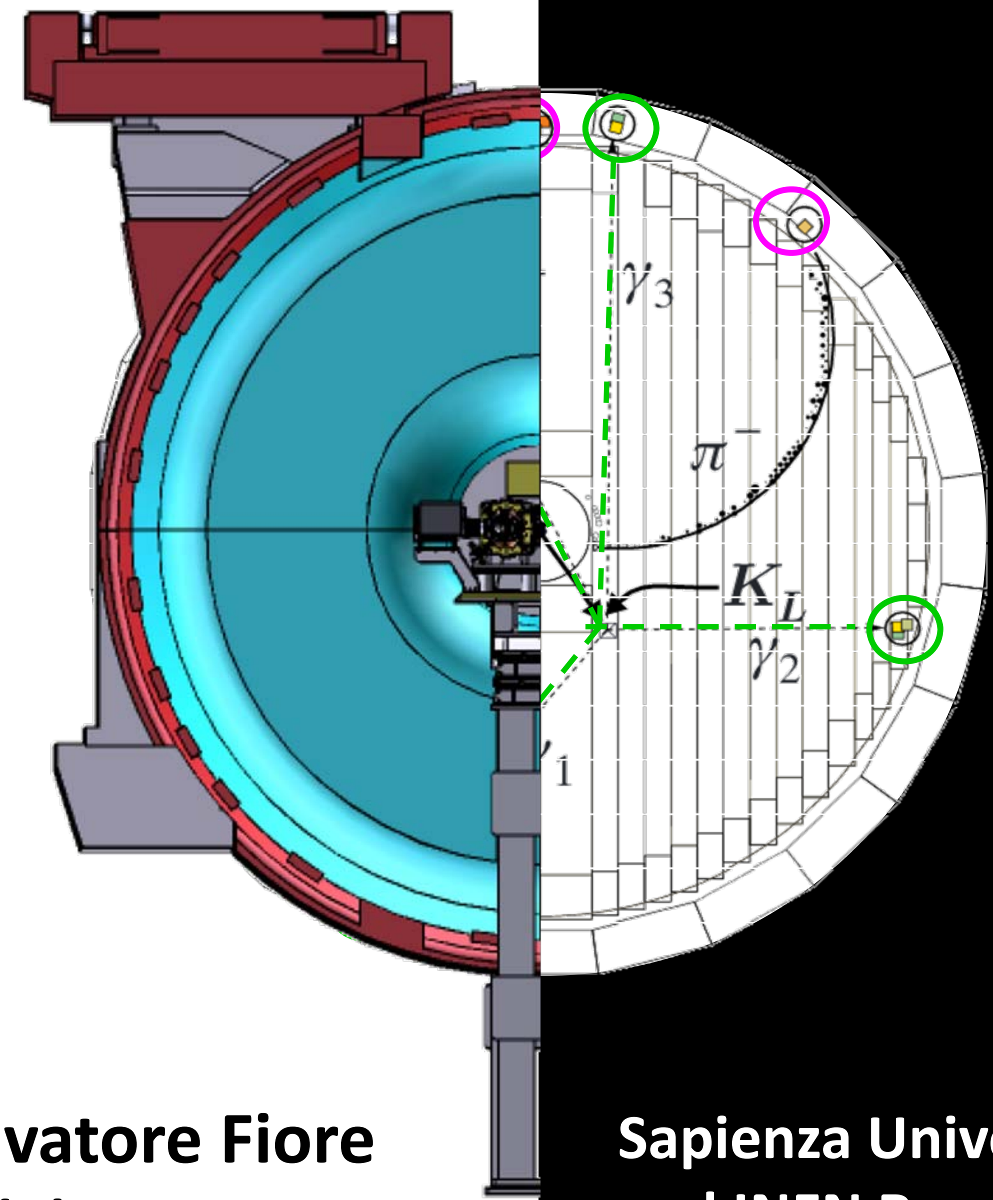
The Low Energy Tagger for the KLOE-2 experiment



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From KLOE to KLOE-2

KLOE has taken data until 2006 on the DAΦNE ϕ-factory at LNF

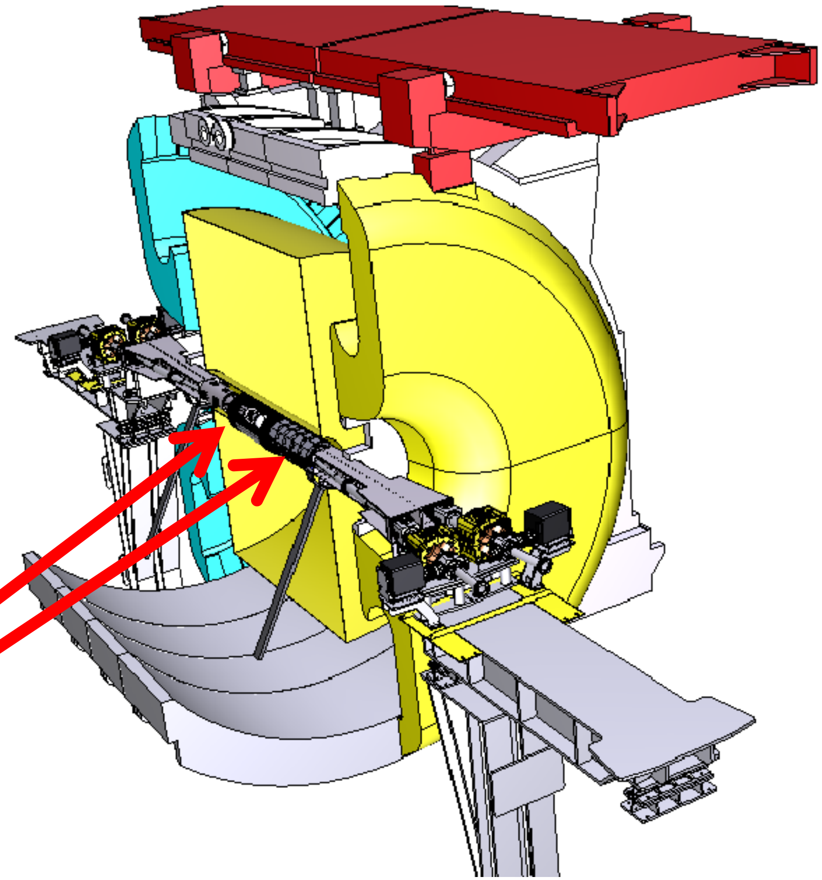
2.4 fb^{-1} have been acquired

KLOE is contributing to knowledge on kaon physics, hadronic physics, quantum interferometry

A new data taking campaign has been approved starting from 2010 (step-0):

- 5 fb-1 will be acquired
- KLOE detector will be upgraded in order to add "γγ physics" to its physics program

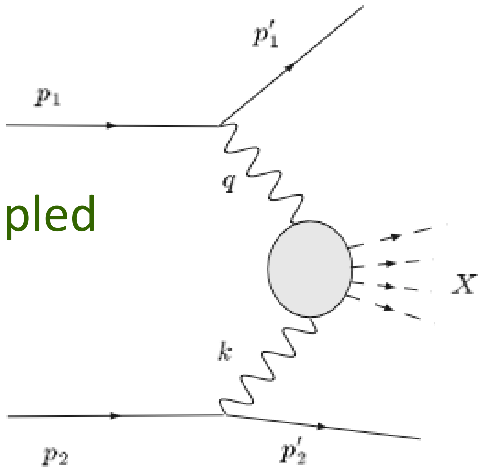
New sub-detectors will be added inside KLOE in order to study these new physics channels at the ϕ peak: a "tagging" system will detect scattered beam particles which emitted a photon at the interaction point



