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

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June 29th, 2000

Menu

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  - Discrete Symmetries
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- KTeV and NA48: The way they measure $\mathrm{Re}(\varepsilon'/\varepsilon)$
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  - Their results
- The future or $\mathrm{Re}(\varepsilon'/\varepsilon)$
  - Complete the analysis in KTeV and NA48
  - KLOE in Frascati: started taking data

What are we looking for?

Discrete Symmetries

Beginning of sixties: Golden age of study of fundamental symmetries C, P and T

$\boxed{\text{Symmetry A}} \Rightarrow \boxed{\text{Experiment invariant wrt A}}$

- ***Parity P:*** Exchanges space coordinates (x,y,z) to (-x,-y,-z)
- ***Charge Conjugation C:*** Exchanges a particle to its anti-particle (electron to positron, a quark to its antiquark, a proton to an antiproton etc)
- ***Time Conjugation:*** Exchanges t$\longrightarrow$-t

$\Rrightarrow$ Theorem : Under Very general assumptions

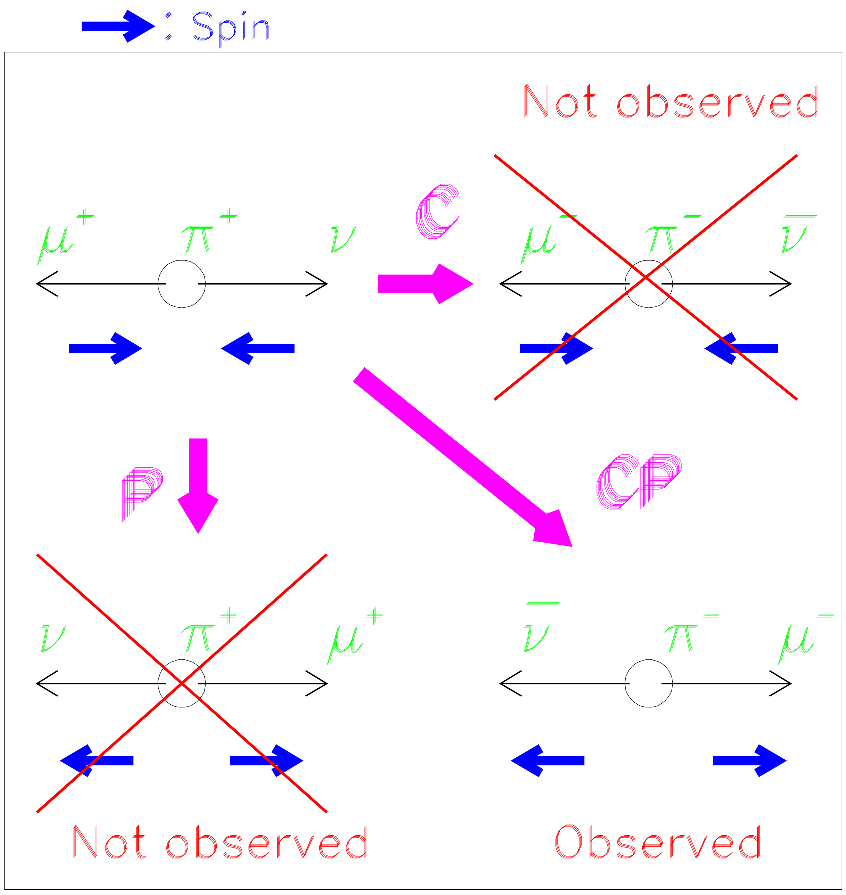
$\boxed{\text{a } \boldsymbol{C}\times\boldsymbol{P}\times\boldsymbol{T} \text{ operation lets physics invariant}}$

CPT conservation is verified experimentaly.What about ***C***,***P*** and ***CP***?

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 in agreement with observations.

Example of the pion decay



CP Violation

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

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

Physical Particles	CP Eigenstates
$\mathrm{K_L} \approx K_{CP=-1} + \epsilon K_{CP=+1}$	$K_{CP=-1} \rightarrow$ 3body
$\mathrm{K_S} \approx K_{CP=+1} + \epsilon K_{CP=-1}$	$K_{CP=+1} \rightarrow$ 2 body

$$\boxed{\text{Mixing parameter } |\epsilon| \approx 2 \cdot 10^{-3} \text{ (1964)}}$$

Observed: $K_L \rightarrow \pi\pi$ coming through two CP State Mixing (represented by ϵ parameter: INDIRECT component)

Question: Apart from state mixing, is there any other way for $\mathrm{K_L} \rightarrow \pi\pi$ $(K_{CP=-1} \rightarrow 2\pi)$?? (represented by $\epsilon^{'}$ parameter : DIRECT component)

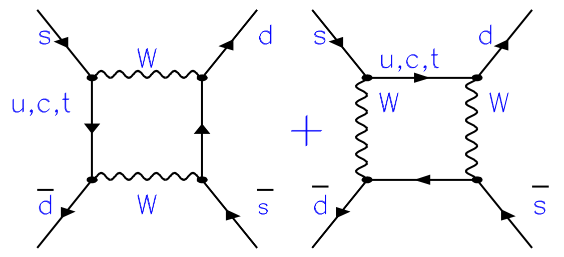
Answer :Direct CP Violation can appear through I=0 and I=2 two pion final states interference

$$\boxed{\epsilon^{'} \approx \frac{i}{\sqrt{2}} e^{i(\delta_2 - \delta_0)} \left| \frac{A_2}{A_0} \right| sin(\phi_2 - \phi_0)}$$

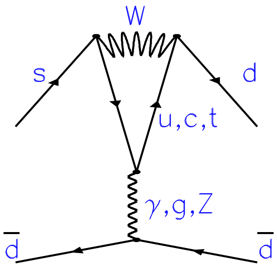
❖Direct CP Violation if $\delta_2 \neq \delta_0$ and $\phi_2 \neq \phi_0$.

$\mathrm{Re}(\varepsilon'/\varepsilon)$ within the Standard Model

CP Violation: naturally included in the Standard Model because of an irreducible phase in three family case.



BOX diagrams (ΔS=2) : ε



Penguins (ΔS=1) : ε'

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) \propto |\, V_{ub}\ V_{cb} \,|\ \eta \left[\frac{1}{m_{strange}}\right]^2 (B_6 - Z(m_{top})B_8)}$$

- B_6: QCD Penguins $\qquad$ B_8: E-W Penguins
- B_6 and B_8:$\approx$ same size. B_8 known within $\pm 20\%$, B_6 withing $\pm 100\%$
- $\mathrm{Re}(\varepsilon'/\varepsilon) = (17^{+14}_{-10}) \times 10^{-4}$ Bertolini et al 98
- $\mathrm{Re}(\varepsilon'/\varepsilon) = (5.2^{+4.6}_{-2.7}) \times 10^{-4}$ Bosch et al 99
- $\mathrm{Re}(\varepsilon'/\varepsilon) \nearrow 15.5 \times 10^{-4}$ Pallante,Pich 99
- $\mathrm{Re}(\varepsilon'/\varepsilon) =(4.6^{+7.7}_{-7.2} \times 10^{-4})$ Ciuchini,Martinelli 2000

$\rightarrow$ See Lubicz's talk

Comments on $\mathrm{Re}(\varepsilon'/\varepsilon)$

One can demonstrate that $\mathrm{Re}(\varepsilon'/\varepsilon)$ is connected to four observable numbers:

$$\mathrm{R}= \frac{\Gamma(\mathrm{K_L} \rightarrow\pi^0\pi^0)}{\Gamma(\mathrm{K_S} \rightarrow\pi^0\pi^0)} / \frac{\Gamma(\mathrm{K_L} \rightarrow\pi^+\pi^-)}{\Gamma(\mathrm{K_S} \rightarrow\pi^+\pi^-)} \approx 1 - 6 \times \mathrm{Re}(\varepsilon'/\varepsilon)$$

The formula:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1-\frac{\Gamma(K_L\rightarrow\pi^0\pi^0)}{\Gamma(K_S\rightarrow\pi^0\pi^0)} / \frac{\Gamma(K_L\rightarrow\pi^+\pi^-)}{\Gamma(K_S\rightarrow\pi^+\pi^-)})/6$$

becomes in experimental conditions:

$$\mathrm{Re}(\varepsilon'/\varepsilon)^{\ meas} = (1-\frac{Nb(K_L\rightarrow\pi^0\pi^0)}{Nb(K_S\rightarrow\pi^0\pi^0)} / \frac{Nb(K_L\rightarrow\pi^+\pi^-)}{Nb(K_S\rightarrow\pi^+\pi^-)})/6$$

Where $\mathrm{Nb}(K_{L,S} \rightarrow \text{final state})$ represents the counted number of such decays within the detector acceptance.

