PADME electromagnetic calorimeter

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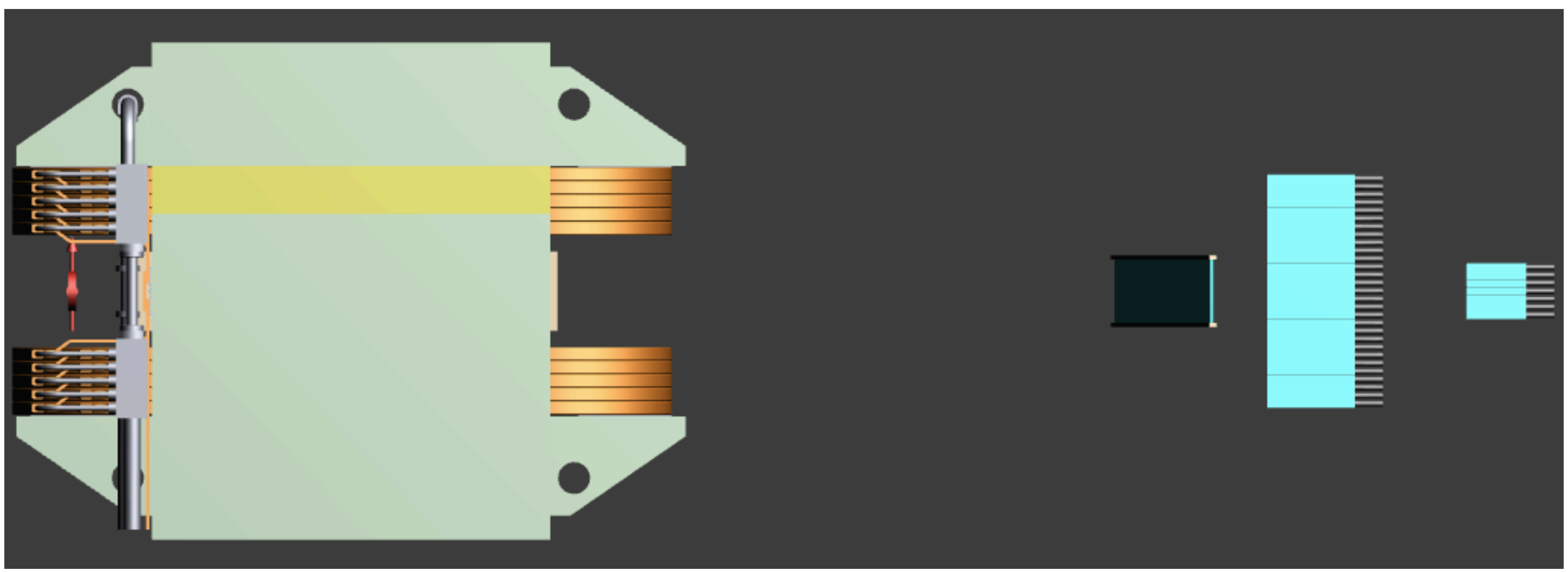
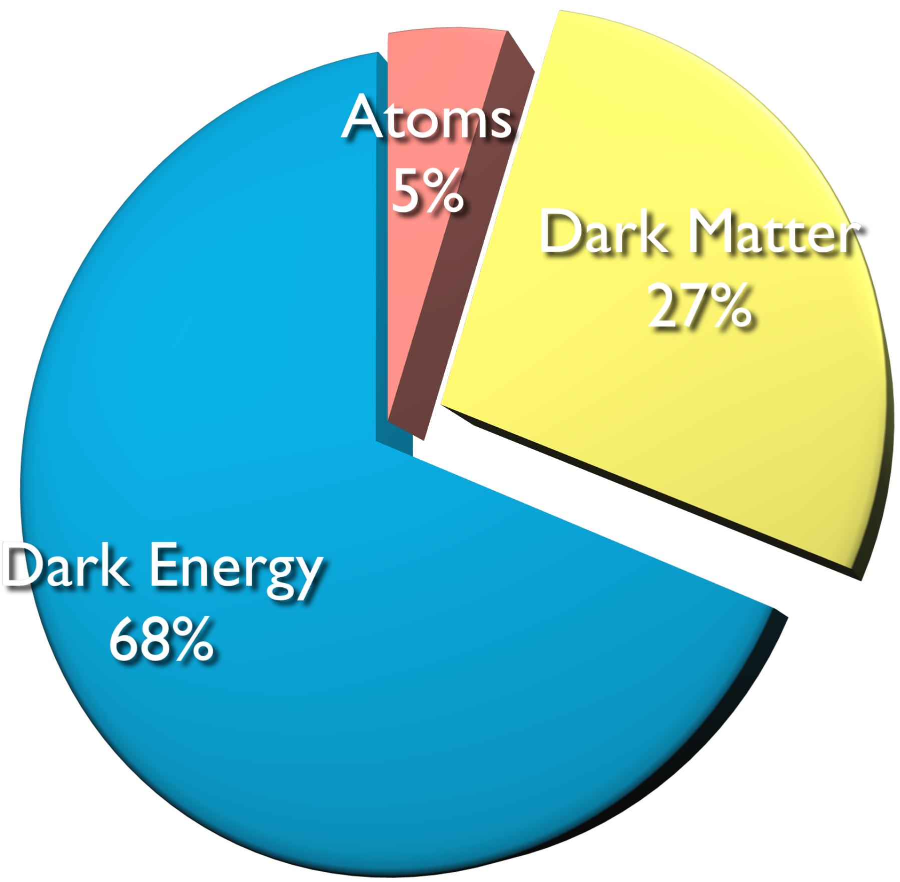


CALOR 2018 - Eugene (OR), USA - May 24, 2018

The Dark Matter problem

Evidences:

- spiral galaxies
- Cosmic Microwave Background
- gravitational lensing
- galaxy clusters
- Big Bang Nucleosynthesis
- large scale structures



Properties:

- stable (half life ~ universe age)
- cold (non relativistic)
- gravitational force
- non baryonic

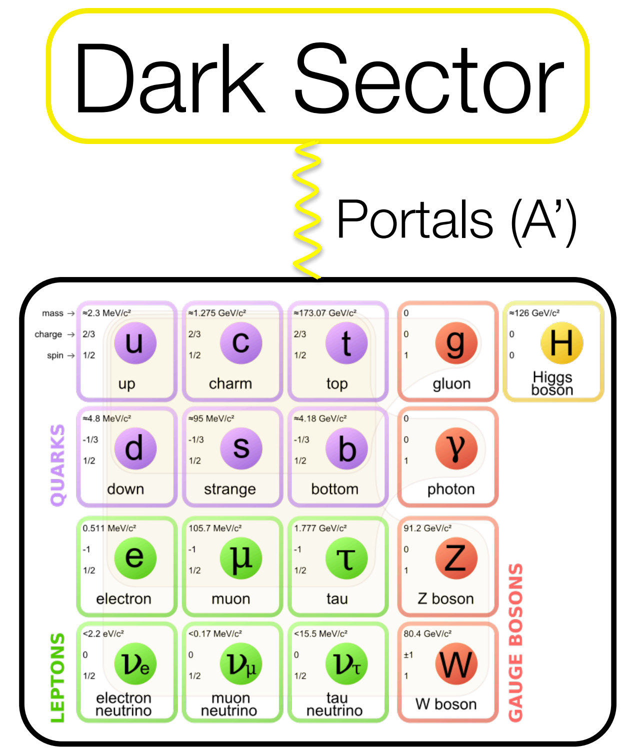
↔

Open questions:

- DM nature
- interaction(s) w/ SM
- A whole new dark sector?
- dark sector forces?

Dark Photon

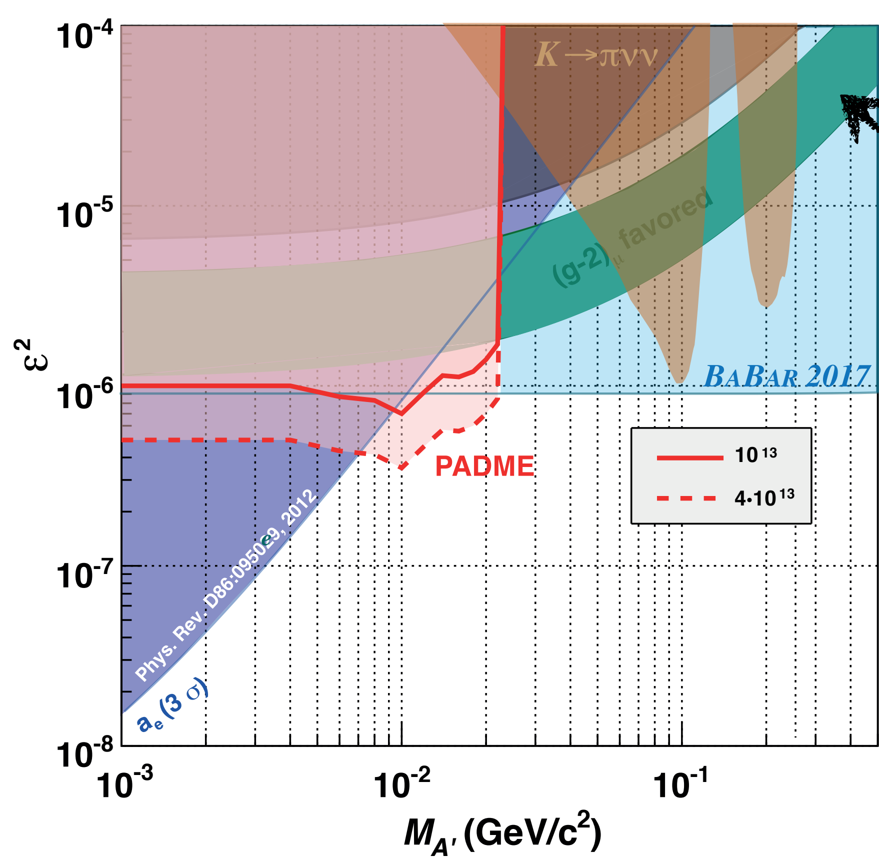
Possible solution to the DM elusiveness:
DM does not interact directly w/ SM, but only by means of "portals".



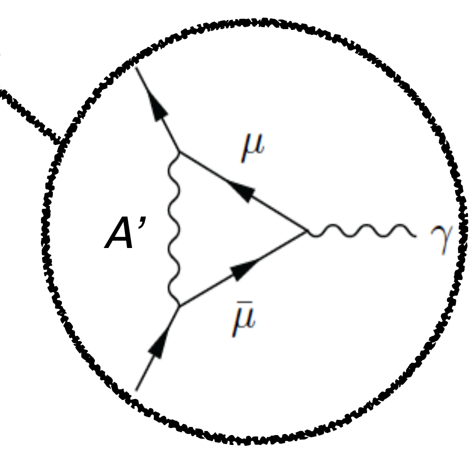
The simplest model adds a U(1) gauge symmetry and its boson: the Dark Photon A'

- SM particles are neutral under this symmetry
- new field couples to the SM w/ effective charge εq

Depending on the model, the A' could (partially) explain the $(g\text{-}2)_\mu$ discrepancy and the ^{8}Be anomaly (see backup)



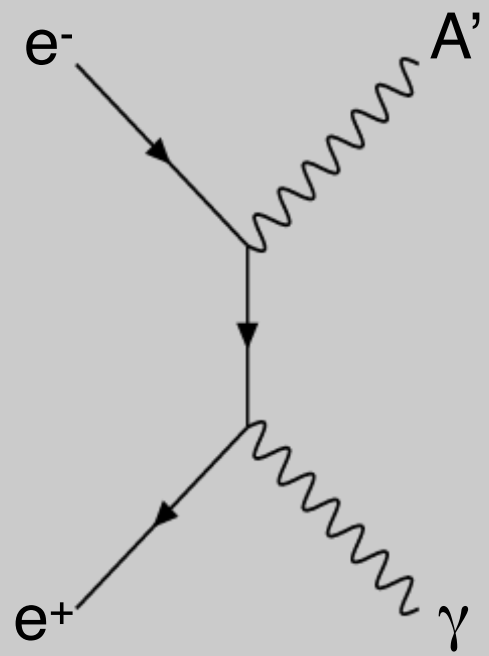
Exclusion plot assuming as A' model the one presented above



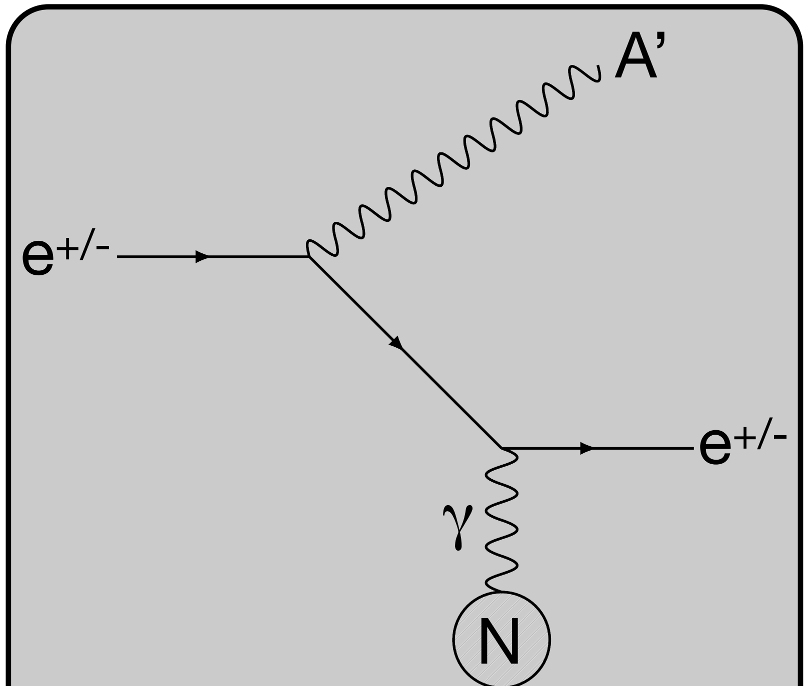
Excluded as only solution of the $(g\text{-}2)_\mu$ problem

Dark photon production and decays

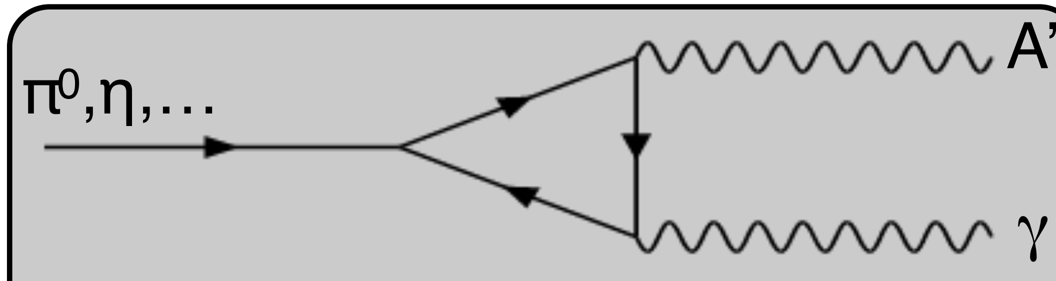
In e^+/e^- collisions Dark Photon can be **produced** in 3 main ways:



Annihilation



Bremsstrahlung



Mesons dec. (after production)

Visible decays

If DM particles w/ $m_{DM} \leq m_{A'}/2$ do not exist:

- $A' \rightarrow SM$ (visible) decays
  - up to $2m_\mu$, $BR(e^+e^-) = 1$ (if $m_{A'} > 2m_e$)

A' lifetime proportional to:

$$1/(\alpha\varepsilon^2 m_{A'})$$

Invisible decays

If DM particles w/ $m_{DM} \leq m_{A'}/2$ exist:

- $A' \rightarrow DM$ (invisible) w/ (likely) $BR \simeq 1$
- SM decays suppressed by a factor ε^2

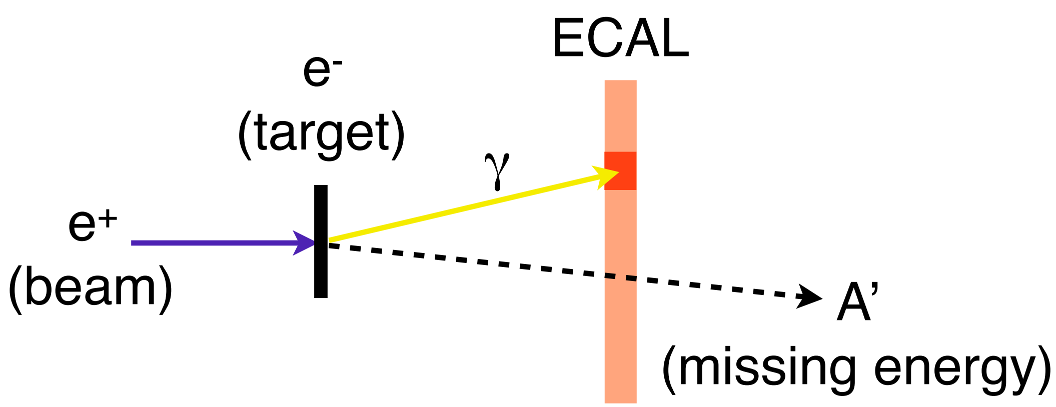
A' lifetime proportional to:

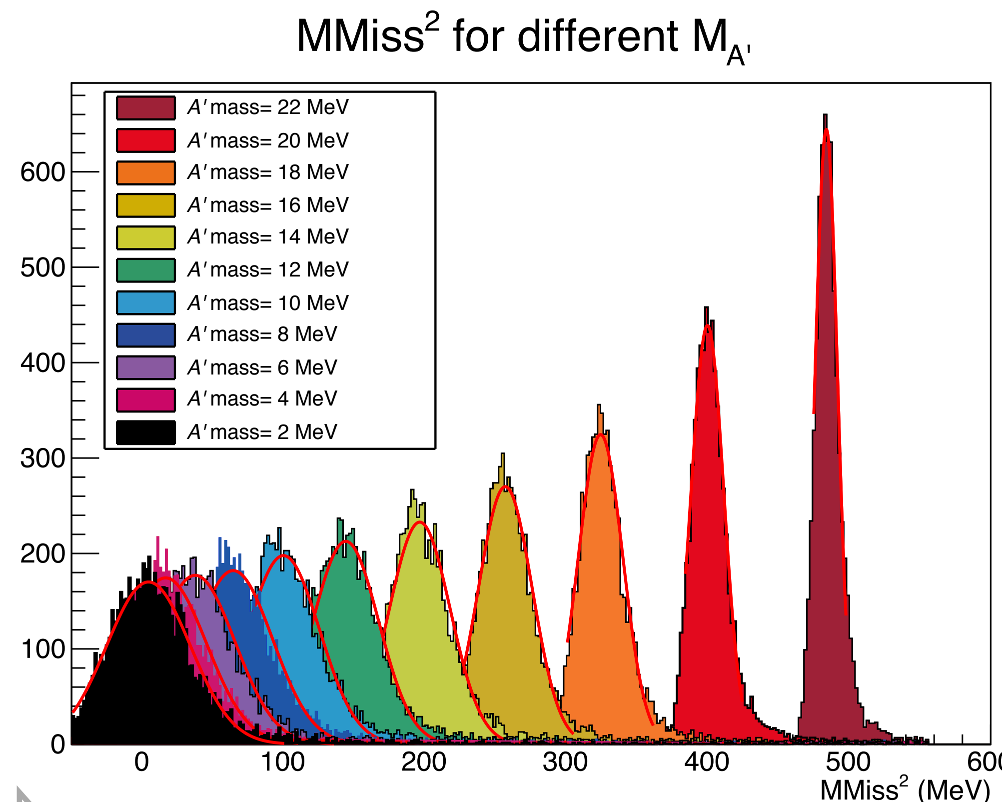
$$1/(\alpha_D m_{A'})$$

α_D: A' coupling constant to the Dark Sector

The PADME approach

A' search in e^+e^- annihilations looking for missing mass (invisible decay) in a kinematically constrained condition





- known beam energy and position
- measured photon energy and position

$$m^2_{Miss} = (\mathbf{P}_{beam} + \mathbf{P}_e - \mathbf{P}_\gamma)^2$$

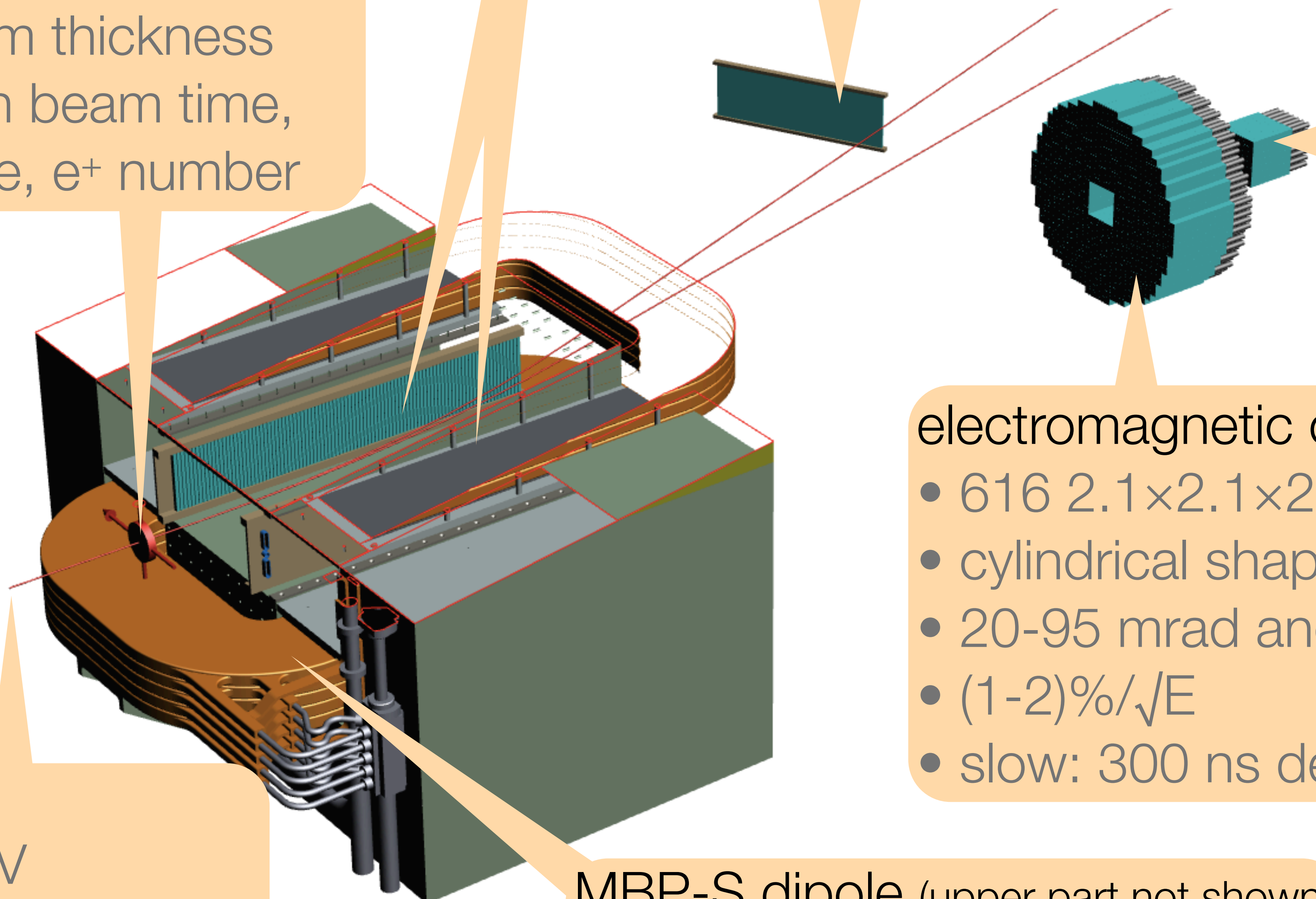
- minimal model dependent assumptions: A' couples to leptons
- can set limits on coupling of any new light particle that can be produced in e^+e^- annihilation: Dark Photon, Axion Like Particles, Dark Higgs

The detector

active target
- diamond (low z)
- 100 μm thickness
- info on beam time, spot size, e^+ number

