Rare Kaon Decays from NA48/2

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on behalf of the **NA48/2** Collaboration:

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PHIPSI'09

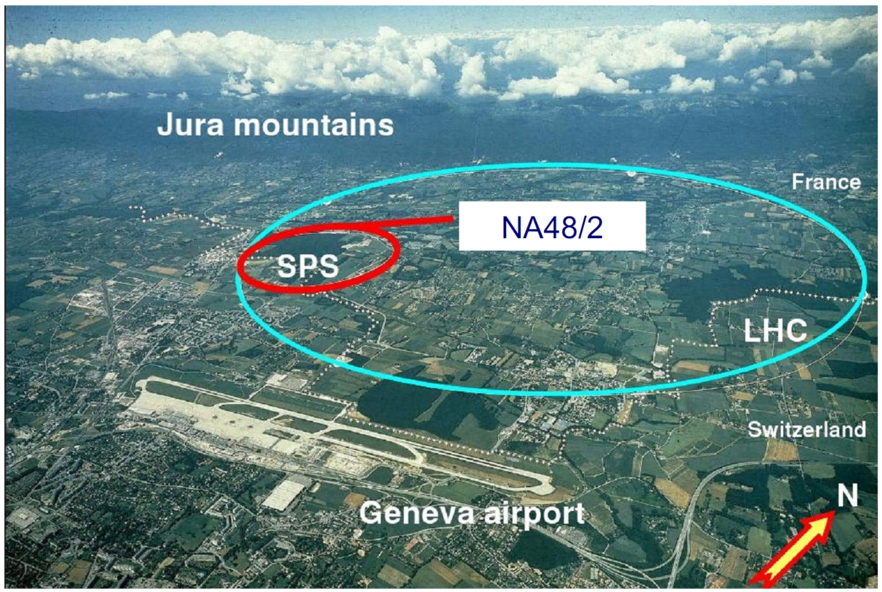
Outline

New Measurements of Radiative Kaon Decays

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

The NA48/2 Experiment

- Fixed target experiment in North Area of SPS



- Devoted to charge asymmetry studies in $K^{\pm} \to 3pi$
- Simultaneous $K^{\pm}$ beams with $p_K = 60 \pm 3$ GeV/c

NA48	1997	ε'/ε run $K_L + K_S$
	1998	ε'/ε run $K_L + K_S$
	1999	ε'/ε run $K_L + K_S$; K_S Hi. Int.
	2000	K_L only; K_S High Intensity; *NO Spectrometer*
	2001	ε'/ε run $K_L + K_S$; K_S High Int.
NA48/1	2002	K_S High Intensity
NA48/2	2003	$K^{\pm}$ High Intensity
	2004	$K^{\pm}$ High Intensity

The NA48/2 Detector

Main detector components:

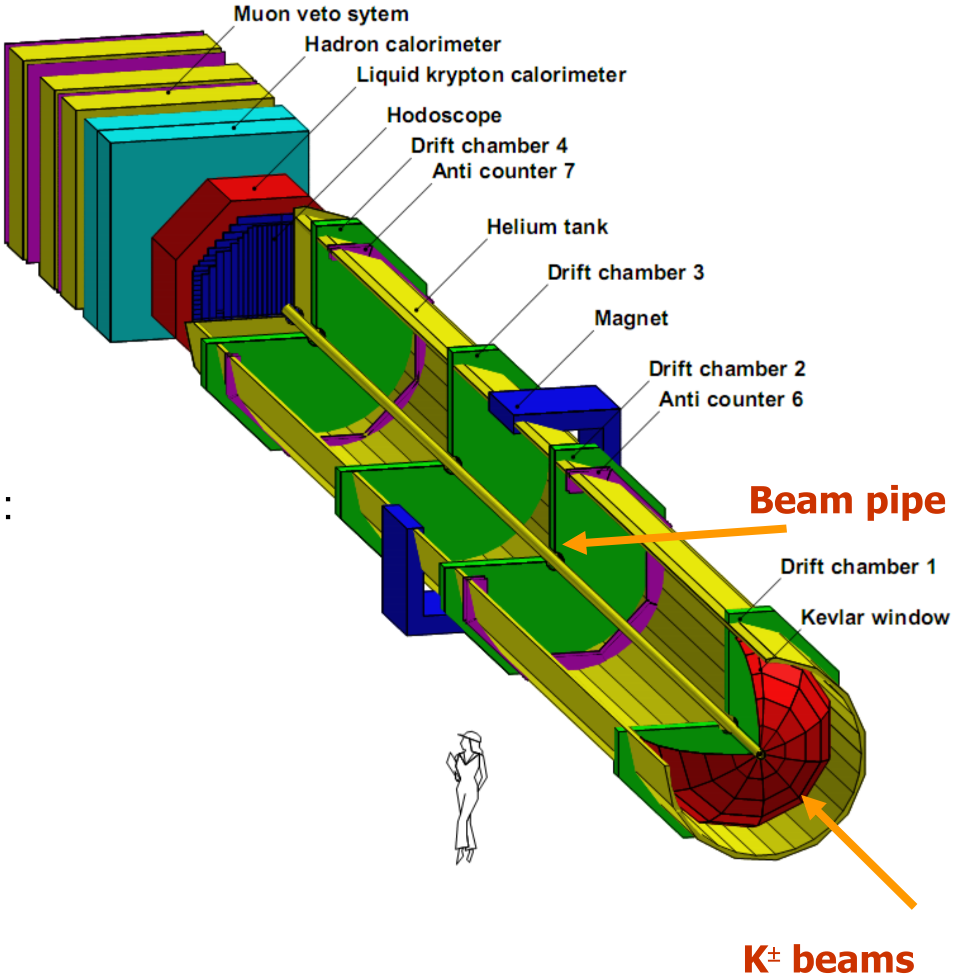
- Magnet spectrometer (4 DCHs):
  1% resolution for p=20 GeV/c
- Liquid Krypton EM calorimeter
  1.4% energy resolution for $E\gamma$ = 2GeV/c

Two main trigger modes:

- Charged. Devoted to $K^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}$ selection:
  3 charged tracks
- Neutral. Devoted to $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \pi^{0}$ selection:
  > 2 em clusters in LKr x or y projection

Total statistics:

$K^{\pm} \rightarrow \pi^{-} \pi^{+} \pi^{\pm}$: ~ $4 \cdot 10^{9}$
$K^{\pm} \rightarrow \pi^{0} \pi^{0} \pi^{\pm}$: ~ $1 \cdot 10^{8}$

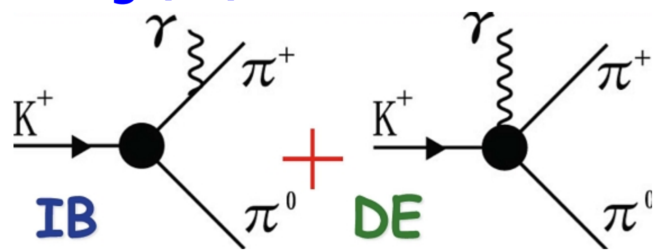


$$\boxed{K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\gamma}$$

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

Two sources of γ radiation:

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



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

$$\frac{\partial\Gamma^\pm}{\partial W} = \underbrace{\frac{\partial\Gamma^\pm_{\mathrm{IB}}}{\partial W}}_{\text{Inner Bremsstrahlung (IB)}} \left[1 + \underbrace{2\cos\left(\pm\phi+\delta_1^1-\delta_0^2\right)|X_E|\,W^2}_{\text{Interference (INT)}} + \underbrace{m_\pi^4 m_K^4\left(|X_E|^2+|X_M|^2\right)W^4}_{\text{Direct Emission (DE)}}\right]$$

known from $K^\pm \to \pi^\pm\pi^0$ and QED

Interference of IB and electric DE. No prediction.

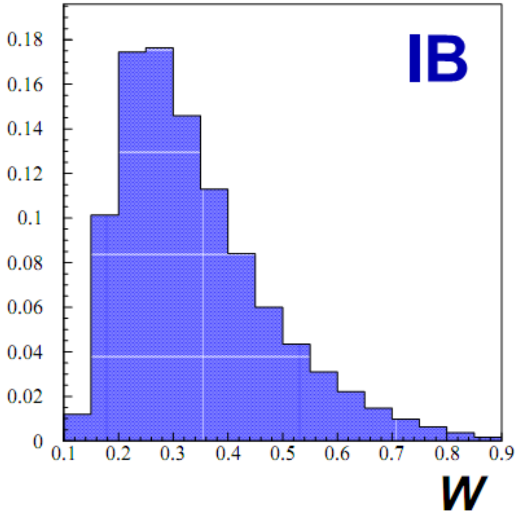
two terms ($\mathcal{O}(p^4)$ ChPT):

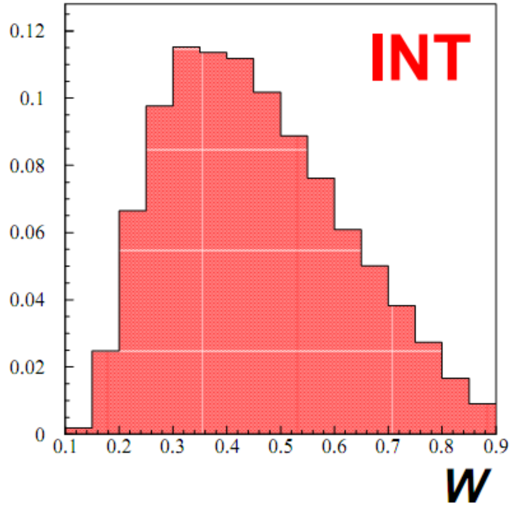
- X_M: magnetic part has two contributions: reducible WZW functional (~ 260 GeV^{-4}) + direct (not known)
- X_E: no prediction

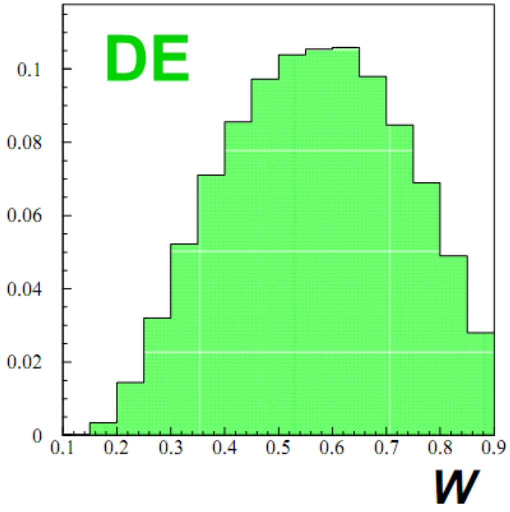
$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Theory

$$\frac{\partial\Gamma^{\pm}}{\partial W} = \underbrace{\frac{\partial\Gamma^{\pm}_{\mathrm{IB}}}{\partial W}}_{\text{Inner Bremsstrahlung (IB)}} \left[1 + \underbrace{2\cos\left(\pm\phi + \delta_1^1 - \delta_0^2\right) |X_E| \, W^2}_{\text{Interference (INT)}} + \underbrace{m_\pi^4 m_K^4 \left(|X_E|^2 + |X_M|^2\right) W^4}_{\text{Direct Emission (DE)}} \right]$$

