New measurement of the $K^+ \to \pi^+\mu^+\mu^-$ decay at NA62

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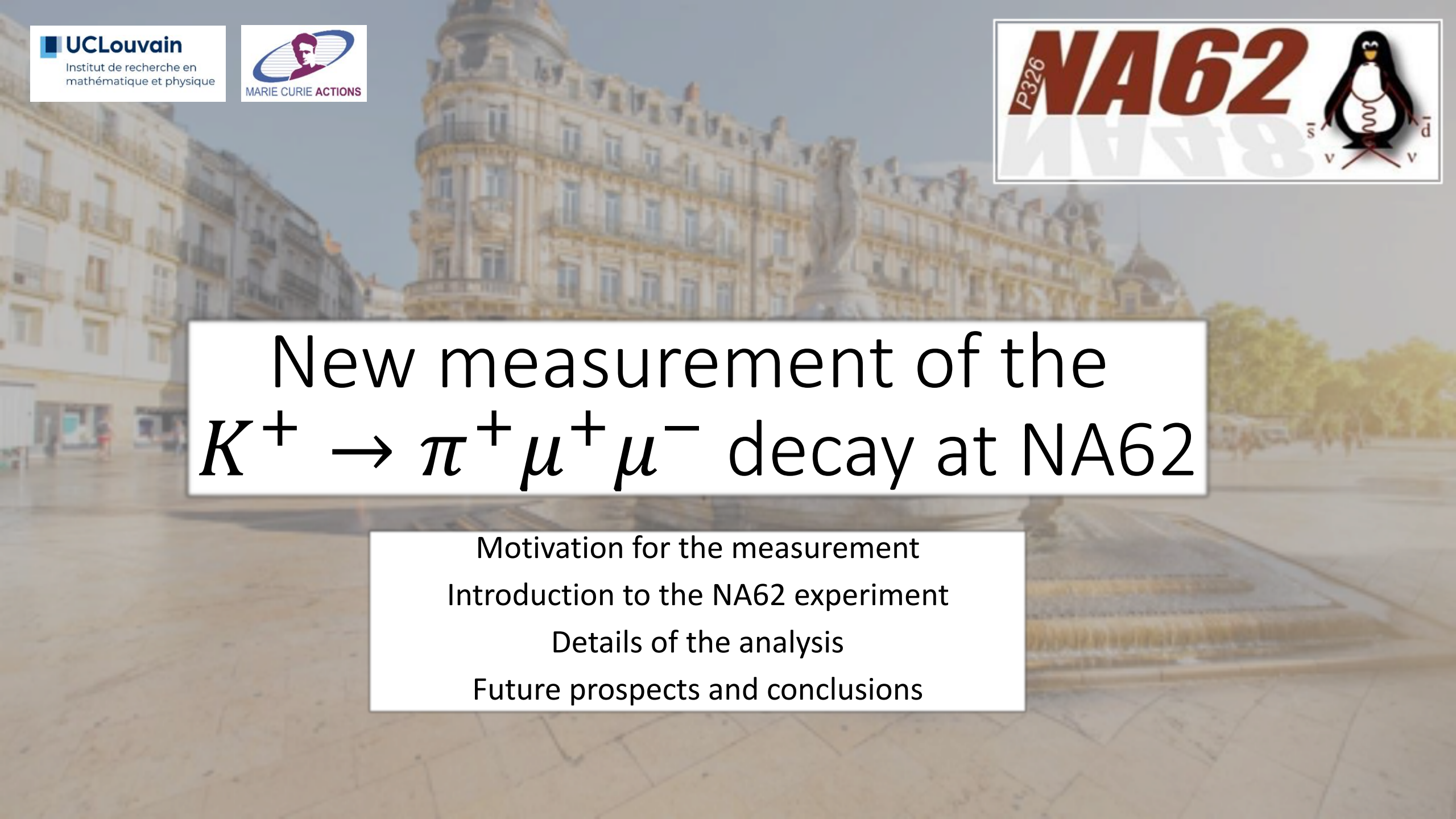

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MARIE CURIE ACTIONS

P326 NA62

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Motivation for the measurement

Introduction to the NA62 experiment

Details of the analysis

Future prospects and conclusions

Motivation

- Recent measurements of $b \to s\ell\ell$ transitions have shown striking deviations from SM predictions: “the B anomalies”

- Could expect similar effects to appear in $s \to d\ell\ell$ transitions
  - In *Minimal Flavour Violation* (MFV) models, correlated effects in B and K processes are anticipated, with the size of the effects dictated by the CKM matrix elements
  - More generally, new physics effects could actually be *larger* in kaon decays than B decays (in relative terms), since the existing CKM suppression in kaons is larger

- A strong motivation for studies of $s \to d\ell\ell$ kaon decays: $K^+ \to \pi^+\ell^+\ell^-$, $K_{S,L} \to \pi^0\ell^+\ell^-$

Motivation

- The $K^+ \to \pi^+ \ell^+ \ell^-$ decay is a *Flavour Changing Neutral Current* $s \to d\ell\ell$ process
- The SM branching fraction is $O(10^{-7})$; dominated by long-distance effects
  [Nucl. Phys. B291 (1987) 692–719], [JHEP 08 (1998) 004], [Phys. Part. Nucl. Lett. 5 (2008) 76–84], [Eur. Phys. J. C70 (2010) 219–231]

$$\frac{d\Gamma}{dz} = \frac{\alpha^2 M_K}{12\pi(4\pi)^4}\lambda^{\frac{3}{2}}(1, z, r_\pi^2)\sqrt{1 - 4\frac{r_\ell^2}{z}}\left(1 + 2\frac{r_\ell^2}{z}\right)|W(z)|^2$$

vector form factor

$z = m^2(\mu^+\mu^-)/m^2(K) = q^2/m_K^2$ $\qquad W(z) = G_F M_K^2(a_+ + b_+ z) + W^{\pi\pi}(z)$

a_+, b_+ are $K^+ \to \pi^+ \ell\ell$ FF parameters, $W^{\pi\pi}(z)$ is a pion loop term

- Ongoing effort to determine FF parameters a_+, b_+ from first principles using Lattice techniques
  [PoS LATTICE2016 (2017) 303], [Phys. Rev. D94 (2016) 114516]

- Short distance physics can be extracted by comparing form-factor parameters between $\pi^+\mu^+\mu^+$ and $\pi^+e^+e^-$ as the SM predicts them to be identical: a probe of *Lepton Flavour Universality*

