Radiative $K^{\pm}$ Decays from NA48/2

Rainer Wanke

Institut für Physik, Universität Mainz

on behalf of the NA48/2 Collaboration

(Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Florence, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna)

2009 KAON International Conference

Tsukuba, June 10, 2009

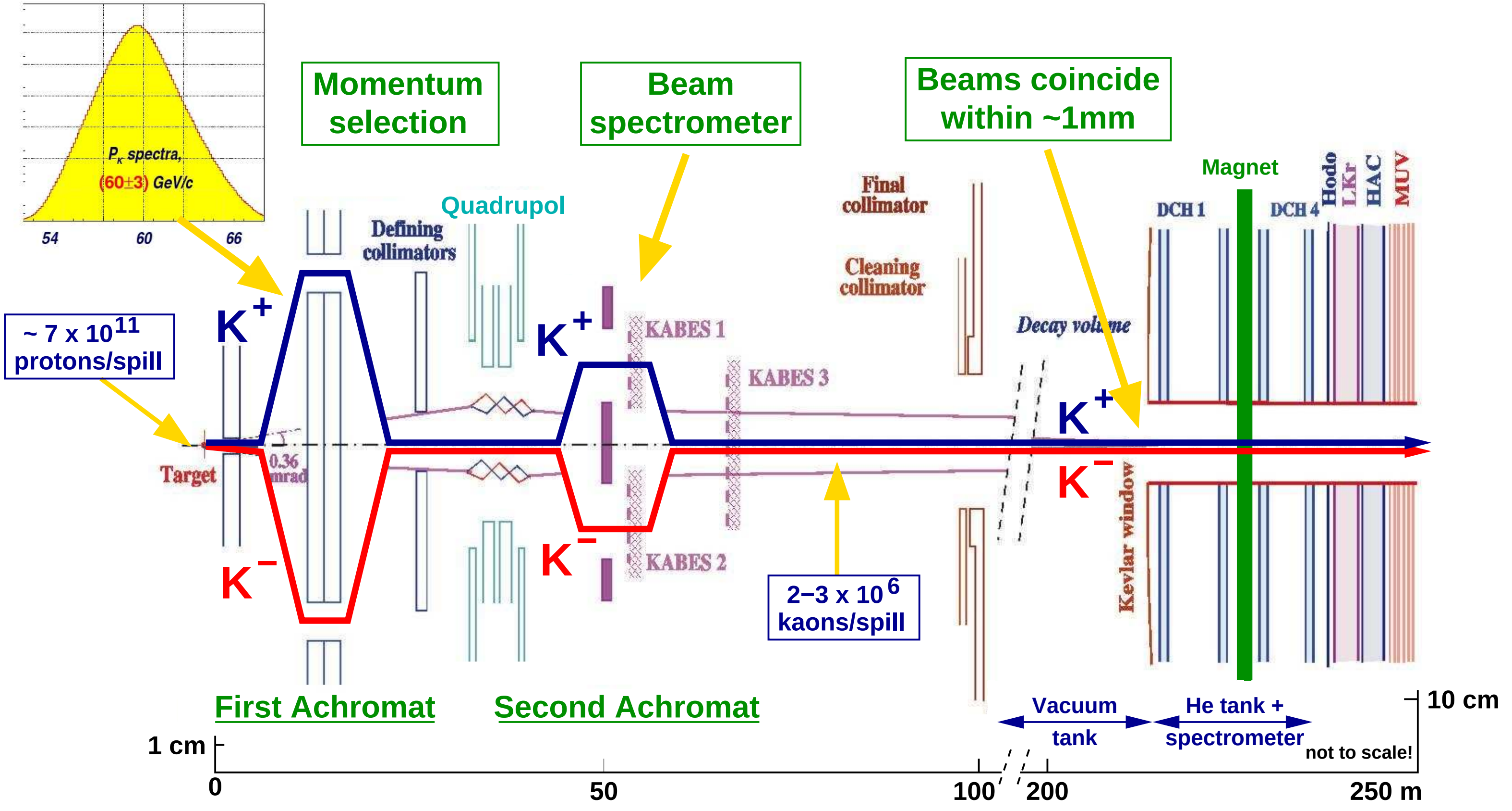
Overview

- $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$
  - **First Measurement of IB-DE Interference**
  - **Search for direct CP Violation**
- $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$
  - **Precise Measurement of the Decay Rate**
- $K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$
  - **First Observation and Measurements of BR and the Decay Distribution**

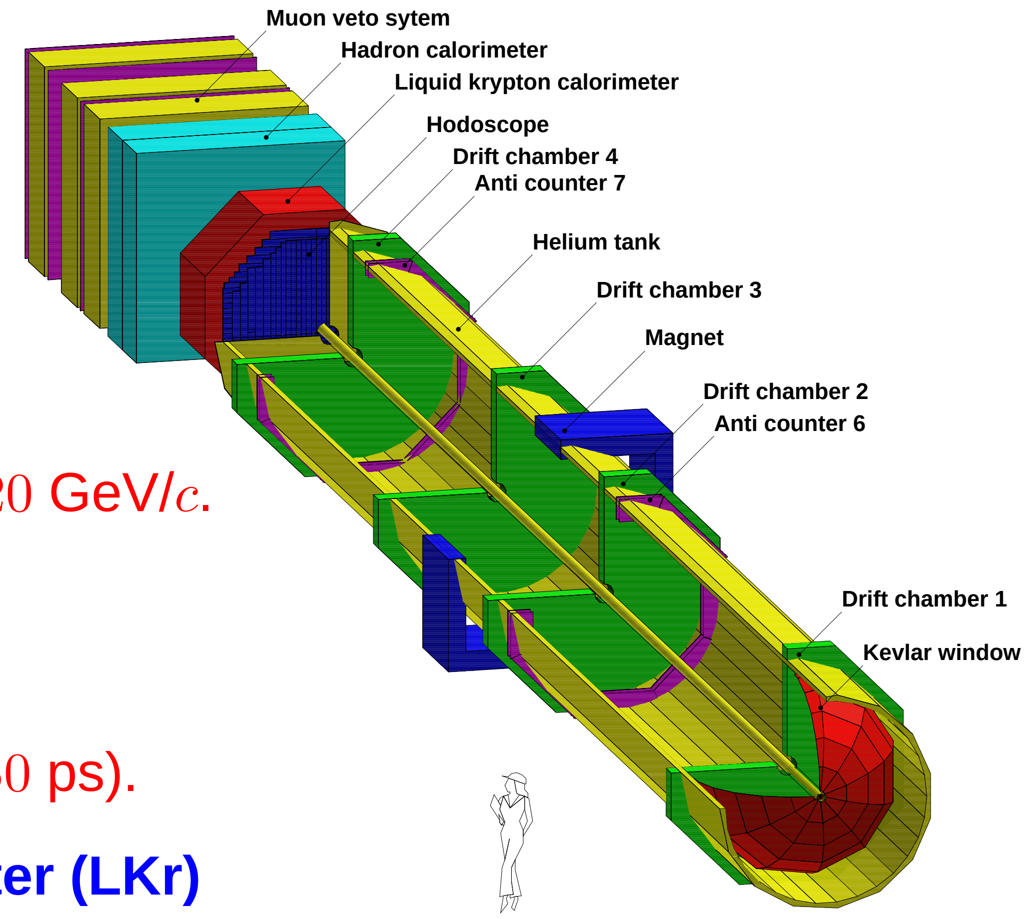
NA48/2 Beamline

NA48/2 experiment in 2003/2004:

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



The NA48 Detector



Detector components:

- **Magnet spectrometer**

  4 sets of drift chambers.

