Rare Kaon Decays

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Electroweak Symmetry Breaking
Weak Decays, CP Violation and CKM
Neutrino Physics
Dark Matter

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- **Volume I: Search for Lepton Flavour Violation**
  - **Measurements of** $K \to e\nu_e / K \to \mu\nu_\mu$
  - **Measurement of** $K \to e\nu\gamma$
- **Volume II: Radiative Kaon Decays**
  - $K^\pm \to \pi^\pm\pi^0\gamma$
  - $K^\pm \to \pi^\pm\gamma\gamma$ **and** $K^\pm \to \pi^\pm e^+e^-\gamma$
  - $K^\pm \to \pi^\pm e^+e^-$

Volume 1

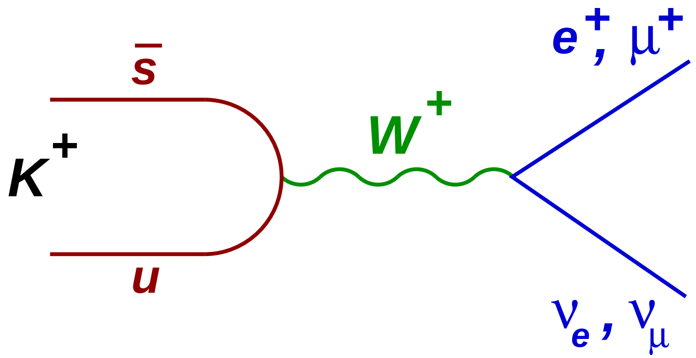
Search for Lepton Flavour Violation in Ke2/Kμ2

$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ - *Motivation*

SM Prediction on $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$:

- Text book exercise for **helicity suppression**

  $\Longrightarrow$ R_K very small.



- **Nearly exact**

  (hadronic uncertainties cancel, only radiative corrections to consider):

$$\mathbf{R_K} = \frac{\Gamma(\mathbf{K}^\pm \to \mathbf{e}^\pm \nu)}{\Gamma(\mathbf{K}^\pm \to \mu^\pm \nu)} = \frac{\mathbf{m_e^2}}{\mathbf{m_\mu^2}} \cdot \left(\frac{\mathbf{m_K^2} - \mathbf{m_e^2}}{\mathbf{m_K^2} - \mathbf{m_\mu^2}} \right)^2 \cdot (1 + \delta \mathbf{R_K^{\mathrm{rad.corr.}}})$$

$$= (2.477 \pm 0.001) \times 10^{-5}$$ (V. Cirigliano, I. Rosell, JHEP 0710:005 (2007))

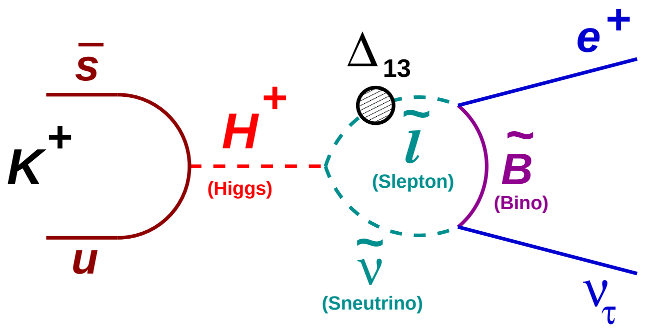
$\Longrightarrow$ **SM prediction has precision of 0.04%!**

$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ beyond the SM

Possible MSSM scenario:

(Masiero, Paradisi, Petronzio, PRD 74, 2006)

'Charged Higgs mediated SUSY LFV contributions can be strongly enhanced, in particular in kaon decays into an electron or a muon and a tau neutrino'



$$R_K^{\text{LFV}} \approx R_K^{\text{SM}} \left[1 + \frac{m_K^4}{M_{H^\pm}^4} \frac{m_\tau^2}{M_e^2} |\Delta_{13}|^2 \tan^6 \beta \right]$$

Example: $\Delta_{13} = 5 \times 10^{-4}$, $M_H = 500\, GeV$, $\tan\beta = 40$:

$$\Longrightarrow \mathbf{R_K^{\text{LFV}} \approx R_K^{\text{SM}} (1 + 0.013)}$$

$\Longrightarrow$ Effect of up to a few percent with a massive charged Higgs!

Experimental siuation:

- **PDG 2008:** three measurements of the 1970s (4.5% rel. error)
- **Now: new precise measurements of KLOE and NA62**

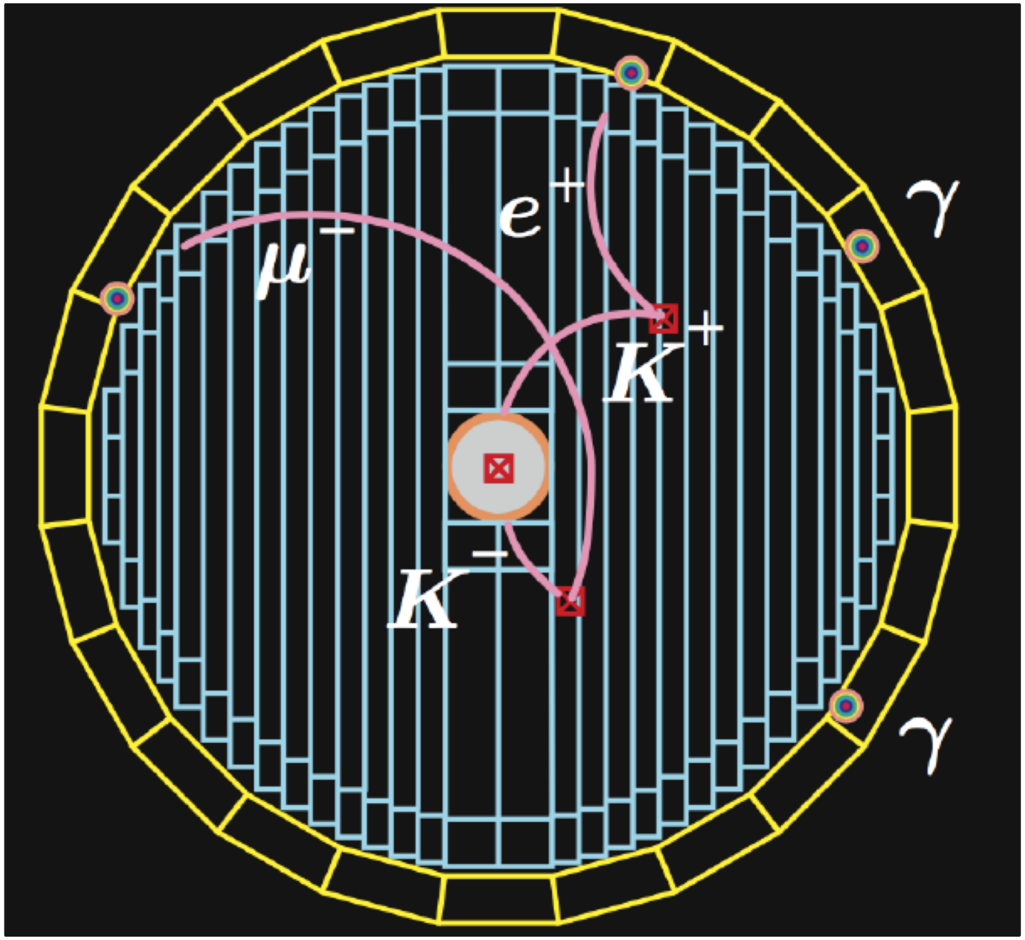
R_K from KLOE

KLOE data:

- $2.2\ \text{fb}^{-1}$ in 2001–05
  $\Longrightarrow$ **$3.3 \times 10^9\ K^+K^-$ pairs**

KLOE kinematics:

- **ϕ decay at rest.**
  - $p_K \approx 100$ MeV
  - Constraint from 2-body decay
- **Particle ID** from kinematics, calorimeter (EMC) and ToF



KLOE: Kinematic Selection

Kinematic separation:

Build $M^2_{\text{lep}} = (E_K - p_{\text{miss}})^2 - p^2_{\text{lep}}$

assuming $m_\nu = 0$

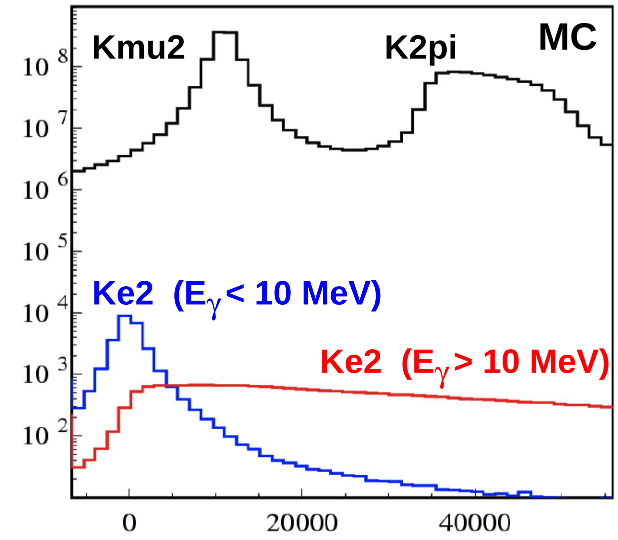
$\Longrightarrow$ $S/B \sim 10^{-3}$

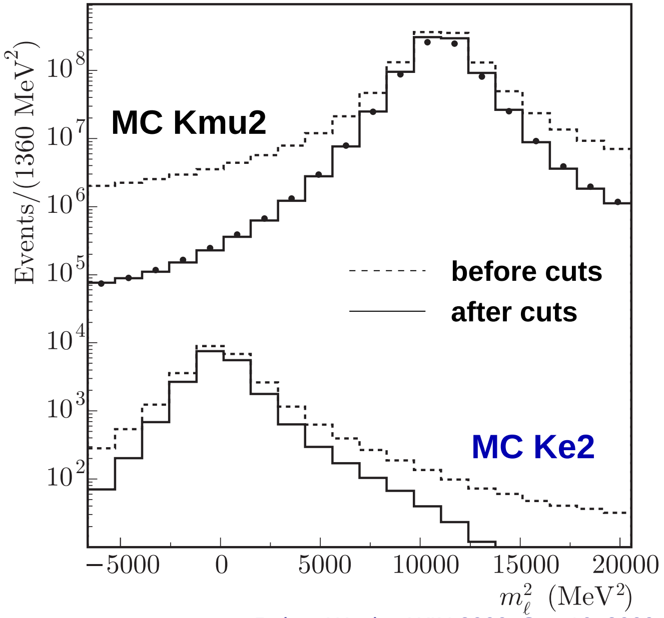
mainly due to tails in $K_{\mu 2}$ momentum resolution

Quality cuts on vertex, tracks;
Consistency with $\phi \to K^+K^-$ decay

$\Longrightarrow$ Still $S/B \sim 0.05$

Particle identification





KLOE: Particle Identification

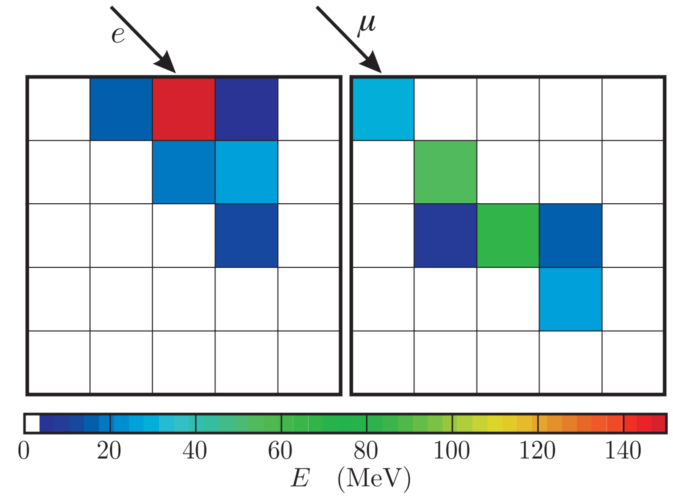
Electron/muon separation:

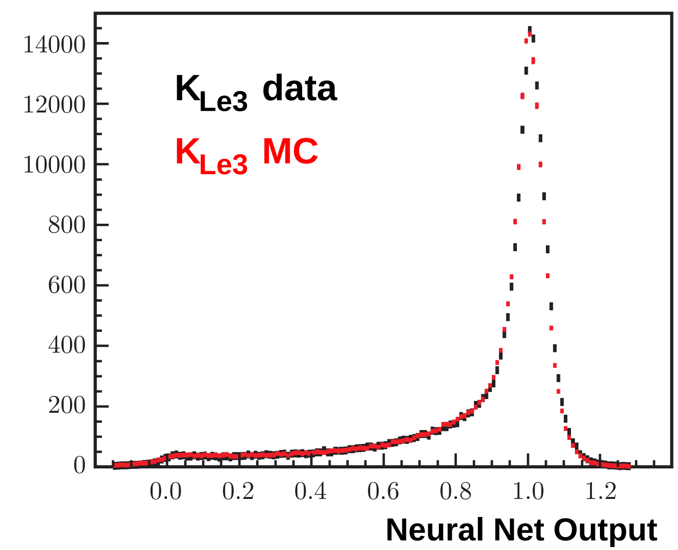
- Exploit **EMC granularity** (5 layers in depth):
  Use **11 shower pattern variables** in EMC cells.

- Add E/p and **time-of-flight** information.