Movation

- LFU predicts a_+ and b_+ to be the same in the ee and $\mu\mu$ mode
- Theoretical work published in [Phys. Rev. D 93, 074038 (2016)] tells us that a_+ can be related to C_{7V}:

$$a_+^{NP} = \frac{2\pi\sqrt{2}}{\alpha} V_{ud}V_{us}^* C_{7V}^{NP} \qquad C_{7V}^{\mu\mu} - C_{7V}^{ee} = \alpha \frac{a_+^{\mu\mu} - a_+^{ee}}{2\pi\sqrt{2}V_{ud}V_{us}^*}$$

- Which can be related to LFU in B decays (assuming MFV):

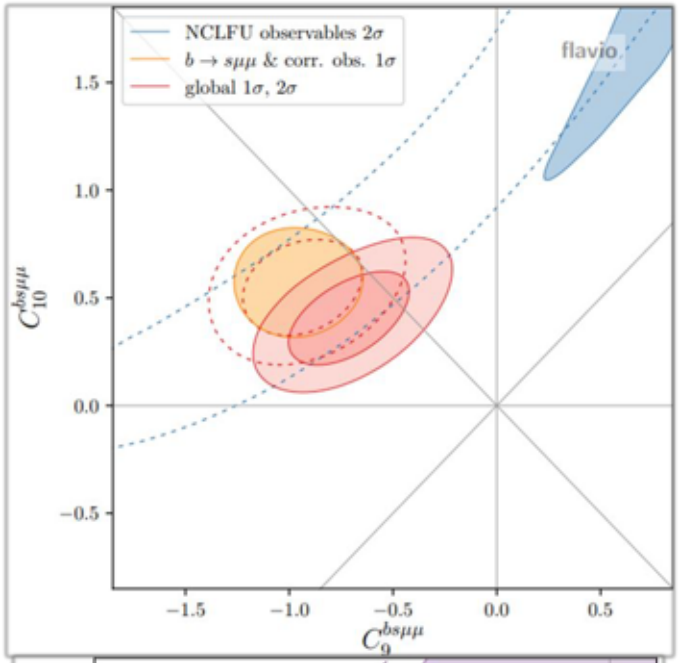
$$C_9^{B,\mu\mu} - C_9^{B,ee} = -\frac{a_+^{\mu\mu} - a_+^{ee}}{\sqrt{2}V_{td}V_{ts}^*} \approx -19 \pm 79$$

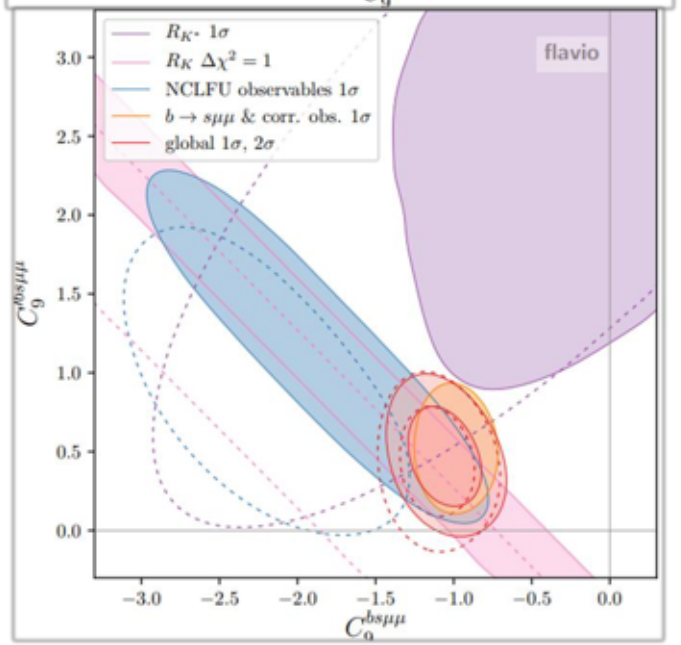
- Largest uncertainty is on $a_+^{\mu\mu}$

Channel	a_+	b_+	Reference
ee	-0.587 ± 0.010	-0.655 ± 0.044	E865 [14]
ee	-0.578 ± 0.016	-0.779 ± 0.066	NA48/2 [15]
$\mu\mu$	-0.575 ± 0.039	-0.813 ± 0.145	NA48/2 [16]

Table 1. Fitted values of coefficients in the vector form factor (5).

- A factor 10 improvement in precision will probe B anomalies.
- Strong motivation to **reduce uncertainty on a_+ in the $\mu\mu$ mode**

