Latest results from NA48/2

Cristina Biino * - INFN Torino

WIN2019:

The 27th International Workshop on Weak Interactions and Neutrinos

Bari, 3-8 June, 2019

*On behalf of the NA48/2 Collaboration

Outline

Low energy QCD and Kaon physics at CERN :

- ★ The NA48/2 experiment

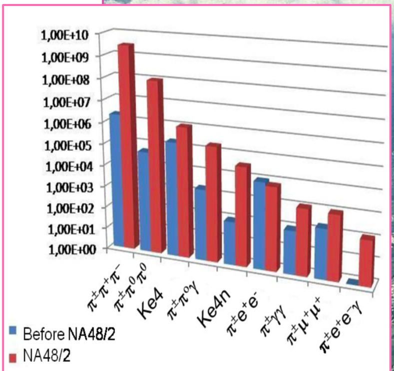
- ★ Precise measurement of $K^{\pm} \rightarrow \pi^0 \ell^{\pm} \nu$ ($K_{\ell 3}$) Form Factors

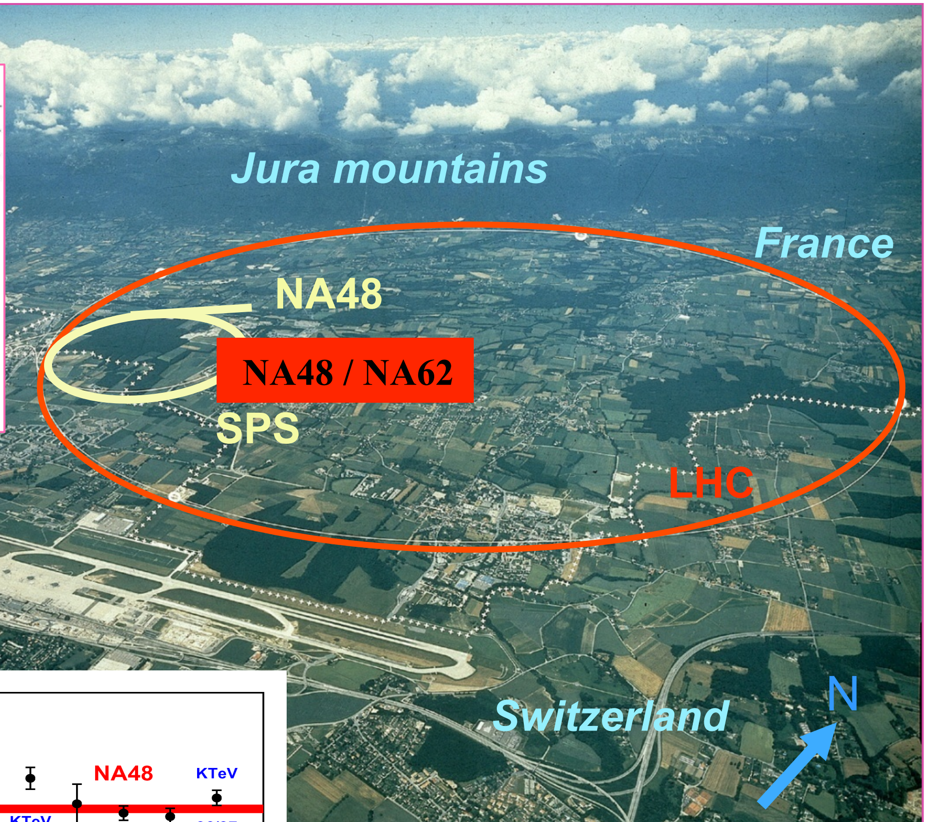
- ★ First observation and study of the rare decay $K^{\pm} \rightarrow \pi^{\pm} \pi^0 e^+ e^-$

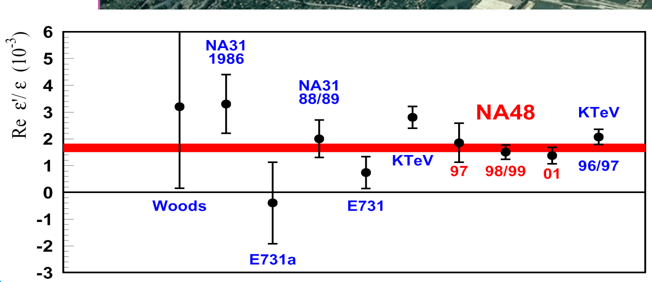
New

NA48 experiment 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:
$\varepsilon'/\varepsilon = (14.7 \pm 2.2)\ 10^{-4}$

~100 physicists from 15 institutes in 8 countries

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

NA48 direct CPV ε'/ε
- 1997: $K_L + K_s$
- 1998: $K_L + K_s$
- 1999: $K_L + K_s$
- 2000: K_L only
- 2001: $K_L + K_s$

NA48/1
- 2002: K_s/hyperons

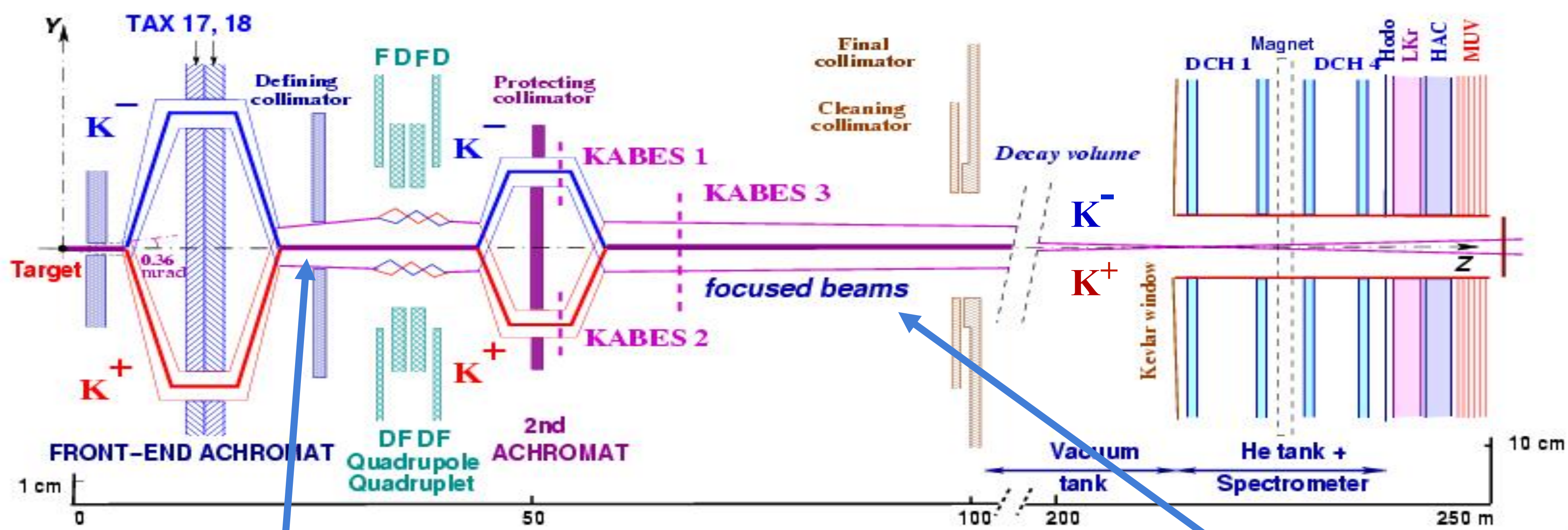
NA48/2
- 2003 $K^+ + K^-$
- 2004 Ag(CPV)

NA62 (R_K)
- 2007 $K^+ + K^-$
- 2008 R_K + tests

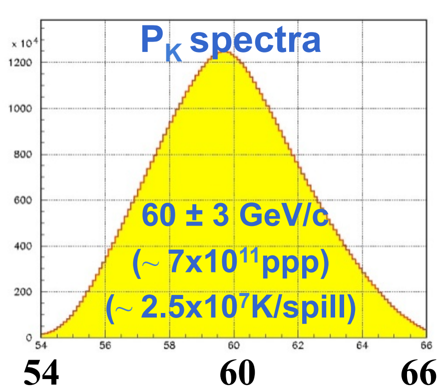
↓ NA62
- 2007 design &
- 2013 construction
- 2012 technical run
- 2013 long shutdown
- 2014 rare kaon decay
- … $K^+ \rightarrow \pi^+ \nu\nu$

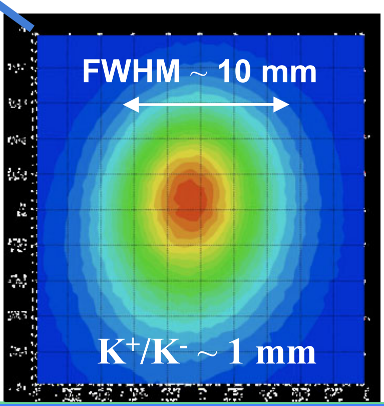
NA48/2 simultaneous $K^{\pm}$ beam

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.

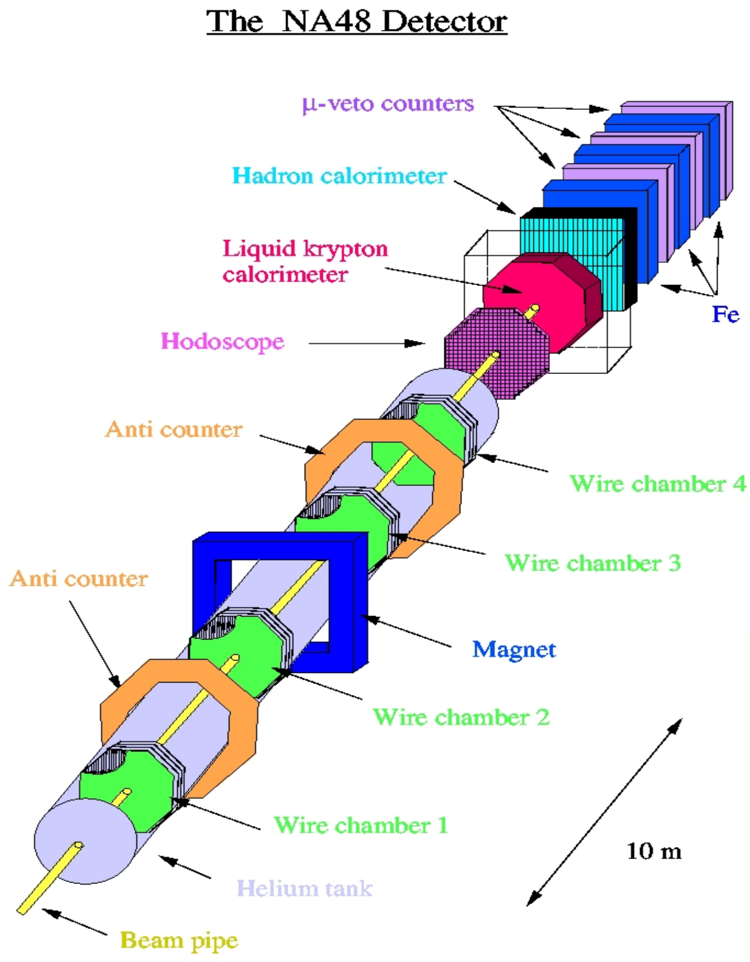


- Simultaneous, unseparated, focused beams
- Kaon decays in the vacuum tank: 22%
- Flux ratio: $K^+/K^- \sim 1.8$
- Similar acceptance for K^+ and K^- decays
- Large charge symmetrization of exp. conditions
- Beams coincide within ~1 mm all along the 114m decay volume
- ~ 2 10^{11} K decays