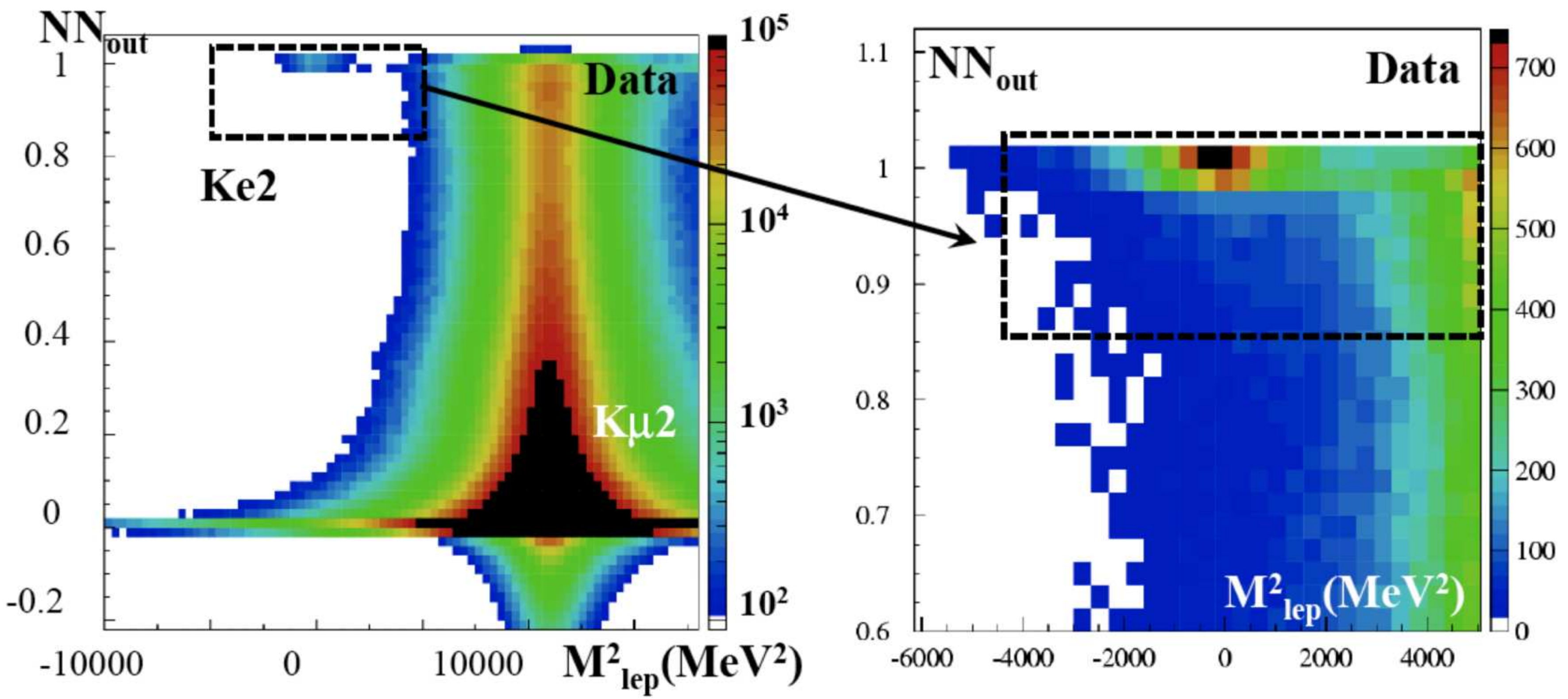
- Combine everything into a **Neural Net.**
  - Correct electron MC with K_{Le3} data.
  - NN trained with K_{Le3} and $K_{\mu2}$ data.

200 MeV electrons/muons:





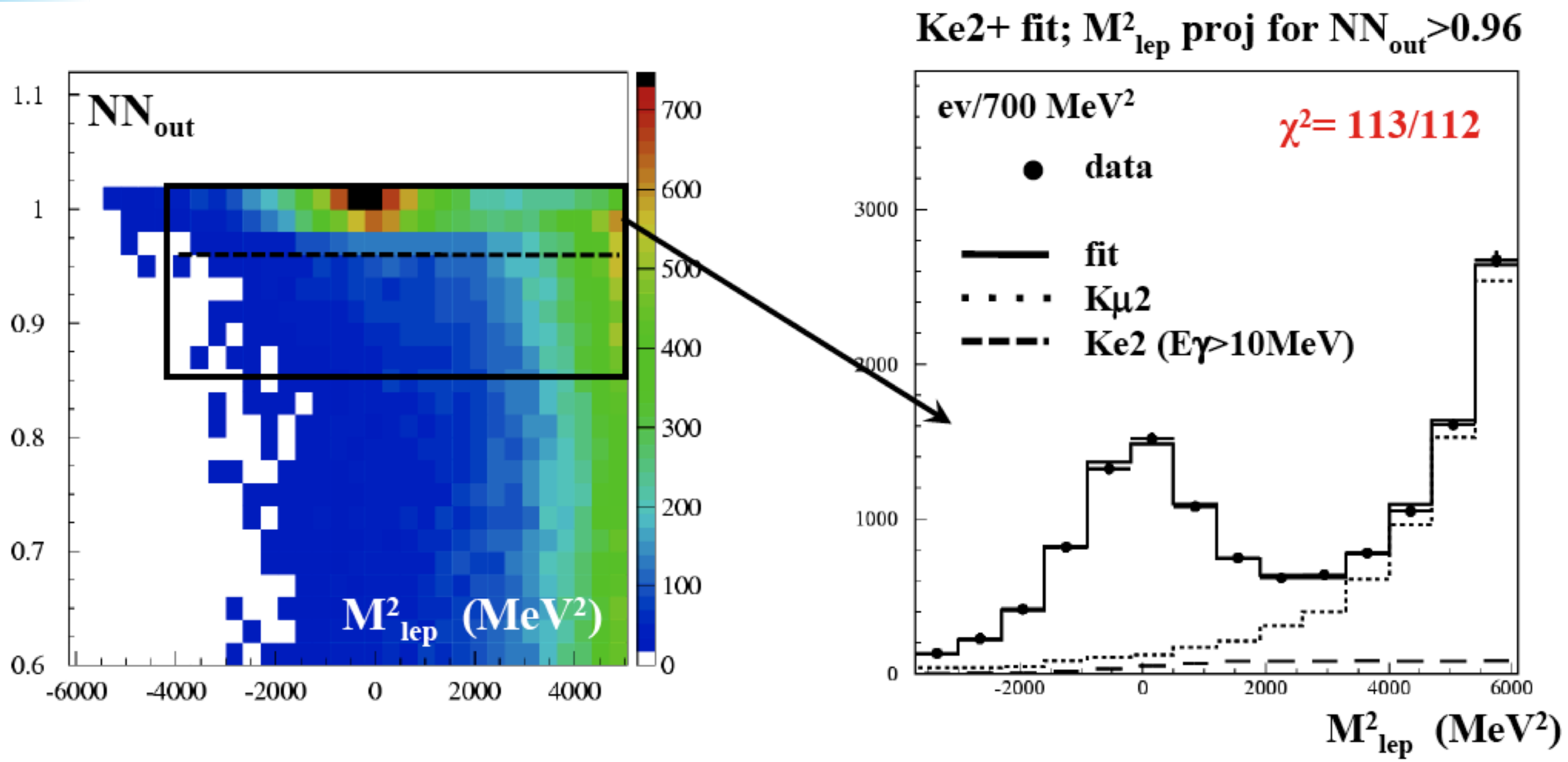
Neural Net Output:



For $0.86 < \mathrm{NN_{out}} < 1.02$ and $-4000 < M^2_{\mathrm{lep}} < 6100$ MeV^2:

$S/B \sim 5$ (with signal acceptance $\sim 15\%$).

KLOE: $Ke2$ signal



Two-dimensional binned likelihood fit in the $(M^2_{\text{lep}}, \text{NN}_{\text{out}})$ **plane:**

$\Longrightarrow$ $\mathbf{7060 \pm 102}\ K^+_{e2}$ and $\mathbf{6750 \pm 101}\ K^-_{e2}$ **candidates**

Have to take into account radiative events. . .

Measurement of $K_{e2\gamma}$ ...

$$\Bigg(\ldots$$

Two contributions to $K_{e2\gamma}$:

- **Inner Bremsstrahlung IB:**

  Radiation from external charged particles $\longrightarrow$ QED.

  Included in Br$(Ke2(\gamma))$.

- **Direct Emission DE (structure dependent, SD):**

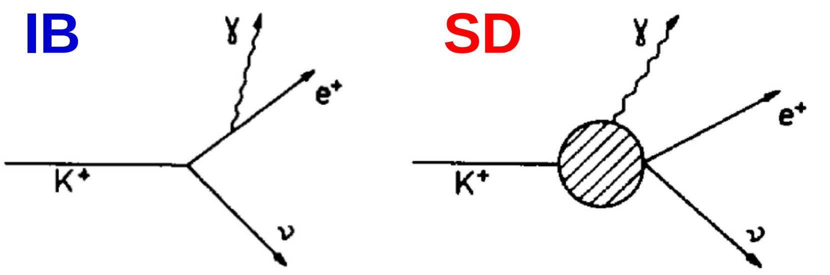
  Radiation from the decay vertex $\longrightarrow$ effective theories, e.g. ChPT.

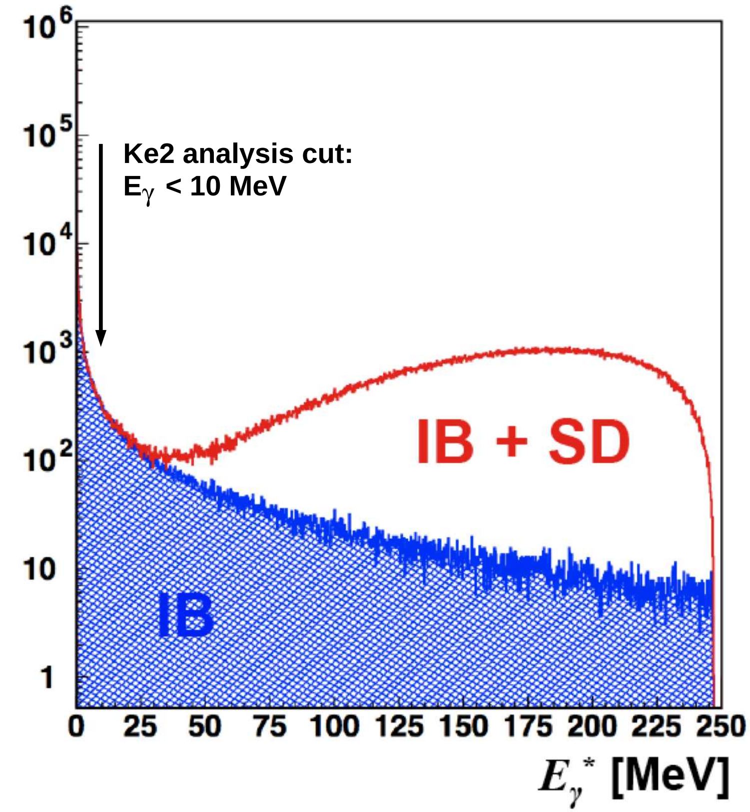
  Not included in Br$(Ke2(\gamma))$.

  $\Longrightarrow$ Needs to be subtracted from $Ke2$ data sample!

Experimental data on SD from the 70's with ΔBr$(SD)/$Br$(SD) \sim 15\%$

$\Longrightarrow$ New KLOE measurement using same $Ke2$ data sample!





$K_{e2\gamma}$ Direct Emission

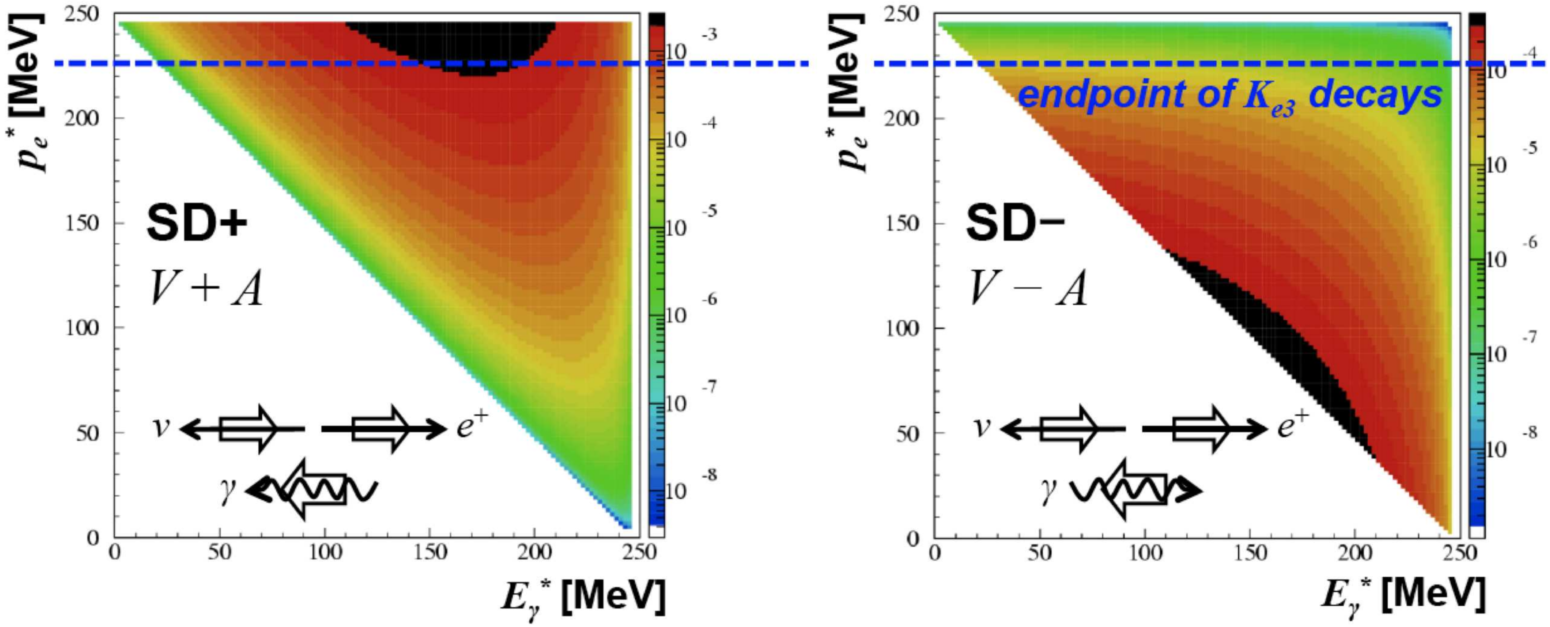
Two components of structure-dependent amplitude:

- **SD+: effective $(V + A)$ coupling**

  High energetic electron $\Longrightarrow$ easy to measure.

