The experimental status of ϵ'/ϵ

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Outline

- CP violation: indirect and direct
- Detectors and beam lines
- Data analysis
- Conclusions

Direct and Indirect CP violation

Kaon Eigenstates — CP value

Strong Eigenstates: $\bar{K}^0 (\bar{d}s)$ $K^0 (d\bar{s})$

CP Eigenstates:

$K_1 = (\bar{K}^0 + K^0)$ +1

$K_2 = (\bar{K}^0 - K^0)$ −1

Mass Eigenstates:

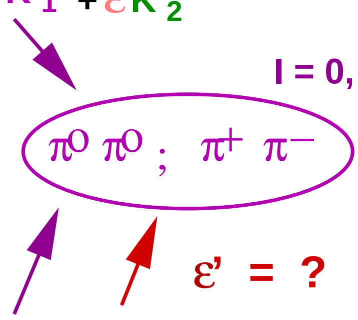
$K_S = K_1 + \varepsilon K_2$ Almost +1

$K_L = \varepsilon K_1 + K_2$ Almost −1

Direct and Indirect CP violation

$K_S = K_1 + \varepsilon K_2$

I = 0, 2



CP = +1

$\varepsilon' = ?$

$K_L = \varepsilon K_1 + K_2$

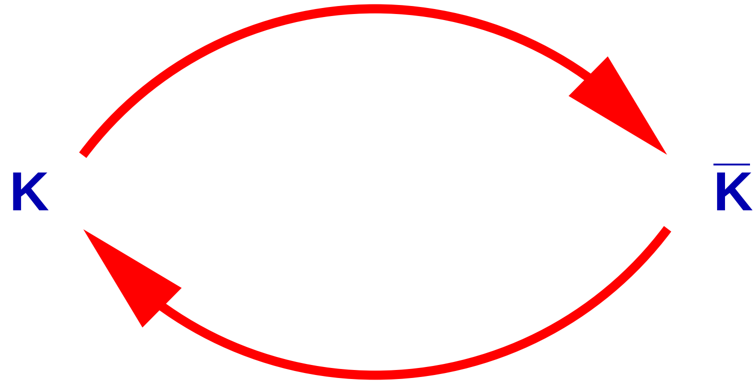
ε = Indirect CP violation (in mixing)

ε = 0.3 %

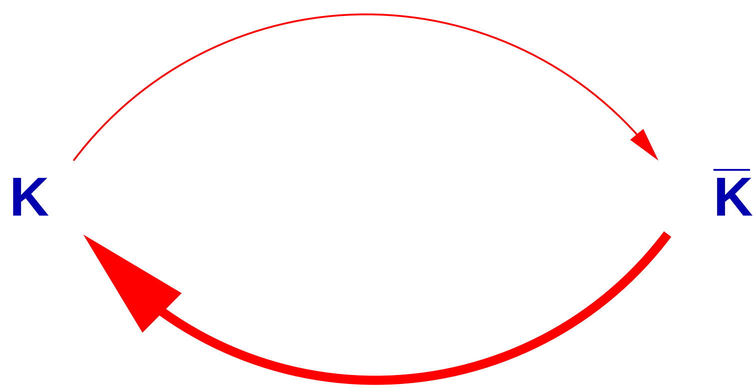
ε' = Direct CP violation (in Decay)

Indirect CP violation

The $K, \bar{K}$ particles mix. This property is independent of CP.



Indirect CP violation, i.e. CP violation in mixing, causes the mixing to be asymmetric:

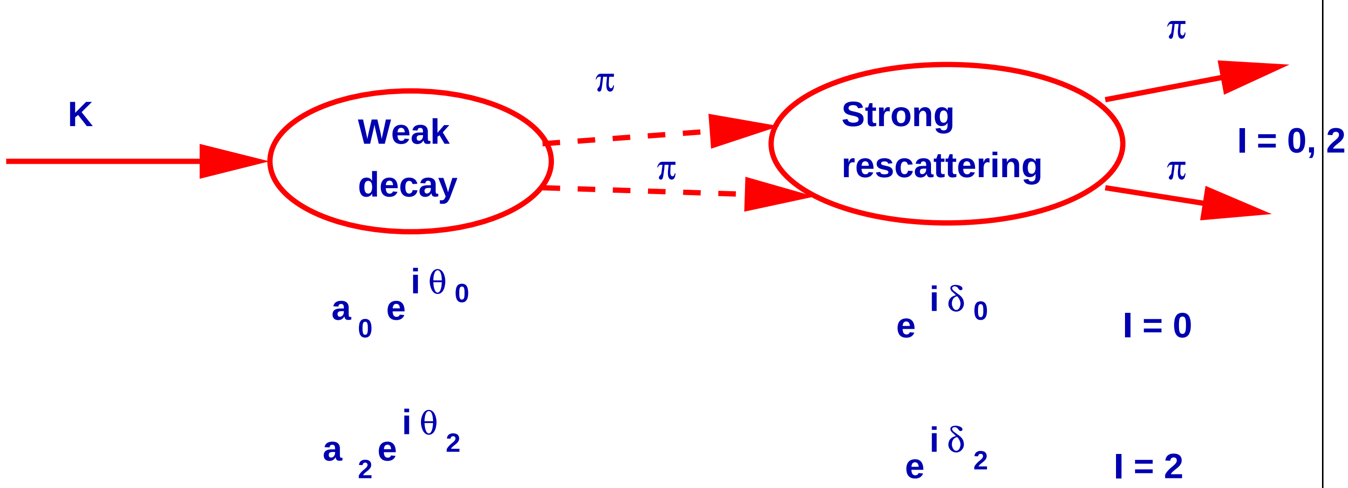


$$|\epsilon_K| = (2.28 \pm 0.013) \cdot 10^{-3}$$

$\bar{K} \to K$ preferred over $K \to \bar{K}$

Direct CP violation

In the decay $K \to \pi\pi$ the 2 pions can have isospin I=0,2. The phase difference of these two channels determines direct CP violation



$$\epsilon'_K = \frac{i}{\sqrt{2}} e^{i(\delta_2 - \delta_0)} \left|\frac{a_2}{a_0}\right| sin(\theta_2 - \theta_0)$$

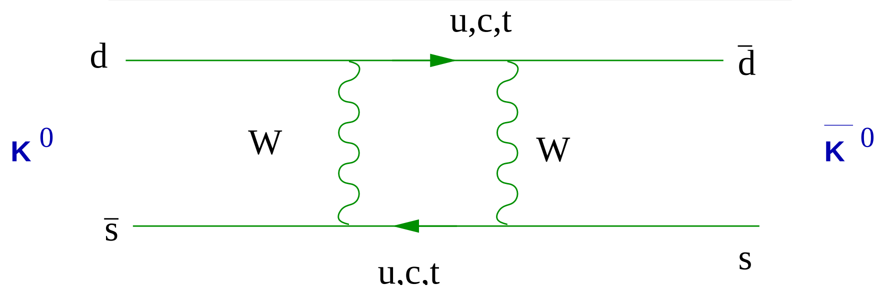
If *Re* $\epsilon' \neq 0$ then the decay amplitude of $\bar{K}, K \to \pi\pi$ is different:

$$K \to \pi\pi \neq \bar{K} \to \pi\pi$$

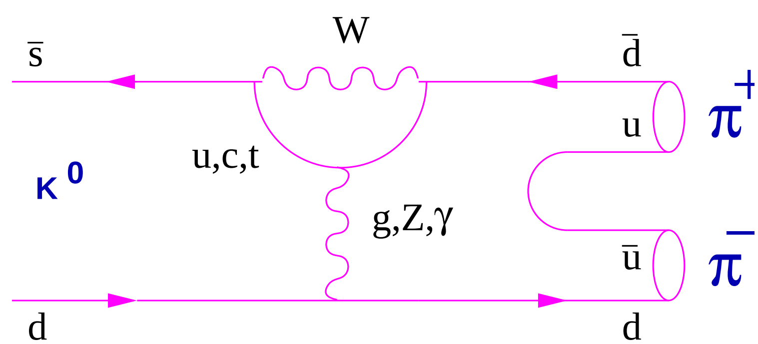
ϵ and ϵ' in the Standard Model

$\rightarrow$ complex phase in the quark mixing matrix:

Box diagram: $\Delta S = 2 \rightarrow \epsilon$



Penguin diagram: $\Delta S = 1 \rightarrow \epsilon'$



$$\mathrm{Re}(\frac{\epsilon'}{\epsilon}) \propto |\mathrm{V_{ub}V_{cb}}|\eta[\frac{1}{\mathrm{m_s}}]^2(\mathrm{B_6} - \mathrm{c}\cdot\mathrm{B_8})$$

Methods

- Large N approach
- Lattice
- Chiral Quark Model
- .....

Results

$\rightarrow$ Very difficult!!

