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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Jump into the unknown

- WIMP miracle – particle with mass ~ O(100 GeV) suitable for a dark matter candidate
  - Weakly interacting
  - Correct matter density in the Universe
- However … no particle with such characteristics discovered so far…
- 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

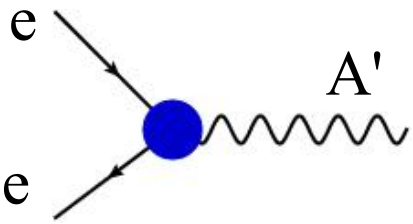
The childhood of DM is over and it is time to stop believing in miracles (even if Santa Claus may bring presents …)

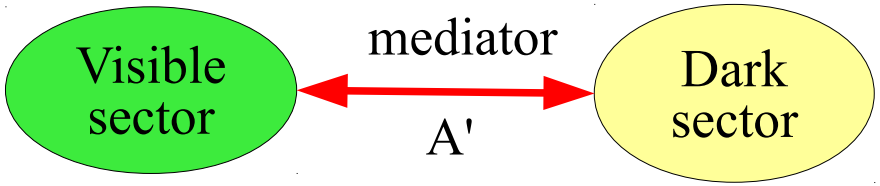
Overview

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

New gauge bosons

- The effective interaction that can be studied is





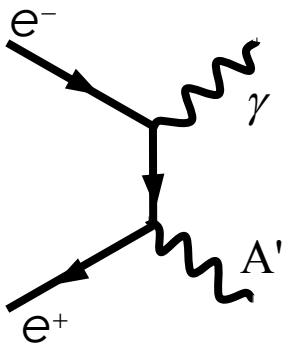
$$\mathcal{L} \sim g' q' \overline{\Psi} (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'^\mu, \quad usually\ \alpha'_a = 0$$

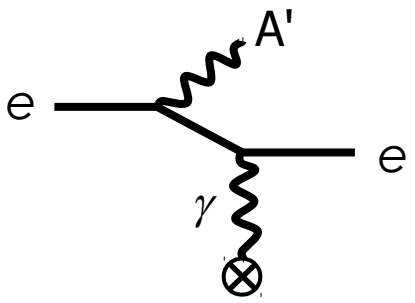
  - $q_f \rightarrow 0$ for some flavours

- Such textbook scenario could address the (g_μ-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?**

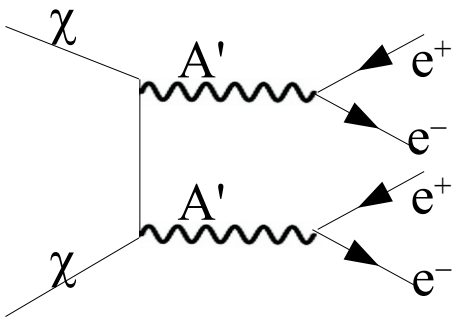
Dark photon phenomenology

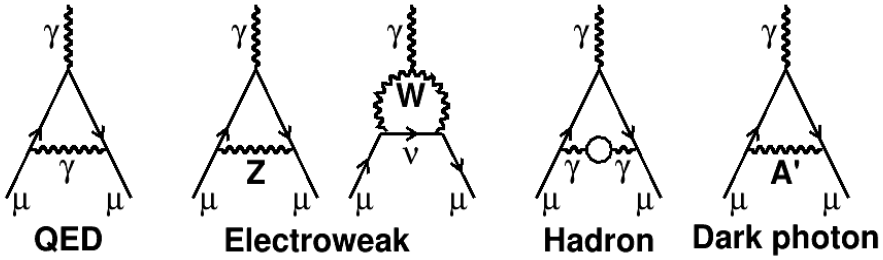
- Production mechanisms
  - Meson decays
  - Bremsstrahlung
  - Annihilation
- Decays
  - To SM model particles if nothing in the DS lighter than A'
  - A' → γγγ, if M(A') < $2m_e$, small width, A' quasi stable
  - To DS particles with Br(A' → χχ) = 1
- Contribution to g-2:
  - About 3 σ discrepancy theory vs experiment

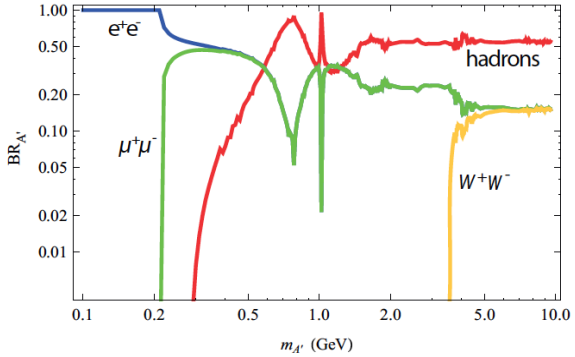




Dark matter annihilation

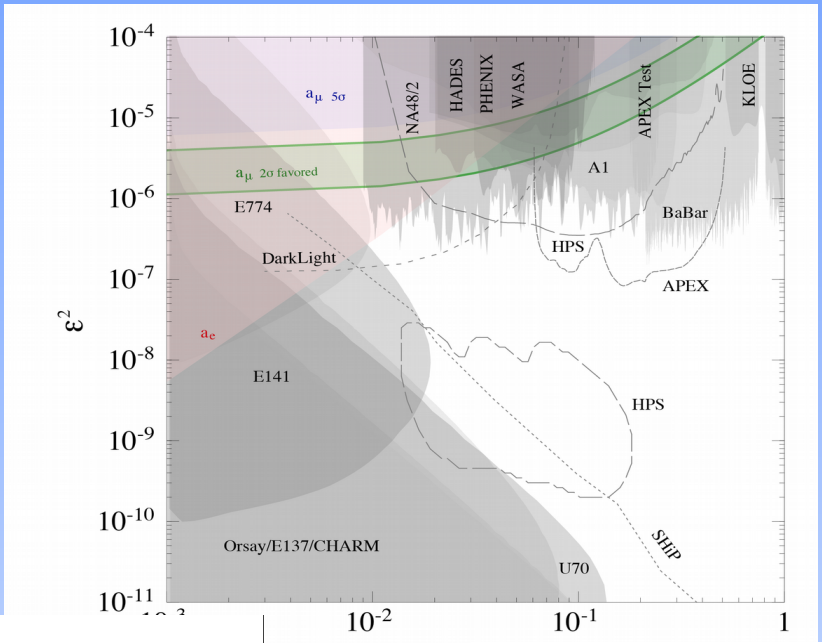


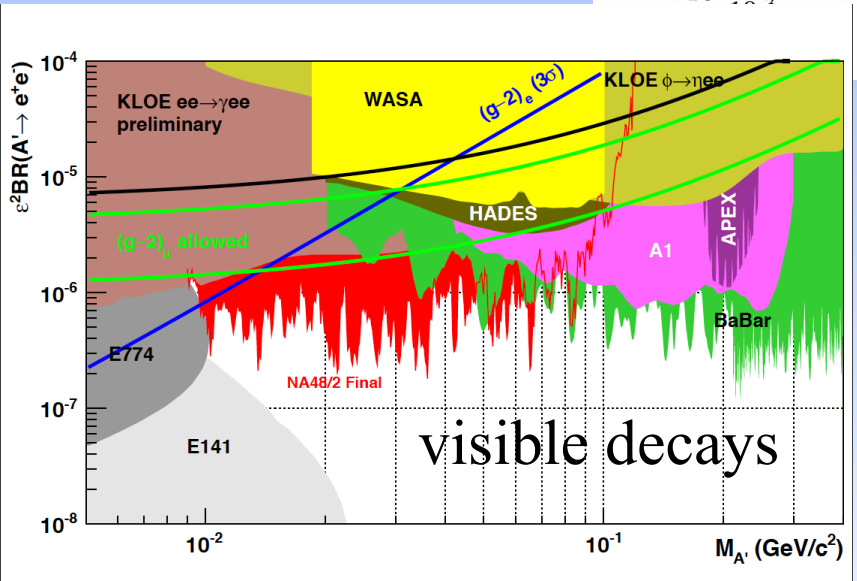




Dark photons

Dark photon
Secluded photon
Paraphoton
A'
U
...





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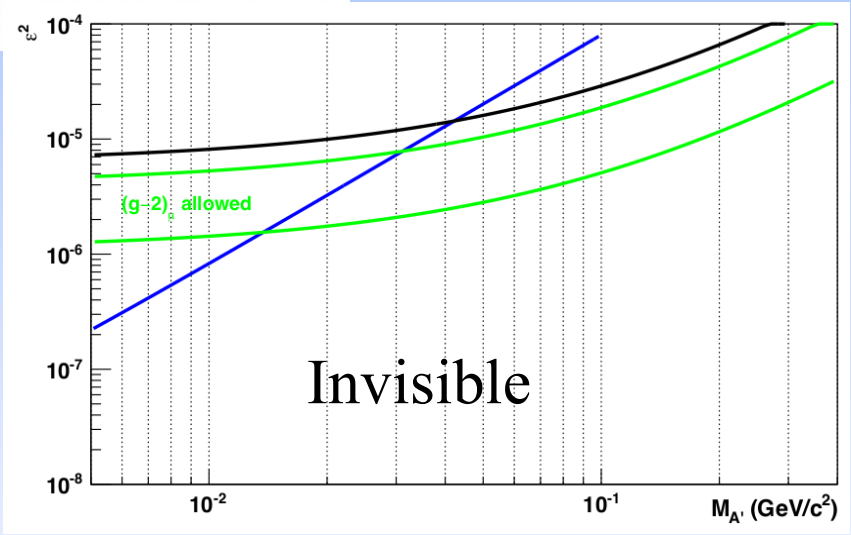
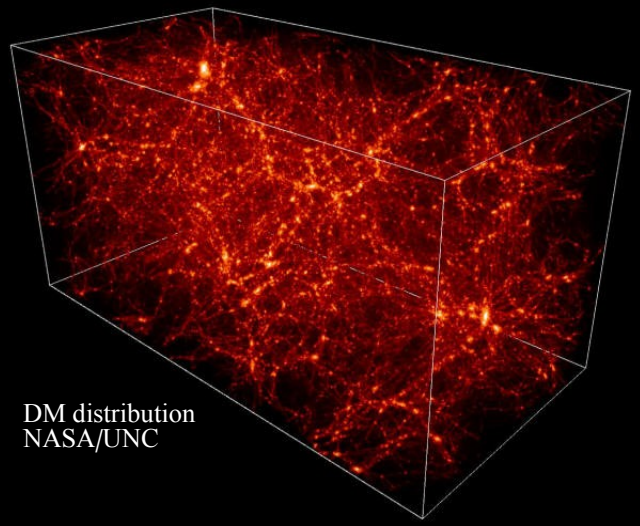
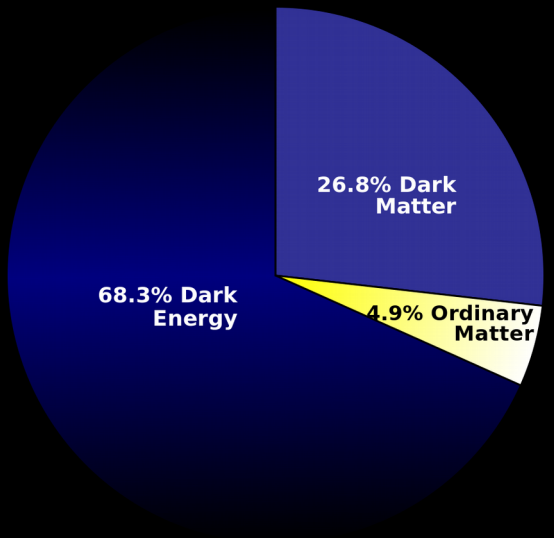


