Precision measurement of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay at NA48/2 and search for CP violation

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on behalf of the NA48/2 collaboration:
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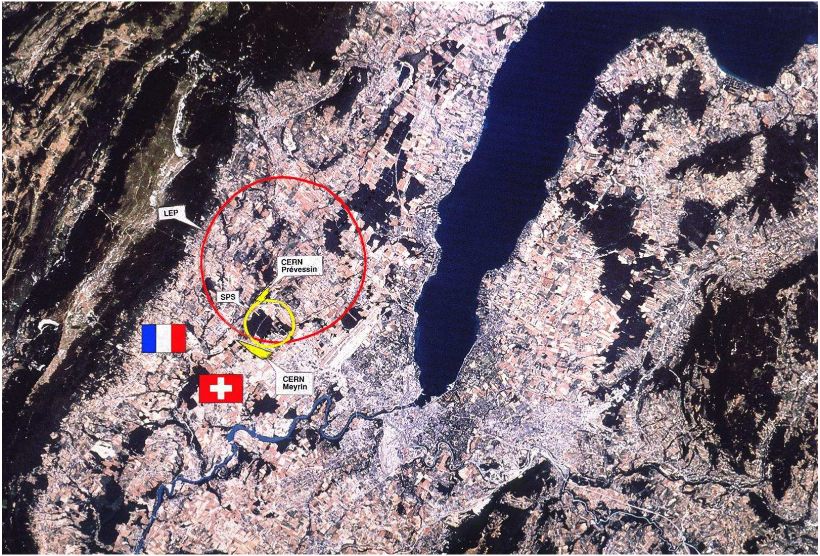
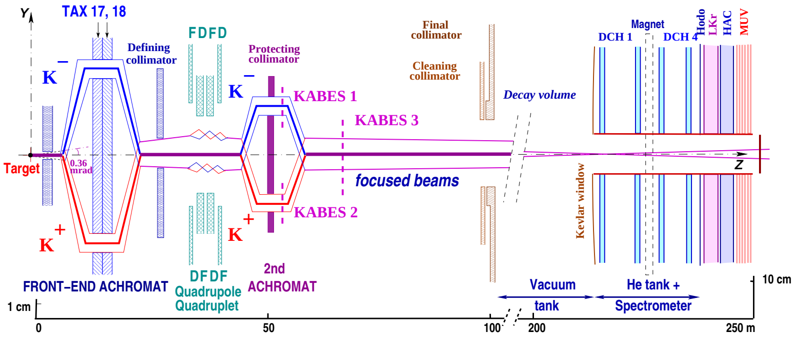
The NA48/2 experiment at CERN SPS

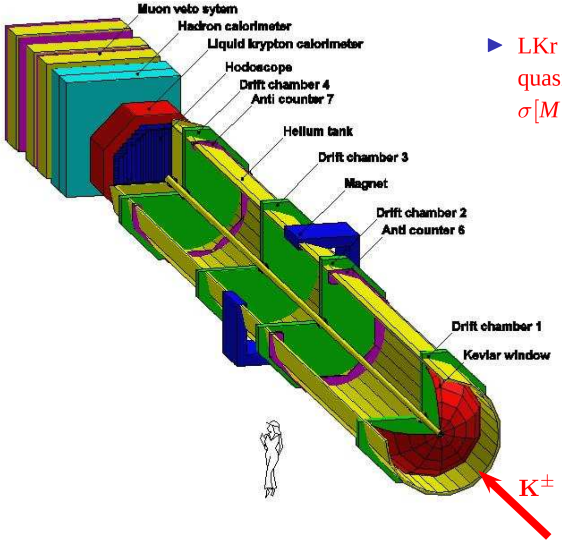


The NA48/2 beams



- Simultaneous [$P = (60 \pm 3)$ GeV/c] K^+ and K^- beams
  $\Rightarrow$ large charge symmetrization of experimental conditions
- Beams coincide within $\sim$ 1 mm along the 114 m decay volume.
- Flux ratio $K^+/K^- \sim 1.8$.

