Precision Measurements of Kaon Radiative Decays at NA48

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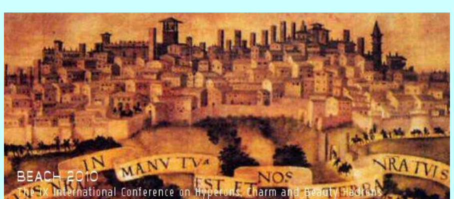
BEACH 2010 – IX International Conference on Hyperons, Charm and Beauty Hadrons



Perugia, 21-26 June, 2010

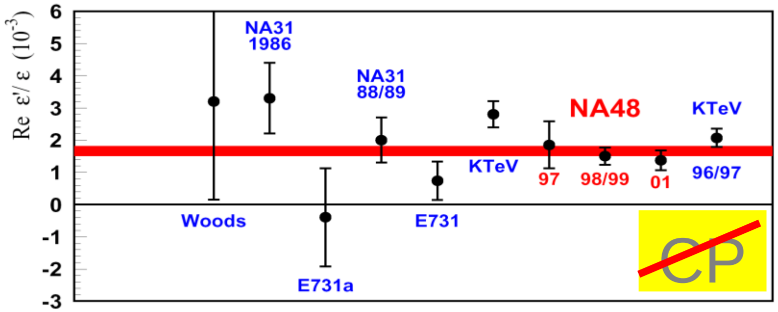
*On behalf of the NA48 collaboration

Outline

- NA48/2 experiment @ CERN SPS
- Study of the $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ decay
  (CERN-PH-EP/2010-006   arXiv:1004.0494v1 [hep-ex])
  - Measurement of DE and INT term fractions
  - Measurement of DE assuming INT=0
  - Limit on CPV parameters (A_N , A_W)
- Measurement of the $K^{\pm}\rightarrow\pi^{\pm}\gamma\gamma$ (preliminary)
- Measurement of the $K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma$
  (*Phys. Lett. B659 (2008), 493)*
- Conclusions

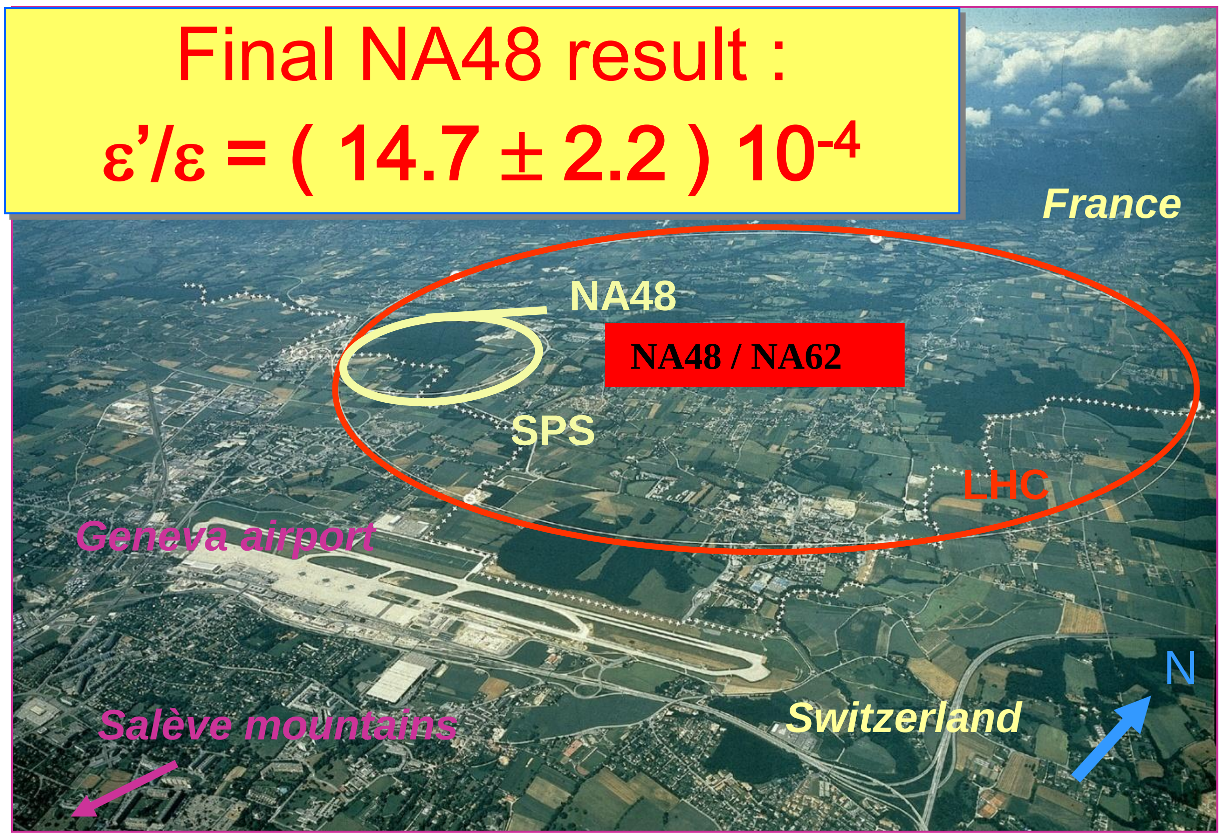
The NA48/NA62 experiment

A fixed target experiment at the CERN SPS dedicated the study of CP violation and rare decays in the kaon sector



Final NA48 result :

$$\varepsilon'/\varepsilon = (14.7 \pm 2.2)\ 10^{-4}$$



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
NA62	2007	$K^\pm_{e2}/K^\pm_{\mu 2}$ run

NA62 phase II

measurement of the decay

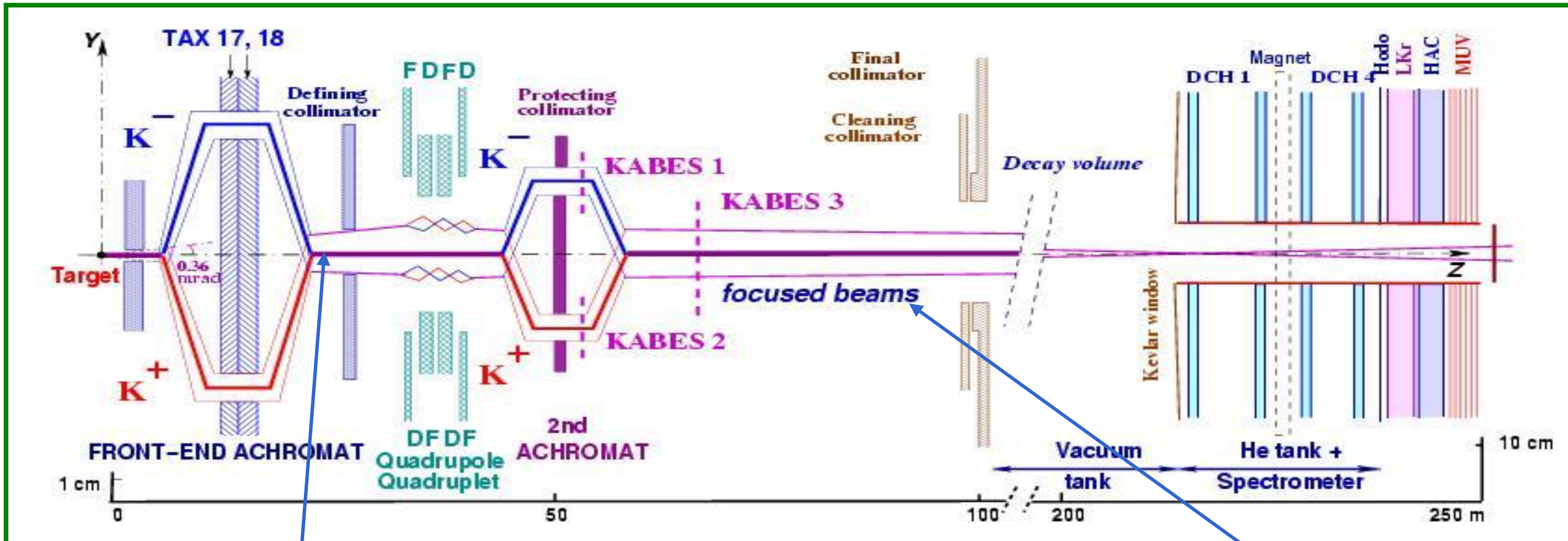
$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

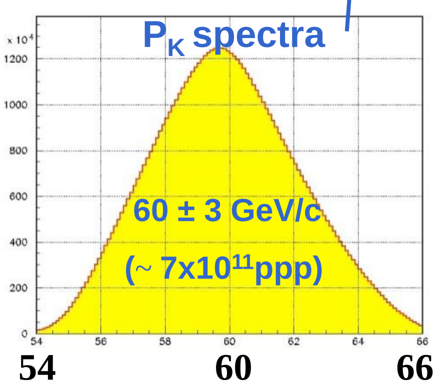
(2008-2010 R&D & construction 2011 start of data taking)

NA48/2 simultaneous $K^{\pm}$ beam

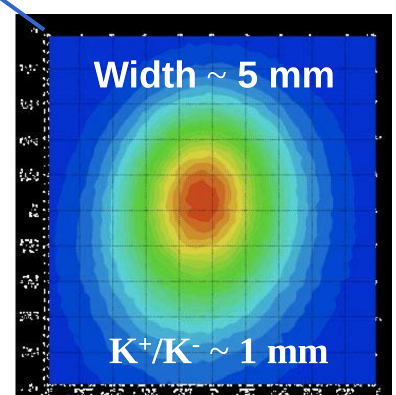
NA48-2 beams: simultaneous K^+/K^-, focused, high momentum, narrow band

designed to precisely measure $K^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}$ ($\pi^0 \pi^0 \pi^{\pm}$) Dalitz-plot density to search for direct CPV and **tuned for K_{e2} measurement.**





- Simultaneous, unseparated, focused beams
- Flux ratio: $K^+/K^- \sim 1.8$
- Similar acceptance for K^+ and K^- decays
- Large charge symmetrization of experimental conditions



NA48 detector

Magnetic spectrometer (4 DCHs)

- 4 views : redundancy $\Rightarrow$ high efficiency;

$\sigma_p/p = (1.0 \oplus 0.044\ p)\%$ (p in GeV/c)

Hodoscope

- fast trigger;
- precise time measurement
  (σ_t = 150 ps) .