HOWEVER:

After measuring $\mathrm{Re}(\varepsilon'/\varepsilon)^{\ meas}$, one has to apply some corrections in order to obtain $\mathrm{Re}(\varepsilon'/\varepsilon)$:

Beam Fluxes, Trigger, geometry, cuts ...

The advantages of measuring a Double Ratio

Corrections on :

$$R = \frac{Nb(K_L \to \pi^0\pi^0)}{Nb(K_S \to \pi^0\pi^0)} \Big/ \frac{Nb(K_L \to \pi^+\pi^-)}{Nb(K_S \to \pi^+\pi^-)}$$

at first order cancel out if:

- They are common to two MODES recorded concurrently
- They are common to two BEAMS recorded concurrently

For instance:

K_L and K_S beam fluxes cancel out if neutral and charged mode are concurrently detected, detector and trigger inefficiencies cancel out if the two beams are concurrent, accidental losses of events (cancel if all modes concurrently detected...

Finally one has to correct for second order differential effects

BUT:

- Acceptance correction and background subtraction might not cancel and would require particular care.

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

Previous generation experiments gave (ended in '93):

E731 FermiLab	$(7.4 \pm 5.9) \cdot 10^{-4}$
NA31 CERN	$(23.0 \pm 6.5) \cdot 10^{-4}$

NA31 and E731: Similarities and differencies

- Both fixed target experiments
- Different methods to build the $\mathrm{K_S}$ beam
- Both measuring $\mathrm{R} = \frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_S} \to \pi^0\pi^0)} / \frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_S} \to \pi^+\pi^-)}$
- E731 was recording one single final mode in simultaneous beams and then changing mode (corresponds to measure $\mathrm{K_L}/\mathrm{K_S} \to \pi^0\pi^0$ and then $\mathrm{K_L}/\mathrm{K_S} \to \pi^+\pi^-$)
- NA31 was recording both final modes in a single beam and then changing beam (corresponds to measure $\mathrm{K_L} \to \pi^0\pi^0/\pi^+\pi^-$ and then $\mathrm{K_S} \to \pi^0\pi^0/\pi^+\pi^-$)
- E731 and NA31 have had different systematics.

New Generation of Experiments: KLOE, KTEV, NA48
designed to achieve a final precision of $\approx$ 1-2 10^{-4}

- NA48 and KTeV are fixed target experiments, continuations of NA31 and E731 respectively. R measured detecting all four modes concurrently
- KLOE is installed in the Φ factory in Frascati

KTeV and NA48

- Both fixed target experiments. Protons hitting target produce Neutral kaon beams.
- Their building-up required R&D in several domains, profitable in the following in 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 thousands 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	Re(ε'/ε) data taking	Checks
1997	Re(ε'/ε) data taking	Re(ε'/ε) data taking
1998	Out-of-Run	Re(ε'/ε) data taking
1999	Re(ε'/ε) +Checks	Re(ε'/ε) data Taking
2000+2001		Re(ε'/ε) + Checks

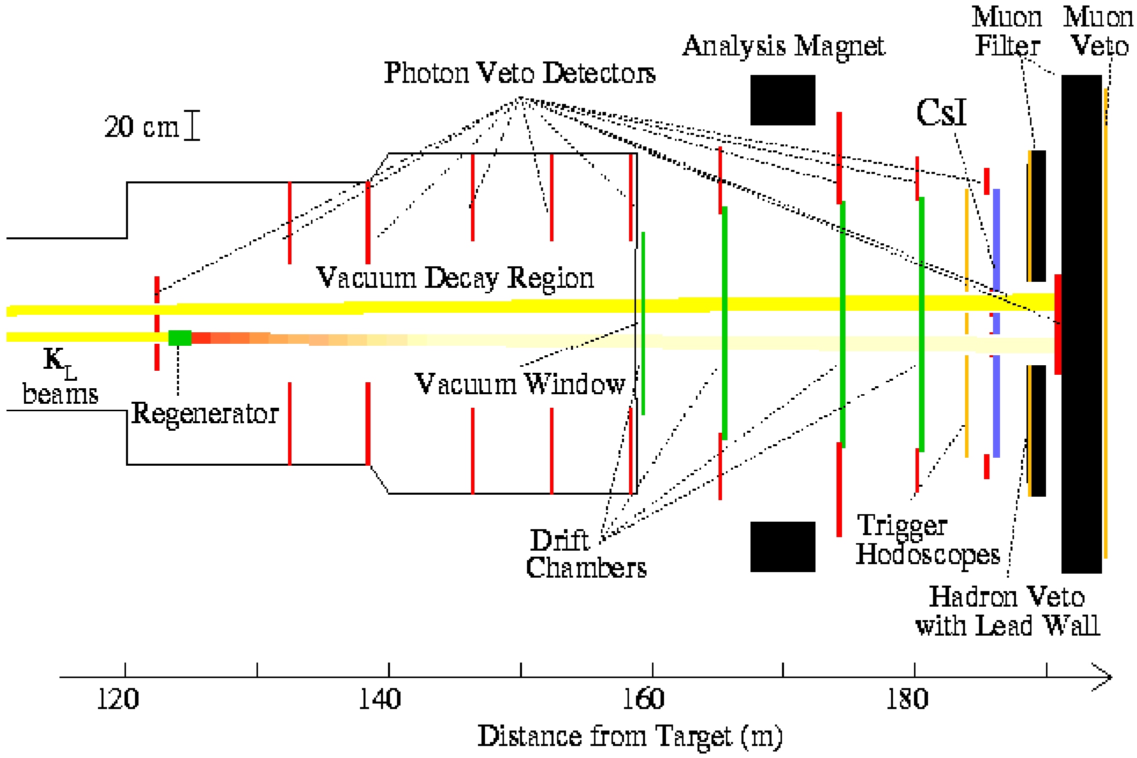
Accumulated Statistics ($K_L \to \pi^0\pi^0$) till <2000:

KTeV $\approx$10.000.000
NA48 $\approx$4.000.000

Announced Results:

KTeV: February '99 on $\approx$10% of the statistics
NA48: June '99 (on 97 data) , March 2000 (on 98 data)

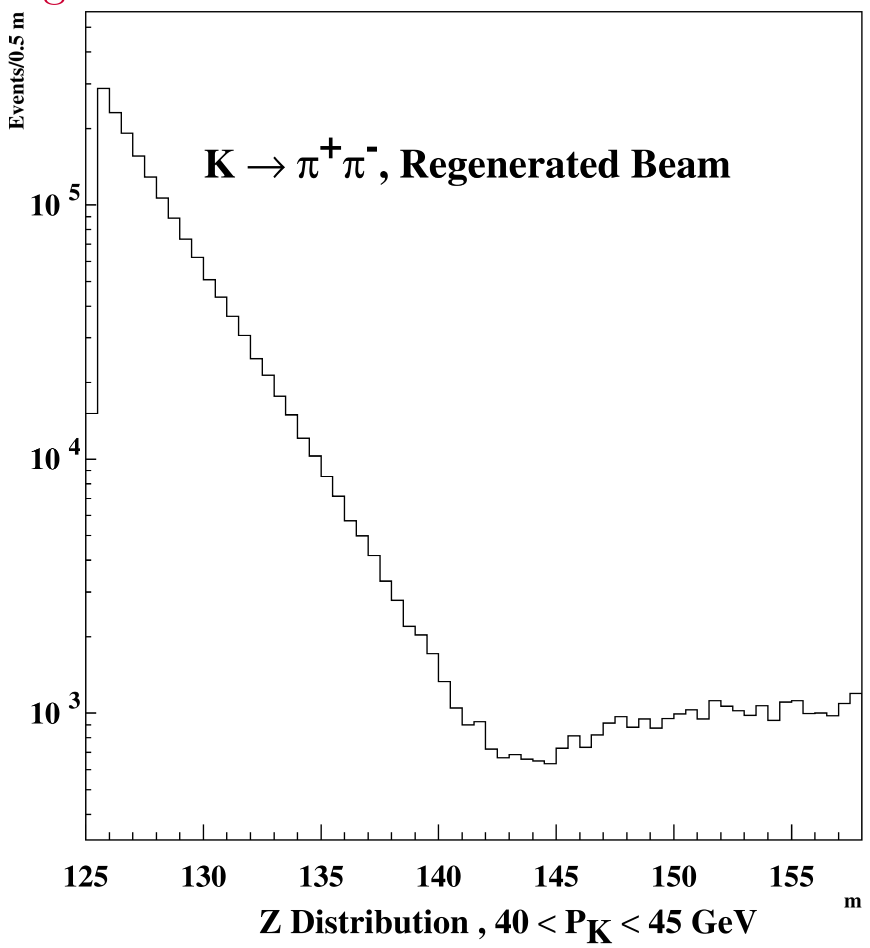
The KTeV beams and detector



- Two PARALLEL K_L beams. One of them goes through a movable “Regenerator” creating a K_S component.
- Charged modes are reconstructed by a spectrometer.
- Neutral modes are reconstructed by a CsI Calorimeter
- A serie of circular photon Vetoes sign photon escaping acceptance.
- At the end of the detector muon vetoes are used to reject $K\mu 3$ background.