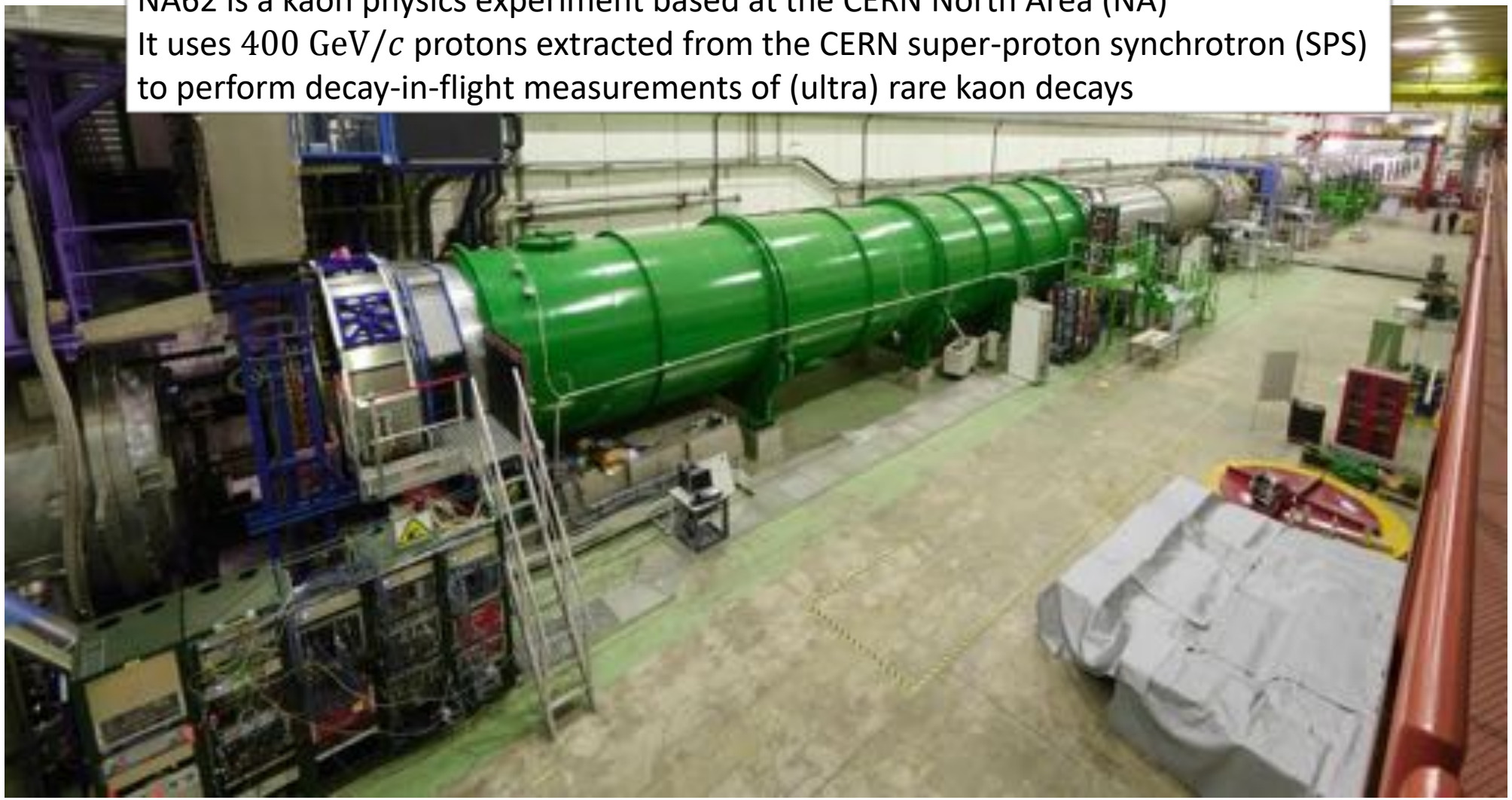




[Eur. Phys. J. C **80**, 252 (2020)]

The NA62 experiment

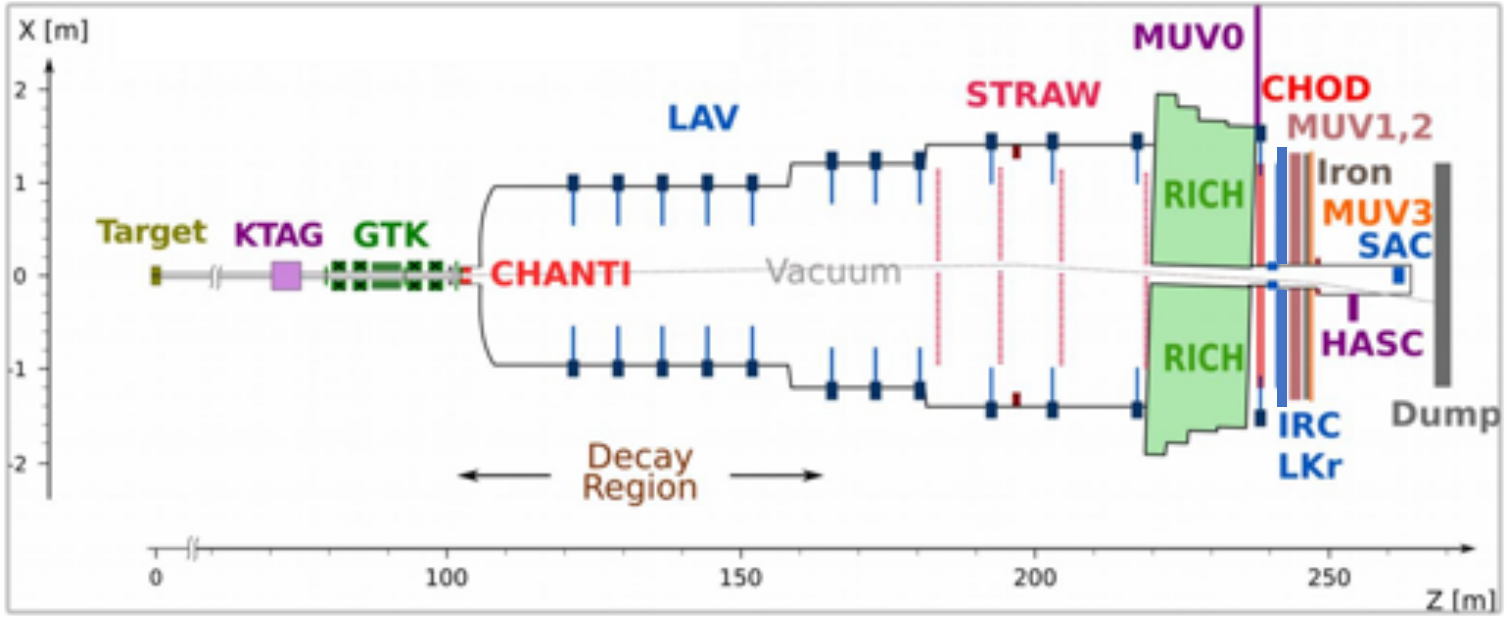
NA62 is a kaon physics experiment based at the CERN North Area (NA)
It uses $400\ \mathrm{GeV}/c$ protons extracted from the CERN super-proton synchrotron (SPS)
to perform decay-in-flight measurements of (ultra) rare kaon decays



