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PADME

STVDIVM VRBIS

First results on the performance of the PADME electromagnetic calorimeter

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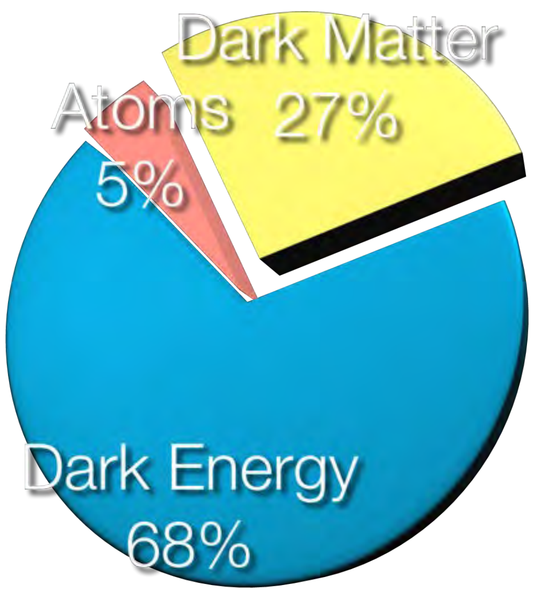
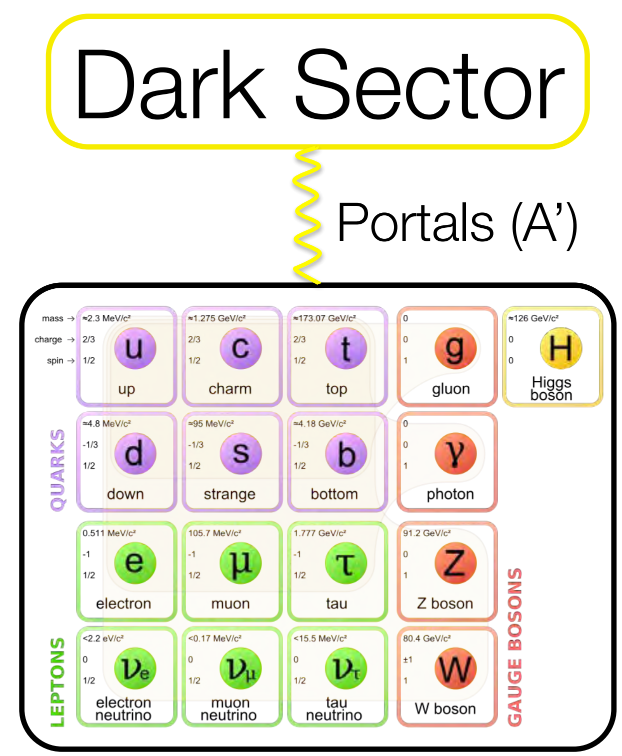
Dark Photon as Dark Matter problem solution



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

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

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



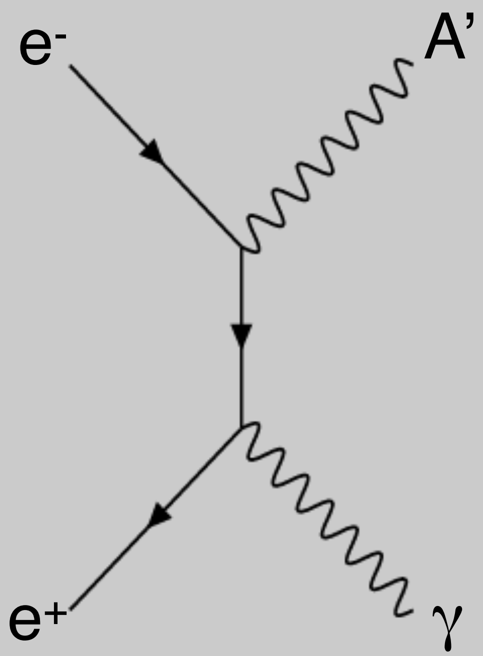
The simplest model adds a U(1) gauge symmetry and its boson: the Dark Photon A'

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

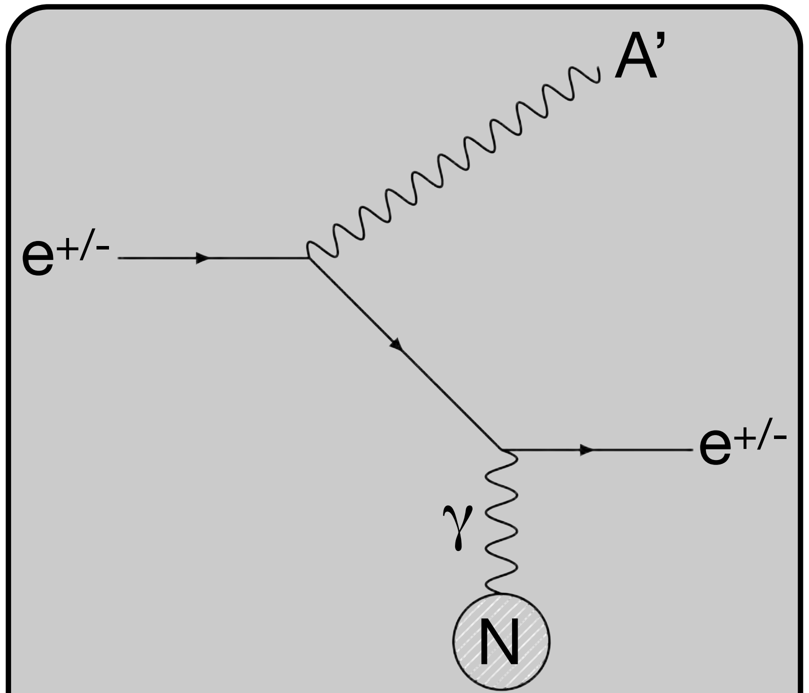
Depending on the model, in addition to DM, the A' could (partially) explain the $(g-2)_\mu$ discrepancy and the ^{8}Be anomaly (see backup)

Dark photon production and decays

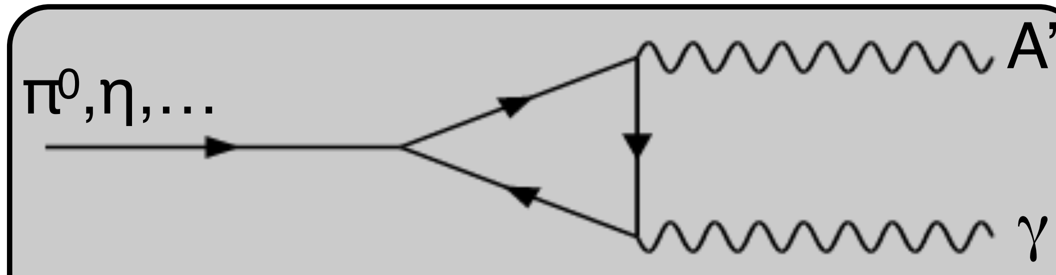
In e^+/e^- collisions Dark Photon can be **produced** in 3 main ways:



Annihilation



Bremsstrahlung



Mesons dec. (after production)

Visible decays

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

- A'→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'→DM (invisible) w/ (likely) BR ≃ 1
- SM decays suppressed by a factor ε^2

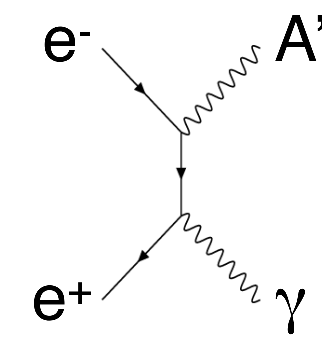
A' lifetime proportional to:

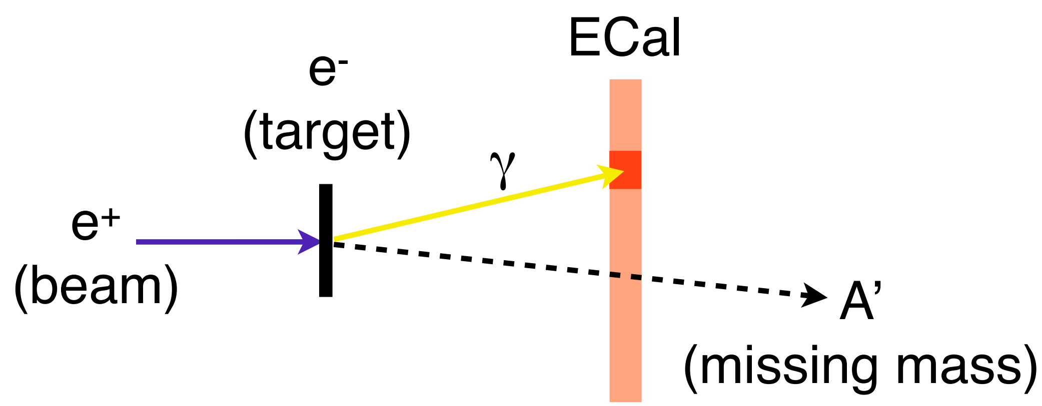
$$1/(\alpha_D m_{A'})$$

α_D: A' coupling constant to the Dark Sector

The PADME (LNF, IT) approach

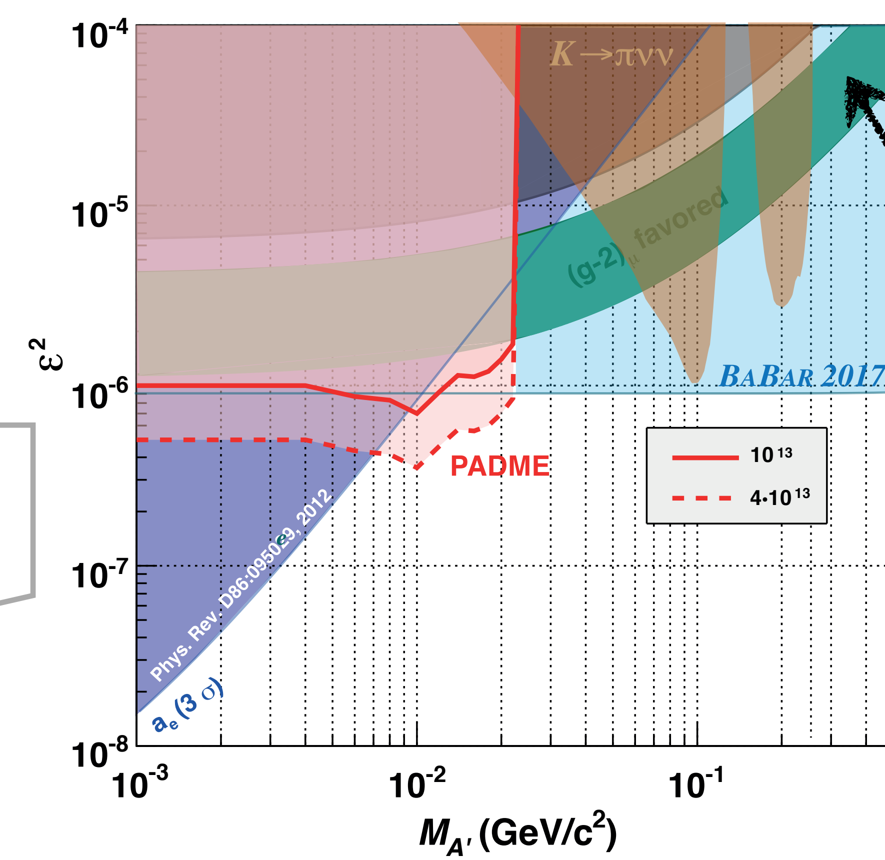
A' search in e^+e^- annihilations looking for missing mass (invisible decay) in a kinematically constrained condition

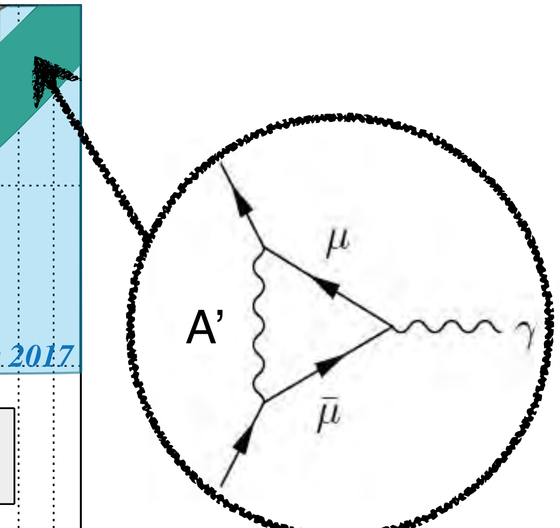




- known beam energy and position
- measured photon energy and position

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

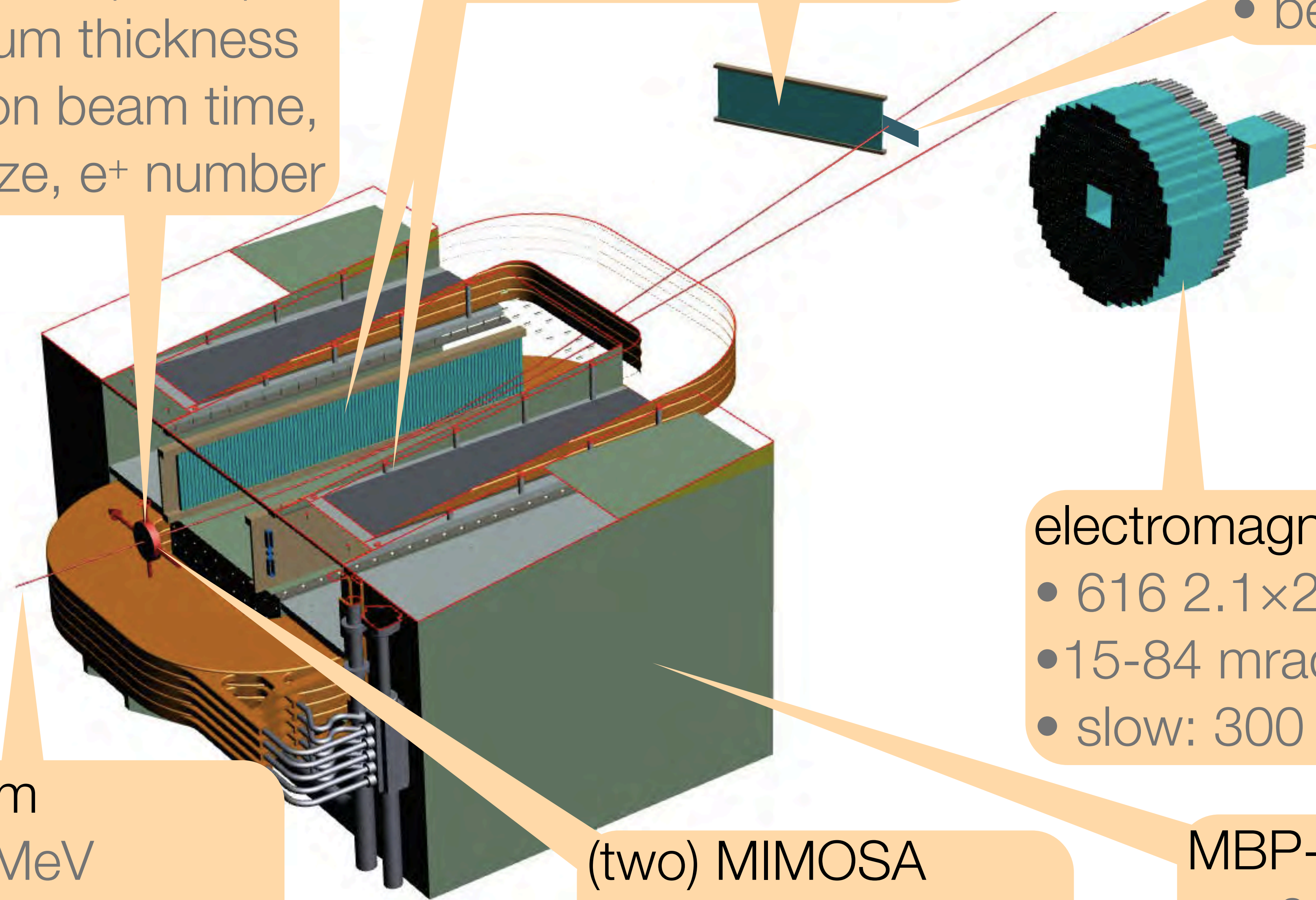




Excluded as only solution of the $(g-2)_\mu$ problem

- 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

TimePix3
- 8.5 h. × 2.8 v. cm^2 array
- beam monitoring (high mult.)

small angle calorimeter
- 25 3×3×14 cm^3 PbF_2
- 0-15 mrad ang. cov.
- fast: 3 ns Cher. light signals

electromagnetic calorimeter
- 616 2.1×2.1×23 cm^3 BGO
- 15-84 mrad ang. cov.
- slow: 300 ns dec. time for scint. light

e^+ beam
- 550 MeV
- 20000 e^+/bunch
- 200 ns bunch, every 20 ms

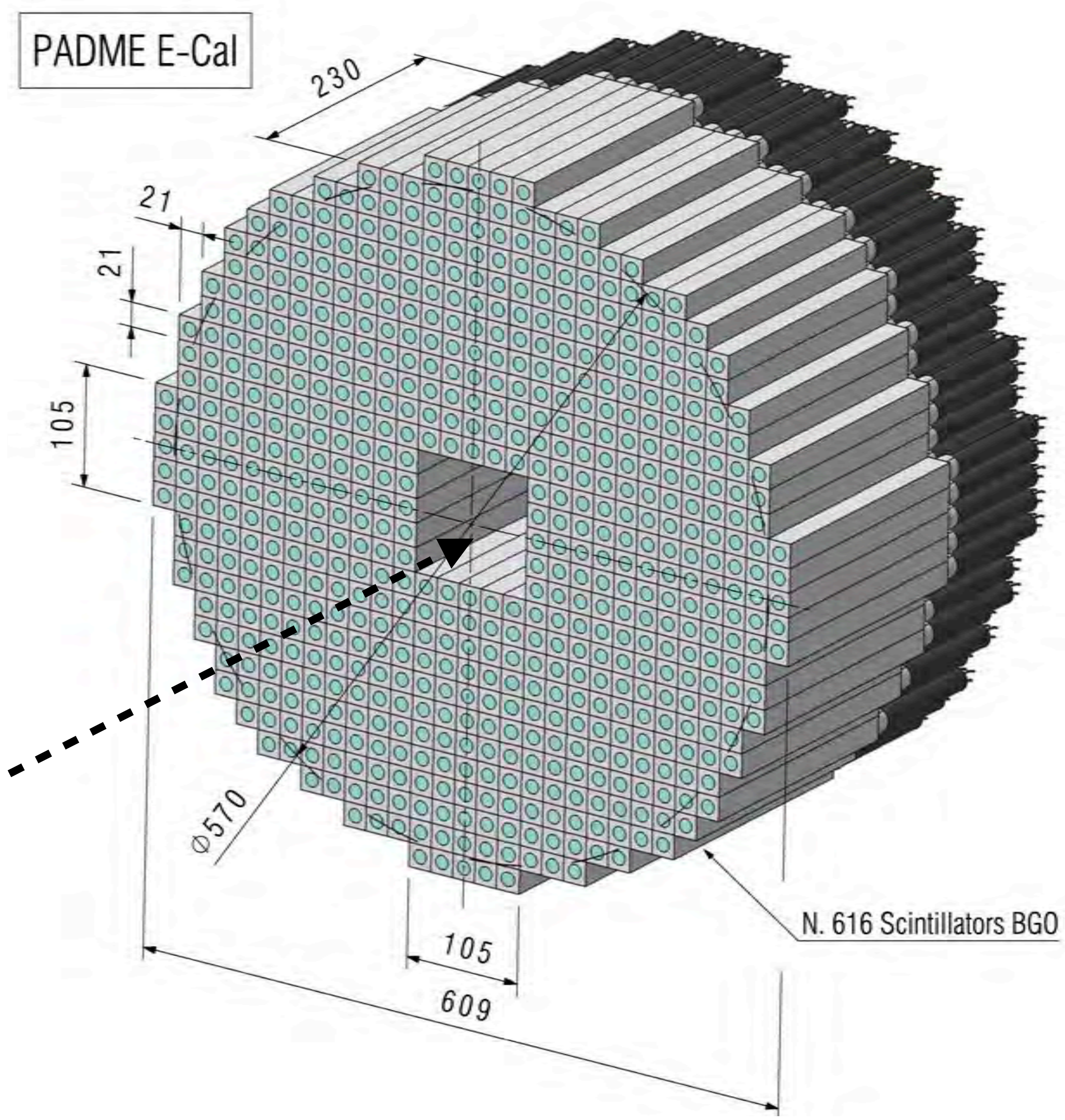
(two) MIMOSA
- beam monitoring (low mult.)
- can stay off-beam

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

Electromagnetic calorimeter (ECal) overview

Features:

- 616 2.1×2.1×23 cm^3 scintillating BGO (τ_{decay} = 300 ns)
- length = 20.5 X_0
- radius: ≈29 cm
- tedlar foils between crystals (no honeycomb structure) to reduce light crosstalk (see backup)
- 3.45 m from the target
- PMT: HZC XP1911
- angular coverage: [15,84] mrad
- central hole (10.5×10.5 cm^2) for Brems. to SAC (faster)
- sampling: 1GS/s, 1024 samples
- w/ current gain (15.3 pC/MeV) a single SU sees photons w/ E_γ < 511 keV



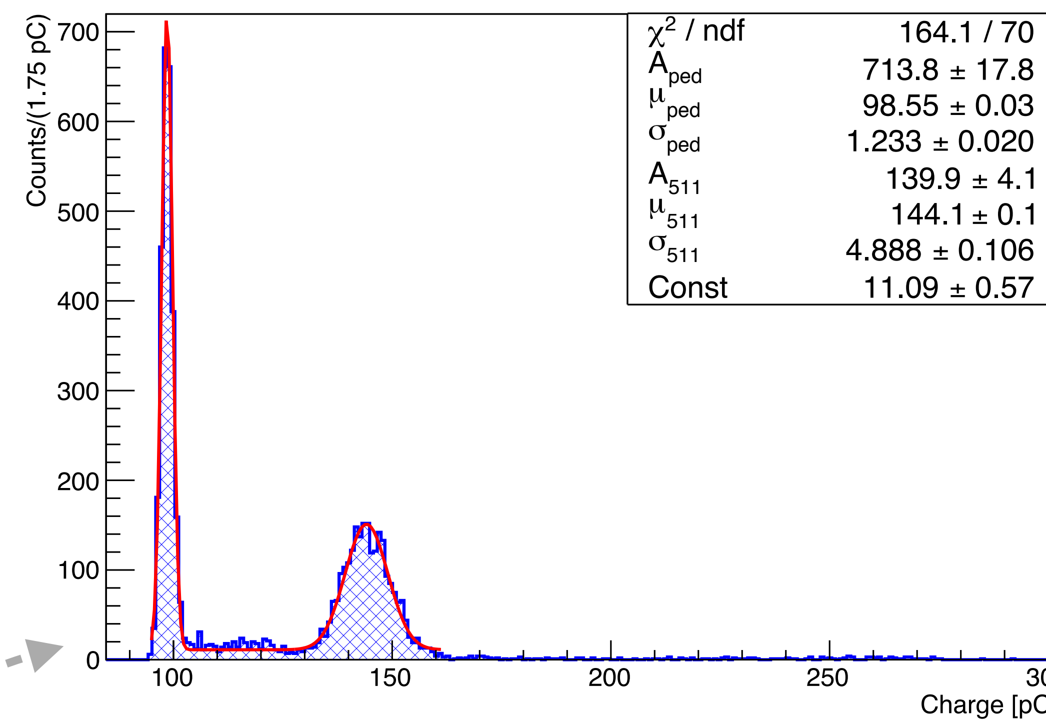
Electromagnetic calorimeter pictures

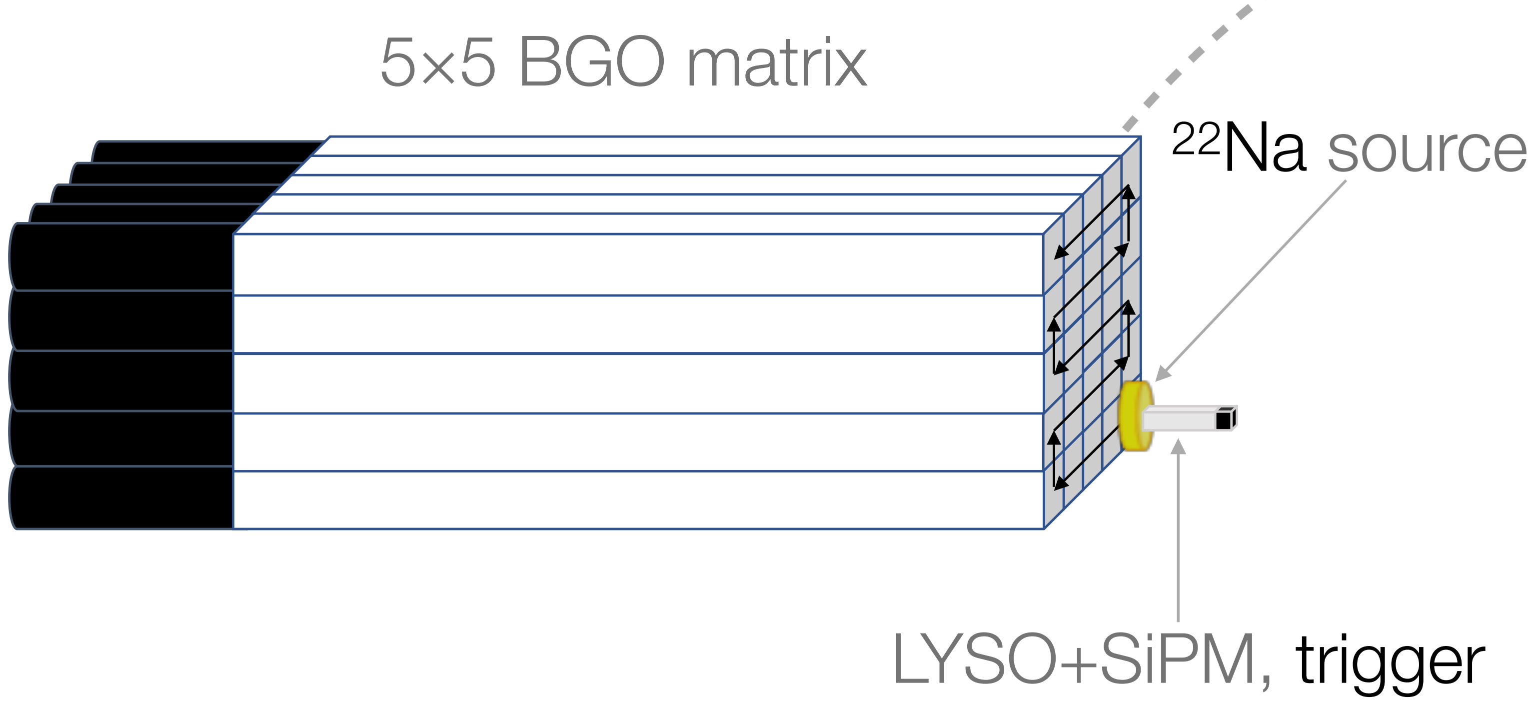
Front view, open

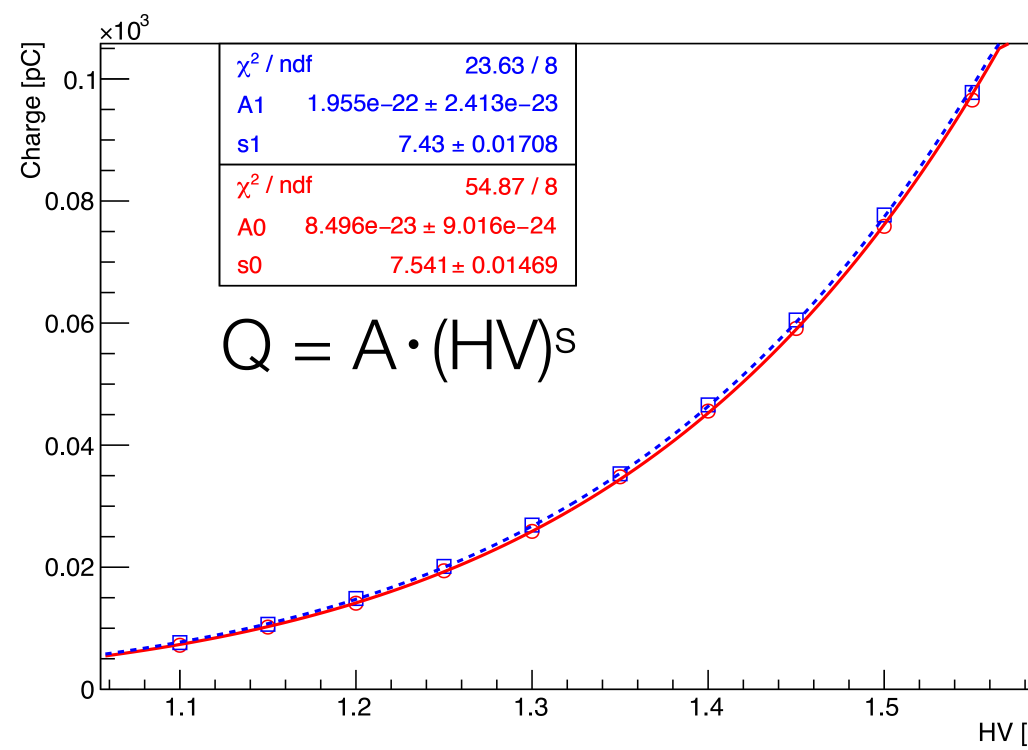
Back view, open

^{22}Na setup for Scintillating Unit (SU) calibration

- 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
- **135 SUs** have been **measured two times** w/ the ^{22}Na source for reproducibility studies

