Search for Direct $\mathcal{CP}$ Violation and $|V_{us}|$ Measurement from NA48/2 $K^{\pm}$ Decays

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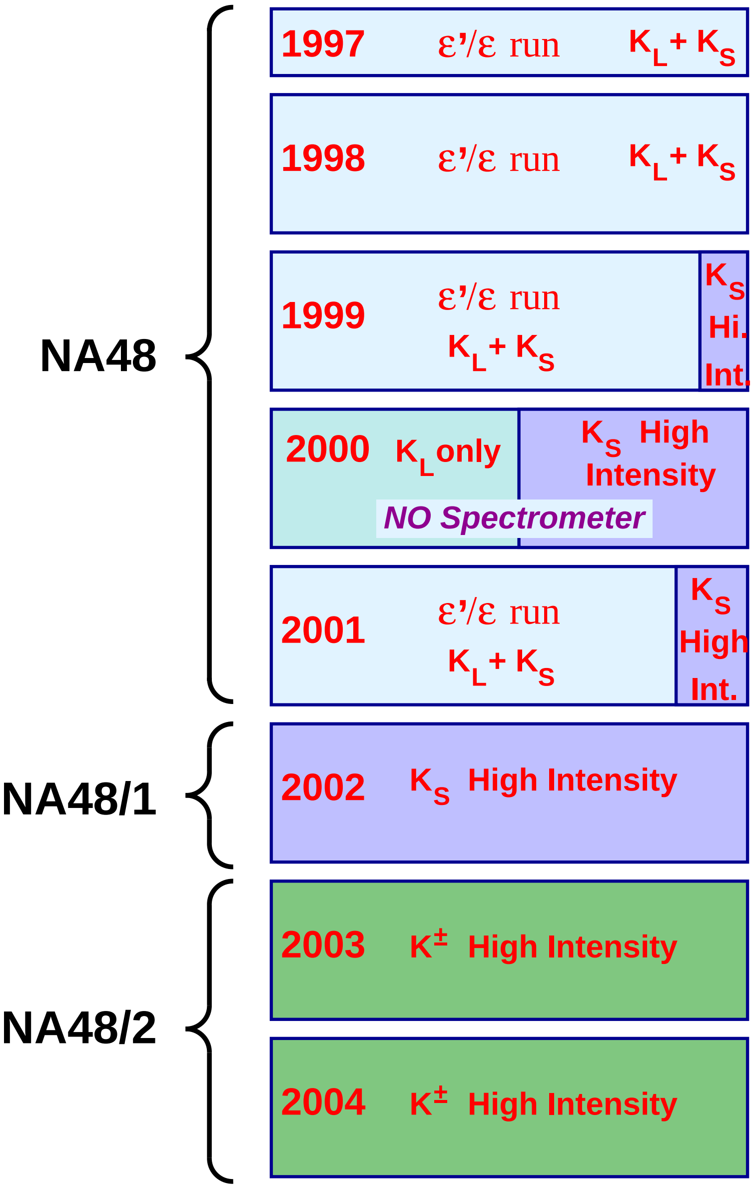
Overview

- $\mathcal{CP}$ Violation
  - Search for Direct $\mathcal{CP}$ Violation in $K^{\pm} \rightarrow 3\pi$ Decays
- $|V_{us}|$ Measurement
  - Precise Measurement of $K^{\pm}_{e3}/K^{\pm}_{2\pi}$ and $K^{\pm}_{\mu 3}/K^{\pm}_{2\pi}$
- Measurement of $\mathrm{K_S e3/K_L e3}$



The NA48 Detector

Detector components:

- **Magnet spectrometer**

  4 sets of drift chambers.

  $\Delta p/p \leq 1\%$ for $p = 20$ GeV/c.

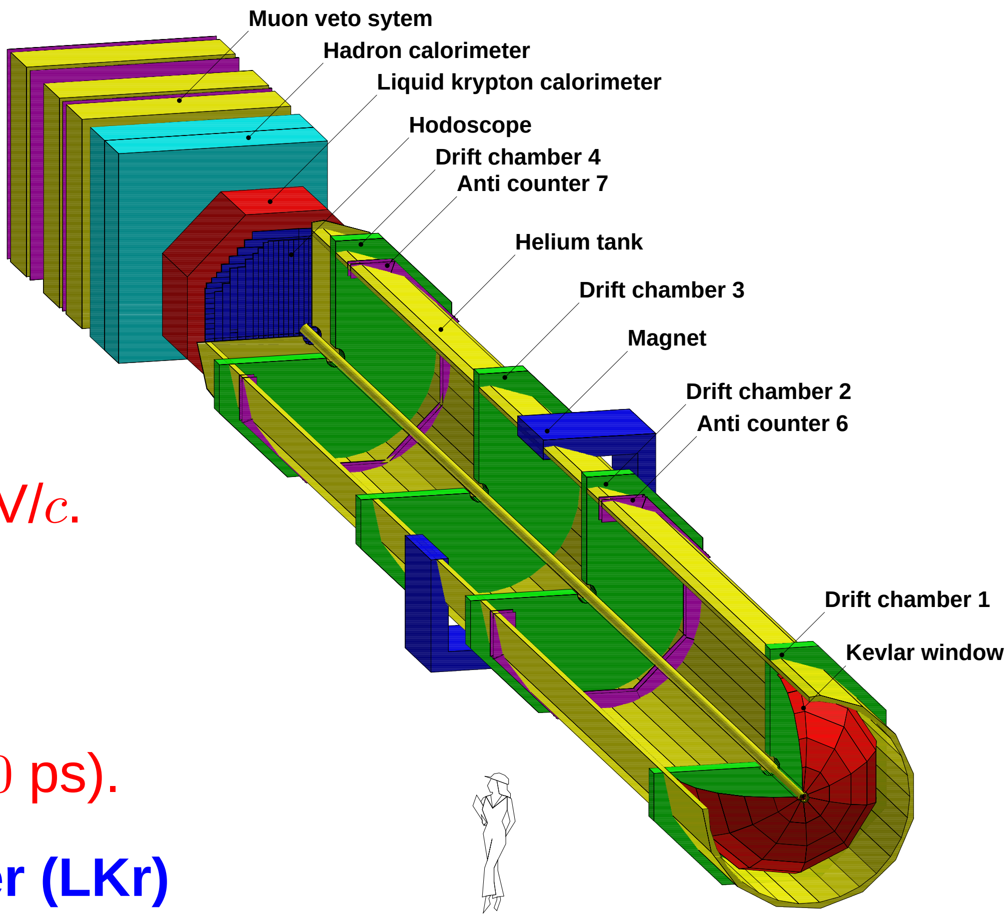
- **Hodoscopes:**

  Fast trigger, precise time measurement ($\sigma_t = 150$ ps).

- **Liquid Krypton Calorimeter (LKr)**

  $\Delta E/E \approx 1.0\%$ for $E_{e,\gamma} = 20$ GeV/c.

- **Hadron calorimeter, photon vetos, muon counters**



Search for Direct CP Violation in $K^{\pm} \rightarrow 3\pi$ Decays

Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm\pi\pi$

$\mathcal{CP}$ violation in $\mathbf{K^\pm \to 3\pi}$:

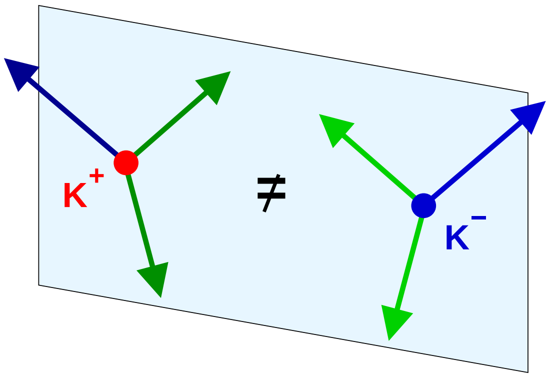
- Possibility for **direct $\mathcal{CP}$ violation** in the $K^\pm$ system:
  — SM $\sim \mathcal{O}(10^{-5} - 10^{-6})$ (Gamiz, Prades, Scimeni, JHEP 10 (2003) 042).
  — New Physics (SUSY) could boost it up to $\mathcal{O}(10^{-4})$.
  (Experimental limit so far: $\mathcal{O}(10^{-3})$.)