  $\Delta p/p \approx 1.4\%$ 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**

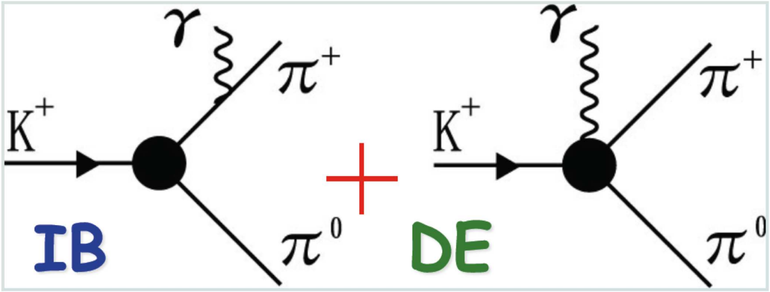
Measurement of

$K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\gamma$ Decays

$K^\pm \to \pi^\pm \pi^0 \gamma$: *Theoretical Framework*

Two sources of γ radiation:

Inner Bremsstrahlung (IB) and **Direct Emission (DE)**



Kinematic variable:

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

$$\frac{\partial \Gamma^\pm}{\partial W} = \underbrace{\frac{\partial \Gamma^\pm_{\text{IB}}}{\partial W}}_{\text{Inner Bremsstrahlung (IB)}} \Big[1 + \underbrace{2 \cos\left(\pm\phi + \delta_1^1 - \delta_0^2\right) |X_E| \, W^2}_{\text{Interference (INT)}}$$

$$+ \underbrace{m_\pi^4 m_K^4 \left(|X_E|^2 + |X_M|^2\right) W^4}_{\text{Direct Emission (DE)}} \Big]$$

$K^\pm \to \pi^\pm\pi^0\gamma$: *Theoretical Framework*

$$\frac{\partial\Gamma^\pm}{\partial W} = \underbrace{\frac{\partial\Gamma^\pm_{\text{IB}}}{\partial W}\Big[\,1}_{\text{Inner Bremsstrahlung (IB)}} + \underbrace{2\cos\left(\pm\phi + \delta_1^1 - \delta_0^2\right)\,|X_E|\,W^2}_{\text{Interference (INT)}}$$

$$+ \underbrace{m_\pi^4 m_K^4\left(|X_E|^2 + |X_M|^2\right)\,W^4}_{\text{Direct Emission (DE)}}\Big]$$

- **IB** is known from $K^\pm \to \pi^\pm\pi^0$ and QED corrections.
- **DE** has two terms ($\mathcal{O}(p^4)$ ChPT):
  - X_M: magnetic part has two contributions: reducible WZW functional (~ 260 GeV^{-4}) $+$ direct (not known)
  - X_E: no prediction in ChPT
- **INT** is interference of IB and electric DE amplitude, no prediction available.

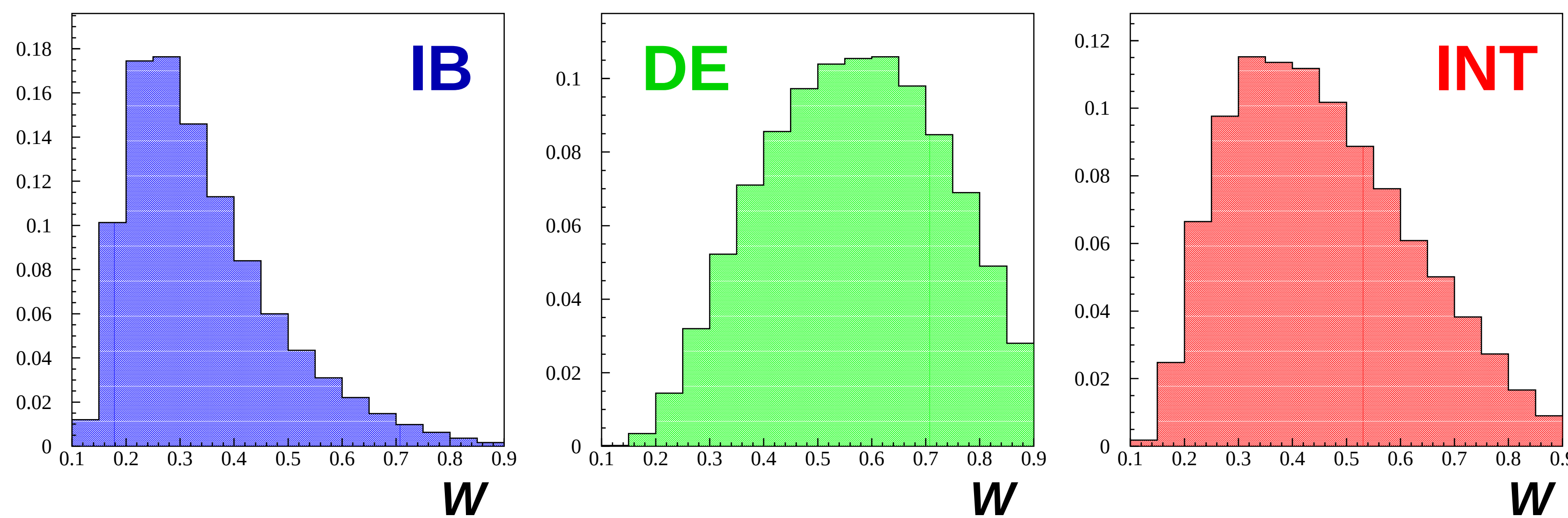
$K^\pm \to \pi^\pm\pi^0\gamma$: *Theoretical Framework*

$$\frac{\partial \Gamma^\pm}{\partial W} = \underbrace{\frac{\partial \Gamma^\pm_{\text{IB}}}{\partial W}}_{\text{Inner Bremsstrahlung (IB)}} \Big[1 + \underbrace{2 \cos\left(\pm\phi + \delta_1^1 - \delta_0^2\right) |X_E|\, W^2}_{\text{Interference (INT)}}$$

$$+ \underbrace{m_\pi^4 m_K^4 \left(|X_E|^2 + |X_M|^2\right) W^4}_{\text{Direct Emission (DE)}} \Big]$$

Inner Bremsstrahlung (IB)   Interference (INT)

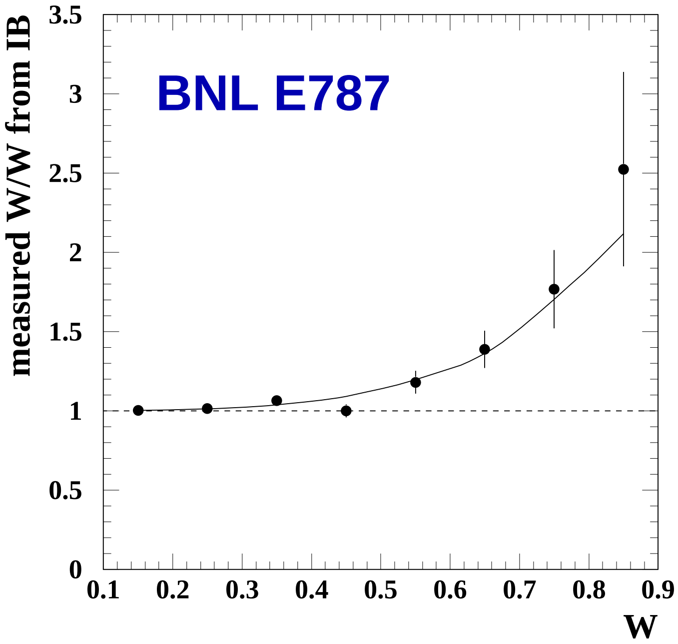
Direct Emission (DE)