The NA62 detector

$400\ \mathrm{GeV}/c$ protons from CERN SPS

Slow extraction in ‘spills’ of 5 seconds



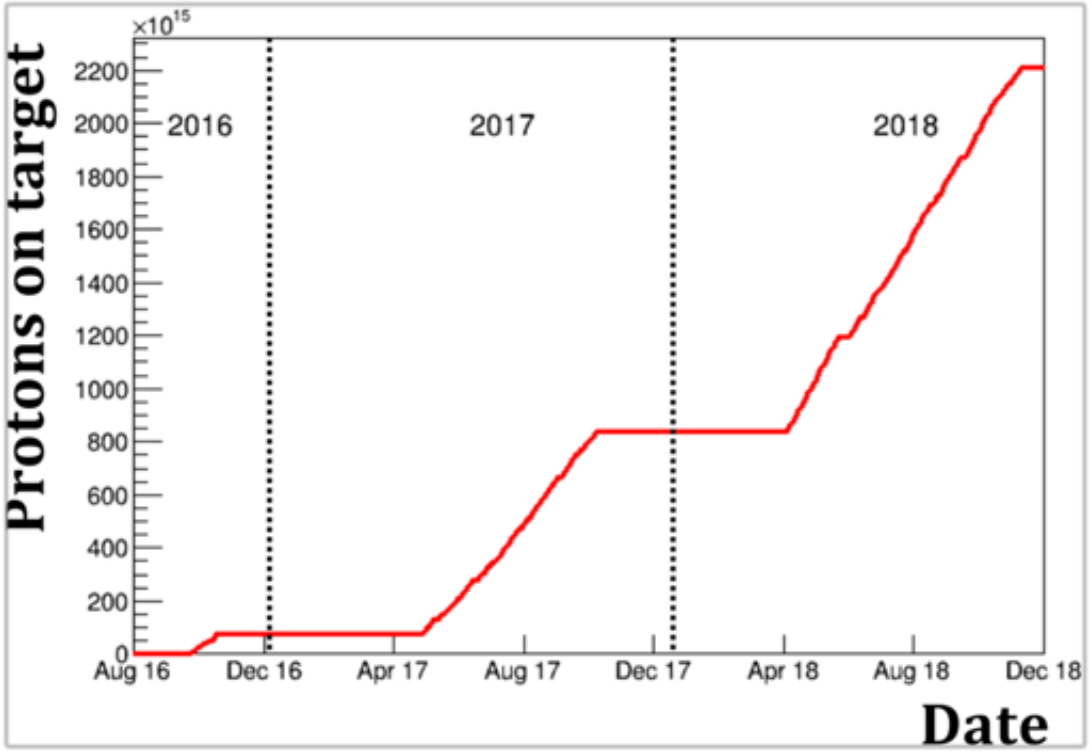
- Proton-target interactions + achromatic selector forms secondary hadron beam with $p \approx 75\ GeV/c$
  - There are $750\mathrm{MHz}$ of particles in the secondary beam; 6% are K^+ $(45\mathrm{MHz})$
- Measurement of all beam particles by kaon tagger **KTAG** and beam-particle tracker **GTK**
- About 15% of K^+ decay within the $\sim 75\mathrm{m}$ vacuum **decay region**, which defines the experiments **fiducial volume**
- Measurement of K^+ decay products by the **STRAW** tracker and **CHOD** detectors
- Particle identification by the **RICH**, the **LKr** and **MUV** calorimeters, and the **MUV3** detector
- Hermetic photon veto provided by the **LAV, LKr, IRC, SAC** photon detectors

NA62 data sample

- Three years of $NA62$ data taking:
  2016: $\sim 1 \times 10^{11}$ K^+ decays
  2017: $\sim 2 \times 10^{12}$ K^+ decays
  2018: $\sim 4 \times 10^{12}$ K^+ decays

- Present result based on **2017** & **2018** data

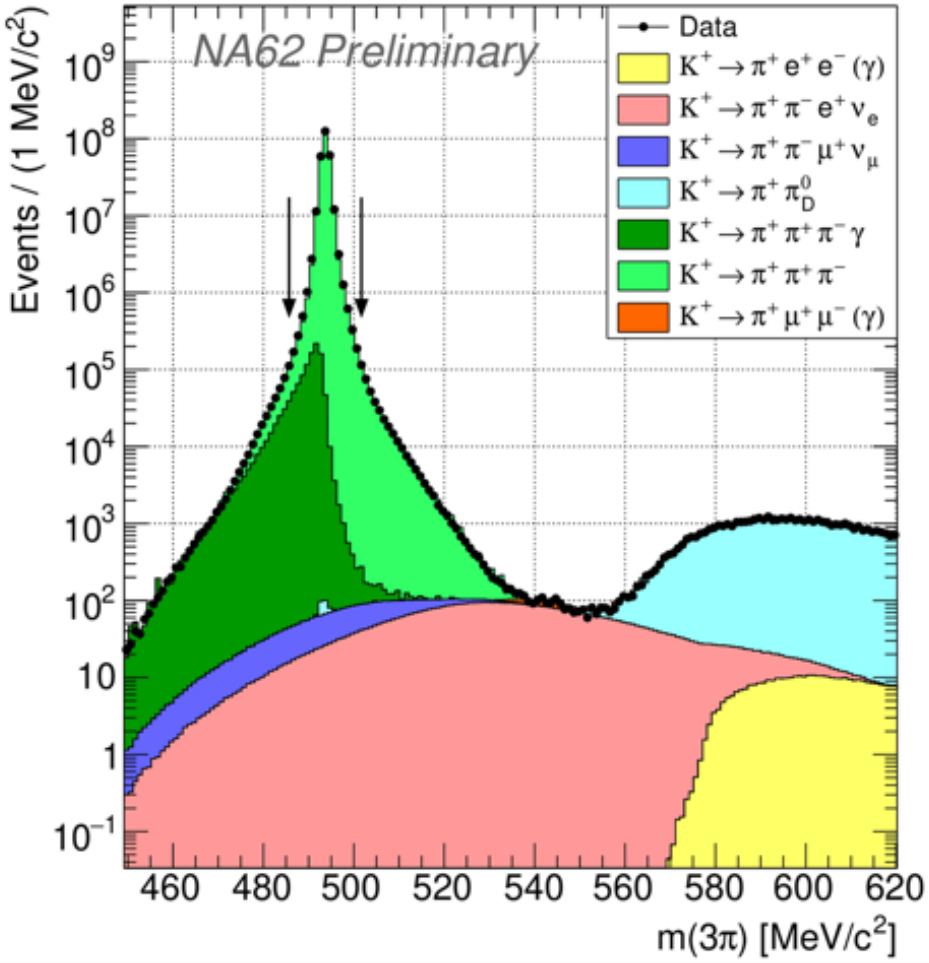
- Triggers employed for the $\pi\mu\mu$ analysis:
  - Generic "multi track" trigger with typical downscaling of $D = 100$
  - Specific "di muon" trigger with downscaling of $D = 2$



NA62 $K^+ \to \pi^+\pi^+\pi^-$ sample

- Generic three-track selection:
  - Three tracks reconstructed in the STRAW spectrometer, consistent with having originated from a K^+ decay in the fiducial volume of the detector
  - Track timing from CHOD and KTAG
  - Electrons suppressed using information from the LKr calorimeter
- $\mathbf{2.78 \times 10^8}$ $K^+ \to \pi^+\pi^+\pi^-$ candidates were selected in the data, to be used as a normalisation channel
- Number of kaon decays in the fiducial volume estimated to be: $N_K \approx 6.76 \times 10^{12}$