NA48 detector & performance



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

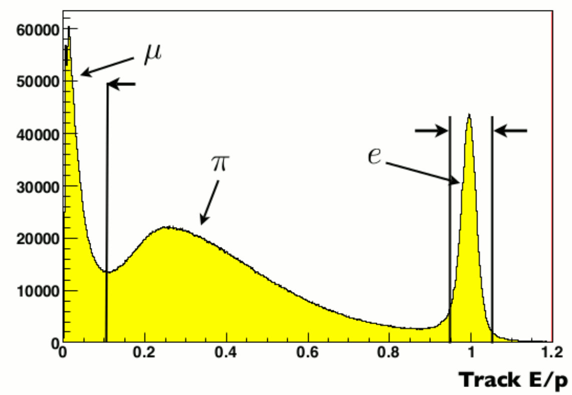
$\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV/)

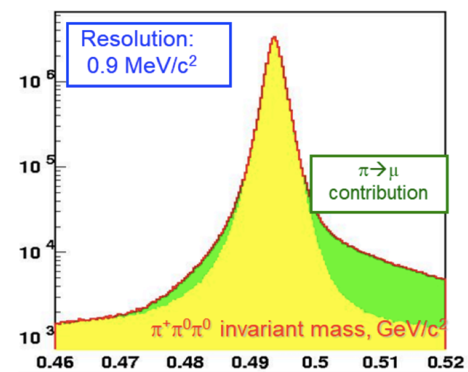
$\sigma_x = \sigma_y = 4.2/E^{\frac{1}{2}} \oplus 0.6$ mm (E in GeV/)

- **Magnetic spectrometer (4 DCHs with 4 views each + dipole magnet) inside the He tank**

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

- **Charged Hodoscope** $\sigma_t = 150$ ps
- **Muon Veto counter, hadron calorimeter, photon vetoes**





Decay region expands over ~ 114 m
Detector expands over ~ 50 m
Similar acceptance for K^+ and K^- beams ensured reversing magnetic fields

But in these analysis use much looser E/p ratio cuts for e /μ discrimination

Mass resolution

★ Measurement of $K^{\pm} \rightarrow \pi^0 \ell^{\pm} \nu_{\ell}$ ($K_{\ell 3}$)

★ Form Factors

New

JHEP 1810 (2018) 150

[arXiv: 1808.09041 [hep-ex] [CERN-PH-EP-2018-231]

Kℓ3 Form Factors parametrization

The differential Kℓ3 decay width can be described in the (E^*_ℓ , E^*_π) Dalitz plot as:

$$\frac{d^2\Gamma(K^\pm_{l3})}{dE^*_l\, dE^*_\pi} = \rho(E^*_l, E^*_\pi) = N\left(\boxed{A_1}\,|f_+(t)|^2 + \boxed{A_2}\,f_+(t)f_-(t) + \boxed{A_3}\,|f_-(t)|^2\right.$$

Kinematic factors

$$\boxed{A_1 = m_K\left(2\,E^*_l\,E^*_\nu - m_K(E^{*,\max}_\pi - E^*_\pi)\right) + m_l^2\ \left((E^{*,\max}_\pi - E^*_\pi)/4 - E^*_\nu\right)}$$

$$\boxed{A_2 = m_l^2\ (E^*_\nu - (E^{*,\max}_\pi - E^*_\pi)/2)},$$

$$\boxed{A_3 = m_l^2\,(E^{*,\max}_\pi - E^*_\pi)/4}.$$

$\ell = e, \mu$

$t = (p_K - p_\pi)^2 = M^2_{\ell\nu}$

$E_\pi^{*,max} = (m^2_K + m^2_{\pi 0} - m^2_\ell) / 2\, m_K$

f_+ and $f\_$ are the vector Form Factors, f_0 the scalar Form Factor (FF)

$f\_(t) = (f_0(t) - f_+(t))\, (m^2_K - m^2_{\pi 0}) / t$

Ke3 decays → only vector form factor **$f_+(t)$**, $t = (p_K - p_\pi)^2$

Kμ3 decays → both vector **$f_+(t)$** and scalar **$f_0(t)$** form factors

$f_+(0)$ cannot be directly measured (lattice QCD calculation) → $f_+(t)$, $f_0(t)$ normalised to $f_+(0)$

Kℓ3 Form Factors parametrization

• Linear and quadratic (Taylor expansion):

$$\tilde{f}_{+,0}(t) = 1 + \lambda_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right)$$

$$\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right) + \frac{1}{2}\cdot\lambda''_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right)^2$$

FF as a function of slope and curvature parameters λ' and λ''

Strong correlations between λ parameters
Absence of their physical meaning

Results can be related to a dispersive fit
[PLB 638(2006) 480, PRD 80(2009) 034034)]

• Pole (resonance):

Assumes the dominance of single vector or scalar resonances K^*
Pole masses m_v and m_s are the only free parameters

$f_+(t)$ described by $K^*(892)$ meson, no dominating resonances for $f_0(t)$

$$\tilde{f}_+(t) = \frac{m_V^2}{m_V^2 - t} \qquad \tilde{f}_0(t) = \frac{m_S^2}{m_S^2 - t}$$

• Dispersive:

Makes use of general chiral symmetry and analiticity constraints, and external inputs from K^- scattering data , via the functions H(t) and G(t).

Kℓ3 Form Factors parametrization

The FF can be parametrized in several ways:

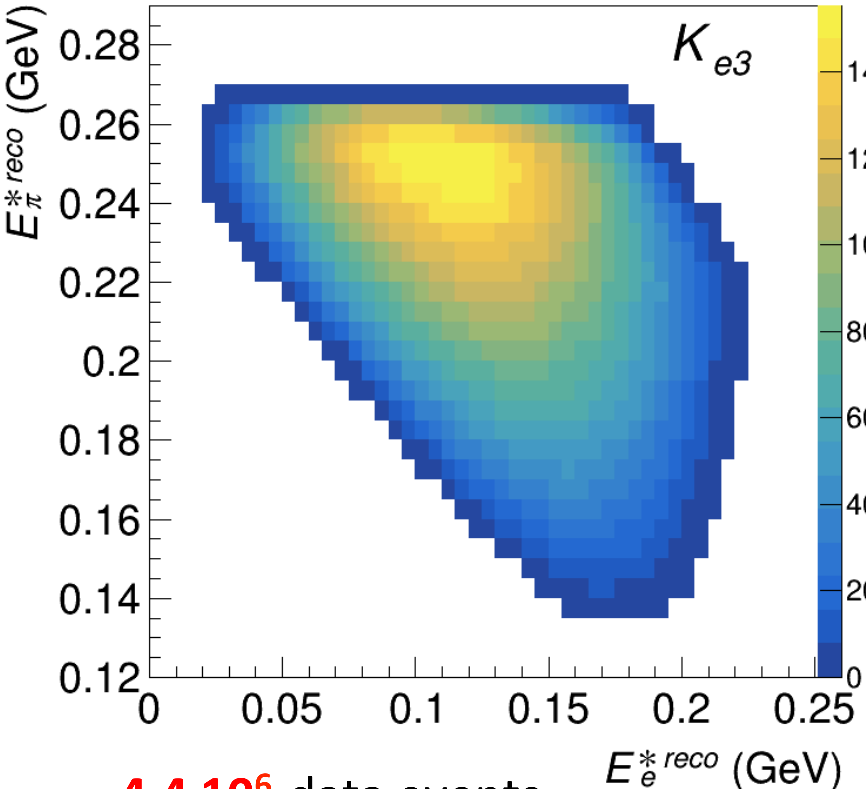
FF Parameterisation	f_+(t,parameters)	f_0(t,parameters)
Taylor expansion	$1+\lambda'_+ \, t/m^2_{\pi+} + \frac{1}{2}\lambda''_+ (t/m^2_{\pi+})^2$	$1 + \lambda'_0 \, t/m^2_{\pi+}$
Pole	$M_V^2 / (M_V^2 - t)$	$M_S^2 / (M_S^2 - t)$
Dispersive* H(t), G(t) functions fixed from theory and other data. Depend on extra external parameters.	$\exp((\Lambda_+ + H(t)) \, t/m^2_{\pi+})$	$\exp((\ln[C] - G(t)) \, t/(m_K^2 - m^2_{\pi 0}))$

* [V. Bernard, M. Oertel, E. Passemar, J. Stern. Phys.Rev. D80 (2009) 034034]

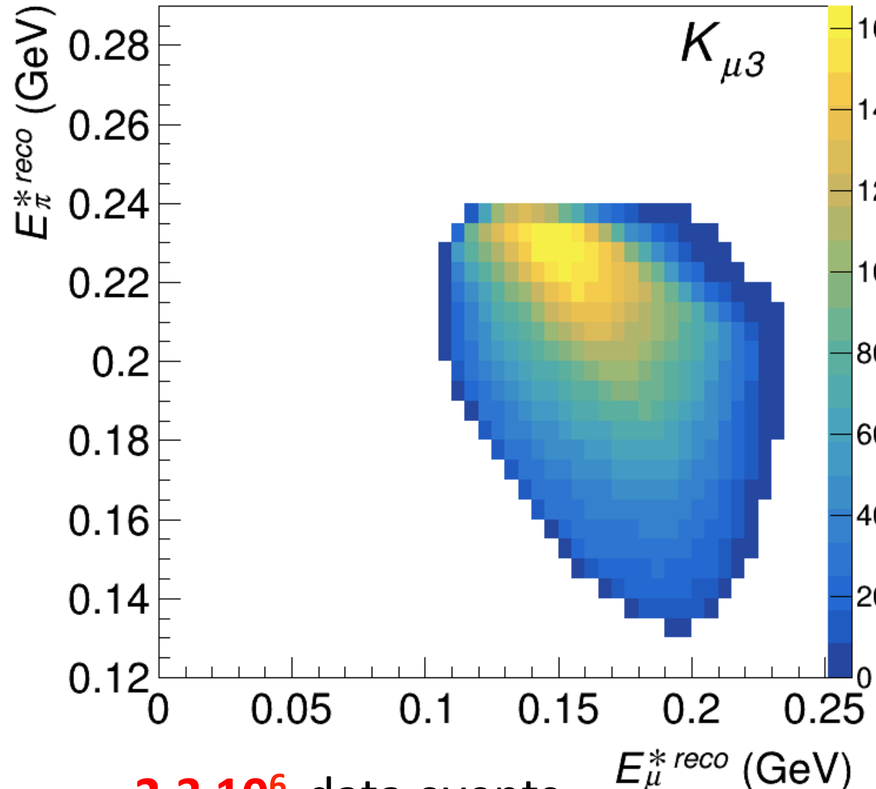
Fit to special data taking samples:

- → **Minimum bias trigger configuration in dedicated run → unbiased sample**
- → **of 4.8 10^8 K decays for high precision measurement of the semileptonic form factors**

Experimental Dalitz plots (5x5 MeV^2 cells)



4.4 10^6 data events
No Bg corr.

