Kaon Physics at CERN: recent results from the NA48/2 & NA62 experiments

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*On behalf of the NA48/2 & NA62 Collaborations

Outline

- Kaon physics at CERN
  - ★ the NA48/2 & NA62 experiments
- High precision measurement of the semileptonic Kl3 decays $K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$ and $K^{\pm} \rightarrow \pi^0 \mu^{\pm} \nu$
  - ★ Introduction & parametrization
  - ★ Form Factors results
- Studies of the rare decay $K^{\pm} \rightarrow \pi^{\pm} \gamma\gamma$

New

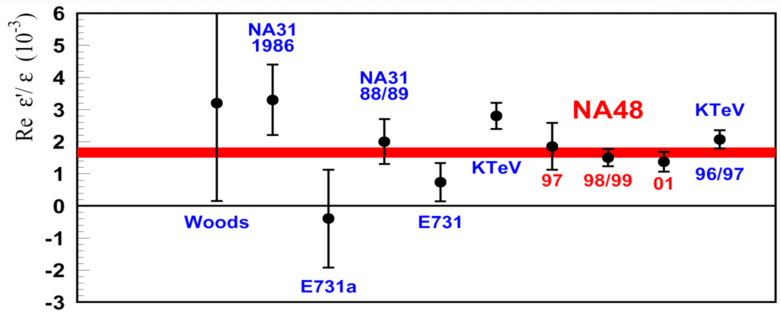
Also at this conference more NA62 results by Paolo Massarotti:

- Lepton universality tests at the NA62 experiment and

- Prospects for $K^+ \rightarrow \pi^+ \nu\nu$ observation at CERN

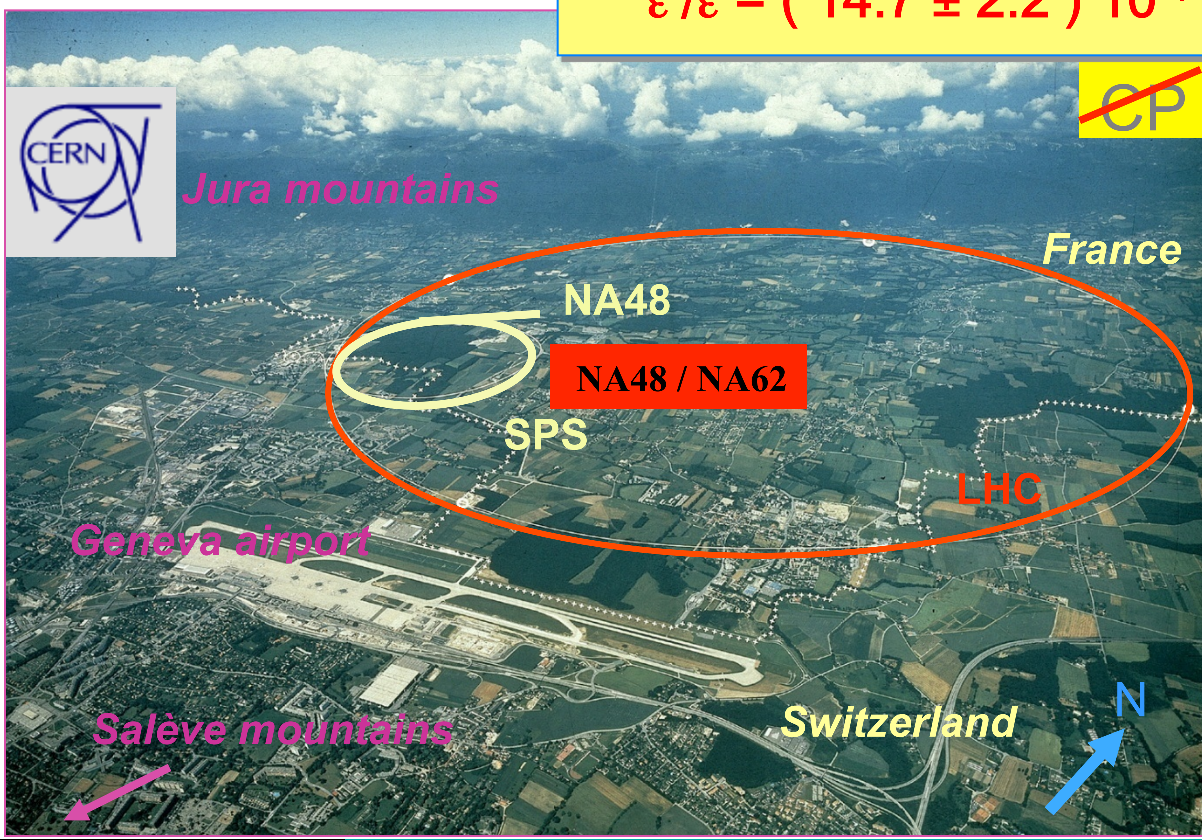
NA48 and NA62 experiments at CERN

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



Direct CP Viol. 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

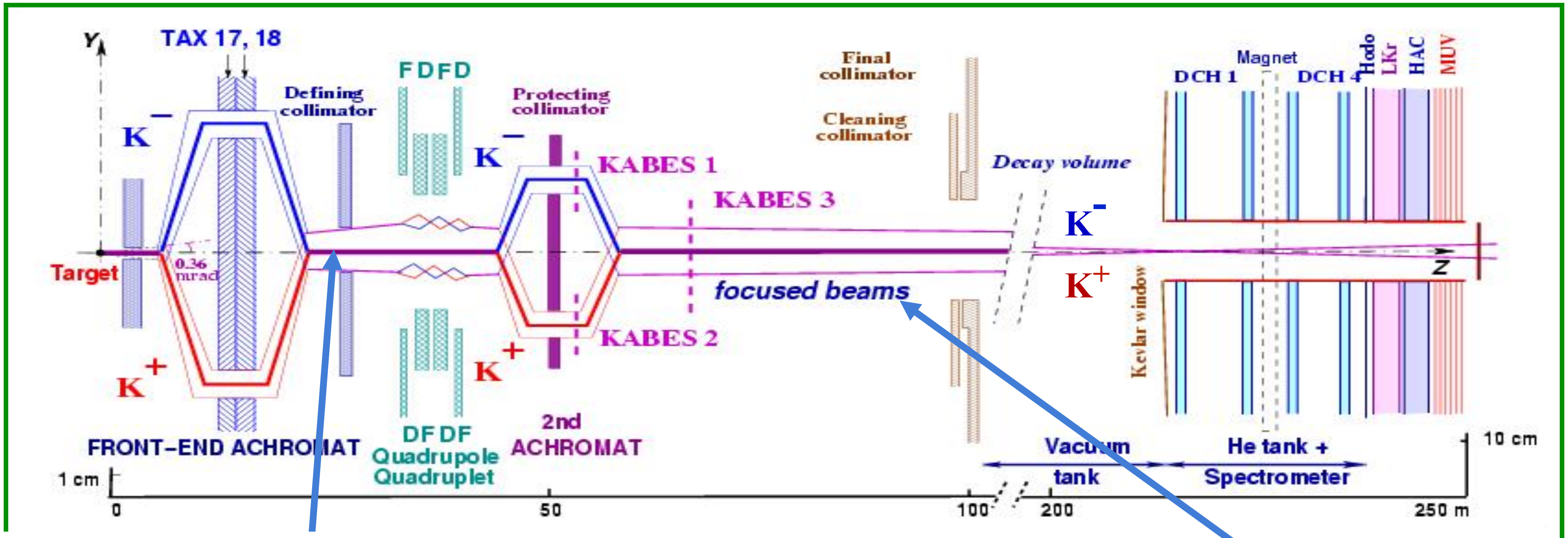
NA48/2
- 2003: $K^{\pm}$ High Intensity
- 2004: $K^{\pm}$ High Intensity

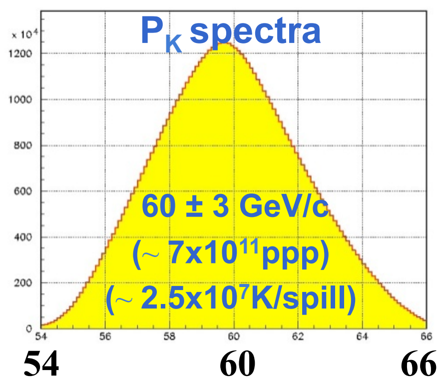
NA62(R_K)
- 2007/08: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ runs

NA62
- 2007–2013: R&D
- 2012: Start $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

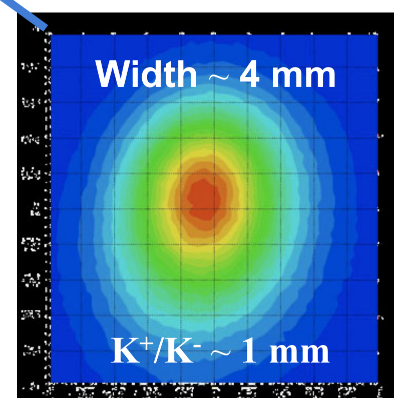
NA48/2 simultaneous $K^{\pm}$ beam

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.





