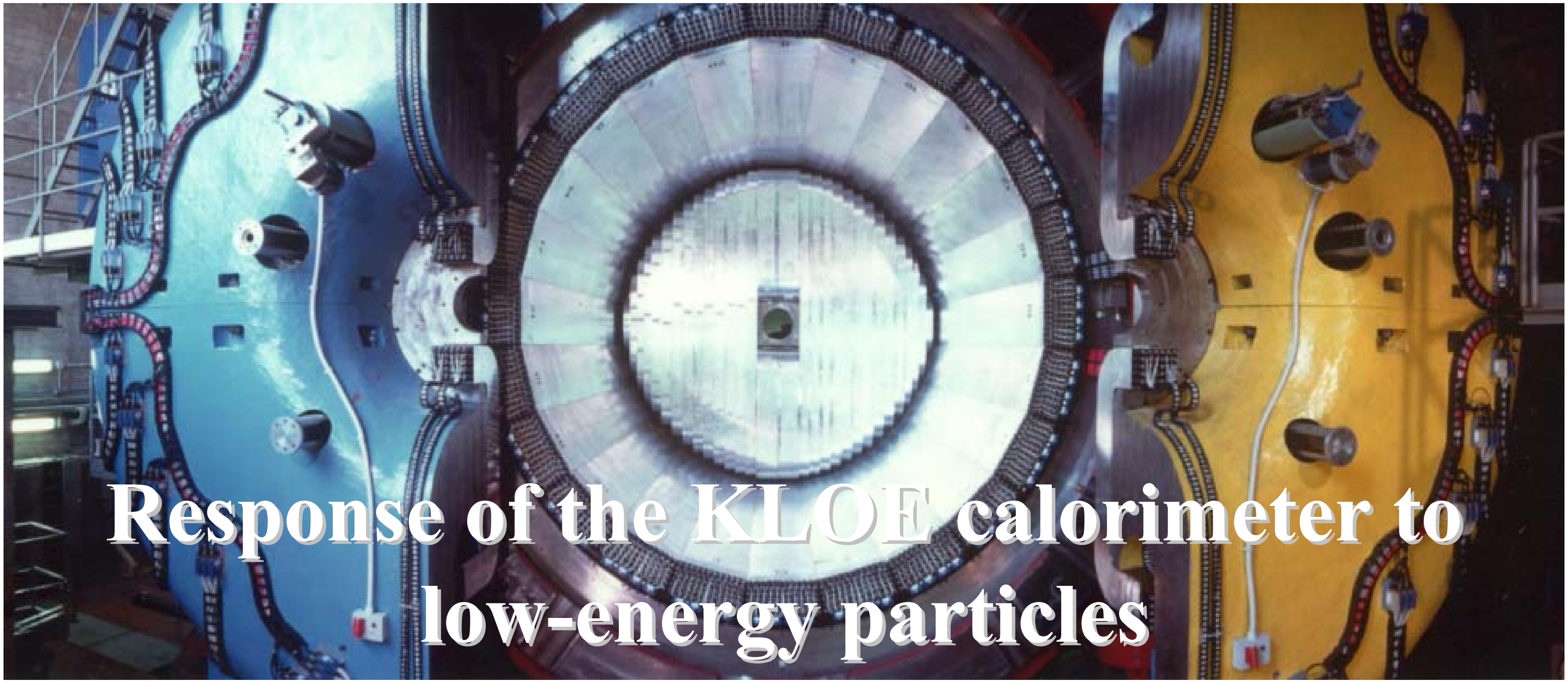


Response of the KLOE calorimeter to low-energy particles

T. Spadaro, INFN/Frascati,
for the KLOE collaboration

11th International Conference on Calorimetry in High Energy Physics
Perugia, 29th March – 2nd April, 2004

KLOE physics

KLOE physics focus: tests of discrete symmetries: **C**, **CP**, **CPT**

Exploit decays of ϕ's produced by e^+e^- collisions at $\sqrt{s} \sim 1020$ MeV

Kaon properties:

$K_S K_L$ (K^+K^-), **|p| ~ 110 MeV**

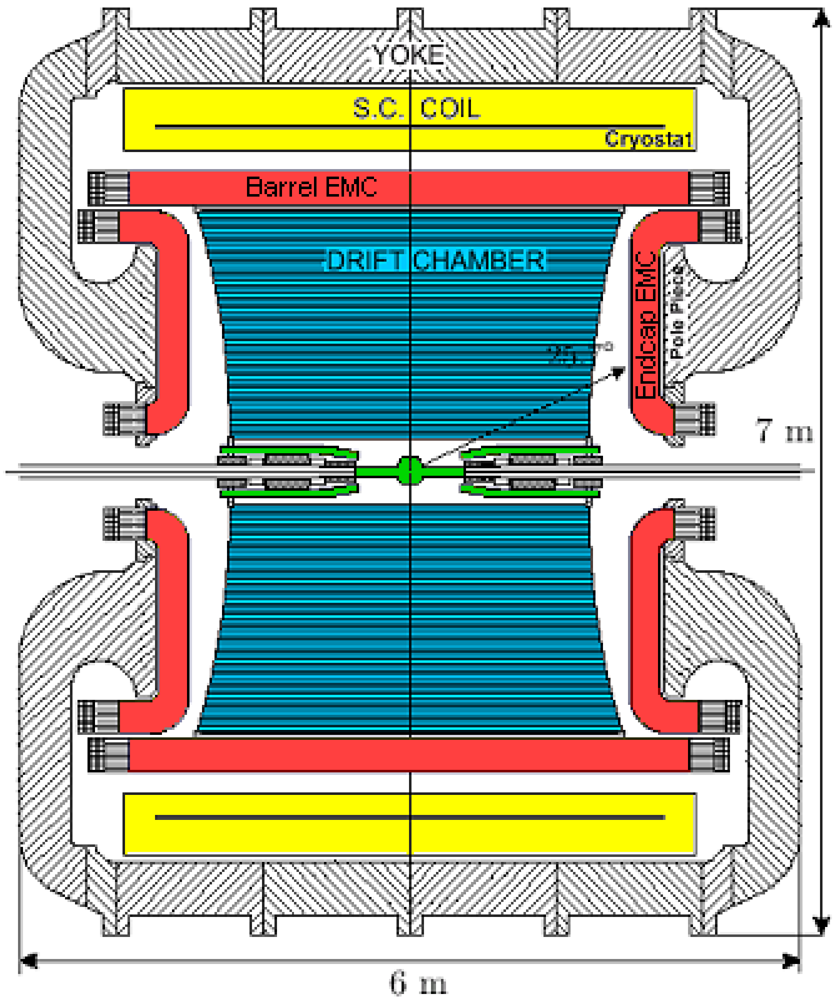
K_S decays near IP: $\pi^+\pi^-$ pairs or γ's in final state, **|p| < 300 MeV**

Accept K_L decays in a cylinder $\varnothing \sim 0.5\lambda_L$: e, μ, π, and γ's, **|p| < 300 MeV**

Calorimeter requirements:

- High γ-detection efficiency from 20 MeV to 500 MeV,
- PID capabilities by TOF, 4π-coverage
- **Measure position of $K_L \to \pi^0\pi^0$ decay from TOF, with a systematic error < 0.5 mm** $\to$ Accuracy of few ps on determination of absolute time scale, during entire time of data collection

The KLOE experiment



Be beam pipe (0.5 mm thick)
Instrumented permanent magnet quadrupoles (32 PMT's)

Drift chamber (4 m ∅ × 3.3 m)
90% He + 10% IsoB, CF frame
12582 all-stereo sense wires

σ_p/p **= 0.4 %** (tracks with $\theta > 45°$)
σ_x^{hit} **= 150 μm (xy), 2 mm (z)**
σ_x^{vertex} **~1 mm**

Superconducting coil (5 m bore)
$B = 0.52$ T ($\int B\, dl = 2$ T·m)

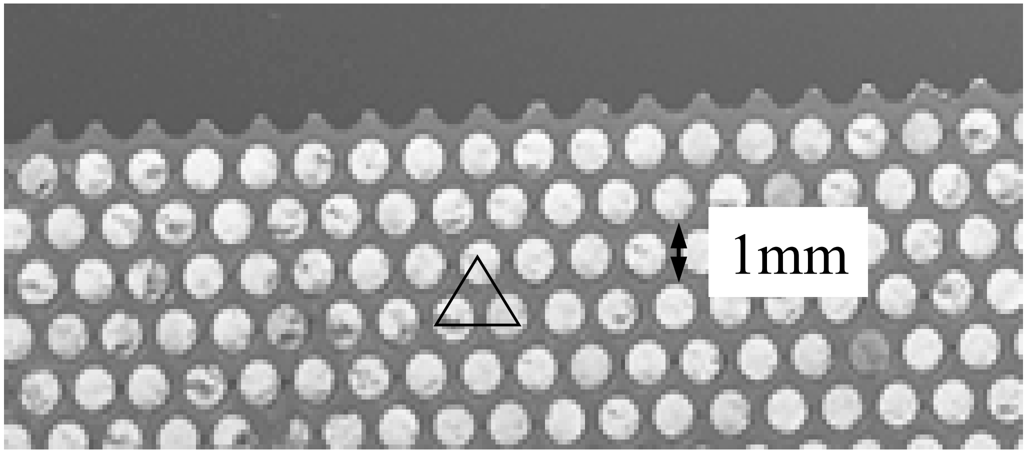
Electromagnetic calorimeter

The KLOE calorimeter

Lead/scintillating-fiber sampling calorimeter (EmC)