Method:

- Rate asymmetry $\boldsymbol{\Gamma(\mathrm{K}^+) \neq \Gamma(\mathrm{K}^-)}$ experimentally not simple.
- **Better:** Measure difference in **Dalitz plot slopes!**
- $\mathbf{K^\pm \to \pi^\pm\pi\pi}$ **matrix element:**

$$|\mathcal{M}(\mathbf{u},\mathbf{v})|^2 \sim 1 + \mathbf{g}\,\mathbf{u} + \mathbf{h}\mathbf{u}^2 + \mathbf{k}\mathbf{v}^2 + \cdots$$

with: $u = (s_3 - s_0)/m_\pi^2$, $v = (s_2 - s_1)/m_\pi^2$



- **Direct $\mathcal{CP}$ violating asymmetry:**

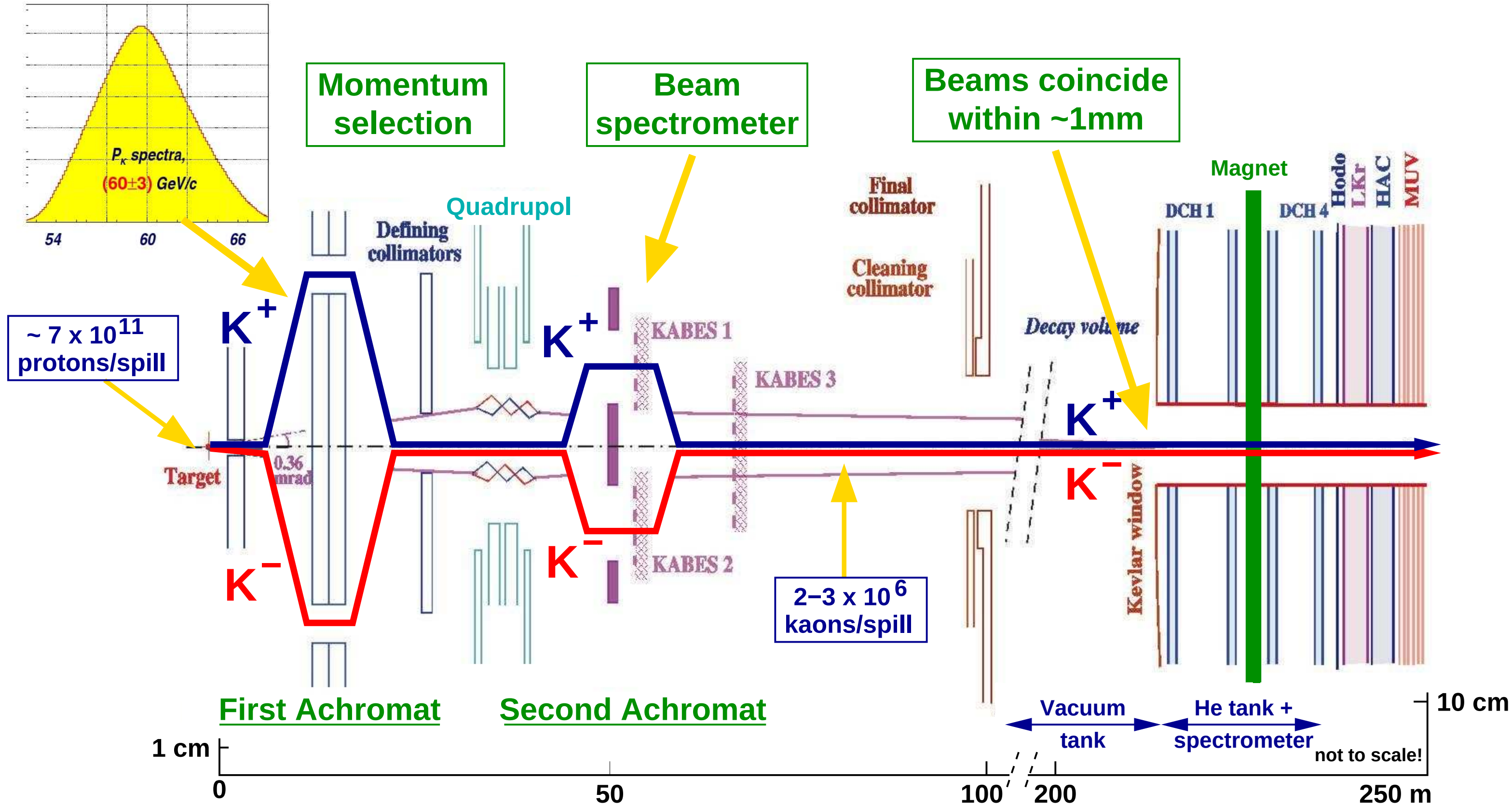
$$\mathbf{A_g} = \frac{\mathbf{g}^+ - \mathbf{g}^-}{\mathbf{g}^+ + \mathbf{g}^-} = \frac{\mathbf{\Delta g}}{\mathbf{2g}}$$

$$g^+ \equiv g(K^+ \to \pi^+\pi\pi)$$
$$g^- \equiv g(K^- \to \pi^-\pi\pi)$$

Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm\pi\pi$

NA48/2 experiment in 2003/2004:

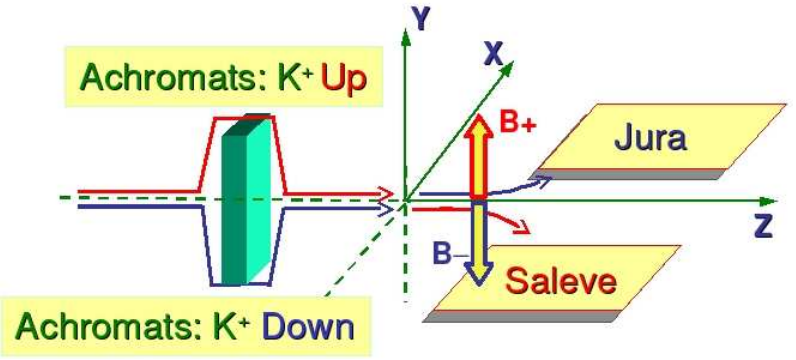
- **Simultaneous K^+ and K^- beams** with $p_{K^\pm} = (60 \pm 3)$ GeV/c.



Search for $\mathcal{CP}$ Violation in $K^{\pm} \to \pi^{\pm}\pi\pi$

Symmetrization of the running conditions:

- Weekly polarity change of the kaon beam-line (achromat).
- Daily polarity change of spectrometer magnet. (every few hours in 2004)



Example: Data taking from Aug 6 to Sep 7, 2003:

1. Week	Achromat –	B+	B-	B+	B-	B+	B-	Supersample 1 12 subsamples
2. Week	Achromat +	B+	B-	B+	B-	B+	B-	
3. Week	Achromat –	B+	B-	B+	B-	B+	B-	Supersample 2 12 subsamples
4. Week	Achromat +	B+	B-	B+	B-	B+	B-	
5. Week	Achromat –	B+	B-					Supersample 3 4 subsamples
	Achromat +	B+	B-					

1 Day

Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm\pi\pi$

Data selection:

- $\mathbf{K^\pm \to \pi^\pm\pi^+\pi^-}$:
  - Just three charged tracks with common vertex, consistent with a $K^\pm \to \pi^\pm\pi^+\pi^-$ decay.
  - No LKr information needed.
  - **Trigger:** 3-track-trigger, integrated efficiency $\sim \mathbf{99.9\%}$.