- Simultaneous, unseparated, focused beams
- Kaon decays in the vacuum tank: 22%
- Flux ratio: $K^+/K^- \sim 1.8$
- Similar acceptance for K^+ and K^- decays
- Large charge symmetrization of experimental conditions



NA48 detector

- **Liquid Krypton EM calorimeter (LKr)**

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

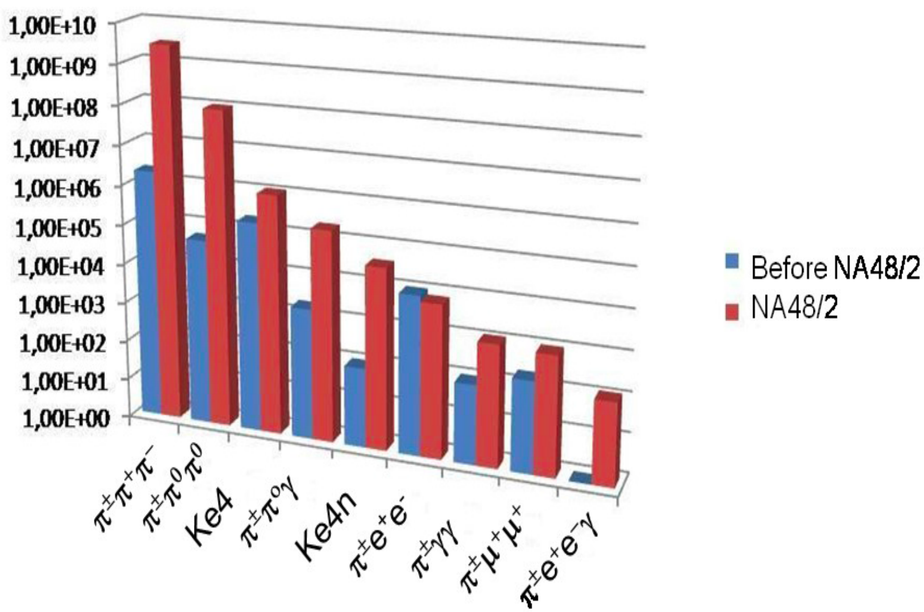
$\sigma_x = \sigma_y = 4.2/E^{\frac{1}{2}} \oplus 0.6$ mm (E in GeV/)

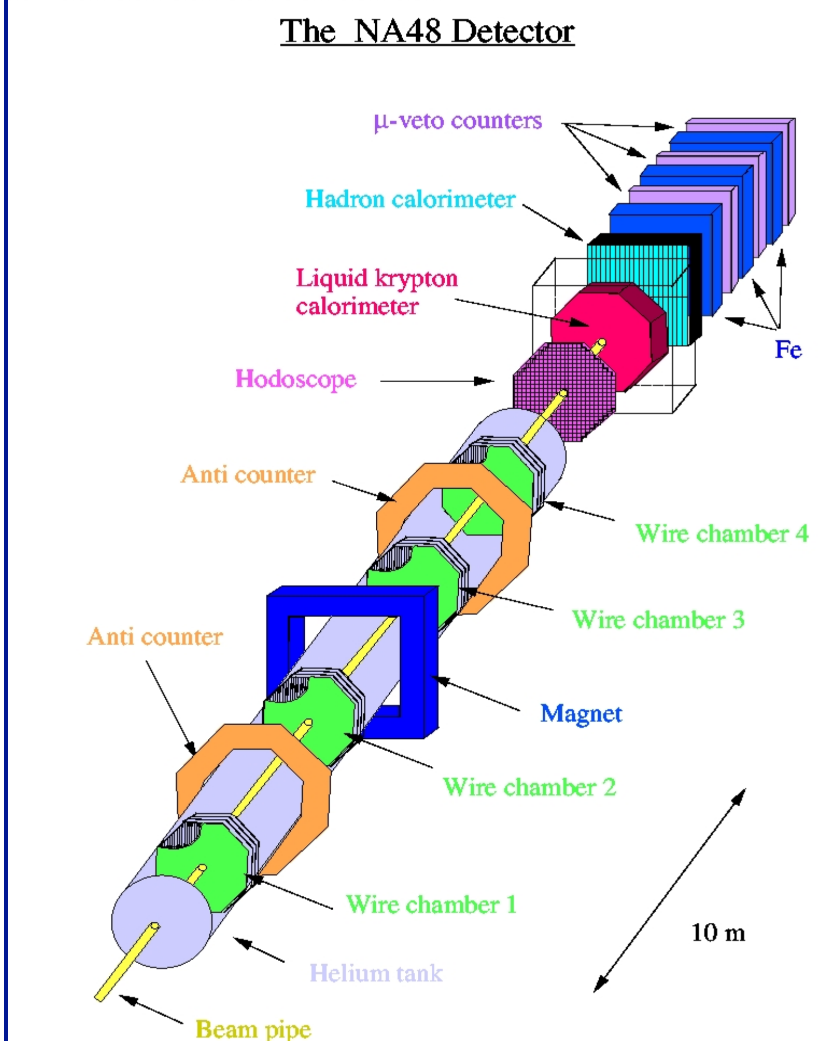
- **Magnetic spectrometer (4 DCHs + dipole magnet)**

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

- **Charged Hodoscope** $\sigma_t = 150$ ps

- **Muon Veto counter**





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

★ $K^{\pm} \rightarrow \pi^{0} l^{\pm} \nu$ (Kl3) Form Factors

|Vus| and Standard Model Test

The most precise test of the CKM unitarity comes from the $|\mathbf{V_{us}}|$ (and the $|\mathbf{V_{ud}}|$) measurement:

$$|\mathbf{V_{ud}}|^2 + |\mathbf{V_{us}}|^2 + \cancel{|\mathbf{V_{ub}}|^2} = 1$$

Departures from unity should be a signal of new physics ➡ G_F in the leptonic decays would be different from G_F in *W* coupling with quarks

In 2004 the CKM unitarity was not completely certified:

$$1 - |\mathbf{V_{ud}}|^2 - |\mathbf{V_{us}}|^2 = 0.0035(15) \quad \textit{from PDG}$$

➡ Efforts from both experimental and theoretical side.

The traditional very clean $K^{\pm}l3$ and many other different decay modes (semileptonic charged kaon decays, leptonic kaon decays, Hyperon, muon decay, tau decay,….) have been considered.

$K^\pm \to \pi^0 l^\pm \nu$ (Kl3) and Vus - Introduction

Precision measurement of $K^\pm \to \pi^0 l^\pm \nu$ (Kl3) provide the most accurate and theoretically cleanest way to access $|V_{us}|$

The rate of $K^\pm \to \pi^0 l^\pm \nu$ (Kl3) is given by the formula:

$$\Gamma(Kl3(\gamma)) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^l (1 + 2\delta^l_{SU(2)} + 2\delta^l_{EM})$$

★ **Theory:**

- $S_{EW} = 1.0232$ – universal short distance EW correction
- $f_+(0)$ – form factor at 0 momentum transfer
- $\delta^l_{SU(2)}$ – Isospin breaking correction
- δ^l_{EM} – Long distance EM effect

★ **Experiment:**

- Γ – branching ratio and lifetime *(inclusive of radiative corrections)*
- I_K^l – integral of the matrix element over phase space

$K^{\pm} \to \pi^0 l^{\pm} \nu$ (Kl3) Form Factors - Introduction

The phase space integral depends on the matrix element.

K_{l3} decays are described by two vector **form factors $f_{\pm}(t)$** and the matrix element can be written as:

$$M = G_F/2\, V_{US} \left(f_+(t) (P_K + P_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t)\, m_l\, \bar{u}_l (1+\gamma_5) u_\nu \right)$$

- $t=q^2$ is the squared 4-momentum transfer to the l-ν system
- $f_-(t)$ can only be measured in $K_{\mu 3}$ decays ($m_e \ll m_K$)
- $f_+(t)$ is the vector form factor and $f_0(t)$ the scalar form factor, related through the formula:

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t)$$

- Both scalar and vector form factors are measured relatively to $f_+(0)$ *(input from theory)*

$$\bar{f}_+(t) = \frac{f_+(t)}{f_+(0)} \qquad \bar{f}_0(t) = \frac{f_0(t)}{f_+(0)}$$

$K^{\pm} \rightarrow \pi^0 l^{\pm} \nu$ Form Factors - Parametrization

- **Pole Parametrization:** assume the exchange of vector (1^-) and scalar (0^+) resonances and mass m_V/m_S. $f_+(t)$ can be described by K*(892), for $f_0(t)$ no obvious dominance is seen

$$\overline{f_{+,0}}(t) = \frac{m^2_{V,S}}{m^2_{V,S} - t}$$

- **Linear and quadratic parametrization:** Taylor expansion in the momentum transfer. No direct physical meaning

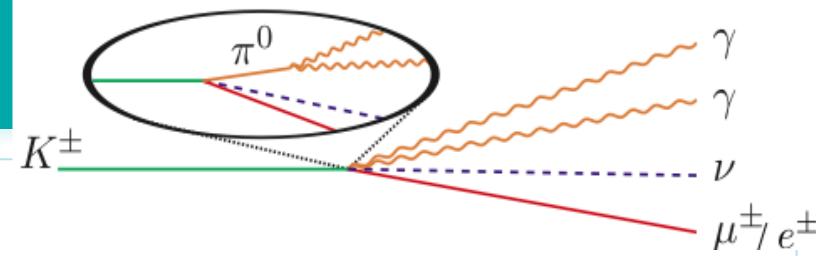
$$\overline{f_{+,0}}(t) = \left(1 + \lambda_{+,0} \frac{t}{m^2_{\pi}} \right)$$

linear

$$\overline{f_{+,0}}(t) = \left(1 + \lambda'_{+,0} \frac{t}{m^2_{\pi}} + \frac{1}{2} \lambda''_{+,0} \left(\frac{t}{m^2_{\pi}} \right)^2 \right)$$

