Indirect CP violation in K_L decays with the NA48 detector

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Outline

- **CP violation in the** $K^0 - \bar{K}^0$ **system**
- **The NA48 detector**
- **Two measurements of indirect CP violation:**
  - $K_{L,S} \to \pi^+ \pi^- e^+ e^-$ **(BR, Form Factors, Asymmetry)**

    $\Rightarrow$ **Results submitted to EPJ**
  - K_{e3} **Charge Asymmetry**

    $\Rightarrow$ **Preliminary**
- **Summary**

CP Violation in the K^0–$\bar{K}^0$system

Strong eigenstates $(J^P = 0^-)$ K^0 $(d\bar{s})$ **S= +1**
$\bar{K}^0$ $(\bar{d}s)$ **S= −1**

CP eigenstates $K_1 = (K^0 + \bar{K}^0)/\sqrt{2}$ **(CP= +1)** $\Longrightarrow$ $\pi\pi$
K^0–$\bar{K}^0$**admixture** $K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$ **(CP= −1)** $\Longrightarrow$ $\pi\pi\pi$

Up to 1964 K_1 and K_2 were belived to be the physical states but the discovery of the decay $K_2 \to \pi\pi$ changed this interpretation

Mass eigenstates $K_S = (K_1 + \epsilon K_2)/\sqrt{1+\epsilon^2}$ $\tau_S = (0.8941 \pm 0.0009) \times 10^{-10} s$
not pure CP eigenstates $K_L = (K_2 + \epsilon K_1)/\sqrt{1+\epsilon^2}$ $\tau_L = (5.17 \pm 0.04) \times 10^{-8} s$

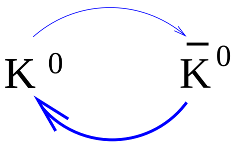
$|\epsilon| \simeq 2.3\ 10^{-3}$ $arg(\epsilon) \simeq 43.5°$

	K_S	K_L
$\pi^+\pi^-$	$(68.60 \pm 0.27) \times 10^{-2}$	$(2.084 \pm 0.032) \times 10^{-3}$
$\pi^0\pi^0$	$(31.40 \pm 0.27) \times 10^{-2}$	$(9.42 \pm 0.19) \times 10^{-4}$
$\pi^+\pi^-\pi^0$	$(3.2^{+1.2}_{-1.0}) \times 10^{-7}$	$(12.58 \pm 0.19) \times 10^{-2}$
$K_{\mu 3}$		$(27.18 \pm 0.25) \times 10^{-2}$
K_{e3}	$(7.2 \pm 1.4) \times 10^{-4}$	$(38.79 \pm 0.27) \times 10^{-2}$

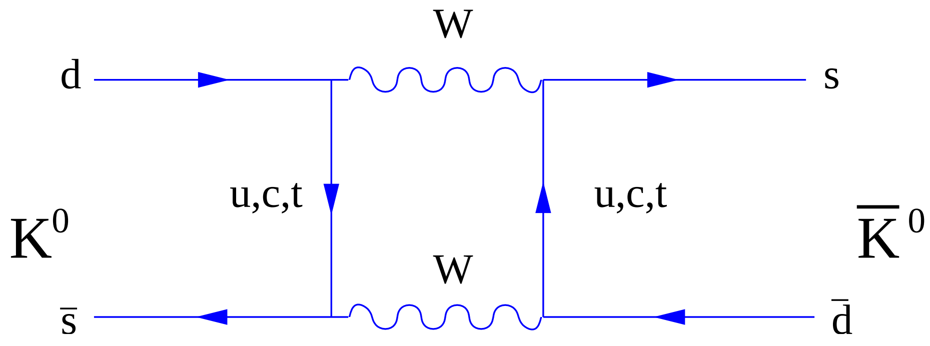
Two ways of violating CP

Indirect CP violation

$\Delta S = 2$ **transitions due to** K^0–$\bar{\mathrm{K}}^0$**mixing**
The mixing is not symmetric:



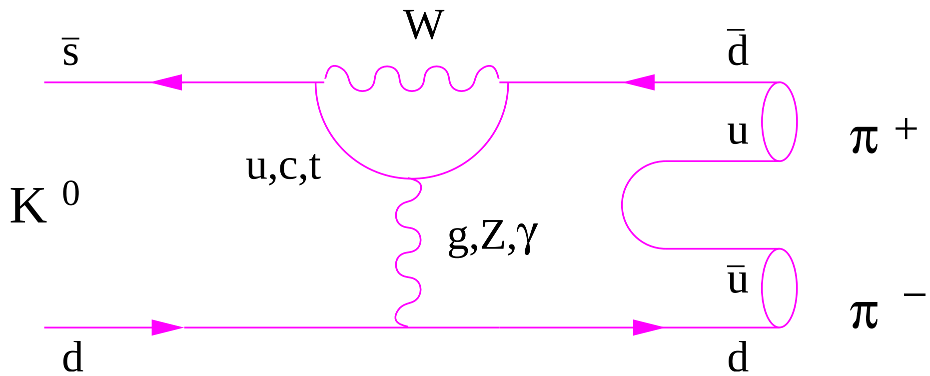
$\bar{\mathrm{K}}^0 \rightarrow \mathrm{K}^0$**preferred over** $\mathrm{K}^0 \rightarrow \bar{\mathrm{K}}^0$



