Recent results from the NA62 and NA48/2 experiments at CERN

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on behalf of the NA62 and NA48/2 collaborations

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Outline

The NA62 experiment

Search for the $K^+ \to \pi^-(\pi^0)\, e^+ e^+$ LNV decays

Measurement of the $K^+ \to e^+ \nu\, \gamma$ decay

First observation of $K^+ \to \pi^0 \pi^0 \mu^+ \nu$ @ NA48/2

Summary

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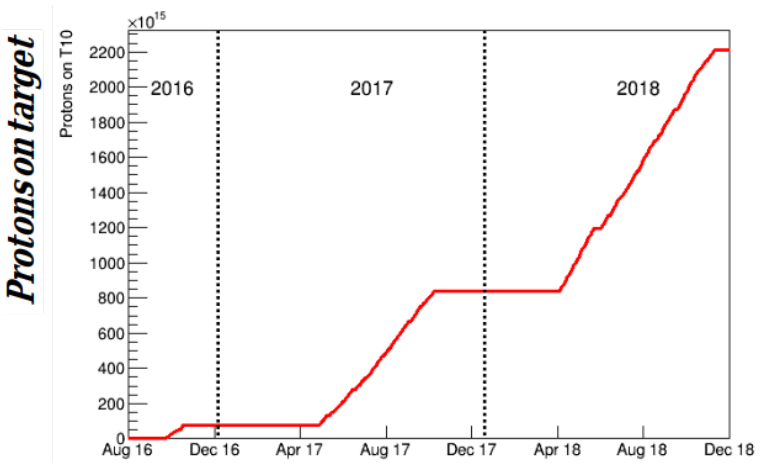
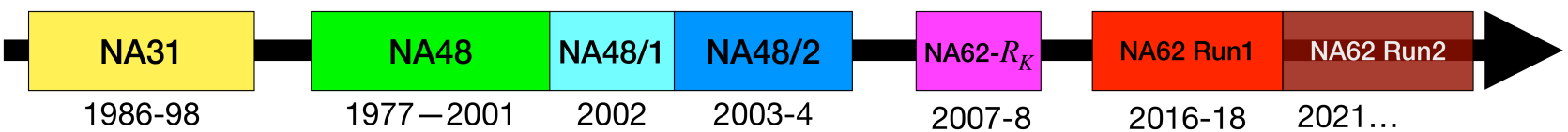
The NA62 experiment



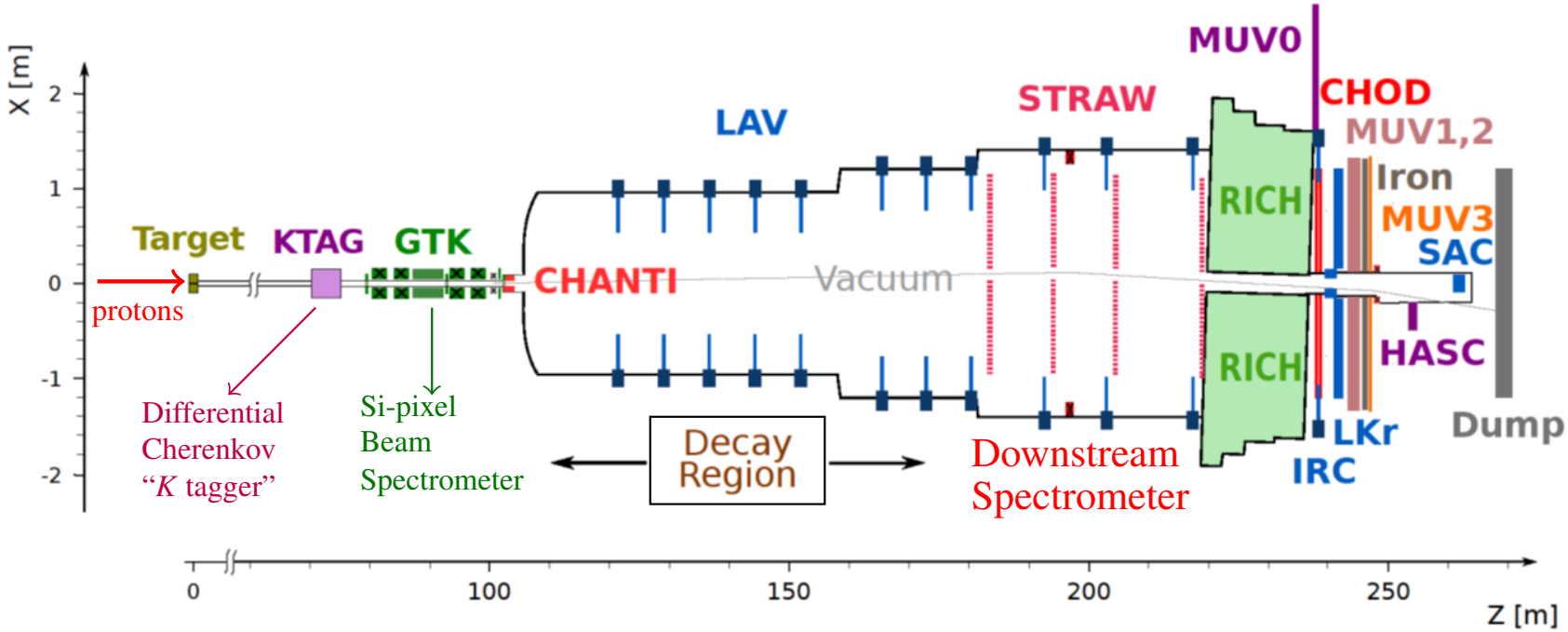
Years 2016–2017–2018:

$\sim 2.2 \times 10^{18}$ protons on target

- Primary goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$)
  [PLB 791 (2019) 156 , JHEP 11 (2020) 042 , JHEP 06 (2021) 093]
- New technique: K^+ decay-in-flight
- Broader Kaon physics programme:
  - Rare K^+ decays (e.g. $K^+ \to \pi^+ \mu^+ \mu^-$)
  - LNV/LFV decays [this talk]
  - Exotics (e.g. HNL, . . .)
  - $K^+ \to e^+ \nu \gamma$ [this talk]



The NA62 beam and detector



- SPS beam: p (400 $\frac{\text{GeV}}{\text{c}}$) — $\sim 2 \times 10^{12}$ ppp on Beryllium target
- secondary hadron beam: — ~500 MHz (70% π^+, 24% p, 6% K^+), 75 $\frac{\text{GeV}}{\text{c}}$
- 60 m long decay region: — ~5 MHz decay rate; vacuum $\mathcal{O}(10^{-6})$ mbar

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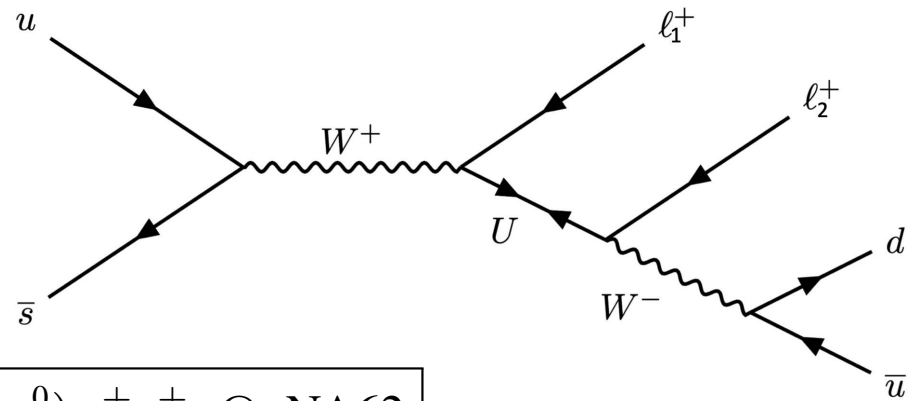
Beam K^+ (75 $\frac{\text{GeV}}{\text{c}}$, 1%rms)	t (KTAG, GTK; $\sigma_t \sim 70,\ 90$ ps); $\vec{p}$ (GTK)
Charged decay products	t (RICH, CHOD; $\sigma_t \sim 70,\ 200$ ps); $\vec{p}$ (STRAW)
γ/multitrack veto	LAV, LKr, IRC, SAC (0–50 mrad), MUV0, HASC
Particle ID	RICH, LKr, MUV1/2/3

Searches for LNV decays

- Observation of Lepton Number Violation (LNV) would be a clear indication of BSM physics
- e.g. $K^+ \to \pi^- l_1^+ l_2^+$ via exchange of a Majorana neutrino (as in $0\nu\beta\beta$ decays) [JHEP 05(2009) 030], [PLB 491 (2000) 285]