PADME

POSITRON ANNIHILATION
INTO
DARK MEDIATOR EXPERIMENT



DM distribution
NASA/UNC



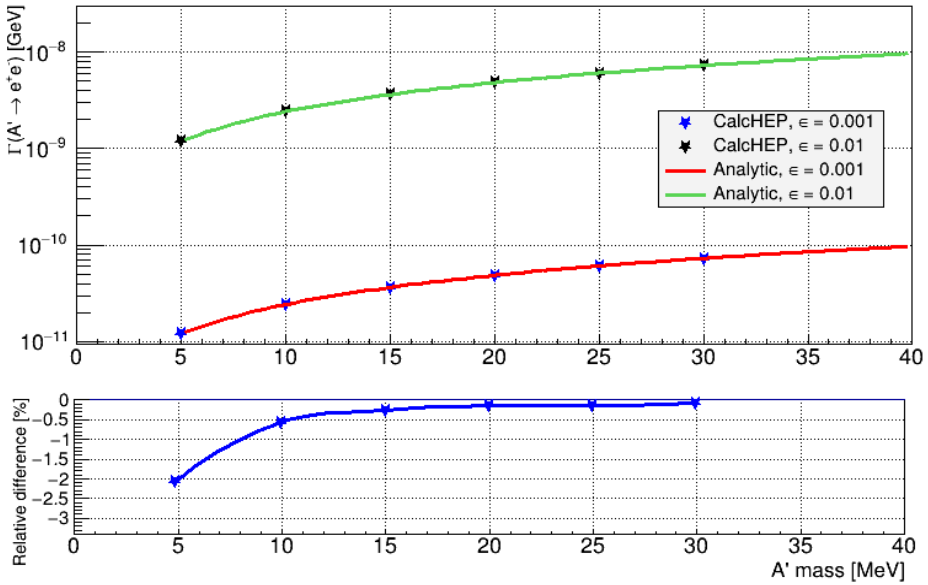
Dark photon

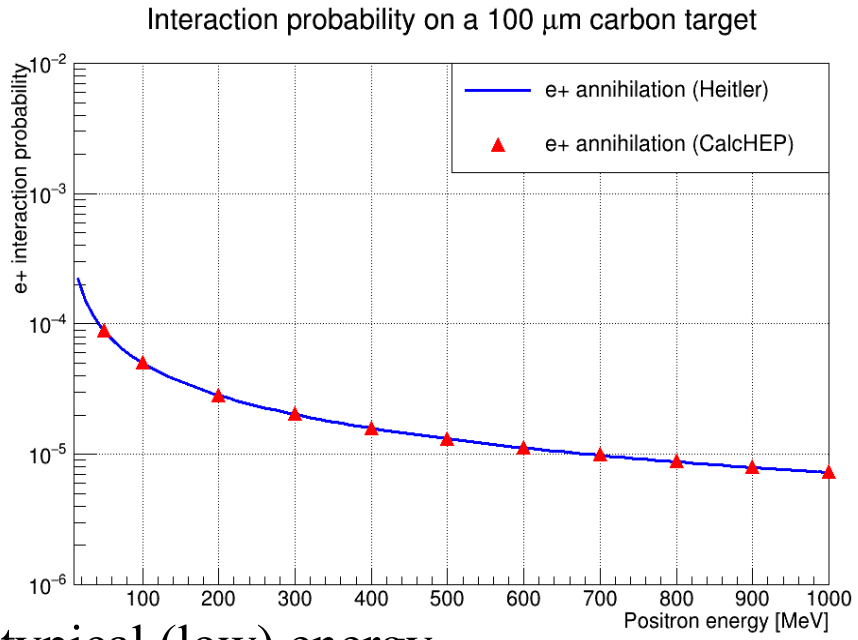
Simple effective model implemented in CalcHEP, used for further studies

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

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

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

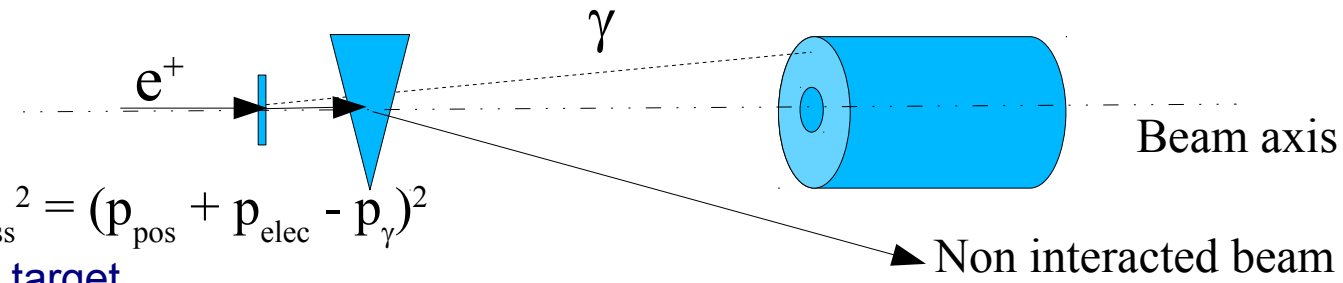




CalcHEP @ non-typical (low) energy

Missing mass technique

Study only the recoil photon



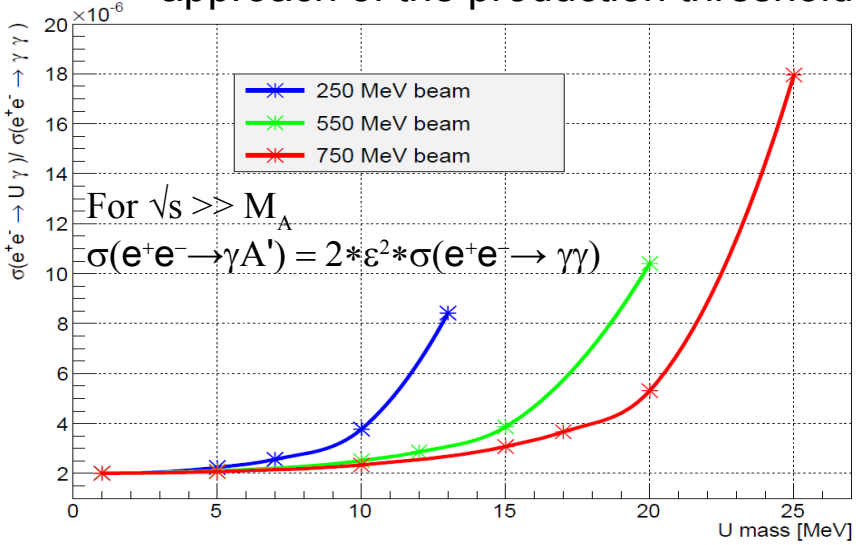
$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$

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

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

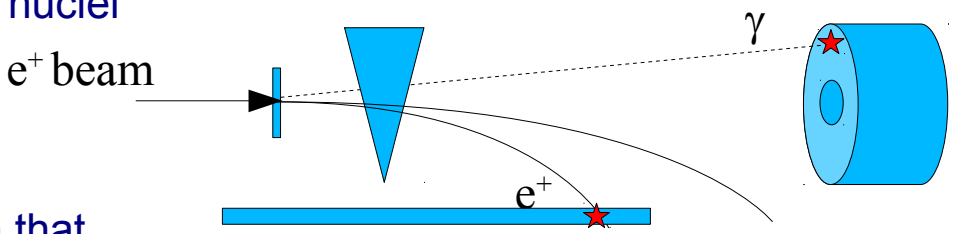
- Clear 2 body correlation
- Background minimization
  - Best possible resolution on energy/angle measurement
  - **Dominant process in e+/e- interactions with matter is bremsstrahlung**
  - Photons vetoing
  - Minimize the interaction remnants + vetoing

Cross section enhancement with the approach of the production threshold

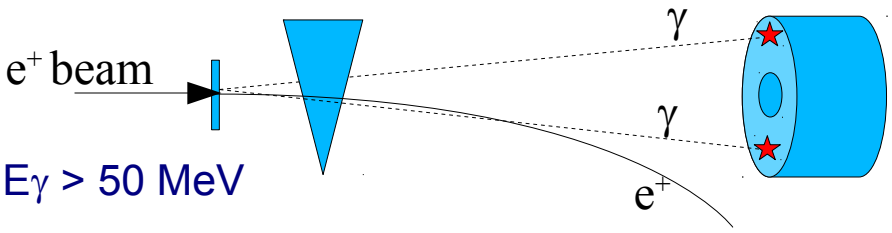


Backgrounds

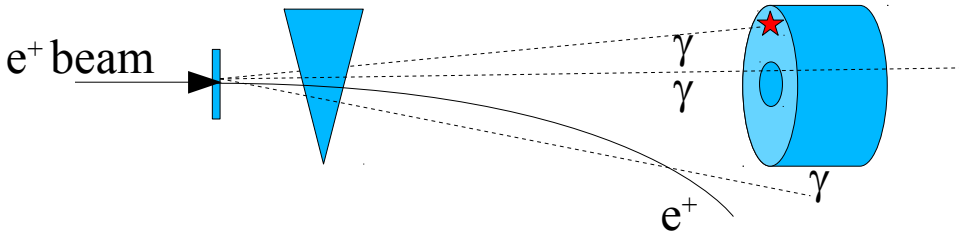
- Bremsstrahlung in the field of the target nuclei
  - Photons mostly @ low energy, background dominates the high missing masses
  - An additional lower energy positron that could be detected due to stronger deflection