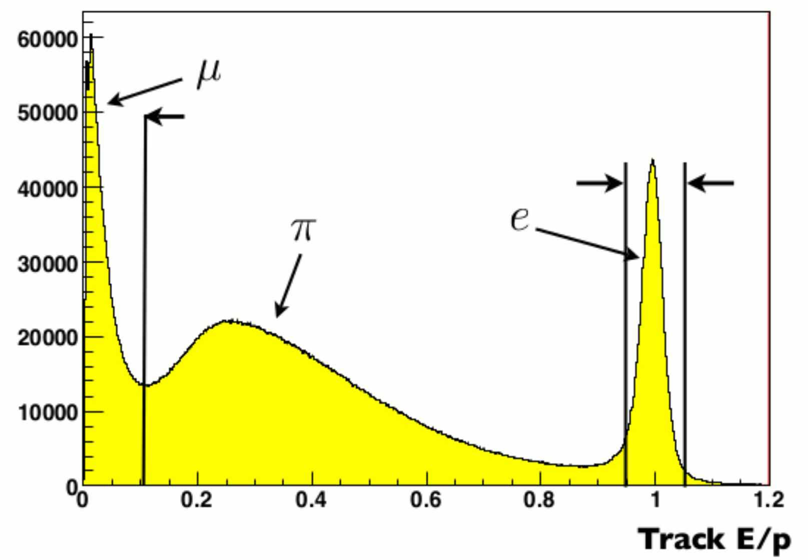
quadratic

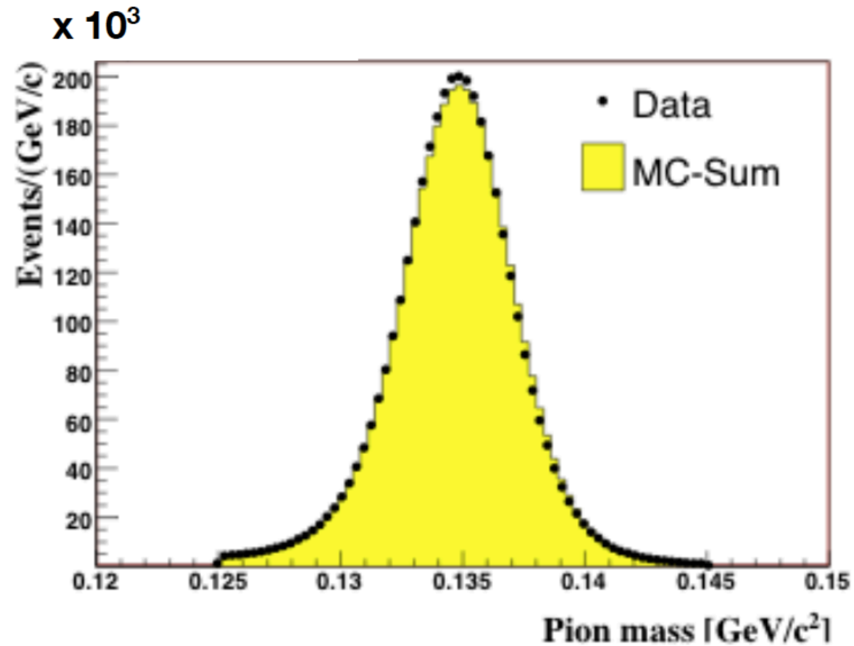
$K^{\pm} \rightarrow \pi^0 l^{\pm} \nu$ events selection



- 1 charged lepton and 2γ, in time
- Lepton tag based on E/p and muon counter
- Cut on the reconstructed γγ mass: $|M_{\gamma\gamma} - M_{\pi 0}| < 10\ MeV/c^2$
- Cut on the missing mass: $M^2_{Miss} < 10\ (MeV/c^2)^2$
- Total Kaon energy (under the hypothesis of a single undetected neutrino): $55 < E_K < 65$ GeV

E/p ratio used for e /π discrimination





- Data collected in 2004 in a 3 day run with a minimum bias trigger:
- 4.0 10^6 $K^{\pm}e3$ candidates selected
- 2.5 10^6 $K^{\pm}\mu 3$ candidates selected

Very low background, at per mill level

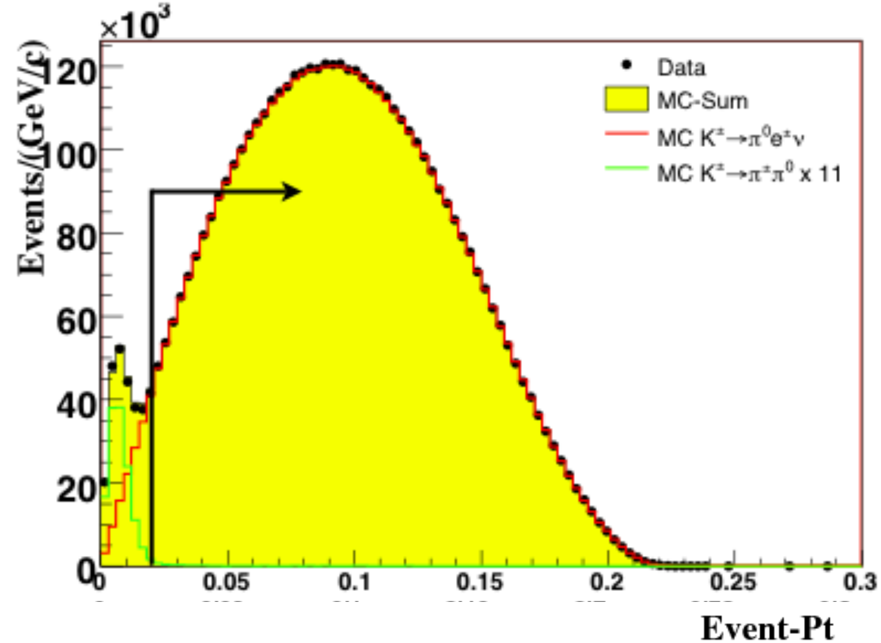
$\pi^{\pm}\pi^{0}$ background suppression

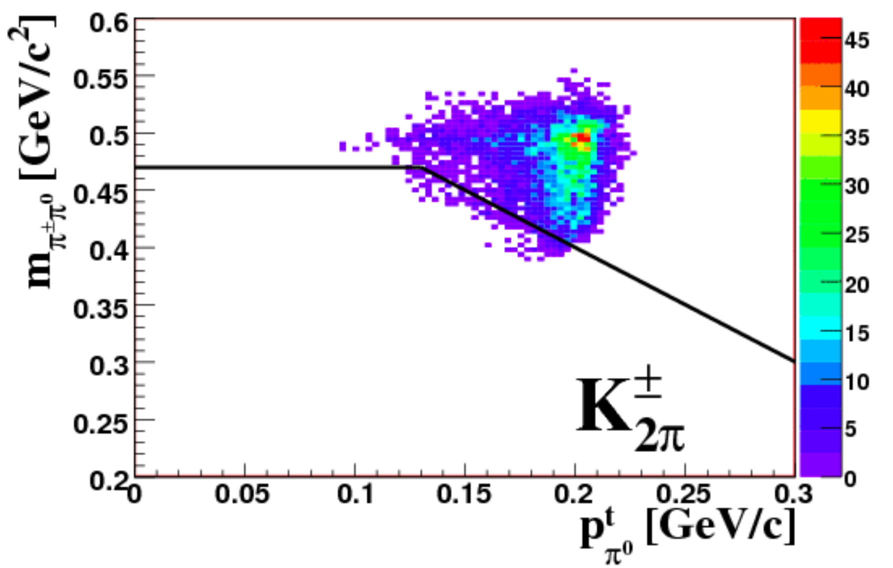
$K^{\pm}e3$

- Misidentification of the pion
- Cut on event $p_t > 0.02$ GeV/c:
  - acceptance loss ~3% and
  - background contamination <0.1%

$K^{\pm}_{\mu 3}$

- Misidentification of the pion or pion decay in flight
- 2D cut in the total mass (in the pion hypothesis) and the π^0 transverse momentum plane:
  - acceptance loss ~24%
  - background contamination ~0.5%

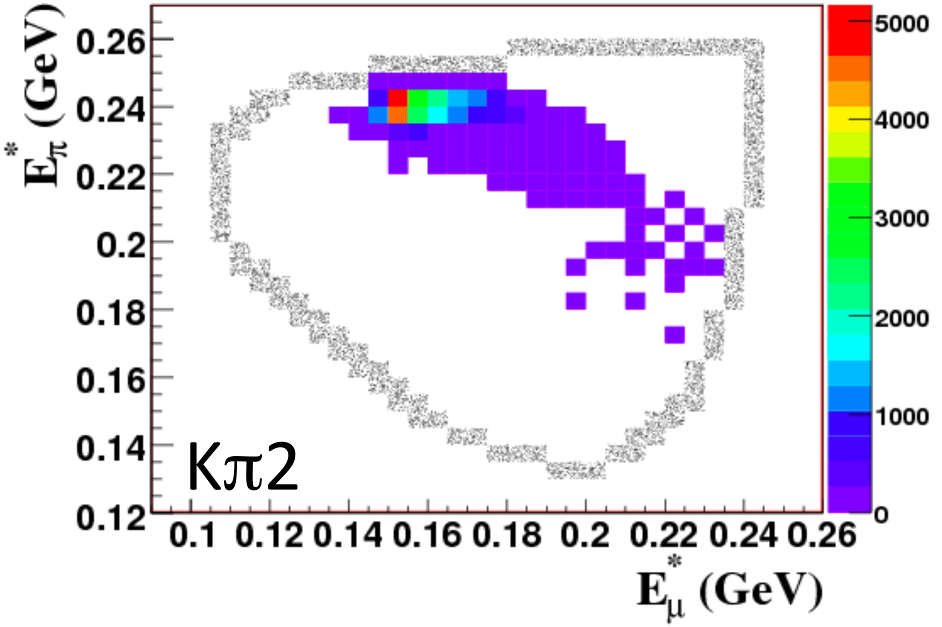


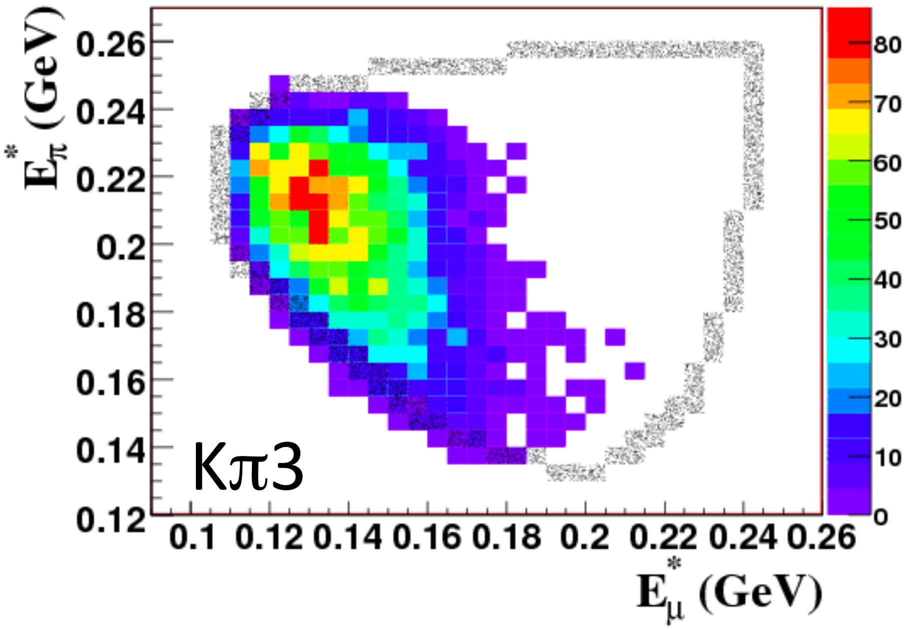


$K^\pm \to \pi^0 l^\pm \nu$ background and Dalitz plot

- The distribution of the residual background in the Dalitz plot is taken into account in the fit
- In the $K\mu3$ there is an additional contribution of the $\pi\pi^0\pi^0$ background (small but it introduces a slope in the Dalitz Plot)