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



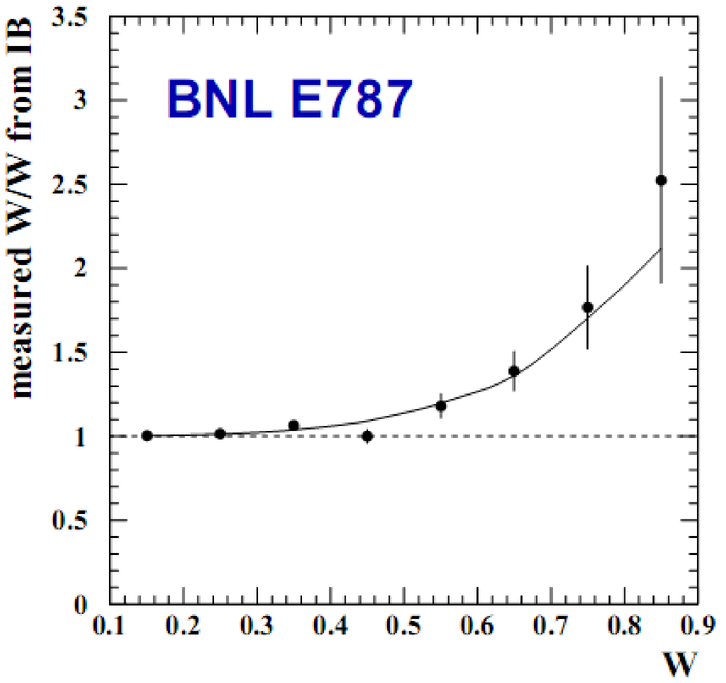




$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Experimental Status

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

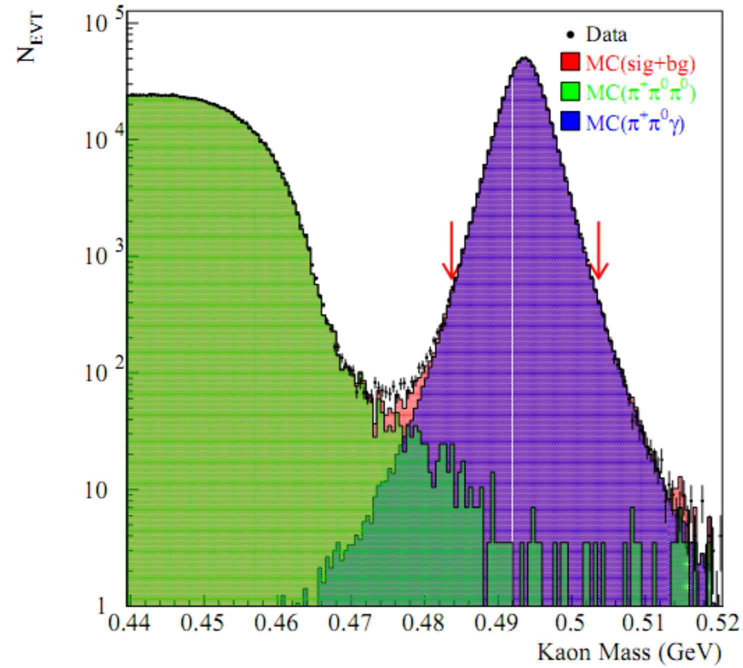


- All previous DE measurements:
  - Kinematic range $55 < T_{\pi}^{*} < 90$ MeV
  - Assumption INT = 0
- So far **neither INT nor CP violation** observed
  - E787. INT = (-0.4 ±1.6)%

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: Data Sample

New NA48/2 Measurement:

- Simultaneous K^+/K^- beams
  $\Longrightarrow$ CPV check possible
- Larger T^*_π region available
  $0 < T^*_\pi < 80$ MeV
- Background negligible:
  $< 1\%$ x DE (mainly $\pi^{\pm}\pi^{0}\pi^{0}$)
- $O(10^{-3})$ mistagging probability for odd γ



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

- More than 1 million events
- For the fit: restrict to $0.2 < W < 0.9$ and $E_\gamma > 5$ GeV
  $\Longrightarrow$ Still 600k $\pi^{\pm}\pi^{0}\gamma$ candidates

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

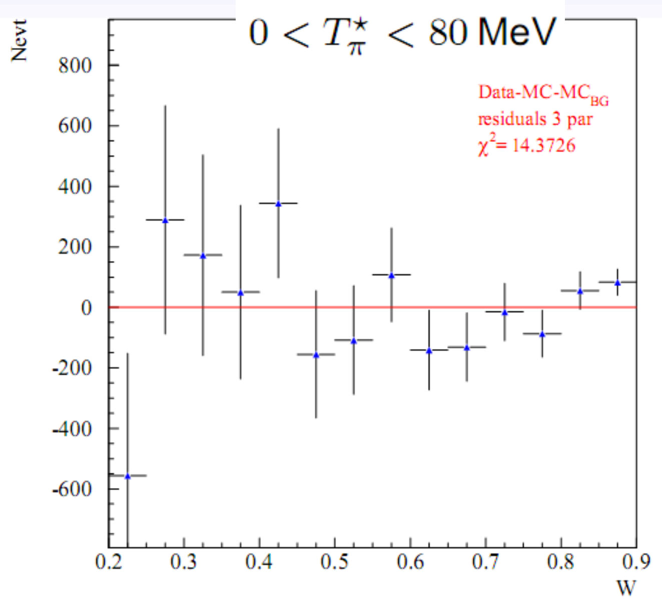
- **Extended Maximum Likelihood Fit**

Correct for acceptances with MC

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

$$\begin{aligned} \textbf{Frac(DE)} &= (\ \ 3.32 \pm 0.15)\times 10^{-2} \\ \textbf{Frac(INT)} &= (-2.35 \pm 0.35)\times 10^{-2} \end{aligned}$$

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

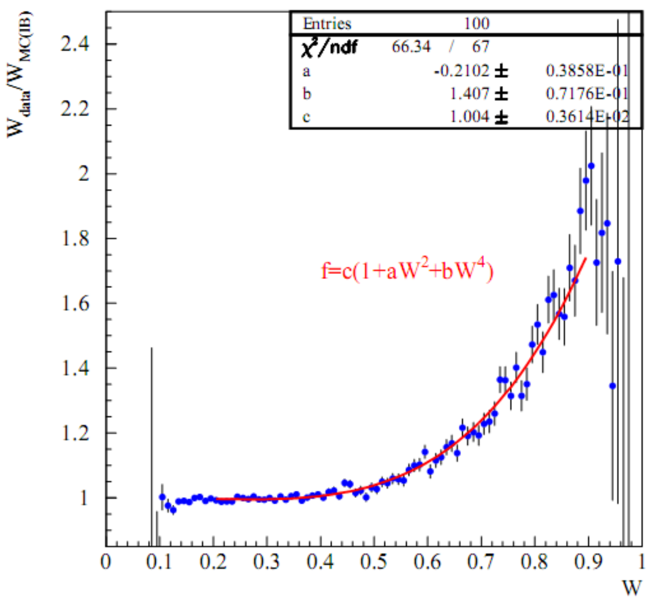


- **Polynomial Fit**

Fit ratio W (Data)/ W (IBMC) with:

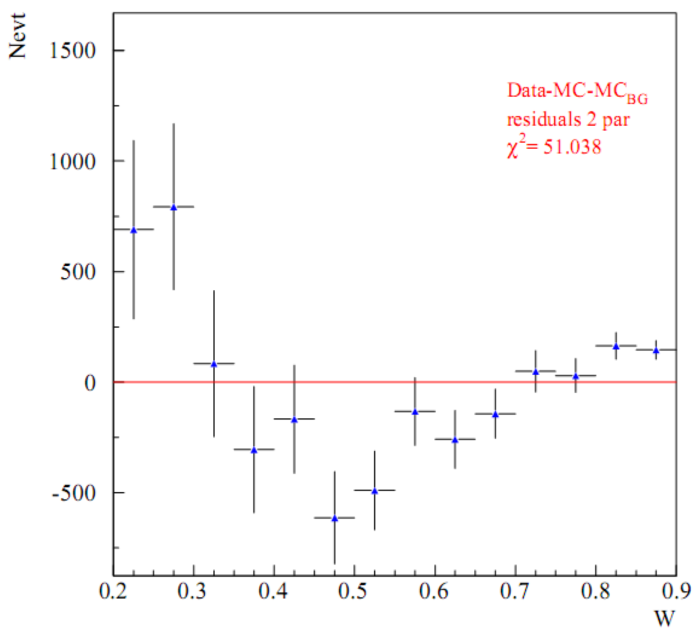
$$F = c\cdot(1+aW^2+bW^4) \implies \textbf{Frac(DE), Frac(INT)}$$

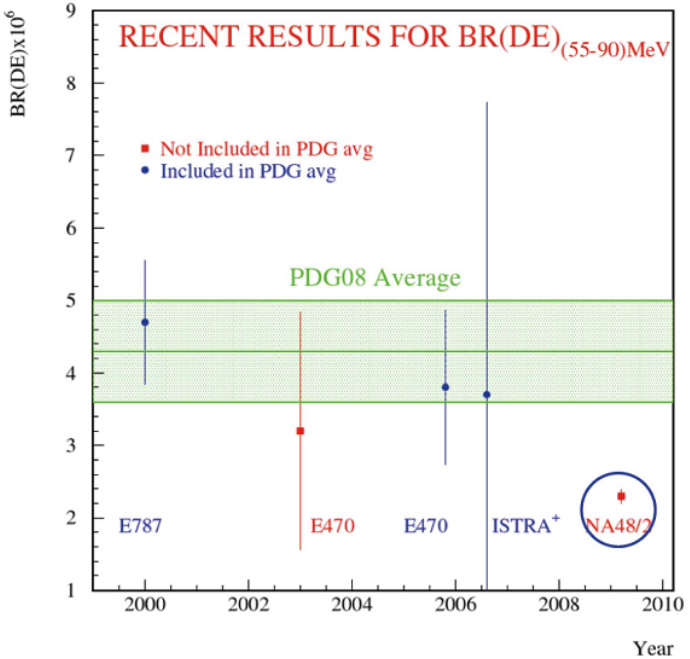
$$\begin{aligned} \textbf{Frac(DE)} &= (\ \ 3.19 \pm 0.16)\times 10^{-2} \\ \textbf{Frac(INT)} &= (-2.21 \pm 0.41)\times 10^{-2} \end{aligned}$$



$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Exp. Comparison

Fit with INT $= 0$ and extrapolation to $55 < T^{\star}_{\pi} < 90$ MeV:





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

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

Need to fit with non-vanishing interference term!

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

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

$$\begin{aligned}
\text{Frac(DE)}_{0<T_\pi^*<80\text{ MeV}} &= (\;\;3.32 \pm 0.15_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-2} \\
\text{Frac(INT)}_{0<T_\pi^*<80\text{ MeV}} &= (-2.35 \pm 0.35_{\text{stat}} \pm 0.39_{\text{syst}}) \times 10^{-2}
\end{aligned}$$

$\rho = -0.93$

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:

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

WZW reducible anomaly prediction: $X_M \approx 270\ \text{GeV}^{-4}$

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

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: CPV Studies

- **Asymmetry in the total rate**

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

with $R = N_{K^+}/N_{K^-} = 1.7998(4)$ from $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$

$$\boxed{\begin{aligned} A_N &= (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-3} \\ |A_N| &< 1.5 \times 10^{-3} \quad (90\%\ \text{CL}) \end{aligned}}$$

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

$$\sin\phi = -0.01 \pm 0.43$$

$$|\sin\phi| < 0.56 \quad (90\%\ \text{CL})$$

- **Asymmetry in the Dalitz plot**

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

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

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

$$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$$

$$K^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}\gamma$$

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

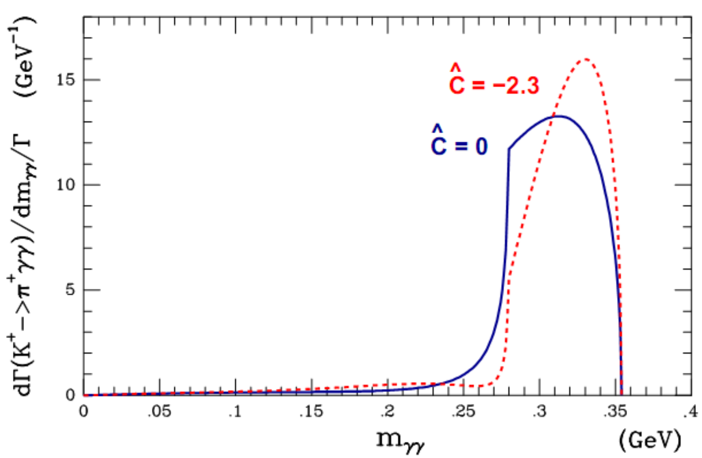
Differential $K^\pm \to \pi^\pm\gamma\gamma$ decay rate

