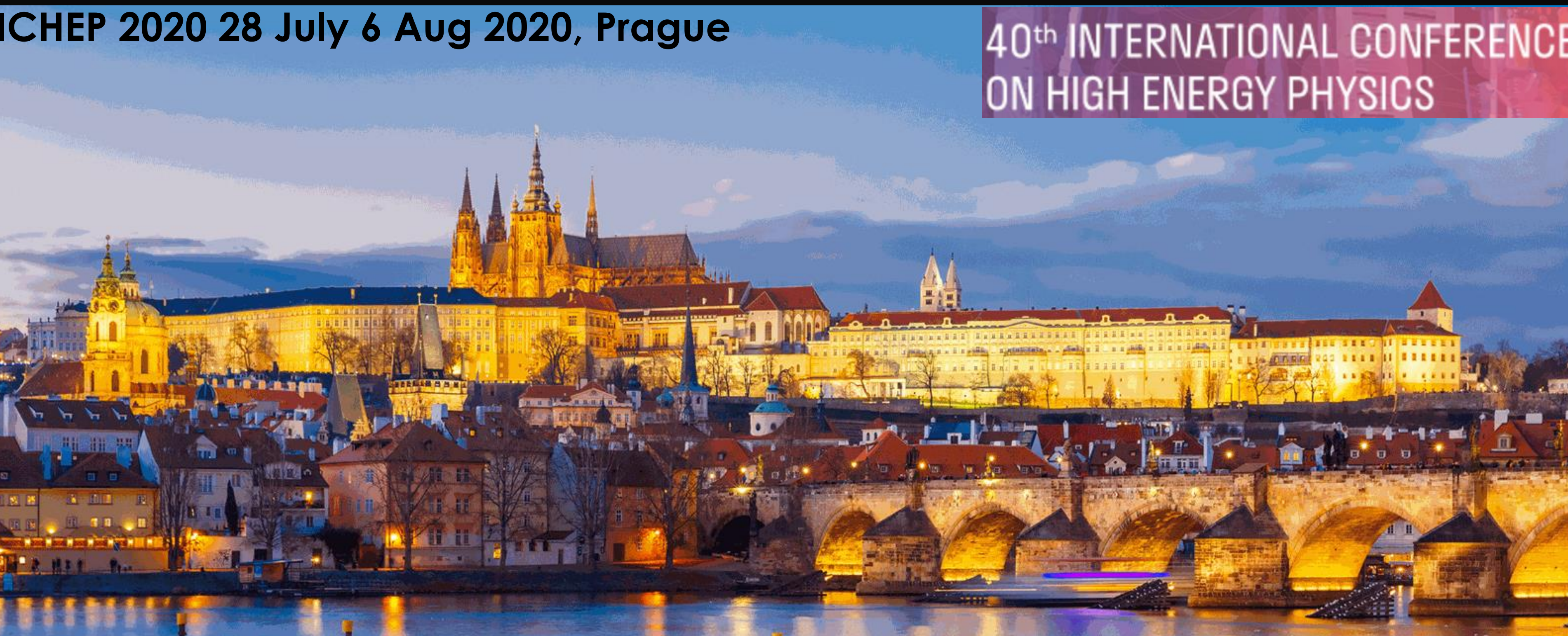
Latest results on rare kaon decays from the NA48/2 experiment at CERN