$K^\pm \to \pi^\pm \pi^0 \gamma$: *Experimental Status*

Previous measurements:

	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	930
PDG 08	$\mathbf{4.3 \pm 0.7}$	



- **All previous DE measurements:**
  - Kinematic range $55 < T_\pi^\star < 90$ MeV (kinetic π energy in K CMS)
  - Assumption: INT $= 0$.
- So far **no Interference nor CP violation observed.**
  - E787: INT $= (-0.4 \pm 1.6)\%$

$K^\pm \to \pi^\pm\pi^0\gamma$: *Data Sample*

New NA48/2 measurement:

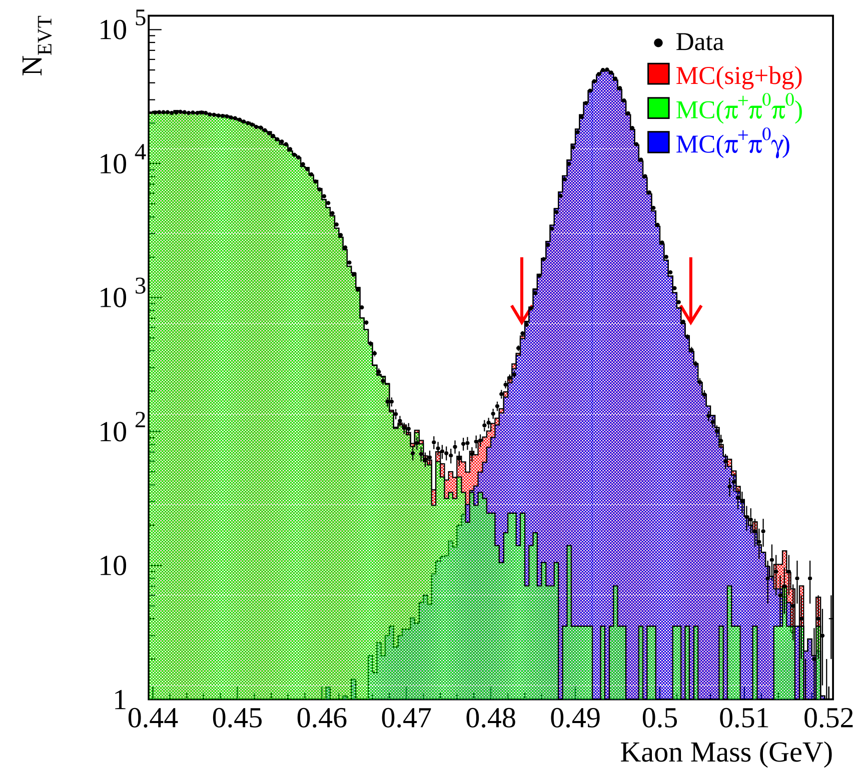
- Both K^+ and K^- in the beam ($\Longrightarrow$ CPV check possible)
- Enlarged $T^\star_\pi$ region w.r.t. previous experiments:

  $$\mathbf{0 < T^\star_\pi < 80\ MeV}$$

- **Background** negligible:

  $< 1\% \times$ **DE** (mainly $\pi^\pm\pi^0\pi^0$)

- $\mathcal{O}(10^{-3})$ mistagging probability for the photon.



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

- More than **1 million events.**
- For the fit: restrict to $0.2 < W < 0.9$ and $E_\gamma > 5$ GeV

  $\Longrightarrow$ Still **600 k $\pi^\pm\pi^0\gamma$ candidates in the fit.**

Extended Maximum Likelihood Fit

Correct for acceptances with MC:

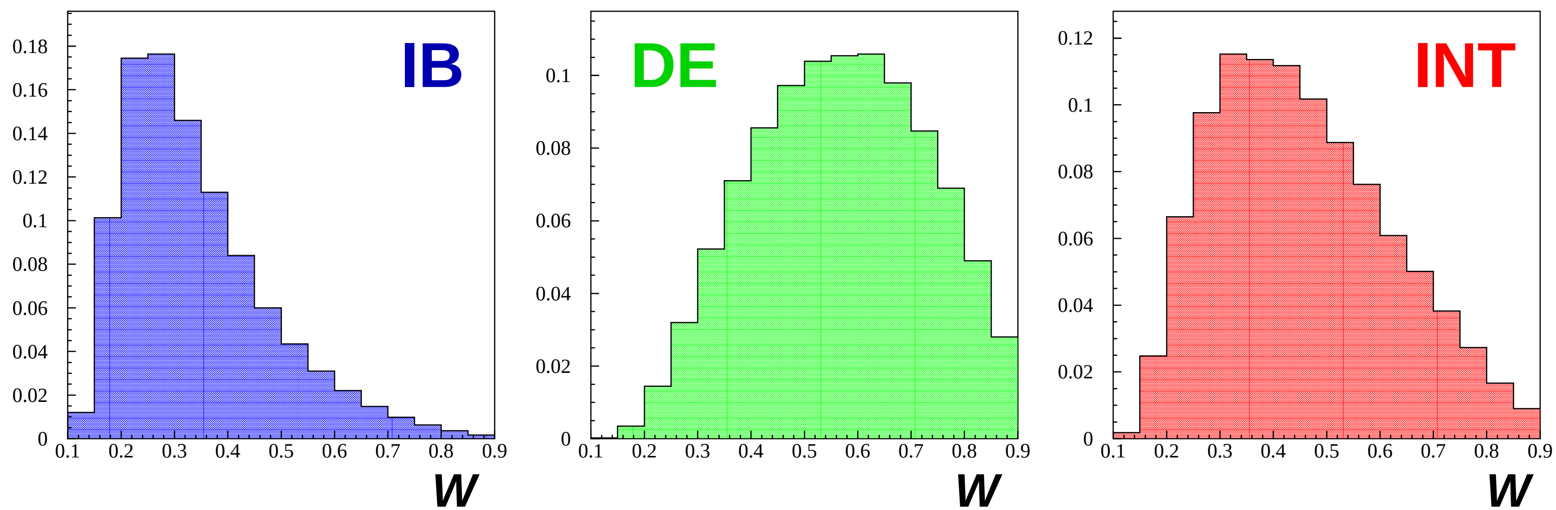
$$\textbf{Data}(i) = N_0[(1-\alpha-\beta)\cdot \textbf{IB}_{\textbf{MC}}(i) + \alpha \cdot \textbf{INT}_{\textbf{MC}}(i) + \beta \cdot \textbf{DE}_{\textbf{MC}}(i)]$$