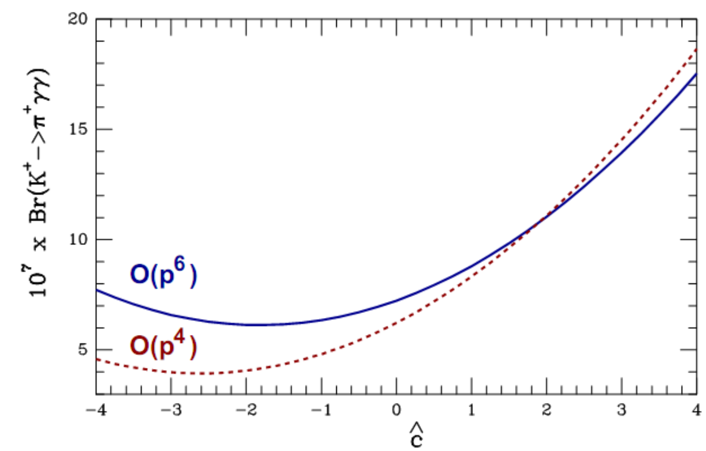
$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A+B|^2+|C|^2\right)+\left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2\left(|B|^2+|D|^2\right)\right]$$

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)





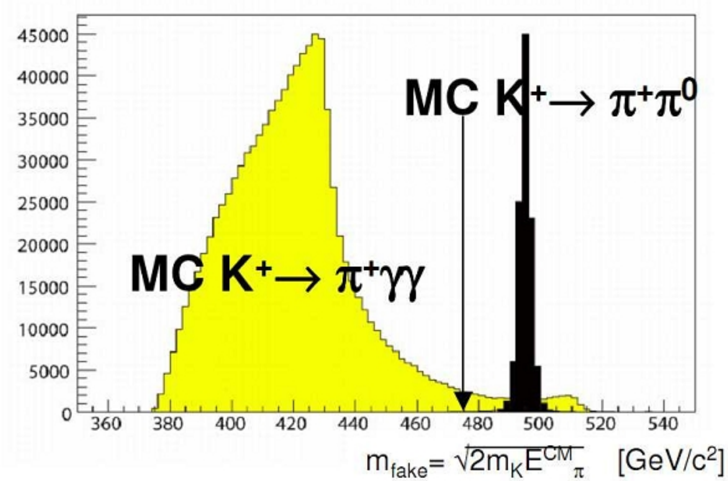
$K^{\pm} \to \pi^{\pm}\gamma\gamma$: Trigger

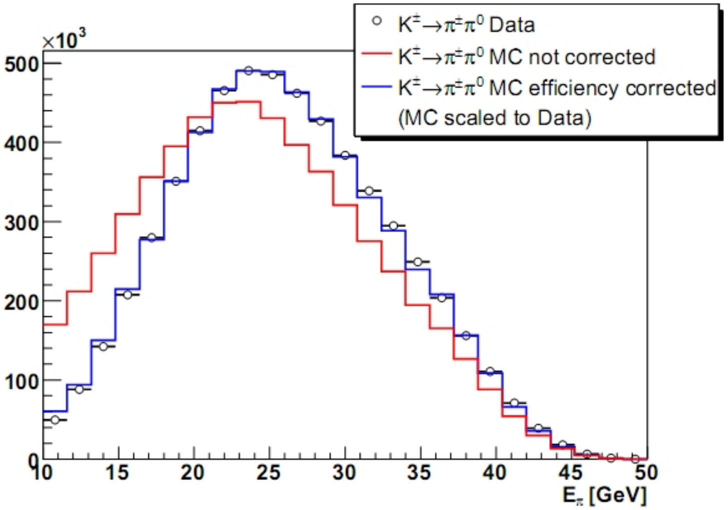
Trigger Efficiency

- $K^{\pm} \to \pi^{\pm}\gamma\gamma$ 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**

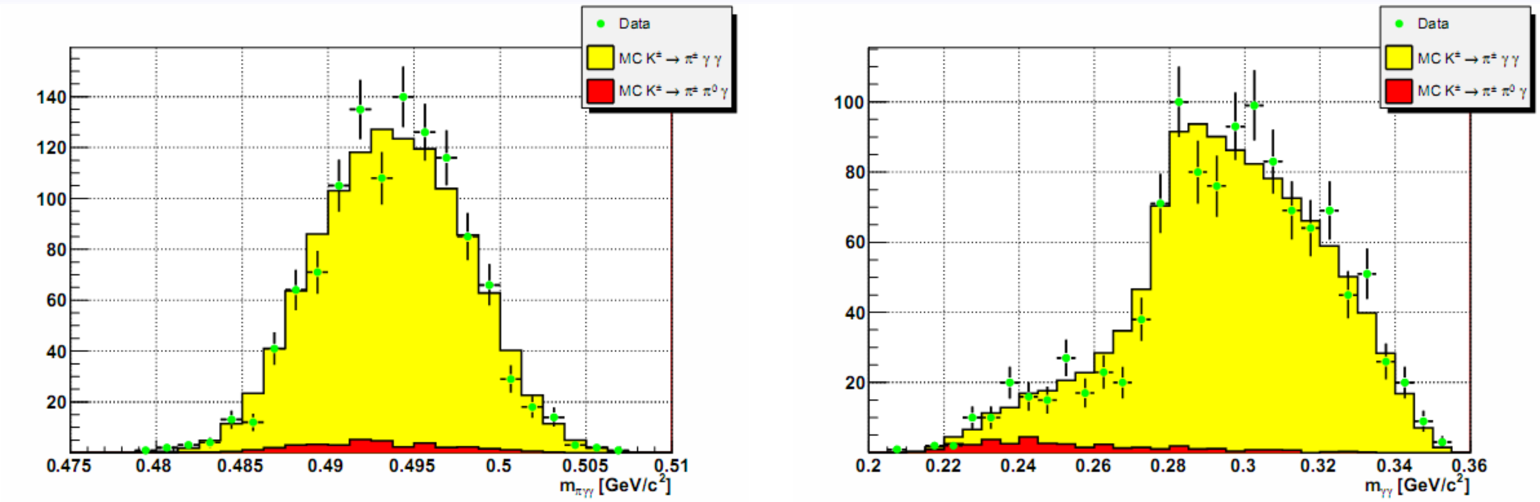
Statistics too low to measure trigger efficiencies from $K^{\pm} \to \pi^{\pm}\gamma\gamma$.