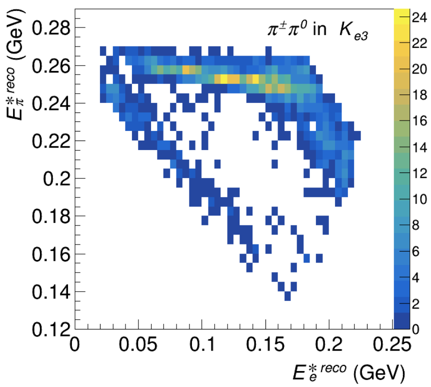


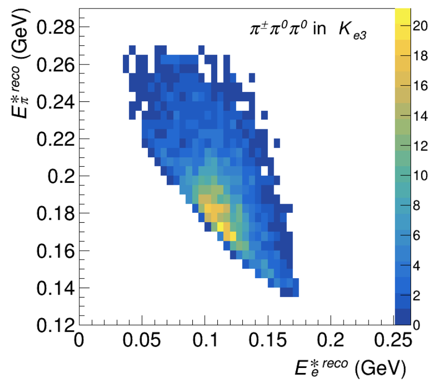
2.3 10^6 data events
No Bg corr.

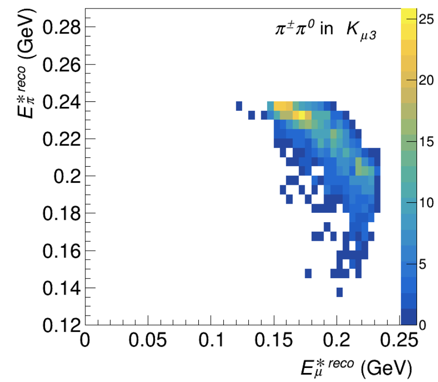
Fit to Dalitz plot density after applying:

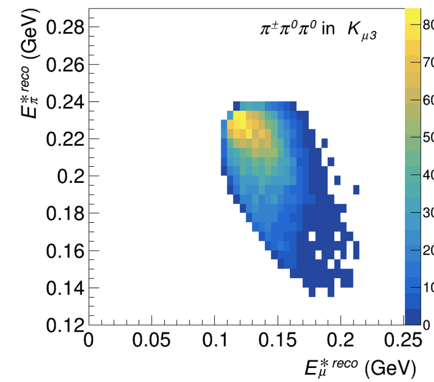
- ✓ Acceptance correction
- ✓ Radiative correction *[C.Gatti, EPJ C45 (2006) 417]*
- ✓ Background subtraction
- ✓ Masking of bins at the border of physical region

Experimental Dalitz plots – background









Process	$\mathcal{B}$ [%]	N_{gen} [10^6]	f_{Ke3} [10^{-3}]	$f_{K\mu3}$ [10^{-3}]
$K^\pm \to \pi^\pm\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	1.72(2)	62.5	0.286(6)	2.192(32)
$K^\pm \to \pi^\pm\pi^0$ ($\pi^0 \to \gamma\gamma$)	20.43(8)	393.2	0.271(6)	0.392(10)
$K^\pm \to \pi^\pm\pi^0_D$ ($\pi^0_D \to e^+e^-\gamma$)	0.243(7)	1.5	0.049(5)	0.0008(8)
$K^\pm \to \pi^0\mu^\pm\nu$ ($\pi^0 \to \gamma\gamma$)[$via\ \mu \to e\bar{\nu}\nu$]	0.033(3)	174.3	0.044(5)	—
$K^\pm \to e^\pm\nu\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	0.0022(4)	5.0	0.019(3)	$< 4 \times 10^{-6}$
$K^\pm \to \pi^\pm\pi^0\gamma$ ($T^*_{\pi+} = 55 - 90MeV, \pi^0 \to \gamma\gamma$)	0.027(2)	35.3	0.0044(3)	0.071(4)
$K^\pm \to \pi^\pm\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to e^+e^-\gamma$)	0.0204(7)	9.9	0.0028(2)	0.0130(5)
$K^\pm \to \mu^\pm\nu\pi^0\pi^0$ ($\pi^0 \to \gamma\gamma, \pi^0 \to \gamma\gamma$)	0.0004(2)	5.0	$0.19(11) \times 10^{-5}$	0.004(2)

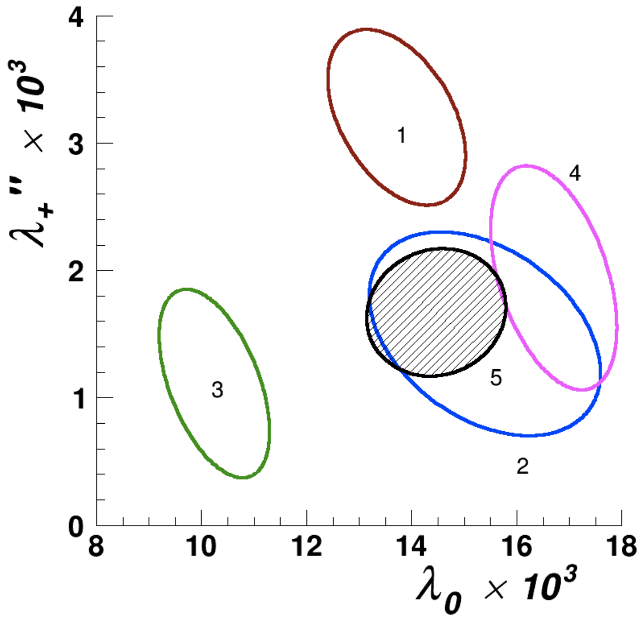
< 0.1% and <0.3% background contamination respectively

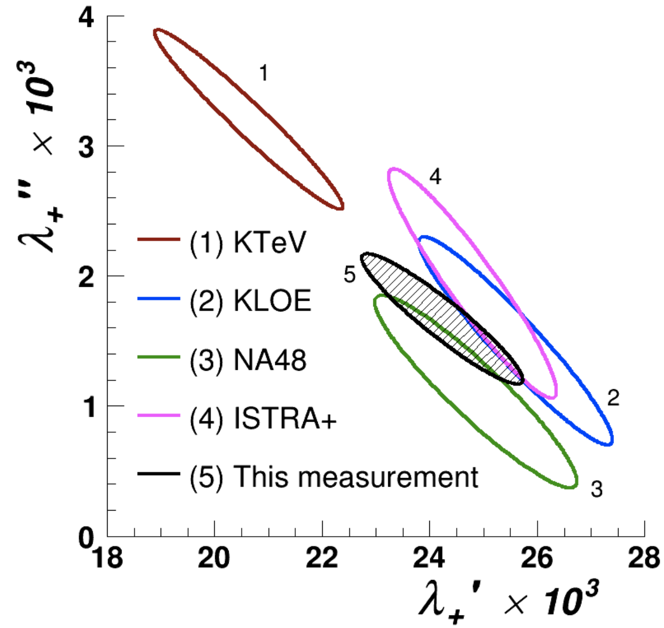
Results of the Kℓ3 (K_{e3} + $K_{\mu3}$) analysis

The units of λ_+', λ_+'', λ_0', Λ_+, and ln C values and errors are in 10^{-3} units. The units of m_V and m_S are in MeV/c^2.

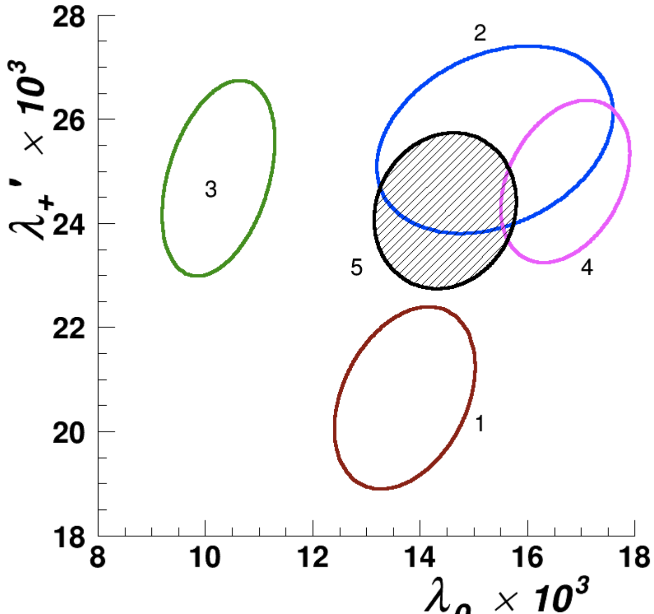
FF parametrization	Taylor expansion			Pole		Dispersive	
	λ_+'	λ_+''	λ_0	m_V	m_S	Λ_+	$\ln C$
Central values	24.24	1.67	14.47	884.4	1208.3	24.99	183.65
Statistical error	0.75	0.29	0.63	3.1	21.2	0.20	5.92
Diverging beam component	0.97	0.35	0.55	1.1	32.2	0.08	9.43
Kaon momentum spectrum	0.00	0.00	0.02	0.1	0.7	0.00	0.19
Kaon mean momentum	0.04	0.01	0.04	0.2	1.7	0.01	0.47
LKr energy scale	0.66	0.12	0.61	4.9	17.4	0.32	5.16
LKr non-linearity	0.20	0.01	0.55	3.1	19.6	0.20	5.77
Residual background	0.08	0.03	0.04	0.1	0.7	0.01	0.16
Electron identification	0.01	0.01	0.01	0.2	0.2	0.01	0.05
Event pileup	0.23	0.08	0.08	0.4	0.2	0.03	0.07
Acceptance	0.23	0.07	0.03	0.7	4.3	0.05	1.11
Neutrino momentum resolution	0.16	0.04	0.04	0.9	3.3	0.06	0.88
Trigger efficiency	0.29	0.13	0.20	1.1	9.9	0.07	2.82
Dalitz plot binning	0.05	0.04	0.06	0.9	1.1	0.06	0.29
Dalitz plot resolution	0.02	0.01	0.03	0.0	1.3	0.00	0.39
Radiative corrections	0.17	0.01	0.57	2.5	20.1	0.16	5.92
External inputs						0.44	2.94
Systematic error	1.30	0.41	1.17	6.7	47.5	0.62	14.25
Total error	1.50	0.50	1.32	7.4	52.1	0.65	15.43
Correlation coefficient	-0.934 (λ_+'/λ_+'') 0.118 (λ_+'/λ_0) 0.091 (λ_+''/λ_0)			0.374		0.354	
χ^2/NDF	979.6/1070			979.3/1071		979.7/1071	

Comparison of combined $K_{\ell 3}$ results





1σ ellipses (39.4% CL) rather than 68% for better visibility



- ✓ The combined result has improved precision and is fully compatible with previous measurements.
- ✓ NA48/2 is the first experiment measur-ing Ke3 and Kμ3 FF for both K^+ and K^-
- ✓ This will allow to decrease the contri-bution of Kℓ3 FF on the |Vus| error.