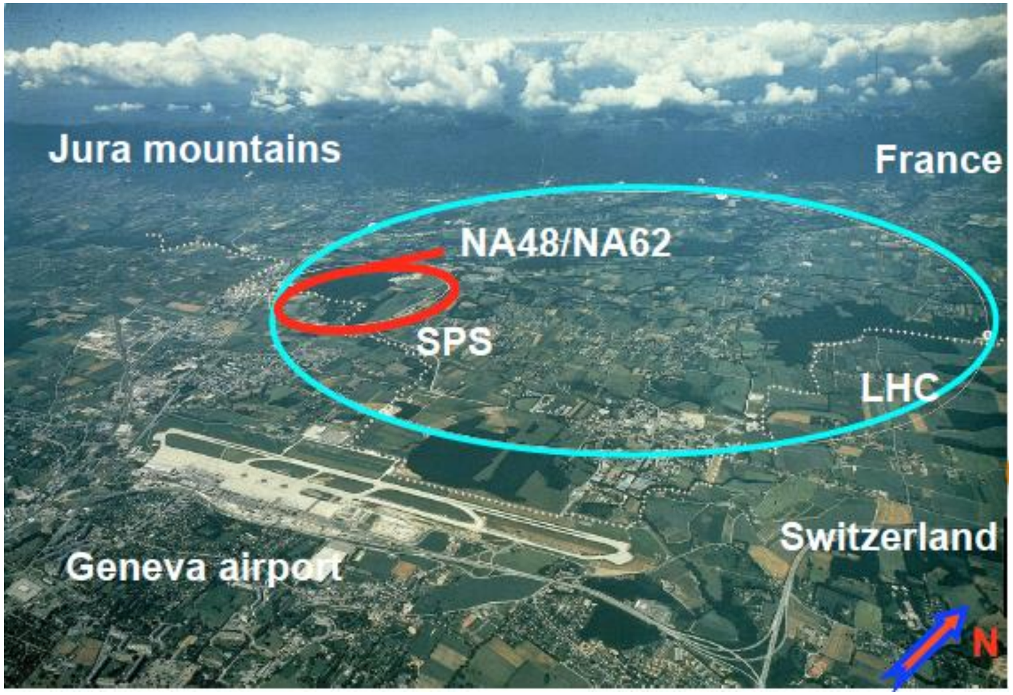


Mauro Raggi, on behalf of the NA48/2 collaboration
Sapienza Università di Roma e INFN Roma
ICHEP 28 Jul 6 Aug 2020, Prague

Outline

- The NA48/2 experiment at the CERN North Area
- First observation of the $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}e^{+}e^{-}$
  - *Phys.Lett.B* 788 (2019) 552-561
- Precise measurement of the charged kaon semi-leptonic form factors
  - *JHEP* 10 (2018) 150
- Conclusions

History of 20 years of kaon at CERN NA



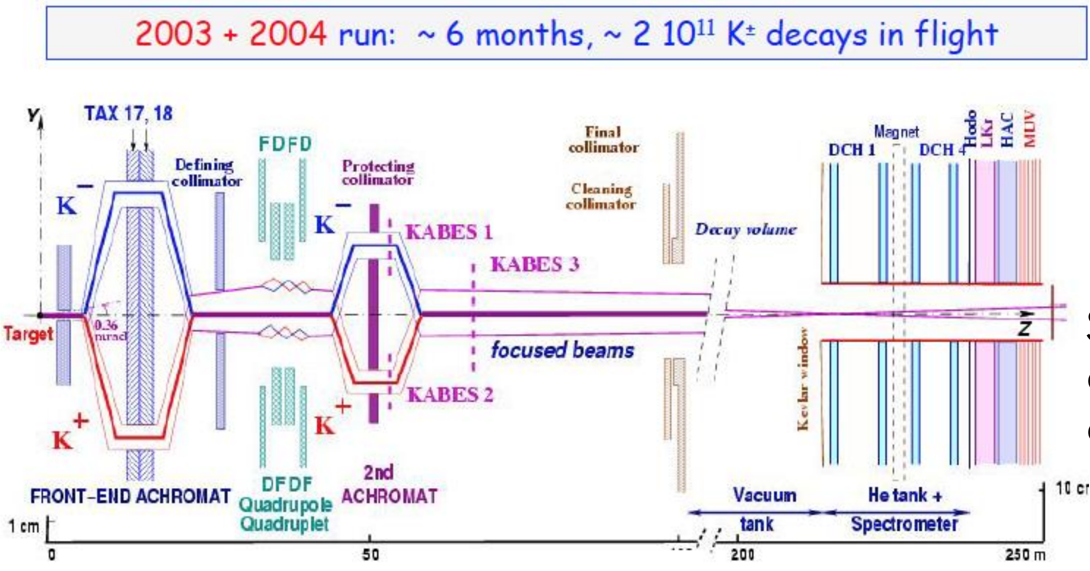
The **NA48/2** collaboration:
still producing result after > 15 years
~100 physicists from 15 Institutes in 8 countries

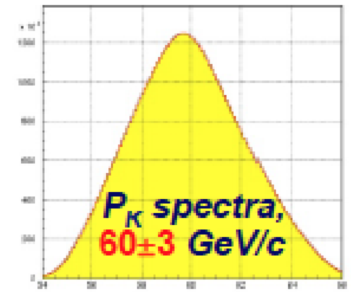
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien

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
↓	2007 design & 2013 construction
NA62	2012technical run 2013 long shutdown 2014 commissioning | & 2018 data taking

The NA48/2 experiment 2003-2004

NA48/2 Data taking: 4 months in 2003 ($K^\pm$) + 4 months in 2004 ($K^\pm$)
Simultaneous K^+ and K^- beam with N_{K+}/N_{K-} ~1.8
Total of ~2 · 10^{11} charged Kaon decays in the fiducial decay region





Simultaneous K^+ and K^- beams: large charge symmetrisation of experimental conditions

Magnetic Spectrometer

- 4 drift chambers and a dipole magnet

$$\frac{s(p)}{p} = (1.02 \oplus 0.044p)\% \quad \text{p in GeV/c}$$

Liquid Krypton EM calorimeter (LKr)

- High granularity (13248 cells of 2x2 cm^2)
- Quasi-homogeneous, 7m^3 liquid Kr (27X_0)

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.4\% \quad \text{E in GeV}$$