$K^+ \to \pi^-(\pi^0)\, e^+e^+$ @ NA62

Use the full 2016–2018 data set

- Search for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^-\pi^0 e^+ e^+$
- Normalize to SM rare decay $K^+ \to \pi^+ e^+ e^-$ (BR$= 3 \times 10^{-7}$)

Triggers:

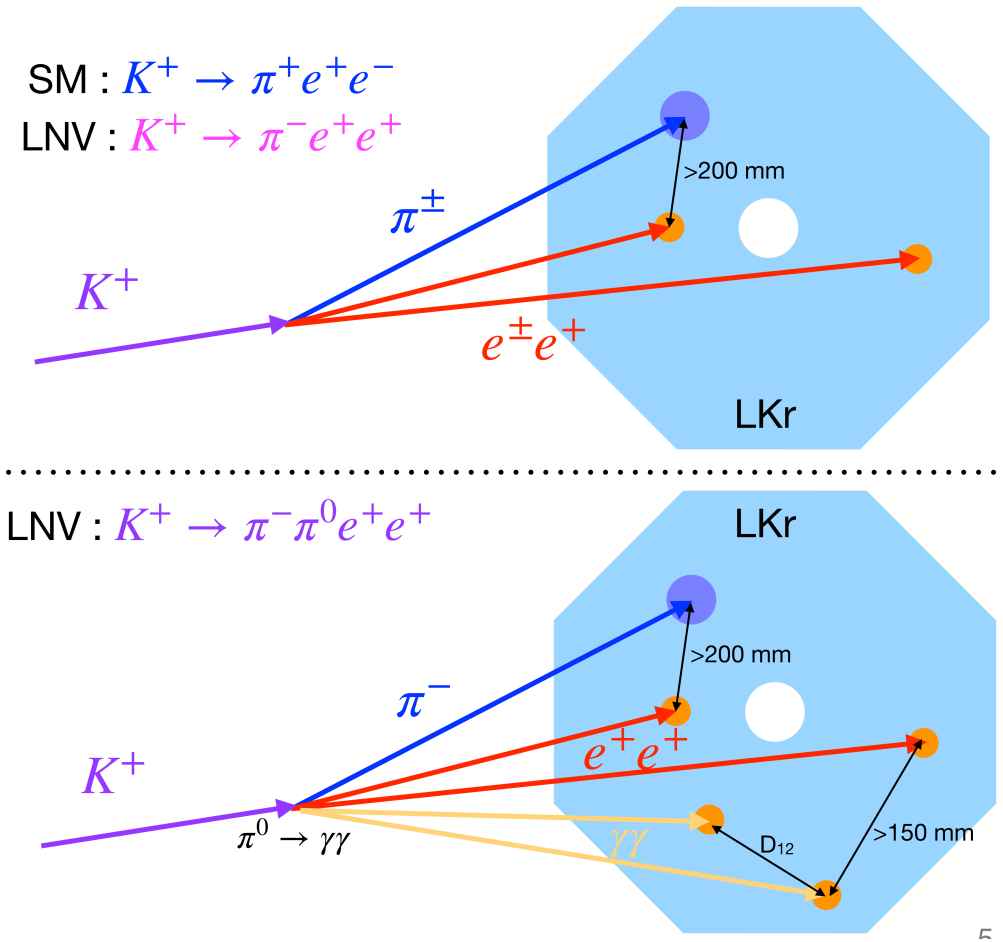
- Hardware L0 + software L1
- "Multi-track" triggers taken concurrently with $\pi\nu\nu$ trigger and downscaled
- Trigger efficiency $> 95\%$

Event selection

- Select 3-track events forming a $Q = +1$ vertex in the FV
- Track momentum within 6–44 GeV/c
- Track separation at LKr > 200 mm
- $|P_{\rm tot} - P_{\rm beam}| < 2(3)$ GeV/c for $\pi ee(\pi\pi^0 ee)$; $P_T < 30$ MeV/c
- LAV photon veto
- e and π identified using $E({\rm LKr})/P$: $0.95 < \frac{E}{P}(e) < 1.05$, $\frac{E}{P}(\pi) < 0.85$

For $K^+ \to \pi^-\pi^0 e^+e^+$ search:

- reconstruct $\pi^0 \to \gamma\gamma$ decay from 2 isolated photons in LKr
- the longitudinal position of π^0 decay $Z_{\pi^0} = Z_{\rm LKr} - D_{12}\sqrt{E_1E_2}/m_{\pi^0}$ must be consistent with the decay vertex



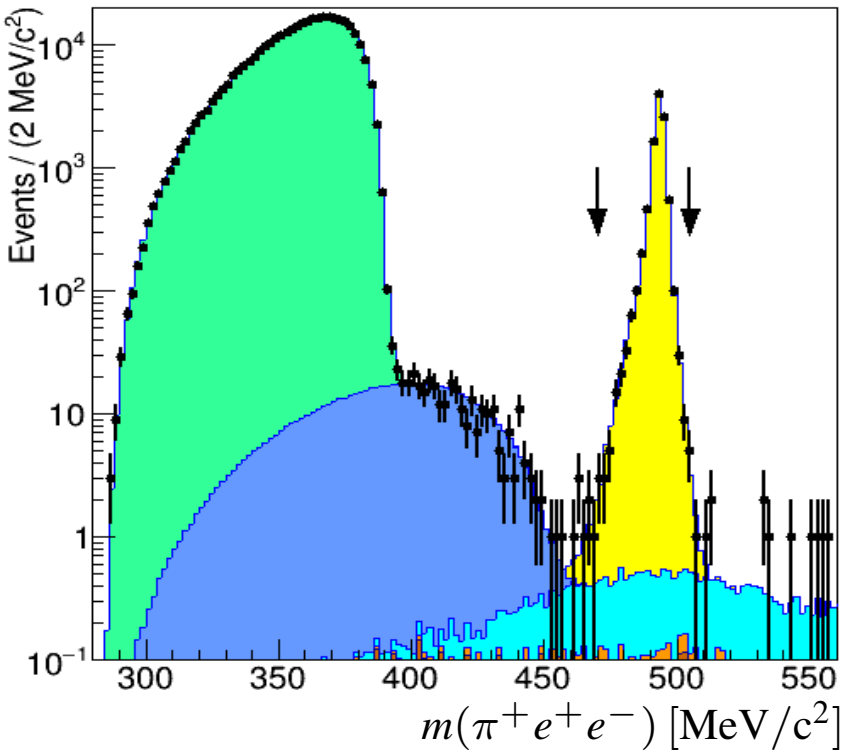
Blind analysis: 1) plot the $\pi^-(\pi^0)e^+e^+$ invariant mass distribution;
2) uncover signal region after finalizing all cuts.

$K^+ \to \pi^- e^+ e^+$ (LNV)

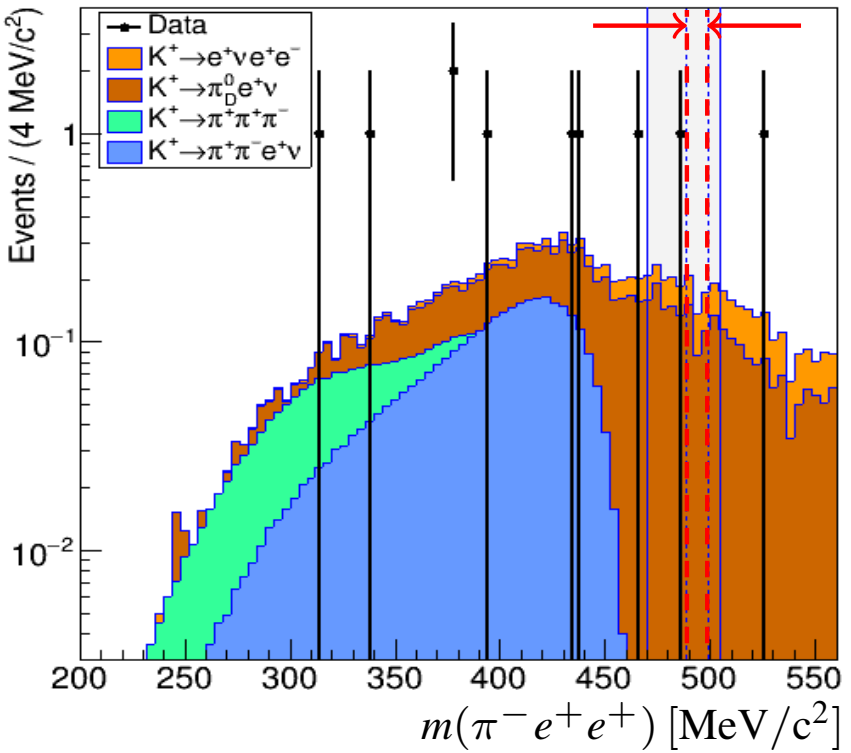
RICH-based e^+ identification used to suppress dominant backgrounds from