- **SD−: effective $(V - A)$ coupling**

  Low energetic electron $\Longrightarrow$ beneath $Ke3$ background, but also suppressed as $Ke2$ background.



KLOE $K_{e2\gamma}$ Measurement

KLOE measurement on $K_{e2\gamma}$:

(arXiv:0907.3594)

$E_\gamma > 10$ MeV, $p_e > 200$ MeV, fits in separate E_γ bins:

1484 signal events

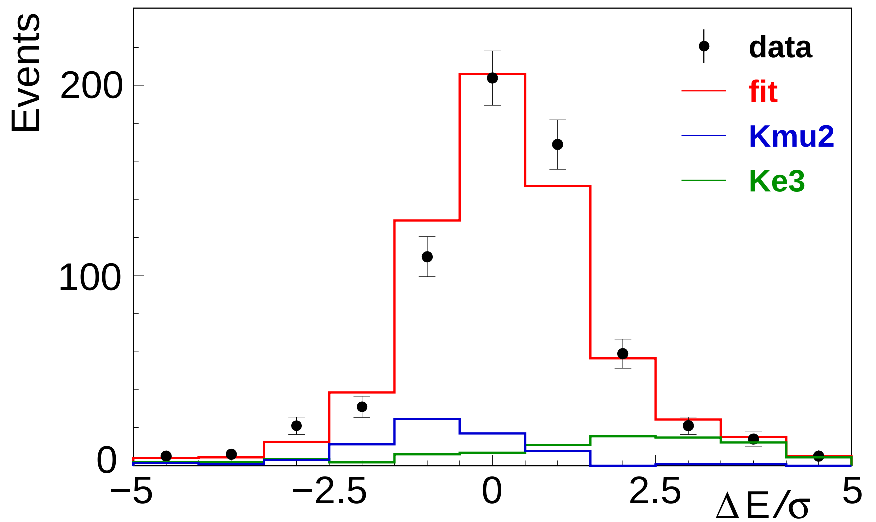
⬇

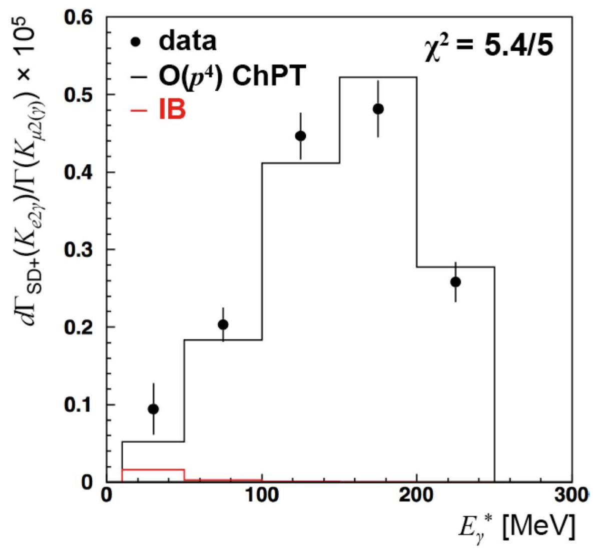
$$\frac{\Gamma(K_{e2\gamma}, SD+)}{\Gamma(K_{\mu2(\gamma)})} = 1.483(66)(13) \times 10^{-5}$$

⬇

- Good agreement with prediction of $\mathcal{O}(p^4)$ ChPT (1.447×10^{-5})
- Reduction of SD contrib. to error on R_K:

$$0.5\% \implies 0.2\%$$





End of $K_{e2\gamma}$ Measurement

$$\ldots\Big)$$

KLOE: Result on R_K

Summary on R_K Systematics:

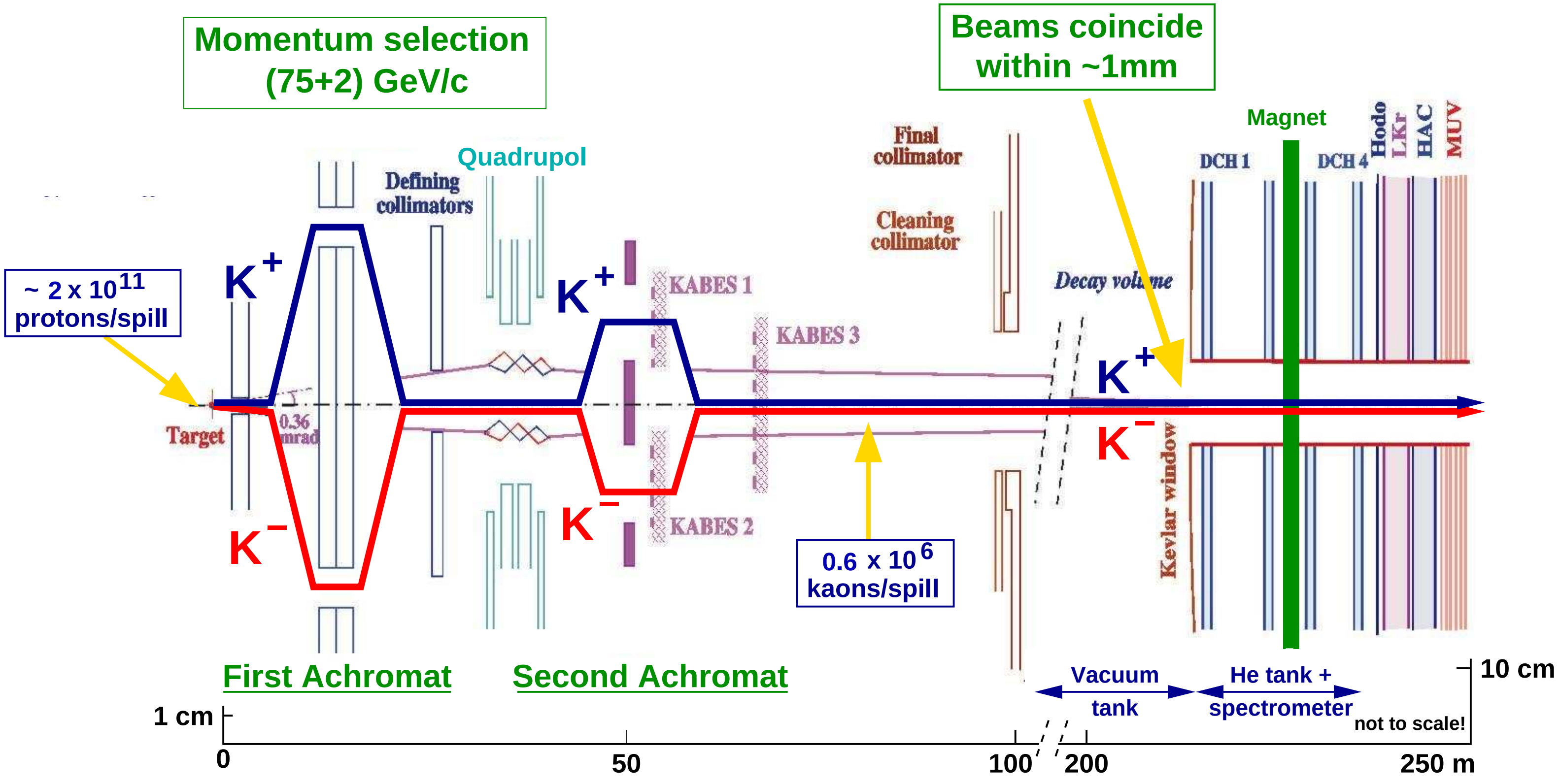
Source	$\Delta R_K / R_K$	Evaluation
Tracking	0.6%	K^+ control samples
Trigger	0.4%	down-scaled events
K_{e2} counts	0.3%	fit stability
K_{e2} DE	0.2%	$K_{e2\gamma}$ measurement
e, μ cluster	0.2%	K_L control samples
Total	0.8%	

KLOE result: (arXiv:0907.3594)

$$R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$$

- **PDG 2008:** $R_K = (2.45 \pm 0.11) \times 10^{-5}$
- **Theory:** $R_K = (2.477 \pm 0.001) \times 10^{-5}$

NA62 in 2007/2008



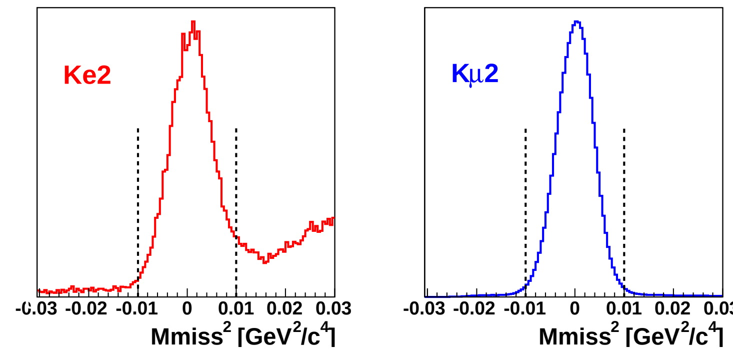
- **NA48/2 beam and detector,** only slightly modified.
- *Kaon momentum:* (75 ± 2) GeV/c
- 4 months data taking with *minimum-bias trigger*

NA62: K_{e2} and $K_{\mu2}$ Selection

Kinematic separation:

Build $M^2_{\text{miss}} = (P_K - P_l)^2$

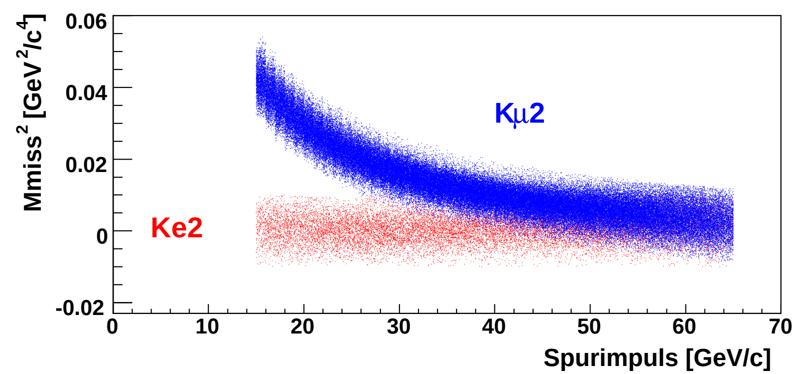
with K momentum 75 GeV/c and e or μ mass



$K_{\mu2}$: Practically background-free

K_{e2}: Bkgd-free for track momenta < 35 GeV/c ($\sim 40\%$ of data)

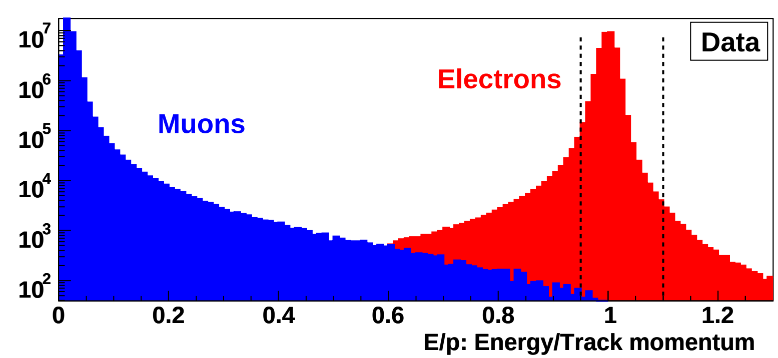
Higher momenta...



Electron identification:

E/p: Ratio of Lkr energy to track momentum

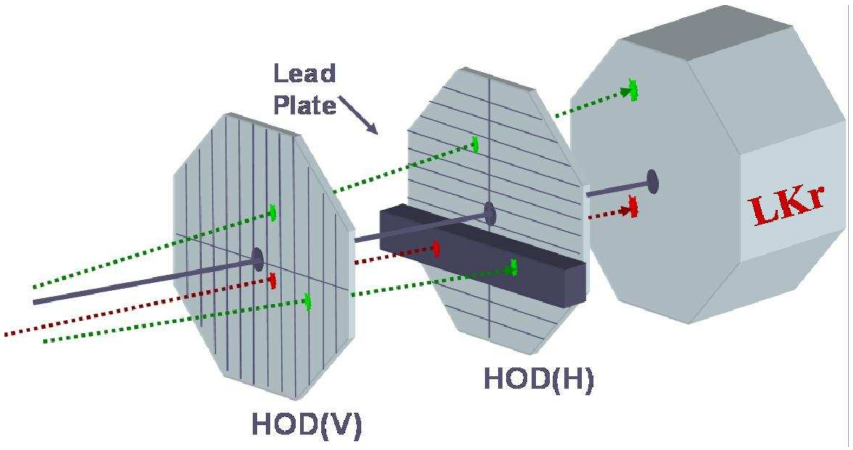
$<$0,1 for muons, $\approx$1 for electrons



NA62: Background from $K_{\mu 2}$ in K_{e2}

Problem:

- **Catastrophic energy loss** of Muons in LKr (∼some 10^{-6})

