A Brief History of the $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement

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December 13th, 2001

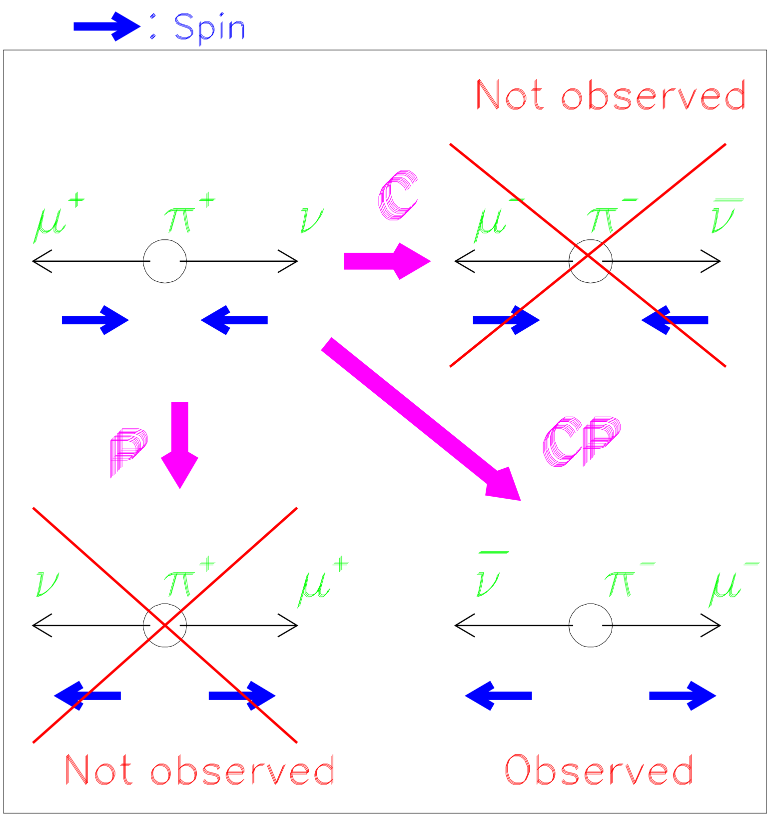
Menu

- What is Re(ε'/ε) ? (see Juliet's lectures)
- How to measure it?
- Historical review of experiments
  - Methods
  - Basic elements of the different detection techniques
  - Examples: the Lead-Glass calorimeter of E731 and the Liquid krypton calorimeter of NA48
  - Steps of Re(ε'/ε) measurement
  - Improvements as time was going on
- Current situation
- What did we learn through this epopee?

Discrete symmetries

- At the beginning of sixties, experiments have demonstrated that Charge symmetry and Parity symmetry were respected in strong and electromagnetic interactions.
- Weak interaction, responsible for particle decays, has been prooved to maximaly violate C and P
- However, their product CP was thought to be valid. This was indeed in agreement with observations.

Exemple: pion decay



- In Kaon system in particular, CP conservation was meaning that $K_L \to$ 3bodies and $K_S \to$ 2bodies.

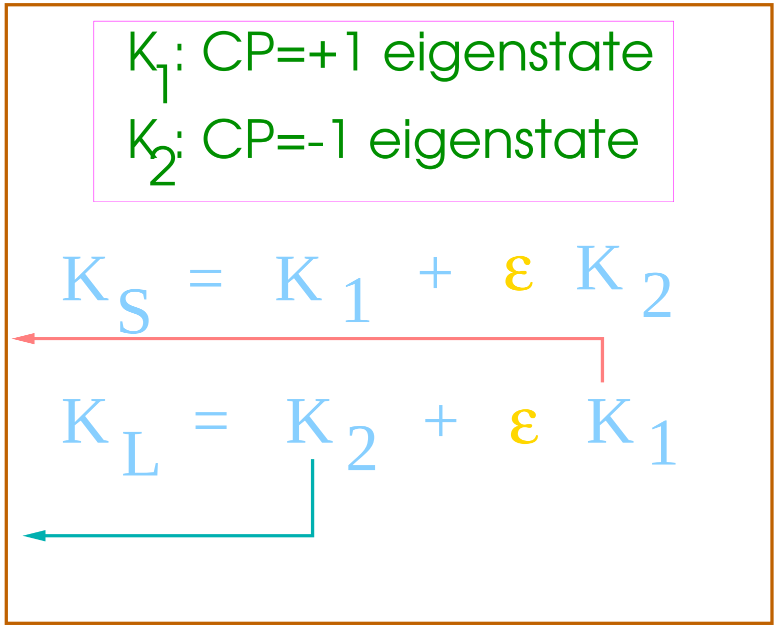
CP VIOLATION

In July '64, Christenson, Cronin, Fitch and Turlay discovered experimentaly a small Violation of CP in the Kaon System, detecting $K_L \rightarrow 2\pi$

$\Rrightarrow$This means that K_L isNOT a pure CP eigenstate.

Current understanding of K_L particle

- In the Standard Model, an irreducible phase in CKM matrix is the source of CP Violation
- Two components: Indirect CP Violation (ε), due to CP-states mixing, and Direct CP Violation (ε') acting in the decay and depending on the decay channel



Why CP Violation is so exciting?

Remarks

❖Violation of symmetries must have a meaning
❖Weak interaction violates maximaly C and P but ..
❖CP is an ALMOST good symmetry for weak interactions.

Questions

- ☞ Does this originate from something fundemental or it arises by accident?
- ☞ What determines the strength of CP Violation?
- ☞ What the world would be if CP Violation had been stronger?
- ☞ Does the observed CP Violation have something to do with Matter-Antimatter asymmetry in the Universe?

Only few rough answers

❖The smallness of ε can be explained by the quark coupling elements: $\varepsilon \sim \sin\theta_{12} sin\theta_{23} sin\delta$
❖ε' is further suppressed wrt ε by a factor 1/22:

$$\varepsilon\text{'} \sim \frac{i}{\sqrt{2}} e^{i(\delta_2-\delta_0)} \mid \frac{A_2}{A_0} \mid sin(\phi_2 - \phi_0)$$

❖We do not understand the philosophy behind the smallness of the phenomenon nor the upstream relation with baryogenesis
☞Hope that by measuring precisely CP Violation in different systems one will better understand the full scheme

The ways a neutral kaon decays

Let's look at the observed decay rates of K_L and K_S particles:

K_L particles
τ_L=5.2×10^{-8}s

✦ $K_L \rightarrow \pi e \nu$	38.78%	CP Cons
✦ $K_L \rightarrow 3\pi^0$	21.13%	CP Cons
✦ $K_L \rightarrow \pi \mu \nu$	17.18%	CP Cons
✦ $K_L \rightarrow \pi^+ \pi^- \pi^0$	12.55%	CP Cons
✦ $K_L \rightarrow \pi^+ \pi^-$	0.206%	CP VIOL
✦ $K_L \rightarrow \pi^0 \pi^0$	0.09%	CP VIOL

K_S particles
τ_S=0.89×10^{-10}s

✦ $K_S \rightarrow \pi^+ \pi^-$	68.61%	CP Cons
✦ $K_S \rightarrow \pi^0 \pi^0$	31.39%	CP Cons
✦ $K_S \rightarrow \pi^+ \pi^- \gamma$	0.18%	CP Cons
✦ $K_S \rightarrow 3\pi^0$	$<1.4 \times 10^{-5}$	CP VIOL

Major difficulties:

☞K_L life is 600 longer than K_S

☞The interesting CP violating modes represent only 0.3% of the K_L decays and must be identified in presence of a huge physical background

How to measure Direct CP Violation?

❖By comparing the observed CP Violation in two different decay channels, namely $K_L \rightarrow \pi^0\pi^0$ and $K_L \rightarrow \pi^+\pi^-$

❖To cancel the isospin difference between K_L into $\pi^0\pi^0$ and $\pi^+\pi^-$ branching ratios one defines:

$$\eta_{00} = \frac{\Gamma(K_L \rightarrow \pi^0\pi^0)}{\Gamma(K_S \rightarrow \pi^0\pi^0)} \qquad \eta_{+-} = \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^+\pi^-)}$$

❖ To compare ε' to ε we use the formula :

$$R = \frac{\Gamma(K_L \rightarrow \pi^0\pi^0)}{\Gamma(K_S \rightarrow \pi^0\pi^0)} \Big/ \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^+\pi^-)} = \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 = 1 - 6 \times \mathrm{Re}(\varepsilon'/\varepsilon)$$

☞ In experimental conditions, notice that:

- ❖ $\Gamma(K \rightarrow \pi\pi) =$ (1/KaonFlux) $\times$ Nb(detected $K \rightarrow \pi\pi$) / DetectionEfficiency
- ❖ Depending on running conditions, several inefficiencies might cancel in R
  - If concurrent $\pi^0\pi^0$and $\pi^+\pi^-$detection, fluxes cancel
  - If concurrent K_L K_S , detection reconstruction inefficiencies cancel
  - Best cancelation if all four modes are recorded concurrently

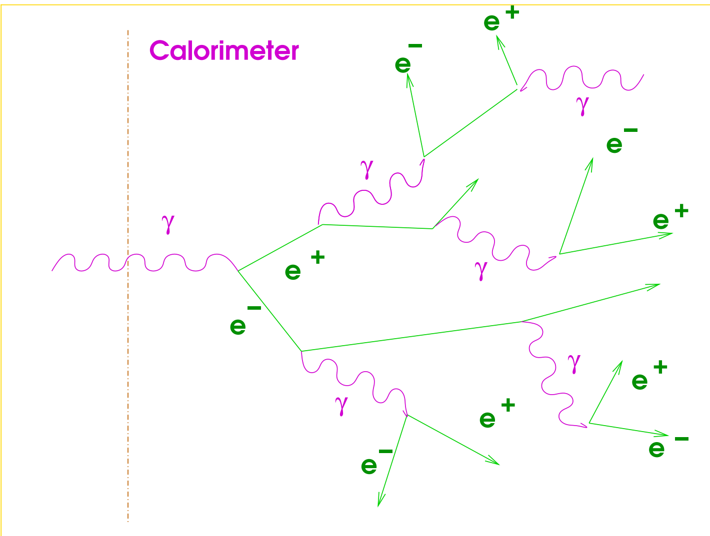
Intermezzo:

Particle detection: a reminder

Detecting a K$\rightarrow \pi^0 \pi^0$ mode

The experimental signature of this decay is four photons, since each π^0 immediately decays into 2 photons. Photons are detected by “calorimetry”. When entering into a dense medium photons follow a multistep interaction process.