Shaded regions are samples of MC simulated events

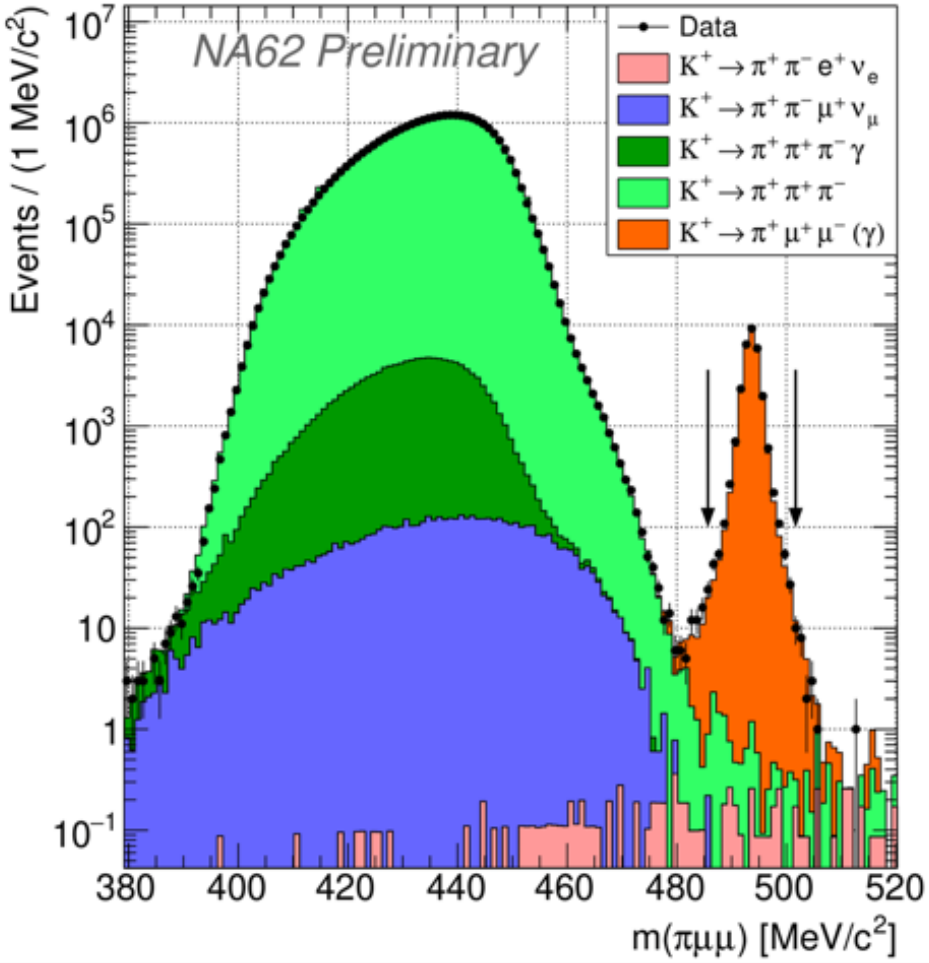


Candidate invariant mass under $\pi\pi\pi$ assumption

NA62 $K^+ \to \pi^+\mu^+\mu^-$ sample

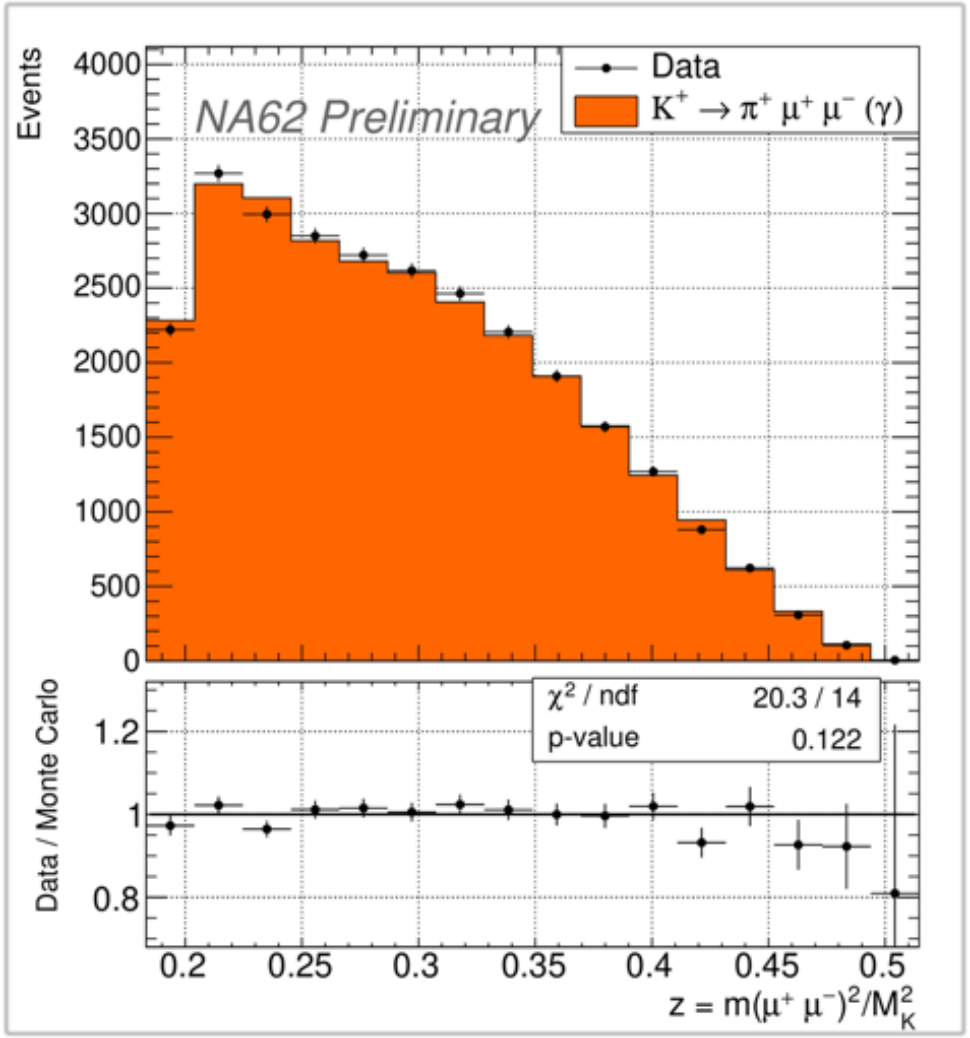
- Specific $\pi^+\mu^+\mu^-$ selection:
  - Muons identified using information from MUV3 and LKr
  - Kinematic cuts applied to further suppress $K^+ \to \pi^+\pi^+\pi^-$ backgrounds
- **28011** $\pi\mu\mu$ candidates were selected in the data
  - About 9x more than NA48/2 measurement [Physics Letters B 697 (2011), pages 107-115]
- Background contamination $O(10)$ events; less than 1 per mille