Present status of gamma-gamma physics

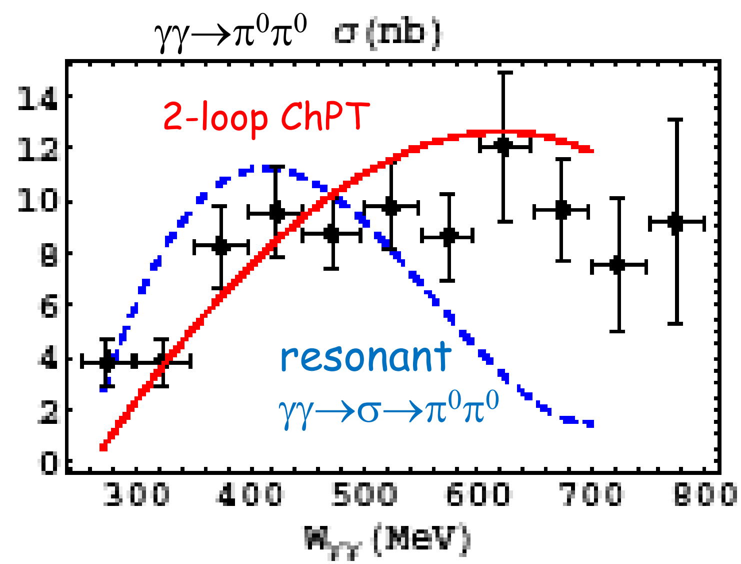
$\gamma\gamma$ physics stands for $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- + X$

this process gives access to $J^{PC} = 0^{\pm+}, 2^{\pm+}$ states, not directly coupled to one photon ($J^{PC} = 1^{--}$): e.g. $\pi\pi$ (σ), η, η', f_0, a_0



In the low-energy region, for $W_{\gamma\gamma}$<1GeV, present experimental situation is unsatisfactory:

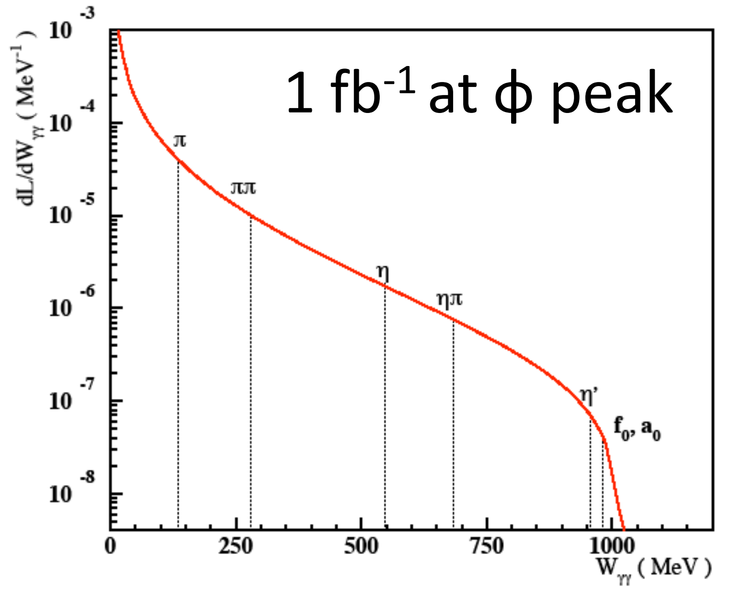
- small data samples and large backgrounds
  → large stat. and syst. uncertainties
- small detection efficiencies and particle ID for low-mass hadronic states



gamma-gamma physics in a Φ-factory

γγ physivs can be done at a ϕ–factory, on the ϕ peak:

Access to many interesting final states through photon emission from both colliding electron and positron



TRUE, BUT…

γγ events acquired at the ϕ peak would suffer from ϕ decays as background

γγ channel	(L = 10 fb^{-1})
$e^+e^- \to e^+e^-\pi^0$	4×10^6
$e^+e^- \to e^+e^-\eta$	1×10^6
$e^+e^- \to e^+e^-\pi^+\pi^-$	2×10^6
$e^+e^- \to e^+e^-\pi^0\pi^0$	2×10^4

	Missing particle	Events	Background for :
$K_S(\pi^0\pi^0)\,K_L$	K_L	$\sim 10^9$	$\pi^0\pi^0$
$K_S(\pi^+\pi^-)\,K_L$	K_L	$\sim 2\times10^9$	$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$	π^0	$\sim 10^9$	
$\eta(\gamma\gamma)\,\gamma$	γ	$\sim 10^8$	η
$\pi^0(\gamma\gamma)\,\gamma$	γ	$\sim 5\times10^8$	π^0

tagging γγ events by detecting e^+e^- is mandatory to reduce backgrounds, together with P_T kinematical selection on the tagged events.

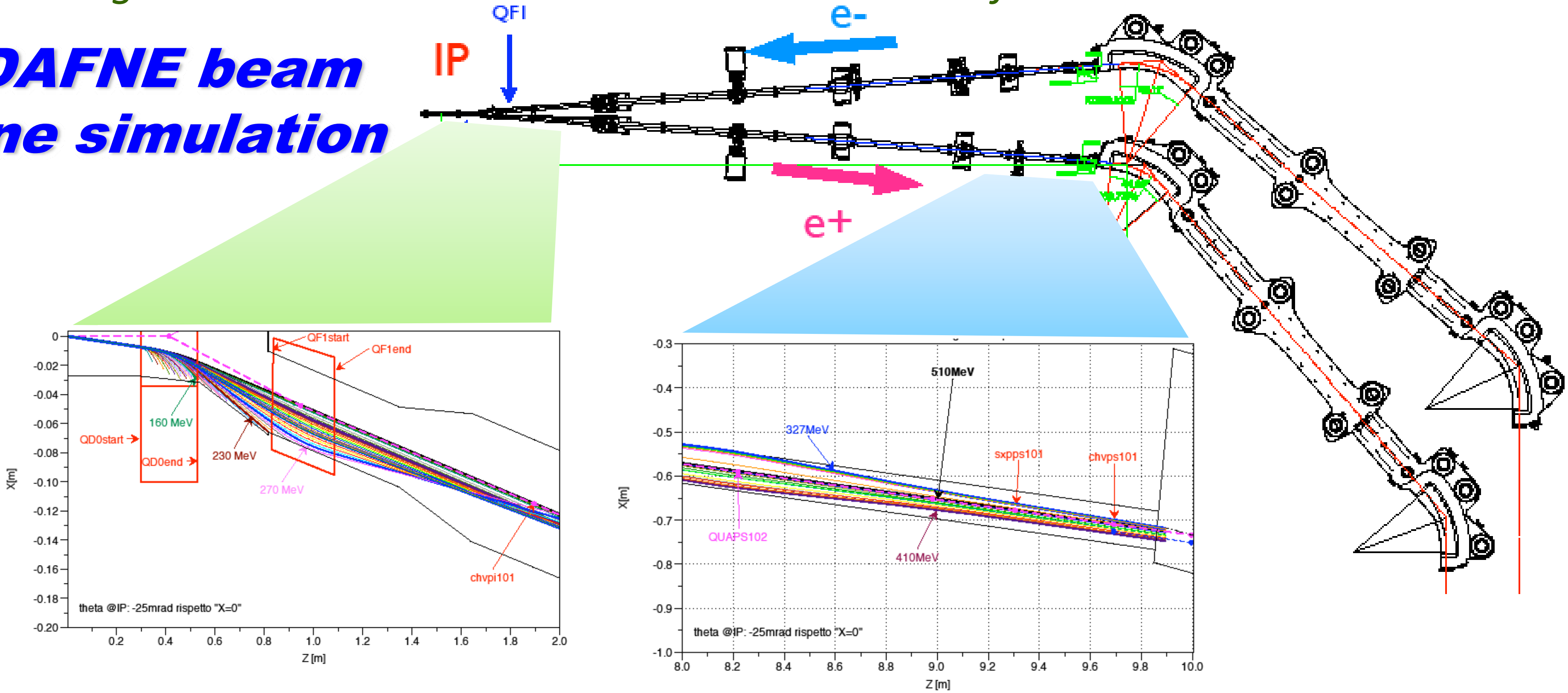
Scattered electrons escape from the KLOE *detector along the DAFNE beam lines*
Magnetic elements will deflect these "off-energy" particles out of vacuum tubes.
A detailed description of the beam optics is necessary to track these particles and locate different escaping regions to place our taggers:

MAD software: *nominal-energy beam simulation*, no detailed off-energy tracking

BDSIM software: *complete simulation* of machine elements and bending power for off-energy particles

Agreement between the two has been checked for 510MeV electrons.

DAFNE beam line simulation

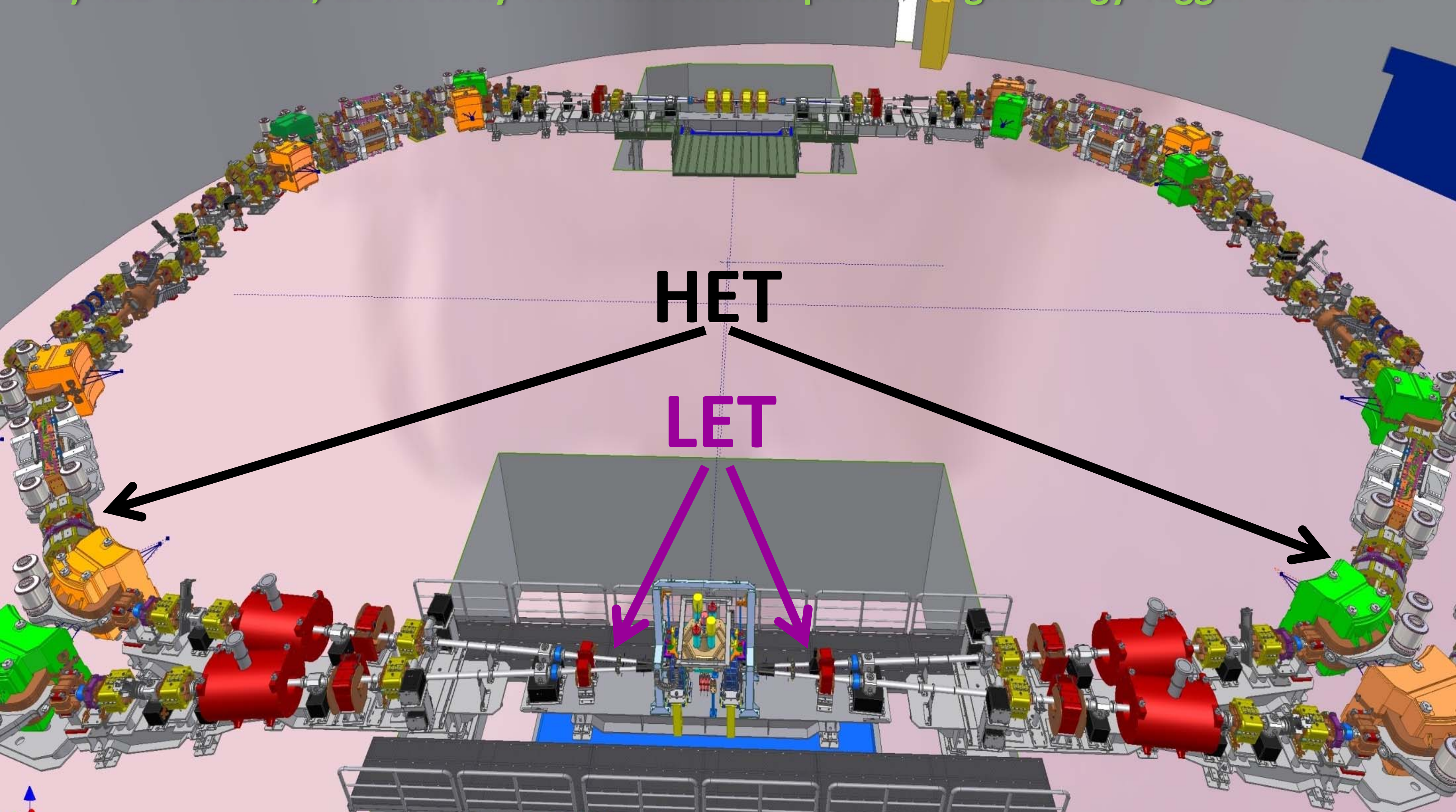


KLOE solenoid magnetic field has also been inserted into beam simulation

Two position for tagging detectors, for two e^+e^- energy ranges, have been found:

1) 160-230 MeV, 1 m away from interaction point “Low Energy Tagger” or LET

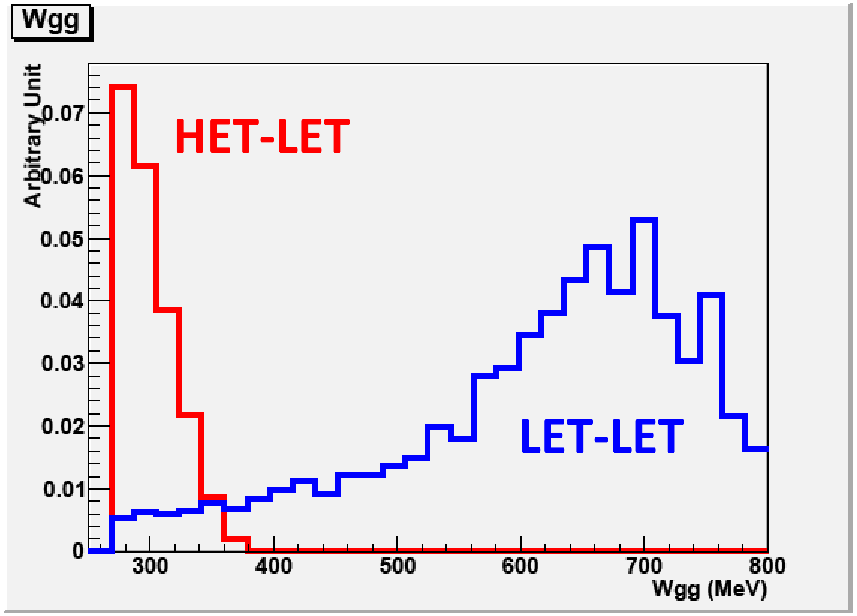
2) 425-490 MeV, 11 m away from interaction point: “High Energy Tagger” or HET



Tagging system acceptance

Depending on the energy of the emitted photons, $\gamma\gamma$ events will be tagged by the coincidence of two LET stations, one LET and one HET, or two HET

- HET-HET will only tag single-π events
- HET-LET and LET-LET will span over the other possible decays

