Performances of the NA48 Liquid Krypton Calorimeter

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on behalf of NA48 COLLABORATION

Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warsaw, Wien

Outline

1. Requirements and Motivations
2. Description, Electronic calibration
3. Pulse Reconstruction
4. Shower Reconstruction
   - Energy Resolution
   - Linearity

1) Requirements and Motivations

NA48 aim:

Measure direct CP violation in K_0 system :

$$R = \frac{N(K_L \rightarrow \pi^0\pi^0)N(K_S \rightarrow \pi^+\pi^-)}{N(K_S \rightarrow \pi^0\pi^0)N(K_L \rightarrow \pi^+\pi^-)} = 1 - 6Re(\epsilon'/\epsilon)$$

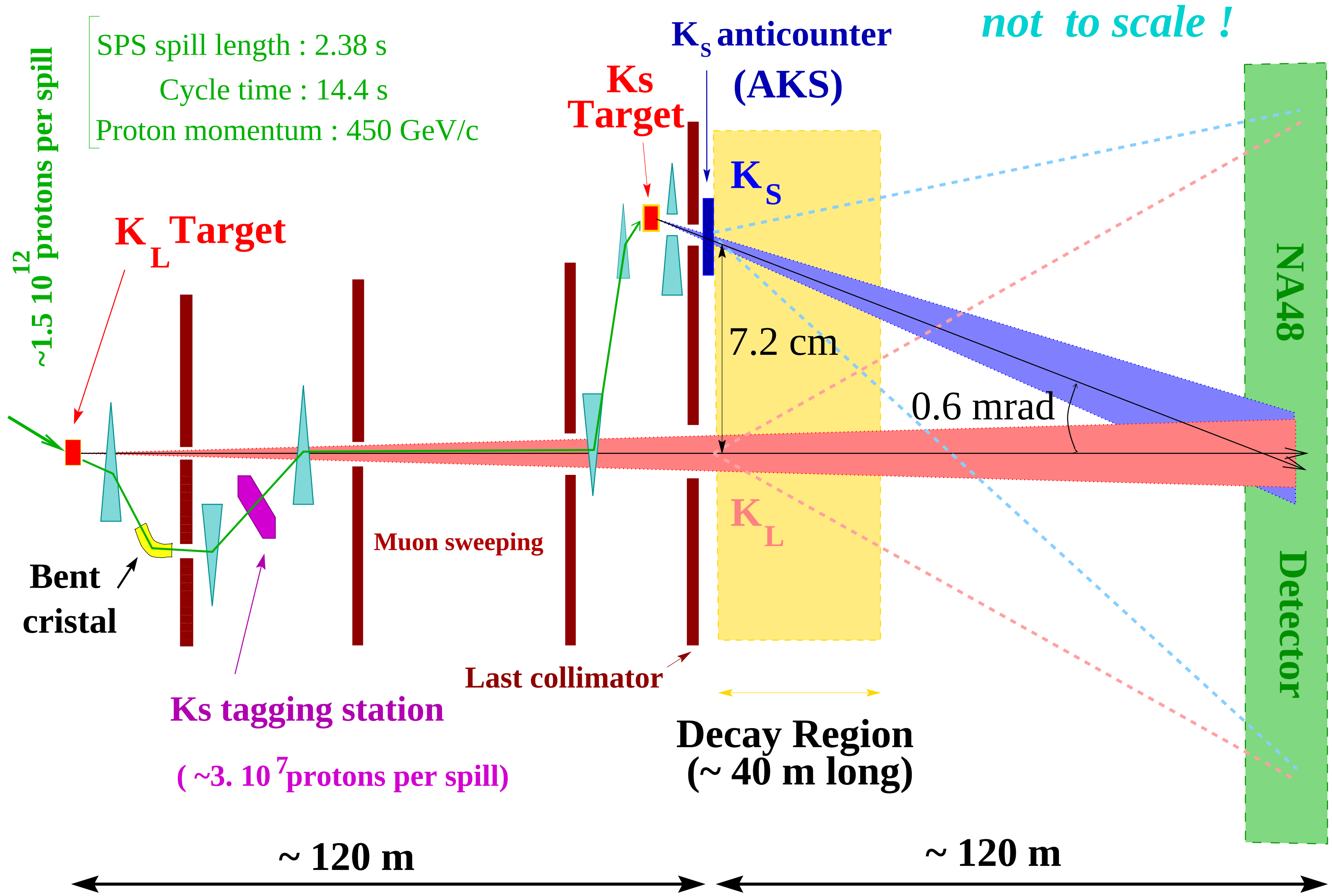
by counting number of decays in the 4 modes

$\pi^0\pi^0$ mode is reconstructed by detecting 4 γ in calorimeter

Aim uncertainty of $\approx$ 0.1% on R $\Rightarrow$

- Need large statistic
- Need good calorimeter resolution to separate $K_L \rightarrow \pi^0\pi^0$ CP violating mode (BR $\approx$ 0.1%) from much more abundant $K_L \rightarrow 3\pi^0$ decays (BR $\approx$ 20%)
- Need very good control of systematic effects to minimise potential biases on R

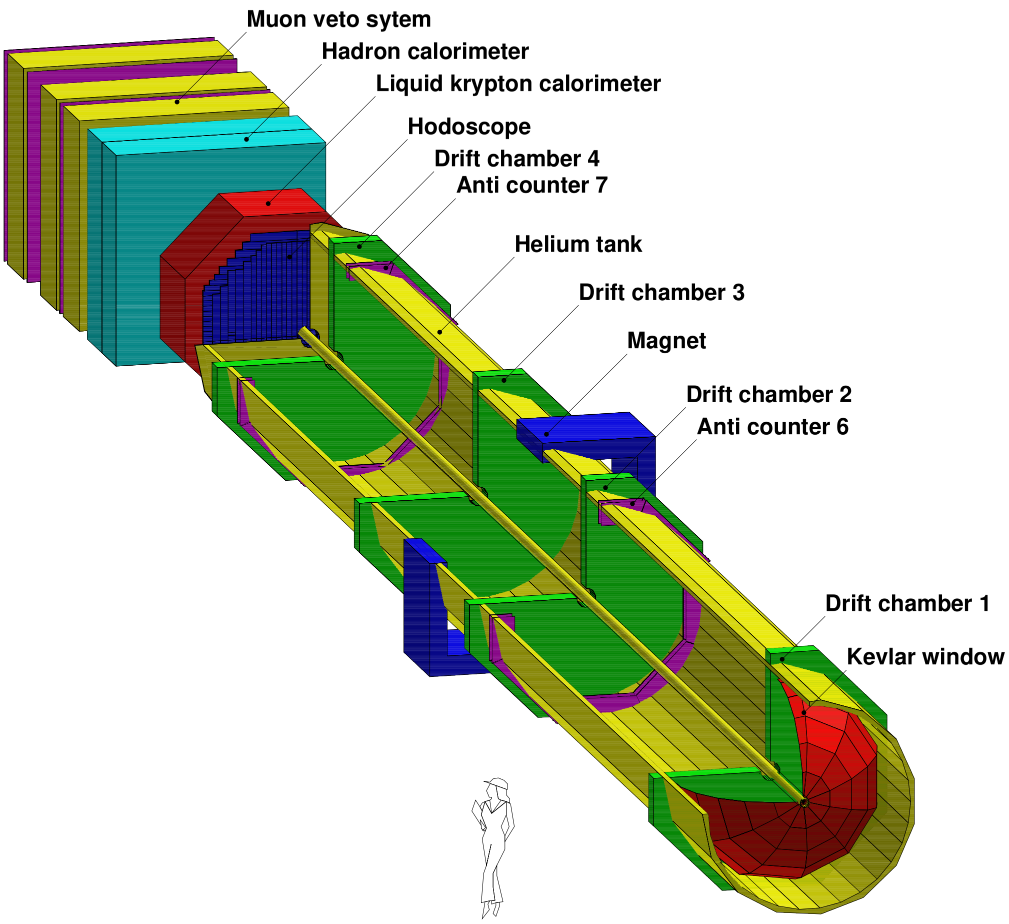
NA48 simultaneous and collinear K_S and K_L beams