$Re(\frac{\epsilon'}{\epsilon}) = 0 - 60 \cdot 10^{-4}$

How to measure $Re(\frac{\epsilon'}{\epsilon})$

Consider:

- $K_S \rightarrow \pi\pi$, CP conserving decay
- $K_L \rightarrow \pi\pi$, CP violating decay

It's possible to show that:

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

So we need to perform a counting experiment:

$$\mathrm{R} = \frac{N(\mathrm{K_L}\rightarrow\pi^0\pi^0)}{N(\mathrm{K_S}\rightarrow\pi^0\pi^0)} / \frac{N(\mathrm{K_L}\rightarrow\pi^+\pi^-)}{N(\mathrm{K_S}\rightarrow\pi^+\pi^-)}$$

and to correct for all possible biases of the counting process (acceptance, trigger, noise..)

The limiting mode is $K_L \rightarrow \pi^o\pi^o$:

$$\mathrm{R} = \frac{\Gamma(\mathrm{K_L}\rightarrow\pi^0\pi^0)=0.0009}{\Gamma(\mathrm{K_S}\rightarrow\pi^0\pi^0)=0.314} / \frac{\Gamma(\mathrm{K_L}\rightarrow\pi^+\pi^-)=0.002}{\Gamma(\mathrm{K_S}\rightarrow\pi^+\pi^-)=0.686}$$

Past and Present of $Re(\frac{\epsilon'}{\epsilon})$

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1993:

NA31 $= 23 \pm 6.5$ | **E731 $= 7.4 \pm 5.9$**

Better experiments needed!

2001:

NA48 $= \ldots \pm \ldots$ | **KTeV $= \ldots \pm \ldots$**

Word Average $Re(\frac{\epsilon'}{\epsilon}) = \ldots \pm \ldots \times 10^{-4}$

Data needed for $Re(\frac{\epsilon'}{\epsilon}) = \pm 2 \cdot 10^{-4}$

Several millions $K_L \to \pi^o\pi^o$ are needed to achieve the required accuracy. For example:

NA48 data set (ml)			
$K_L \to \pi^0\pi^0$	3.29	$K_L \to \pi^+\pi^-$	14.45
$K_S \to \pi^0\pi^0$	5.21	$K_S \to \pi^+\pi^-$	22.22

(KTeV has $\sim$ 10 ml $K_L \to \pi^o\pi^o$!)

Statistical error on $Re(\frac{\epsilon'}{\epsilon})$: 1.7 $\times 10^{-4}$

A gigantic amount of data is needed to control systematics, taken with very stable and fast data acquisition system.

Raw data taken:

- D0, RUN I (four years) $\sim$ 40 TB
- ZEUS RUN I $\sim$ 30 TB
- BABAR $\sim$ 50 TB
- NA48 $\sim$ 170 TB

For NA48, only ~ 100 events out of $\sim 16k$ triggers are good $\pi\pi$ modes, the rest is to control the systematic errors.

If you had missed 10^{-4} $K_L \to \pi^o\pi^o$ $Re(\frac{\epsilon'}{\epsilon})$ would be wrong by 1.6 $\times 10^{-4}$

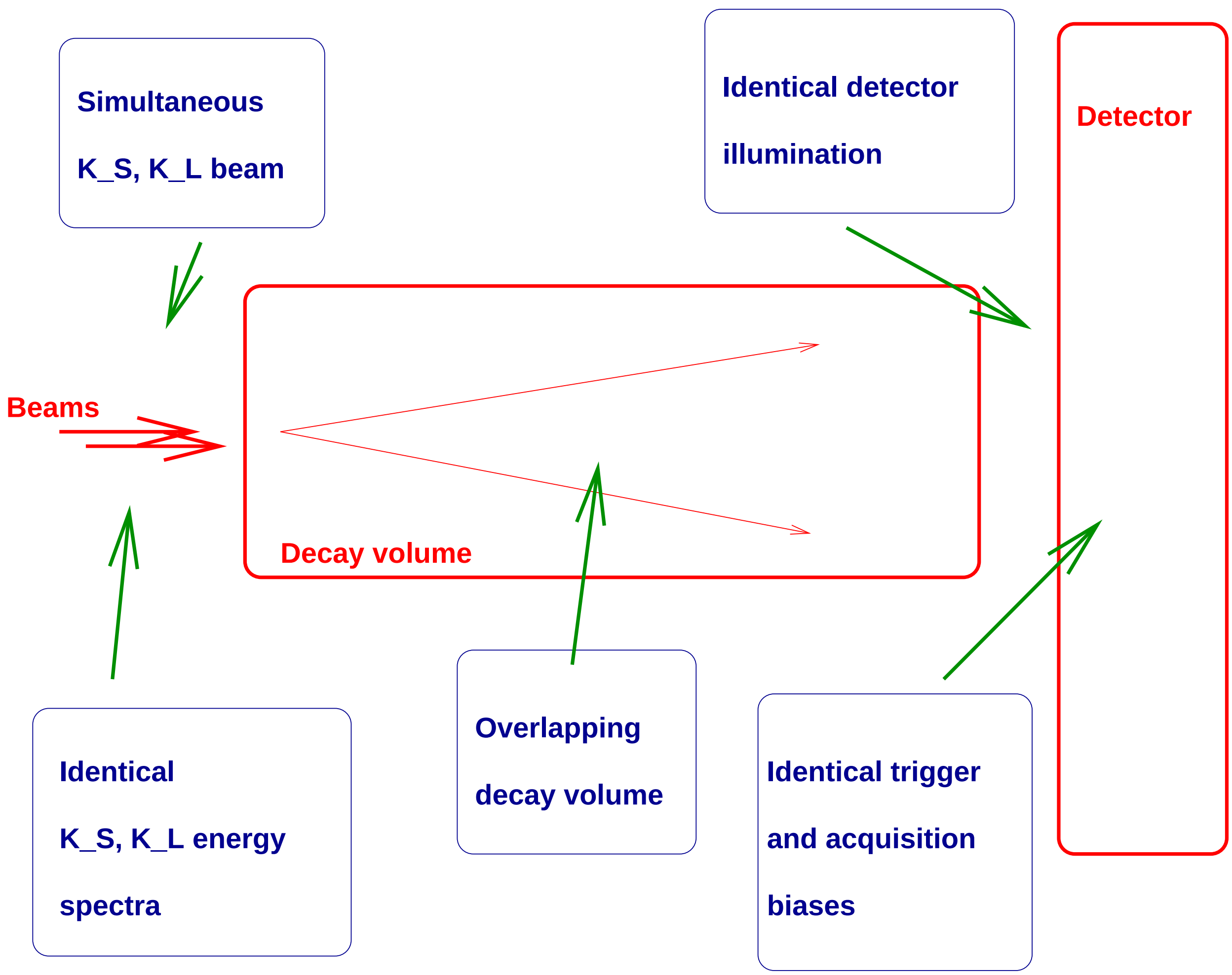
Experimental method

Consider:

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\ Re(\frac{\epsilon'}{\epsilon})$$

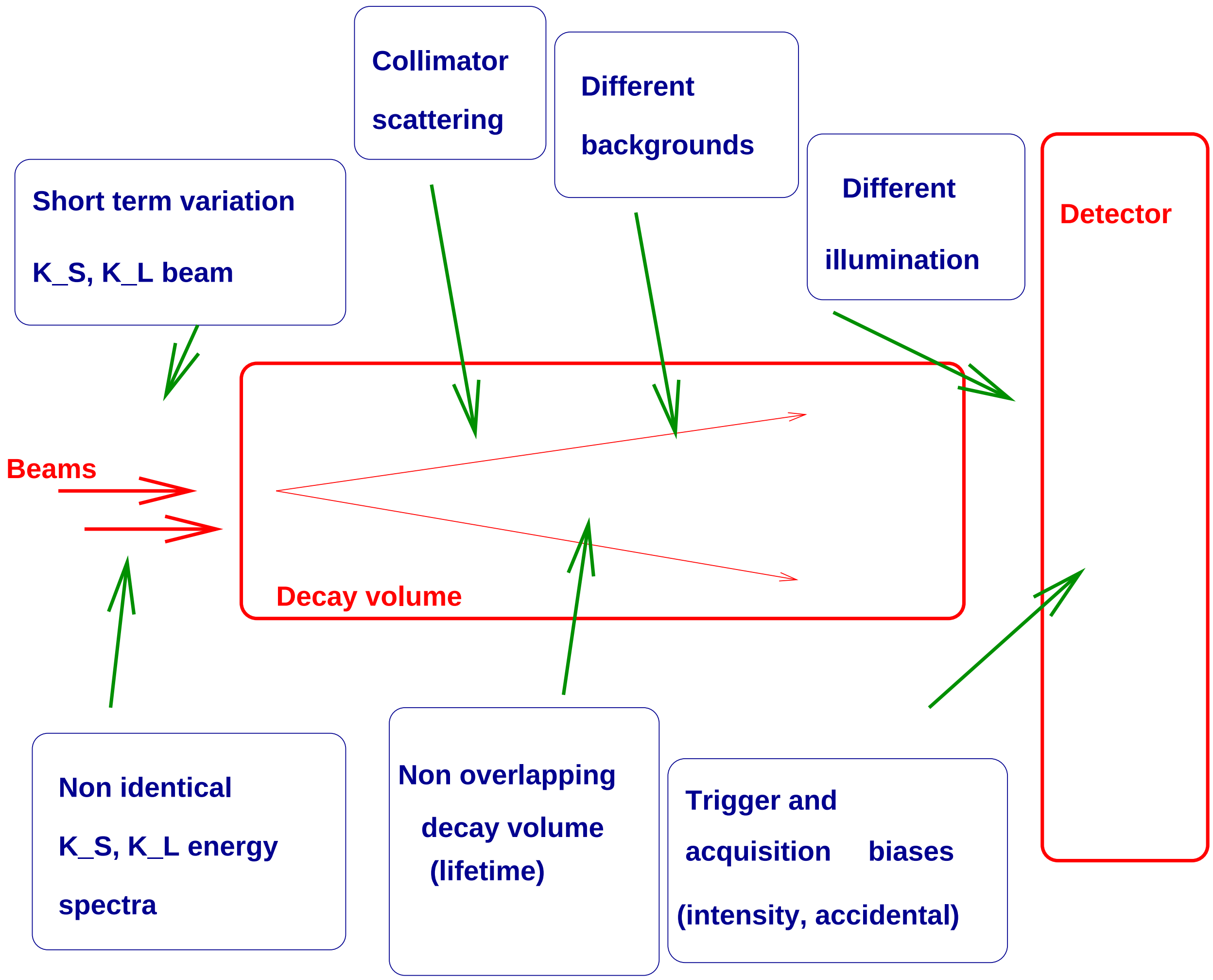
To reach a precision of $\sim 2 \cdot 10^{-4}$ on $Re(\frac{\epsilon'}{\epsilon})$ you can exploit the cancellations of the double beam method where for perfectly overlapping and concurrent beams the corrections are minimized!