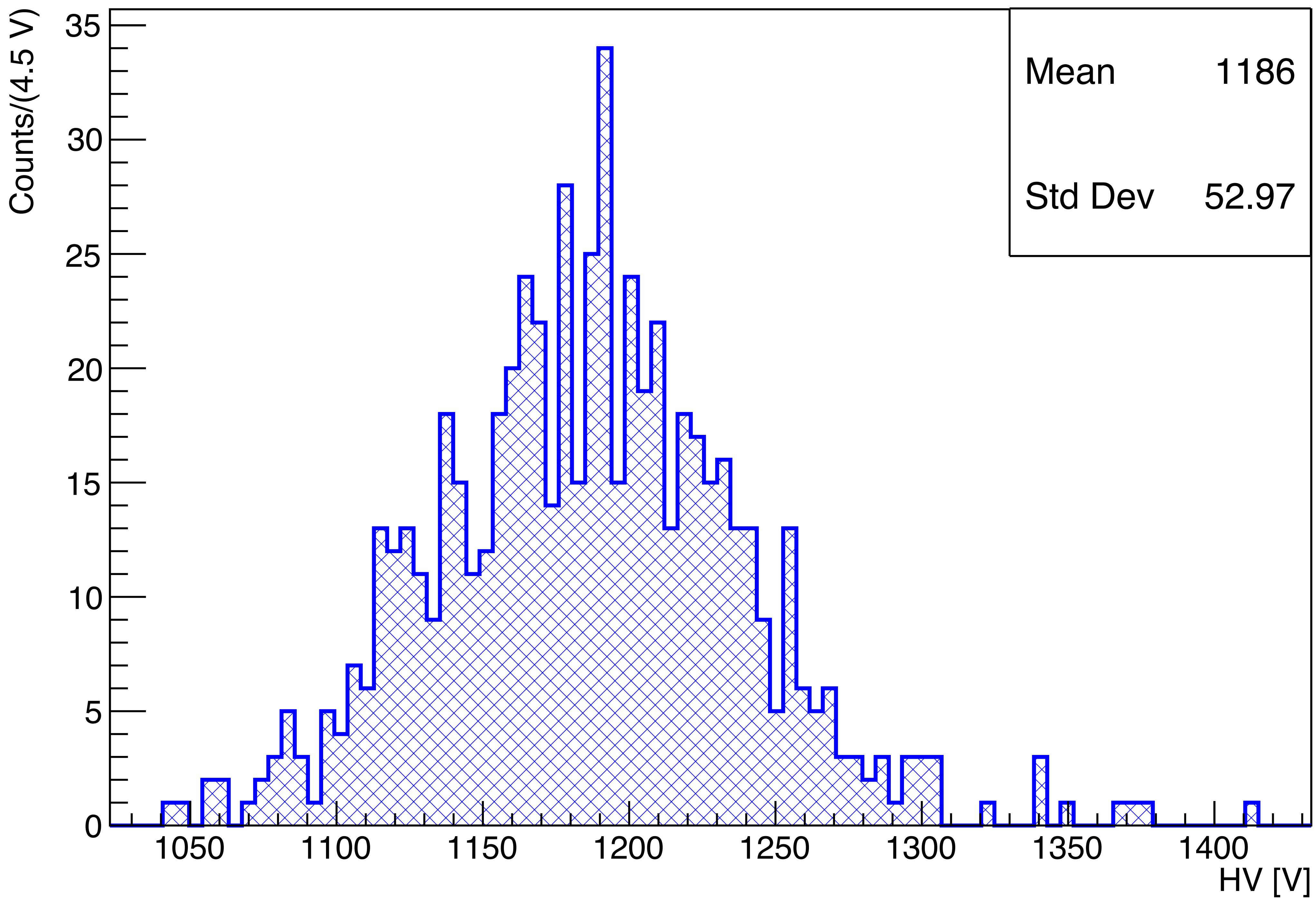






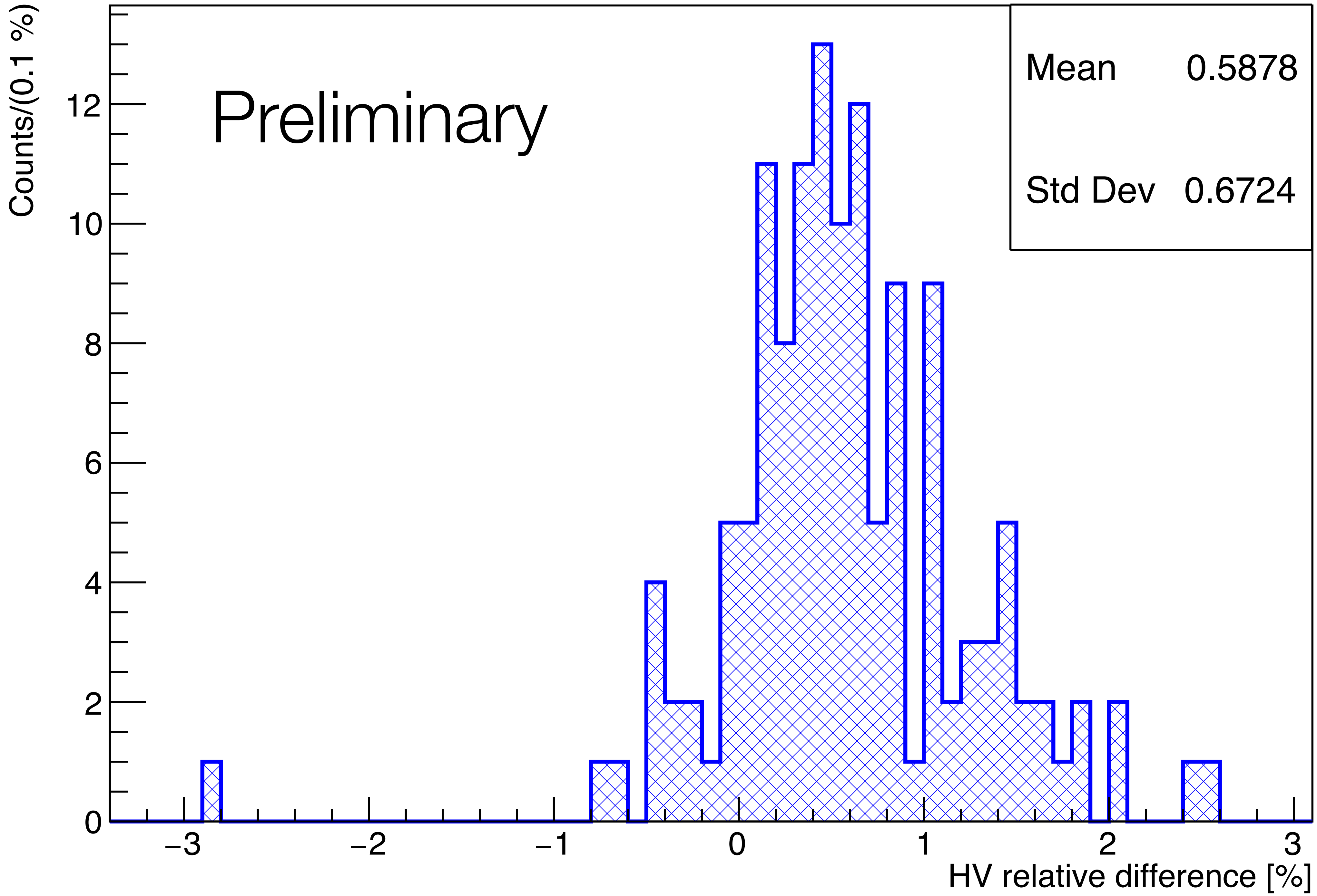
ECal HV distribution

HV distribution for all the 616 HZC XP1911 to set SU at 15.3 pC/MeV



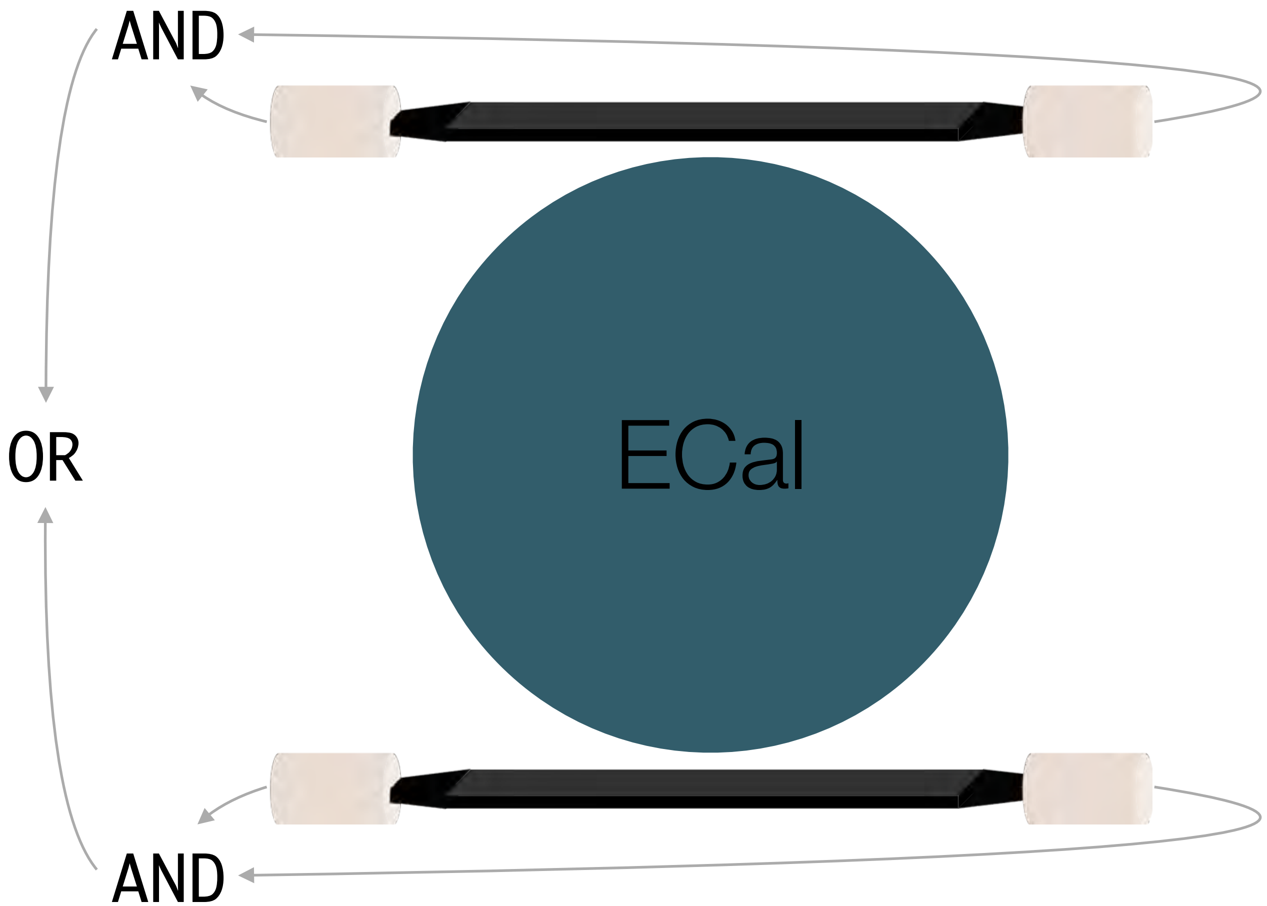
HV values stability

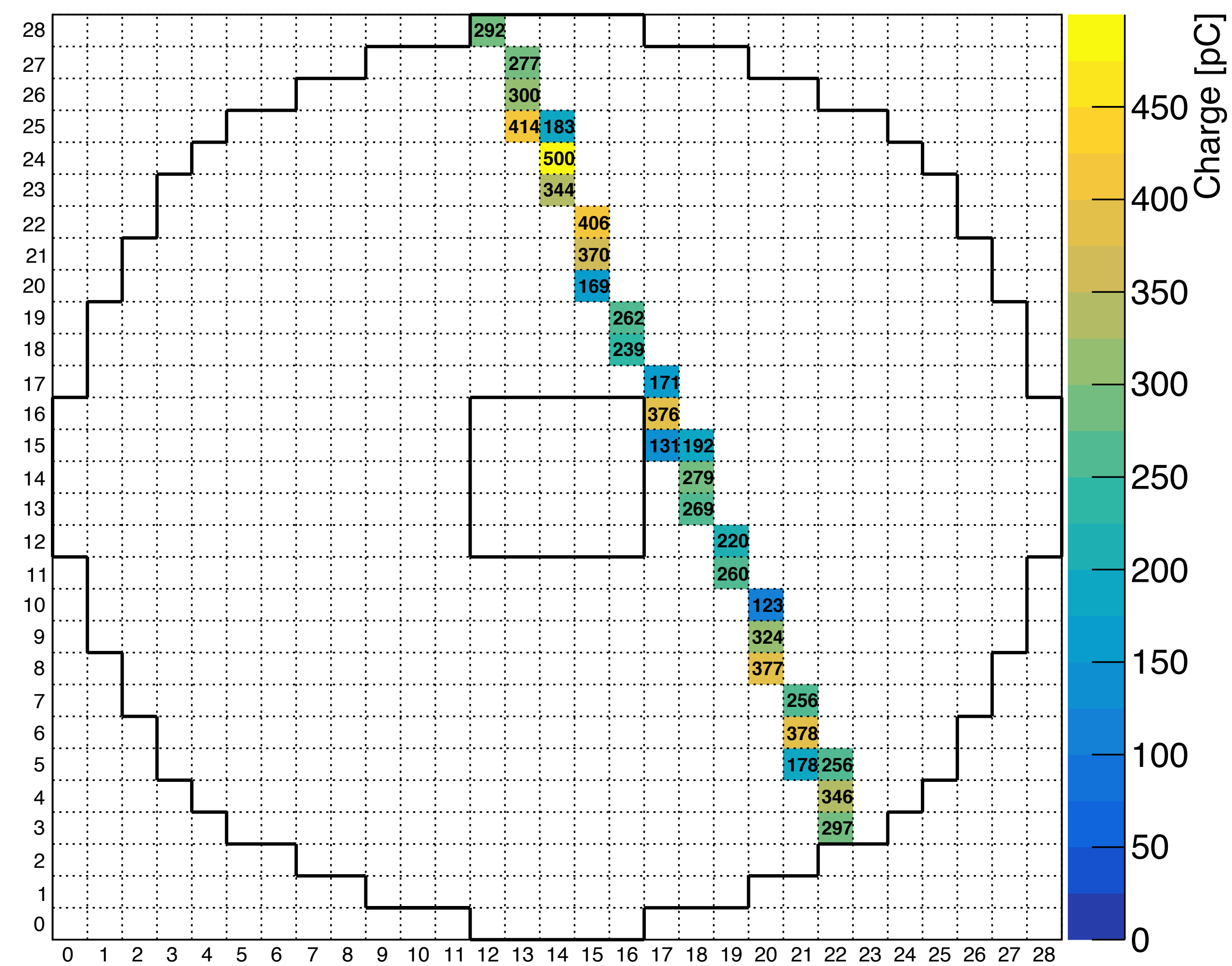
Distribution of the HV relative difference for the 135 SU that undergone two measurements, when requiring for 15.3 pC/MeV



Cosmic rays in ECal

The trigger is formed of 2 paddles, each one read by 2 PMTs, one above, one below ECal.

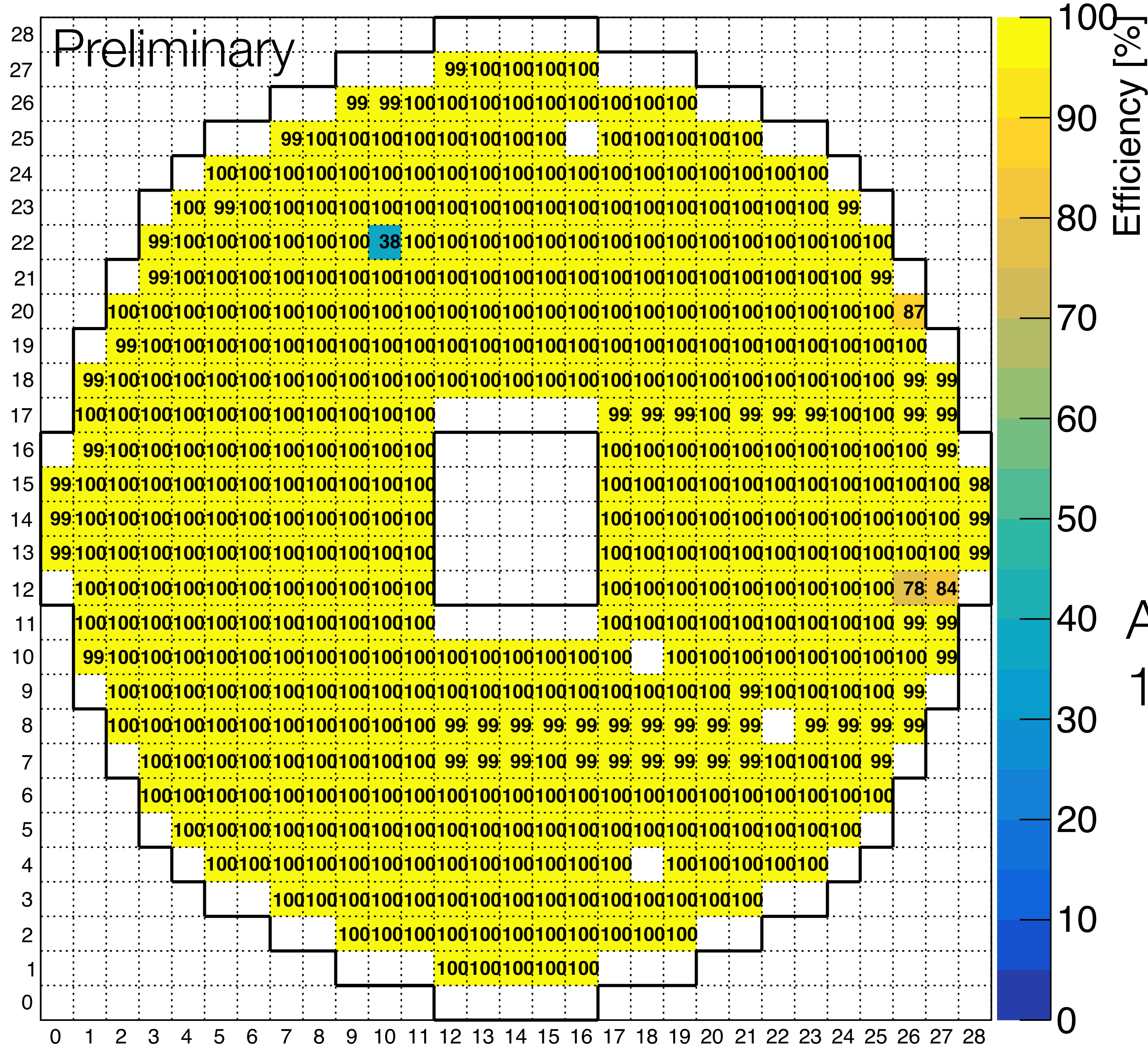




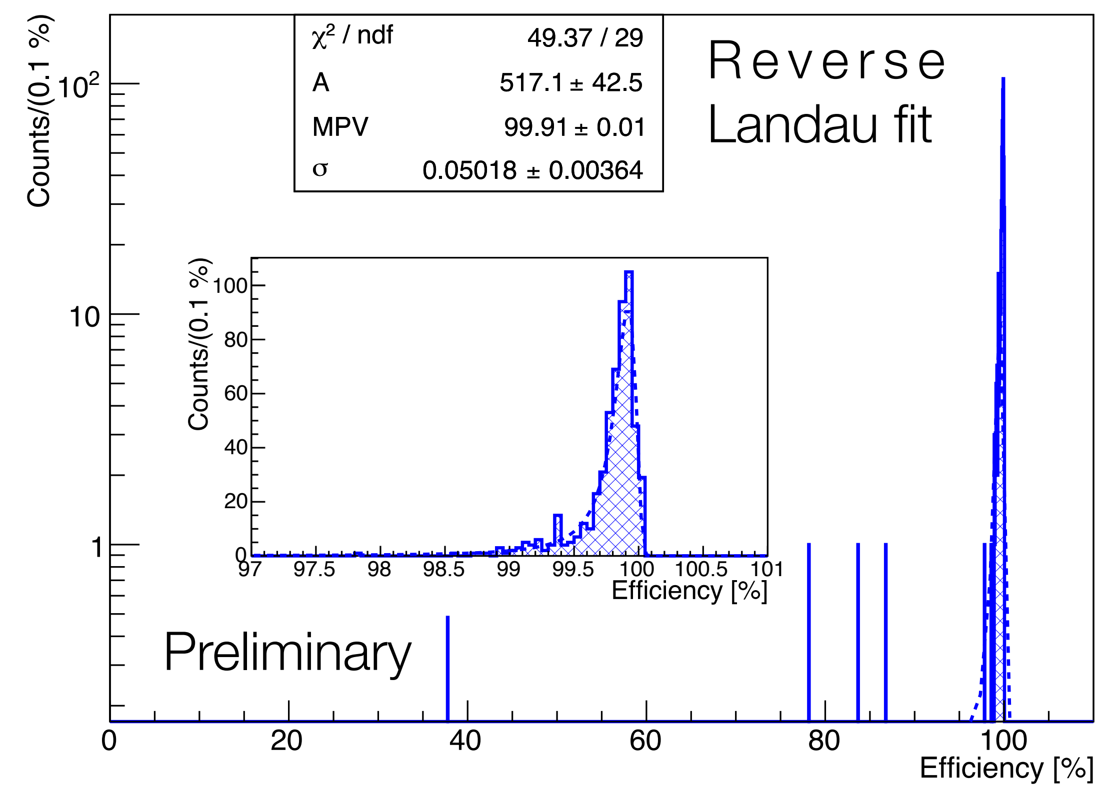
Trigger logic:

set in this way to increase the trigger rate

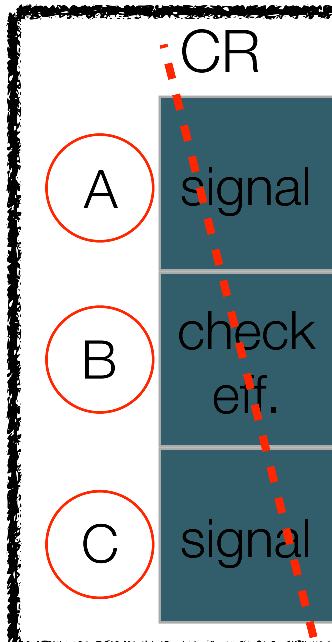
SUs efficiency using CRs



Light yield varies w/ temperature (-0.9%/°C) → efficiency may vary



At ≈17.5 MeV (CRs energy loss in SU) and 15.3 pC/MeV, ECal efficiency is ≈100%



Efficiency evaluation

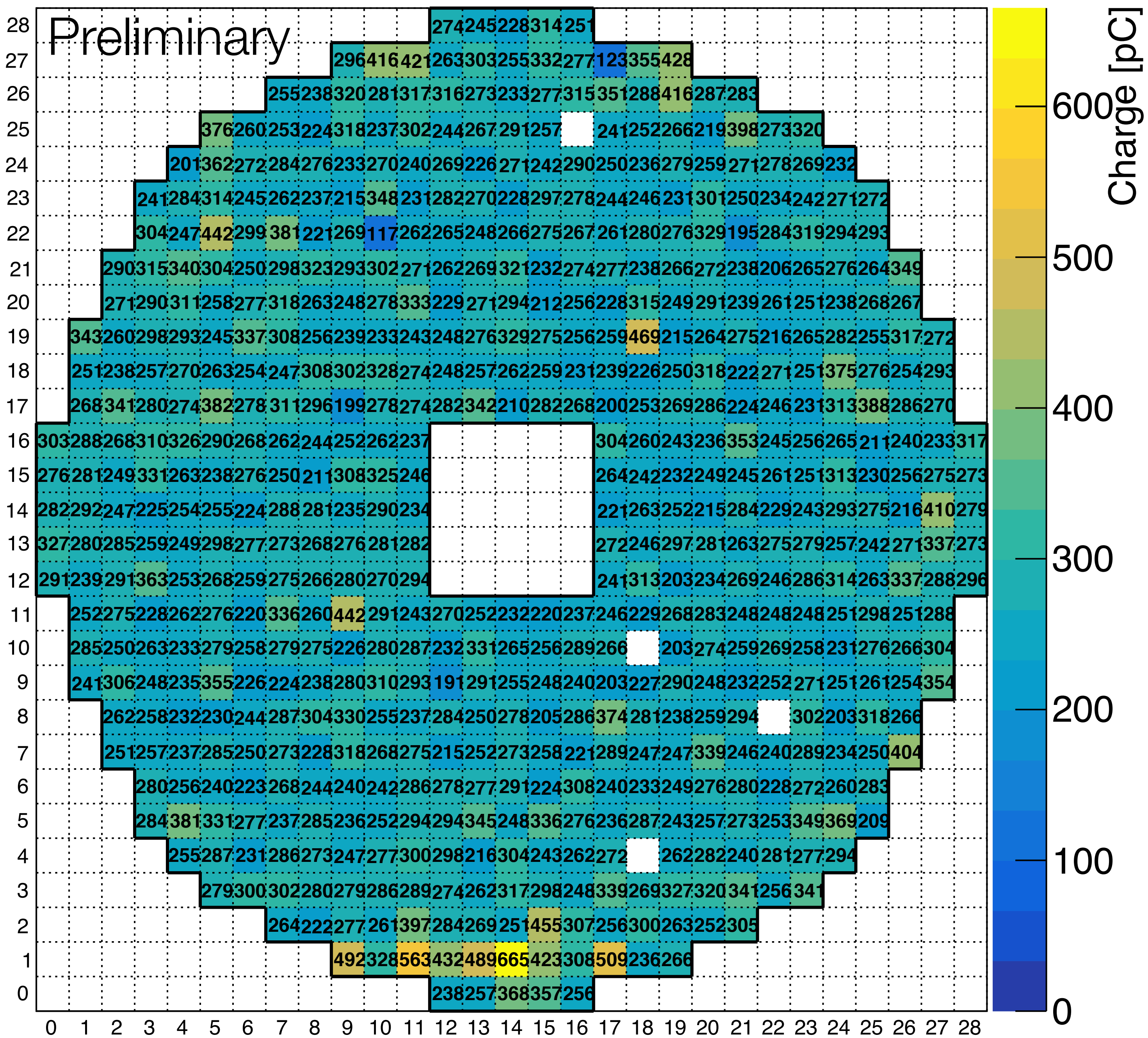
$$Eff_{\mathbf{B}} = \frac{\mathbf{A} \cap \mathbf{B} \cap \mathbf{C}}{\mathbf{A} \cap \mathbf{C}}$$