- $\mathbf{K^\pm \to \pi^\pm\pi^0\pi^0}$:
  - One charged track and 4 photons, consistent with a $K^\pm \to \pi^\pm\pi^0\pi^0$ decay from a common vertex.
  - **Trigger:** 1 track $+ \geq 2$ Lkr clusters. Missing-mass requirement for $\pi^\pm\pi^0$ suppression. Integrated efficiency $\approx \mathbf{99.75\%}$

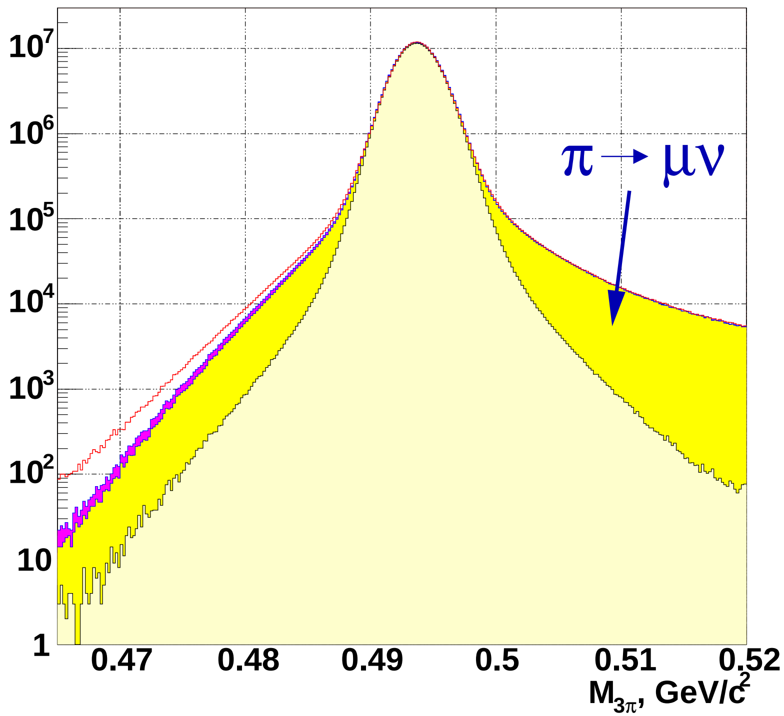
Search for $\mathcal{CP}$ Violation in $K^{\pm} \to \pi^{\pm}\pi\pi$

Total Yields: (practically bkg-free)

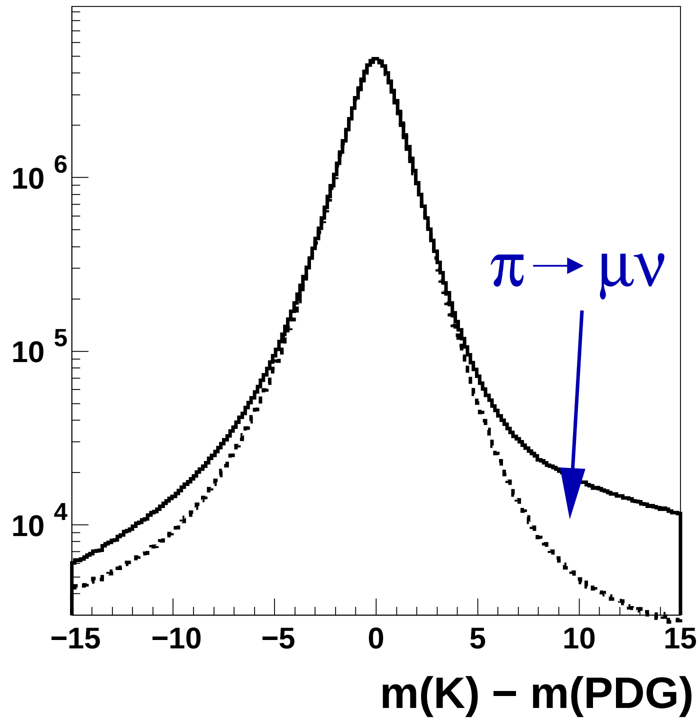
$\mathbf{K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}}$: $\mathbf{3.1 \times 10^{9}}$ **events**

$\mathbf{K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}}$: $\mathbf{9.1 \times 10^{7}}$ **events**

$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

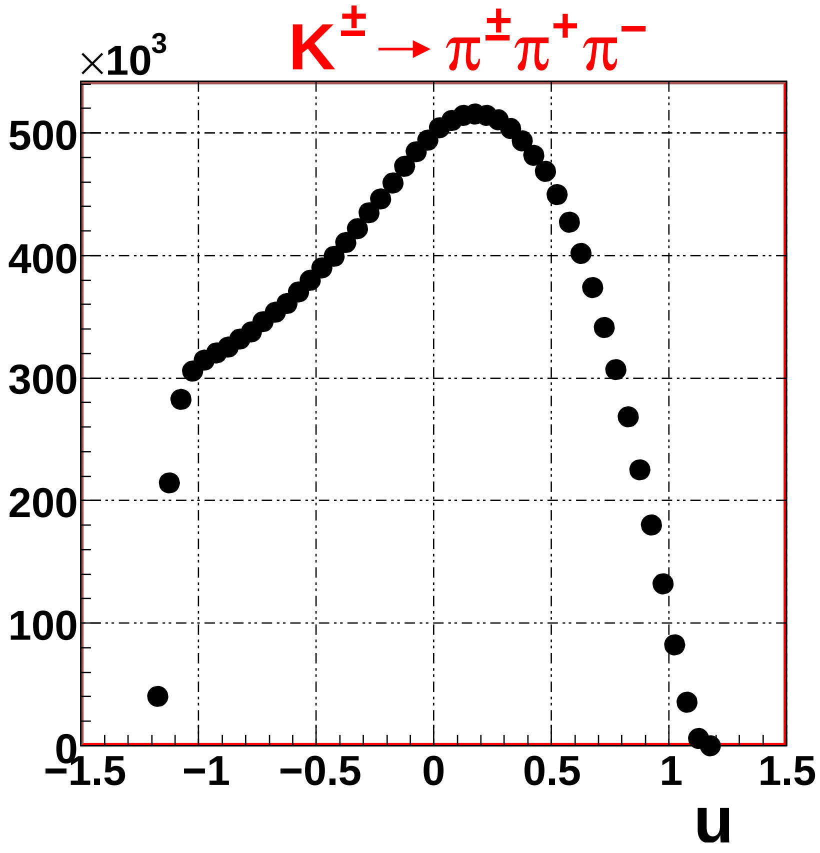


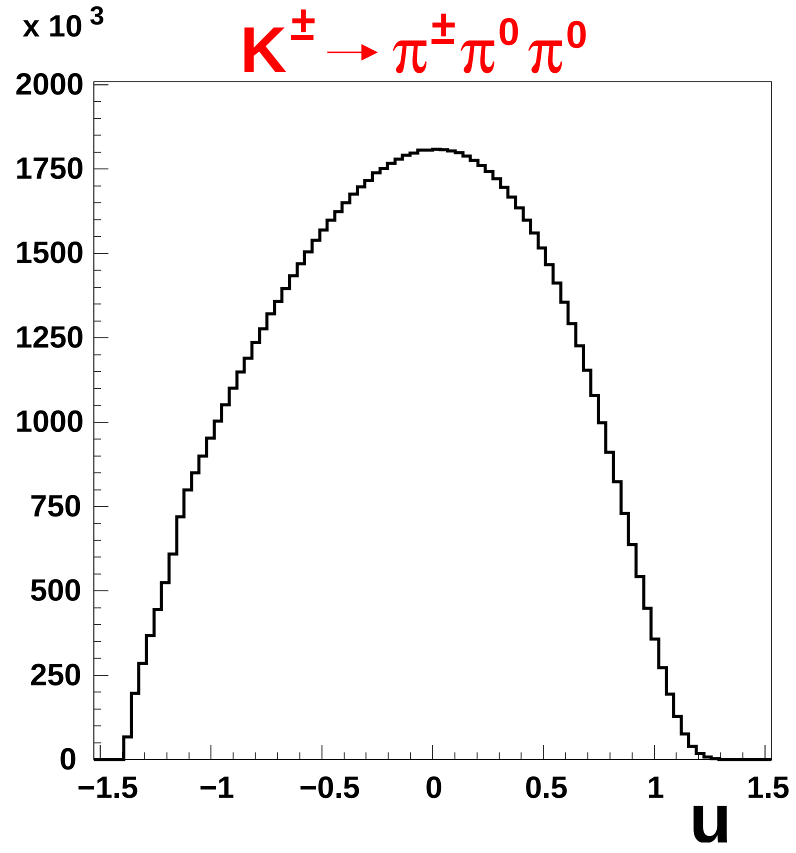
$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$