The KTeV regenerator

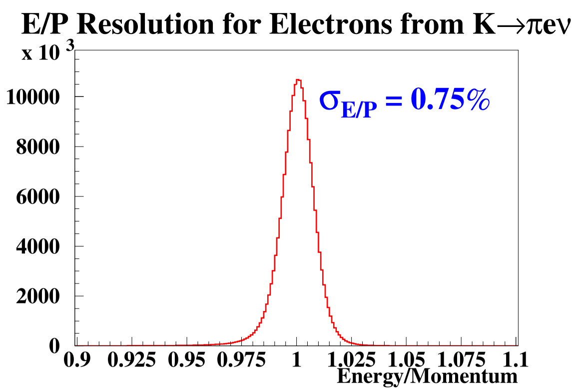
- One of the two $\mathrm{K_L}$ beams goes through a serie of plastic scintillator blocks $(2\lambda_I)$.
- Because of their different quark content, $K^0(\mathrm{d}\bar{s})$ and $\overline{K^0}$ $(\bar{d}\mathrm{s})$ have different nuclear cross-sections and their initial mixture is modified when going through the matter.
- At the end of the block the initial pure $\mathrm{K_L}$ beam is regenerated to $\mathrm{K_L} + \rho \mathrm{K_S}$.
- Inelastic interactions within the regenerator are identified by a serie of photomultipliers detecting the recoiling products.
- A small slightly diffracted Kaon component survives in the regenerated beam.

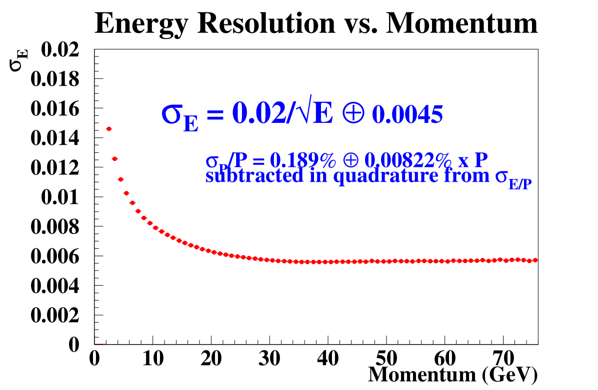


The KTeV CsI Calorimeter

- 3100 blocks of pure CsI crystals, 50cm long (27 X^0), in two sizes: 2.5×2.5cm in the central region and 5×5cm in the outer region.
- An optimized wrapping allowed to obtain a light collection uniform to 5%, calibrated by a Cs-137 source moved along the length of the crystal.

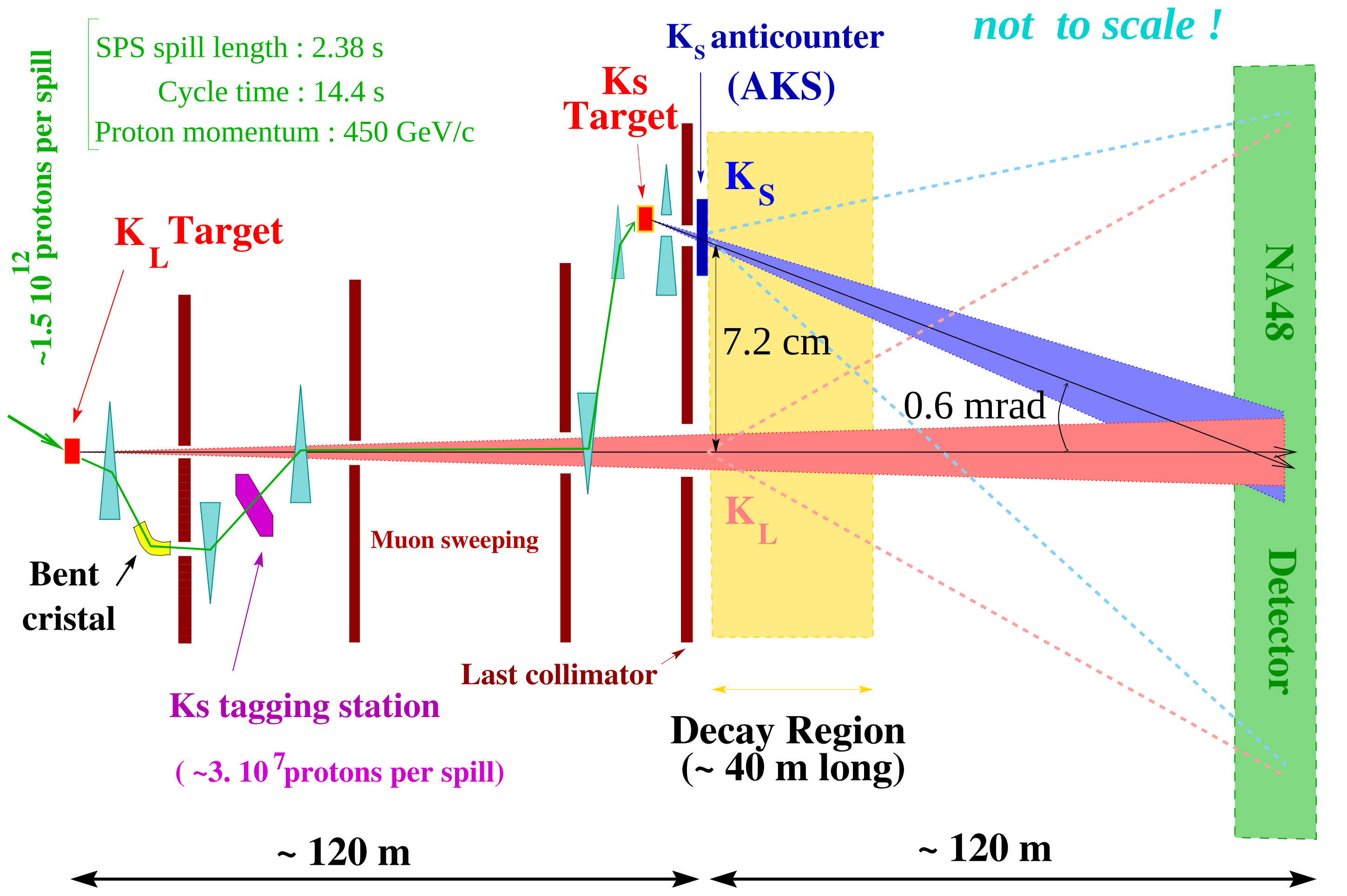
CsI Calorimeter Performance





CsI is Calibrated with Electrons from K $\to \pi e \nu$ Decays.