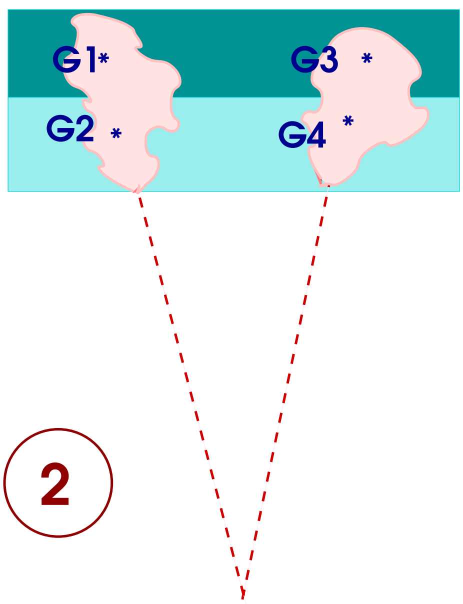
- The photon first converts into an electron-positron pair
- Each electron and positron looses energy by photon emission (bremsstrahlung) when interacting with a nucleus. The photons continue to interact by pair production etc
- The subsequent cascade stops when the available energy is completely absorbed.
- The dimensions of the whole shower depend on the medium density
- One measures the released energy (=current)



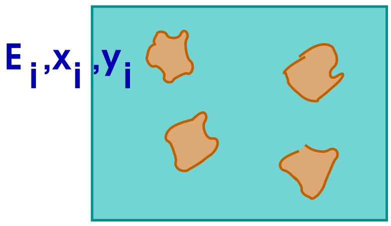
Detecting a K$\rightarrow \pi^0 \pi^0$ mode (cntd)

To reconstruct the event decay vertex requires to know the photon directions. One can use several methods:

1. Convert at least a photon to an electron-positron pair and reconstruct the vertex as the charged track intersection with the beam axis.
2. Use a longitudinaly segmented calorimeter and recontruct the photon incidence angle.
3. Reconstruct the vertex from four photons energies and positions PLUS an additional constraint, Kaon invariant mass or pion invariant mass.



G1,G2,G3,G4 : Centre of gravity / calorimeter / photon



$$D_V^2 = \sum (E_i E_j r_{ij}^2) / M_K^2$$

$$M_{ij}^2 = (E_i E_j r_{ij}^2) / D_V^2$$

3

r_{ij} = Distance $\gamma_i - \gamma_j$

D_V = Distance of the Vertex

M_{ij} = Invariant mass $\gamma_i \gamma_j$

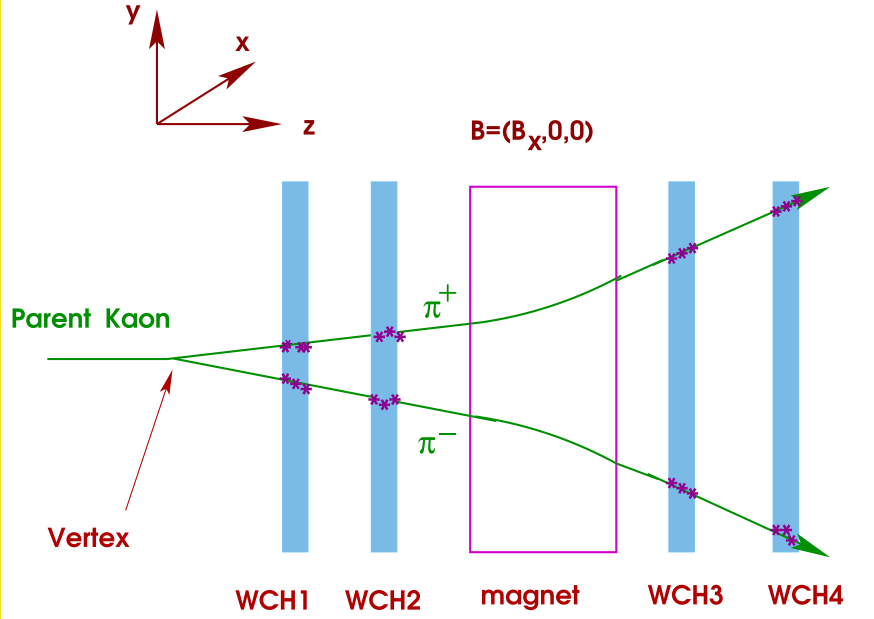
M_K = Total Invariant Mass

Detecting a K$\rightarrow \pi^+ \pi^-$ mode

The experimental signature of such a decay is the observation of two charged tracks (π^+ and π^-) emerging from a point (the decay vertex).
To reconstruct kinematically the event one needs to know the vertex coordinates and the momenta of the tracks. This is usually done using a spectrometer.

It consists of an ensemble of wire chambers filled with a light gas and located before and after a central magnet

- The charged particle ionizes the gas. The so-liberated electrons migrate to the closest wire. The readout current allows the localization of the road the particle went throught.
- The magnet modifies the trajectory of the particle depending on its charge and speed. This allows the reconstruction of the momentum and the identification of the charge



Principle of a magnet use for K-> $\pi^+\pi^-$

Detecting a K$\rightarrow \pi^+ \pi^-$ mode (cntd)

Let us follow one pion from K$\rightarrow \pi^+ \pi^-$ going through a homogeneous magnetic field (0, B_Y,0) and following the Z axis.

- It will undergo a force leading to a momentum deflection by:

$$\Delta P_X = -q \int B_Y \, dz$$

- The sign of the deflection gives the charge of the particle

- The more energetic the pion is, the less deflected its initial trajectory will be

- By measuring the pion incident angles wrt to Z axis before and after the magnet one gets the pion momentum quadrivector

$$P = q \int \frac{B_Y}{(sin\theta_{bef} - sin\theta_{aft})} \, dz$$

- The invariant mass of the $\pi^+ \pi^-$ pair is given by:

$$M^2_{\pi\pi} = (\sqrt{p_1^2 + m_\pi^2} + \sqrt{p_2^2 + m_\pi^2})^2 - (\vec{p_1}^2 + \vec{p_2}^2)$$

$\mathrm{Re}(\varepsilon'/\varepsilon)$ **History:**

From the pioneers to today

The pioneers

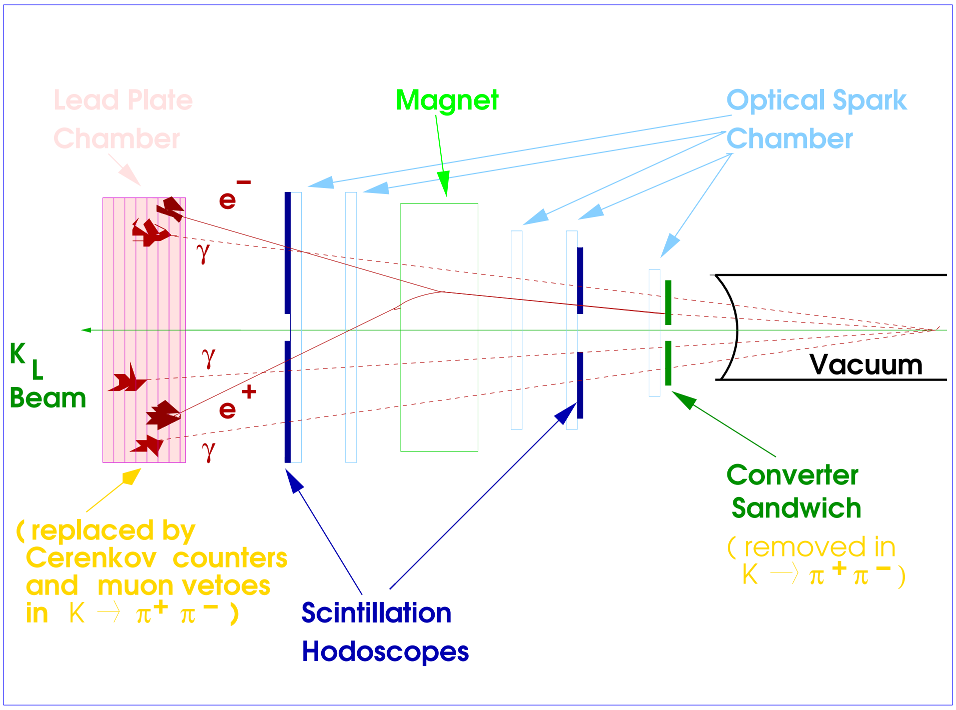
- 1964: Discovery of CP Violation (ε) at Brookhaven observing $\mathrm{K_L} \rightarrow \pi^+\pi^-$(56 events containing 11 estimated background events)
- 1965: Confirmation of the discovery by two other groups (CERN and Harwell).
- Search for η_{00} started later. Two announcements have been published in 1968 by CERN and Princeton groups
- First evaluations of the double ratio (=1-6Re(ε'/ε)) were published in 1972 as the ratio of measured η^{00} and η^{+-}