Search for $\mathcal{CP}$ Violation in $K^{\pm} \to \pi^{\pm}\pi\pi$

Dalitz plot projections on u: (full NA48/2 data set)





Search for $\mathcal{CP}$ Violation in $K^{\pm} \to \pi^{\pm}\pi\pi$

Extraction of Δg:

- $|\mathcal{M}(\mathbf{u})|^2 \approx \mathbf{1} + \mathbf{g\,u} + \mathbf{h\,u^2} + \cdots$ ($k\,v^2$ negligible)

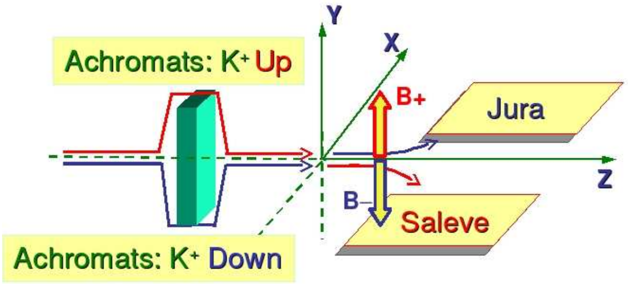
$$\Longrightarrow \quad \mathbf{R(u)} \equiv \frac{\mathbf{N^+(u)}}{\mathbf{N^-(u)}} \propto \mathbf{1} + \frac{\mathbf{\Delta g\,u}}{\mathbf{1+g\,u+h\,u^2}}$$

- **Cancellation of systematics:** Compare similar data samples:

  K^+ and K^- with opposite Achromat polarity (**U**p $\leftrightarrow$ **D**own) and opposite Spectrometer polarity (**J**ura $\leftrightarrow$ **S**aleve)

  $\Longrightarrow$ 4 separate single ratios for 4 possible K^+ paths:

  $\mathbf{R_{UJ}(u)},\ \mathbf{R_{US}(u)},\ \mathbf{R_{DJ}(u)},\ \mathbf{R_{DS}(u)}$



- **Fit quadruple ratio:**

$$\mathbf{R^4(u)} \equiv \mathbf{R_{UJ}(u)} \cdot \mathbf{R_{US}(u)} \cdot \mathbf{R_{DJ}(u)} \cdot \mathbf{R_{DS}(u)} = \mathbf{N}\left(\mathbf{1} + \frac{\mathbf{\Delta g\,u}}{\mathbf{1+g\,u+h\,u^2}}\right)^{\mathbf{4}}$$

Search for $\mathcal{CP}$ Violation in $K^{\pm} \to \pi^{\pm}\pi\pi$

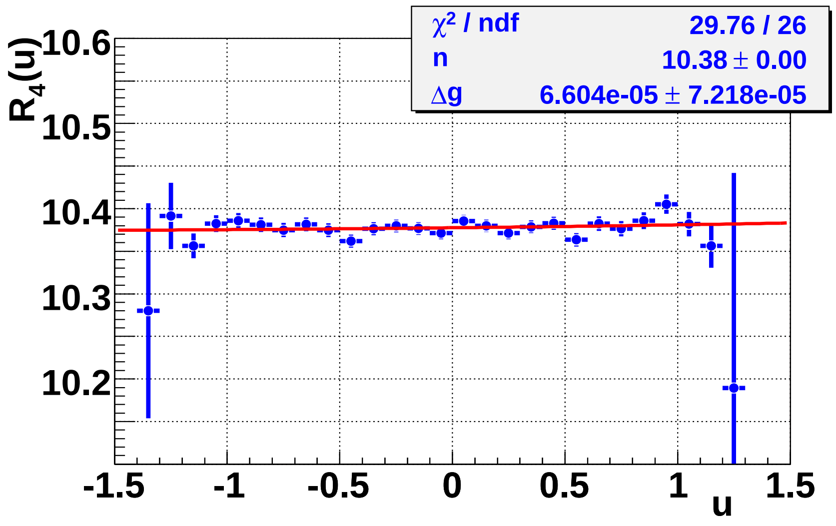
Slope difference for $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$:

$$\Delta g^{\pi^{\pm}\pi^{+}\pi^{-}} = (0.7 \pm 0.7_{\text{stat}} \pm 0.4_{\text{trig}} \pm 0.6_{\text{syst}}) \times 10^{-4}$$

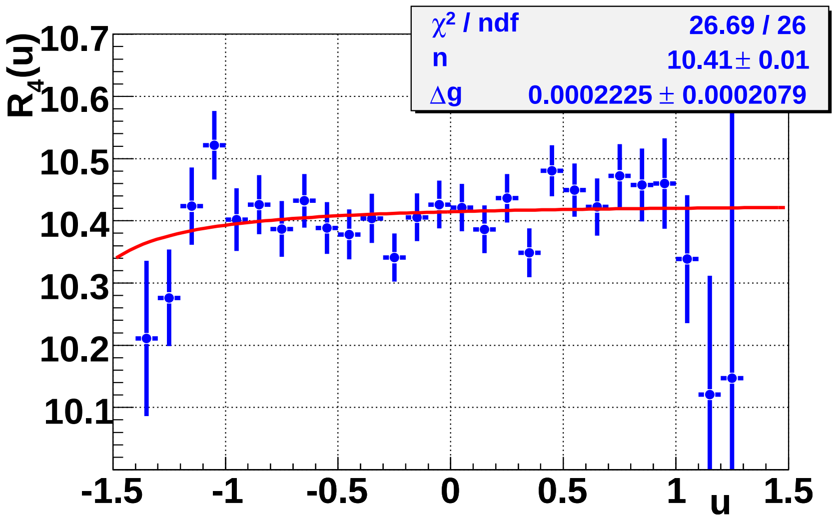
Slope difference for $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$:

$$\Delta g^{\pi^{\pm}\pi^{0}\pi^{0}} = (2.2 \pm 2.1_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4}$$

$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$



$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$

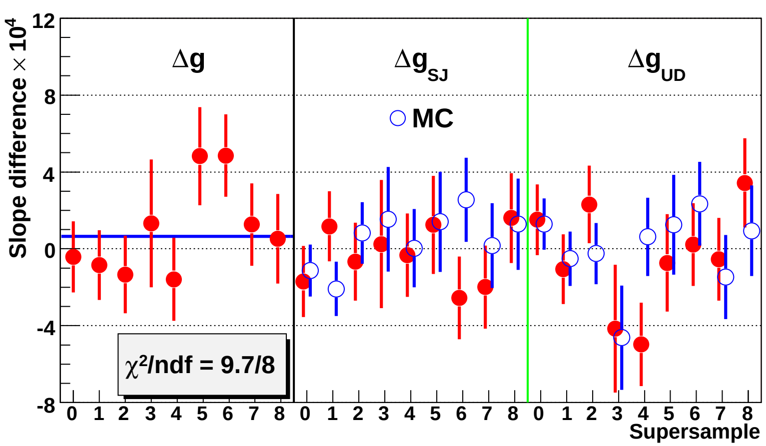


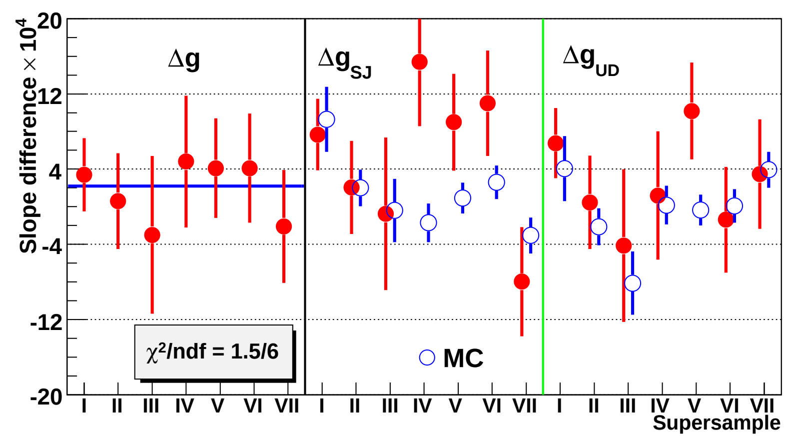
Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm\pi\pi$