Polynominal Fit

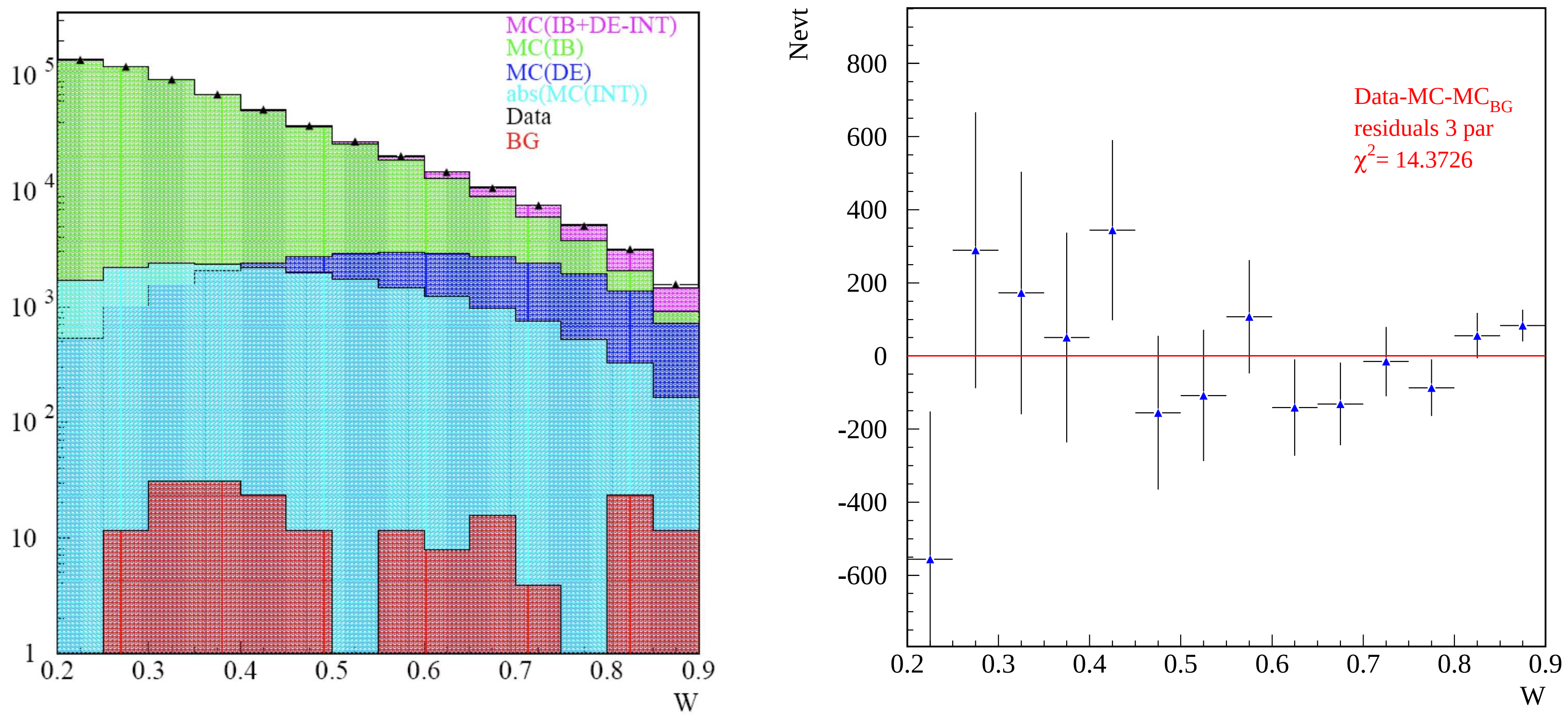
(used as cross-check)

Fit the **ratio** $\boldsymbol{W}$(Data)$/\boldsymbol{W}$(IB_{MC}) with polynomial function:

$$F = c \cdot (1 + aW^2 + bW^4) \quad \Longrightarrow \quad$$ **Frac(DE), Frac(INT)**



Fit with the "Likelihood method":



$$\textbf{Frac(DE)} = (\;\;3.32 \pm 0.15) \times 10^{-2}$$

$$\textbf{Frac(INT)} = (-2.35 \pm 0.35) \times 10^{-2}$$

with: $\text{Frac(DE)} = \frac{\text{Br(DE)}}{\text{Br(IB)}}$,

$\text{Frac(INT)} = \frac{\text{Br(INT)}}{\text{Br(IB)}}$,

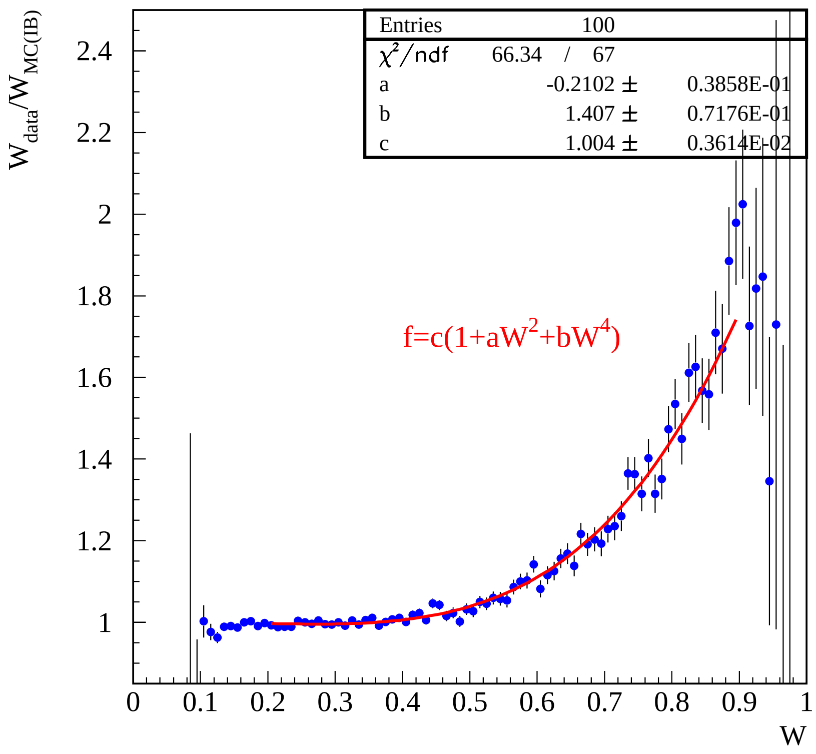
and $0 < T_{\pi}^{\star} < 80$ MeV

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

Fit with a Polynomial:

Assumes equal acceptances for IB, DE, and INT as function of W.

Used as cross-check.



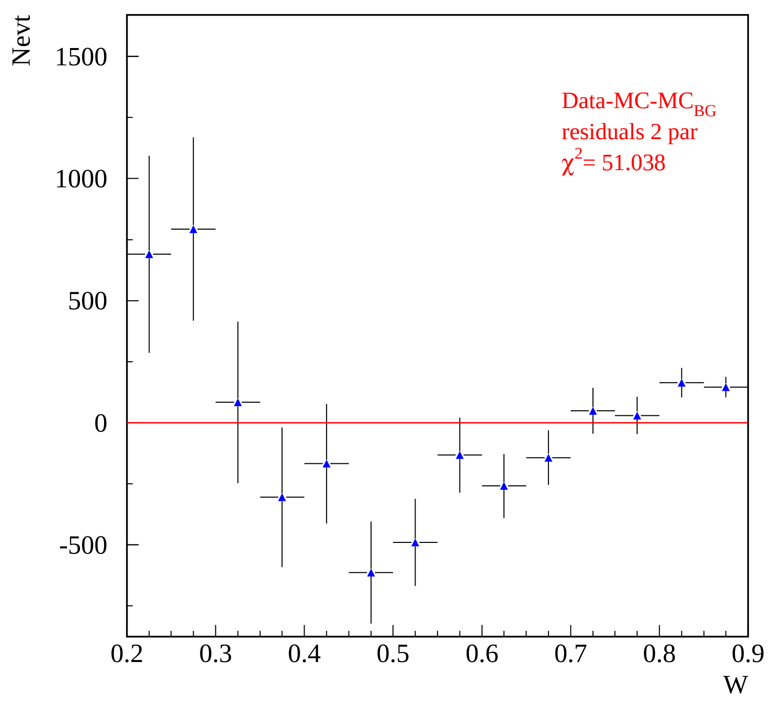
$$\text{Frac(DE)} = (\ \ 3.19 \pm 0.16) \times 10^{-2}$$