(high energy) e^+/e^- veto
- plastic scintillator bars

small angle calorimeter
- 25 3×3×14 cm^3 PbF_2
- 0-20 mrad ang. cov.
- fast: 3 ns Cher. light signals



electromagnetic calorimeter
- 616 2.1×2.1×23 cm^3 BGO
- cylindrical shape w/ central hole
- 20-95 mrad ang. cov.
- $(1\text{-}2)\%/\sqrt{E}$
- slow: 300 ns dec. time for scint. light

e^+ beam
- 550 MeV
- 5000 e^+ per bunch
- 40 ns bunch, every 20 ms

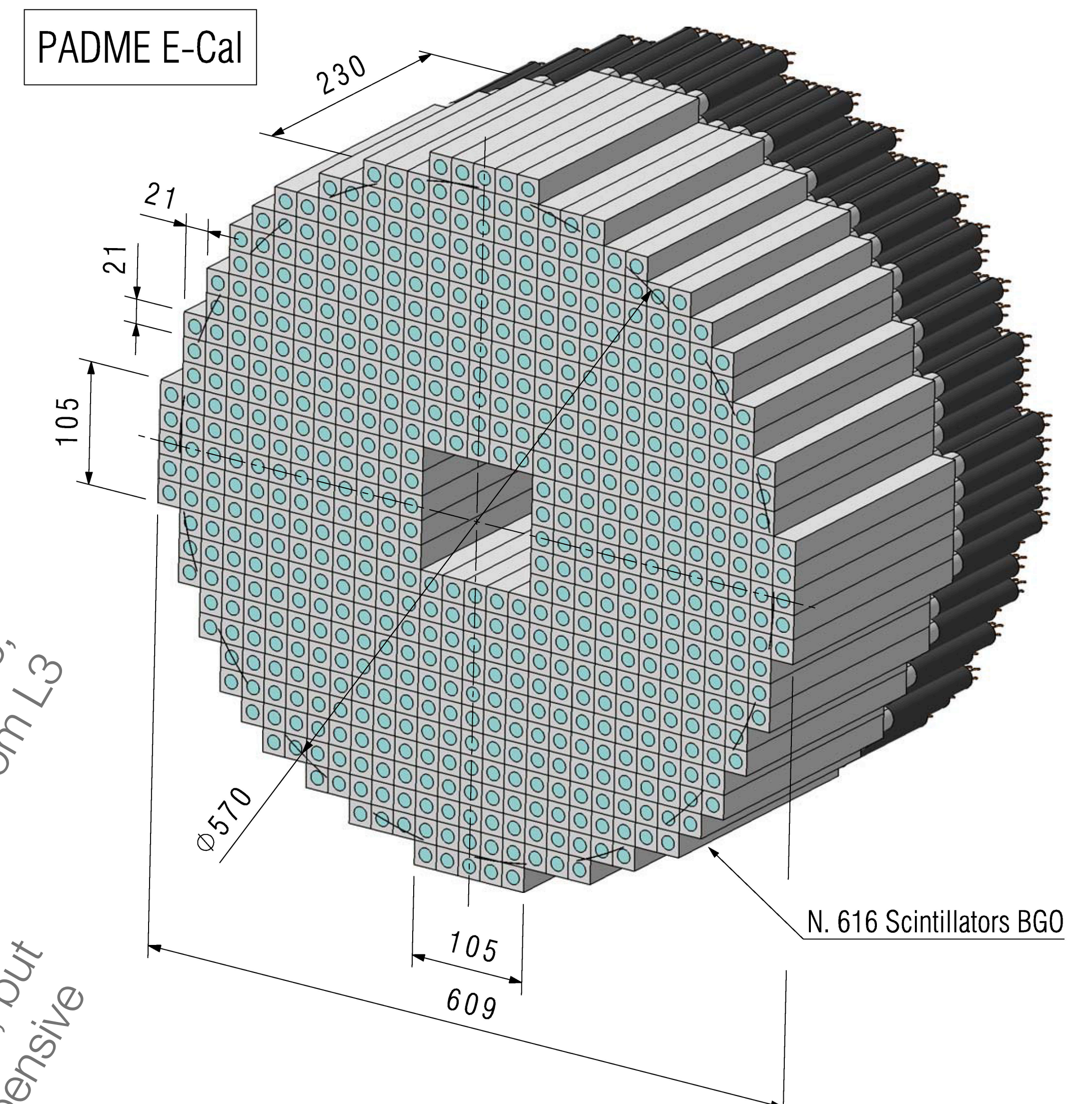
MBP-S dipole (upper part not shown)
- 0.5 T
- 1 m lenght. × 23 cm gap

ECAL overview

Required characteristics:

- $\sigma_E \simeq (1\text{-}2)\%/\sqrt{E(\text{GeV})}$
  - good light yield
  - containment
- cluster time resolution < 1 ns
- angular resolution ≲ 2 mrad
- angular coverage: [20,93] mrad
- angular acceptance: [26,83] mrad
- central hole for brems. to SAC (faster)

616 BGO 2.1×2.1×23 cm^3
@ 3m from the target



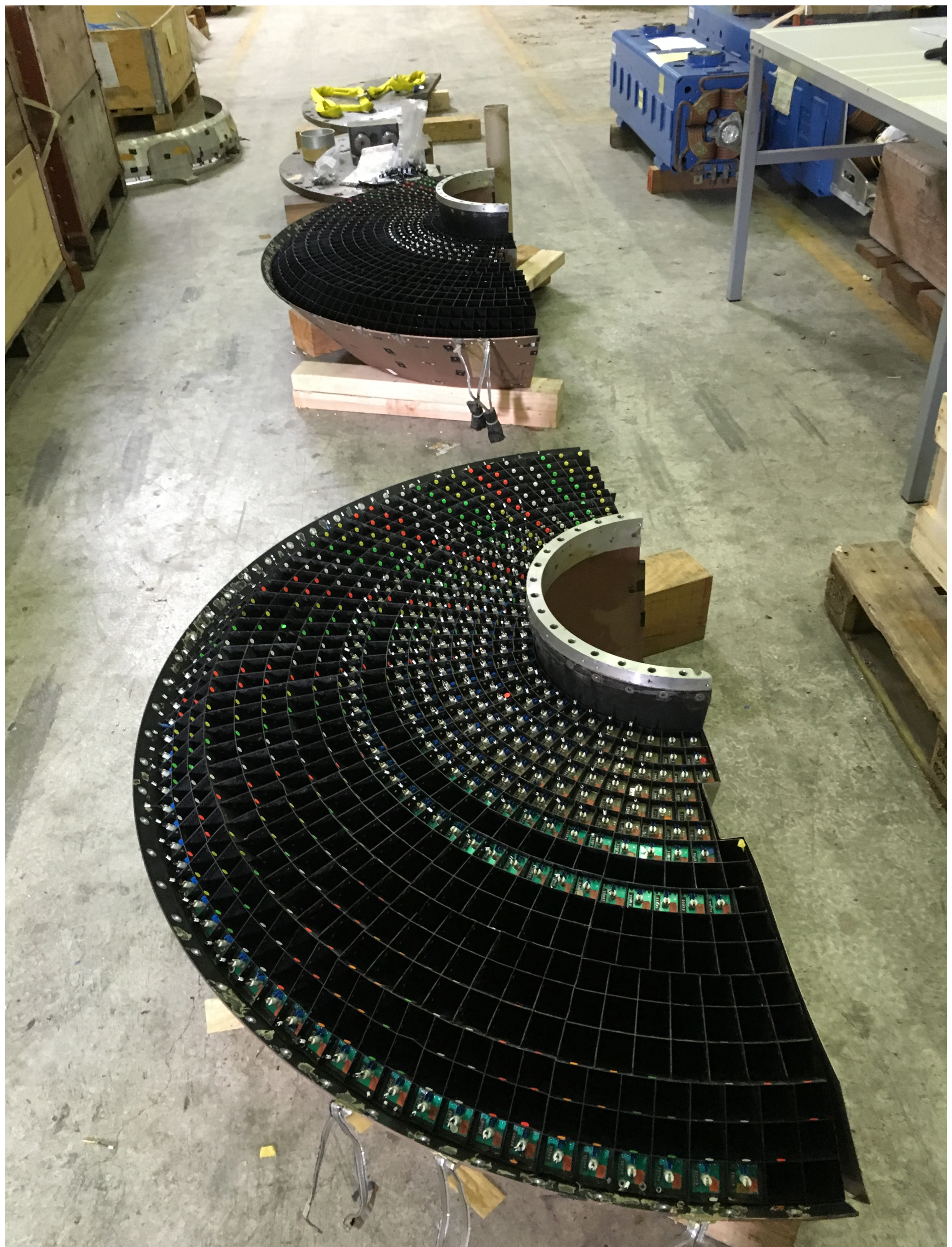
Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	$\lambda_{\max}$	$n^\natural$	Relative output†	Hygro-scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s 0.9^f	300^s 220^f	1.50	36^s 4.1^f	no	-1.9^s 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 6^f	420^s 310^f	1.95	3.6^s 1.1^f	slight	−1.4
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s 10^f	425^s 420^f	2.20	0.3^s 0.077^f	no	−2.5
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

2° best choice, for free from L3

best choice, but very expensive

Crystal procurement

L3 half-endcaps where crystals are…



…taken

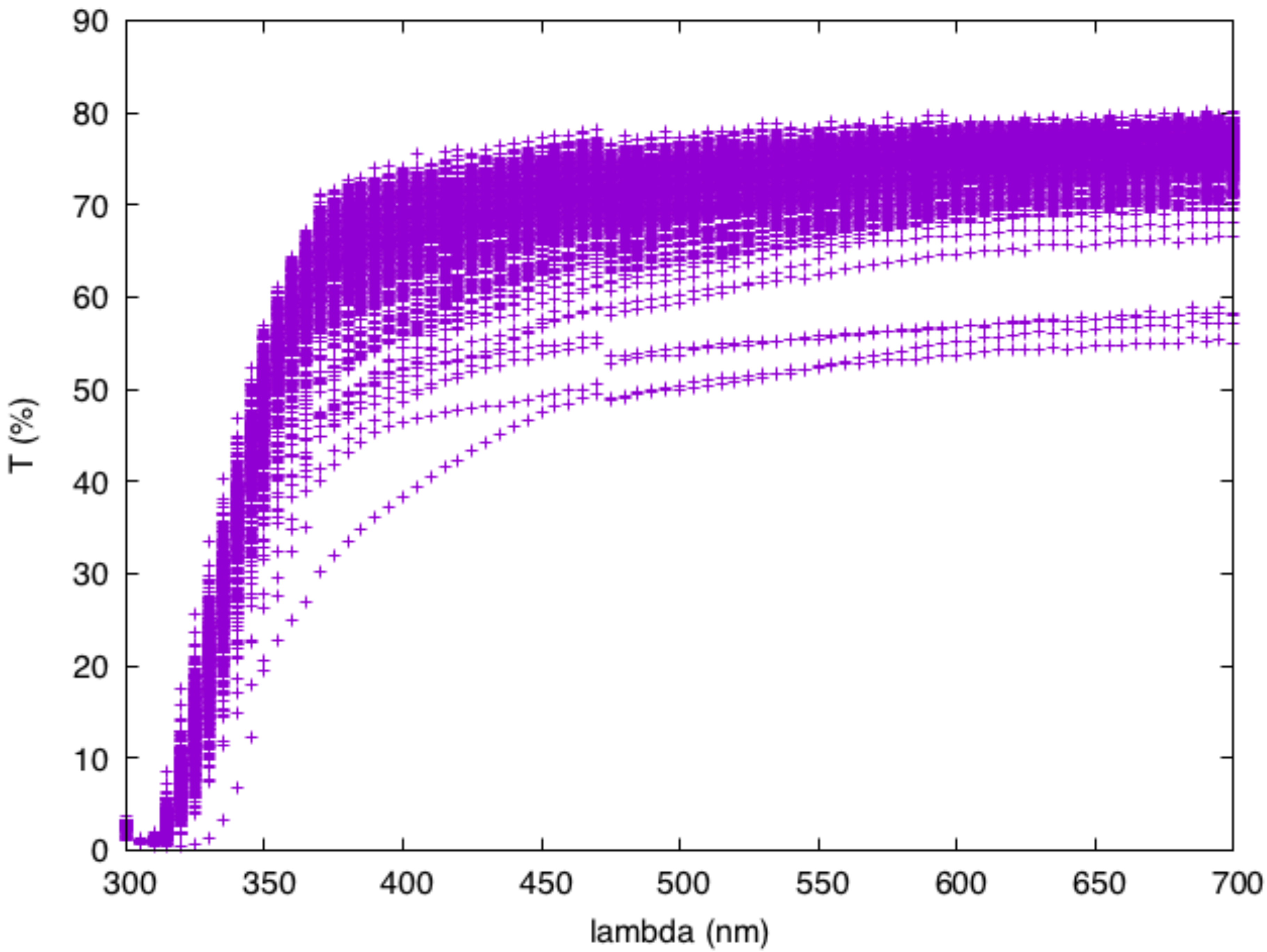
Crystal optical properties

After crystals selection the following steps are executed:

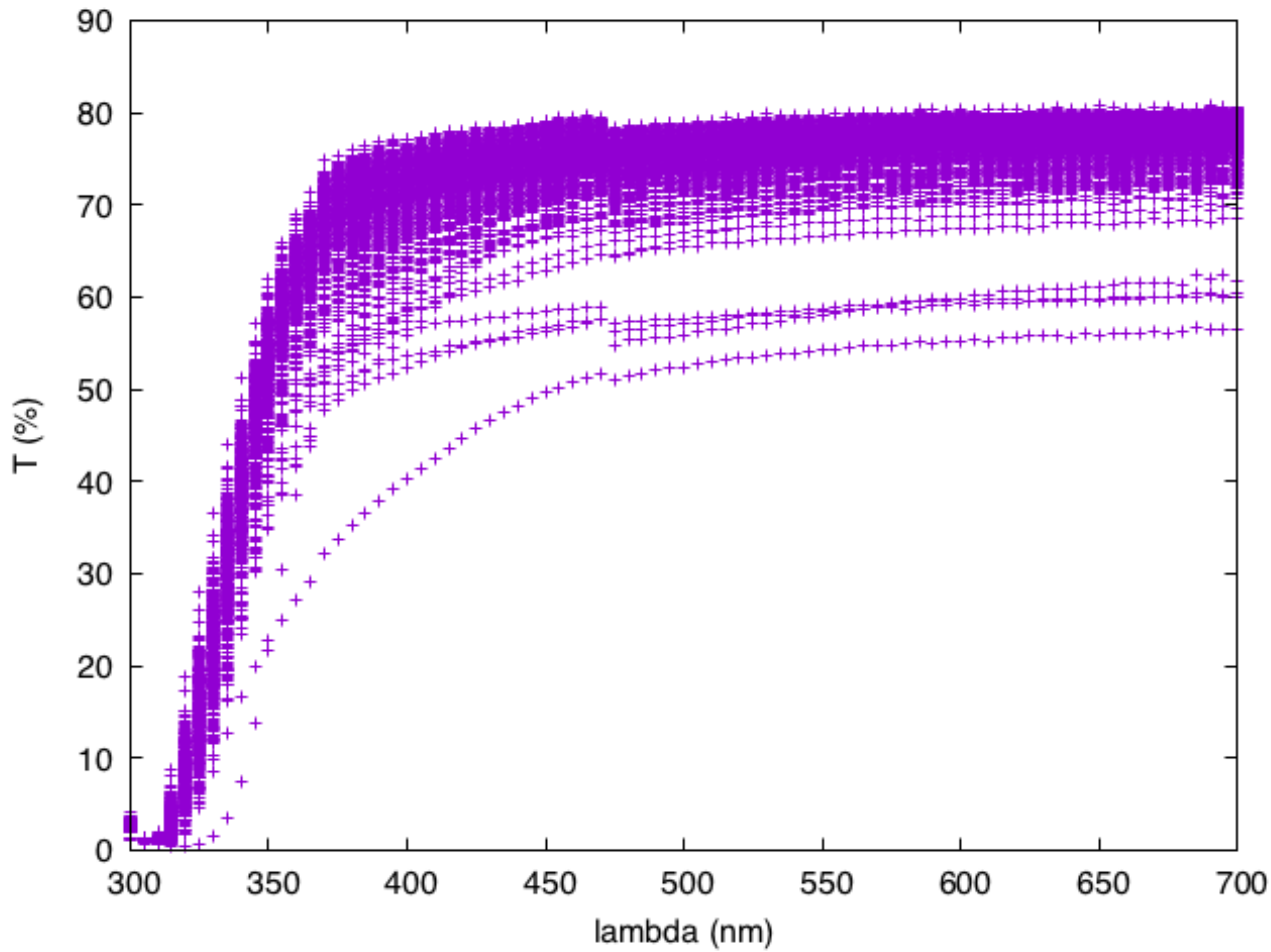
- Photosensor removal (mechanically after 48h in acetone)
- Paint removal (with water)
- Transmittance measurement
- Annealing
  - T_{amb} → 200 °C in 3 h
  - 200 °C for 6 h
  - 200 °C → T_{amb} “natural”
- Transmittance measurement

Everything is performed at CERN at LAB27

Transmittance before annealing

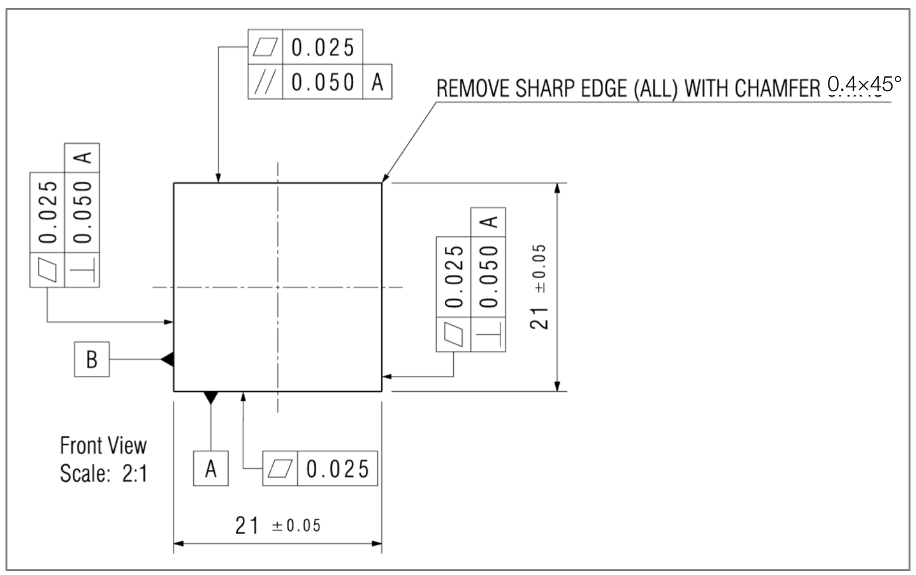


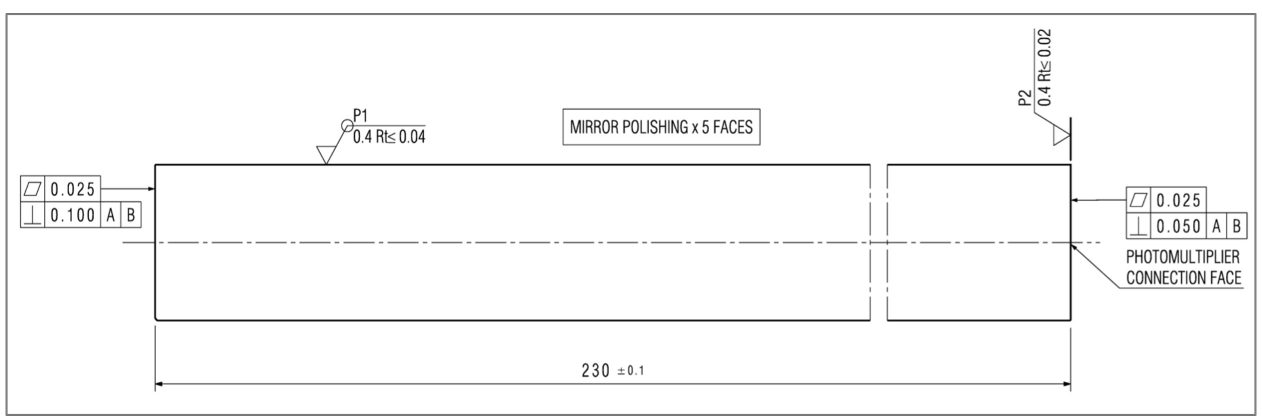
Transmittance after annealing



Crystals cut and polished at SILO (Italy)

They produced identical parallelepipeds starting from different truncated pyramid shapes (L3 endcaps geometry was pointing)

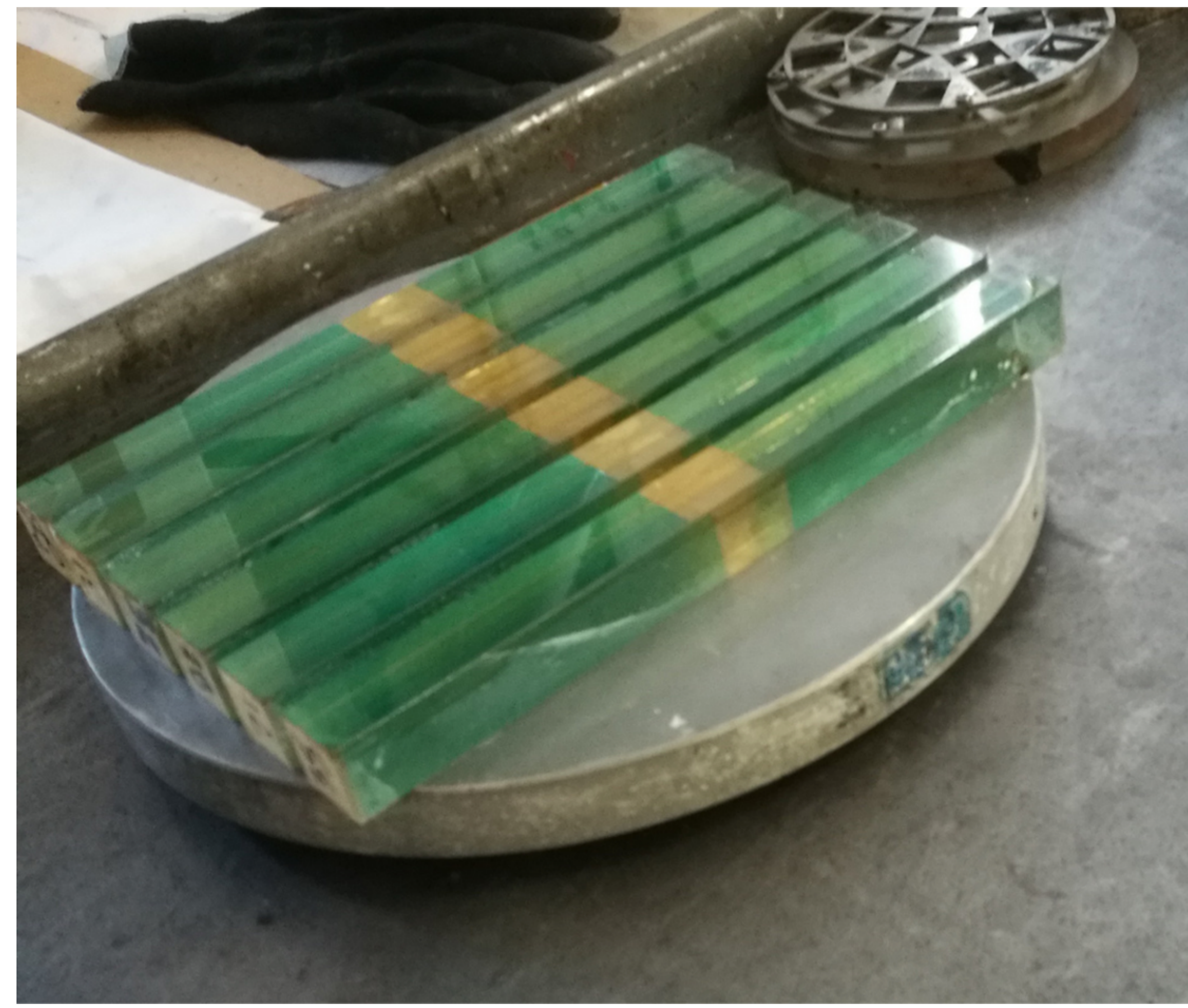




⏥ Planarity

// Parallelism

⊥ Perpendicularity

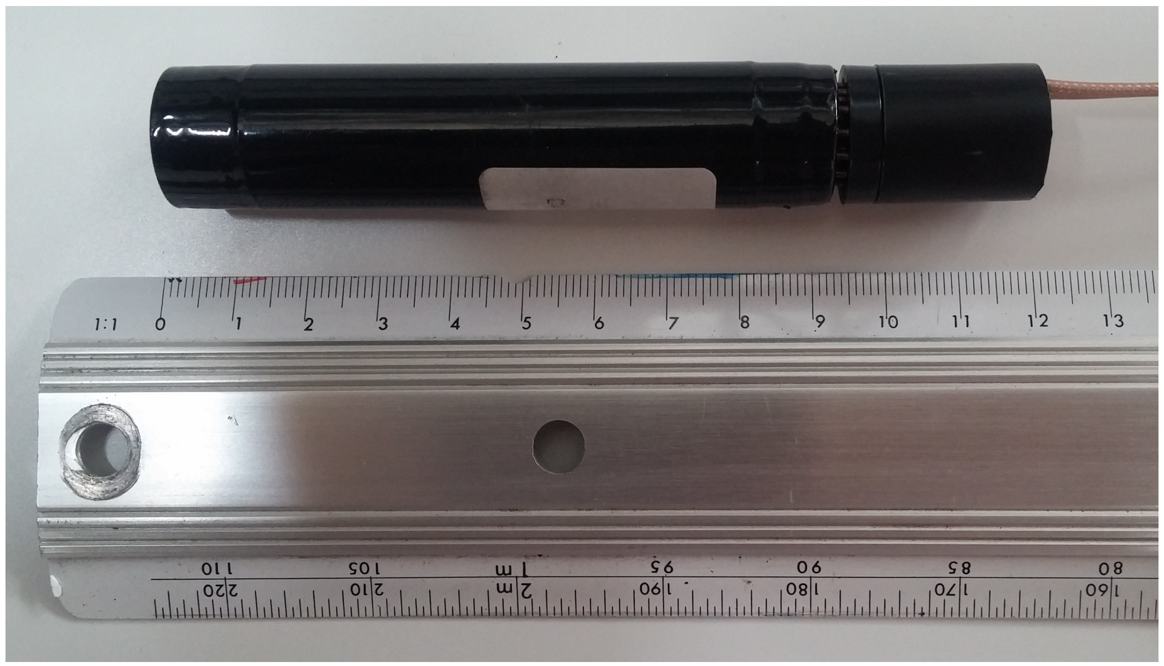


Mechanical tolerances (more stringent limits are set for the square shape)