$$\mathrm{K_L} = \mathrm{K_2} + \varepsilon\,\mathrm{K_1}$$

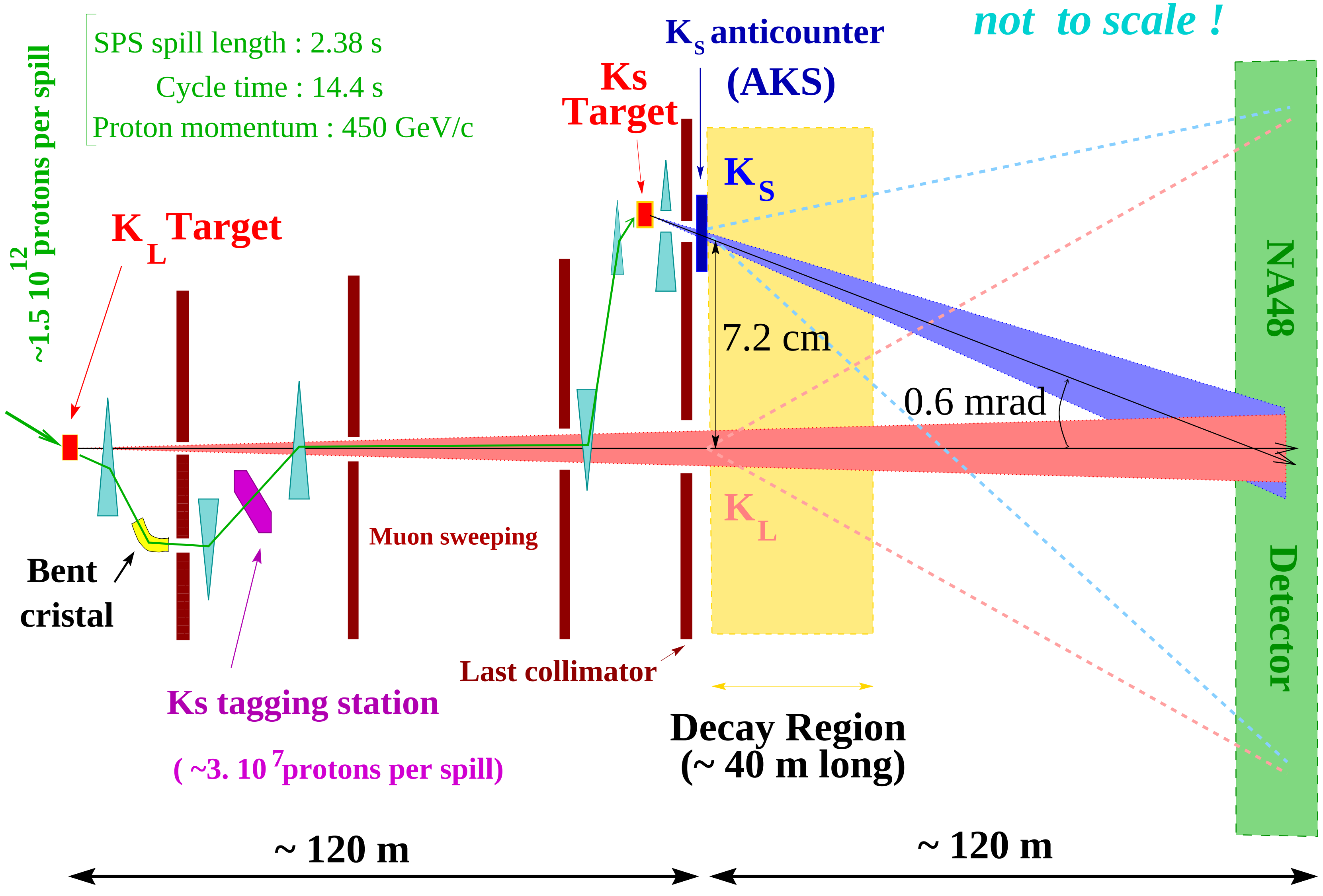
Direct CP violation

$|A(K^0 \rightarrow f)| \neq |A(\bar{K}^0 \rightarrow \bar{f})|$
$\Delta S = 1$ **transitions** $\Rightarrow \epsilon'$
Two amplitudes (I=0, 2) in the final state
Phase difference in the two channels



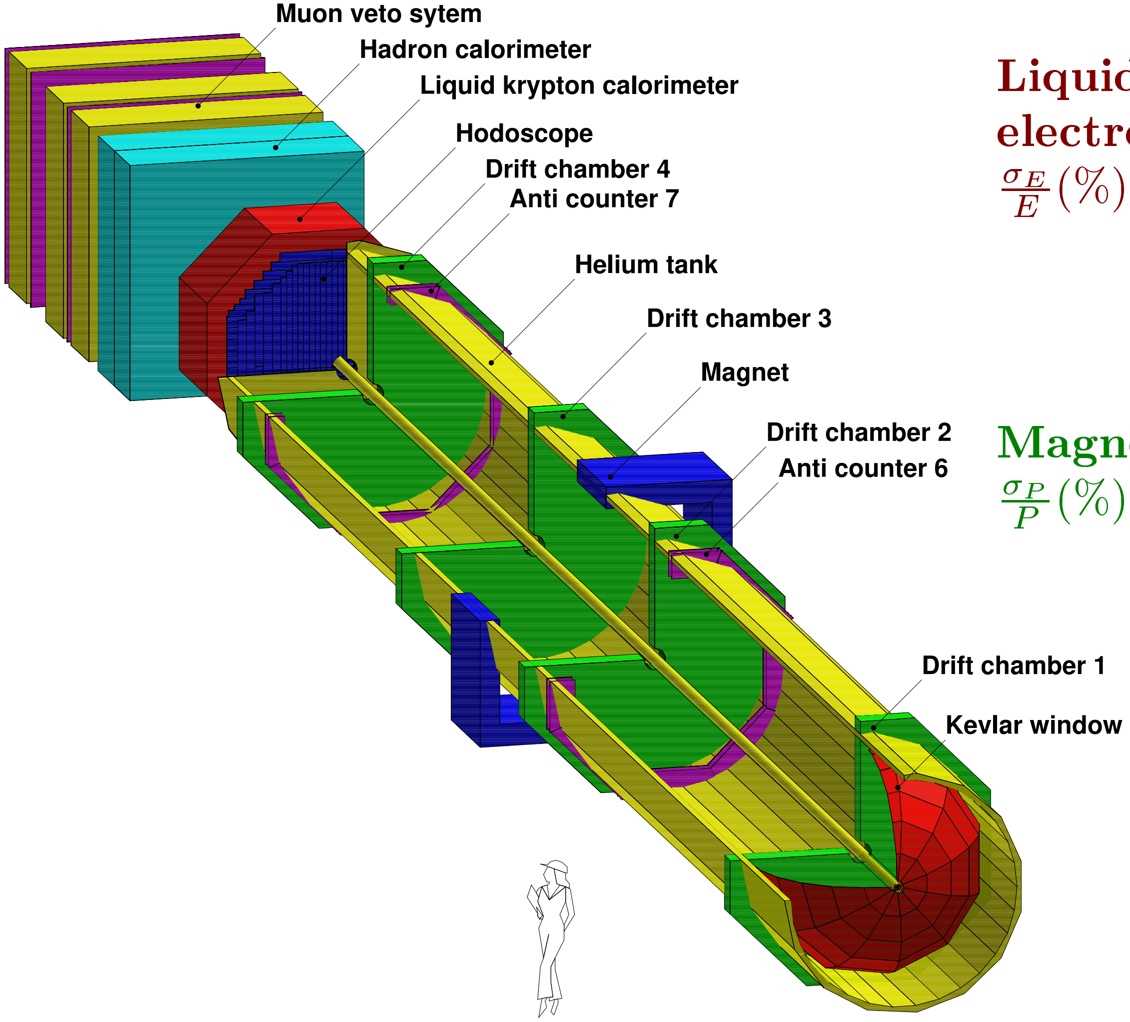
CP violation: $K_L \rightarrow \pi\pi,\ \pi^+\pi^-\gamma,\ \pi^+\pi^-e^+e^-$ **and** $\delta_{e,\mu}$ **processes**

The beams



SPS spill length : 2.38 s
Cycle time : 14.4 s
Proton momentum : 450 GeV/c
~1.5 10^12 protons per spill
K_L Target
Ks Target
K_S anticounter
(AKS)
not to scale !
K_S
7.2 cm
0.6 mrad
K_L
NA48
Detector
Bent cristal
Muon sweeping
Last collimator
Ks tagging station
(~3. 10^7 protons per spill)
Decay Region
(~ 40 m long)
~ 120 m
~ 120 m