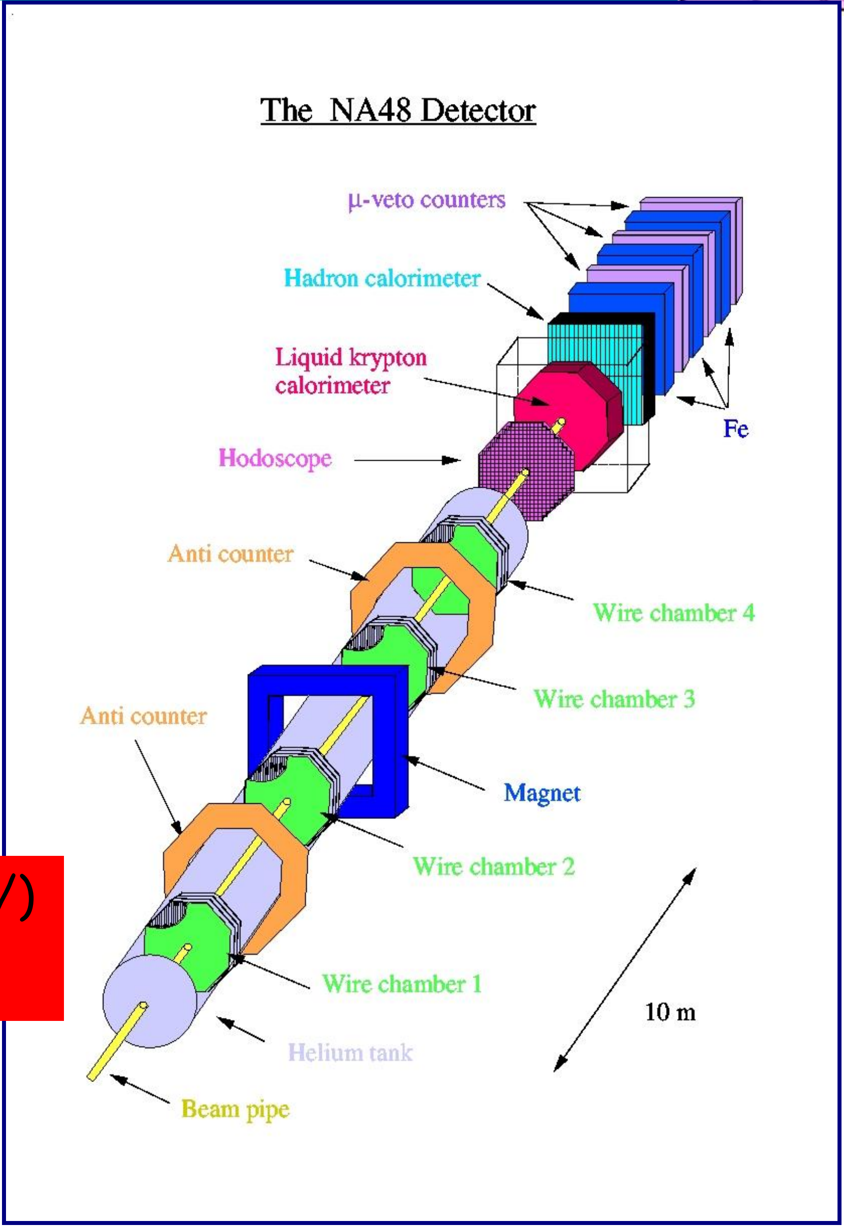
Liquid Krypton EM calorimeter (LKr)

- Quasi-homogeneous ionization chamber
- 27 electromagnetic radiation lengths long active volume
- Segmented transversally 13248 cells, 2x2 cm2
- Energy resolution (E in GeV):

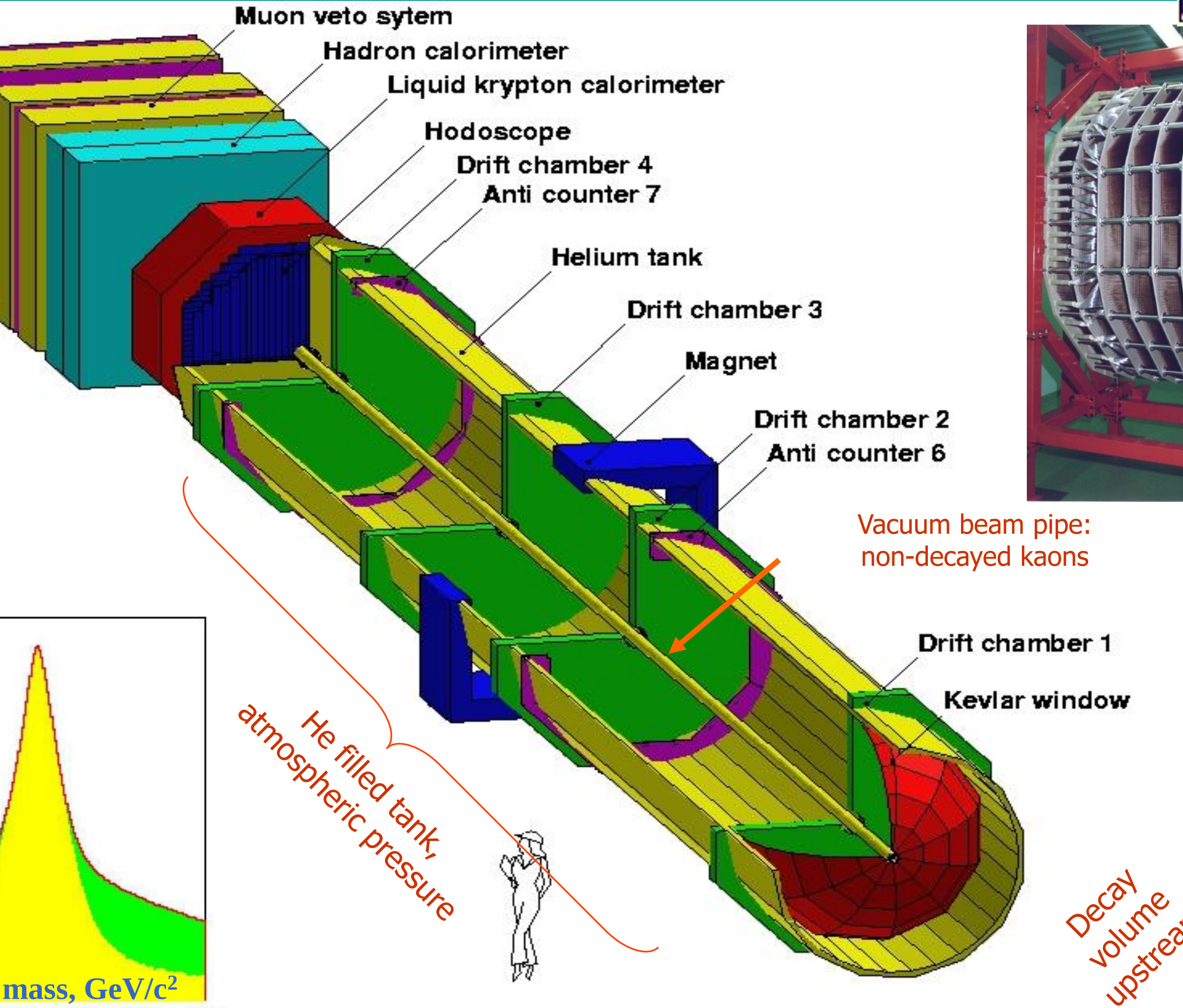
$\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV/)

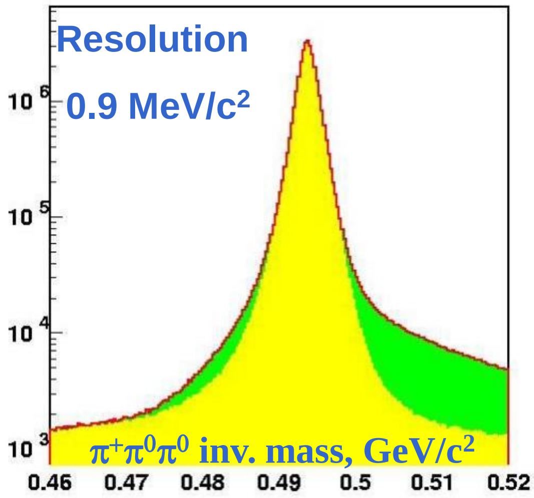
$\sigma_x = \sigma_y = 0.42/E^{\frac{1}{2}} + 0.6$ mm

Cambridge, CERN, Chicago, Dubna, Edimburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