K_S and K_L beams are distinguished by proton tagging upstream of the K_S target

$\Rightarrow$ Need good event time measurement

NA48 detector



- $K_{\rm L,S} \to \pi^+\pi^-$
  - Magnetic spectrometer ($\sigma_{X,Y} \sim 90\ \mu$m)
  - $\sigma(P)/P \simeq 0.5\ \% \oplus 0.009\ P[\mathrm{GeV}/c]\ \%$ ($\sim 1\ \%$ for 100 GeV/c track momentum)
  - Hodoscope for timing measurements ($\sigma_t \sim 200\ ps$)
  - Muon veto to reject $\pi\mu\nu$ background.

$\pi^0\pi^0$ Selection

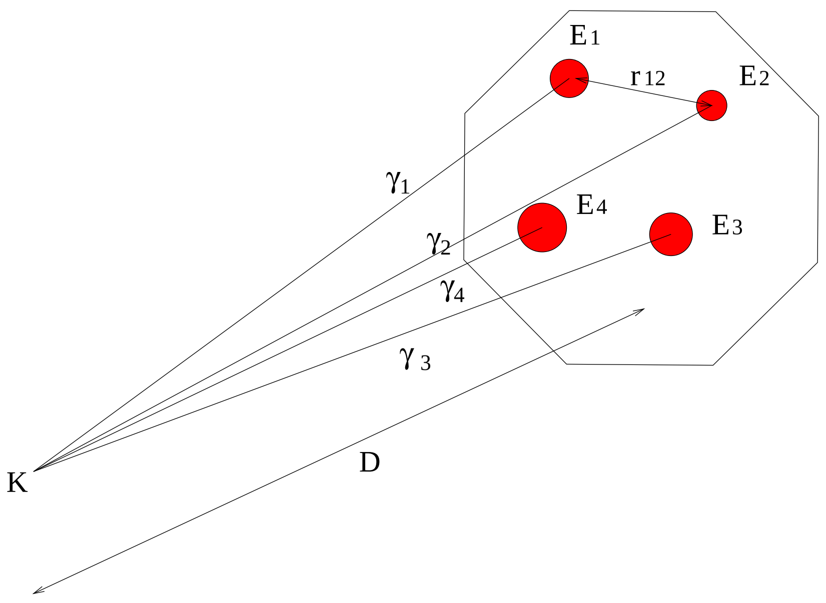
- Measure (E,x,y) of 4 γ in calorimeter
- Reconstruct decay vertex position assuming Kaon mass for 4 γ:

$$D = \sqrt{\Sigma E_i E_j r_{ij}^2}/M_K$$

- $\Rightarrow$ Decay region definition relies on calorimeter information
- Photon pairing to get best π^0 masses :

$$m_{ij} = \sqrt{E_i E_j} r_{ij}/D$$

- $\Rightarrow$ Required mass resolution $\approx$ 1 MeV/c^2



Requirements

- Energy resolution ≈ 1%, for <E> ≈ 25 GeV
- Position resolution ≈ 1mm
- Good time resolution (better than 500 ps)

- Non Linearity ≈ 0.1% between few GeV to 100 GeV

- Stands the K_L decay rate (≈ 500 kHz)
- Good stability over several years

NA48 choice

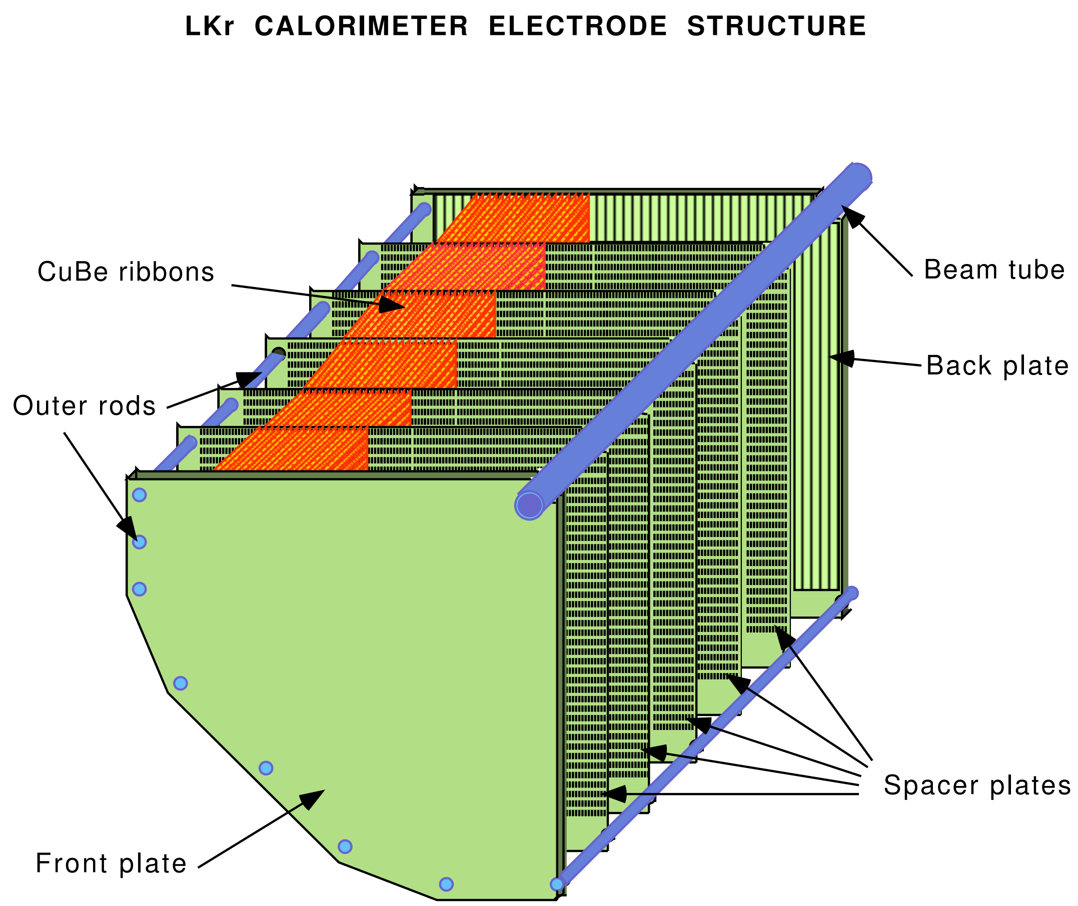
Quasi homogeneous Liquid Krypton calorimeter

- Almost fully active calorimeter $\Rightarrow$ very good resolution
- Cold noble liquid $\Rightarrow$ very good stability
- Initial current readout with fast shaping $\Rightarrow$ high rate, good time resolution

Summary of noble liquid characteristics :

	Z	density (g/cm^3)	X0 (cm)	R(Moliere) (cm)	T(bath) (K)
Ar	18	1.39	14.0	9.2	87.3
Kr	36	2.41	4.7	6.1	119.8
Xe	58	3.06	2.8	5.7	165.1