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

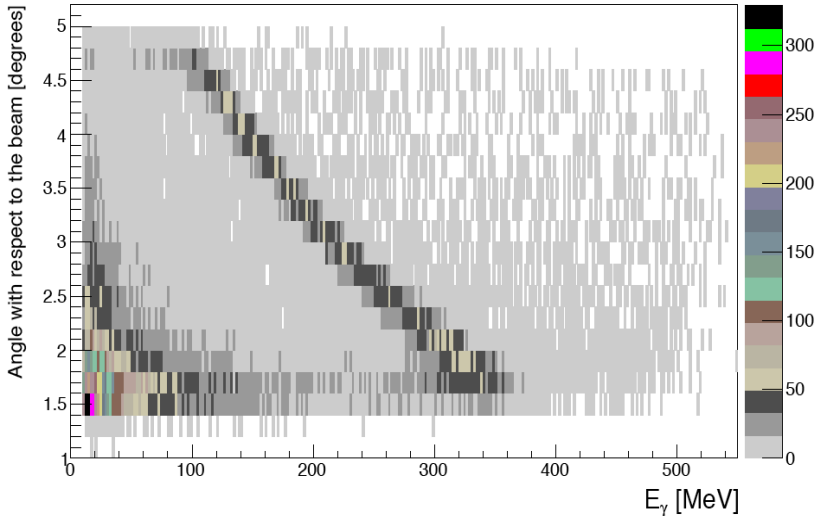


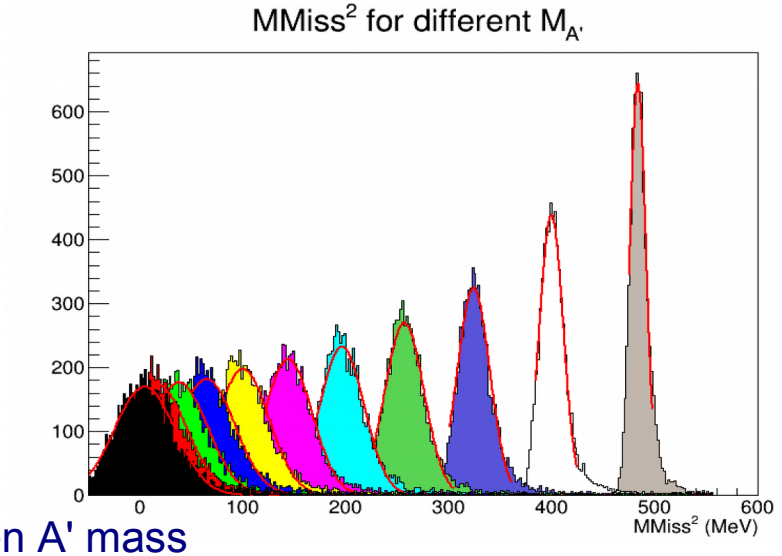
- 3 photon annihilation
  - Symmetry is lost – decrease in the vetoing capabilities
  - Does not peak



- Radiative bhabha scattering
  - Topology close to bremsstrahlung

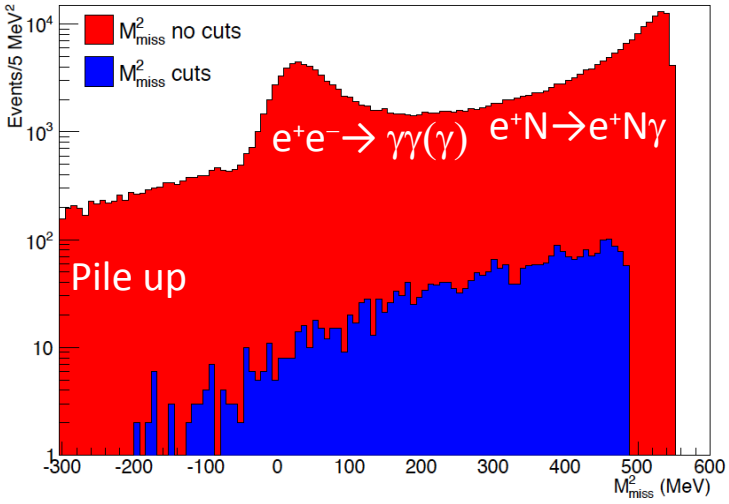
Measurement strategy





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

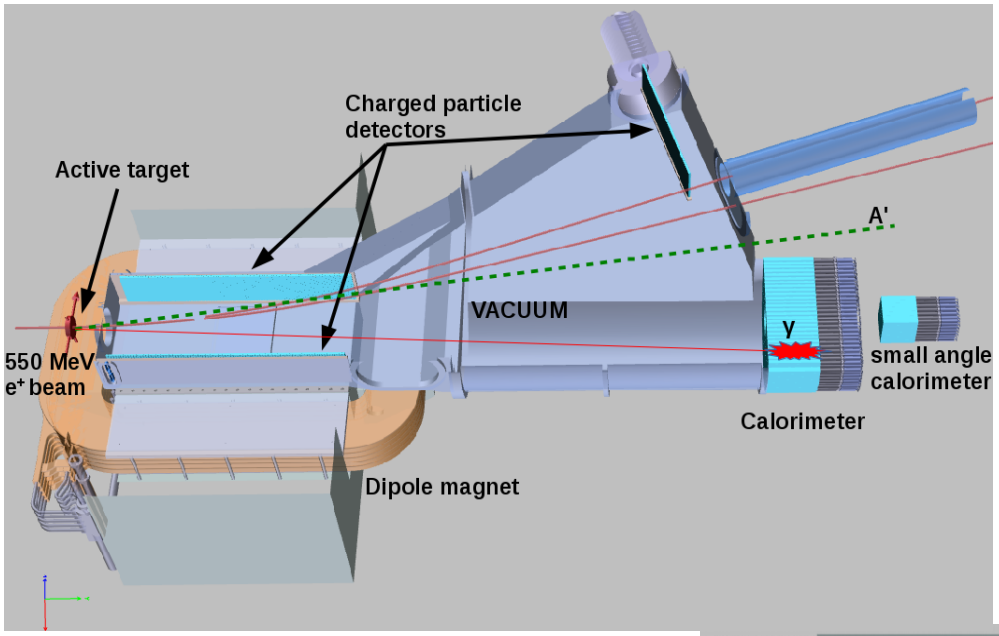
Background process	Cross section e^+@550 MeV beam	Comment *Carbon target*
$e^+e^- \rightarrow \gamma\gamma$	1.55 mb	
$e^+ + N \rightarrow e^+ N \gamma$	4000 mb	$E\gamma > 1$MeV
$e^+e^- \rightarrow \gamma\gamma\gamma$	0.16 mb	CalcHEP, $E\gamma > 1$MeV
$e^+e^- \rightarrow e^+e^-\gamma$	180 mb	CalcHEP,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



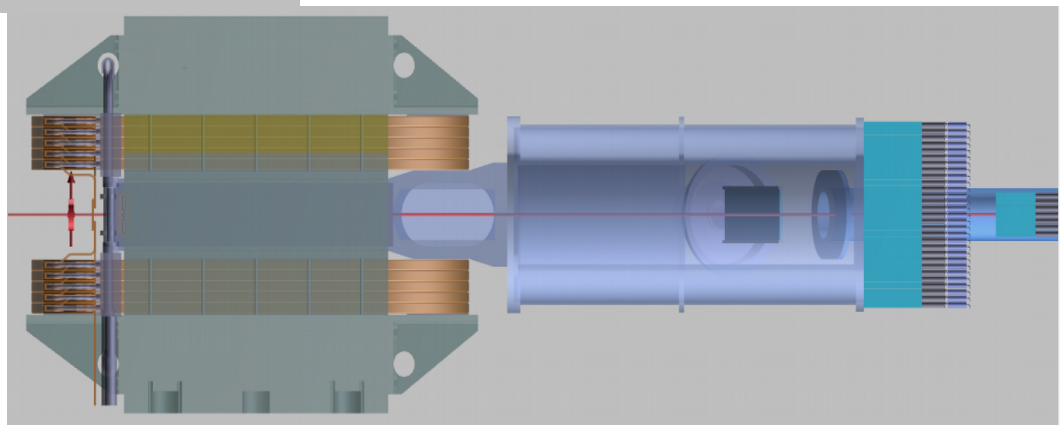
PADME experiment

Positron Annihilation into Dark Matter Experiment

Adv. HEP 2014 (2014) 959802



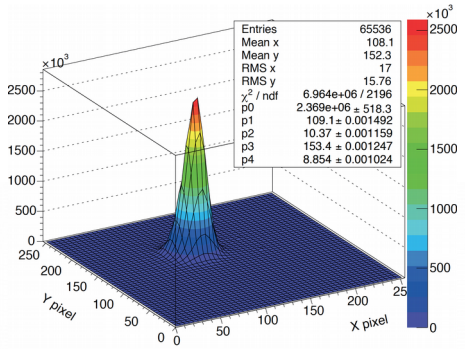
- Small scale fixed target experiment
- M. Raggi, V. Kozhuharov and P. Valente:
  - e^+ @ Frascati Beam test facility
  - Solid state target
  - Charged particles detectors
  - Calorimeter