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)

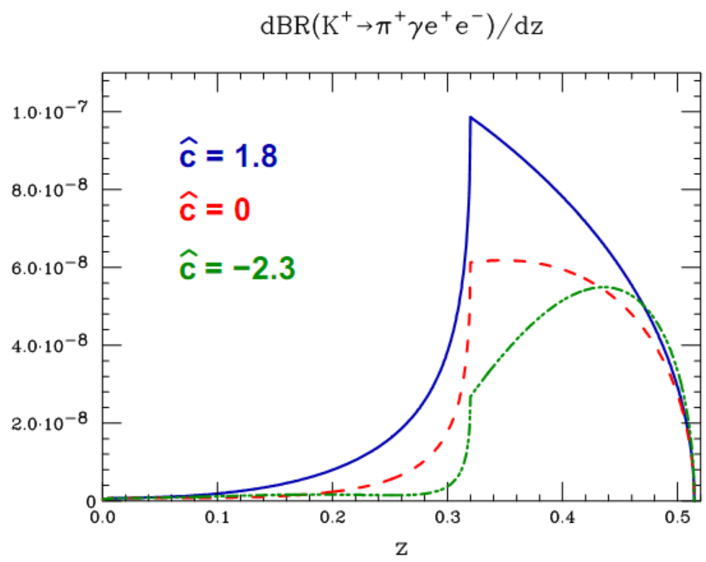
$$\mathbf{Br}(K^{\pm} \to \pi^{\pm}\gamma\gamma)_{\hat{c}=2,\mathcal{O}(p^6)} = (1.07 \pm 0.04_{stat} \pm 0.08_{syst}) \cdot 10^{-6}$$

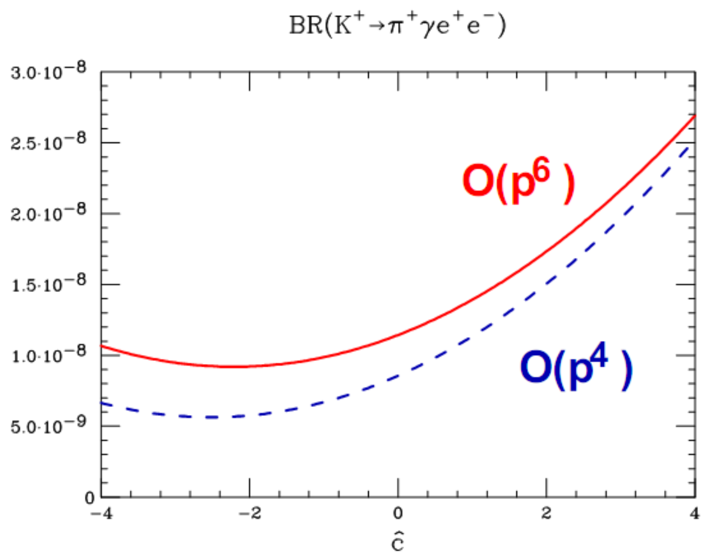
Model independent measurement and $\hat{c}$ extraction in preparation.

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

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

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





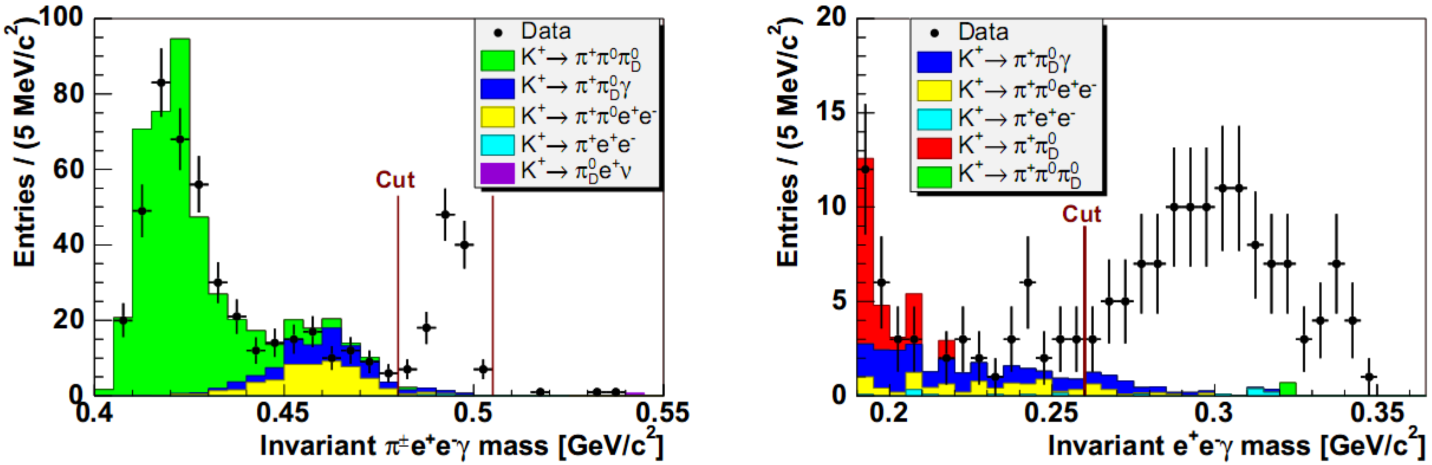
$K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$: Fit of $m_{ee\gamma}$

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!**

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



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.

Thank You !