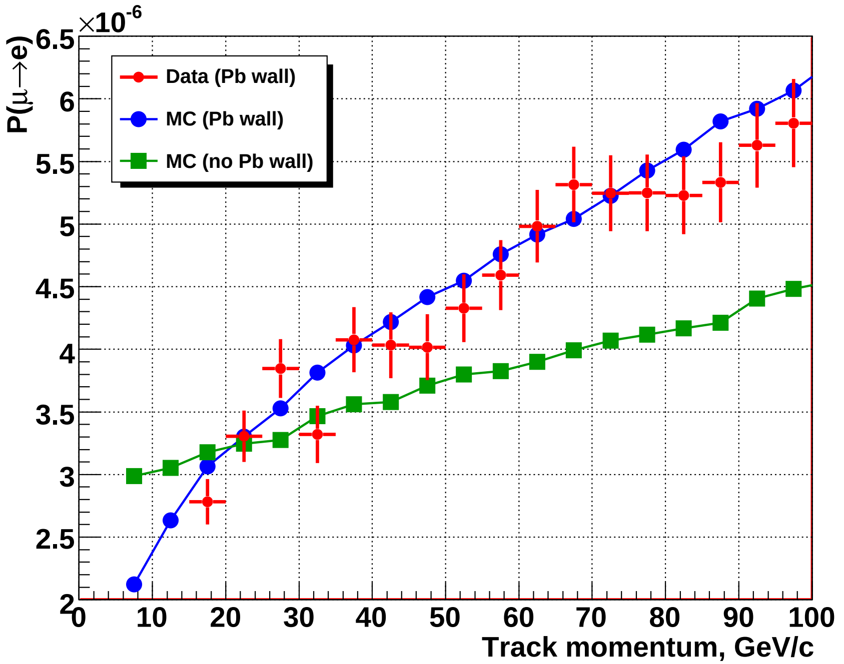


Solution:

- Special **muon runs**
- During data taking: **lead bar** ($9X_0$) before LKr

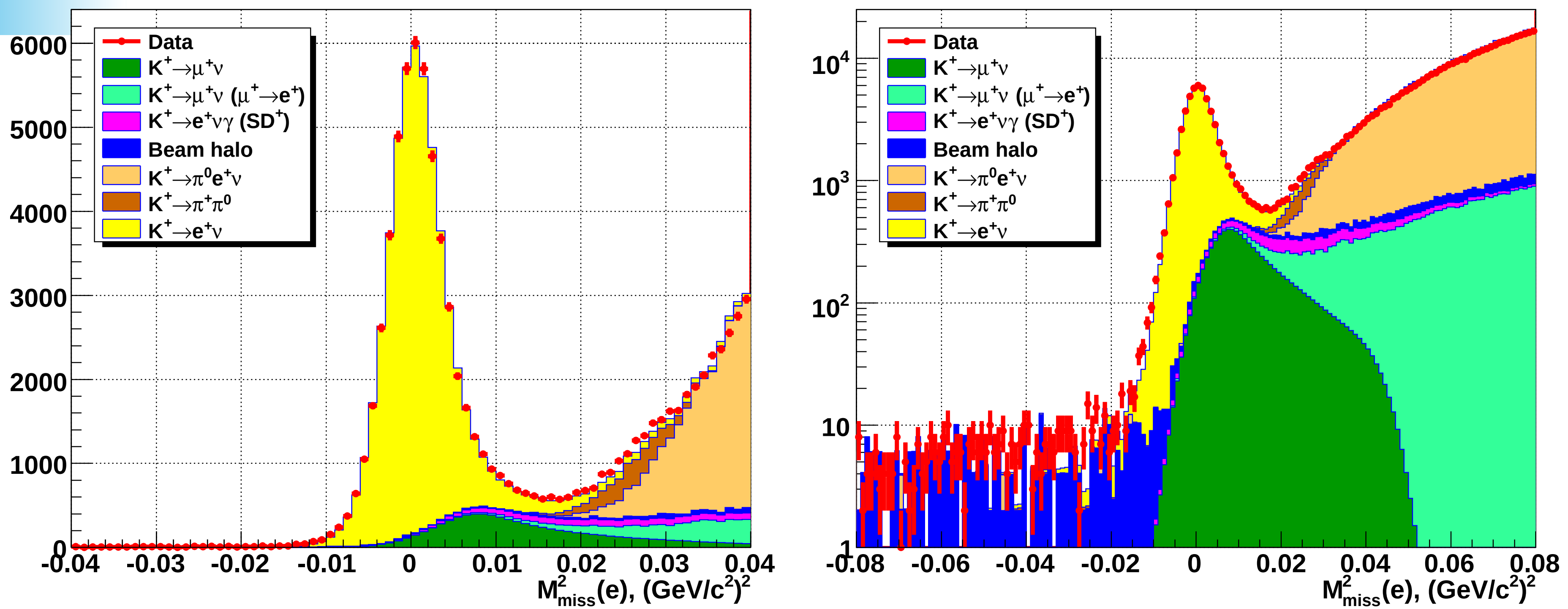
  $\Longrightarrow$ Only muons pass

  MC correction (GEANT4) for muon energy loss in lead



$\Longrightarrow$ **B/S$_{K\mu 2} = (6.3 \pm 0.2)\ \%$**

NA62: 40% of Ke2 Data Set



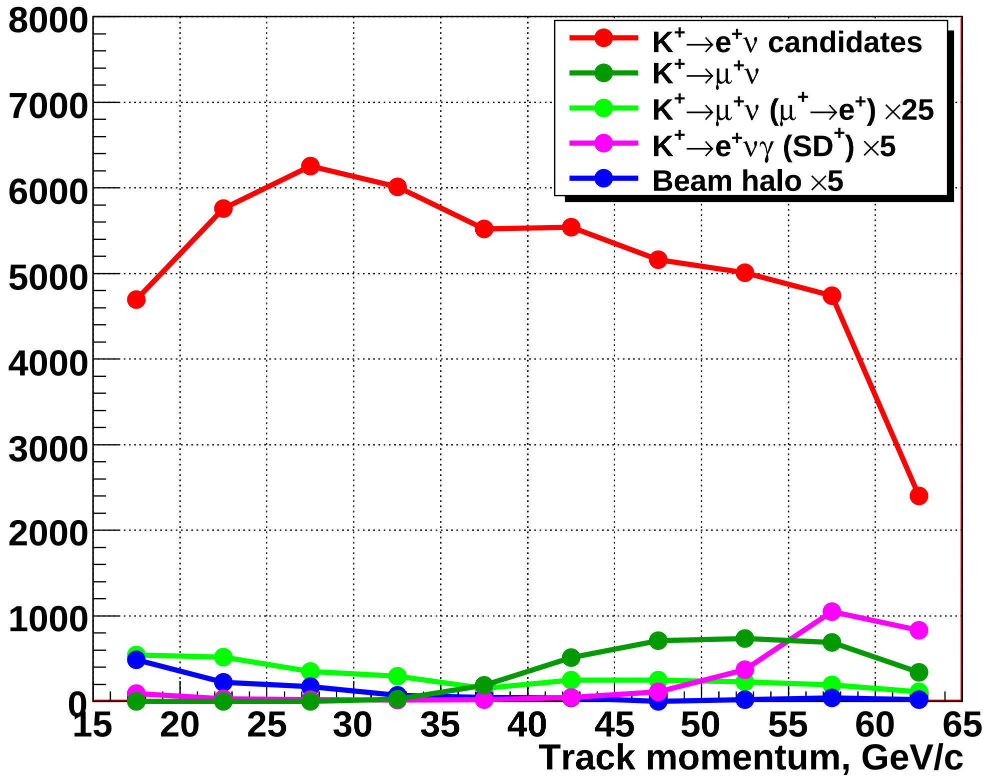
51 089 $K^+ \to e^+\nu_e$ candidates

Total NA62 data set:

~ 120k K^+ and ~ 15k K^- candidates

NA62: Background Summary

Statistics in momentum bins:



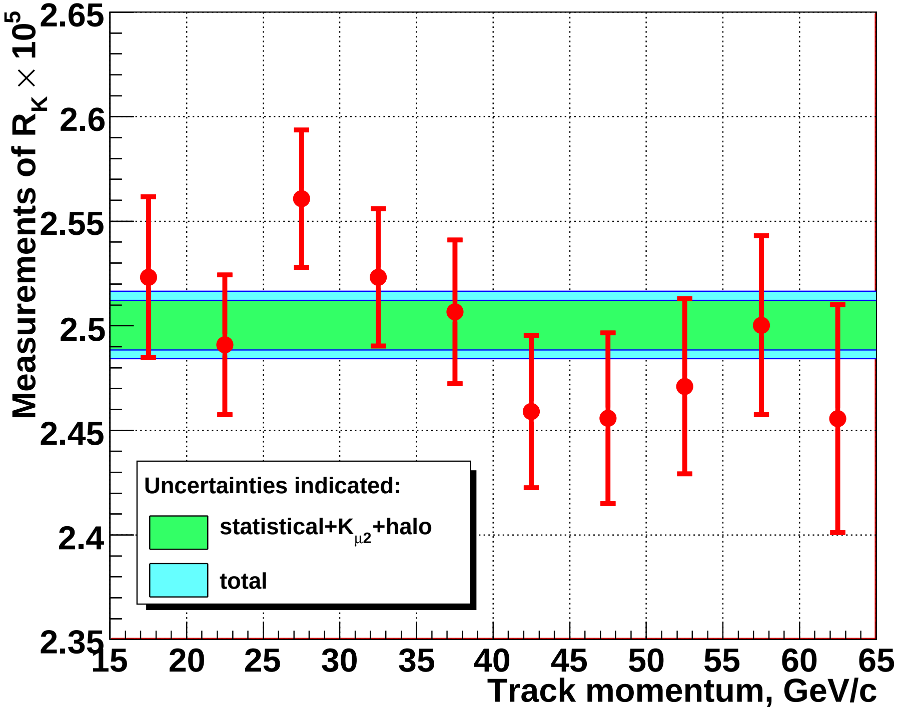
Backgrounds:

Source	$B/(S+B)$ [%]
$K_{\mu 2}$	6.28 ± 0.17
$K_{\mu 2}$, $\mu \to e$	0.23 ± 0.01
$K_{e2\gamma}$ (SD$^+$)	$1.02 \pm 0.15^{(\star)}$
Beam halo	0.45 ± 0.04
K_{e3}	0.03
$K_{2\pi}$	0.03
Total	$\mathbf{8.03 \pm 0.23}$

$^{(\star)}$ KLOE measurement not used yet.

NA62: Result on R_K

Independent measurements in momentum bins:



Uncertainties:

Source	$\Delta R_K \times 10^{-5}$
Statistical	**0.012**
$K_{\mu 2}$	0.004
$K_{e2\gamma}$ (SD$^+$)	0.004
Beam halo	0.001
Electron ID	0.001
IB simulation	0.007
Acceptance	0.002
Trigger timing	0.007
Total	**0.016**

NA62 preliminary

$$R_K = (2.500 \pm 0.012 \pm 0.011) \times 10^{-5}$$

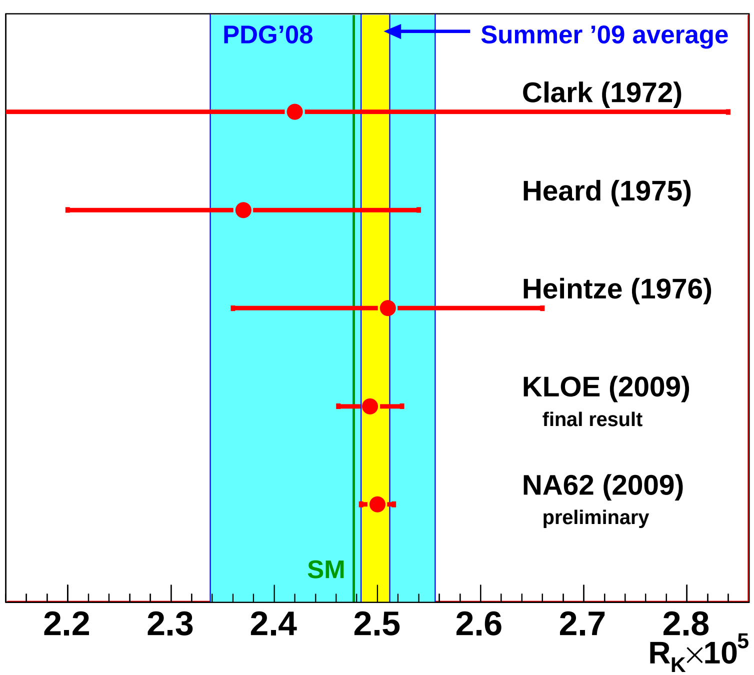
Precision: 0.64% $\Longrightarrow$ Expected to improve to $0.4 - 0.5\%$ with full data set.