The NA48/2 detectors



- LKr electromagnetic calorimeter: quasi-homogeneous, high granularity $\sigma[M(\pi^{\pm}\pi^0\pi^0)] = 1.4$ MeV/c^2
  - Magnetic spectrometer: 4 DCH + dipole magnet $\sigma[M(3\pi^{\pm})] = 1.7$ MeV/c^2

  $\Rightarrow$ e/π discrimination (E/p)
  - Scintillator hodoscope for charged fast trigger: $\sigma(t) = 150$ ps
  - hadron calorimeter
  - muon counters
  - photon vetoes

The NA48/2 experiment at CERN SPS

The $K^{\pm} \to \pi^{+}\pi^{-}\gamma$ decay

Measurement of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay rates

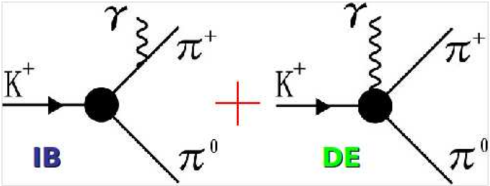
CP violation searches

Conclusions

$K^\pm \to \pi^\pm\pi^0\gamma$: Theory

Two sources of γ radiation:

Inner Bremsstrahlung (IB) and Direct Emission (DE)



Two kinematic variables:

$$T^*_\pi = \pi^\pm \text{ kinetic energy in } K^\pm \text{ rest frame}$$

$$W^2 = \frac{(p_\pi \cdot p_\gamma)(p_K \cdot p_\gamma)}{m_K^2 m_\pi^2}$$

After integrating on T^*_π:

$$\frac{d\Gamma^\pm}{dW} = \frac{d\Gamma^\pm_{IB}}{dW}\Big[1 \qquad \Leftarrow \text{(IB)}$$

$$+ 2m_K^2 m_\pi^2 \cos(\pm\phi + \delta_1^1 - \delta_0^2)\, X_E\, W^2 \qquad \Leftarrow \text{(INT)}$$

$$+ m_K^4 m_\pi^4 \left(|X_E|^2 + |X_M|^2\right) W^4 \Big] \qquad \Leftarrow \text{(DE)}$$

$K^\pm \to \pi^\pm \pi^0 \gamma$: Theory

$$\frac{d\Gamma^\pm}{dW} = \frac{d\Gamma^\pm_{IB}}{dW} \Big[1 \qquad \Leftarrow \text{(IB)}$$

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$$+ m_K^4 m_\pi^4 \left(|X_E|^2 + |X_M|^2\right) W^4 \Big] \qquad \Leftarrow \text{(DE)}$$

IB is known from $K^\pm \to \pi^\pm \pi^0$ (Low theorem) + QED corrections
$\Rightarrow$ dominant, although suppressed by $\Delta I = 1/2$ rule

DE amplitude contains two terms $\left[\, \mathcal{O}(p^4) \text{ ChPT} \,\right]$:

- magnetic dipole X_M with two contributions:
  – reducible Wess-Zumino-Witten functional (~ 260 GeV^{-4})
  – direct (non known)
- electric dipole X_E: no prediction in ChPT

INT is interference between IB and electric DE (X_E) amplitudes

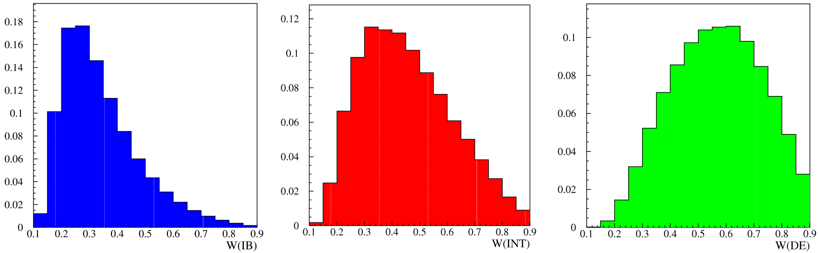
$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Theory