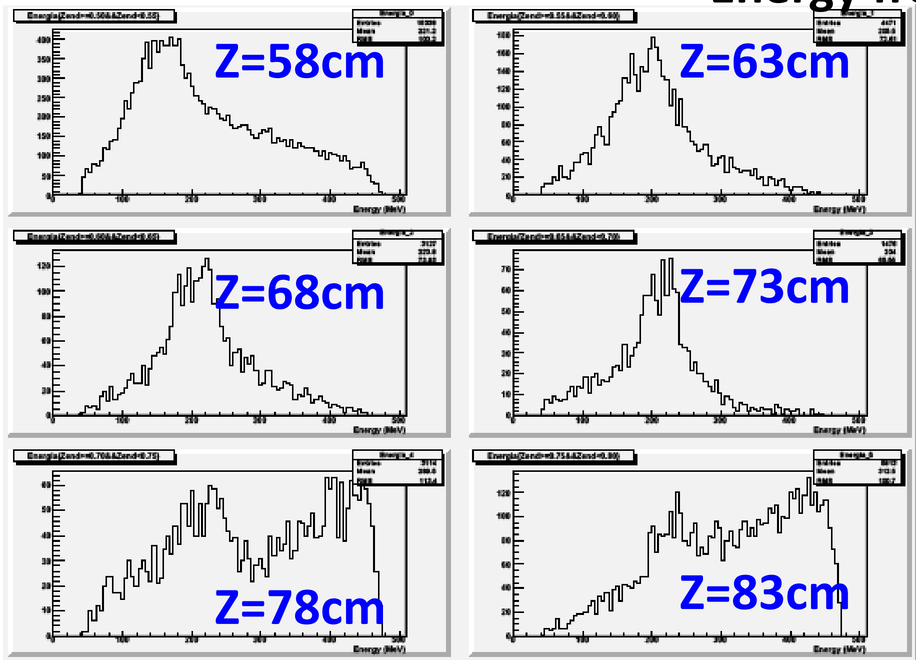


In order **to get 5% energy resolution on the LET-LET coincidence** (the most demanding one), **we must reach 8% energy resolution on the single LET station**

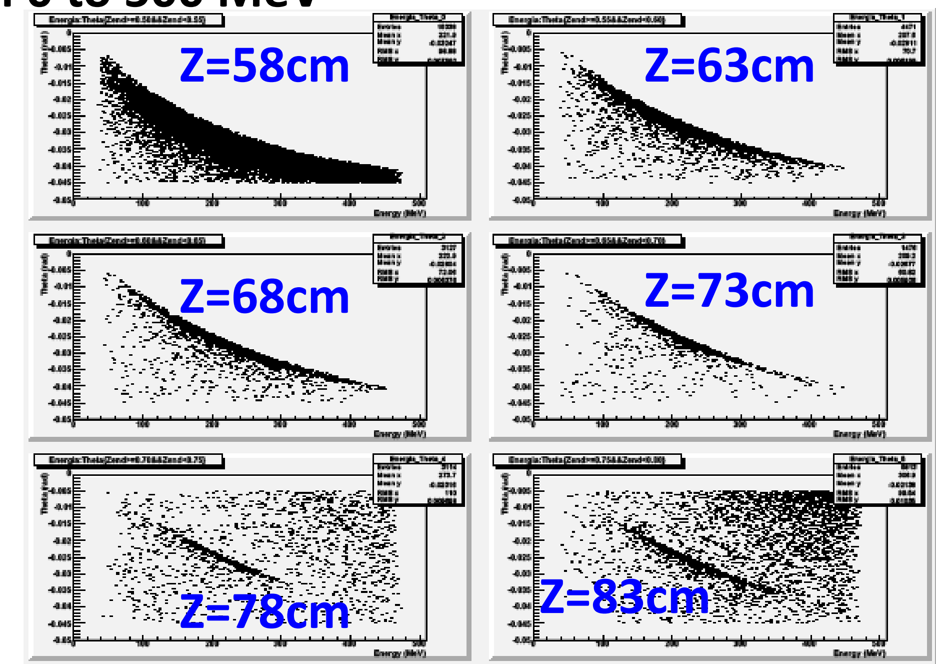
Combining all the three possible tagging combinations, we can get 500 pb^{-1} of clean $\gamma\gamma$ physics during step-0

LET: a tracker or a calorimeter?

Energy from 0 to 500 MeV



electron energy vs. beam escape position Z with respect to the interaction point



electron energy vs. emission angle θ with respect to nominal beam direction

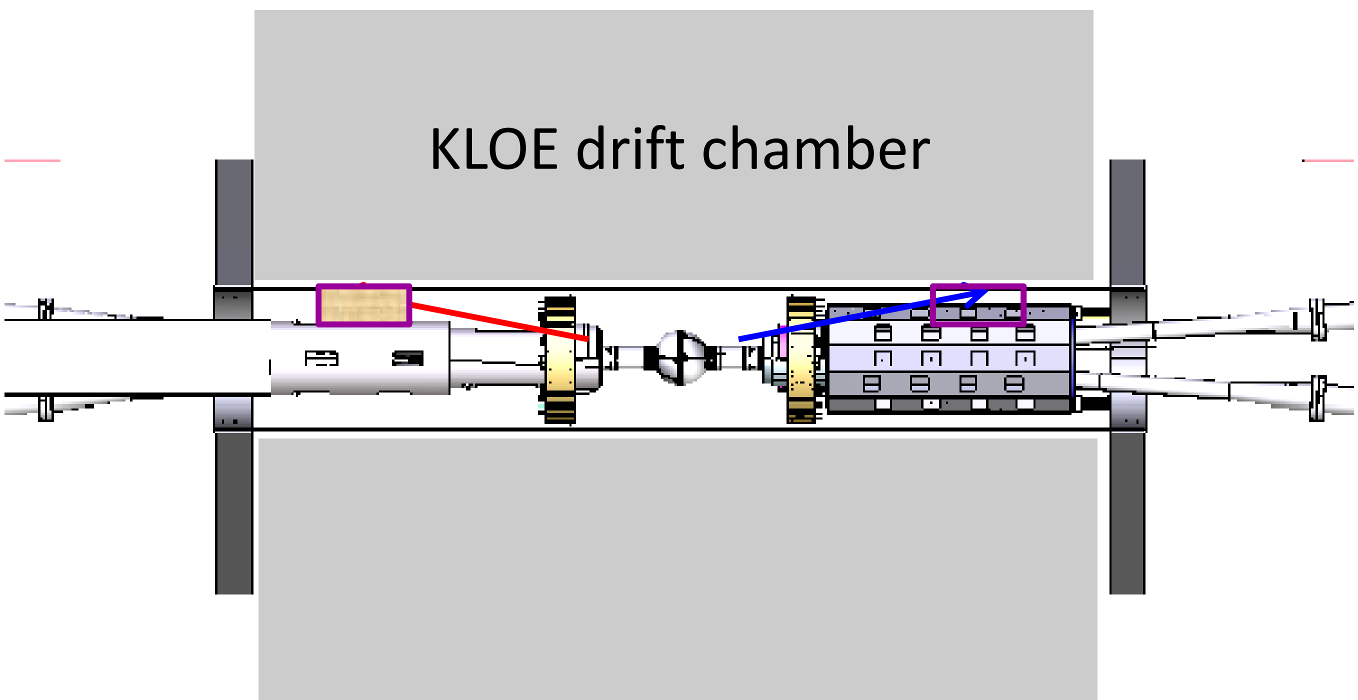
at LET position the *off-energy leptons show no correlation* between *energy, escape position and emission angle*:

a calorimeter is necessary to measure their energy (for HET is different)

Space and environmental costraints

Placing the LET inside KLOE detector imposes many tight costraints:

- available space limits the active volume of the calorimeter → high density (low X_0)
- presence of KLOE B-field: magnetic-insensitive photodetectors



Electrons and positrons escape from the beam pipe with 11° angle

Which scintillator?