$\mathbf{K^\pm \to \pi^\pm\pi^+\pi^-}$	$\mathbf{10^4} \times \delta(\mathbf{\Delta g})$
Spectrom. alignment	± 0.1
Spectrom. B field	± 0.3
Beam geometry	± 0.2
Pile-up	± 0.2
Resolution/fitting	± 0.2
Total	$\mathbf{\pm 0.5}$
Trigger (stat.)	$\mathbf{\pm 0.4}$

$\mathbf{K^\pm \to \pi^\pm\pi^0\pi^0}$	$\mathbf{10^4} \times \delta(\mathbf{\Delta g})$
Shower overlap	± 0.5
L1 inefficiency	± 0.1
L2 inefficiency	± 0.3
Stray magn. fields	± 0.1
Pile-up	± 0.2
Total	$\mathbf{\pm 0.6}$

$\Longrightarrow$ Check analyses with non-asymmetric control samples:





Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm\pi\pi$

For final result on charge asymmetry build

$$\mathbf{A_g} = \frac{\mathbf{g^+ - g^-}}{\mathbf{g^+ + g^-}} = \frac{\mathbf{\Delta g}}{\mathbf{2g}}$$

with: $\mathbf{g(\pi^\pm\pi^+\pi^-) = -0.21134}$ and $\mathbf{g(\pi^\pm\pi^0\pi^0) = 0.626}$.

<u>**Final NA48/2 result for $\mathbf{K^\pm \to \pi^\pm\pi^+\pi^-}$:**</u> (EPJ C52 (2007) 852)

$$\mathbf{A_g = (-1.5 \pm 1.5_{\text{stat}} \pm 0.9_{\text{trig}} \pm 1.3_{\text{syst}}) \times 10^{-4}}$$

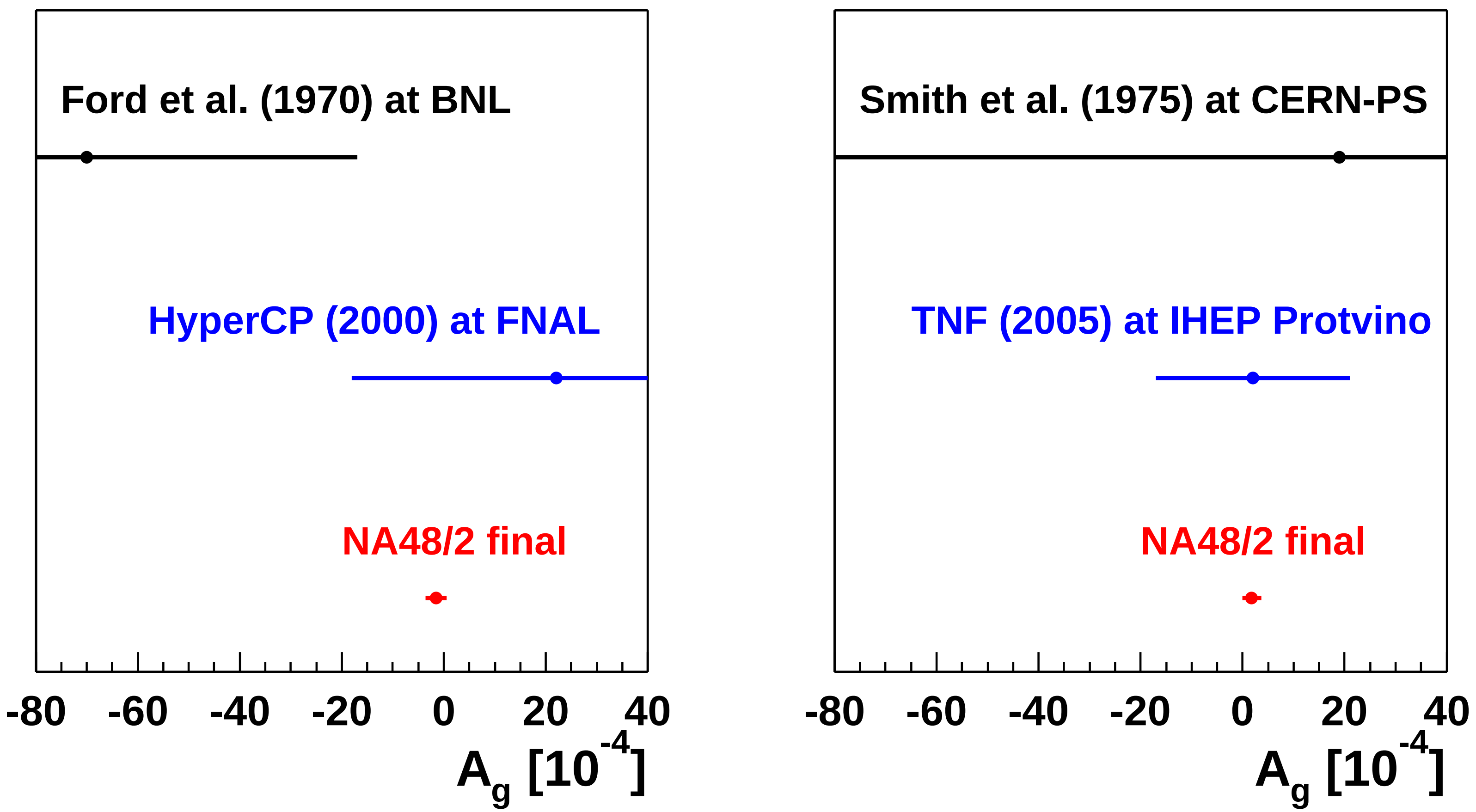
<u>**Final NA48/2 result for $\mathbf{K^\pm \to \pi^\pm\pi^0\pi^0}$:**</u> (as above)

$$\mathbf{A_g = (1.8 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4}}$$

$\Longrightarrow$ **No indication for CP violation in $\mathbf{K^\pm}$ beyond the SM!**

Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm \pi\pi$

Comparsion with previous measurements:



$|\mathbf{V_{us}}|$ Measurement

$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

Minimum bias data taking in 2003:

- 8 hours low intensity K^+/K^- with min. bias trigger.

  $\Longrightarrow$ Measurement of leptonic and semileptonic decays.

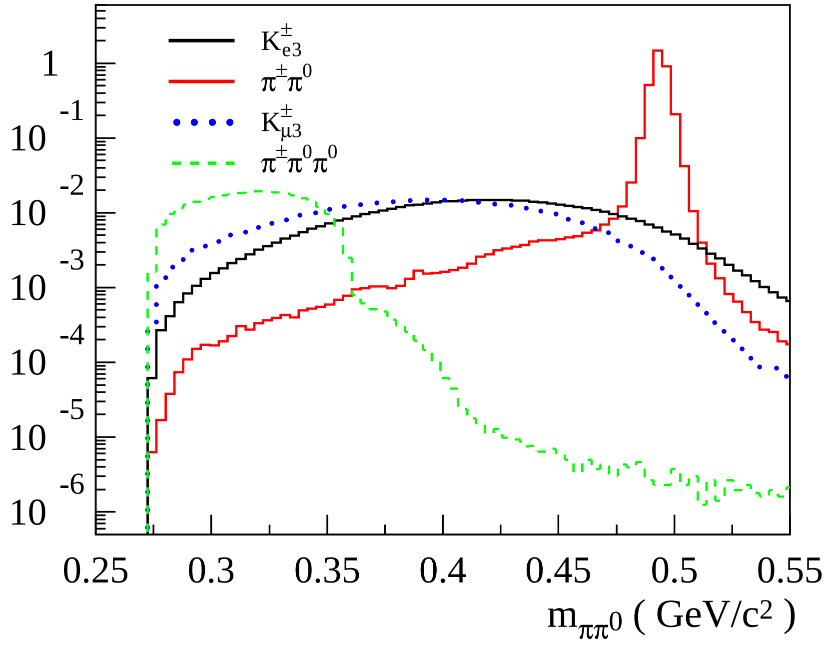
Method of the Measurement:

- Normalize K_{e3} and $K_{\mu 3}$ to $K_{2\pi}$

  $\Longrightarrow$ very similar topologies and selection criteria.