- **Example of the Princeton experiment**

  - Use the Brookhaven $\mathrm{K_L}$ beam of mean momentum 6GeV/c.
  - Detect in two consecutive data periods $K_L \rightarrow \pi^0\pi^0$ and then $K_L \rightarrow \pi^+\pi^-$
  - $\mathrm{K_S}$ beam created regenerating the $\mathrm{K_L}$ going throught an uranium bloc : $\mathrm{K_L} \rightarrow \mathrm{K_L}' + \rho \mathrm{K_S}$
  - Detect in two consecutive data periods $K_S \rightarrow \pi^0\pi^0$ and then $K_S \rightarrow \pi^+\pi^-$
  - Deduce the double ratio by combining the four modes recorded in four different data taking periods.
  - The four beam fluxes were measured by a beam monitor with a 3% precision

The Princeton experiment (1972)

See M.Banner et al., Phys.Rev.Lett. 28, 1597 (1972)
(5 Physicists)



- $\pi^0\pi^0$detection
  - Require the conversion of a photon into the $0.1X_0$ Converter sandwich. The intersection of the backward extrapolated track with the beam axis gives the decay vertex
  - Trigger on conversion hits the two Scintillator hodoscopes
  - Require 3 deeply interacting photon showers- this eliminates $3\pi^0$ decays with smaller photon energies
  - From the photon energies, positions and vertex one computes the 2 best $\gamma\gamma$ combinations

The Princeton experiment (cntd)

- the $\pi^+\pi^-$ detection
  - Remove the converting sandwich
  - Trigger on two charged tracks emerging from the magnet with small transverse momentum
  - Replace the Lead plate chamber by an ensemble of CerenKov counters and Muon vetoes to detect the electron from $K_L \rightarrow \pi e \nu$ and the muon from $K_L \rightarrow \pi \mu \nu$ respectively.
  - Reconstruct the invariant $\pi^+\pi^-$ mass

Results:

Charged Mode : $| \rho |^2 / | \eta_{+-} |^2 = 126 \pm 6$
Obtained statistics: 2000 vacuum events 14000 regenerator events

Neutral mode : $| \rho |^2 / | \eta_{00} |^2 = 120.0 \pm 14$
Obtained statistics: 124 ± 11 vacuum events and 1228 ± 50 regenerator events

Remark: ρ same for charged and neutral, since only depends on the regenerator material

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = 1.05 \pm 0.14$$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1\text{-R})/6 \Rightarrow \mathrm{Re}(\varepsilon'/\varepsilon) = -0.008 \pm 0.02$$

The first generation: the eighties

In late seventies, new theoretical works showed that $\mathrm{Re}(\varepsilon'/\varepsilon)$ could be large enough to be measurable.

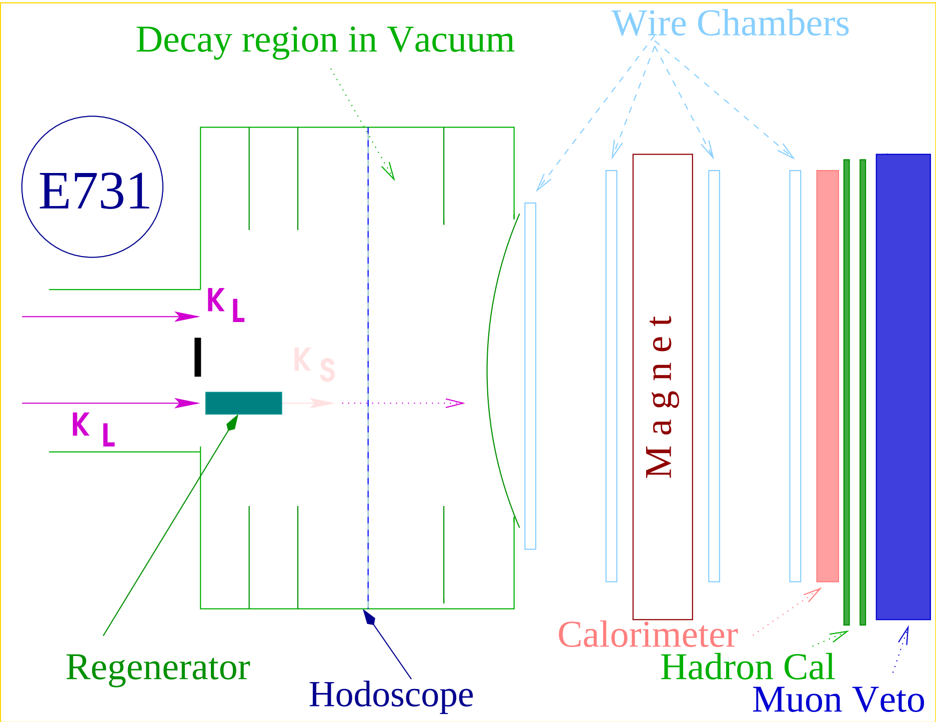
J.Ellis, M.K.Gaillard and D.V.Nanopoulos, Nucl.Phys. B 109, 213 (1976).
G.J.Gilman and M.B.Wise, Phys.Lett.B 206, 169 (1979).

New, dedicated, precise experiments have been designed for that purpose.

- Goal: achieve total error <0.001.
  - Intense beams and long data taking to increase statistics.
  - To squeeze down the systematics record simultaneously as much as possible modes.
- Two groups separated by the Atlantic ocean: E731 based in FermiLab and NA31 based at CERN.
  - E731 was a Chigago University, FermiLab, Princeton and Saclay collaboration, with a total of ∼30 Physicists.
    The experiment has been proposed in 1983 and published its last result in 1993.
  - NA31 was a CERN, Dortmund, Edinburgh, Mainz, Orsay, Pisa and Siegen collaboration, with a total of ∼ 50 Physicists.
    It has been proposed late 1981 and finished the data analysis in 1993.

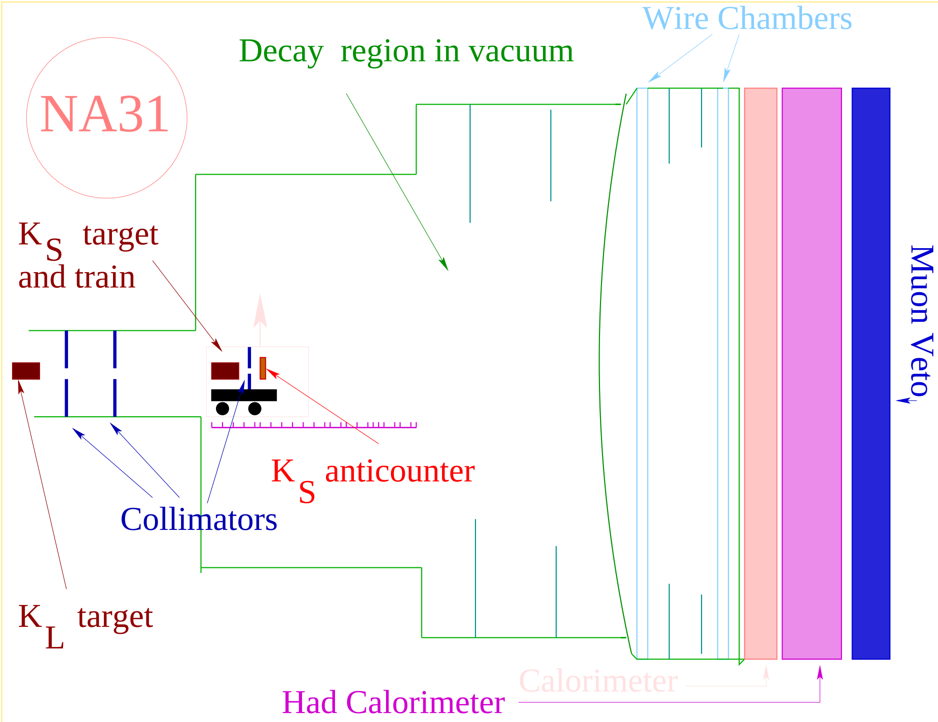
The E731 scheme

- ✥Fixed target experiment using a 800GeV primary proton beam.
- ✥E731 was measuring a single mode ($\pi^0\pi^0$ or $\pi^+\pi^-$) in simultaneous K_L and K_S beams.
- ✥Two parallel K_L beams were produced in a primary target 120m upstream the decay region.
- ✥Close to the decay region, one of the K_L beams was travelling through a block of matter, giving birth to a regenerated K_S component.
- ✥A lead-glass calorimeter was detecting neutral final modes.
- ✥Charged modes were measured by a magnetic spectrometer



The NA31 scheme

- Fixed targed experiment using the SPS 450GeV proton beam.
- NA31 was measuring simultaneously $\pi^0\pi^0$ and $\pi^+\pi^-$ either in K_S or in K_L beam.
- The K_L beam is produced in a primary target located 120m from the decay region.
- In K_S mode, the proton beam is brought close to the decay region where it strikes a second target.
- A liquid-argon calorimeter, segmented longitudinally in two halves, was detecting neutral final modes.
- Charged modes are measured by two wire chambers and hadronic calorimetry.