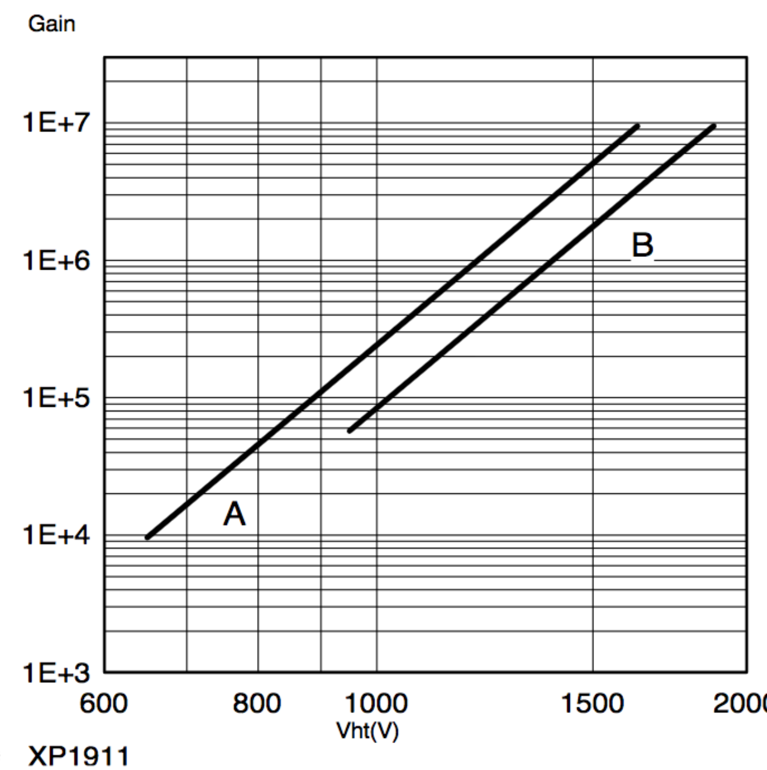
We performed a quality check at LNF on some crystals, to verify that dimensions are within specification, w/ positive results

HZC XP1911

We modified the mechanical design

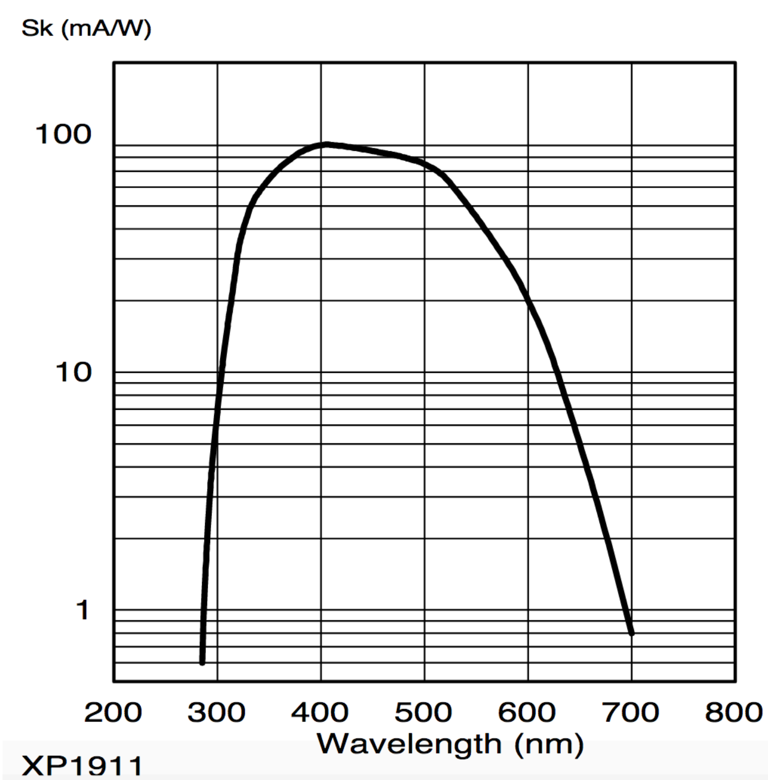


Typical gain curve

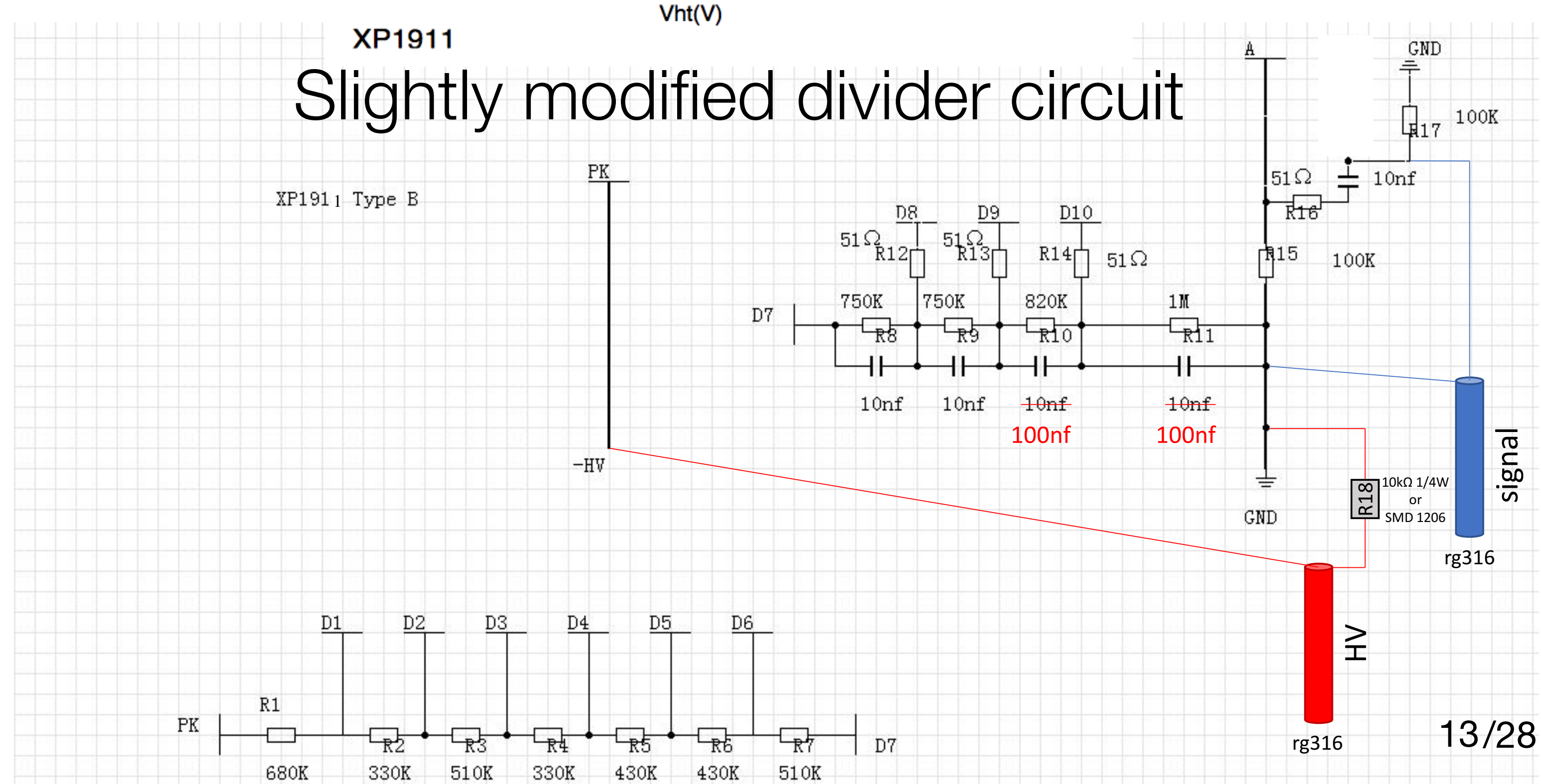


Type B: higher linearity

Typical spectral characteristics

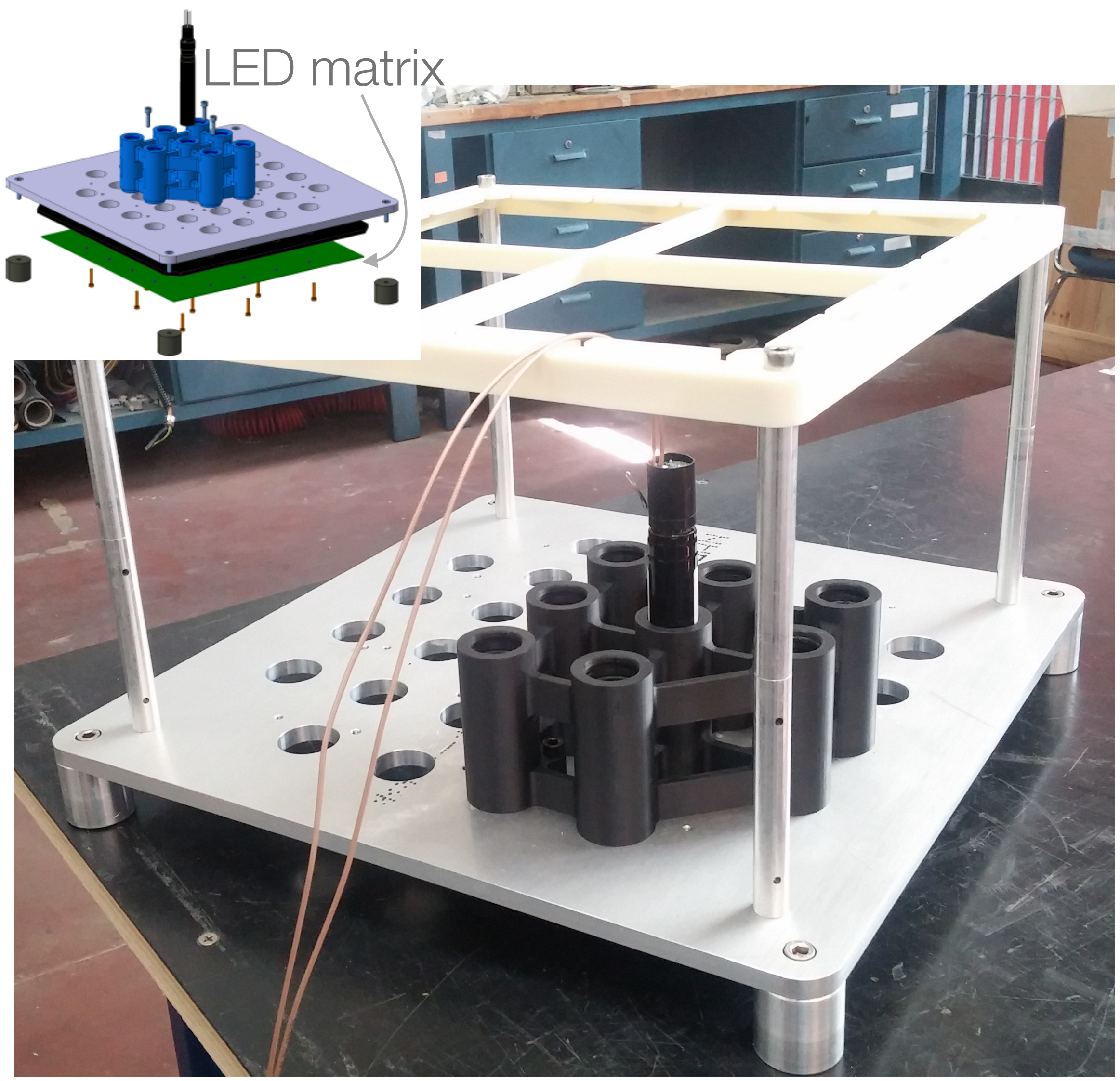


Slightly modified divider circuit

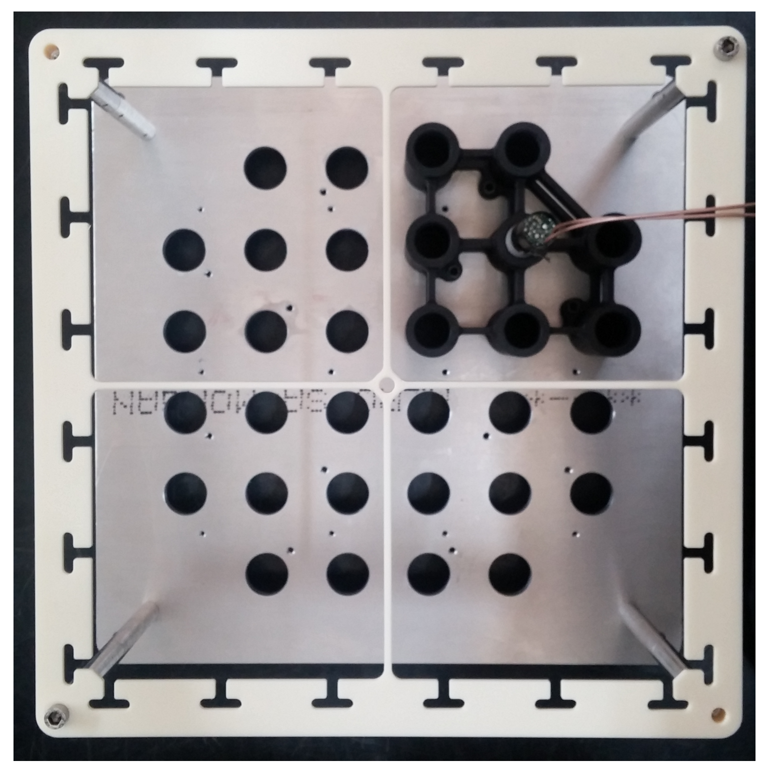


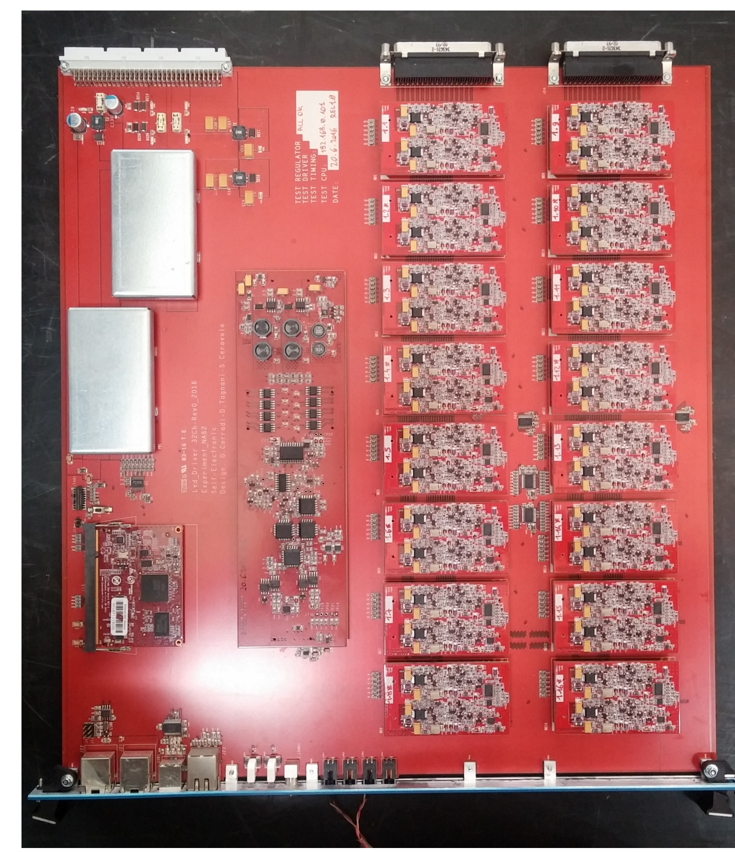
PMTs test

32 **PMTs** at a time were **tested with a LED matrix** (one per tube):
pulsing the LEDs we see if the PMT works and its response to the light.
If results are good, tubes are sent to SILO for gluing.