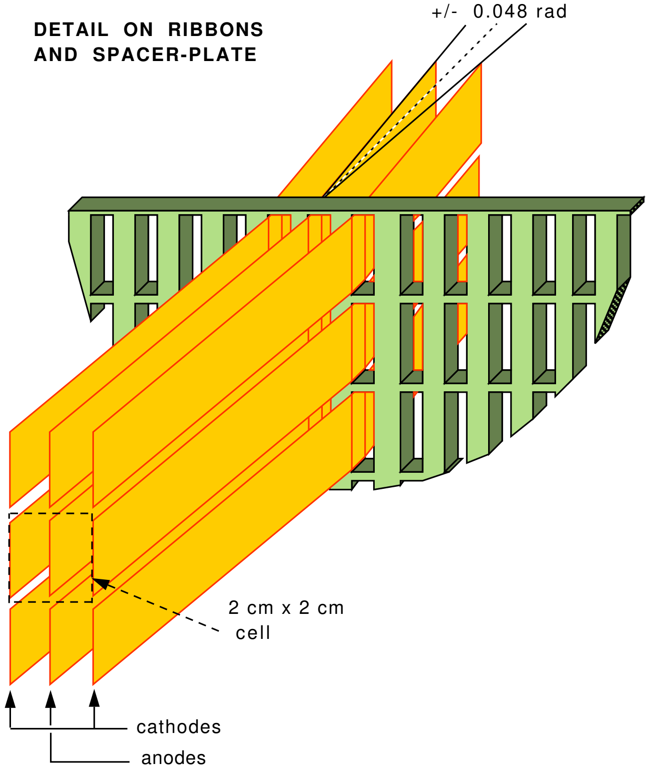
2) The Lkr calorimeter

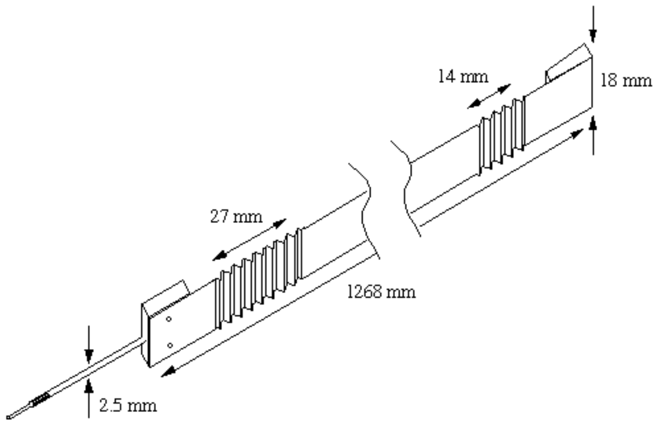


- 127 cm long, 27 radiation lengths
- Electrodes ”parrallel” to beam axis with small accordion angle ($\pm$ 48 mrad)
- $\approx$ 13000 cells of 2×2 cm^2
- Gap size $\approx$ 1cm
- 2mm vertical separation between electrodes
- Projective structure towards the middle of the K decay region, 114 m upstream of the calorimeter
- Total amount of matter before Lkr $\approx$ 0.8 X0

Electrode Structure

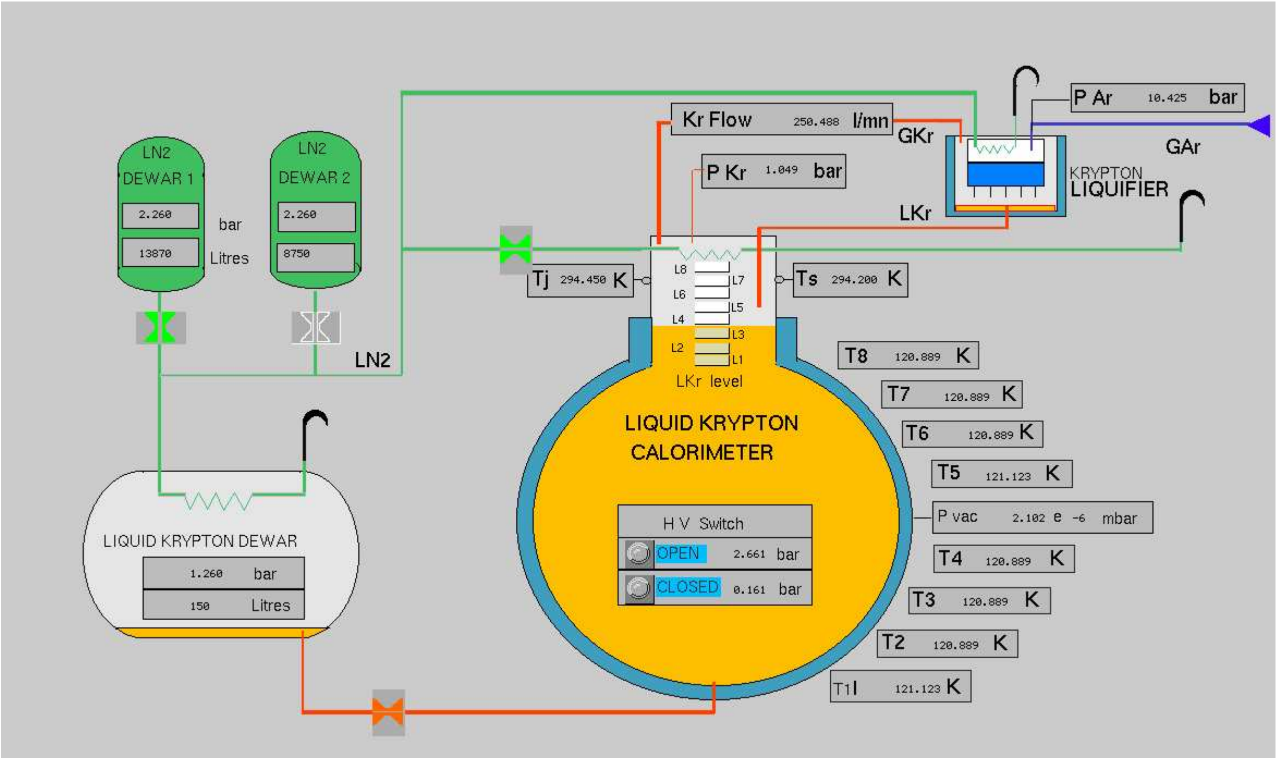
The gap accuracy is enforced by 5 spacer planes, every 21 cm in z, which guide the ribbons in the zig-zag geometry