The NA48 Detector



Liquid krypton electromagnetic calorimeter

$$\frac{\sigma_E}{E}(\%) = \frac{3.2}{\sqrt{E}} \oplus \frac{9.0}{E} \oplus 0.42(GeV)$$

e/π **separation**

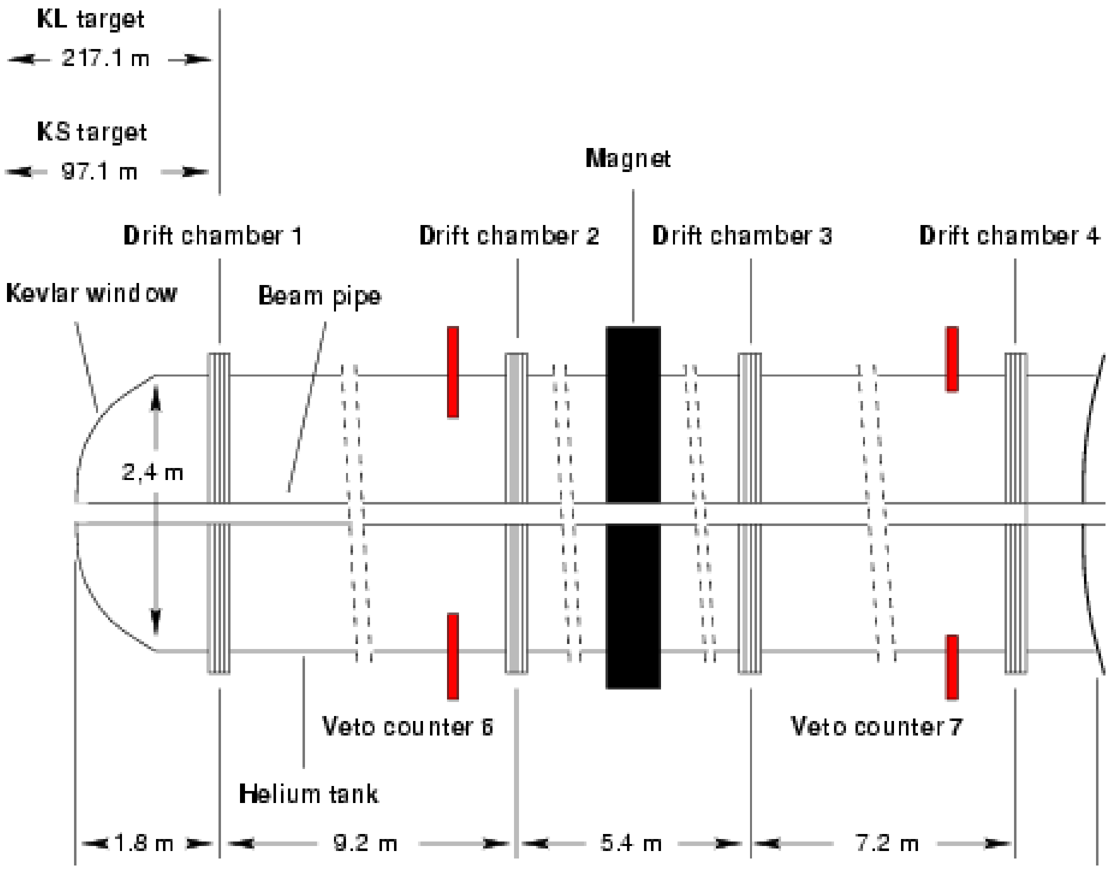
Magnetic Spectrometer

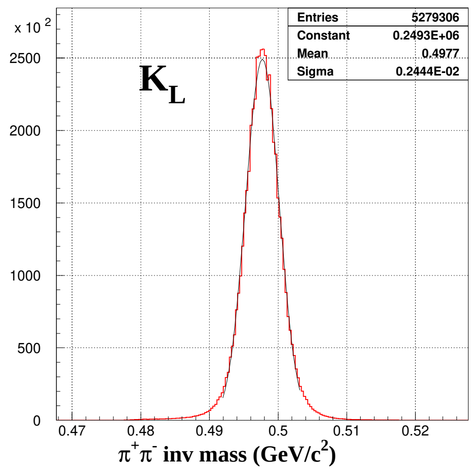
$$\frac{\sigma_P}{P}(\%) = 0.48 \oplus 0.009P(GeV/c)$$

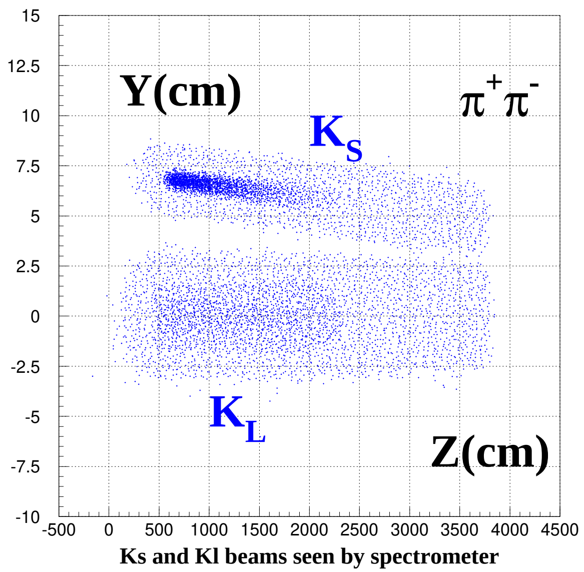
Charged particles

The NA48 Magnetic Spectrometer

4 drift chambers + magnet $\rightarrow$ 265 MeV/c p_t kick







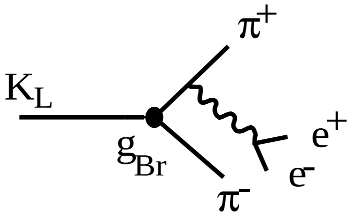
Vertex reconstruction allows beam separation

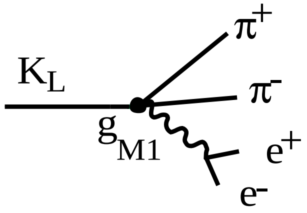
Kaon mass resolution $\sim$ 2.5 MeV/c^2

$\mathrm{K_L} \to \ \pi^+ \ \pi^- \ \mathrm{e}^+ \ \mathrm{e}^-$ Physics

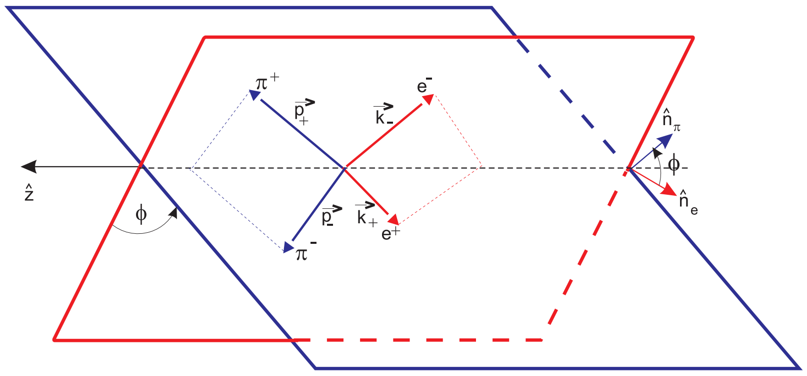
Main contributions to the $K_L \to \ \pi^+ \ \pi^- \ e^+ \ e^-$ decay:

CPV inner bremsstrahlung (IB) **CPC direct M1 emission (DE)**





The interference between the IB (CP=+1) and the DE (CP=-1) amplitudes produces a CP–violating circular polarization of the γ^*



$$\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2\phi \ + \ \Gamma_2 \sin^2\phi \ + \ \Gamma_3 \sin\phi\cos\phi$$

$$\sin\phi\cos\phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z} \ (\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

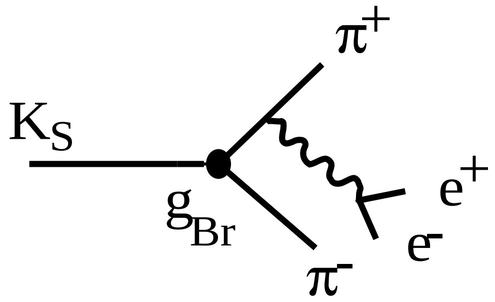
$$\mathrm{A}_\phi = \frac{\mathrm{N}_{\sin\phi\cos\phi>0} - \mathrm{N}_{\sin\phi\cos\phi<0}}{\mathrm{N}_{\sin\phi\cos\phi>0} + \mathrm{N}_{\sin\phi\cos\phi<0}}$$