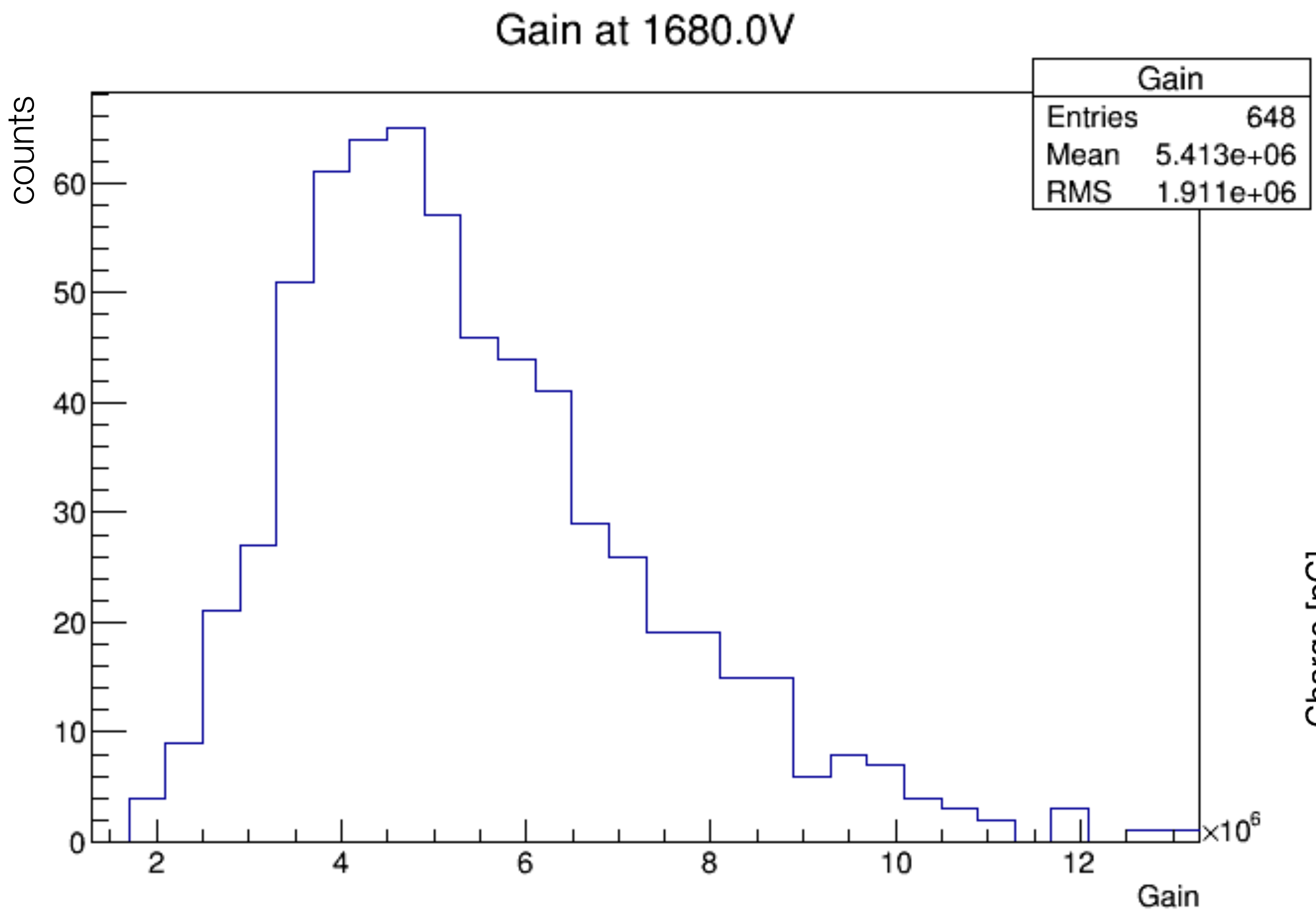


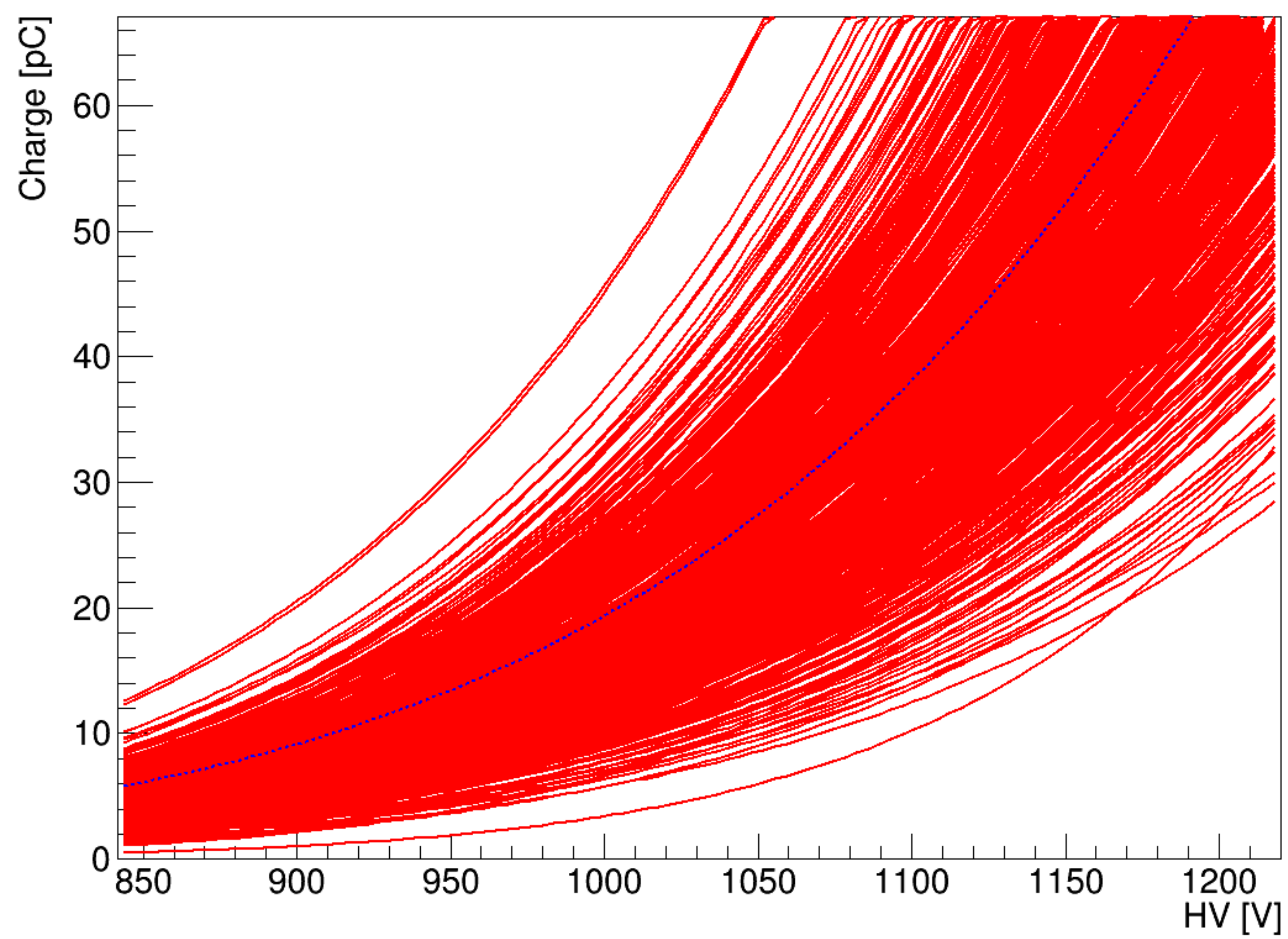
Mechanics for PMTs test

Mechanics top view



LED driver board

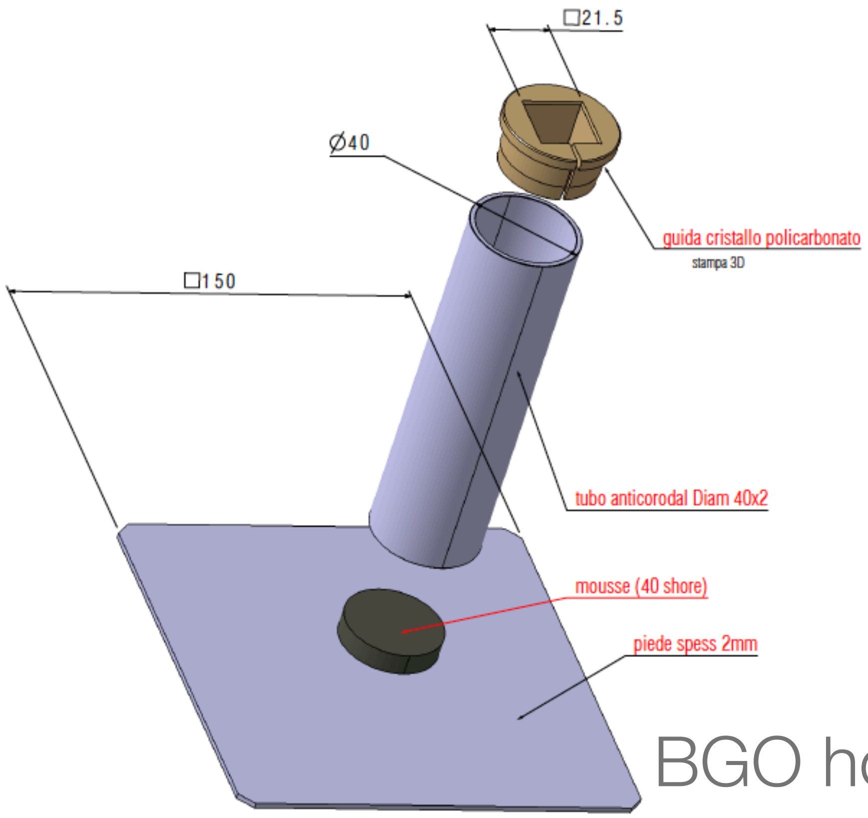
Global PMT results



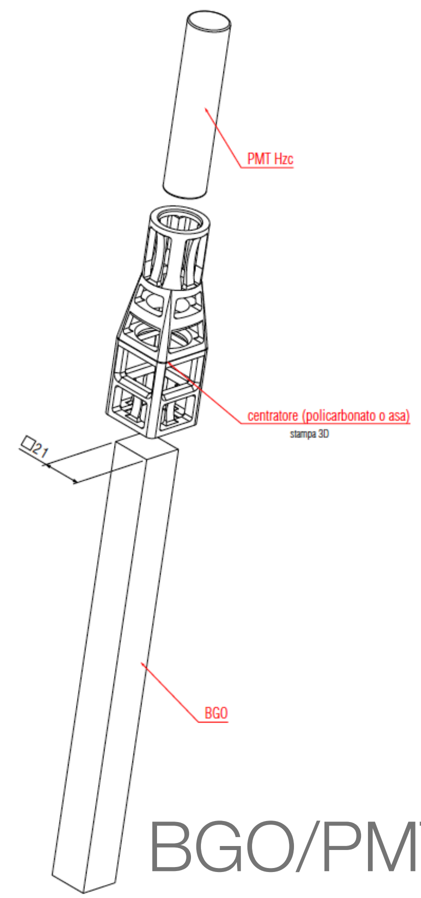


Gluing and painting at SILO

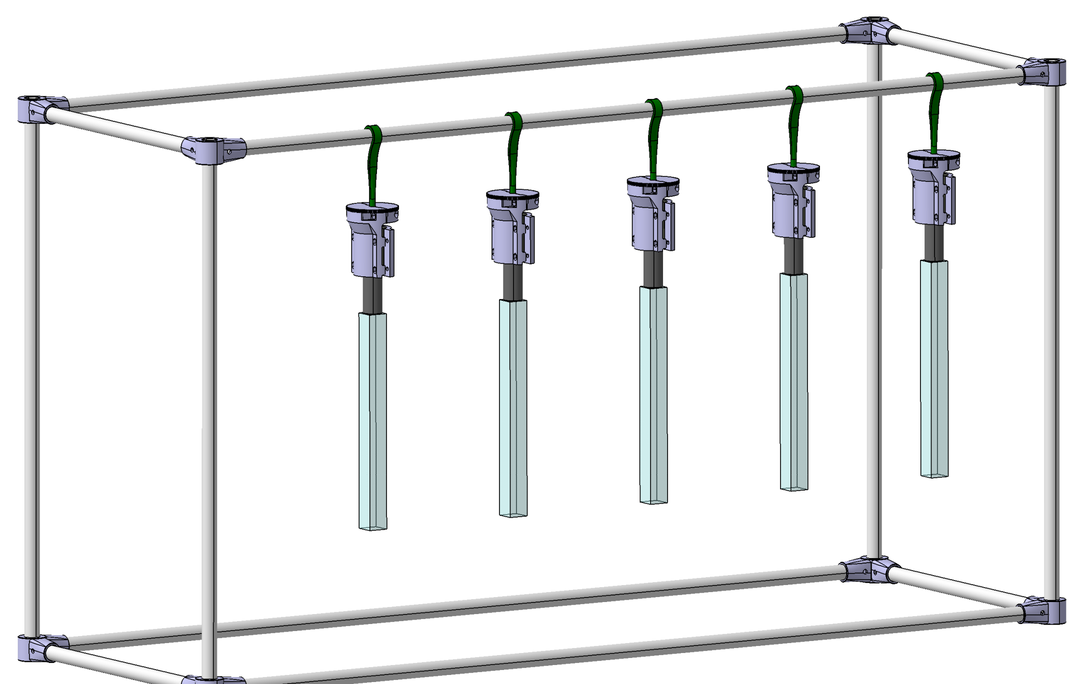
- Glue: EJ-500



BGO holder



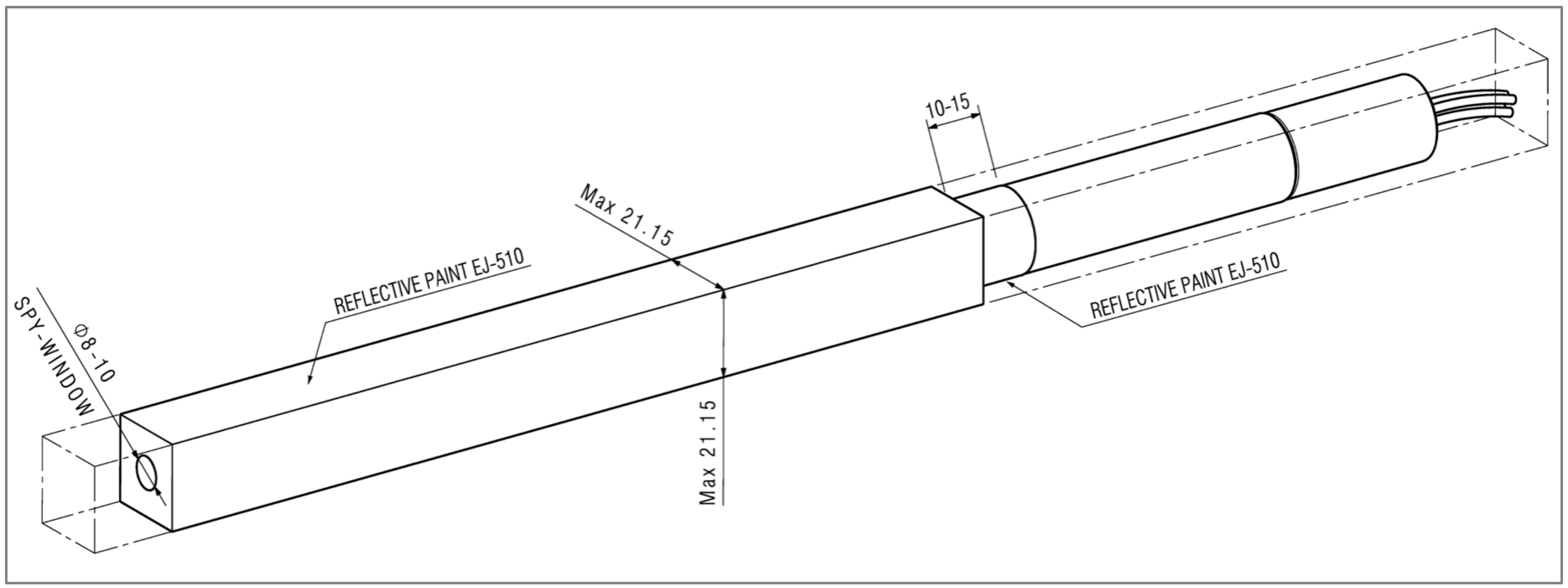
BGO/PMT centering



- Paint: EJ-510
- 3 layers of white paint (≈100μm)

Scintillating Units (SU)

Maximum footprint after painting

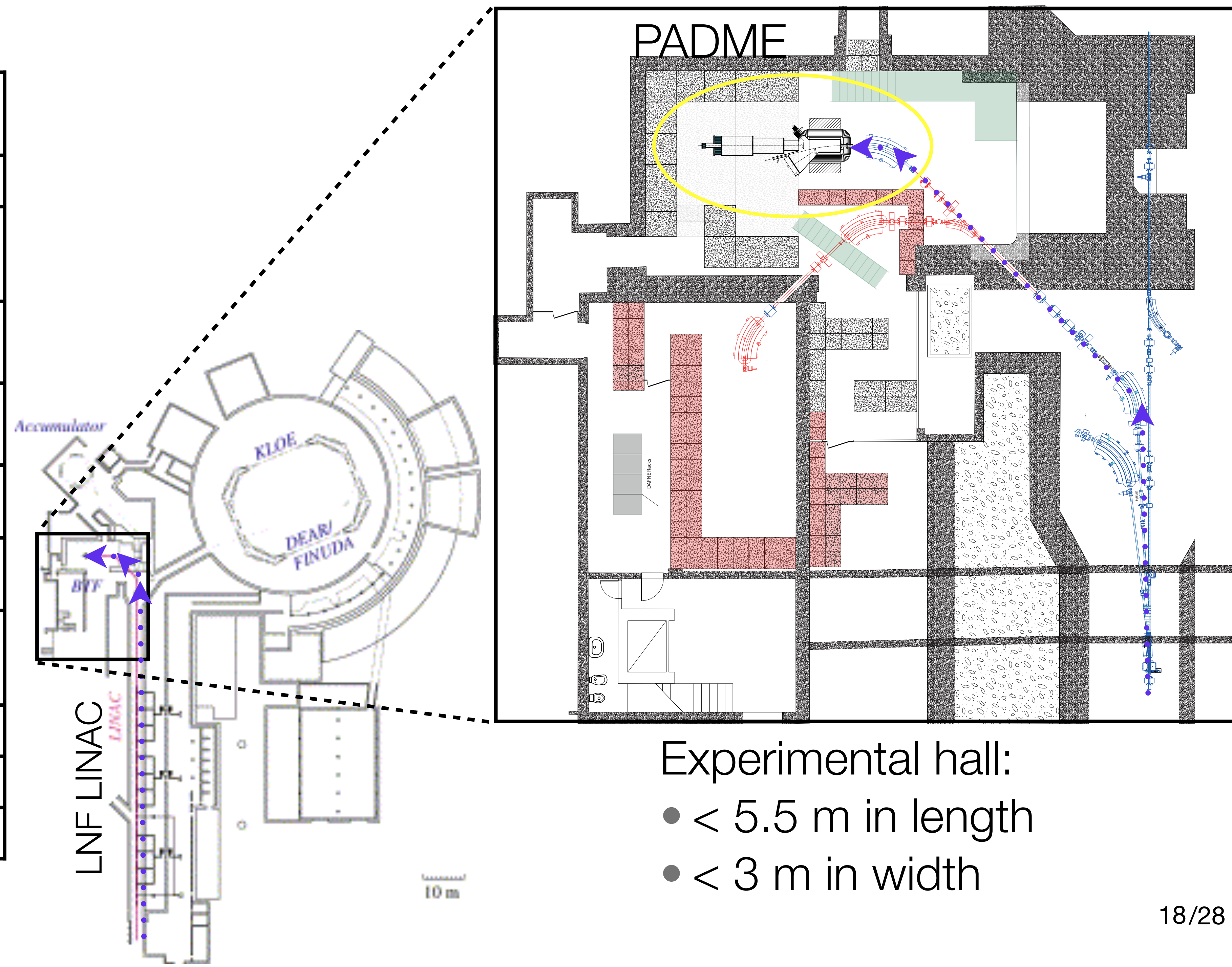


Currently we have 580 2.1×2.1×23cm^3 painted and glued units at LNF

The LNF Beam Test Facility (BTF)

PADME experimental hall be is the Beam Test Facility of the Laboratori Nazionali di Frascati (~Rome, IT), the same place where the test beams have been performed.

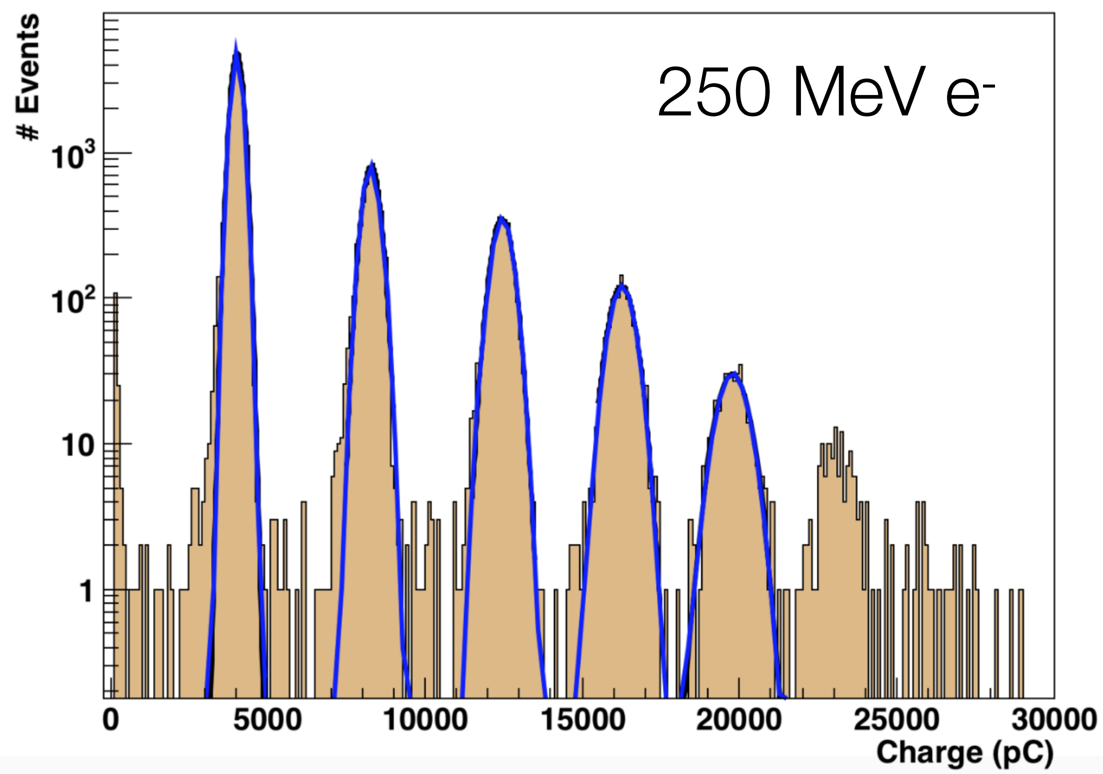
	Dedicated mode	
	W/ target	W/o target
Particle species	e^+/e^- selectable by user	
Energy [MeV]	25-700 (e^+) 25-700 (e^-)	250-730 (e^+) 250-530 (e^-)
Energy spread	1%	
Rep. rate [Hz]	1-49 selectable by user	
Pulse duration [ns]	1.5-40 selectable by user	
Intensity [particles/bunch]	$1\text{-}10^5$ depending on energy	$10^3\text{-}3 \cdot 10^{10}$
Max average flux	$3.125 \cdot 10^{10}$ particles/s	
Spot size [mm]	0.5-25 (y) × 0.6-55 (x)	
Divergence [mrad]	1-1.5	



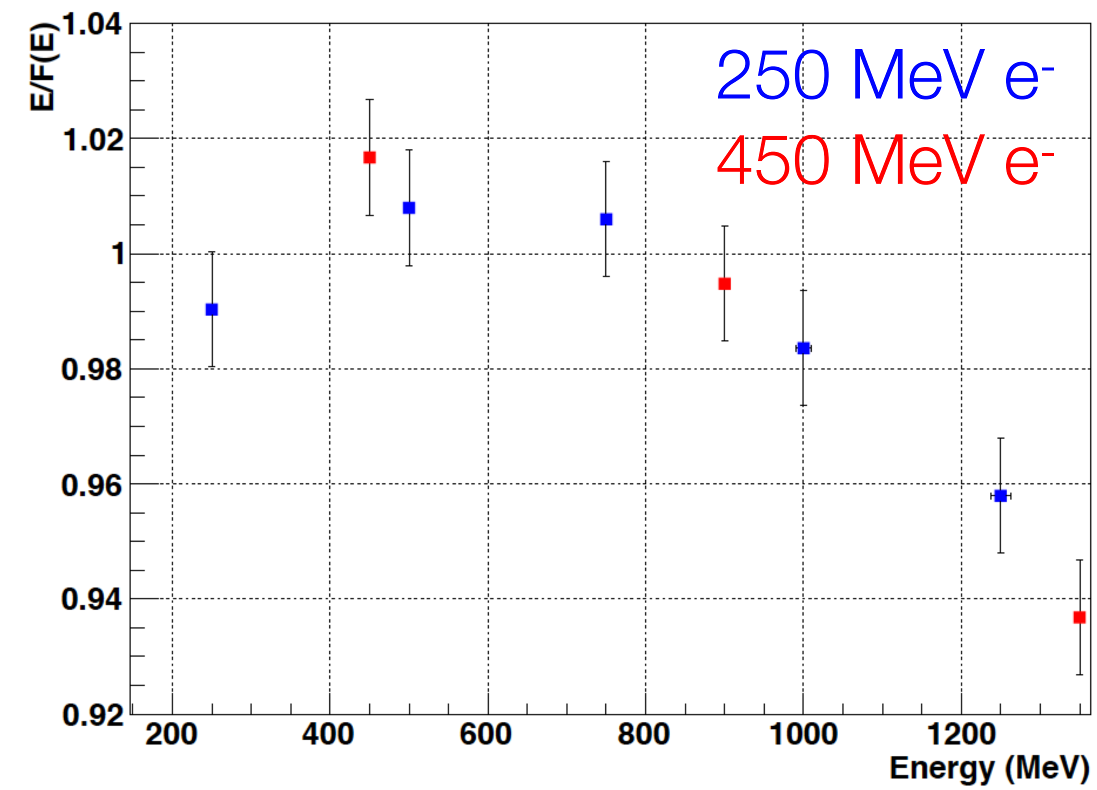
Experimental hall:
- < 5.5 m in length
- < 3 m in width

Calorimeter prototype performance @ BTF

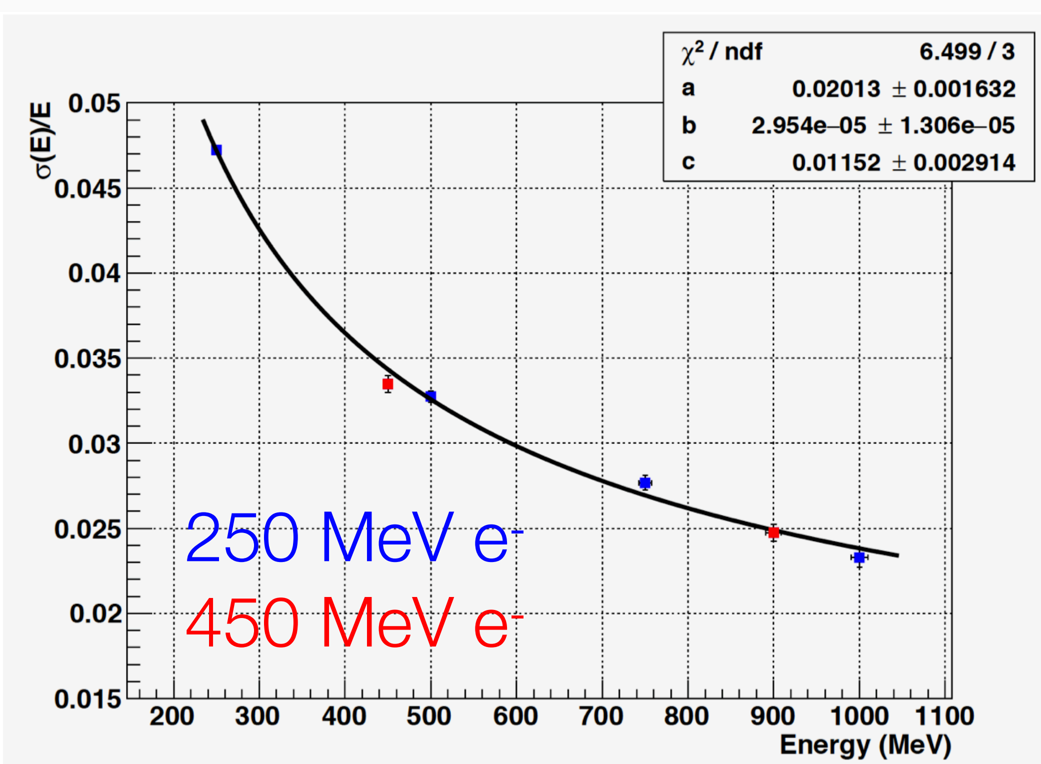
Charge spectrum



Linearity residuals



Energy resolution



Linearity is within 2% up to 1GeV (gain 5×10^5)

Energy resolution is within the expectation, with reference to the L3 experience

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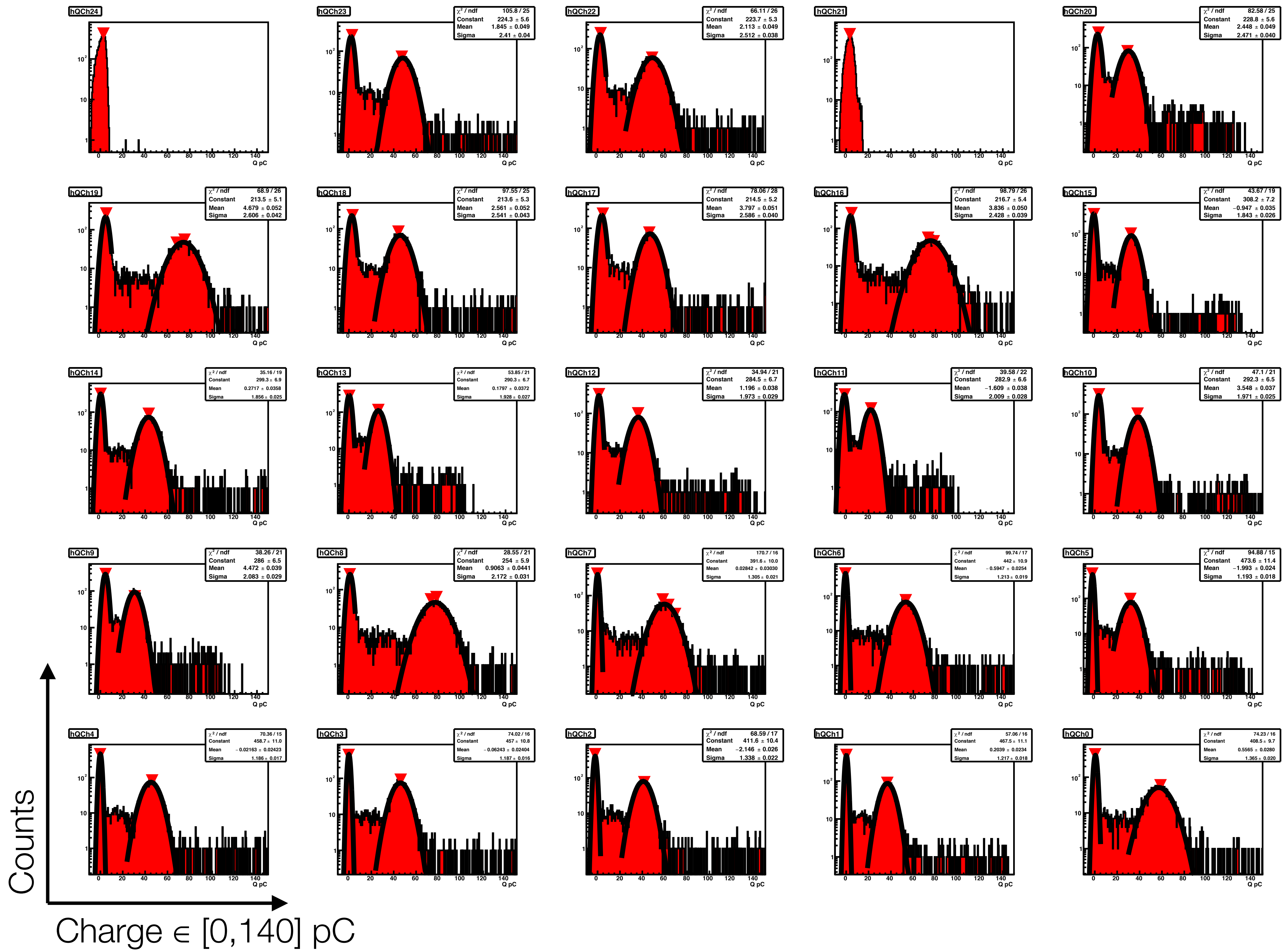
^{22}Na setup

- A 3×3×20 mm^3 LYSO crystal read by a SiPM is used as trigger
- ^{22}Na source faced to each crystal, to exploit its γ back-to-back emission: one in the trigger, one in the SU
- 10 HV tested on PMTs: from 1100V to 1550V in steps of 50V

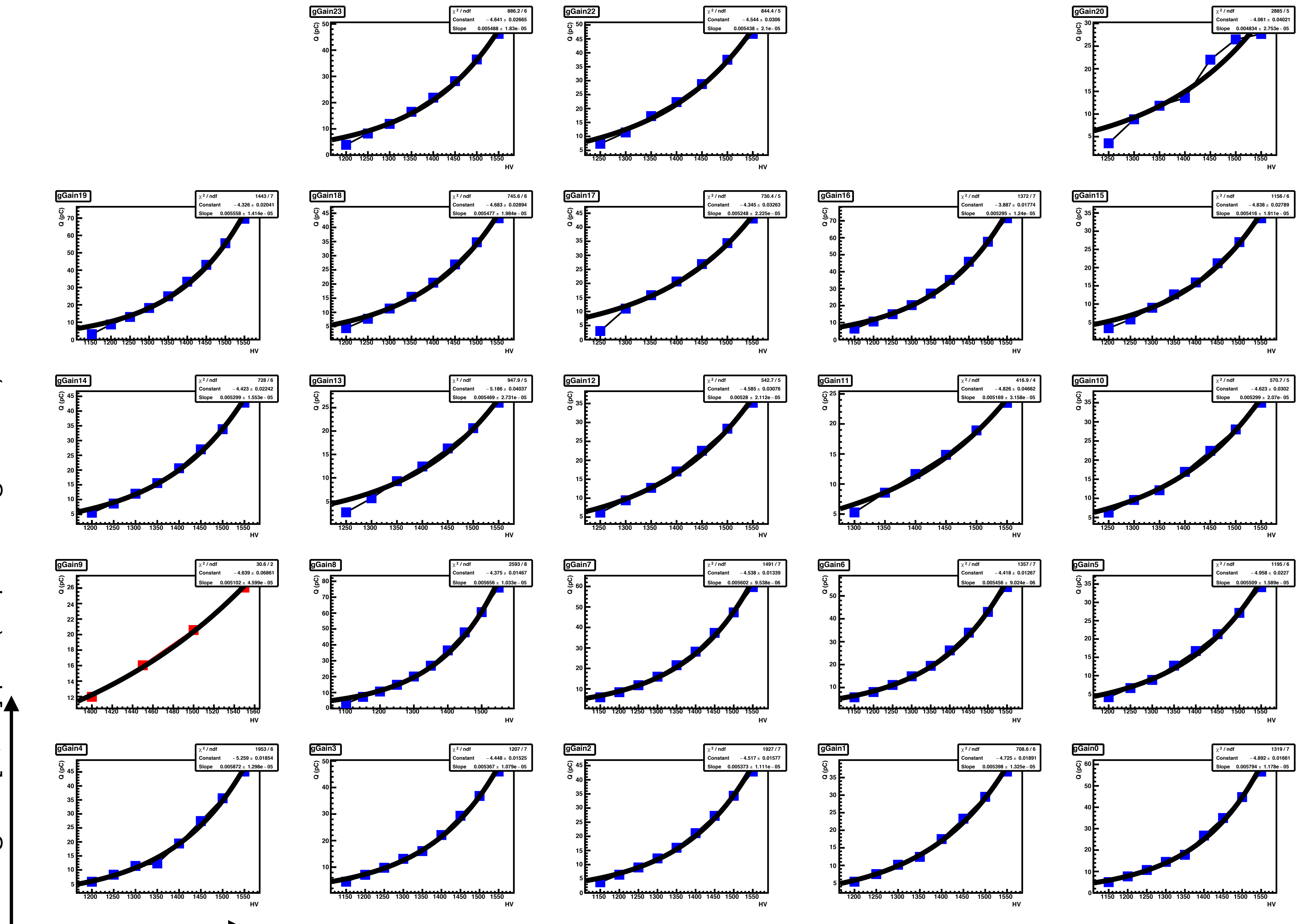
Reconstructed spectra w/ ^{22}Na source

Charge is given by an integration window of 1 μs (≃150 ns pre-pulse), sampled at 1GS/s



Example of ^{22}Na spectra at 1550 V

Gain curves w/ ^{22}Na 511 keV peak



Charge ∈ [0,75] pC (depending on ch.)