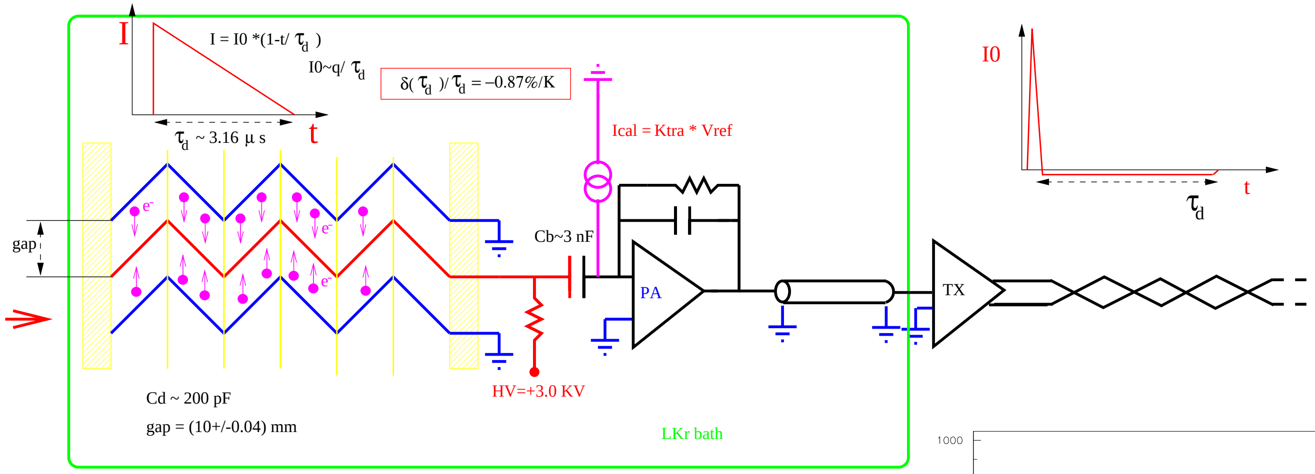
- Spacer planes : fibber glass reinforced epoxy, 5 mm thick ($\approx$ 0.025 X0)
- Accuracy of gap $\approx \pm 45\mu$m ($\approx \pm$ 0.45%)
- Overall size known to $\approx 3\times10^{-4}$
- Electrodes : 98% Cu, 1.8% Be, 0.2% Co, dimensions 40μm $\times$ 18mm $\times$ 127 cm

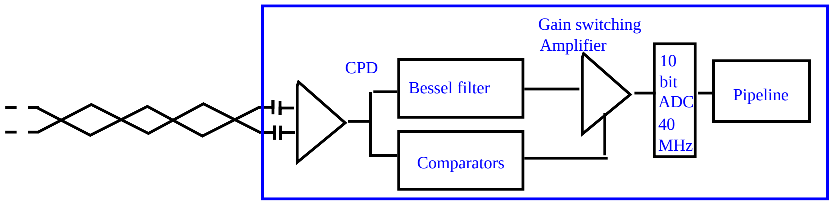
Cryogenic system

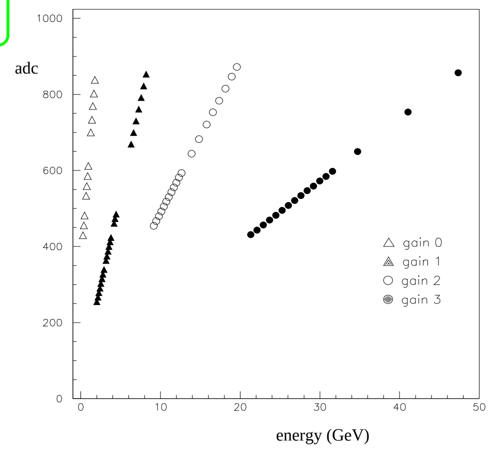


- ≈ 10 m^3 of Lkr at 120K
- Kr purification $\Rightarrow$ e$-$ lifetime $> 100\ \mu$s
- Temperature variations in the calorimeter $< \pm\ 0.3$ K $\Rightarrow$ no effect on the response

Readout





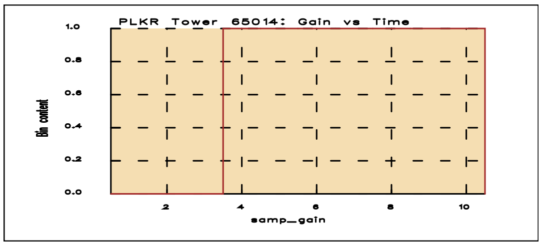


(4 offsets + 4 slopes) * 13212 channels = 105696 constants

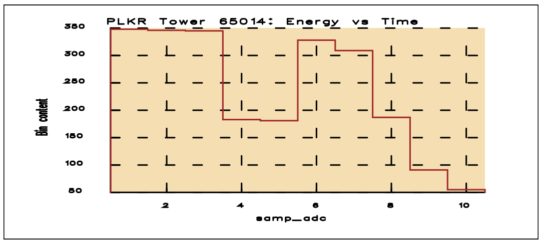
- initial current $I_0 = q.v_d/d$ (for constant $\vec{E}$) $v_d \approx 3100\ \mathrm{m.s}^{-1}$
- Pulse width after shaping $\approx$ 70 ns
- Gain switching + 10 bits ADC $\Rightarrow$ dynamic range $\approx$ 3.5 MeV to 50 GeV
- Electronic noise per channel $\approx$ 10 MeV

Example of pulse :

Gain information



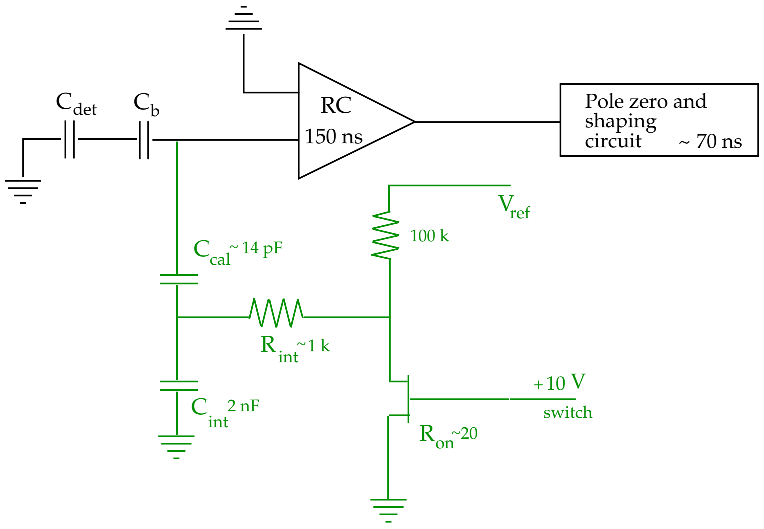
ADC information



- ADC clock frequency : 40 MHz
- Asynchronous with event time arrival
- Gain Switching based on derivative of signal before shaping
  $\Rightarrow$ Gain choice done typically 2-3 samples before the maximum of the shaped signal
  (the first sample after a gain change is not correctly measured)
- Gain ratio $\approx$ 2.5
- $E = g_i \times (ADC - Offset_i)$
- Use $Offset_0 \approx 370$ ADC counts to measure undershoots of out-of-time pulses
- Read 10 time samples per event
  $\Rightarrow$ Allow to check is signal sits on undershoot of a earlier shower

Electronic calibration

Dispersion of gains of electronic chain $\approx 3\%$ $\Rightarrow$ electronic calibration



- $I_{cal}(t) = I_0 e^{-\frac{t}{\tau}}$, $\tau \approx 2\ \mu$s
- $I_0 = \kappa \times V_{ref}$
- $\kappa \propto C_{cal}$
- Dispersion of $\kappa \approx 10\%$
- κ measured by comparing signal given by calibration output to signal given by a reference injected current, before final assembly, for each calib. channel (done both at warm and cold in 96, at warm in 98). Accuracy $\approx 1\%$
- Gain stability : better than 0.1%

Calorimeter Operation

- 1996 : Part of the readout electronic
- 1997 : First data taking with full calorimeter operationnel

High Voltage = 1500 V (pb with some blocking capacitors)
⇒ small space charge effect
(see S.Palestini et al, NIM A421(1999)p75)

Winter 1997/1998 : Intervention to change all blocking capacitors

- 1998,1999,2000 : data taking with High Voltage = 3000 V

⇒

- ≈ no space charge effect
- Electronic noise lower by ≈ 25%

Typically 50-70 misfunctionning channels (out of 13000)