Prediction from Heiliger and Sehgal (1993): $A_\phi \simeq 14\%$

Largest CP asymmetry ! ...but small branching ratio

$K_S \to \pi^+ \pi^- e^+ e^-$ Physics

The dominant contribution to the decay is the CP-conserving IB process:



➜ **NO CP-violation asymmetry is expected**

- **First observation of this decay reported by NA48 (PLB 496 (2000) 137)**
- **Can be related to IB component of the $K_L$decay:**

$$BR(K_L^{IB} \to \pi^+ \pi^- e^+ e^-) = \mathrm{BR}(K_S \to \pi^+ \pi^- e^+ e^-) \frac{\tau_L}{\tau_S} |\eta_{+-}|^2$$

- **Important to cross-check the K_L analysis**

Data ($K_{L,S}$) collected during the normal ε'/ε runs in 1998 and 1999

Most of the K_S sample from short high intensity run in 1999

$\mathrm{K_L} \rightarrow \ \pi^+ \ \pi^- \ e^+ \ e^-$ Background

Very good tracking
High resolution in LKR for e/π separation

$\mathrm{K_L} \rightarrow \ \pi^+ \ \pi^- \ \pi^0_{\mathrm{D}}(\gamma)$ lost

Large Background ($> \times 10^3$)
Kinematical cuts: $P^2_{\perp}, P'^2_0$

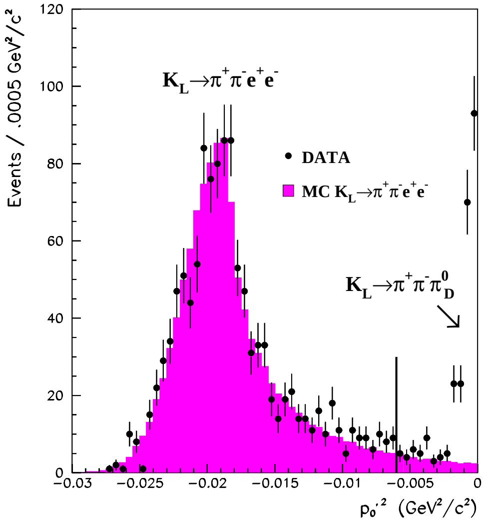
Two overlapping $\mathrm{K_{e3}}$

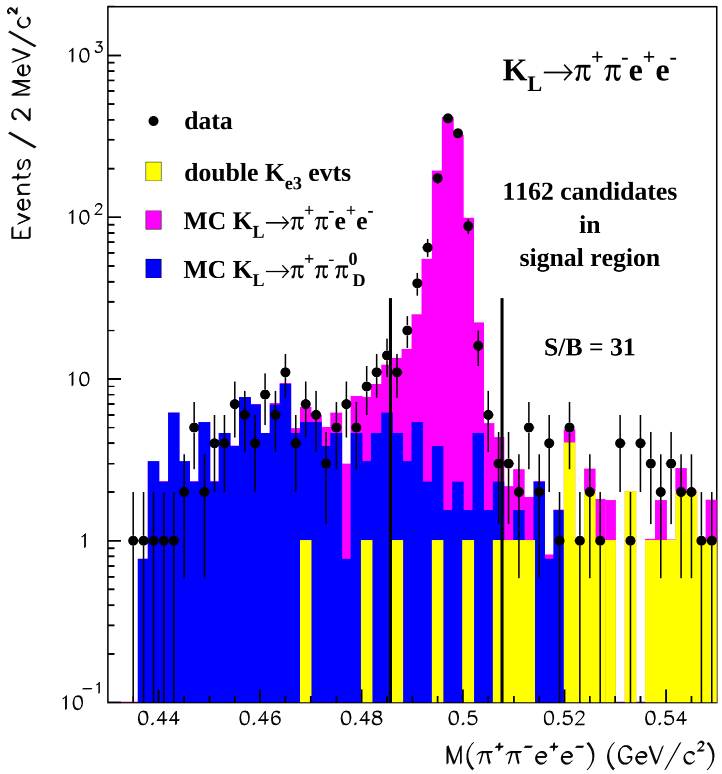
$\pi^+ e^- \ \ \pi^- e^+$ vertex times
in $\pm$ 1.5 ns time window

$\mathrm{K_L} \rightarrow \pi^+\pi^-\gamma +$ conv.
$\mathrm{K_L} \rightarrow \pi^+\pi^- +$ acc.$\gamma +$ conv.

Negligible

Normalization channel for BR
is fully rec. $\mathrm{K_L} \rightarrow \ \pi^+ \ \pi^- \ \pi^0_{\mathrm{D}}$





$K_S \rightarrow \pi^+ \pi^- e^+ e^-$ Background

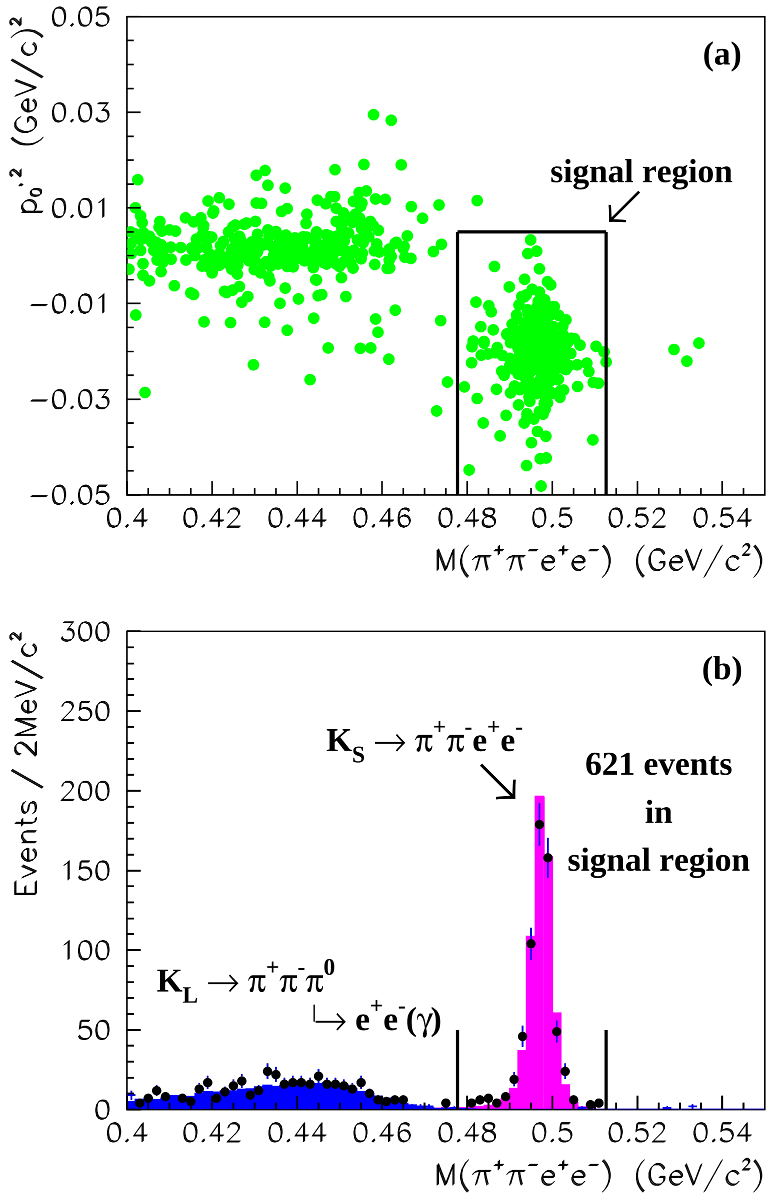
$K_L \rightarrow \pi^+ \pi^- \pi^0_D(\gamma)$ lost