The NA48 Beam Lines

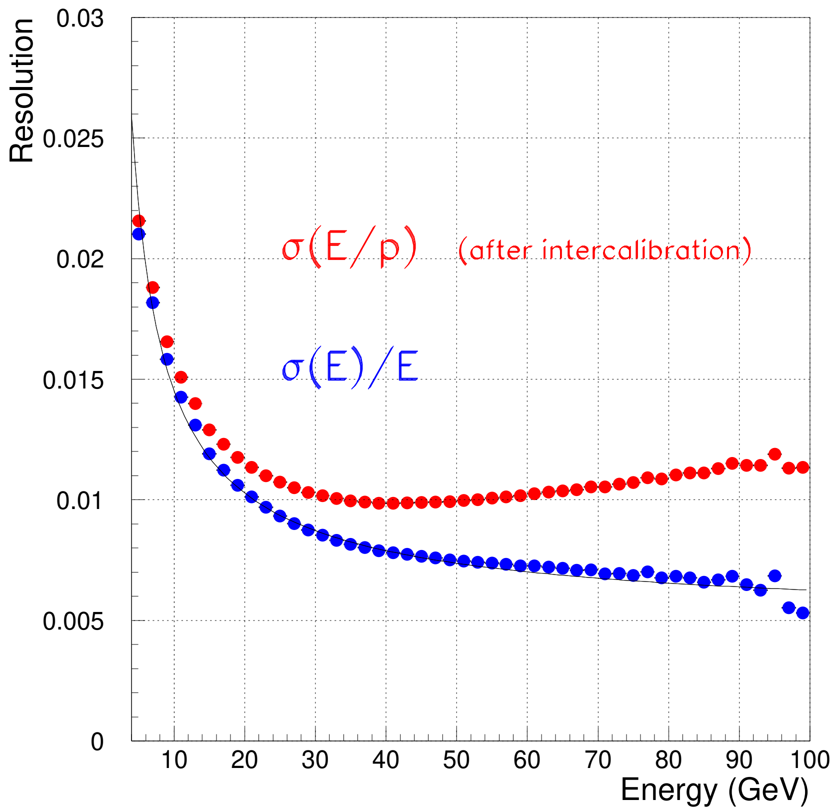


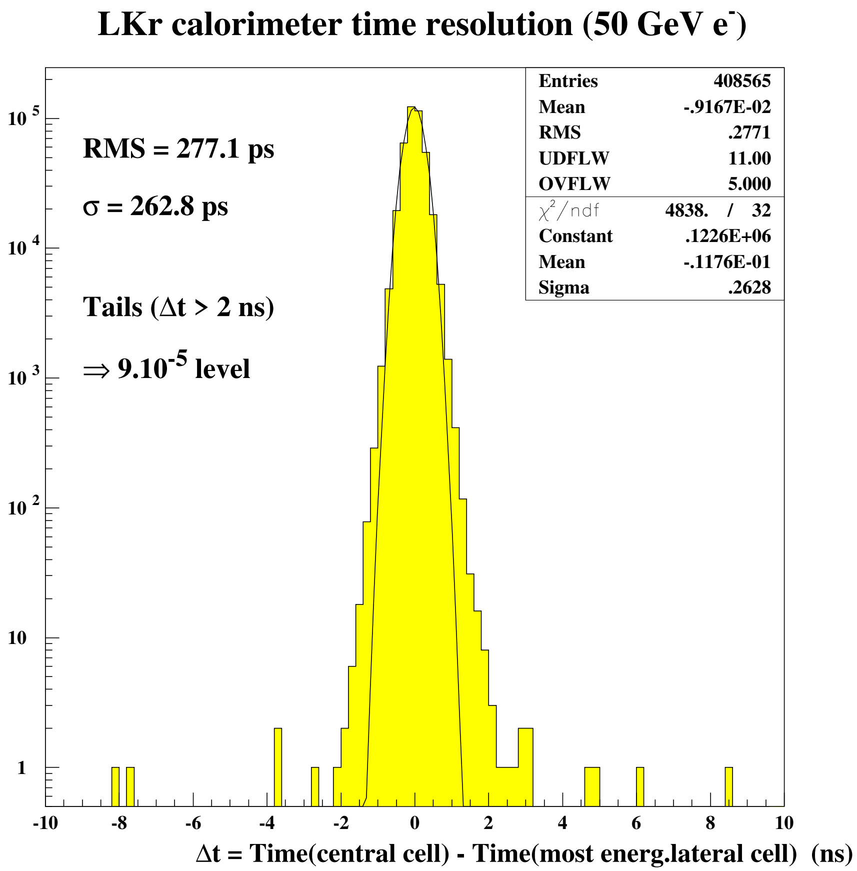
- K_S are distinguished from K_L by tagging the protons upstream of the K_S target
- NA48 detects all four modes concurrently and within the same fiducial region

The NA48 LKR Calorimeter

Homogeneous calorimeter made of $\approx 10m^3$ of liquid Krypton and Cu-Be-Co readout electrods ($\approx$13000 cells 2cm$\times$2cm$\times$127cm).

The NA48 calorimeter Performances





No tails: mandatory to distinguish K_S to K_L

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{100MeV}{E} \oplus 0.5\%$$

Identification of $\pi^+\pi^-$ modes

In both Experiments

- Both experiments use a spectrometer made of a magnet and four wire chambers
- Using spectrometer information one can reconstruct decaying particle's vertex position, mass and momentum.

	KTeV	NA48
P_T Kick	400MeV/c	250MeV/c
$\pi^+\pi^-$ mass Resolution	1.6MeV	2.2MeV

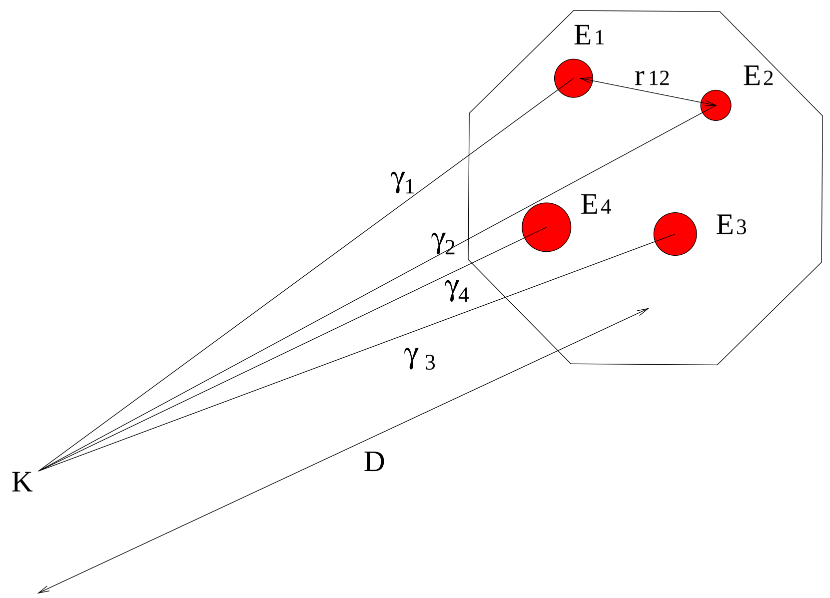
- $K_{\mu 3}$ background is rejected by muon vetoes
- K_{e3} background is rejected using E/P
- A P_T cut rejects signal-like 3-body background and scattered events
- After all, one has to evaluate the remaining background under the signal region

Identification of $\pi^0\pi^0$ modes

In both Experiments

- $K \rightarrow \pi^0\pi^0$ are reconstructed using energies and position of the four photons in the calorimeter.
- KTeV reconstructs the Kaon Mass and Vertex decay.
- NA48 reconstructs π^0 Mass and Kaon Vertex decay.
- Both experiments compute a χ^2 representing the event compatibility with a $2\pi^0$ final state.
- The $3\pi^0$ background with fused or lost photons is located in the tails of the χ^2 distribution which are cut-out.
- After all, one has to evaluate the remaining background under the signal region.

Example: The NA48 case

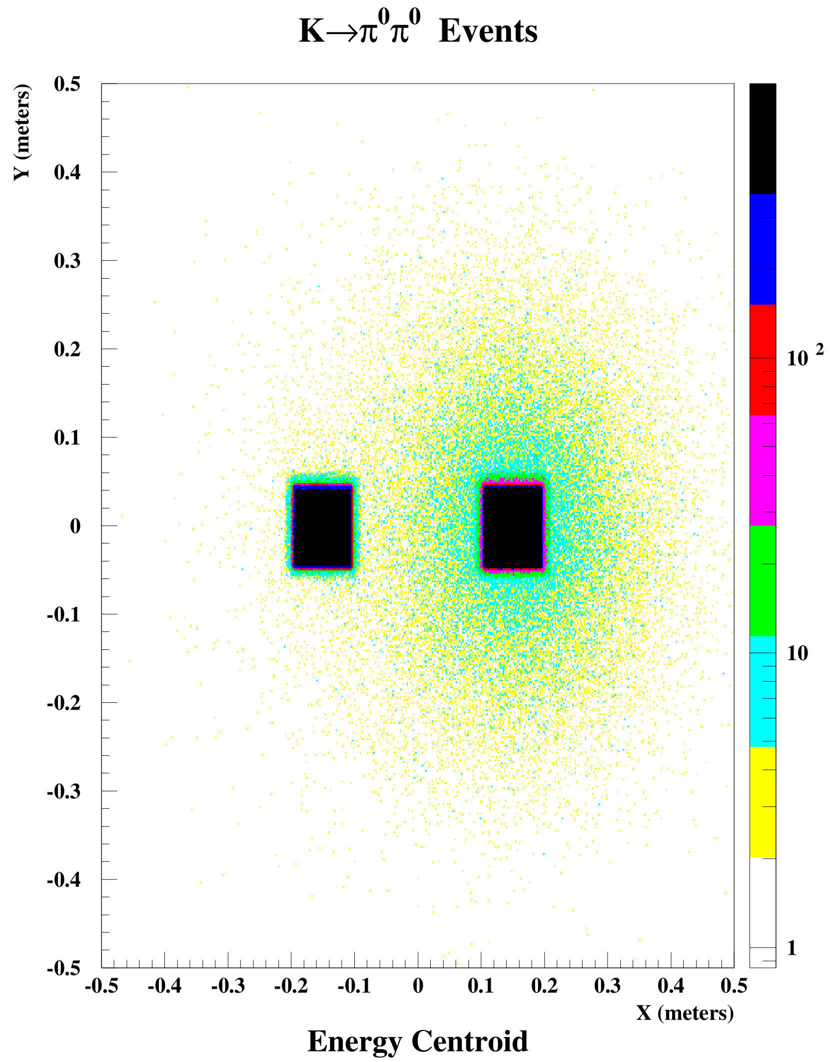


$$D = \sqrt{\sum E_i E_j \times r_{ij}^2} \,/ M_K \qquad m_{ij} = \sqrt{E_i E_j r_{ij}^2} / D$$

Distinguishing a K_L from a K_S decay in KTeV

Reminder: Vacuum and regenerated beams are parallel

- Charged decays: From the reconstructed X-Y position of the Vertex, the Beam origin is unambiguous (10cm between the two beam holes).
- Neutral Decays: K_L and K_S are separated using the Centre of Gravity (Energy Centroid) in the Calorimeter.