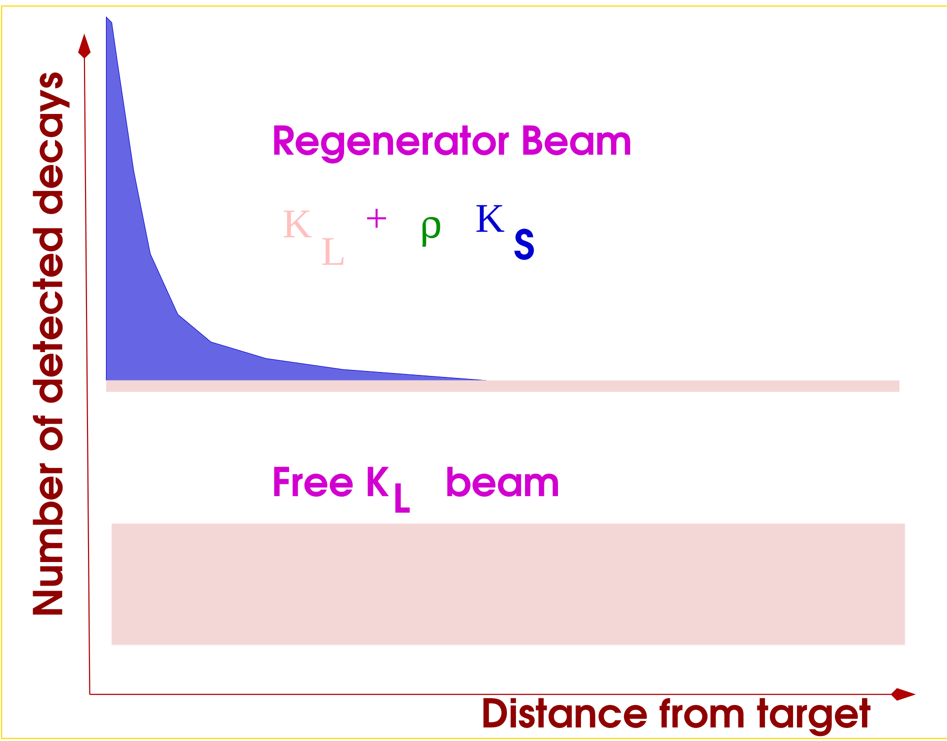


The E731 originality

The regenerator

☞ One of the two parallel K_L beams passes through it

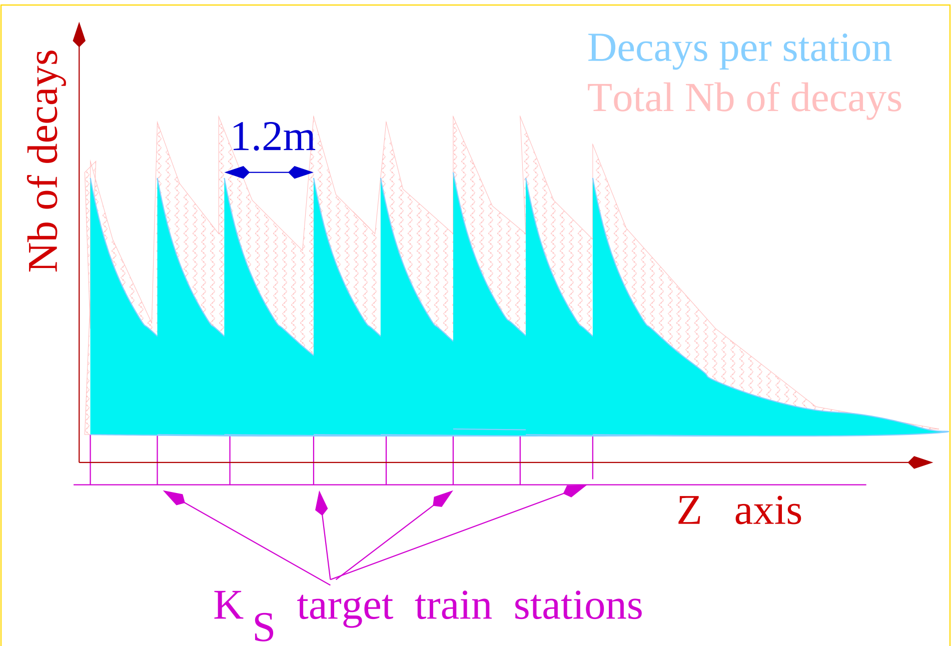
- Allows to have simultaneous K_S and K_L beams
- Allows to keep similar energy spectra between the initial K_L and the produced K_S beam
- Moving frequently the regenerator from one K_L line to the other, one can symmetrize the illumination of the detector for both K_S and K_L beams
- Incoherent regeneration and inelastic processes modify the kinematics of a fraction of the outcoming particles



The NA48 originality

The K_S target train

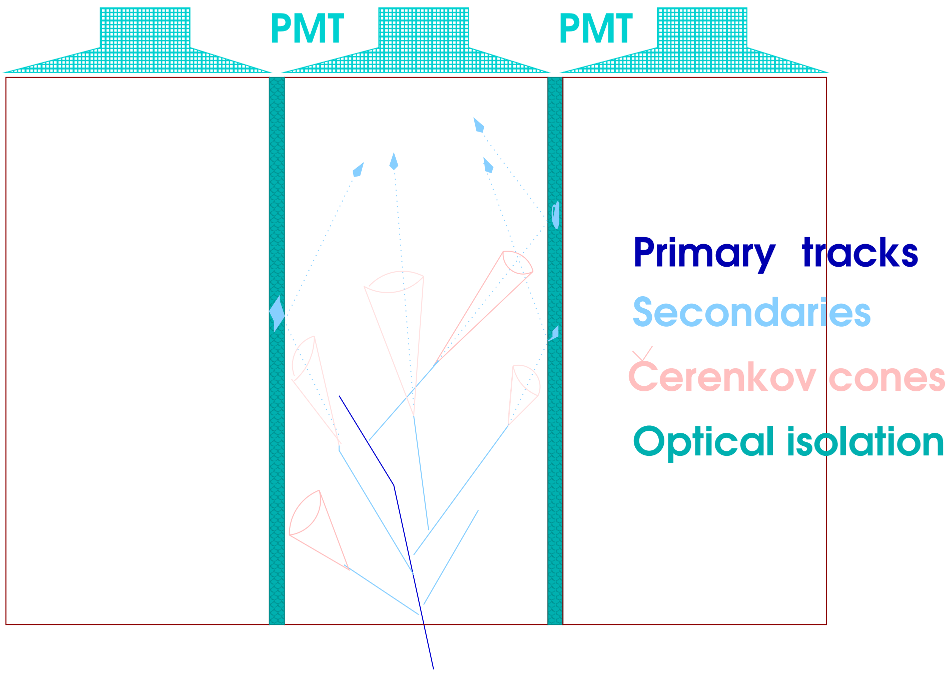
- The K_S target together with the collimation system can move in 41 different positions located every 1.2m along the beginning of the decay region
- Allows to occupy the whole K_L decay region with K_S decays with a quite similar decay distribution. This helps to keep some corrections and systematics small
- Despite the short collimation of the K_S beam line, one finally obtains a quite clean beam
- The space occupancy of the K_S train station implies running alternatively K_S and K_L beams



The E731 calorimeter: lead glass

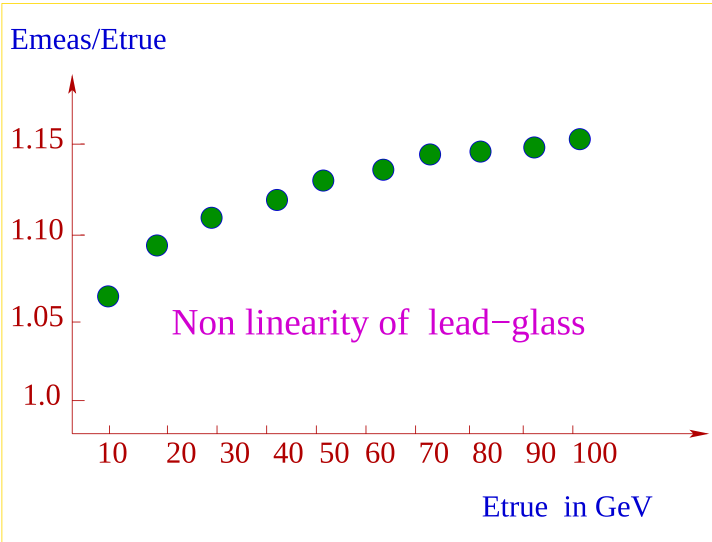
❖804 units of 5.8×5.8cm^2 and 60cm long lead-glass blocks, readout by photomultiplier tubes. The signal was integrated over 150ns and digitised by a ADC system.
❖When a particle goes through, its interaction with the lead atoms gives secondaries emitting Čerenkov light at an angle cosθ_c=1/β_n, where n is the index of refraction. In the lead glass n≈1.6 ⇒the production angle is 51^o.
❖Most of the light has to be reflected in the cell edges. The non reflected part is lost.