$K^+ \to \pi^+ \pi^0_D (\pi^0_D \to e^+e^-\gamma)$ and $K^+ \to \pi^+ e^+ e^-$ with double π/e mis-ID

$\pi^+e^+e^-$ (normalization)



$\pi^-e^+e^+$ (LNV) [signal region]



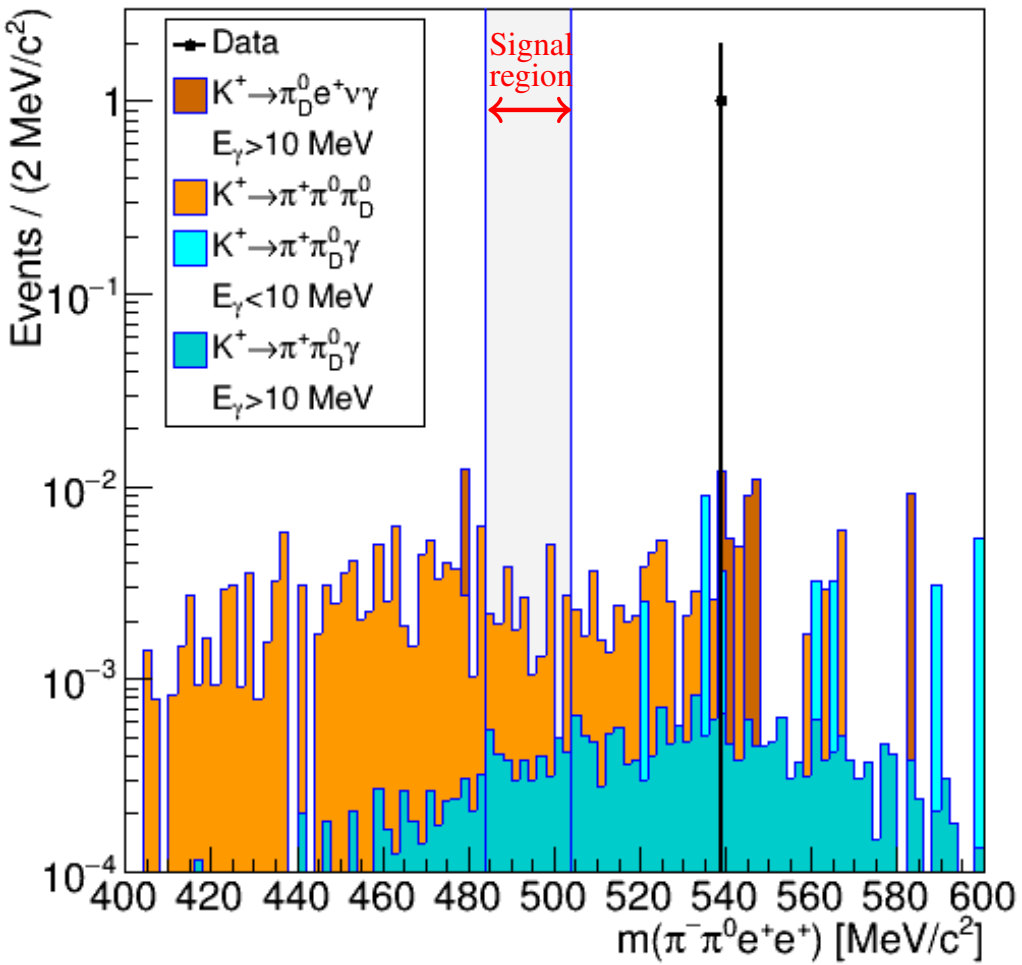
- Observed $\pi^-e^+e^+$ candidate events in signal region: 0
- Expected background events: 0.43 ± 0.09

$\mathrm{BR}(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ at 90% CL. [PLB 830 (2022) 137172]

Factor 4 improvement w.r.t. previous measurement [PLB 797 (2019) 134794]

$K^+ \to \pi^-\pi^0 e^+e^+$ (LNV)

$\pi^-\pi^0\, e^+e^+$ (LNV) selection



Observed candidate events in signal region: 0

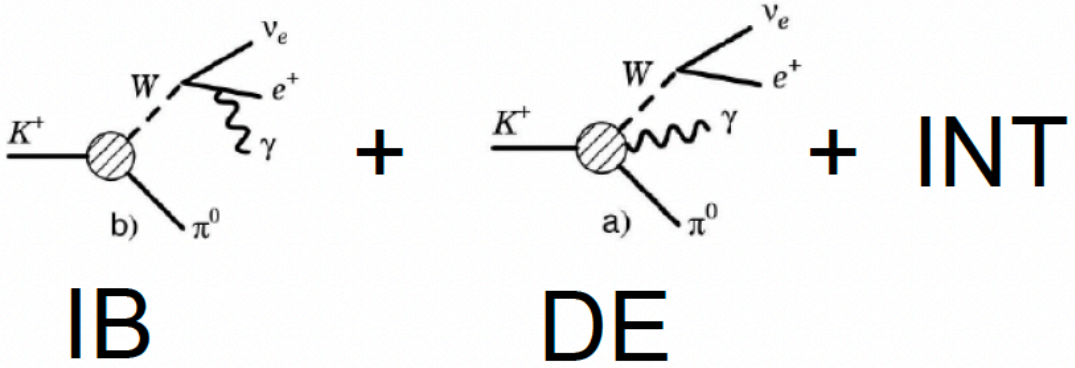
Expected background events: 0.44 ± 0.02

First search for this mode

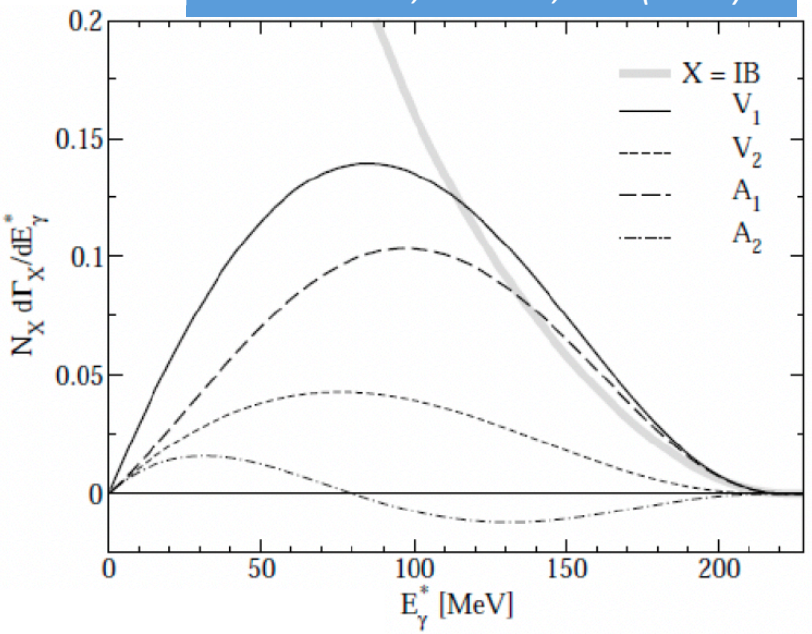
$\mathrm{BR}(K^+ \to \pi^-\pi^0\, e^+e^+) < 8.5 \times 10^{-10}$ at 90% CL.

[PLB 830 (2022) 137172]

The $K^+ \to \pi^0 e^+ \nu \gamma$ ($K_{e3\gamma}$) decay



Kubis et al., EPJ C50, 557 (2007)



- Dominant Inner Bremsstrahlung (IB) decay amplitude:
  - divergent for $E_\gamma \to 0$ and $\theta_{e\gamma} \to 0$
  - parametrized in terms of K_{e3} form factors
- Direct Emission (DE) $\approx 1\%$ of total amplitude:
  - calculated up to $\mathcal{O}(p^6)$ in ChPT

BR($K^+ \to \pi^0 e^+ \nu \gamma$) : present status

Define three kinematical regions $(j = 1, 2, 3)$ **:**

$$R_j = \frac{\mathbf{BR}(K^{j\ \mathrm{cut}}_{e3\gamma})}{\mathbf{BR}(K_{e3})} = \frac{\mathbf{BR}(K^+ \to \pi^0 e^+ \nu\gamma)[E^{j\ \mathrm{cut}}_{\gamma},\ \theta^{j\ \mathrm{cut}}_{e\gamma}]}{\mathbf{BR}(K^+ \to \pi^0 e^+ \nu)}$$

- Cuts are applied on photon energy E_γ and photon-positron opening angle $\theta_{e\gamma}$ (in the Kaon rest frame)

Theory | Measurements

Akimenko et al., PAN 70, 702 (2007)

