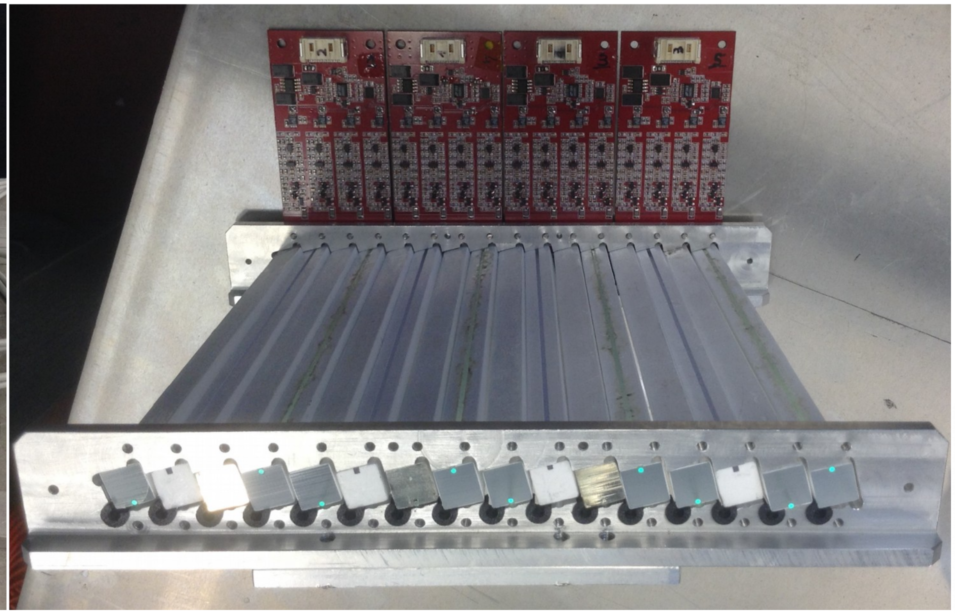


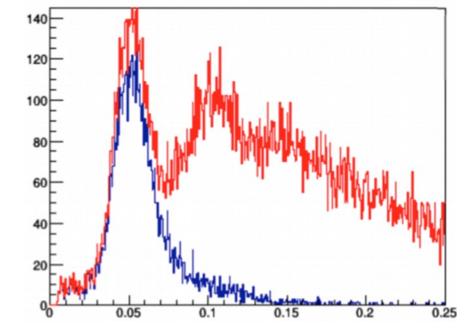


- 10 × 10 × 184 mm^3 scintillator bars
  - Available already
- Mechanics design completed
- SiPM electronics prototype available
- Efficiency > 99%, $\sigma(t) < O(1\ \text{ns})$