It is not possible to evaluate efficiency for a SU on the border

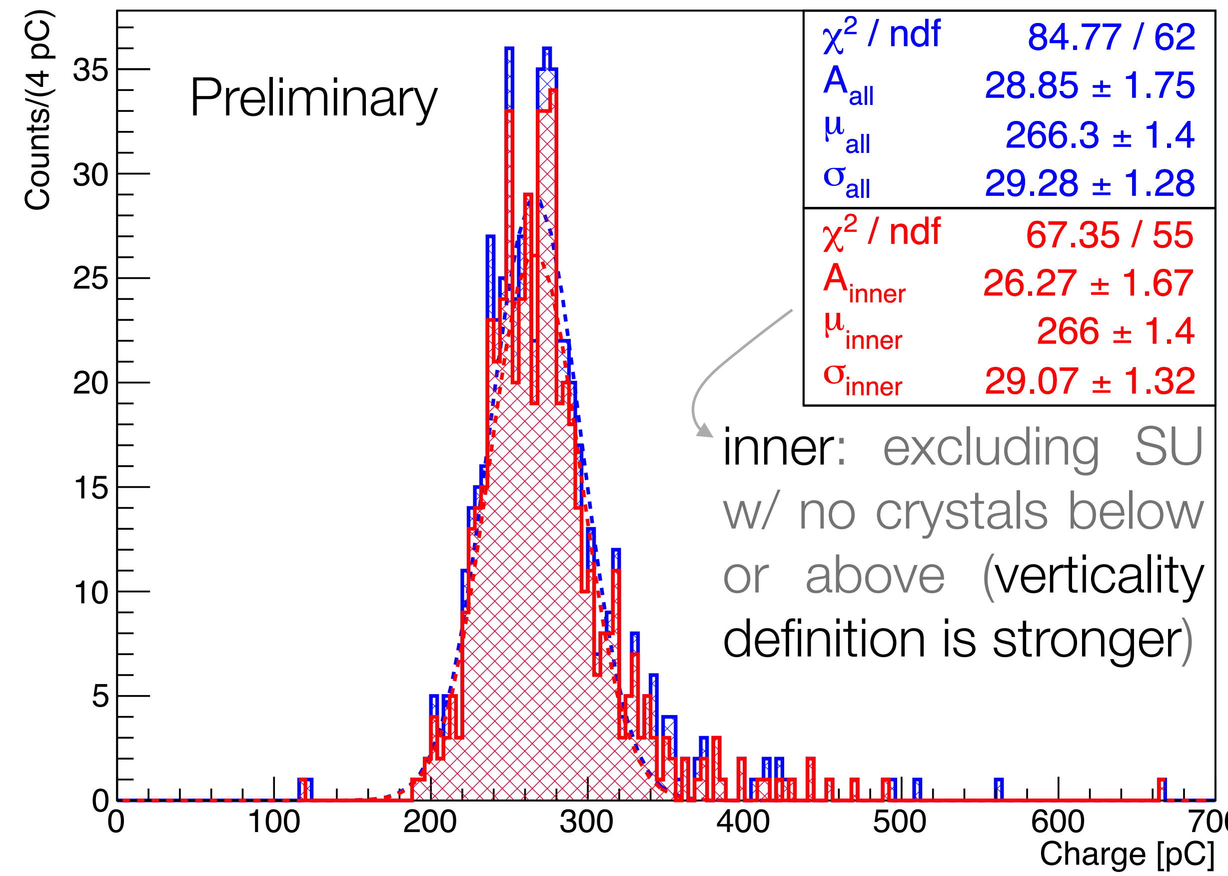
Vertical CRs charge spectrum MPV in SUs

All cosmic charge distributions are fitted w/ a Landau (for verticality see backup)

MPVs map



MPVs distribution

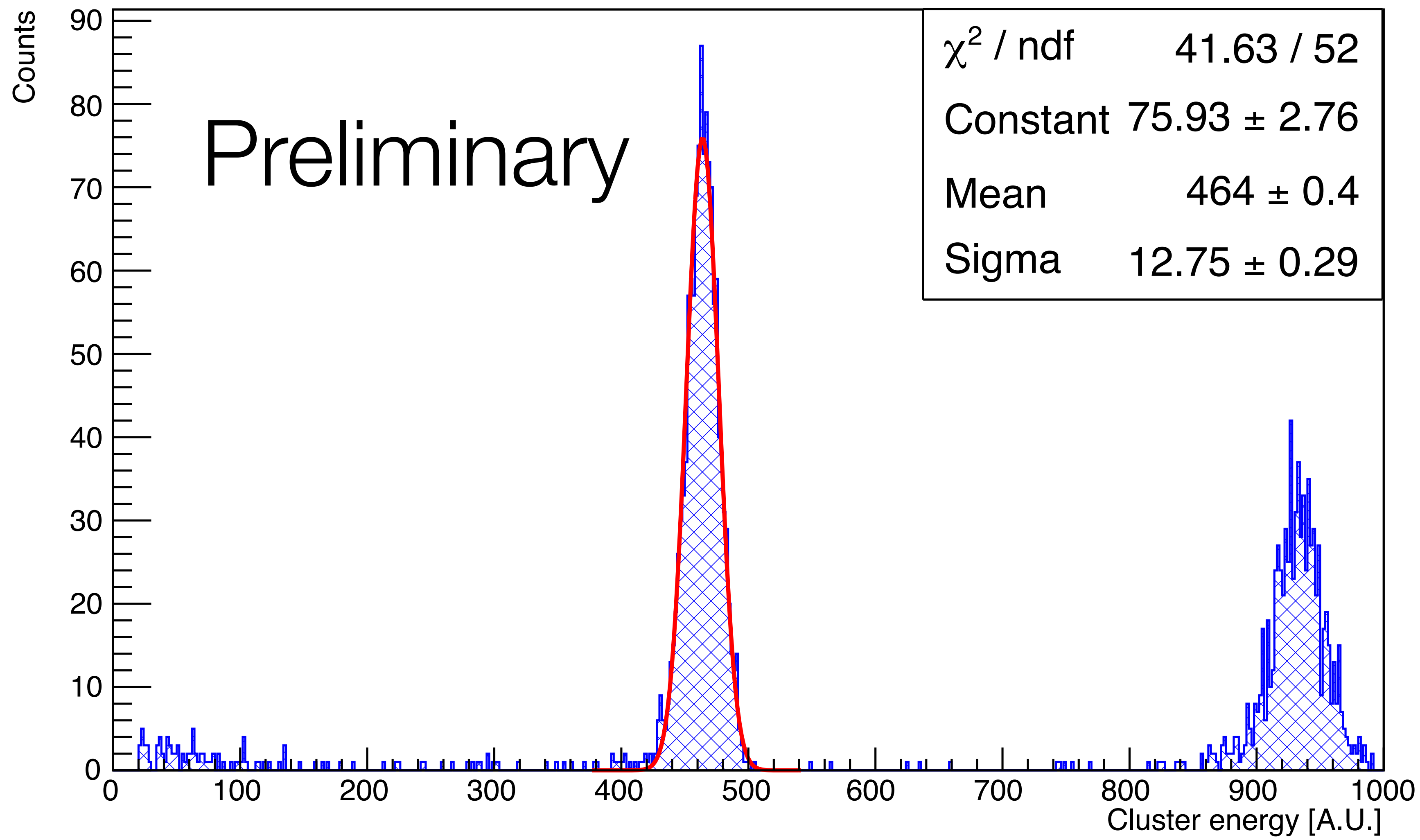


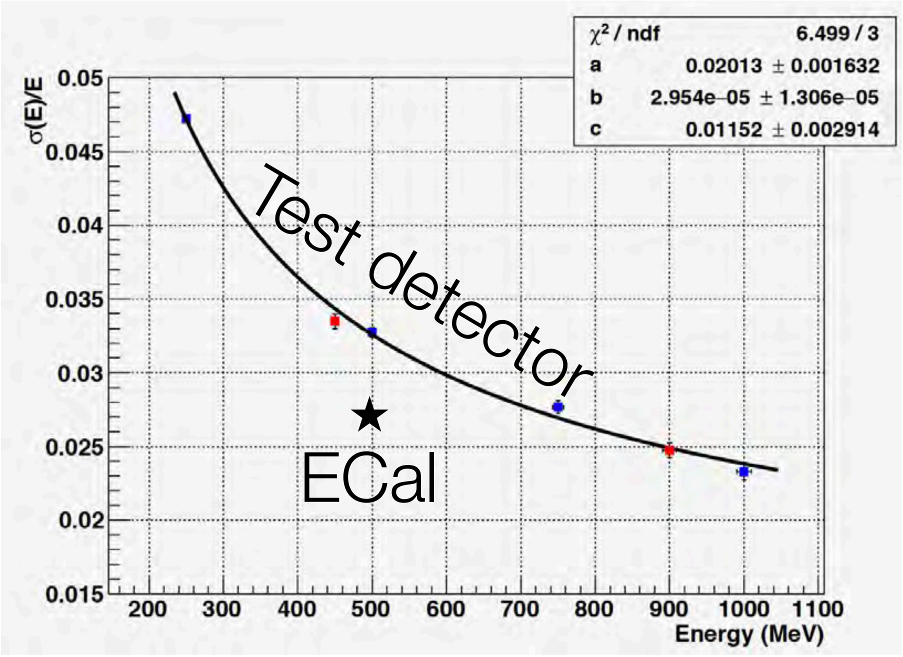
- At ≈17.5 MeV (CR energy loss in SU) and 15.3 pC/MeV, ECal gain equalisation is 29.28/266.3 = 11%
- Charge MPVs used to improve energy resolution w/ SUs charge equalisation

Light yield varies w/ temp. (-0.9%/°C) → MPVs may vary → temperature monitoring

ECal energy resolution

Energy resolution has been evaluated using a beam w/ a single e+ per bunch directly on ECal and applying a simple clusterisation algorithm





NIM A, 862 (2017) 31

Energy resolution is better than the one obtained w/ a test detector, which was already within our goal/L3 expectation

Energy resolution at 490 MeV is 12.75/464 = 2.7%
(including the beam energy spread)

Conclusions

- Dark Photon is predicted by many physics models, that could explain different experimental observations: Dark Matter, $(g-2)_\mu$, ^8Be 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 component of the detector
- Scintillating units performances
  - very low threshold ≲ 0.5 MeV
  - good stability w/ variations < 3% (mean value: 0.6%)
  - efficiency (using CRs): ≈100%
- Electromagnetic calorimeter performances
  - gain equalisation at 15.3 pC/MeV from the ^{22}Na calibration (using CRs): 11%
  - good energy resolution: 2.7% at 490 MeV (including the beam energy spread), even better than prototype results

Don’t miss our posters!

I. Oceano: “The performance of the diamond active target of the PADME experiment”

F. Oliva: “Performance of the charged particle detectors of the PADME experiment”

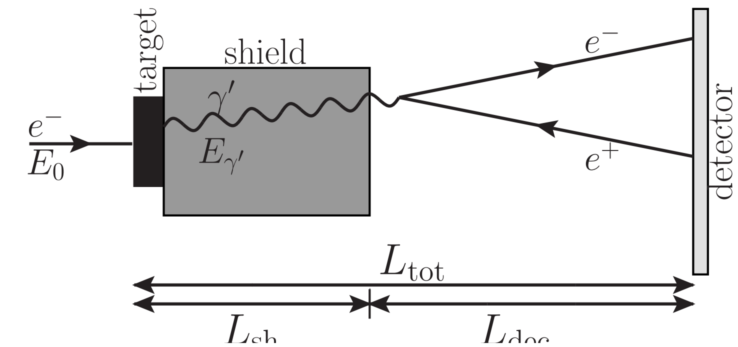
Backup

Dark Photon searches

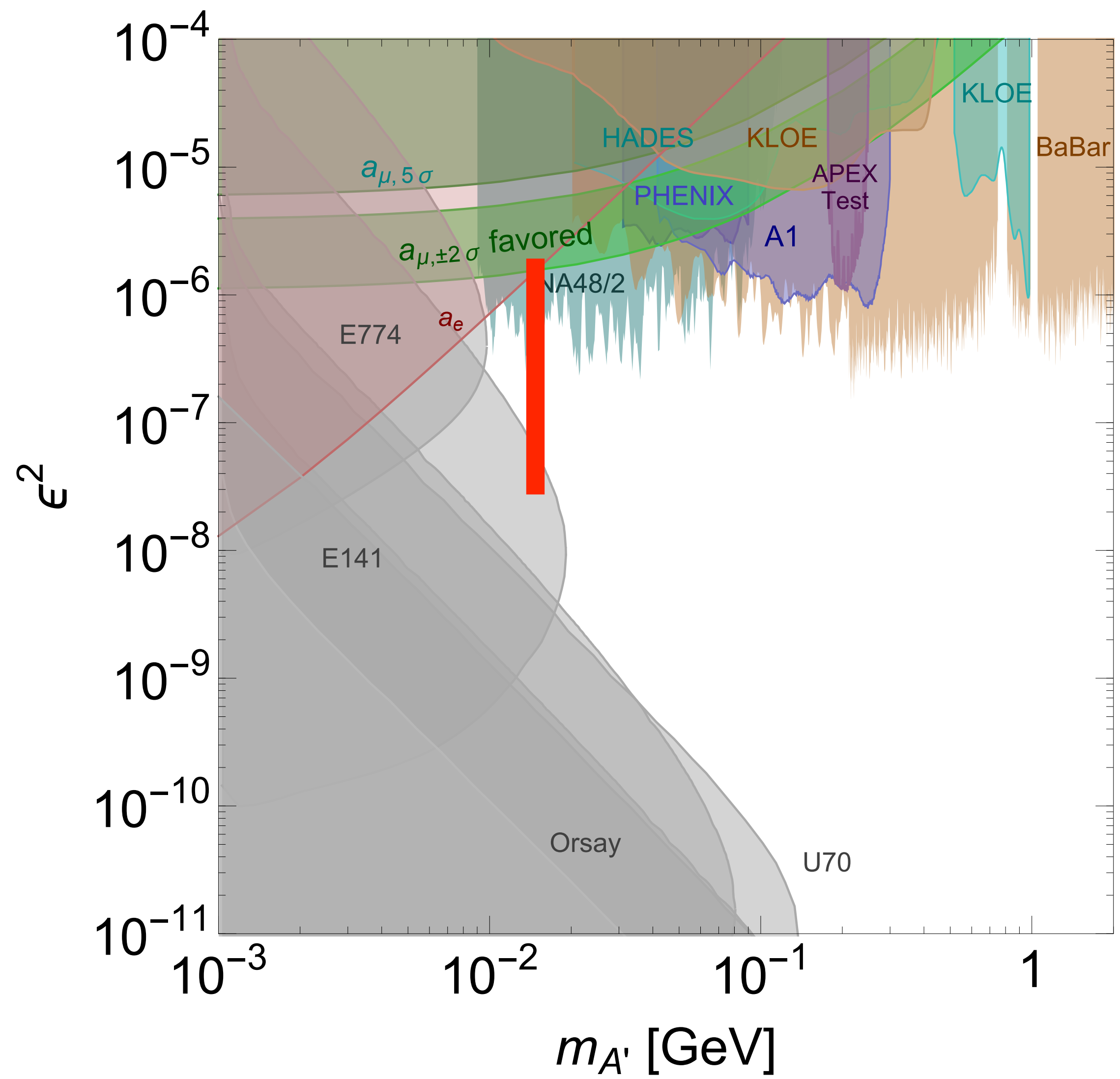
Visible search status

Techniques:

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



- fixed target (bremsstrahlung, annihilation)
  - bump hunt in invariant mass spectrum, displaced vertices



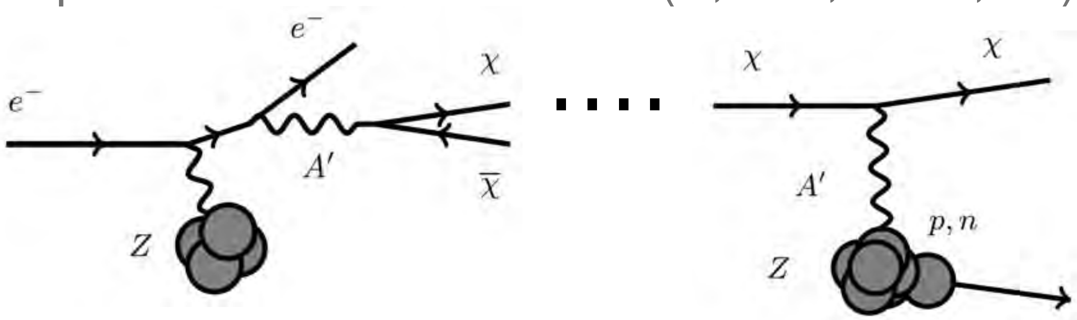
- meson decay
  - only if A' couples w/ quarks
  - old experiments reanalysis

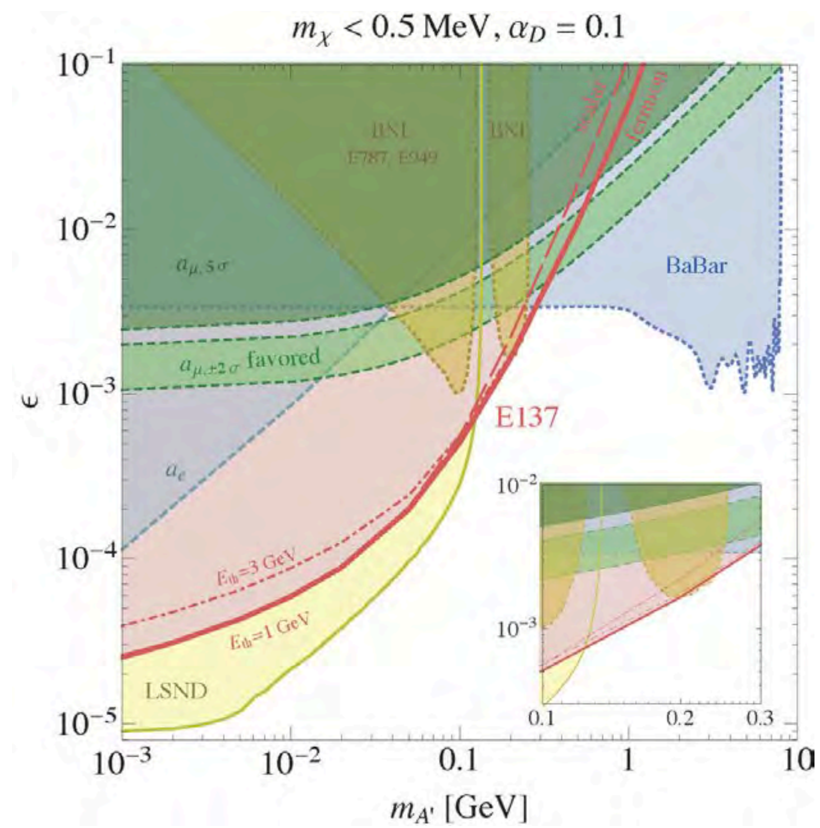
(g-2)$_\mu$ excluded in the simplest model, but still a lot of interest. In particular the ^{8}Be anomaly.

Invisible search status

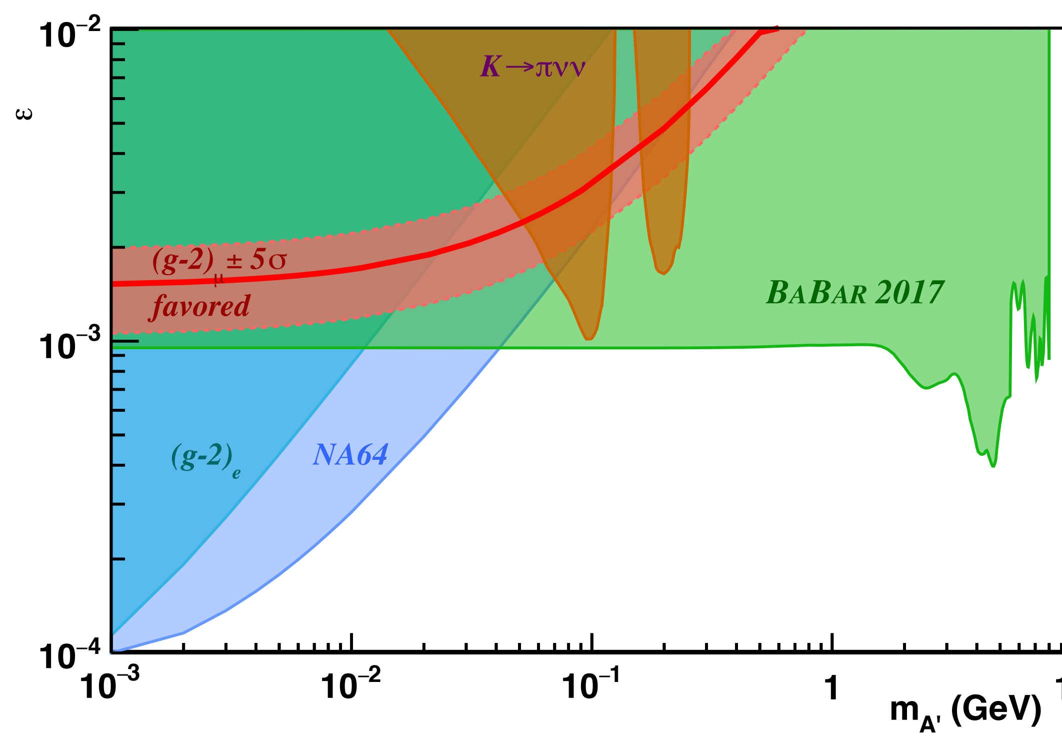
Techniques:

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





- missing energy/momentum search (bremsstrahlung)
  - not kinematically constrained process
  - observed energy/momentum smaller than expected



Not directly comparable

- missing mass search (annihilation)
  - kinematically constrained process
  - no assumption on A' decay chain