30 are dead PA in Lkr (very stable situation)
the calorimeter is kept always cold

≈ 20 to 40 are related to warm electronic

3) Pulse reconstruction

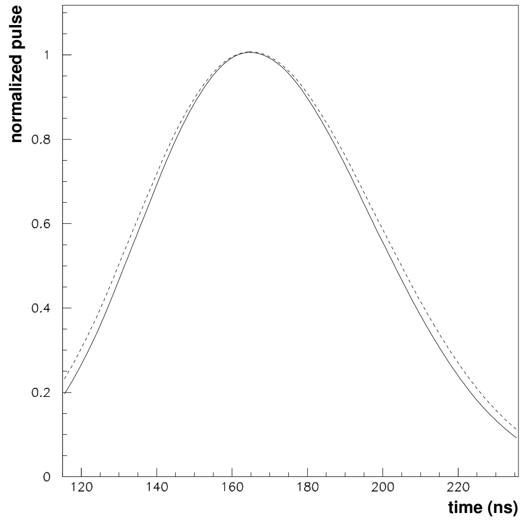
Use Digital Filter method :

$$E = \Sigma a_i \times s_i, \qquad T = \frac{1}{E}\Sigma b_i \times s_i$$

s_i signal for sample i; a_i, b_i digital filter coefficients :

- Derived from observed pulse shape in calibration events
- Binned as a function of T

Divide channels into 10 categories according to observed pulse width

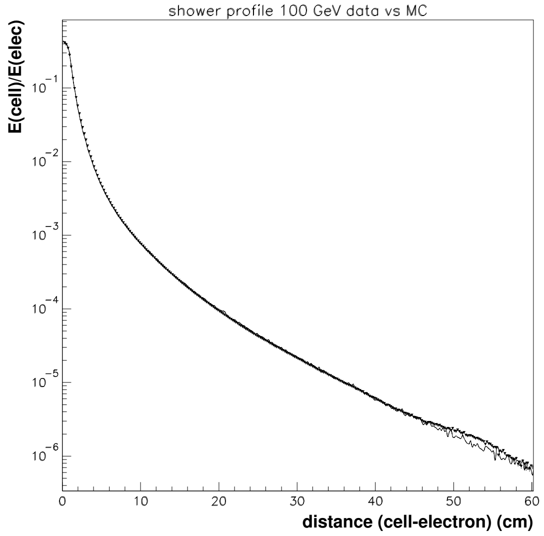


$\Rightarrow$ Accuracy to reconstruct calibration pulses : $\approx 0.1\%$ on E, < 150 ps on T

Use three samples centred around maximum (compromise between noise reduction and sensitivity to accidental showers)

(except few cases when one of these samples is not well measured)

3) Shower Reconstruction



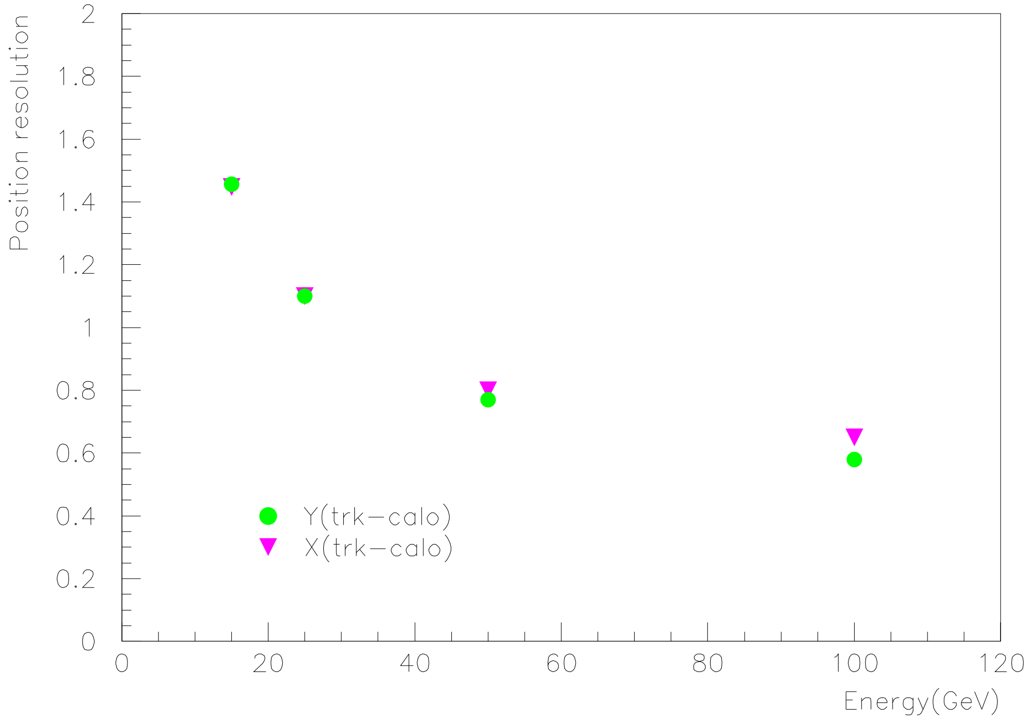
Sampling term limited by size used to collect shower energy
From GEANT, expect :

R=∞	$1.2\%/\sqrt{E}$
R=11 cm	$2.8\%/\sqrt{E}$
R= 7 cm	$3.5\%\sqrt{E}$

Compromise between noise (increases with R)
and sampling term (decreases with R)
$\Rightarrow$ Use R=11 cm to measure shower energy ($\approx$ 100 cells)
(independent of energy to avoid bias on linearity)

Position is measured using 3×3 cells

Position Resolution



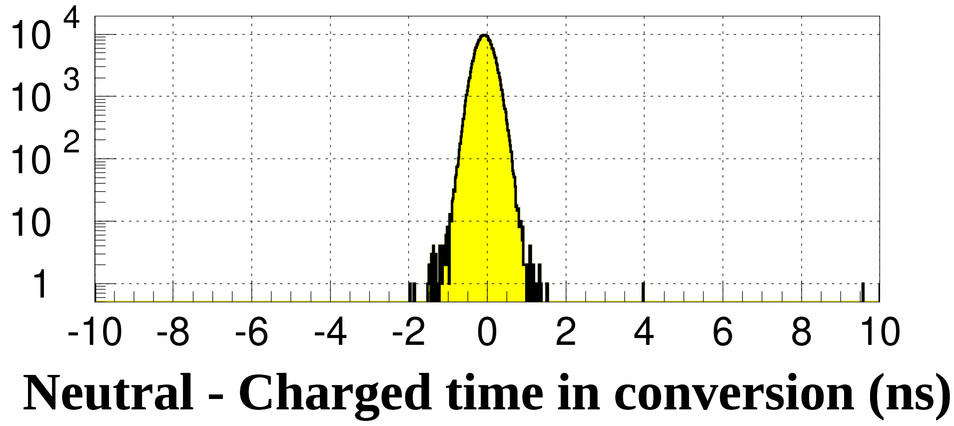
Position resolution measured with electron beam sent to the calorimeter in 96.