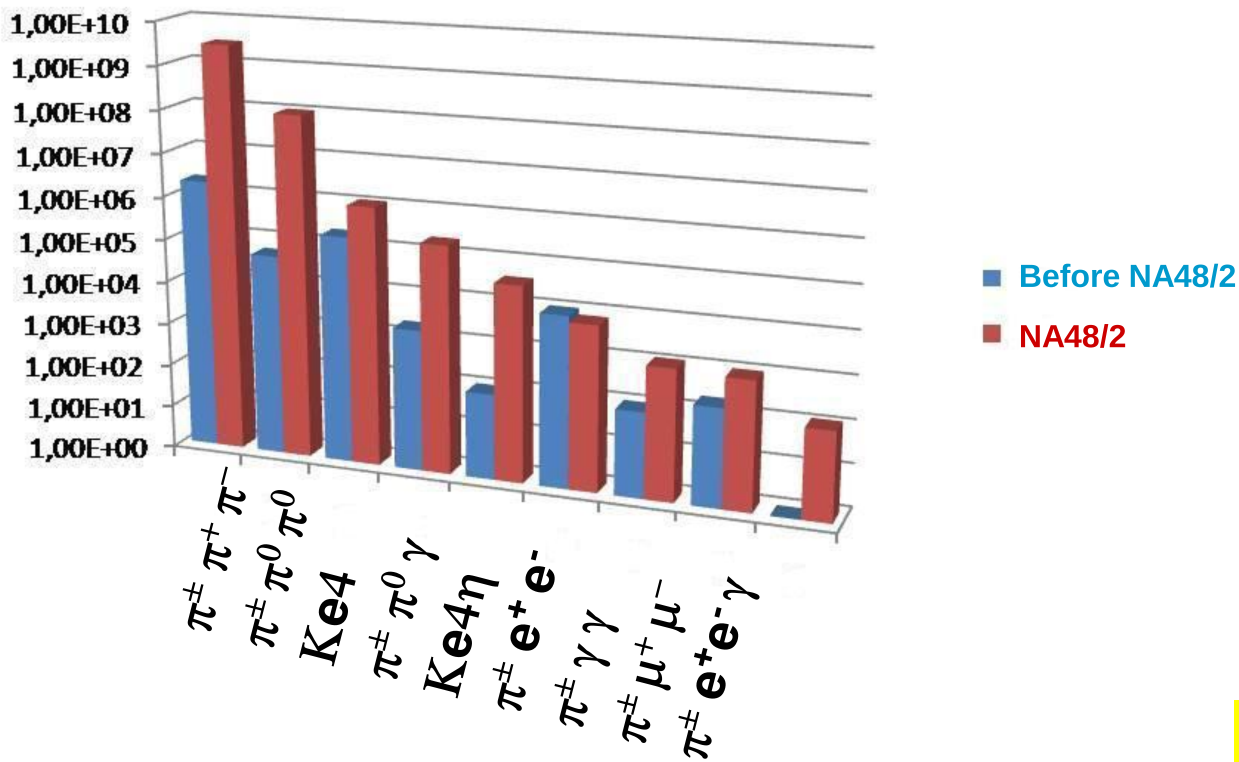


The NA48/NA62 experiment



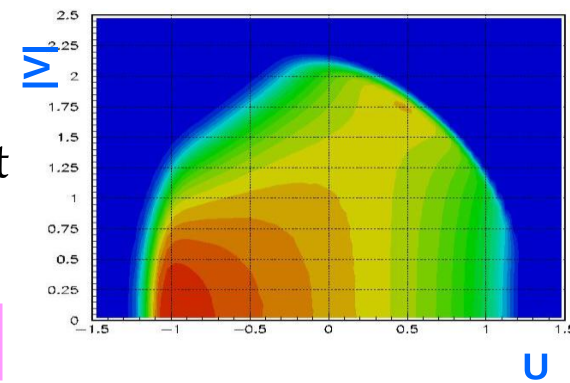


NA48/2 Data taking



NA48 Experimental hall

- Unprecedented statistics in many channels
- Two years of data taking (2003 and 2004)
- Main purpose was to measure direct CP violation in charged kaon decays, through asymmetry in Dalitz plot distribution
- New limits on CP violation in charged kaon decays



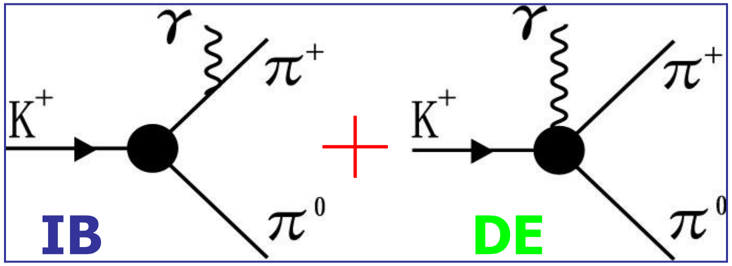
A_g^{ch}= (-1.5 ± 2.1) × 10^{-4}

A_g^0 = (1.8 ± 1.8) x 10^{-4}

$K^{\pm} \rightarrow \pi^{\pm} \pi^{0}\gamma$ rare decay

arXiv:1004.0494 and CERN-PH-EP-2010-006

Theoretical framework and motivation



Lorentz invariant $W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_k m_\pi)^2}$

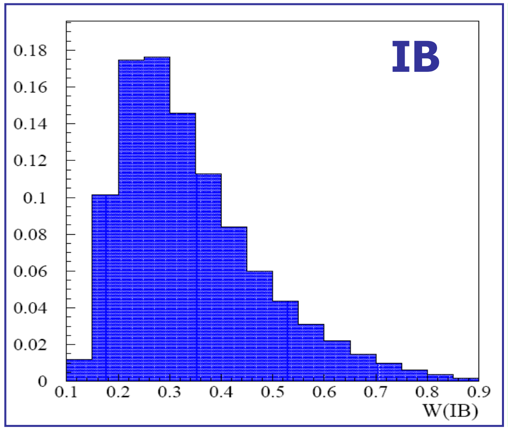
DE can occur via electric and magnetic dipole transitions $\mathbf{X_E}$ and $\mathbf{X_M}$

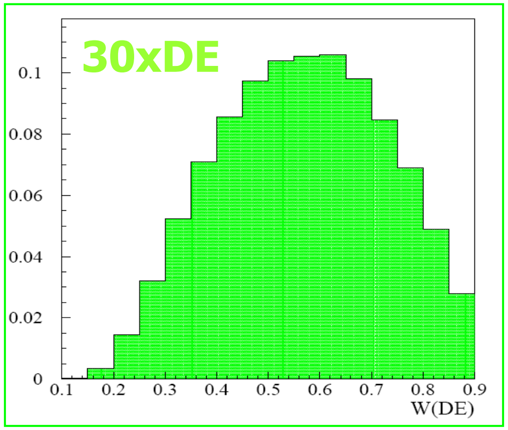
Differential rate

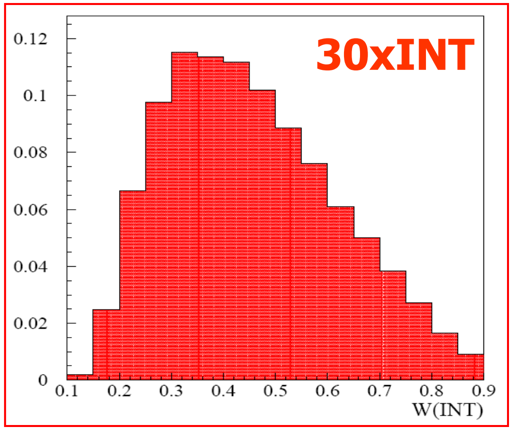
$$\frac{\partial\Gamma^{\pm}}{\partial W} = \underbrace{\frac{\partial\Gamma^{\pm}_{IB}}{\partial W}}_{\mathbf{IB}}\left[1 + \underbrace{2\cos(\pm\phi+\delta_1^1-\delta_0^2)\, m_\pi^2 m_K^2\, |X_E|\, W^2}_{\mathbf{INT}} + \underbrace{m_\pi^4 m_K^4 \left(|X_E|^2 + |X_M|^2\right) W^4}_{\mathbf{DE}}\right]$$

Inner Bremsstrahlung(IB)	:	**BR = $(2.75\pm0.15)\cdot10^{-4}$ PDG ($55<T^*_\pi<90$ MeV)**
Direct Emission (DE)	:	**BR = $(4.3\pm0.7)\cdot10^{-6}$ PDG ($55<T^*_\pi<90$ MeV)**
Interference (INT)	:	**not yet measured**

Very different distributions!





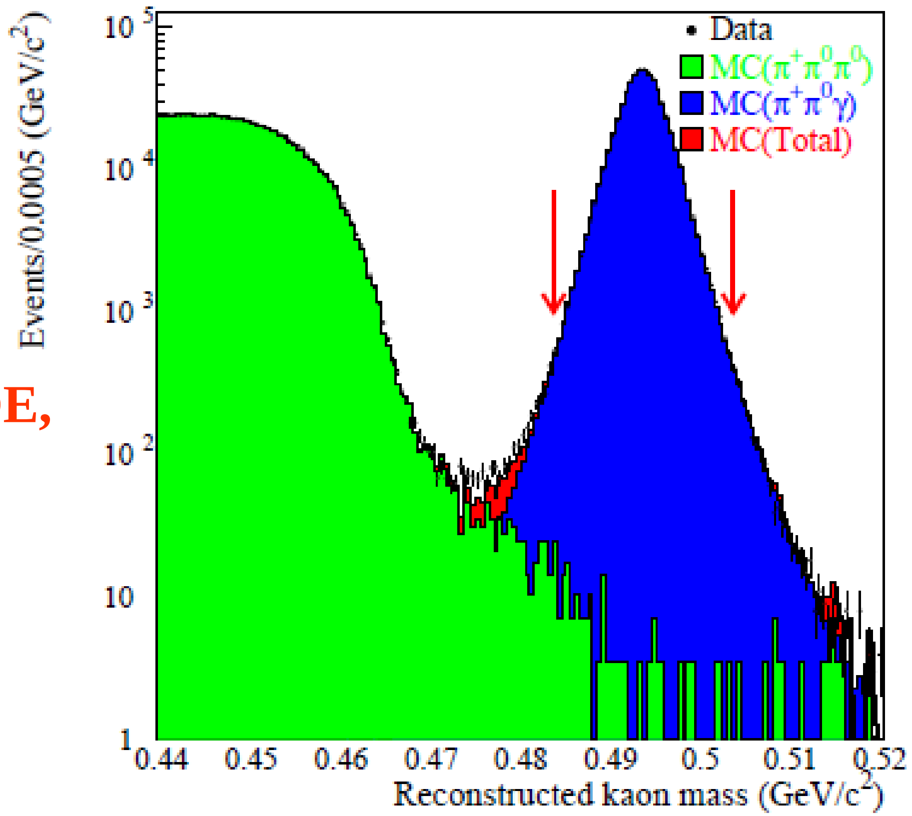


Event reconstruction and signal region

- **NA48/2 measurement of $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \gamma$ decay**

T^{*}_{π} : kinetic energy of the Pion in the kaon cms

- Fit performed with both polynomial and likelihood techniques
- **simultaneous K^{+} and K^{-} beams:** possibility to study CP violating effects
- **Background contribution <1% wrt DE,** mainly from $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$
- **Larger T^{*}_{π} region** in the low energy part $(0 < T^{*}_{\pi} < 80\text{ MeV})$ wrt previous experiments