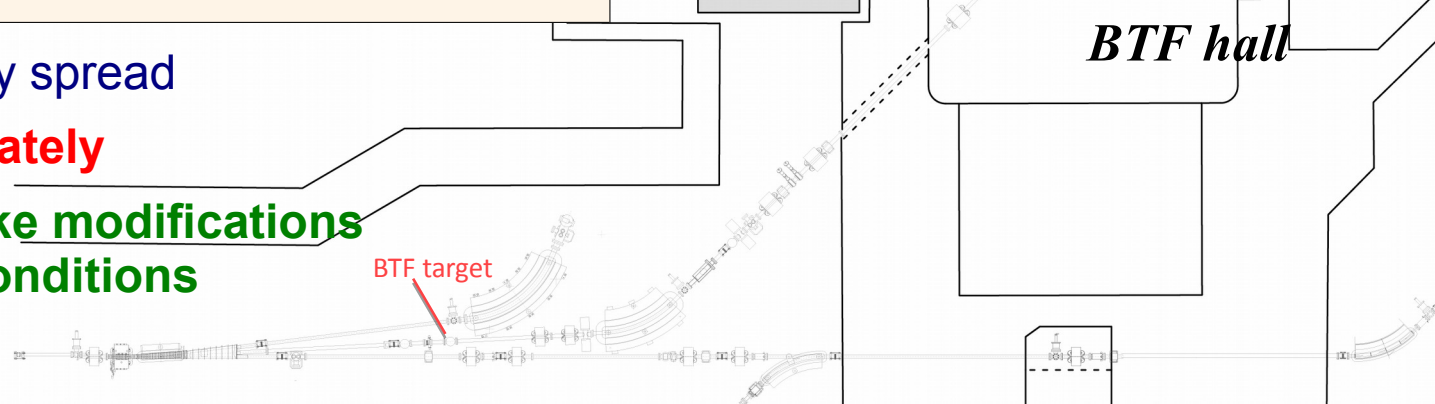
BTF @ LNF

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			

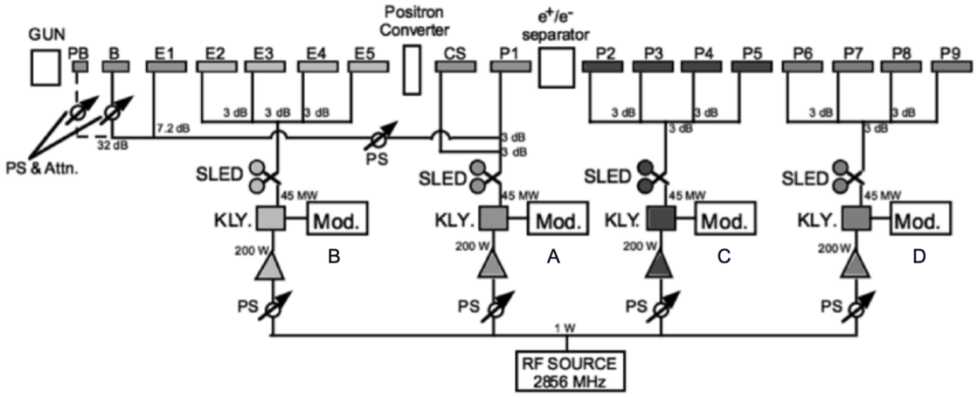
RMS_x = 0.9 mm
RMS_y = 0.9 mm



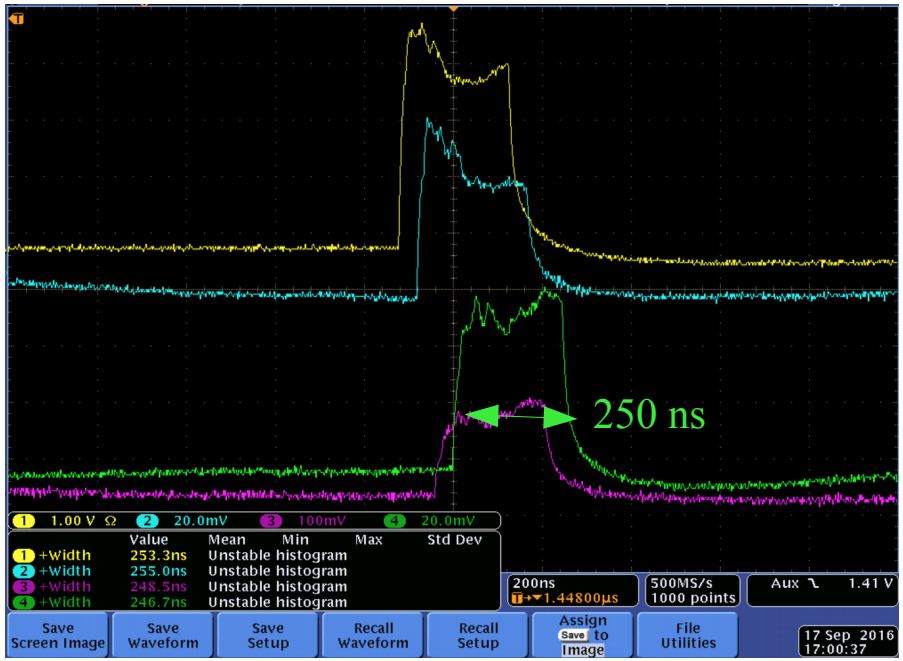
- Small beam energy spread
- **Available immediately**
- **Possibility to make modifications to optimize the conditions**



BTF @ LNF

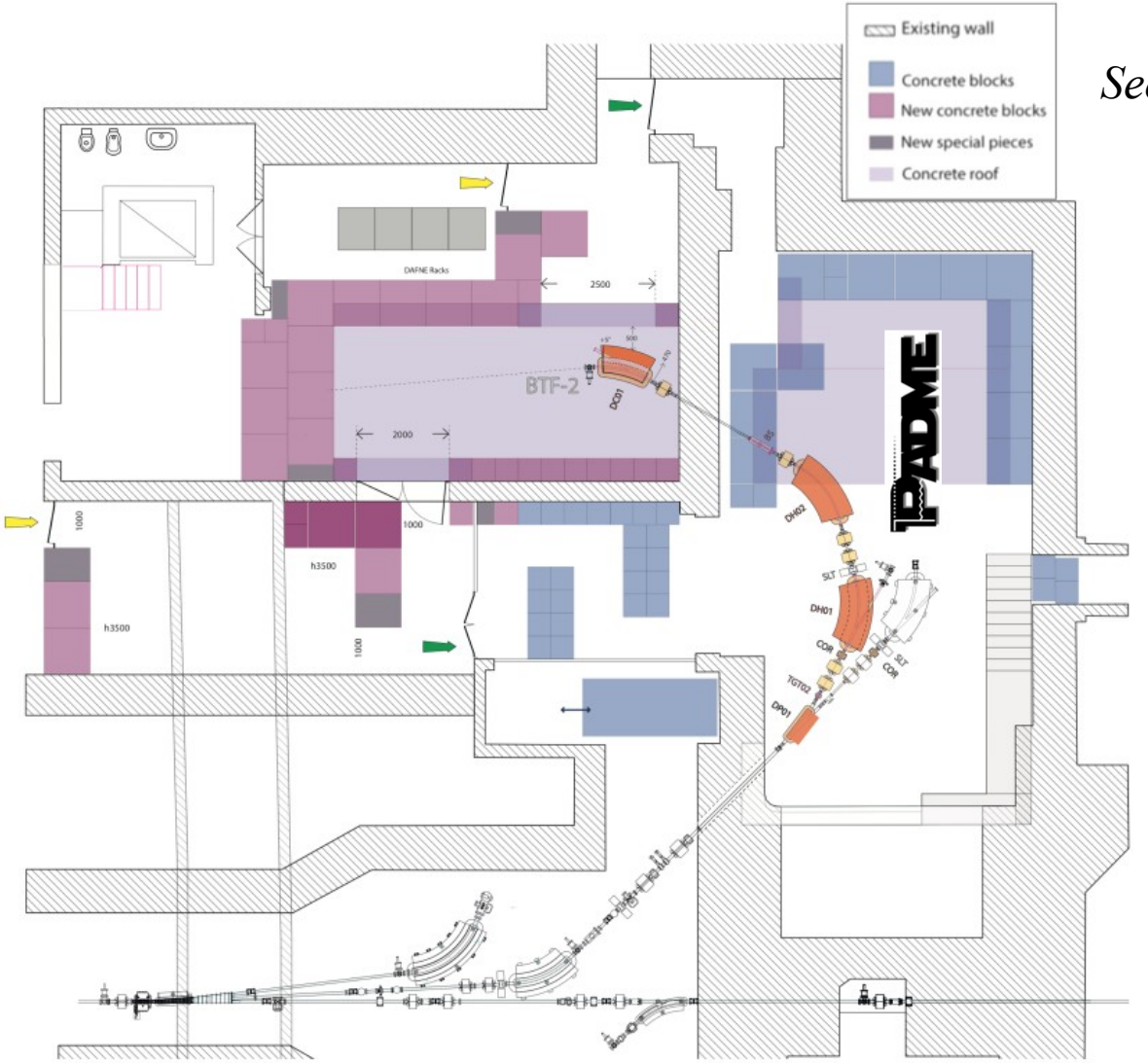


The linac achieved 250 ns bunch length



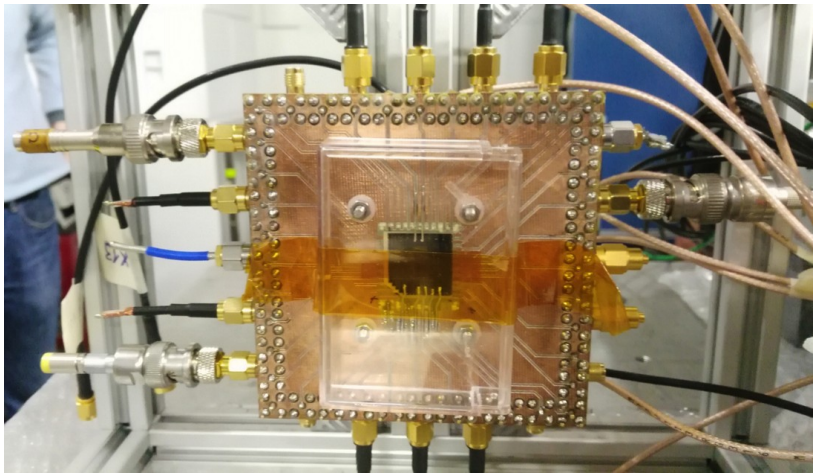
- PADME requirement: > 10^{13} positrons on target
- Repetition rate: 49 Hz
  - 5000 e^+, 40 ns bunch length
- Positron production:
  - Positron converter
  - BTF target
- Bunch length limited by the RF compression at SLED
  - A longer pulse allows increasing the number of positrons/pulse
  - RF power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