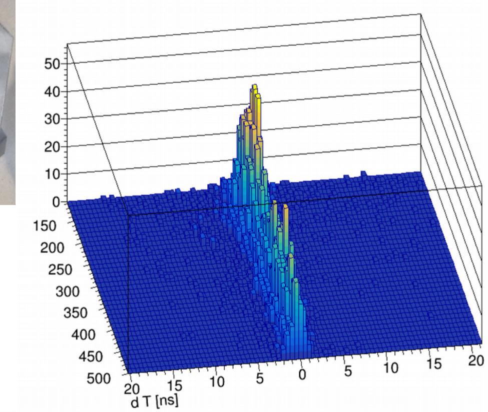
Charged particle vetoes

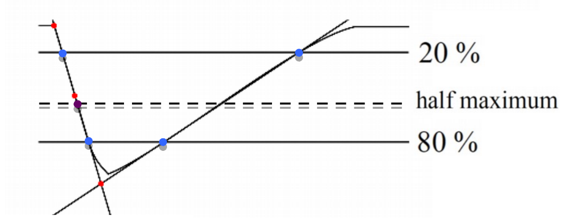






Δt vs charge

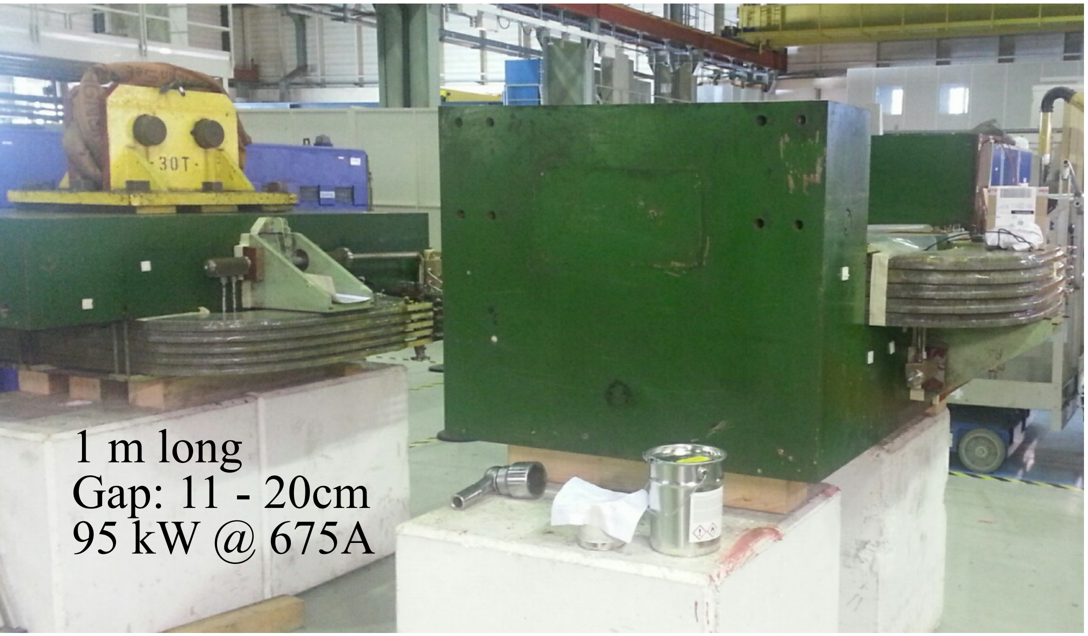


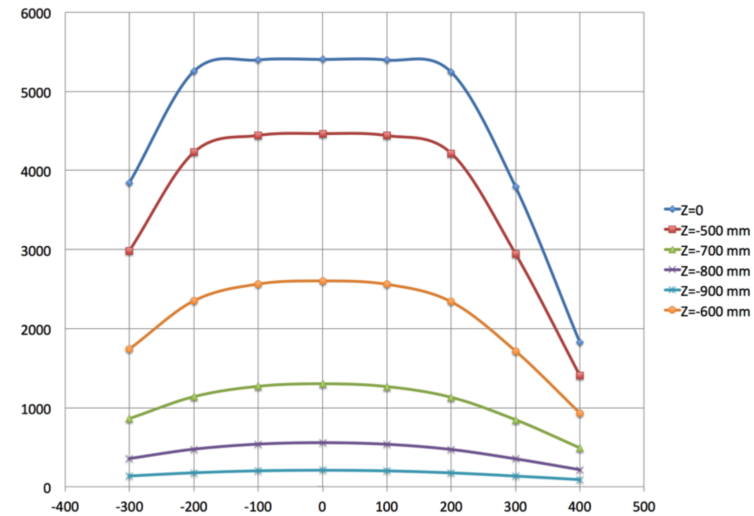


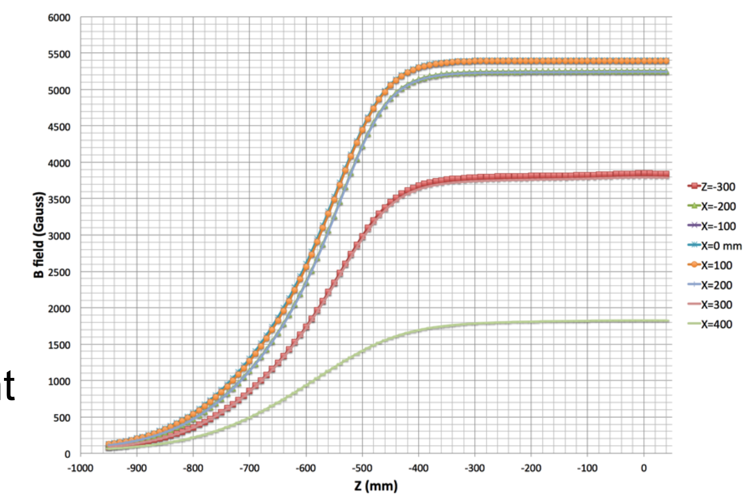
$$T_{\text{Mean}} = \frac{\sum_{peak} A_i * t_i}{\sum_{peak} A_i}$$

- Different resolution values obtained using different definitions of timing
- Already well below 1 ns resolution level at the level without any calibration and very preliminary analysis
- Front-end electronics prototype working extremely well