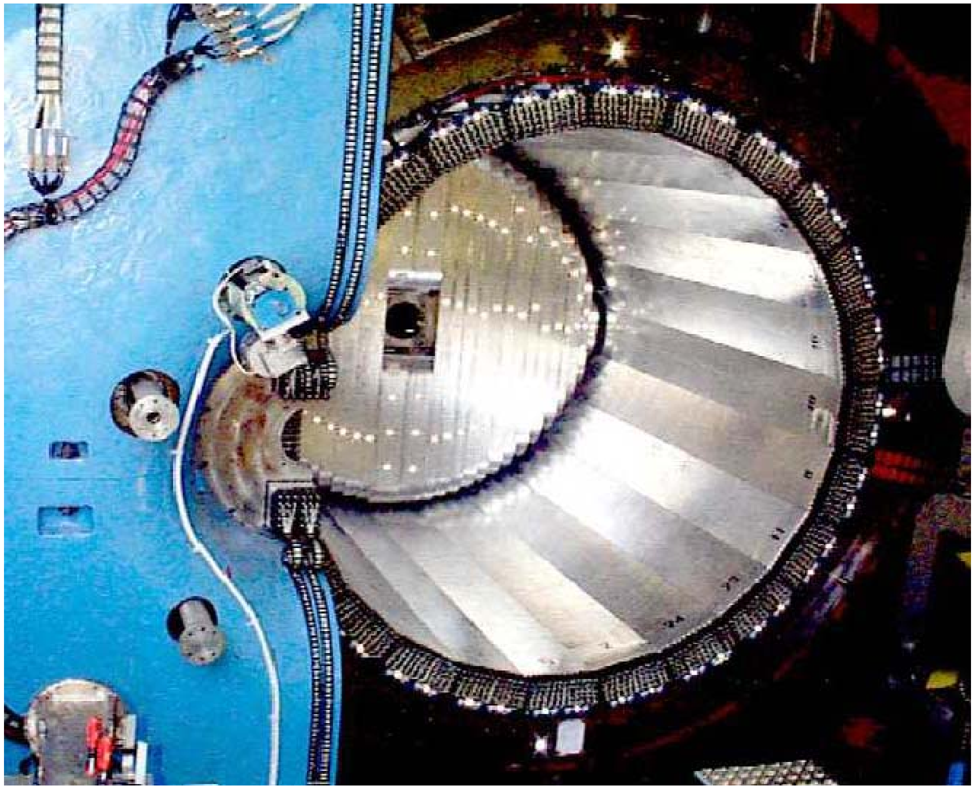
- **Compact structure:** module depth of 23 cm ~ 19 X^0
- **Good energy resolution,** 12% sampling fraction for mips
- **Uniformity of energy response wrt the impact angle:** fibers at vertices of quasi-equilateral triangles
- **Excellent time resolution:** reduced light transit-time fluctuations wrt a Pb-scintillator slab structure

Volume composition	Fib : Pb : glue = 48 : 42 : 10
⟨ Density ⟩	$\rho \sim 5$ g cm^{-3}
Rad. Length	$X^0 \sim 1.2$ cm
Light att. Length	$\lambda \sim 400$ cm
⟨ # of p.e. ⟩ / side @ 2m	$n_{pe} \sim 0.6$ / MeV



The KLOE calorimeter

Hermeticity: Side-on particle impact, module length of 475 cm
Barrel (24 modules) + 2 Endcaps (32 modules)
Each module read out by both sides, 4.4 x 4.4 cm^2 granularity, 4880 PMT's



Calibration of the KLOE calorimeter

Calibration of energy response:

- **cosmic-ray events** from a dedicated run, 2 days every period of stable data taking, to intercalibrate response plane by plane
- **selection of $e^+e^- \to e^+e^-$**, every 200 nb^{-1}, to intercalibrate response between columns
- **selection of $e^+e^- \to$** $\gamma\gamma$, every 200 nb^{-1}, to set absolute energy scale

Stability of energy scale at 0.5% level throughout entire data set

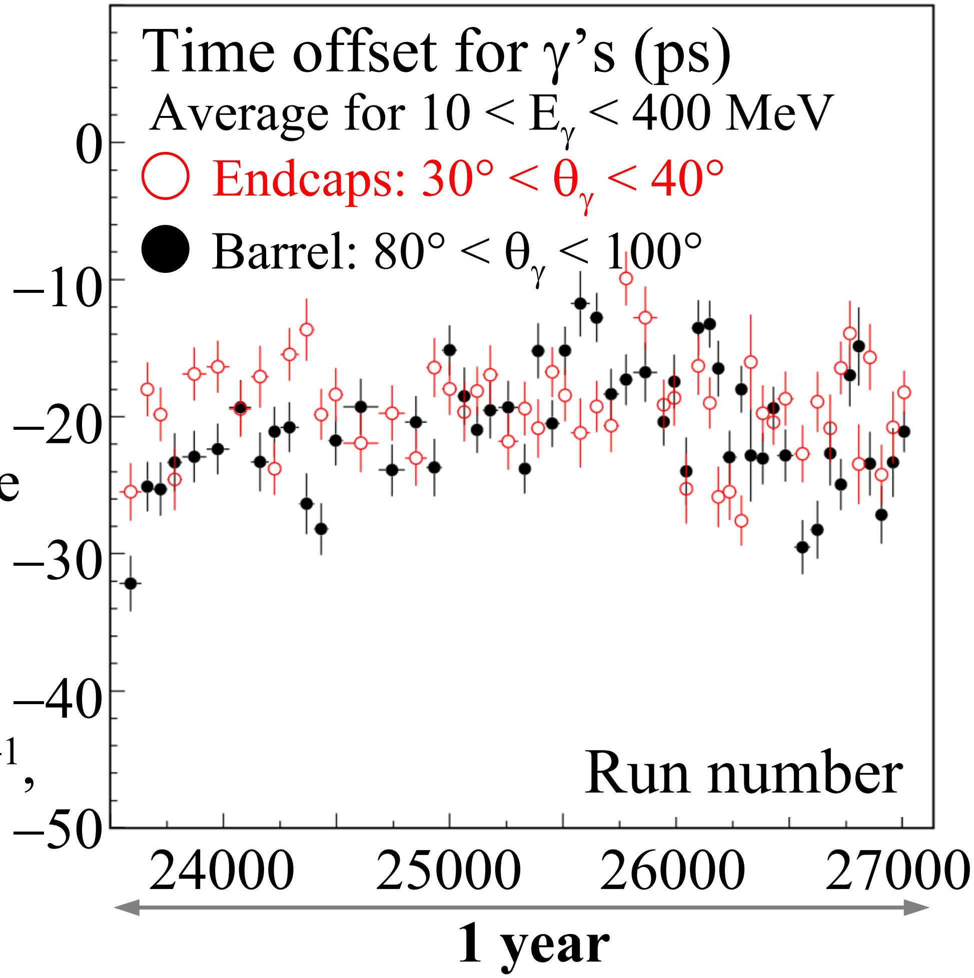
Calibration of the KLOE calorimeter

Measurement of time and coordinate along the fibers:

$$t\ (\mathrm{ns}) = \frac{t^A + t^B}{2} - \frac{t_0^A + t_0^B}{2} - \frac{L}{2v}$$

$$s\ (\mathrm{cm}) = \frac{v}{2}\left(t^A - t^B - t_0^A + t_0^B\right)$$

- **cosmic-ray events** from a 5' dedicated run, every 1–2 days, to intercalibrate response plane by plane
- **selection of $e^+e^- \to e^+e^-$**, $\gamma\gamma$, every 200 nb^{-1}, to set time offsets
- **selection of $e^+e^- \to \gamma\gamma$** every 200 nb^{-1}, to set absolute time scale



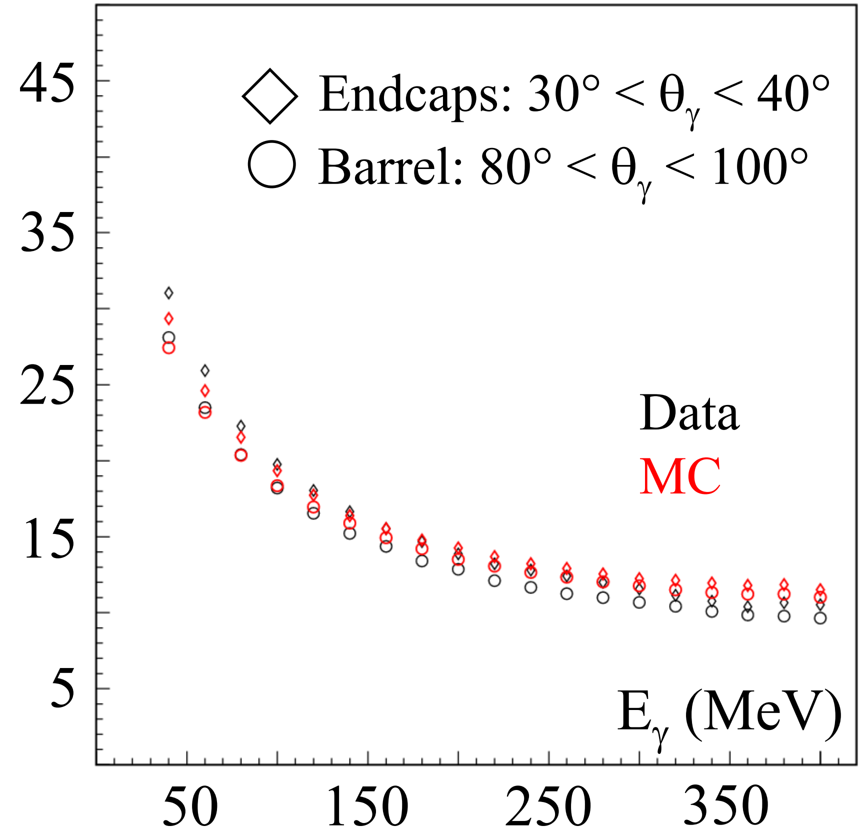
Stability of time offset better than 10 ps throughout entire data set

Energy response for e.m. showers

Check of energy response in data and MC, use tagged γ's from $\phi \to \pi^+\pi^-\pi^0$

- **Non-linearity < 2% above 50 MeV**
- **σ_E/E** = 5.7% / **$\sqrt{}$E[GeV]**

Fractional resolution, σ_E/E (%)



Simulation: approximated structure, alternating Pb-scintillator slabs:

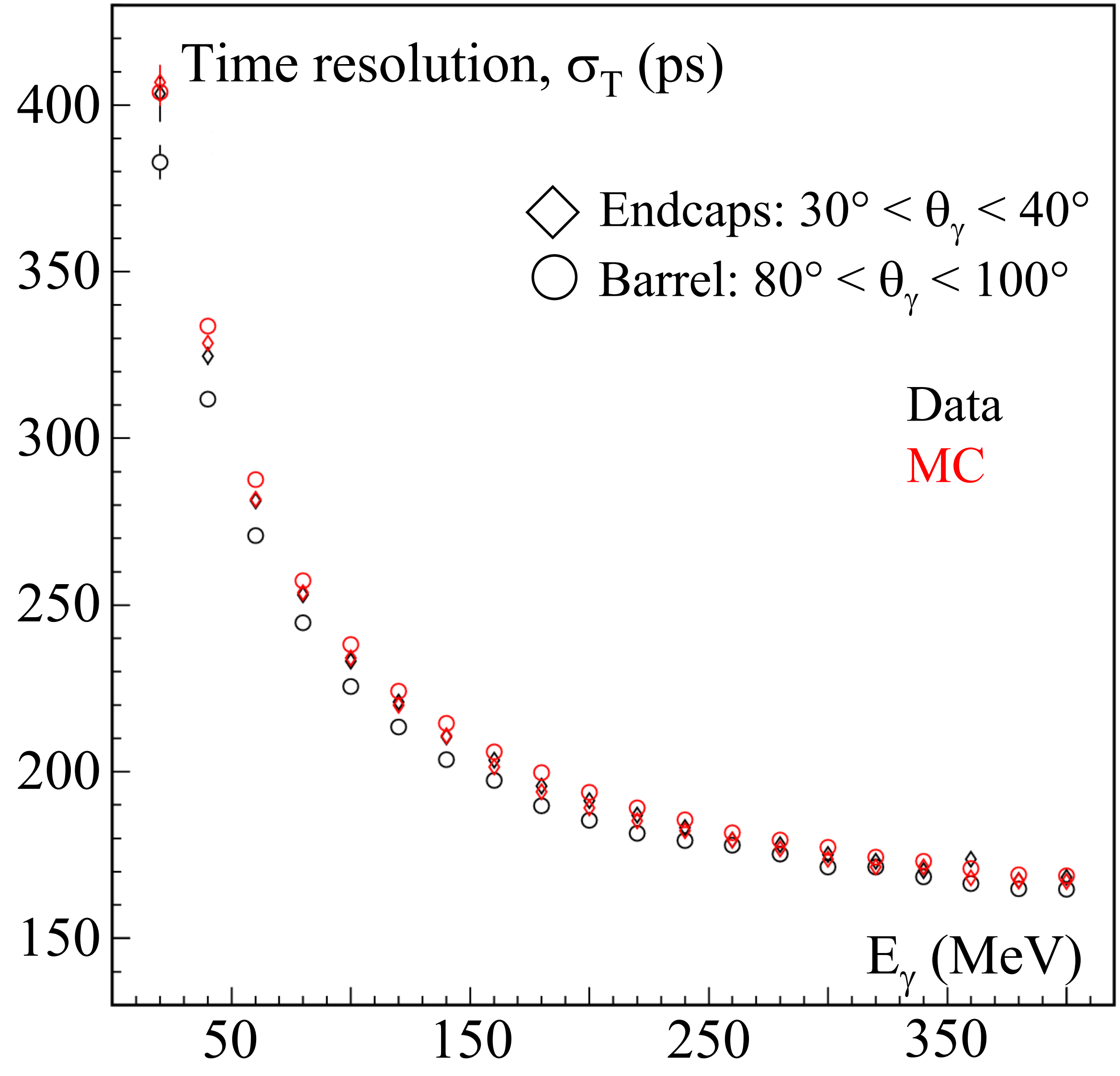
- Faster than detailed description of individual fibers
- Same number of Pb layers as in real detector
- Slab thickness tuned using γ interaction length measured in data

Time measurement

Check of time measurement in data and MC, use tagged γ's from $\phi \to \pi^+\pi^-\pi^0$

$\sigma_T = 54 / \sqrt{E[\mathrm{GeV}]} \oplus 50\ \mathrm{ps}$

Value of stochastic term in σ_T determined by characteristic fiber scintillation time, $\tau \sim 2$ ns, and p.e. statistics



New procedure for energy calibration

New procedure possibly applied in the next data taking,
using showers from γγ events

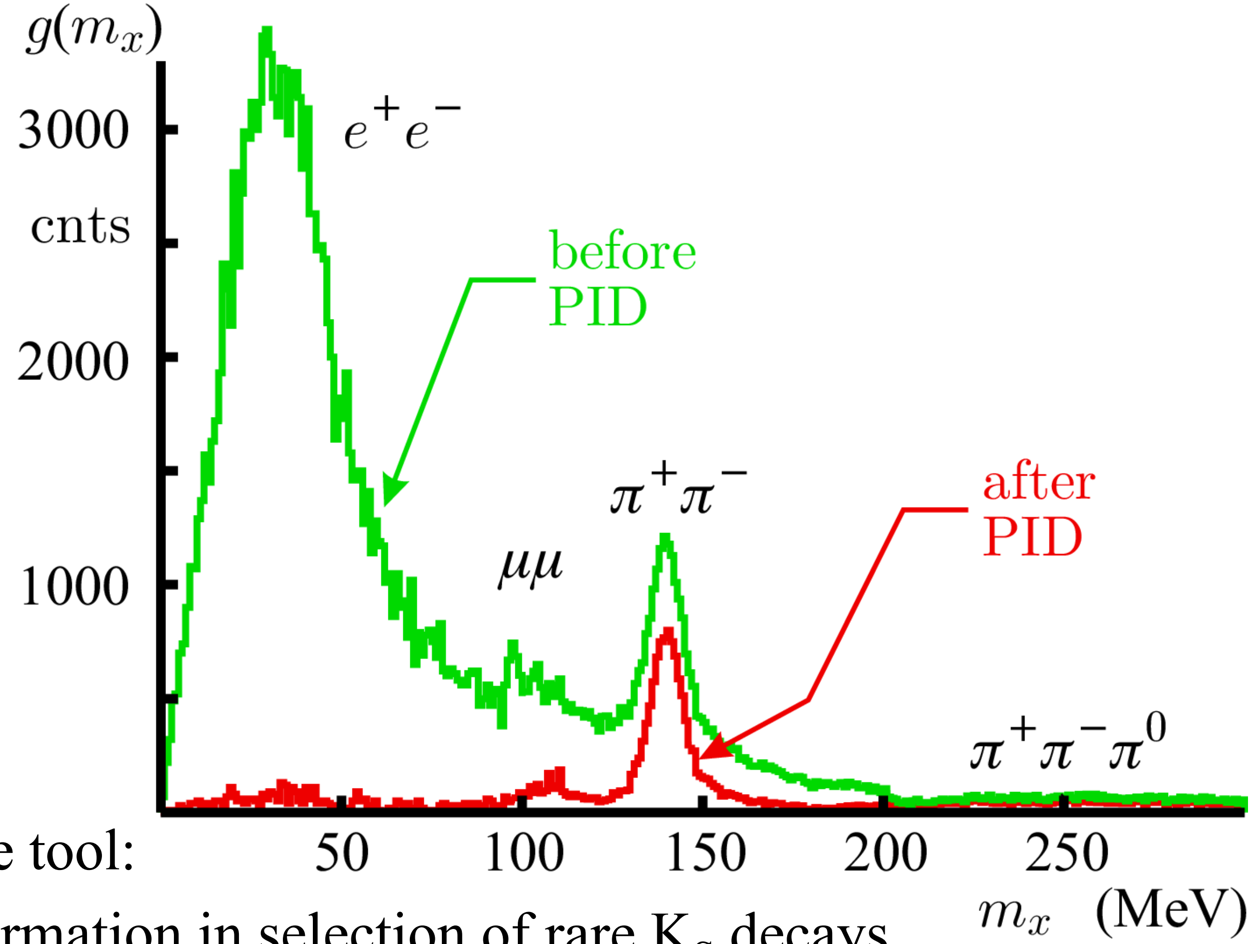
Advantages wrt usage of cosmic rays:

- Minimize energy resolution @ 500 MeV
- Collection simultaneous with data acquisition
- Collection time much smaller
- More uniform detector illumination, particularly on endcaps

Guarantee stability during data taking, important whenever energy-based PID techniques are used

PID from calorimeter information

TOF + distribution of energy release exploited to identify π's from e's and μ's in the analysis of $e^+e^- \to \pi\pi\gamma$ events

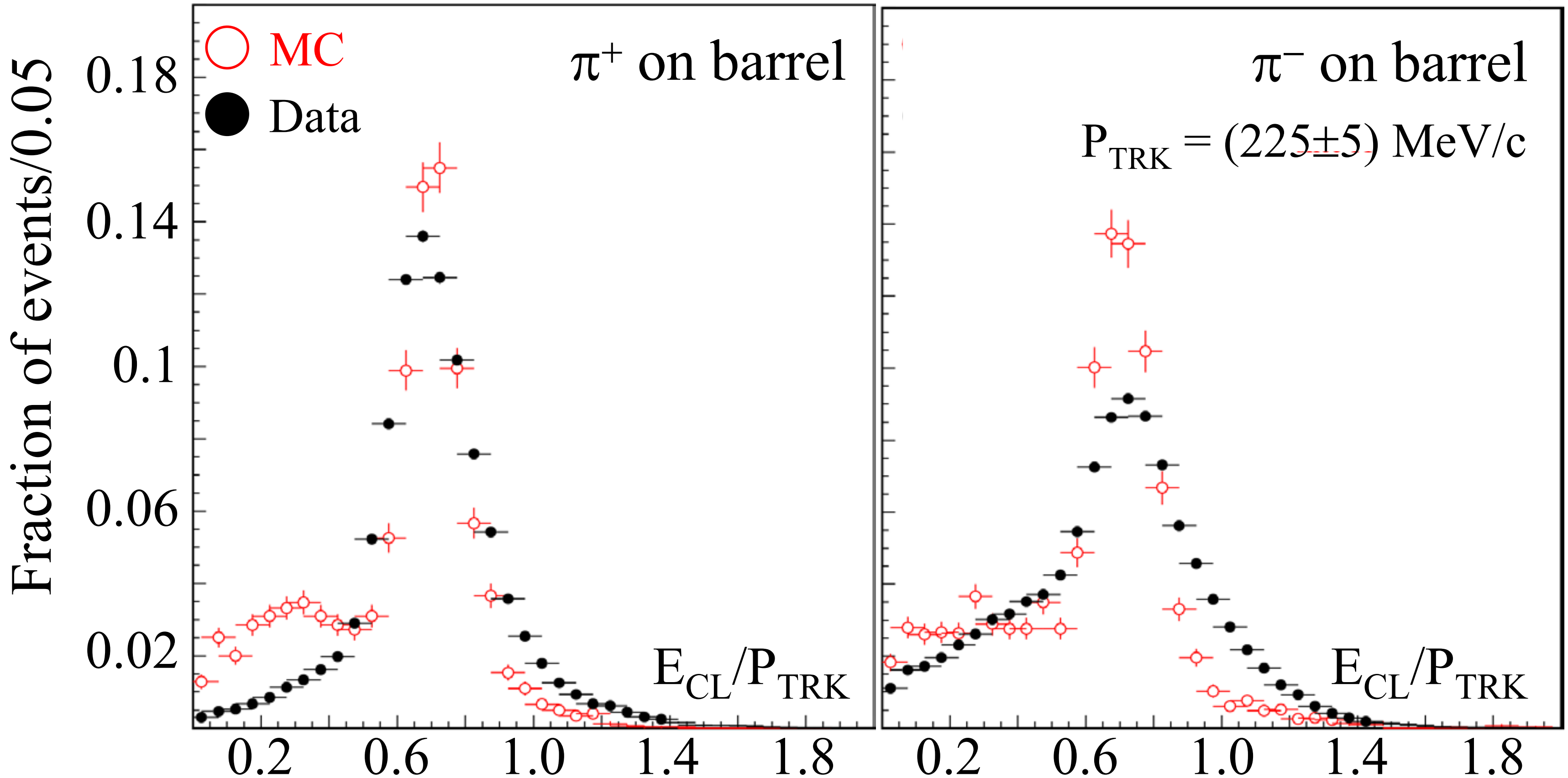


Energy-based PID valuable tool:

- To complement DC information in selection of rare K_S decays
- To obtain control samples useful for efficiency measurement, in the analysis of main K_L decays

Simulation of response to low-energy π's

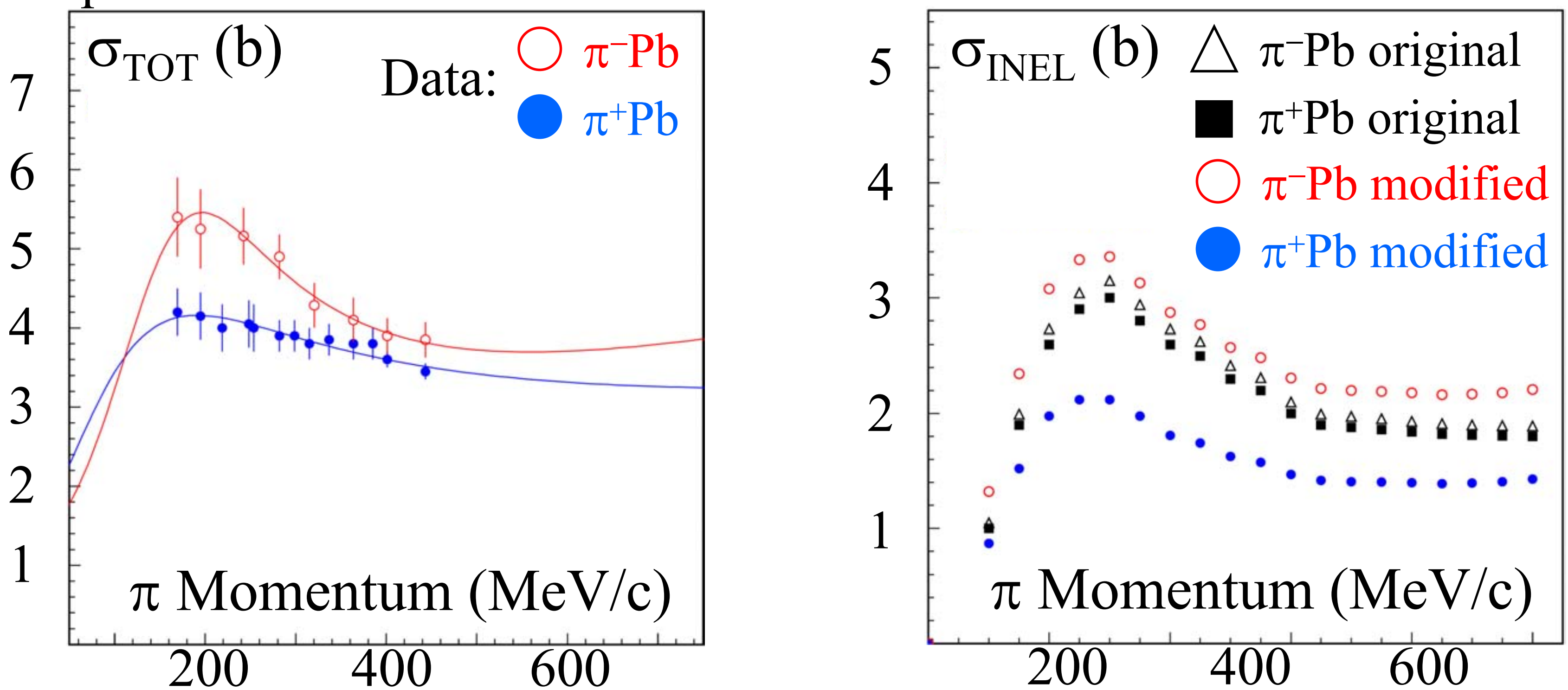
MC code: particle tracking using GEANT 3.21,
Nuclear interactions of hadrons in calorimeter based on GHEISHA package



π response not correctly simulated
Data-MC comparison sensitive to inelastic interactions

Simulation of response to low-energy π's

Little data available in the literature for low-energy π-Pb reactions, but:
– Cross sections peak slightly above the Δ(1230) resonance
– Total cross section is different for π^+ and π^-, $\sigma_{\pi+Pb}$ ~ 4b, $\sigma_{\pi-Pb}$ ~ 5.5b @ peak
– Elastic process accounts for as much as 30% of the total cross section



Original MC description: π^+, π^- inelastic cross sections same to within 5%

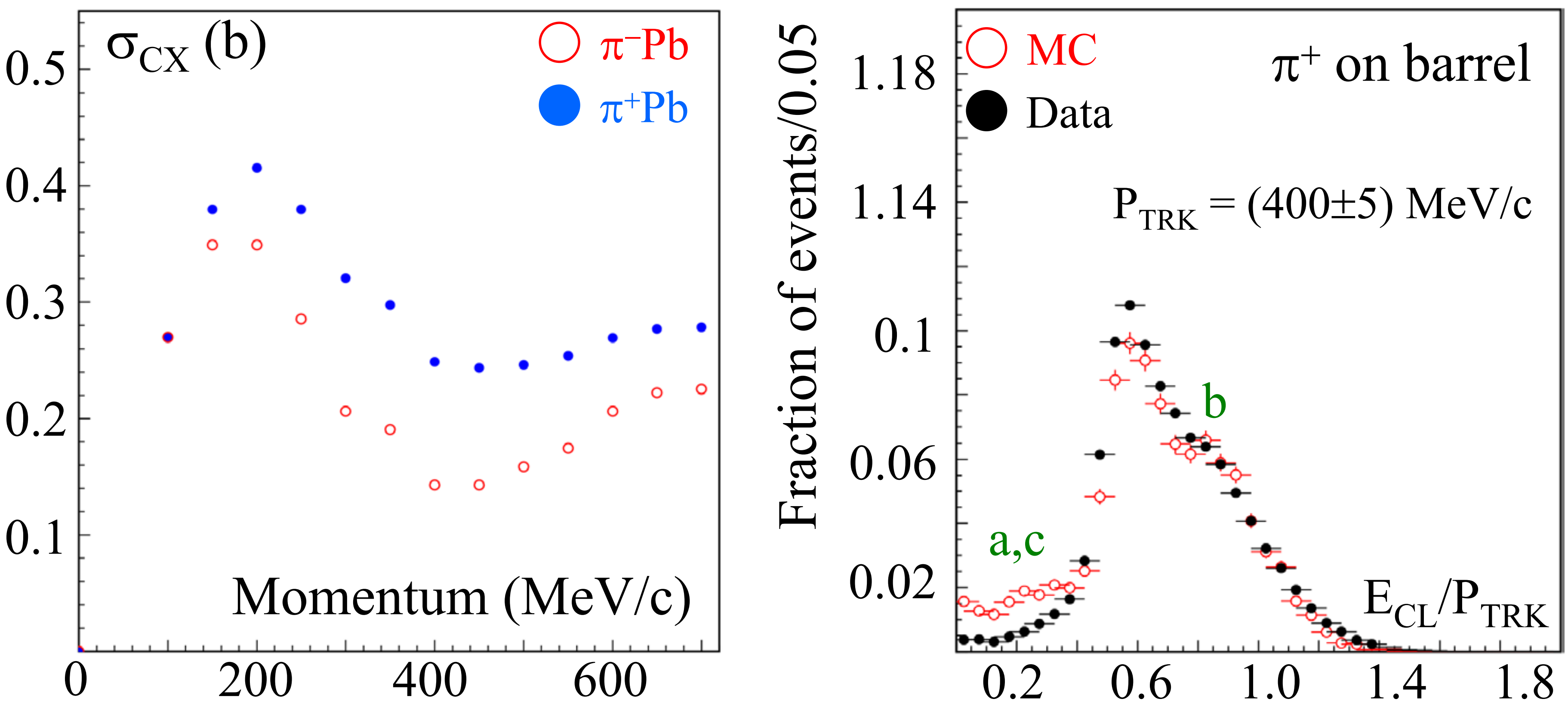
Simulation of response to low-energy π's