Pion energy vs Muon energy (CM)





Radiative effects

- Radiative corrections included at first order:

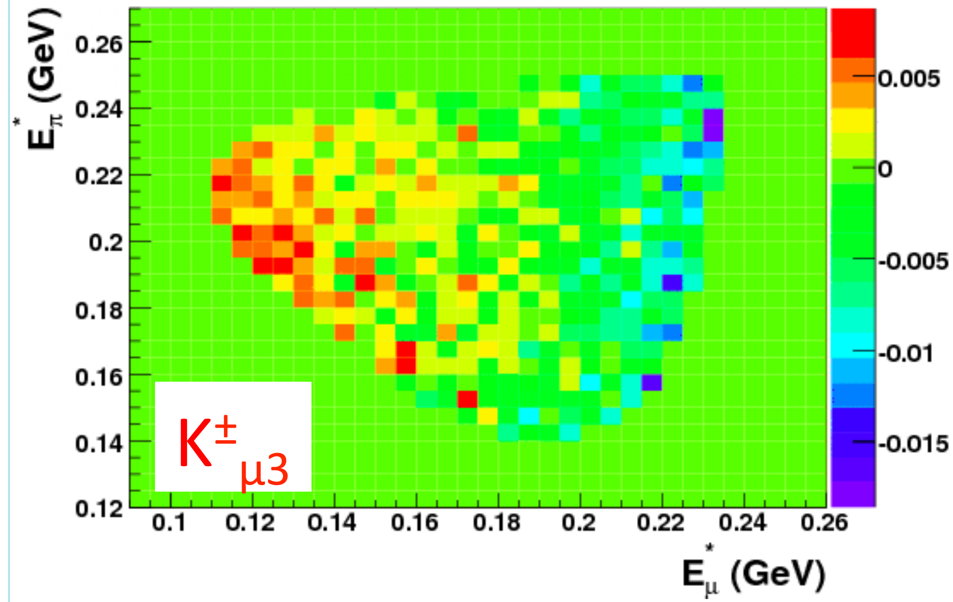
$$\Gamma_{Kl3} = \Gamma^0_{Kl3}+\Gamma^{RAD}_{Kl3} = \Gamma^0_{Kl3}(1+2\delta^{l3}_{EM})$$

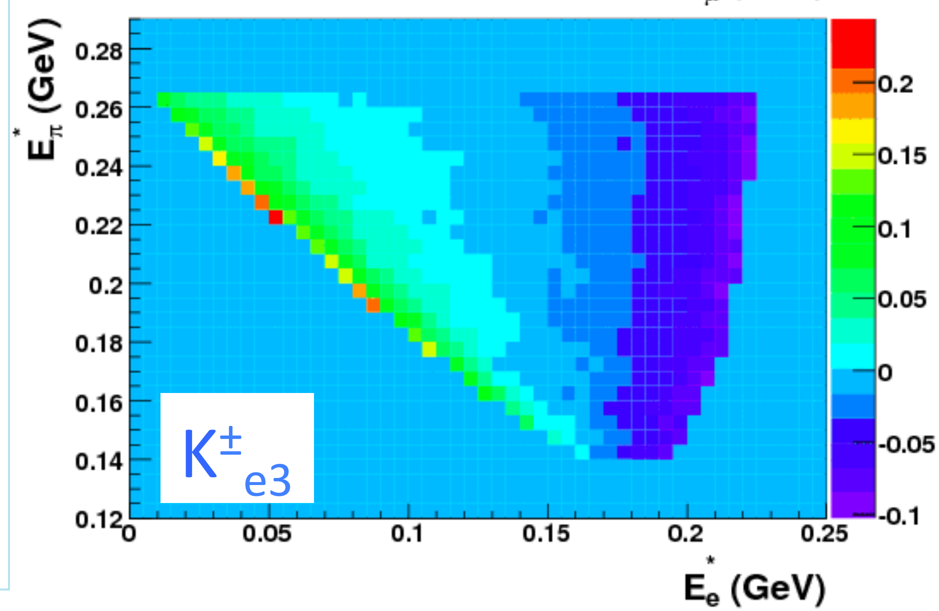
- Simulation code based on KLOE code *[C.Gatti EPJ C45 (2006) 417]*

- Parameters for normalization from *[JHEP 11 (2008) 06]*

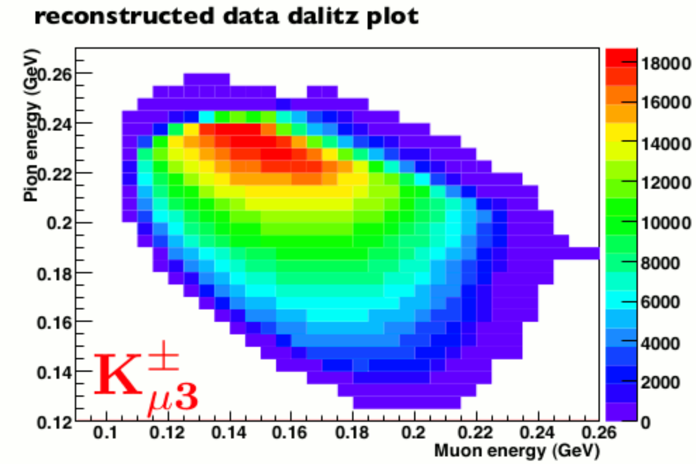
	δ_{EM}
Ke3	(0.050 ± 0.125)%
Kμ3	(0.008 ± 0.125)%

- ~ 10% effect on Ke3,
  ~ 1% effect on Kμ3



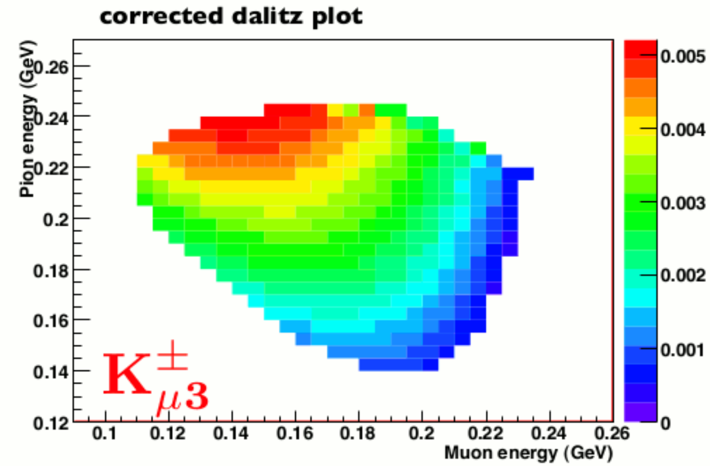


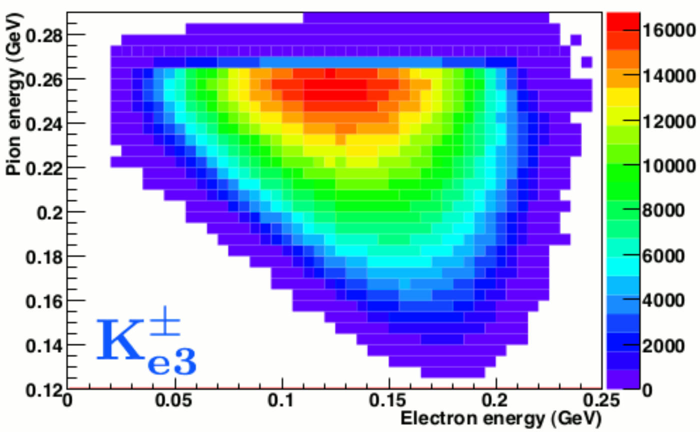
Dalitz plot - corrections and fitting



Pion energy vs Lepton energy

(E^*_l and E^*_π in CM)

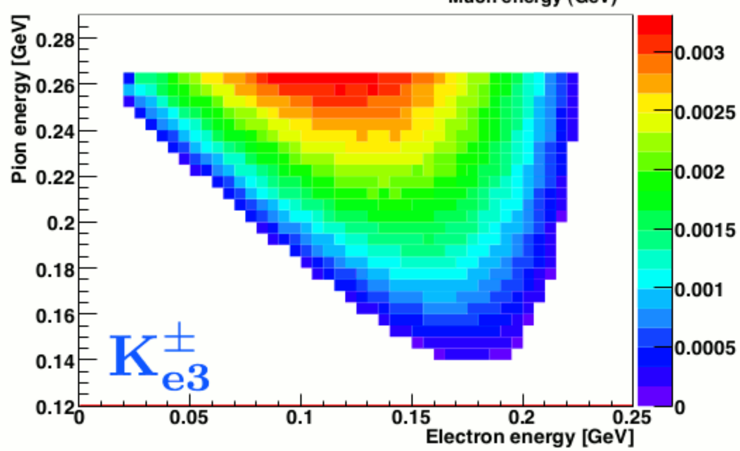




Applied corrections:

- Background subtraction.
- Acceptance.
- Radiative corrections.