Active volume: homogeneous crystal calorimeter with X_0 ~1 cm (~15 X_0 in ~ 15 cm)
Energy range is limited: 160-230 MeV → at least 2 photoelectrons/MeV needed to get 5% resolution (stochastic term). "Fast" scintillating time for bunch crossing correlation

Two candidates on the market: **$PbWO_4$ and LYSO(Ce)**

Parameter: Units:	ρ g/cm^3	MP °C	X_0^* cm	R_M^* cm	dE/dx MeV/cm	λ_I^* cm	τ_{decay} ns	λ_{max} nm	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$ %/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	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	6.6	30.7	630^s	300^s	1.50	36^s	no	-1.3^s
							0.9^f	220^f		3.4^f		$\sim0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.2	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	420	1.82	83	no	−0.2
GSO(Ce)	6.71	1950	1.38	2.23	8.9	22.2	600^s	430	1.85	3^s	no	−0.1
							56^f			30^f		

Photosensor choice: Silicon Photomultipliers

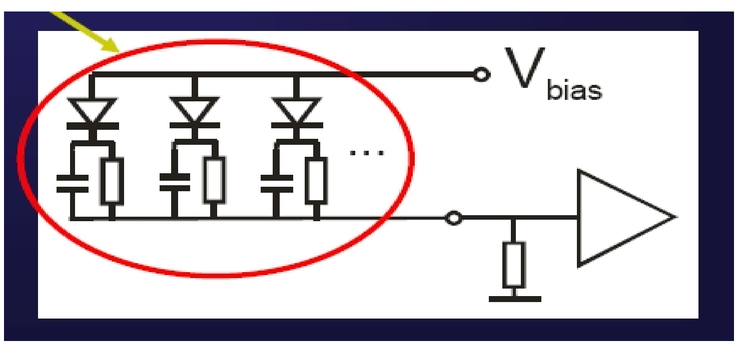
- *KLOE B field =0.5T in the LET* placement region → magnetic insensitive photosensor
- *O(*10^2) photoelectrons expected: high gain necessary

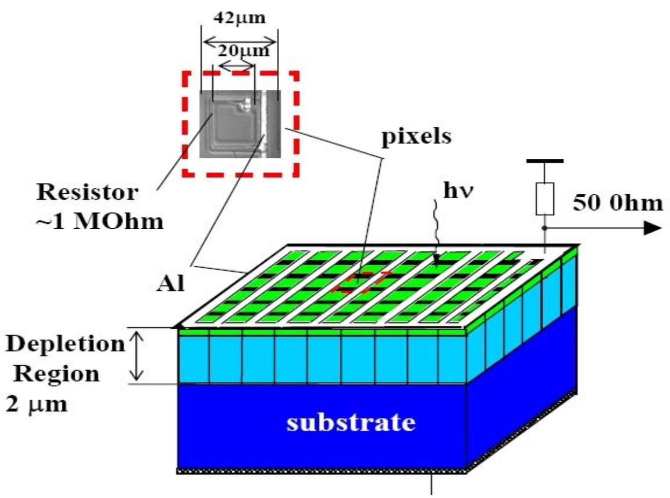
SiPM (Silicon Photomultipliers) could be the solution

SiPM (a.k.a. G-APD or MPPC) are arrays of very small Avalanche Photodiodes (APDs) operated in geiger mode, parallel-connected via individual quenching resistors. The sum of the "digital" signals of each G-APD, one for each photolectron, makes the device analog again.

Advantages with respect to their parents (APD) and grandparents (PIN diodes):

- ✓ high gain (10^6 w.r.t. PIN, 10^4 w.r.t. APD)
- ✓ thin (no fake signals due to leaking shower particles reaching photosensor)
- ✓ no avalanche fluctuations from excess noise factor (geiger mode)
- ✓ low bias voltage (70V or less)





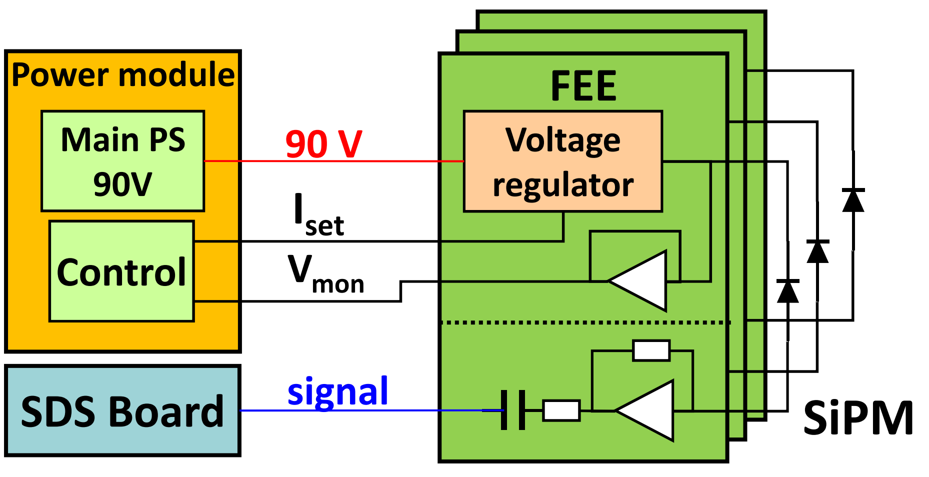
SiPM front-end electronics

The front end electronics has been *custom designed* to *satisfy the detector requirements* and to be *compatible with the KLOE Electromagnetic Calorimeter (EmC) readout chain*. Main requirements:

- ✓ very stable, low noise power supply for the SiPMs,
- ✓ working voltage setting and monitor for each SiPM channel,
- ✓ low noise, good linearity, low power consumption preamplifier,

Power module:

- main switching power supply: 90V, 10 parallel channels
- Control: - SiPM working voltage setting via control current
  - SiPM working voltage monitor

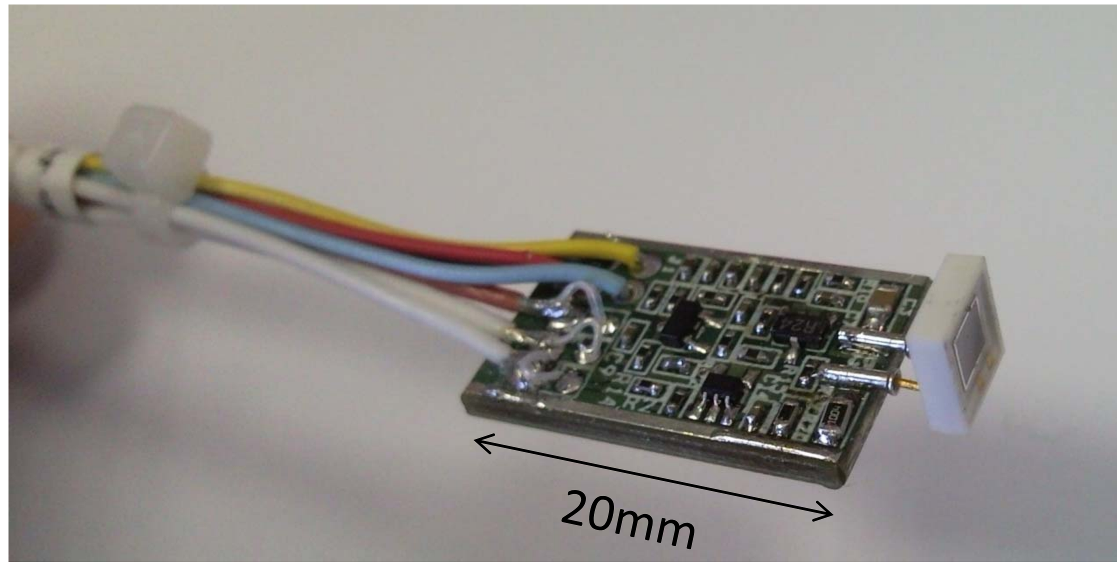


FEE:

- on board voltage regulator:
  high stability, low noise, distributed regulation
  - » adjustable in the range 60-80 V with 5 mV precision
  - » 0.002 % load regulation
  - » 0.02% long term stability
  - » 10μV RMS output noise (10Hz-10kHz)
  - » 2mA supplied current
- transimpedance preamplifier
  Low noise, low power consumption
  - – 2 transistor configuration with bootstrap technique
  - – 24 mW power consumption
  - – 2 μV/√Hz noise

High packing factor: 10X20 mm^2 board

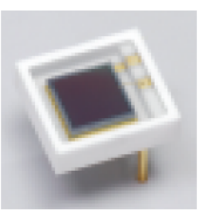
We coupled this front-end electronics to Hamamatsu SiPM (MPPC) S10362-33-050C with 3600 pixels, 3x3 mm^2 active area



NEW Active area 3 × 3 mm type *4

[Typ. unless otherwise noted, Ta=10 °C (S10362-33-025C/-100C), Ta=25 °C (S10362-33-050C)]

HAMAMATSU

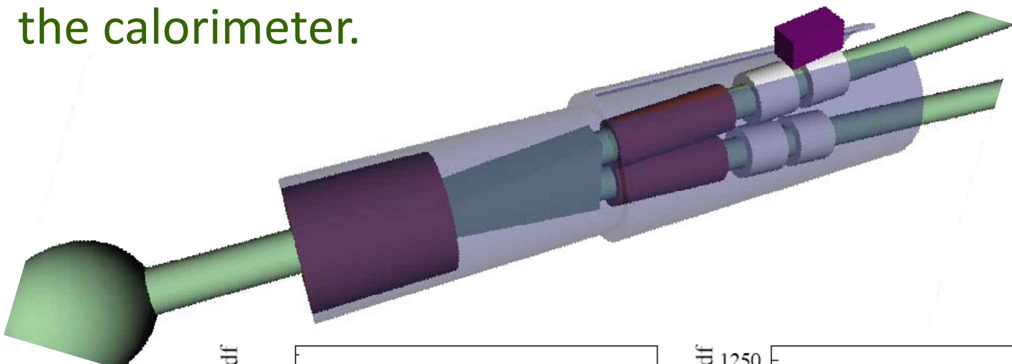

S10362-33-025C /-050C/-100C

Parameter	Symbol	S10362-33 series			Unit
		-025C	-050C	-100C	
Chip size	-	3.5 × 3.5			mm
Effective active area	-	3 × 3			mm
Number of pixels	-	14400	3600	900	-
Pixel size	-	25 × 25	50 × 50	100 × 100	μm
Fill factor *1	-	30.8	61.5	78.5	%
Spectral response range	λ	270 to 900			nm
Peak sensitivity wavelength	λp	400			nm
Quantum efficiency (λ=λp)	QE	70 Min.			%
Recommended operating voltage range	-	70 ± 10 *3			V
Dark count	-	1.5	3	3.5	Mcps
Dark count Max.	-	5	5	5	Mcps
Terminal capacitance	Ct	320			pF
Gain	M	2.75×10^5	7.5×10^5	2.4×10^6	-

Monte Carlo simulation of LET stations

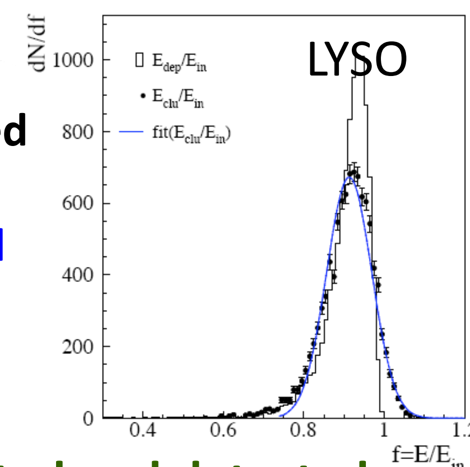
A complete Monte Carlo simulation with GEANT4 is being used to model the LET detectors.

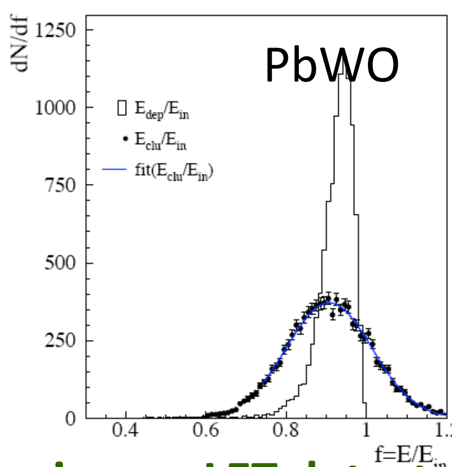
Simulations for energy resolution, with respect to calorimeter dimensions and placement, will be used to validate test-beam data and choose the final design for the calorimeter.



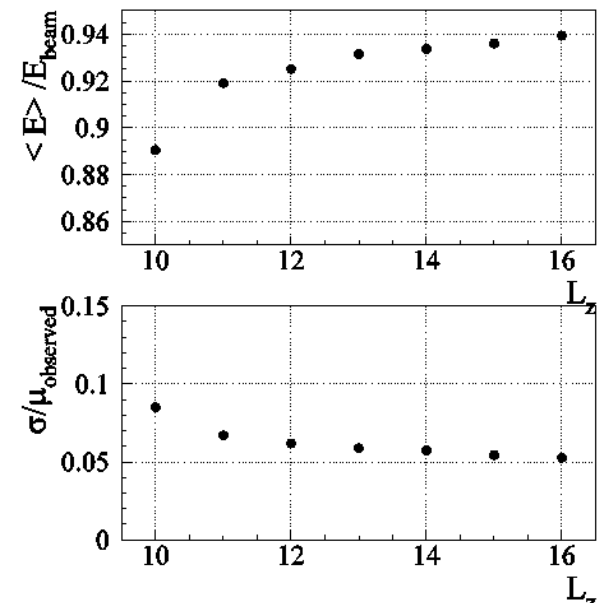
Deposited (black)

Detected (blue)





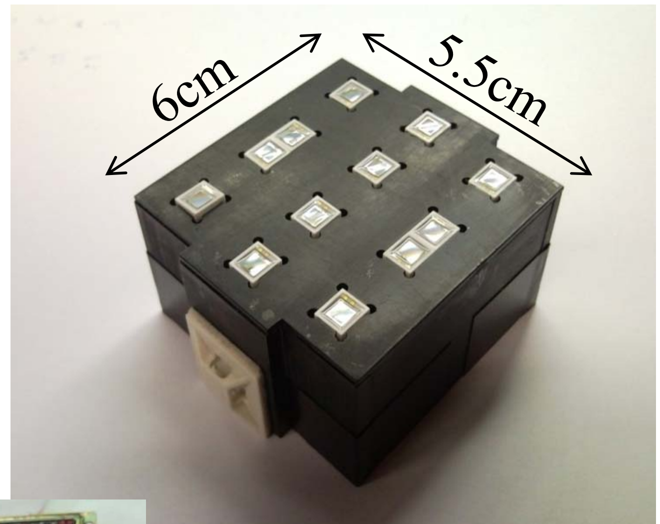
Deposited and detected energy in one LET detector, averaged over the impinging off-energy beam particles.