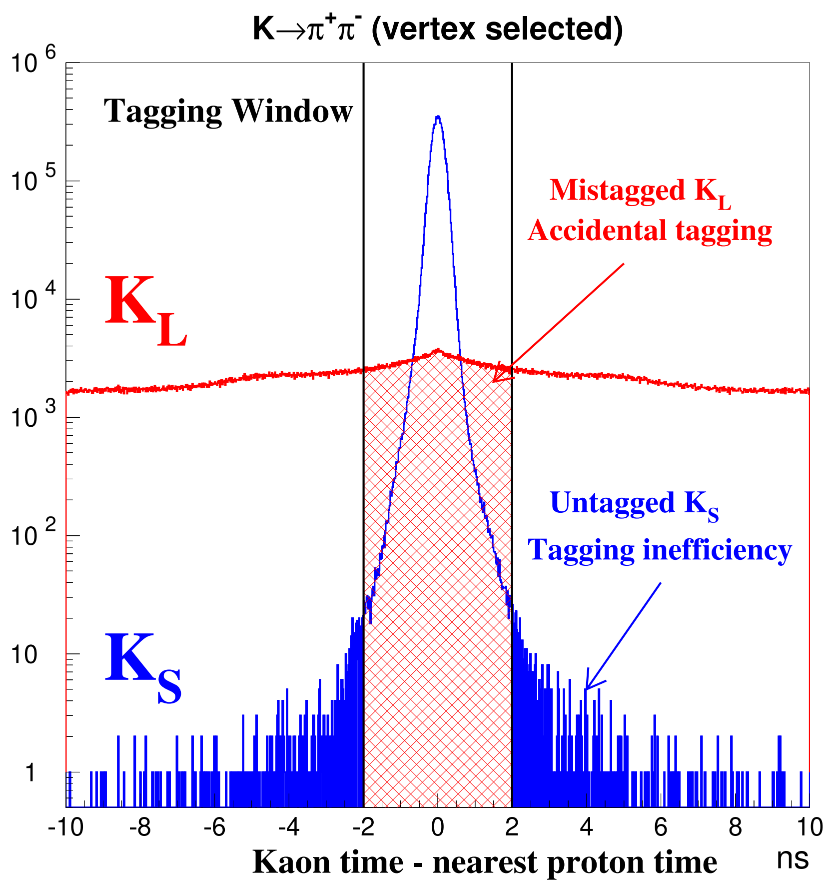


Particular care to treat scattered events

Distinguishing a K_L from a K_S decay in NA48

Time Coincidences between Event Time and nearest K_S proton in Tagger, for both charged and neutrals.

Example: Tagging Charged Events (1998 data)

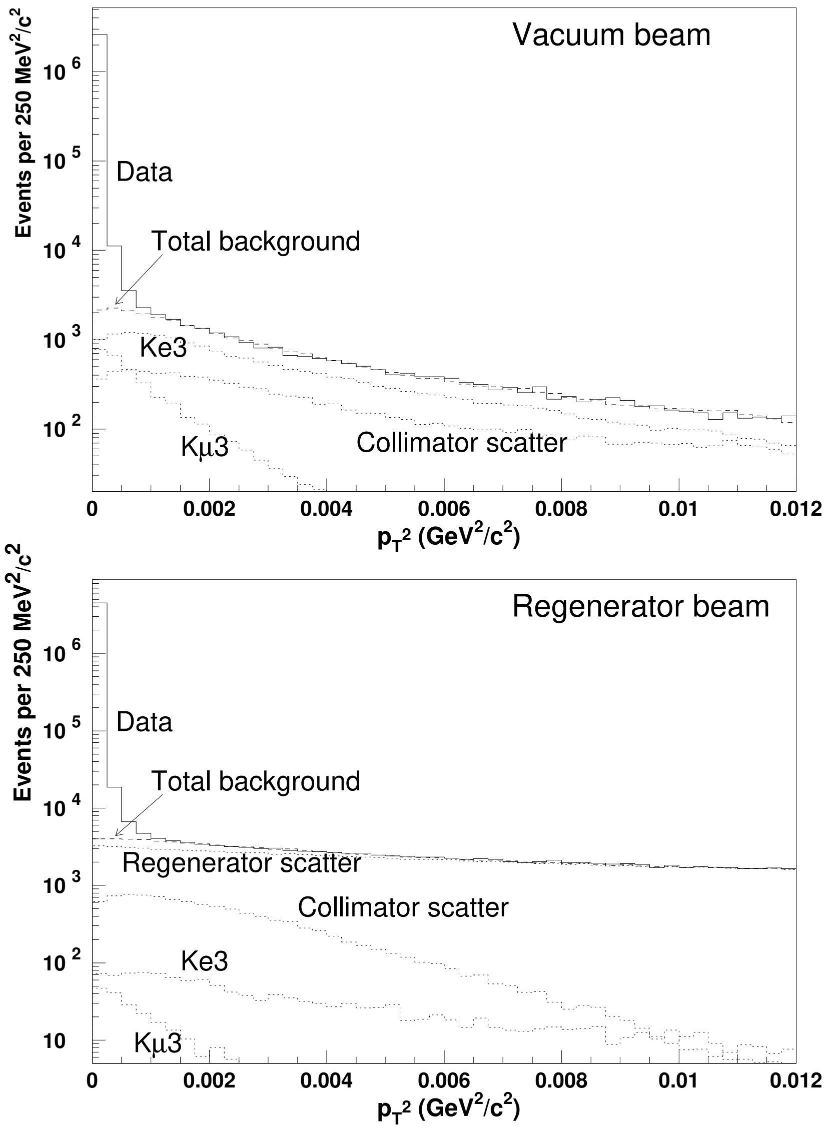


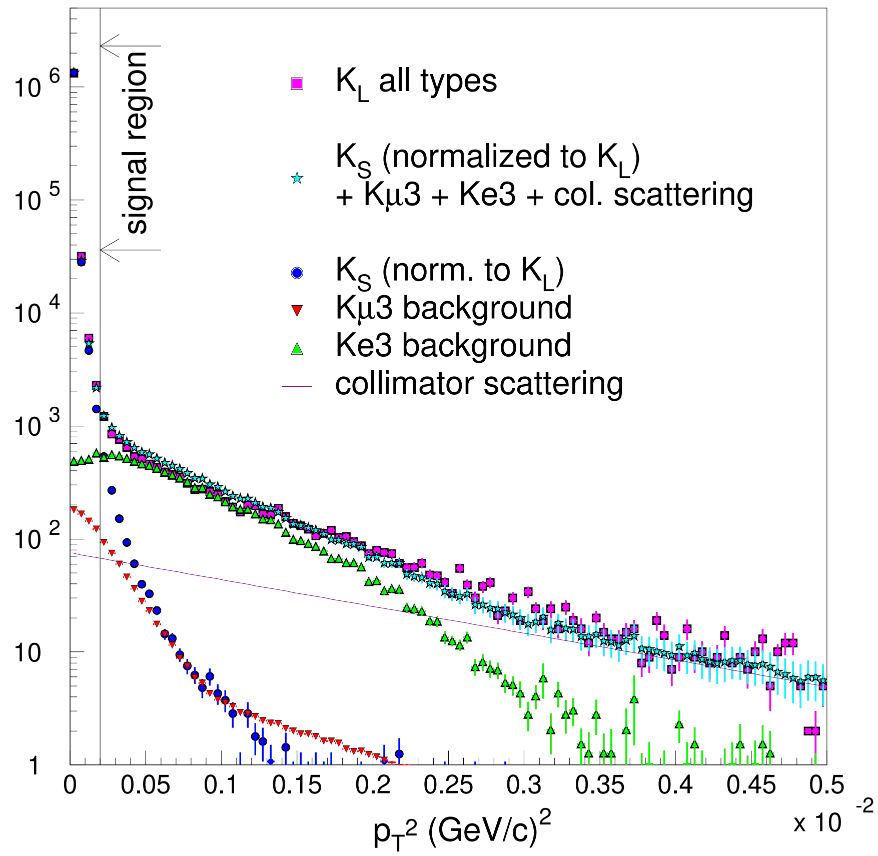
Tagging Inefficiency : $\alpha^{+-}_{SL} = (1.97 \pm 0.05) \times 10^{-4}$