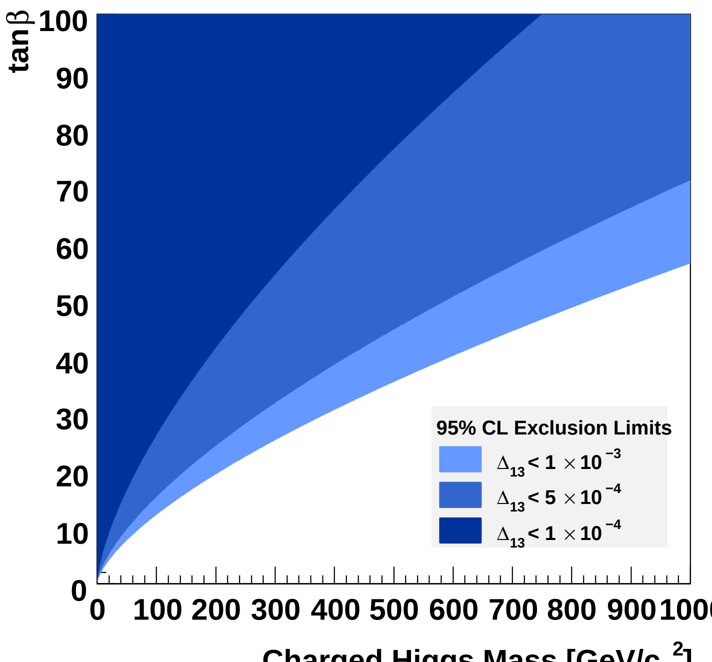
Summary on R_K Measurements

World average: Dominated by new KLOE and NA62 measurements

$$R_K = (2.498 \pm 0.014) \times 10^{-5}$$

- **SM prediction:** $R_K = (2.477 \pm 0.001) \times 10^{-5}$ ($1.5\,\sigma$ away)
- **Exclusion region in** $(\tan\beta, m(H^{\pm}))$ **plane** (depending on Δ_{13})





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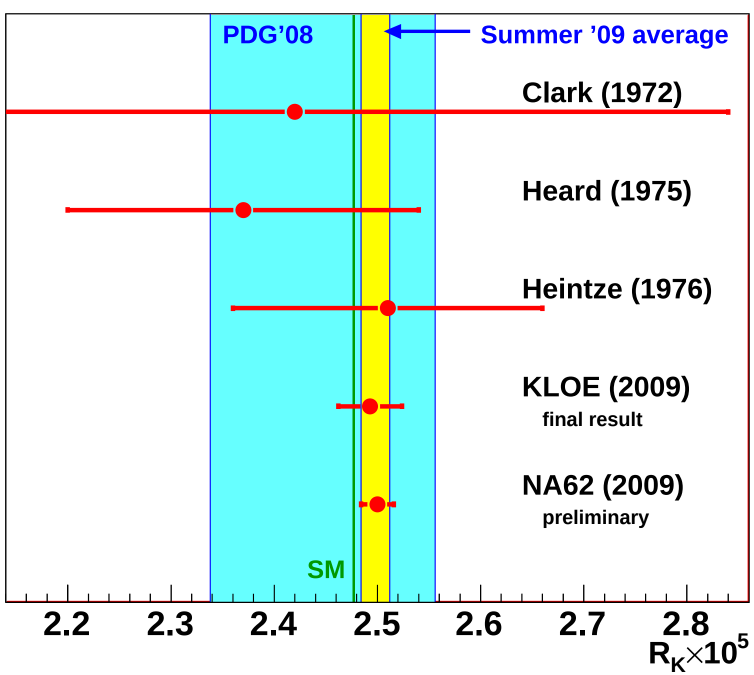
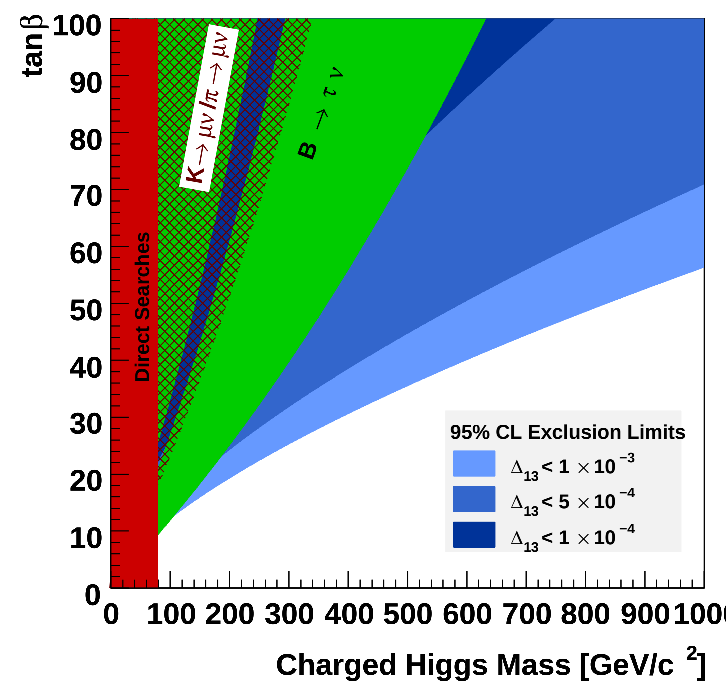




Volume 2

Radiative Decays:

$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$

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

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

$K^\pm \rightarrow \pi^\pm e^+ e^-$

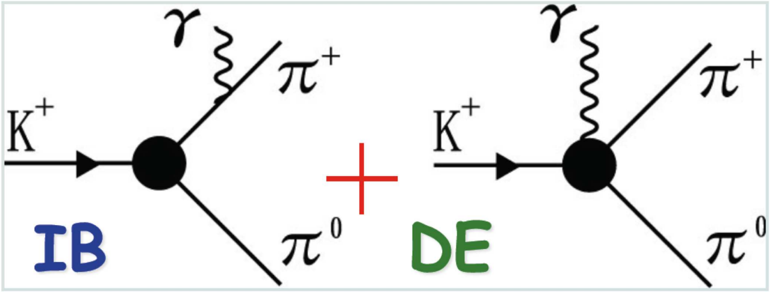
Measurement of

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

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

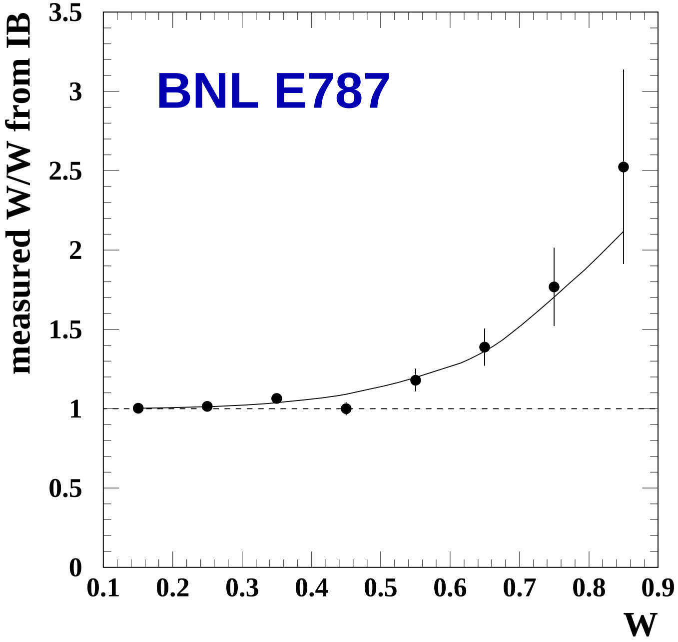
$$+ \underbrace{m_\pi^4 m_K^4 \left(|X_E|^2 + |X_M|^2\right) W^4}_{\text{Direct Emission (DE)}} \Big]$$

- **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 (~ 270 GeV^{-4}) $+$ direct (not known)
  - X_E: no prediction in ChPT
- **INT** is interference of IB and electric DE amplitude, no prediction available.

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: *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	4.3 ± 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 $= (-0.4 \pm 1.6)\%$

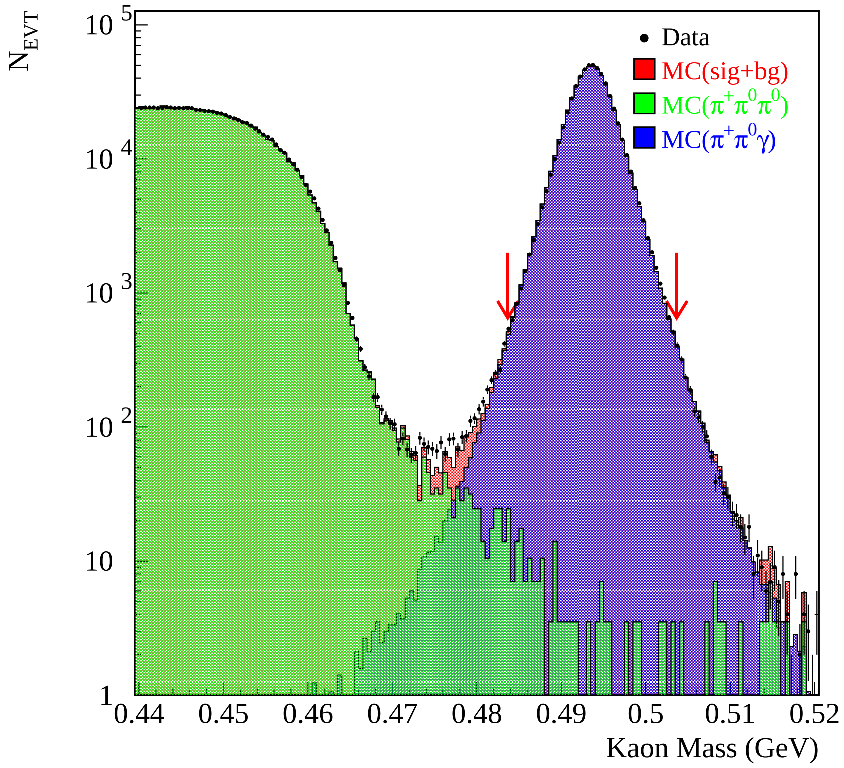
$K^\pm \to \pi^\pm\pi^0\gamma$ ***from NA48/2***

New NA48/2 measurement:

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

  $$\mathbf{0 < T_\pi^\star < 80 \text{ MeV}}$$
- **Background** negligible:

  $< 1\% \times$ **DE** (mainly $\pi^\pm\pi^0\pi^0$)
- $\mathcal{O}(10^{-3})$ mistagging probability for the photon.



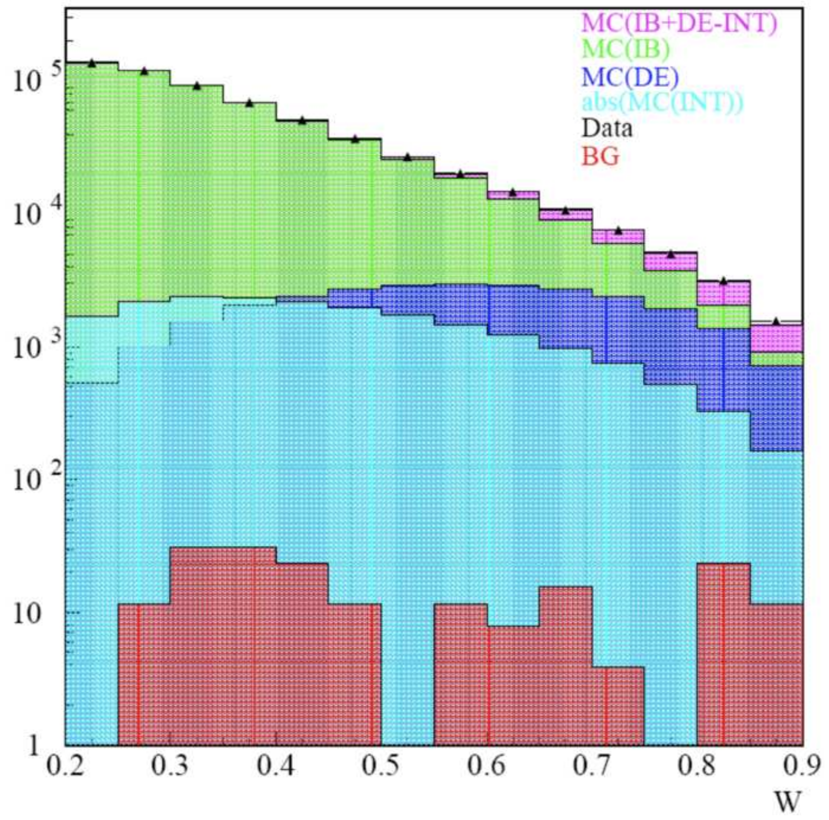
Total $K^\pm \to \pi^\pm\pi^0\gamma$ data sample:

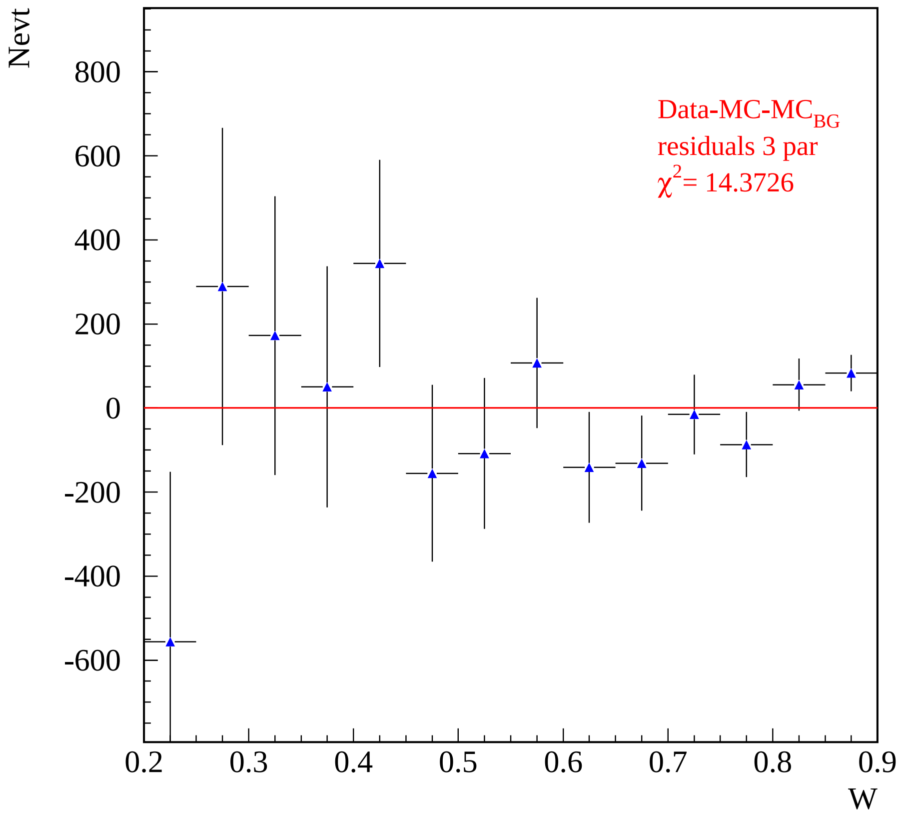
- More than **1 million events.**
- For the fit: restrict to $0.2 < W < 0.9$ and $E_\gamma > 5$ GeV