The ChPT and Kaon decays

- The basic $\Delta S=1$ $O(p^4)$ chiral lagrangian can be written as:

$$L_{\Delta S=1} = L^2_{\Delta S=1} + L^4_{\Delta S=1} = \underbrace{G_8 F^4 \langle \lambda_6 D_\mu U^\dagger D^\mu U \rangle}_{K\to 2\pi/3\pi,\ \gamma\gamma} + \underbrace{G_8 F^2 \sum N_i W_i}_{K^+\to\pi^+\gamma\gamma,\ K\to\pi\gamma\gamma}$$

- 37 poorly known N_i coefficients and W_i operators

- Combinations of such couplings are accessible by measuring Kaon decays branching fractions and form factors D'Ambrosio PoS(EFT09)061

- NA48/2 can access all the charged decay with very high precision

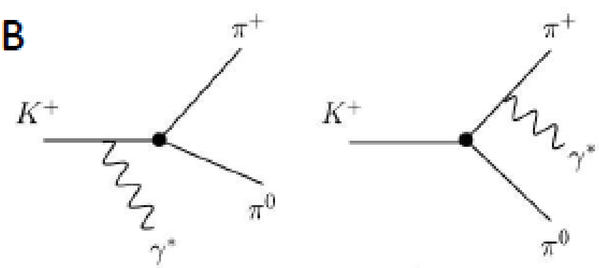
Decay	$\mathscr{L}^4_{\Delta S=1}$ counterterms	
$K^+ \to \pi^+ l^+ l^-$	$N^r_{14} - N^r_{15}$	NA48/2 ee PLB 677 (2009) 246-254 μμ PLB 697 (2011) 107-115
$K_S \to \pi^0 l^+ l^-$	$2N^r_{14} + N^r_{15}$	NA48/1 ee Phys.Lett. B576 (2003) 43-54 μμ PLB 599 (2004) 197-211
$K^\pm \to \pi^\pm \gamma\gamma$	$N_{14} - N_{15} - 2N_{18}$	NA48/2 Phys.Lett. B730 (2014) 141-148
$K_S \to \pi^+\pi^-\gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	
$K^\pm \to \pi^\pm\pi^0\gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	NA48/2 EPJC 68 (2010) 75-87
$K_L \to \pi^+\pi^- e^+e^-$	$N^r_{14} + 2N^r_{15} - 3(N^r_{16} - N_{17})$	NA48 Eur.Phys.J. C30 (2003) 33-49
$K^+ \to \pi^+\pi^0 e^+e^-$	$N^r_{14} + 2N^r_{15} - 3(N^r_{16} - N_{17})$	**This talk!**
$K_S \to \pi^+\pi^- e^+e^-$	$N^r_{14} - N^r_{15} - 3(N^r_{16} + N_{17})$	NA48 Eur.Phys.J. C30 (2003) 33-49

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

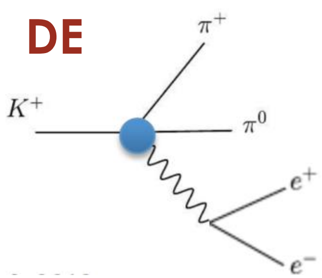
Theoretical framework $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$

- Theory of $\pi^{+}\pi^{0}e^{+}e^{-}$ has been very recently developed
  - L. Cappiello, O. Cata', G. D'Ambrosio, D.Gao EPJ C72 (2012) 1872
  - L. Cappiello, O. Cata', G.D'Ambrosio, EPJ C78 (2018) 265
- $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$ offers various opportunity of chiral tests:
  - Interference $\Gamma_B\ \Gamma_E$ can confirm the discrepancy in sign with the theoretical prediction observed by NA48/2 in $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\gamma$ EPJC 68 (2010) 75-87
  - Magnetic interference is genuine $\pi^{+}\pi^{0}e^{+}e^{-}$ and can be used to extract the sign of the magnetic term Γ_M (impossible to extract in $\pi^{\pm}\pi^{0}\gamma$).
  - P violating observables in the dilepton pair coupling can be used to access short distance physics using K^{+} only (NA62)
  - Charge asymmetry not contaminated by indirect CP violation (as in K^{0})
- Never observed so far!

IB



DE



Theoretical expectations:

IB (99%),

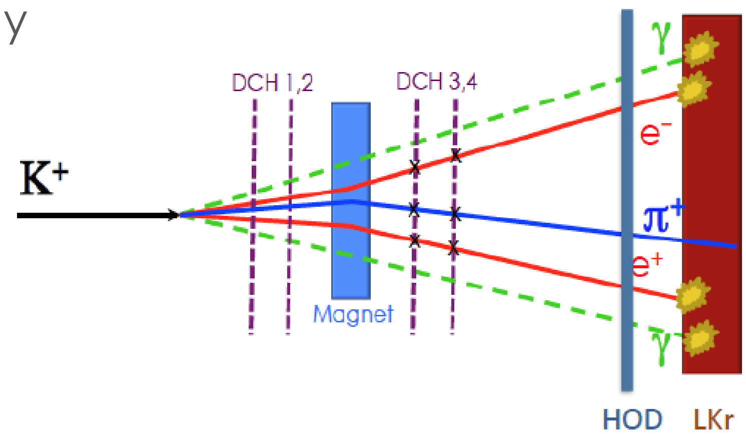
DE (M) (1.39%)