Scintillating material selection

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

2nd best choice, for free from L3

best choice, but very expensive

BGO emission spectrum

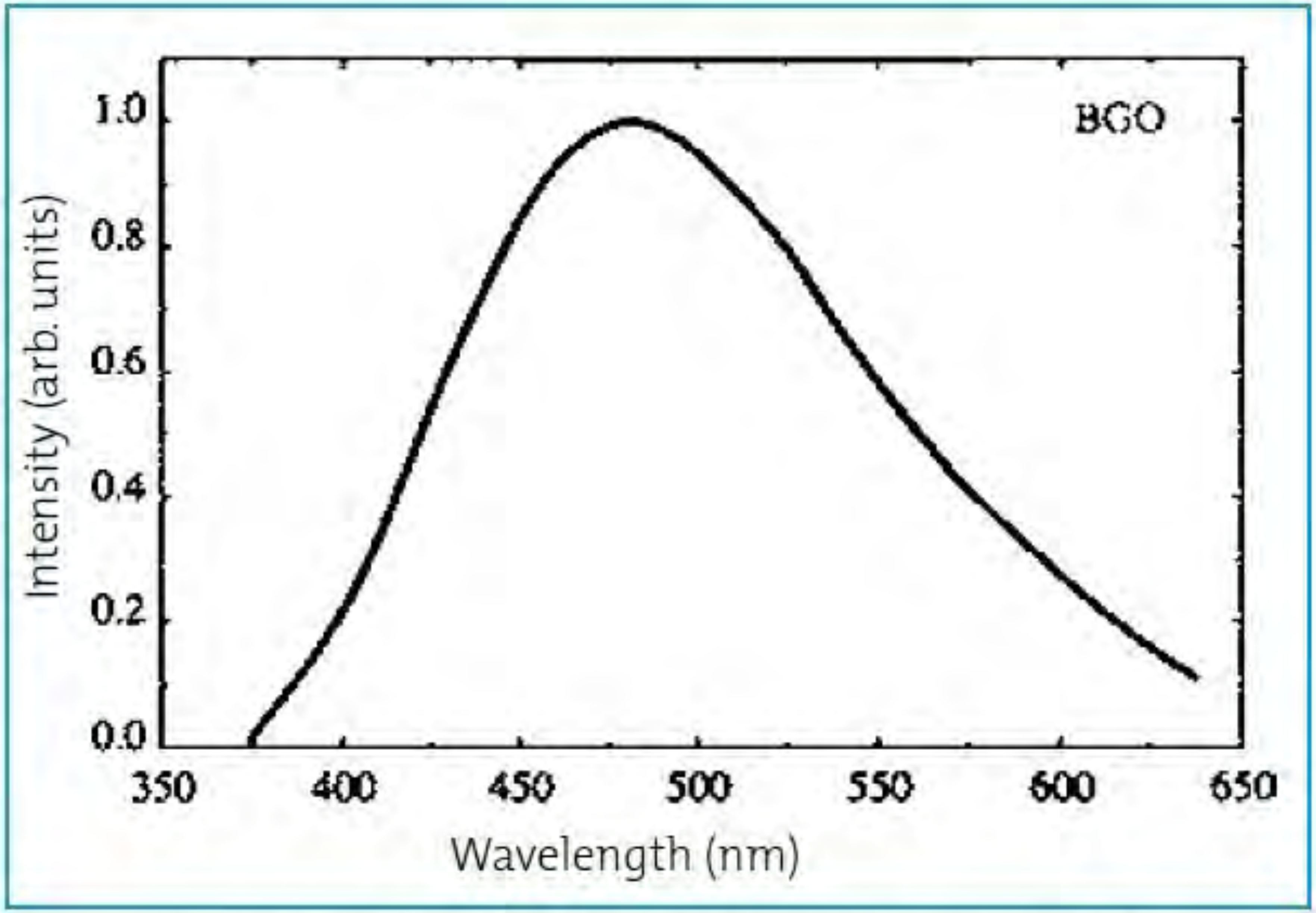
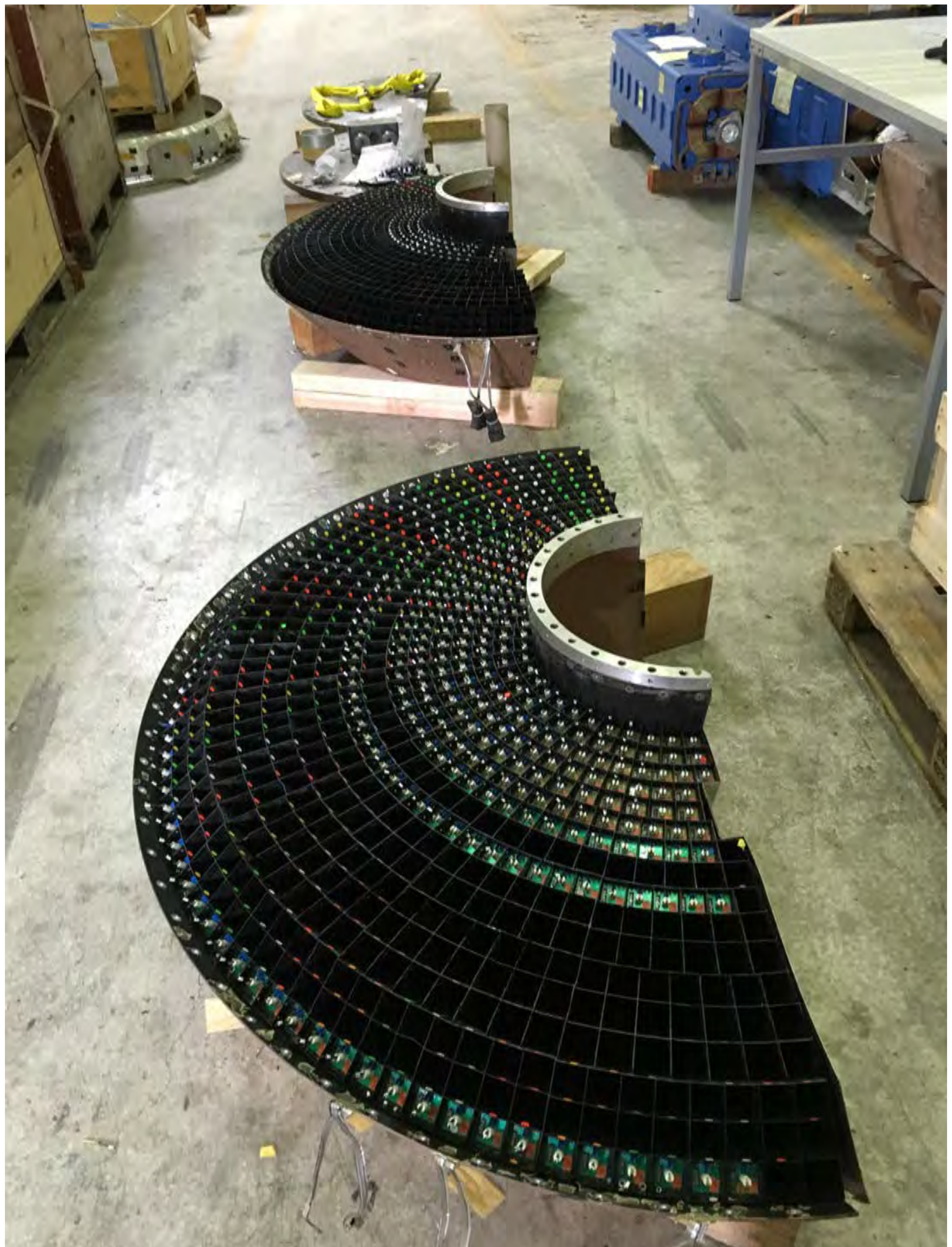


Figure 1. Scintillation emission spectrum of BGO

Crystal procurement

L3 half-endcaps where crystals are…



…taken

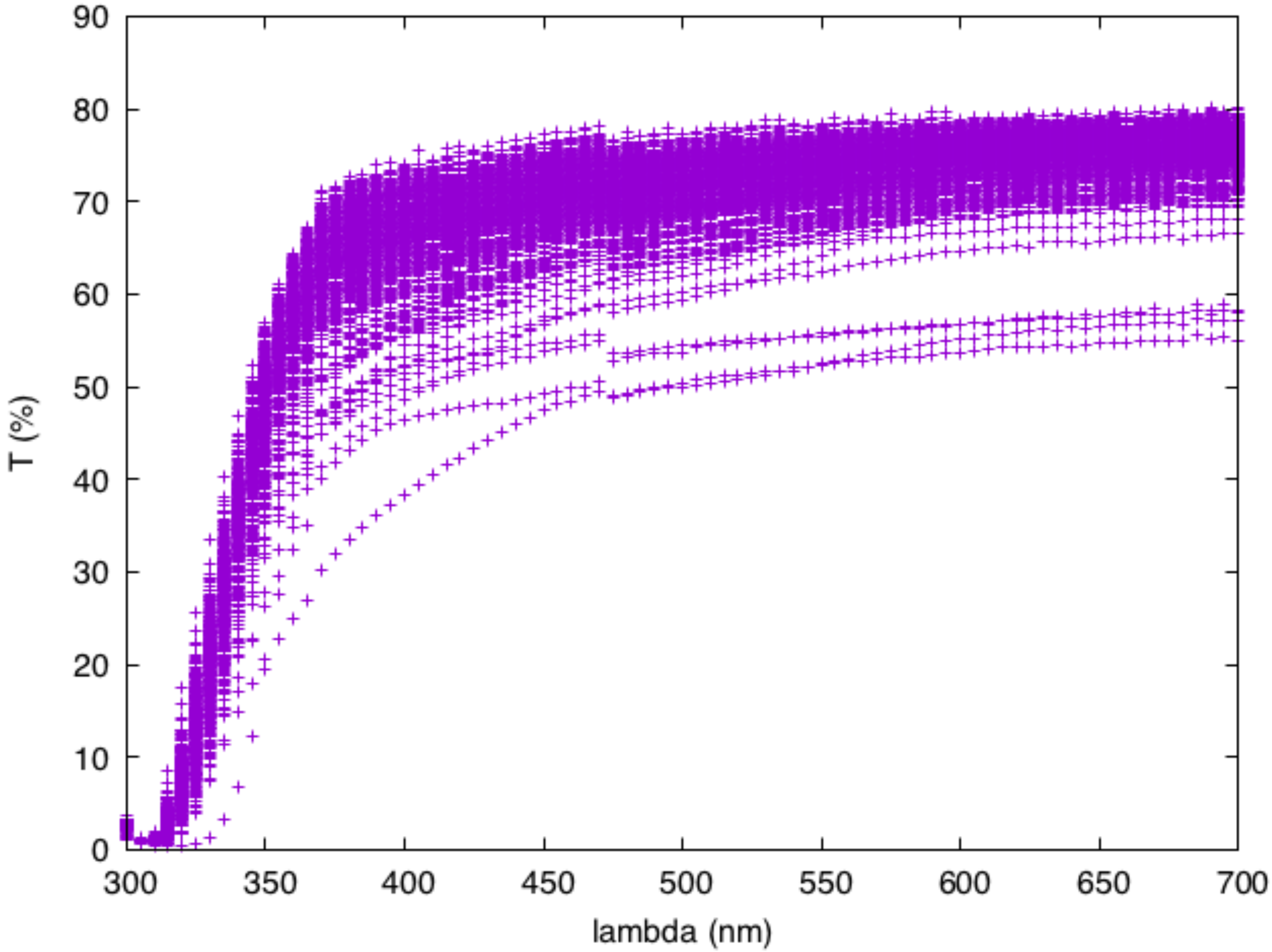
Crystal optical properties

After crystal selection the following steps are executed:

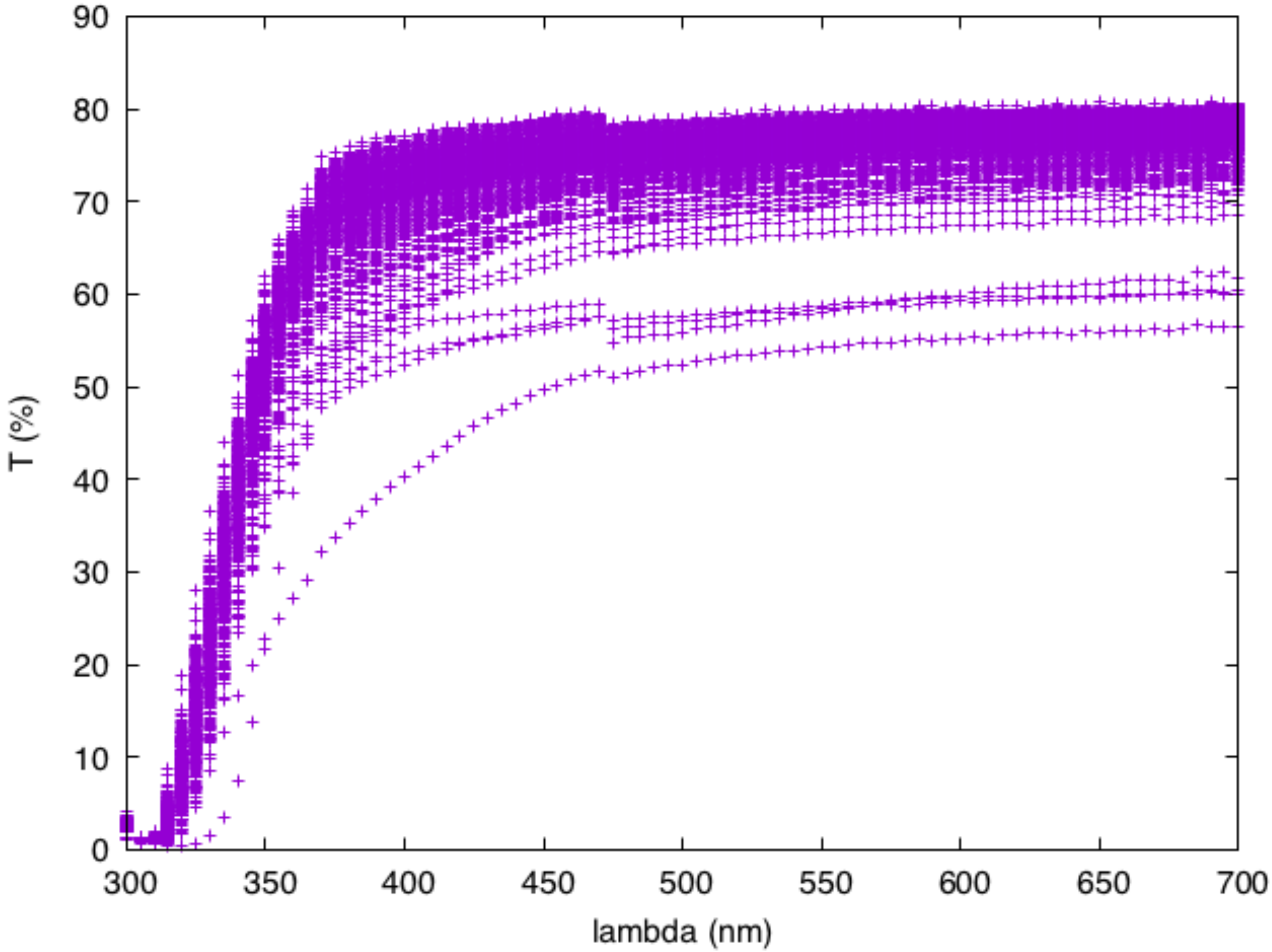
- Photosensor removal (mechanically after 48h in acetone)
- Paint removal (w/ water)
- Transmittance measurement
- Annealing
  - T_{amb} → 200 °C in 3 h
  - 200 °C for 6 h
  - 200 °C → T_{amb} “natural”
- Transmittance measurement

Everything is performed at CERN at LAB27

Transmittance before annealing

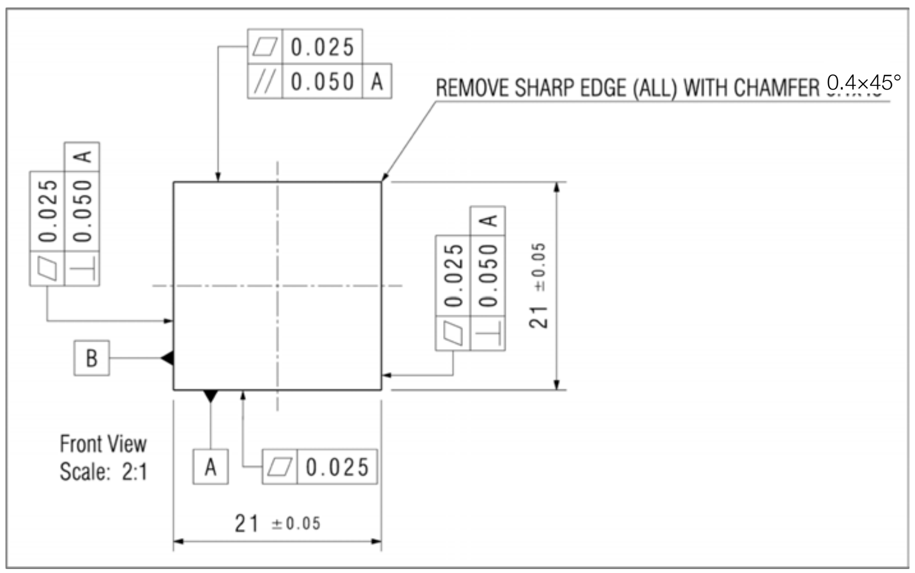


Transmittance after annealing



Crystals cut and polished at SILO (Italy)

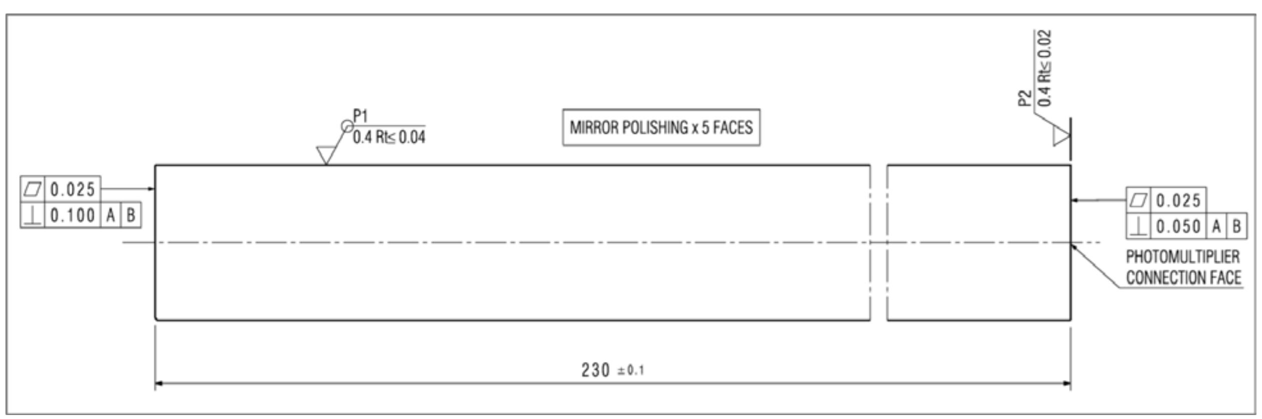
They produced identical parallelepipeds starting from different truncated pyramid shapes (L3 endcaps geometry was pointing)



Planarity

Parallelism

Perpendicularity



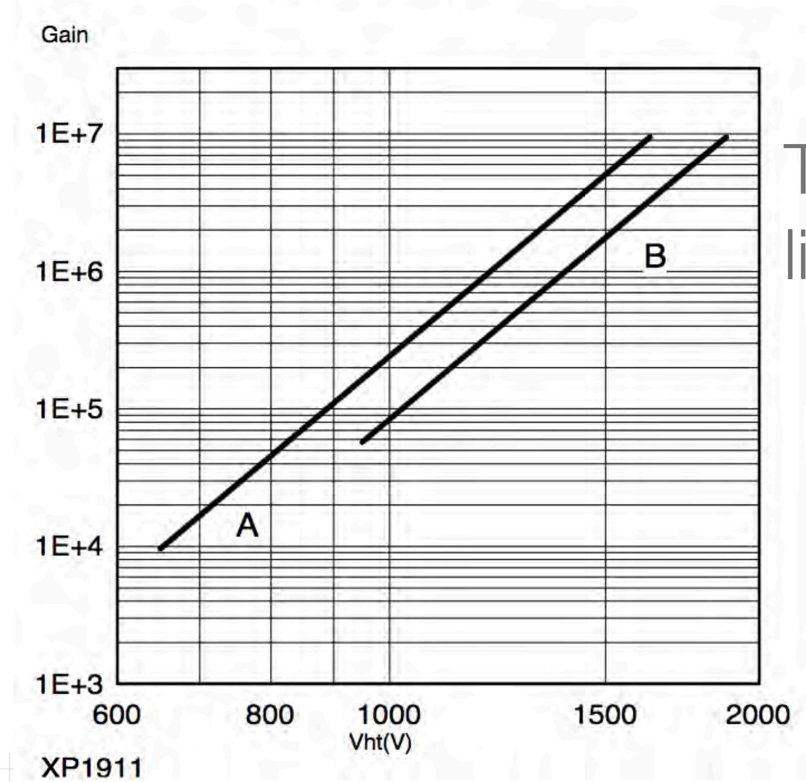
Mechanical tolerances (more stringent limits are set for the square shape)

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

HZC XP1911

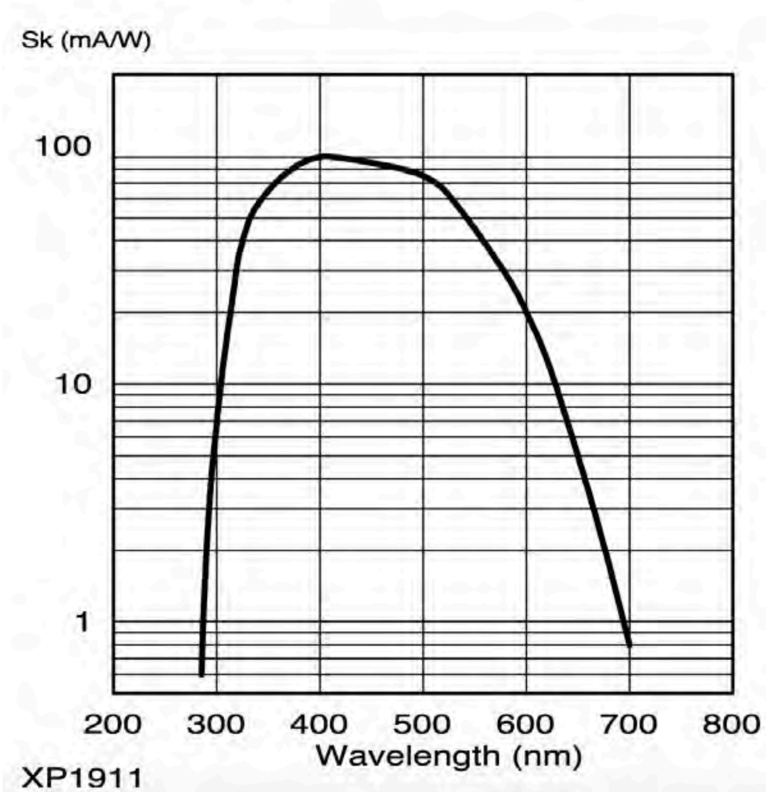
We modified the mechanical design

Typical gain curve

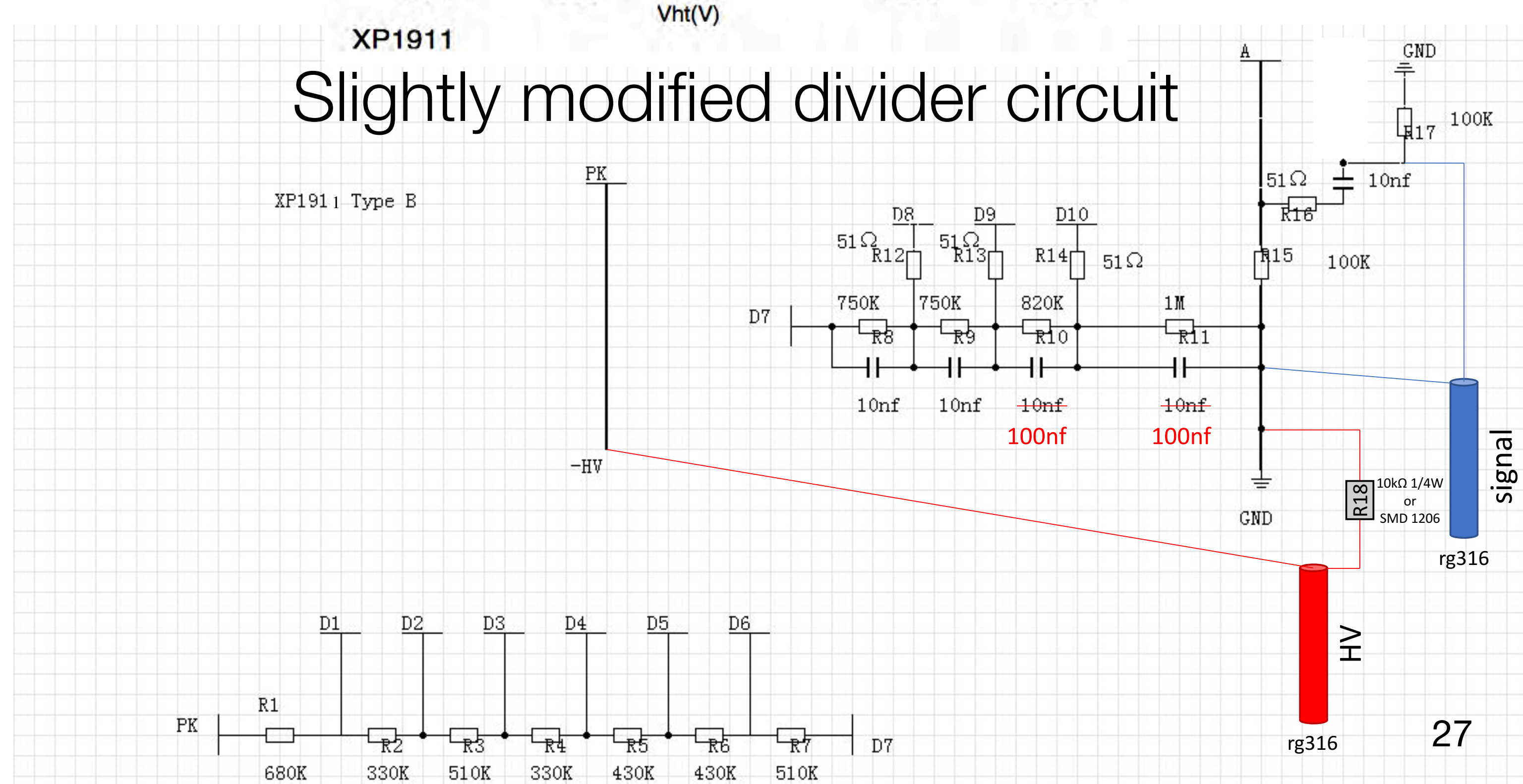


Type B: higher linearity

Typical spectral characteristics

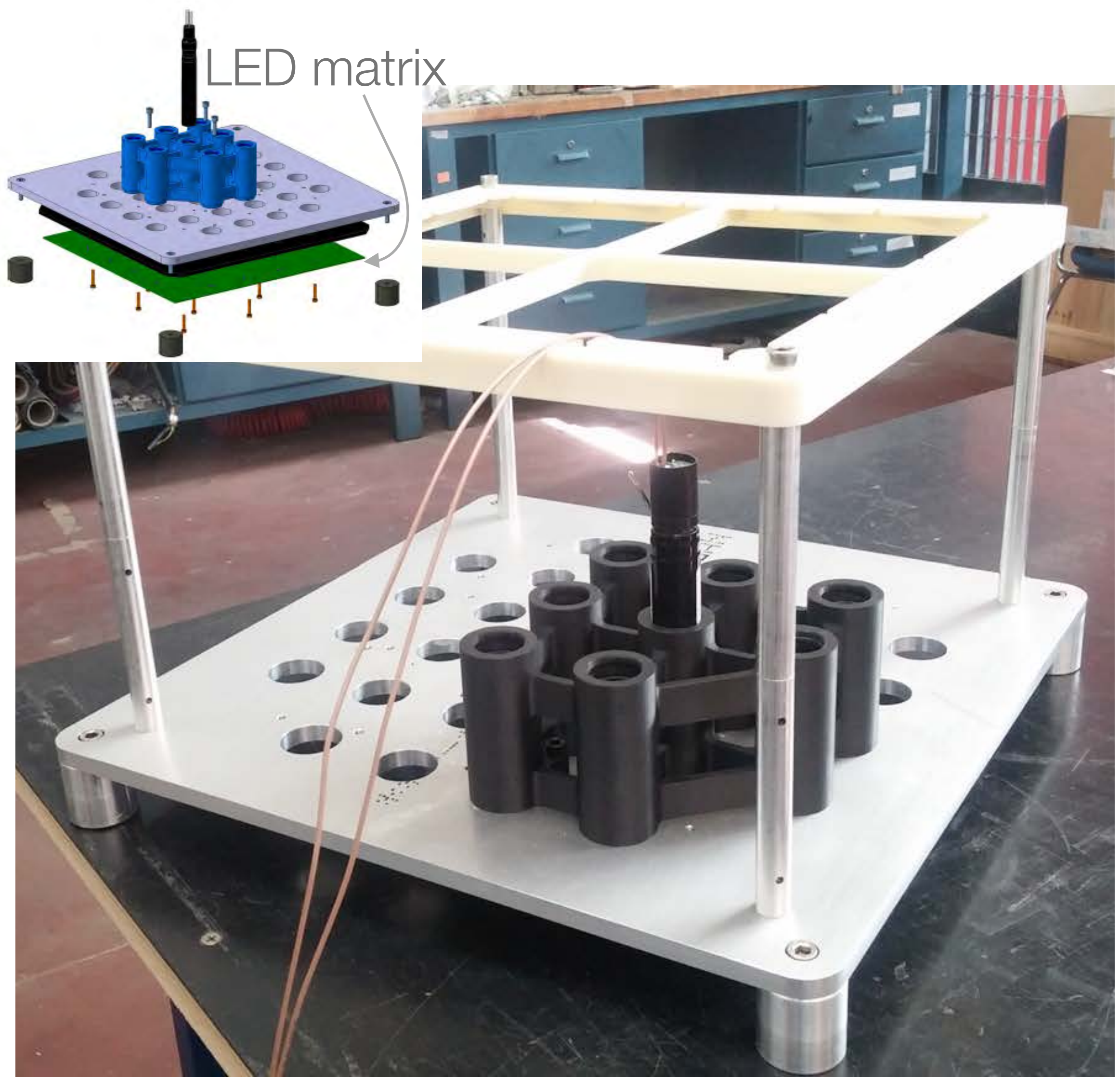


Slightly modified divider circuit



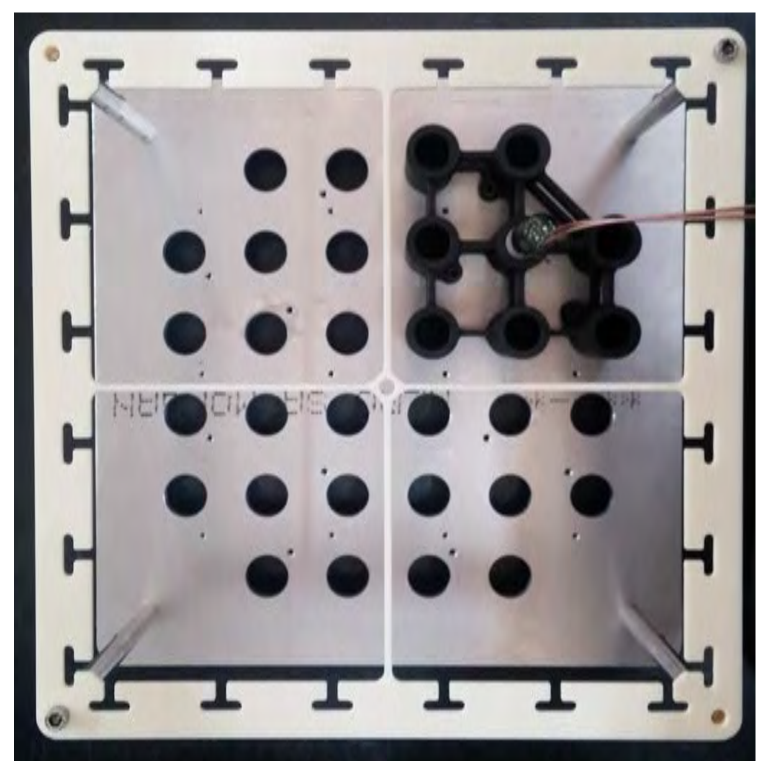
PMTs test

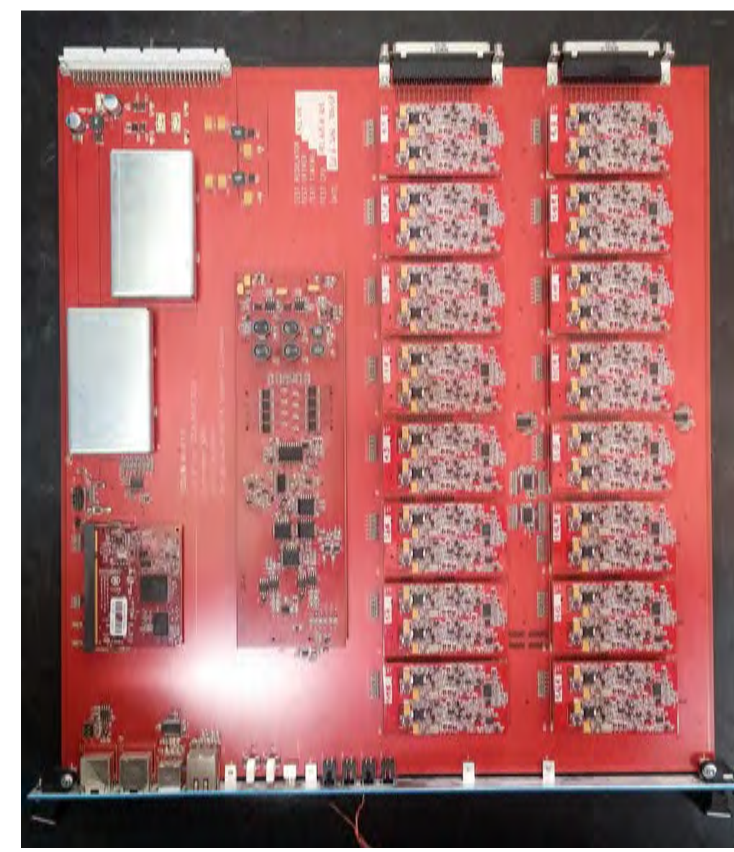
32 **PMTs** at a time were **tested w/ a LED matrix** (one per tube):
pulsing the LEDs we see if the PMT works and its response to the light.
If results are good, tubes are sent to SILO for gluing.