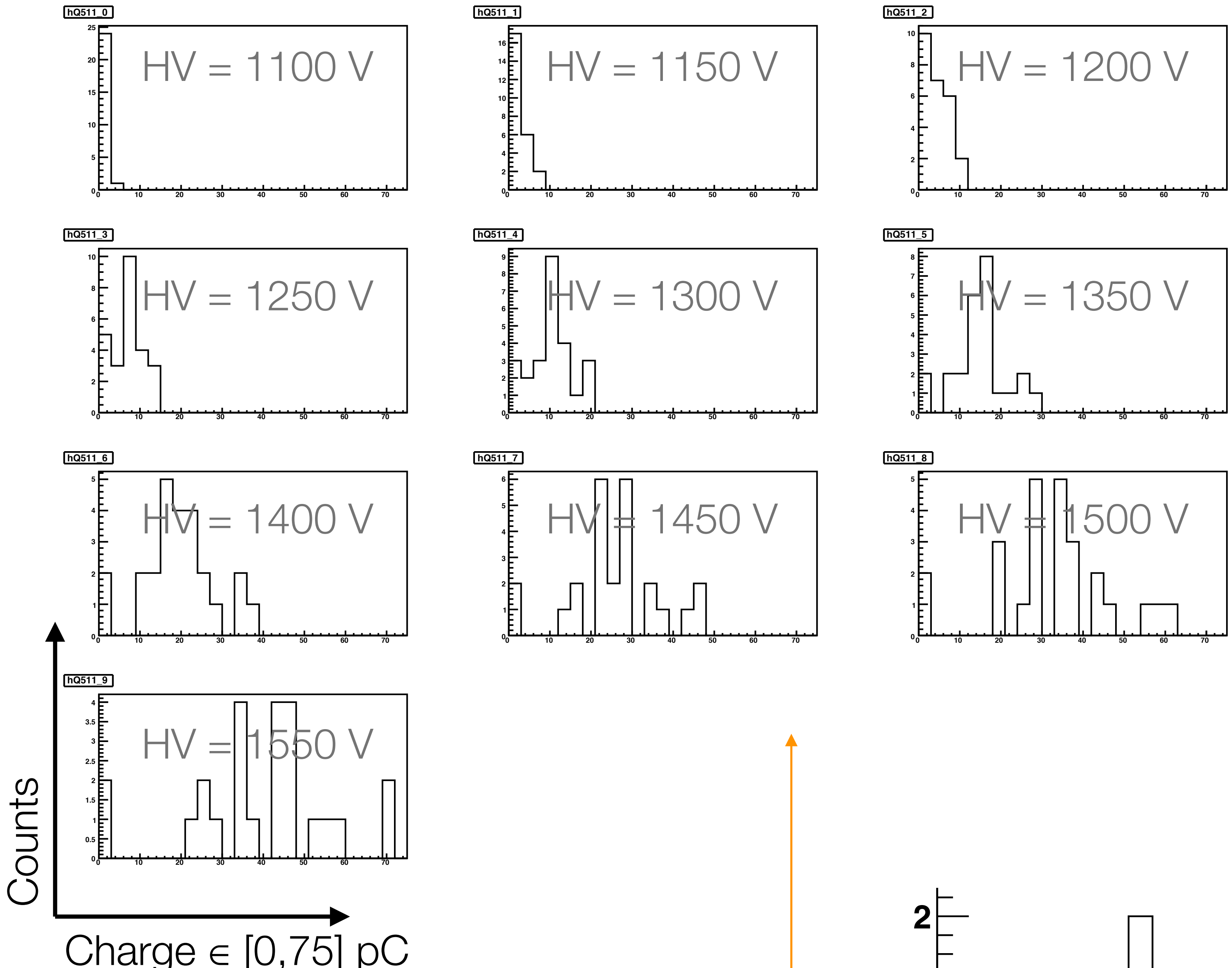
HV ∈ [1100,1550] V depending on ch.

Fitting function: $Q = \text{const} \cdot (HV)^{\text{slope}}$

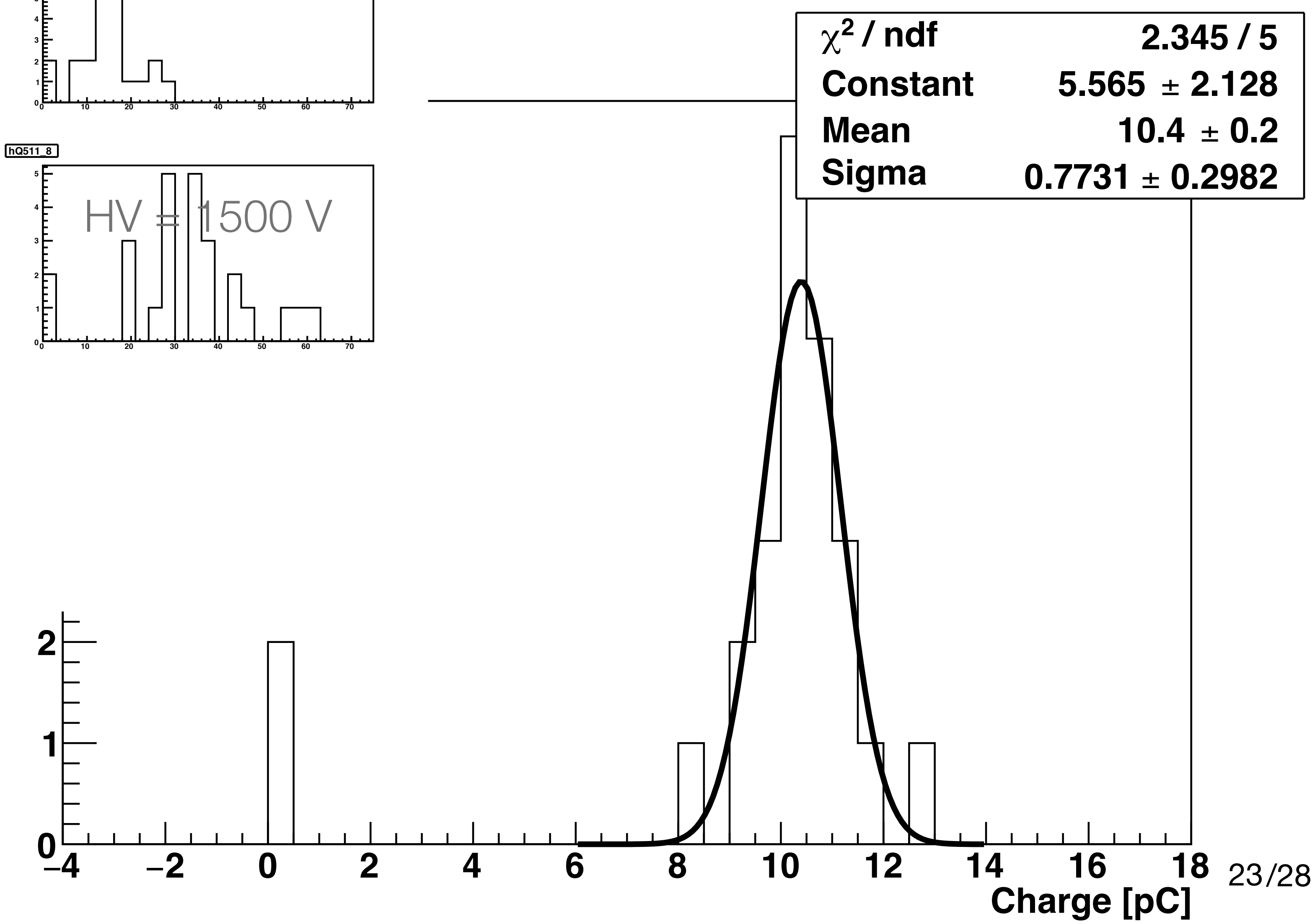
fit parameters

Gain equalization

511 keV peak mean distributions



Equalization at 20 pC/MeV

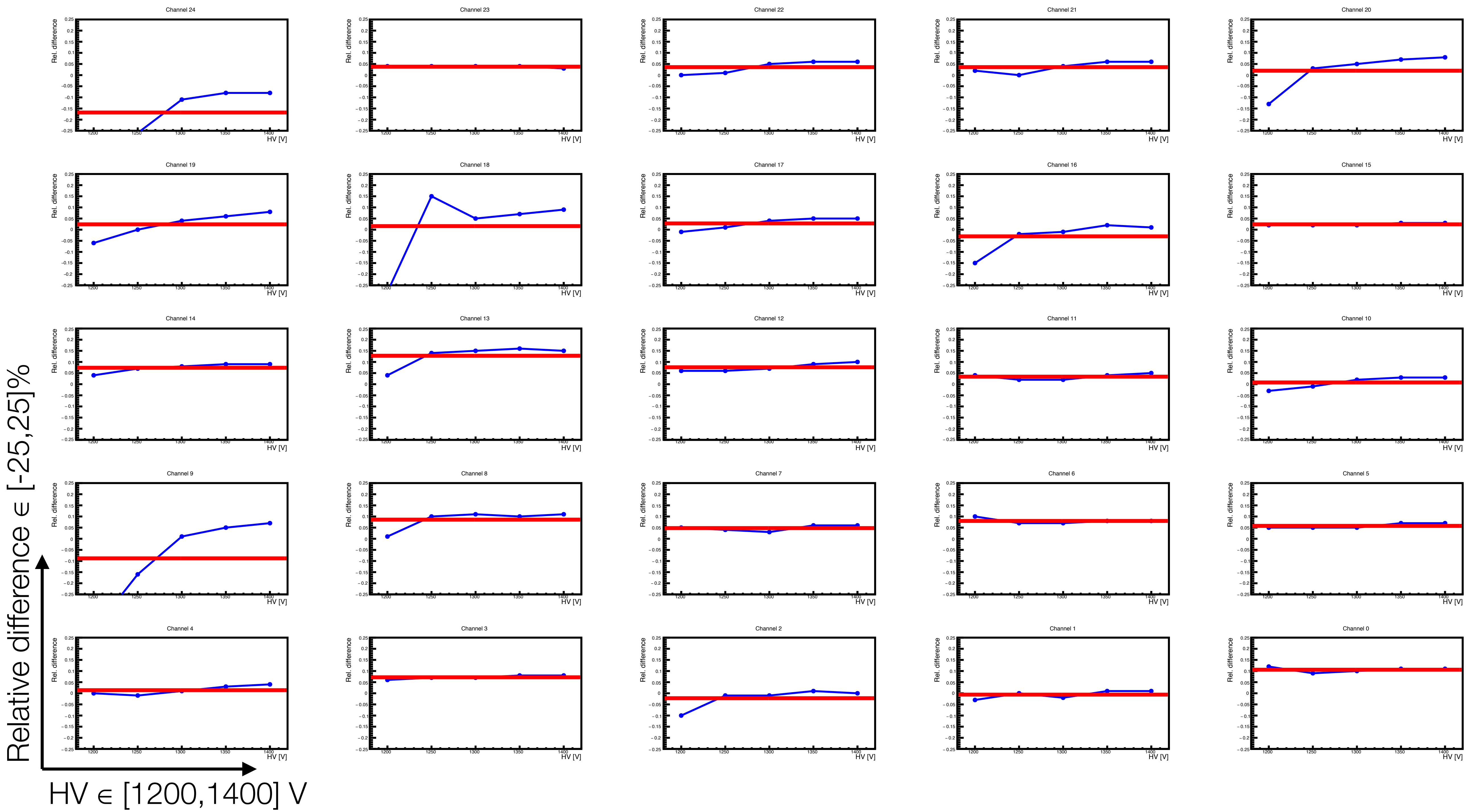


Peaks distribution for fixed HVs

Reproducibility

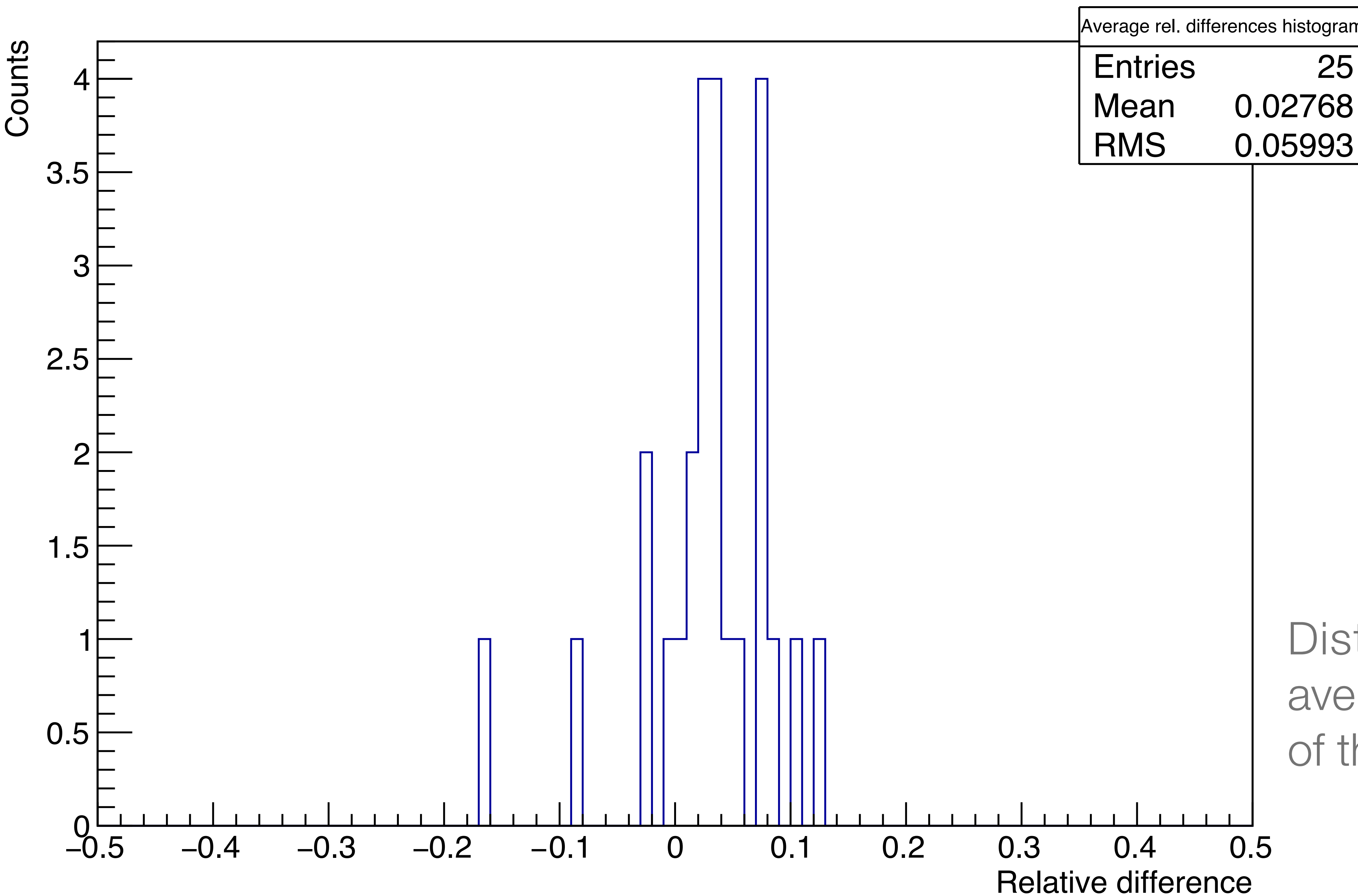
For each SU of a group of 25 we performed 2 times the same HV scan

Relative difference of the 511 keV peak charge as a function of the HV



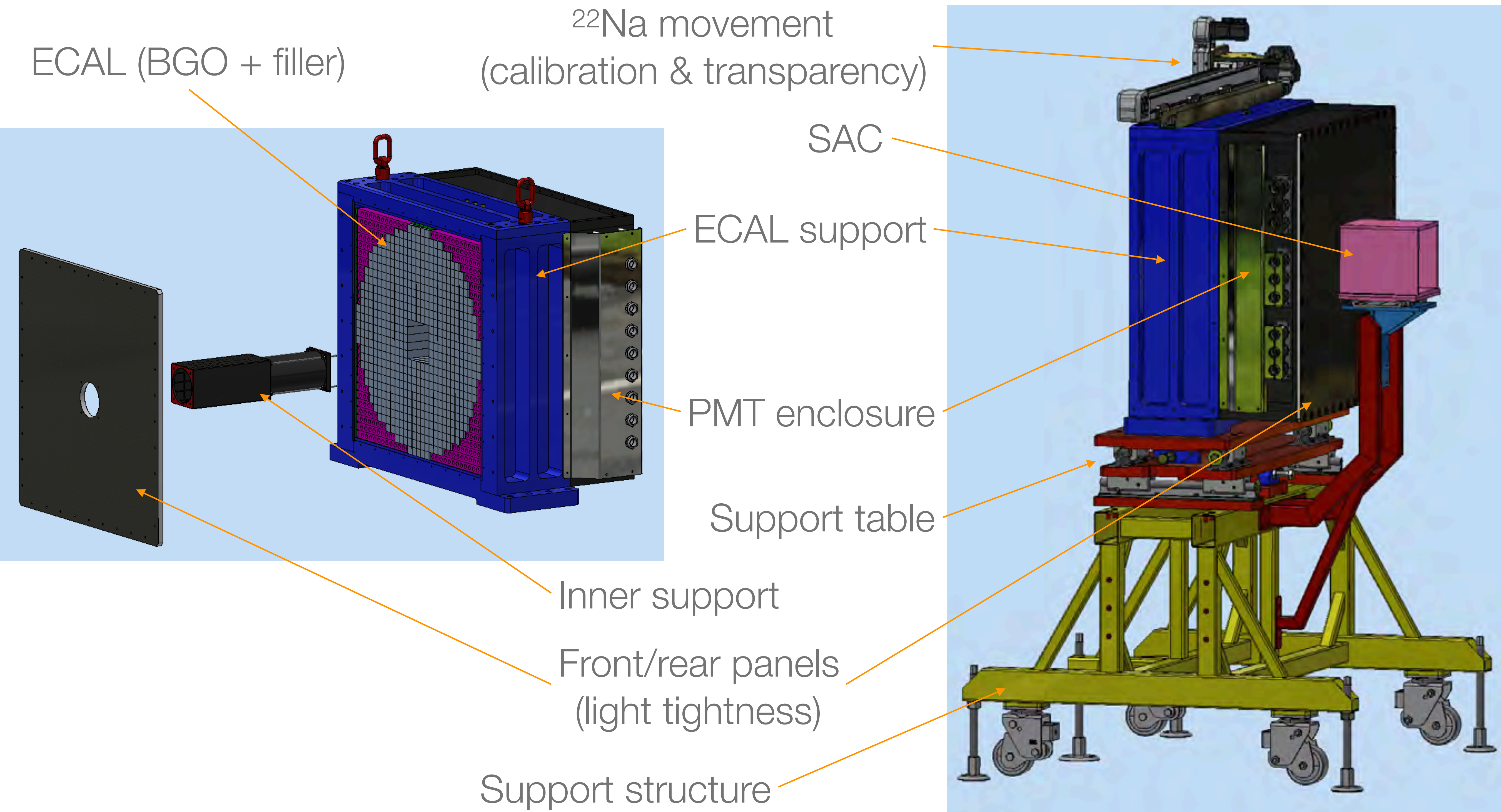
Charge relative differences distribution

- Larger relative variations are due to small absolute values
- Measurements have been done in different conditions (daylight, black cover positioning,…) that may have produced systematic variations



Distribution of the averages (red lines) of the previous slide

Calorimeter mechanical design

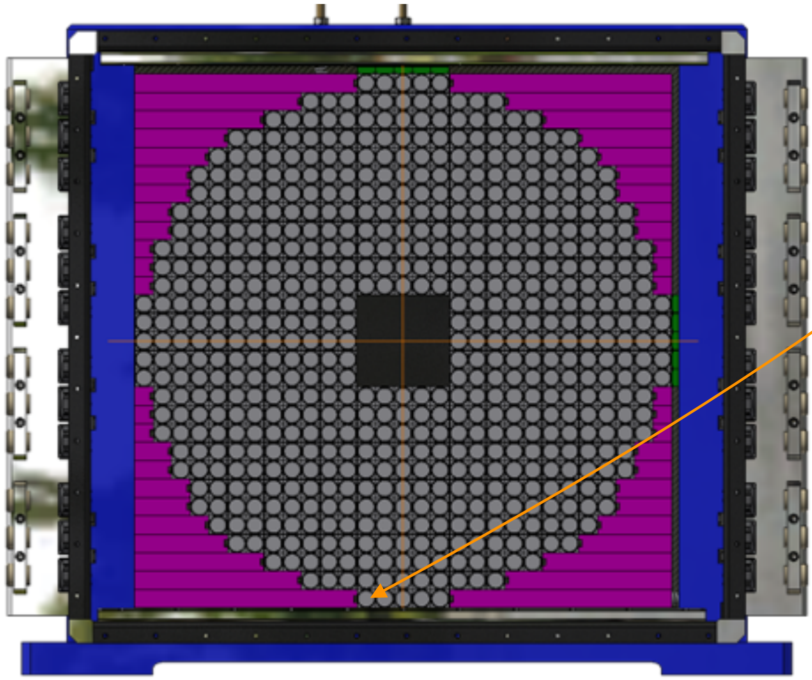


ECAL assembly procedure

Procedure:

for each layer

- first crystal bottom left
- complete first layer
- block layer with locking screws
- equalize for different SU heights
- go to next layer



front view

Ready for the assembly!