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

$K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$: Fit of the Data

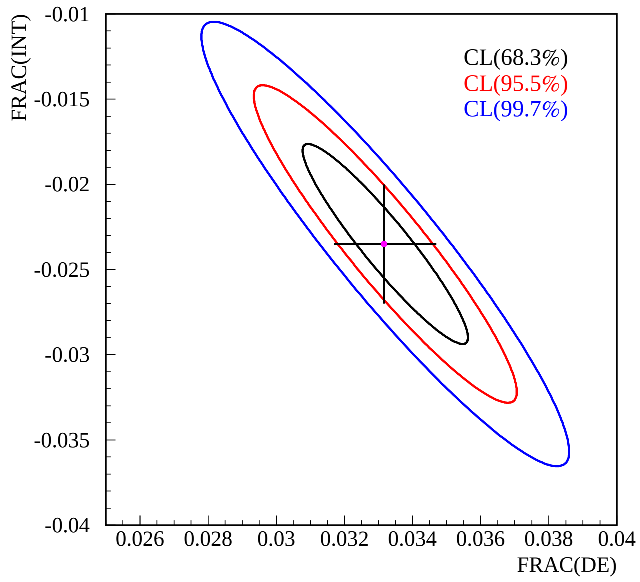
Likelihood-Fit of the data W distribution:





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:

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

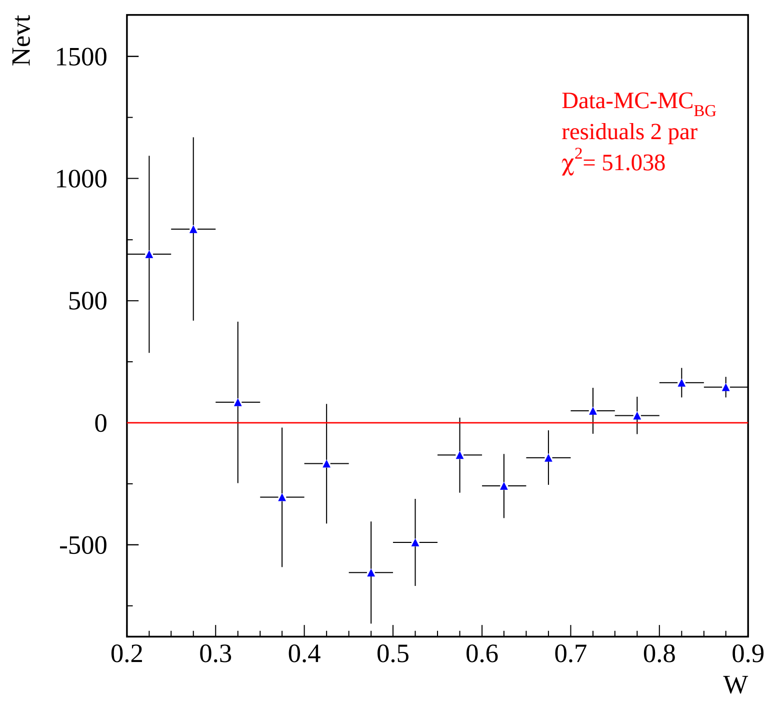
$$\text{Frac(INT)}_{0<T^\star_\pi<80\text{ MeV}} = (-2.35 \pm 0.35_{\text{stat}} \pm 0.39_{\text{syst}}) \times 10^{-2}$$

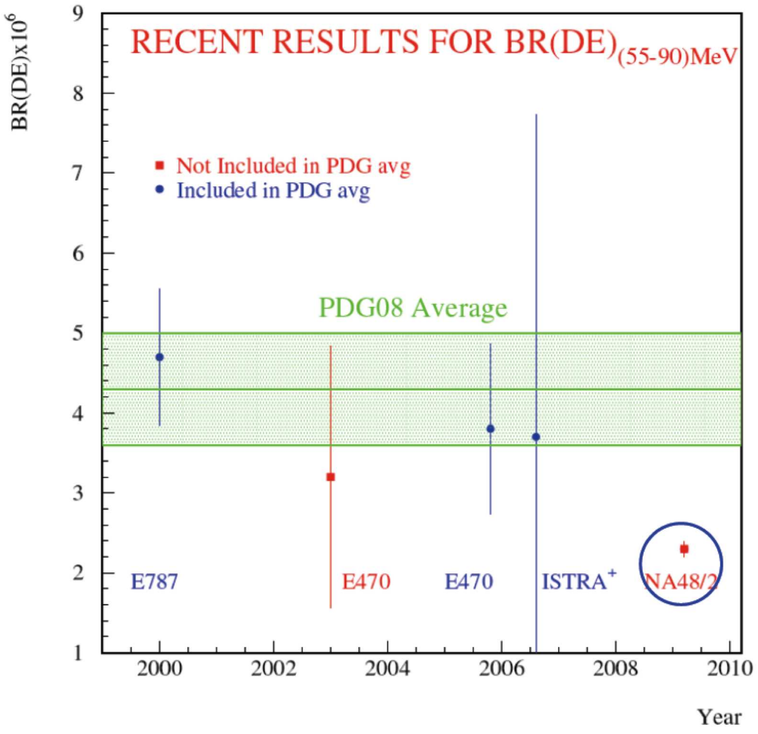
Correlation: $\rho = -0.93$

First observation of the interference term!

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

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!

$K^\pm \to \pi^\pm \pi^0 \gamma$: *Results*

Magnetic and electric components:

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

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

Approximations:

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

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

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

Limits on direct CP Violation:

- Rate Asymmetry: $A_N = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$ (normalized to $K^\pm \to \pi^\pm \pi^0 \pi^0$)

$$\Longrightarrow \begin{aligned} A_N &= (0.0 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-3} \\ \sin\phi &= -0.01 \pm 0.43, \end{aligned}$$

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

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

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

Measurements of $K^{\pm} \to \pi^{\pm}\gamma\gamma$ and $K^{\pm} \to \pi^{\pm}e^{+}e^{-}\gamma$

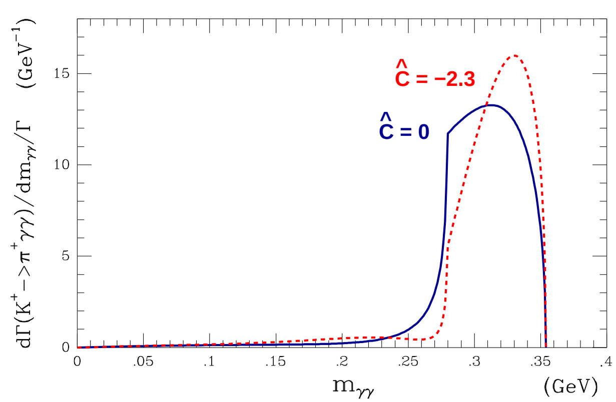
Differential $K^\pm \to \pi^\pm\gamma\gamma$ decay rate:

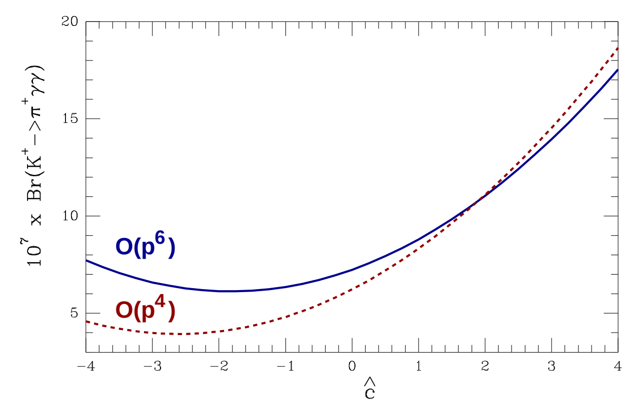
$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A+B|^2+|C|^2\right)+\left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2\left(|B|^2+|D|^2\right)\right]$$

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

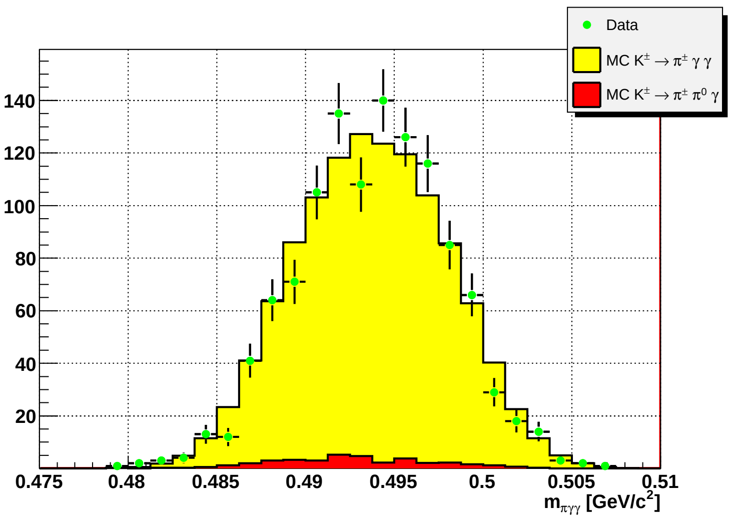
- $A(z,\hat{c})$ contains **loops** and $\hat{c}$ of $\mathcal{O}(1)$.
- $C(z)$ contains **poles and tadpoles.**
  (Gerard, Smith, Trine, Nucl. Phys. B 730 (2005) 1)

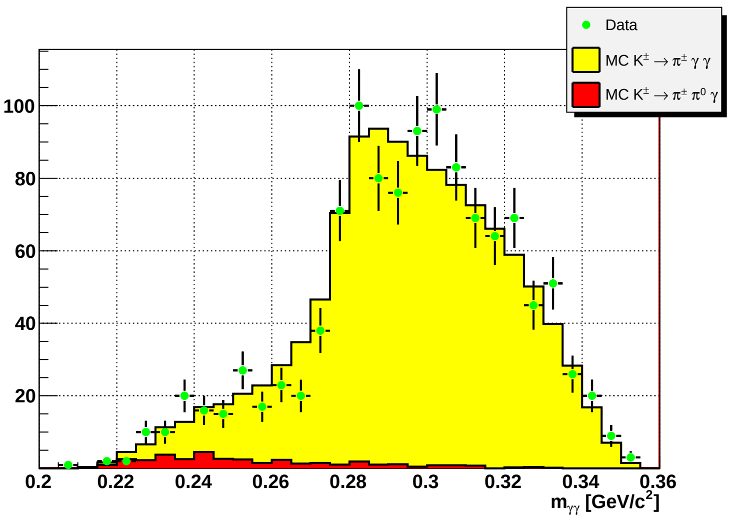
At $\mathcal{O}(p^6)$: Unitarity corrections, could increase Br by $30-40\%$.
(D'Ambrosio, Portolés, Nucl. Phys. B 386 (1996) 403)





$K^\pm \to \pi^\pm\gamma\gamma$: *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 $\hat{c} = 2$:

(NA48/2 preliminary)

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

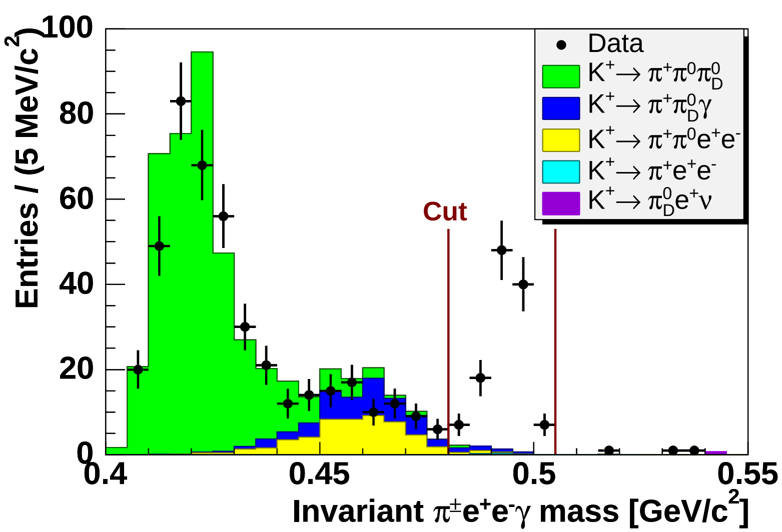
Model independent measurement and $\hat{c}$ extraction in preparation.

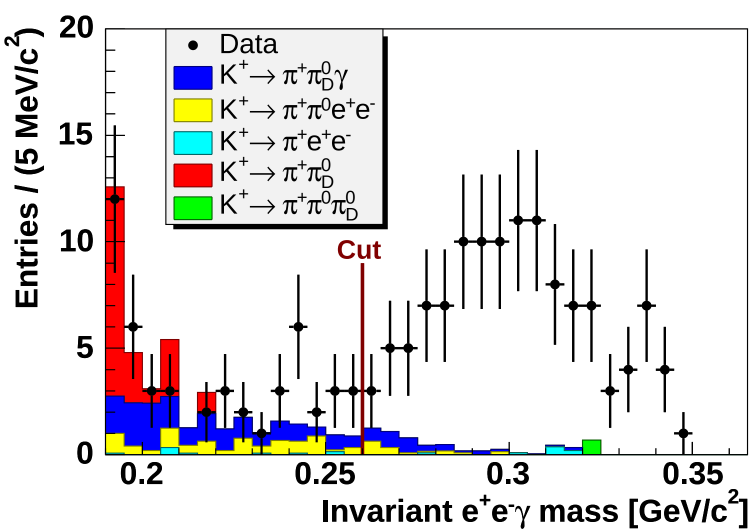
$K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$:

- Same as $K^{\pm} \to \pi^{\pm}\gamma\gamma$, but with internal photon conversion.
- **120 $K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma$ candidates** (selection through 3-track-trigger).
- Computing BR in bins of $m_{ee\gamma}$.