Ideal detector:

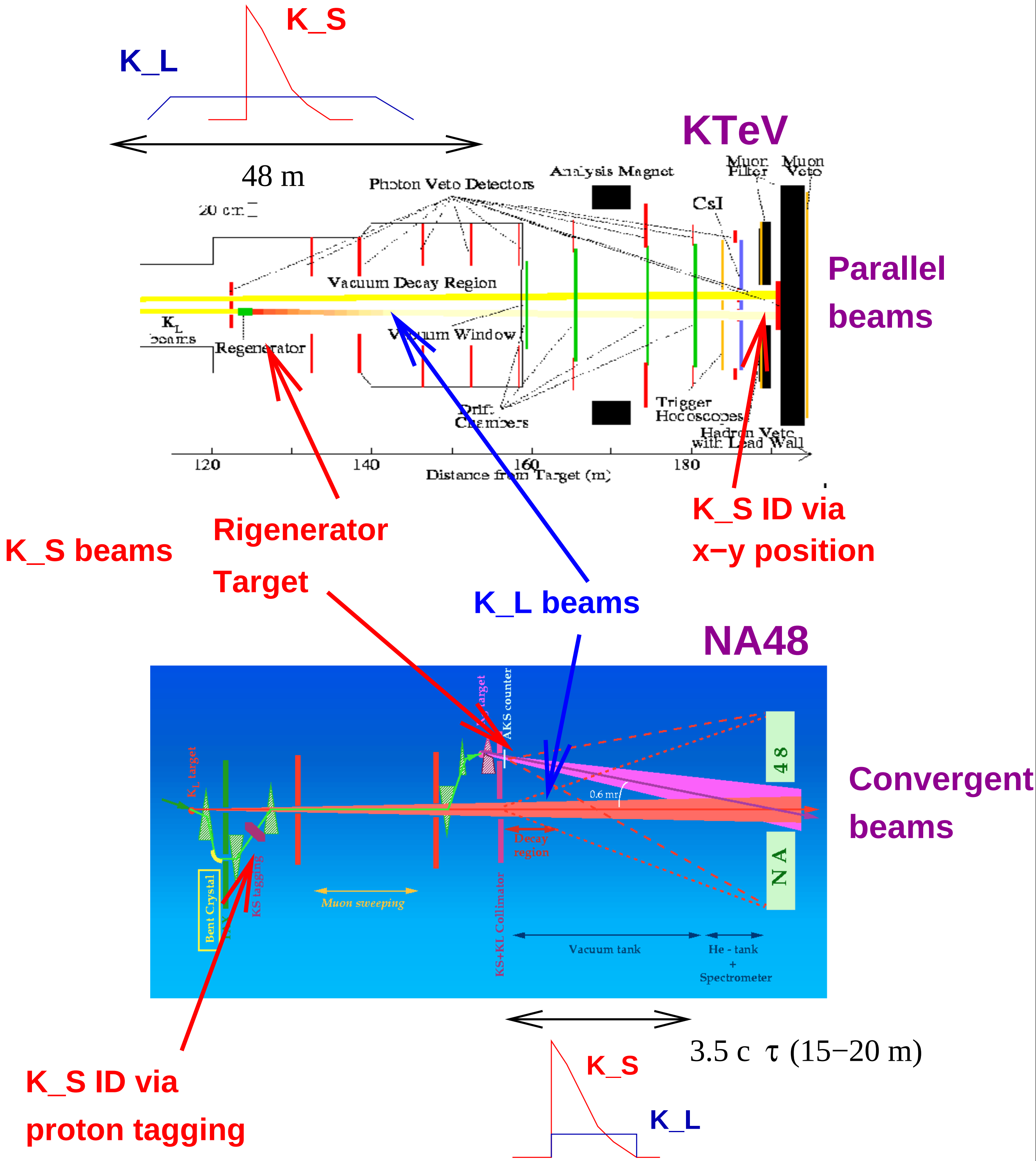


Experimental method II

Both KTeV and NA48 are almost ideal fixed target experiments measuring R using the double ratio method recording the 4 modes concurrently.
But:



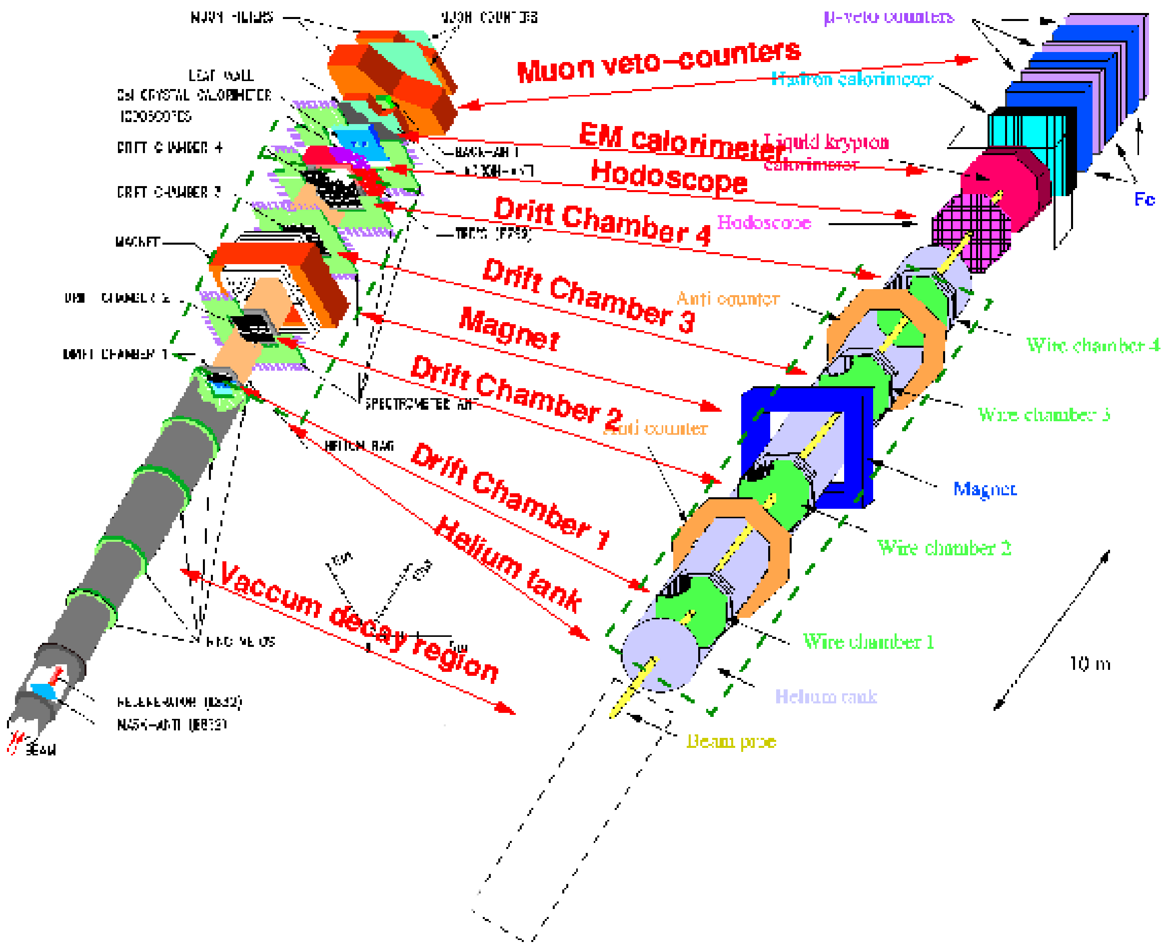
KTeV-NA48: the beams



KTeV-NA48: the detectors

Similar but NOT identical..