Conclusions

- Dark Photon is predicted by many physics models, that could explain different experimental results: Dark Matter, $(g-2)_\mu$, ^{8}Be anomaly
- PADME is an experiment hosted at the Laboratori Nazionali di Frascati searching for invisible Dark Photon decays
- The electromagnetic calorimeter is one of the most important components of the detector and is currently under construction
- Calorimeter readout: 616 HZC XP1911 (PMTs) w/ ≃5% gain uniformity at nominal HV
- Scintillating units
  - very low threshold ($\lesssim$ 0.5 MeV)
  - good reproducibility w/ variations < 3%
- ECAL prototype
  - energy resolution is compatible with the L3 results: $2\%/\sqrt{E(\mathrm{GeV})}$
  - good charge reconstruction linearity w/ variations < 2% up to 1 GeV

Backup

Dark Photon searches

Publishing
Approved
Proposal

BGO emission spectrum

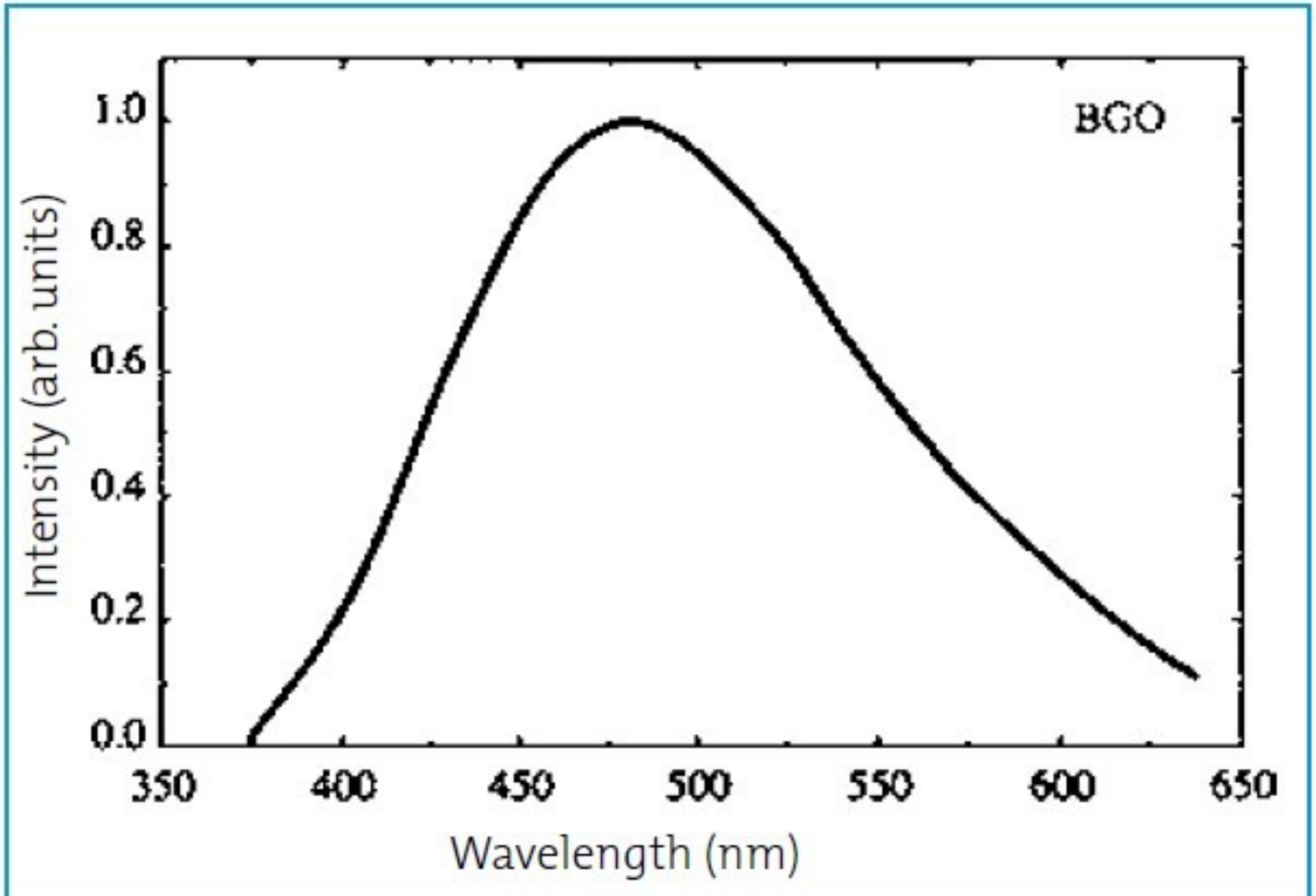
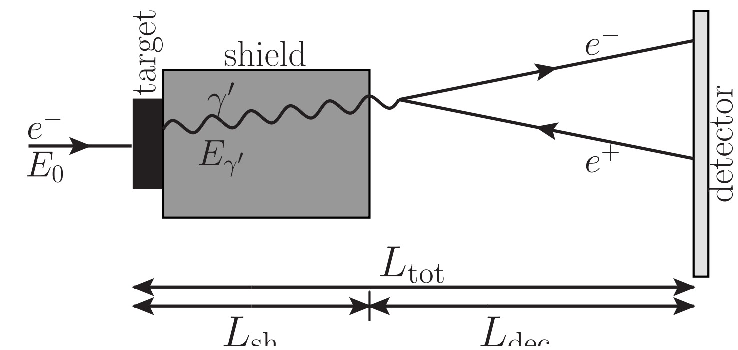


Figure 1. Scintillation emission spectrum of BGO

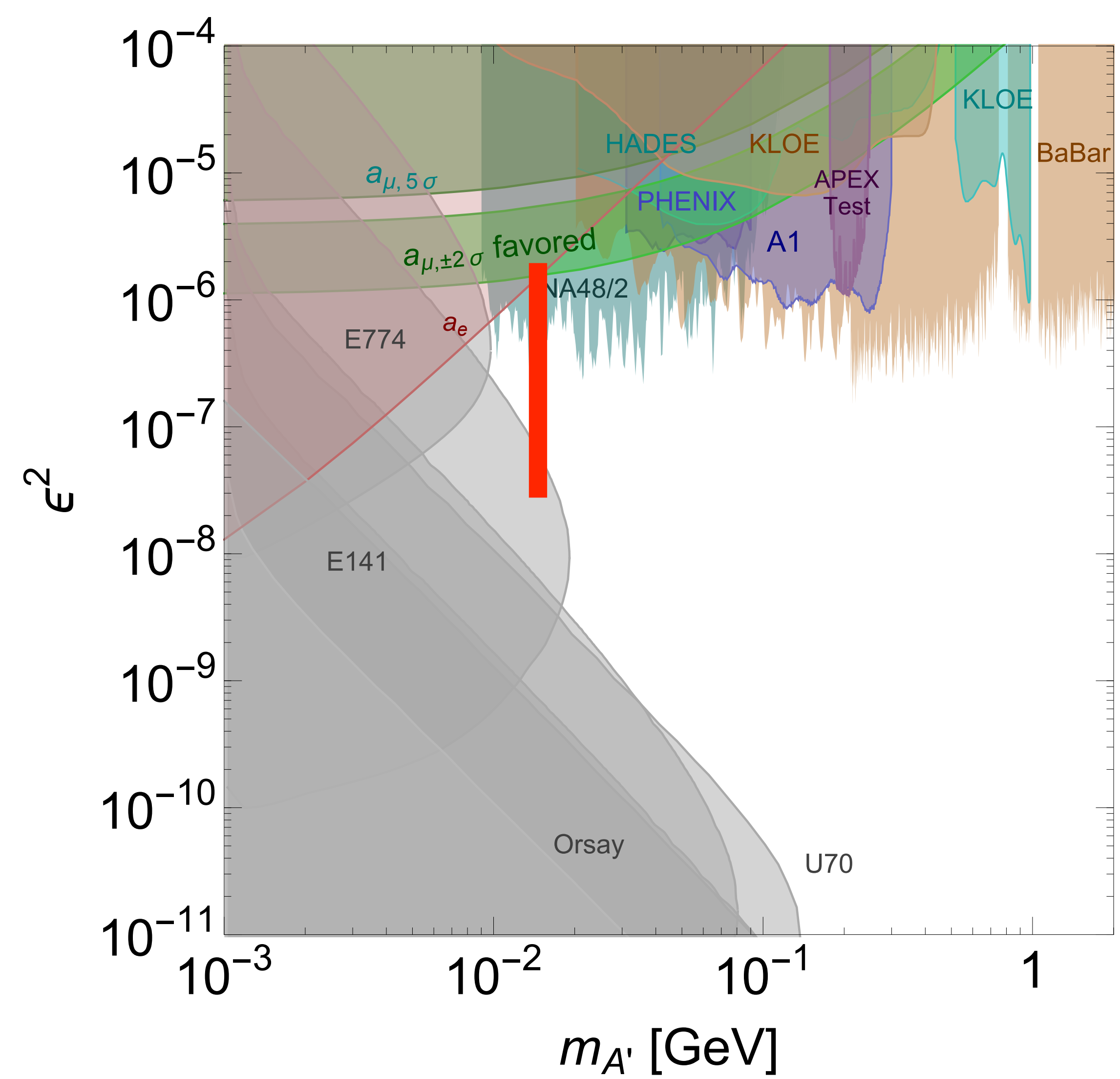
Visible search status

Techniques:

- beam dump (bremsstrahlung)
  - A' decay products detection after high z target (A' production) + shield (SM absorption)



- fixed target (bremsstrahlung, annihilation)
  - bump hunt in invariant mass spectrum, displaced vertices
- meson decay
  - only if A' couples w/ quarks
  - old experiments reanalysis

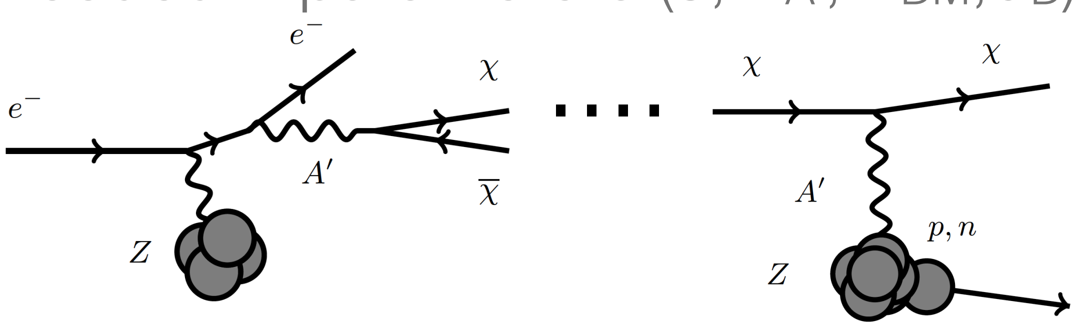


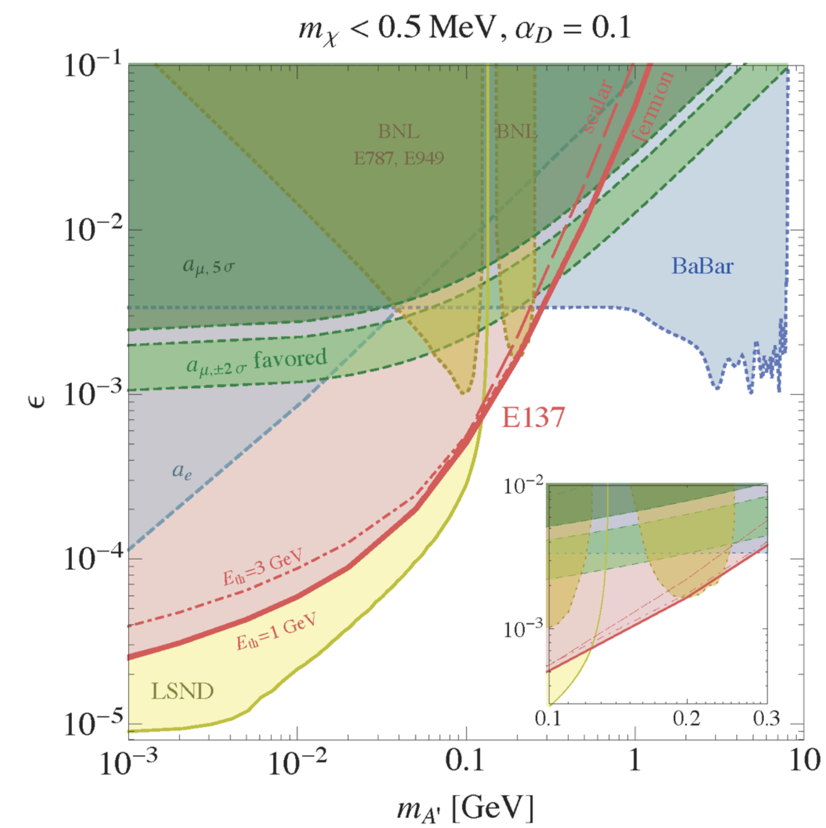
(g-2)$_\mu$ excluded in the simplest model, but still a lot of interest. In particular the ^{8}Be anomaly.

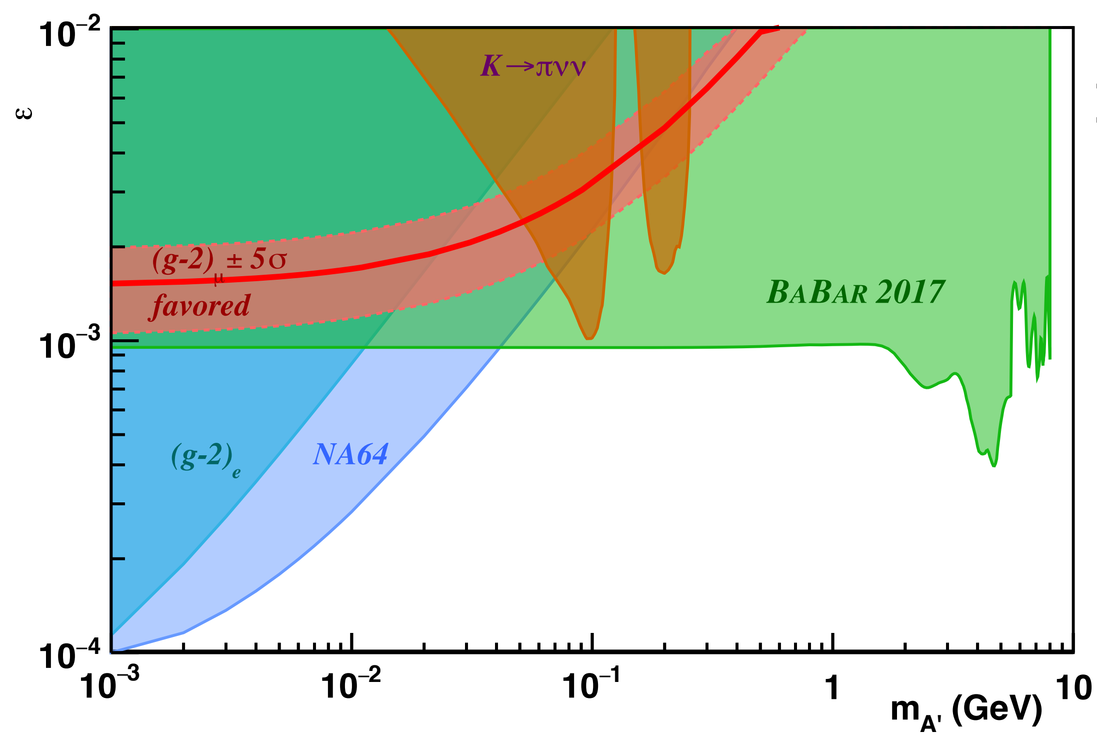
Invisible search status

Techniques:

- DM scattering (bremsstrahlung)
  - detect the produced DM by scattering
  - needed 4 parameters (ε,$m_{A'}$,m_{DM},α_D)







Not directly comparable

- missing energy/momentum search (bremsstrahlung)
  - not kinematically constrained process
  - observed energy/momentum smaller than expected
- missing mass search (annihilation)
  - kinematically constrained process
  - no assumption on A' decay chain

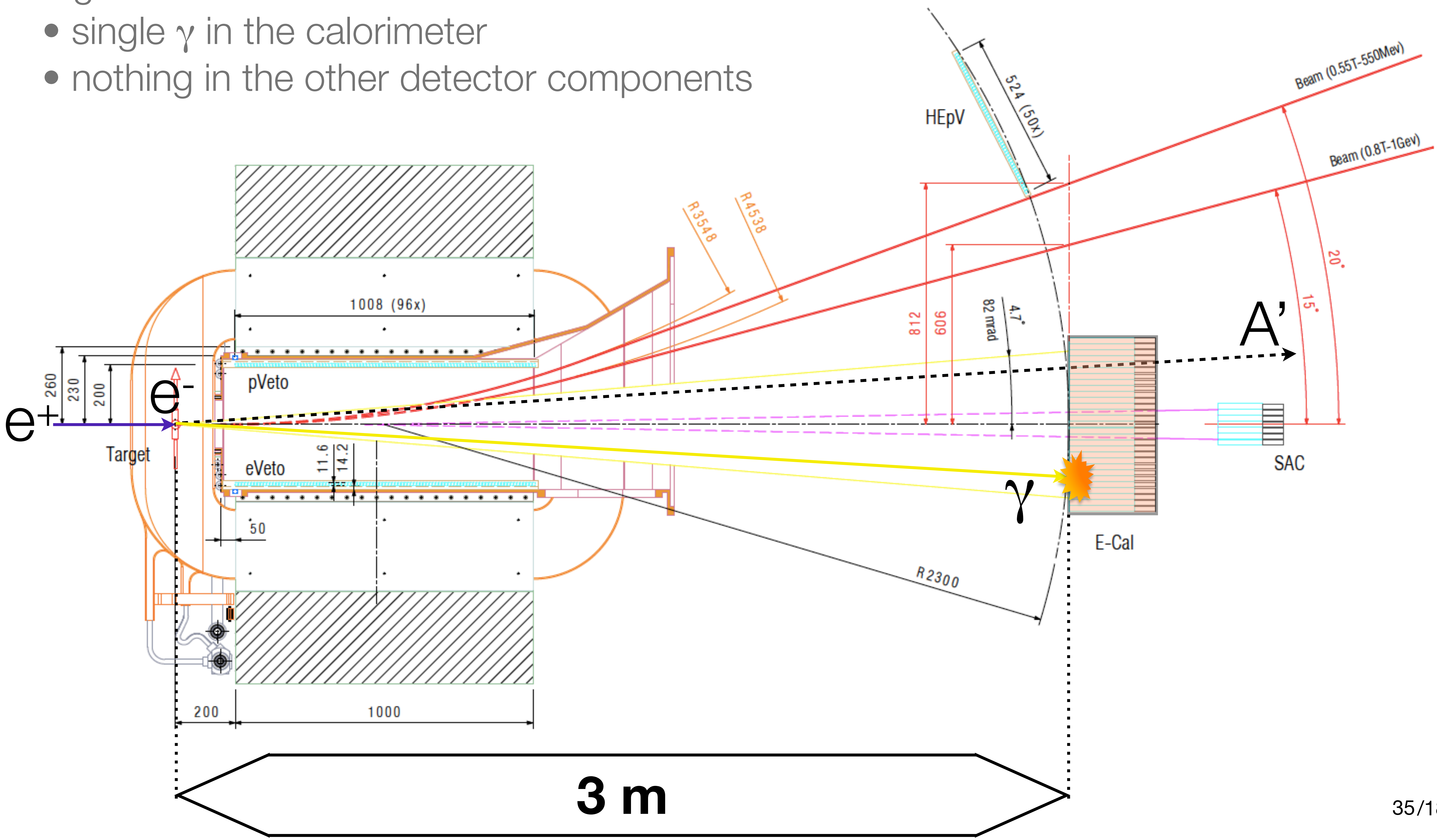
Beam Test Facility parasitic and dedicated modes

	Parasitic mode (DAΦNE working)		Dedicated mode	
	W/ target	W/o target	W/ target	W/o target
Particle species	e^+/e^- selectable by user	e^+/e^- depending on DAΦNE mode	e^+/e^- selectable by user	
Energy [MeV]	25-500	510	25-700 (e^+) 25-700 (e^-)	250-730 (e^+) 250-530 (e^-)
Energy spread	1% @ 500 MeV	1%	1%	
Rep. rate [Hz]	10-49 depending on DAΦNE mode		1-49 selectable by user	
Pulse duration [ns]	10		1.5-40 selectable by user	
Intensity [particles/bunch]	$1\text{-}10^5$ depending on energy	$10^7\text{-}1.5 \cdot 10^{10}$	$1\text{-}10^5$ depending on energy	$10^3\text{-}3 \cdot 10^{10}$
Max average flux	$3.125 \cdot 10^{10}$ particles/s			
Spot size [mm]	0.5-25 (y) × 0.6-55 (x)			
Divergence [mrad]	1-1.5			

Detector top view (w/ signal)

Signal:

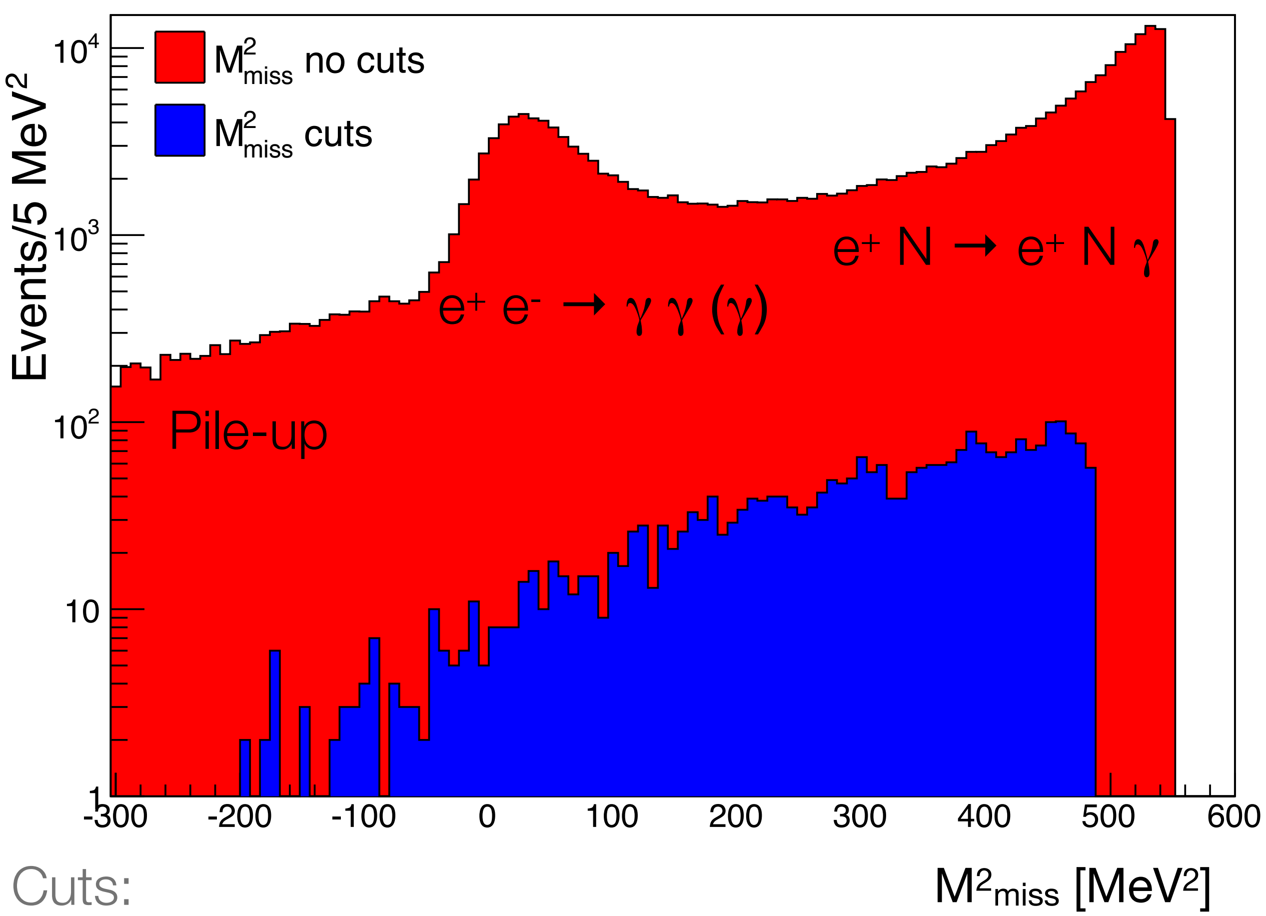
- single γ in the calorimeter
- nothing in the other detector components



Backgrounds

Largest backgrounds:

- $e^+ e^- \to \gamma\gamma(\gamma)$
- $e^+ N \to e^+ N \gamma$
- pile-up

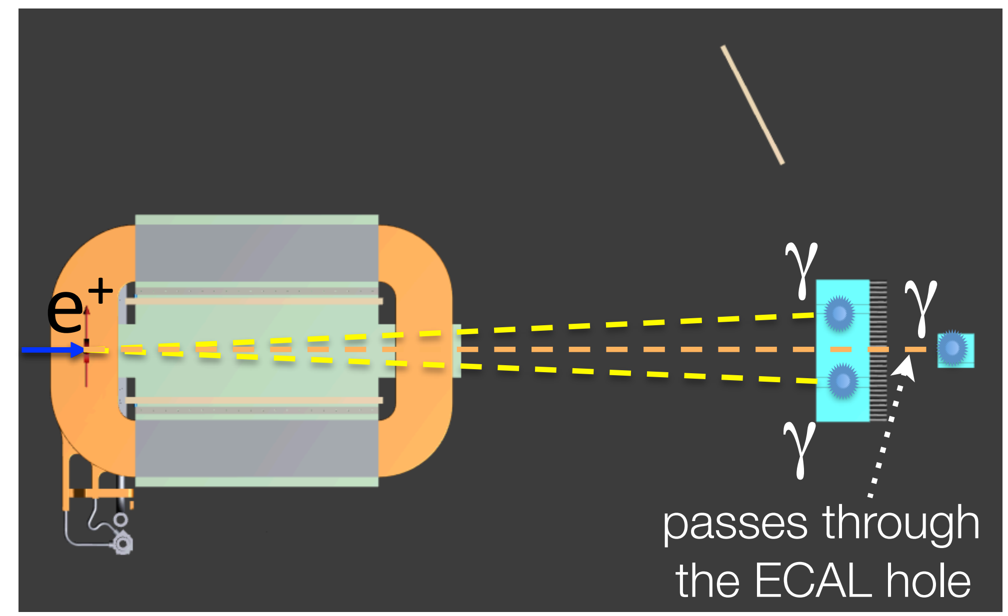


Cuts:

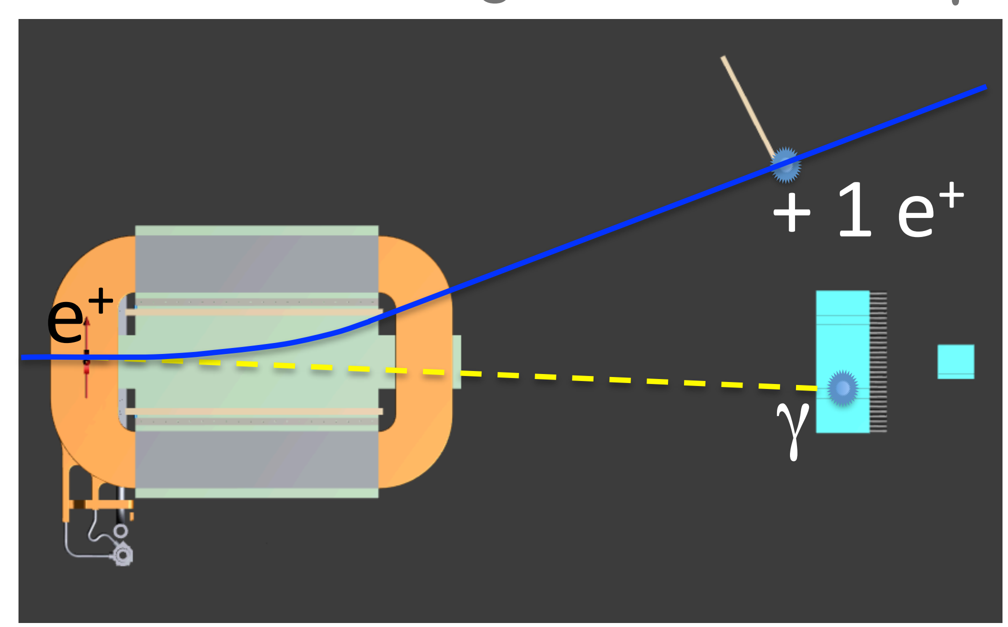
- 1 cluster in ECAL fiducial volume
- no hits in vetoes
- no γ in the SAC w/ E_γ > 50 MeV
- 20-150 MeV < E_γ < 120-350 MeV (depending on $m_{A'}$)