Magnet

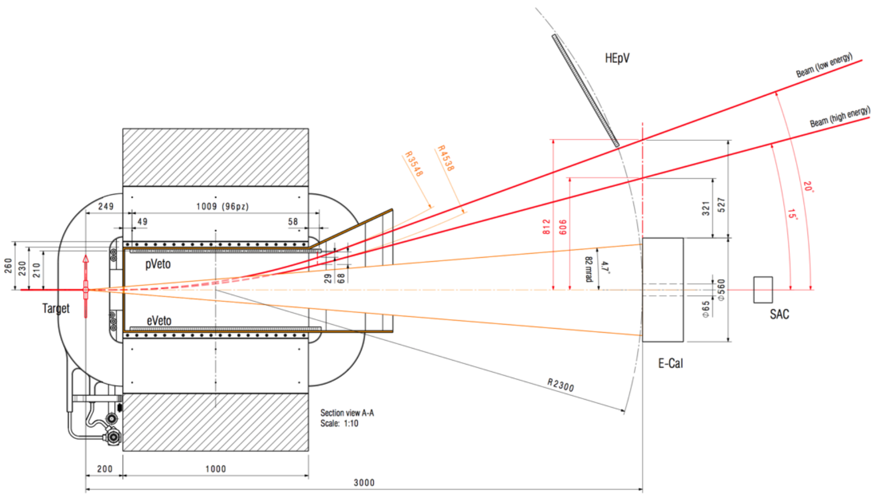


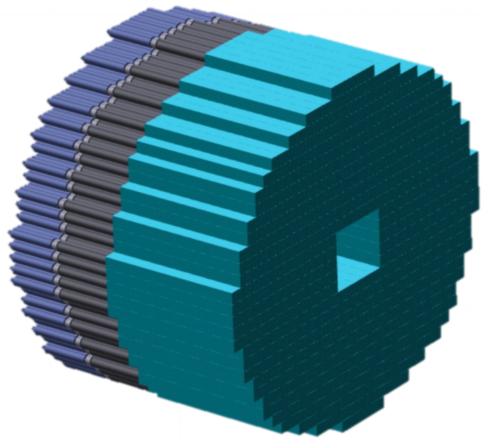


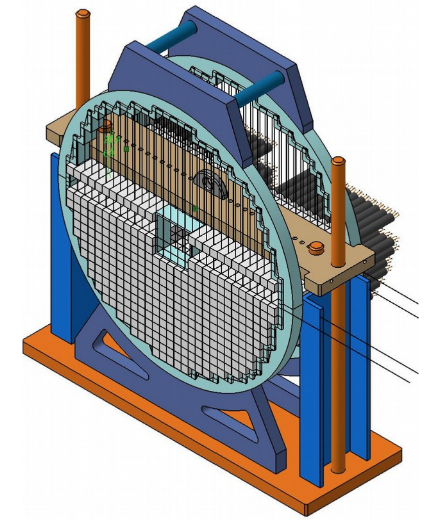


- MBP-S series, on loan from CERN
  Many thanks to TE-MSC-MNC
- Poles: 100 cm length, 52 cm width
- Variable gap 11 to 20 cm, further extended to 23 cm
- Detailed field mapping: good B field quality
- Fringe field not negligible, even outside the coils, relevant for the precise beam steering onto the active target