KTeV | **NA48**

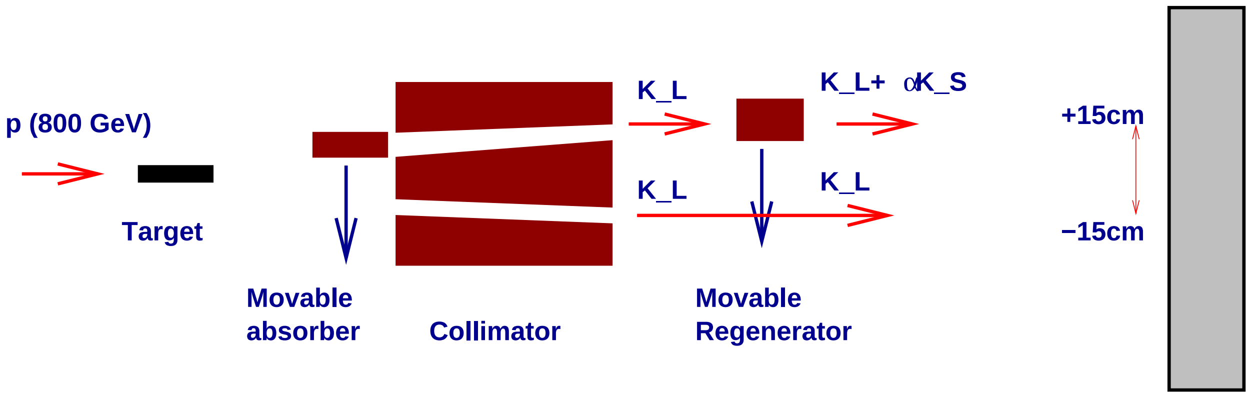


- CsI Cal= $\frac{\sigma_E}{E} = \frac{2\%}{\sqrt{E}} + 0.45\%$
- $\sigma(M_{oo}) = 1.5$ MeV
- Dch=$0.17\% + 0.007 \cdot p\%$
- P_t kick= 400 MeV/c
- $\sigma(M_{+-}) = 1.6$ MeV

- Lkr Cal= $\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} + 0.4\%$
- $\sigma(M_{oo}) = 2.5$ MeV
- Dch=$0.48\% + 0.009 \cdot p\%$
- P_t kick= 250 MeV/c
- $\sigma(M_{+-}) = 2.5$ MeV

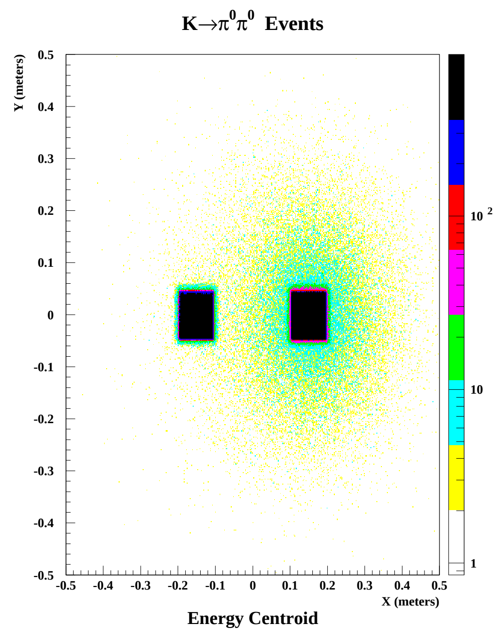
KTeV: How to make and tag a K_S

To make a K_S beam, KTeV uses a regenerator:



To tag a K_S, KTeV uses the position in the detector:

- Charged decays: vertex x-y position
- Neutral decays: energy centroid in the Cal.



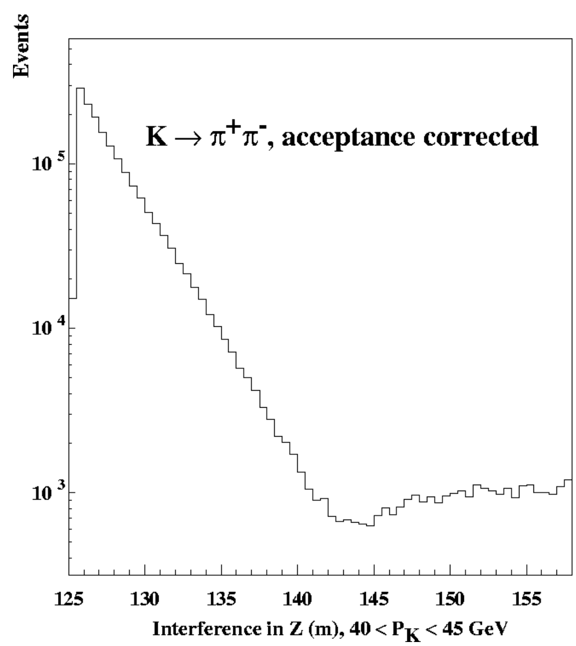
KTeV: How to make and tag a K_S (II)

The movable regenerator is the heart of the system:

This photo is looking upstream.

- Scintillator plates read out by top and bottom PMTs.
- The PMTs electronics are water-cooled, necessitated by operation in vacuum.
- It moves from one beam to the other once per minute.

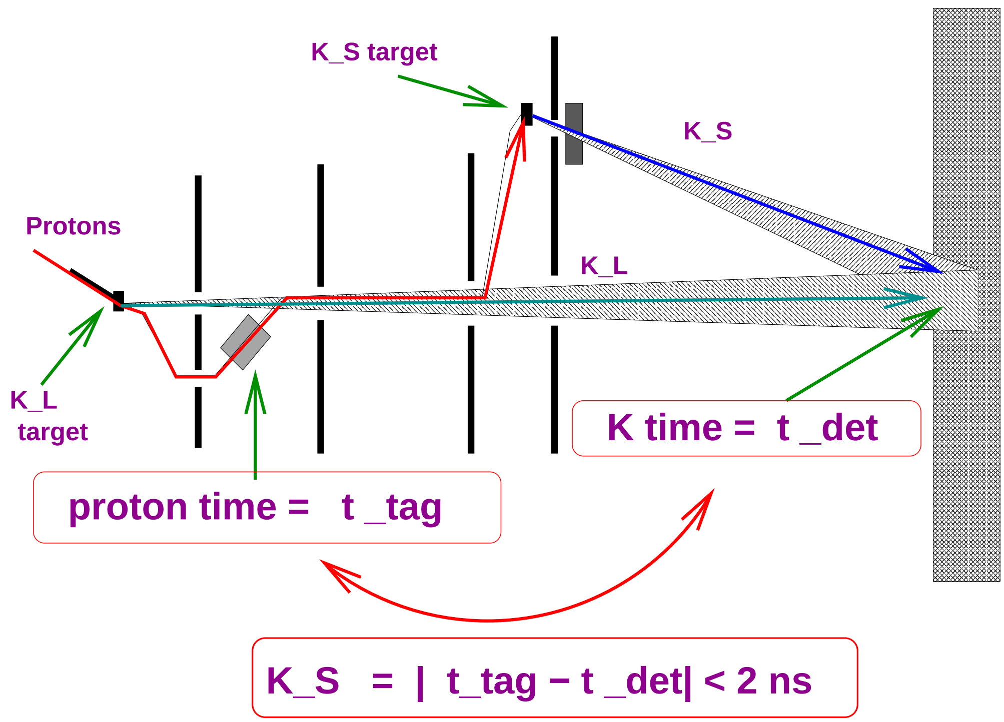
The decay vertex distribution for the regenerated beam is:



Corrections needed for diffractive and inelastic events (obtained from MC)

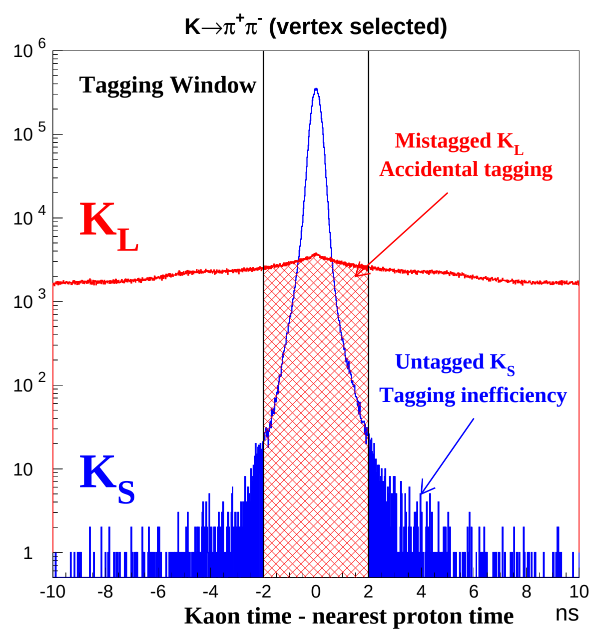
NA48: How to make and tag a K_S

To make a K_S beam, NA48 uses a berillium target:



To tag a K_S, NA48 uses the timing of the parent proton

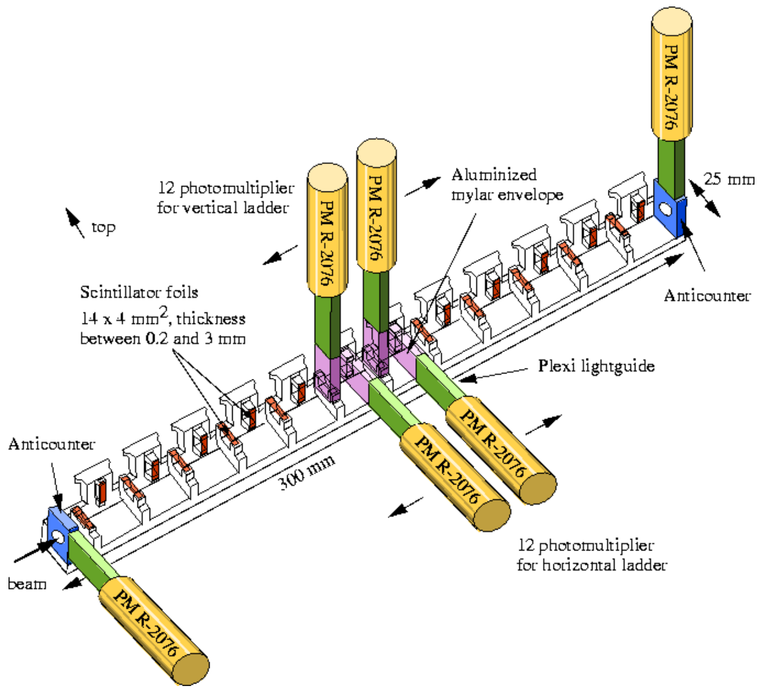
- K_L : τ_{det} is uncorrelated to τ_{tag}
- K_s : τ_{det} is correlated to τ_{tag}
- Done for both charged and neutral decay



NA48: How to make and tag a K_S (II)

The tagger is the heart of the system:

- Two scintillator ladders
- Dimensions: 4mm thick, 15 mm long, variable widths
- A proton crosses at least 2 scint.
- Read by 960 MHz flash ADC, 100ns window per trigger



⟹ Two ways of misidentification:

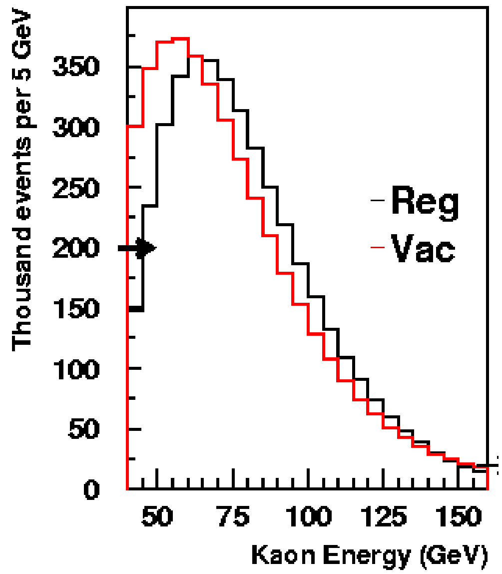
- Tagging Inefficiency: a K_S does not have a parent proton: $K_S \rightarrow K_L$
- Accidental Tagging: a proton is tagged without K_S: $K_L \rightarrow K_S$

KTeV-NA48: kaons energy spectra

To exploit the cancellation of detector effects between K_S-charged/K_L-charged and K_S-neutral/K_L-neutral decays, K_S and K_L should have the same energy spectrum.

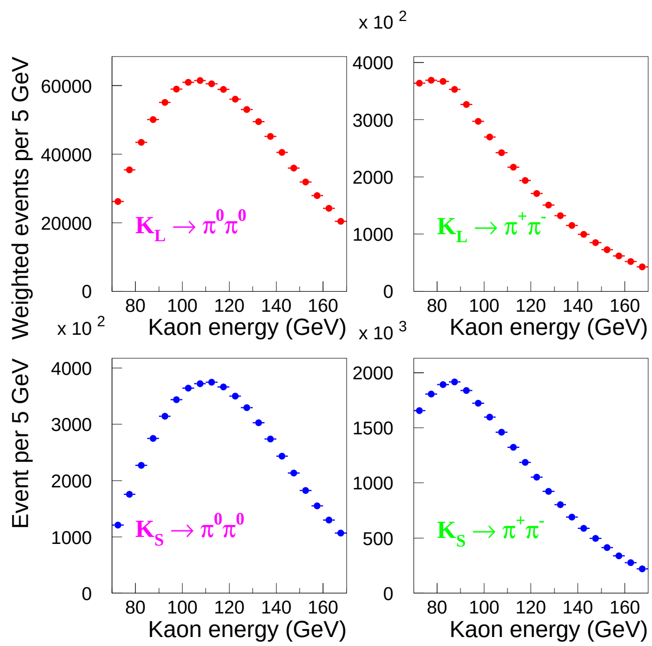
KTeV

The regenerator produces a K_S energy spectrum similar to the K_L



NA48

The targeting angles of the proton beam on the K_S and K_L targets are tuned to deliver similar spectra



Residual differences are reduced by performing the analysis in energy bins

KTeV-NA48: counting experiments

Once the detector and the beam work as they should, we start counting:

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

We need to apply all corrections which do not cancel in the double ratio:

- K_L, K_S misidentifications
- K_L backgrounds
- Trigger efficiencies
- Collimator scattering
- Accidental overlapping
- Detector biases (calorimeter energy-scale, Dch allignement
- Montecarlo simulation
- Regenerator physics
- Acceptance
- ....

everything at 10^{-4}...

KTeV-NA48: identify $K \to \pi^+\pi^-$

Both experiments use their spectrometers to reconstruct the K vertex, mass and momentum.

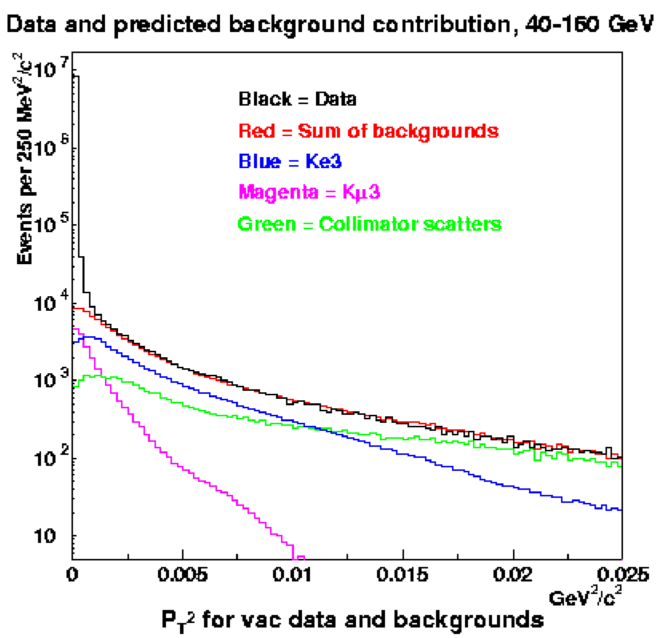
Note: large background only to $K_L \to \pi^+\pi^-$ due to e, μ misidentification and small ν missing p_t

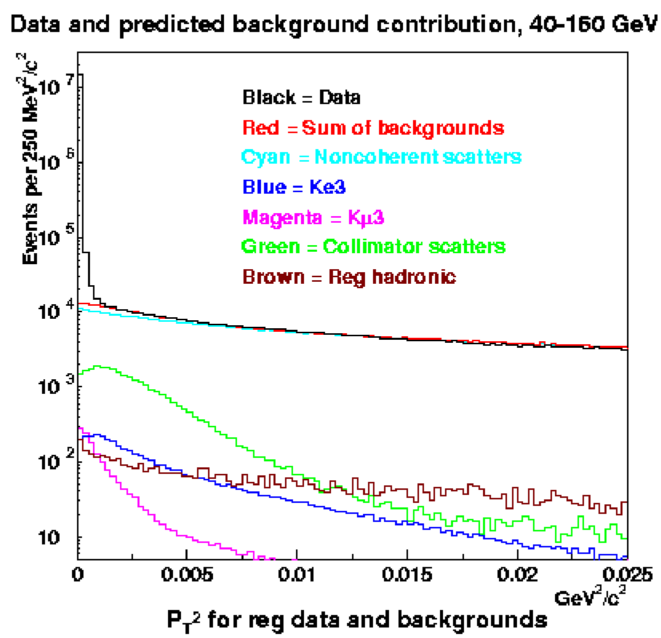
$K_L \to \pi^+\pi^- \sim 0.2$ % $K_L \to \pi\mu\nu \sim 27\%$ $K_L \to \pi e\nu \sim 39\%$	$K_S \to \pi^+\pi^- \sim 68.6$ %

Very dangerous: background to a single mode!