K_L misstagged as K_S : $\alpha^{+-}_{LS} = (11.05 \pm 0.01)\%$

More analysis to measure α^{00}_{SL} and α^{00}_{LS}

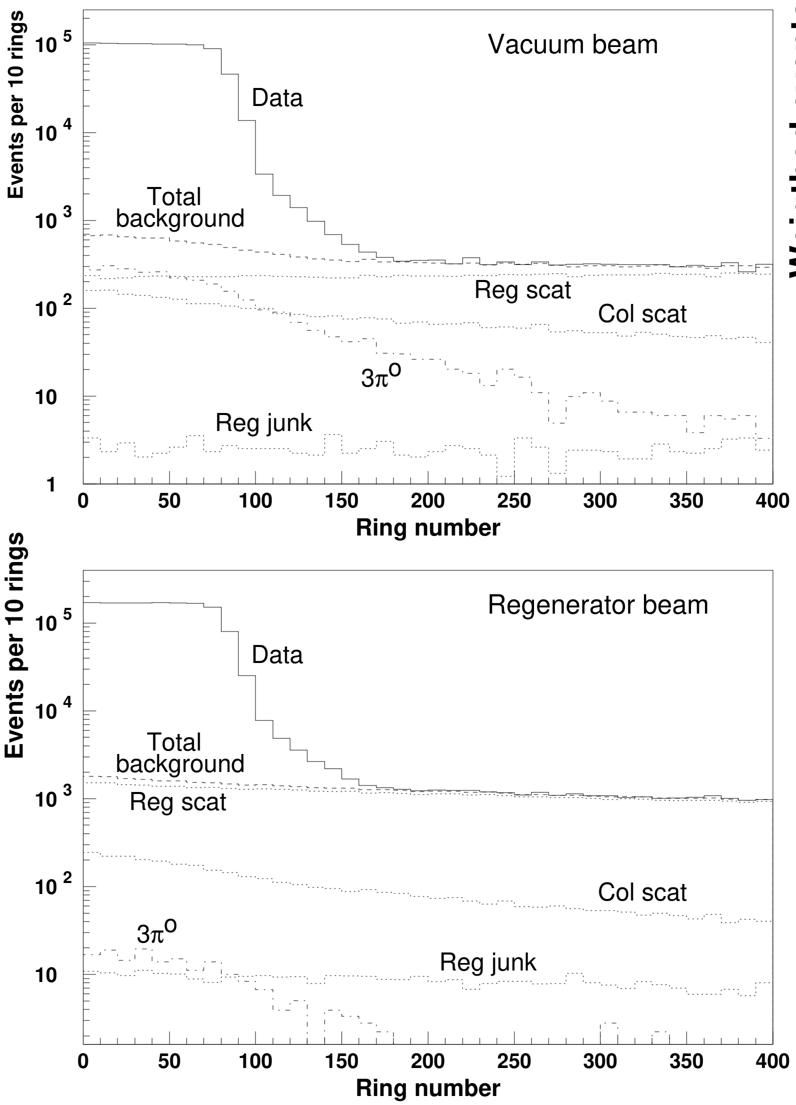
Charged Background in KTeV and NA48

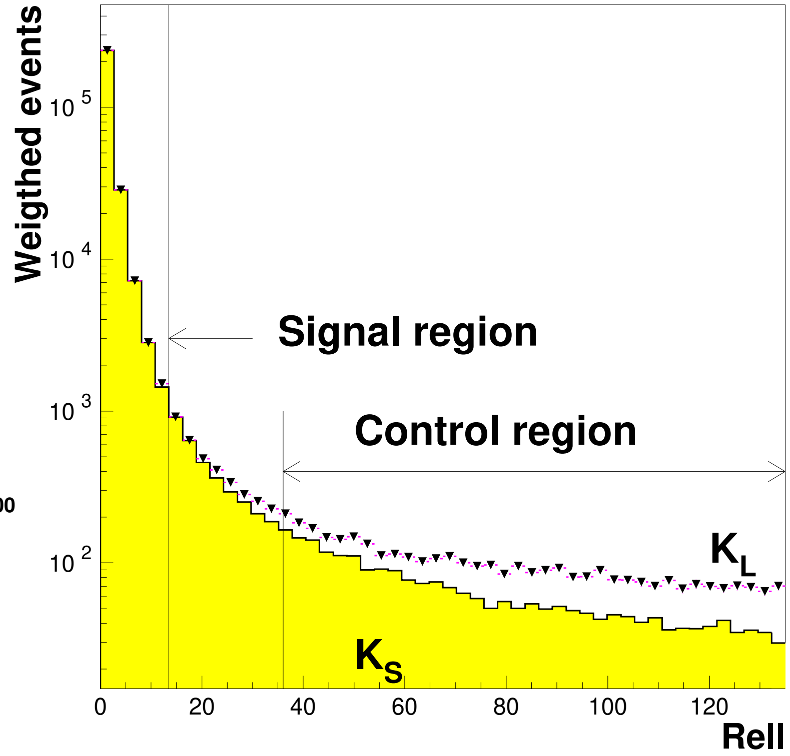




$\Leftarrow$ KTEV $\Uparrow$ NA48

Neutral Background in KTeV and NA48





⇐ KTEV ⇑ NA48

Remaining Backgrounds in KTeV and NA48

ORIGINS: 3 Body decays and Beam construction and collimation.

Under K$\rightarrow \pi^+\pi^-$ signal

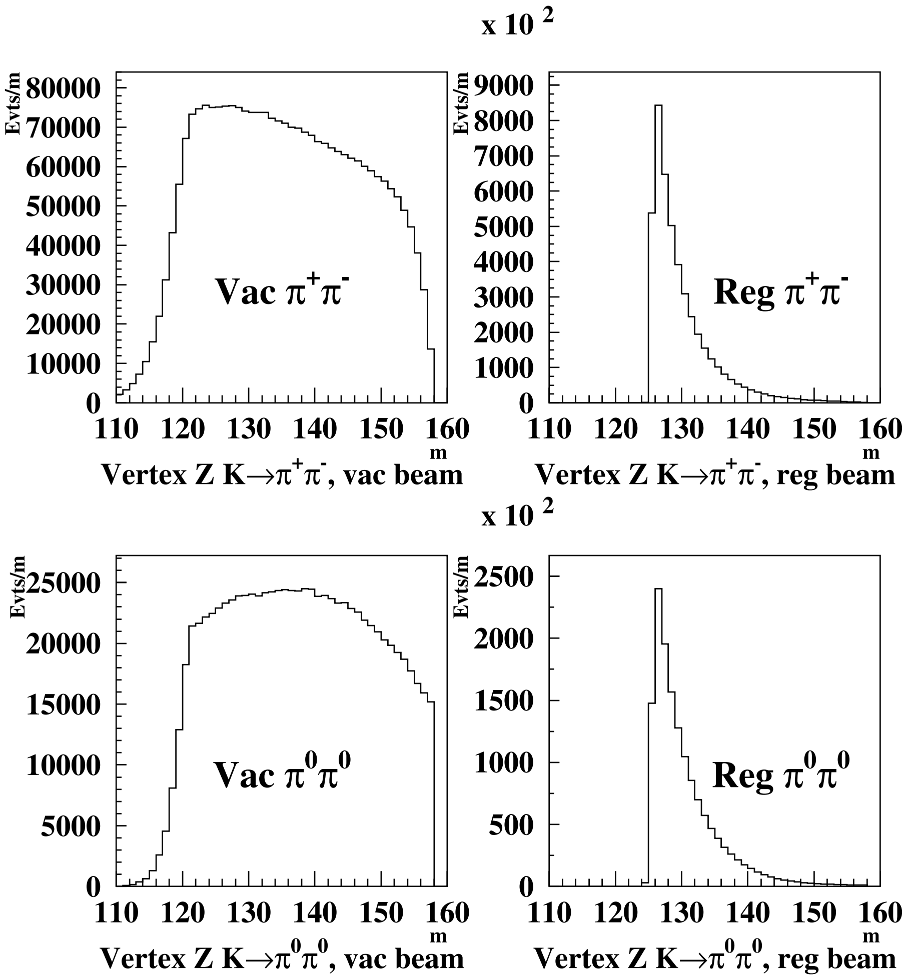
Background source	KTeV Vacuum	KTEV Regener.	NA48
K_{e3} +$K_{\mu 3}$	0.69×10^{-3}	0.03×10^{-3}	1.9×10^{-3}
Scatt. in Collimator	0.14×10^{-3}	0.14×10^{-3}	-
Scatt. in Regenerator	-	0.73×10^{-3}	-
TOTAL	0.83×10^{-3}	0.89×10^{-3}	$1.9\ \times10^{-3}$