Mechanics for PMTs test

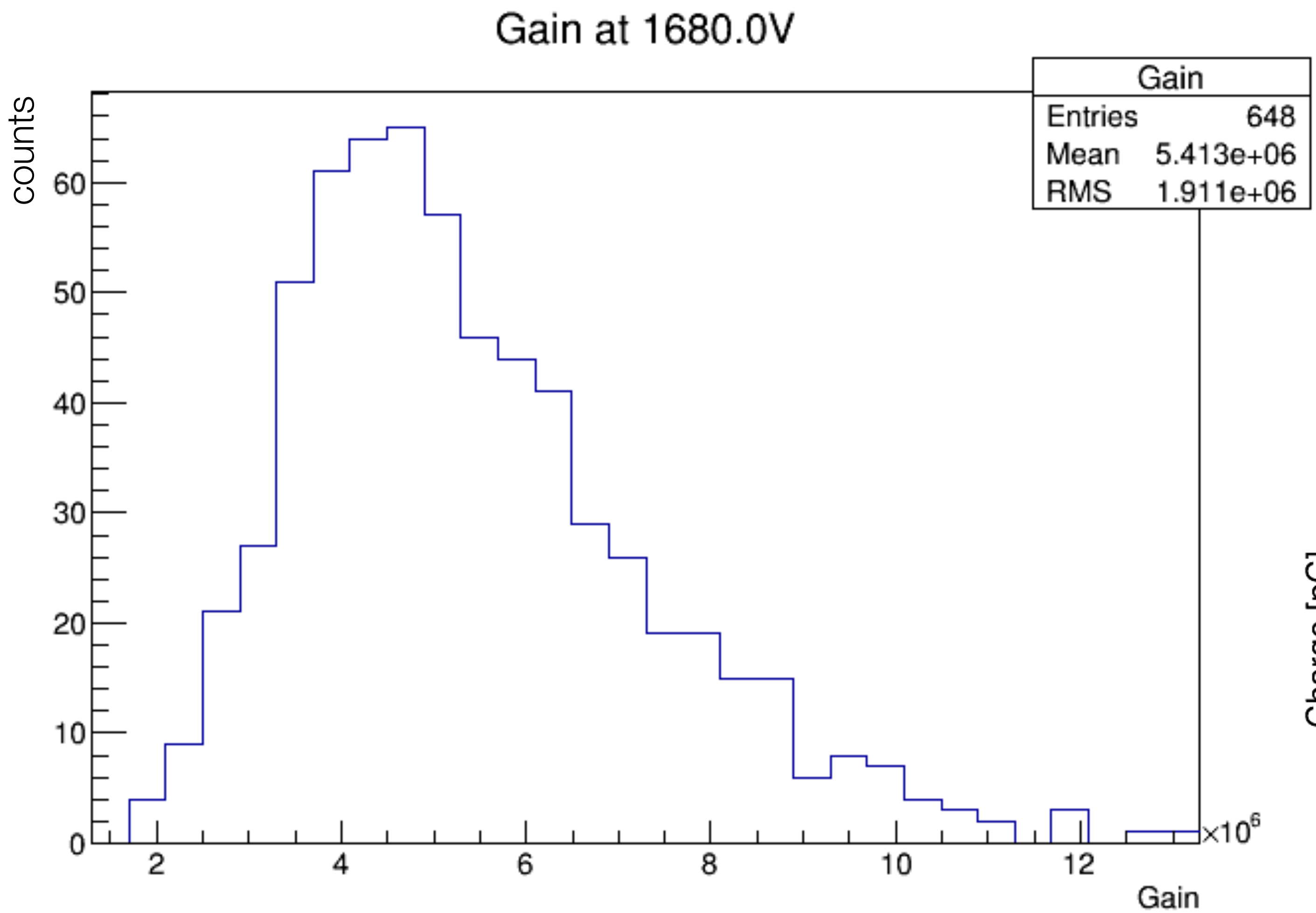
Mechanics top view

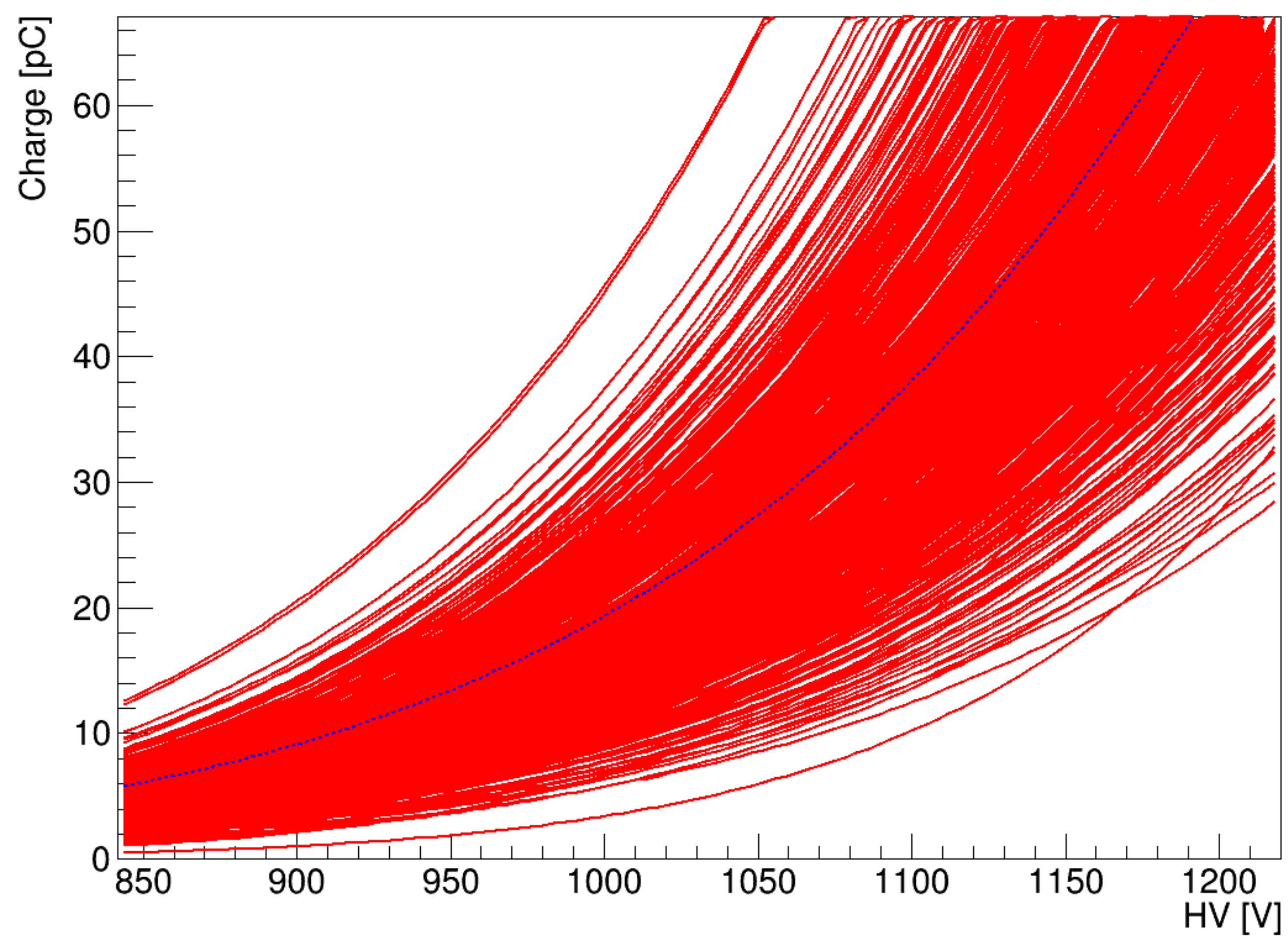




LED driver board

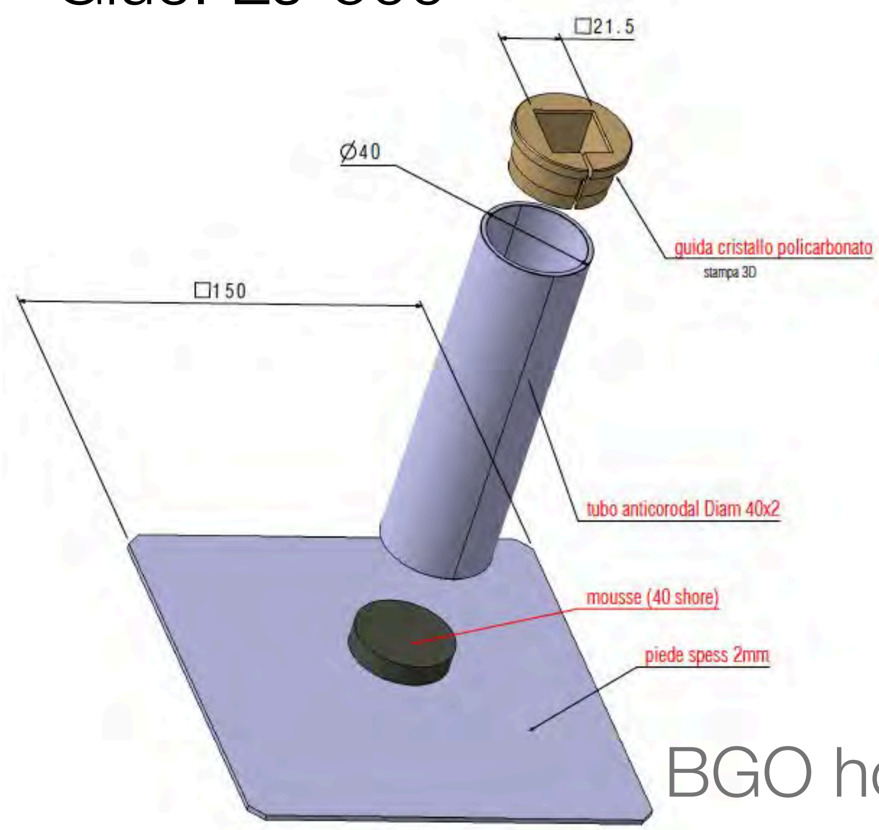
Global PMT results



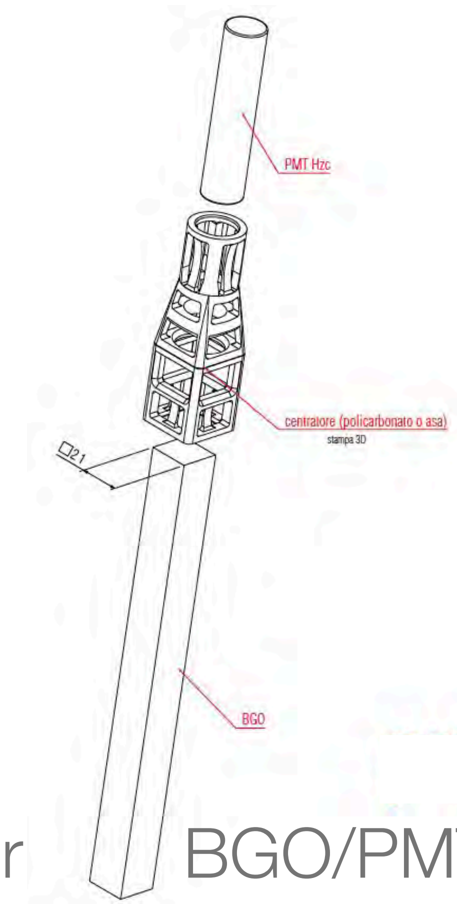


Gluing and painting at SILO

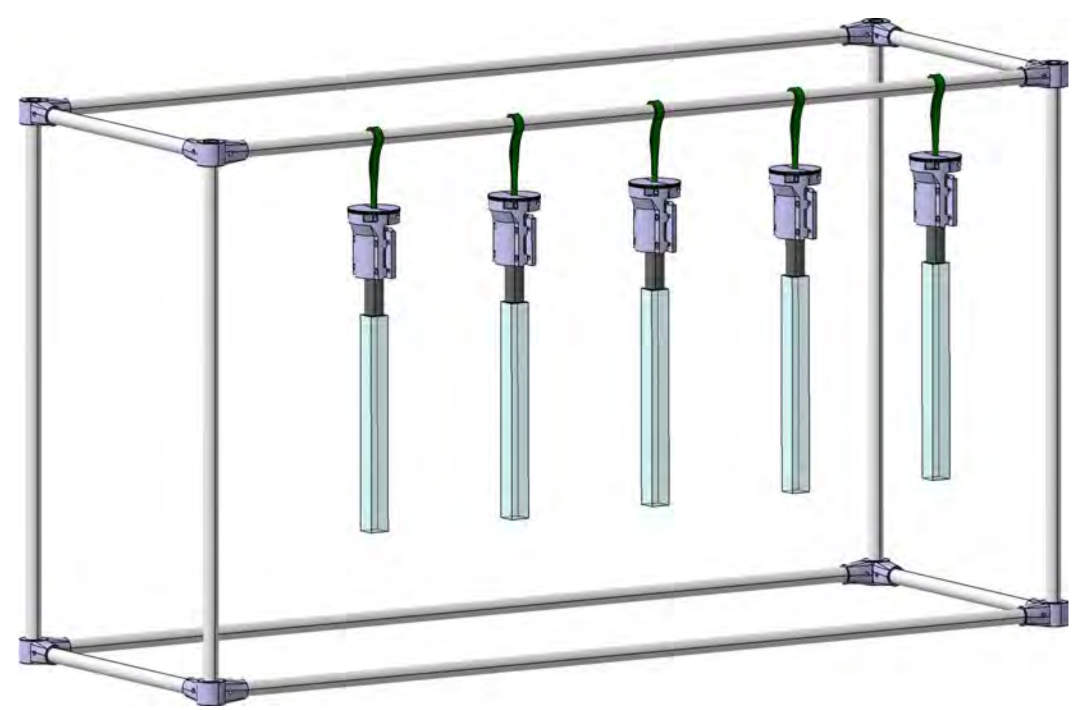
- Glue: EJ-500



BGO holder



BGO/PMT centering

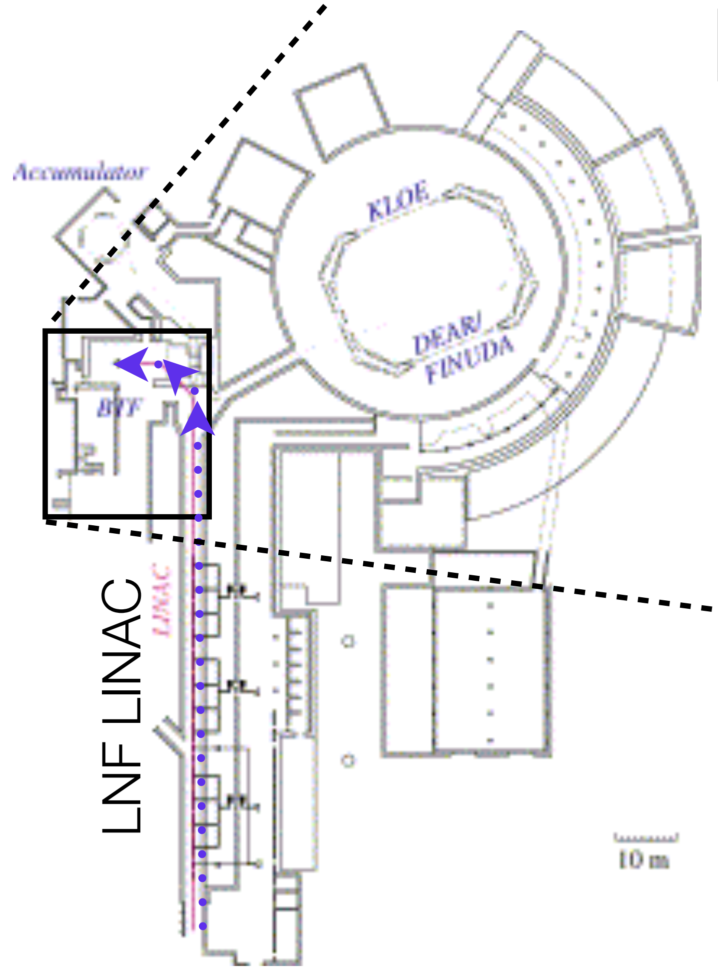


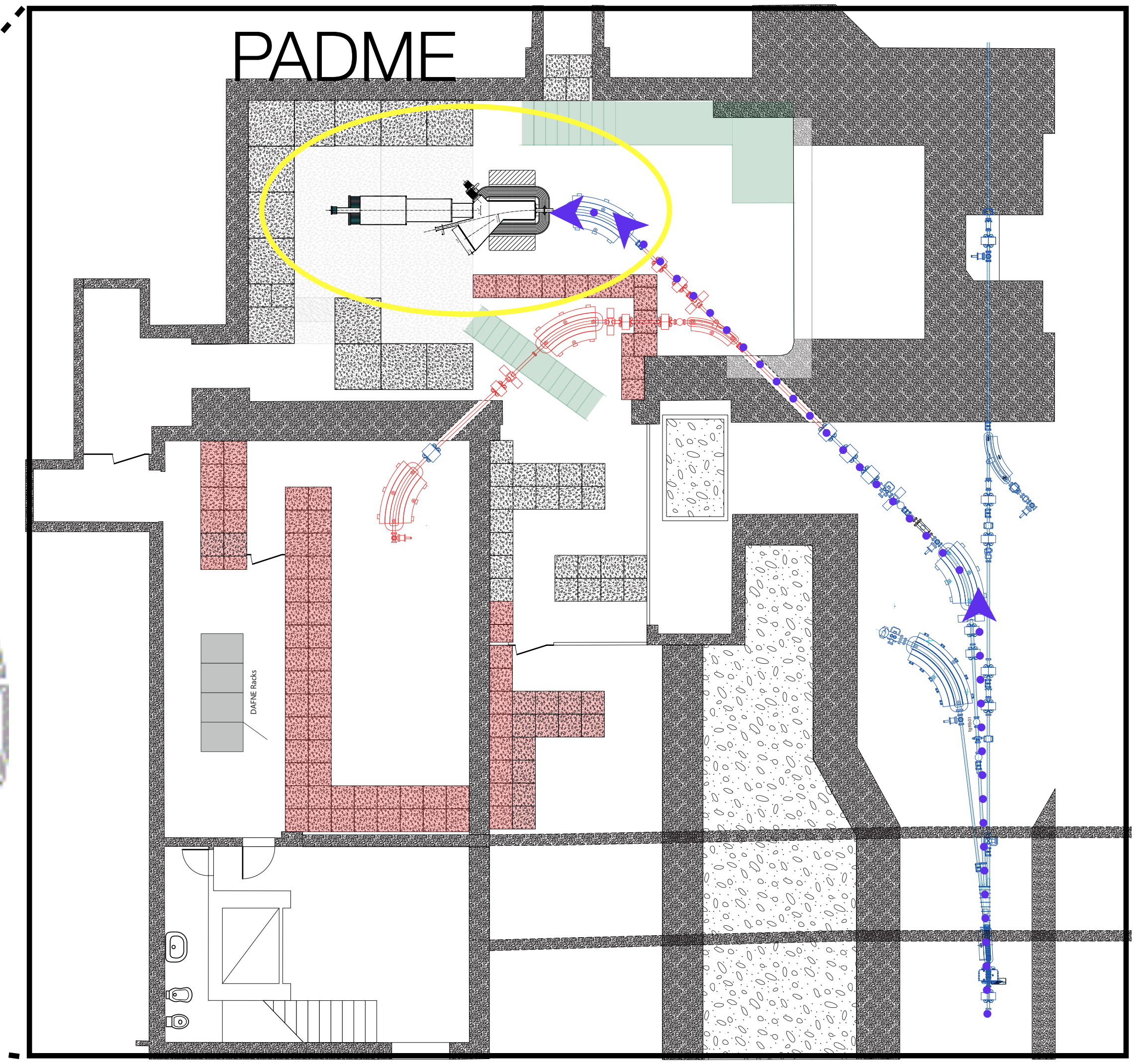
- Paint: EJ-510
- 3 layers of white paint (≈100μm)

The LNF Beam Test Facility (BTF)

PADME experimental hall 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:

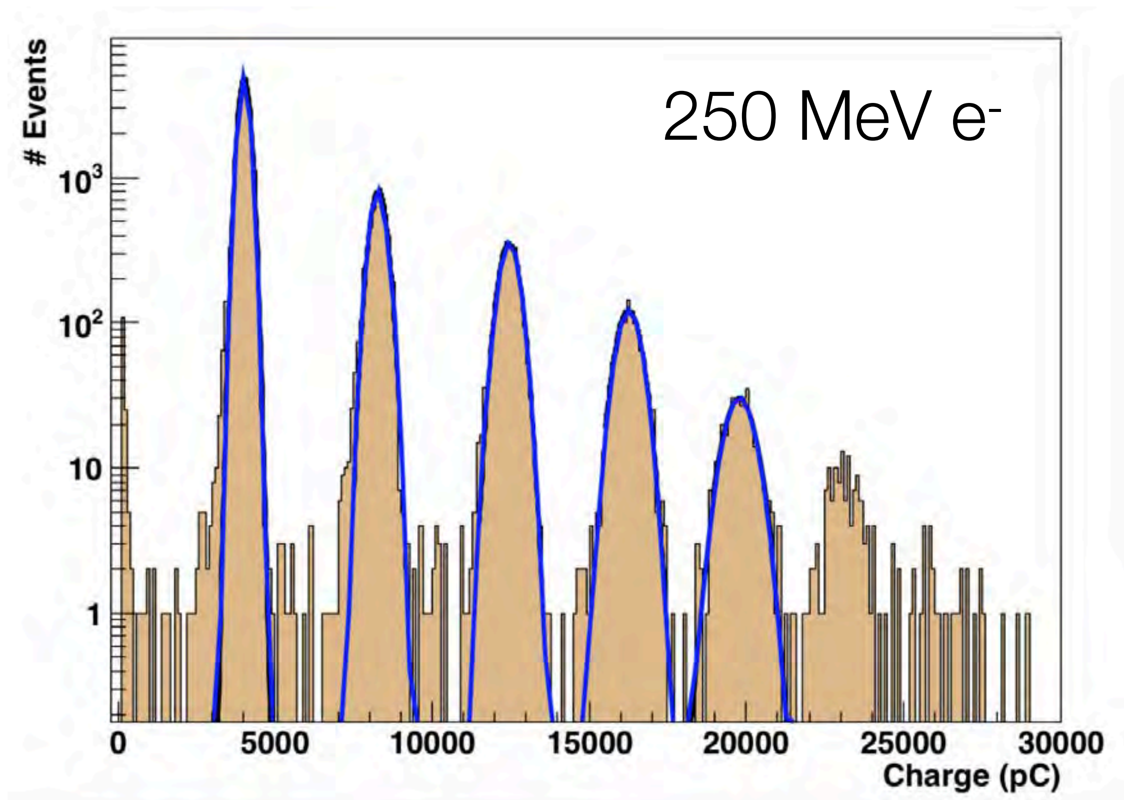
- < 5.5 m in length
- < 3 m in width

Beam Test Facility parasitic and dedicated modes

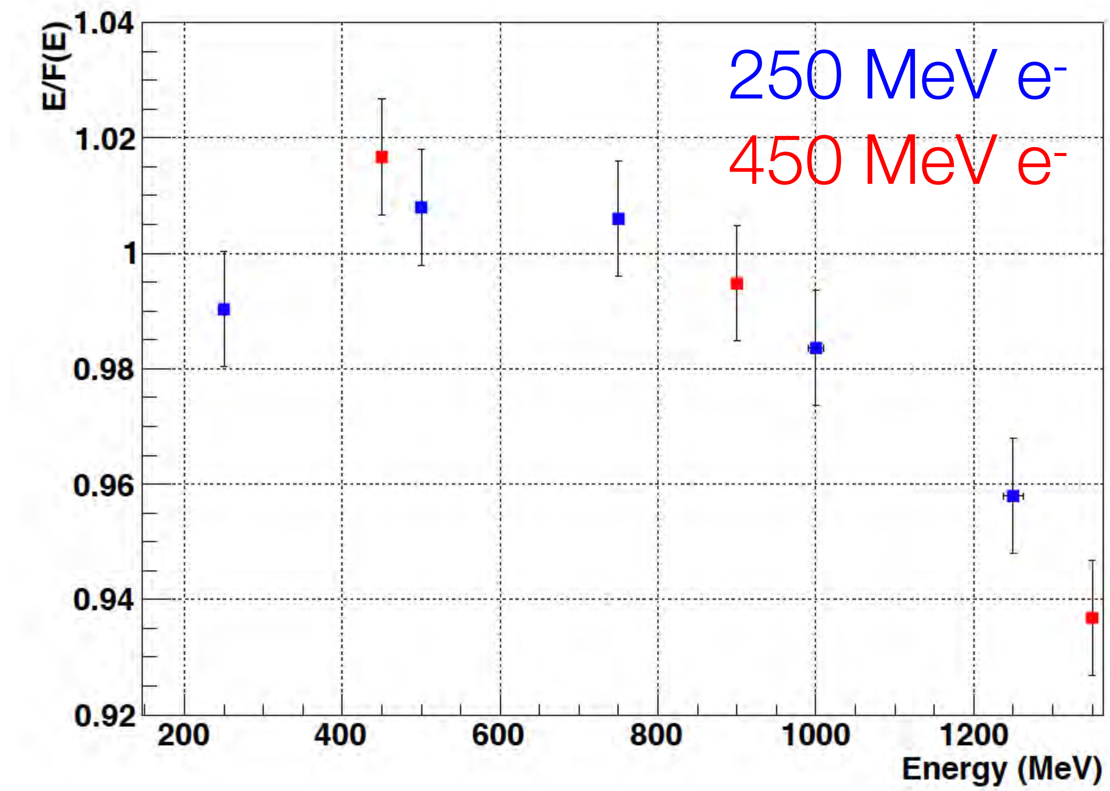
	Parasitic mode (DAΦNE working)		Dedicated mode	
	W/ target	W/o target	W/ target	W/o target
Particle species	e^+/e^- selectable by user	e^+/e^- depending on DAΦNE mode	e^+/e^- selectable by user	
Energy [MeV]	25-500	510	25-700 (e^+) 25-700 (e^-)	250-730 (e^+) 250-530 (e^-)
Energy spread	1% @ 500 MeV	1%	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			