$$\frac{d\Gamma^{\pm}}{dW} = \frac{d\Gamma^{\pm}_{IB}}{dW} \Big[1 \qquad \Leftarrow \text{(IB)}$$

$$+ 2m_K^2 m_\pi^2 \cos(\pm\phi + \delta_1^1 - \delta_0^2)\, X_E\, W^2 \qquad \Leftarrow \text{(INT)}$$

$$+ m_K^4 m_\pi^4 \left(|X_E|^2 + |X_M|^2\right) W^4 \Big] \qquad \Leftarrow \text{(DE)}$$

Monte Carlo W-distributions

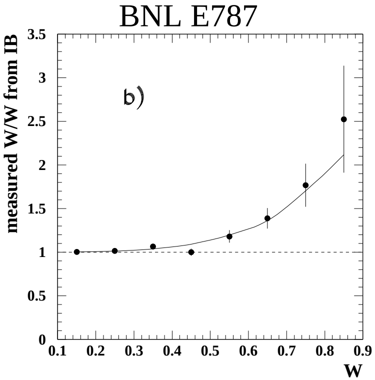


W (IB) W (INT) W (DE)

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: Previous measurements

PDG 08: BR = $(275 \pm 15) \cdot 10^{-6}$

	BR(DE) $\times$**10**^{6}	Stat.
E787	4.7 ± 0.9	20 k
E470	3.8 ± 1.1	10 k
ISTRA+	3.7 ± 4.0	0.9 k
PDG 08	4.3 ± 0.7	



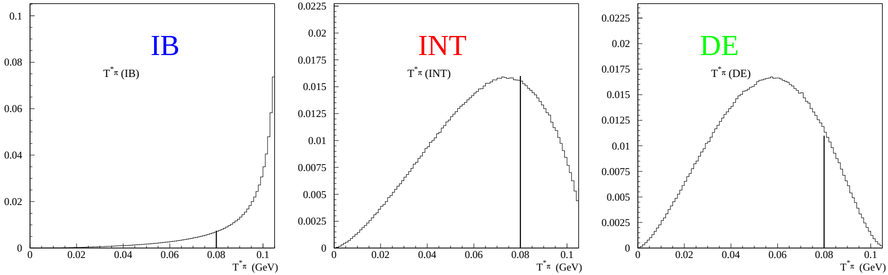
Previous DE measurements:

- Kinematic range 55 MeV $< T^*_\gamma <$ 90 MeV
- Photon mistagging probability $> 10\%$
- Assumption: INT = 0

So far no interference nor CP violation observed.

- E787: INT / IB $= (-0.4 \pm 1.6)$ %

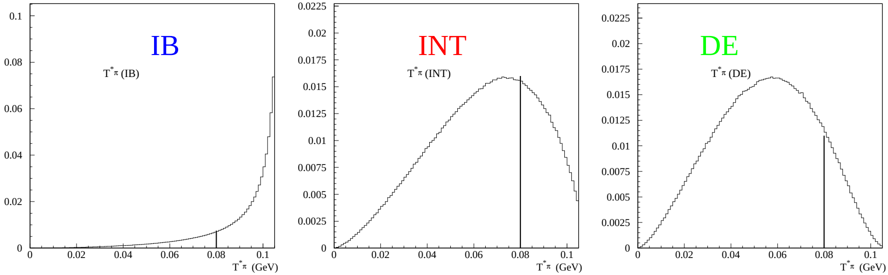
$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: T^{*}_{π} range



55 MeV < T^{*}_{π} < 90 MeV region used in previous experiments to reject background (mainly $\pi^{\pm}\pi^{0}$ and $\pi^{\pm}\pi^{0}\pi^{0}$)

But... this excludes most of DE events.