Under K$\rightarrow \pi^0\pi^0$ signal

Background source	KTeV Vacuum	KTeV Regener.	NA48
$K_L \rightarrow 3\pi^0$	2.7×10^{-3}	0.1×10^{-3}	0.66×10^{-3}
Scatt. in Collimator	1.5×10^{-3}	1.4×10^{-3}	1.2×10^{-3}
Scatt. in Regenerator	3.0×10^{-3}	10.7×10^{-3}	-
Regenerator junk	-	0.1×10^{-3}	
TOTAL	7.3×10^{-3}	12.2×10^{-3}	1.86×10^{-3}

KTeV Acceptance to four modes

Reconstructed Vertex Z Distributions

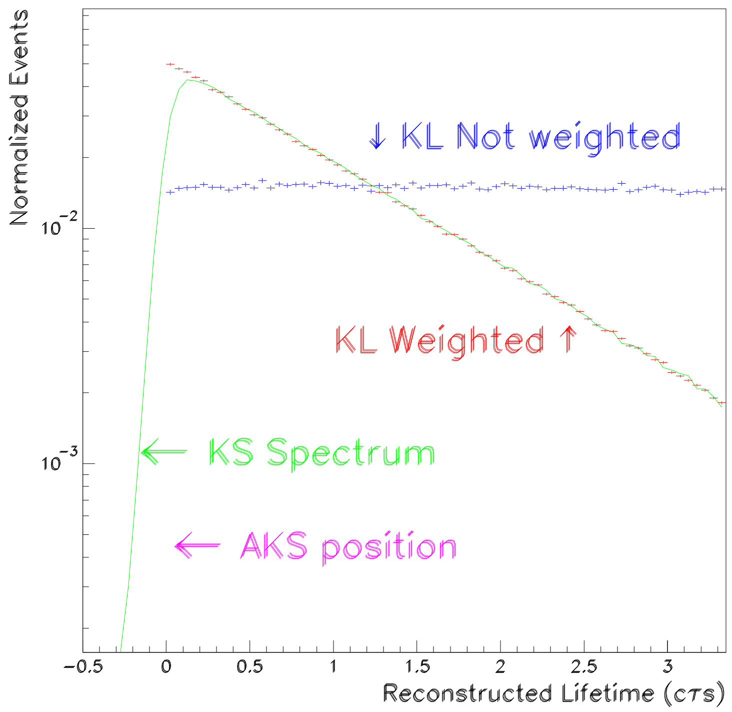


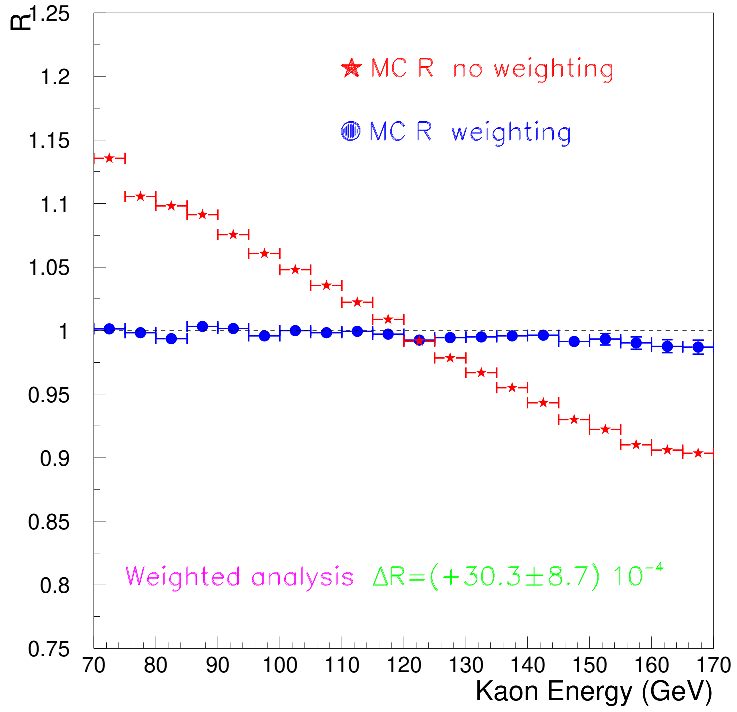
Data Sample	Average Acceptance
Vacuum (K_L) Beam $\to \pi^+\pi^-$	23.13%
Regenerated (K_S) Beam $\to \pi^+\pi^-$	30.77%
Vacuum (K_L) Beam $\to \pi^0\pi^0$	10.36%
Regenerated (K_S) Beam $\to \pi^0\pi^0$	13.05%
Acceptance Correction on R	5.5%

Titanesque simulation work to well constraint the acceptance correction

NA48 Acceptance to four modes

Fiducial Volume : 70GeV<Energy<170GeV and <3.5lifetimes in τ_S units.
NA48 weights K_L events by the reconstructed K_S lifetime to minimize K_L K_S decay spectra difference





Weighting minimizes the acceptace correction down to 0.3%. Price to pay: 35% decrease of the statistical accuracy on R

Fitting R in KTeV

After background subtraction, one has four decay distributions
Vacuum beam ($\pi^0\pi^0$ and $\pi^+\pi^-$) and
Regenerator Beam ($\pi^0\pi^0$ and $\pi^+\pi^-$).

- Decay distributions are corrected for acceptance using a Very Detailed Monte Carlo Simulation

  $\Rightarrow$ Full Kaon evolution and regeneration

  $\Rightarrow$ Complete simulation of trigger, detector resolutions, inefficiencies and precise acceptance apertures.

  $\Rightarrow$ Acceptance is calculated in small bins (2GeV$\times$2m) to minimize corrections.

- The MC corrected data distributions are fitted in 10GeV bins with no Z binning.
- Several parameters come out of the fit, among them $\mathrm{Re}(\varepsilon'/\varepsilon)$.
- The analysis remained blind until the end of the systematic studies

N.B. Because of L3 trigger inefficiency during 1996 data taking, KTeV used for its first result Neutrals from 1996 and Charged from 1997 run. This implied some additional systematic checks

Fitting R in NA48

After background subtraction, one has four decay distributions, of
Tagged $\pi^0\pi^0$ and $\pi^+\pi^-$ modes (with $\pm$2ns coincidence with a proton in tagger) and
Weighted Untagged $\pi^0\pi^0$ and $\pi^+\pi^-$ (without any proton in tagger within $\pm$2ns)

- Correct for the misstagging fraction of K_L both Tagged and Untagged samples.
- Correct for trigger inefficiencies.
- Compute acceptance correction for R in 20 bins of 5GeV.
- Combine the 20 values using an unbiased estimator.

REMARK: Both experiments fit the double ratio in Energy Bins.

$$\Downarrow$$

!! This requires the knowledge of the energy scale!!

The Neutral Energy Scale Problem

In both Experiments

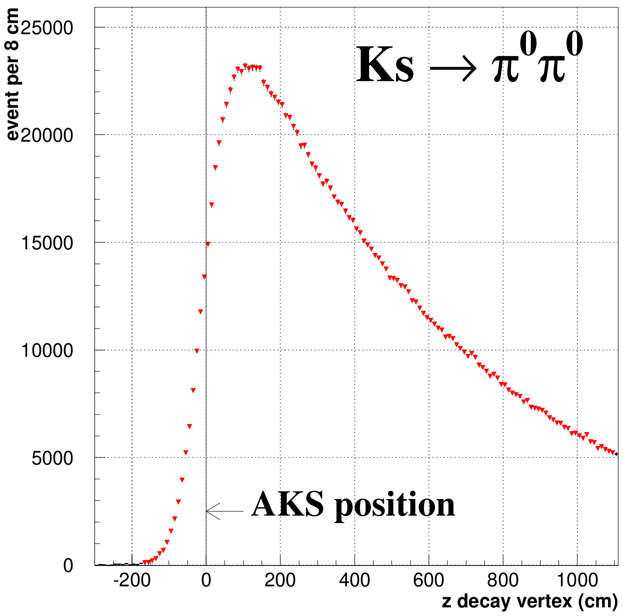
From reconstruction:

A shift on energy in the calorimeter translates to an apparent decay vertex displacement.

Idea!! $\Rrightarrow$ Follow the reconstructed position of a known geometrical object.