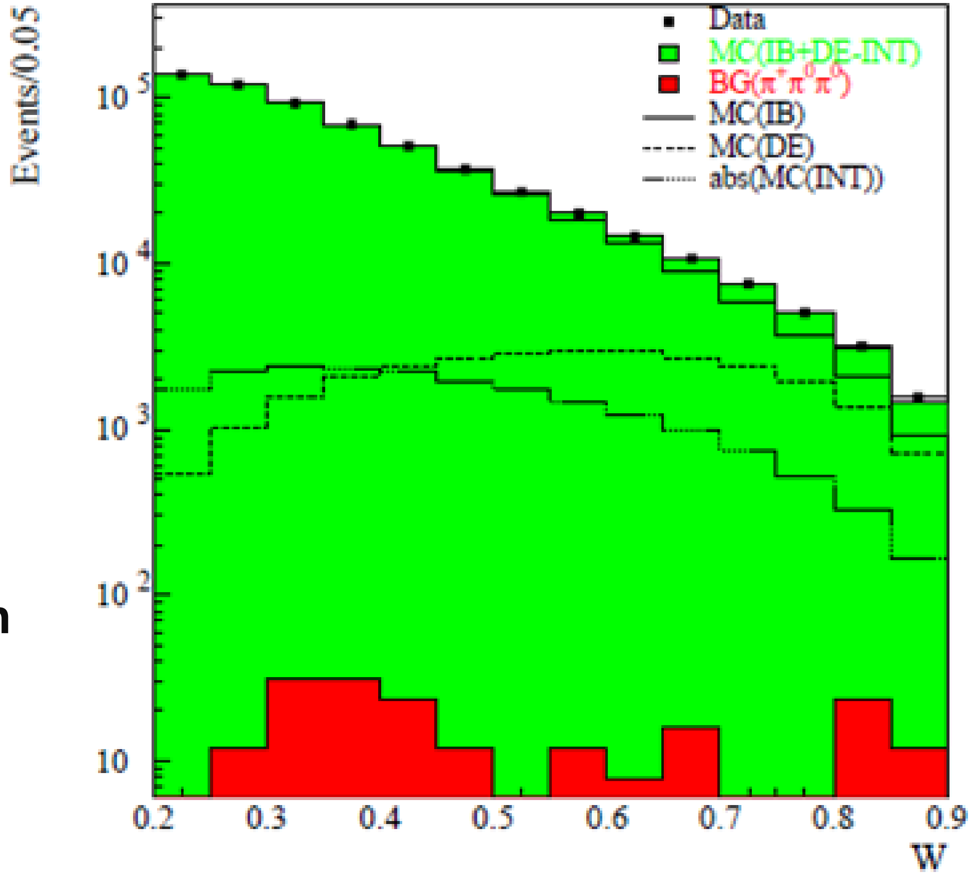


- **W resolution better than 1×10^{-2}**
- **Order ‰ γ mistagging prob.** for IB, DE and INT

Event reconstruction and signal region

- **NA48/2 measurement of $K^{\pm} \to \pi^{\pm} \pi^{0} \gamma$ decay**

- **High statistics:**
  - **more than 1 M reconstructed events (the full number is used for the CPV measurements)**
  - **after a cut on W [0.2, 0.9] and on E_{γ} (> 5GeV), still 600 k events left in the region $M_K \pm 10$ MeV for the measurement of DE and INT fraction**



Fitting techniques and fit results

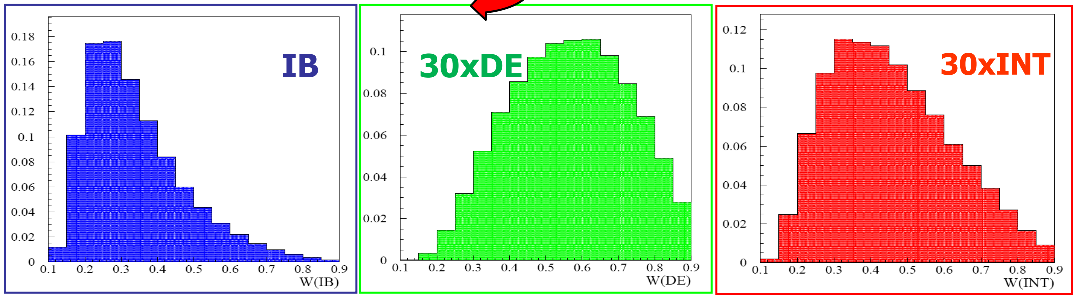
- Extended Maximum Likelihood Fit

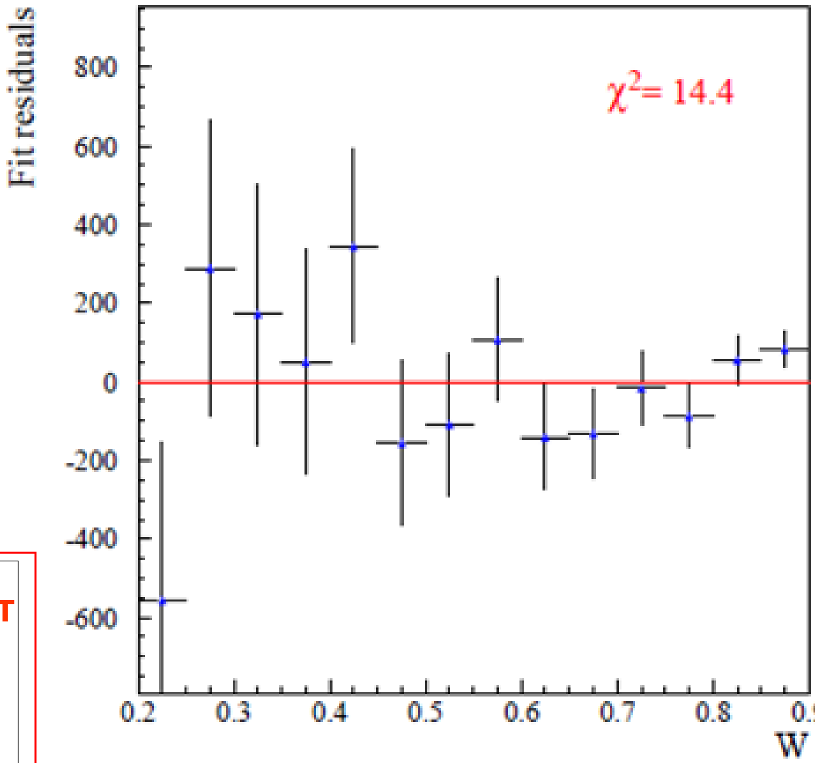
  (main method)

- An algorithm assigns weights to MC W distributions of the 3 components to reproduce data

$$Data(i) = (1-\alpha-\beta)\cdot IB(i) + \alpha\cdot DE(i) + \beta\cdot INT(i)$$

- This algorithm relies on the very different W distributions





Systematics	DE x 10^{-2}	INT x 10^{-2}
Acceptance	<0.10	<0.15
L1trigger	0.01	0.03
L2 trigger	--	0.30
Energy scale	0.09	0.21
Total	0.14	0.39

Final result (2003+2004 data):

$Frac(DE)_{T^*\pi(0\text{-}80)MeV}$ = BR(DE) / BR(IB) = $(3.32 \pm 0.15_{stat} \pm 0.14_{sys})*10^{-2}$

$Frac(INT)_{T^*\pi(0\text{-}80)MeV}$ = BR(INT) / BR(IB) = $(-2.35 \pm 0.35_{stat} \pm 0.39_{sys})*10^{-2}$

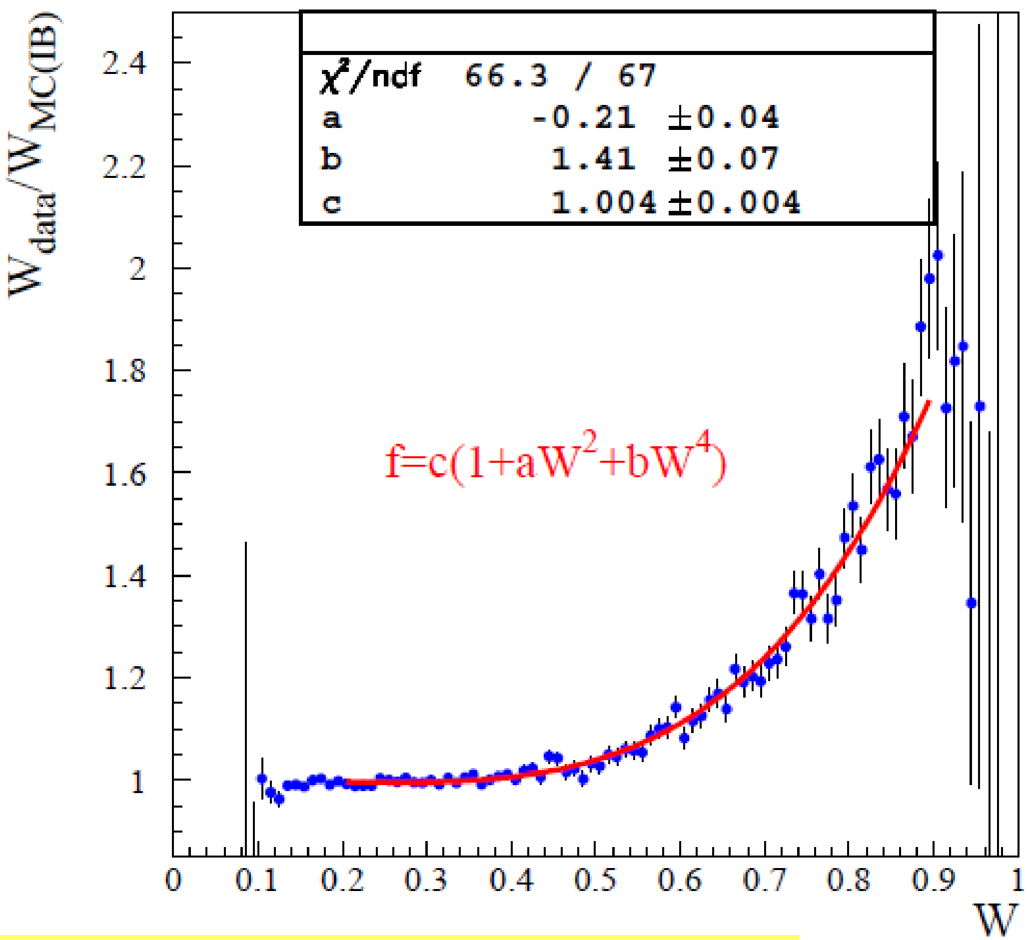
Fitting techniques and fit results

- Polynomial Fit
  (used as cross-check)

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

- The ratio W(Data)/W(MC_{IB}) is fitted
  with polynomial function:

$$F = c \cdot (1 + aW^2 + bW^4)$$



Final result (2003+2004 data): **(cross-check)**

Frac(DE)$_{T^*\pi(0\text{-}80)MeV}$ = BR(DE) / BR(IB) = $(3.19 \pm 0.16_{stat})\cdot 10^{-2}$