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: T_{π}^{*} range



55 MeV $< T_{\pi}^{*} <$ 90 MeV region used in previous experiments to reject background (mainly $\pi^{\pm}\pi^{0}$ and $\pi^{\pm}\pi^{0}\pi^{0}$)
But... this excludes most of DE events.

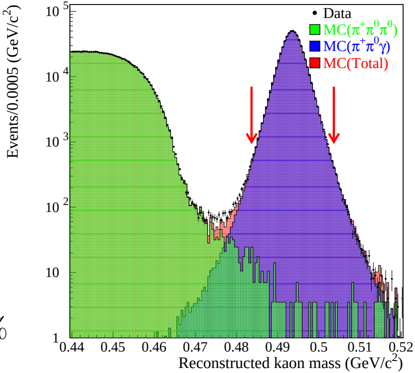
$\Downarrow$

This measurement is performed in the region $0 < T_{\pi}^{*} < 80$ MeV to improve statistics and sensitivity to DE

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Data sample

New NA48/2 measurement:

- Both K^{+} and K^{-} in the beam ($\Rightarrow$ CPV check possible)
- Enlarged T^{*}_{π} region: $0 < T^{*}_{\pi} < 80$ MeV
- Background $< 0.01\%$ (mainly $\pi^{\pm}\pi^{0}\pi^{0}$)
- γ mistagging probability $< 0.1\%$

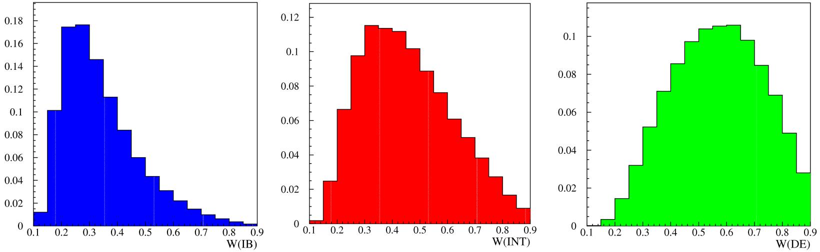


Total $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ data sample:

- More than **1 million events**
- For the fit: restrict to $\mathbf{0.2 < W < 0.9}$ and $\mathbf{E_{\gamma} > 5}$ **GeV** $\Rightarrow$ still **600 000 $\pi^{\pm}\pi^{0}\gamma$ candidates in the fit**

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Fit techniques

- **Poissonian Maximum Likelyhood Fit** in bins of W^2
  Correct for acceptance with MC
  Data(i) = $N_0[(1-\alpha-\beta)\cdot$ IB$_{MC}(i)$ + $\alpha\cdot$ INT$_{MC}(i)$ + $\beta\cdot$ DE$_{MC}(i)$]

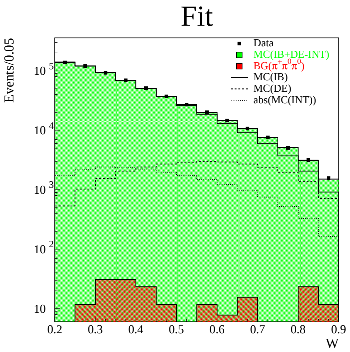


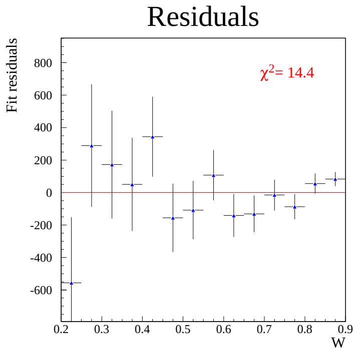
W (IB) W (INT) W (DE)

- **Polynomial Fit** *(used as cross-check)*
  Fit the ratio W(Data) / W(IB)$_{MC}$ with polynomial function:
  $F(W) = c \cdot (1 + aW^2 + bW^4) \Rightarrow$ Frac(DE), Frac(INT)

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Fit Results

Fit with the "Maximum Likelyhood" method:





$$\text{Frac(DE)} = (3.32 \pm 0.15) \cdot 10^{-2}$$
$$\text{Frac(INT)} = (-2.35 \pm 0.35) \cdot 10^{-2}$$

with: Frac(DE) = Br(DE) / Br(IB)
Frac(INT) = Br(INT) / Br(IB)

and $0 < T^{*}_{\pi} < 80$ MeV.