Cut on p_t and single track e/p are used to remove part of the background. The left-over contribution is fitted/modelled and then statistically subtracted

KTeV: (MC estimate)





Back/Sign(Vac) $\approx$ 0.10%   Back/Sign(Rcg) $\approx$ 0.09 %

Na48 = ~0.19 % (Data estimate)

KTeV-NA48: identify $K \to \pi^o\pi^o$

Both experiments use their calorimeters to reconstruct the K vertex, mass and momentum.

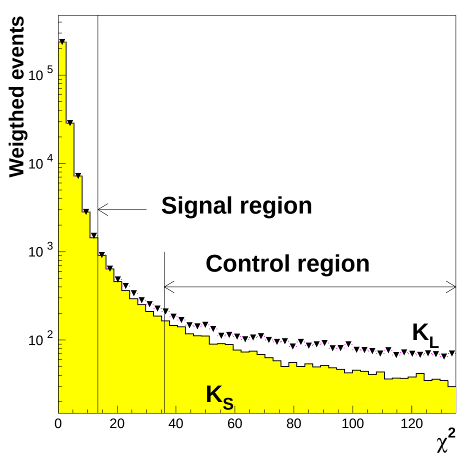
Note: large background only to $K_L \to \pi^o\pi^o$ due to losses and fusions of γ EM showers

$K_L \to \pi^o\pi^o \sim 0.09$ % $K_L \to \pi^o\pi^o\pi^o \sim 21$ %	$K_S \to \pi^o\pi^o \sim 31.4$ %

Very dangerous: background to a single mode!

Cuts on the pions and kaon masses, extra shower and calorimeter positions are used to remove part of the background. The left-over contribution is fitted/modelled and subtracted

NA48 $=$ 0.7 % (Data estimate)

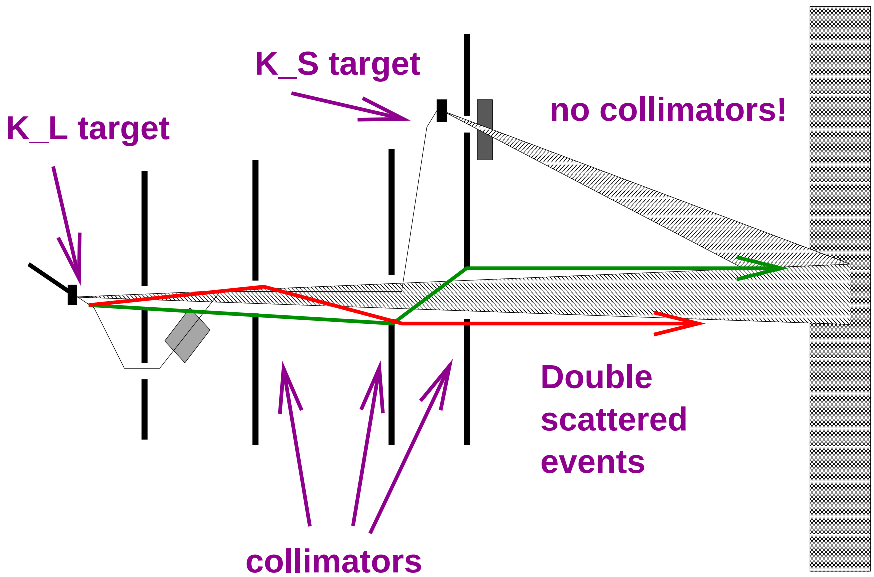


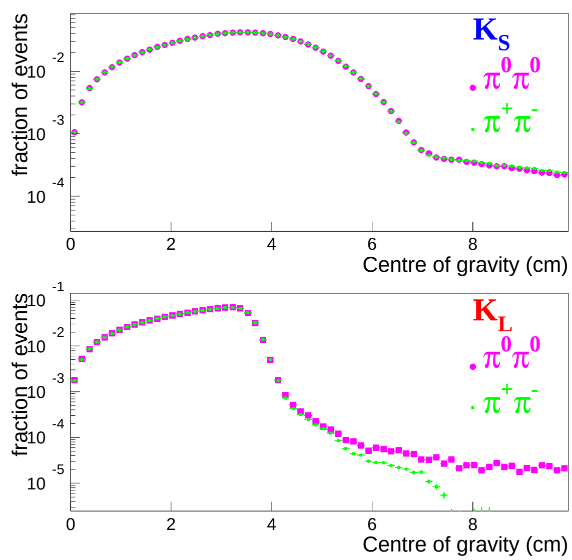
KTeV $=$ ~0.5 % vacuum, ~1.2 % regen. (MC estimate)

KTeV-NA48: collimator scattering

Backgrounds at the collimators/regenerators (KTeV) contaminate differently the 4 modes.

NA48: Different tails in the 'center of gravity' (COG) distribution

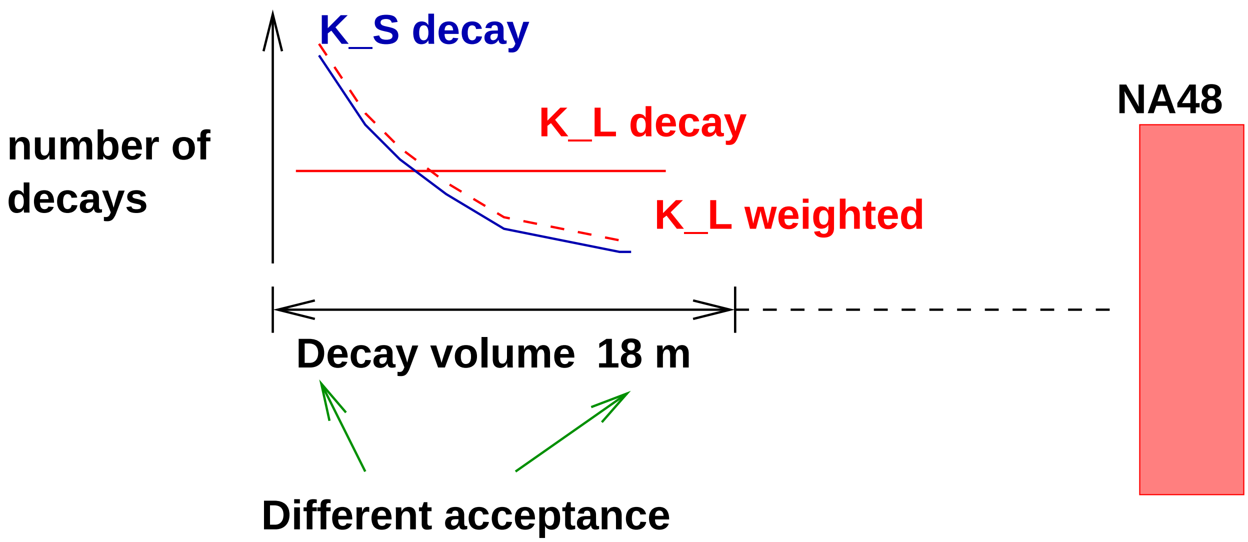




KTeV: the scattering in the collimator and regenerator is carefully simulated in the MC.

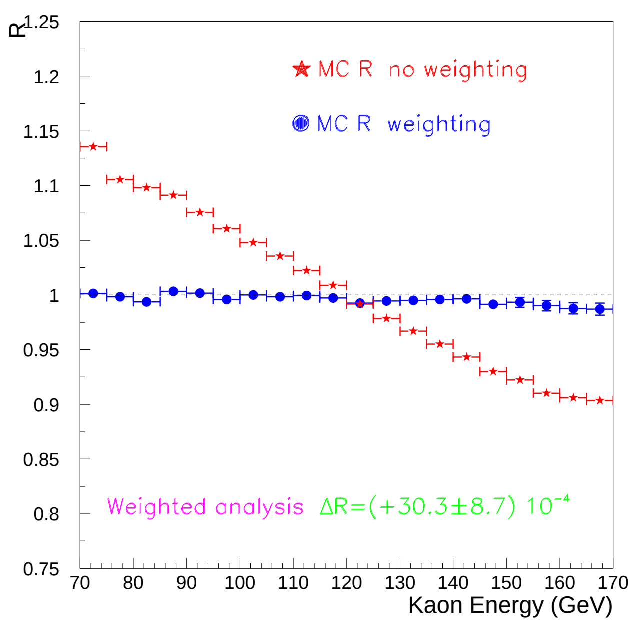
NA48: acceptance correction

NA48 uses proper time reweighting to equalize the K_S and K_L decay distribution since early decays have different acceptance than later ones



➡ The remaining acceptance corrections are small but different from zero because the two beams are slightly displaced (by 7 cm out of 115 m!)