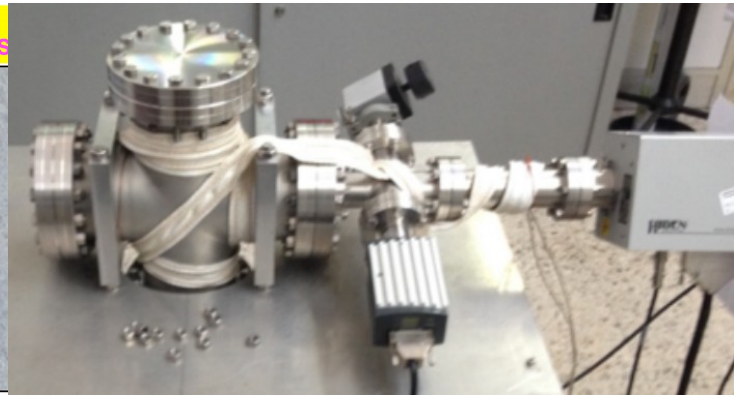
BTF infrastructure upgrade

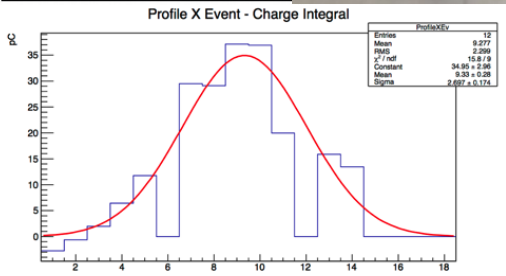


See L. Foggetta's talk

Diamond target







Motorized support structure ready: vacuum tests ongoing

Polycrystalline diamonds

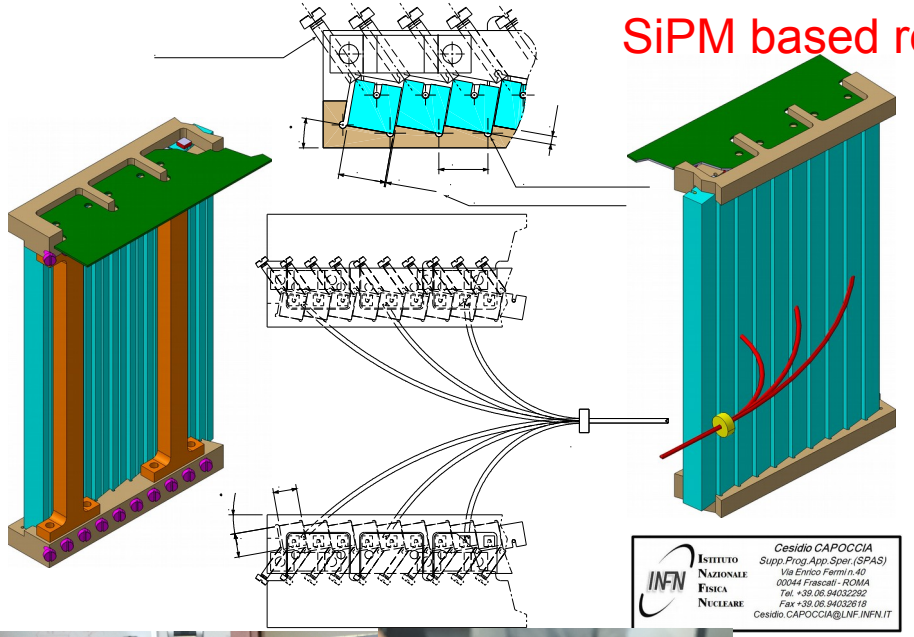
- 100 mm thickness:
- 16 × 1 mm² strip and X-Y readout in a single detector
- Samples with graphitized and metalized strips available
- PADME prototype 20 × 20 mm² produced and tested 2015
- Low noise CSA integrated in the 16 channel chip AMADEUS from IDEAS

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

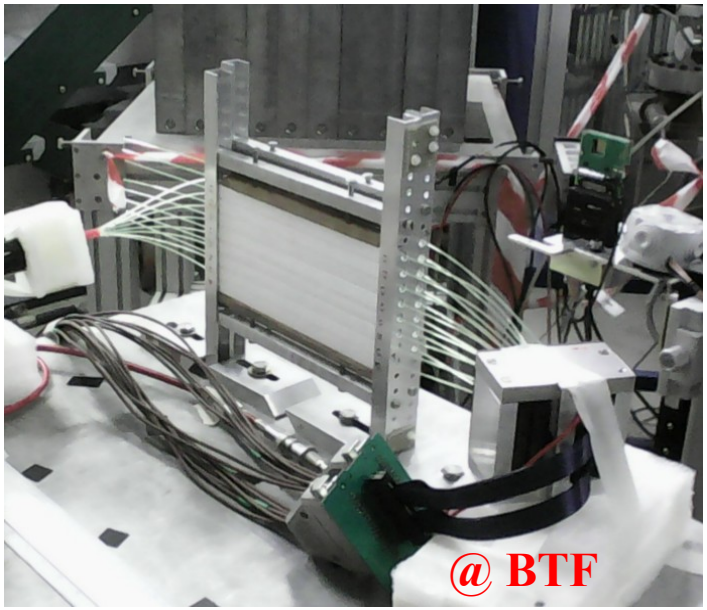
Charged particle vetoes

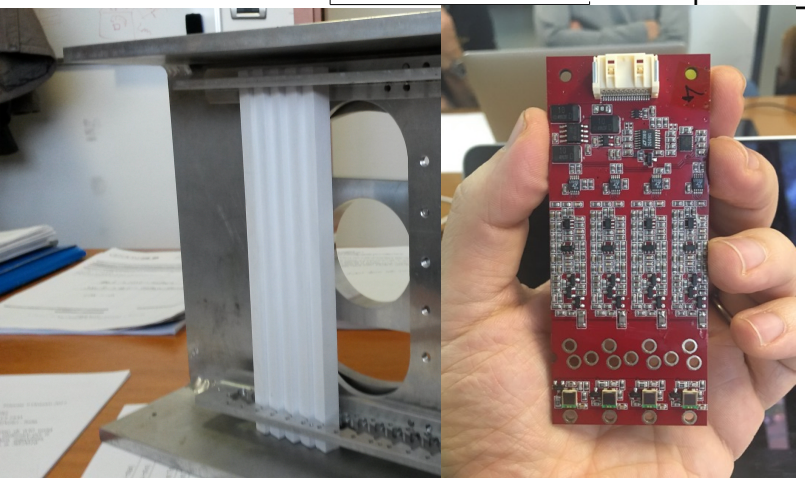
- Plastic scintillator detector

SiPM based readout



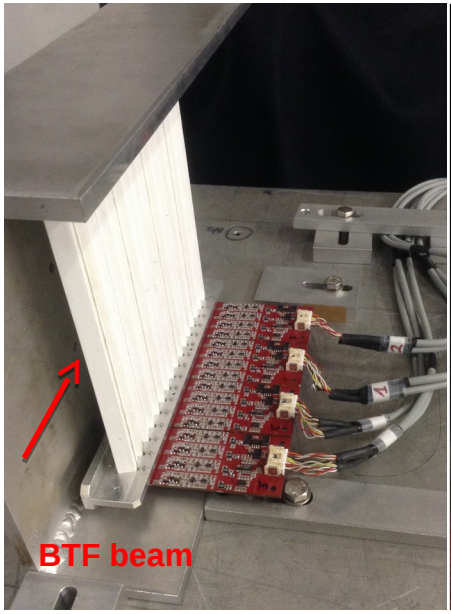
Tracker prototype for test with MAPMT

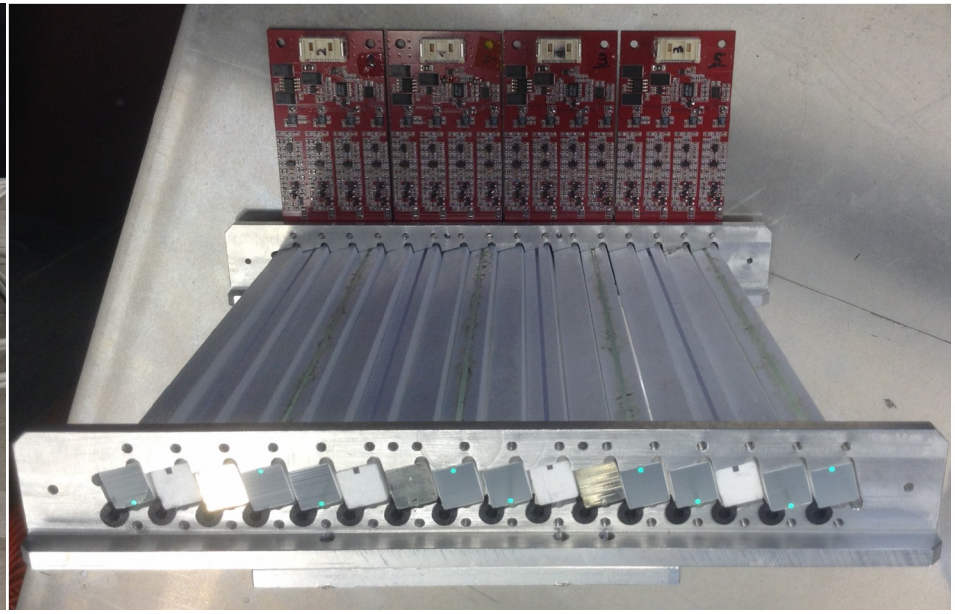


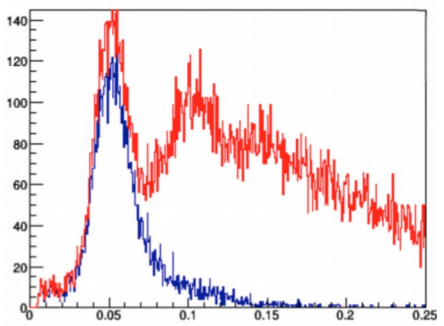


- $10 \times 10 \times 184\ mm^3$ scintillator bars
  - Available already
- Mechanics design completed
- SiPM electronics prototype available
- Efficiency > 99%, $\sigma(t) < O(1\ ns)$