Corrections applied before the fitting



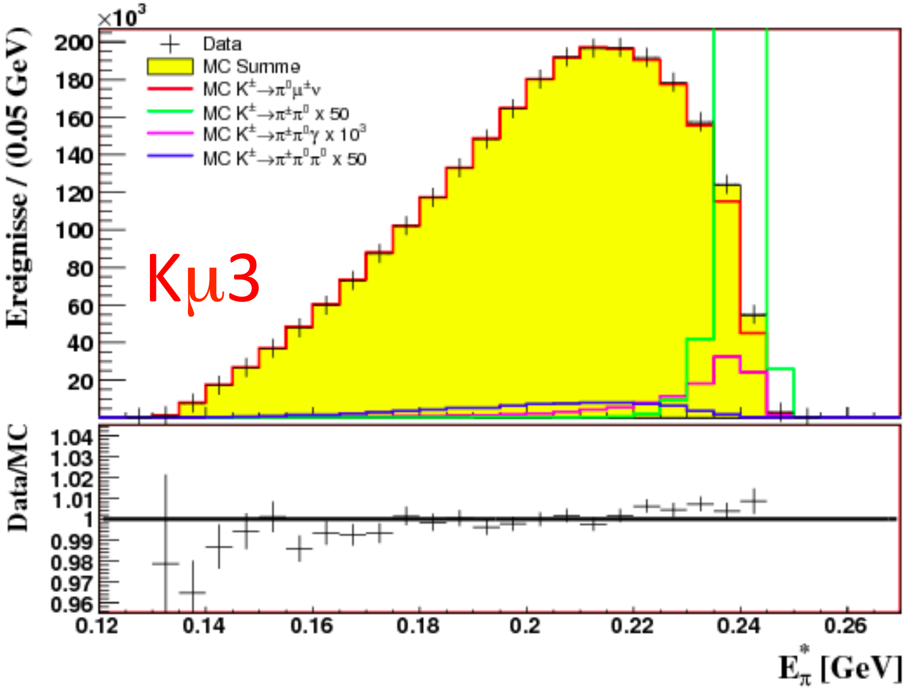
$$\rho(E^*_l, E^*_\pi) = \frac{d^2N(E^*_l, E^*_\pi)}{dE^*_l \, dE^*_\pi} \propto A f^2_+(t) + B f_+(t)(f_0 - f_+)\frac{(m_K^2 - m_\pi^2)}{t} + C\left[(f_0 - f_+)\frac{(m_K^2 - m_\pi^2)}{t}\right]^2$$

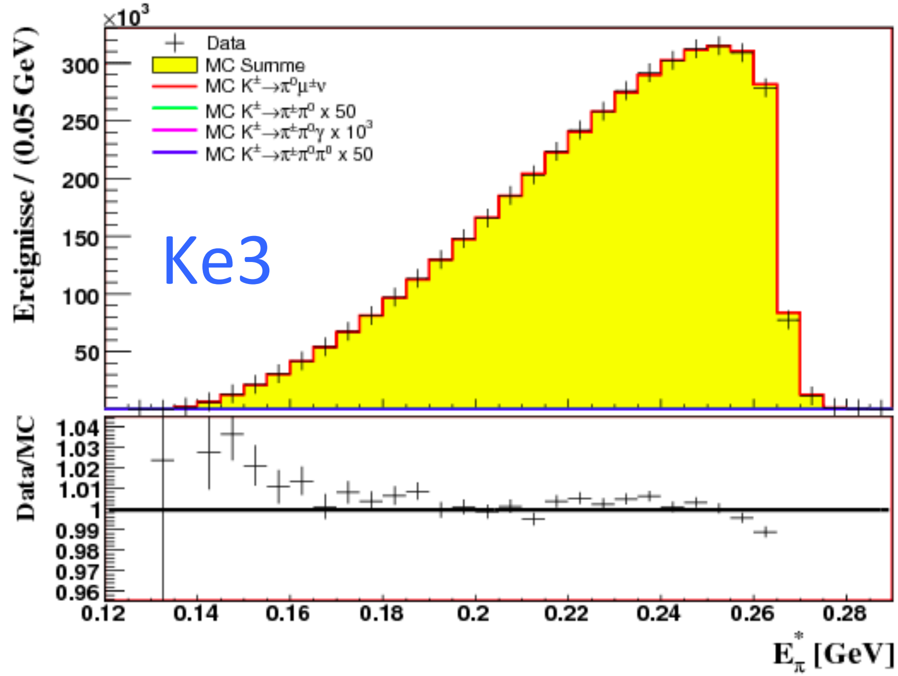
A, B, C = known kinematical terms

Fit in 5x5 MeV^2 cells

π^0 energy in the kaon rest frame

Data vs MC





- Data vs MC disagreement below 1%
- Residual differences taken into account in the systematics

Systematic errors

$K^{\pm}_{\mu 3}$	$\Delta\lambda'_+$	$\Delta\lambda''_+$ $\times 10^{-3}$	$\Delta\lambda_0$	Δm_V MeV/c^2	Δm_S
Kaon Energy	±0.1	±0.0	±0.3	±1	±8
Vertex	±1.0	±0.5	±0.1	±2	±7
Bin size	±0.8	±0.4	±0.7	±3	±10
Energy scale	±0.3	±0.1	±0.1	±0	±1
Acceptance	±0.2	±0.1	±0.3	±2	±5
$K_{2\pi}$ background	±1.7	±0.5	±0.6	±3	±0
2nd Analysis	±0.1	±0.1	±0.2	±2	±5
FF input	±0.3	±0.8	±0.1	±7	±3
Systematic	±2.2	±1.1	±1.0	±9	±16
Statistical	±3.0	±1.1	±1.4	±8	±31

$K^{\pm}_{e3}$	$\Delta\lambda'_+$ $\times 10^{-3}$	$\Delta\lambda''_+$	Δm_V MeV/c^2
Kaon Energy	±0.3	±0.1	±6
Vertex	±0.2	±0.1	±0
Bin size	±0.0	±0.1	±2
Energy scale	±0.1	±0.0	±0
Acceptance	±0.2	±0.0	±3
2nd Ana	±0.9	±0.4	±1
FF input	±0.4	±0.0	±1
Sytematic	±1.1	±0.4	±7
Statistical	±0.7	±0.3	±3

$K^{\pm}\mu 3$

- Main error coming from the K2π background
- Total error dominated by the statistics

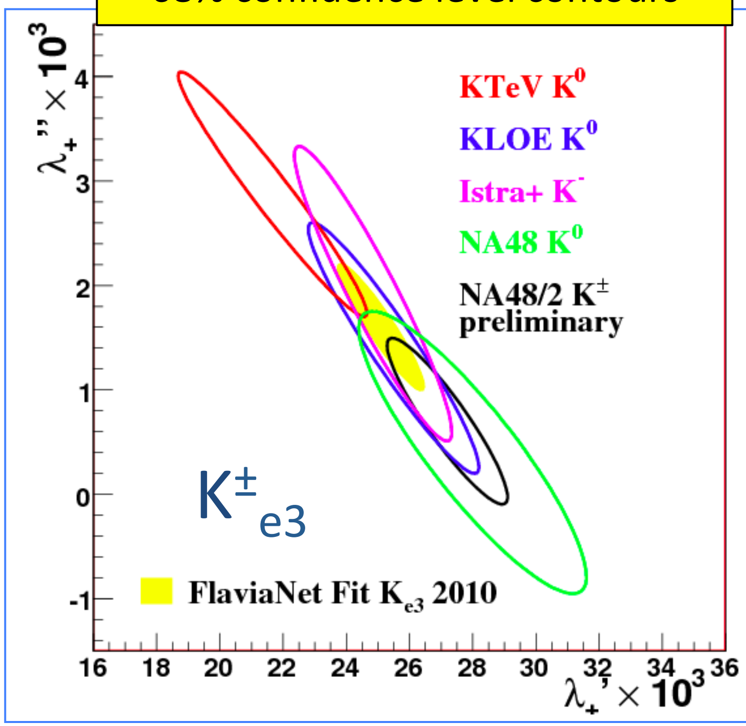
$K^{\pm}e3$

- Total error dominated by the systematics

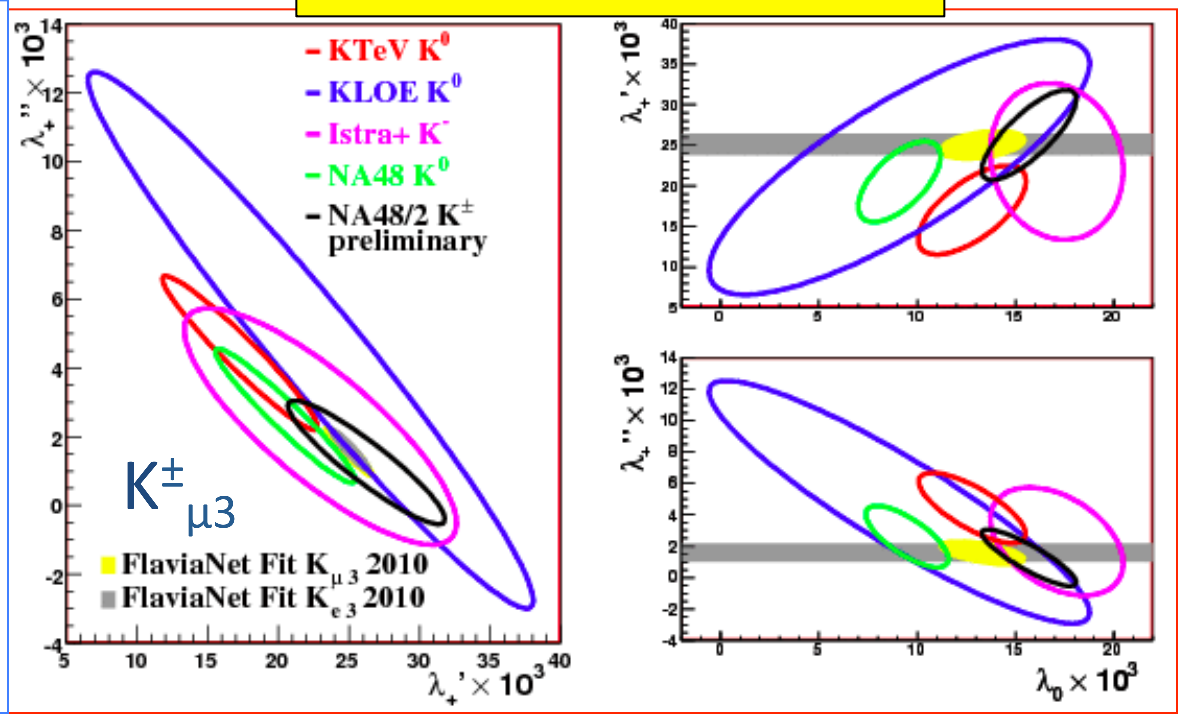
$K^\pm \to \pi^0 l^\pm \nu$ - Preliminary Results