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: Polynomial fit

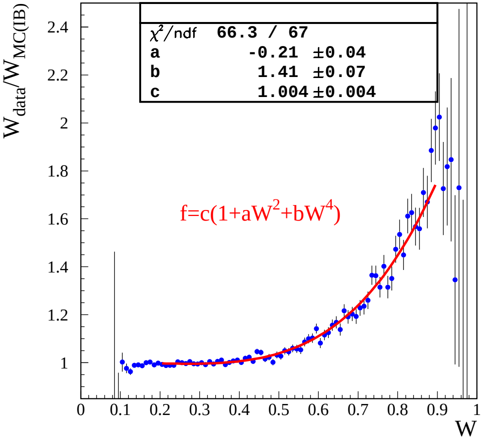
Fit with a Polynomial:

$$f(W) = c(1 + aW^2 + bW^4)$$

Assumes same acceptance
as a funcion of W
for IB, DE and INT

$$\Downarrow$$

used as a cross-check

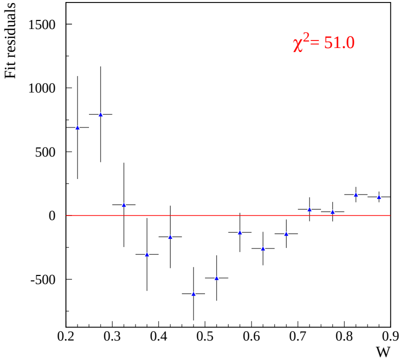


$$\text{Frac(DE)} = (3.19 \pm 0.16) \cdot 10^{-2}$$
$$\text{Frac(INT)} = (-2.21 \pm 0.41) \cdot 10^{-2}$$

$\Rightarrow$ Excellent agreement with Maximum Likelihood Fit

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Fit with no Interference term

Fit with INT = 0:

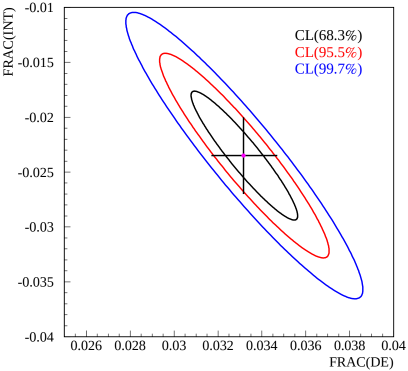


$\Rightarrow$ Clear disagreement with INT = 0 hypothesis!

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Final results

Systematics:

Source	DE $\times 10^2$	INT $\times 10^2$
Acceptance	0.10	0.15
L1 trigger	0.01	0.03
L2 trigger	0.05	0.30
Energy Scale	0.09	0.21
Total	0.14	0.39



Final NA48/2 results on $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ fractions:

$$\text{Frac(DE)} = (3.19 \pm 0.16) \cdot 10^{-2}$$

$$\text{Frac(INT)} = (-2.21 \pm 0.41) \cdot 10^{-2}$$

Correlation: $\rho = -0.93$

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Extraction of X_E and X_M

Approximations for extracting X_E and X_M :

- $\phi = 0$
- $\cos(\delta_1^1 - \delta_0^2) = \cos 6.5^0 \approx 1$

Magnetic and electric components (first measurement):

$$X_E = (-24 \pm 4_{\text{stat}} \pm 4_{\text{syst}})\ \text{GeV}^{-4}$$
$$X_M = (254 \pm 11_{\text{stat}} \pm 11_{\text{syst}})\ \text{GeV}^{-4}$$