Frac(INT)$_{T^*\pi(0\text{-}80)MeV}$ = BR(INT) / BR(IB) = $(-2.21 \pm 0.41_{stat})\cdot 10^{-2}$

Fit results

Final result (2003+2004): extended ML fit

$\mathrm{Frac(DE)}_{T^*\pi(0\text{-}80)\mathrm{MeV}}$ = BR(DE) / BR(IB) = $(3.32 \pm 0.15_{stat} \pm 0.14_{sys})*10^{-2}$

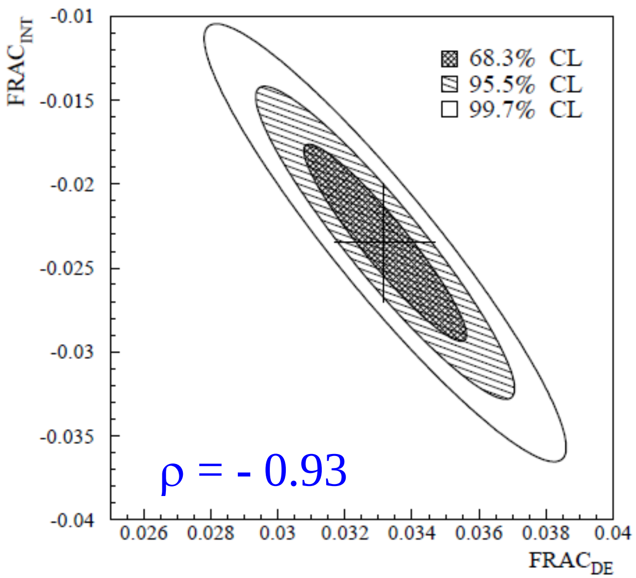
$\mathrm{Frac(INT)}_{T^*\pi(0\text{-}80)\mathrm{MeV}}$ = BR(INT) / BR(IB) = $(-2.35 \pm 0.35_{stat} \pm 0.39_{sys})*10^{-2}$

Final result (2003+2004): polynomial fit

$\mathrm{Frac(DE)}_{T^*\pi(0\text{-}80)\mathrm{MeV}}$ = BR(DE) / BR(IB) = $(3.19 \pm 0.16_{stat})*10^{-2}$

$\mathrm{Frac(INT)}_{T^*\pi(0\text{-}80)\mathrm{MeV}}$ = BR(INT) / BR(IB) = $(-2.21 \pm 0.41_{stat})*10^{-2}$

INT has never been observed before!



$K^{\pm}\rightarrow\pi^{\pm}\,\pi^{0}\,\gamma$ – first extraction of X_E X_M

Under the following approximations:

$\phi = 0$ and $\cos(\delta_1^1-\delta_0^2) = \cos(6.5°) \sim 1$

X_E and X_M can be extracted using the formulae:

$$X_E = \frac{Frac(INT)}{2\cdot(0.105\cdot m_K^2 m_\pi^2)}$$

$$X_M = \sqrt{\frac{Frac(DE) - m_K^4 m_\pi^4\,|X_E|^2\,2.27\cdot10^{-2}}{2.27\cdot10^{-2}\cdot m_K^4 m_\pi^4}}$$

WZW reducible anomaly prediction for $X_M \sim 270$ Gev^{-4}

Magnetic and electric components

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

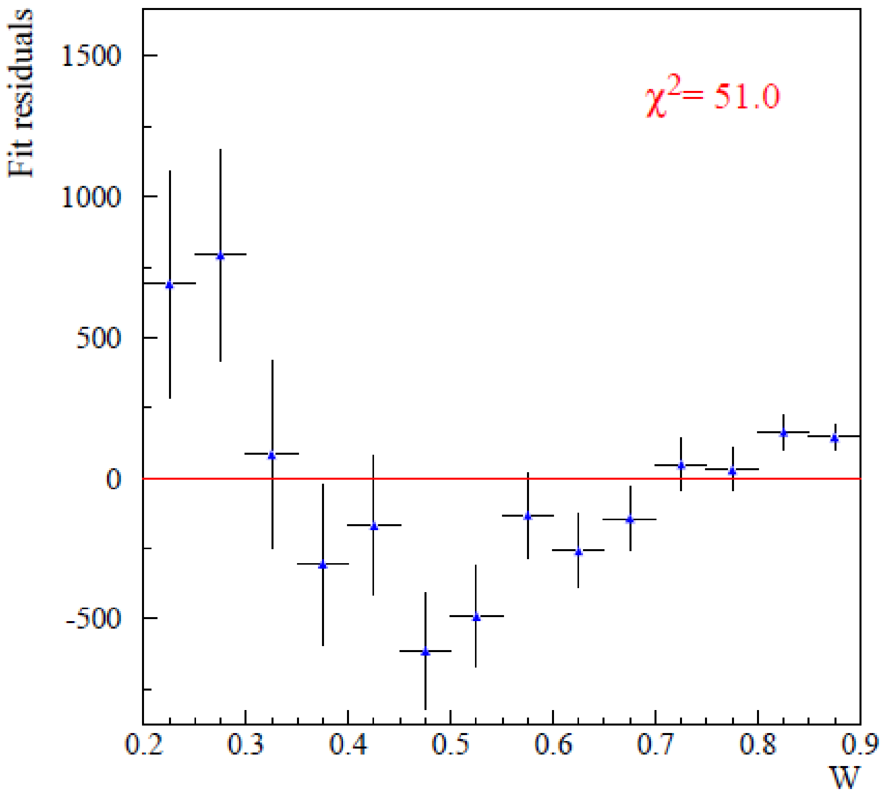
$X_M = (254 \pm 11_{stat} \pm 11_{sys})$GeV^{-4}

Fit to data with INT=0

In order to compare the NA48/2 results with those from previous measurements, the ML fit of the selected sample has been redone setting the interference term to zero, and the result for DE extrapolated to

$$55 < T < 90 \text{ MeV.}$$

In the figure you can see the ML fit residuals.



The χ^2 demonstrates that the data distribution cannot be properly described without an interference term and that the DE-only fit is not appropriate for this data.

Comparison with previous experiments

The BR(DE) assuming INT=0 (T_π*= 55-90) MeV using polynomial fit technique

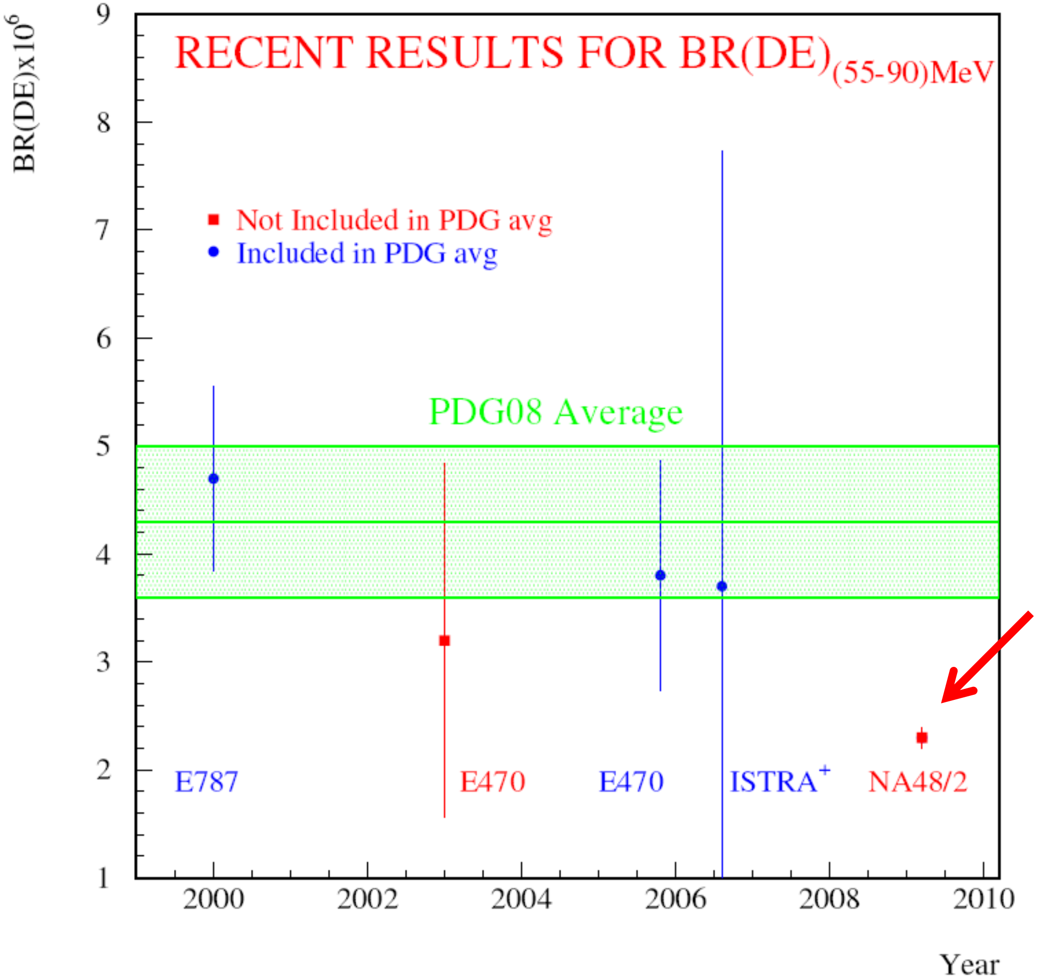
Measured in $0<T^*_\pi<80$ MeV extrap. to $55<T^*_\pi<90$ MeV using MC. $BR(IB)_{55\text{-}90}=2.61\cdot 10^{-4}$

- **$BR(DE)_{T^*\pi(55\text{-}90)MeV} =$**

  $(2.32\pm0.05_{stat}\pm0.077_{sys})\cdot 10^{-6}$

- **$PDG08_{avg} = (4.3 \pm 0.7)\cdot 10^{-6}$**

Remember that the bad χ^2 probab. of the polynomial fit: indicates that INT=0 is a wrong assumption



CP violation asymmetry in K^+ and K^-

Since the decay of $K^\pm \to \pi^\pm \pi^0 \gamma$ with direct photon emission is not suppressed by $I = 1/2$ rule, it has always been considered a good channel to search for CP violation charge rate asymmetry:

H.Y. Cheng, Phys Rev D 49, 3771 (1994); G. Colangelo, G. Isidori, J. Portoles, Phys Lett B 470, 134 (1999)