➡ The weight is always smaller than one, so you pay a price: 35 % decrease of statistical accuracy on R but a much smaller MC correction



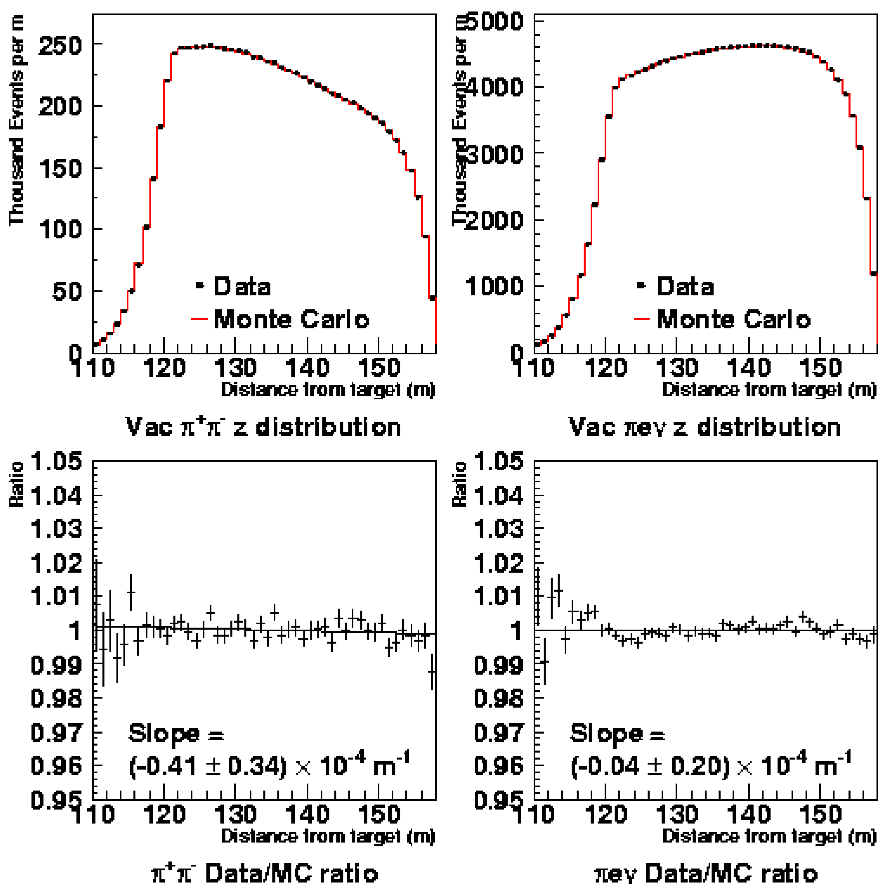
KTeV: acceptance correction

KTev uses a detailed MC predictions of the acceptance of each beam to correct the data.

- The correction is large but is mainly due to detector geometry
- Important to understand details of detector response
- Use large statistics mode ($k_{e3}, K_L \rightarrow 3\pi^o$) to cross check the MC

Example:

$1997\ K \rightarrow \pi^+\pi^-\ \&\ K_{e3}$



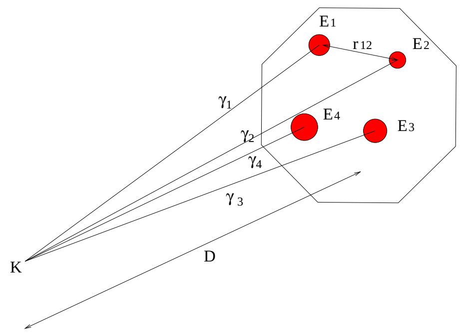
NA48-KTeV: Calorimeter energy scale

An energy scale error gives an error on R
(NA48, $E_K = 100$ GeV):

$$\sigma_R \sim 0.7\sigma_E$$

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

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

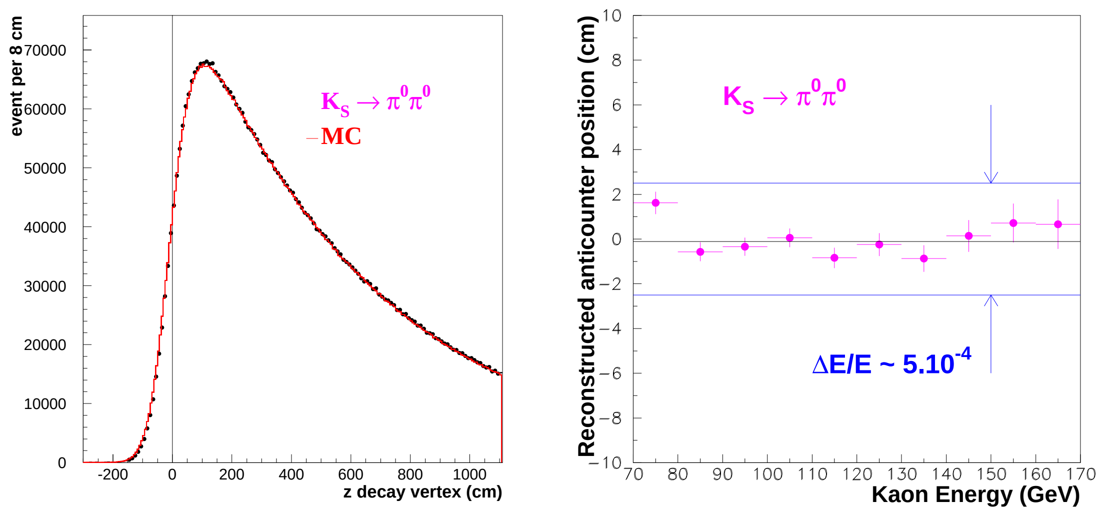


Energy scale and distance scale are related:

$$\frac{\Delta E_K}{E_K} = -\frac{\Delta z_K}{z_K}$$

Method: adjust the energy scale to match a detector edge (regenerator for KTeV, AKS for NA48)

NA48:



Uncertainties from energy scale, transverse size, non-linearities, non uniformities, non-gaussian tails...

NA48-KTeV: what has been left out

A very large amount of important things have been left out. To quote a few of them:

- Detailed detector performance
- Reconstruction techniques
- Background studies
- Beam accidental activities
- Monte Carlo studies
- The art of calorimetry
- $\Delta m = m_{K_L} - m_{K_S}$
- τ_S
- $Im(\epsilon'/\epsilon)$
- η-mass
- ....

NA48-KTeV: event counts

In May and June of this year NA48 and KTeV updated their analyses.
The results presented are based on:

	$K_L \rightarrow$		$K_S \rightarrow$	
	$\pi^+\pi^-$	$\pi^o\pi^o$	$\pi^+\pi^-$	$\pi^o\pi^o$
KTeV	11.2	3.4	19.4	5.6
NA48	14.4	3.3	22.2	5.2

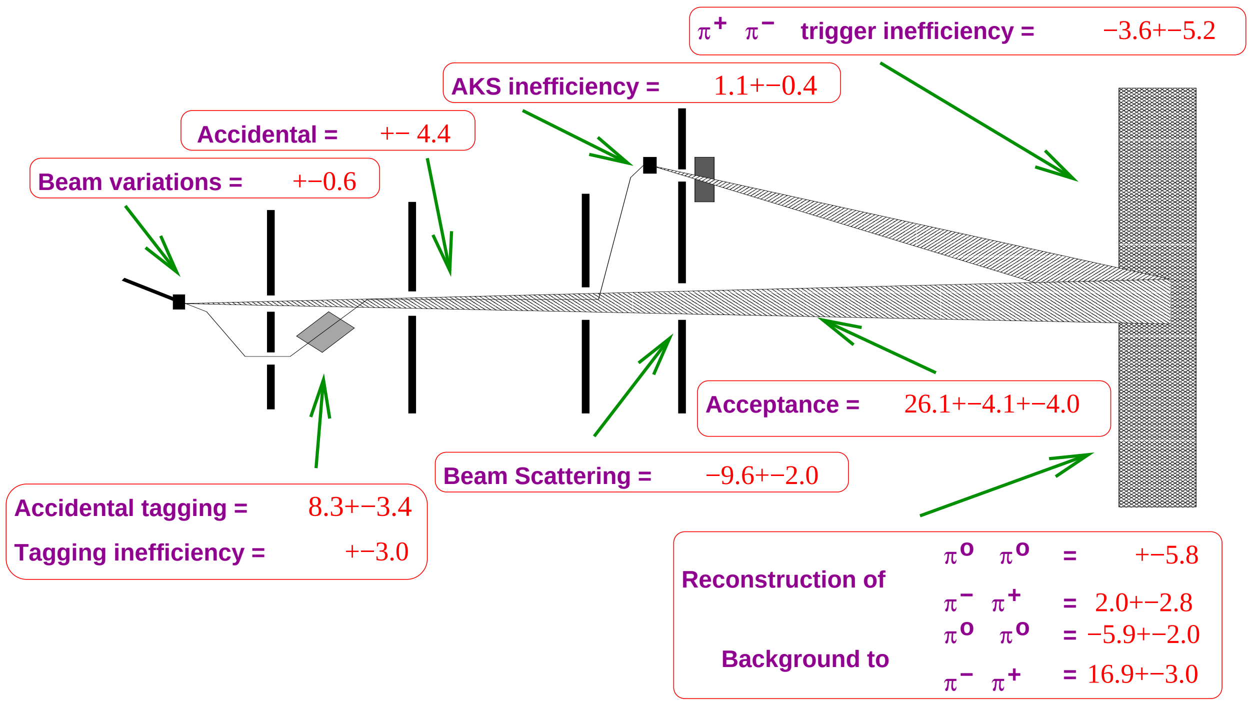
Statistical errors on R:

NA48: $\sim 10.1 \cdot 10^{-4}$
(it includes proper time reweighting)

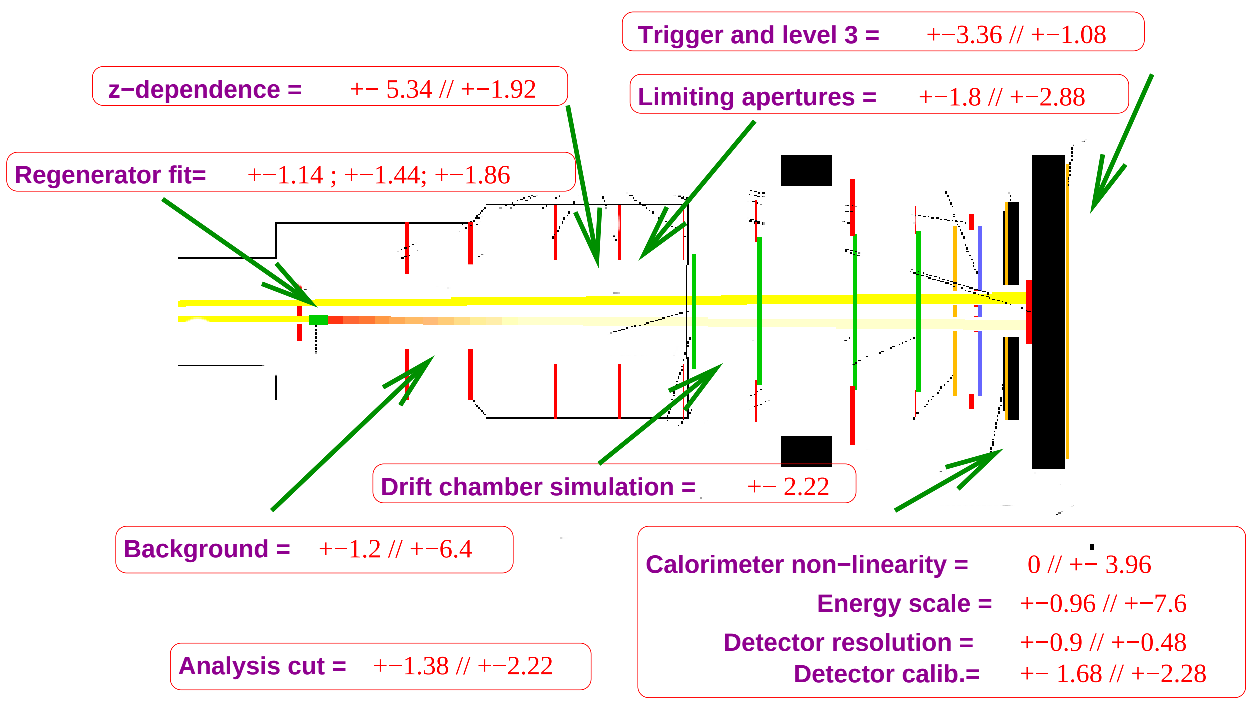
KTeV: $\sim 9.5 \cdot 10^{-4}$

KTeV-NA48: R-systematics

NA48 : correction +- error



KTeV : error for charged // neutral modes



NA48: Systematic uncertainties

➡ Systematic uncertainties on R

	on R in 10^{-4}	
$\pi^+\pi^-$ trigger inefficiency	-3.6	$\pm$ 5.2
AKS inefficiency	+1.1	$\pm$ 0.4
Reconstruction of $\pi^0\pi^0$	—	$\pm$ 5.8
Reconstruction of $\pi^+\pi^-$	+2.0	$\pm$ 2.8
Background to $\pi^0\pi^0$	-5.9	$\pm$ 2.0
Background to $\pi^+\pi^-$	+16.9	$\pm$ 3.0
Beam scattering	-9.6	$\pm$ 2.0
Accidental tagging	+8.3	$\pm$ 3.4
Tagging inefficiency	—	$\pm$ 3.0
Acceptance statistical	+26.7	$\pm$ 4.1
Acceptance systematic		$\pm$ 4.0
Accidental activity	—	$\pm$ 4.4
Long term variations of K_S /K_L	—	$\pm$ 0.6
Total	+35.9	$\pm$ 12.6

➡ some uncertainties depend on statistics of control samples or MC

➡ Systematic uncertainties on $Re(\frac{\epsilon'}{\epsilon})$ = 2.05

KTeV: Systematic uncertainties

Systematic uncertainties on $Re(\frac{\epsilon'}{\epsilon})$

Systematic Uncertainties for Combined Result

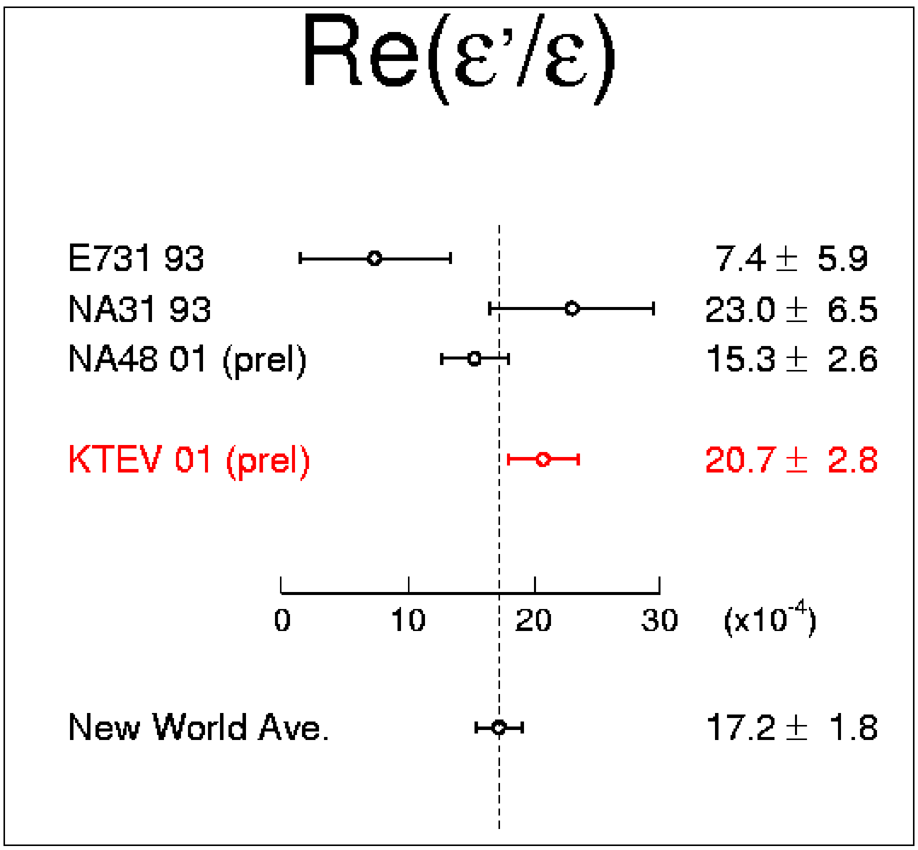
Source of uncertainty	Uncertainty ($\times 10^{-4}$) from $\pi^+\pi^-$	from $\pi^0\pi^0$
Class 1: Data collection		
Trigger and level 3 filter	**0.56**	**0.18**
Class 2: Event reconstruction, selection, backgrounds		
Energy/Resolution scale	**0.16**	**1.27**
Calorimeter nonlinearity	—	**0.66**
Detector calib, align	**0.28**	**0.38**
Analysis cut variations	**0.23**	**0.37**
Background subtraction	**0.20**	**1.07**
Class 3: Detector acceptance		
Limiting apertures	**0.30**	**0.48**
Detector resolution	**0.15**	**0.08**
Drift chamber simulation	**0.37**	—
z dependence	**0.89**	**0.32**
Class 4: Kaon flux and physics parameters		
Reg-beam attenuation	**0.19**	
Δm, τ_S	**0.24**	
Reg phase screening	**0.31**	
TOTAL	**2.36**	

NA48-KTeV: results

The latest NA48 and KTeV results on $Re(\frac{\epsilon'}{\epsilon})$:

NA48: $Re(\frac{\epsilon'}{\epsilon}) = 15.3 \pm 2.6$

KTeV: $Re(\frac{\epsilon'}{\epsilon}) = 20.7 \pm 2.8$



$\chi^2/dof = 5.65/3$
(17% conf.)

$$Re(\frac{\epsilon'}{\epsilon}) = 17.2 \pm 1.8$$

Conclusions

$$Re(\frac{\epsilon'}{\epsilon}) = 17.2 \pm 1.8$$

⟹ After many years direct CP violation has been established

- Finally, there is good agreement between the experiments
- KTeV has an equivalent amount of data on tape
- NA48 in 2001 is working on a measurement at lower beam intensity
- Hopefully KLOE can soon join the game