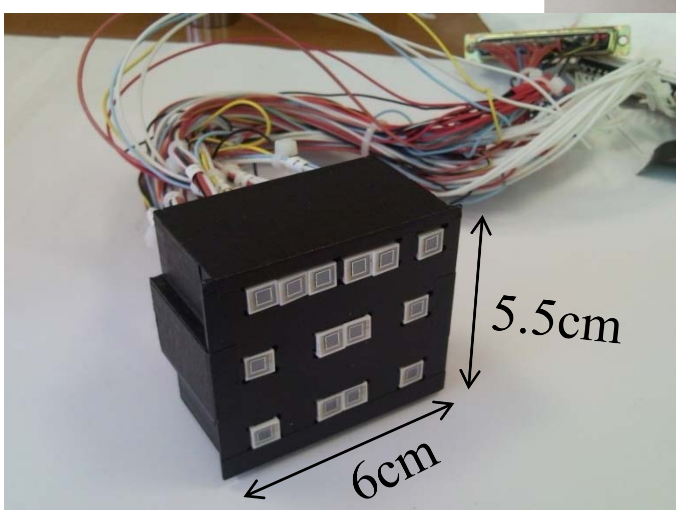


Shower containment (upper) and expected resolution (lower) with respect to length

SiPM+FEE mounting options

Different mechanical supports have been realized to couple the SiPMs to crystals in different configurations for cosmic rays, LED pulsing and e^- test beams

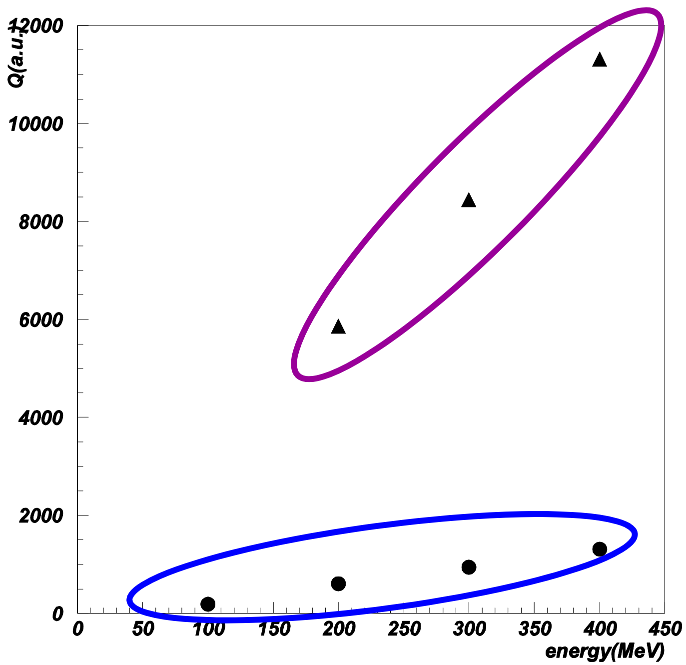




Test beam campaign at LNF-BTF

- *Electron beam tests have been made, and are still ongoing*, at the Frascati Beam Test Facility BTF with "single" electrons of *energy ranging from 150 to 500 MeV* (lower energy tests ongoing in these days)

✓ First tests: PbWO vs. LYSO (single crystals with single SiPM) :
  - ✓ 20x20x130 mm^3 crystals
  - ✓ 3x3 mm^2 SiPM (light collection on end face reduced by 45 times)



LYSO without optical grease, with optic attenuator

both: SiPM gain $=10^6$, amplifier gain =20

PbWO with optical grease

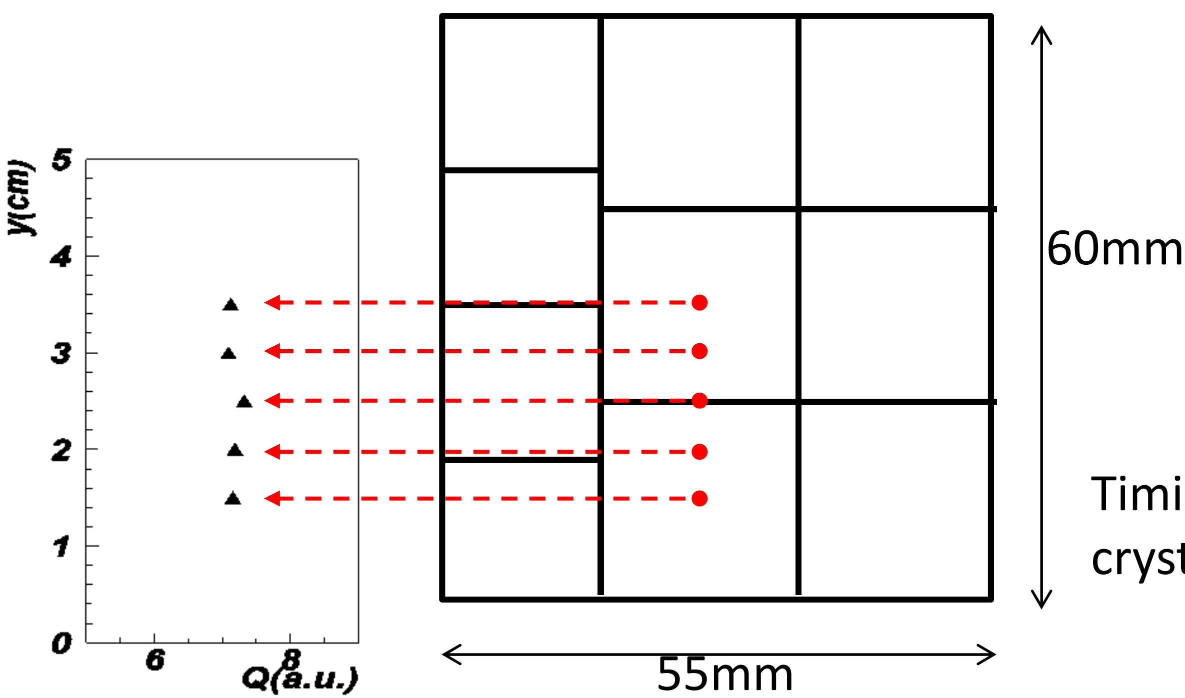
Light Yeld for PbWO showed too poor for our pourposes

LYSO is instead promising as for light yeld and emission time

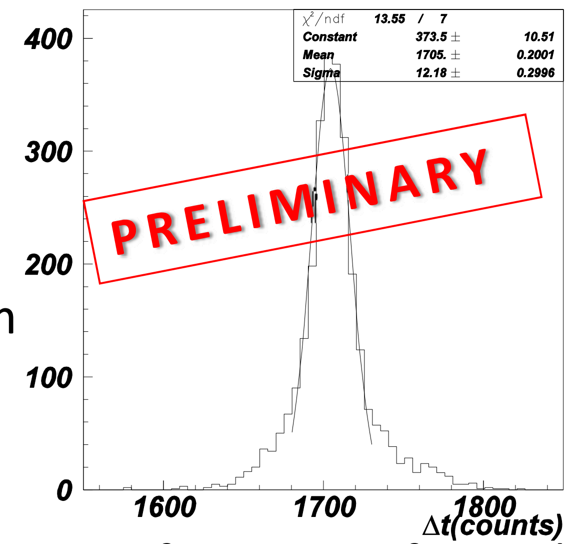
Ongoing test beam

- An array of 14 SiPM is now mounted on a crystal matrix of 60x55x130 mm^3, made of both LYSO and PbWO, to test its energy resolution, linearity, timing capabilities.
- Amplifier gain has been lowered from 20 to 2
- Last but not least, the coupling between this detector prototype and the KLOE EMC DAQ chain is being tested