INT(IB,DE(E)) (0.39% negative)

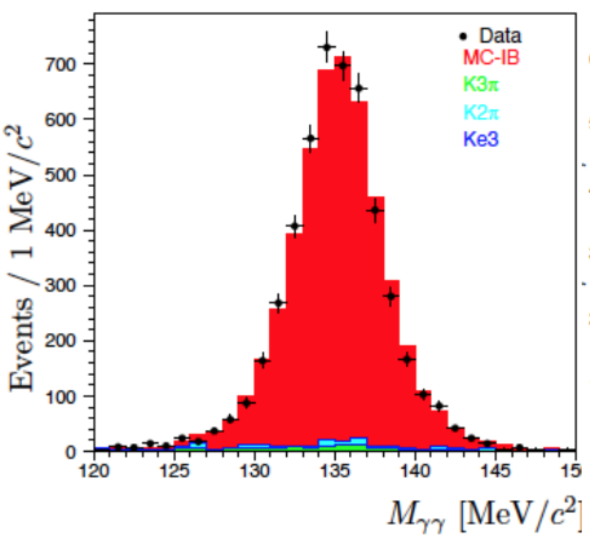
based on $K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\gamma$ EPJC 68 (2010) 75-87 DE measurement

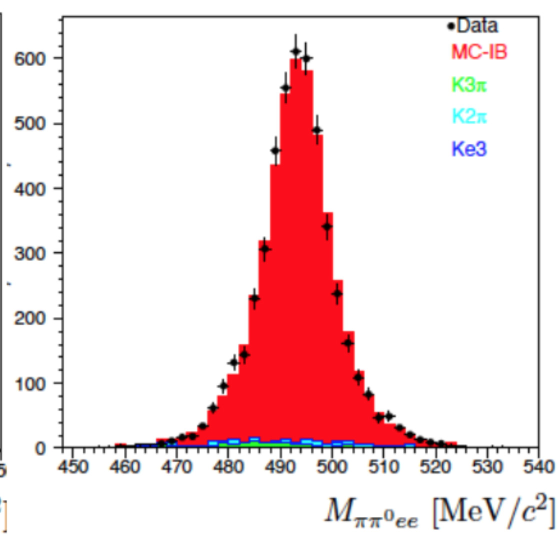
The measurement technique

- Strongly constrained final state with high particle multiplicity
  - 5 particles: $\pi^{\pm}\pi^{0}e^{+}e^{-} \Rightarrow$ 2e 1π and 2γ (considering only π^{0} □$\gamma\gamma$ decay)
  - $M_{\gamma\gamma}=M_{\pi 0}$ and $M_{\pi\gamma\gamma ee} = M_{K}$ constraints can be used to reject background
  - Tracks and gammas pointing the same decay vertex



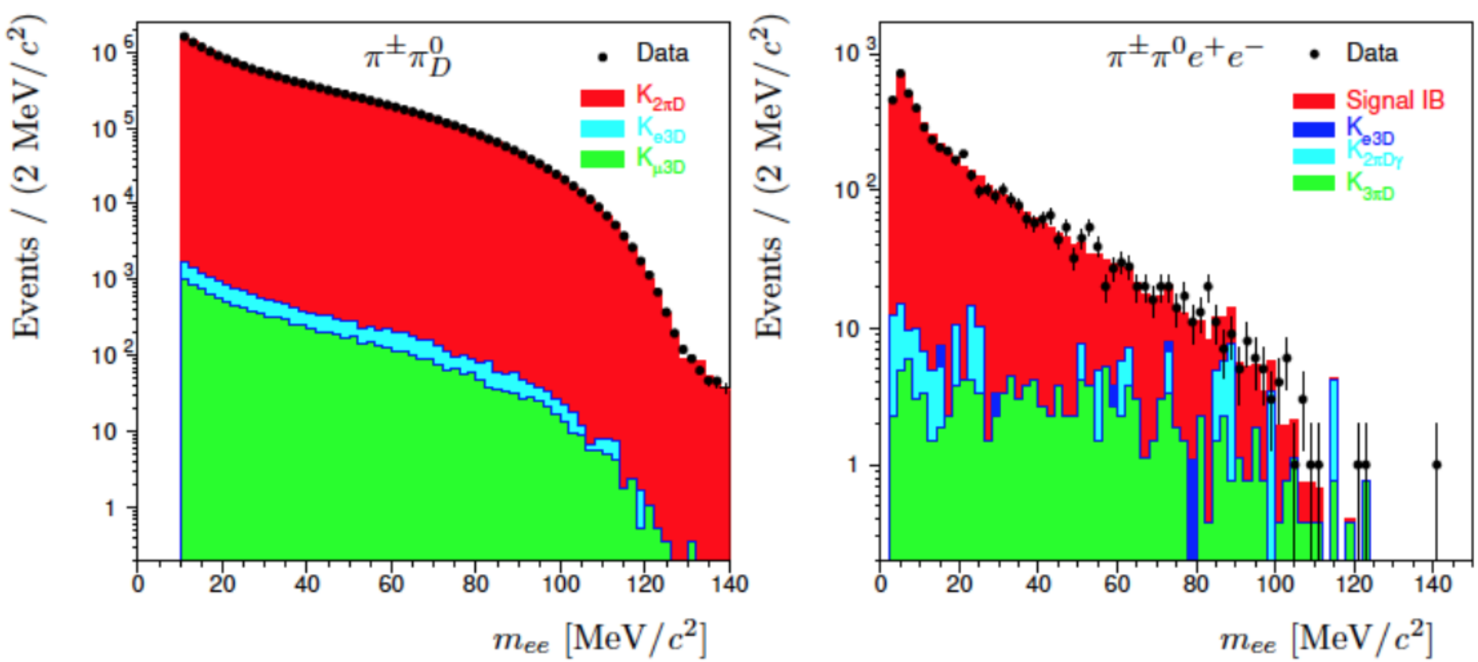
- Normalized to very similar $K^{\pm}$□$\pi^{\pm}\pi^{0}_{D}$
  - 4 particles: $\pi^{\pm}\pi^{0}_{D} \Rightarrow \pi^{\pm}e^{+}e^{-}\gamma$
  - Very abundant decay
  - Precision limited by BR(π^{0}_{D})