- ☞ ≤1400 tracks /GeV produced in lead glass → fluctuations on the response ≥1/$\sqrt{1400}$=2.6%
- ☞ Per GeV, ∼1000 photoelectrons are produced
- ☞ The resulting energy resolution is bounded by 4% per deposited GeV



The E731 calorimeter: lead glass (cndt)

- The emitted light is attenuated along the 60cm to the PMT. Low energy showers developing early in the lead-glass, are more attenuated than energetic ones whose centre of gravity is deeper in the block.
  This results to a non-linearity $E_{true} \propto E^{0.97}_{measured}$.



- The collected light might depend on the x,y position of incoming particle.
- Lead-glass undergoes radiation damages especially around the beam pipe. The emitted light can decrease up to 5% per week.
- ☞ The response is calibrated looking at the E/p response of electrons continuously during the run.

Final performances for reconstructed photons:

Linearity 0.1% and $\sigma(E)/\mathrm{E}=0.05/\sqrt{E}\oplus 0.025$

The NA31 calorimeter

In a Liquid Argon bath (at -190^{o}C) 80 lead plates alternate along the z axis with 80 electrodes planes with printed strips of 1.1cm.
The electrodes are readout horizontaly or verticaly.
Longitudinaly the calorimeter is divided into two halfs, 60cm long each.
In each half all horizontal (and all vertical) strips are readout together.
The signal is brought by cables at the feedthroughts of the cryostat.

- The detector response is stable, and insensitive to radiations
- The longitudinal segmentation offers an identification tool of pions vs electrons: Electrons start showering early (front part) while pions later.
- The performances of the detector give:

$$\sigma(E)/\mathrm{E}=0.075/\sqrt{E} \oplus 0.100/E \oplus 0.006$$

  - The first term is due to the fluctuation of energy loss, in particular in the lead absorbers.
  - The second term represents the noise for a photon after reconstruction (16MeV per channel).
  - The constant term shows that the response is uniform within 0.6%
- Because of the cryogenic installation, the access to the detector requires long preparation time.

ANALYSIS for $\mathrm{Re}(\varepsilon'/\varepsilon)$

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle K_S from K_L
- Subtract the remaining background from K_L samples
- Evaluate corrections to the Double ratio and systematics
- Checks and stability of the result

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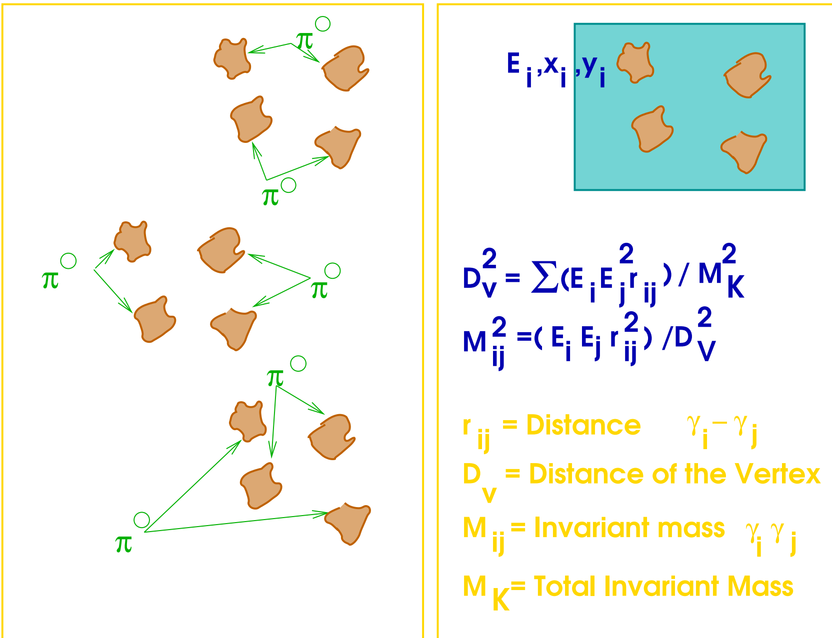
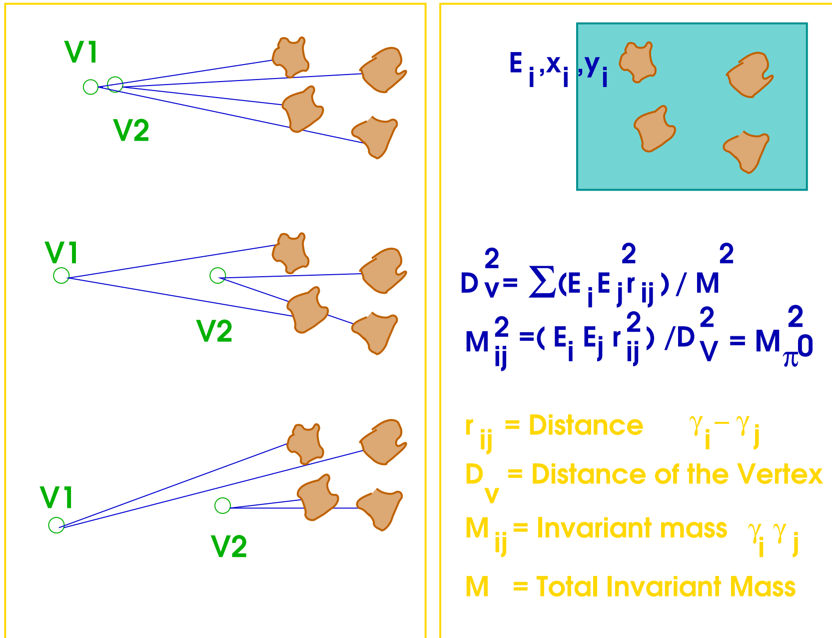
NA31 The $K \to \pi^0 \pi^0$ reconstruction E731

Assume that the total invariant mass is equal to the Kaon Mass: this fixes the vertex. Among the three combinations, choose the γ pairing with mass compatible with π^0's.

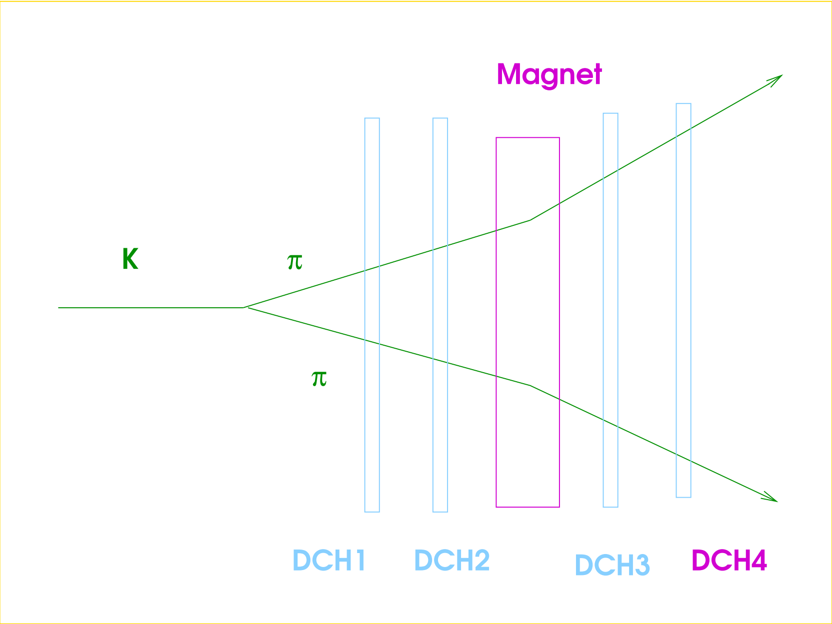
Assume that the two invariant $\gamma - \gamma$ masses are equal to the π^0 one. Among the three, choose the photon combination giving V1 compatible to V2.



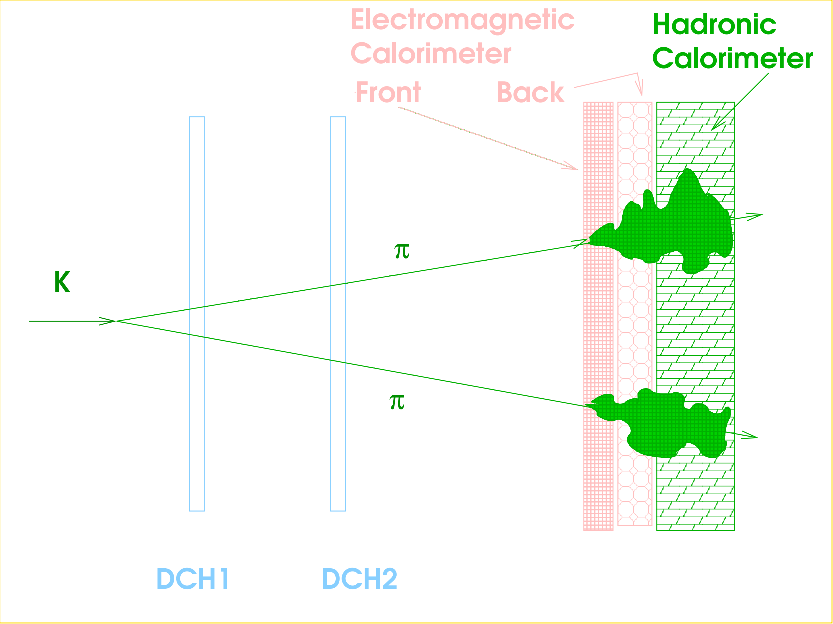


E731 The K$\rightarrow\pi^+ \pi^-$ reconstruction NA31

From the magnetic spectrometer one has the vertex and the pion momenta and one can compute the invariant mass.