$\Longrightarrow$ **Model independent measurement!**

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





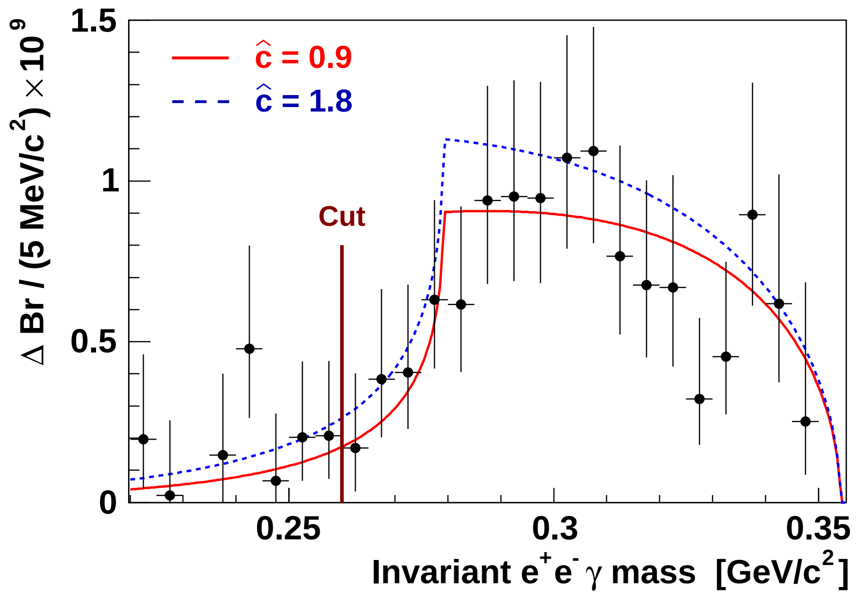
$K^\pm \to \pi^\pm e^+ e^- \gamma$: *Fit of* $m_{ee\gamma}$ *distribution*

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)

Measurement of

$K^{\pm} \longrightarrow \pi^{\pm} e^{+} e^{-}$ Decays

$K^\pm \to \pi^\pm e^+ e^-$: *Motivation*

$K^\pm \to \pi^\pm \gamma^\star \to \pi^\pm l^+ l^-$: Suppressed FCNC, proceeding through single virtual photon exchange

Amplitude:

$$\frac{d\Gamma}{dz} \sim P(z) \cdot |W(z)|^2$$

($z = \left(\frac{m_{ll}}{m_K}\right)^2$, $P(z)$ = phase space factor)

Several models available:

(1) polynomial: $W(z) = G_F m_K^2\, f_0\, (1 + \delta z)$

(2) ChPT $\mathcal{O}(p^6)$: $W(z) = G_F m_K^2\, (a_+ + b_+ z) + W^{\pi\pi}(z)$

(D'Ambrosio *et al.*, JHEP 9808 (1998) 4)

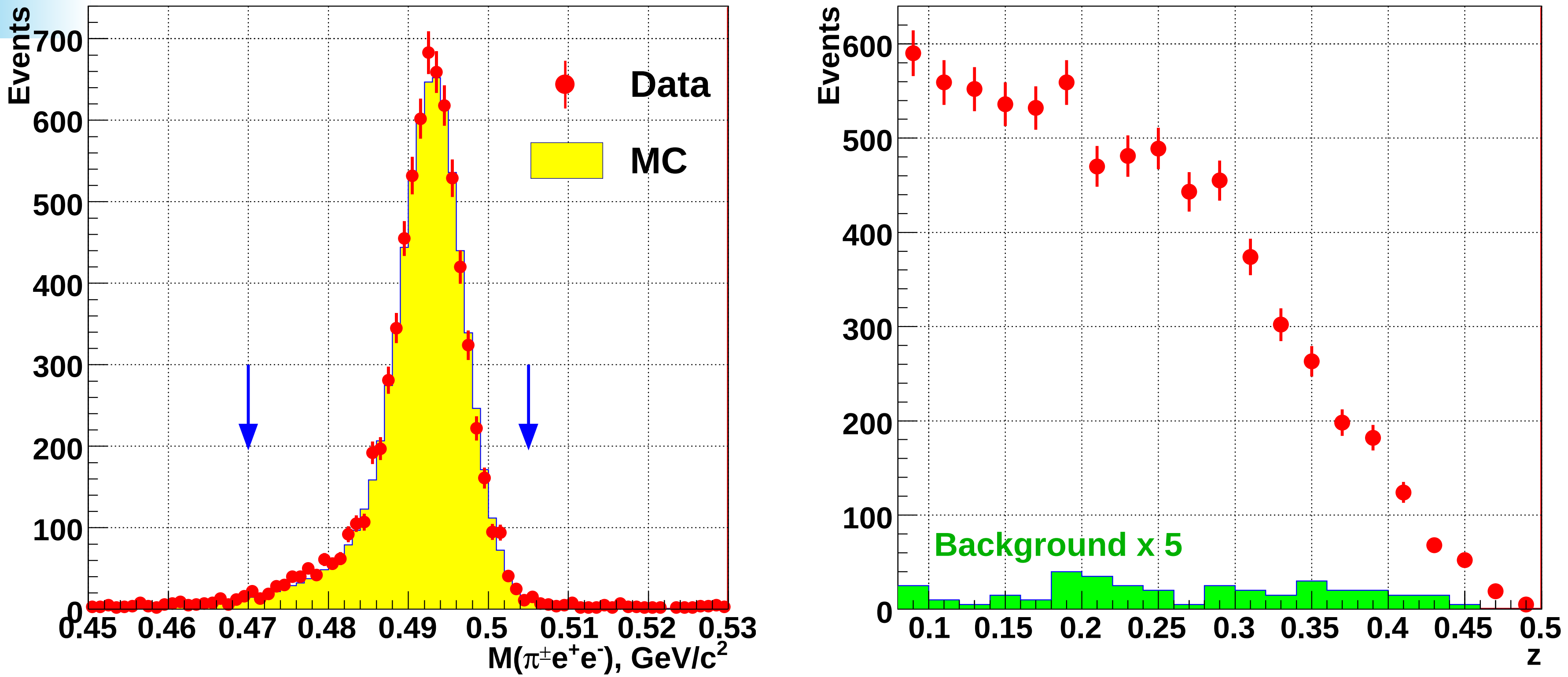
(3) ChPT, large N_c QCD: $W(z) = W(w, w, z)$

(Friot, Greynat, de Rafael, PLB 595 (2004) 301)

(4) "Mesonic" ChPT: $W(z) = W(m_a, m_\rho, z)$

(Dubnickova *et al.*, Phys.Part.Nucl.Lett. 5 (2008) 76)

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

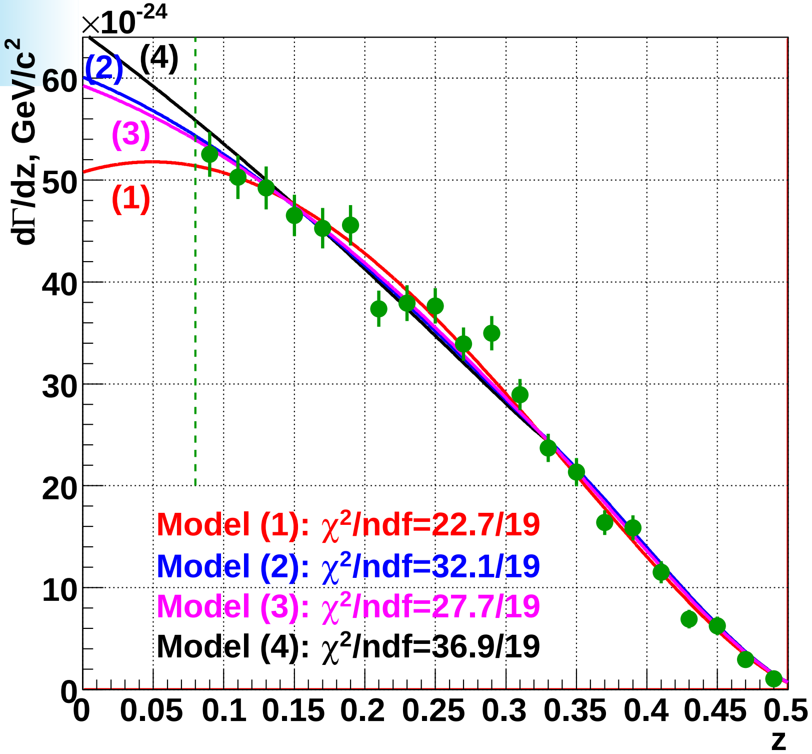


<u>Whole NA48/2 data set:</u>

7253 $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$ candidates

Background/Signal: $\sim 1.0\%$

$K^\pm \to \pi^\pm e^+ e^-$: *Fit Results*



Fitted Model parameters:

(1) $f_0 = 0.531 \pm 0.012$
$\delta = 2.32 \pm 0.15$

(2) $a_+ = -0.578 \pm 0.012$
$b_+ = -0.779 \pm 0.053$

(3) $w = 0.057 \pm 0.005$
$\beta = 3.45 \pm 0.24$

(4) $m_a = (951 \pm 28)$ MeV
$m_\rho = (795 \pm 10)$ MeV

(PLB 677 (2009) 246)

$$\text{Br}(K^\pm \to \pi^\pm e^+ e^-) = 3.11\,(4)_{\text{stat}}\,(5)_{\text{syst}}\,(8)_{\text{ext}}\,(7)_{\text{model}} \times 10^{-7}$$

Also limit on direct CP violation: $\frac{\text{Br}^+ - \text{Br}^-}{\text{Br}^+ + \text{Br}^-} = (-2.1 \pm 1.5 \pm 0.6)\%$

Most precise measurements in this channel

$K^{\pm} \to \pi^{\pm} e^{+} e^{-}$: *Comparison of Results*

- $K^{\pm} \to \pi^{\pm} e^{+} e^{-}$ **branching fraction in full z range:**

Measurement	**Sample**	**Br** $\times 10^7$
Bloch *et al*, PL 6 (1975) B201	41 (K^+)	2.70 ± 0.50
Alliegro *et al*, PRL 68 (1992) 278	500 (K^+)	2.75 ± 0.26
Appel *et al* [E865], PRL 83 (1999) 4482	10 300 (K^+)	2.94 ± 0.15
NA48/2, PLB 677 (2009) 246	7 300 ($K^{\pm}$)	3.11 ± 0.12

- **Form factor slope δ:**

Measurement	**Process**	**Slope** δ
Alliegro *et al*, PRL 68 (1992) 278	$K^+ \to \pi^+ e^+ e^-$	1.31 ± 0.48
Appel *et al* [E865], PRL 83 (1999) 4482	$K^+ \to \pi^+ e^+ e^-$	2.14 ± 0.20
Ma *et al* [E865], PRL 84 (2000) 2580	$K^+ \to \pi^+ \mu^+ \mu^-$	$2.45^{+1.30}_{-0.95}$
NA48/2, PLB 677 (2009) 246	$K^{\pm} \to \pi^{\pm} e^+ e^-$	2.32 ± 0.18

Conclusions

Measurement of $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$ KLOE, NA62

- Precision 0.56%, has improved by one order of magnitude.
- Becomes sensitive to physics beyond the SM.

Radiative Kaon Decays KLOE, NA48/2

- $K^\pm \to e^\pm \nu \gamma$
  New very precise measurement, agrees with $\mathcal{O}(p^4)$ ChPT.
- $K^\pm \to \pi^\pm \pi^0 \gamma$
  First observation of interference between IB and DE.
- $K^\pm \to \pi^\pm \gamma\gamma$
  $40\times$ the statistics of previous experiments.
- $K^\pm \to \pi^\pm e^+ e^- \gamma$
  First observation and measurement of Br and $\hat{c}$.
- $K^\pm \to \pi^\pm e^+ e^-$
  Very clean signal, good agreement with theoretical models.

Spares

The NA48 Detector

Detector components:

- **Magnet spectrometer**

  4 sets of drift chambers.

  $\boldsymbol{\Delta p/p \approx 1.4\%}$ for $p = 20$ GeV/c.