★ First observation of the $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ rare decay

New

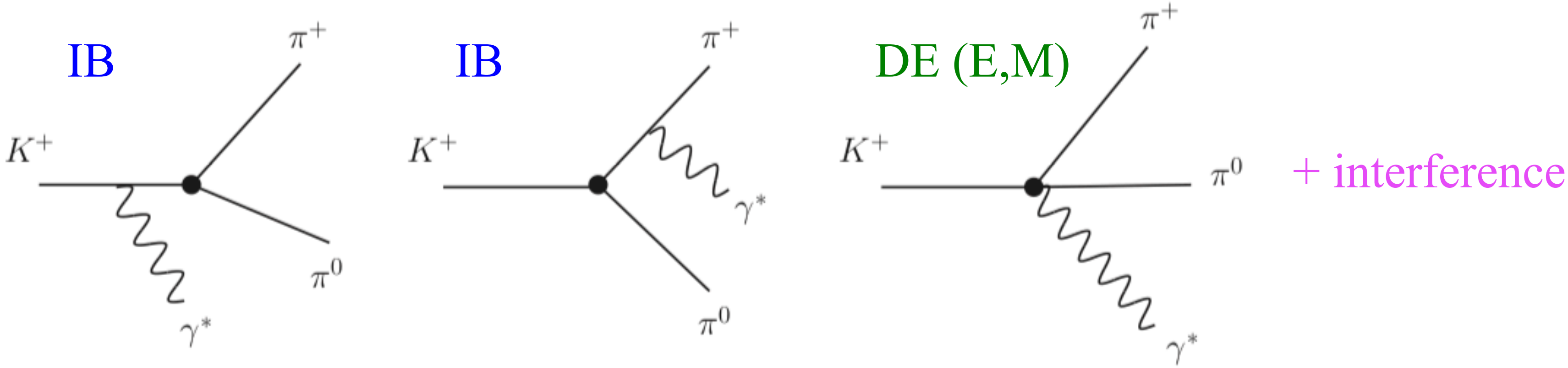
Phys.Lett. B788 (2019) 552-561

[arXiv: 1809.02873 [hep-ex]]

[CERN-PH-EP-2018-246]

$K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ decays - motivation

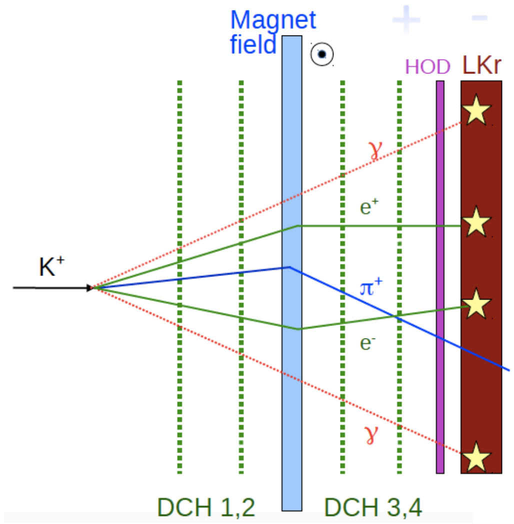
- Never observed so far
- Proceeds through virtual photon exchange: $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma^{*} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$
- The differential decay rate is described in terms of three compo-nents: Inner Bremsstrahlung **(IB)**, Direct Emission **(DE (M,E))** and Interference **(INT)**
- Predicted BR by Chiral Perturbation Theory *[1,2,3]*.



$$\frac{d^3\Gamma}{dE_\gamma^* dT_c dq^2} = \frac{d^3\Gamma_{IB}}{dE_\gamma^* dT_c dq^2} + \frac{d^3\Gamma_{E}}{dE_\gamma^* dT_c dq^2} + \frac{d^3\Gamma_{M}}{dE_\gamma^* dT_c dq^2} + \frac{d^3\Gamma_{INT}}{dE_\gamma^* dT_c dq^2}$$

[1] [H.Pichl, EPJ C20 (2001) 371; [2] L.Cappello, O.Cata, G.D'Ambrosio, D. Gao EPJ C72 (2012) 1872;
[3] L.Cappello, O.Cata, G.D'Ambrosio, EPJ C78 (2018) 265]

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ - event analysis

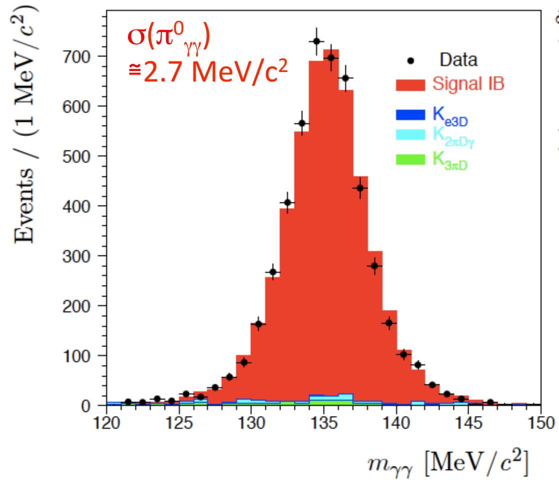


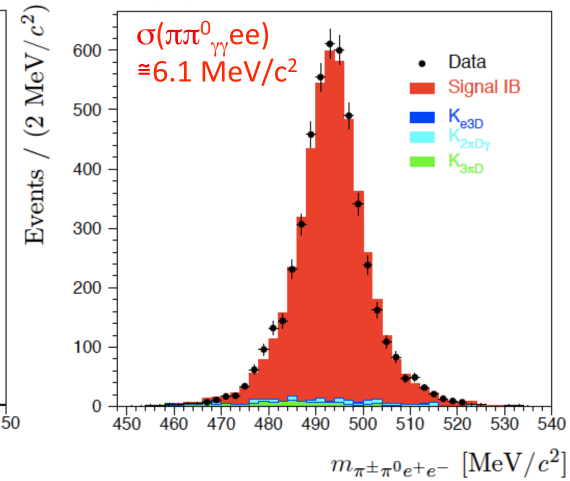
The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0} e^{+}e^{-}$ decay rate is measured relative to the normalization decay $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$ collected concurrently with the same trigger logic.

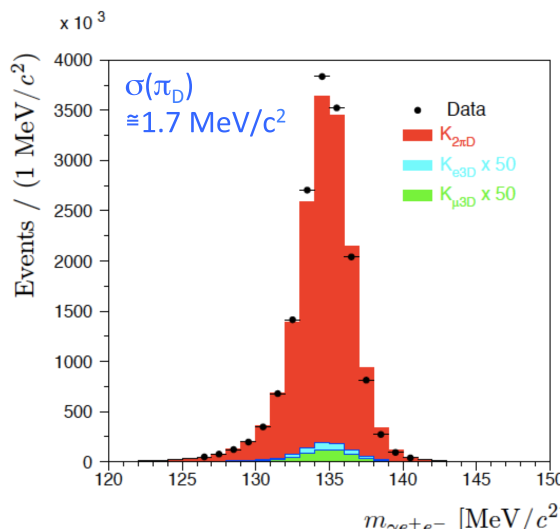
Signal and Normalization have similar:

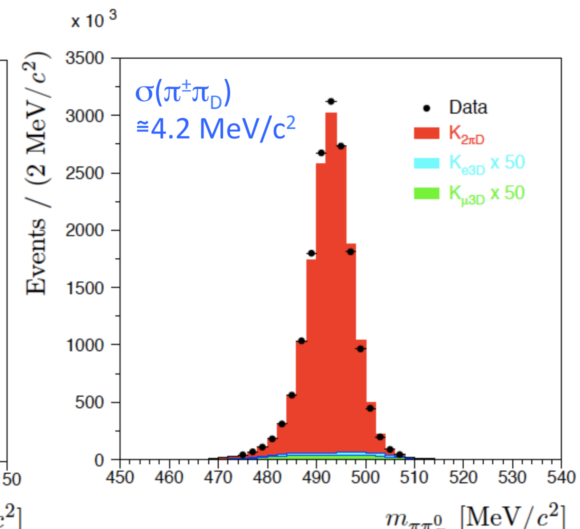
- ✓ Topology, but with one gamma less
- ✓ Kinematics constraints on reconstructed masses but different resolution
- ✓ Cuts
- ✓ Trigger efficiency for signal and normalization (99.7%)

Signal: $\pi^{\pm}(\pi^{0} \rightarrow \gamma\gamma)\, e^{+}e^{-}$









Normalization: $\pi^{\pm}\pi^{0}_{D} \rightarrow \pi^{\pm}\gamma e^{+}e^{-}$

$BR(K^{\pm} \rightarrow \pi^{\pm}\pi^{0}) = (20.67 \pm 0.08)\%$ and $\Gamma(\pi^{0}_{D})/\Gamma(\pi^{0} \rightarrow \gamma\gamma) = (1.188 \pm 0.035)\%$

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ - background evaluation

Background contributions are estimated from MC simulation:

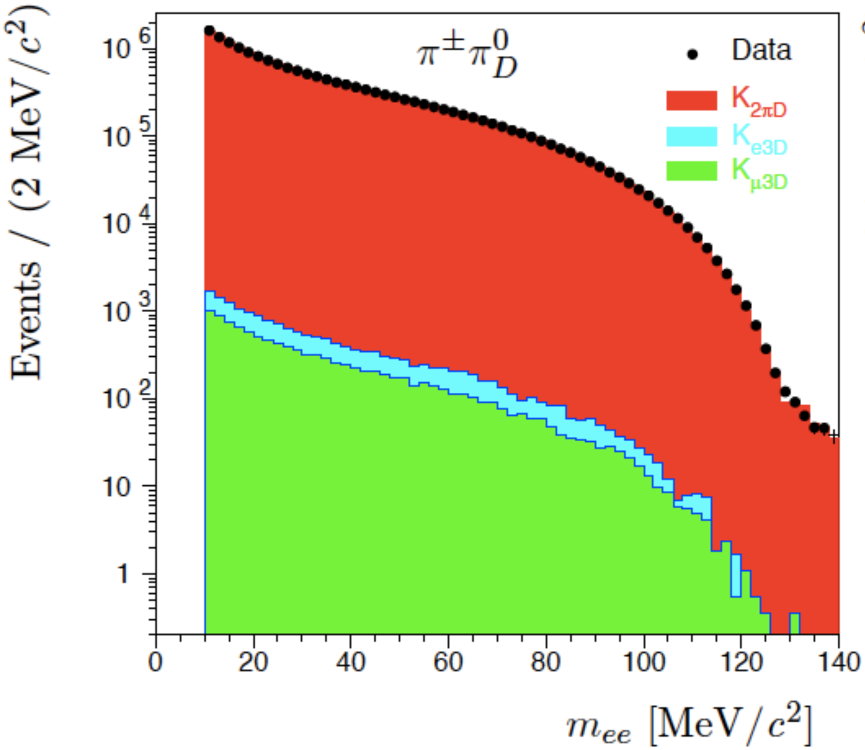
Normalization:
$\pi^{\pm}\pi^{0}_{D} \rightarrow \pi^{\pm}\gamma e^{+}e^{-}$