Selection results

- Signal candidates: 4919(70)
  - 241(20) estimated Background events (mostly $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}_{D}$)
  - ~5% background contribution



The BR ratio measurement

- First measurement of the **BR($K^\pm \longrightarrow \pi^\pm\pi^0 e^+e^-$)**

  BR = $(4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext})\ 10^{-6} = (4.237 \pm 0.145)\ 10^{-6}$

  Phys.Lett.B 788 (2019) 552-561

  - Dominated by 3% external error on BR(π^0_D)
  - Very good agreement with predictions in EPJ C78 (2018) 265
  - Theory BR(IB) only ($4.183\text{x}10^{-6}$) and BR(total) $4.229\text{x}10^{-6}$

- First evidence of the existence of DE(M) components obtained by NA48/2 with limited statistical sensitivity
  - NA48/2 **DE(M)/IB =($1.14\pm0.43_{stat}$)%** theory DE(M)/IB =$1.41\pm0.14_{ext}$
  - NA48/2 INT(BE)/IB =($-0.14\pm0.36_{stat}$)% theory INT(BE)/IB = $-0.39\pm0.28_{ext}$

- Preferred negative sign for the INT term seem to confirm the measurement in $K^\pm\longrightarrow \pi^\pm\pi^0\gamma$ EPJC 68 (2010) 75-87

- Different asymmetries investigated with single–sided UL
  - ~2% @ 90% CL

Semileptonic Kℓ3 FF and V_{US}

Semileptonic Kℓ3 FF and V_{US}

- Kℓ3 FF are useful ingredients to the determination of V_{US}

$$\Gamma\left(K \to \pi l \nu[\gamma]\right) = Br(K_{l3})/\tau = C_K^2 \frac{G_F^2 m_K^5}{192\pi^3} S_{EW}^K |V_{us}|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl} \left(1 + 2\Delta_{EM}^{Kl} + 2\Delta_{SU(2)}^{K\pi}\right)$$

- Experimental inputs and theory inputs

E. Passemar Kaon 19

- Kℓ3 FF are used to determine the **I_{kl} phase space integral**

$$I_{K\ell} = \frac{2}{3}\int_{m_\ell^2}^{t_0} \frac{dt}{M_K^8}\,\bar{\lambda}^{3/2}\left(1+\frac{m_\ell^2}{2t}\right)\left(1-\frac{m_\ell^2}{2t}\right)^2 \times \left(\bar{f}_+^2(t) + \frac{3m_\ell^2\Delta_{K\pi}^2}{(2t+m_\ell^2)\bar{\lambda}}\bar{f}_0^2(t)\right),$$

- **Vector form factor** and **scalar form factor**
  - **Ke3 = $K^\pm \to \pi^0 e^\pm \nu$** only has **vector** form factor
  - **Kμ3 = $K^\pm \to \pi^0 \mu^\pm \nu$** has both **vector** and **scalar** form factors