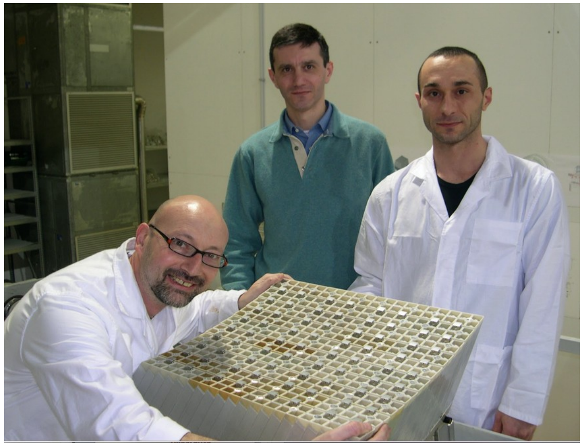
Calorimeter design



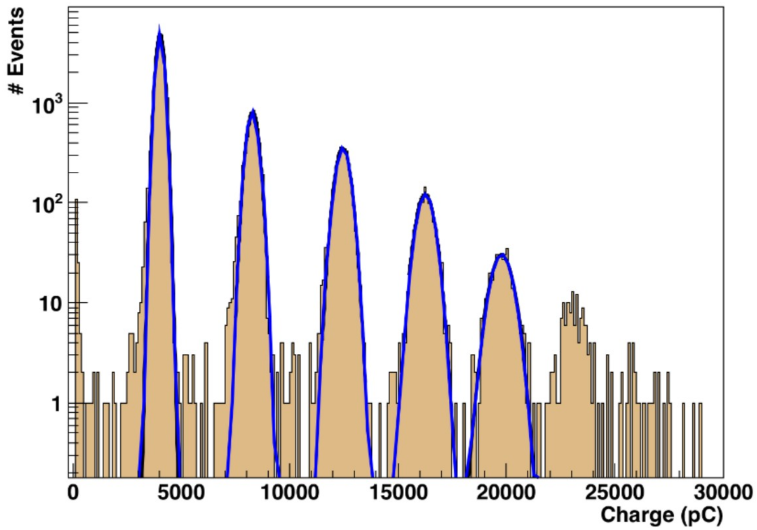




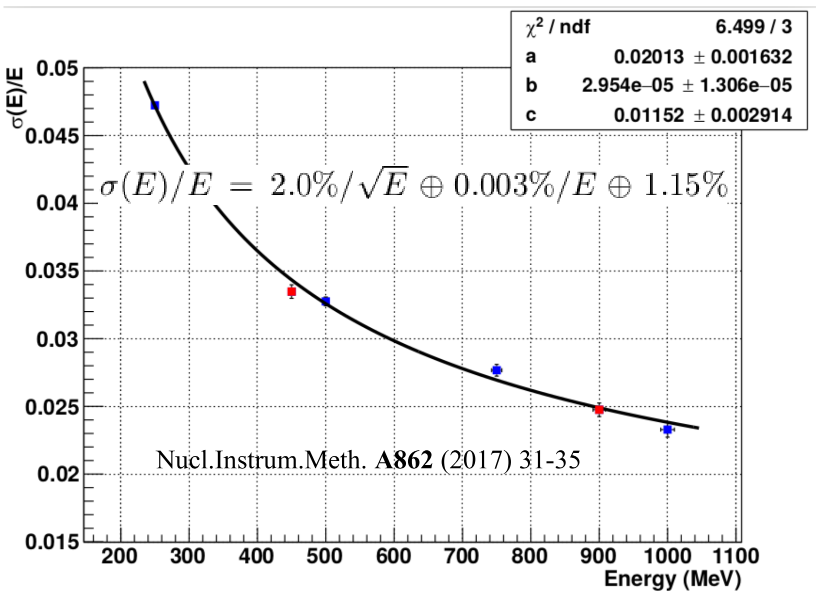
- BGO crystals available from L3 experiment (agreement with L3, C.C.Ting, INFN)
- Cylindrical shape: radius 280 mm, depth of 230 mm
  - Inner hole 100 mm side
  - 616 crystals 21 × 21 × 230 mm^3
  - Angular resolution ~ O(1 mrad)
  - Angular acceptance (20 – 83) mrad
- HZC XP1911 PMT, 19 mm diameter
- Readout: waveform digitizers @ 1-5 GS/s



Calorimeter design

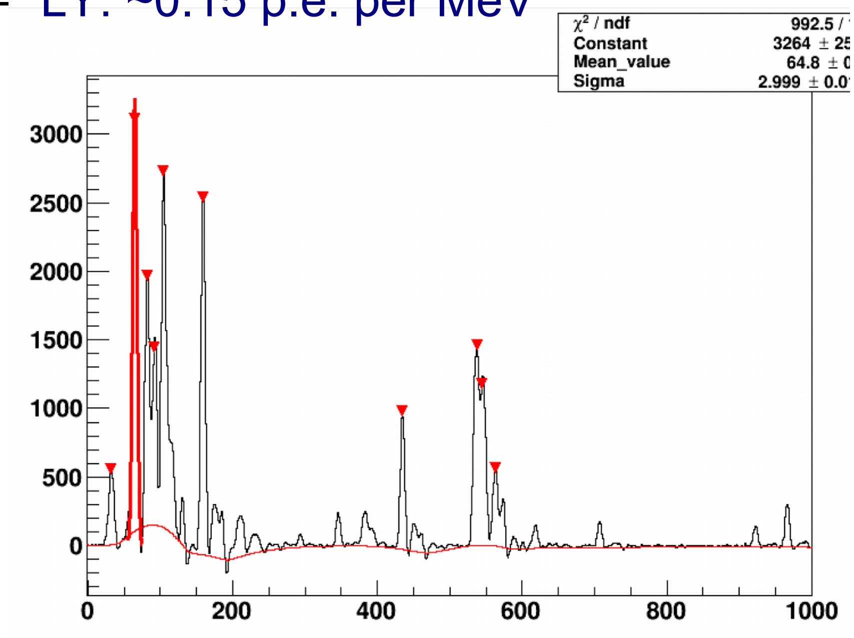


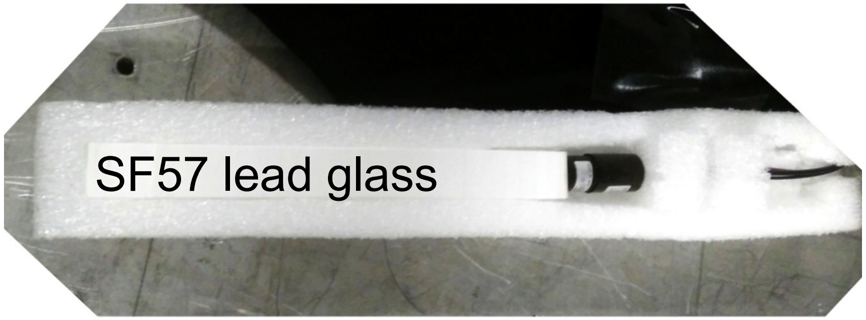
Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03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