Much smaller than in K_S
Looser kinematical cuts

Background from K_L beam

Use proton time info

Normalization channel for BR is $K_L \rightarrow \pi^+ \pi^- \pi^0_D$ (produced at the K_S target)



$K_{L,S} \to \pi^+ \pi^- e^+ e^-$ **Asymmetry**

$K_L \to \pi^+ \pi^- e^+ e^-$

$$A_\phi^L = (14.2 \pm 3.6)\%$$

Clear signature of indirect CP violation

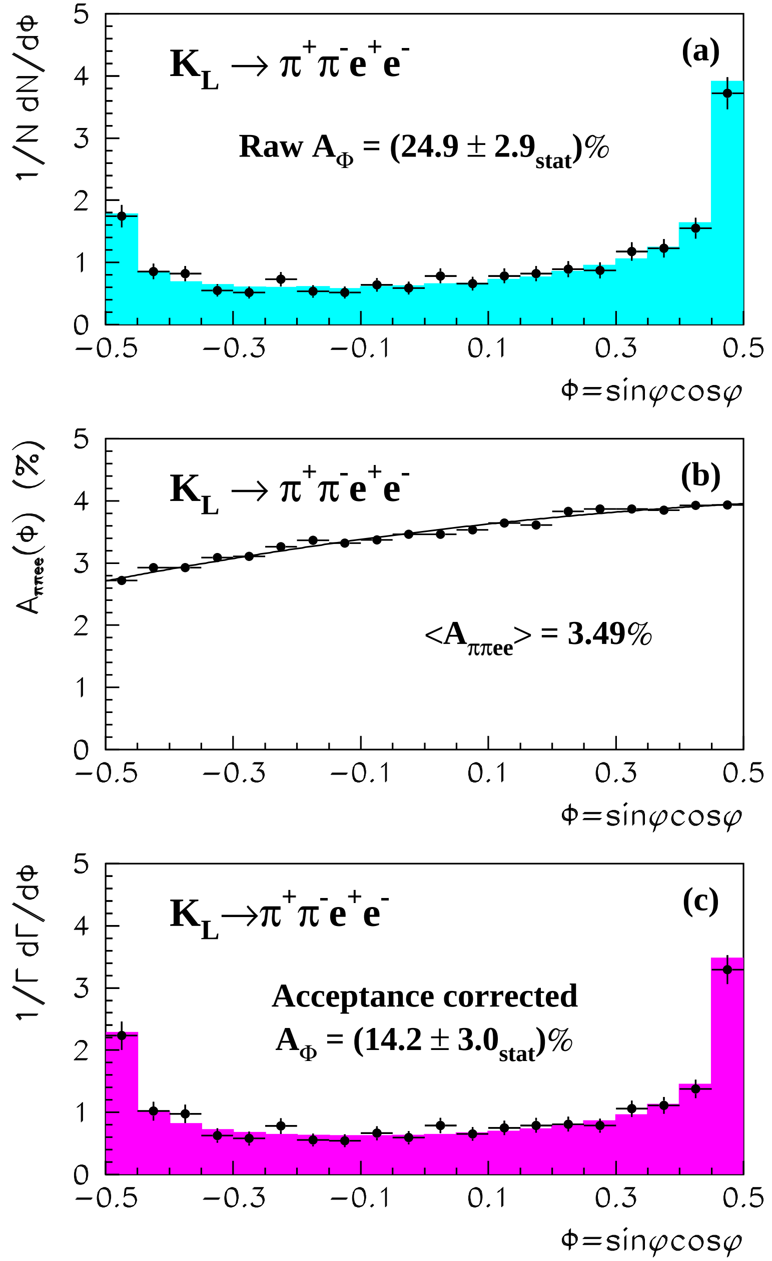
In agreement with theory predictions and KTeV results

$K_S \to \pi^+ \pi^- e^+ e^-$

$$A_\phi^S = (-1.1 \pm 4.1)\%$$

NO asymmetry observed

A_ϕ^L is not generated by an asymmetry in the detector elements



$\mathrm{K_{L,S}} \to \ \pi^+ \ \pi^- \ \mathrm{e}^+ \ \mathrm{e}^-$ Branching Ratios

Branching Ratio:

$$\frac{BR(\mathrm{K_{L,S}} \to \ \pi^+ \ \pi^- \ \mathrm{e}^+ \ \mathrm{e}^-)}{BR(\mathrm{K_L} \to \ \pi^+ \ \pi^- \ \pi^0_\mathrm{D})} = \frac{N^{L,S}_{\pi\pi ee}}{N^{L,S}_{\pi\pi\pi^0_D}} \ \frac{A^{L,S}_{\pi\pi\pi^0_D}}{A^{L,S}_{\pi\pi ee}} \ R^{L,S}_{\epsilon} R^{L,S}_{K}$$

$$R^{L,S}_{\epsilon} = \epsilon_{\pi\pi\pi^0_D}/\epsilon_{\pi\pi ee} \simeq 1; \qquad R^L_K = 1; \qquad R^S_K \simeq 0.13$$

$\mathrm{K_L} \to \ \pi^+ \ \pi^- \ \mathrm{e}^+ \ \mathrm{e}^-$ $\quad BR = (3.08 \pm 0.20) \times 10^{-7}$

- **Main systematic uncertainty from the applied model and acceptance**

$\mathrm{K_S} \to \ \pi^+ \ \pi^- \ \mathrm{e}^+ \ \mathrm{e}^-$ $\quad BR = (4.69 \pm 0.30) \times 10^{-5}$

- **Main systematic uncertainty from acceptance**

The results are in agreement with Heiliger and Sehgal predictions

$K_L \rightarrow \pi^+ \pi^- e^+ e^-$ Form Factors

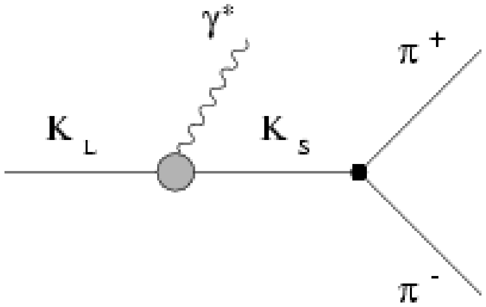
The form factor for the M1 DE has to be modified to include the effects related to the vector meson propagator:

$$g_{M1} \rightarrow \tilde{g_{M1}} \left[1 + \frac{a_2/a_1}{(M_\rho^2 - M_K^2) + 2 M_K E_\gamma^*} \right]$$