- Need to measure both **Ke3 Kμ3 to get full determination of** the form factors

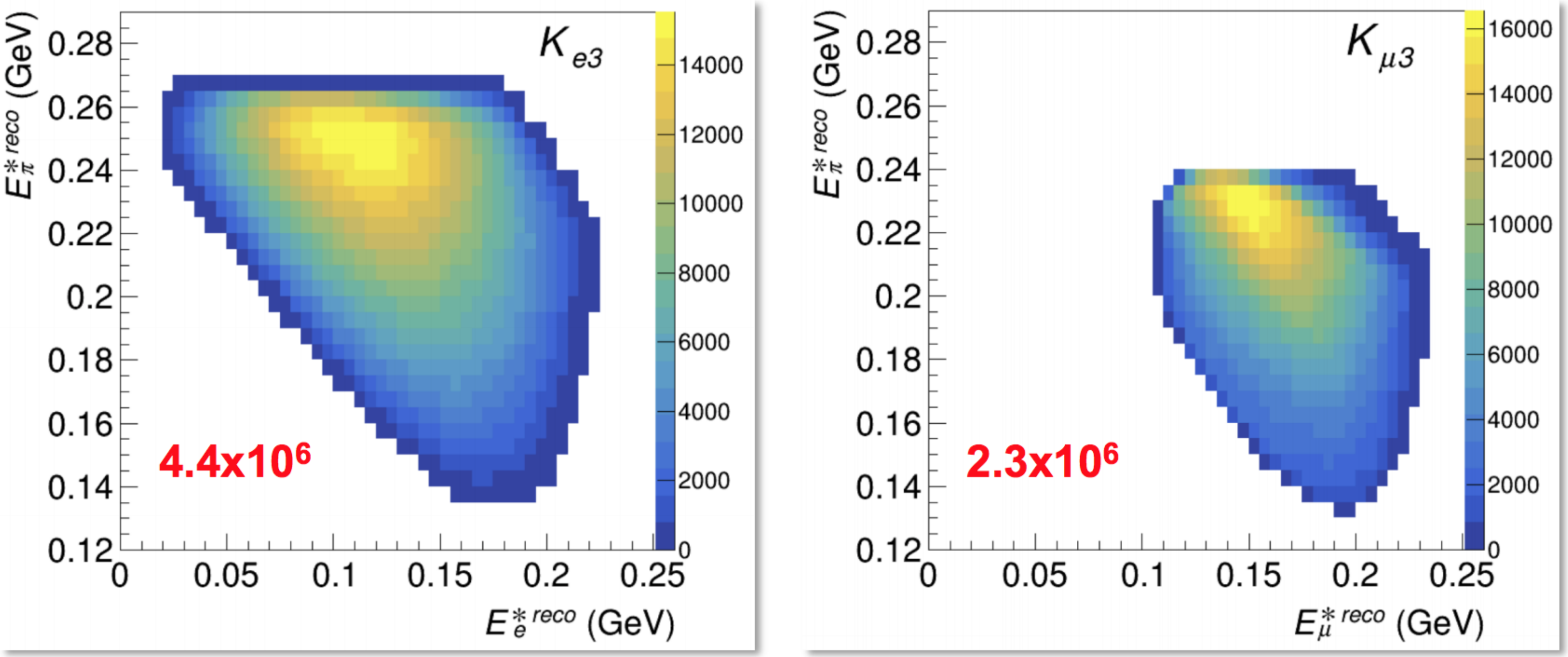
Different FF parameterization

- There are different expressions to parameterize the FFs
  - Quadratic (based on Taylor expansion)
  - Pole parameterization
  - Dispersive relations

FF Parametrization	$f^+(t)$	$f^0(t)$
Quadratic	$1+\lambda'_+\left(\frac{t}{m_\pi^2}\right)+\frac{1}{2}\lambda''_+\left(\frac{t}{m_\pi^2}\right)^2$	$1+\lambda'_0\left(\frac{t}{m_\pi^2}\right)$
Pole	$\frac{M_V^2}{M_V^2-t}$	$\frac{M_S^2}{M_S^2-t}$
Dispersive	$e^{(\Lambda_+ + H(t))\left(\frac{t}{m_\pi^2}\right)}$	$e^{(\ln(C)-G(t))\left(\frac{t}{M_K^2-M_\pi^2}\right)}$

NA48/2 data sample

- 3 days special run with dedicated trigger configuration in 2004:
  - 16 runs, 4 days in 2004
- Collected $K^{\pm}$ semi-leptonic decay samples:
  - 4.4×10^6 Ke3
  - 2.3×10^6 Kμ3



FF fit procedure

- Generate the MC Dalitz Plot (λ_{gen} value for the form factors)
  - to test a different set of form factor parameters MC is reweighted using **1)**
  - W_R radiative correction for the new point in the Dalitz plot (Ke3 only)
- Extract the most probable value of FF minimizing χ^2 in **2)**
  - $\omega_{i,data}$ and $\omega_{i,bkg}$ contents of experimental signal and background contribution in the i-th bin
  - $\omega_{i,MC}$ the reweighted bin in the i-th MC distribution

1)