The Vertex is given by the two chambers. Momenta and mass are computed from the energy deposited in the front and back electromagnetic calorimeter and the hadronic one.



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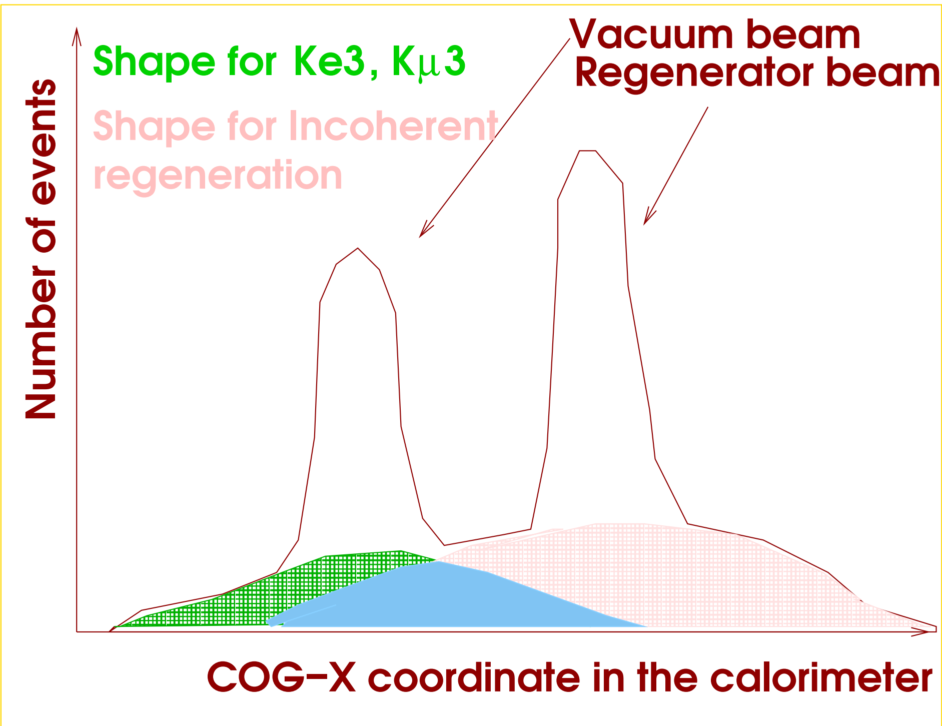
K_S and K_L separation

✦For NA31 no problem, since the two beams are recorded separately.

✦In E731, for a given decay in the regererated beam (K_S): there is a small probability to reconstruct the event in the opposit beam because of the scattering in the regenerator or because of incoherent scattering.

In that case, the separation is done in statistical basis looking at the centre of gravity in the calorimeter.



Example	Vacuum beam	Regererator beam
Scattering in $\pi^0\pi^0$	2.3%	2.5%

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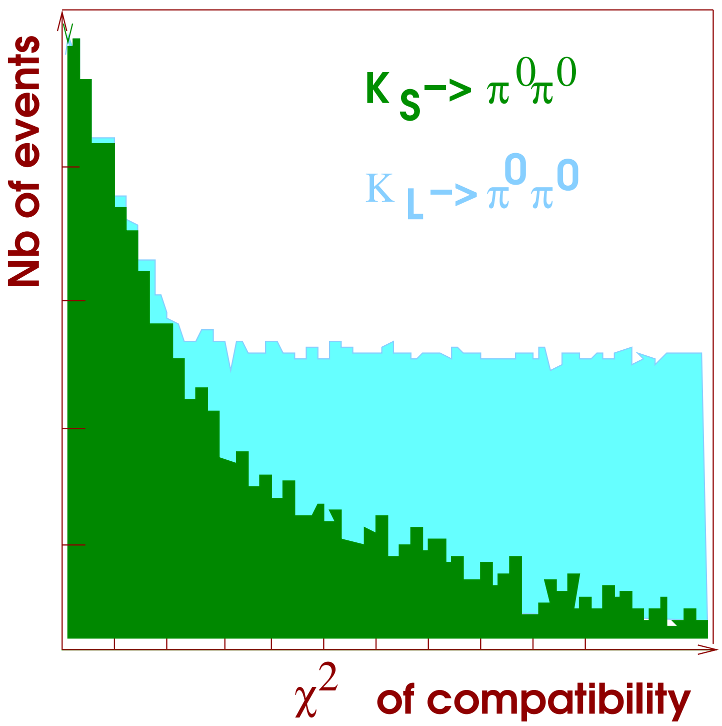
What about $K_L \rightarrow 3\pi^0$ background?

Let's imagine a $K_L \rightarrow 3\pi^0$ decay with two photons escaping acceptance or fused.
In this case, the assumptions about invariant masses are wrong in both analyses. Notice that escaping photons are in general detected by the circular vetoes.
The pollution from the remaining background is identified looking at one distribution for K_L and K_S candidates and comparing with MC predictions.



The signal is defined looking at K_S distribution. The remaining background under the signal :

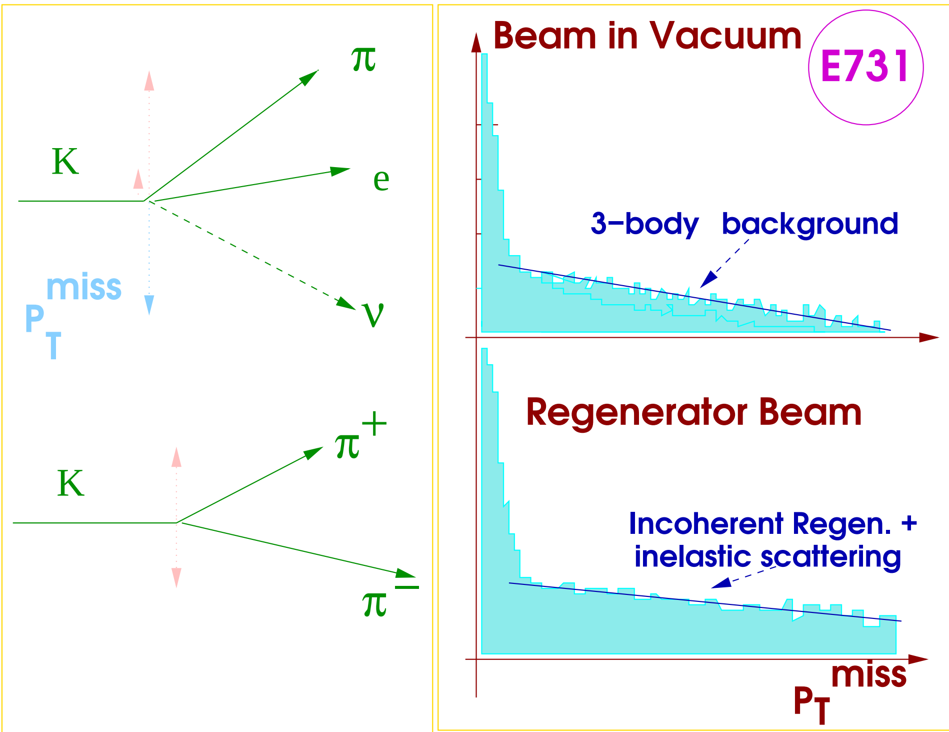
E731 (1.78±0.03)% NA31 (2.70±0.14)%

What about K_{e3} and $K_{\mu 3}$?

❖K_{e3} and $K_{\mu 3}$ where the electron or the muons are faking a pion.

❖Electron are identified either by E/P (using the magnet in E731) or with calorimetric criteria (in NA31). Muons interact in the dedicated muon vetoes.

❖ Because of the undetected neutrino, such events have a large transverse momentum and invariant mass which doesn't agree with the Kaon one.



Under the $\pi^+\pi^-$ signal:

E731 : (0.34±0.01)%   NA31 : (0.65±0.20)%

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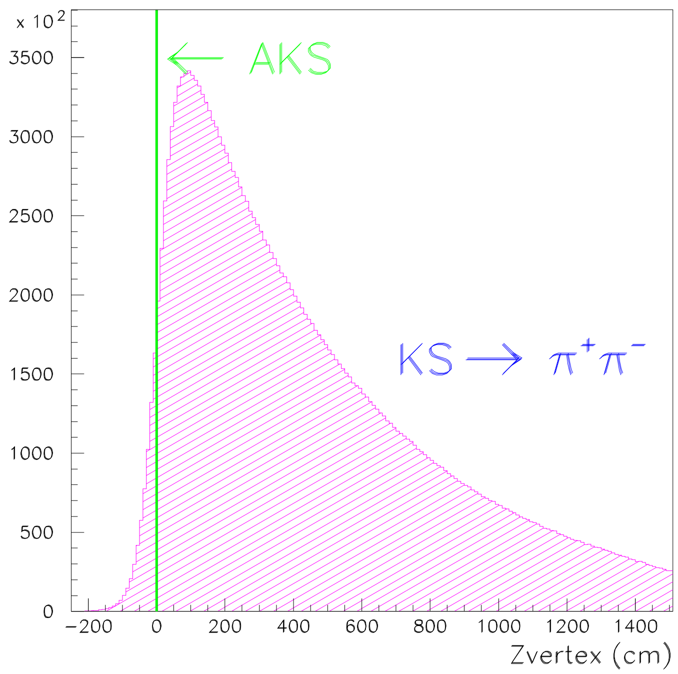
The double ratio