Inelastic processes:

a. quasi-elastic interactions, incident π lose energy producing nuclear excitation

b. charge-exchange (CX): $\pi^- p \rightarrow \pi^0 n$ (absent in original GHEISHA code, due to a bug)

c. evaporation of low-energy pions and nucleons

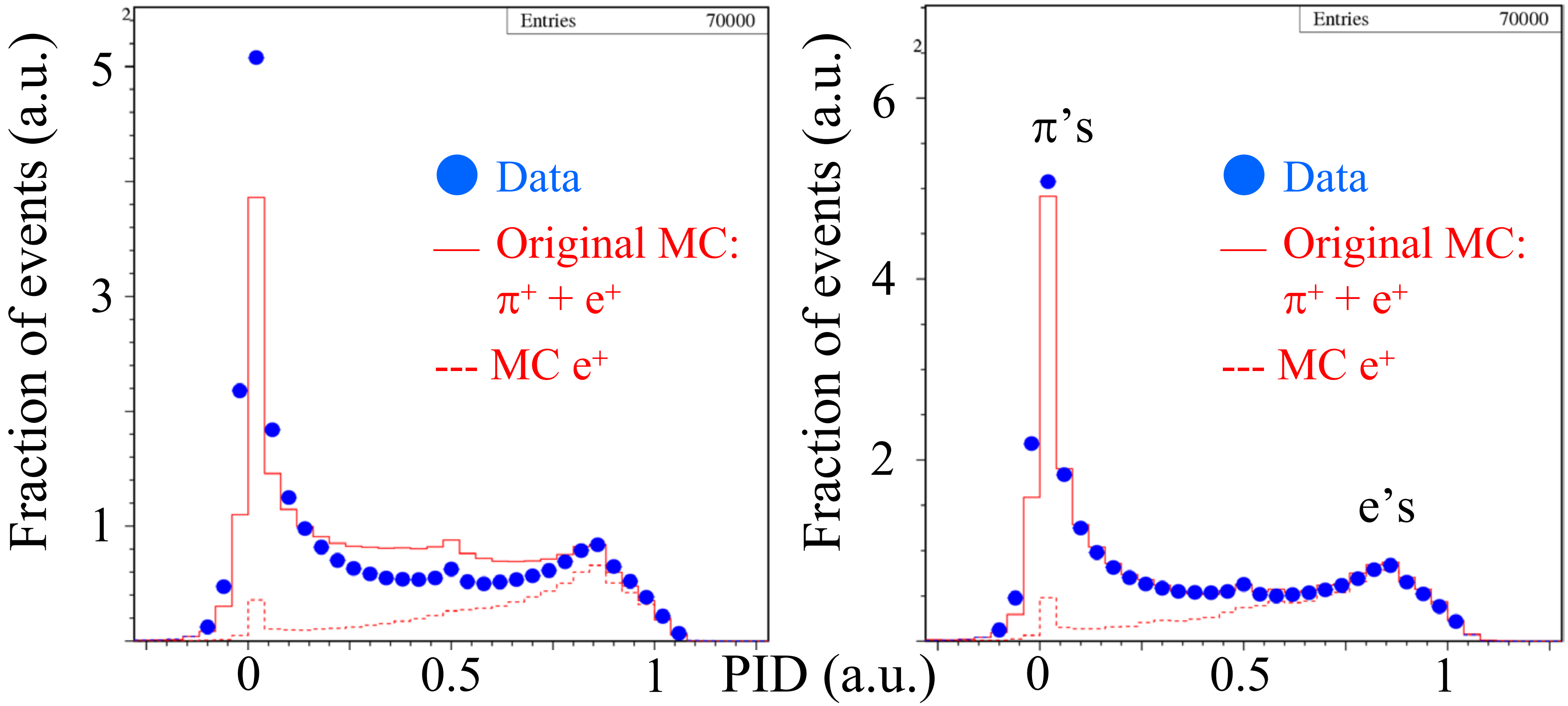


Simulation of response to low-energy π's

Check reliability of modified simulation

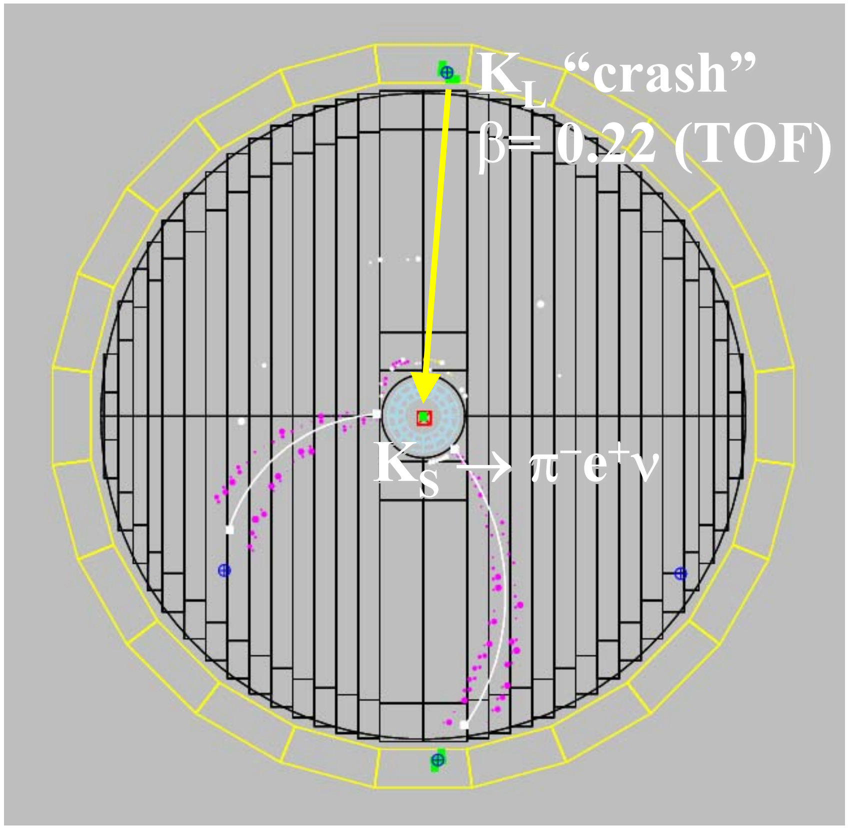
Build a PID variable parametrizing cluster shape as a function of P_{TRK} in data

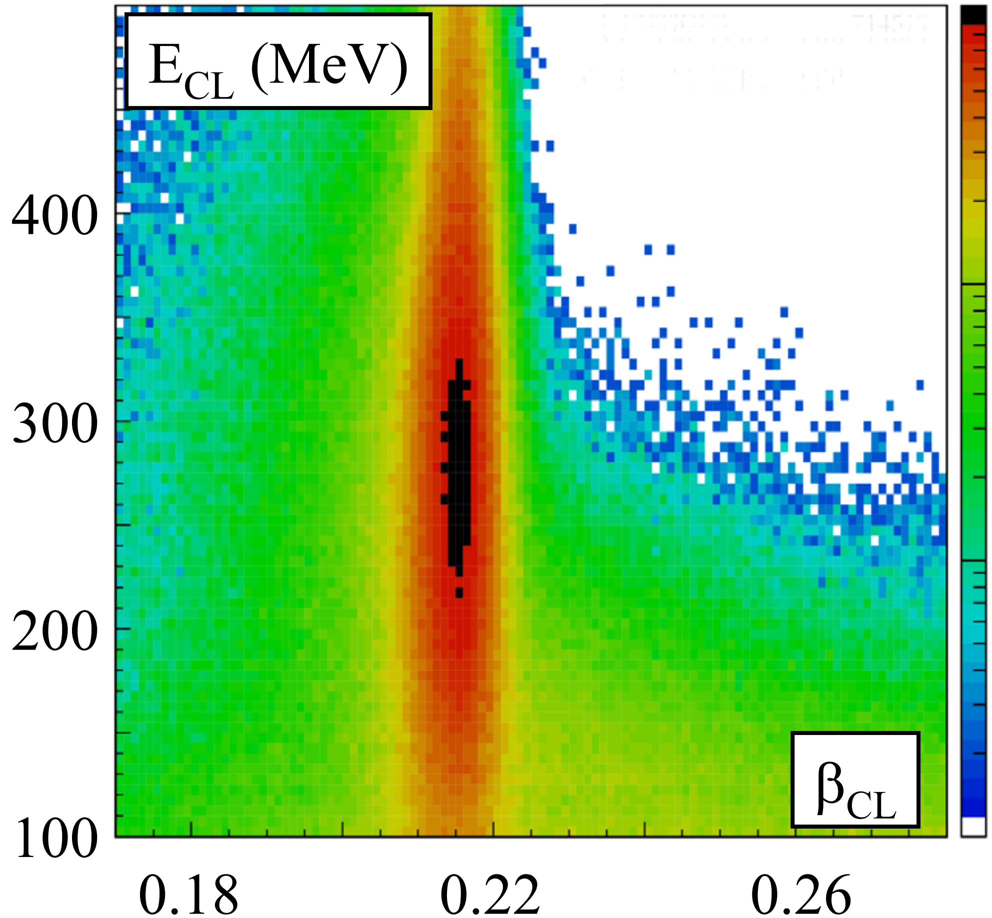
Compare data and MC using K_L semileptonic decays



EmC PID capability: π identification efficiency 80%, e rejection power of 15

K_S tagging from K_L interactions in EmC





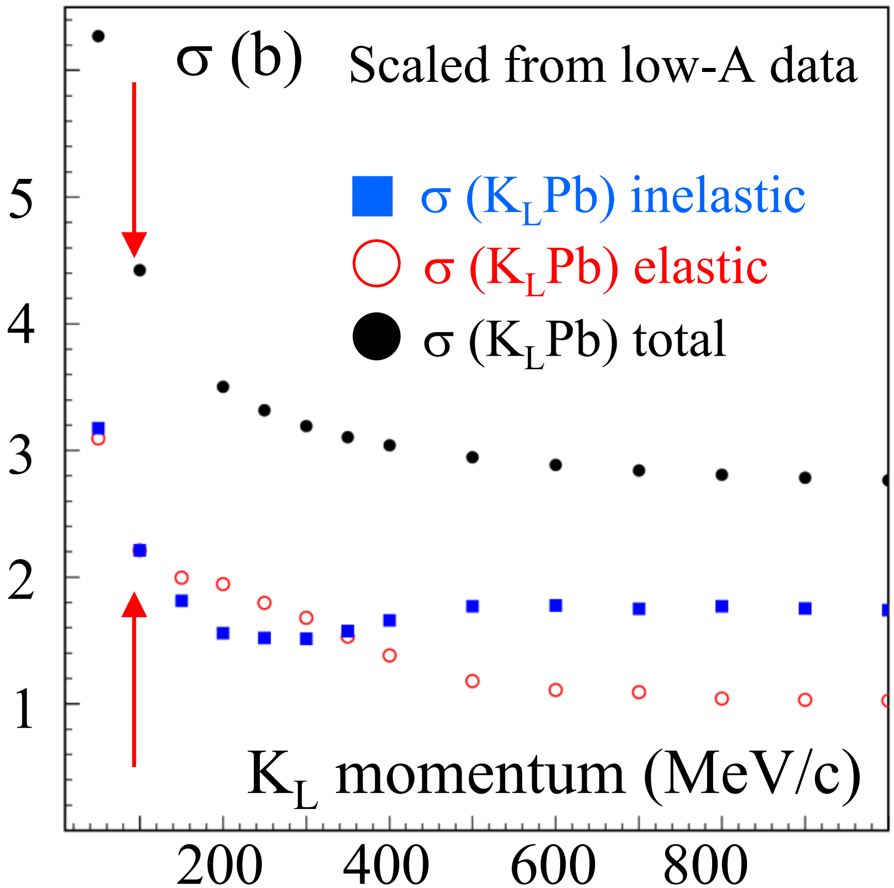
K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)
K_S angular resolution: ~ 1° (0.3° in ϕ)
K_S momentum resolution: ~ 1 MeV