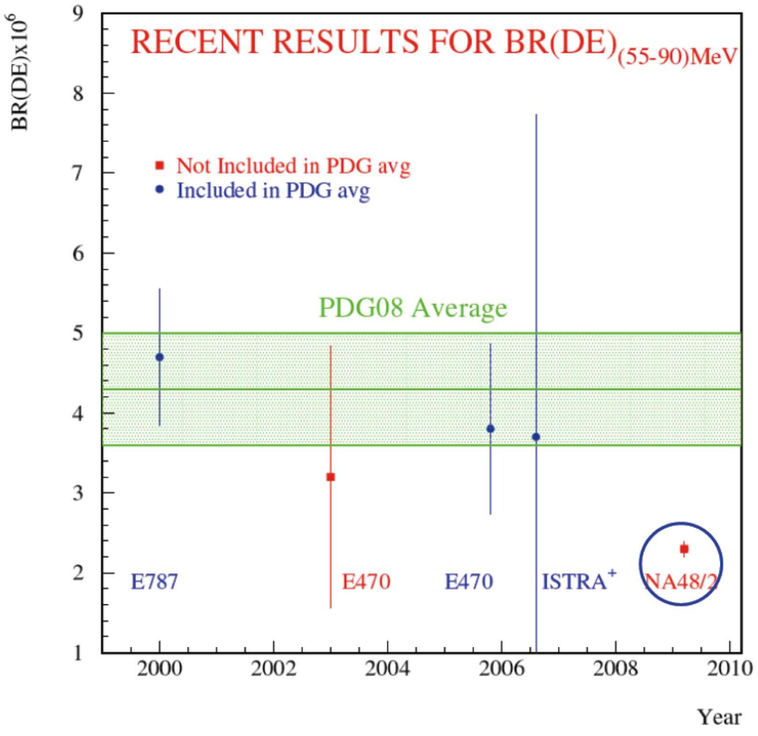
$$\text{Frac(INT)} = (-2.21 \pm 0.41) \times 10^{-2}$$

$\Longrightarrow$ **Very good agreement with maximum likelihood fit!**

$K^\pm \to \pi^\pm \pi^0 \gamma$: *Comparison with Previous Experiments*

Fit with INT $= 0$ and extrapolation to $55 < T_\pi^\star < 90$ MeV:





$$\text{Br(DE)}^{\text{INT}=0}_{55<T_\pi^\star<90\text{ MeV}} = (2.32 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}}) \times 10^{-6}$$

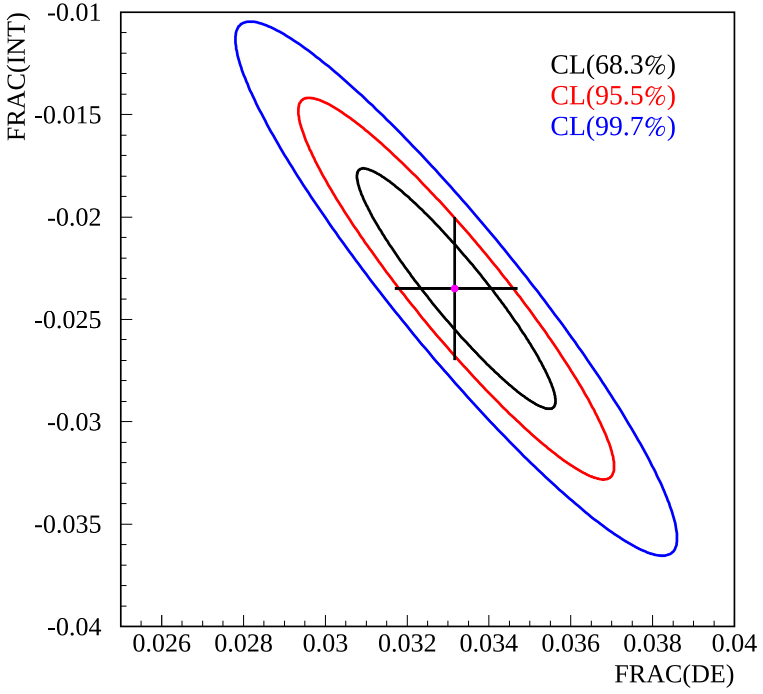
$\Longrightarrow$ **Clear disagreement with INT $= 0$ hypothesis!**

Need to fit with non-vanishing interference term!

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: *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	—	0.30
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:

$$\text{Frac(DE)}_{0<T^{*}_{\pi}<80\text{ MeV}} = (\ \ 3.32 \pm 0.15_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-2}$$

$$\text{Frac(INT)}_{0<T^{*}_{\pi}<80\text{ MeV}} = (-2.35 \pm 0.35_{\text{stat}} \pm 0.39_{\text{syst}}) \times 10^{-2}$$

Correlation: $\rho = -0.93$

First Extraction of X_E *and* X_M

Approximations for extracting X_E and X_M:

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

⬇

$$X_E = \frac{\text{Frac(INT)}}{2 \cdot 0.105 \cdot m_K^2 m_\pi^2}, \quad X_M = \sqrt{\frac{\text{Frac(DE)} - m_K^4 m_\pi^4 |X_E|^2 \cdot 0.0227}{0.0227 \cdot m_K^4 m_\pi^4}}$$

Magnetic and electric components:

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

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

$\Longrightarrow$ **NA48/2 measurement points to reducible anomaly only**

$K^\pm \to \pi^\pm\pi^0\gamma$: *CP Violation Studies*

Decay rate may depend on kaon charge:

$$\frac{\partial\Gamma^\pm}{\partial \mathbf{W}} = \frac{\partial\Gamma^\pm_{\text{IB}}}{\partial \mathbf{W}}\left[\mathbf{1} + \underbrace{\mathbf{2}\cos\left(\pm\phi + \delta^{\mathbf{1}}_{\mathbf{1}} - \delta^{\mathbf{2}}_{\mathbf{0}}\right)|\mathbf{X_E}|\,\mathbf{W^2}}_{\text{INT}} + \mathbf{m}^{\mathbf{4}}_{\pi}\mathbf{m}^{\mathbf{4}}_{\mathbf{K}}\left(|\mathbf{X_E}|^{\mathbf{2}} + |\mathbf{X_M}|^{\mathbf{2}}\right)\mathbf{W^4}\right]$$

- If $\phi \neq 0$: $\Gamma(K^+ \to \pi^+\pi^0\gamma) \neq \Gamma(K^- \to \pi^-\pi^0\gamma)$!
  $\Longrightarrow$ **CP violation!**
- **SM prediction** on asymmetry: $\mathbf{2 \cdot 10^{-6} - 10^{-5}}$ for $50 < E^\star_\gamma < 170$ MeV.
- **Possible SUSY contributions** can push the asymmetry up to $\mathbf{10^{-4}}$ in some W regions.
- Two possible measurements:
  - **Asymmetry in the total rate** $\Longrightarrow$ need normalization ($K_{3\pi}$)
  - **Asymmetry in the Dalitz plot**

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: *CP Violation Studies*

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

$\Longrightarrow$ **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 $R = N_{K^+}/N_{K^-} = 1.7998(4)$ from $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$.