- Events are counted in a given "fiducial region": energy range between E_a and E_b and vertex from $V_a \rightarrow V_b$.
  - ☞ Energy and vertex measurements must be the same for charged and neutral modes
  - ☞ To control the energy one follows the reconstructed edge of the well-known K_S anticounter (NA31) or regenerator edge(E731) positions



- Each sample is corrected for trigger inefficiencies, acceptances etc
- One forms the double ratio in N energy bins
- The N double ratios are combined to the final one
- One checks the stability of the result with variation of cuts, within the time in the run etc

The result of the first generation

	NA31(1993)	E731(1993)
$\mathrm{Re}(\varepsilon'/\varepsilon)$	$(23.0\pm4.1_{stat}\pm5.1_{syst})\times10^{-4}$	$(7.4\pm5.2_{stat}\pm2.9_{syst})\times10^{-4}$
Nb of $K_L \rightarrow\pi^0\pi^0$	428k	410K

$$\Downarrow$$

- ☞ E731 result indicated that $\mathrm{Re}(\varepsilon'/\varepsilon)$ is compatible with zero.
- ☞ NA31 found that $\mathrm{Re}(\varepsilon'/\varepsilon)$ is large with a 3.3σ significance
- ☞ E731 and NA31 were differing by $(15.6\pm8.8)\times10^{-4}$, meaning that their respective results were compatible at 8% level only
- ✤ Both groups decided to pursue hunting $\mathrm{Re}(\varepsilon'/\varepsilon)$ doing more precise experiments, down to 1-2$\times10^{-4}$

  – KTeV: 12 institutions (US+Japan), 100 physicists. Natural “continuation” of E731.

  – NA48: 16 european institutions, 130 physicists. Natural continuation of NA31.

KTeV and NA48: $\mathrm{Re}(\varepsilon'/\varepsilon)$ The return

- Both fixed target experiments. Protons hitting target produce Neutral kaon beams.
- Their building-up required R&D in several domains, which were beneficial to LHC and Tevatron experiments.
- Both designs were challenging, requiring stable and very precise detectors (essentially in calorimetry), fast electronics and powerful acquisition and computing systems to handle hundreds of Tbytes.
- Both suffered in their start-up year (KTeV in 96, NA48 in 97) because of electronics and (or) detector problems.

Year	KTeV	NA48
1996	$\mathrm{Re}(\varepsilon'/\varepsilon)$ data taking	Checks
1997	$\mathrm{Re}(\varepsilon'/\varepsilon)$ data taking	$\mathrm{Re}(\varepsilon'/\varepsilon)$ data taking
1998	Out-of-Run	$\mathrm{Re}(\varepsilon'/\varepsilon)$ data taking
1999	$\mathrm{Re}(\varepsilon'/\varepsilon)$ +Checks	$\mathrm{Re}(\varepsilon'/\varepsilon)$ data Taking
2000+2001		$\mathrm{Re}(\varepsilon'/\varepsilon)$ + Checks

Accumulated Statistics ($K_L \to \pi^0\pi^0$)

KTeV ≈10.000.000 NA48 ≈5.000.000

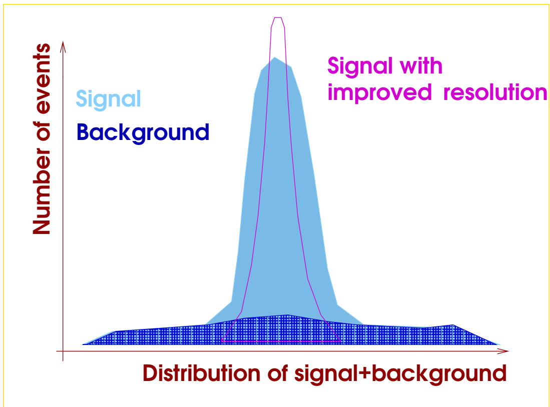
Both started announcing results in 99

The second generation: generalities

Theoretical context: Since the end of eighties, a better understanding of the penguin contributions, showed that $\mathrm{Re}(\varepsilon'/\varepsilon)$ can be very small ($\sim$ few 10^{-4}) if the top mass is 130 GeV.
A higher observed value of $\mathrm{Re}(\varepsilon'/\varepsilon)$ would therefore signal new physics.

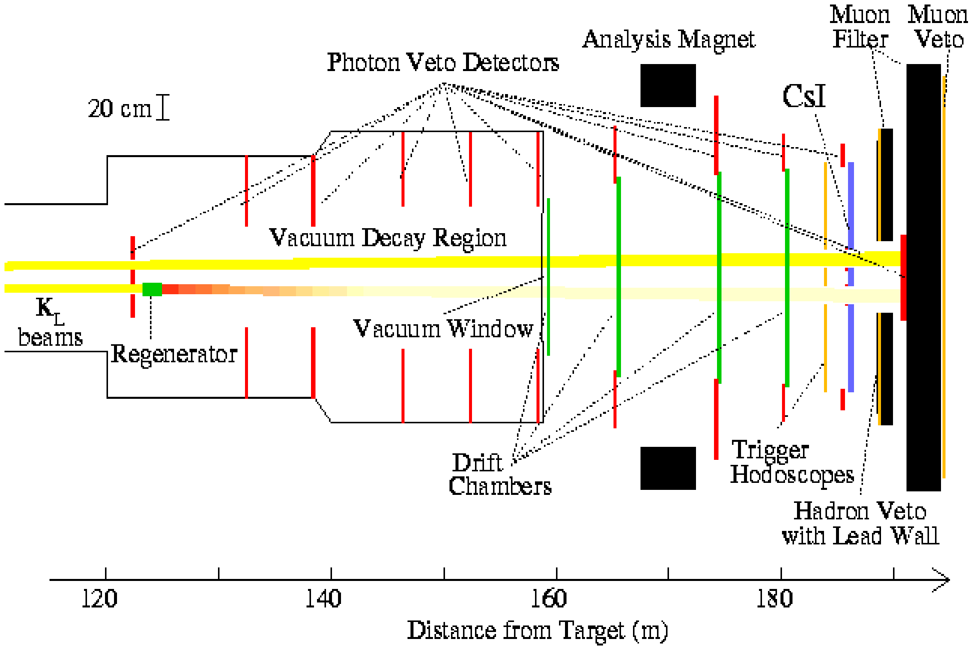
To achieve precision 1-2$\times 10^{-4}$, KTeV and NA48 had to:

- Increase the statistics
  - More intense beams and stable detectors
- Reject further the 3-body backgrounds
  - Stronger and fast trigger decisions
  - Design new, precise detectors with better resolutions: better separation of close showers in calorimeter, better coordinate building precision in WCH.



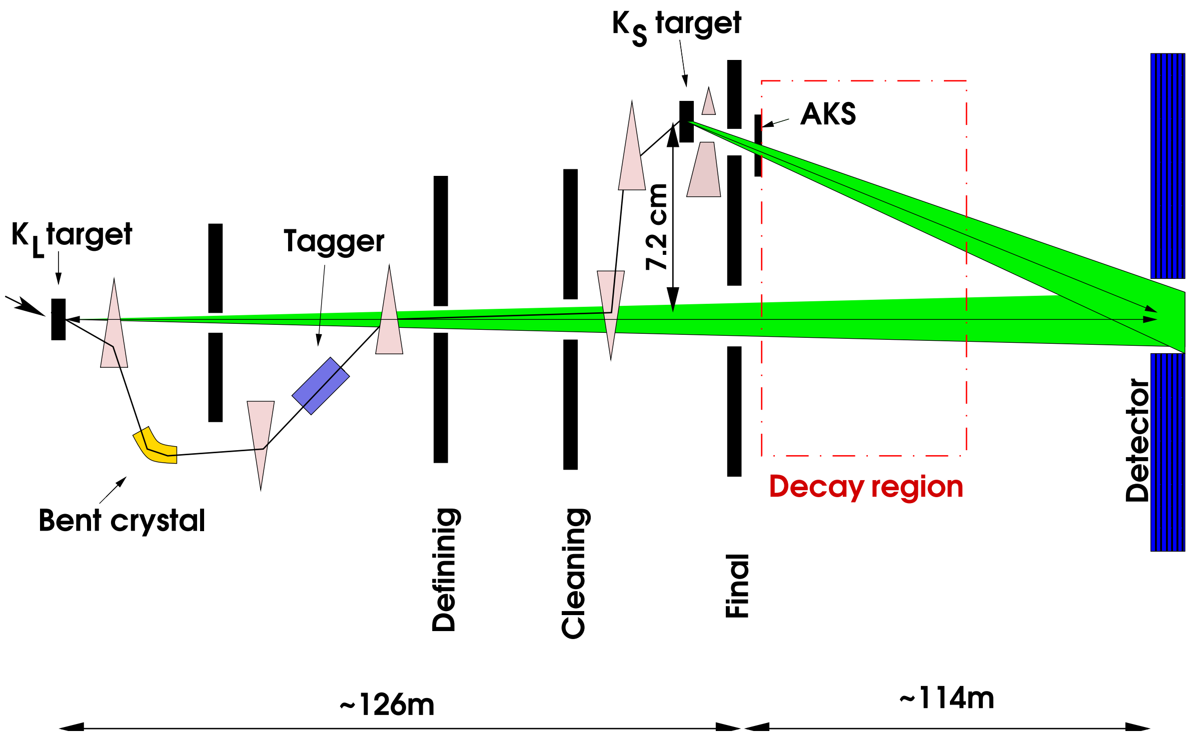
  - Sampling the readout of the sensitive detectors to recognise pileup events
- Decrease the systematics
  - All four modes together to cancel as much as possible beam, trigger, and accidental effects

The KTeV beam and detector



- Two PARALLEL K_L beams. One of them goes through a movable active Regenerator creating a K_S component.
- Charged modes are reconstructed by a spectrometer.
- Neutral modes are reconstructed by a CsI Calorimeter: 3100 blocks of pure crystal. Resolution:
  $$\frac{\sigma(E)}{E} = \frac{2\%}{\sqrt{E}} \oplus 0.45\%$$
- A serie of circular photon Vetoes sign photon escaping acceptance.
- At the end of the detector muon vetoes are used to reject $K\mu3$ background.