Backgrounds geometry

Annihilation (+ISR): $e^+ e^- \to \gamma\gamma(\gamma)$

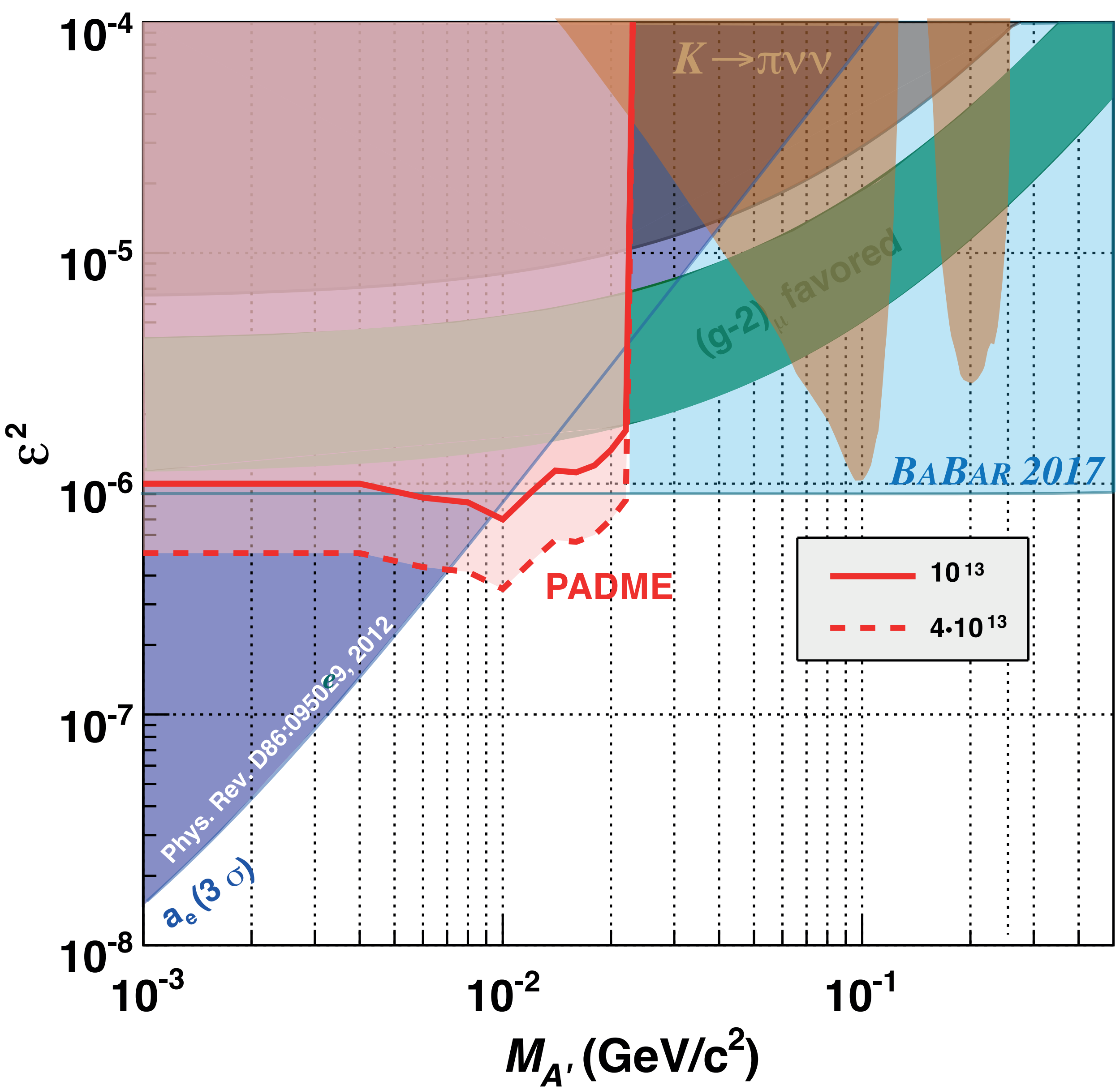


Bremsstrahlung: $e^+ N \to e^+ N \gamma$



Sensitivity

Based on $2.5 \cdot 10^{10}$ fully GEANT4 simulated 550 MeV e^+ on target events.
Number of BG events is extrapolated to 10^{13} e^+ on target.



PADME can explore in a model-independent way the region down to $\varepsilon \approx 10^{-3}$ w/:

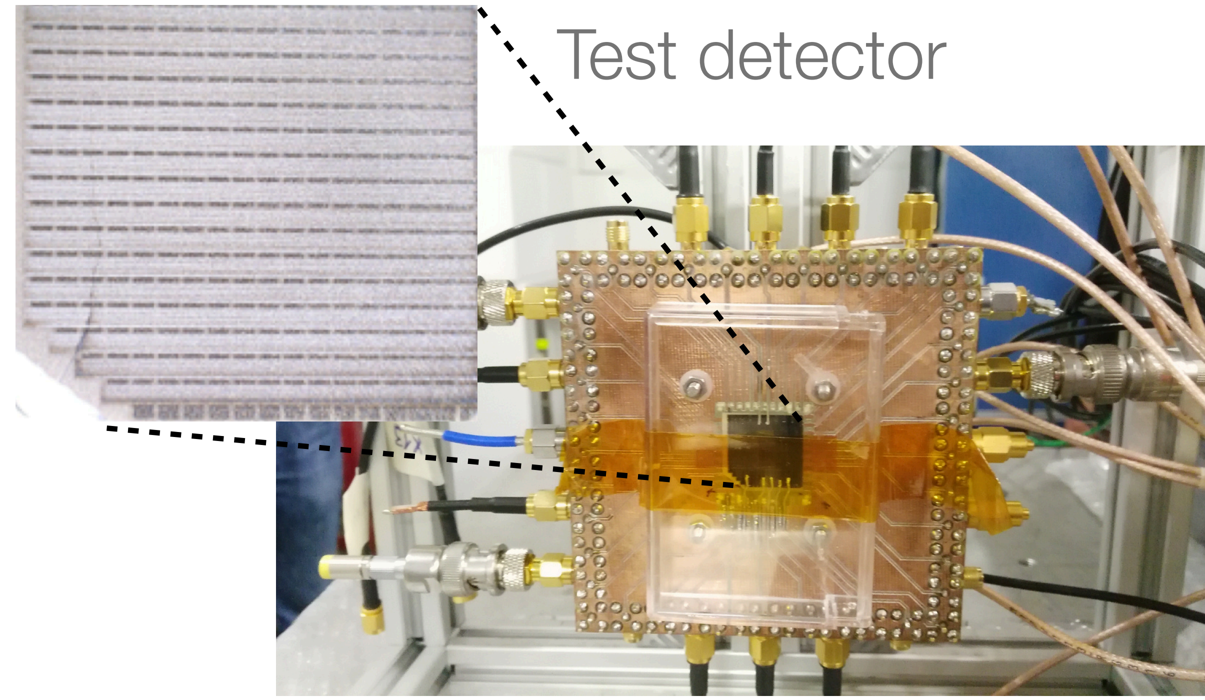
- $m_{A'} < 23.7$ MeV ($E_{beam} = 550$ MeV)
- $m_{A'} < 27.7$ MeV ($E_{beam} = 750$ MeV)
- $m_{A'} < 32$ MeV ($E_{beam} = 1$ GeV)

Active target

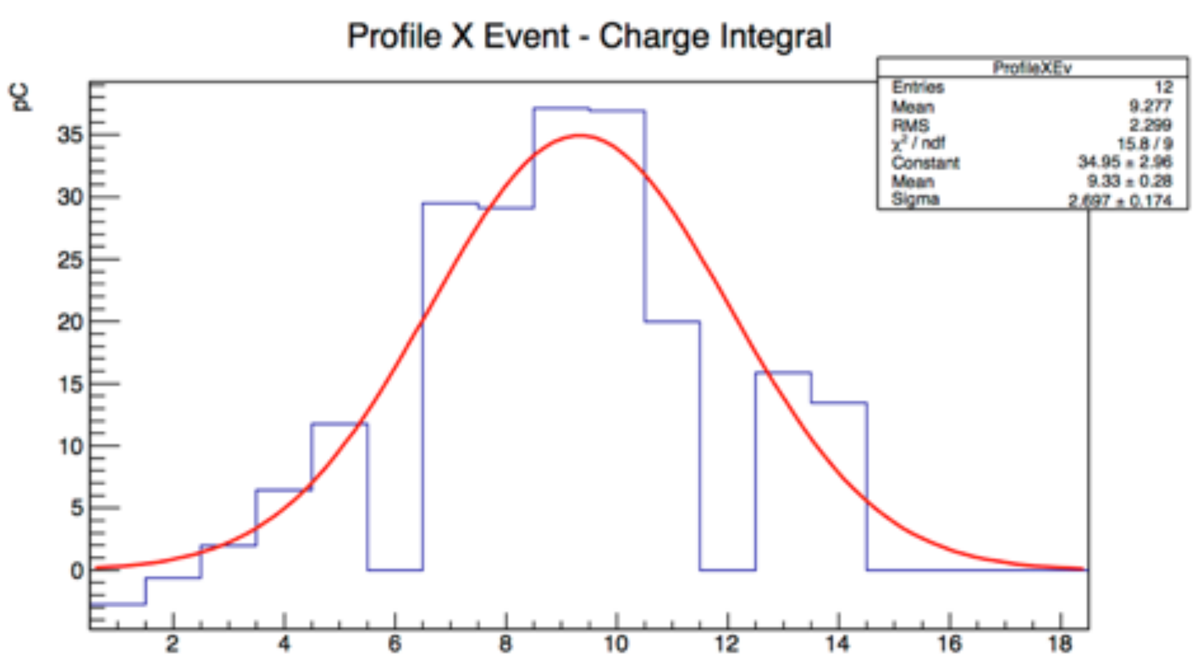
Features:

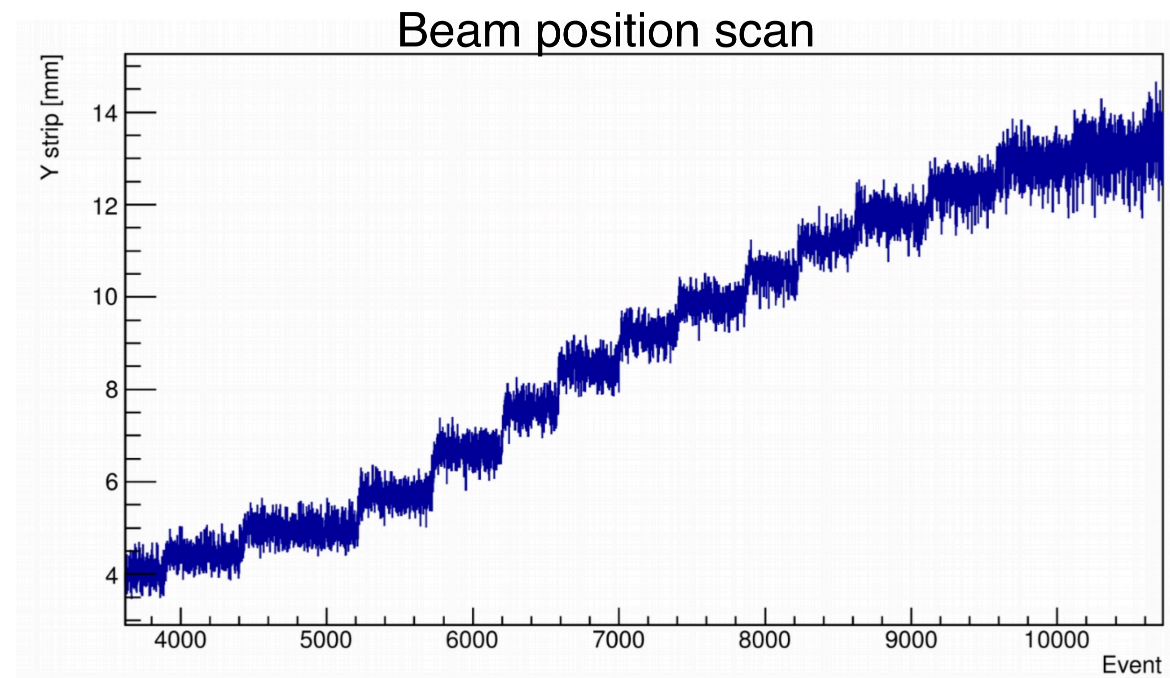
- Diamond (low z, reduced brems.)
- Dim.: 20×20×0.1 mm^3
- 19 horiz.×19 vert. active graphitic strips (average informations on beam)
- σ_{x-y}(beam position) < 2 mm
- in vacuum w/ movement system

Test detector



Test detector results (18 h.×18 v. active strips)



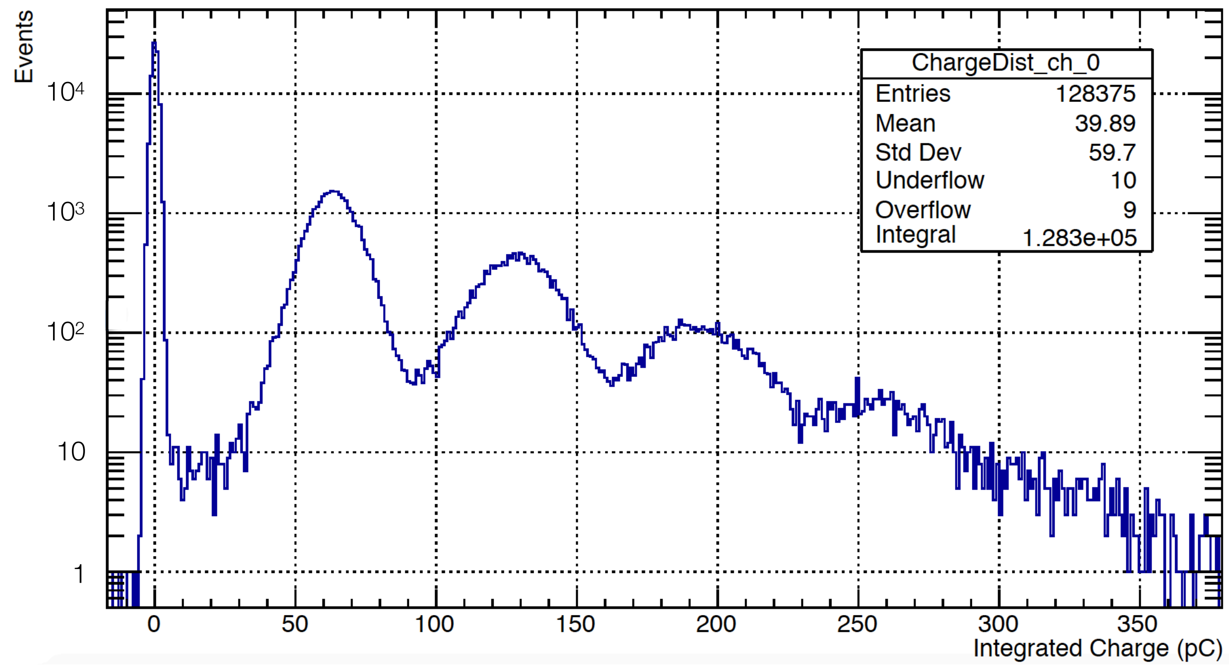


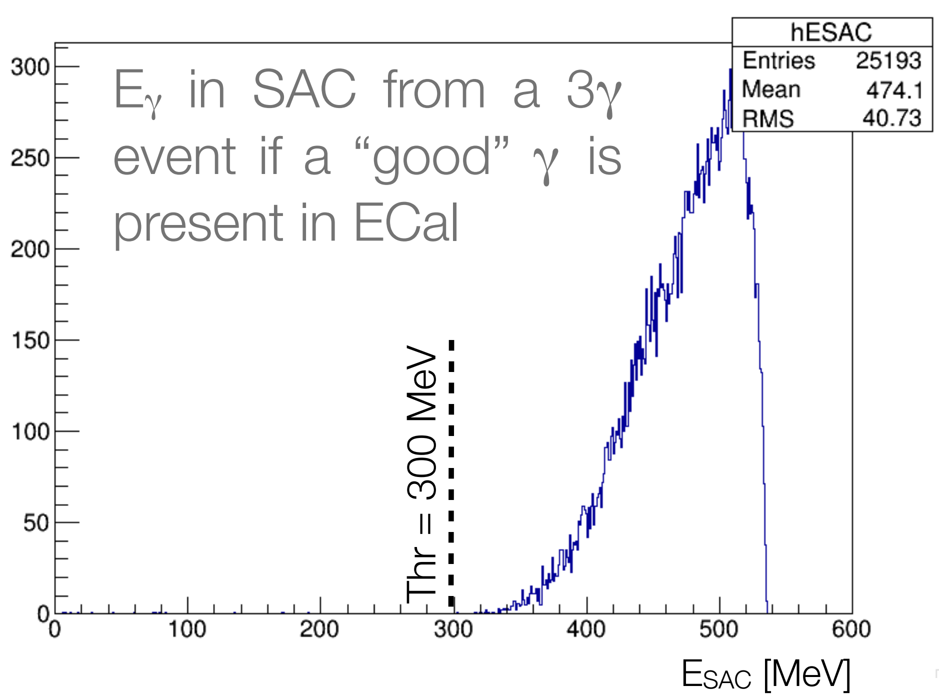
Spatial resolution: 0.2 mm (x-axis) × 0.3 mm (y-axis)

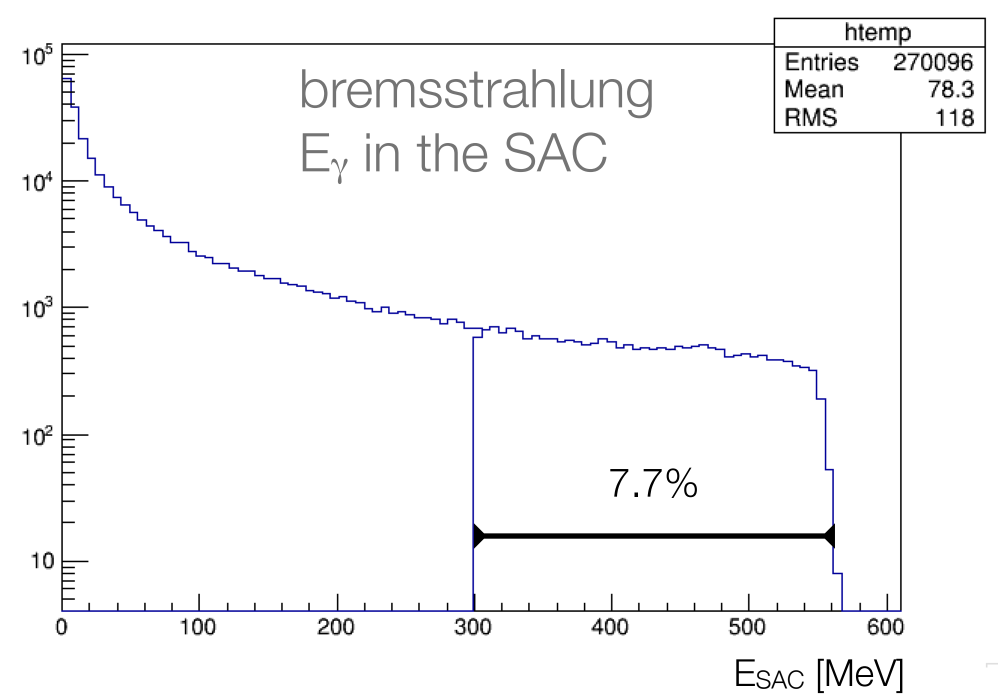
Small Angle Calorimeter (SAC)

Characteristics:

- $\sigma_E \simeq 10\%$
- Cherenkov → 3-4 ns signals
- angular coverage: [0,20] mrad
- crystal wrapped w/ tedlar (only direct light)