Shaded regions are samples of MC simulated events



Candidate invariant mass under $\pi\mu\mu$ assumption

Fit to the form-factor parameters



Fitting procedure:

- z spectrum of simulated $K^+ \to \pi^+\mu^+\mu^-$ events reweighted to best fit the data by minimising $\chi^2(a, b)$

Best fit of FF parameters:

$$a = -0.592 \pm 0.013_{\text{stat}}$$
$$b = -0.699 \pm 0.046_{\text{stat}}$$

- Goodness of fit:

$$\chi^2/ndf = 20.3/14,\ p\text{-value} = 0.122$$

- Correlation coefficient:

$$\rho_{\text{stat}}(a, b) = -0.973$$

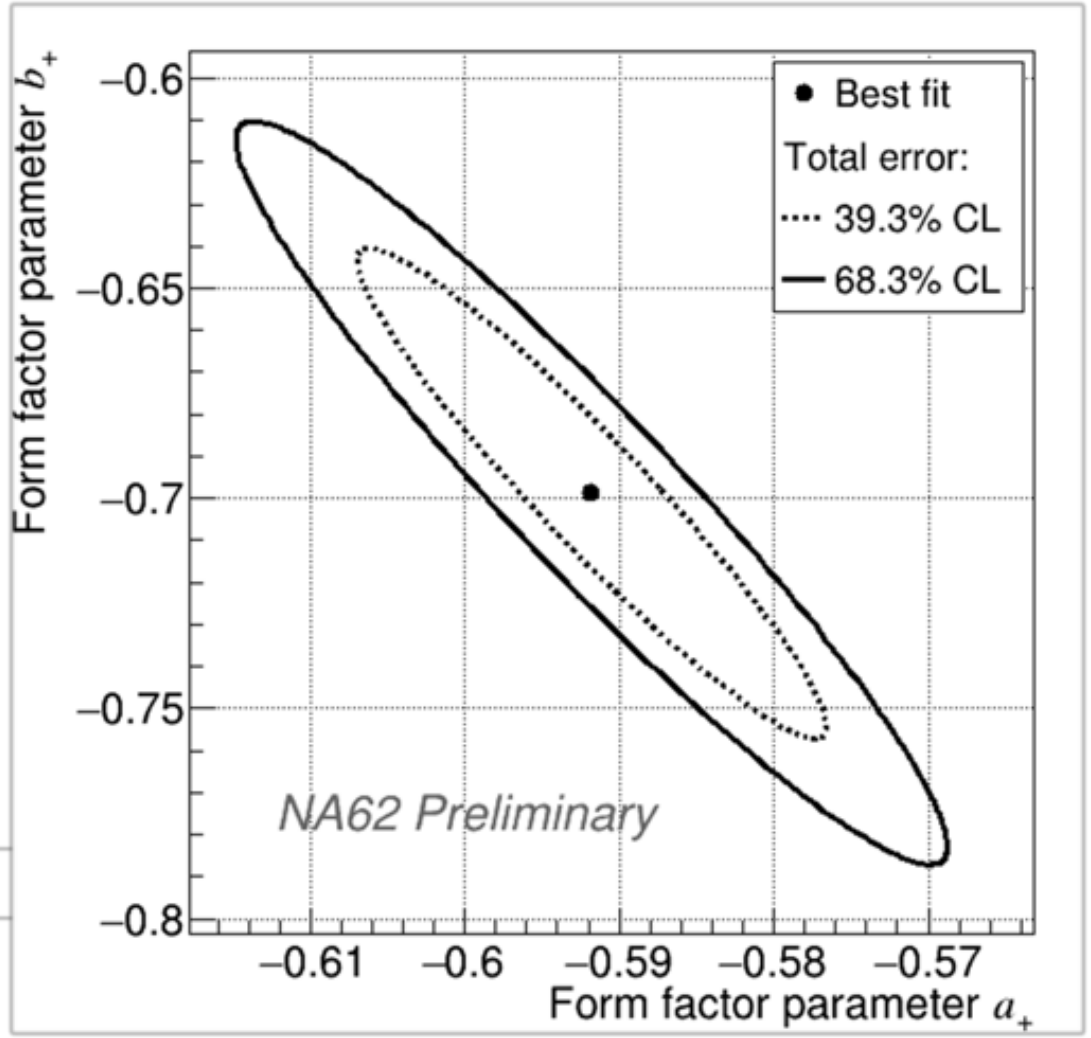
- Model-dependent branching fraction:

$$B(K^+ \to \pi^+\mu^+\mu^-) = (9.27 \pm 0.07_{\text{stat}}) \times 10^{-8}$$

Detailed fit results

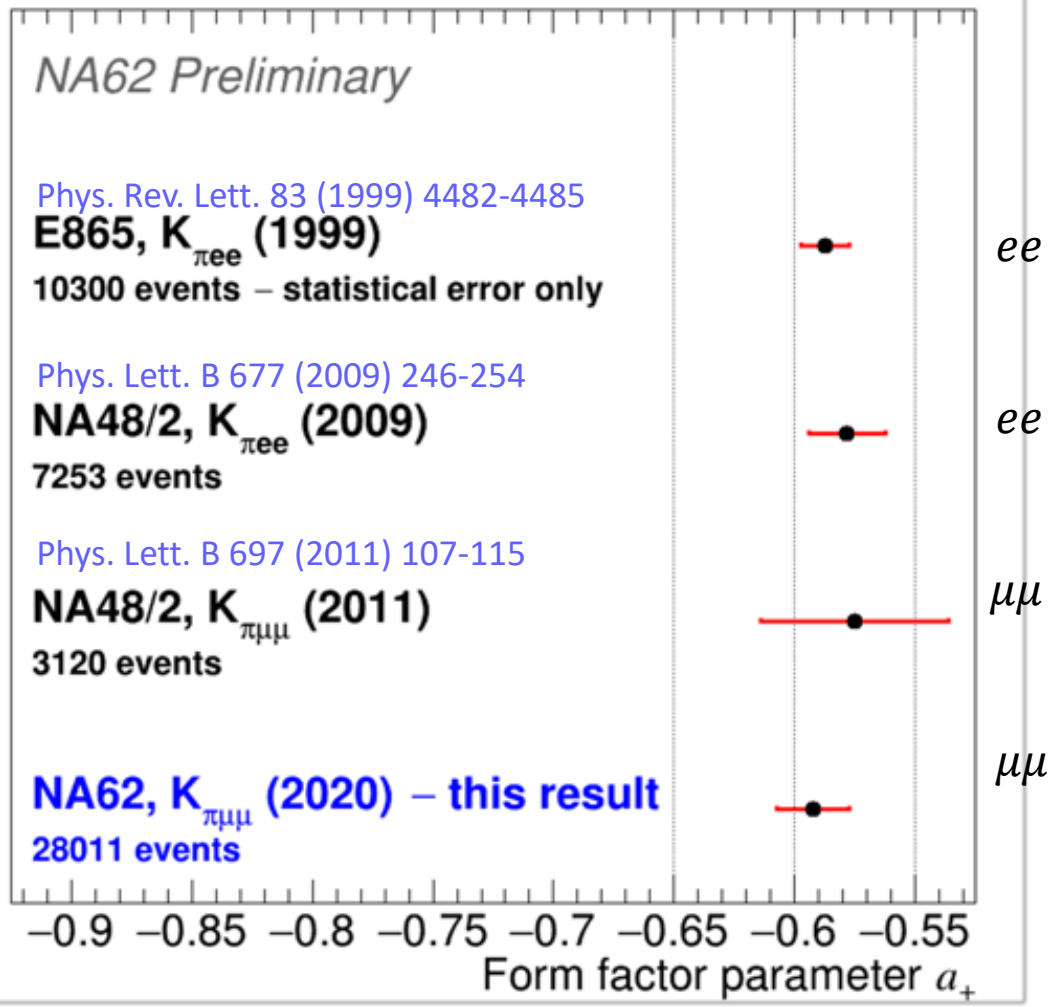
	a	b	$\mathcal{B}_{\pi\mu\mu} \times 10^8$
Best fit	-0.592	-0.699	9.27
Errors	δa	δb	$\delta\mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam & pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.04
Background	0.000	0.001	0.01
Total systematic	0.007	0.035	0.08
External			
PDG error on $\mathcal{B}(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11

Note: a_+ measurement limited by statistical uncertainty



Comparison with existing measurements

- The NA62 measurement of $a_+^{\mu\mu}$ is the worlds most precise determination
- The result is consistent with the earlier NA48/2 measurement, and is consistent with existing measurements of a_+^{ee}
- No indication of discrepancy with SM predictions, including LFU violation



Future prospects

- NA62 will continue running from 2021 through 2024 [CERN-SPSC-2019-039]
  - Beam intensity to be increased by $\sim 50\%$
  - Prospects for $\mathrm{K}^+ \to \pi^+\ell^+\ell^-$ under study (depends strongly on the trigger setup)

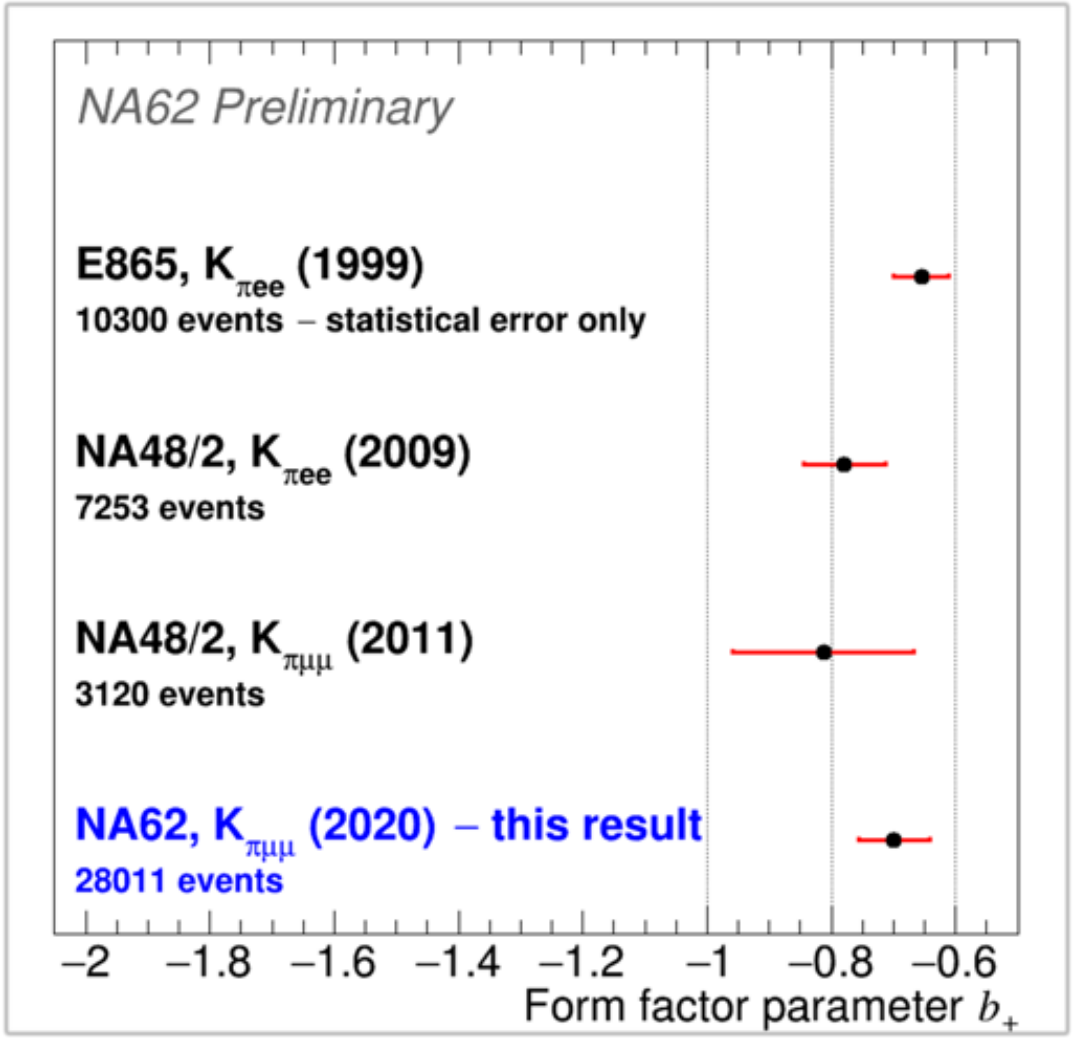
- Designs for a high-intensity kaon facility at CERN are being prepared [arXiv:2009.10941]
  - New K_L^0 experiment with x6 beam intensity (relative to 2021+)
    - Potential for improved $K_L^0 \to \pi^0\ell^+\ell^-$ measurement to be assessed
  - Further K^+ experiment with x4 beam intensity