Signal:
$\pi^{\pm}(\pi^{0} \rightarrow \gamma\gamma)\ e^{+}e^{-}$

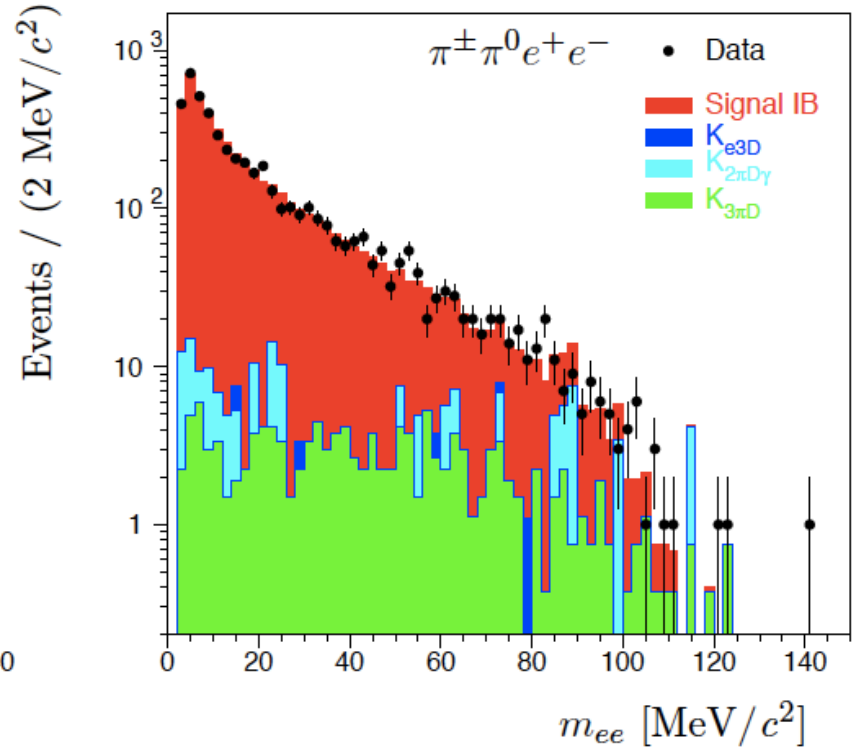
	Decay	N. of background events	R = background/ signal (%)
Normalization	$K_{\mu 3D}$	10,437 ± 119	
Normalization	K_{e3D}	6,851 ± 106	
Total			0.106
Signal	$K_{3\pi D}$	132 ± 8	
Signal	$K_{2\pi D\gamma}$	102 ± 19	
Signal	K_{e3D}	7 ± 3	
	Total		4.9 ± 0.4

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ decays – selection results

Normalization



Signal



Candidates N_N	16.3 x 10^6
Background N_{BN}	17288 ± 159
Acceptance A_N	3.981%
L1 eff. ε_{L1S}	(99.767±0.003)%
L2 eff. ε_{L2S}	(98.495±0.006)%

Special data taking: $(1.717\pm0.007_{stat}\pm0.052_{ext})10^{11}$ kaon decays (both K^+ and K^-) used for this analysis

Candidates N_S	4919
Background N_{BS}	241 ± 21
Acceptance A_S	0.662%
L1 eff. ε_{L1S}	(99.729±0.009)%
L2 eff. ε_{L2S}	(98.604±0.021)%

Branching Ratio measurement

$$BR = BR(\pi^\pm\pi^0) \times \Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma}) \times (N_S - N_{BS})/(N_N - N_{BN}) \times (A_N \times \varepsilon_N)/(A_S \times \varepsilon_S)$$

$BR(K^\pm \to \pi^\pm\pi^0) = (20.67 \pm 0.08)\%$
$\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma}) = (1.188 \pm 0.035)\%$

Final result:

$BR = (4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext})\ 10^{-6}$

The error is dominated by the external error of $\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma})$.

In perfect agreement with ChPT *Ref. [3]* predictions*:*

- For IB only:

$BR(IB) = 4.183\ 10^{-6}$

- When including all DE and INTERFERENCE terms:

$BR(IB+DE+INT) = 4.229\ 10^{-6}$

Statistical, Systematic and **External uncertainties:**

Source	$\delta BR/BR \times 10^2$
N_s	1.426
N_{bs}	0.416
N_n	0.025
N_{bn}	negl.
Total statistical	**1.486**
A_s (MC statistics)	0.171
A_n (MC statistics)	0.051
$\varepsilon(L1_s \times L2_s)$ (MC statistics)	0.023
$\varepsilon(L1_n \times L2_n)$ (MC statistics)	0.007
Acceptance geometry control	0.083
Acceptance time variation control	0.064
Background control	0.280
Trigger efficiency (systematics)	0.400
Model dependence	0.285
Radiative effects	0.490
Total systematic	**0.777**
$BR(K_{2\pi})$	0.387
$\Gamma(\pi^0_D)/\Gamma(\pi^0_{\gamma\gamma})$	2.946
Total external	**2.971**

Kinematic space study

- The contribution of (DE + INTERFERENCE) is expected to be ~1% of the BR, dominated by IB, so is not possible to measure it within the current statistical precision.
- It was pointed out that the contributions of IB, M, and IB-E terms have different distributions in the Dalitz plot (T^*_π , E^*_γ) for different ranges of q^2 values → we therefore proceed with a detailed study of the kinematic space.
- Data splitted in N1 x N2 x N3 exclusive 3d-boxes, all with equal populations followed by the minimization of a $\chi 2$ estimator to obtain the fractions M/IB and (IB-E)/IB reproducing the data.

T^*_π , E^*_γ and q^2 are the charged pion kinetic energy, the virtual photon energy in the kaon rest frame, and the e^+e^- mass squared.

	DATA	THEORY
M/IB	$0.0114 \pm 0.0043_{stat}$	$1/71 = 0.0141 \pm 0.0014_{ext}$
(IB-E)/IB	$-0.0014 \pm 0.0036_{stat}$	$-1/253 = -0.0039 \pm 0.0028_{ext}$
X^2/ndf	98.2/87	
probability	19 %	
corrrelation	0.06	

Asymmetry investigations

The simplest CP-violating asymmetry is the charge asymmetry between K^+ and K^- partial rates:

$$A_{CP} = \frac{\Gamma(K^+ \to \pi^+\pi^0 e^+ e^-) - \Gamma(K^- \to \pi^-\pi^0 e^+ e^-)}{\Gamma(K^+ \to \pi^+\pi^0 e^+ e^-) + \Gamma(K^- \to \pi^-\pi^0 e^+ e^-)}$$

$BR(K^+) = (4.151 \pm 0.0078_{stat})\ 10^{-6}$

$BR(K^-) = (4.394 \pm 0.0108_{stat})\ 10^{-6}$

➔ $A_{CP} = -0.0284 \pm 0.0155_{stat}$

the error is statistical only, the systematic and external errors cancel in the ratio.

This value is translated to a single-sided limit: **$|A_{CP}| < 4.82\ 10^{-2}$ at 90% CL**

Several **CP-violating asymmetries** and a **long-distance P-violating asymmetry** have been evaluated and found to be consistent with zero, leading to upper limits:

$$|A^{\phi*}_{CP}| < 3.11\ 10^{-2},\ |A^{\phi}_{CP}| < 2.50\ 10^{-2} \text{ at 90\% CL .}$$

The long-distance P-violating asymmetry: **$A^{(L)}_{P} < 2.07\ 10^{-2}$ at 90% CL**

These asymmetries are integrated over particular regions of the angular variable Φ (angle between the dipion and dilepton planes in the kaon rest frame).

They can give access to the interference term IB-M and to the sign of the M term.

Summary of NA48/2 recent results

JHEP 1810 (2018) 150

Precise measurement of $K^{\pm} \rightarrow \pi^0 \ell^{\pm} \nu$ ($K_{\ell 3}$) Form Factors

- $K_{\ell 3}$ form factors have been measured using ~$4.4 \cdot 10^6$ K_{e3} and ~$2.3 \cdot 10^6$ $K_{\mu 3}$ events, from NA48/2 data taking, with negligible background $\mathcal{O}(0.1\%)$.
- For the first time the measurement is done simultaneously in K^+ and K^-.
- The combined result has improved precision and is fully compatible with previous measurement.
- This will allow to decrease the contribution of $K_{\ell 3}$ FF on the |Vus| error.

First observation of the rare decay $K^{\pm} \rightarrow \pi^{\pm} \pi^0 e^+ e^-$

Phys.Lett. B788 (2019) 552

- 4919 events of the process $K^{\pm} \rightarrow \pi^{\pm}\pi^0\gamma^* \rightarrow \pi^{\pm}\pi^0 e^+e^- \rightarrow \pi^{\pm}\gamma\gamma\, e^+e^-$ have been observed for the first time:

$$BR = (4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext})\ 10^{-6}$$

- Background contamination is 4.9 %.
- Uncertainty is dominated by external error (on $BR(\pi^0_D)$).
- The result on the BR is in agreement with the ChPT prediction.
- The relative contribution, $(M)/IB = (1.14 \pm 0.43s_{tat})\ 10^{-2}$, is found consistent with the theoretical expectation of $(1.4 \pm 0.14_{ext})\ 10^{-2}$. The $(IB-E)/IB = (-0.14 \pm 0.36stat)\ 10^{-2}$, is also in agreement with the prediction of $(-0.39 \pm 0.28ext)\ 10^{-2}$ but with limited signifi-cance due to the lack of data statistics in the high m_{ee} region.
- Several CP-violating asymmetries and a long-distance P-violating asymmetry have been evaluated and found to be consistent with zero.

★ Thank you!

★ Extra material →

$K^{\pm}_{\ell 3}$ decays - theory

$K^{\pm} \to \pi^0 \ell^{\pm} \nu_{\ell}$ (ℓ=e,μ): accurate and theoretically cleanest way to access $|V_{us}|$

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\,\pi^3} C_K^2 S_{EW} |V_{us}|^2 |f_+(0)|^2 I^{\ell}_K (1 + \delta^{\ell}_{SU(2)} + \delta^{\ell}_{EM})^2$$

★ **Theoretical input:**

- C_K — Clebsch-Gordan coefficient (1 for K^0 and $1/\sqrt{2}$ for $K^{\pm}$)
- S_{EW} — Universal short distance EW correction (1.0232±0.0003)
- $f_+(0)$ — Form factor at zero momentum transfer (@0.5%) *[EPJC 69 2010, 399]*
- $\delta^{\ell}_{SU(2)}$ — Isospin breaking correction (charged mode only) *[EPJC 69 2010, 399]*
- δ^{ℓ}_{EM} — Long distance EM correction

★ **Experimental input:**

- $\Gamma(K_{\ell 3})$ — Branching ratios and Kaon lifetimes
- I^{ℓ}_K — Phase space integral - depends on form factors