$$a_2/a_1 = (-0.81^{+0.07}_{-0.13}\ {}_{stat} \pm 0.02_{syst}) GeV^2$$

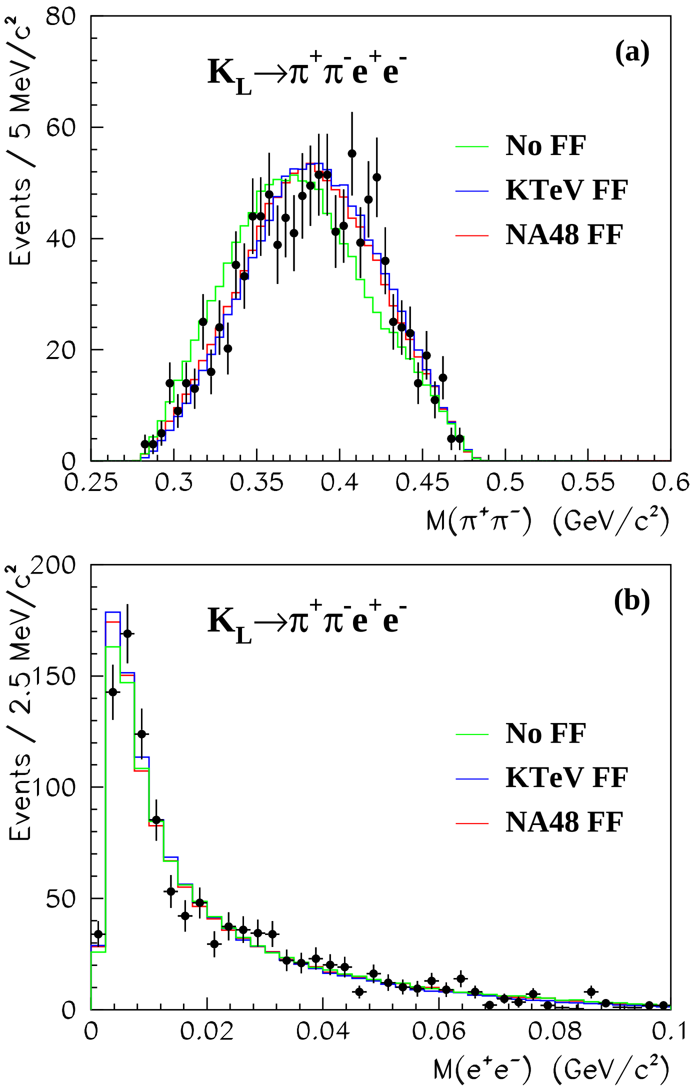
$$\tilde{g_{M1}} = 0.99^{+0.28}_{-0.27}\ {}_{stat} \pm 0.07_{syst}$$

Charge Radius:



$$g_{CR} = 0.19 \pm 0.04_{stat} \pm 0.02_{syst}$$

In agreement with KTeV results

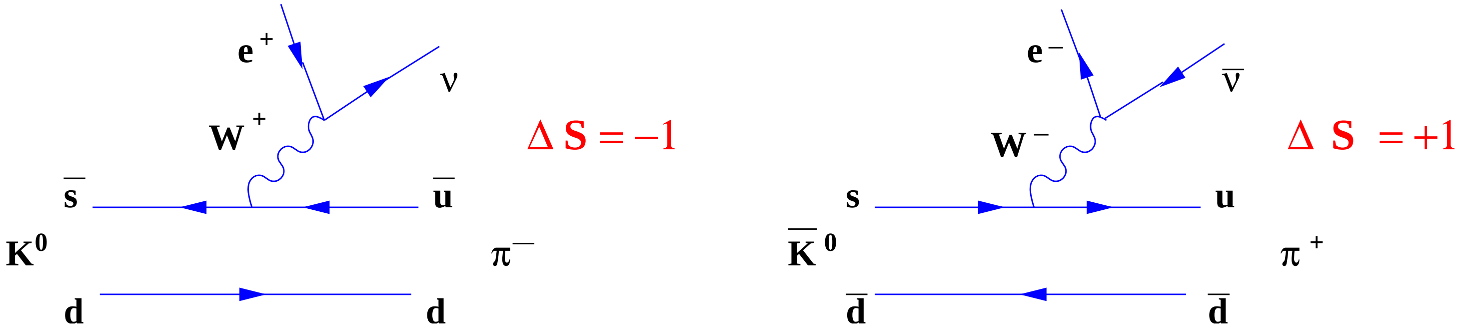


K_{e3} Charge Asymmetry

The charge asymmetry δ_ℓ in $\mathrm{K_L}$ semi–leptonic decays is another manifestation of indirect CP violation

Assuming CPT conservation and $\Delta S = \Delta Q$ rule:

$$\delta_e = \frac{BR(K_L \to \pi^- e^+ \nu_e) - BR(K_L \to \pi^+ e^- \bar{\nu}_e)}{BR(K_L \to \pi^- e^+ \nu_e) + BR(K_L \to \pi^+ e^- \bar{\nu}_e)} \simeq 2\Re e(\epsilon)$$



$\Delta S = \Delta Q$ not an exact rule in SM

Expected violation in 2^{nd} order processes

$$\delta_e = 2\Re e(\epsilon)\frac{1-|x|^2}{|1-x|^2} \qquad x = \frac{A(\bar{K}^0 \to \pi^- e^+ \nu_e)}{A(K^0 \to \pi^- e^+ \nu_e)} \quad |x| \simeq 10^{-7} \div 10^{-6}$$

Beyond the sensitivity of this measurement

δ_e The Measurement

- **Counting experiment**

$$\delta_e = \frac{N(K_{e3}^{+}) - N(K_{e3}^{-})}{N(K_{e3}^{+}) + N(K_{e3}^{-})}$$

- **Data collected in 2001**
- $\sim 2 \times 10^{8}\ K_{e3}$ **events selected**
- **Knowledge of the detector response to the different charges at the level of 10^{-5} required**

  $\Rightarrow$ **Corrections for fake asymmetries:**

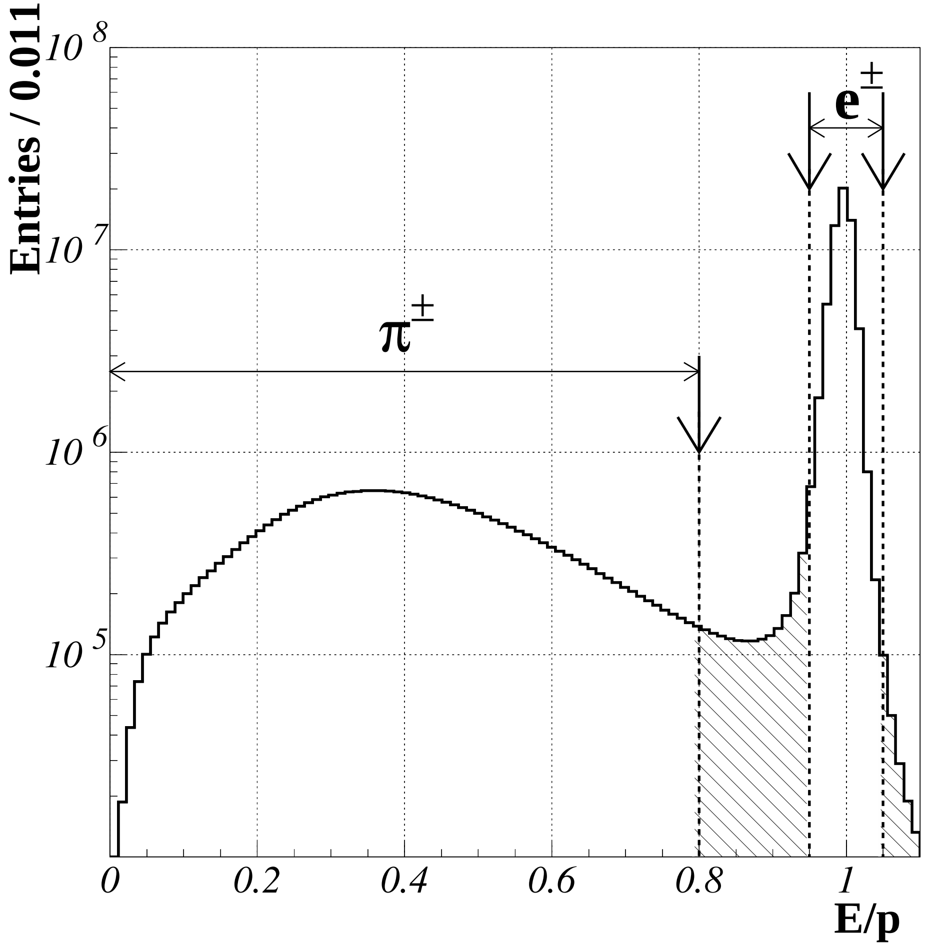
$$\delta_e^{TRUE} \simeq \delta_e^{MEAS} + \frac{\Delta\mathcal{P}}{2}$$