Kubis et al., EPJ C50, 557 (2007)

Polyarus et al., EPJ 81, 2, 161 (2021)

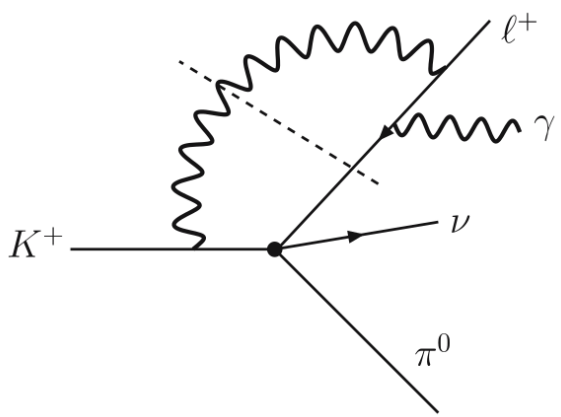
Region	E_γ cut	$\theta_{e,\gamma}$ cut	$O(p^6)$ ChPT [EPJ C 50, 557]	ISTRA+	OKA
R_1 ($\times 10^2$)	$E_\gamma > 10$ MeV	$\theta_{e,\gamma} > 10^\circ$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
R_2 ($\times 10^2$)	$E_\gamma > 30$ MeV	$\theta_{e,\gamma} > 20^\circ$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
R_3 ($\times 10^2$)	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

- Most recent calculation of $R_2 = (0.56 \pm 0.02)\%$ Khriplovich et al., PAN 74, 1214 (2010)

$K^+ \to \pi^0 e^+ \nu\gamma$ decay: T-asymmetry

T-odd observable ξ (in the Kaon rest frame) and **T-violating** asymmetry A_ξ :

$$\xi = \frac{\overrightarrow{p_\gamma} \cdot (\overrightarrow{p_e} \times \overrightarrow{p_\pi})}{m_K^3} \quad ; \quad A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$



Non-zero A_ξ values due to NLO (one-loop) electromagnetic and hadronic corrections

[Müller et al., EPJ C 48 (2006) 427]

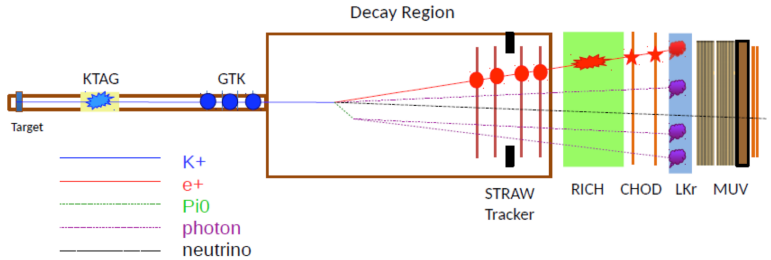
Theoretical predictions: $\left|A_\xi^{\text{SM and beyond}}\right| < 10^{-4}$

State of the art (measurements):

$$A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$$

No measurements provided for R_1 and R_2

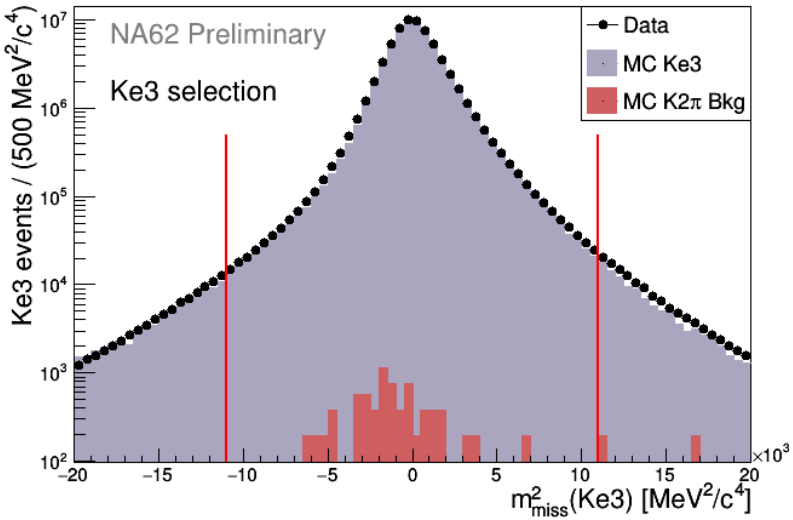
$K_{e3(\gamma)}$ event selection



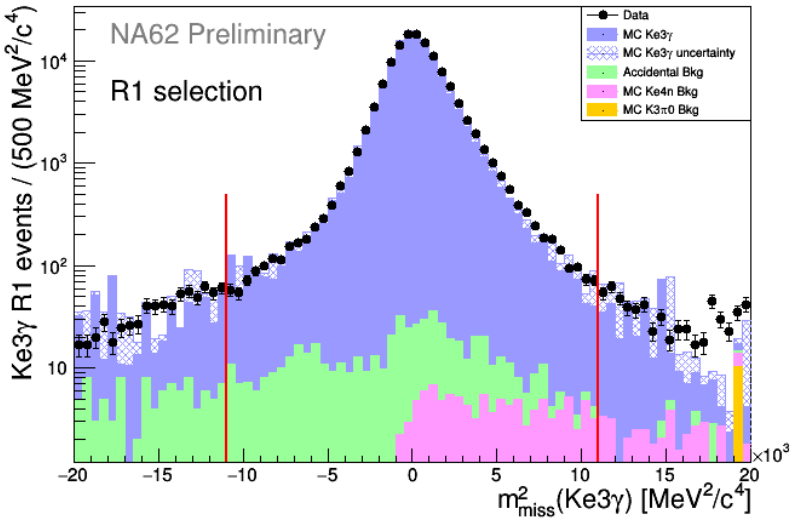
- 2017–2018 data sample
- Use K_{e3} as normalization channel
- K^+ : track and momentum reconstructed in GTK, identified in KTAG
- e^+ : track and momentum reconstructed in STRAW, identified by RICH and from E(LKr)/P(STRAW)
- Decay vertex identified by K^+ and positron tracks
- $\pi^0 \to \gamma\gamma$ identified selecting two photons in LKr and reconstructing the invariant mass (assuming they originate from the vertex)
- Radiative γ identified as an extra in-time gamma in LKr
- No in-time extra activity in Veto system and MUV
- Dedicated kinematic cuts to reject $K^+ \to \pi^+\pi^0(\pi^0)$ backgrounds
- Final kinematic selection based on the **missing** (neutrino) **mass** both for signal and normalization channels:

$$m^2_{miss}(K_{e3\gamma}) = (P_K - P_e - P_{\pi^0} - P_\gamma)^2 \qquad m^2_{miss}(K_{e3}) = (P_K - P_e - P_{\pi^0})^2$$

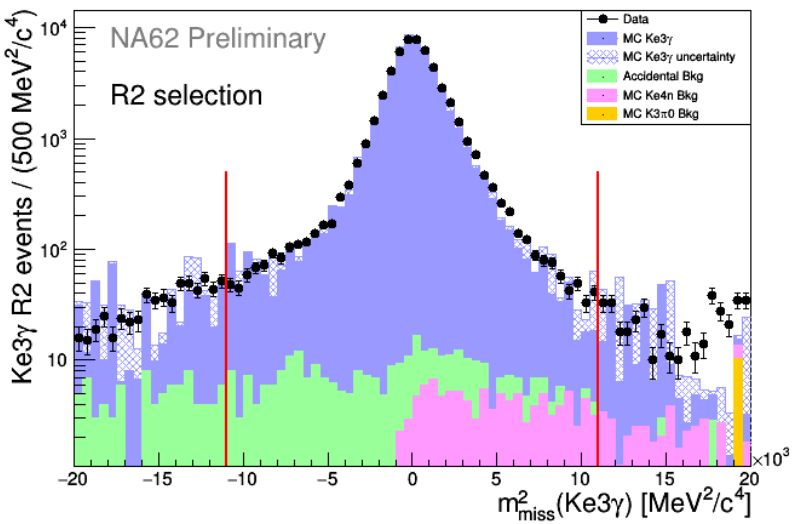
$K_{e3(\gamma)}$ selected events



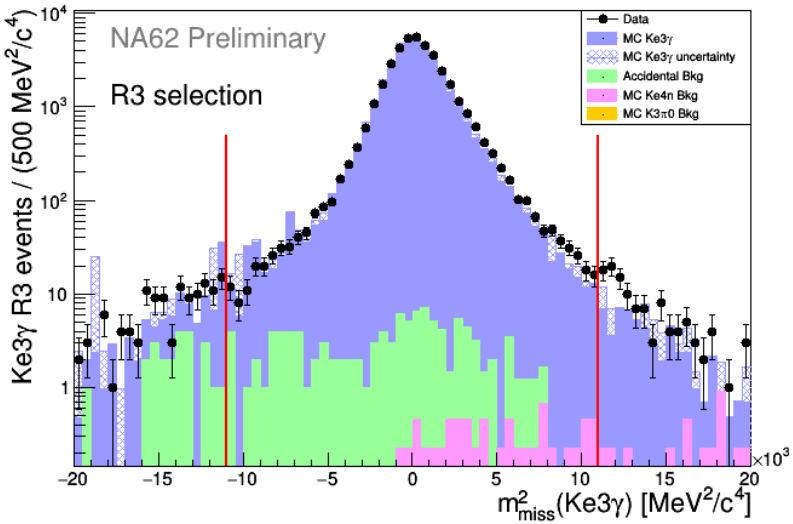
Normalization: 66M events, B/S $\sim 10^{-4}$