$$A_N = (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-3}$$

$$|A_N| < 1.5 \times 10^{-3} \quad (90\%\ \text{CL})$$

$\Longrightarrow$ **First limit on $\sin\phi$:**

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

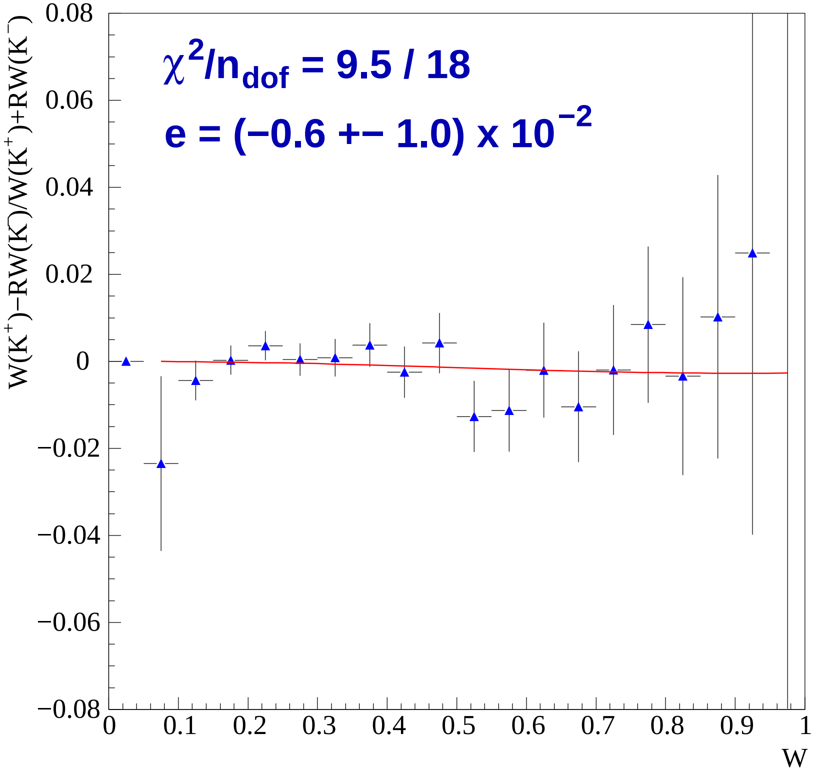
$K^\pm \to \pi^\pm\pi^0\gamma$: *CP Violation Studies*

Fit of asymmetry in W spectrum:

$$\frac{d\Gamma^\pm}{dW} = \frac{d\Gamma^\pm_{\text{IB}}}{dW}\left(1 + (a \pm e)W^2 + bW^4\right)$$

Single parameter fit to:

$$\frac{dA_W}{dW} = \frac{e \cdot W^2}{1 - 0.247\,W^2 + 1.463\,W^4}$$



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

compatible with A_N.

$\Longrightarrow$ **No CP asymmetry observed in $K^\pm \to \pi^\pm\pi^0\gamma$!**

Measurement of

$K^{\pm} \longrightarrow \pi^{\pm}\gamma\gamma$ **and** $K^{\pm} \longrightarrow \pi^{\pm}e^{+}e^{-}\gamma$

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

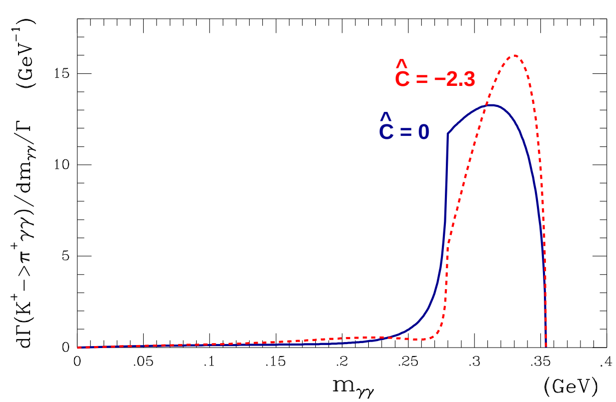
Differential $K^{\pm} \to \pi^{\pm}\gamma\gamma$ decay rate:

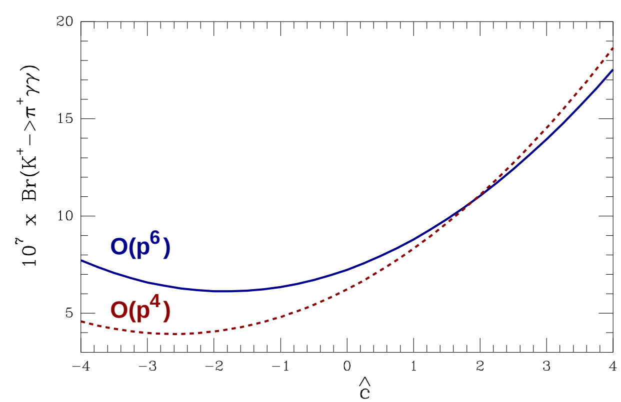
$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A+B|^2+|C|^2\right)+\left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2\left(|B|^2+|D|^2\right)\right]$$

At $\mathcal{O}(p^4)$: (Ecker, Pich, de Rafael, Nucl. Phys. B 303 (1988) 665)

- $A(z,\hat{c})$ contains **loops** and $\hat{c}$ of $\mathcal{O}(1)$.
- $C(z)$ contains **poles and tadpoles.**
  (Gerard, Smith, Trine, Nucl. Phys. B 730 (2005) 1)

At $\mathcal{O}(p^6)$: Unitarity corrections, could increase Br by $30-40\%$.
(D'Ambrosio, Portolés, Nucl. Phys. B 386 (1996) 403)





$K^\pm \to \pi^\pm\gamma\gamma$: *Trigger*

Trigger efficiency:

- $K^\pm \to \pi^\pm\gamma\gamma$ selected through neutral trigger.
- **L1:** More than 2 e.m. clusters required.

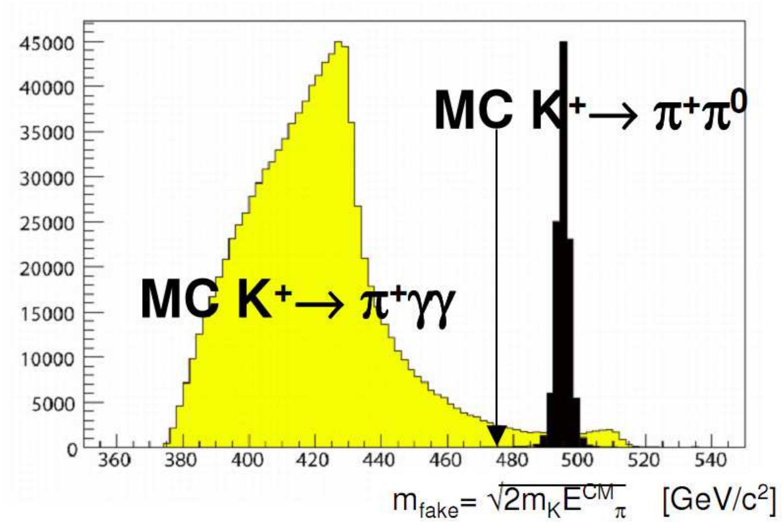
  $\Longrightarrow$ $\approx 50\%$ **efficiency**
- **L2:** Rejection of $K^\pm \to \pi^\pm\pi^0$ by cutting on $E^\star_\pi$.