- **Background dangerous only if charge asymmetric**

  $\Rightarrow$ **Negligible, the differencies $\pm$ are at the level of $\sim 10^{-6}$**

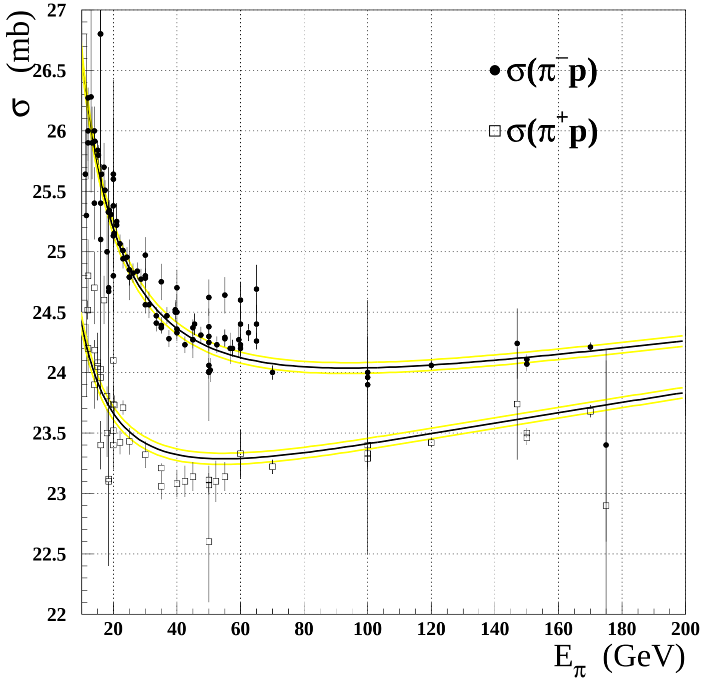
δ_e Event Selection

- **1 vertex with 2 tracks ($\pm$)**
- **P $>$ 10 GeV/c**
- **e, π identified by E/P:**
  $\pi \quad E/P < 0.8$
  $e \quad 0.95 < E/P < 1.05$
- **NO hits in MUV**
- **$P_0'^2$ cut to remove $\pi^+\pi^-\pi^0$**



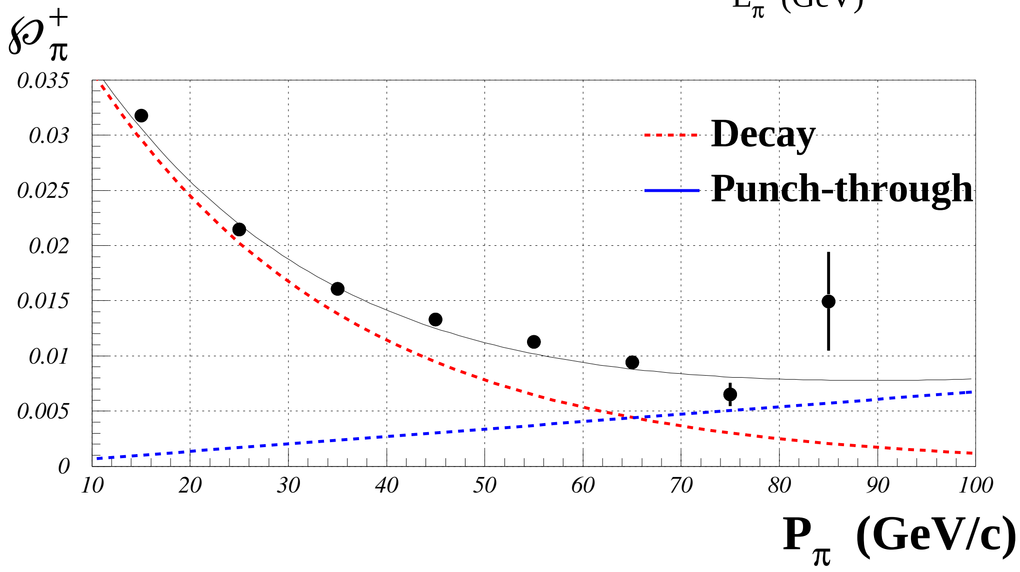
δ_e Corrections for π Interactions

Differencies in π^+/π^- energy deposition
$\Rightarrow$ Fake asymmetries
Ionization: charge insensitive
Nuclear interactions: $\mathcal{P}^+ \neq \mathcal{P}^-$
especially at low π momenta



Need corrections for:

Trigger: $2trk \times E_{TOT}$
requires total energy in LKR and
HAC $>$ 35 GeV
$\rightarrow$ use control sample to evalute $\epsilon^{\pm}_{ETOT}$



Pion ID (through E/P cut)

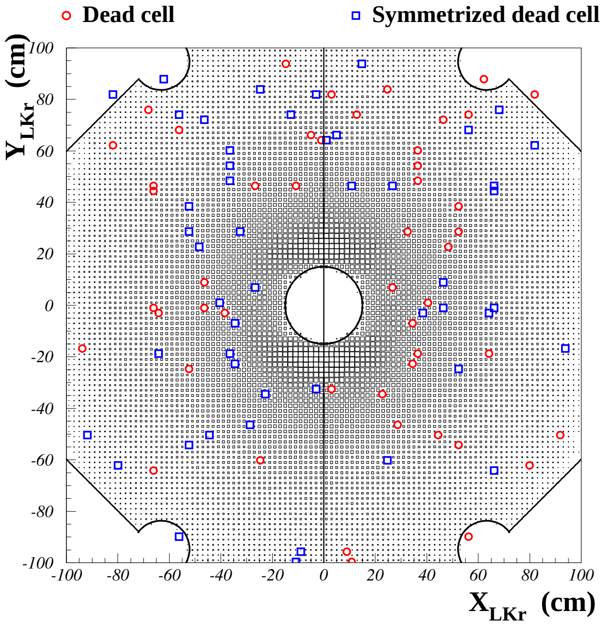
π punchthrough
(events with μ are rejected)
$\rightarrow$ use $\pi^+\pi^-\pi^0$ sample