Signal(R1): 130K events, B/S $\simeq 0.5\%$



Signal(R2): 54K events, B/S $\simeq 0.6\%$



Signal(R3): 39K events, B/S $\simeq 0.3\%$

$K^+ \to \pi^0 e^+ \nu \gamma$: preliminary R_j measurements

NA48/2 preliminary results based on 2017–2018 data set

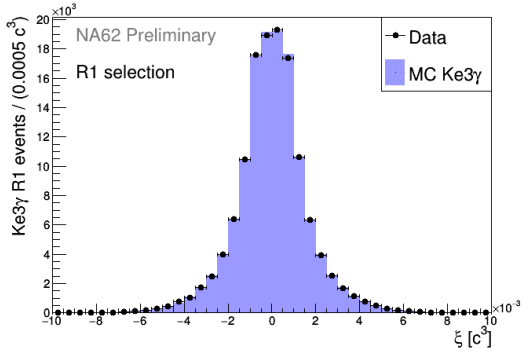
	$O(p^6)$ *ChPT*	ISTRA+	OKA	**NA62 preliminary**
R_1 ($\times 10^2$)	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$\mathbf{1.684 \pm 0.005 \pm 0.010}$
R_2 ($\times 10^2$)	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$\mathbf{0.599 \pm 0.003 \pm 0.005}$
R_3 ($\times 10^2$)	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$\mathbf{0.523 \pm 0.003 \pm 0.003}$

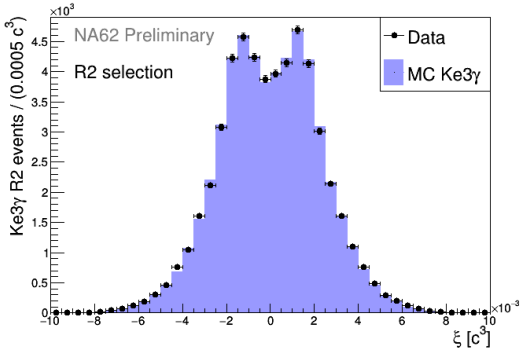
[Kubis et al.]

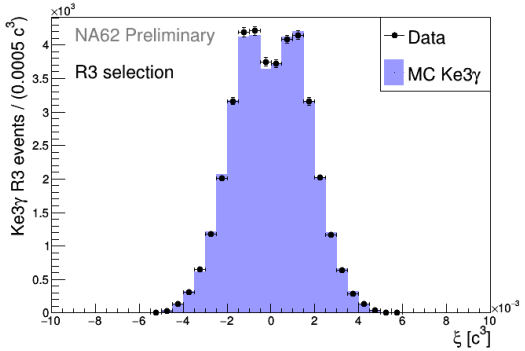
- Improved precision (factor between 2 and 3.6) w.r.t. previous results
- Measured values are 6–7% lower than predictions by Kubis et al.(2007)
- NA62 result for R_2 is half way between the two latest theoretical predictions:

Theor(R_2)= $(0.640 \pm 0.008)\%$ [Kubis et al., EPJ C50 (2007) 557]
Theor(R_2)= $(0.56 \pm 0.02)\%$ [Khriplovitch et al., PAN 74 (2011) 1214]

NA62 preliminary A_ξ measurements







$$A_\xi = A_\xi^{\text{Data}} - (A_\xi^{\text{MC-reco}} - A_\xi^{\text{MC-gene}}) \simeq A_\xi^{\text{Data}} - A_\xi^{\text{MC-reco}}$$

	R_1 selection	R_2 selection	R_3 selection
A_ξ^{Data} $(\times 10^2)$	0.2 ± 0.3	0.1 ± 0.4	-0.6 ± 0.5
$A_\xi^{\text{MC-reco}}$ $(\times 10^2)$	0.3 ± 0.2	0.4 ± 0.3	0.3 ± 0.5
$A_\xi^{\text{MC-gene}}$ $(\times 10^2)$	-0.01 ± 0.01	0.00 ± 0.02	-0.01 ± 0.02
A_ξ $(\times 10^2)$	$-0.1 \pm 0.3_{\text{stat}} \pm 0.2_{\text{MC}}$	$-0.3 \pm 0.4_{\text{stat}} \pm 0.3_{\text{MC}}$	$-0.9 \pm 0.5_{\text{stat}} \pm 0.4_{\text{MC}}$

- R_3 T-asymmetry precision improved by a factor greater than 3:
$$A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$$
- First T-asymmetry measurements ever performed for R_1 and R_2
- T-asymmetry consistent with zero, sensitivity still far from theoretical predictions

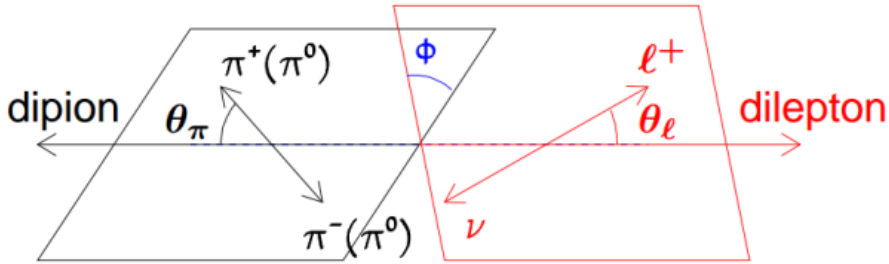
$K^\pm \to \pi\pi\, l^\pm\nu$ (K_{l4}) – current status

Theory

K^+(at rest) $\to$ $\pi\,\pi$ $l^+\nu$ $(l = e, \mu)$

Five kinematic variables
(Cabibbo-Maksymowicz 1965):

$S_\pi = M^2_{\pi\pi}$, $S_e = M^2_{l\nu}$,
$\cos\theta_\pi$, $\cos\theta_l$, ϕ



- The $K^\pm \to \pi\pi\, l^\pm\nu$ amplitudes depend on F, G, H, R form factors.
- $\pi^0\pi^0$ in s-wave $\Rightarrow$ no dependence on $\cos\theta_\pi$, ϕ; only F and R contribute.
- Negligible R contribution to K_{e4} due to the small electron mass.

Measurements

K_{l4} mode	BR $[10^{-5}]$	$N_{\text{candidates}}$	Experiment
K^{+-}_{e4}	4.26 ± 0.04	1 108 941	NA48/2 (2012)
K^{00}_{e4}	2.55 ± 0.04	65 210	NA48/2 (2014)
$K^{+-}_{\mu4}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K^{00}_{\mu4}$	?		

$K^\pm \to \pi^0\pi^0\mu^\pm\nu$ ($K^{00}_{\mu 4}$) at NA48/2

Goals:

- first observation
- ChPT test
- check of R presence

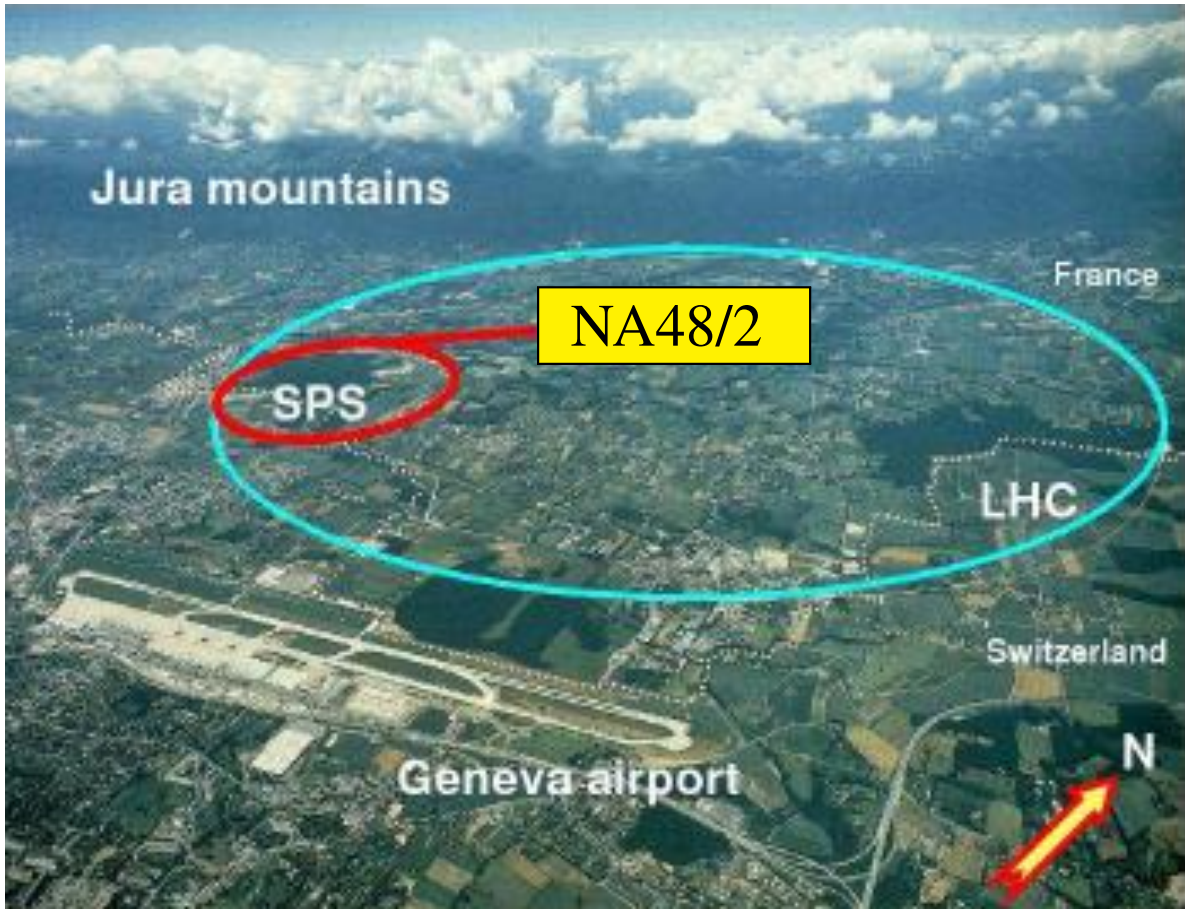
Analisys challenge:

suppression of huge background from $K^\pm \to \pi^0\pi^0\pi^\pm$ ($\pi^\pm \to \mu^+\nu$)

Form factors:

- Use the experimental $F(S_\pi, S_l)$ parameterization from K^{00}_{e4}, according to lepton universality [NA48/2 JHEP 08 (2014) 159]
- For $R(S_\pi, S_l)$ use ChPT calculation [J.Bijnens, G.Colangelo, J.Gasser, Nucl.Phys.B 427 (1994) 427]

The NA48/2 experiment



The NA48/2 collaboration:

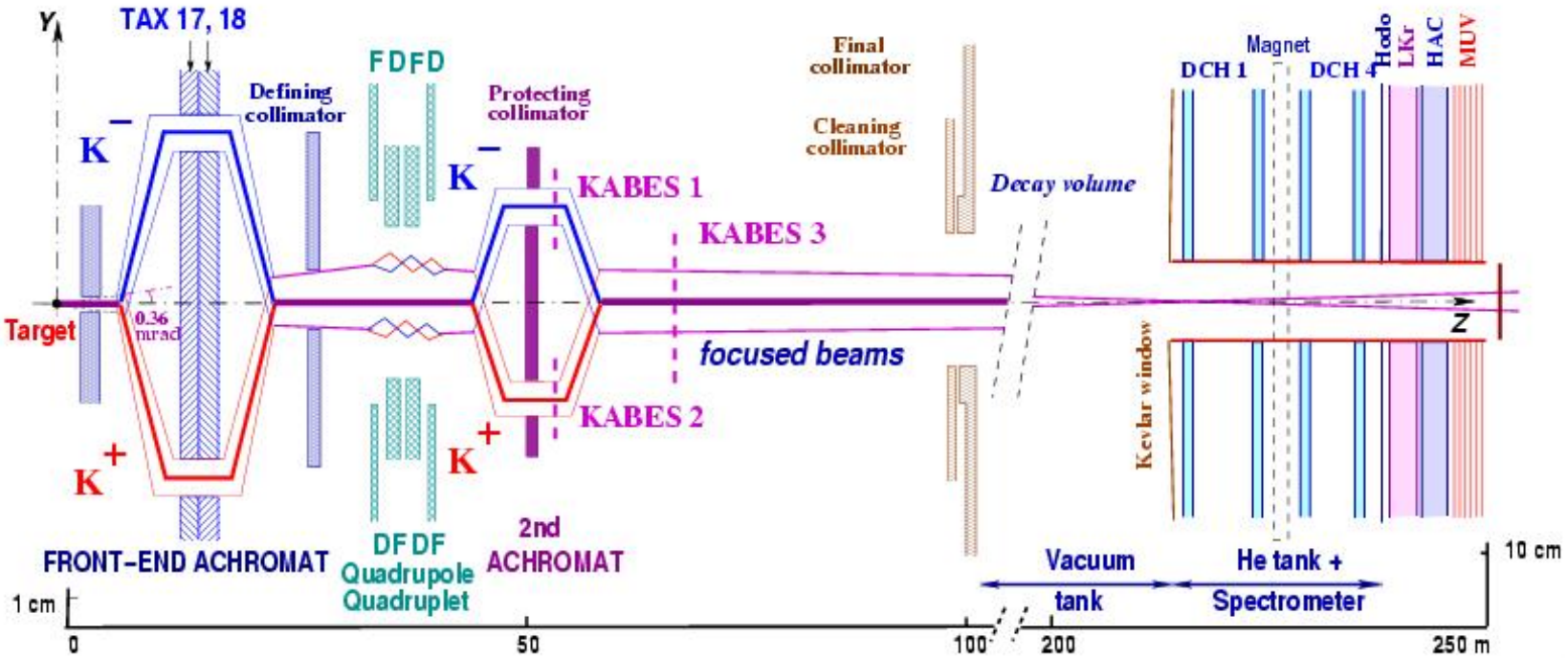
$\sim$ 100 physicists from 15 institutes in 8 countries

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

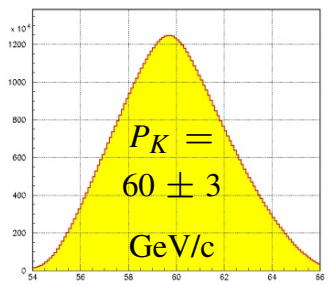
- NA31 (1984–1990)
  K_L/K_S, direct CPV:
  First evidence
- NA48 (1997–2001)
  K_L/K_S, direct CPV:
  Precise measurement
- NA48/1 (2002), K_S:
  K_S/hyperon rare decays
- NA48/2 (2003–2004)
  K^+/K^-: CPV search,
  charge asymmetry
- NA62-R_K (2007–2008)
  K^+/K^- : e/μ universality
- NA62 (2014–), K^+ :
  Rare Kaon decays,
  $K^+ \to \pi^+\nu\bar{\nu}$