- Asymmetry in the total rate :

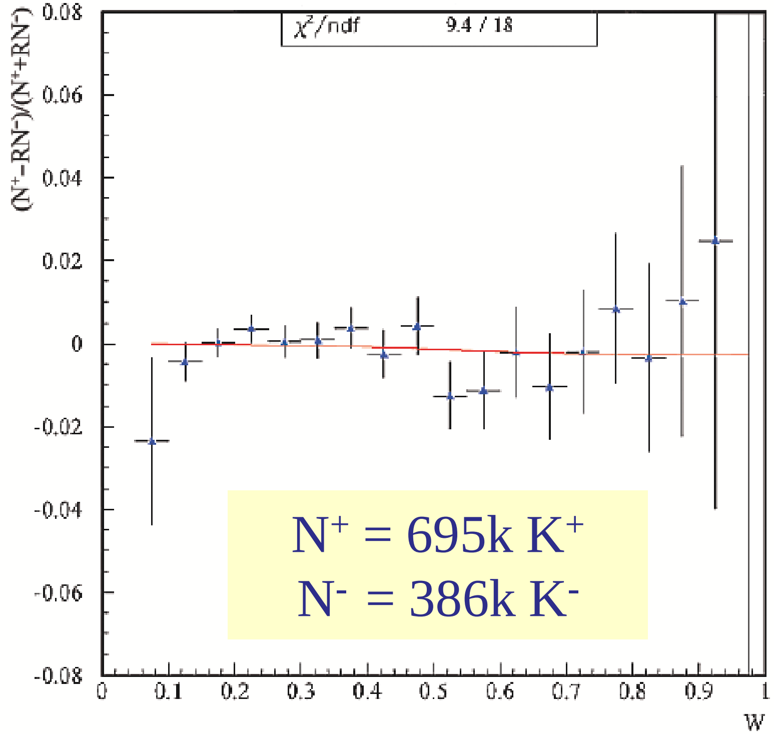
$$A_N = (N_+ - RN_-) / (N_+ + RN_-) =$$
$$= (0.0 \pm 1.0_{stat} \pm 0.6_{sys}) \times 10^{-3}$$

where $R = N_{beam}(K^+)/N_{beam}(K^-) = 1.7998(4)$ from $K^\pm \to \pi^\pm \pi^0 \pi^0$ decay used as normalization.

$|A_N| < 1.5 \times 10^{-3}$ @ 90% CL

First limit on $\sin\Phi = -0.01 \pm 0.43$;

$|\sin \Phi| < 0.56$ @ 90% CL



- Asymmetry in the Dalitz plot:

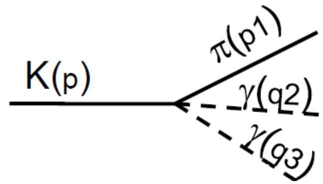
$$d\Gamma^\pm /dW = d\Gamma^\pm_{IB}/dW \,(1 + (a \pm e)W^2 + b\, W^4)$$

$$A_W = e \int I_{INT} / I_{IB} = (-0.6 \pm 1.0_{stat}) \times 10^{-3}$$

NO CP asymmetry observed in $K^\pm \to \pi^\pm \pi^0 \gamma$

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

$K^\pm \longrightarrow \pi^\pm \gamma\gamma$ Decay: Theory



$y = p(q_2 - q_3)/m_K^2$
$z = (q_2 + q_3)/m_K^2$

In the Chiral Perturbation Theory framework the differential rate of the $K^\pm(p) \longrightarrow \pi^\pm(p_3)\,\gamma(q_1)\,\gamma(q_2)$ process (no $\mathcal{O}(p^2)$ contribution) is:

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_{K^\pm}}{(8\pi)^3} \cdot \left[z^2 \cdot \left(|A+B|^2 + |C|^2\right) + \boxed{\left(y^2 - \frac{1}{4}\lambda\left(1, z, r_\pi^2\right)\right)^2} \cdot \left(|B|^2 + |D|^2\right) \right]$$

relevant only @ low $m_{\gamma\gamma}$

$$y = \frac{p \cdot (q_1 - q_2)}{m_{K^\pm}^2} \qquad z = \frac{(q_1+q_2)^2}{m_{K^\pm}^2} = \frac{m_{\gamma\gamma}^2}{m_{K^\pm}^2}$$

- The leading contribution at $\mathcal{O}(p^4)$ is given by $A(z, \hat{c})$ (loops) which is responsible for a cusp at $m_{\gamma\gamma} = m_{2\pi}$

- C (WZW) corresponds to ~10% of A at $\mathcal{O}(p^4)$

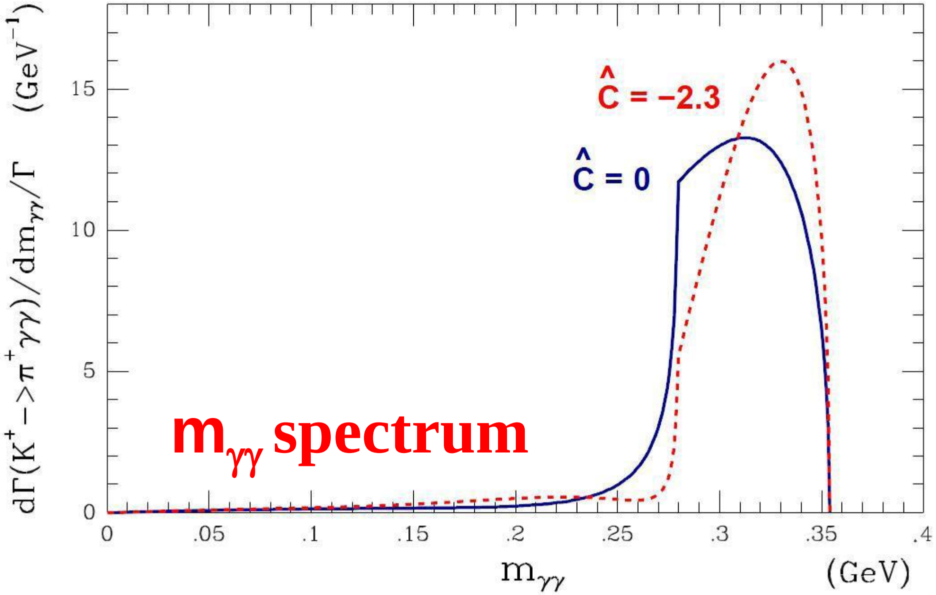
- B, D = 0 at $\mathcal{O}(p^4)$

[Ecker, Pich, de Rafael, Nucl. Phys. B303 (1988), 665]

- $\mathcal{O}(p^6)$ unitarity corrections can increase the BR by 30÷40%

[D'Ambrosio, Portoles, Nucl. Phys. B386 (1996), 403]

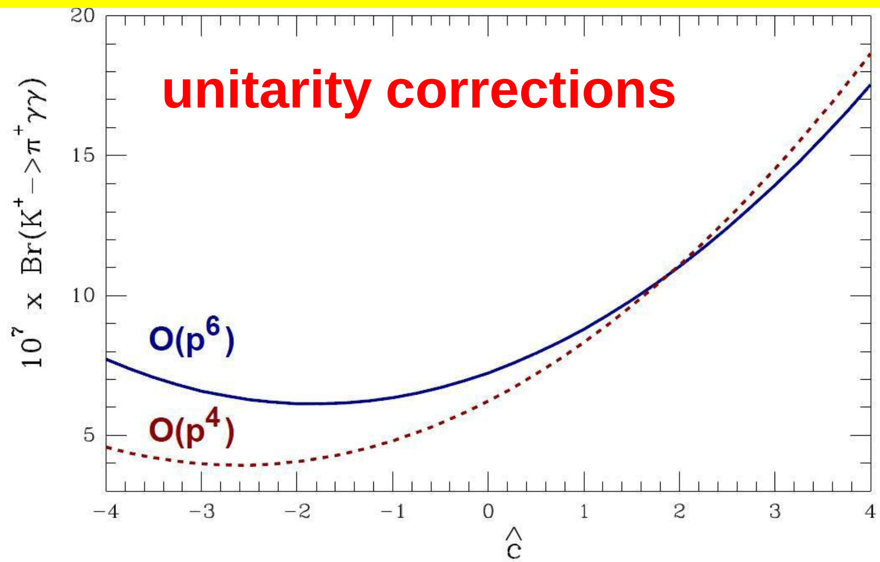
$K^{\pm} \longrightarrow \pi^{\pm} \gamma \gamma$ Decay: Theory