Quadratic	λ'_+ (10^{-3})	λ''_+ (10^{-3})	λ_0 (10^{-3})
$K^\pm_{\mu 3}$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K^\pm_{e3}$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	
Pole (MeV/c^2)	m_V		m_S
$K^\pm_{\mu 3}$	$873 \pm 8_{stat} \pm 9_{syst}$		$1183 \pm 31_{stat} \pm 16_{syst}$
$K^\pm_{e3}$	$879 \pm 3_{stat} \pm 7_{syst}$		

68% confidence level contours



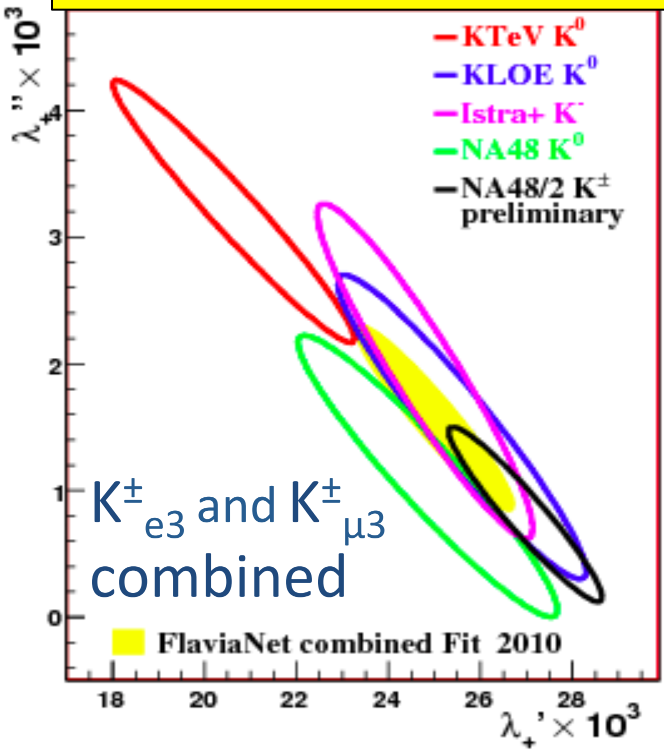
68% confidence level contours



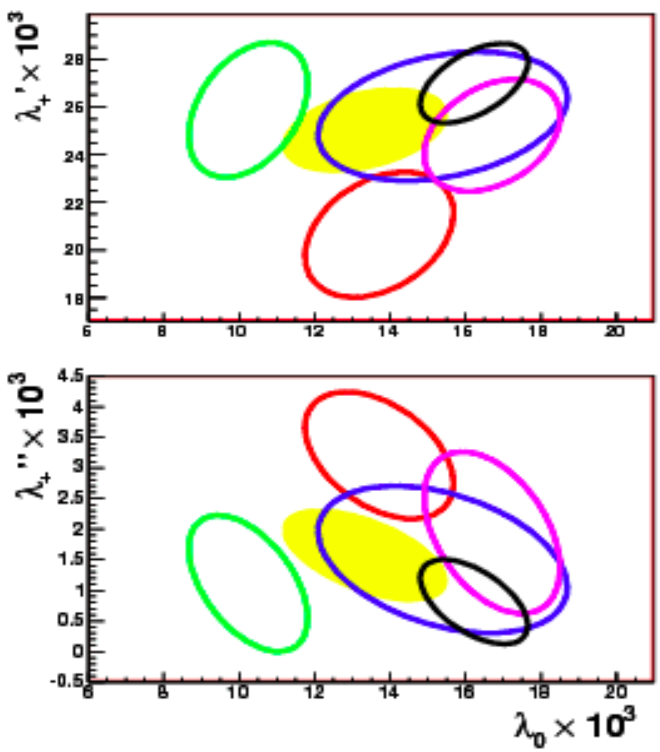
$K^{\pm} \rightarrow \pi^0 l^{\pm} \nu$ - Preliminary Combined Results

Quadratic ($\times 10^{-3}$)	λ'_+ (10^{-3})	λ''_+ (10^{-3})	λ_0 (10^{-3})
$K^{\pm}_{\mu 3} K^{\pm}_{e3}$ combined	26.98 ± 1.11	0.81 ± 0.46	16.23 ± 0.95
Pole (MeV/c^2)	m_V		m_S
$K^{\pm}_{\mu 3} K^{\pm}_{e3}$ combined	877 ± 6		1176 ± 31

68% confidence level contours



$K^{\pm}_{e3}$ and $K^{\pm}_{\mu 3}$ combined

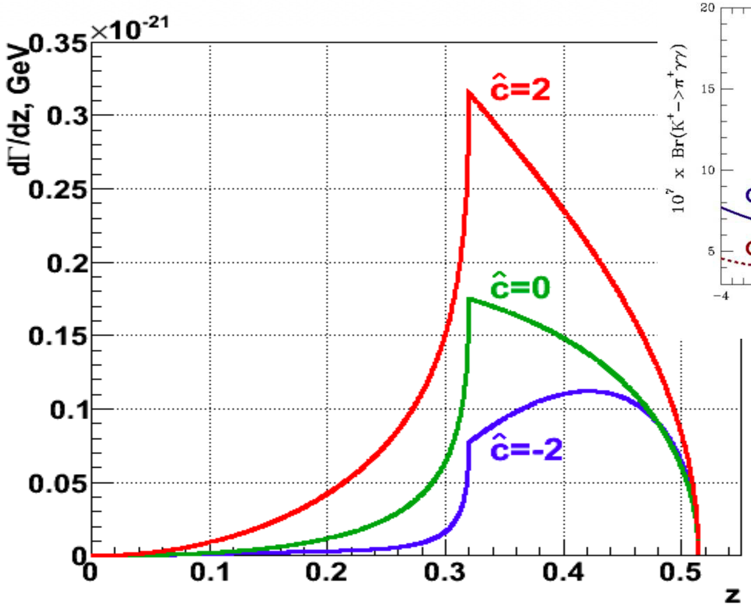


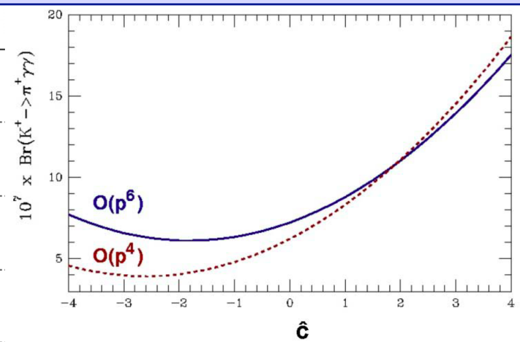
- NA48/2 is the first experiment which measures both K^+ and K^- , for both Ke3 and Kμ3.
- Results for $K^{\pm}$e3 and $K^{\pm}$μ3 from NA48/2 in good agreement
- High precision preliminary results, competitive with the world average. Smallest error in the combined result.
- $O(10^7)$ decays collected in 2007/8 by NA62 ($O(10^6)$ in K^0l3).....

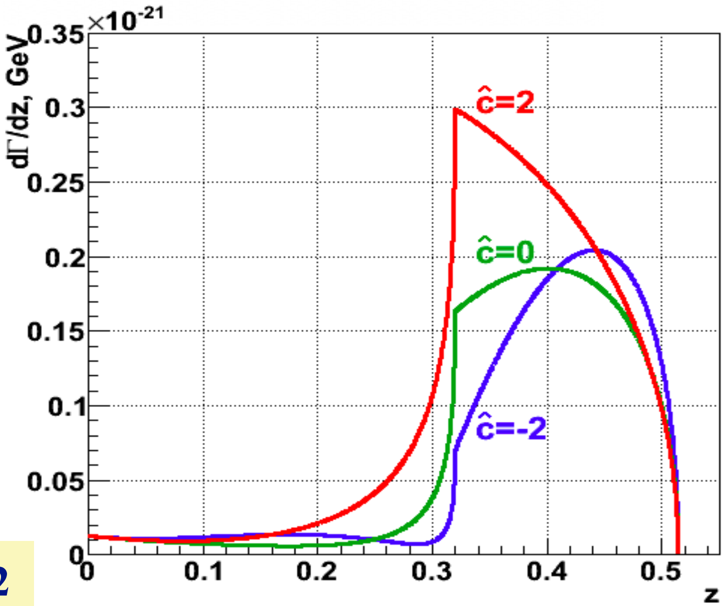
★ $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ Rare Decay

$K^{\pm} \to \pi^{\pm}\gamma\gamma$ – Introduction on ChPT description

Rate & spectrum depend on a single unknown O(1) parameter $\hat{c}$







$z = (m_{\gamma\gamma} / m_K)^2$

Leading contribution at $O(p^4)$:
cusp at $2m_{\pi}$ threshold (z =0.32)
[Ecker, Pich, De Rafael, NPB303 (1988) 665]