Position resolution better than 1mm above 25 GeV

Time Resolution

Event time = Average of photon times

Use K $\rightarrow 3\ \pi^0 \rightarrow (n)\gamma\ e^+e^-$ to check photon time measurement, by comparing photon time to time reconstructed with e^+e^- (measured by scintillator counters)



Event time resolution $<$ 250 ps

No tail outside $\pm$ 2 ns

Crucial for K_L/K_S identification in NA48

Energy Resolution (I)

Main tool to study in situ the performances of the calorimeter :

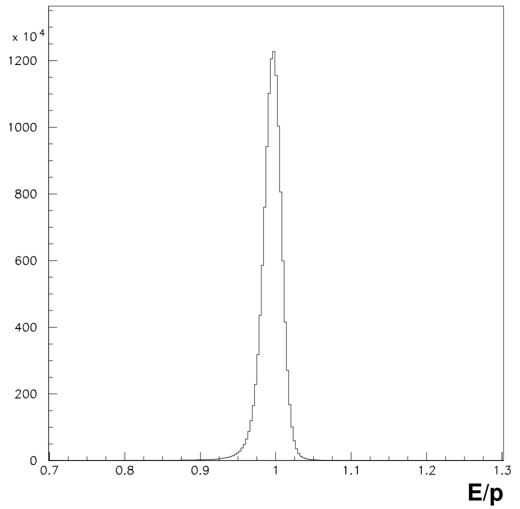
$$K_L \rightarrow \pi^{\pm} e^{\mp} \nu \text{ decays}$$

Spectrometer $\Rightarrow$ Impulsion p (resolution $\approx$ 0.5% to 1%)
Calorimeter $\Rightarrow$ Energy E

In ideal world, $$\frac{E}{p} = 1$$

Taking p as "perfect", this allows to study

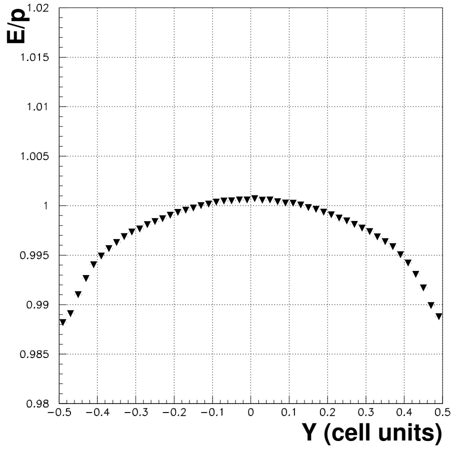
- variations in energy response
- the uniformity of the response
- the energy resolution
- the linearity



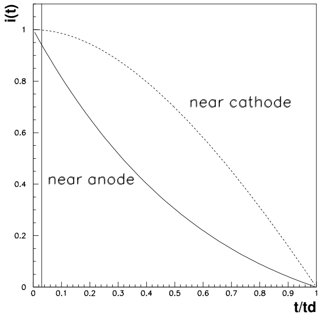
total statistic accumulated in 98+99 $\approx 150\times10^6$ events

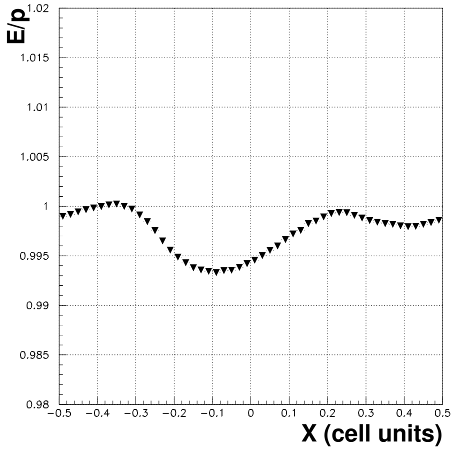
Energy Resolution : Modulation of response

Lower electric field in the middle between electrodes ⇒ lower response at top/bottom of cells



Finite integration time ⇒ lower response close to the anode

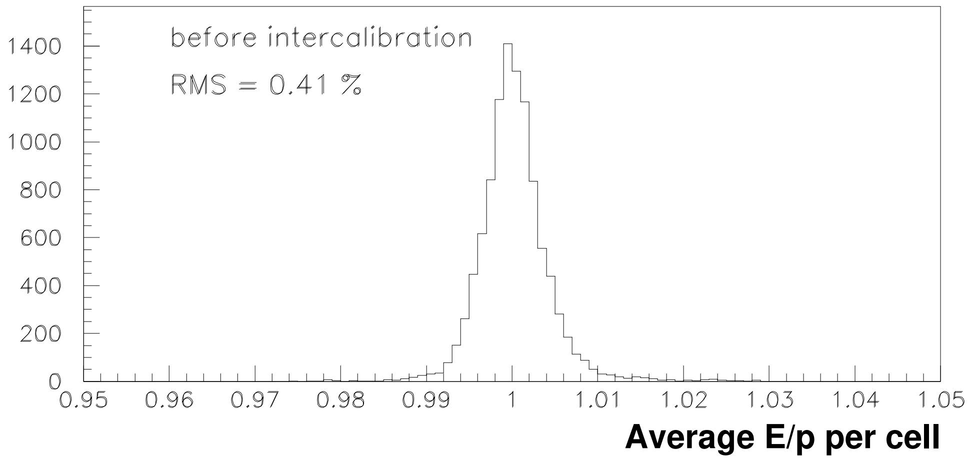


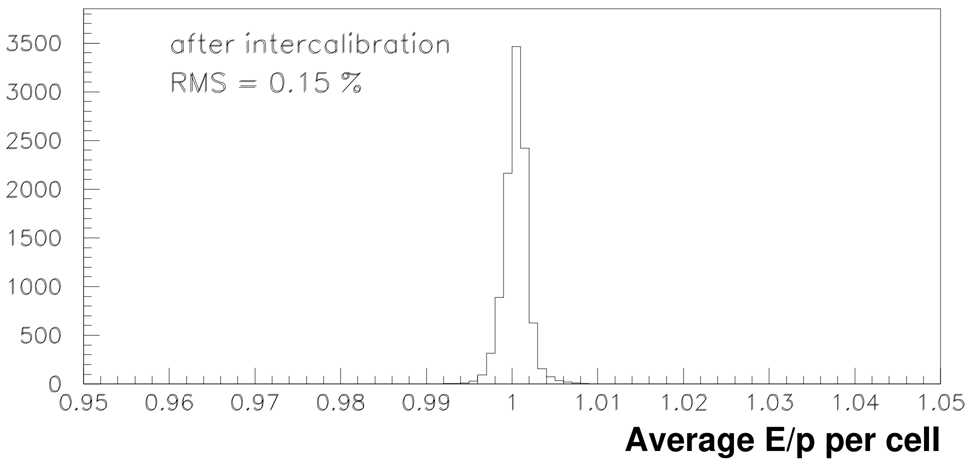


Variations are smooth (thanks to accordion angle in x) ⇒ can be corrected using measured shower position ⇒ Residual variations ≈ 0.1%

Energy Resolution : Uniformity

Compute $< \frac{E}{p} >$ for each cell
Variations $\Leftrightarrow$ Non uniformity in calibration