Preliminary results are very promising:



Scan along the crystal front faces, across one "crack"



Timing performance of a single LYSO crystal: 400ps time reolution

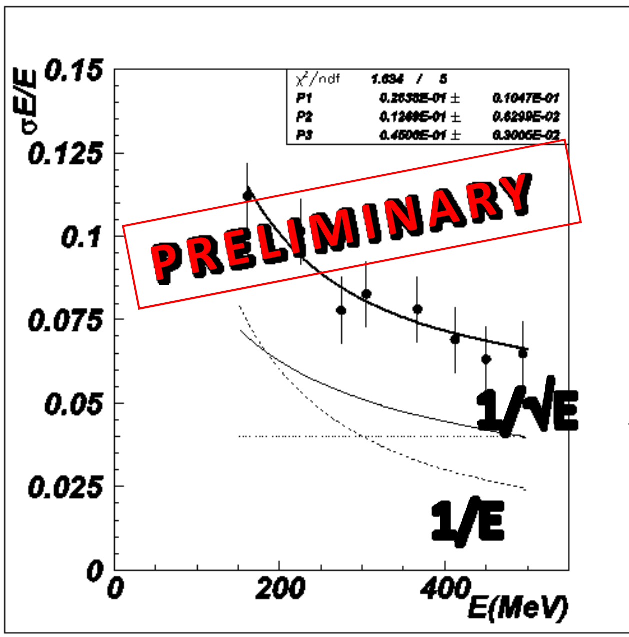
Test beam preliminary results

Energy resolution has been evaluated by summing over 2/3 of the crystals (PbWO crystals are being calibrated) so lateral leakage is still high

Stochastic term= 2.8%/√E consistent with ~2 PE/MeV as expected from gain and amplification

Uncorrelated noise contributes with 0.7%/E , other test-beam setup-driven noise contributions are being investigated

Constant term is consistent with what expected from leakage

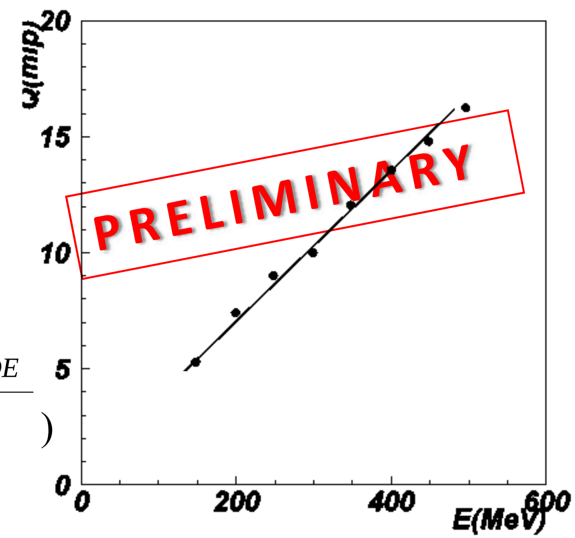


The output signal is proportional to the number of fired cells as long as the number of photons in a pulse (N_{photon}) times the photodetection efficiency PDE is significantly smaller than the number of cells N_{total}:

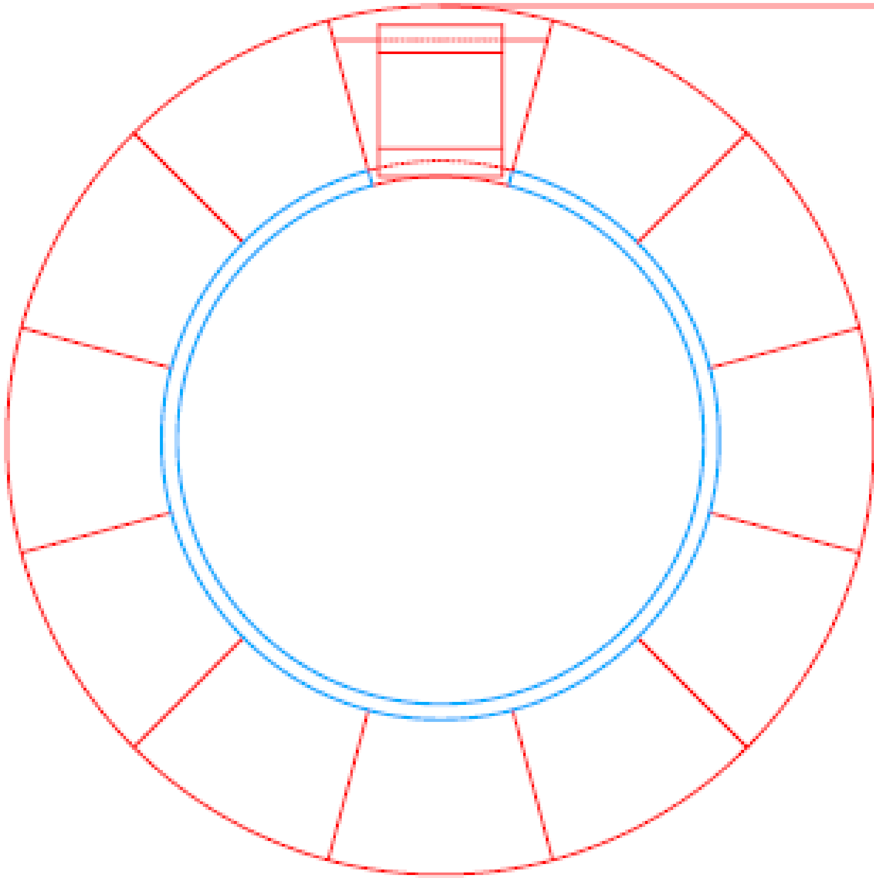
$$A \approx N_{firedcells} = N_{total} \cdot (1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}})$$

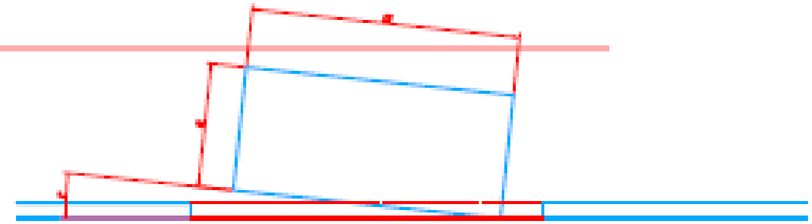
2 or more photons in 1 cell look exactly like 1 single photon.

When 50% of the cells fire the deviation from linearity is 20%.



Very good linearity: SiPM pixels not saturated → < 1000 p.e. @ 500 MeV





Mechanical integration is now aiming at defining the dimensions of the LET stations, their exact placement around the beam pipe and within the space allocated for CCALt in step-1

A combined light pulsing-radioactive source calibration is being designed to monitor detector gain

Temperature sensors will be placed close to SiPMs to monitor temperature variations, and eventually correct bias voltage.

Conclusions

By these test-beam results we will finalize the design of the LET stations:

- *crystals will be wrapped by Tyvek™* to increase LYSO light yield
- we will use *3x3mm², 14400 pixel Hamamatsu MPPC* to increase photoelectron statistics without SiPM pixel saturation

→4 times photoelectrons available, 35% photon detection efficiency, lower temperature dependance of gain and dark count

→we can expect to stay within 7% total energy resolution in the LET energy acceptance

Final design will be ready before summer,

and then…

LET… there be light!