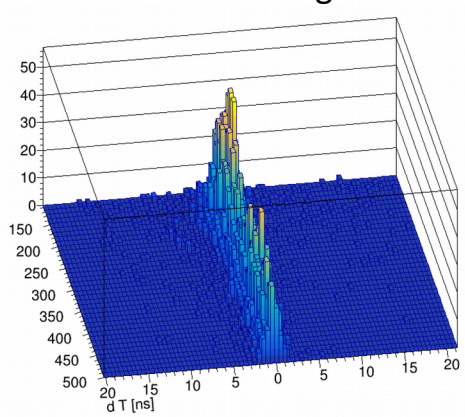
Charged particle vetoes



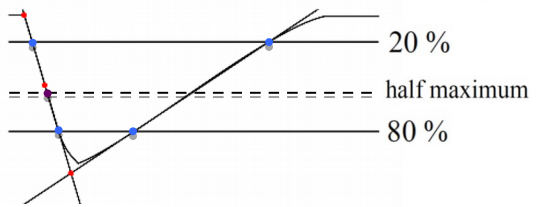




Δt vs charge

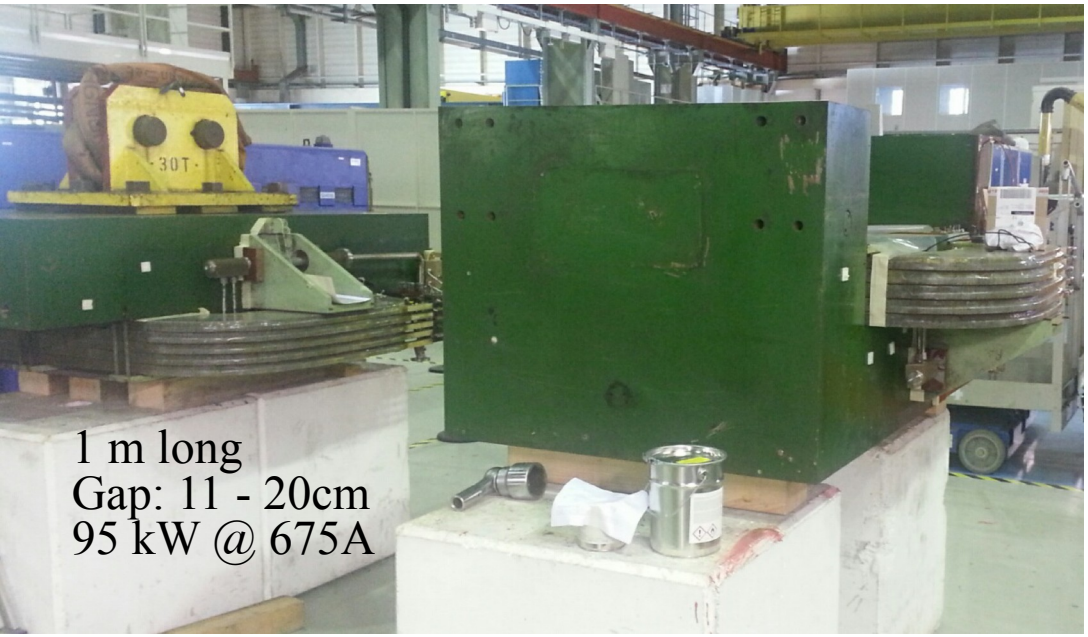


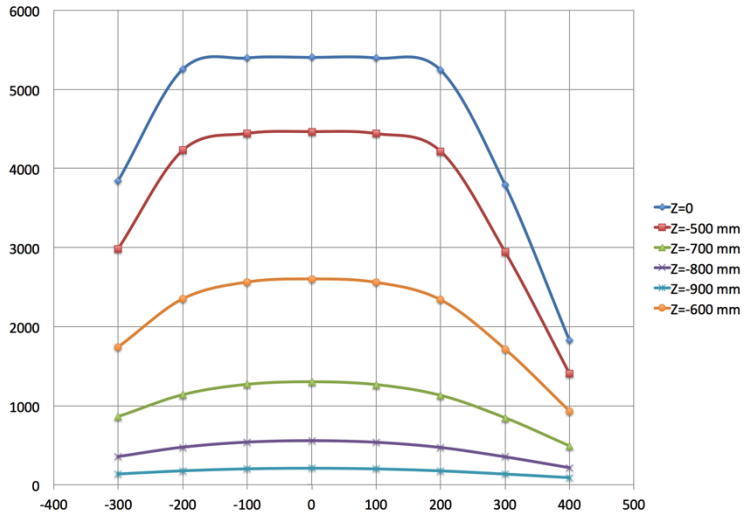
- Different resolution values obtained using different definitions of timing
- Already well below 1 ns resolution level at the level without any calibration and very preliminary analysis
- Front-end electronics prototype working extremely well

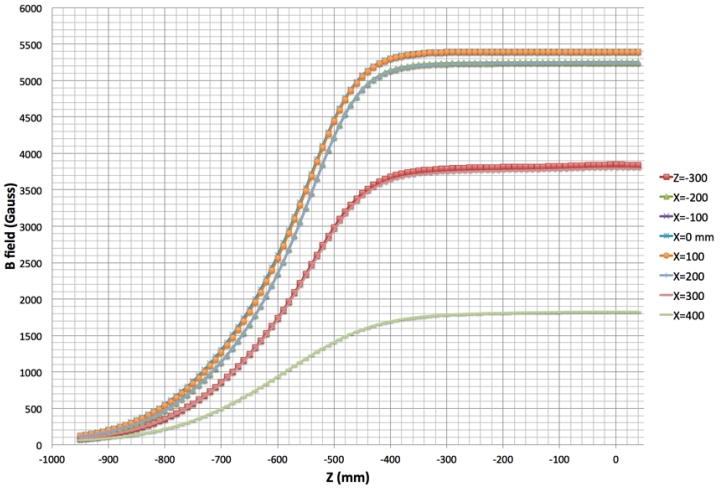


$$T_{\text{Mean}} = \frac{\sum_{peak} A_i * t_i}{\sum_{peak} A_i}$$

Magnet

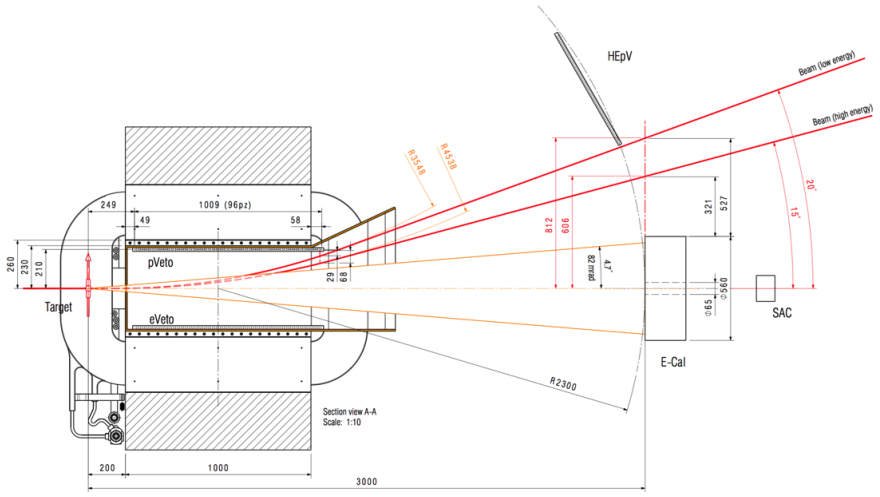


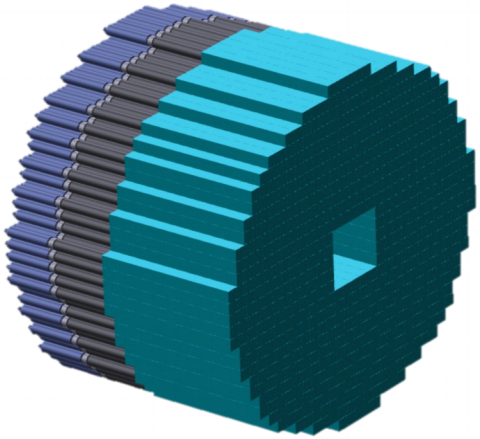


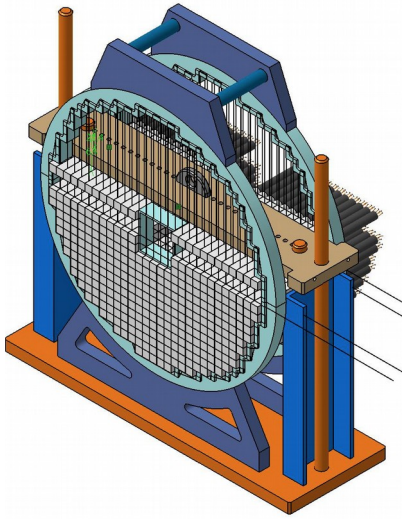


- MBP-S series, on loan from CERN
  Many thanks to TE-MSC-MNC
- Poles: 100 cm length, 52 cm width
- Variable gap 11 to 20 cm, further extended to 23 cm
- Detailed field mapping: good B field quality
- Fringe field not negligible, even outside the coils, relevant for the precise beam steering onto the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