Calorimeter prototype performance @ BTF

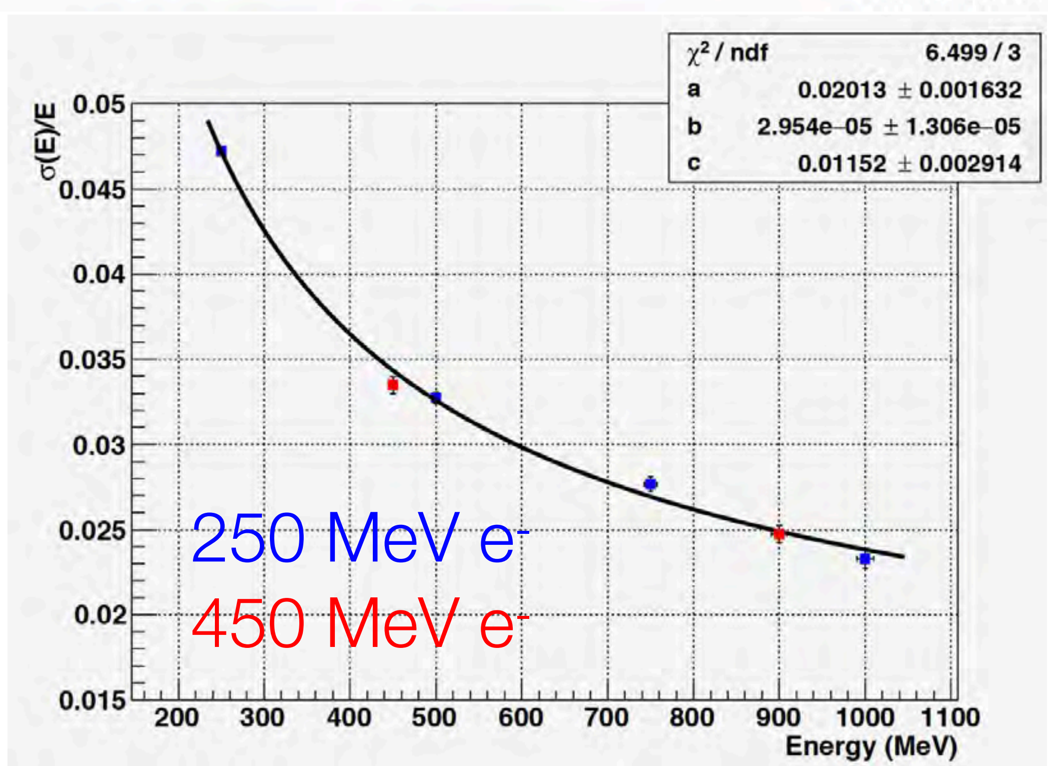
Charge spectrum



Linearity residuals



Energy resolution



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

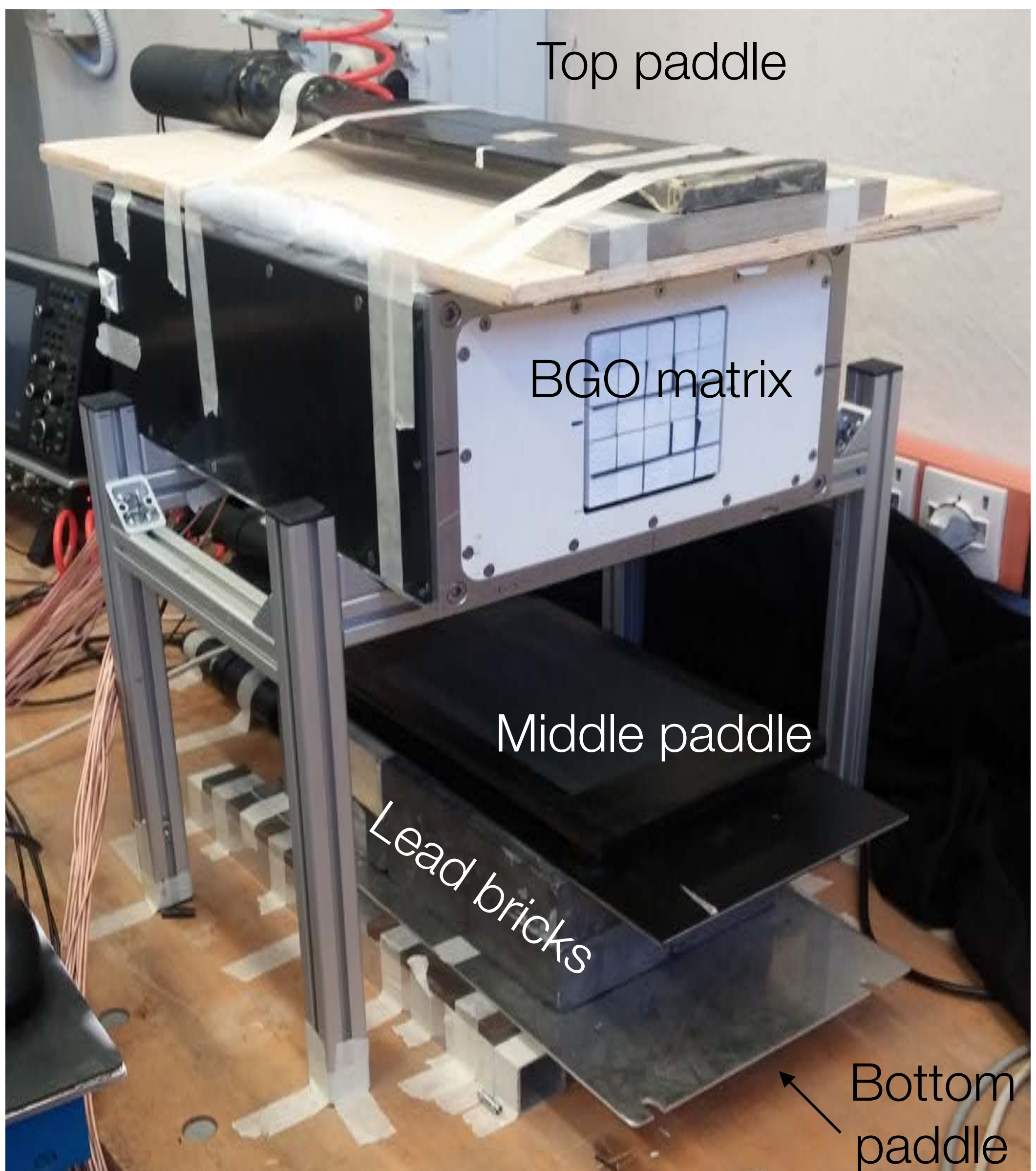
Energy resolution is within the expectation, w/ reference to the L3 experience

NIM A, 862 (2017) 31

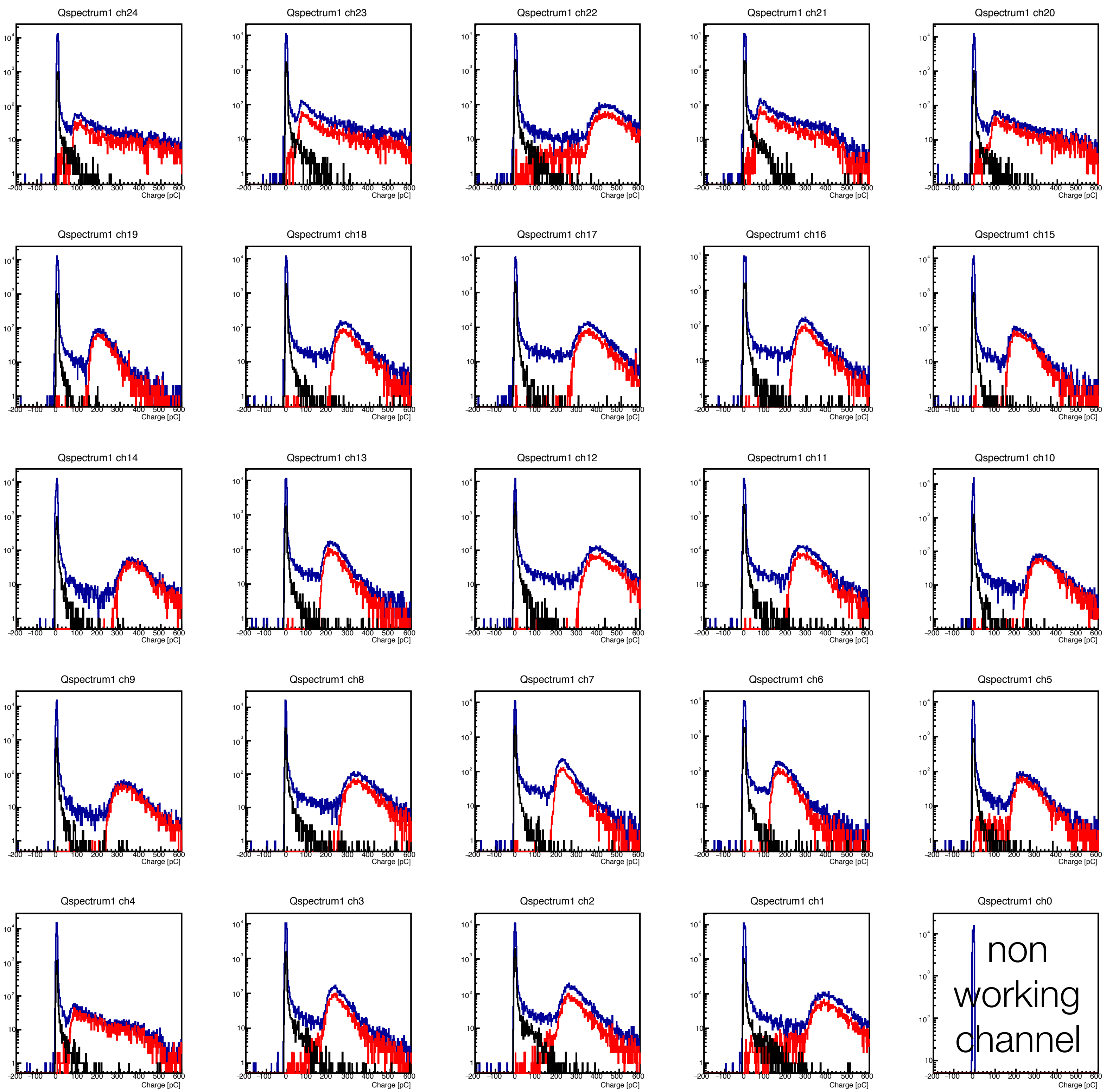
Cosmic ray setups

We performed **CR runs** w/ 2 different **setups**:

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



Cosmic rays charge spectra (5×5 matrix)



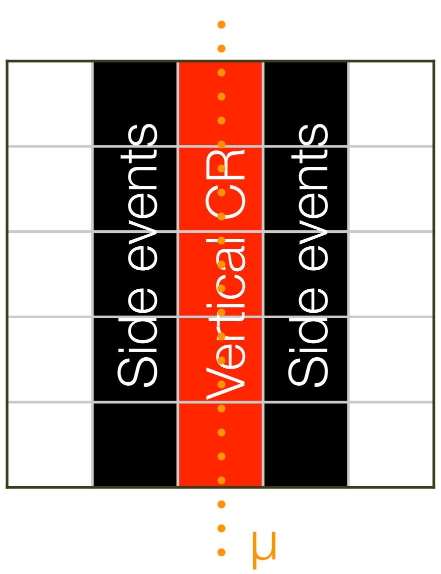
All events

Vertical CR

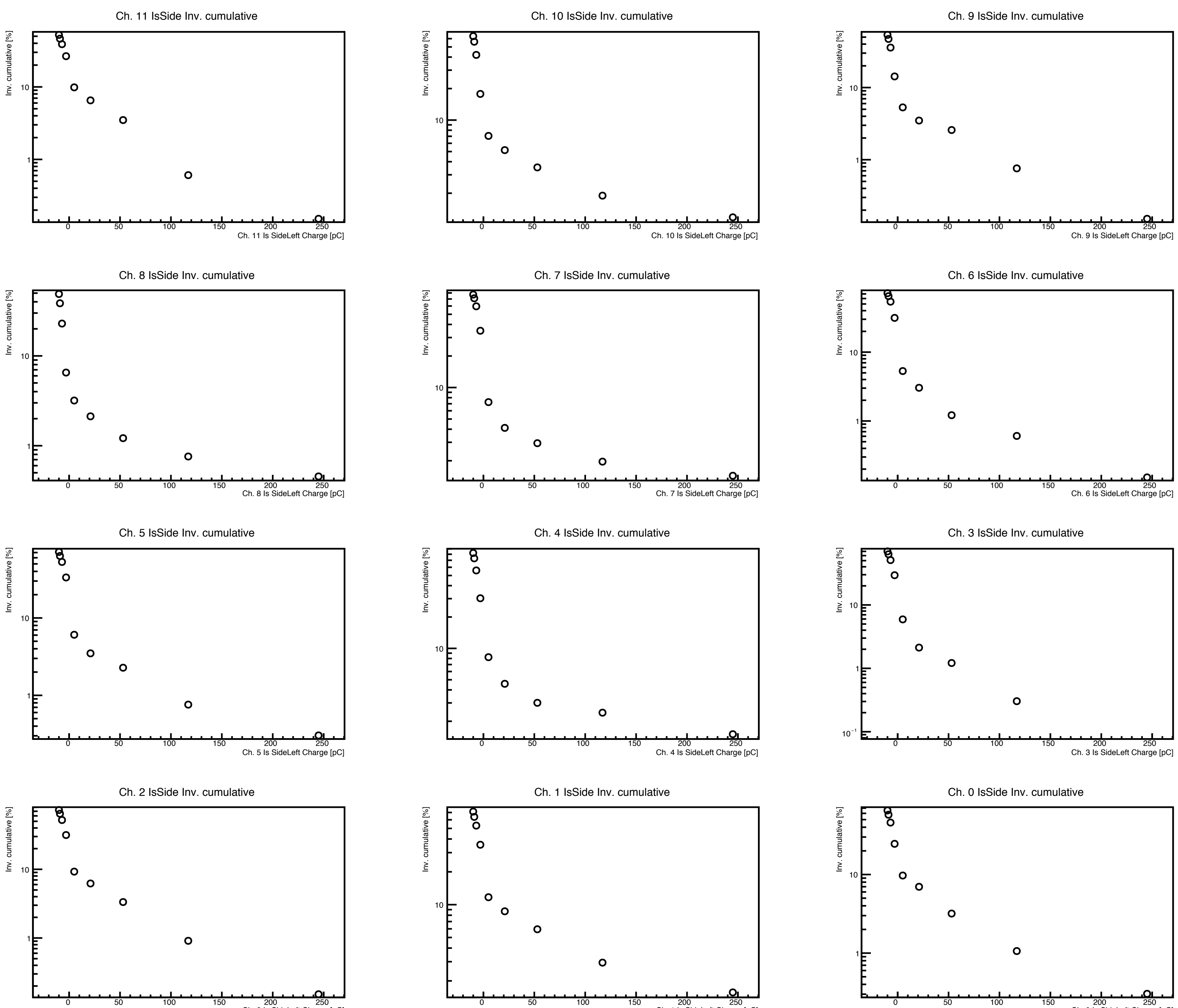
Side events (vertical CR passes through a crystal on the side)

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

Example:
μ passing through central column



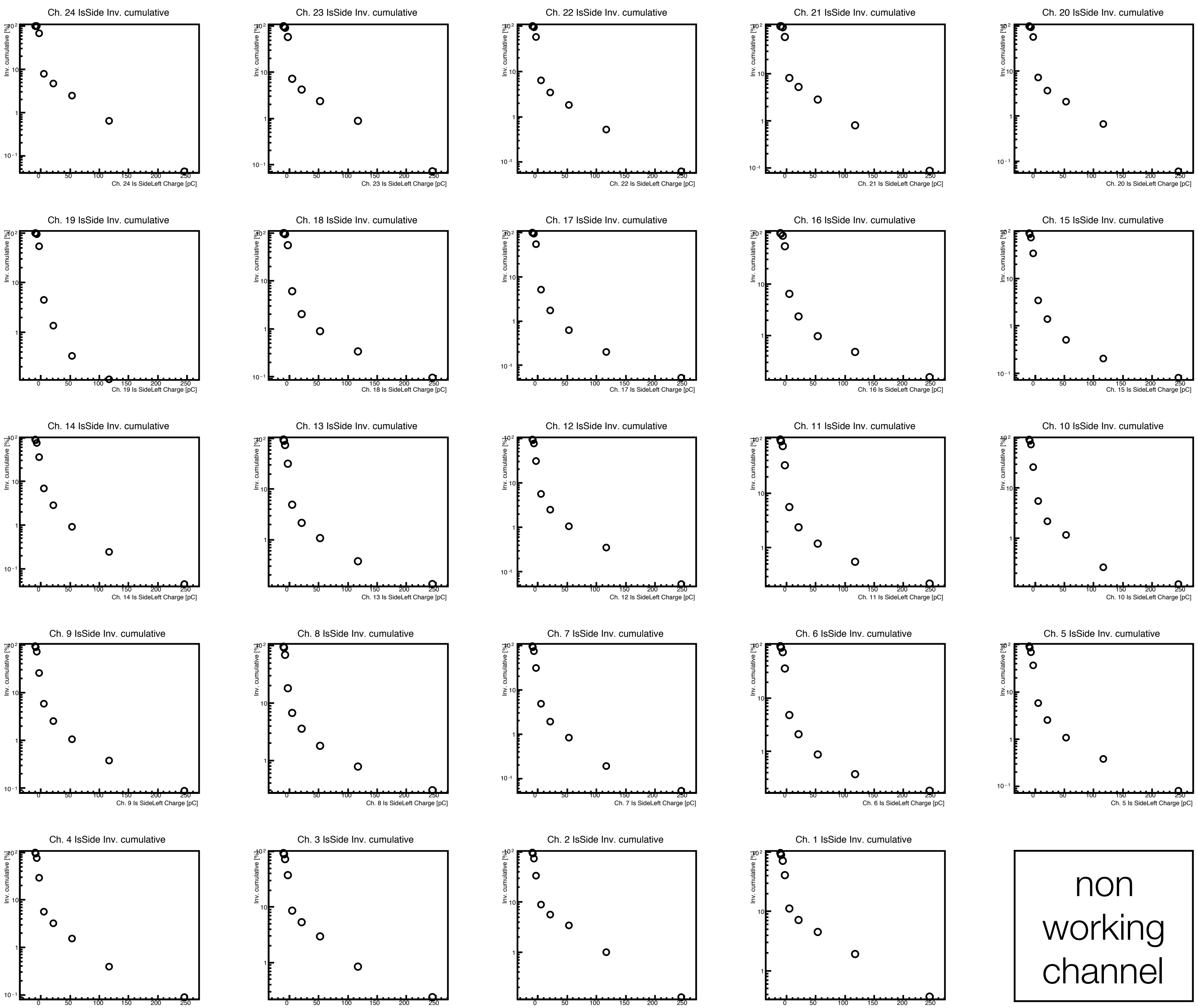
Optical crosstalk without tedlar (4×3 matrix)



Inverse cumulative of the Side events w/o tedlar

1% is reached at ≳100pC

Optical crosstalk with tedlar (4×3 matrix)



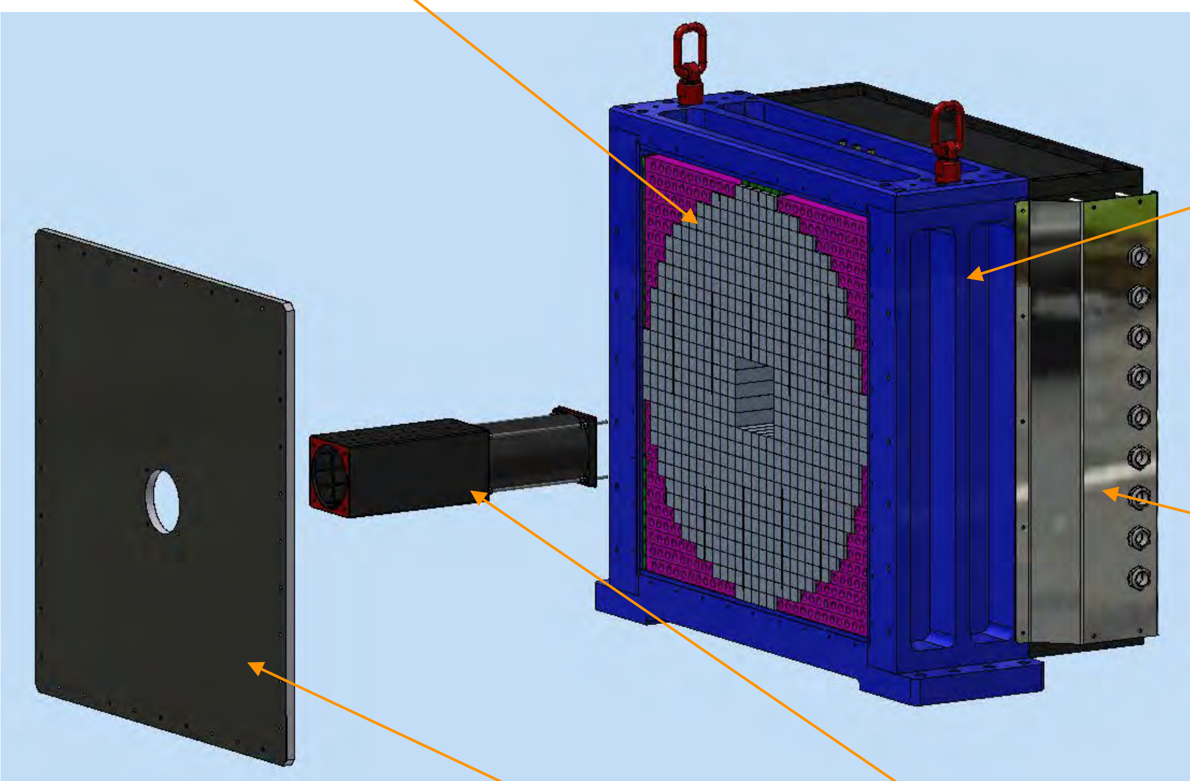
Inverse cumulative of the Side events w/ tedlar

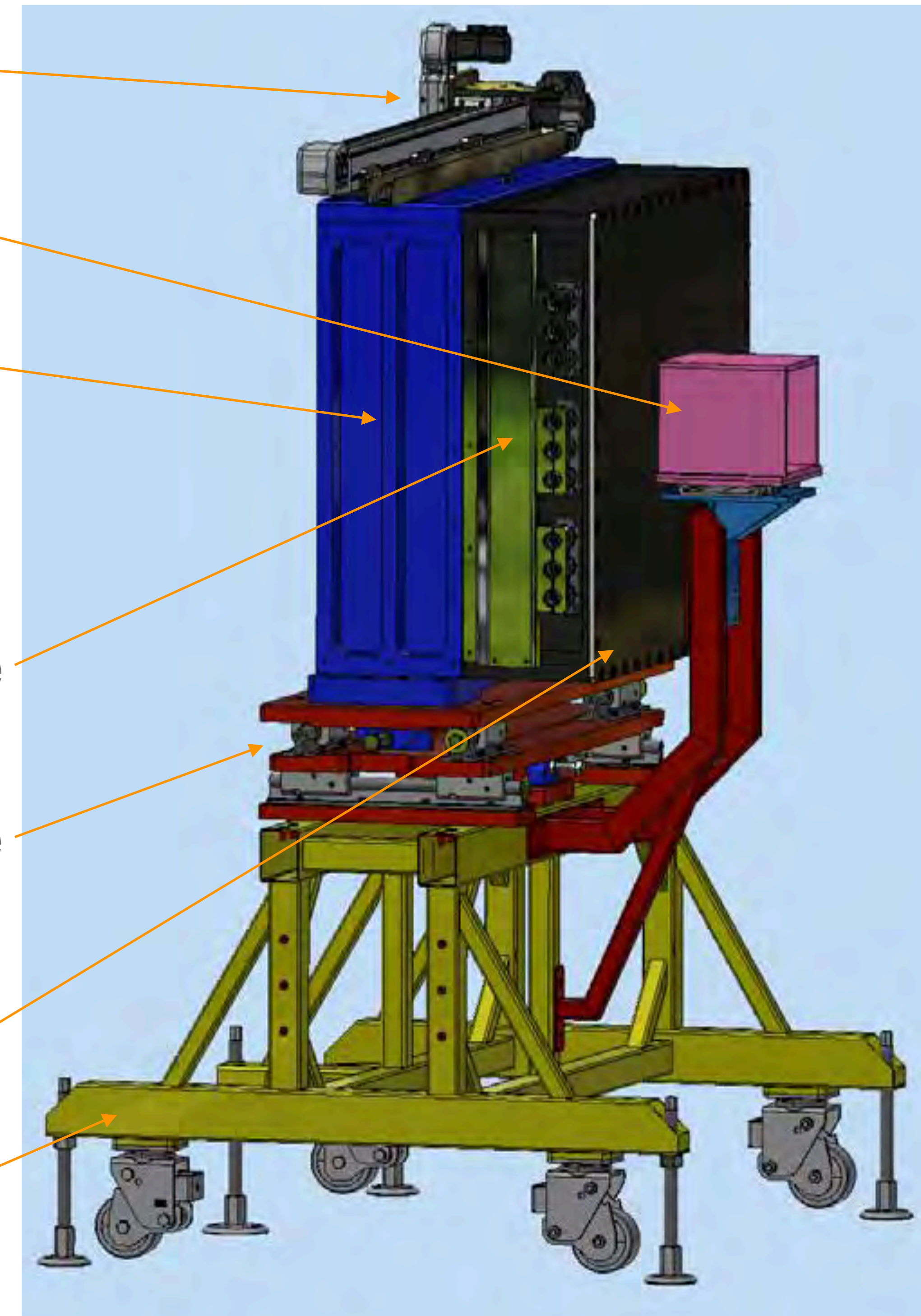
1% is reached at ~50pC

Tedlar is effective in preventing optical crosstalk

Tedlar will be used for the ECAL assembly (it also accommodates different SU heights)