- Select one track $+$ two photons, consistent with a π^0 from a common decay vertex.

- Distinction of K_{l3} and $K_{2\pi}$ mainly through kinematics.



$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

Particle identification:

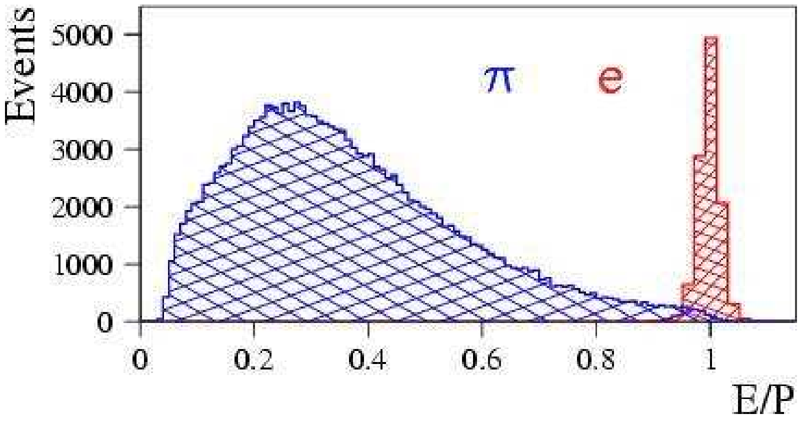
- **Electrons:** $\mathbf{E/p > 0.95}$

  $\Longrightarrow$ Efficiency $\approx \mathbf{98.6\%}$

- **Pions:** $\mathbf{E/p < 0.95}$

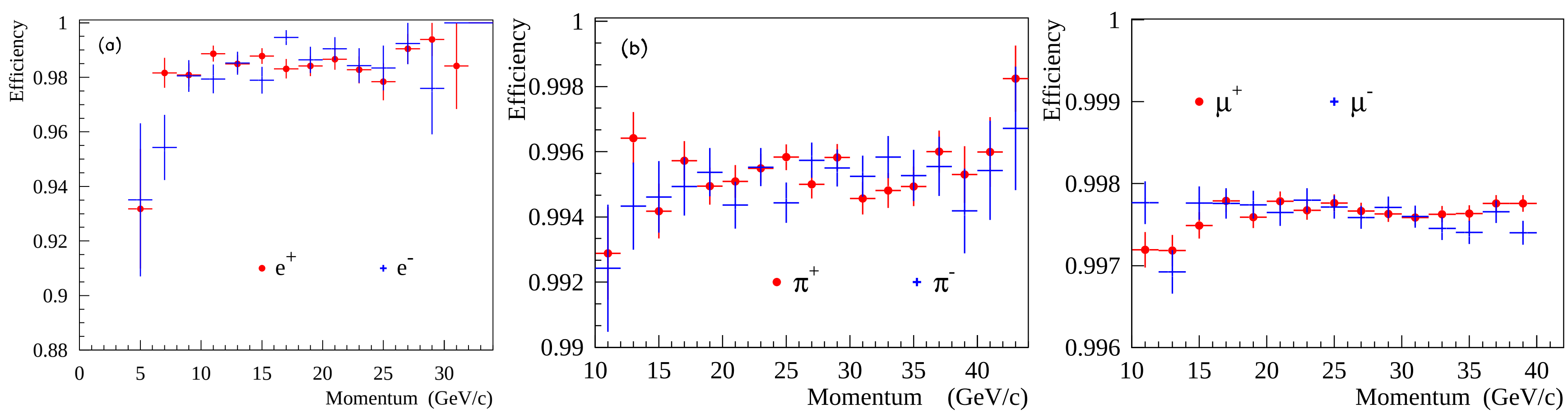
  $\Longrightarrow$ Efficiency $\approx \mathbf{99.5\%}$

Illustration from data



- **Muons:** In-time hits in first two muon counters.

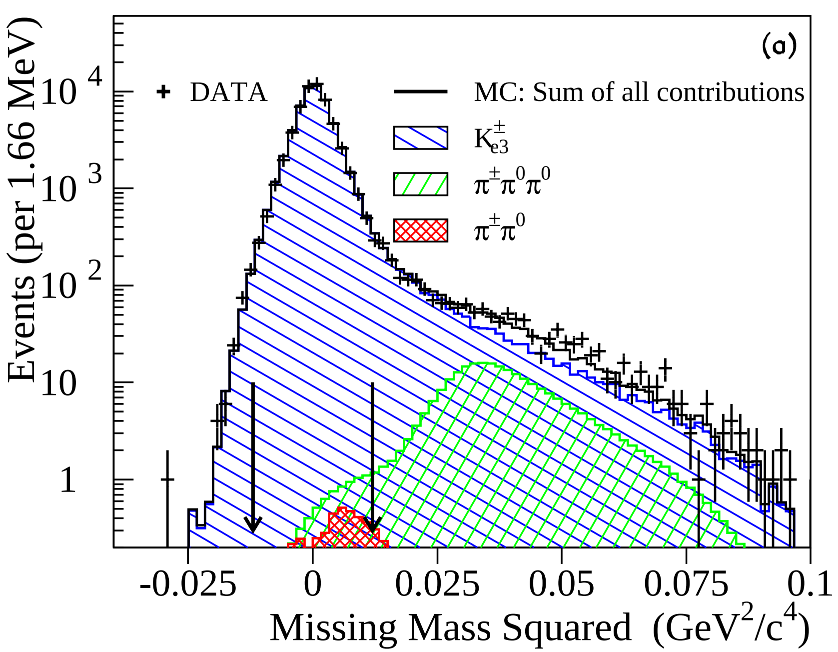
  $\Longrightarrow$ Efficiency $\approx \mathbf{99.8\%}$

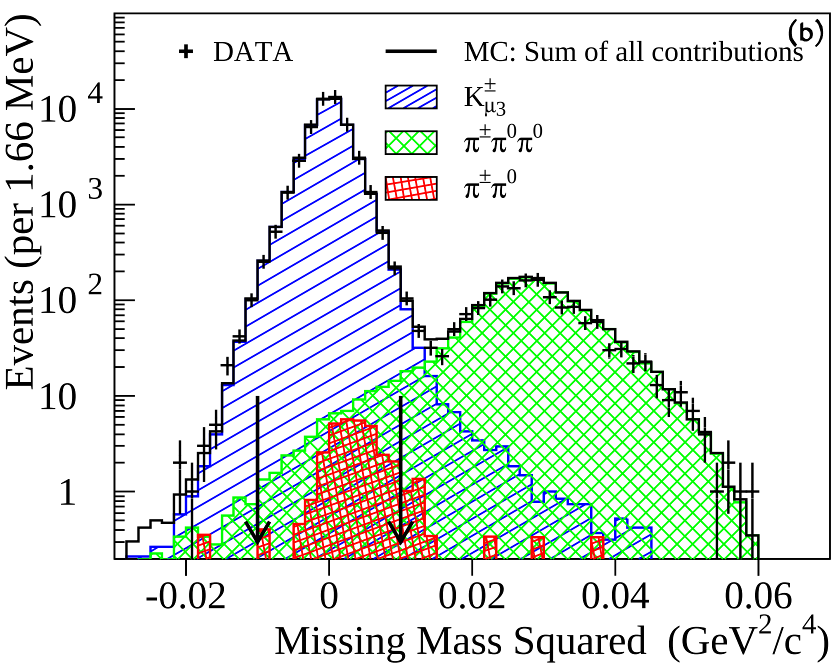


$|V_{us}|$ Measurement from $K_{l3}^{\pm}$

Yields after all selection criteria applied:

Channel	Acc × P-ID	K$^+$	K$^-$	Background
Ke3	$\sim 7.0\%$	**56 195**	**30 898**	$< 0.1\%$
Kμ3	$\sim 9.3\%$	**49 364**	**27 525**	$\sim 0.2\%$
K2π	$\sim 14.2\%$	**461 837**	**256 619**	$\sim 0.3\%$

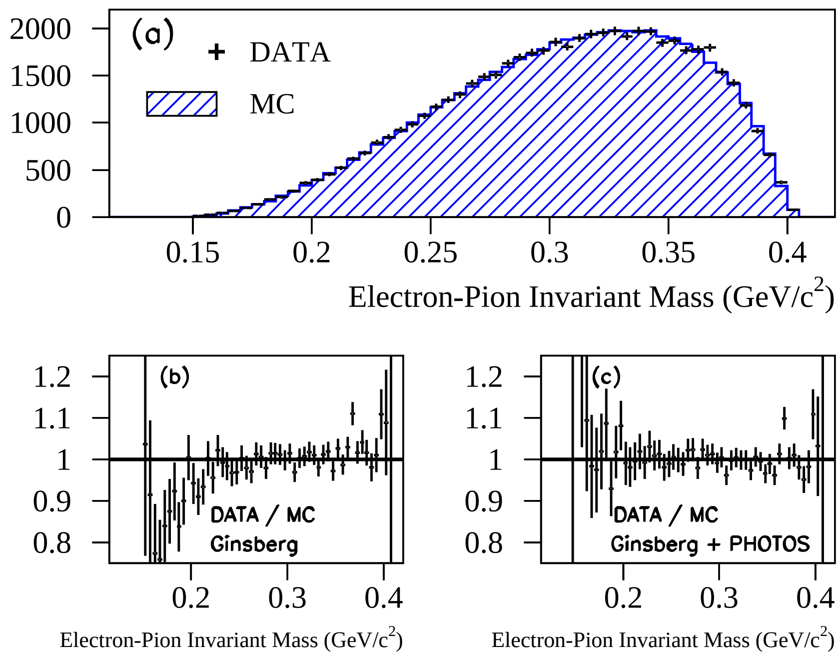


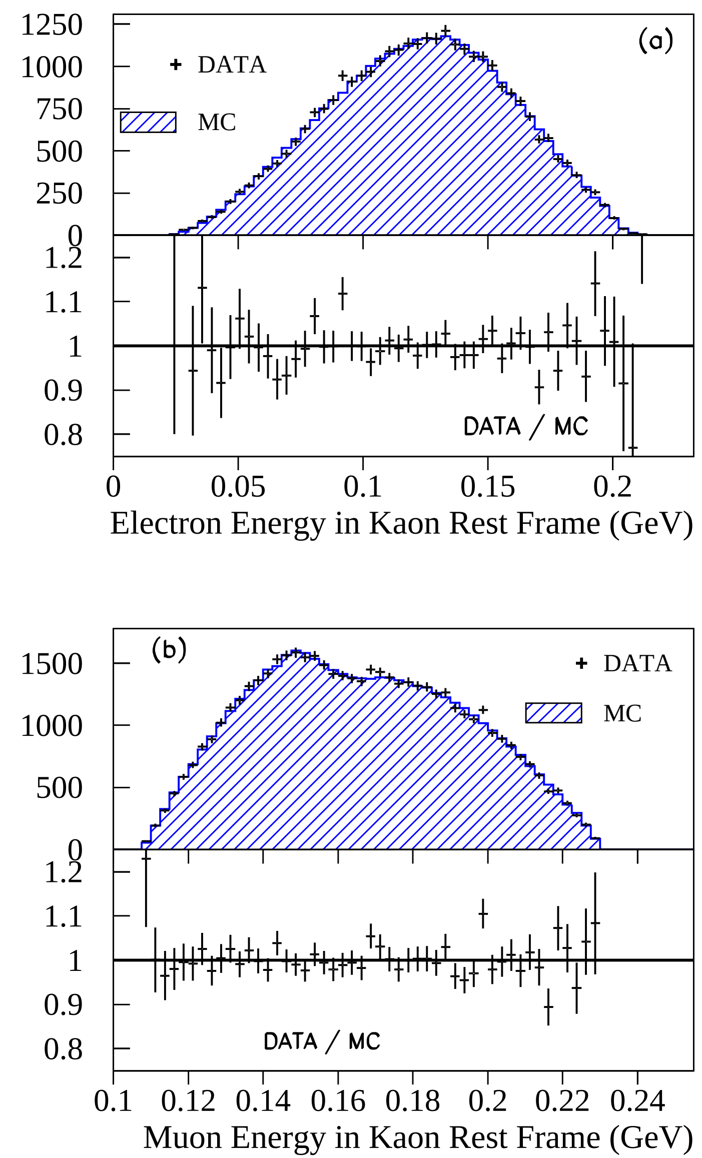


$|V_{us}|$ Measurement from $K^{\pm}_{l3}$

Radiative corrections:

- Using **Ginsberg** prescription for real and virtual photons.
- Real bremsstrahlung photons added with **PHOTOS.**





$\Longrightarrow$ **Very good description of data!**

$|V_{us}|$ *Measurement from* $K^{\pm}_{l3}$

Form factors:

- Quadratic expansion for $f_+(t)$ ($\lambda'_+ = 0.02485(163)$, $\lambda''_+ = 0.00192(62)$) and linear expansion for $f_0(t)$ ($\lambda_0 = 0.00196(34)$) from PDG'06.
- Form factor variations within their errors and difference to pole model parametrization taken as systematic uncertainties.

Results:

$$\mathcal{R}_{\mathbf{Ke3/K2\pi}} = \mathbf{0.2470} \pm \mathbf{0.0009}_{\text{stat}} \pm \mathbf{0.0004}_{\text{sys}}$$

$$\mathcal{R}_{\mathbf{K\mu3/K2\pi}} = \mathbf{0.1636} \pm \mathbf{0.0006}_{\text{stat}} \pm \mathbf{0.0003}_{\text{sys}}$$

Accuracy of 0.4%!

Systematics:

- $\mathbf{Ke3/K2\pi}$: Mainly $Ke3$, $K2\pi$ acceptance, trigger efficiency.
- $\mathbf{K\mu3/K2\pi}$: Mainly $K\mu3$ form factors and $Ke3$, $K2\pi$ acceptance.

Statistical uncertainties dominate

$|V_{us}|$ *Measurement from* $K^{\pm}_{l3}$

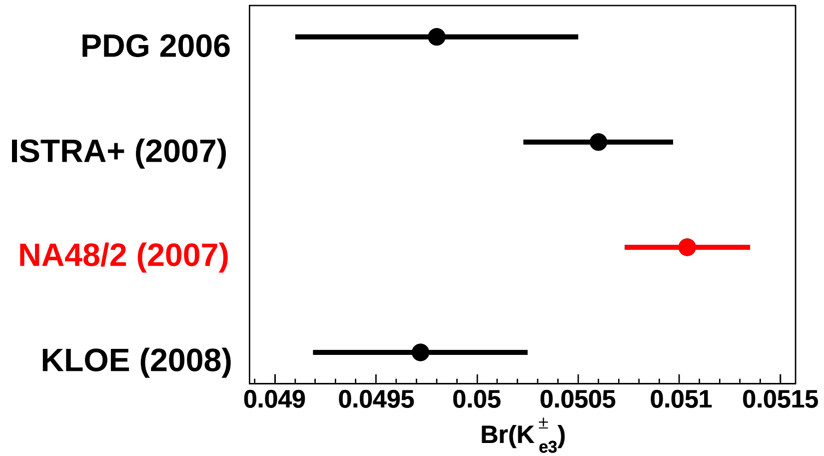
Absolute BR's: *(Update w.r.t. publication)*