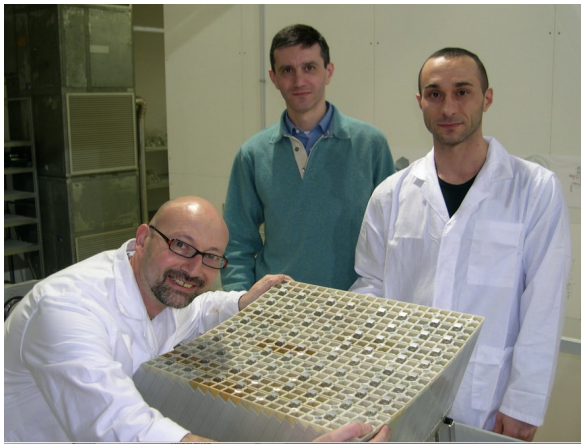
Calorimeter design



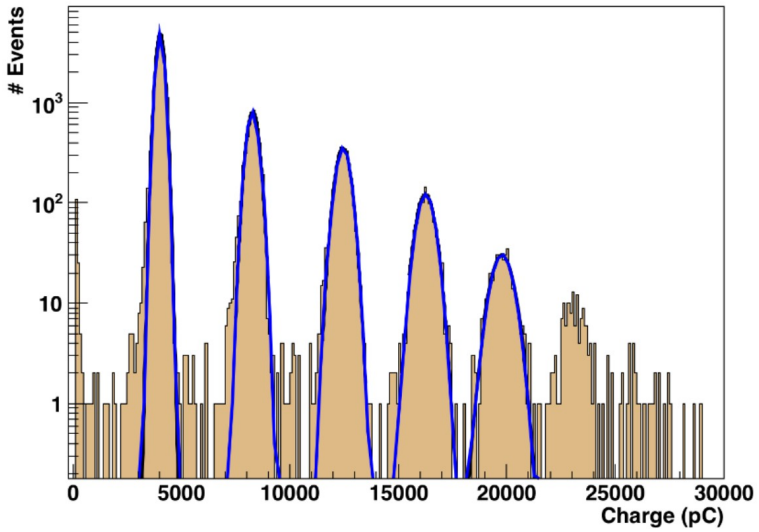




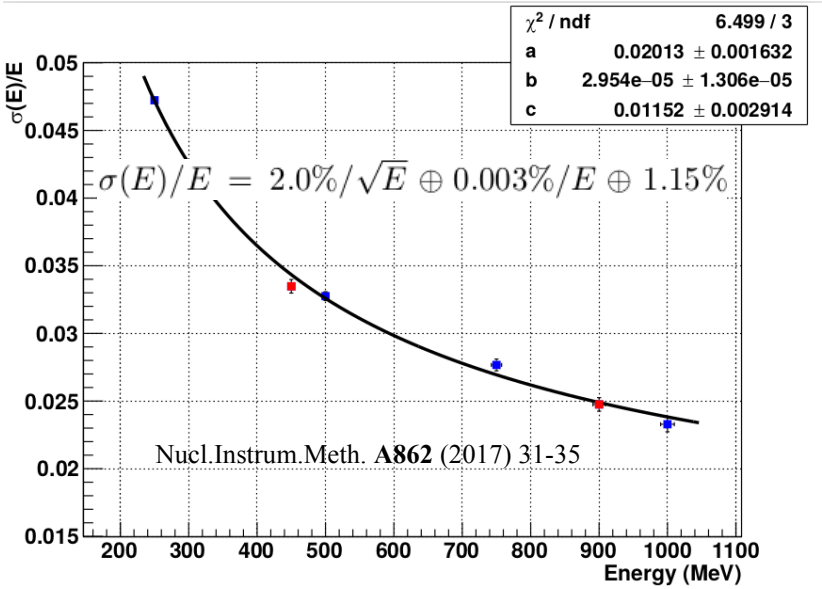
- BGO crystals available from L3 experiment (agreement with L3, C.C.Ting, INFN)
- Cylindrical shape: radius 280 mm, depth of 230 mm
  - Inner hole 100 mm side
  - 616 crystals 21 × 21 × 230 mm^3
  - Angular resolution ~ O(1 mrad)
  - Angular acceptance (20 – 83) mrad
- HZC XP1911 PMT, 19 mm diameter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



Calorimeter design

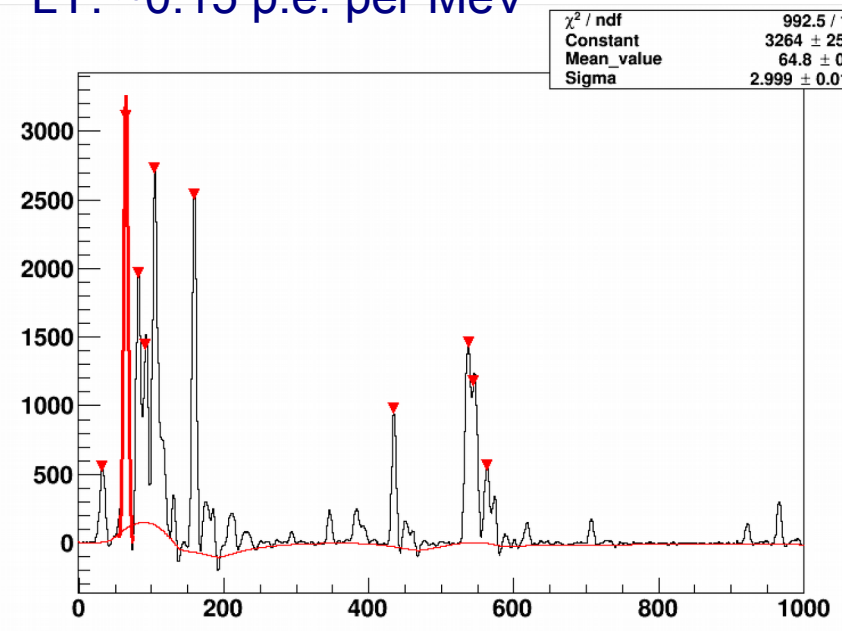


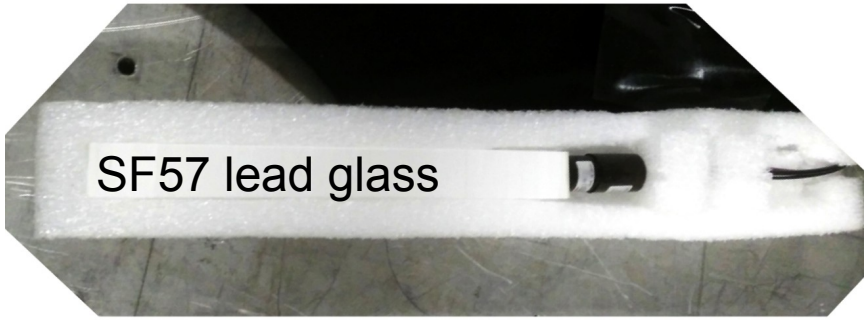
Parameter:	ρ	MP	$X_0^\star$	$R_M^\star$	dE^*/dx	$\lambda_I^\star$	τ_{decay}	$\lambda_{\max}$	$n^\natural$	Relative output†	Hygro-scopic?	$d(\text{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	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