Calorimeter mechanical design



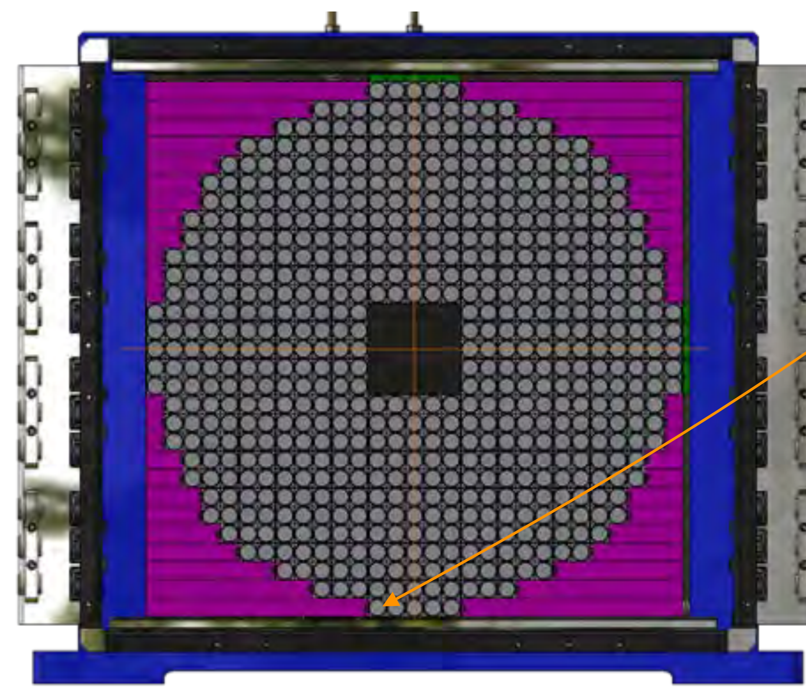


ECAL assembly procedure

Procedure:

for each layer

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



front view

ECal structure before the assembly

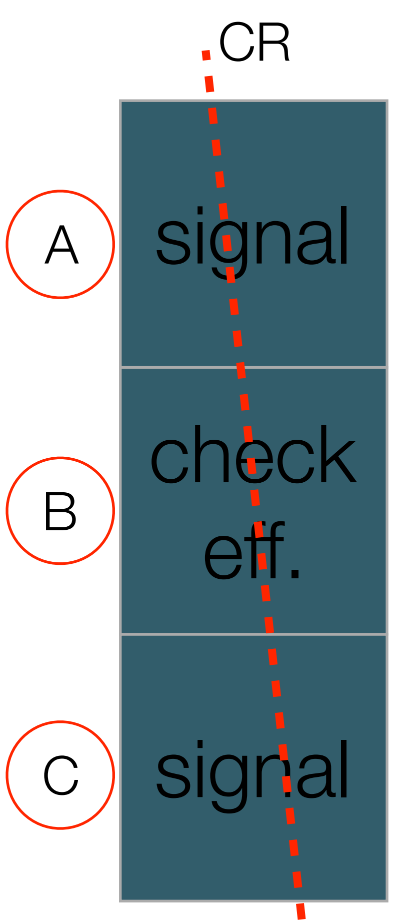
Vertical CR in and SU efficiency

A CR is considered as passing vertically through a SU if:

- the SU above and the SU below have signal
- the 3 SU are vertically aligned
- there are only those SUs w/ a signal in these 3 layers
- if the SU is on the border the 2 crystals above or below are used

Verticality does not give any information about longitudinal point of interaction

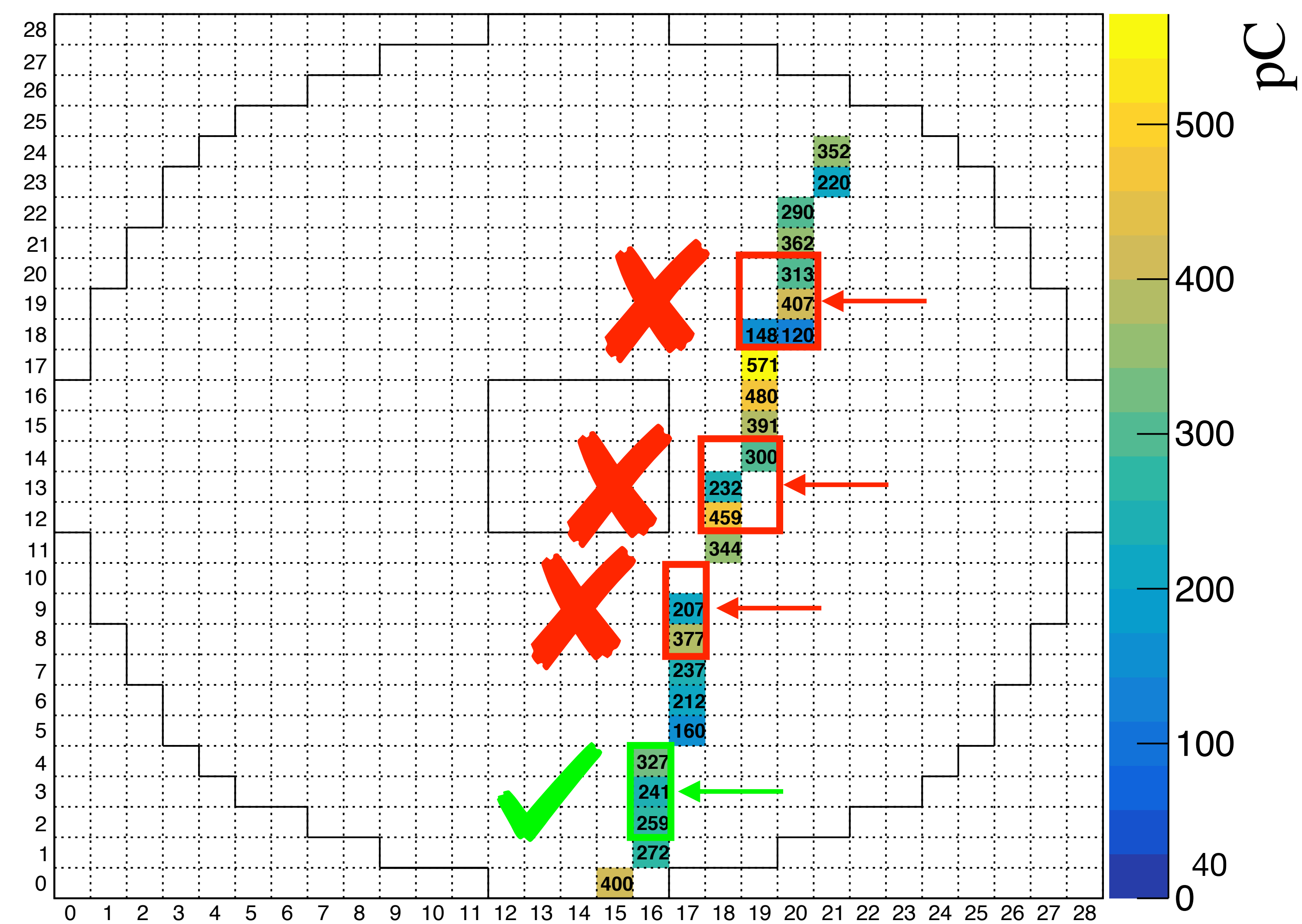
SU Efficiency



$$Eff_{\mathbf{B}} = \frac{\mathbf{A} \cap \mathbf{B} \cap \mathbf{C}}{\mathbf{A} \cap \mathbf{C}}$$

It is not possible to evaluate efficiency for a SU on the border

ECal ev. 48 (0 3032)

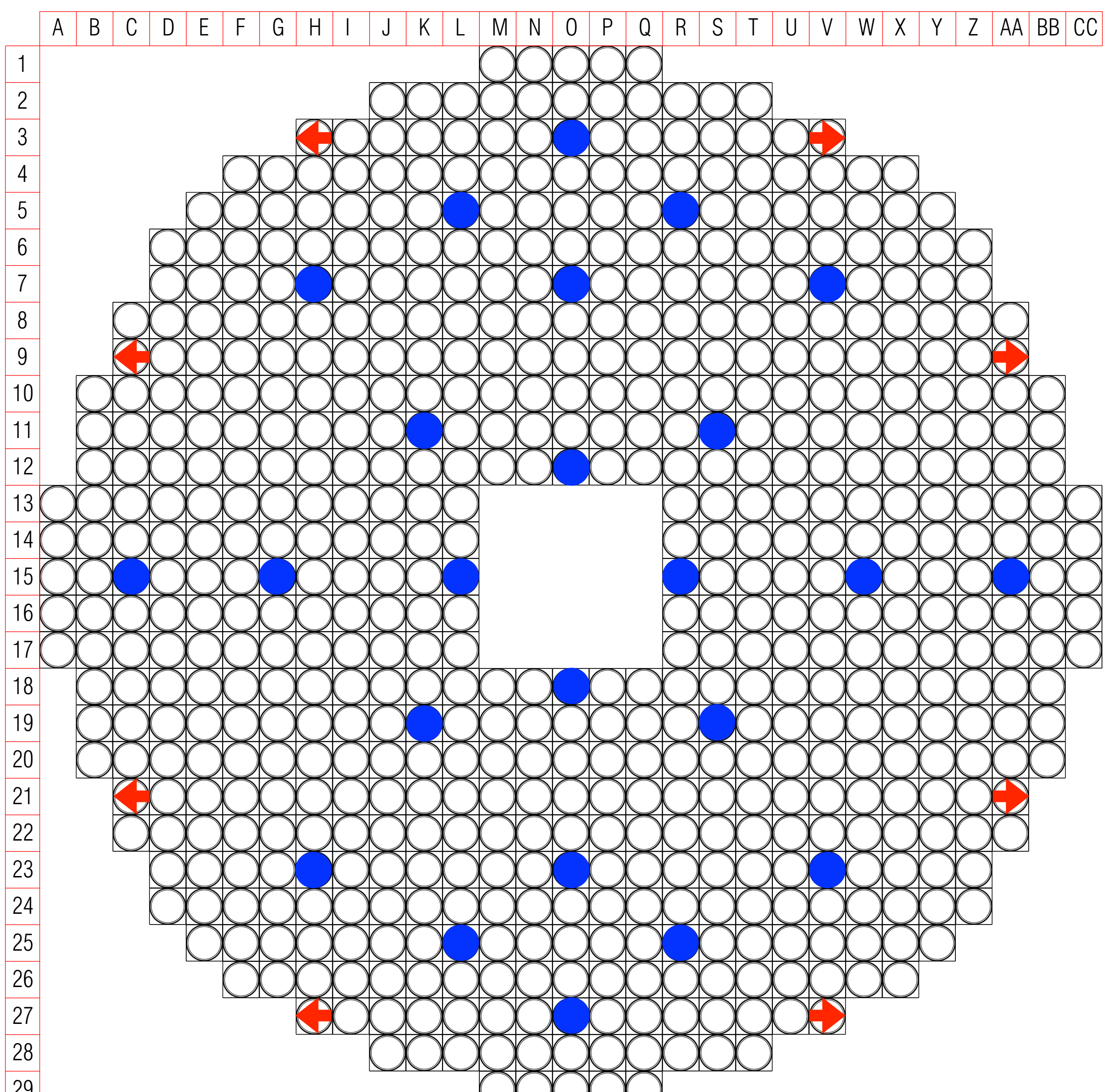


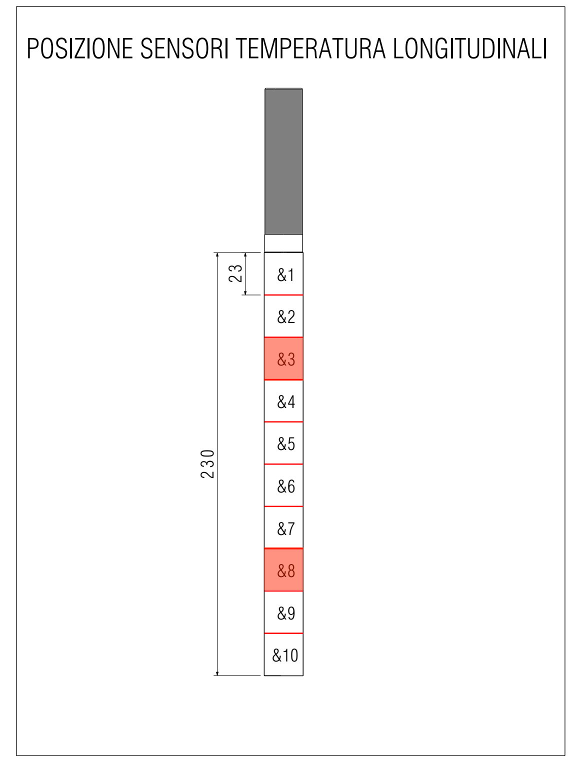
BGO thermometers

Positions:

Back (rear part of crystal)

Side (2 along the crystal side)





Position along side

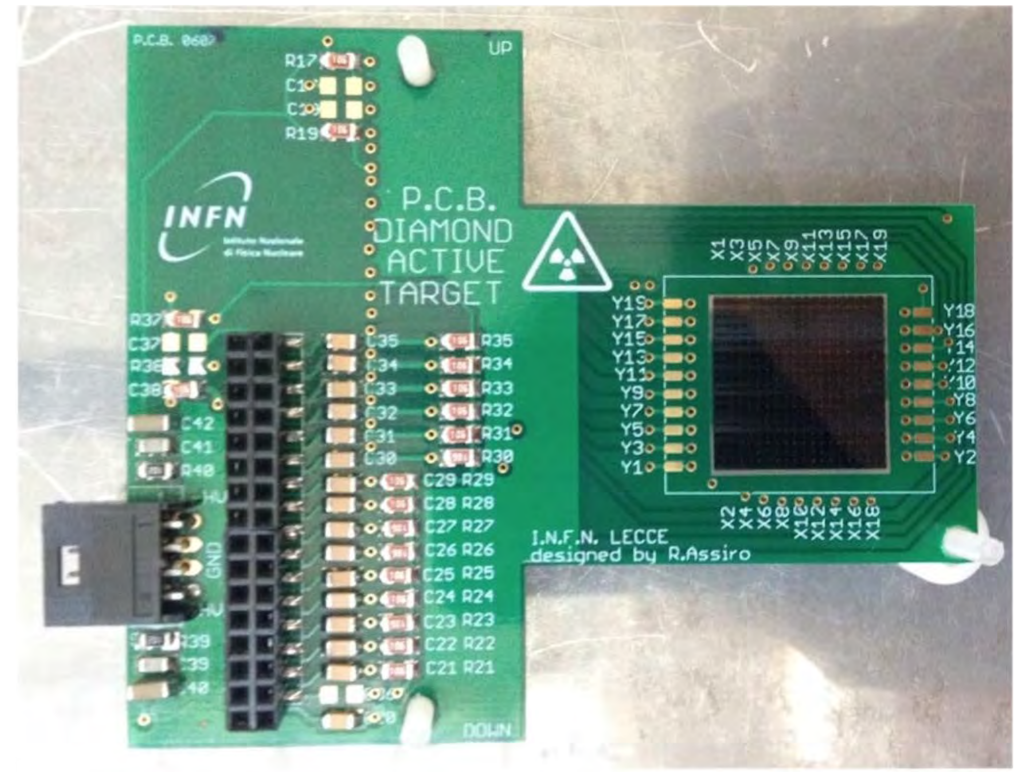
24 + 16 thermometers:

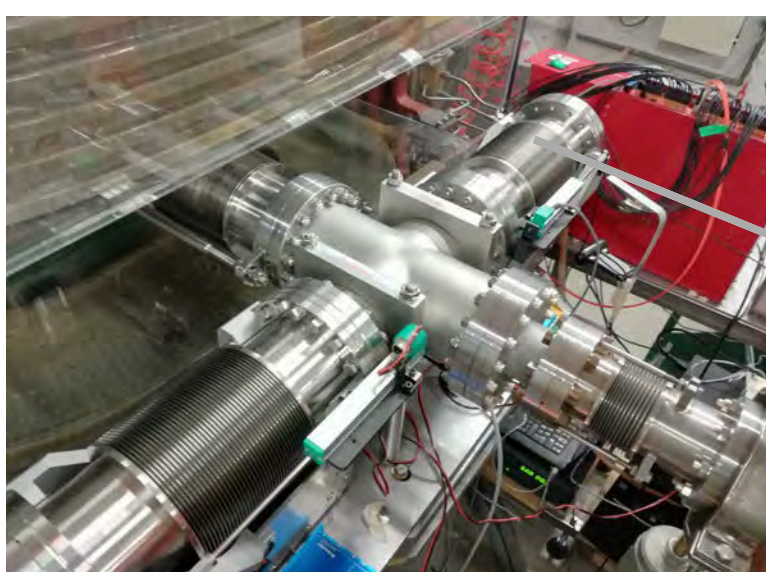
- Pt1000
- thin film, 10mm tails
- dimensions: 1.2×1.6 mm^2
- temperature range: (-50, 500°C)
- self-heating:< 0.5 °C/mW
- thermal response: 0.1 s
- stability: ±0.05%

Active target

Features:

- Diamond (low z, reduced brems.)
- Dim.: 20×20×0.1 mm^3
- 19 h. × 19 v. active graphitic strips (1 mm pitch, 0.15 mm interstrip distance, electric resistance ~2.5kΩ)
- 16 h.×16 v. strips are read
- in vacuum w/ movement system
- $\sigma_{x\text{-}y}$(beam position): 0.6mm





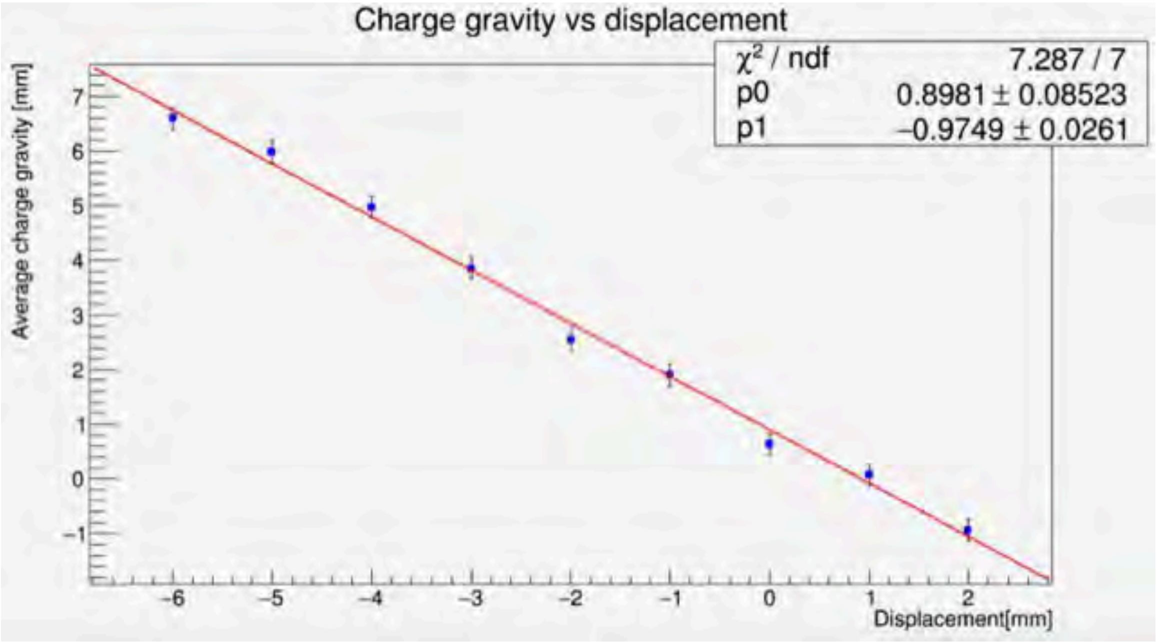
Two IDEAS boards equipped w/ 16 channel AMADEUS chip to readout

Active target operations

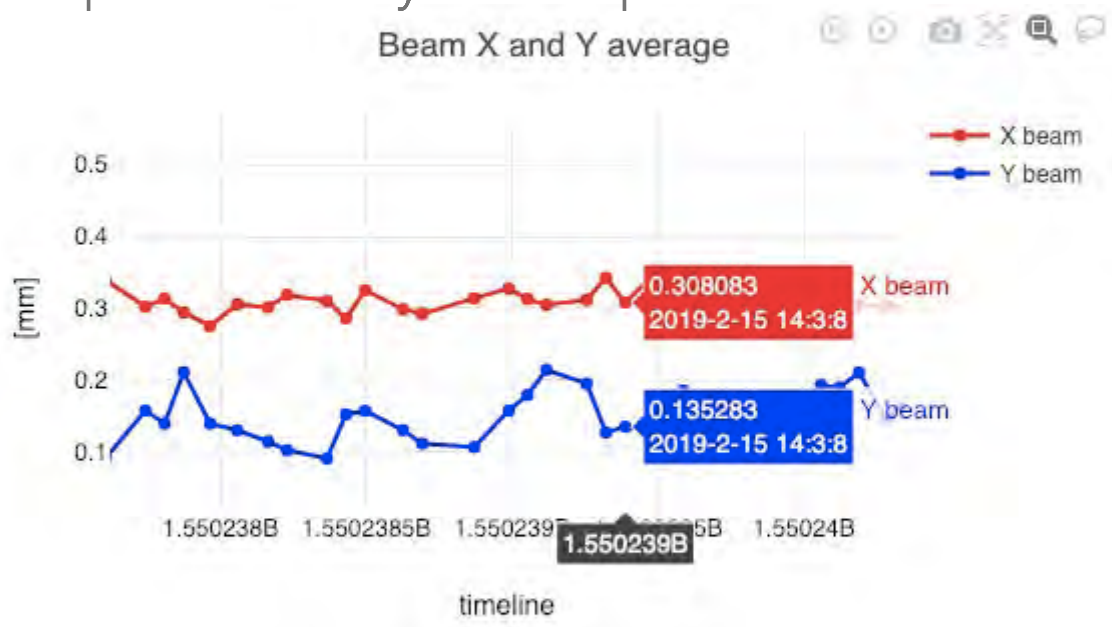
The target has been continuously and stably operated since **September 2018**

The diamond detector performances measured on situ show excellent beam monitor capability:

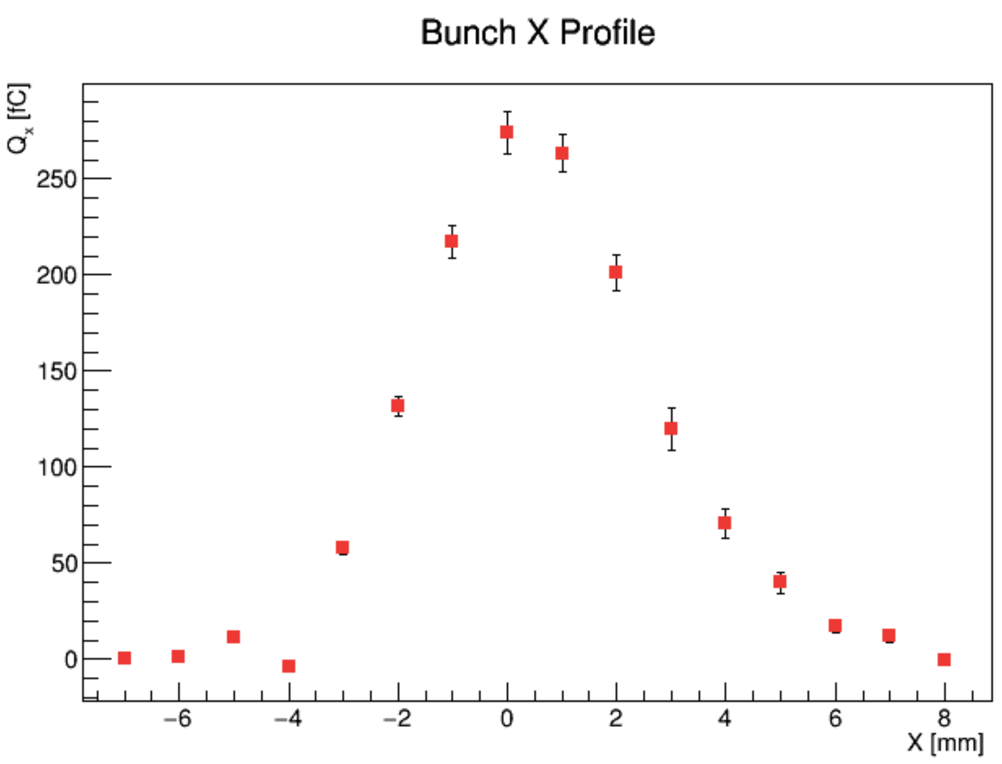
- single bunch X and Y beam profiles
- good spatial resolution and linearity w/ charge weighting algorithm
- linear response to beam multiplicity (many calibration runs performed using a lead glass Cherenkov calorimeter)