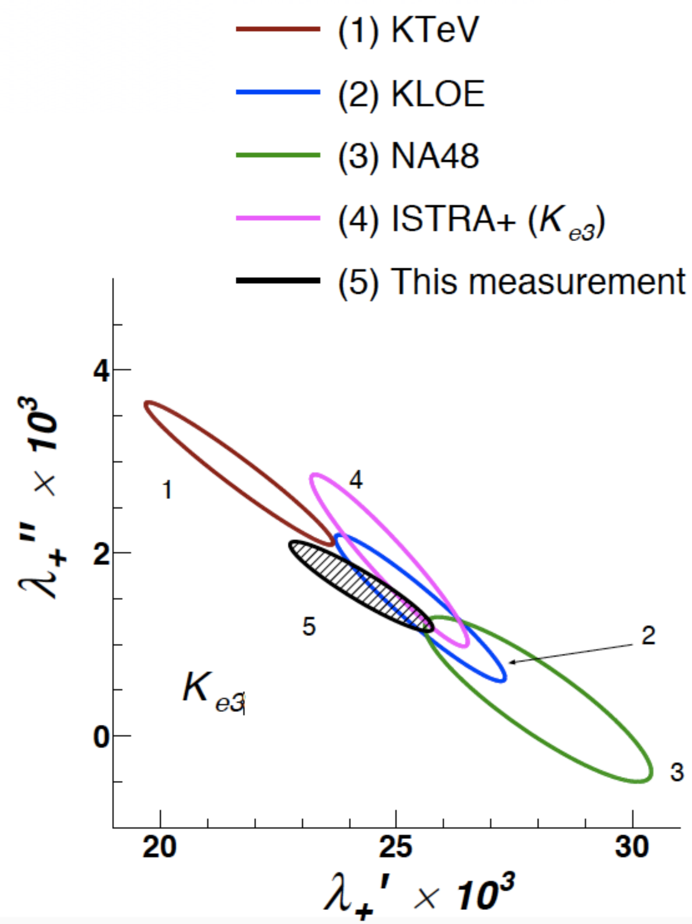
Ke3 decays → only vector form factor **$f_+(t)$**, $t = (p_K - p_{\pi})^2$

Kμ3 decays → both vector **$f_+(t)$** and scalar **$f_0(t)$** form factors

$f_+(0)$ cannot be directly measured (lattice QCD calculation) → $f_+(t)$, $f_0(t)$ normalised to $f_+(0)$

Results of the K_{e3} analysis

	λ'_+	λ''_+	m_V	Λ_+
Central values	24.26	1.64	885.2	24.94
Statistical error	0.78	0.30	3.3	0.21
Diverging beam component	0.89	0.31	1.4	0.10
Kaon momentum spectrum	0.00	0.00	0.1	0.01
Kaon mean momentum	0.03	0.01	0.1	0.01
LKr energy scale	0.69	0.14	5.0	0.33
LKr non-linearity	0.28	0.01	3.4	0.22
Residual background	0.08	0.04	0.4	0.02
Electron identification	0.02	0.01	0.2	0.01
Event pileup	0.24	0.08	0.5	0.03
Acceptance	0.29	0.08	1.2	0.08
Neutrino momentum resolution	0.18	0.04	1.1	0.07
Trigger efficiency	0.33	0.13	1.0	0.07
Dalitz plot binning	0.07	0.01	0.7	0.05
Dalitz plot resolution	0.06	0.04	0.4	0.02
Radiative corrections	0.20	0.01	2.9	0.19
External inputs				0.44
Systematic error	1.30	0.39	7.2	0.64
Total error	1.51	0.49	7.9	0.67
Correlation coefficient	−0.929		—	—
χ^2/NDF	569.1/687		568.9/688	569.0/688

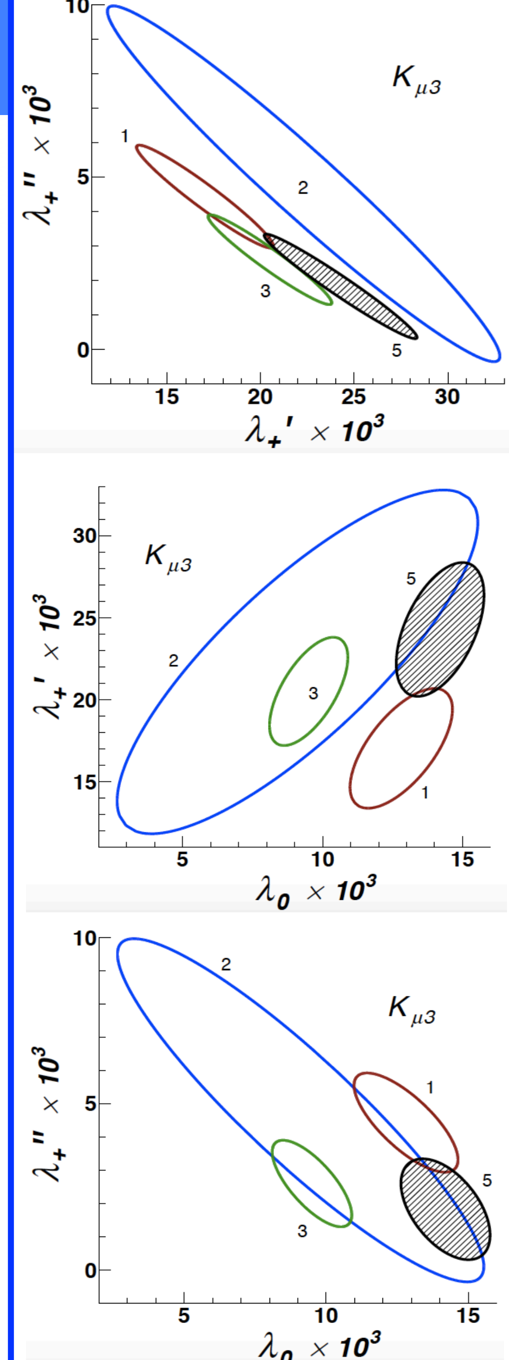


The units of λ_+', λ_+'' and Λ_+ values and errors are in 10^{-3} units.

The units of m_V are in MeV/c^2.

Results of the $K_{\mu 3}$ analysis

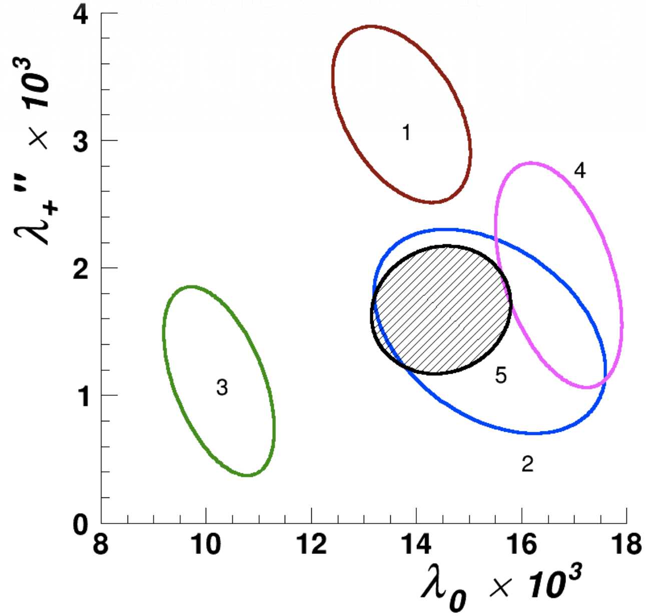
	λ'_+	λ''_+	λ_0	m_V	m_S	Λ_+	$\ln C$
Central values	24.27	1.83	14.20	878.4	1214.8	25.36	182.17
Statistical error	2.88	1.05	1.14	8.8	23.5	0.58	6.31
Diverging beam component	2.03	0.78	0.13	0.9	30.9	0.04	8.98
Kaon momentum spectrum	0.08	0.02	0.00	0.1	0.9	0.01	0.24
Kaon mean momentum	0.06	0.00	0.06	0.8	2.4	0.06	0.63
LKr energy scale	0.31	0.01	0.53	4.5	19.4	0.30	5.55
LKr non-linearity	0.93	0.38	0.25	1.3	21.7	0.08	6.26
Residual background	0.13	0.00	0.02	1.7	1.3	0.11	0.31
Event pileup	0.04	0.01	0.03	0.0	0.7	0.00	0.18
Acceptance	0.70	0.18	0.18	2.9	0.3	0.20	0.14
Neutrino momentum resolution	0.09	0.03	0.08	0.2	2.1	0.01	0.59
Trigger efficiency	0.60	0.08	0.23	5.1	5.7	0.35	1.72
Dalitz plot binning	1.50	0.63	0.63	2.8	3.6	0.18	0.85
Dalitz plot resolution	0.04	0.01	0.02	0.1	0.4	0.01	0.18
Radiative corrections	0.32	0.10	0.54	0.7	23.7	0.04	6.73
External inputs						0.46	2.87
Systematic error	2.89	1.09	1.07	8.3	49.2	0.72	14.45
Total error	4.08	1.52	1.57	12.1	54.5	0.92	15.76
Correlation coefficients	-0.974 (λ'_+/λ''_+) 0.511 (λ'_+/λ_0) -0.513 (λ''_+/λ_0)			0.029		0.104	
χ^2/NDF	409.9/381			409.9/382		410.3/382	

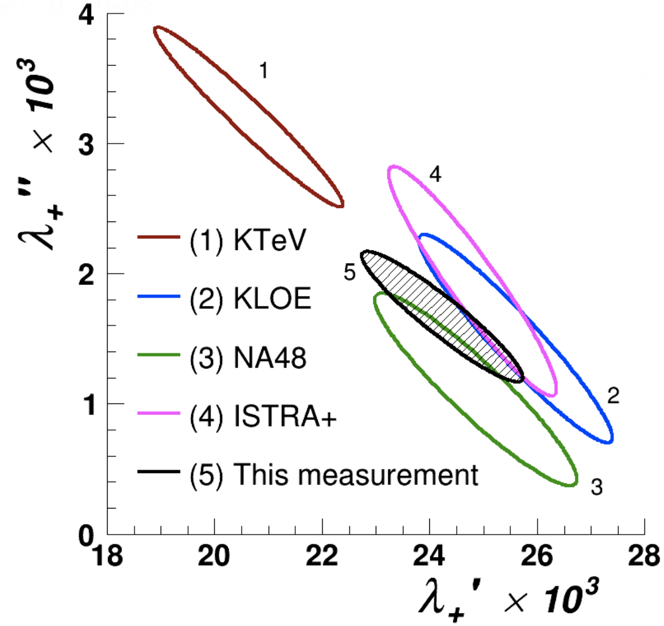


(1) KTeV
(2) KLOE
(3) NA48
(4) ISTRA+ (K_{e3})
(5) This measurement

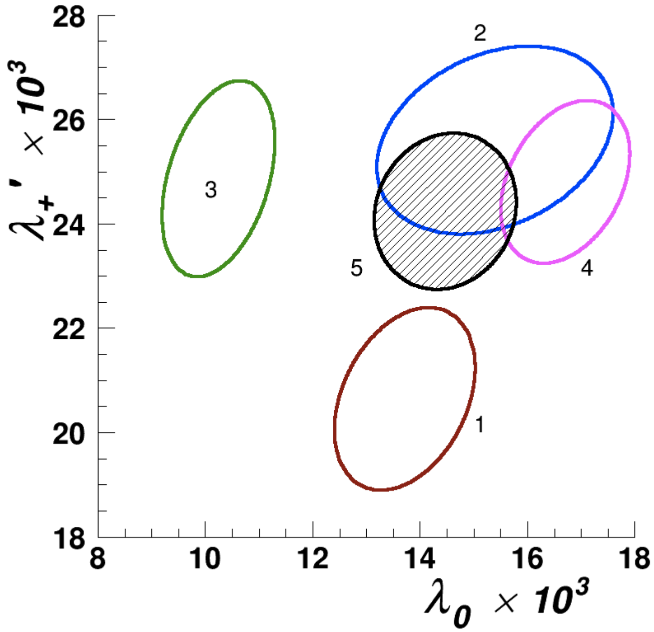
The units of λ_+', λ_+'', λ_0', Λ_+, and ln C values and errors are in 10^{-3} units.
The units of m_V and m_S are in MeV/c^2.