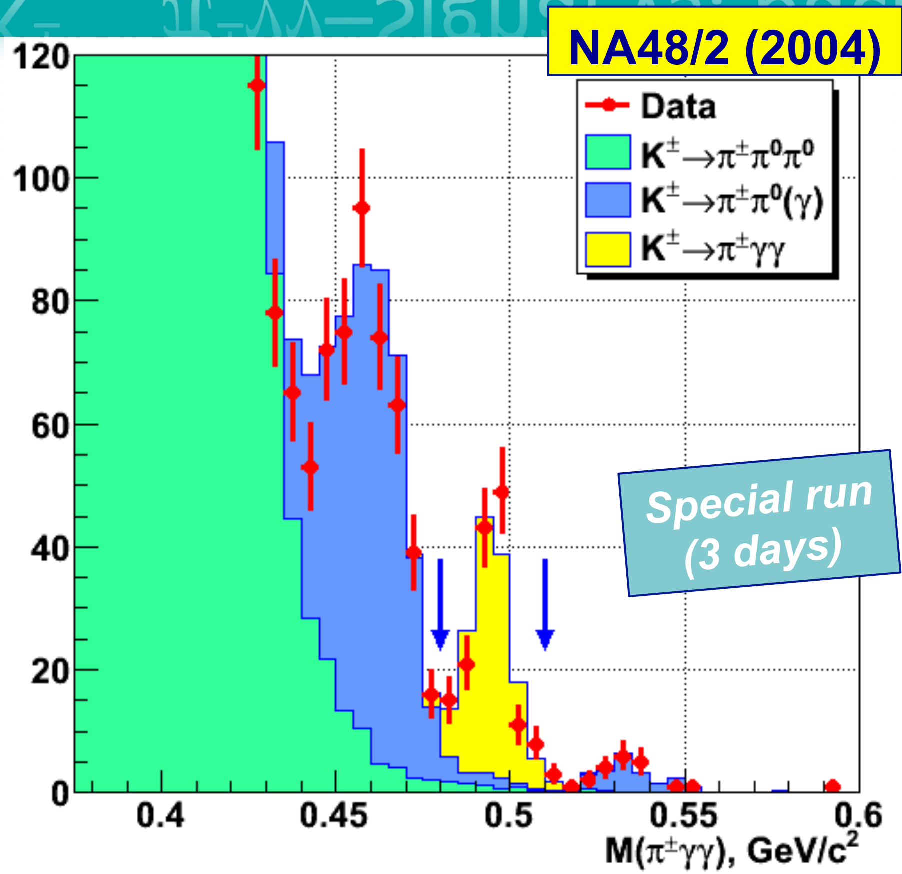
$O(p^6)$ 'Unitarity corrections' may increase BR at low $\hat{c}$ by 30-40% & result in a non-zero rate at $m_{\gamma\gamma} \to 0$
[D'Ambrosio, Portoles, PLB386 (1996) 403]

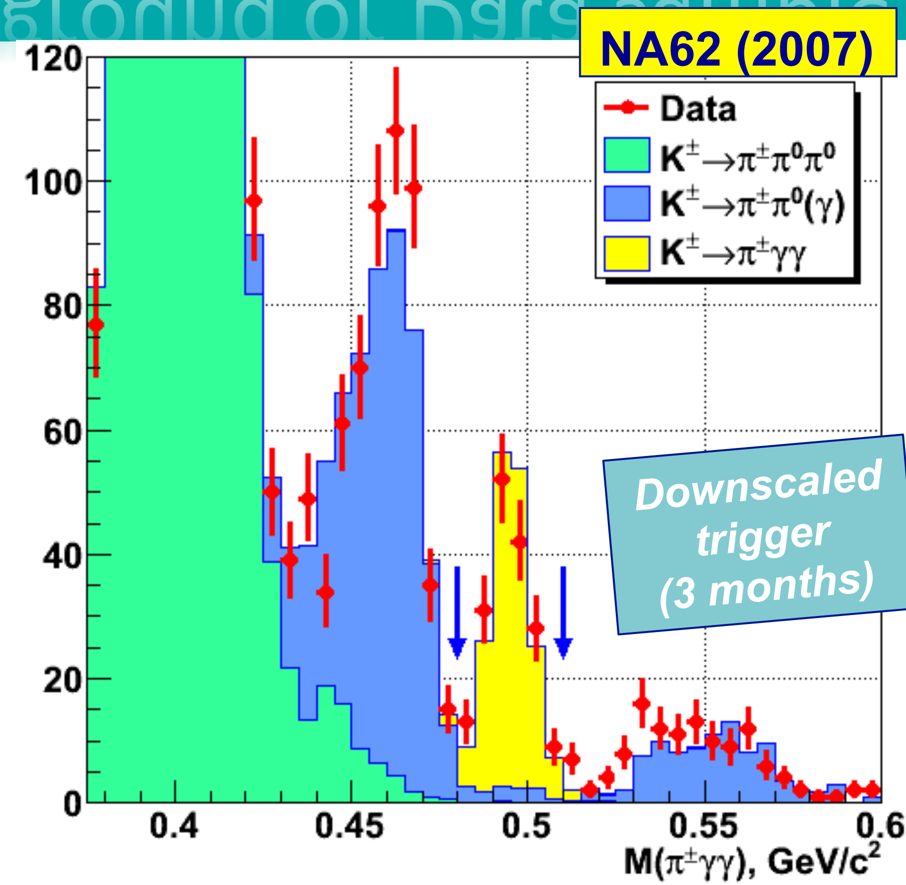
BNL E787: *31 candidates with 5 bkg events; BR = $(1.10 \pm 0.32)\times10^{-6}$* with $\hat{c}$ = 1.80 ± 0.6 *[PRL79 (1997) 4079]*

$K^{\pm} \to \pi^{\pm}\gamma\gamma$ – Event selection

- One and only one reconstructed track in the acceptance of the main detectors.
- z of the decay inside the fiducial decay volume (98 m region). Vertex defined by the Closest Distance of Approach (CDA) between the tracked pion and the nominal $K^{\pm}$ beam directions.
- Reconstructed track momentum: 10(8) <p< 40(50) GeV/c for NA48/2 (NA62).
- $E/p < 0.85$ [E is the energy deposited by the track in the LKr; p is the track momentum measured by the spectrometer.
- Two independent clusters in the LKr with $E_{\gamma} > 3$ GeV
- Both clusters in time with the reconstructed track.
- The reconstructed $\pi^{\pm}\gamma\gamma$ invariant mass should be in the range (0.48-0.51) GeV/c2 (15 MeV/c^2 from $K^{\pm}$ mass)
- $0.2 < z = (m_{\gamma\gamma}/m_K)^2 < 0.54$ ($z = 0.075$ for $\pi^{\pm}\pi^0$ decays).

$K^\pm \to \pi^\pm\gamma\gamma$ – Signal vs. background or Data sample

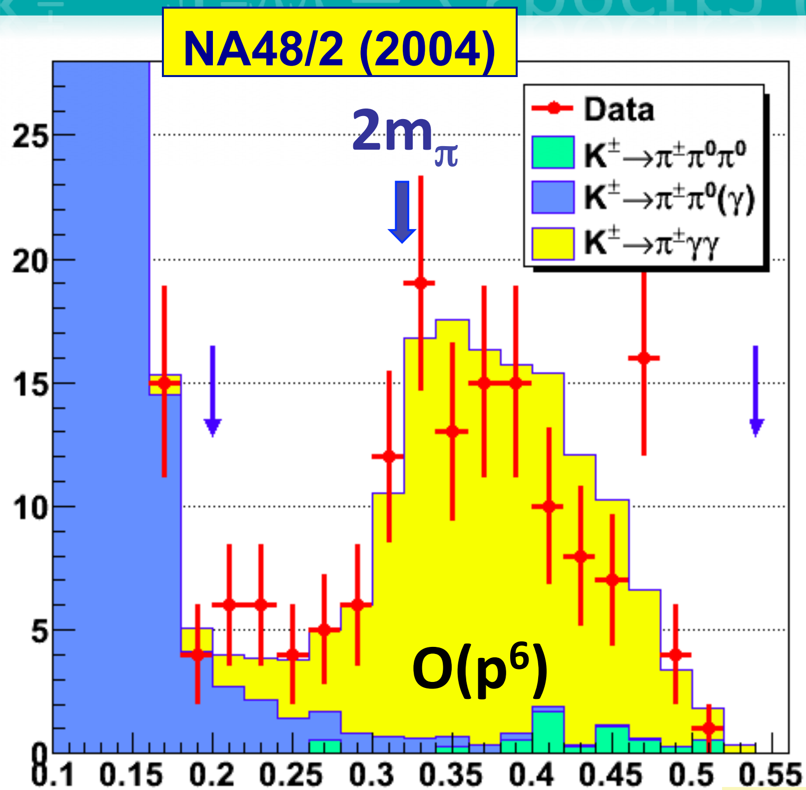


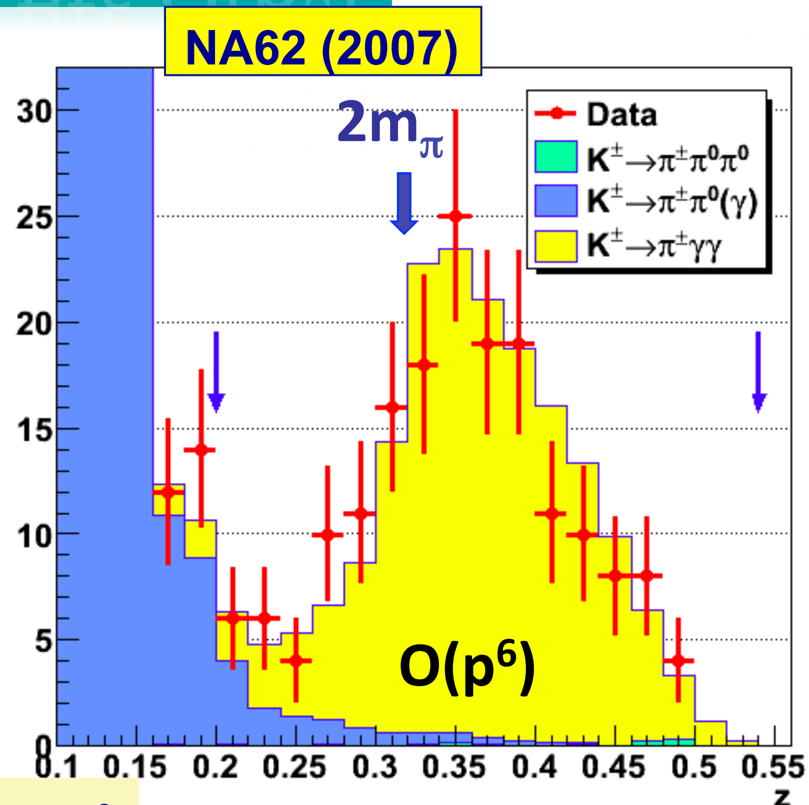


$K^\pm \to \pi^\pm\gamma\gamma$ candidates	147
$K^\pm \to \pi^\pm\pi^0(\gamma)$ background	11.0 ± 0.8
$K^\pm \to \pi^\pm\pi^0\pi^0$ background	5.9 ± 0.7
$K^\pm \to \pi^\pm\gamma\gamma$ signal	**130 ± 12**