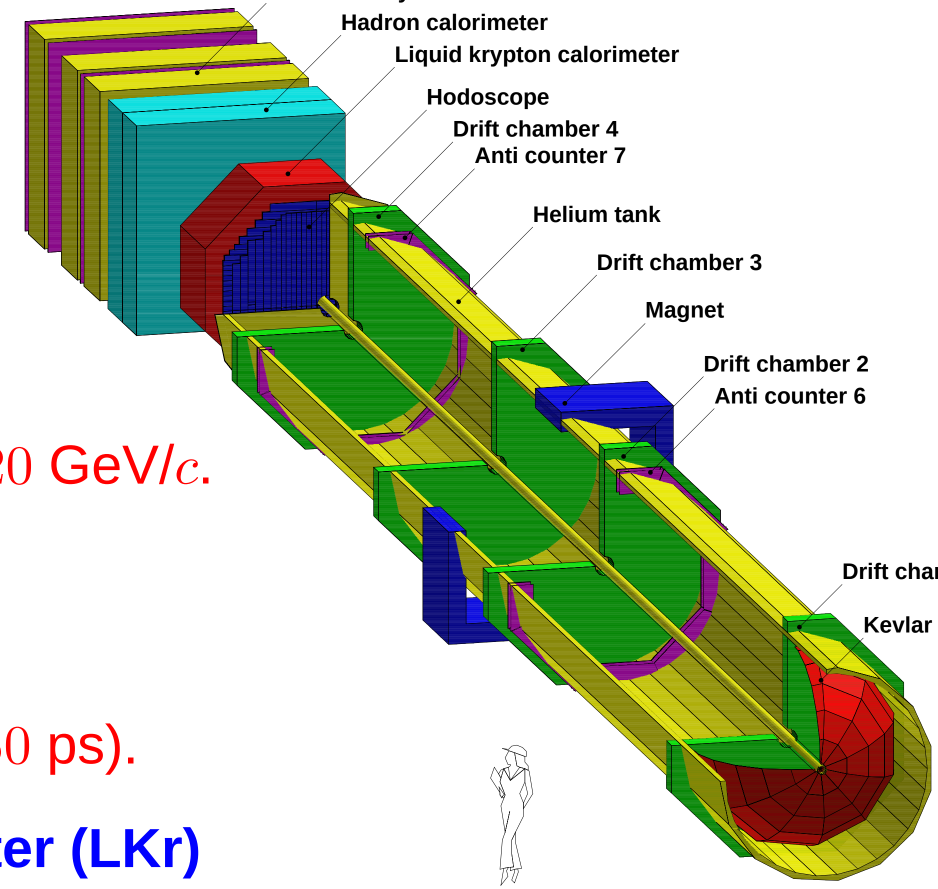
- **Hodoscopes:**

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

- **Liquid Krypton Calorimeter (LKr)**

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

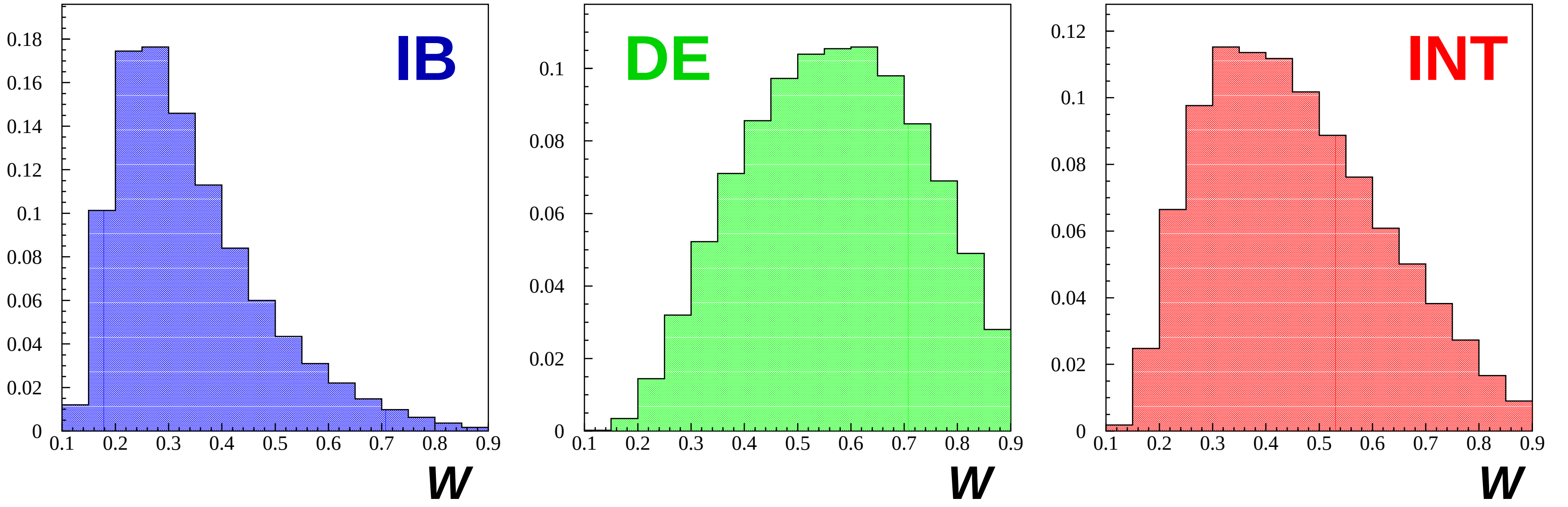
- **Hadron calorimeter, photon vetos, muon counters**



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

$$\frac{\partial \Gamma^{\pm}}{\partial W} = \underbrace{\frac{\partial \Gamma^{\pm}_{IB}}{\partial W}}_{\text{Inner Bremsstrahlung (IB)}} \Big[1 + \underbrace{2 \cos\left(\pm\phi + \delta^1_1 - \delta^2_0\right) |X_E| \, W^2}_{\text{Interference (INT)}}$$

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



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

- **Extended Maximum Likelihood Fit**

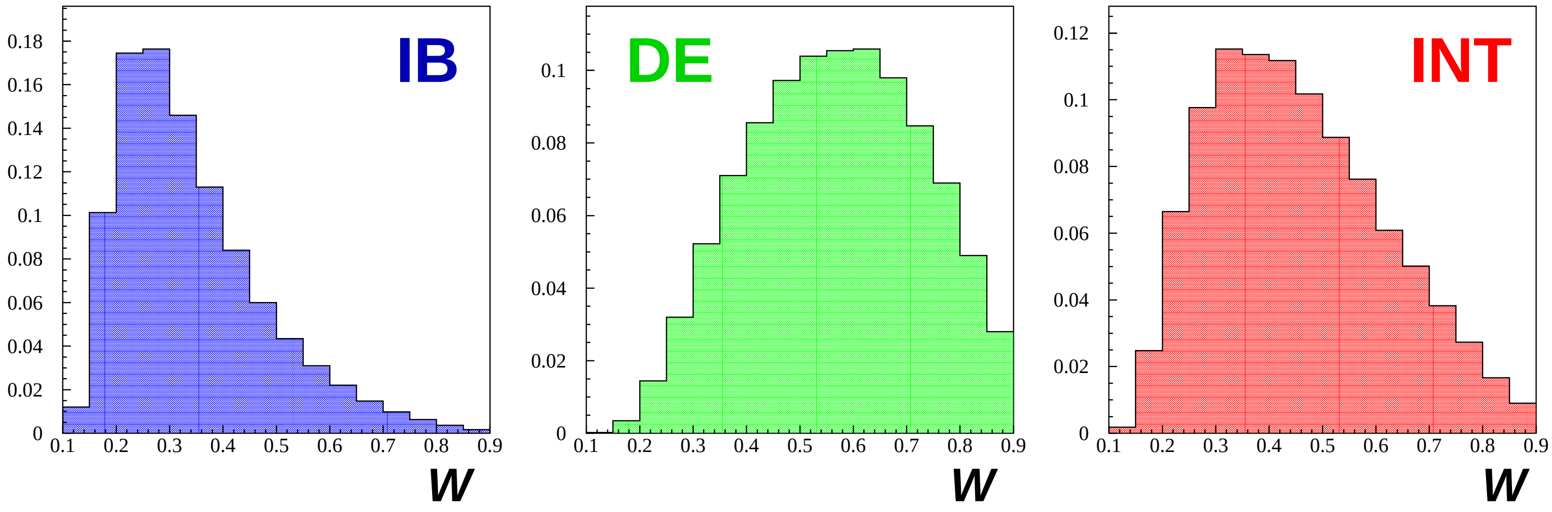
  Correct for acceptances with MC:

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

- **Polynominal Fit** *(used as cross-check)*

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

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

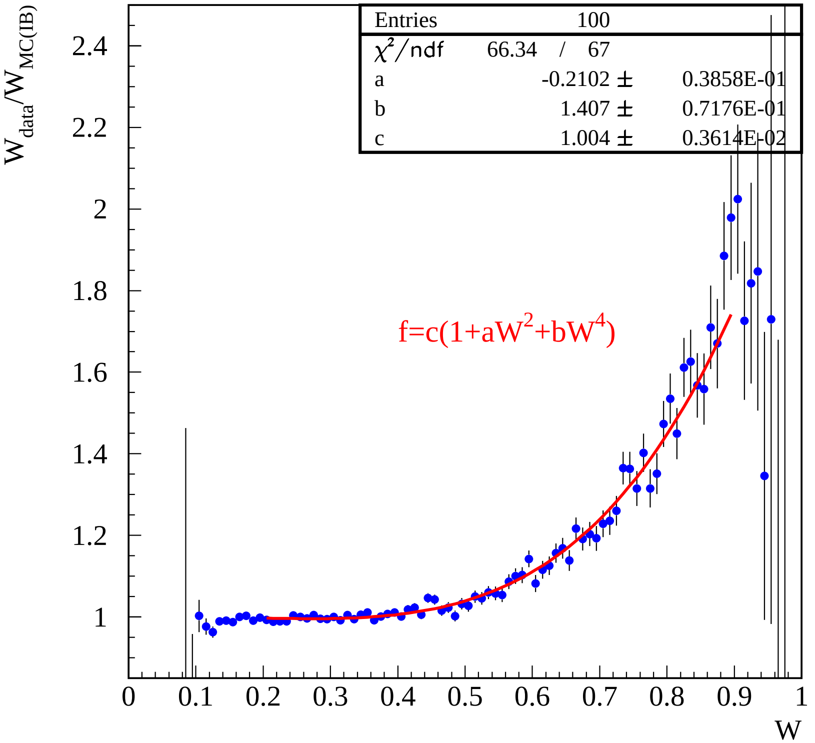


$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: *Polynomial Fit*

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!**

$K^\pm \to \pi^\pm \pi^0 \gamma$: *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 $\sin\phi$:**

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

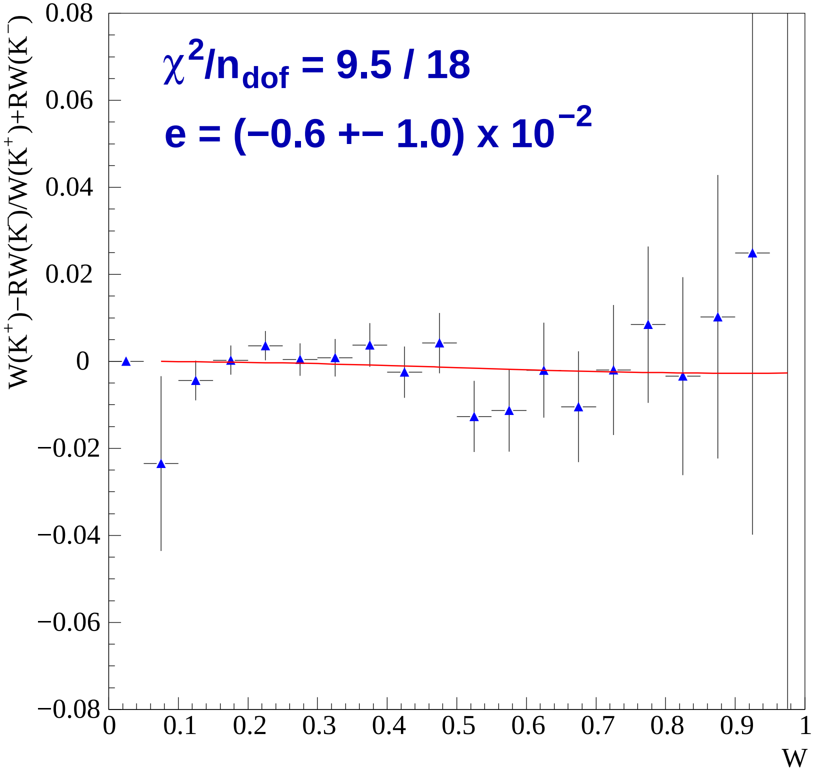
$K^\pm \to \pi^\pm\pi^0\gamma$: *CP Violation Studies*

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:

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



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

compatible with A_N.

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

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

Trigger efficiency:

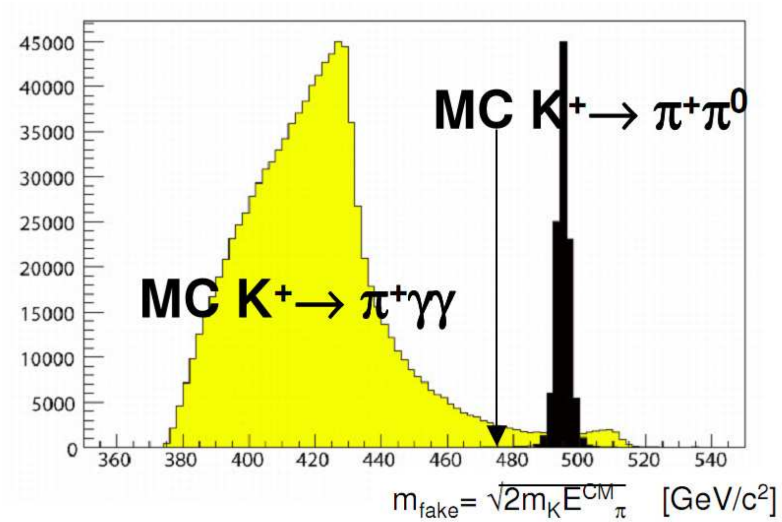
- $K^\pm \to \pi^\pm\gamma\gamma$ selected through neutral trigger.
- **L1:** More than 2 e.m. clusters required.

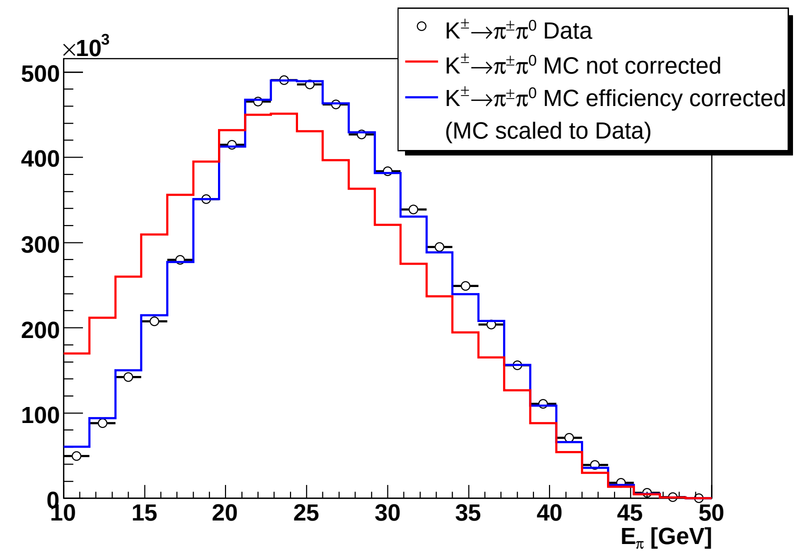
  $\Longrightarrow$ **$\approx 50\%$ efficiency**
- **L2:** Rejection of $K^\pm \to \pi^\pm\pi^0$ by cutting on $E_\pi^\star$.

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

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

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





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

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)