Comparison of $K_{\ell 3}$ results





1σ ellipses (39.4% CL) rather than 68% for better visibility



KTeV: *T.Alexopoulos et al., Phys. Rev. D 70 (2004) 092007.*

KLOE: *F.Ambrosino et al, Phys. Lett. B 636 (2006) 166, and JHEP 0712 (2007) 105.*

NA48: *A.Lai et al., Phys. Lett. B 604 (2004) 1 and Phys. Lett. B 647 (2007) 341.*

ISTRA+: *O.Yushchenko et al., Phys. Lett. B 581 (2004) 31 and Phys. Lett. B 589 (2004) 111* → *as reviewed in M.Antonelli et al. (FlaviaNet Working Group on Kaon Decays), Eur. Phys. J. C 69 (2010) 399.*

$K^{\pm}_{\ell 3}$ - Event-weighting fit procedure

• Experimental Dalitz plot is corrected for the simulated background.
• For each fit iteration, the model Dalitz plot is filled with MC simulated reconstructed center-of-mass pion and lepton energies. Each event is weighted by:

$$w = \rho_0\,(E_\pi^{true}, E_\ell^{true}, FF_{fit}) \,/\, \rho_0(E_\pi^{true}, E_\ell^{true}, FF_{MCgenerator})$$

where ρ_0 is the non-radiative Dalitz density formula (for Ke3 an additional factor is applied to conform the universal correction).

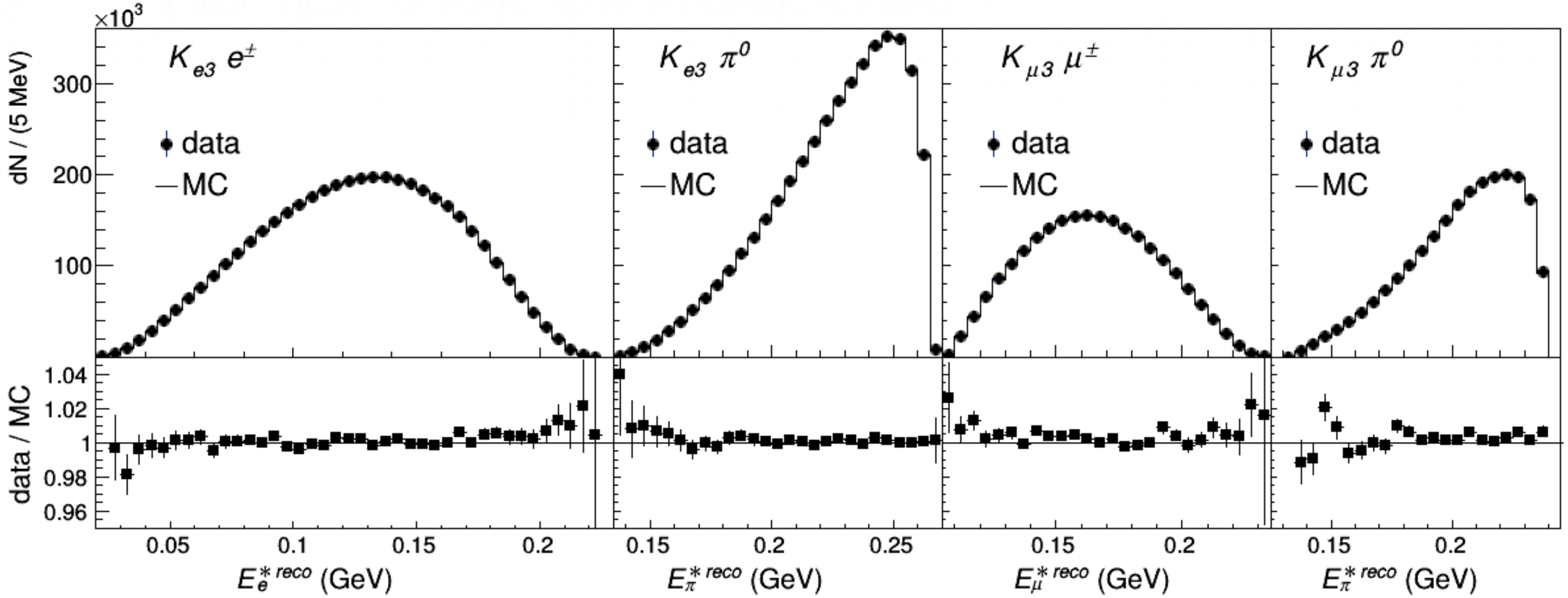
• MINUIT package is used to search for the most probable FF_{fit} parameters minimizing the standard $\chi 2$ value:

$$\boxed{\chi^2 = \Sigma_{i,j}\frac{(D_{i,j} - MC_{i,j})^2}{(\delta D_{i,j})^2 + (\delta MC_{i,j})^2}}$$

where i,j are the Dalitz plot cell indices, $D_{i,j}$ is the background-corrected experimental data content of the cell, $MC_{i,j}$ is the weighted MC bin content, and $\delta D_{i,j}$ $\delta MC_{i,j}$ are the corresponding statistical errors. Background correction contribution also has some dependence on FF due to the signal acceptance sensitivity.

➔ At least 20 data events per cell are required in the fit area.

$K^{\pm}_{\ell 3}$ - Dalitz plot projections



Reconstructed lepton energy and pion energy distributions for data after background subtraction and simulated samples according to the fit results using the Taylor expansion model (other parametrisation plots look very similar).

The fit results and systematic uncertainties are available:

- For **K_{e3}**
- For **$K_{\mu 3}$**
- For the combined Kℓ3 result: joint fits minimizing $\chi 2(K_{e3}) + \chi 2(K_{\mu 3})$ with a common set of fit parameters.

JHEP 1810 (2018) 150
[arXiv: 1808.09041 [hep-ex]]
[CERN-PH-EP-2018-231]

$K^{\pm}_{\ell 3}$ - Radiative corrections

In the detailed GEANT3-based Monte Carlo simulation, the Kℓ3 decays are modeled accord-ing to **ref[5] *[C.Gatti, Eur. Phys. J. C 45 (2006) 417]*** including both the Dalitz plot density and radiative corrections, with exactly one photon emitted in each decay, and tracked through the detector if its energy in the laboratory frame is above 1 MeV. This approach takes into account the infrared divergence of photon radiation by extending the soft-photon approxi-mation to the whole energy range. The implementation has been validated using the KLOE experimental data.

On the other hand, model-independent (universal) radiative corrections have been propos-ed in **ref[6] *[V.Cirigliano et al , Eur. Phys. J. C 23 (2002) 121]***. Using these corrections FFs are free from uncertainties due to radiative corrections by construction, and their deviation from FFs defined in absence of electromagnetic interaction can be estimated.

In this analysis, the approach *[5]* is used, and the Dalitz plot density is corrected by event-by-event weights $w_r(E^*_\ell , E^*_\pi)$ equal to the ratio of densities obtained within the formulations of *[6] and [5]*.

In the Ke3 case, the weighting leads to $d\Gamma/dE^*_e$ variations as large as 2%.

In the Kμ3 case, the weights have been found to be $w_r(E^*_\mu; E^*_\pi) = 1$ within the required precision.

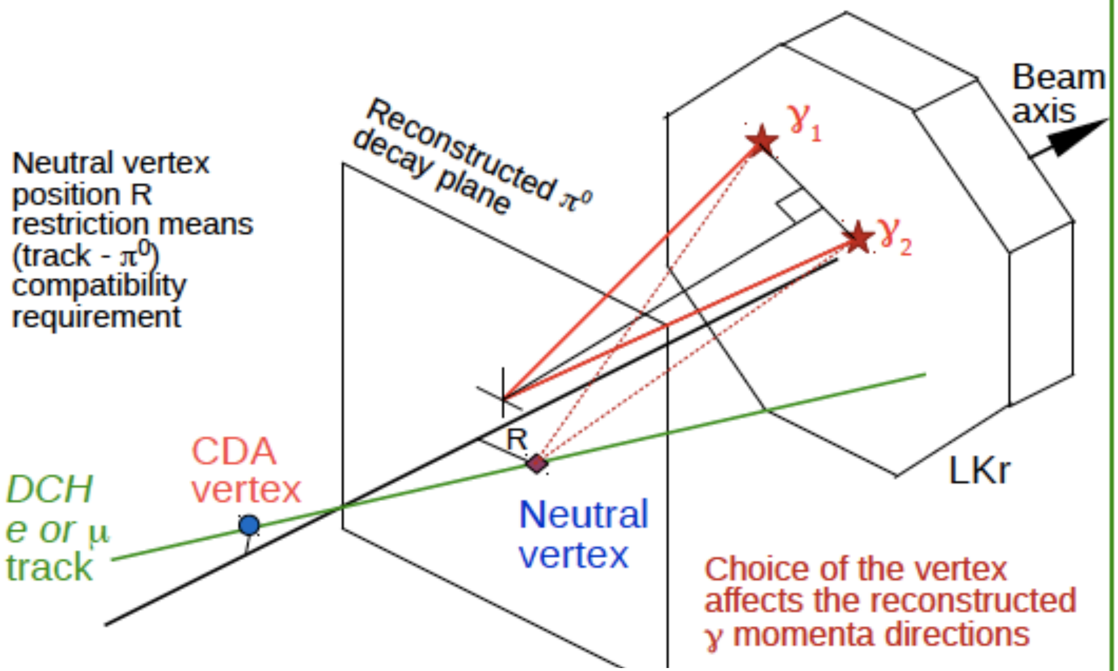
A linear approximation for the vector and scalar FFs $f_+(t) = f_0(t) = 1+.0296\ t/m^2_\pi$ is used to generate the simulated samples.

$K^{\pm}_{\ell 3}$ decays – event selection

Selection:

π^0 :

- A pair of clusters in-time (within 5 ns) without any in-time extra clusters (to suppress BG)
- Distance between the clusters in a pair > 20 cm
- $E(\pi^0)$ > 15 GeV (for the trigger efficiency)
- Z of decay: from 2γ assuming π^0 mass («neutral Z»); Z > 200 cm downstream the last collimator
- DCH1 inner flunge cut for the both γ



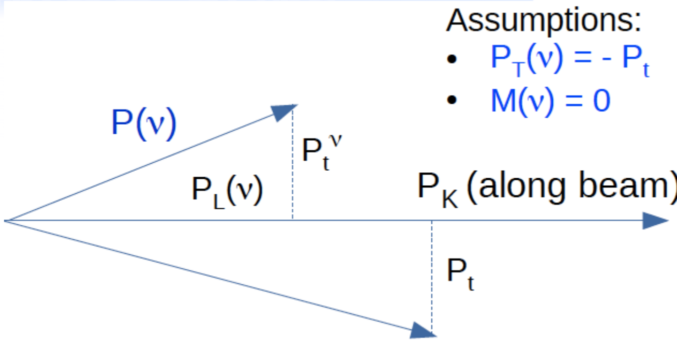
Track selection and identification

- A good track in-time with the π^0 within 10 ns.
- No extra good track within 8 ns (against showers).
- If **2.0 > E_{LKr}/P_{DCH} > 0.9**, it is an electron of K_{e3} .
- If **E_{LKr}/P_{DCH} < 0.9** (for true muons it cuts nothing) and there is a MUV muon associated, it is a $K_{\mu 3}$ muon.