$K^\pm \to \pi^\pm\gamma\gamma$ candidates	175
$K^\pm \to \pi^\pm\pi^0(\gamma)$ background	11.1 ± 1.0
$K^\pm \to \pi^\pm\pi^0\pi^0$ background	1.3 ± 0.3
$K^\pm \to \pi^\pm\gamma\gamma$ signal	**163 ± 13**

$K^\pm \to \pi^\pm\gamma\gamma$ – z spectra ChPT fits $O(p^6)$





$z = (m_{\gamma\gamma} / m_K)^2$

- Visible region is above the $K^\pm \to \pi^\pm \gamma \gamma$ peak with $m_{\gamma\gamma} = m_{\pi 0}$:

  $z > 0.2$ or $m_{\gamma\gamma} > 220$ MeV/c^2

- Cusp-like behavior at $z = (2m_\pi/m_K)^2$ is observed

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ – fit results

$\hat{C}$ =	O (p4)	O (p6)
NA48/2 (2004)	$1.36 \pm 0.33_{stat} \pm 0.07_{syst}$ = 1.36 ± 0.34	$1.67 \pm 0.39_{stat} \pm 0.09_{syst}$ = 1.67 ± 0.40
NA62 (2007)	$1.71 \pm 0.29_{stat} \pm 0.06_{syst}$ = 1.71 ± 0.30	$2.21 \pm 0.31_{stat} \pm 0.08_{syst}$ = 2.21 ± 0.32
combined	$1.56 \pm 0.22_{stat} \pm 0.07_{syst}$ = 1.56 ± 0.23	$2.00 \pm 0.24_{stat} \pm 0.09_{syst}$ = 2.00 ± 0.26

[D'Ambrosio, Portolés, PLB386 (1996) 403]

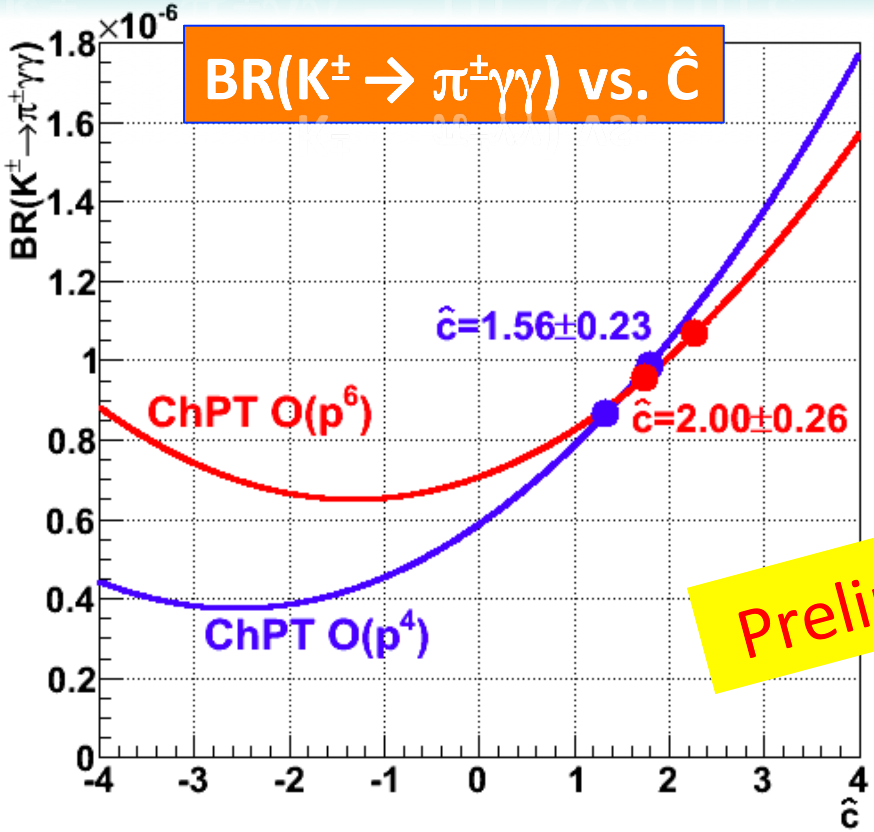
Preliminary

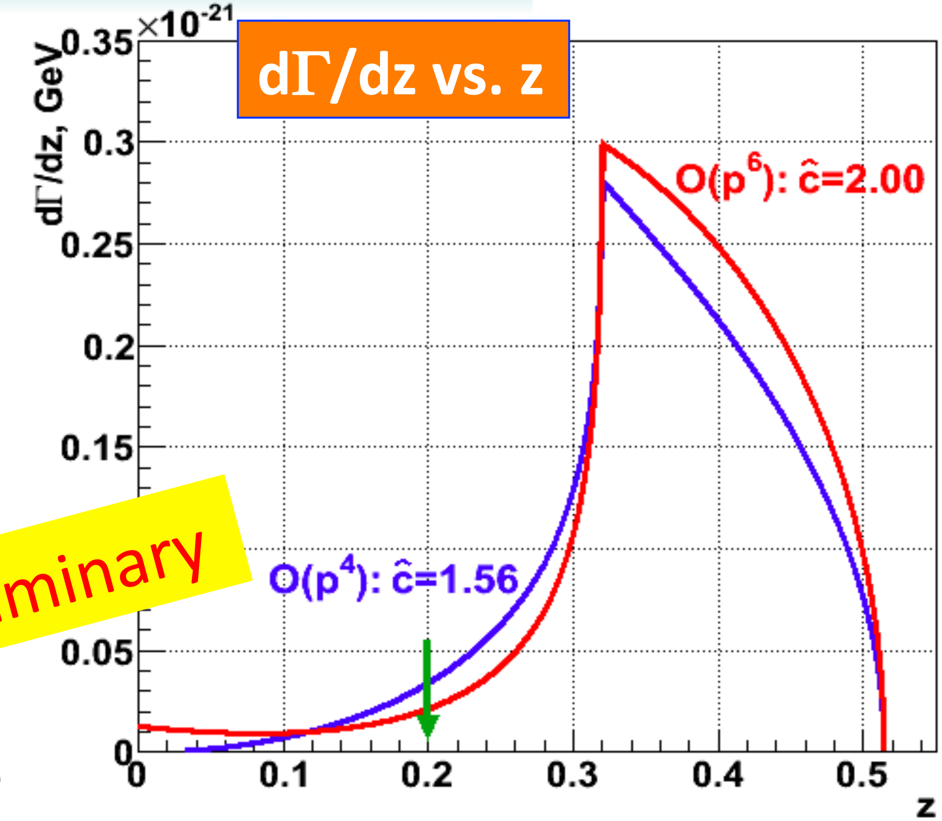
ChPT **O(p6) combined BR fit (model dependent):**

$BR = (1.01 \pm 0.06)\times 10^{-6}$

- **The combined 2004+2007 results contain correlated uncertainties**
- **From PDG (= BNL E787): $BR = (1.10 \pm 0.32)\times 10^{-6}$** *[PRL79 (1997) 4079]*

$K^\pm \to \pi^\pm\gamma\gamma$ – fit results





- Total number of candidates (NA48/2 and NA62): 322
- Background contamination: (9±1)% due to $K^\pm \to \pi^\pm\pi^0(\gamma)$ and $K^\pm \to \pi^\pm\pi^0\pi^0$ with merged photon clusters in the LKr calorimeter
- Very low systematic uncertainties
- ChPT O(p4) vs O(p6) models cannot be discriminated so far.

Summary & Future

NA48/2: 4 million $K^{\pm}e3$ and 2.5 million $K^{\pm}\mu 3$ events with very small background analysed

- Very precise preliminary results on $K^{\pm}e3$ and $K^{\pm}\mu 3$ form factors, competitive with the current world averages
- First measurement for both K^+ and K^- decays

NA62: (NA48 successor) 2007/08 data for measurement of $\Gamma(K \rightarrow e\nu)/\Gamma(K \rightarrow \mu\nu)$

- Huge $K^{\pm}e3$ and $K^{\pm}\mu 3$ statistics of $O(10^7)$ events on tape.

Also special run with neutral beam

- $O(10^6)$ events of each $K^0_L e3$ and $K^0_L \mu 3$ on tape

NA48/2(2004)&NA62(2007): New measurement of the $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay with minimum bias trigger data has been presented

- New precise experimental data on ChPT parameter $\hat{c}$
- ChPT $O(p4)$ vs $O(p6)$ models cannot be discriminated

NA62: Foreseen to start the data taking for the main goal of NA62 in 2014 to measure the Branching Ratio of the very rare decay $K^+ \rightarrow \pi^+\nu\nu$

- 5×10^{12} K^+ decays/year for a record SES of ~10–12
- $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ (and many other decays…) will be killed by the main trigger, but extra-triggers can be added and special runs could be scheduled
- Good opportunity for new studies, suggestions are welcome!