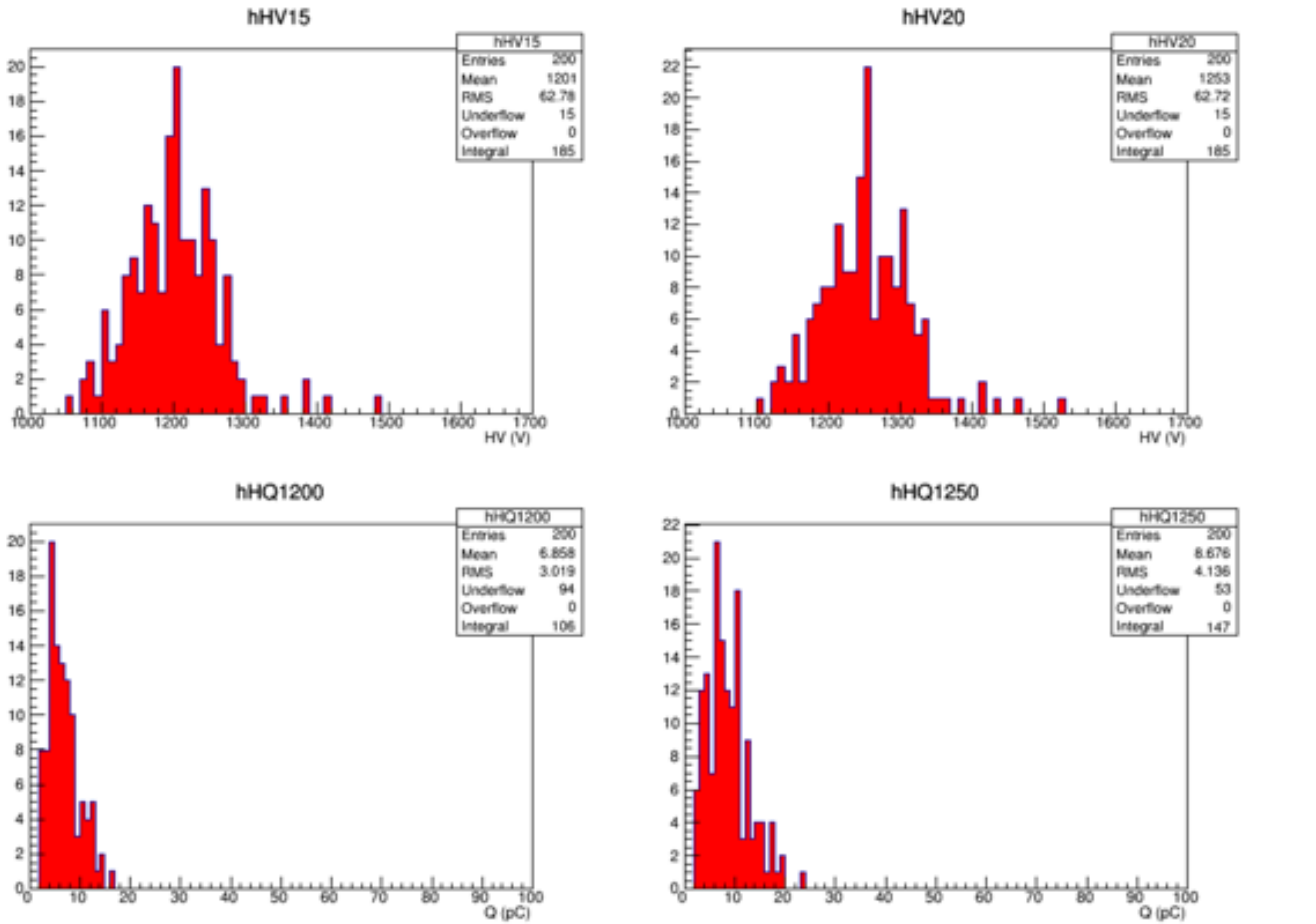




SAC must be sensible to photons over 300 MeV and blind under 100 MeV

HV (given charge) and charge (given HV) histo

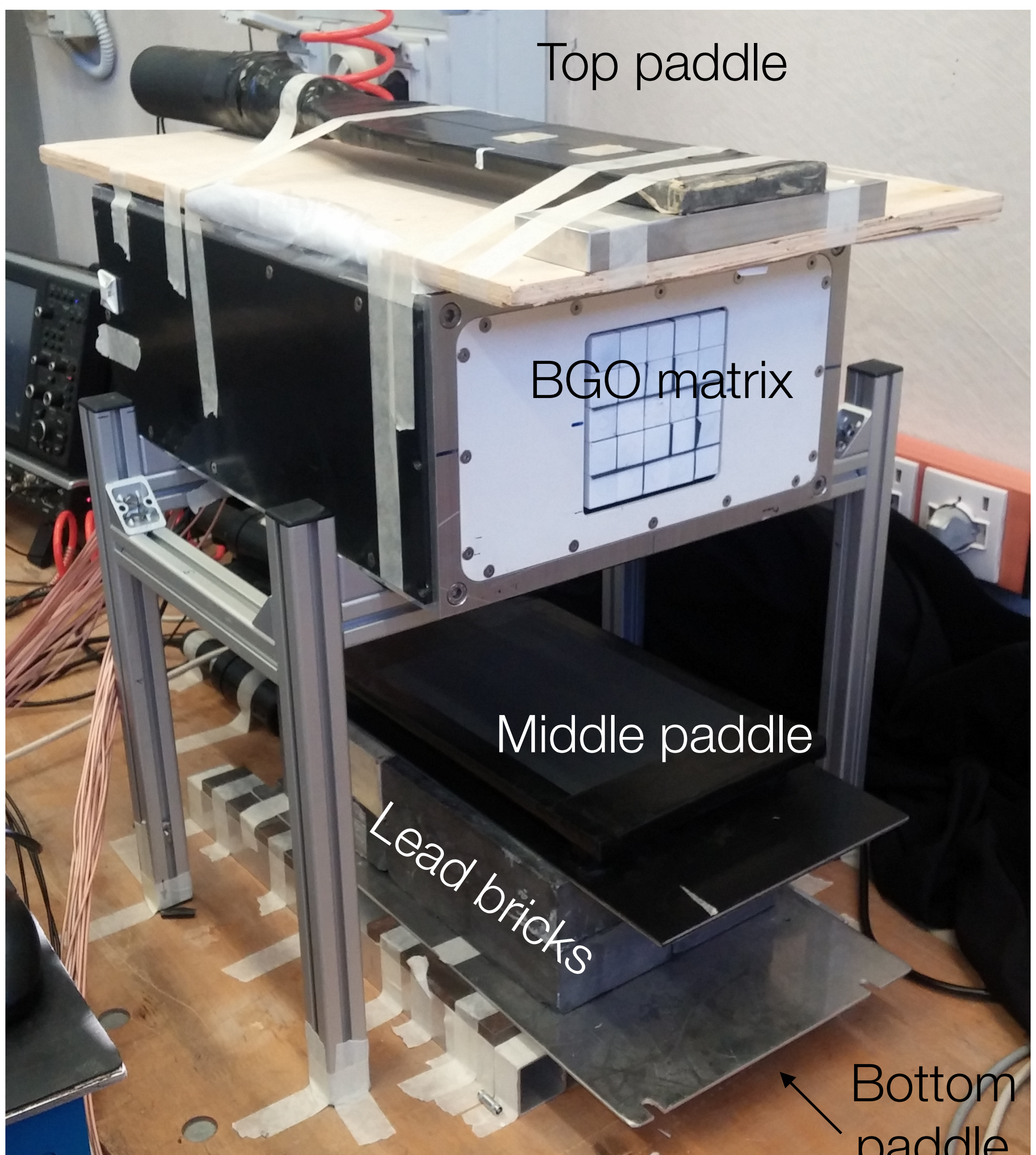
From ^{22}Na source measurements



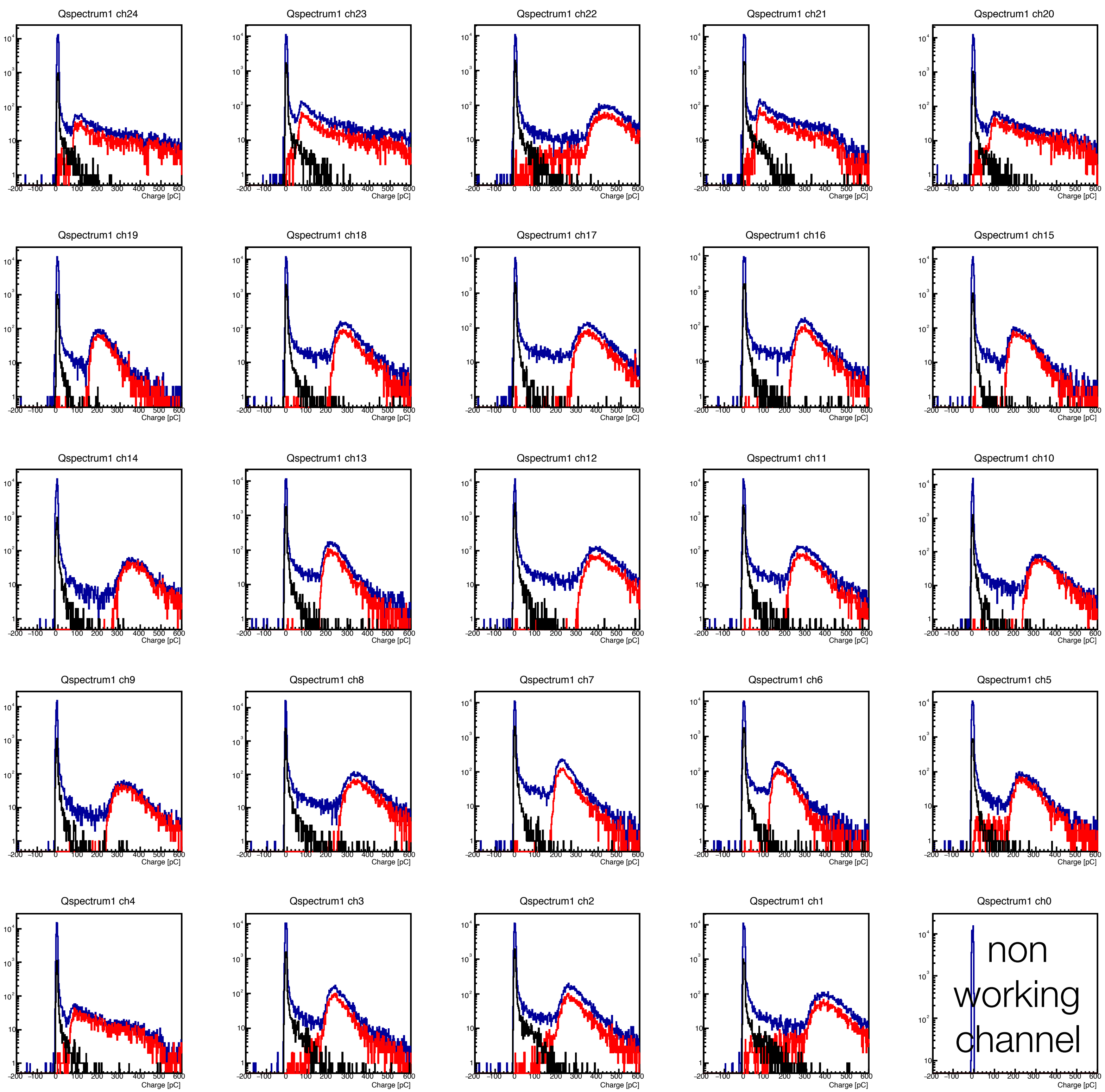
Cosmic ray setups

We performed **CR runs** with 2 different **setups**:

- **4×3 matrix**
- **5×5 matrix with 50μm tedlar** foils between crystals (see next slides)



Cosmic rays charge spectra (5×5 matrix)



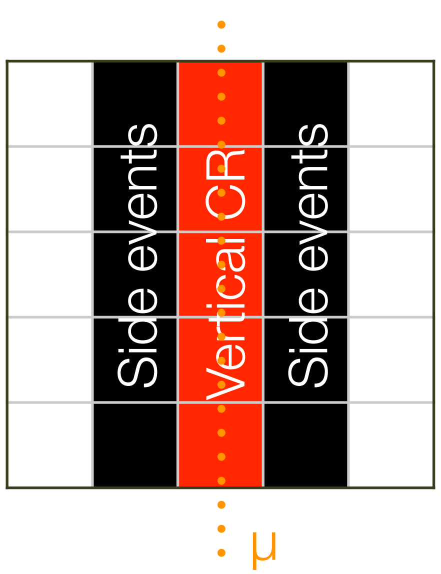
All events

Vertical CR

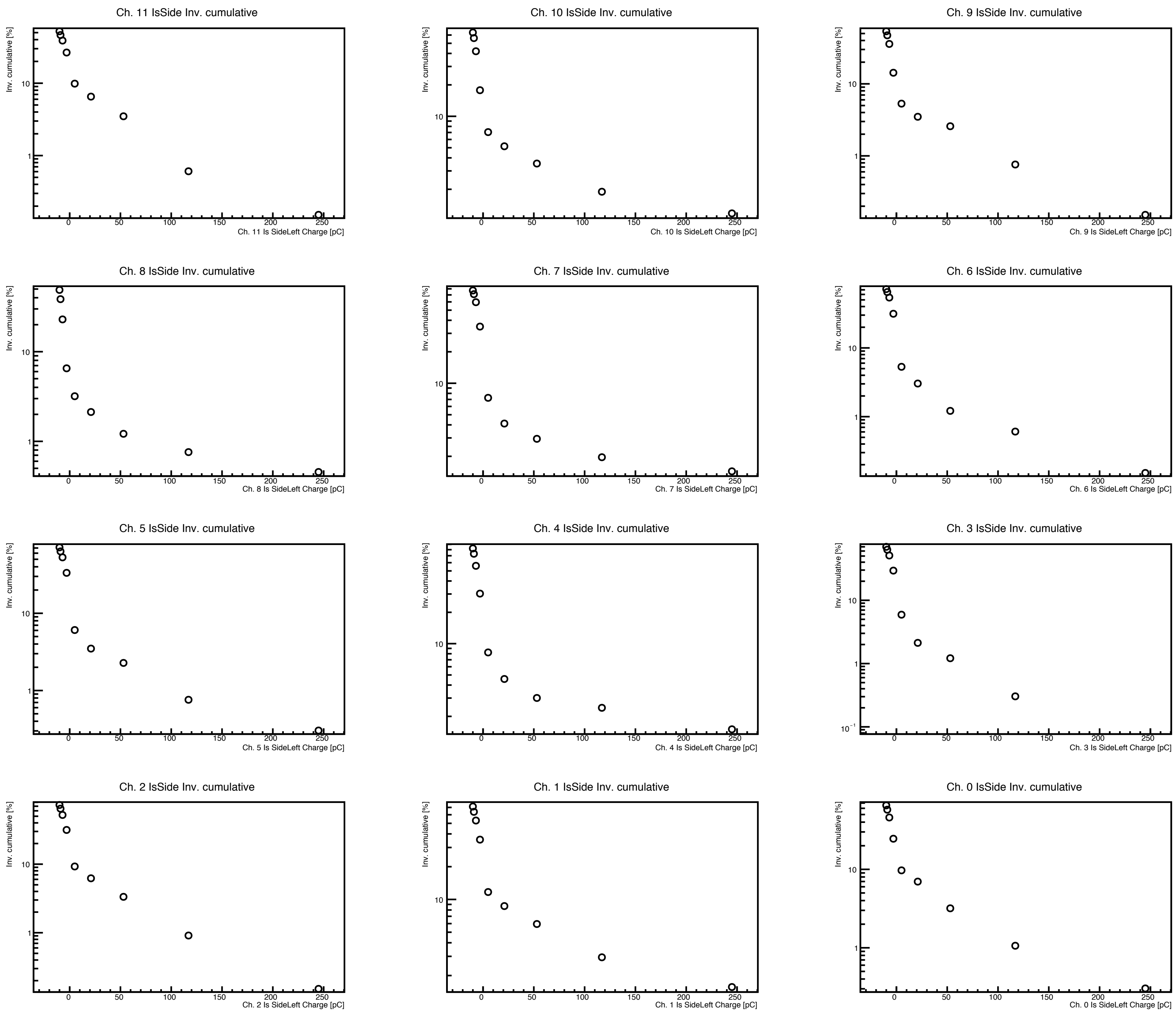
Side events (vertical CR passes through a crystal on the side)

Verticality is obtained requiring that the 5 largest signals are in column

Example:
μ passing through central column



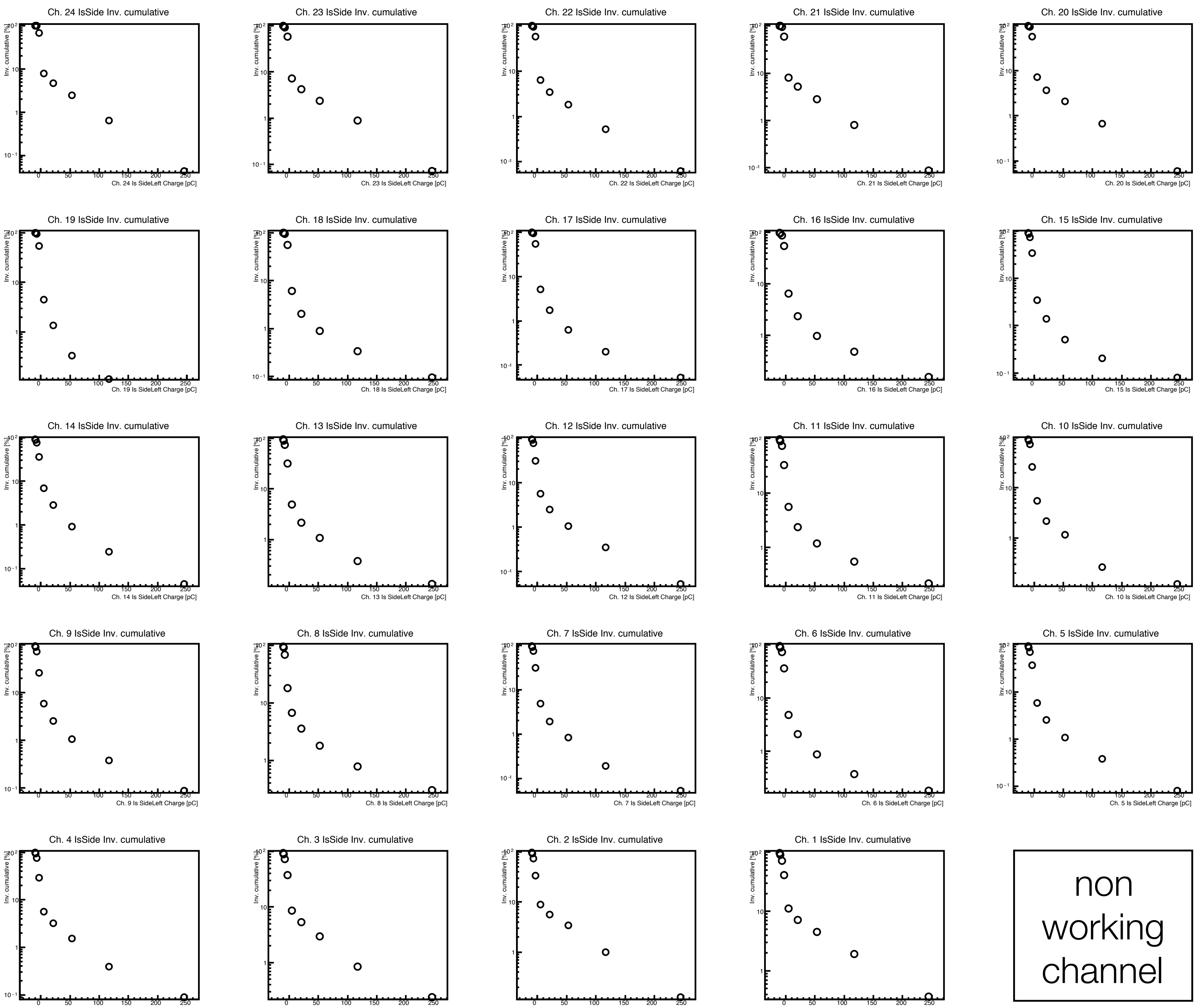
Optical crosstalk without tedlar (4×3 matrix)



Inverse cumulative of the Side events without tedlar

1% is reached at ≳100pC

Optical crosstalk with tedlar (4×3 matrix)



Inverse cumulative of the Side events with tedlar

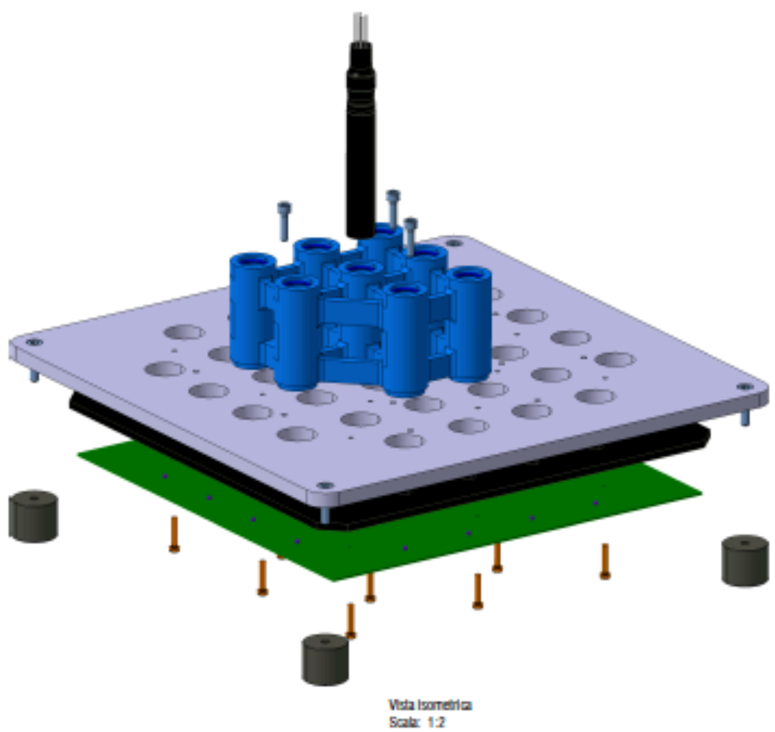
1% is reached at ~50pC

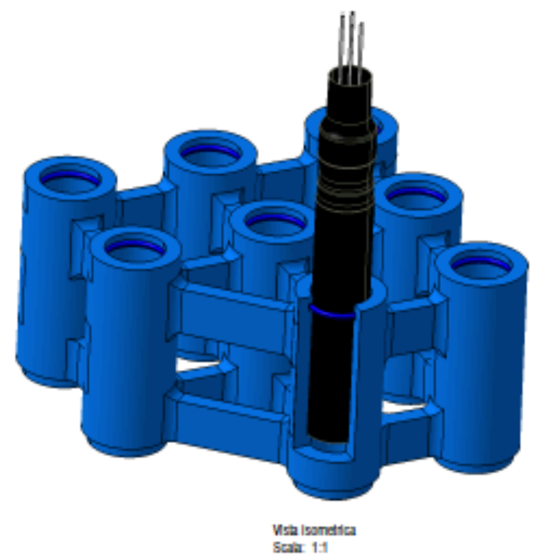
Tedlar is effective in preventing optical crosstalk

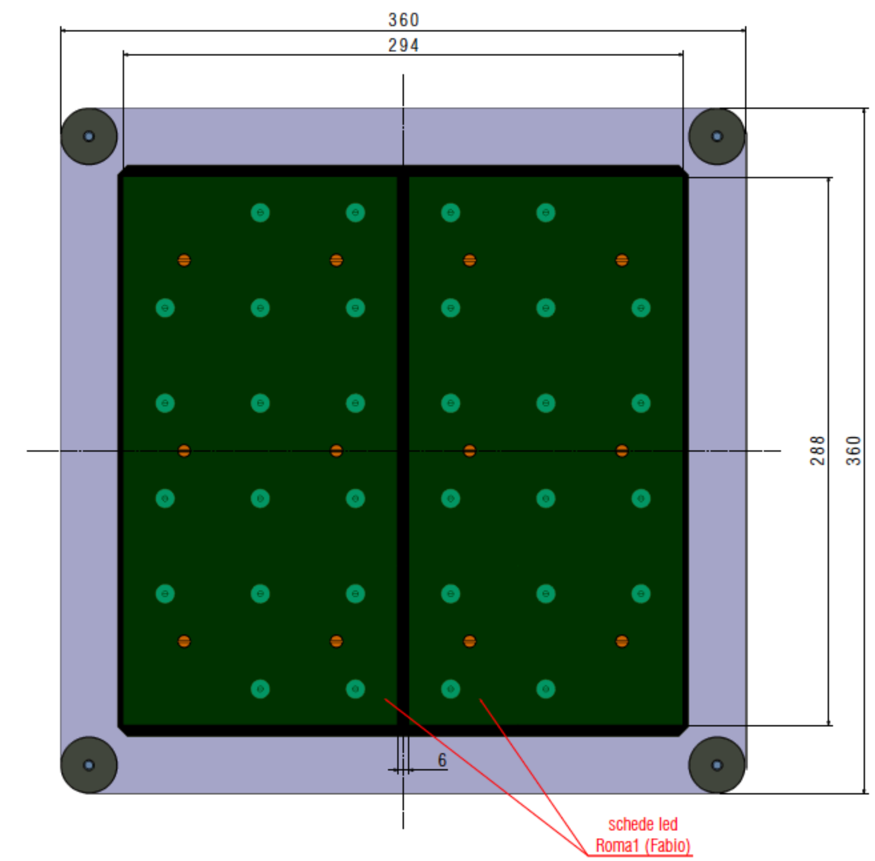
Tedlar will be used for the ECAL assembly

(it also accommodates different SU heights)

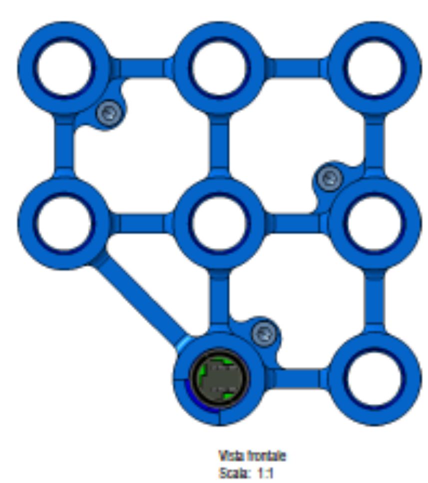
PMTs test station

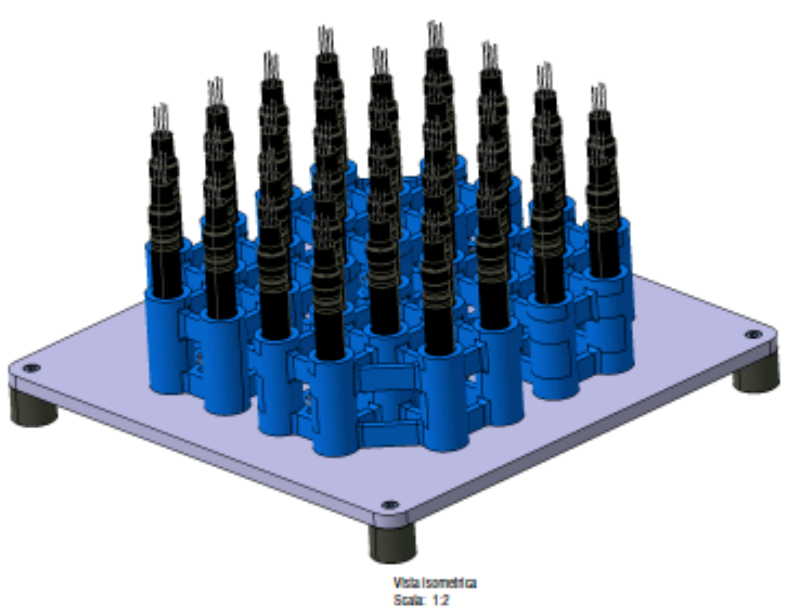




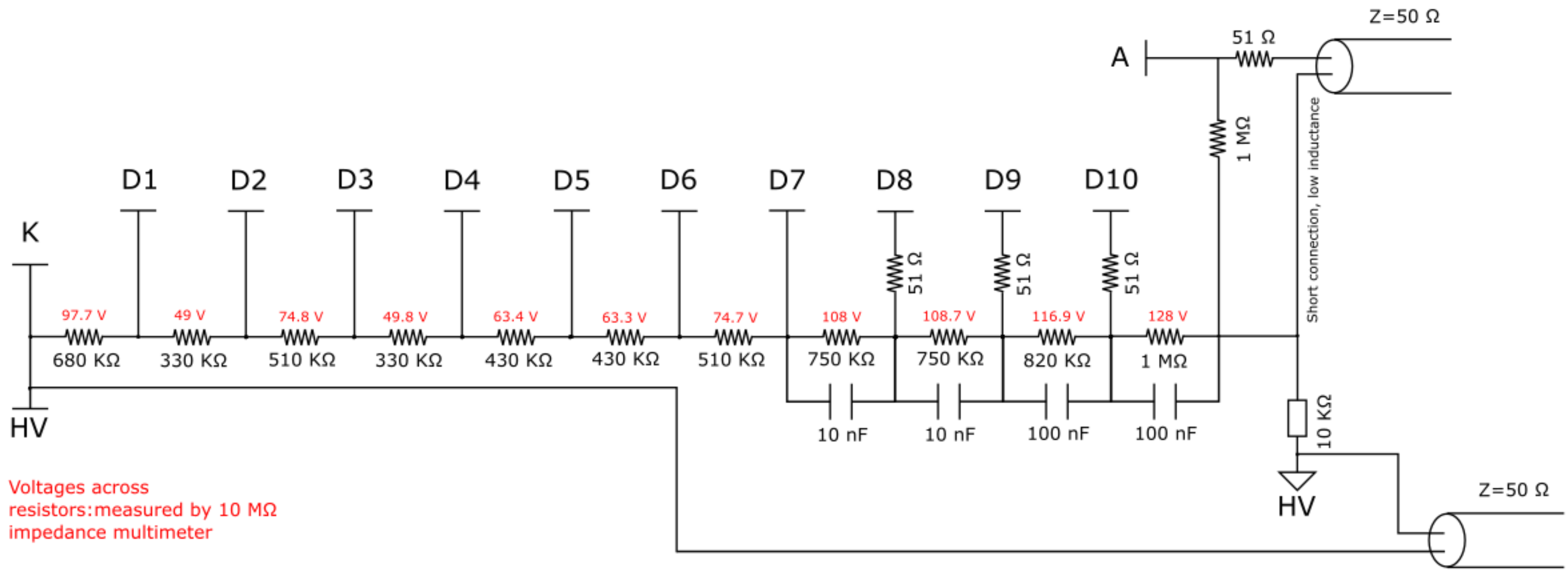


Seen from below





XP1911 divider new design



PMTs dimensions test

DIMENSIONAL TEST WITH ''TUBE'' ID=20,4 H8

GOOD CASE:
Photomultiplier pass through

BAD CASE:
Photomultiplier does not pass through