Loose **E_{LKr}/P_{DCH}** cuts <=> negligible related systematics.

Neutral vertex is chosen
(no transverse bias): $Z_{decay} = Z(\pi^0)$;
X_{decay}, Y_{decay} = impact point of reconstructed charged track on Z_{decay} plane

Background suppression selection cuts

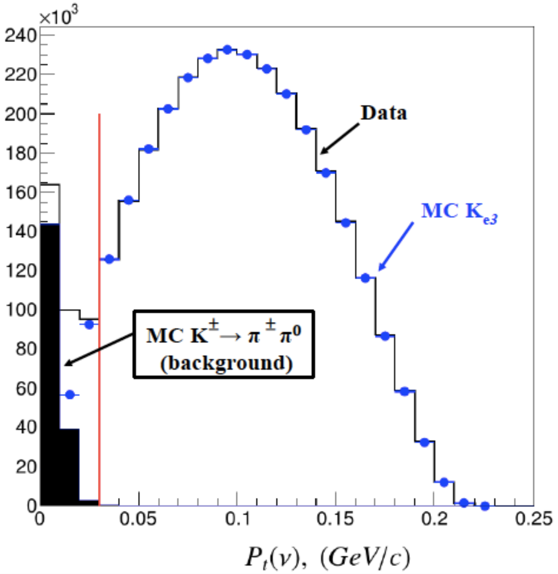


Specific Ke3 selection cuts

- Neutrino transversal momentum with respect to the beam axis $P_t > 0.03$ GeV/c

Against $K^{\pm} \rightarrow \pi^{\pm} \pi^0$ with $\pi^{\pm}$ misidentified as $e^{\pm}$.

- $p_L(\nu)^2 = E(\nu))^2/c^2 - (p_t(\nu))^2 > 0.0014\ \mathrm{GeV}^2/c^2$, negative tail and zero region sensitive to beam shape



Specific Kμ3 selection cuts

- cut against $\pi^{\pm}\pi^0\pi^0$: $(P_2 - P_1) < 60$ GeV, a difference between two P solution is large when one pion is missing
- against the background from $K^{\pm} \rightarrow \pi^{\pm}\pi^0$ with $\pi^{\pm} \rightarrow \pi\ \mu^{\pm}\nu$

  $m(\pi^{\pm}\pi^0) < 0.47\ \mathrm{GeV/c}^2$

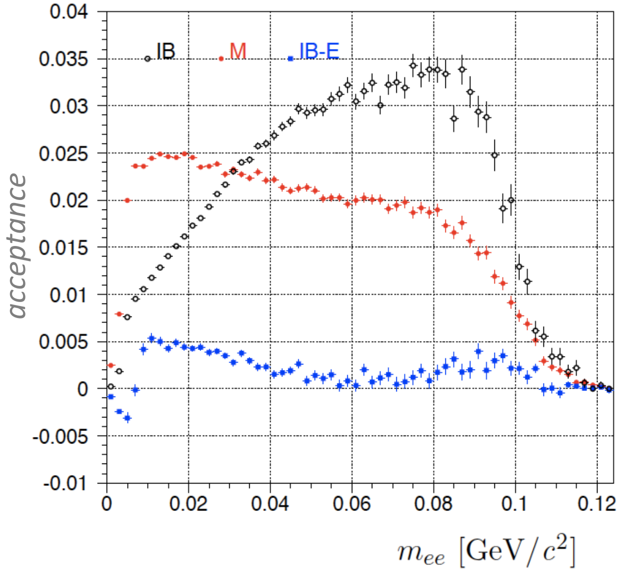
  $m(\pi^{\pm}\pi^0) < (0.6 - P_t(\pi^0))\ \mathrm{GeV/c}^2$

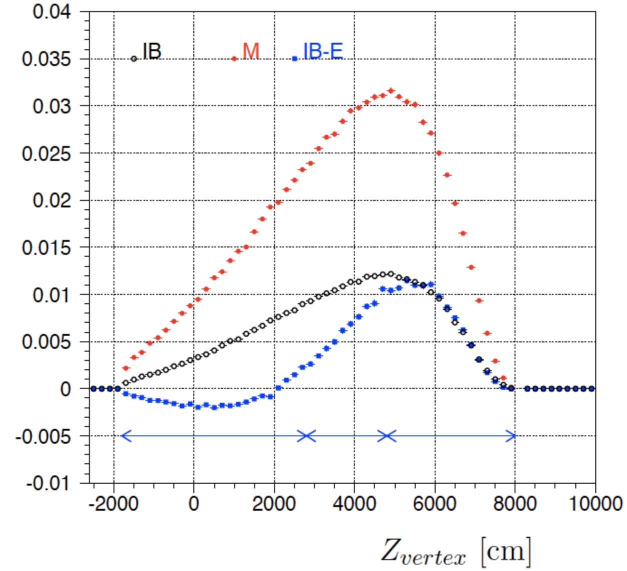
$m(\mu^{\pm}\nu) > 0.16\ \mathrm{GeV/c}^2$ (to exclude π^+ mass region)

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ – Acceptance

- The normalization channel acceptance A_n (3.981%) is computed using the simulation of $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}_{D}$ according to *[❖]* followed by π^{0}_{D} decay according to the most re-cent "Prague" radiative decay calculation.

The MC samples for the different $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ signal contributions IB, DE and INT have been generated separately according to the recent theoretical description *[2]* and global acceptances are obtained for each of the three main components of the signal process: IB (0.645 ± 0.001)%, M (1.723 ± 0.003)% and IB-E (0.288 ± 0.001)%. The signal acceptance A_s is then obtained from a weighted average of the single-component acceptances, using relative contributions to the total rate with respect to IB computed.

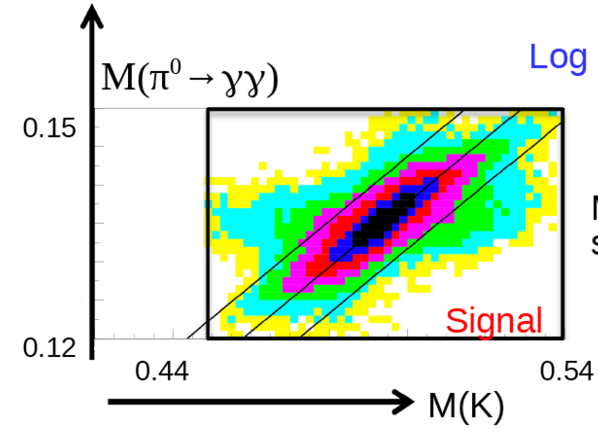




[❖] C.Gatti, Eur.Phys.J. C45 (2006) 417

$K^{\pm} \to \pi^{\pm}\pi^{0}e^{+}e^{-}$ – event reconstruction and selection

Signal: $\pi^{\pm}(\pi^{0} \to \gamma\gamma)\ e^{+}e^{-}$

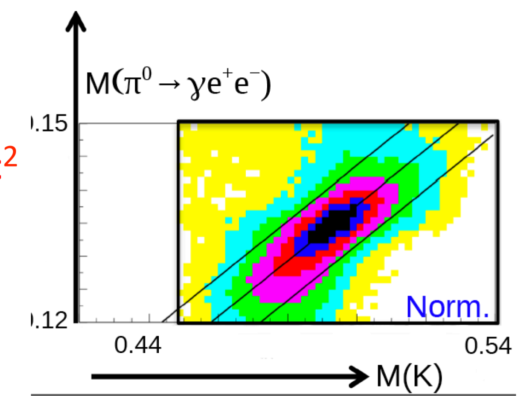


Normalization: $\pi^{\pm}\pi^{0}_{D} \to \pi^{\pm}\gamma e^{+}e^{-}$

Very abundant:

$BR(\pi^{\pm}\pi^{0}_{D}) \times BR(\pi^{0}_{D}) = 22.66\ \% \times 1.17\ \% = 2.425\ 10^{-3}$

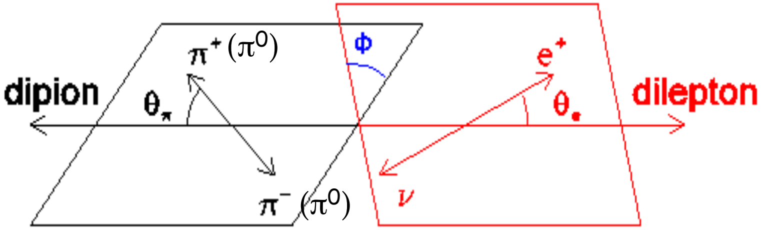
- 3 charged tracks in both cases, forming a vertex, but only one photon in the normalization channel;
- No PID from LKr, only kinematics => no LKr acceptance cuts on tracks;
- Assign electron mass to the track with a charge opposite to kaon charge;
- For both other tracks try using both M(e) and $M(\pi^{\pm})$;
- Reconstruct $M(\pi^{0})$ and $M(K^{\pm})$;
- The mass resolutions (Gaussian rms) obtained from data:
  Signal mode: $\sigma(\pi^{0}_{\gamma\gamma}) \simeq 2.7\ MeV/c^2$, $\sigma(\pi\pi^{0}_{\gamma\gamma}ee) \simeq 6.1\ MeV/c^2$
  Norm. mode: $\sigma(\pi^{0}_{D}) \simeq 1.7\ MeV/c^2$, $\sigma(\pi^{\pm}\pi_{D}) \simeq 4.2\ MeV/c^2$
- $|M(\pi^{0}) - M_{PDG}| < 15\ MeV/c^2$;
- $|M(K^{\pm}) - M_{PDG}| < 45\ MeV/c^2$;
- $|M(\pi^{0}) - 0.42\ M(K^{\pm}) + 72.3\ MeV/c^2| < 6\ MeV/c^2$



Other asymmetry investigations - (2)

Electroweak (or beyond Standard Model) phases change sign under charge conjugation when switching from K^+ to K^-, unlike the strong phase $\delta = \delta_0^2 - \delta_0^1$ that governs the final state interaction of the pion system. These phases can be investigated through asymmetries between K^+ and K^- partial rates.

Other asymmetries are defined using the so-called Cabibbo-Maksymowicz variables to describe the kinematic space of the decay and selecting particular integration regions of the angular variable.



These asymmetries can be obtained by combining the branching ratios measured in various parts of the variable space.

$$A_{CP}^{\phi^*} = \frac{\int_0^{2\pi} \frac{d\Gamma_{(K^+ - K^-)}}{d\phi} d\phi^*}{\int_0^{2\pi} \frac{d\Gamma_{(K^+ + K^-)}}{d\phi} d\phi}, \quad \text{where} \int_0^{2\pi} d\phi^* \equiv \left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi} \right] d\phi,$$

i.e. $A^{\Phi^*}_{CP}$ asymmetry is related to the interference IB-M term

$$A_{CP}^{\tilde{\phi}} = \frac{\int_0^{2\pi} \frac{d\Gamma_{(K^+ - K^-)}}{d\phi} d\tilde{\phi}}{\int_0^{2\pi} \frac{d\Gamma_{(K^+ + K^-)}}{d\phi} d\phi}, \quad \text{where} \int_0^{2\pi} d\tilde{\phi} \equiv \left[\int_0^{\pi/2} + \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi} \right] d\phi.$$