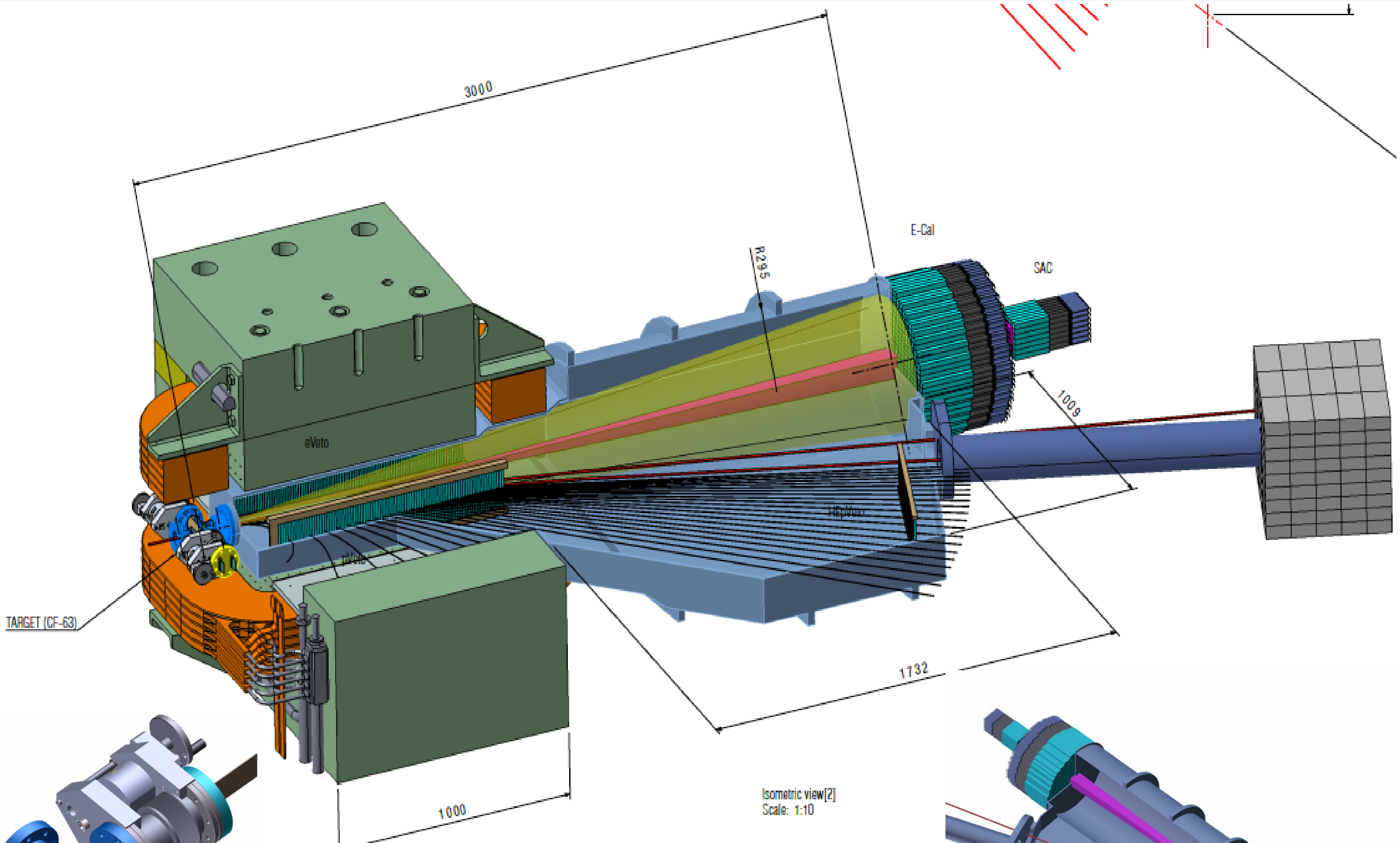
Small angle photon veto

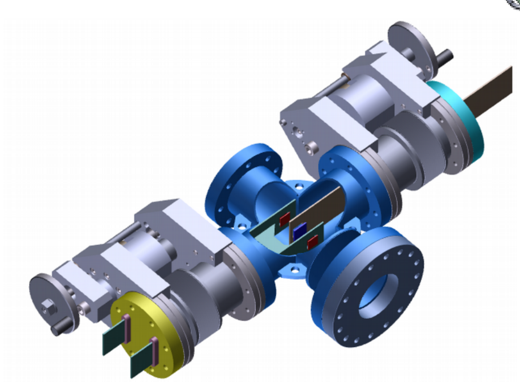
- Veto the high energy photons emitted at small angles with respect to the non deflected positron beam
  - High occupancy → excellent time resolution & short pulses
  - Cerenkov light detector
- Initial tests: lead glass from OPAL calorimeter
  - 25 of 30 x 30 x 200 mm^3 bar coupled to R9880U-110 PMT
  - RO: CAEN V1742 @ 5 GS/s, 700 ps signal width
  - LY: ~0.15 p.e. per MeV