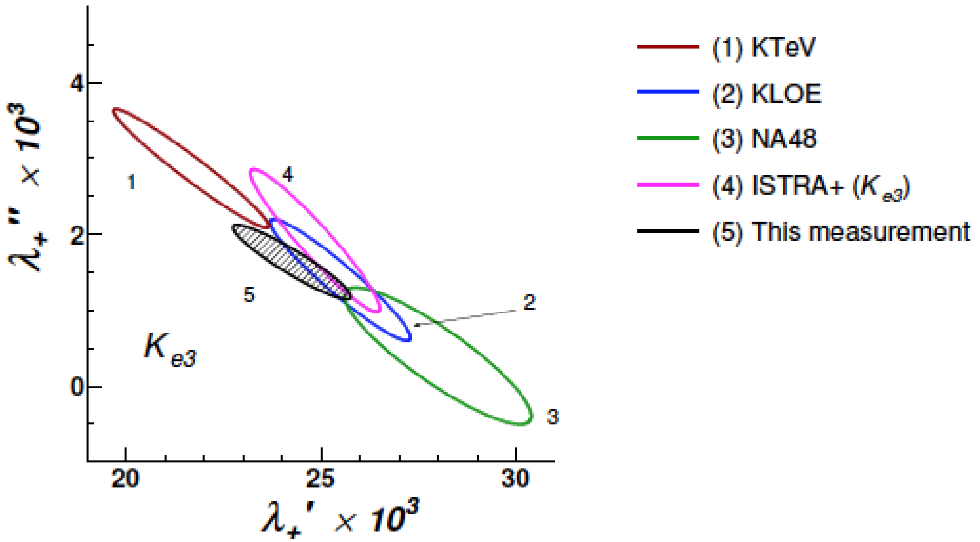
$$w\left(\vec{L}\right) = w_R(E_l, E_\pi)\frac{\rho\left(\vec{L}, E_l, E_\pi\right)}{\rho\left(\overrightarrow{\lambda_{gen}}, E_l, E_\pi\right)}$$

2)

$$\chi^2 = \sum_{bins}\frac{\left(\omega_i^{data} - N\cdot\omega_i^{MC} - \omega_i^{bkg}\right)^2}{\sigma_{i,data}^2 + N^2\cdot\sigma_{i,MC}^2 + \sigma_{i,bkg}^2}$$

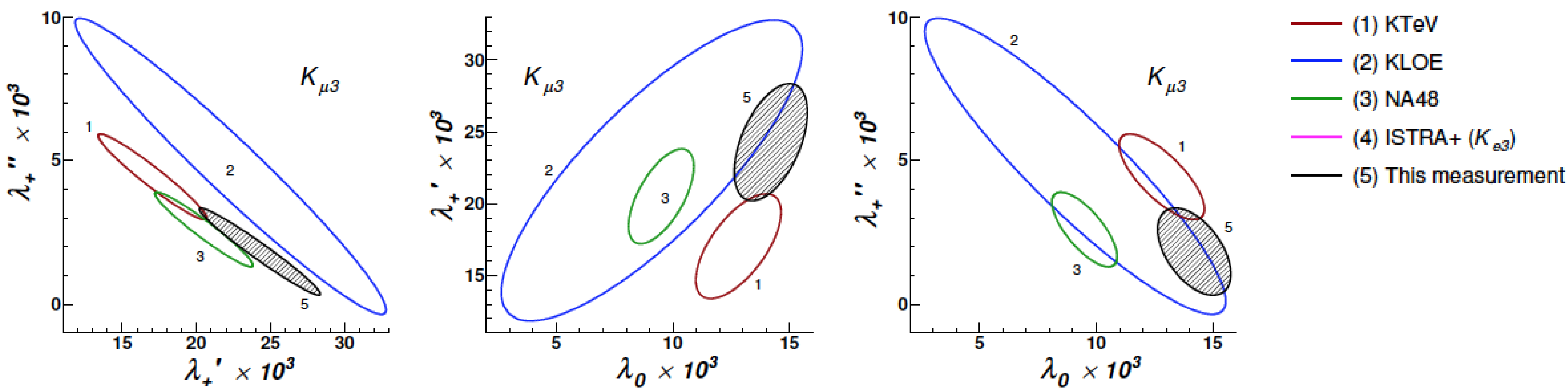
Ke3 vector FF results

	Quadratic (10^{-3})		Pole (MeV)	Dispersive (10^{-3})
	λ'_+	λ''_+	M_V	Λ_+
Central value	*24.26*	*1.64*	*885.2*	*24.94*
σ_{stat}	0.78	0.30	3.3	0.21
σ_{syst}	1.30	0.39	7.2	0.64
Total error	*1.51*	*0.49*	*7.9*	*0.67*
χ^2**/ndf**	569.1/687		568.9/688	569.0/688
Correlation	-0.929		-	-