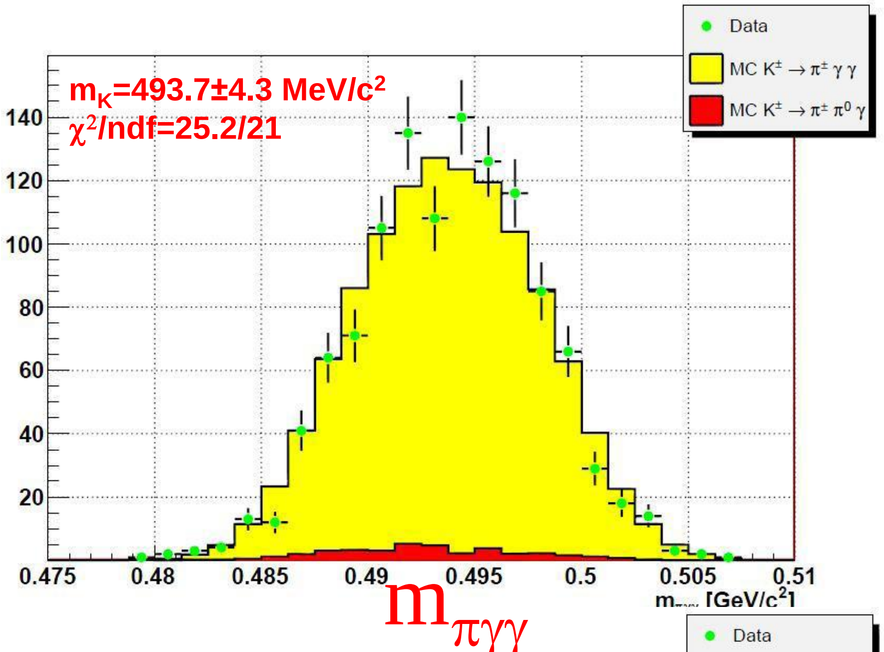
cusp-like behaviour
at 2π threshold

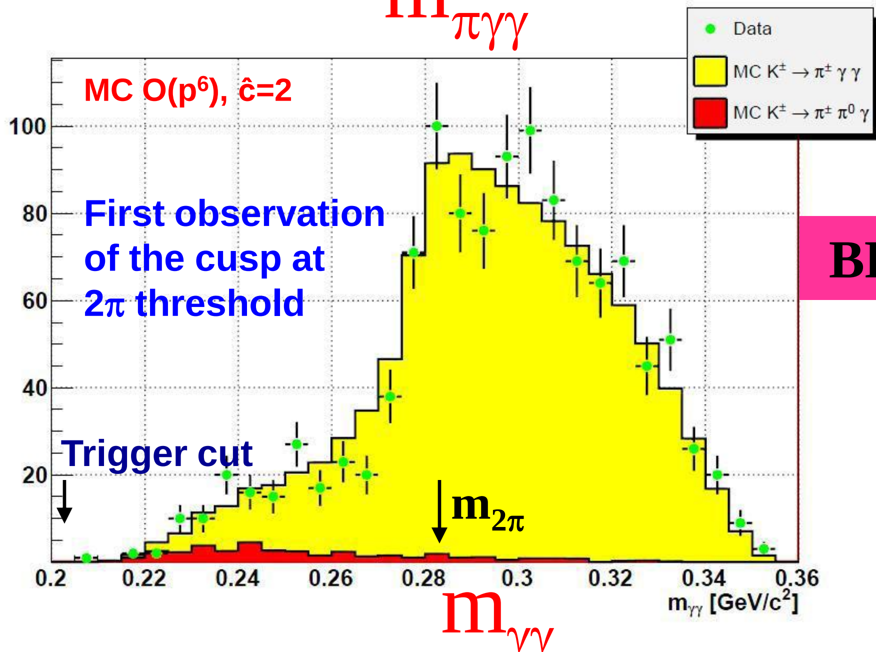
$BR(K^+ \to \pi^+\gamma\gamma) = (5.26 + 1.64\cdot\hat{c} + 0.32\cdot\hat{c}2 + 0.49)\cdot 10^{-7} \geq 4\cdot 10^{-7}$

Both decay spectrum and rate strongly depend on the single ĉ parameter ($\mathcal{O}$(p))



$K^{\pm} \longrightarrow \pi^{\pm}\gamma\gamma$ Decay: Result





- 1164 events found in 20% of NA48/2 data *(~40 times previous world sample)*

- Main background: $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$ (3.3%)
- Main systematics from trigger efficiency determination

- Data shape ($m_{\gamma\gamma}$) follows ChPT description (MC $\mathcal{O}(p^6)$ and ĉ=2 shown for qualitative comparison)

- Our model dependent BR determination is :

$BR(K^{+}\to\pi^{+}\gamma\gamma) = (1.07 \pm 0.04_{stat} \pm 0.08_{syst})\cdot 10^{-6}$

assuming $\mathcal{O}(p^6)$ *and* **ĉ=2**

- Overtaken the previous result from E787 with 31 events candidates:

$$BR(K^{+}\to\pi^{+}\pi\gamma\gamma) = (1.10\pm0.32)\cdot 10^{-6}$$

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

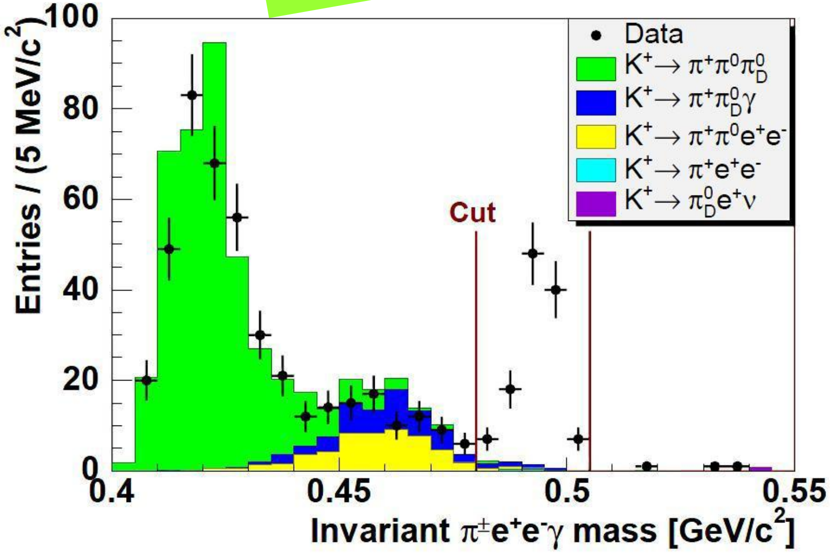
$K^\pm \rightarrow \pi^\pm e^+e^- \gamma$ Decay Results

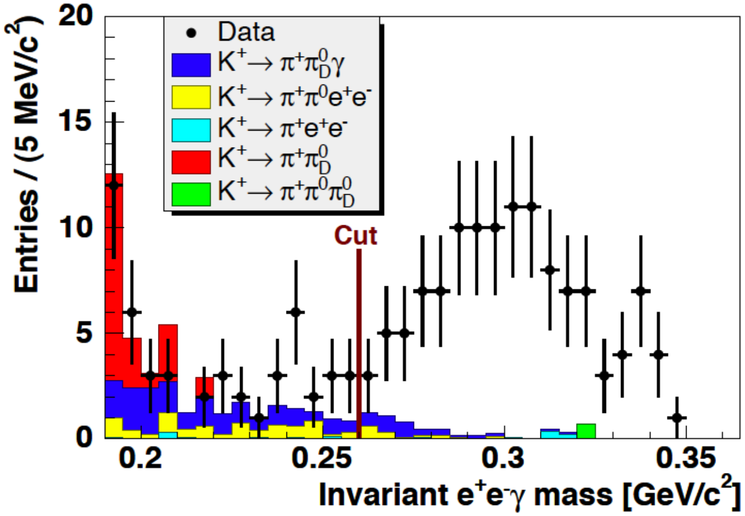
$\mathcal{O}(p^6)$ ChPT prediction **$BR(\pi^\pm e^+e^- \gamma) = (0.9 \div 1.6) \cdot 10^{-8}$**

[Gabbiani, PRL D59, 094022]

Never observed before!

- 120 events candidates
- Background from $K^+ \rightarrow \pi^+ \pi^0_D \gamma$ (6.1%)
- BR computed in bins of $m_{ee\gamma}$
- no assumption on $m_{ee\gamma}$ (model independent measurement)
- Cut on $m_{ee\gamma} > 260$ MeV/c^2





$BR(K^\pm \rightarrow \pi^\pm e^+e^- \gamma) =$
$(1.19 \pm 0.12_{stat} \pm 0.04_{syst}) \cdot 10^{-8}$

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

- Assuming ChPT $\mathcal{O}(p^4)$, the $\hat{c}$ value is

$\hat{c}$ = (0.90 ± 0.45) χ^2/ndf=8.1/17; prob=96.4%

[Gabbiani, Phys. Rev. Lett. D59 (1999), 094022]

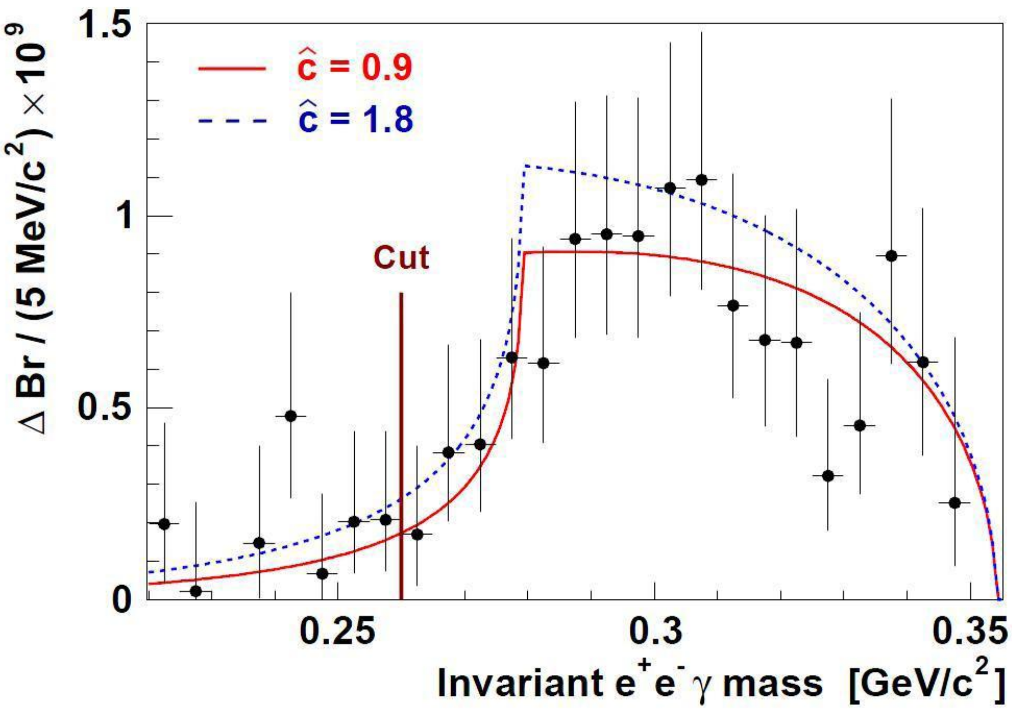
extracted from $m_{ee\gamma}$ distribution

(1.2 σ away from BNL E787 value in $K^+ \rightarrow \pi^+\gamma\gamma$: $\hat{c}$ =1.8 ± 0.6) *[Phys. Lett. B659 (2008), 493]*

- From this, the model dependent ChPT BR is:

$BR(K^{\pm} \rightarrow \pi^{\pm} e^+e^- \gamma)$ =
$(1.29 \pm 0.13_{exp} \pm 0.03_{\hat{c}})\cdot 10^{-8}$

[Batley et al. Phys.Lett.B659:493, 2008]



Conclusions

NA48-2 exp: $K^{\pm} \to \pi^{\pm} \pi^{0} \gamma$

- First measurement of DE and INT fraction for $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay
- Incompatibility of data with INT=0 hypothesis has been established
- Non vanishing interference has been observed for the first time
- Magnetic and electric part of DE have been separated:
  - $X_E = -24 \pm 4_{stat} \pm 4_{sys}$ GeV^{-4}
  - $X_M = 254 \pm 6_{stat} \pm 6_{sys}$ GeV^{-4}
- CPV parameter $A_N < 1.5 \bullet 10^{-3}$ in both rates and Dalitz plot