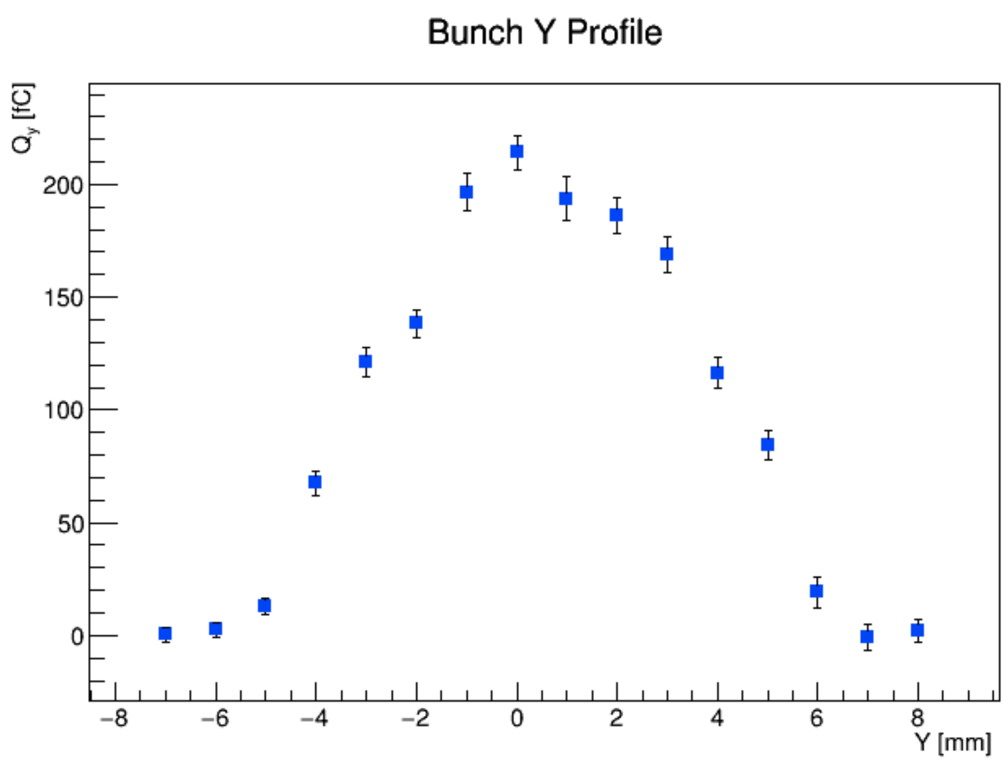
Timeline trends of the vert. and horiz. beam position and the number of e^+ on target are provided by the experiment monitor

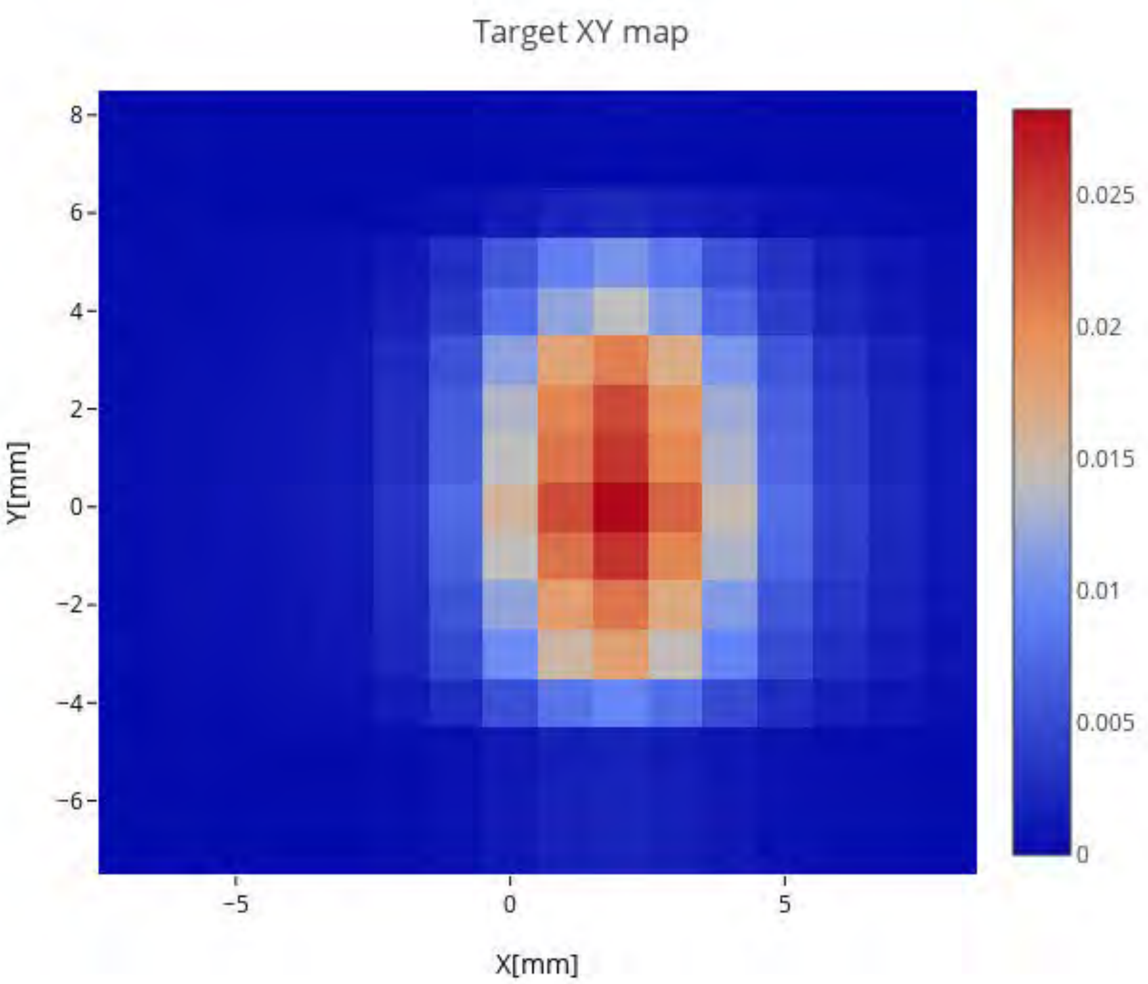


Beam profile with target



Strips X3 and X5 are not working: charge linear interpolation using lateral strips (not in this plot)

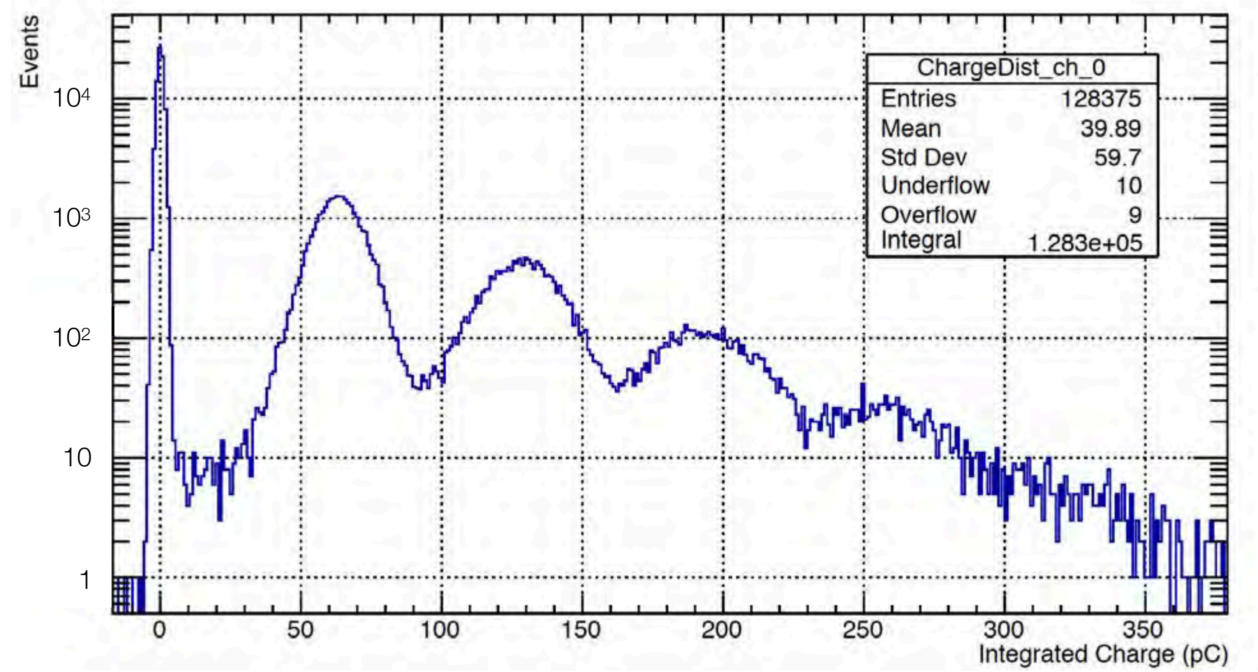


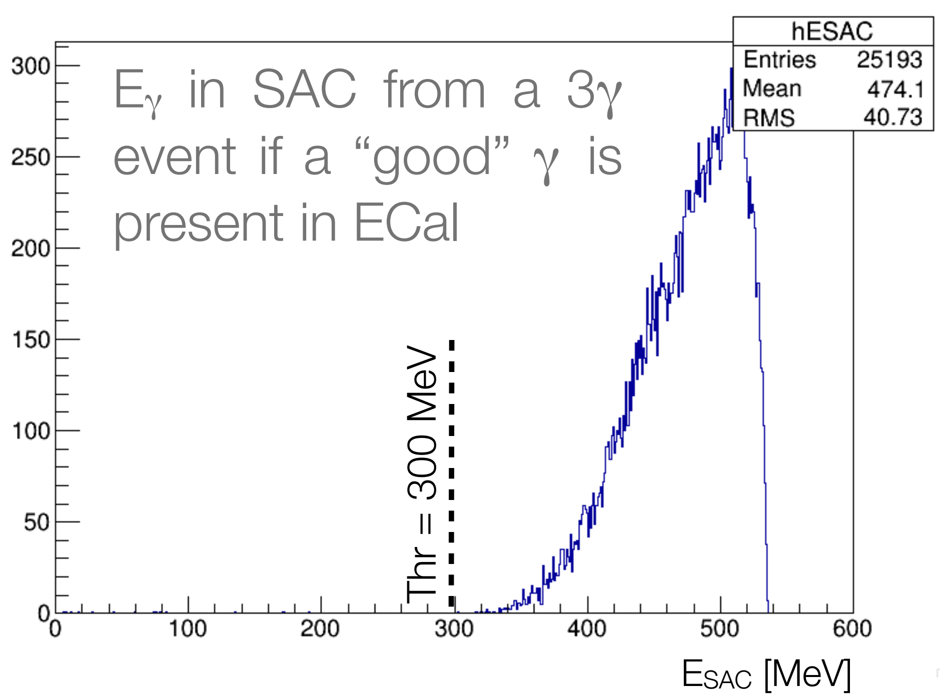


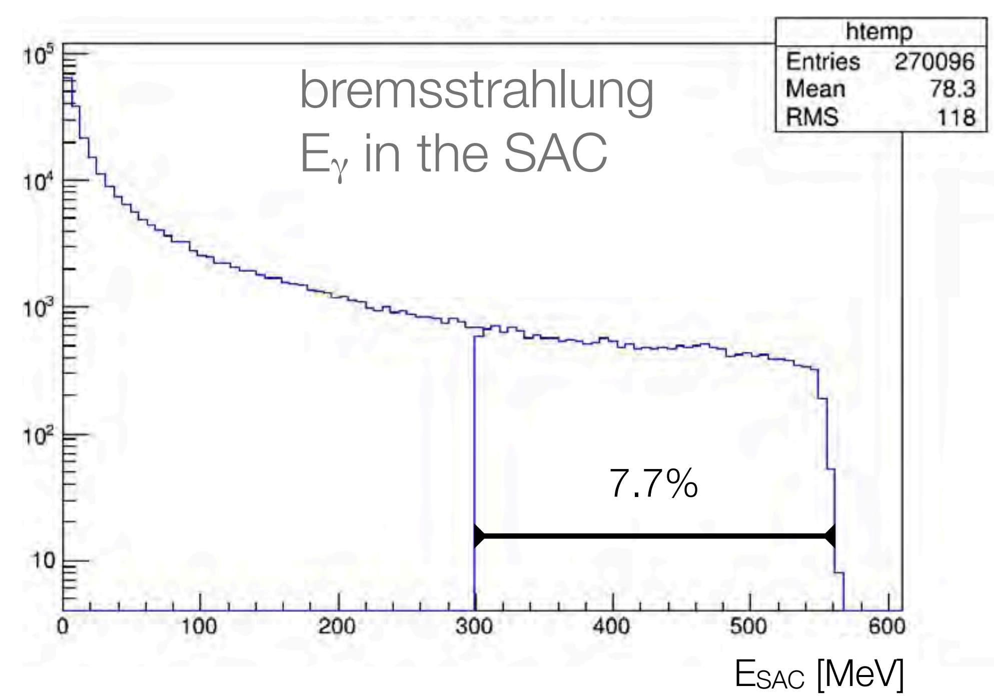
Small Angle Calorimeter (SAC)

Characteristics:

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





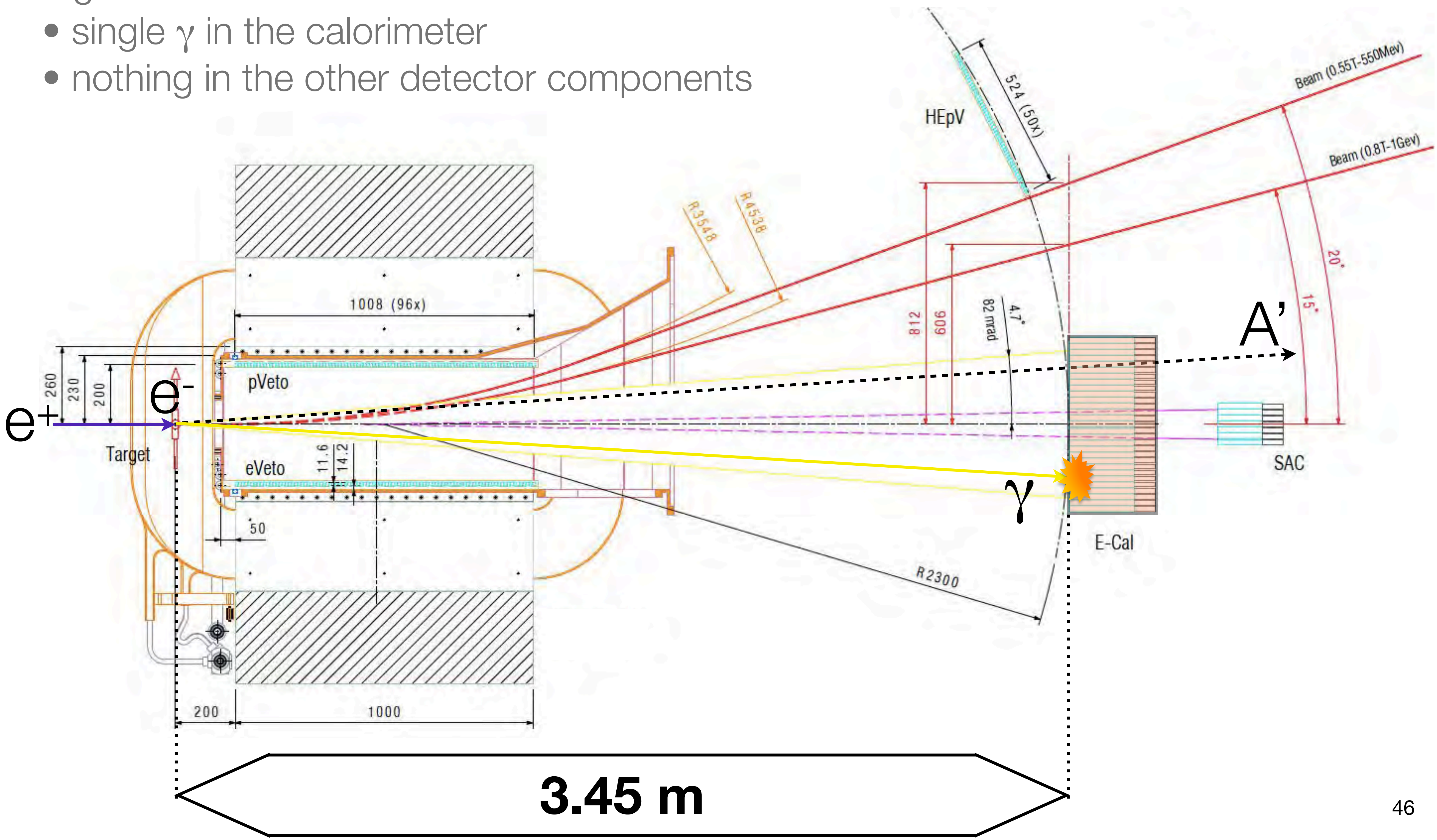


SAC must be sensible to photons over 300 MeV and blind under 100 MeV

Detector top view (w/ signal)

Signal:

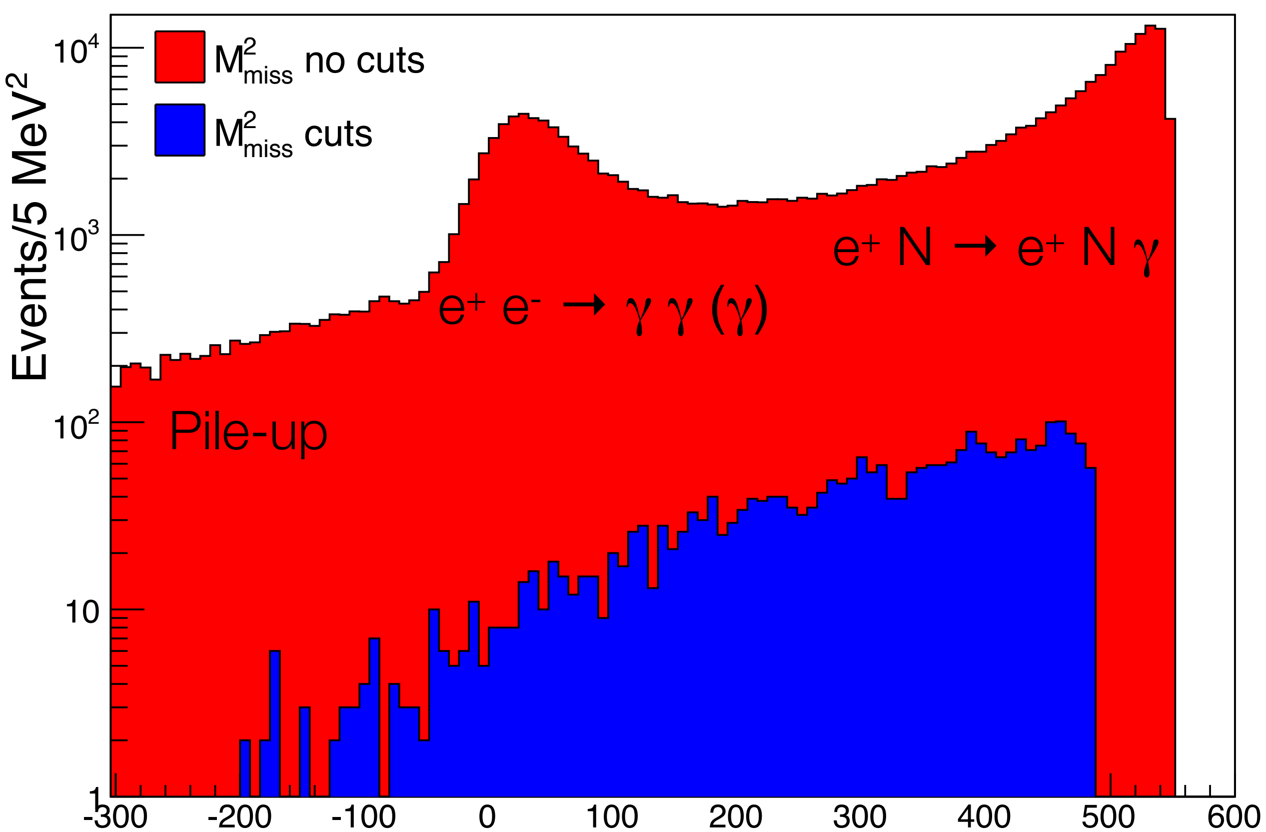
- single γ in the calorimeter
- nothing in the other detector components



Backgrounds

Largest backgrounds:

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



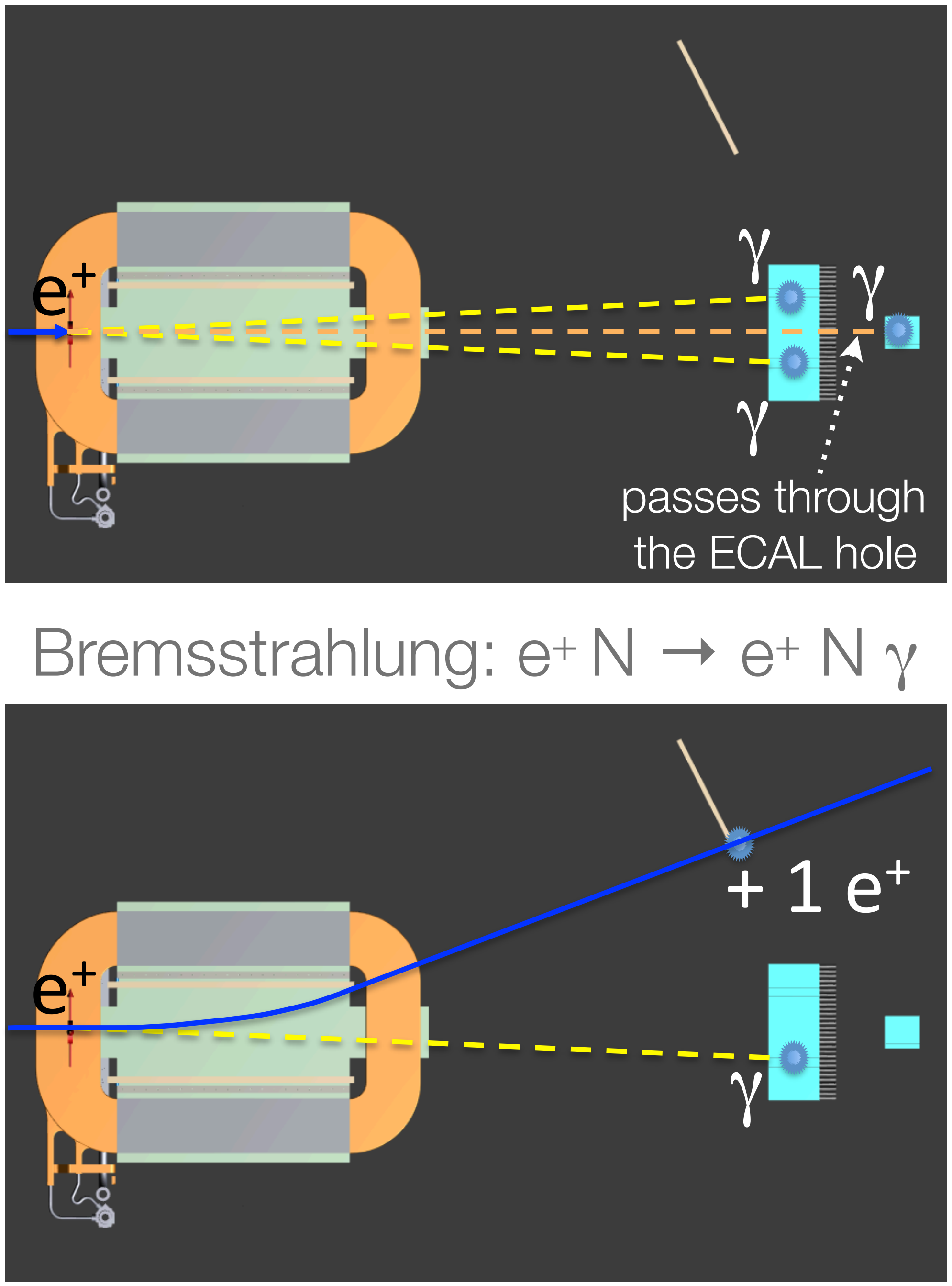
Cuts:

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

Backgrounds geometry

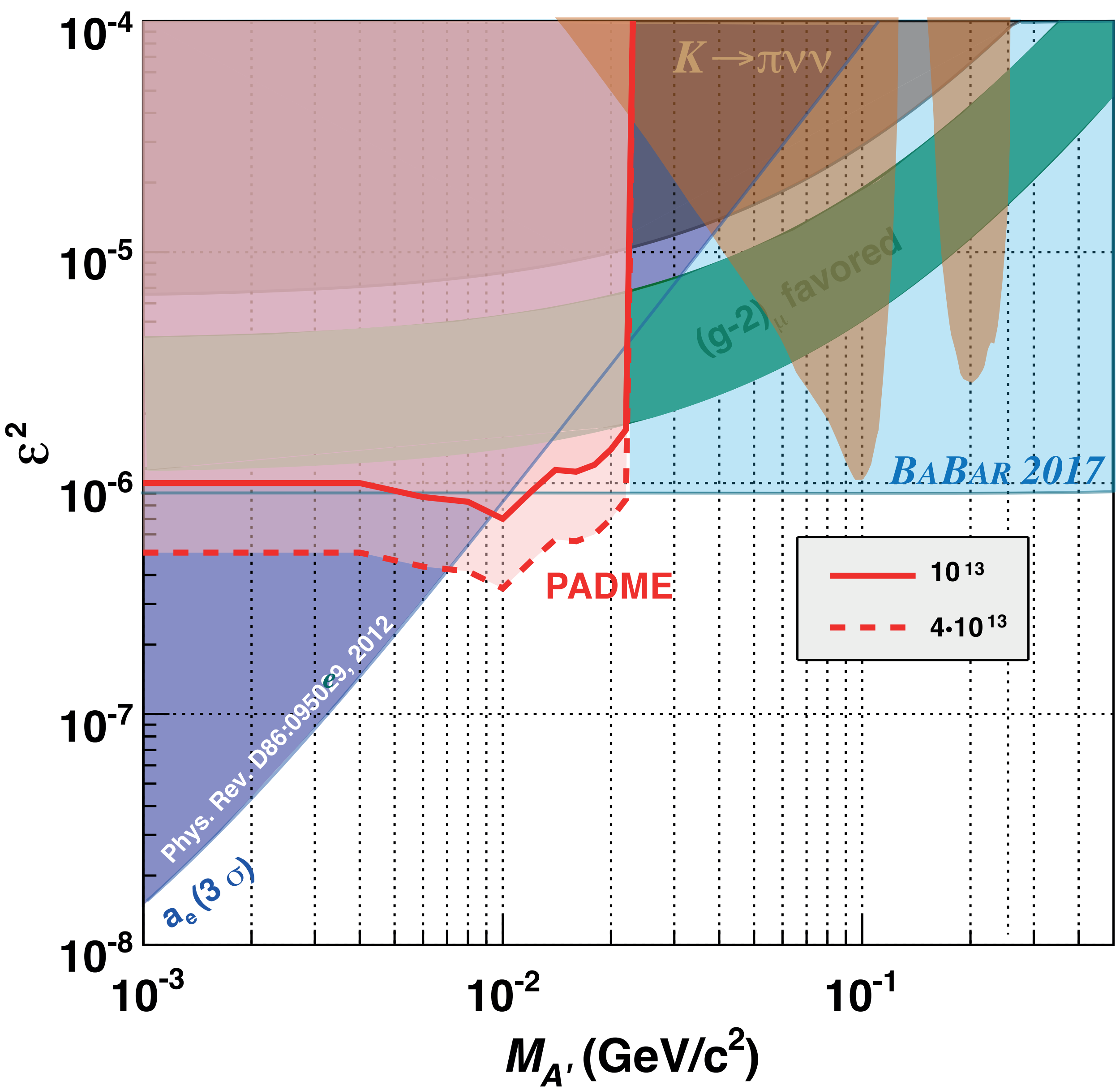
Annihilation (+ISR): $e^+ e^- \rightarrow \gamma\gamma(\gamma)$

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



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)