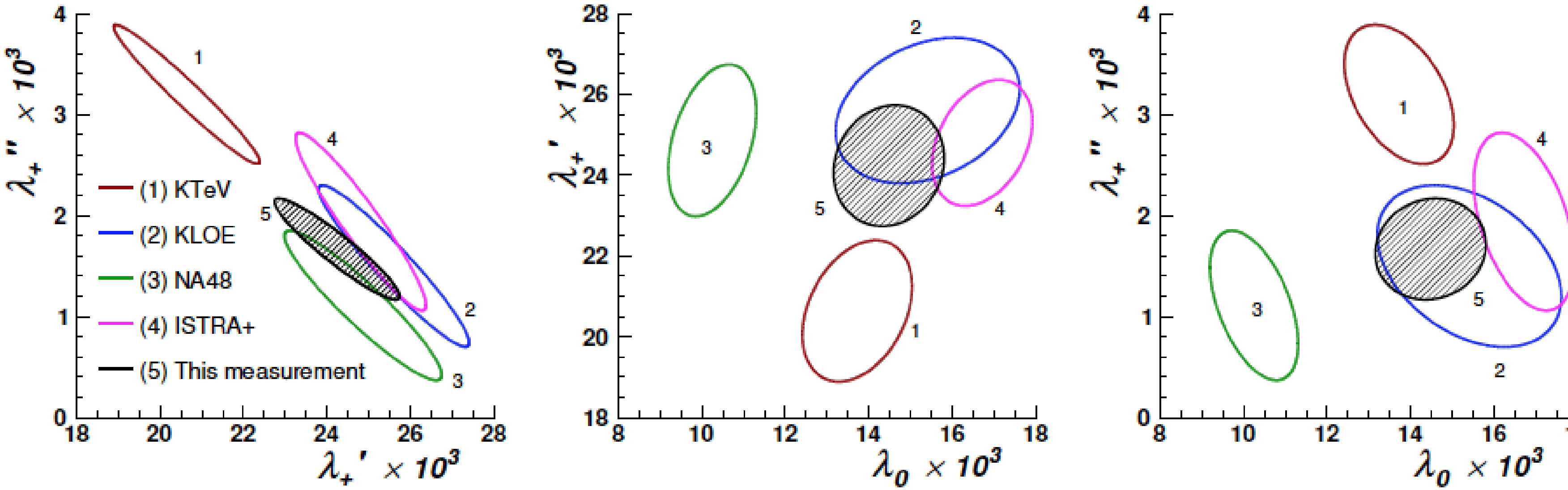


Kμ3 vector + scalar FF results

	Quadratic (10^{-3})			Pole (MeV)		Dispersive (10^{-3})	
	λ'_+	λ''_+	λ'_0	M_V	M_S	Λ_+	ln(C)
Central value	*24.27*	*1.83*	*14.20*	*878.4*	*1214.8*	*25.36*	*182.17*
σ_{stat}	2.88	1.05	1.14	8.8	23.5	0.58	6.31
σ_{syst}	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*
χ^2/ndf	409.9/381			409.9/382		410.3/382	
Correlation	-0.974 (λ'_+/λ''_+); 0.551(λ'_+/λ'_0); -0.513(λ''_+/λ'_0)			0.029		0.104	



Combined results FlaviaNet summary



- NA48 measurement obtained by simultaneous Ke3 and Km3 data minimizing χ^2 (Ke3)+ χ^2 (Kμ3) with a common set of parameters
- Comparison with other results courtesy of the Flavianet working group.

Conclusions

- A first measurement of the BR($K^{\pm} \longrightarrow \pi^{\pm}\pi^{0}e^{+}e^{-}$) has been performed by NA48/2 experiment based on 4919 candidate events:

$$BR = (4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext})\ 10^{-6} = (4.237 \pm 0.145)\ 10^{-6}$$

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- First evaluation of the DE(M) contribution (1.1 ± 0.4)%, in agreement with ChPT prediction

- Kl3 FF are measured with a 3 days NA48/2 special run data
  JHEP 1810 (2018) 150
  - ~$4.4 \cdot 10^{6}$ Ke3 and ~$2.3 \cdot 10^{6}$ Kμ3 events,
  - Simultaneous K^{+} and K^{-} samples

- The combined results has a precision comparable to previous measurements and it's fully compatible with them.

Spare slides

Error budget ppee

Normalization candidates	16 316 690 (4 039)
Background	17 292 (159)
A (rad cor HKN)	3.981 (2) %
L1 efficiency	99.767(3) %
L2 efficiency	98.495(6) %

Signal candidates	4919 (70)
Background	241 (20)
A(rad cor) eff	0.662(1) %
L1 efficiency	99.73(1) %
L2 efficiency	98.60(2) %

See B. Bloch-Devaux
KAON 2019

September 10, 2019

Source	$\delta BR/BR \times 10^2$	
Ns	1.426	stat 1.486
Nbs	0.416	
Nn	0.025	
Nbn	Negl.	
As (MC stat)	0.171	syst 0.777
An (MC stat)	0.051	
L1n x L2n (MC stat)	0.007	
L1s x L2s(MC stat)	0.023	
A (geometry control)	0.083	
A (time variation)	0.064	
Trigger efficiency	0.400	
Model dependence	0.285	
Radiative effects	0.490	
$BR\pi\pi^0$	0.87	external 2.971
$BR\pi^0D/BR\pi^0\gamma\gamma$	2.946	