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

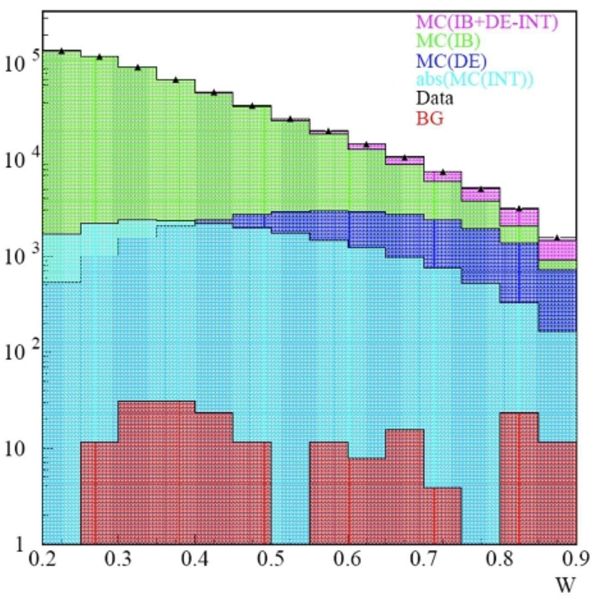
Extended Maximum Likelihood Fit

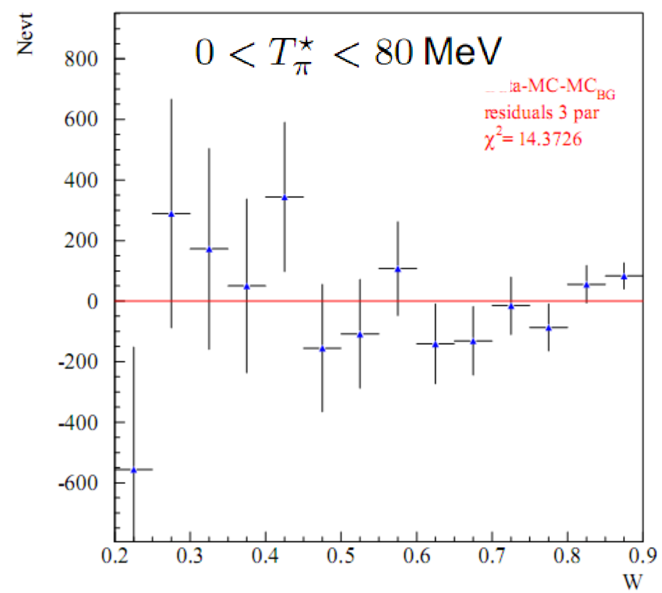
Correct for acceptances with MC

$$\textbf{Data}(i) = N_0[(1-\alpha-\beta)\cdot \mathbf{IB_{MC}}(i) + \alpha\cdot \mathbf{INT_{MC}}(i) + \beta\cdot \mathbf{DE_{MC}}(i)]$$

$$\boxed{\begin{aligned} \textbf{Frac(DE)} &= (\ \ \mathbf{3.32 \pm 0.15}) \times \mathbf{10^{-2}} \\ \textbf{Frac(INT)} &= (\mathbf{-2.35 \pm 0.35}) \times \mathbf{10^{-2}} \end{aligned}}$$

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

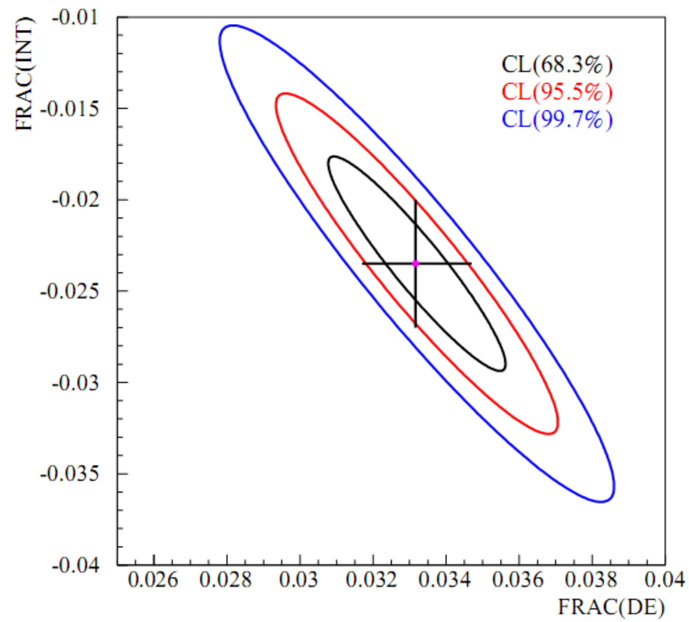




$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Final Results

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: $\rho = -0.93$

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

Decay rate may depend on kaon charge:

$$\frac{\partial\Gamma^{\pm}}{\partial W} = \frac{\partial\Gamma^{\pm}_{IB}}{\partial W}\left[1 + \underbrace{2\cos\left(\pm\phi + \delta_1^1 - \delta_0^2\right)|X_E|\, W^2}_{\text{INT}} + m_\pi^4 m_K^4 \left(|X_E|^2 + |X_M|^2\right) W^4\right]$$

- 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: $2 \cdot 10^{-6} - 10^{-5}$ for $50 < E_\gamma^\star < 170$ MeV.

- **Possible SUSY contributions** can push the asymmetry up to 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**

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

Asymmetry in the total rate

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

$$\boxed{\begin{aligned} A_N &= (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-3} \\ |A_N| &< 1.5 \times 10^{-3} \quad (90\%\ \text{CL}) \end{aligned}}$$

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

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

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

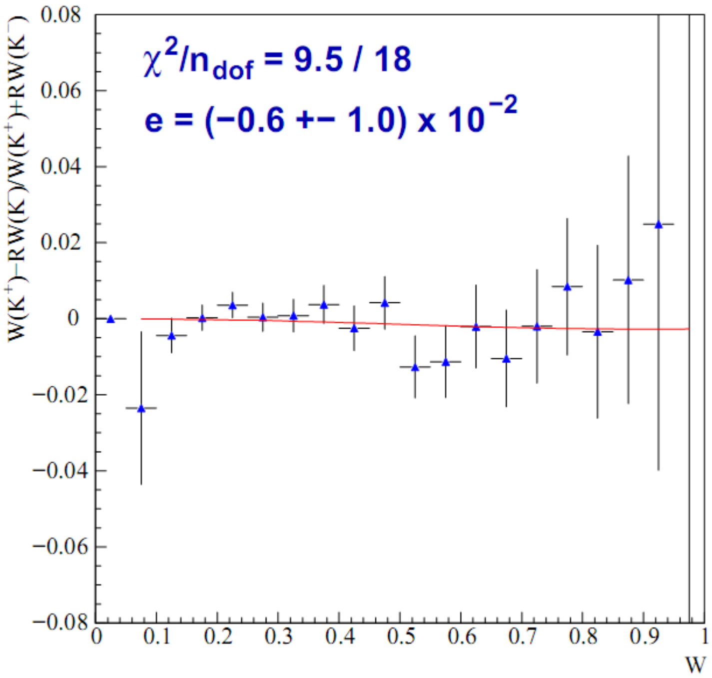
Asymmetry in the Dalitz plot

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:

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



$$\boxed{A_W = e\int \frac{\text{INT}}{\text{IB}} = (-0.6 \pm 1.0) \times 10^{-3}}$$ compatible with A_N.