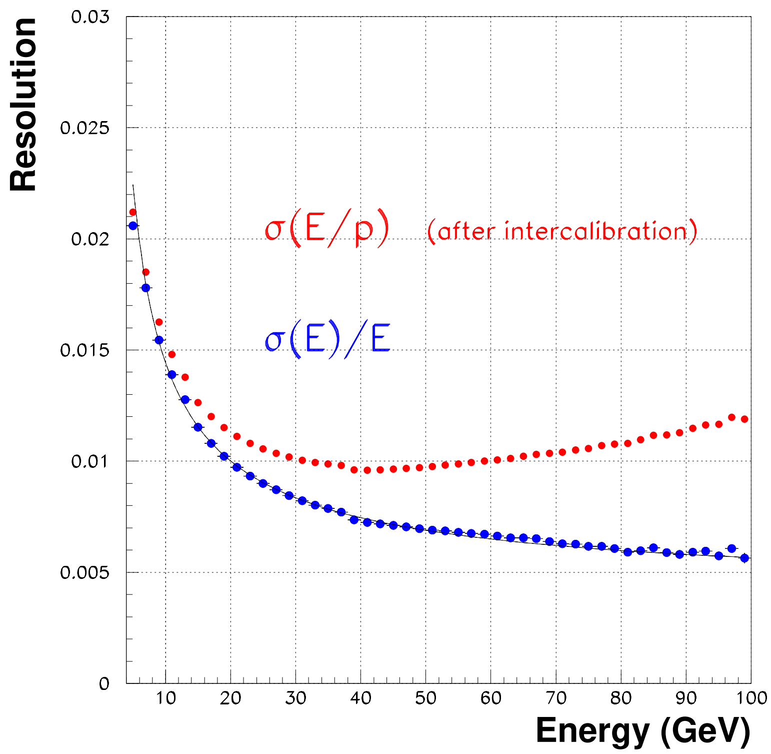


Using Electronic Calibration $\Rightarrow$ Dispersion = 0.4%
Consistent with accuracy of κ measurements $\approx$ 1%
($\leq$ 40% of shower energy is in the impact cell)

Derive 1 static correction factor/cell $\Rightarrow$
Dispersion = 0.15% (applying 98 factors to 99 data sample)

Energy Resolution

Unfold p resolution from E/p measured resolution
$\Rightarrow$ E resolution



In $K_L \rightarrow \pi e \nu$, energy measurement is based on 7*7 cells
(tighter zero suppression than in $\pi^0\pi^0$ events)
Extrapolate resolution to the nominal 11 cm radius cluster

$$\Rightarrow \frac{\sigma(E)}{E} \approx \frac{(3.2\pm0.2)\%}{\sqrt{E}} \oplus \frac{(0.09\pm0.01)}{E} \oplus (0.42\pm0.05)\%$$

(where E is in GeV)

(coherent noise contribution to overall noise is almost negligible)

Sampling term predicted by GEANT : $\approx \frac{2.8\%}{\sqrt{E}}$

Energy Resolution : Comparison of different contributions

Illustrate the relative sizes of the various components to the energy resolution
For the average energy of 25 GeV :

- Sampling term : $\approx 0.64\%$
- Electronic noise: $\approx 0.35\%$
- Constant term : $\approx 0.42\%$

The overall resolution is 0.85%
The largest contribution is the sampling term

Energy Resolution : Constant term

What are the contributions to the constant term in resolution ?

- GEANT simulation: $\approx 0.2\%$ constant term
  residual variations with impact point, fluctuations in longitudinal shower development, $\cdots$
- Intercalibration accuracy: $\approx 0.15\%$
- Geometry (gap size) : ≈ 0.1 to 0.2%
- Pulse reconstruction :
  - accuracy to reconstruct calibration pulses $\approx 0.1\%$
  - Physics signal shape slightly different from calibration $\Rightarrow \approx 0.15\%$

  $\Rightarrow \approx 0.2\%$ constant term contribution

Account qualitatively for the constant term observed in the data $(0.42 \pm 0.05)\%$

Energy Resolution : Tails

Previous resolution is the result of gaussian fit

$\approx$ 1% of showers have measured energy $\geq 3\ \sigma$ lower than average

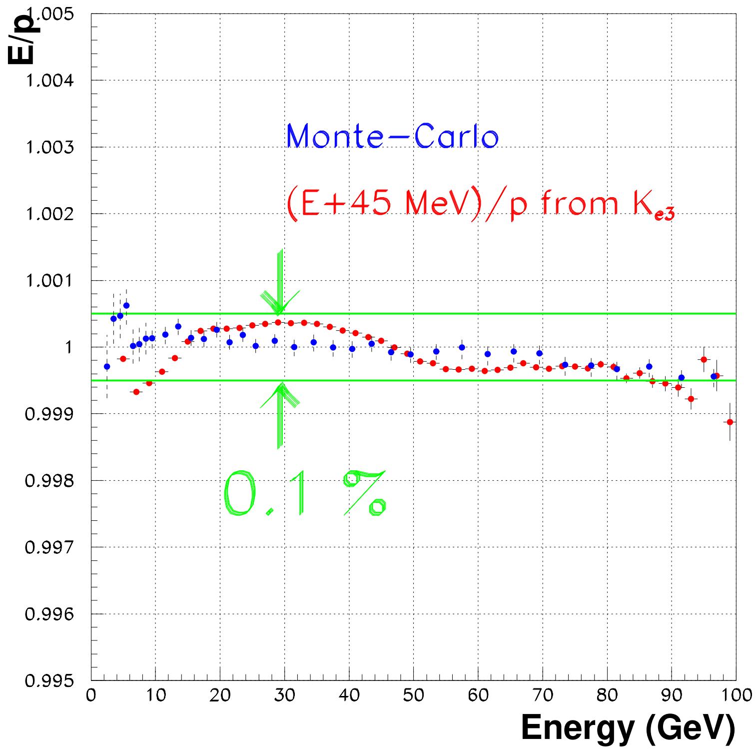
This is interpreted as coming mostly from $\pi^{\pm}$ production in electromagnetic shower
γ p $\rightarrow \pi^{\pm}$ N (for instance)

$\Rightarrow$ far reaching low side tail :

$\approx$ 0.1% of electrons have $\frac{E}{p} < 0.8$

Energy Response Linearity

Use linear electronic calibration
Add 45 MeV to electron energy (energy loss in cryostat, from GEANT)



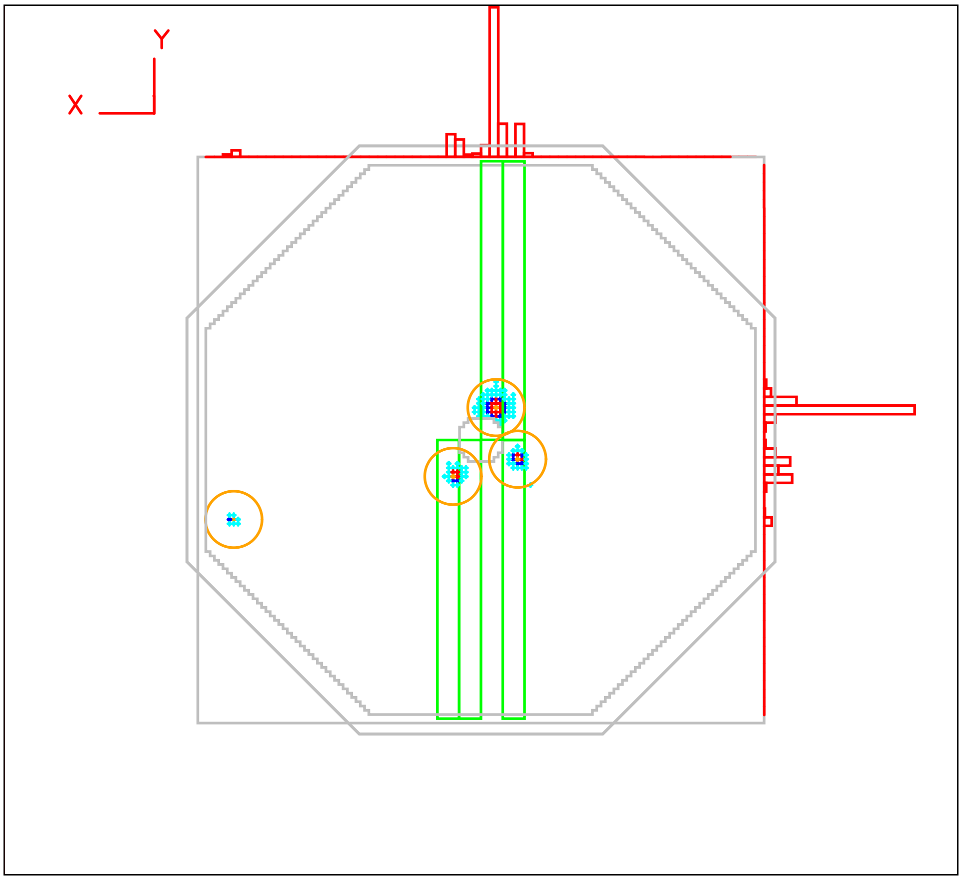
$\Rightarrow$ Non linearity $\approx 0.1\%$
(from 5 to 100 GeV)