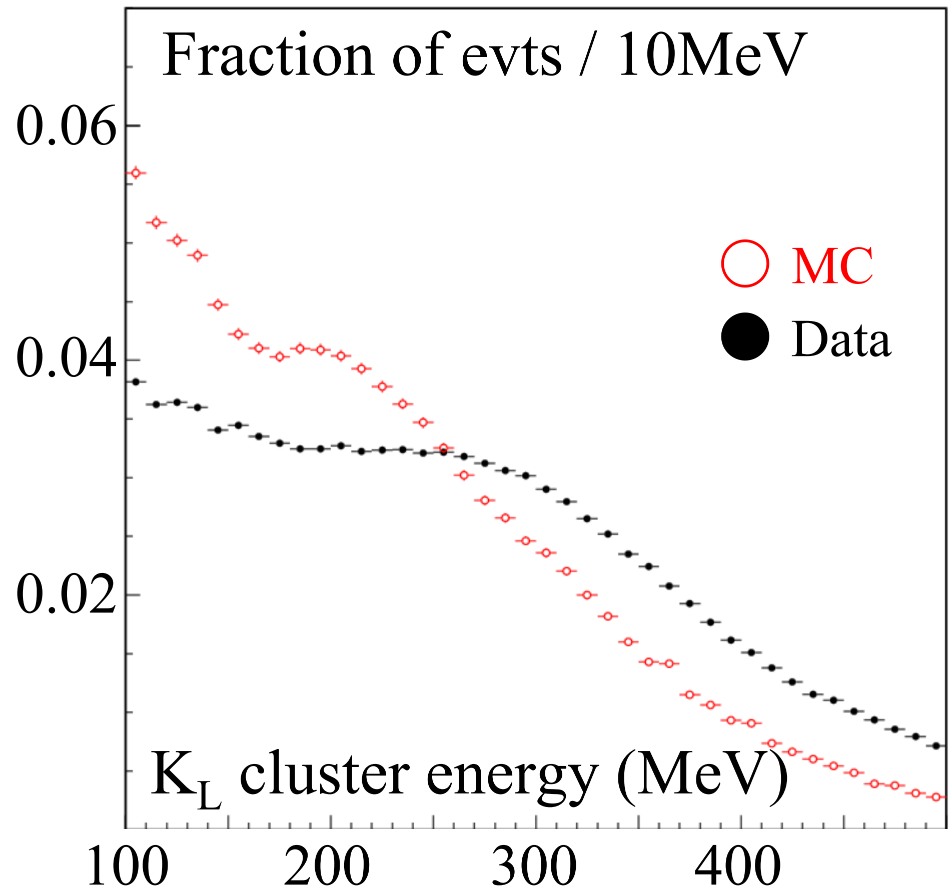
Cut on K_L cluster energy, E_{CL}, vs estimated velocity, β_{CL}

Simulation of K_L response

Tune only inelastic cross section, elastic process equivalent to punch-through
Scarce data in the literature for K_L-Pb interactions at 100 MeV

Original MC, energy spectrum softer than data





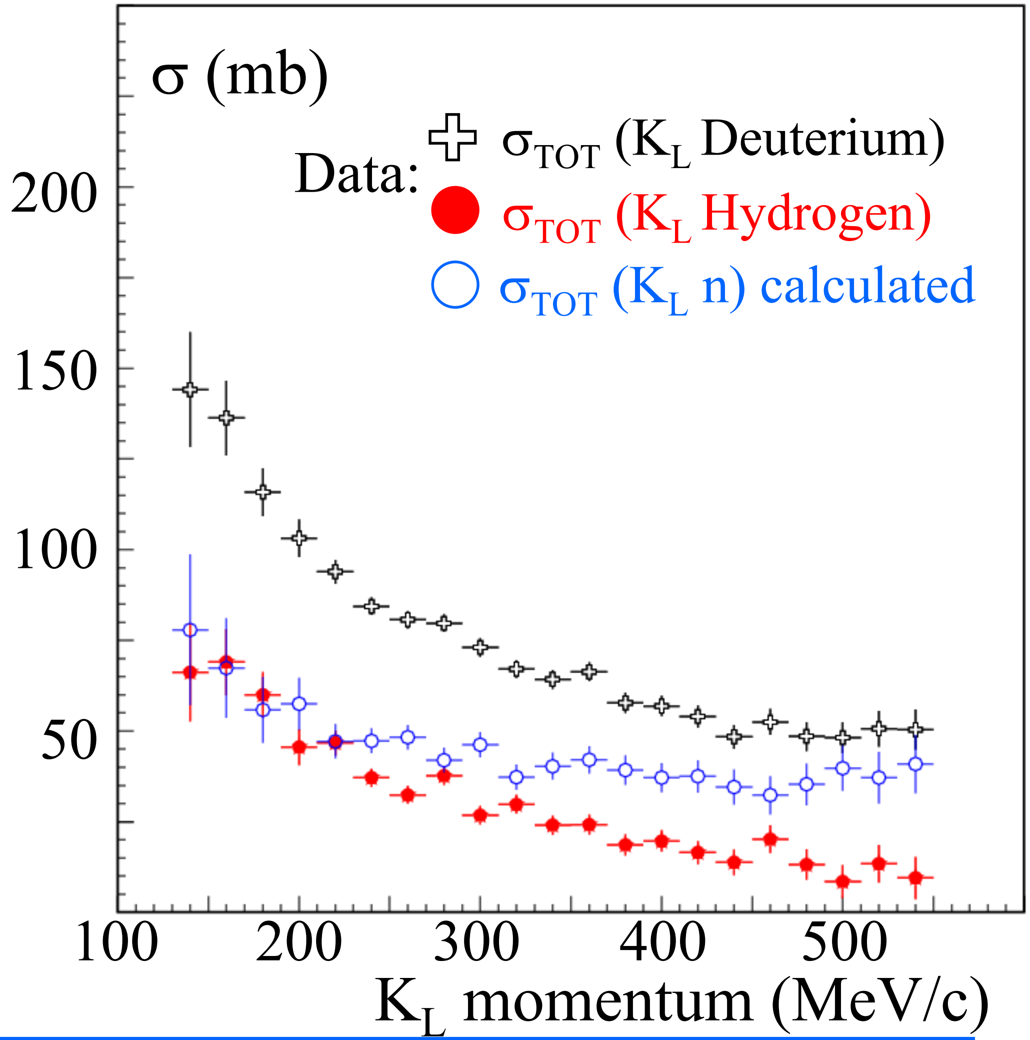
Simulation of K_L response

Original MC, inelastic interactions: sample p or n as target according to Z/A, but

Difference expected for K_L p and K_L n cross sections:

- K_L n cross section from D and H data. For nucleons in Pb nuclei, Fermi motion introduces a ≈300 MeV spread on a 110-MeV monochromatic K_L beam
- Different reactions for $\bar{K}^0$ on protons and neutrons:

$\bar{K}^0 p \to \Sigma^0\pi^+$	$\bar{K}^0 n \to \Sigma^+\pi^-$
$\bar{K}^0 p \to \Lambda\pi^+$	$\bar{K}^0 n \to \Sigma^-\pi^+$
	$\bar{K}^0 n \to \Sigma^0\pi^0$
	$\bar{K}^0 n \to \Lambda\pi^0$



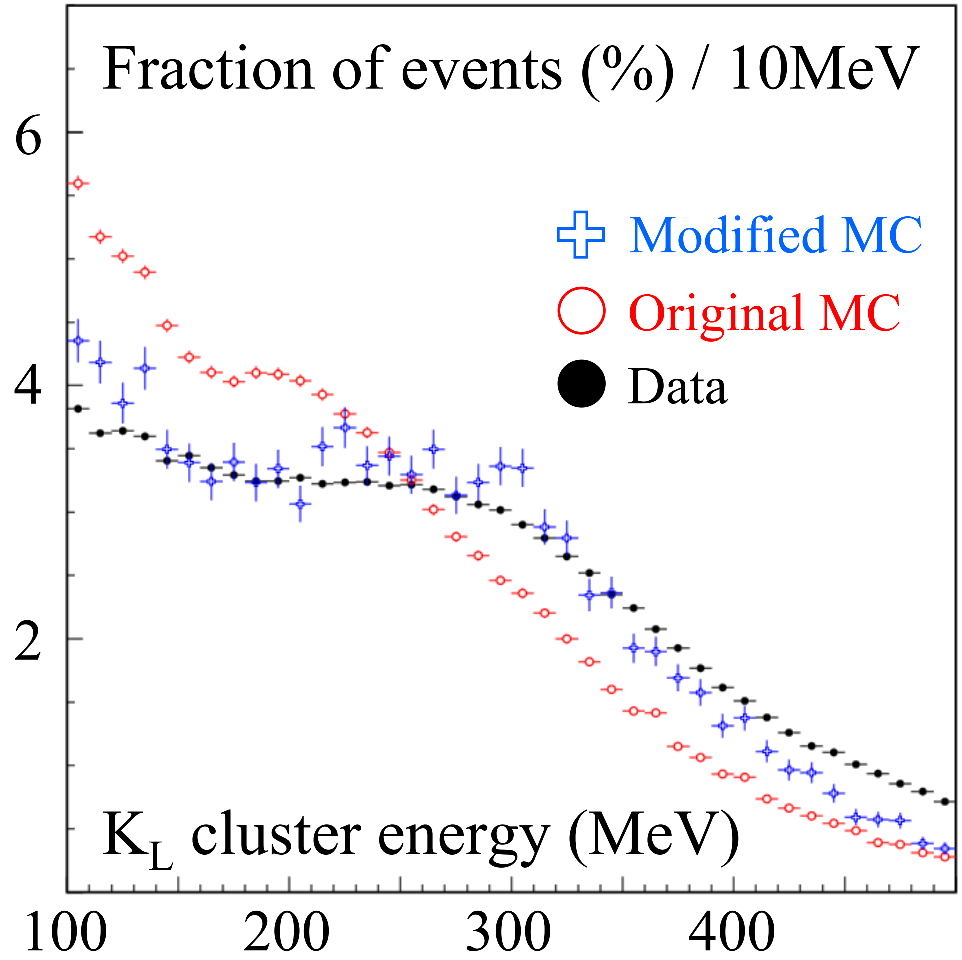
Simulation of K_L response

Better agreement obtained by enhancing K_L n cross section by 50%

Good agreement wrt time response

Can get tagging efficiency for various energy cuts from MC, w accuracy at the level of few %