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

$K^\pm \to \pi^\pm \gamma\gamma$ Decays

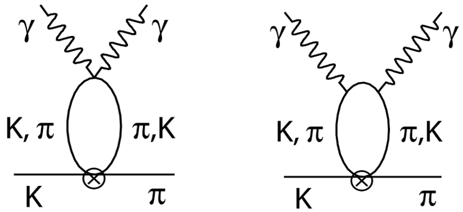
$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{2^9\pi^3}\left[z^2(|A+B|^2+|C|^2)+\left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2\cdot(|B|^2+|D|^2)\right]$$

$$y = \frac{p_K(q_1-q_2)}{m_K^2}, \qquad z = \frac{(q_1+q_2)^2}{m_K^2}. \qquad \lambda(a,b,c) = a^2+b^2+c^2-2(ab+bc+ca), \; r_\pi = \frac{m_\pi}{m_K}$$

$O(p^4)$

[Nucl.Phys.B303(1988) 665; hep-ph/0508189]

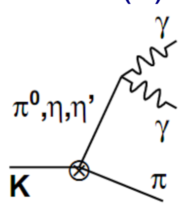
A: • Loop diagrams ⇒ **cusp** at $\pi^+\pi^-$ threshold: $\mathbf{m_{\gamma\gamma} = 2m_{\pi+}}$

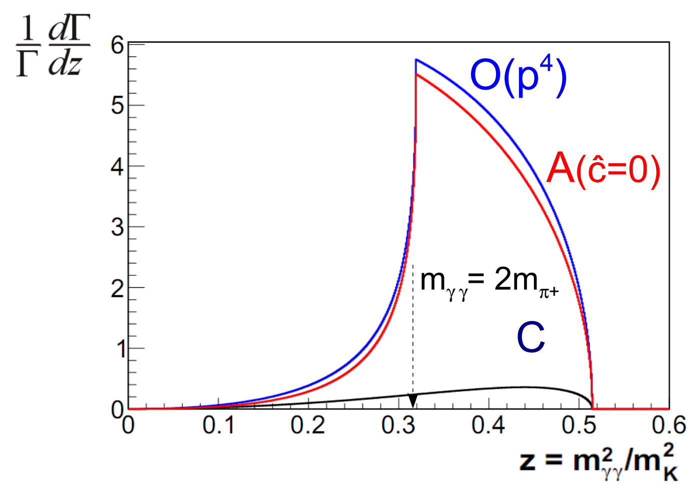


• Tree level **counterterms** ⇒ **ĉ** parameter

Model dependent. Predicted of O(1)

C: • Poles and tadpoles



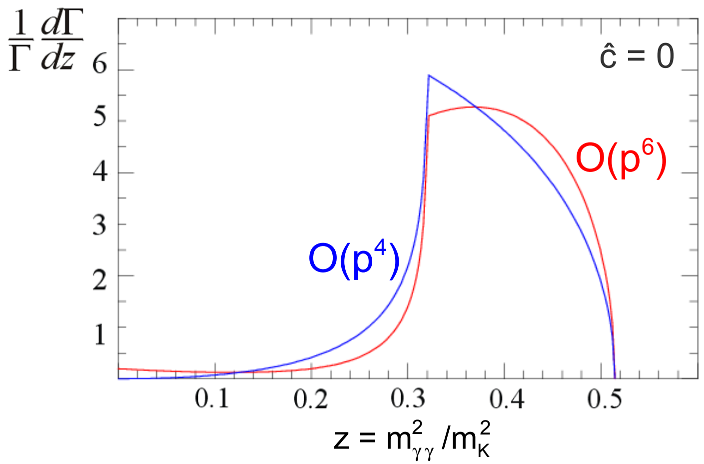


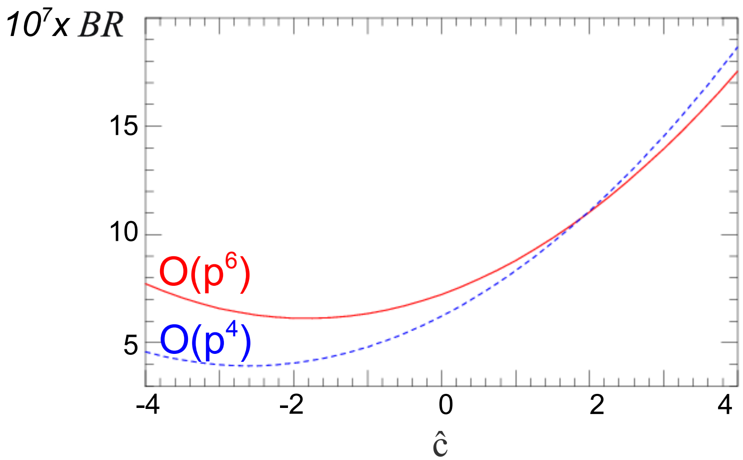
$O(p^6)$

[Nucl.Phys. B386 (1996), 403]

• **Unitarity corrections** by $K^\pm \to \pi^\pm\pi^+\pi^-$ at $O(p^4)$ can increase BR by 30- 40% and modify spectrum

$K^{\pm}\to\pi^{\pm}\gamma\gamma$ Decays





Measurement of branching ratio and spectrum determine
model dependent ĉ and whether $O(p^6)$ corrections explain observed rate and shape

E787 (Brookhaven) (1997) $K^{\pm}\to\pi^{\pm}\gamma\gamma$ selected events: 31 (0.16< z <0.39)	**ĉ = 1.8 ± 0.6** **BR**($K^{\pm}\to\pi^{\pm}\gamma\gamma$) = **(1.10 ± 0.32)** x **10^{-6}**
E949 (Brookhaven) (2005) $K^{\pm}\to\pi^{\pm}\gamma\gamma$ No event observed (z < 0.04)	**BR**($K^{\pm}\to\pi^{\pm}\gamma\gamma$, z <0.04) < **8.3** x **10^{-9}**
NA48/2 (CERN) (2008) $K^{\pm}\to\pi^{\pm}e^+e^-\gamma$ selected events: 120. Full spectrum	**ĉ = 0.90 ± 0.45**