The NA48 beam and detector

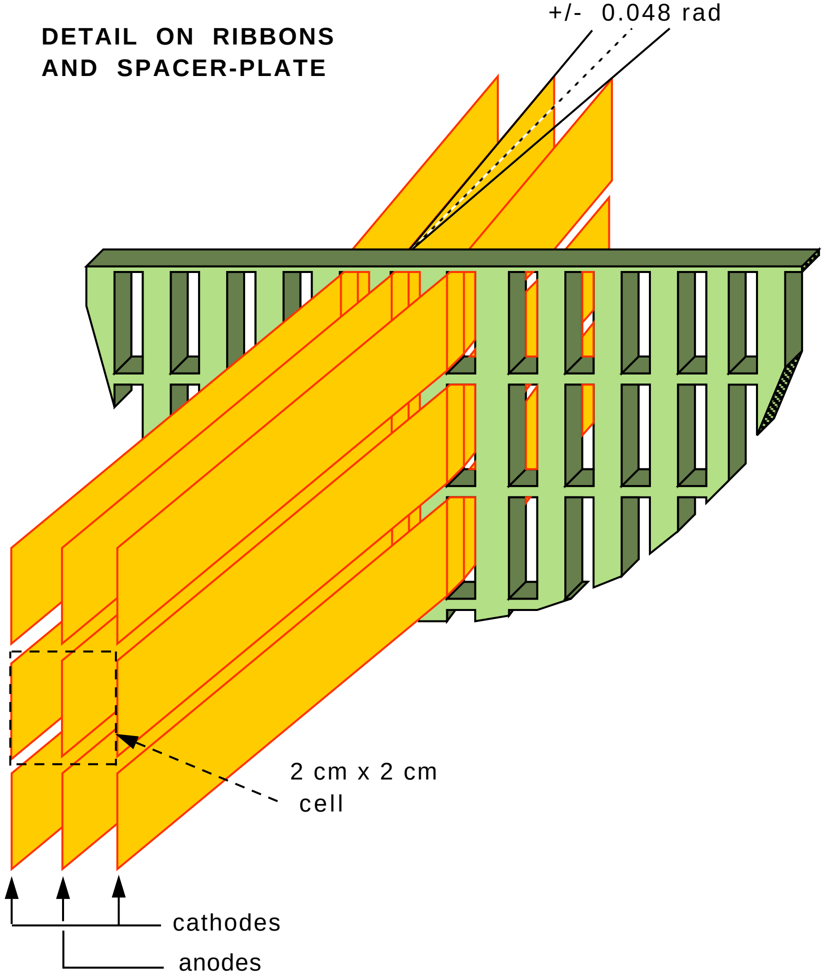


- Parallel K_L and K_S beams. The K_S beam is created close to the detector by deviated protons striking a second target.
- $K_L \rightarrow \pi^+\pi^-$ decays are detected by a magnetic spectrometer.
- $K_L \rightarrow \pi^0\pi^0$ decays are reconstructed by a Liquid-Krypton Calorimeter
- K_S decays are identified by time coincidences of the event time measured by the detectors with the proton time measured in the tagger
- Muon counters identify the $K_{\mu 3}$ decays.
- All detectors offer precise redundant time information

The LKr calorimeter

- It's a quasi-homogeneous detector
- made of $\sim 10\text{m}^3$ of Liquid Krypton and readout electrodes, held by strings in the front and back planes.

- One cell: $2\text{cm}\times 2\text{cm}\times 126\text{cm}$
- Electrodes follow a $\pm 45^o$ sig-zag every 24cm to minimize the passive material for showers in normal incidence.
- It contains a total of ~ 13260 cells.



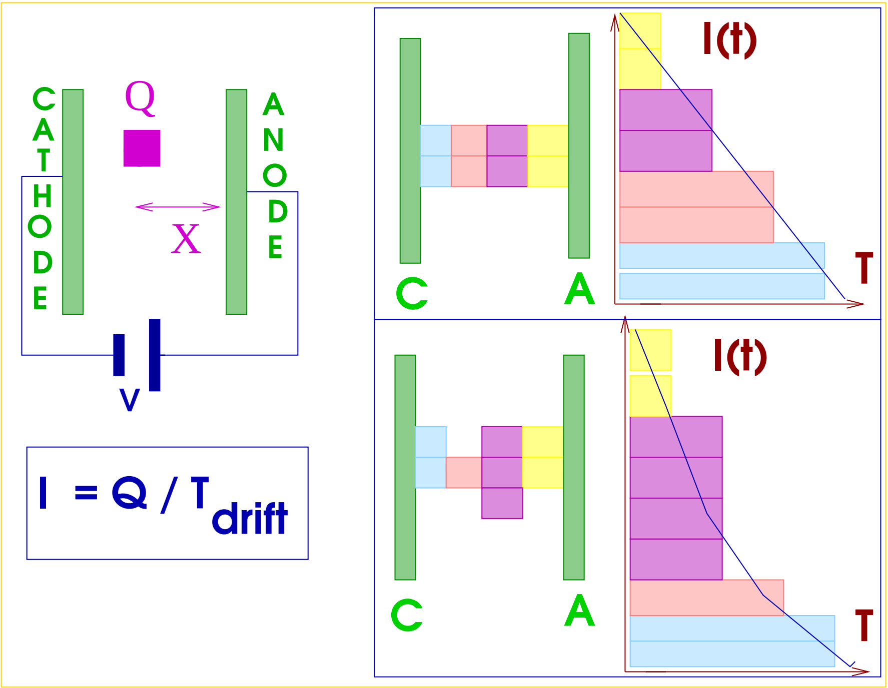
The LKr calorimeter: the readout principle

- A crossing charge Q ionizes the liquide giving e^+e^- pairs
- Because of the field, electrons migrate to the anode
- The electron motion leads to current induction in the anode

$$I=Q\frac{\vec{E}\vec{V_D}}{V}=\frac{Q}{V}\times E\times V_D= Q/V\times V/D\times D/t_D=$$

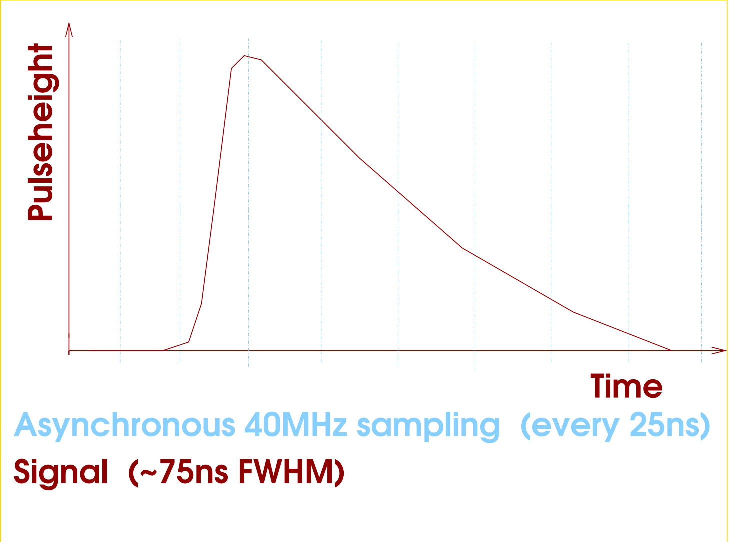
$$\Rightarrow I=\frac{Q}{t_D}$$

- Uniform charge distribution: triangular current
- Non uniform distribution: current's shape distorded
- BUT: the current at $t\rightarrow 0$ is only proportional to the deposited charge



To get uniform current response:
$\rightarrow$ *Initial Current Readout Technique*

The LKr calorimeter: performances



- Collected signal is shaped with 75ns FWHM.
- It is sampled asynchronously every 25ns and digitised.
- Energy and time per cell are reconstructed making a digital filtering of 3 samples (Max±1)

Studying the E/P response of electrons:

- Quite stable detector
- $\approx 0.3\%$ of channels were misbehaving and have been declared dead
- Linearity good to 0.1% after all corrections.
- Resolution for photons:

$$\frac{\sigma(E)}{E} = \frac{(3.2 \pm 0.2)\%}{\sqrt{E}} \oplus \frac{(9 \pm 1)\%}{E} \oplus (0.42 \pm 0.05)\%$$

  - Sampling term dominated by fluctuations outside the shower box (of $\sim$11 cm radius).
  - Good uniformity over $\approx$13200 cells

ANALYSIS for $\mathrm{Re}(\varepsilon'/\varepsilon)$: start again

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays.
- Disentangle K_S from K_L
- Subtract the remaining background from K_L samples
- Evaluate corrections to the Double ratio and systematics
- Checks and stability of the result