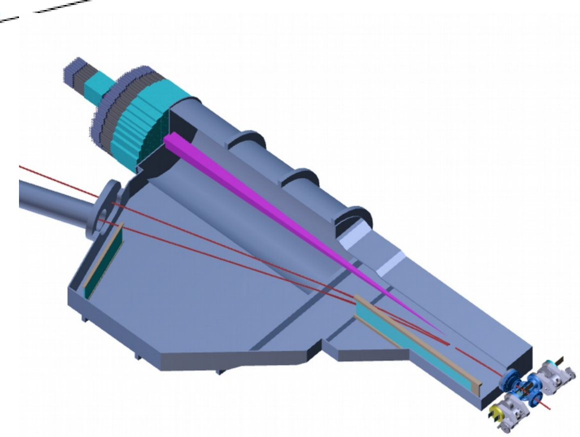




Design progress







Test beam data

A long path of learning

Period (1 week)	Beam	Intensity	Milestone
September 2014	Positron	$10^4 - 10^{10}$	Test of diamond with graphite strips
November/ December 2014	Positron	$10^4 - 10^{10}$	Background for beam dump, shielding First check on BGO crystals
May 2015	electron	1	LYSO vs BGO crystals
May 2015	electron	1	LYSO vs BGO Calorimeter prototype
June 2015	electron	1	BGO calorimeter prototype
November 2015	electron	1	Spectrometer and target prototype
March 2016	electron	$1 - 10^4$	Mimosa/Timepix3 test for PADME
April 2016	positron	$1 - 10^4$	Test of PADME Ecal and Diamond target
July 2016	positron	$1 - 10^3$	ECAL resolution, PMT choice Sc+WLS spectrometer prototype (MAPMT)
November 2016	positron	$1 - 10^{10}$	ECAL prototype irradiation Spectrometer time resolution
April 2017	positron	1 – 10	Veto electronics certification
June 2017	positron	1 – 10	ECAL final test
July 2017	positron	$1 - 10^5$	PADME target region

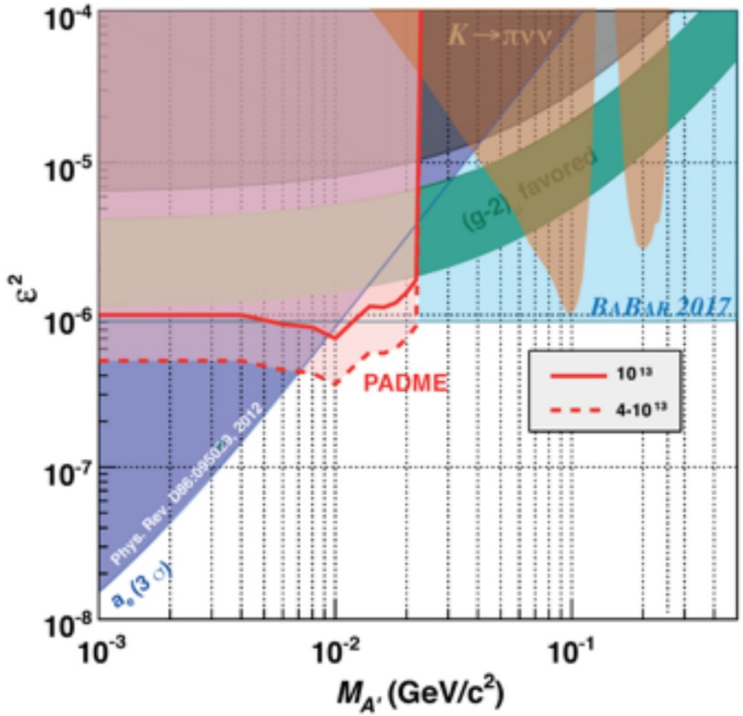
And multiple tests with RA sources…

Sensitivity estimation

Selection

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

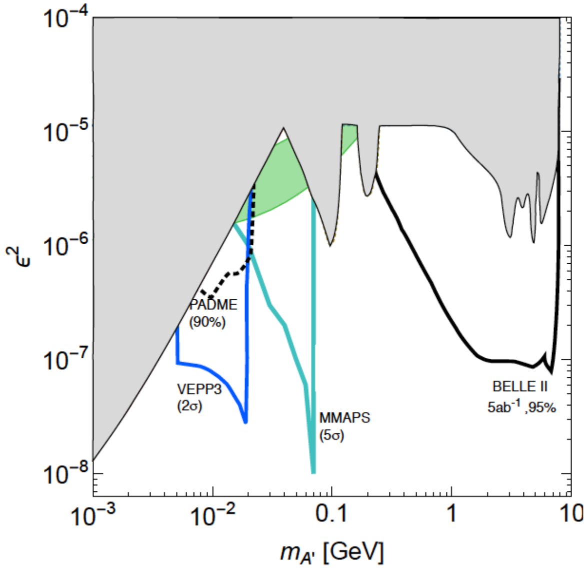
- Single cluster in the Calo
- 30 mrad < θcl < 65 mrad
- Cluster energy:
  $E^{CL}_{min}(M_{A;})$ in 50 – 150 MeV
  $E^{CL}_{max}(M_{A'})$ in 120 – 350 MeV
- ± 1σ cut on the missing mass
- Veto on positrons in ± 2 ns time window
- Using $N_{signal} = \sigma(N_{background})$ to derive limits