- Regenerator edge in KTeV
- K_S Anticounter in NA48

What matters for $\mathrm{Re}(\varepsilon'/\varepsilon)$ is the following-up and the precision on energy scale knowledge



Sensitivity: 0.1% on energy scale $\rightarrow \approx 10^{-4}$ on $\mathrm{Re}(\varepsilon'/\varepsilon)$

Size of some corrections on R in KTeV and NA48

N.B. : Divide by 6 to get effects on $\mathrm{Re}(\varepsilon'/\varepsilon)$!!

Origin of corrections	KTev $\times 10^{-4}$	NA48 (1998 data)$\times 10^{-4}$
Charged Trigger	± 3.0	-1.4$\pm$11.5
Neutral Trigger	± 1.8	-
$K_{e3} + K_{\mu 3}$	6.6$\pm$(*)	+19$\pm$3.0
Charged Scattering	-7.2$\pm$(*)	-
$3\pi^0$	-26.0$\pm$(**)	-6.6 $\pm$2.0
Neutral Scattering	+75.0$\pm$(**)	-9.9$\pm$3.0
Acceptance Correction	$\approx$-550$\pm$13.4	+31.1$\pm$8.7
Ch. Energy Scale	0$\pm$0.7	+2$\pm$2.
Neut. Energy Scale	0$\pm$5.5	0$\pm$ 10.2
Tagging Correction	-	+0.6$\pm$9
Accidental effects	***	+2$\pm$12.2
Additional corrections	± 6.3	-
Total Correction on R	$\approx$-500$\pm$16.7(syst)	36.8$\pm$23.8 (syst ****)

(*) Sum of (*)=1.2
(**) Sum of (**)=4.8
(***) Included in acceptance correction
(****) A large part of the error is statistically limited

Recent results of KTeV and NA48

- KTEV
  - 96 Result published (Phys.Rev.Lett.83,22-27,1999)

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (28.0\pm3(\mathrm{stat})\pm2.8(\mathrm{syst}))\times10^{-4}}$$

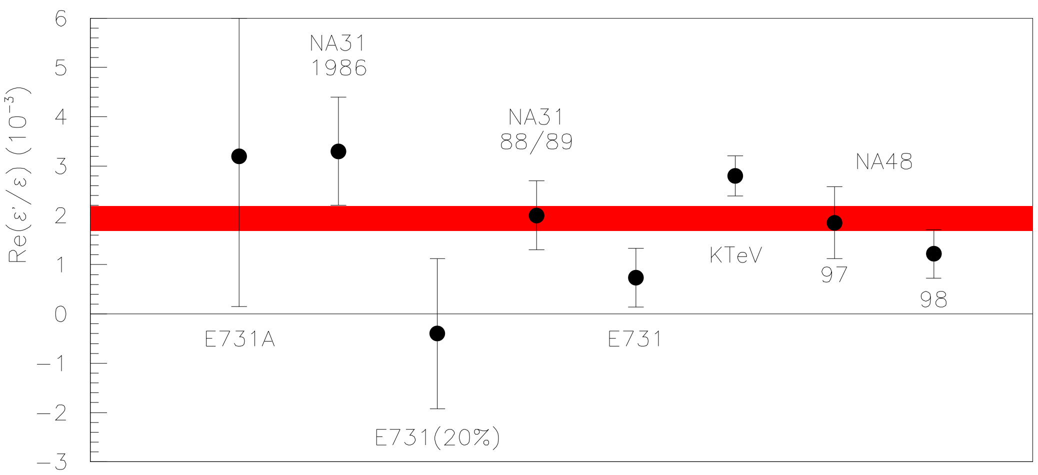
- NA48 :
  - 1997 Result published (Phys.Lett.B,465,335-348,1999)
    $\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5\pm4.5(\mathrm{stat})\pm5.8(\mathrm{syst}))\times10^{-4}$
  - Preliminary 1998 Result:
    $\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2\pm2.9(\mathrm{stat})\pm4.0(\mathrm{syst}))\times10^{-4}$
  - Combined 1997+1998 result:

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0\pm4.3)\times10^{-4}}$$

New World average result:

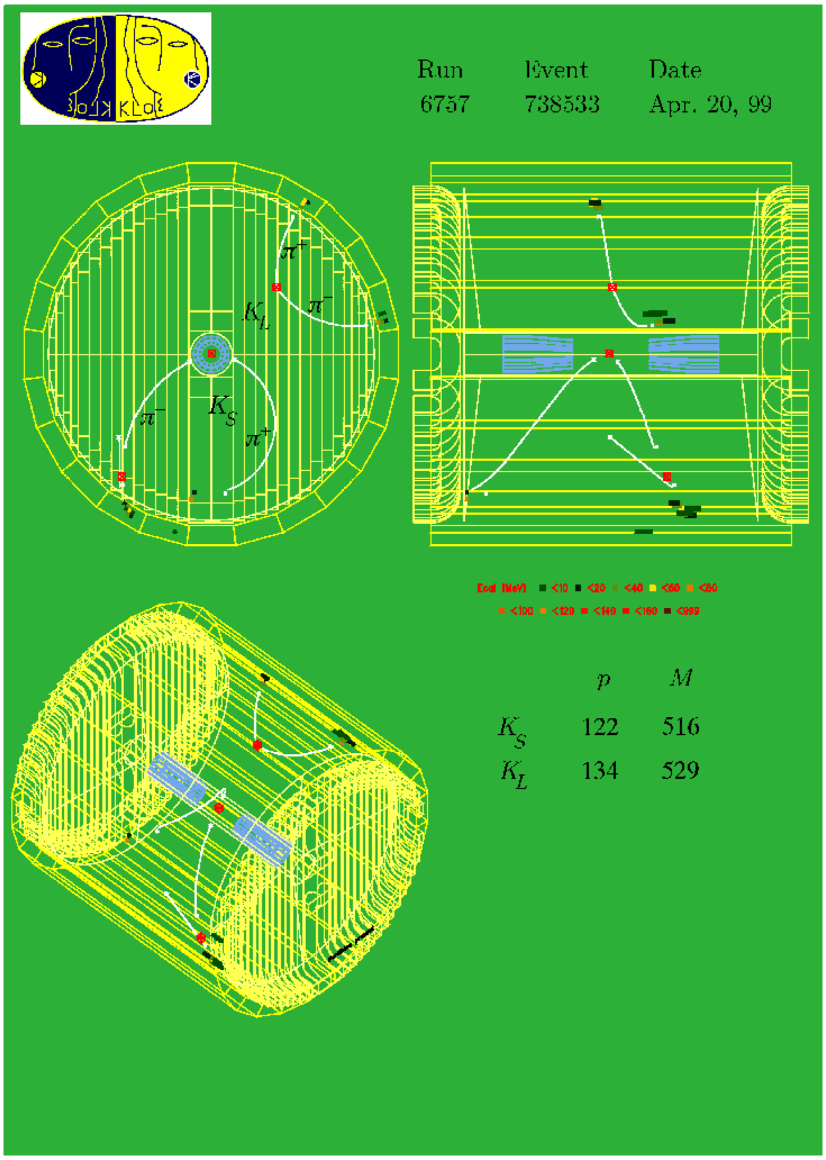
$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (19.4\pm2.5)\times10^{-4}} \quad \chi^2=10.4/3$$

Comparison of most recent results on $\mathrm{Re}(\varepsilon'/\varepsilon)$



The KLOE experiment

- Located in DAΦNE rings cross point.
- Low Energy: $e^+e^- \to \Phi$. Then $\Phi \to \mathrm{K_L\ K_S}$ in 34%.
- Started taking data in 1999
- Two methods to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$. Different environement and systematics



Conclusions

- The existence of important Direct CP Violation is confirmed, but its precise amount is still controversial
  - KTeV : $\mathrm{Re}(\varepsilon'/\varepsilon) = (28.0 \pm 4.1) \times 10^{-4}$
  - NA48 : $\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0 \pm 4.3) \times 10^{-4}$
  - World Av. : $\mathrm{Re}(\varepsilon'/\varepsilon) = (19.4 \pm 2.5) \times 10^{-4}$

    Means that :

$$\frac{K^0 \to \pi^+\pi^- - \overline{K}^0 \to \pi^+\pi^-}{K^0 \to all} = (8.6 \pm 1.1) \times 10^{-6}$$

- The analysis of the KTeV and NA48 complete data sets will bring more information, with more systematic checks and much higher statistics
- Because of its different method first KLOE result is expected with excitement
- While Direct CP Violation looks larger than expected, it couldn't explain the Matter-Antimatter asymmetry observed in the Universe.
- Extending CP Violation study in other systems we will certainly learn more about
- All constraints together might give an hint about an eventual stronger Violation in higher scales

Checks on result Stability in KTeV and NA48