Energy cut (MeV)	Tagging efficiency (%)		
	Data	Original MC	Modified MC
100	33.50(2)	33.37(7)	35.7(2)
200	22.31(2)	18.23(5)	22.8(2)
300	11.98(1)	7.42(4)	11.0(2)



Conclusions

KLOE calorimeter performance fulfills requirements for $e^{\pm}$, γ detection

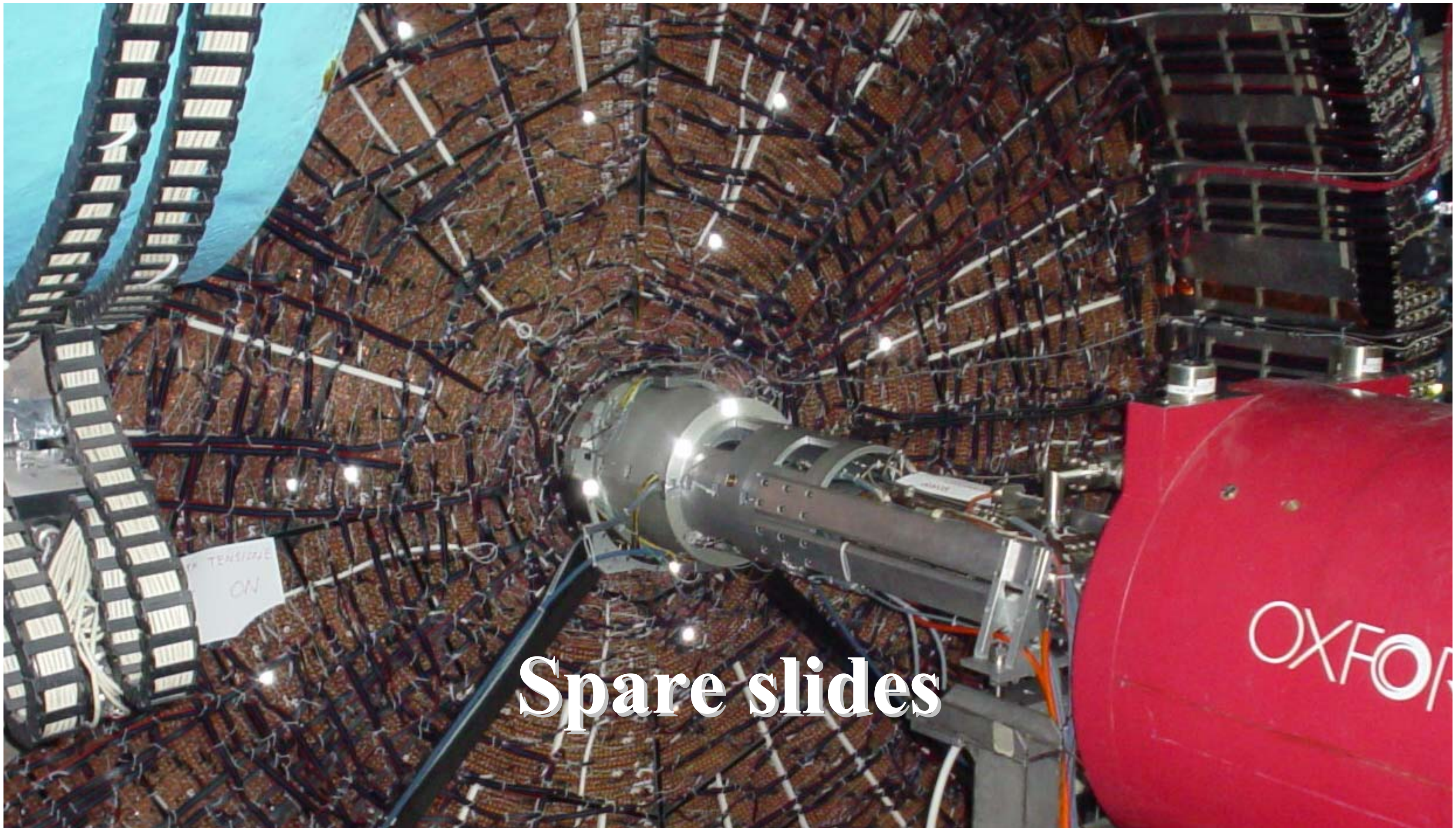
Detailed study of response to low-energy $\pi^{\pm}$ ($\mu^{\pm}$) completed:

- Data and MC compared for each particle species, in bins of momentum
- Agreement greatly improved, simple corrections to MC description of hadronic interactions
- PID technique implemented, used distribution of energy release, no TOF: efficiency for $\pi^{\pm}$ of 80%, with a rejection power against $e^{\pm}$ of 15

Description of K_L interactions in matter is an important issue:

- Identification of K_L interactions is the most efficient K_S tagging technique
- Uncertainties in the simulation of K_L energy release affect analyses even of higher-energy data (e.g. $b \to s\gamma$ @ Belle)
- Data-MC agreement for response to 100-MeV momentum K_L's improved by simply correcting choice of target nucleon in MC

Spare slides



Calibration of the KLOE calorimeter

Measurement of energy for the side A,B of the i^{th} cell:

- Subtract pedestals $\mathbf{S_{0,i}}$ from the integrated charge $\mathbf{S_i}$,
- Normalize to charge $\mathbf{S_{M,i}}$ from mips,
- Pass from charge to MeV ($\mathbf{k_E}$)
- Correct for light attenuation $\mathbf{A_i}$ in fibers as a function of path **s** along fibers

$$E_i^{A,B}\ (\mathrm{MeV}) = \frac{S_i^{A,B} - S_{0,i}^{A,B}}{S_{\mathrm{M},i}} \times \kappa_E \qquad E_i\ (\mathrm{MeV}) = (E_i^A A_i^A + E_i^B A_i^B)/2$$

- **cosmic-ray events** from a dedicated run, 2 days every period of stable data taking, to intercalibrate response $\mathbf{S_{M,i}}$ plane by plane

- **selection of $e^+e^- \to e^+e^-$**, every 200 nb^{-1}, to intercalibrate response $\mathbf{S_i}$ between columns

- **selection of e^+e^-** $\to \gamma\gamma$, every 200 nb^{-1}, to set absolute energy scale $\mathbf{k_E}$

Calibration of the KLOE calorimeter

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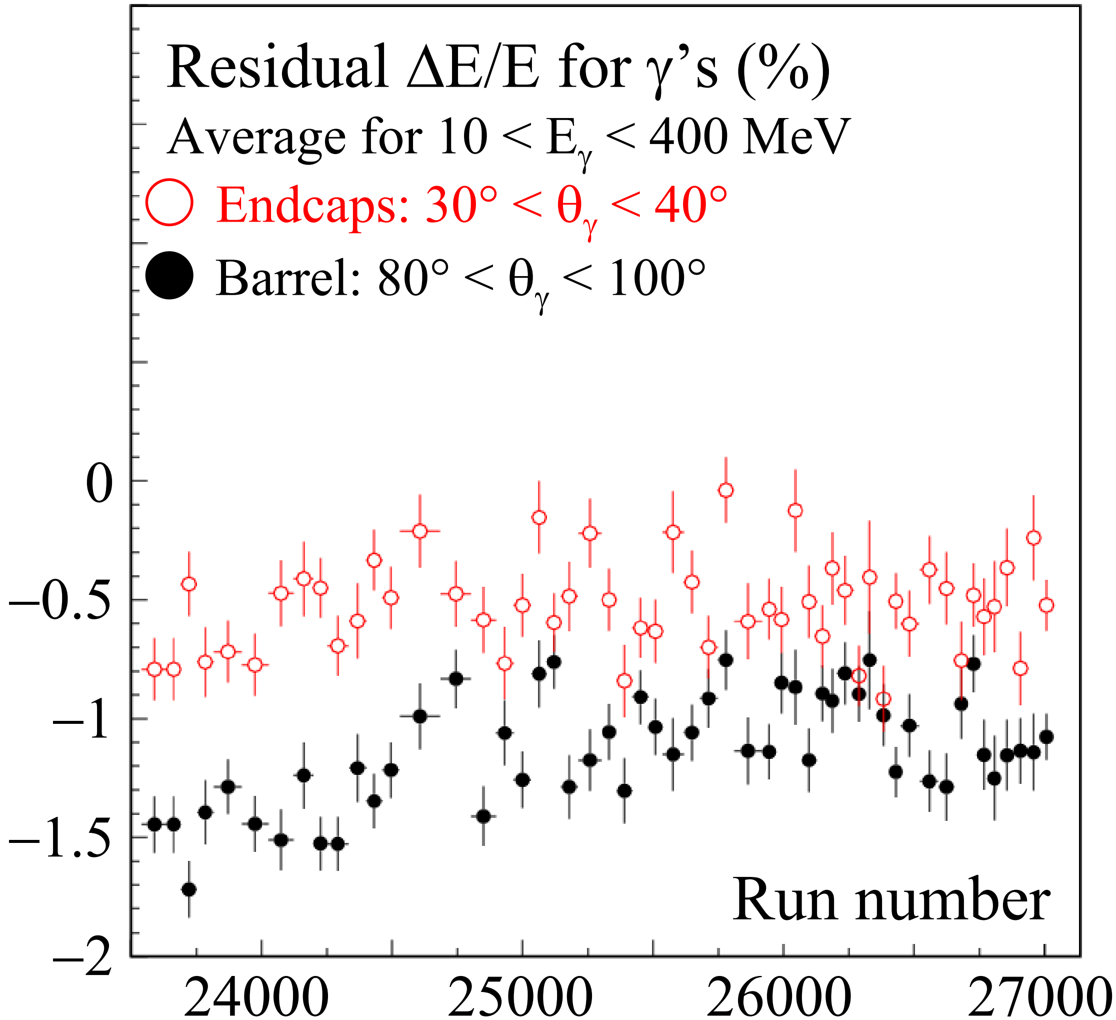
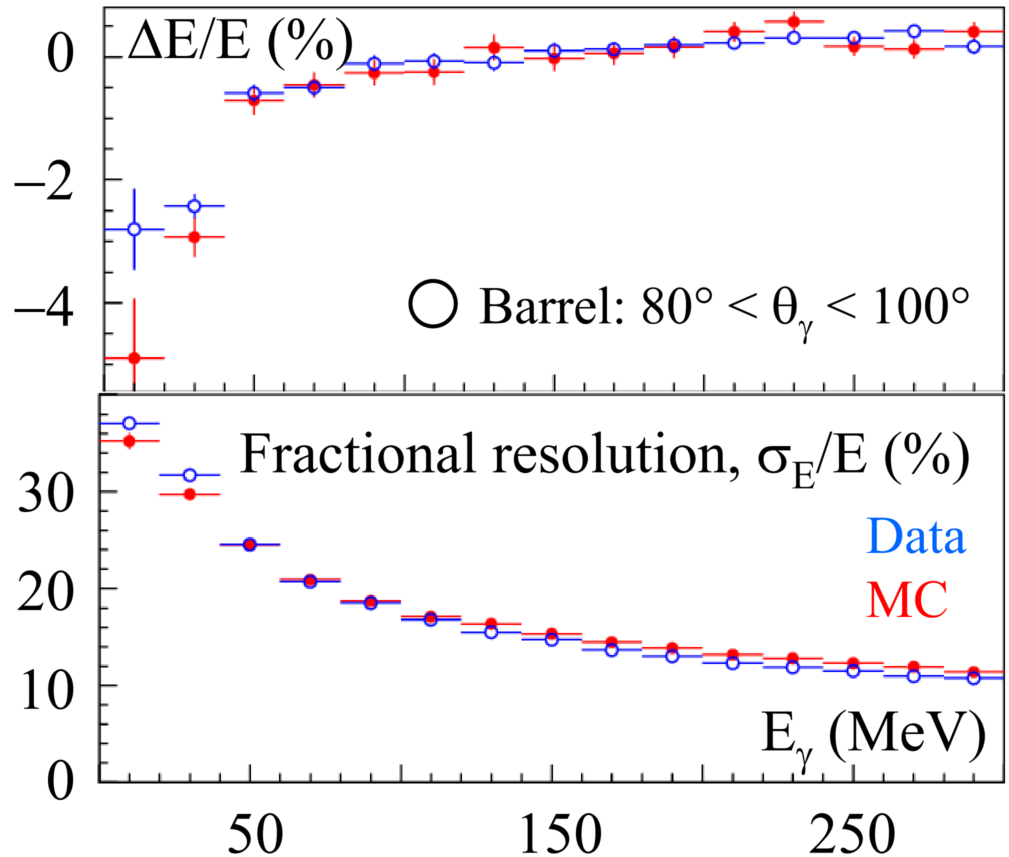