The NA48/2 Kaon beam

2003 + 2004 run: ~ 6 months, $\sim 2 \times 10^{11}$ $K^\pm$ decays in flight



Simultaneous $K^\pm$ beams

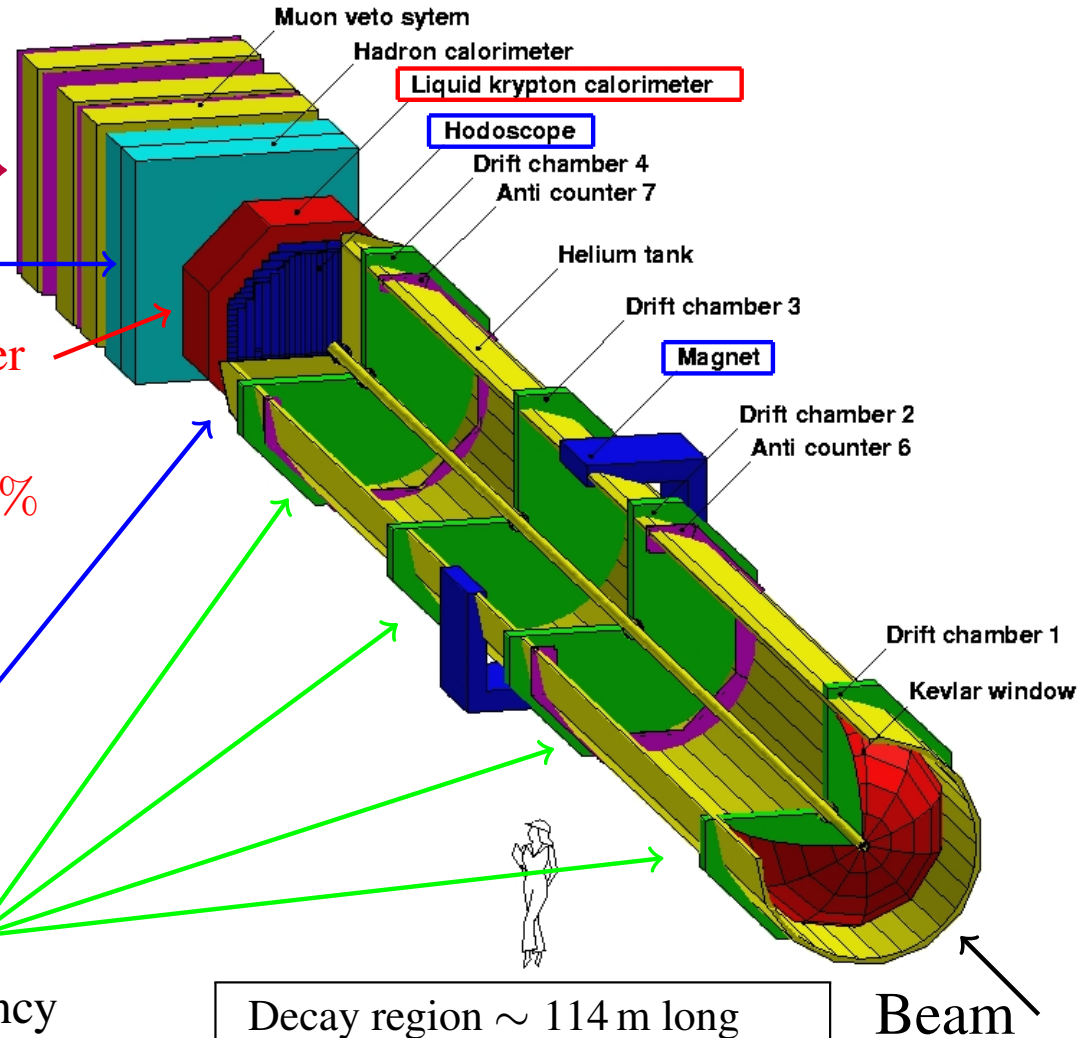


KABES (Kaon Beam Spectrometer) resolutions:

- $\sigma(X, Y) \sim 800\,\mu$m
- $\sigma(P_K)/P_K \sim 1\%$
- $\sigma(T) \sim 600$ ps

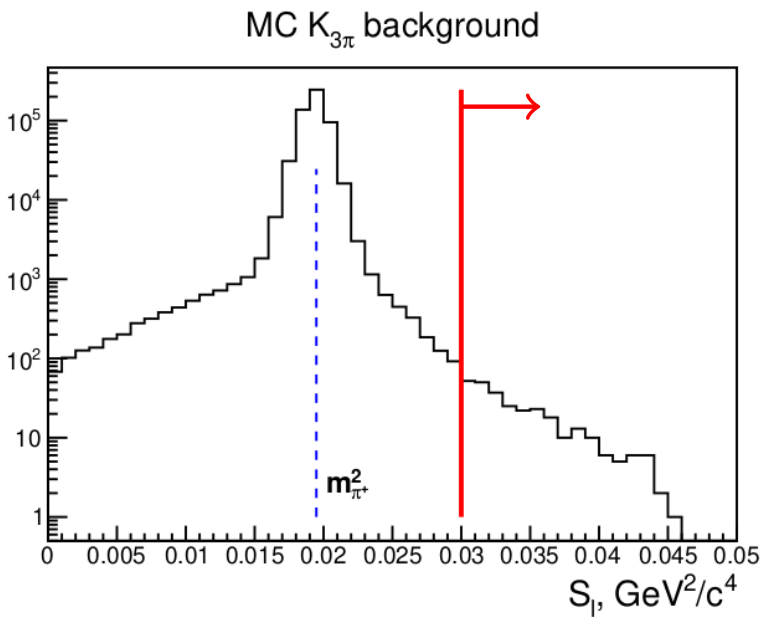
The NA48/2 detectors

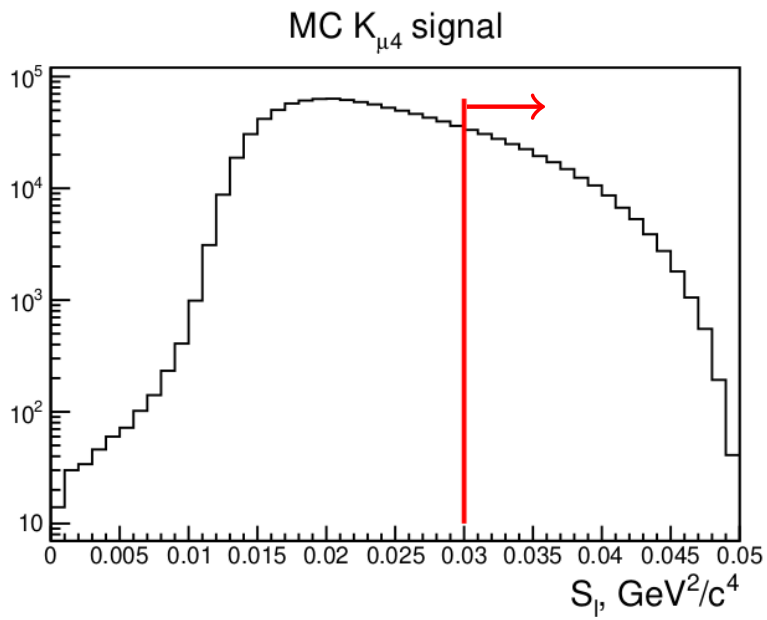
- Muon detectors (scintillators)
- Hadron calorimeter
- Liquid Krypton (LKr) EM calorimeter
  high granularity, quasi-homogeneous
  $\sigma_E/E = 3.2\%/E^{1/2} \oplus 9\%/E \oplus 0.42\%$
  (E in GeV)
  $\sigma_x = \sigma_y \sim 1.5$ mm at 10 GeV
- Scintillator hodoscope (2 planes)
  fast trigger, $\sigma_t = 150$ ps
- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy $\Rightarrow$ efficiency
  $\sigma_p/p = 1.02\% \oplus 0.044\%\, p$ (p in GeV/c)
- Photon vetos



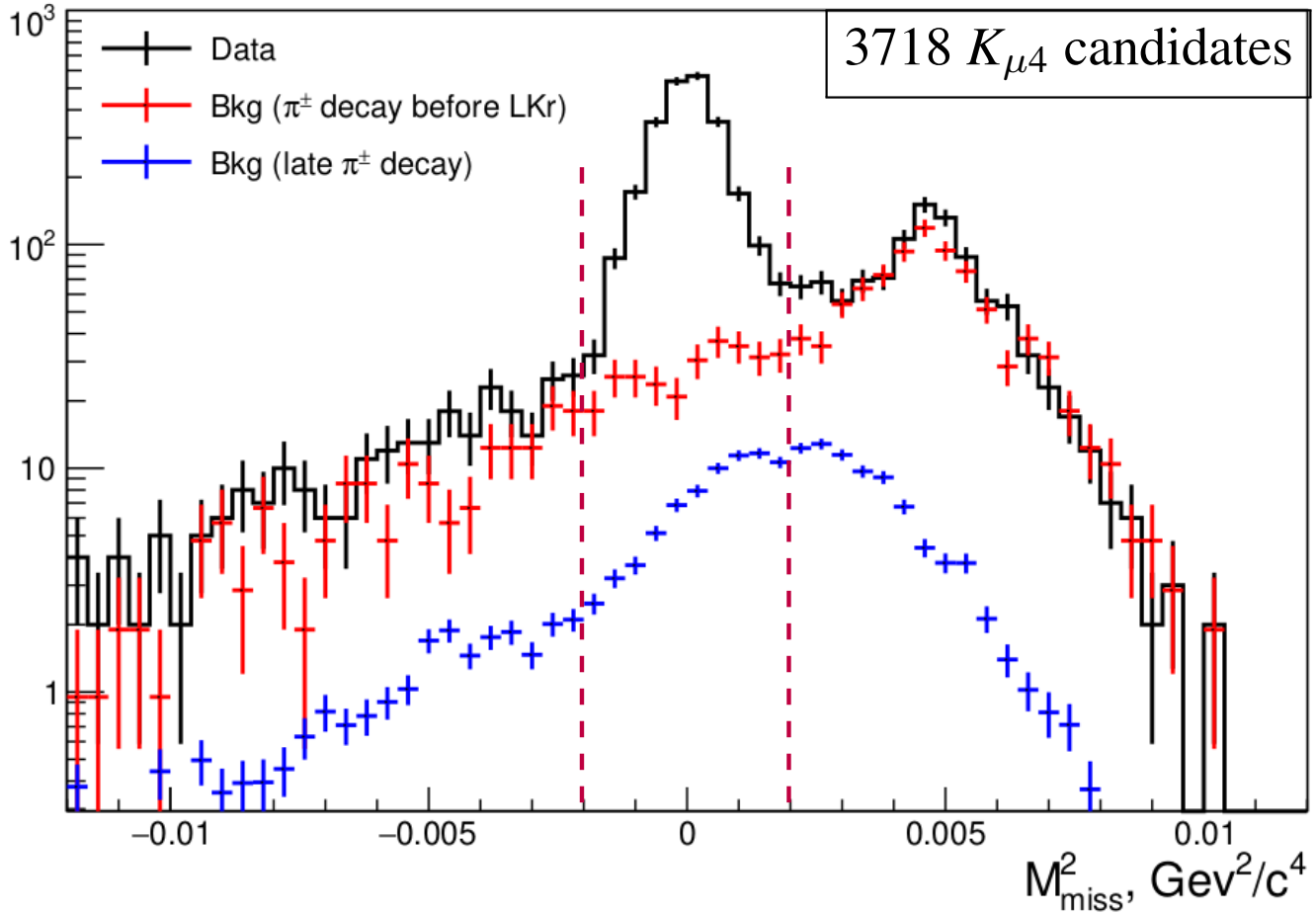
$K^\pm \to \pi^0\pi^0\mu^\pm\nu$ event selection