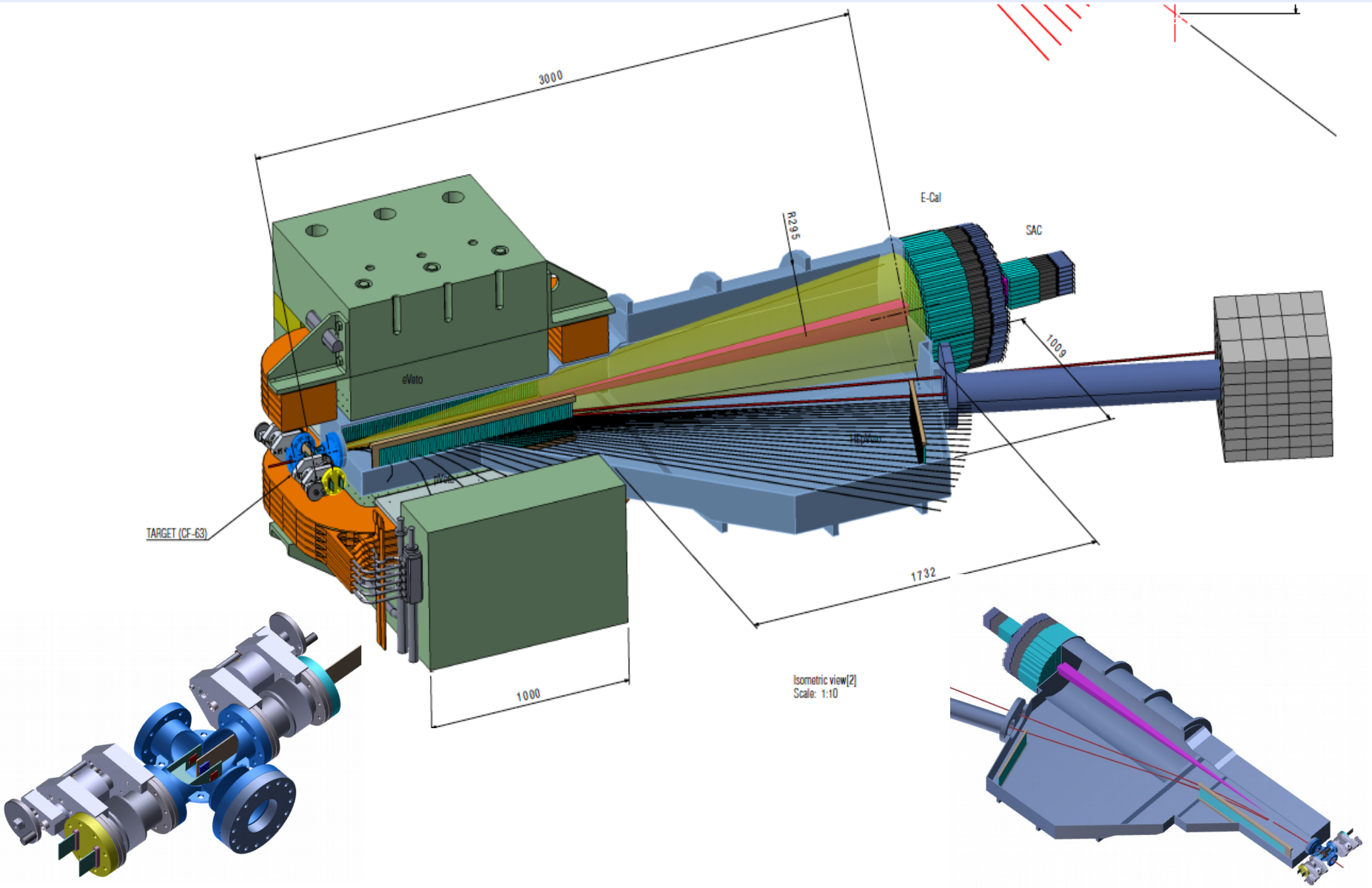
Small angle photon veto

- 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

Or the 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

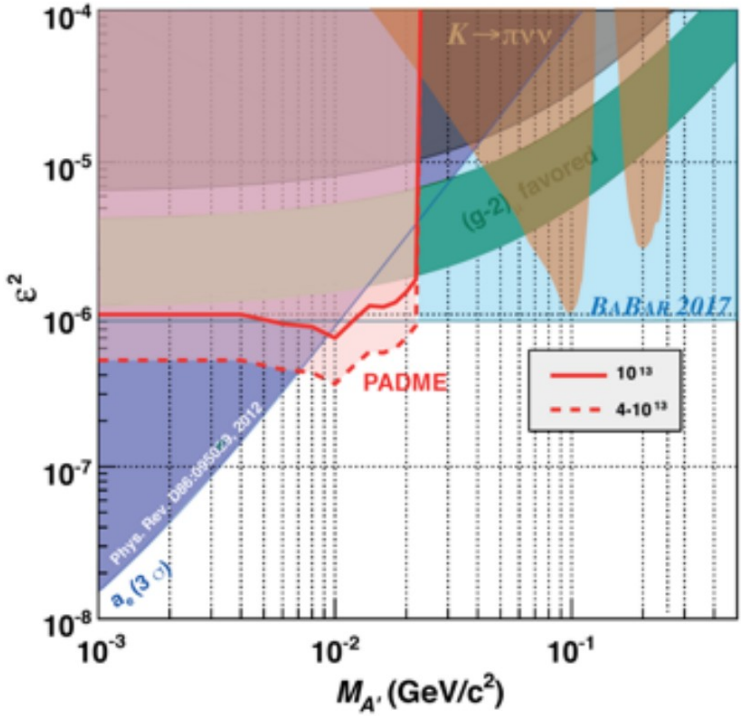
And multiple tests with RA sources…

Sensitivity estimation

Selection

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

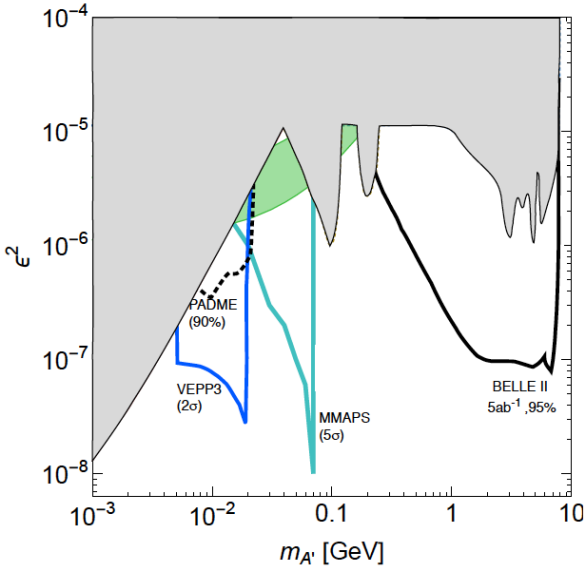
- Single cluster in the Calo
- 30 mrad < θcl < 65 mrad
- Cluster energy:
  $E^{CL}_{min}(M_{A;})$ in 50 – 150 MeV
  $E^{CL}_{max}(M_{A'})$ in 120 – 350 MeV
- ± 1σ cut on the missing mass
- Veto on positrons in ± 2 ns time window
- Using $N_{signal} = \sigma(N_{background})$ to derive limits



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

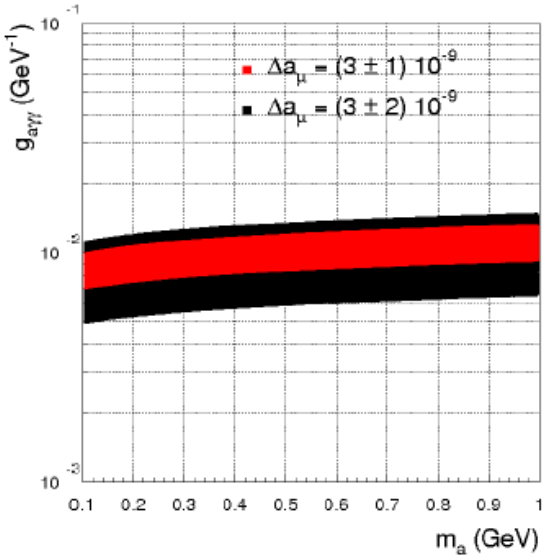
PADME physics case

Dark Photon arXiv:1608.08632v1



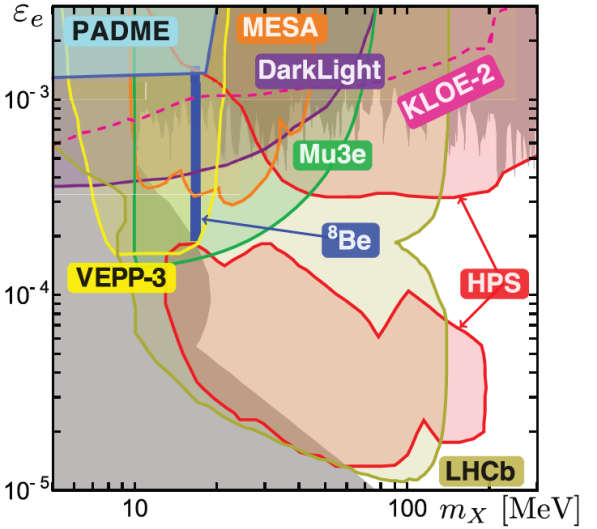
Invisible final state A'→χχ

ALPs and g-2 arXiv 1607.01022v2



ALPs final state a→γγ

Fifth force arXiv:1608.03591v1



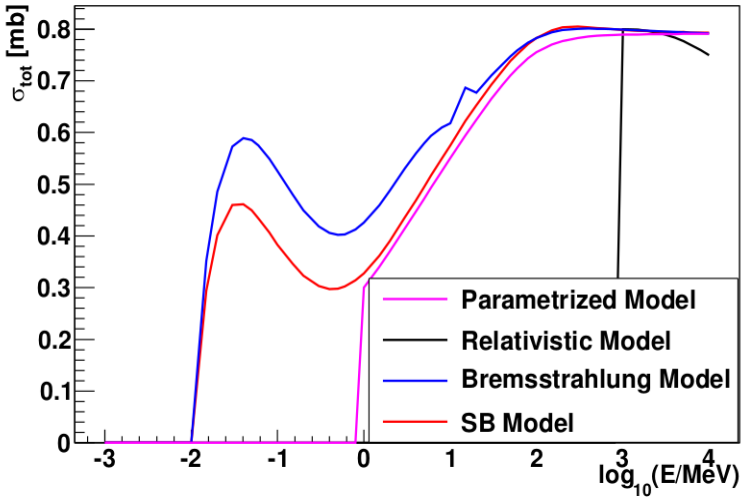
Final state X→ee

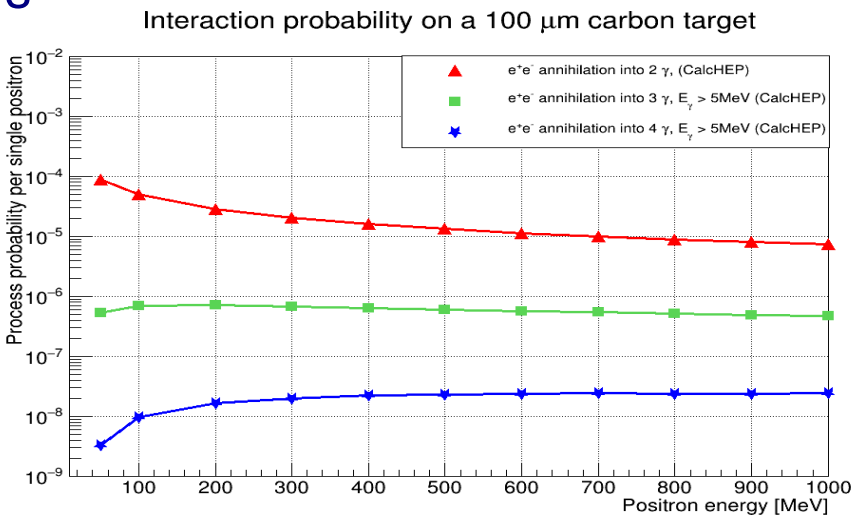
PADME is one of the experiments able to provide valuable input

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



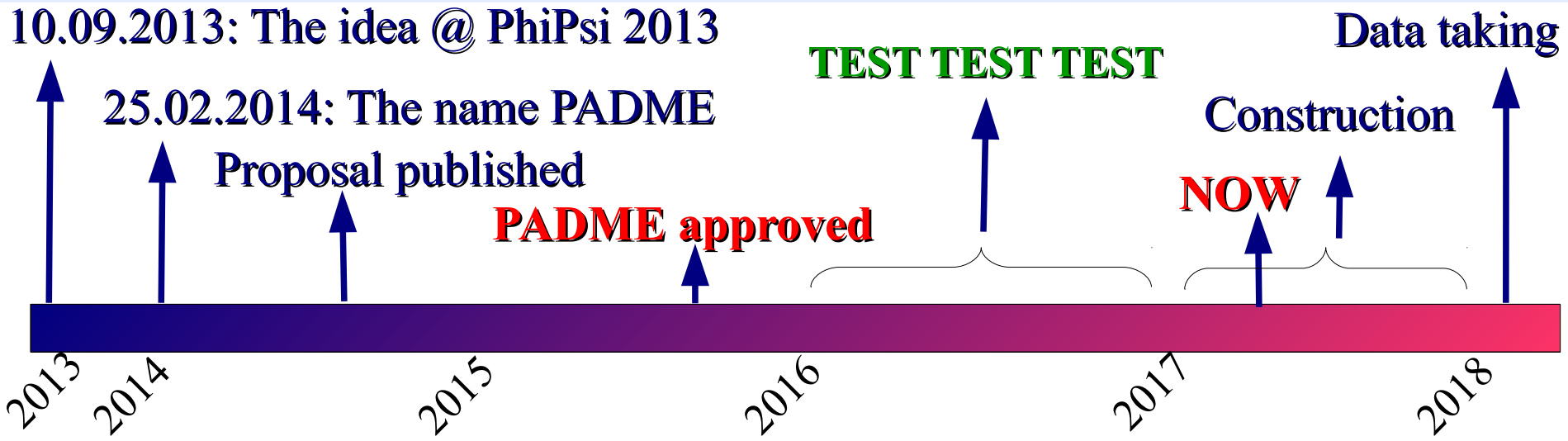


- GEANT4 model uncertainties on bremsstrahlung
  - Parametric: 4-5 % for E_{e+} > 1 MeV, SB model: 3-5% for E_{e+} > 50 MeV
  - Measurement of differential cross section dσ/dEdθ interesting for PADME

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

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

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

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	$2x10^{22}$ e^-/cm^2	$O(2x10^{23})$ e^-/cm^2	$5x10^{15}$ e^-/cm^2
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA
$e^+e^- \rightarrow \gamma\gamma$ 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**