- Accessible regions:
  - E=550MeV: $M_{A'}$ < 23.7 MeV
- Improvements possible
  - Increase beam energy
  - Extend the bunch length

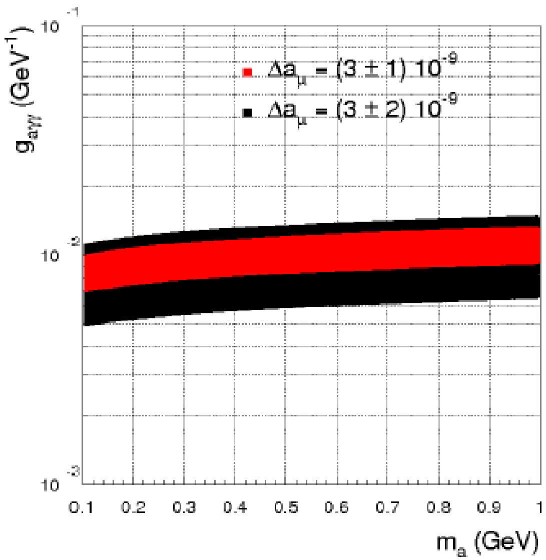
PADME physics case

Dark Photon arXiv:1608.08632v1



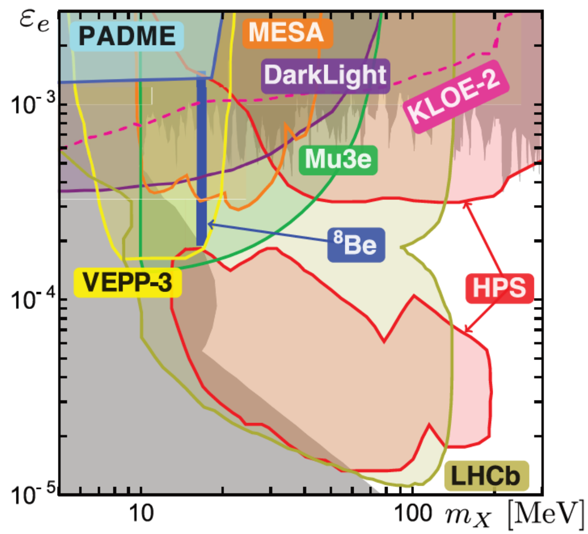
Invisible final state A'→χχ

ALPs and g-2 arXiv 1607.01022v2



ALPs final state a→γγ

Fifth force arXiv:1608.03591v1



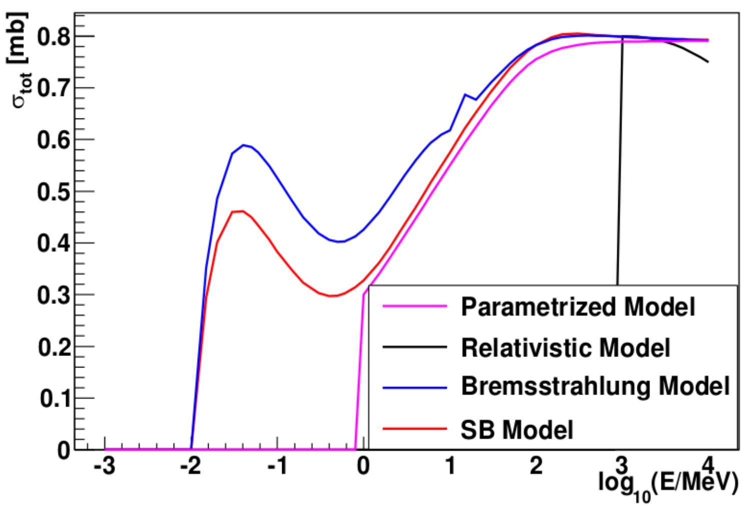
Final state X→ee

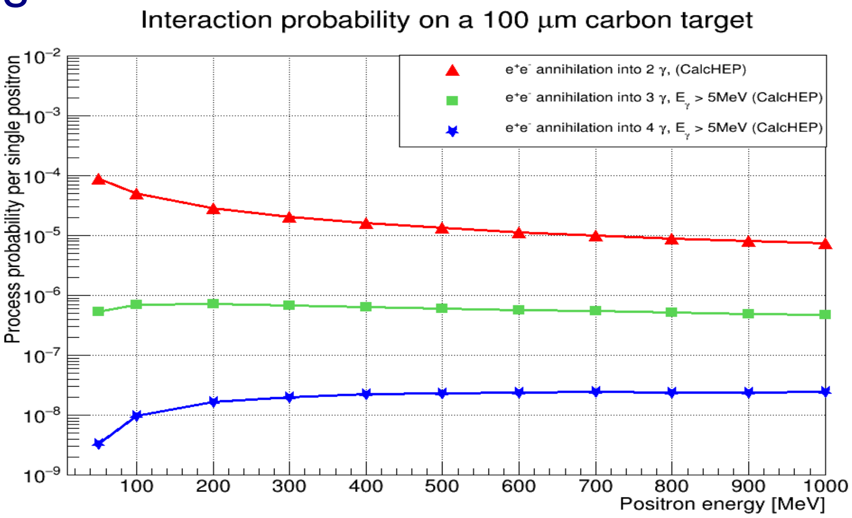
PADME is one of the experiments able to provide valuable input

Optimization of the sensitivity of the experiment for non A' searches.