NA48-2 exp: $K^{\pm} \to \pi^{\pm} \gamma \gamma$

- First possibility for shape study
- Preliminary BR measurement at $\mathcal{O}(p^6)$ and $\hat{c} = 2$:

  $BR(K^{\pm} \to \pi^{\pm}\pi^{0}\gamma\gamma) = (1.07 \pm 0.04_{stat} \pm 0.08_{syst}) \cdot 10^{-6}$
- Model independent measurement and $\hat{c}$ extraction in preparation

NA48-2 exp: $K^{\pm} \to \pi^{\pm} e^{+}e^{-} \gamma$

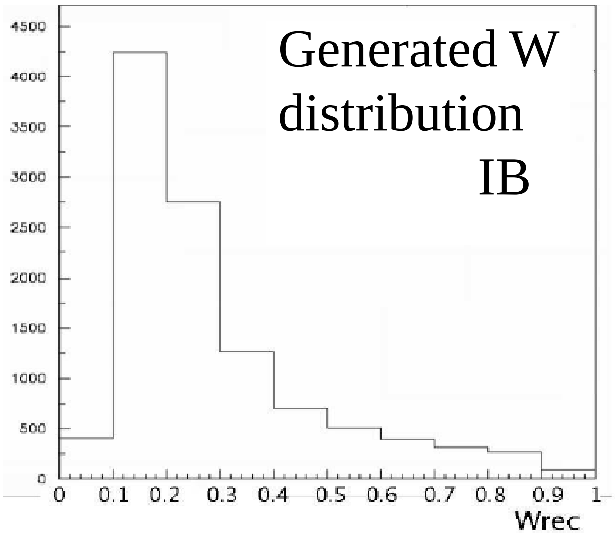
- First observation and measurement of BR and shape

  $BR(K^{\pm} \to \pi^{\pm} e^{+} e^{-} \gamma) = (1.19 \pm 0.12_{stat} \pm 0.04_{sys}) \cdot 10^{-8}$

  $\hat{c} = (0.90 \pm 0.45)$

Spares

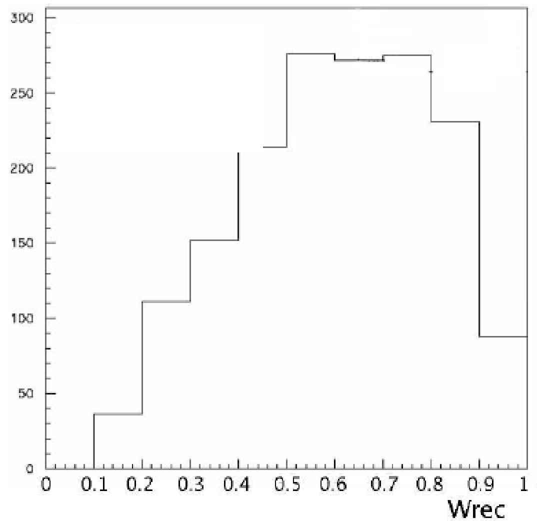
Mistagging self background to DE



Reconstruction

$$W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_K^* \cdot P_\gamma^*)}{(m_K m_\pi)^2}$$

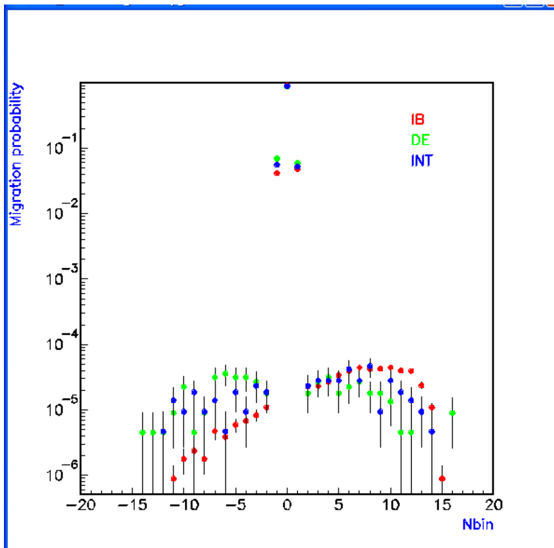
Wrong γ in W



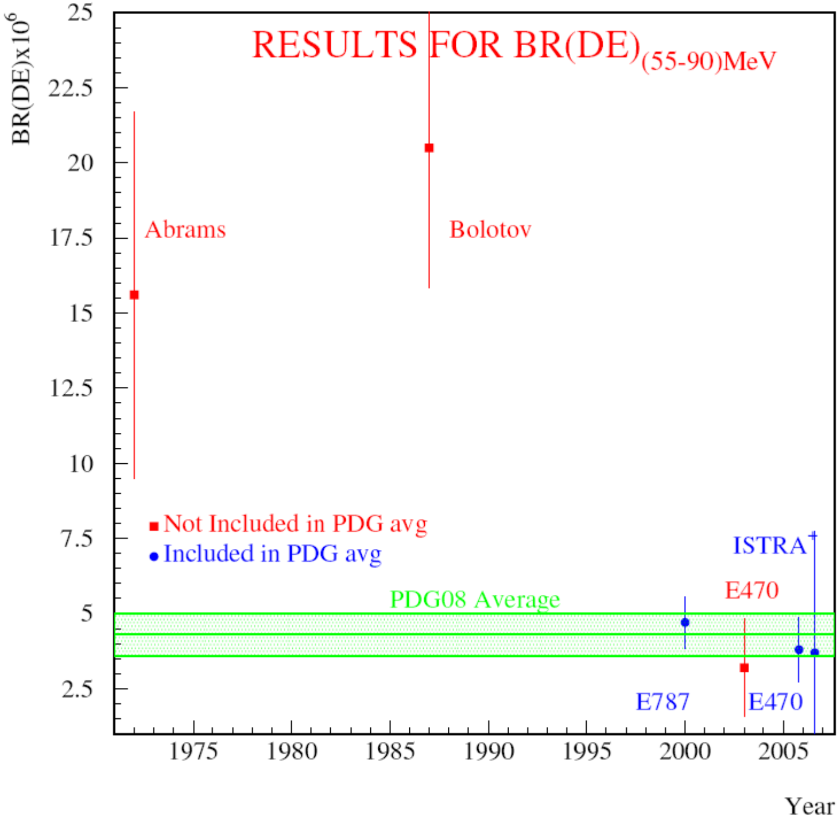
Reconstructed IB events using a γ from the π^0 look like DE!!!
Mistagging lead to overestimated DE

NA48/2 mistag

Mistag(IB) =$(0.52\pm0.06)\cdot10^{-3}$
Mistag(DE) =$(0.48\pm0.23)\cdot10^{-3}$
Mistag(INT)=$(0.49\pm0.24)\cdot10^{-3}$



Previous results

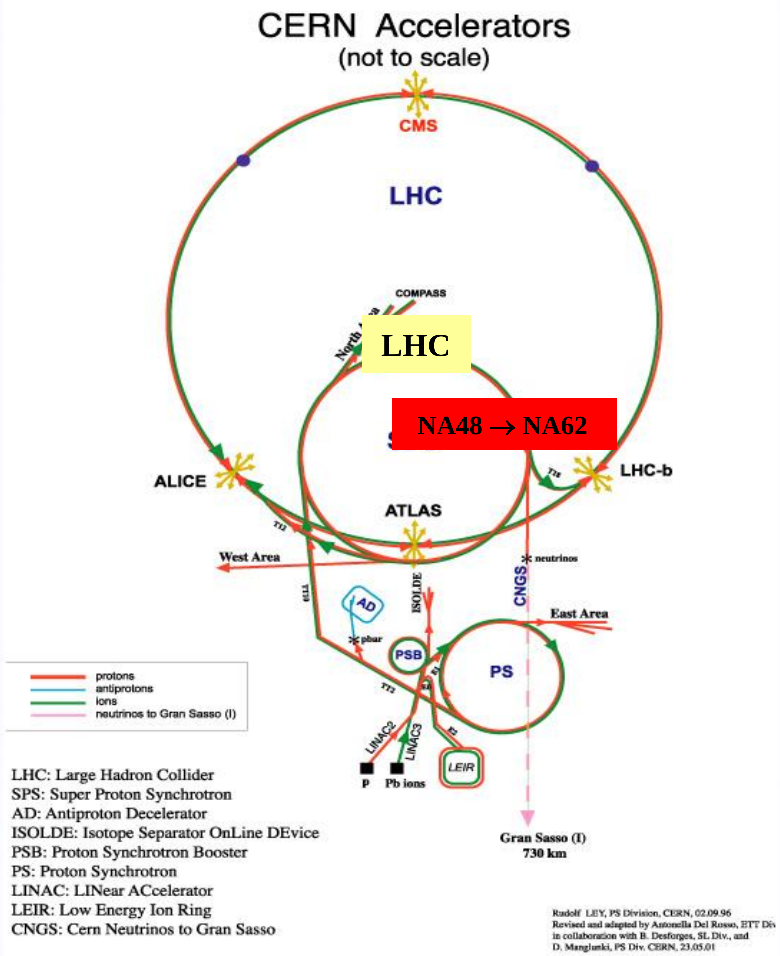


	DE±err	stat
E787	$(4.7\pm0.9)\cdot10^{-6}$	20K
E470	$(3.8 \pm 1)\cdot10^{-6}$	10K
ISTRA+	$(3.7 \pm 4)\cdot10^{-6}$	930
PDG 08	$(4.3\pm0.7)\cdot10^{-6}$	//

Assumption INT=0 in all the DE measurement (55-90)MeV
No Interference and no CPV observed

- INT(E787) = (-0.4 ± 1.6)% T^*_π (55-90) MeV

The NA48/NA62 experiment



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

NA62 phase I

Dedicated 2007 run to measure:

$$R_K = \frac{\Gamma\left(K^\pm \to e^\pm \nu_e\right)}{\Gamma\left(K^\pm \to \mu^\pm \nu_\mu\right)}$$

NA62 phase II

measurement of the decay

$$K^+ \to \pi^+ \nu \bar{\nu}$$

(2008-2010 R&D
& construction
2011 start of data taking)