Stability at 0.5% level throughout entire data set

Energy response for e.m. showers

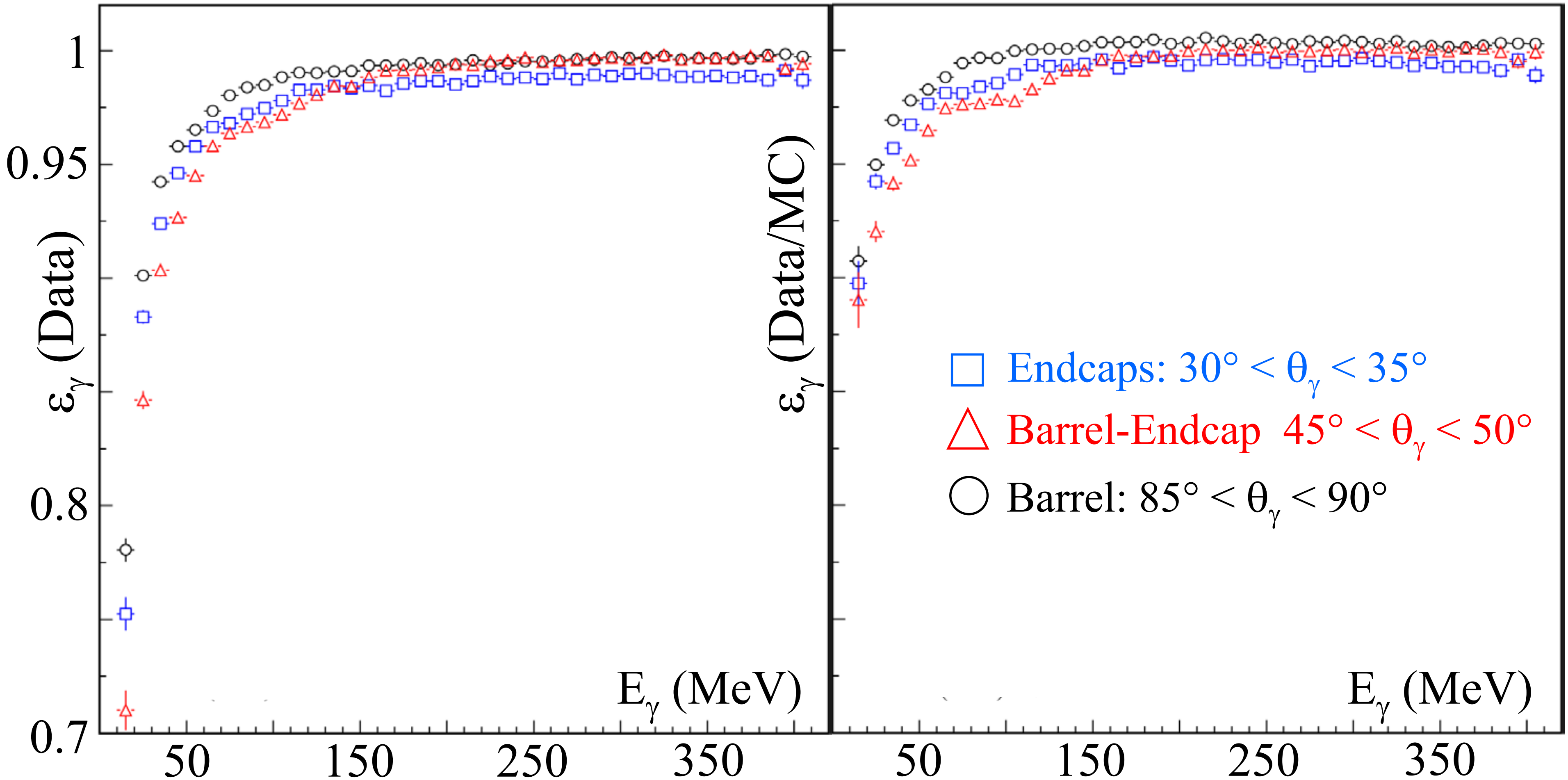
Check of energy response in data and MC, use tagged γ's from $\phi \to \pi^+\pi^-\pi^0$

- **Non-linearity < 2% above 50 MeV**
- σ_E/E = 5.7% / √E[GeV]



Efficiency of photon detection

Efficiency measurement in data and MC, use tagged γ's from $\phi \to \pi^+\pi^-\pi^0$



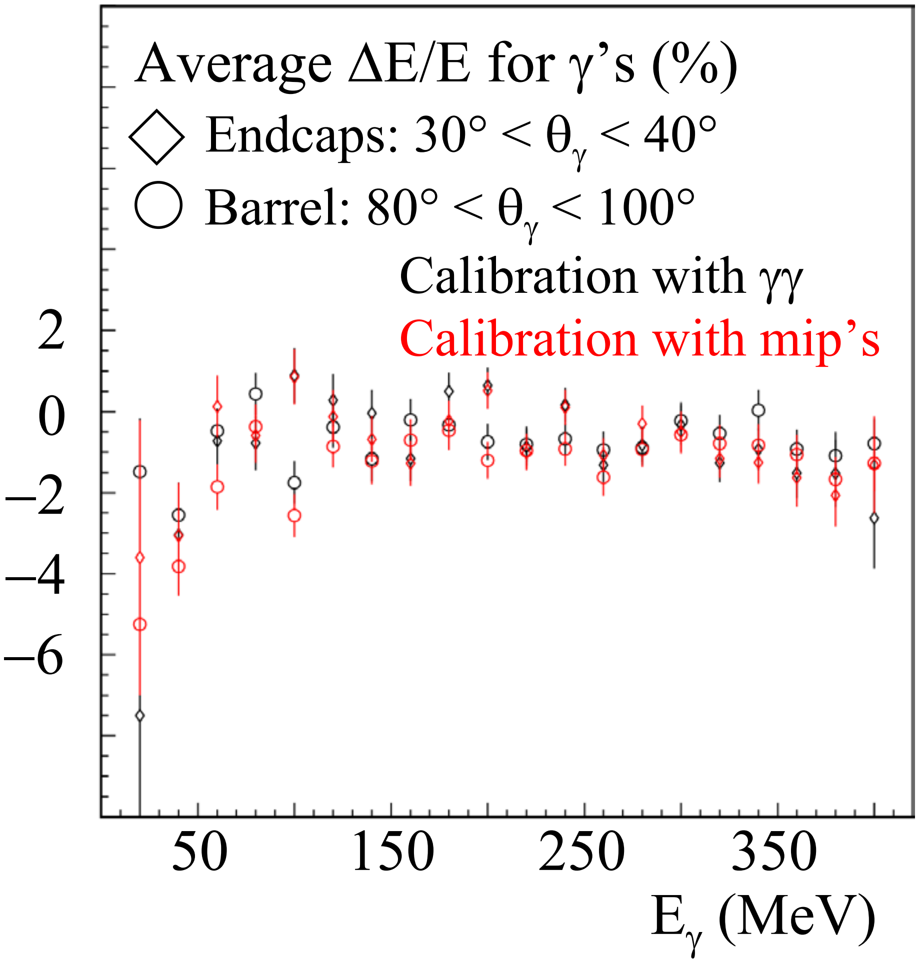
Efficiency > 95% for photon energy above 50 MeV

New procedure for energy calibration

New procedure possibly applied in the next data taking, **using γγ events**

Advantages wrt usage of cosmic rays:

- Minimize energy resolution @ 500 MeV
- Collection simultaneous with data acquisition
- Collection time much smaller
- More uniform detector illumination, particularly on endcaps



Guarantee stability during data taking, important whenever energy-based PID techniques are used

Simulation of K_L response

Better agreement obtained by enhancing K_L n cross section by 50%

Good agreement for the time response