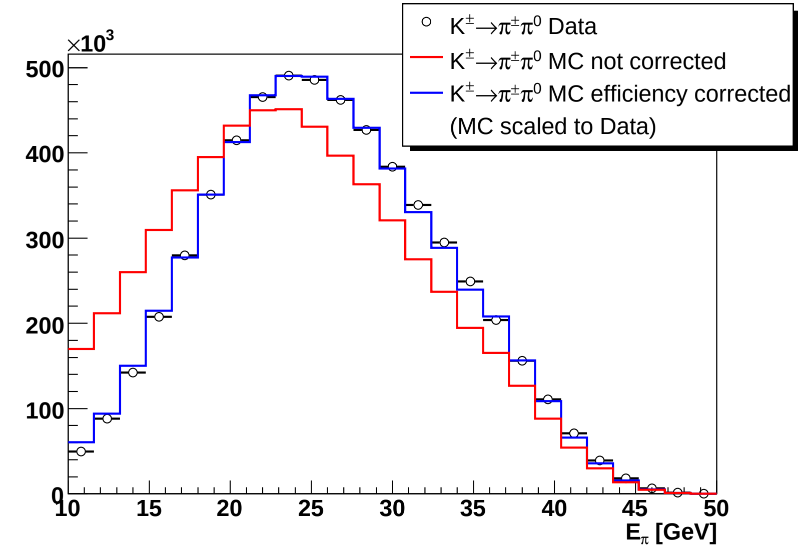
  $\Longrightarrow$ $\approx 80\%$ **efficiency**

Statistics too low to measure trigger efficiencies from $K^\pm \to \pi^\pm\gamma\gamma$.

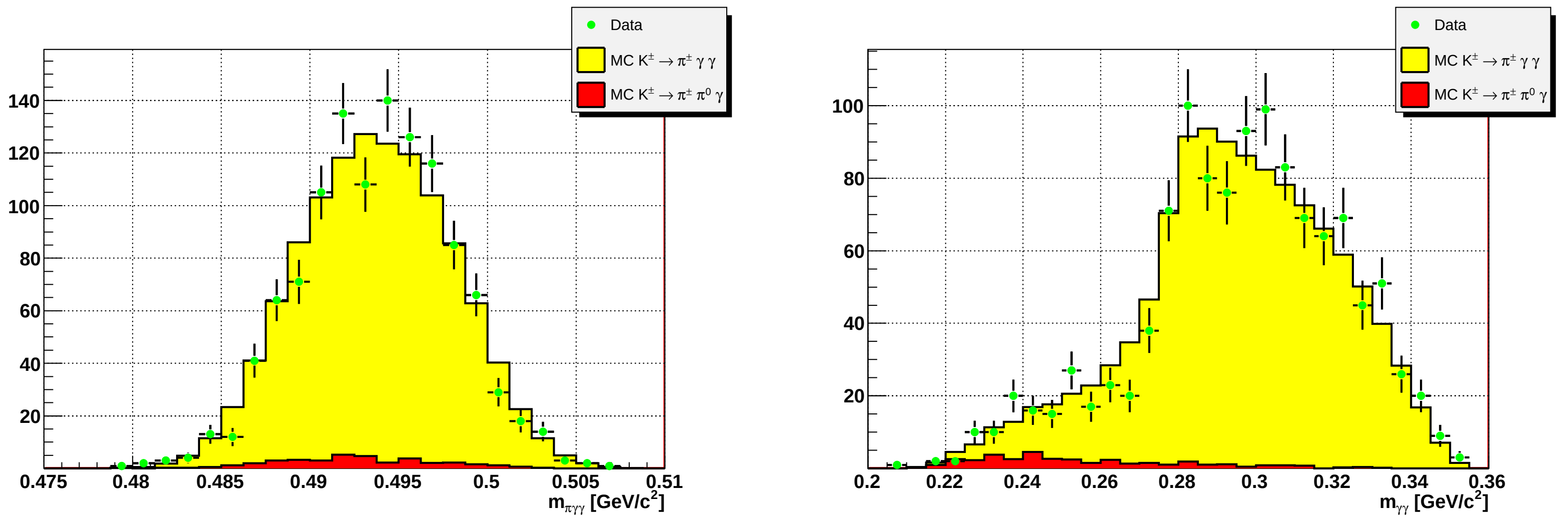
⬇

Use background events and **correct for different kinematics.**





$K^\pm \to \pi^\pm\gamma\gamma$: *Branching Fraction*



- **1164 $K^\pm \to \pi^\pm\gamma\gamma$ candidates** in 40% of NA48/2 data.
  (About 40 times more than previous world sample!)
- **Background:** **3.3%,** mainly from $K^\pm \to \pi^\pm\pi^0\gamma$.
- **Systematics:** Mainly from trigger efficiency determination.

Assume ChPT $\mathcal{O}(p^6)$ and $\hat{c} = 2$:

(preliminary)

$$\mathbf{Br}(K^\pm \to \pi^\pm\gamma\gamma)_{\hat{c}=2,\mathcal{O}(p^6)} = (1.07 \pm 0.04_{\text{stat}} \pm 0.08_{\text{syst}}) \cdot 10^{-6}$$

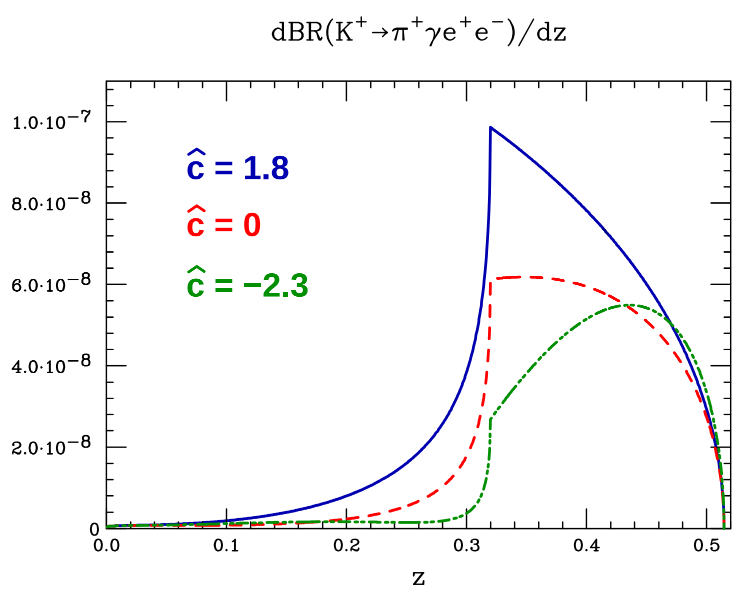
Model independent measurement and $\hat{c}$ extraction in preparation.

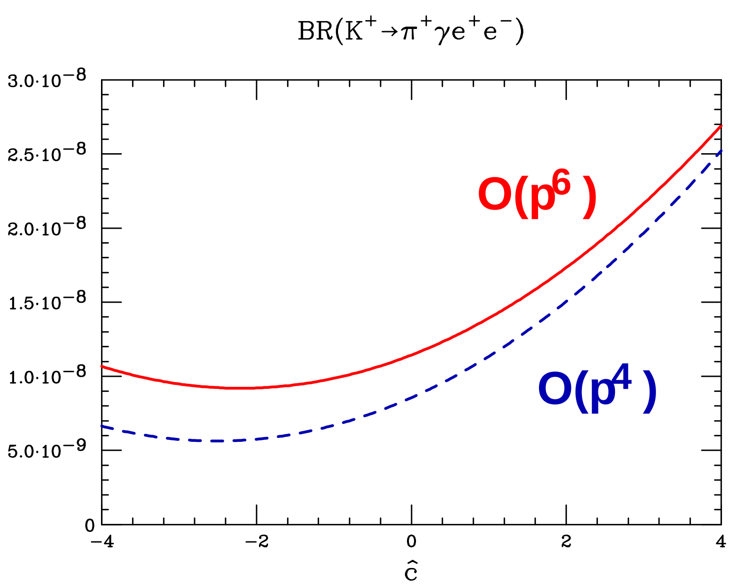
$K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$: *Theory*

$\boldsymbol{K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma}$:

Same as $K^{\pm} \to \pi^{\pm}\gamma\gamma$ with an internal γ conversion.