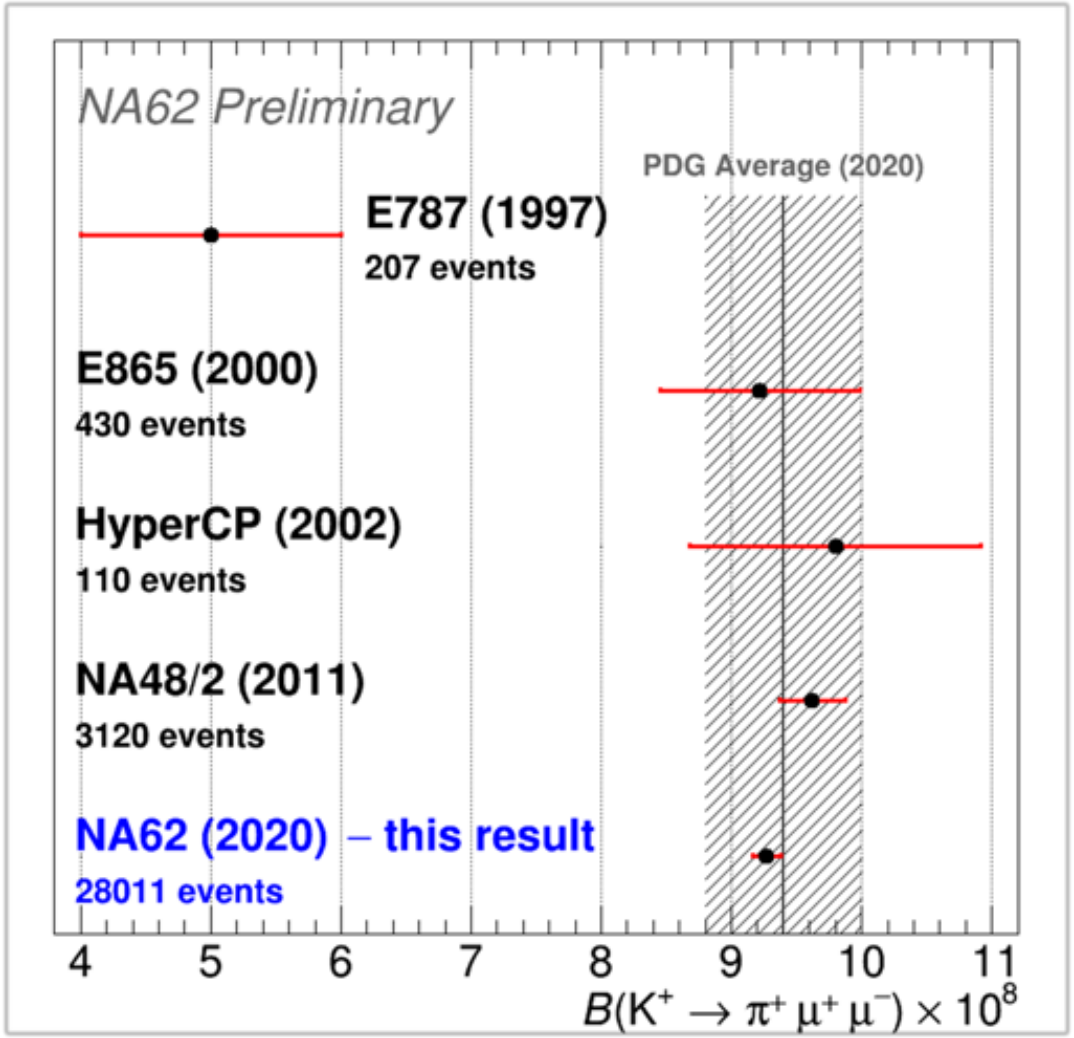
- Kaon prospects at LHCb Run 3 recently examined [J. High Energ. Phys. (2019) 2019: 48]
  - New GPU-based software trigger to collect strange hadron decays with 100% efficiency
  - LHCb can record $O(10k)$ $K^+ \to \pi^+\mu^+\mu^-$ decays each year
  - Unique capability to study $K_S^0 \to \pi^0\mu^+\mu^-$ decays

Summary

- New physics effects such as Lepton Flavour Universality can be probed in rare K^+ decays
  - Such measurements are strongly motivated by (anomalous) results in rare B decays
- The NA62 experiment at CERN is the worlds only dedicated K^+ experiment
- NA62 has made the *worlds most precise* determination of the $K^+ \to \pi^+\mu^+\mu^-$ form-factor parameters a_+ and b_+ using data collected in 2017 and 2018
- No sign of Lepton Flavour Universality violation so far
- Excellent prospects for further measurements, at NA62 and elsewhere

Backup


NA62 Preliminary
E865, K$_{\pi ee}$ (1999)
10300 events – statistical error only
NA48/2, K$_{\pi ee}$ (2009)
7253 events
NA48/2, K$_{\pi\mu\mu}$ (2011)
3120 events
NA62, K$_{\pi\mu\mu}$ (2020) – this result
28011 events
−2 −1.8 −1.6 −1.4 −1.2 −1 −0.8 −0.6
Form factor parameter b_+


NA62 Preliminary
PDG Average (2020)
E787 (1997)
207 events
E865 (2000)
430 events
HyperCP (2002)
110 events
NA48/2 (2011)
3120 events
NA62 (2020) – this result
28011 events
4 5 6 7 8 9 10 11
$B(K^+ \to \pi^+ \mu^+ \mu^-) \times 10^8$