From simulation, expect $\leq 0.1\%$ non linearity
later shower development at high energy
+ gap opening (i $\propto \frac{1}{gap}$)

Residual small non linearity probably coming from ADC

$\mathbf{K} \rightarrow \pi^0\pi^0$

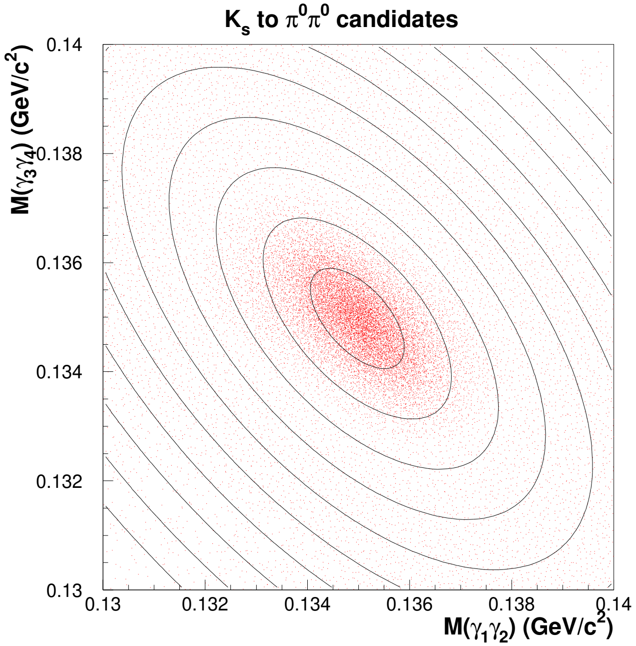
Typical $\mathrm{K} \rightarrow \pi^0\pi^0$ event :

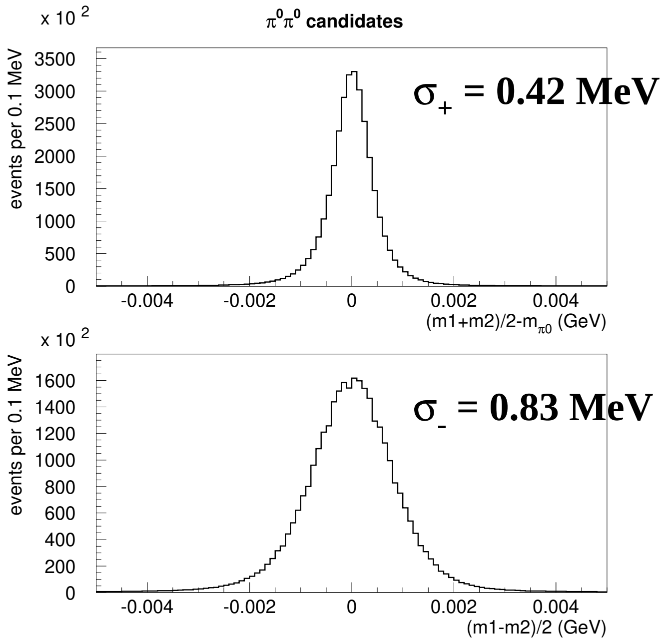


Need to correct for energy contamination from one shower to another

π^0 mass reconstruction

Fix K decay vertex assuming Kaon mass for 4 γ
Compute π^0 masses





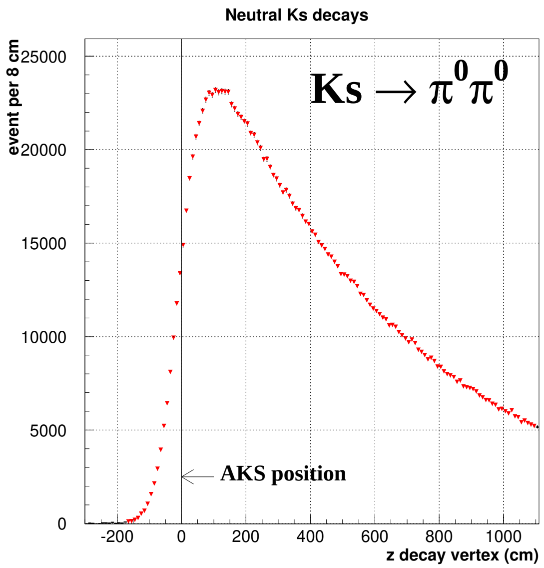
After π^0 mass cut, residual background from $K_L \to 3\pi^0$ is :

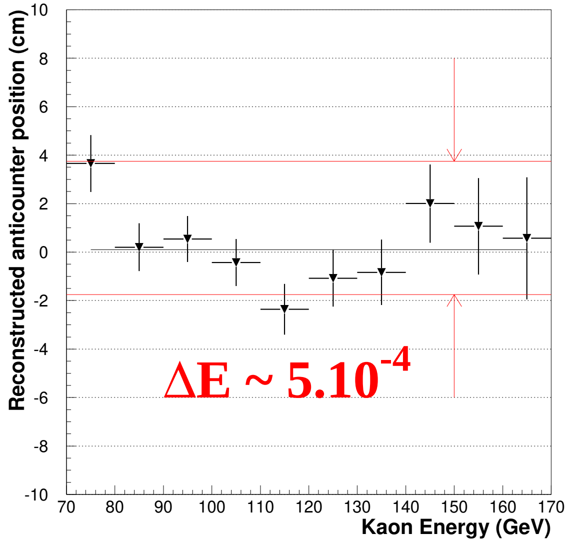
$(0.066 \pm 0.020)\%$ ($\Rightarrow$ very small !)

Energy Scale

In the neutral mode : $D = \sqrt{\sum E_i E_j \times (r_{ij})^2} \; / M_K$

$\Rightarrow$ Need good knowledge of Energy scale to define fiducial region
(the decay region definition should be the same for $\pi^0\pi^0$ and $\pi^+\pi^-$ decays)
Known anti-K_S counter position (vetoes decays upstream) $\rightarrow$ adjust Energy scale (1 factor)





Accuracy of energy scale setting $\approx$ few 10^{-4}

Variations with time $< 5 \times 10^{-4}$

Conclusions

The performances of the NA48 Lkr calorimeter have been studied in situ

- Time resolution : $\approx$ 500 ps per photon
- Position resolution : better than 1mm above 25 GeV
- Energy resolution : better than 1 % above 20 GeV
  (constant term $\approx$ 0.5% after Ke3 intercalibration)
  ($\approx$ 0.65% before)
- Non linearity : $<$ 0.2 % in 5-100 GeV energy range
- Very stable operation over 4 years

$\Rightarrow$ matches requirements for precise measurement of direct CP violation in K_0 system