- $\boldsymbol{\mathcal{O}(p^4)}$: BR and $m_{ee\gamma}$ determined by $\hat{c}$
- $\boldsymbol{\mathcal{O}(p^6)}$: Unitarity corrections $\Longrightarrow$ change in BR by $30 - 40\%$.
  (Gabbiani, Phys. Rev.. Lett. D 59 (1999) 094022)





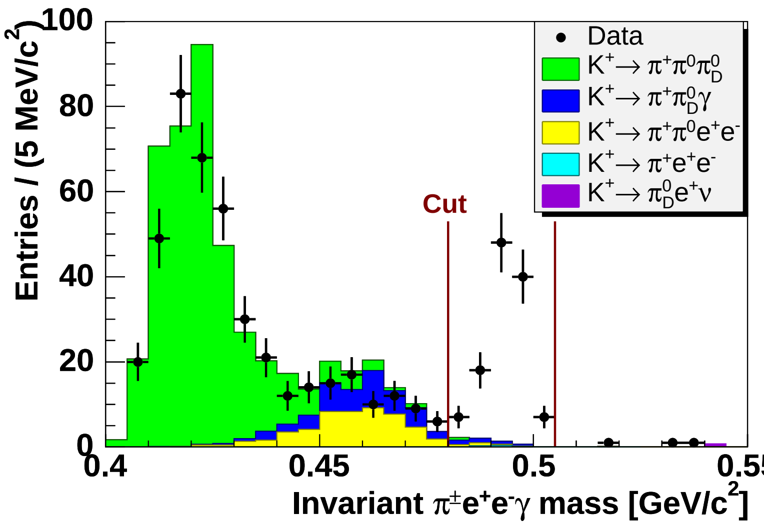
$K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$: *Branching Fraction*

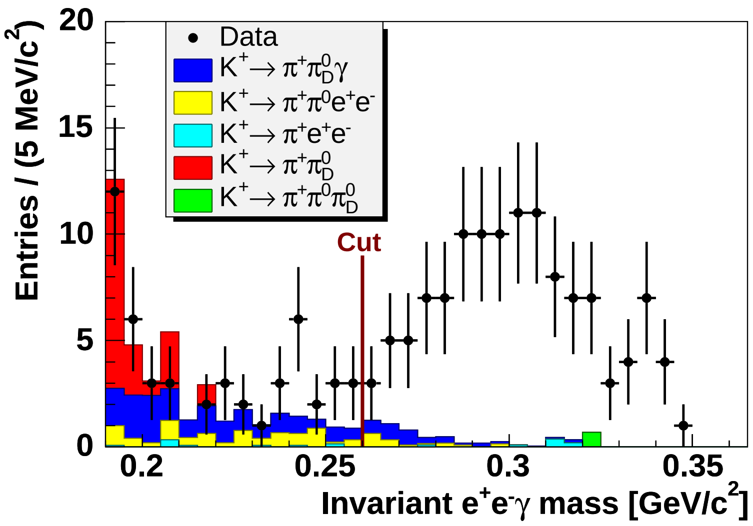
Model independent measurement:

- **120 $K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$ candidates** (selection through 3-track-trigger).
- Normalization to $K^{\pm} \to \pi^{\pm} \pi^0_D \to \pi^{\pm} e^{+} e^{-} \gamma$.
- Computing BR in bins of $m_{ee\gamma}$.

$\Longrightarrow$ **No assumption on $m_{ee\gamma}$ distribution used!**

$$\mathrm{Br}(K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma)_{m_{ee\gamma} > 260\ \mathrm{MeV}} = (1.19 \pm 0.12_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}) \cdot 10^{-8}$$





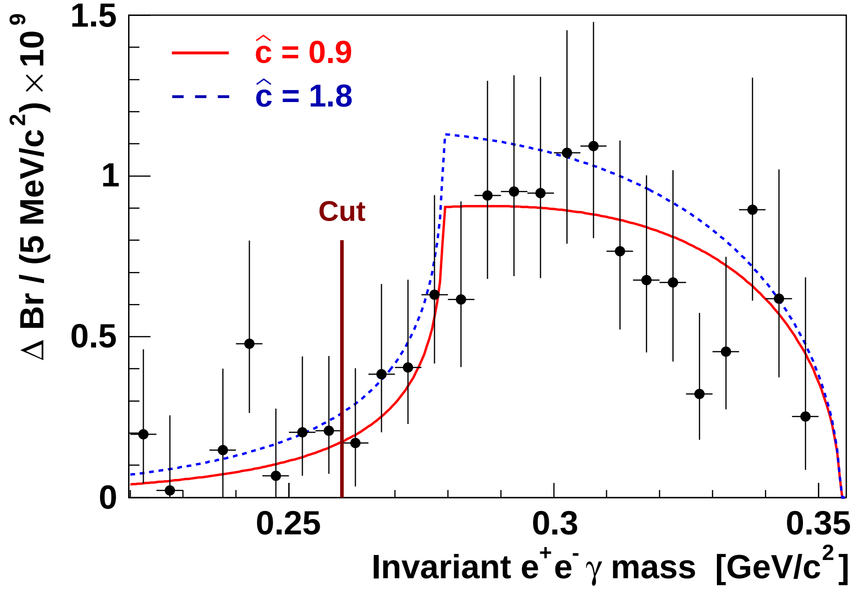
$K^\pm \to \pi^\pm e^+ e^- \gamma$: *Fit of* $m_{ee\gamma}$ *distribution*

Model dependent measurement:

Fit $m_{ee\gamma}$ distribution for $\hat{c}$ using $\mathcal{O}(p^6)$ ChPT:

$$\hat{c} \;=\; 0.90 \pm 0.45$$

$(\chi^2/N_{\text{dof}} = 8.1/17)$



From this, the branching fraction is extrapolated to $m_{ee\gamma} < 0.26$ MeV:

$$\text{Br}(K^\pm \to \pi^\pm e^+ e^- \gamma) \;=\; (1.29 \pm 0.13_{\text{exp}} \pm 0.03_{\hat{c}}) \times 10^{-8}$$

(PLB 659 (2008) 493)

Conclusions

- $K^\pm \to \pi^\pm \pi^0 \gamma$:
  - More than 1 million reconstructed events with tiny background.
  - First observation and measurement of interference between IB and DE amplitudes.
  - Limits of $\mathcal{O}(10^{-3})$ on direct CP violation in $K^\pm \to \pi^\pm \pi^0 \gamma$.
- $K^\pm \to \pi^\pm \gamma\gamma$:
  - More than $40\times$ the statistics of previous experiments.
  - Preliminary measurement of the branching fraction.
- $K^\pm \to \pi^\pm e^+ e^- \gamma$:
  - First observation of the decay with 120 events.
  - Measurements of the branching fraction and the $ee\gamma$ decay distribution.