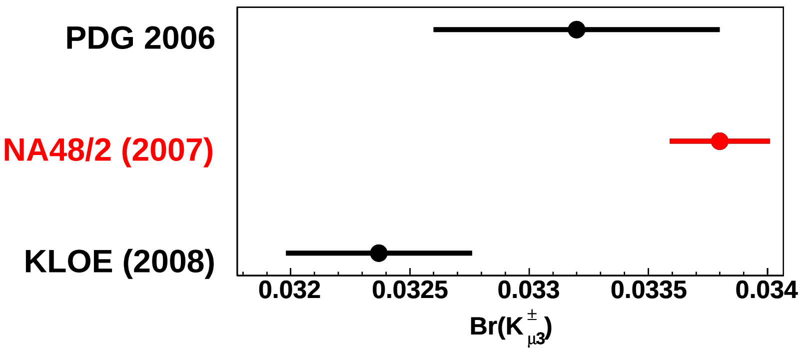
Use new KLOE measurement of Br$(K_{2\pi(\gamma)}) = 0.2065(5)(8)$,
shifted ($+0.06\%$) to $\tau_{K^\pm} = 12.370(19)$ ns (average PDG'06 & KLOE'08):

$$\text{Br}(\mathbf{K^{\pm}_{e3}}) = \mathbf{0.05104} \pm \mathbf{0.00019}_{\text{stat}} \pm \mathbf{0.00008}_{\text{sys}} \pm \mathbf{0.00023}_{\text{norm}}$$

$$\text{Br}(\mathbf{K^{\pm}_{\mu3}}) = \mathbf{0.03380} \pm \mathbf{0.00013}_{\text{stat}} \pm \mathbf{0.00006}_{\text{sys}} \pm \mathbf{0.00015}_{\text{norm}}$$

Most precise single measurements!





(ISTRA+ scaled to new Br$(K_{2\pi}.)$)

$|V_{us}|$ *Measurement from* $K^{\pm}_{l3}$

Determination of $|\mathbf{V_{us}}|$:

Use $\tau_{K^\pm} = 12.370(19)$ ns (average PDG'06 & KLOE'08)

and $\delta^{e/\mu}_{\text{em}}$, $\delta^{e/\mu}_{SU(2)}$, $I^{e/\mu}_K$ from Flavianet note:

$$\mathbf{Ke3} : |\mathbf{V_{us}}|\mathbf{f_+(0)} = \mathbf{0.21794\,(43)_{\text{exp}}\,(52)_{\text{norm},\tau}\,(61)_{\text{ext}}} = \mathbf{0.2179(9)}$$

$$\mathbf{K\mu3} : |\mathbf{V_{us}}|\mathbf{f_+(0)} = \mathbf{0.21818\,(46)_{\text{exp}}\,(52)_{\text{norm},\tau}\,(66)_{\text{ext}}} = \mathbf{0.2182(10)}$$

$\Longrightarrow$ **Very good agreement between $\mathbf{K_{e3}}$ and $\mathbf{K_{\mu3}}$**

Combination of $\mathbf{K_{e3}}$ and $\mathbf{K_{\mu3}}$ (correlations taken into account):

$$|\mathbf{V_{us}}|\,\mathbf{f_+(0)} = \mathbf{0.2180 \pm 0.0008}$$

Finally: Use $\mathrm{f}_+(0) = \mathbf{0.964 \pm 0.005}$ (RBC-UKQCD'07):

$$|\mathbf{V_{us}}| = \mathbf{0.2261 \pm 0.0014}$$

Test of Lepton Universality:

Build ratio $\mathbf{Ke3/K\mu 3}$:

$$\mathcal{R}_{\mathbf{K\mu 3/Ke3}} = \mathbf{0.663} \pm \mathbf{0.003}_{\text{stat}} \pm \mathbf{0.001}_{\text{sys}}$$

Most precise measurement so far and consistent with lepton universality (SM prediction: $\mathcal{R}_{K\mu 3/Ke3} = 0.661(3)$ with $\delta^{e/\mu}_{\text{em}}$, $\delta^{e/\mu}_{SU(2)}$, $I^{e/\mu}_{K}$ from Flavianet note).

Turn it around: Assume lepton universality and determine f.f. slope λ_0:

(Bijnens, Colangelo, Ecker, Gasser, hep-ph/9411311)

$$\mathcal{R}_{K\mu 3/Ke3} = \frac{0.645 + 2.087\,\lambda_+ + 1.464\,\lambda_0 + 3.375\,\lambda_+^2 + 2.573\,\lambda_0^2}{1 + 3.457\,\lambda_+ + 4.783\,\lambda_+^2}$$

Use $\lambda_+ = 0.0296 \pm 0.0008$ (PDG'06):

$$\Longrightarrow \quad \lambda_0 = \mathbf{0.0155} \pm \mathbf{0.0020}$$

Measurement of $\mathrm{K_S e3 / K_L e3}$

Measurement of $K_S e3/K_L e3$

NA48/1: High-intensity K_S beam.
Equal production rates of K_S and K_L at the target.

$\Longrightarrow$ Can measure $K_S e3$ decays with respect to $K_L e3$:

$$\frac{dN}{dt}(\pi e \nu) \;\propto\; |\eta|^2 e^{-t/\tau_S} + e^{-t/\tau_L} \quad \text{with} \quad \eta \equiv \frac{A(K_S e3)}{A(K_L e3)}$$

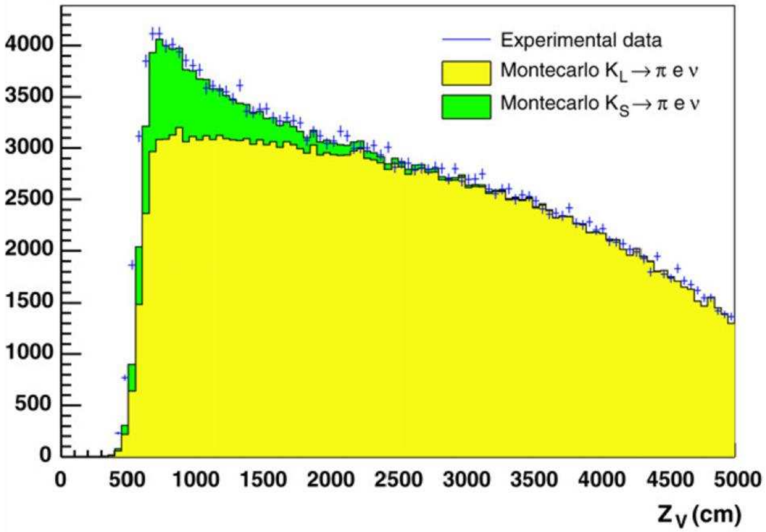
Select $\pi^\pm e^\mp \nu$ regardless of K_S, K_L.
Backgrounds are negligible.

In total: $\sim$ **400 000 events**

(about 4% are $K_S e3$)

Fit to the shape: (PLB 653 (2007) 145)

$$|\eta|^2 = 0.993 \pm 0.026_{\text{stat}} \pm 0.022_{\text{sys}}$$



Use PDG'06 (Br$(K_L e3) = 0.4053(15)$, $\tau_L = 51.14(21)$ ns, $\tau_S = 89.58(6)$ ps)

$$\Longrightarrow \quad \text{Br}(K_S e3) = (7.05 \pm 0.18_{\text{stat}} \pm 0.16_{\text{sys}}) \times 10^{-4}$$

In good agreement with KLOE 2006, but larger error.

Conclusions

- **Search for CP violation in $K^+ \to 3\pi$:**
  - Final result with the full NA48/2 data set.
  - Limits improved by one order of magnitude to $\mathcal{O}(10^{-4})$

    $\Longrightarrow$ **No sign for new physics.**

- **$|V_{us}|$ from K_{l3} Decays:**
  - Very precise measurements of $\Gamma(K^{\pm}_{e3})/\Gamma(K^{\pm}_{2\pi})$ and $\Gamma(K^{\pm}_{\mu 3})/\Gamma(K^{\pm}_{2\pi})$.
  - $|V_{us}|$ determined from these data: $|V_{us}| = 0.2261 \pm 0.0014$

- **Ratio $K_S e3/K_L e3$:**
  - $\text{Br}(K_S e3) = (7.05 \pm 0.18_{\text{stat}} \pm 0.16_{\text{sys}}) \times 10^{-4}$