- Use $K^\pm \to \pi^\pm\pi^0\pi^0$ as normalization channel
- First set of common cuts for signal and normalization: select one charged particle and 2 π^0s from a common origin
- Dedicated kinematical cuts to select signal events
- Reject $K^\pm \to \pi^\pm\pi^0\pi^0$ events with $\pi^\pm \to \mu^\pm\nu$ decay in flight by imposing $S_l \equiv M^2(\mu^\pm\nu) > 0.03\,\mathrm{GeV}^2/\mathrm{c}^4$





$K^\pm \to \pi^0\pi^0\mu^\pm\nu$ – residual background



- 2437 events in the M^2_{miss} signal region [-0.002,+0.002] GeV^2/c^4
- $354 \pm 33_{\text{stat}} \pm 62_{\text{syst}}$ expected background events

$K^\pm \to \pi^0\pi^0\mu^\pm\nu$ Branching Ratio

NA48/2 preliminary results

- For the restricted phase space:

$$\mathrm{BR}(K^\pm \to \pi^0\pi^0\mu^\pm\nu,\ S_l > 0.03\ \frac{\mathrm{GeV}^2}{\mathrm{c}^4}) = (0.65 \pm 0.019_{\mathrm{stat}} \pm 0.024_{\mathrm{syst}}) \times 10^{-6}$$
$$= (0.65 \pm 0.03) \times 10^{-6}$$

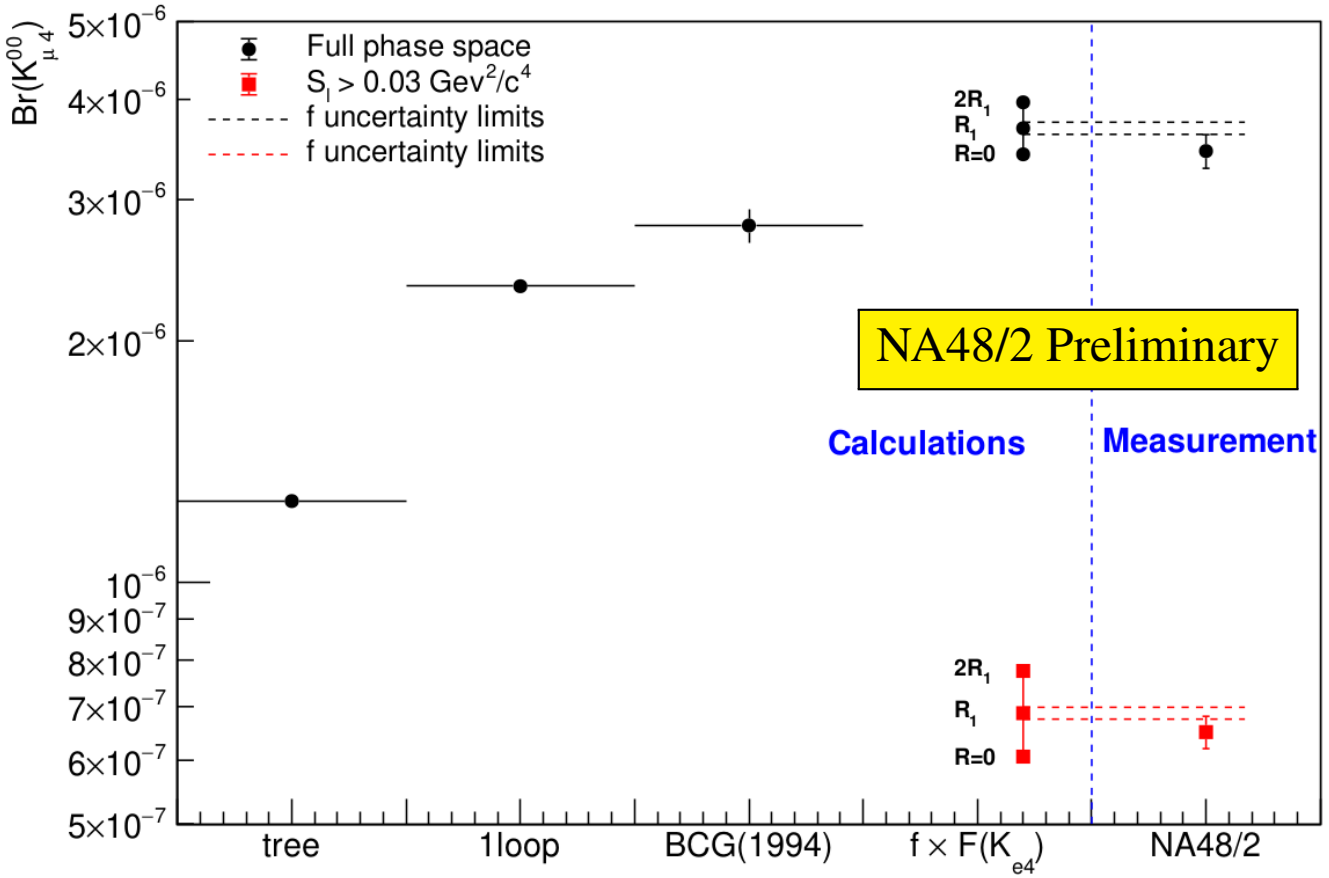
- For the full phase space:

$$\mathrm{BR}(K^\pm \to \pi^0\pi^0\mu^\pm\nu) = (3.4 \pm 0.10_{\mathrm{stat}} \pm 0.13_{\mathrm{syst}}) \times 10^{-6}$$
$$= (3.4 \pm 0.2) \times 10^{-6}$$

$K^\pm \to \pi^0\pi^0\mu^\pm\nu$ – Comparison with theory

Theory: J. Bijnens, G. Colangelo, J. Gasser, Nucl. Phys. B 427 (1994) 427

- tree approsimation;
- 1-loop;
- 'beyond 1-loop' with measured F from [Rosselet et al., Phys.Rev.D 15(1977) 574]



Recalculated now with:

- $F(K_{e4})$ from NA48/2 [JHEP 08 (2014) 159]
- $R_1 = R(1\text{ loop})$;
- 1-loop (F, R) phase;
- 2020 PDG constants.

NA48/2 preliminary results are consistent with a contribution of the R form factor, as from 1-loop ChPT calculation

Summary

- Searches for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \pi^0 e^+ e^+$ **LNV** decays have been performed at **NA62** using 2016–2018 data:
  - world-best limits obtained, sensitivity limited by the dataset size.
  - Results published in Phys. Lett. B 830 (2022) 137172
- New preliminary **NA62** results on $K^+ \to \pi^0 e^+ \nu\gamma$ decay:
  - experimental precision in branching fracion ratios (R_j) improved by a factor between 2.0 and 3.6, relative uncertainties $< 1\%$
  - measured T-asymmetries still compatible with zero, experimental sensitivity far from theoretical expectations
  - first T-asymmetry measurement for R_1 and R_2 , improvement by a factor greater than 3 for R_3
- **NA48/2** observed for the first time the $K^\pm \to \pi\pi\, e^\pm \nu$ (K_{e4}) decay:
  - preliminary measurements of the branching fraction are consistent with ChPT predictions for the R form factor