WZW reducible anomaly predictions: $X_M \approx 260\ \text{GeV}^{-4}$

$\Rightarrow$ NA48/2 X_M measurement points to WZW reducible anomaly only

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: CP violation studies

$$\frac{d\Gamma^{\pm}}{dW} = \frac{d\Gamma^{\pm}_{IB}}{dW}[1 \ + 2m_K^2 m_\pi^2 \cos(\pm\phi + \delta_1^1 - \delta_0^2) X_E W^2$$
$$+ m_K^4 m_\pi^4 (|X_E|^2 + |X_M|^2] W^4$$

- $\phi \neq 0 \;\Rightarrow\; \Gamma(K^+ \to \pi^+\pi^0\gamma) \neq \Gamma(K^- \to \pi^-\pi^0\gamma)$
- SM prediction on asymmetry:
  $2 \cdot 10^{-6} \sim 10^{-5}$ for $50\ \text{MeV} < E^*_\gamma < 170\ \text{MeV}$.
- Possible SUSY contributions can push the asymmetry up to 10^{-4} in some W regions.
- Two possible measurements:
  – Asymmetry in the total rate $\Rightarrow$ needs normalization ($K_{3\pi}$)
  – Asymmetry in the Dalitz plot $\Rightarrow$ W spectrum

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: CP violation studies

For CP asymmetry analysis: remove cuts on W range and E_{γ}^{min}

$\Rightarrow$ 1.08 million events for CPV analysis.

Measurement of rate asymmetry:

$$A_N = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} = \frac{N_{\pi^+\pi^0\gamma} - R \cdot N_{\pi^-\pi^0\gamma}}{N_{\pi^+\pi^0\gamma} + R \cdot N_{\pi^-\pi^0\gamma}}$$

with $R = N_{K^+}/N_{K^-} = 1.7798(4)$ from $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$

$$\Downarrow$$

$$A_N = (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-3}$$
$$A_N < 1.5 \cdot 10^{-3} \quad (90\%\ \text{CL})$$

$\Rightarrow$ First limit on $\sin(\phi)$:

$$\sin(\phi) = -0.01 \pm 0.43\ , \qquad |\sin(\phi)| < 0.56\ \ (90\%\ \text{CL})$$

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: CP violation studies

Fit of asymmetry in W spectrum:

$$\frac{d\Gamma^{\pm}}{dW} = \frac{d\Gamma^{\pm}_{IB}}{dW}\left[\, +(a \pm e)W^2 + bW^4 \right]$$

$$\Downarrow$$

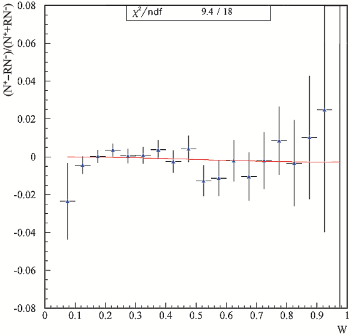
Single parameter fit to:

$$\frac{dA_W}{dW} = \frac{e \cdot W^2}{1 - 0 - 247W^2 + 1.463W^4}$$

$$\Downarrow$$

$$\boxed{\boldsymbol{A_W = e\int \frac{\mathrm{INT}}{\mathrm{IB}} = (-0.6 \pm 1.0) \times 10^{-3}}}$$

compatible with A_N.



No CP asymmetry observed in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$!

Conclusions

- More than 1 million $K^{\pm} \to \pi^{+}\pi^{0}\gamma$ events with tiny background
- First observation and measurement of interference between IB and DE amplitudes
- $X_E = (-24 \pm 4_{\text{stat}} \pm 4_{\text{syst}})\ \text{GeV}^{-4}$ measured for the first time
- Measured $X_M = (-24 \pm 4_{\text{stat}} \pm 4_{\text{syst}})\ \text{GeV}^{-4}$ consistent with WZW reducible anomaly only
- $\mathcal{O}(10^{-3})$ limits on direct CP violation in $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decays
- May 2010: paper accepted for publication in EPJ C