δ_e Acceptance Corrections

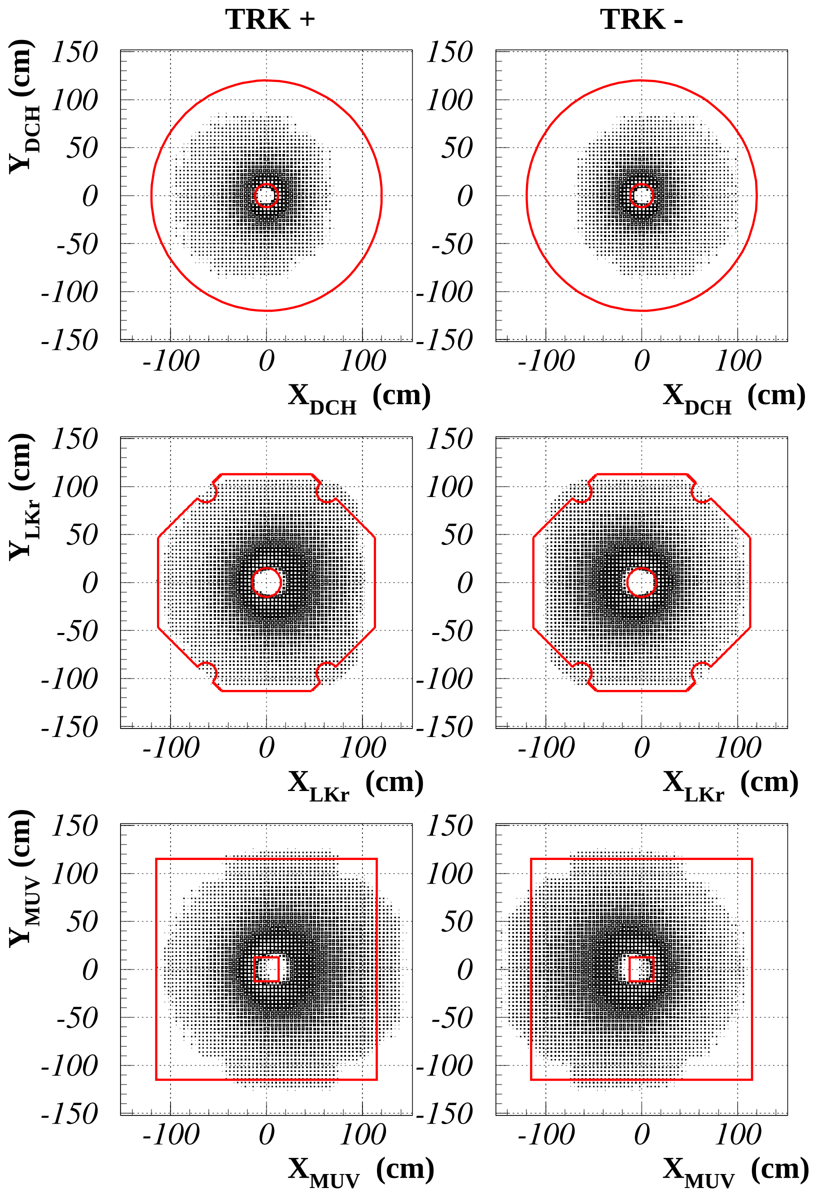
Possible left–right detector asymmetries (misalignements, not uniform detection efficiency)

Cured with periodic magnetic field inversion

Symmetrization of LKR dead cell cut

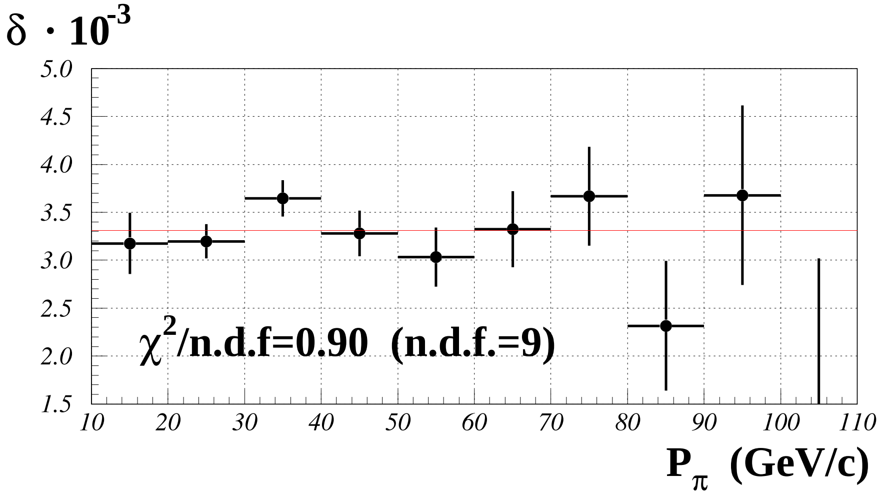


Use MC to evaluate residual effects



δ_e Preliminary Result

Corrections	10^{-5}		
Trigger	+25.7	±	5.8
Pion ID	-16.7	±	2.4
Punch Trough	-1.9	±	2.3
Acceptance		±	2.0
Background		±	0.3



$$\delta_e = (3.319 \pm 0.070_{stat} \pm 0.068_{syst}) \times 10^{-3}$$

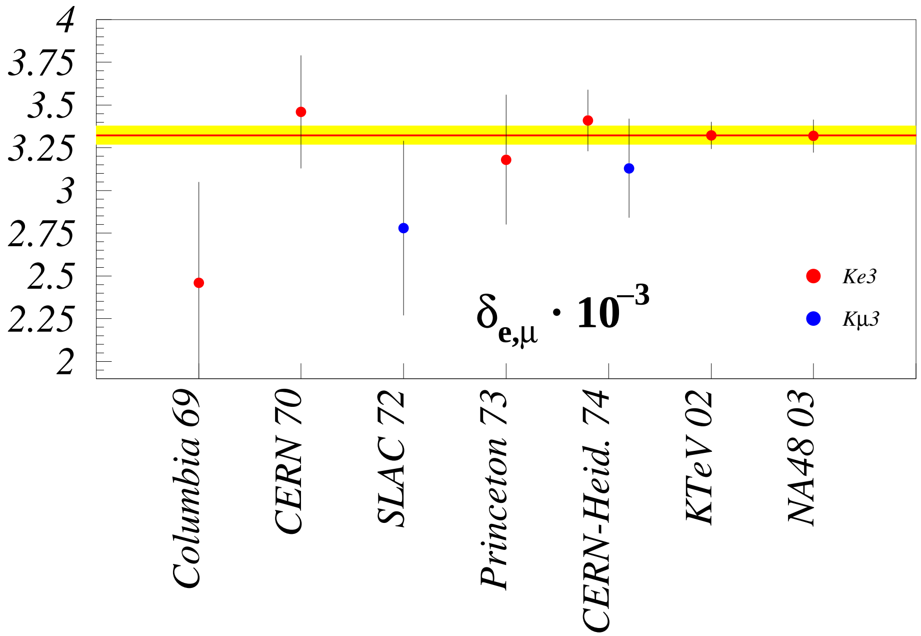
New world averages:

$$\boxed{\delta_e = (3.323 \pm 0.056) \times 10^{-3}}$$

$$\delta_\ell = (3.309 \pm 0.055) \times 10^{-3} \ (\chi^2/ndf = 4.2/7)$$

CPT test using 2π data:

$$\Re e(Y + \frac{x - \bar{x}}{2} + a) = (-5 \pm 33) \times 10^{-6}$$



Summary

Latest results from $K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$ and δ_e

But NA48 is much more than this:

- **Rare Kaon decays**
- **Rare Hyperon decays**
- **Direct CP violation (next talk):**
  - $Re\left(\frac{\epsilon'}{\epsilon}\right)$
  - **Charged Kaon program**