PADME physics case

- PADME is able to perform measurements of few low energy electromagnetic physics parameters





- GEANT4 model uncertainties on bremsstrahlung
  - Parametric: 4-5 % for E_{e+} > 1 MeV;SB model: 3-5% for E_{e+} > 50 MeV
  - Measurement of differential cross section dσ/dEdθ interesting for PADME

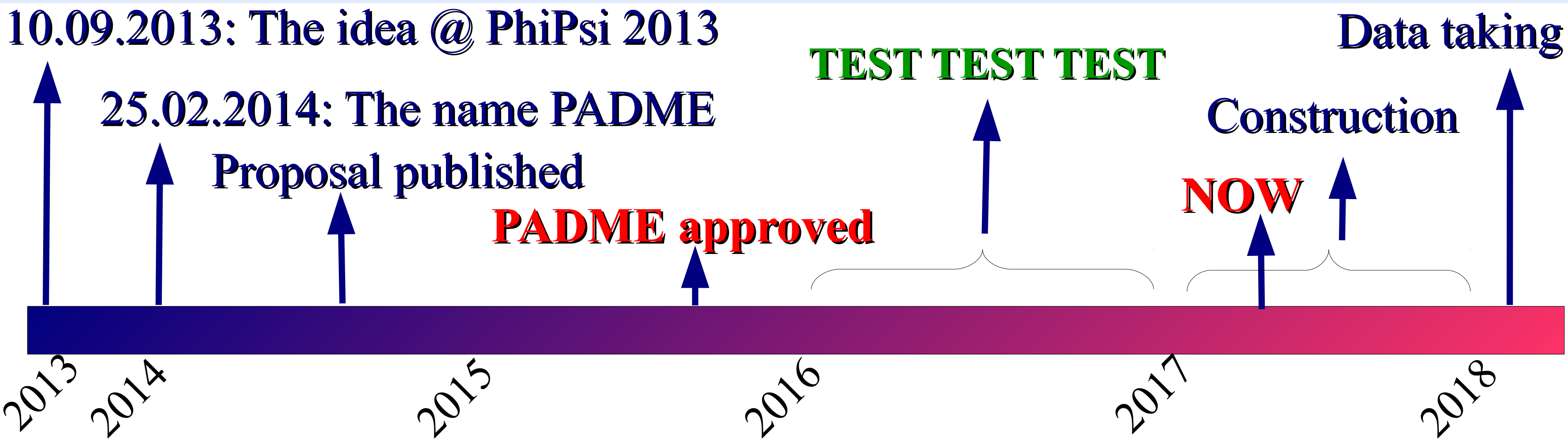
- $\Gamma(\text{annihilation}) = \Gamma(e^+e^- \rightarrow \gamma\gamma) + \Gamma(e^+e^- \rightarrow \gamma\gamma\gamma) + \Gamma(e^+e^- \rightarrow \gamma\gamma\gamma\gamma) + \ldots \approx 1.05 \text{ x } \Gamma(e^+e^- \rightarrow \gamma\gamma)$

Measurement of $\Gamma(e^+e^- \rightarrow \gamma\gamma\gamma)$ at the % level

Searches in annihilation status

	PADME	MMAPS	VEPP3
Place	LNF	Cornell	Novosibirsk
Beam energy	550 MeV	Up to 5.3 (**6.0**) GeV	500 MeV
$M_{A'}$ limit	23 MeV	74 MeV	22 MeV
Target thickness	2×10^{22} e^-/cm^2	$O(2\times10^{23})$ e^-/cm^2	5×10^{15} e^-/cm^2
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA
$e^+e^- \to \gamma\gamma$ rate [s^{-1}]	15	2.2×10^6	1.5×10^6
ε^2 limit (plateau)	**10^{-6} (*10^{-7} SES*)**	**$10^{-6} - 10^{-7}$**	**10^{-7}**
Time scale	2017 - 2018	?	2020 (ByPass)
Status	**Approved**	**Funds identification**	**Approved**

Conclusions



- A portal for a complete physics program devoted to the dark photon searches is open – visible, invisible, thin target, thick target, dump, electron or positron
- Interesting parameter space could be covered, using 10^3 – 10^5 e^+/bunch.
- PADME was **APPROVED** by INFN CSN1 in 2015 and **fully financed** under the What Next INFN program
- Test beam, technology fixes and construction ongoing

Data taking – starting in spring next year