



# Precision measurements with the NA62 experiment at CERN

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# Seeking new physics through kaons

Flavour physics is a special laboratory to look for physics beyond the Standard Model (SM)

- ✓ Loops are sensitive to the presence of new physics
- ✓ In rare processes new interactions can give major contributions
- ✓ New interactions can have different symmetries with respect to the SM

Strange particles provided many building blocks in the construction of the SM

- Discovery of strange particles: first observation of a quark-flavour not present in the ordinary matter [*Nature* 160 4077 (1947) 855]
- Postulation of neutral meson oscillation [*Phys. Rev.* 97 (1955) 1387]
- $\theta/\tau$  puzzle: first hint of P violation [*Phys. Rev.* 104 (1956) 254]
- Discovery of CP violation in the  $K^0$  mixing [*Phys. Rev. Lett.* 13 (1964) 138]
- 3 quark-model to describe the observed meson / baryon spectra [*Phys. Lett.* 8 (1964) 214]
- Prediction of the c quark to explain the unexpectedly low observed branching ratio of the decay  $K_L \rightarrow \mu^+ \mu^-$  [*Phys. Rev. D* 2 (1970) 1285]
- First evidence of direct CP violation in the  $K^0$  (NA31@ CERN) [*Phys. Lett. B* 206 (1988) 169]
- Measurement of direct CP violation in the  $K^0$  (NA48@CERN, KTeV@FNAL)  $\mathcal{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$  [*Phys. Lett. B* 544 (2002) 97, *Phys. Rev. D* 83 (2010) 092001]

Kaons still keep their capacity to provide a deep insight into nature

# Seeking new physics through kaons

Different strategies for a  $K^+$  factory to search for new physics:

Search for deviations with respect to SM predictions

- Flavour Changing Neutral Current (FCNC) processes, e.g.
  - ✓ The golden channel  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$   see Riccardo Fantechi's talk
  - ✓  $K^+ \rightarrow \pi^+ e^+ e^-$ ,  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$   this talk
- Other rare kaon decays, e.g.
  - ✓ Lepton universality with  $R_k = \Gamma(K^+ \rightarrow e^+ \nu_e) / \Gamma(K^+ \rightarrow \mu^+ \nu_\mu)$
  - ✓  $K^+ \rightarrow \pi^0 e^+ \nu_e \gamma$   this talk

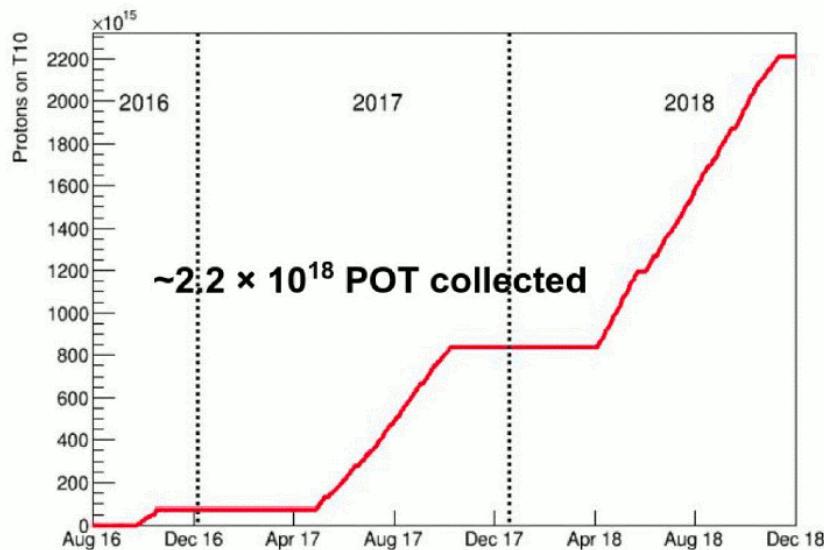
Search for processes forbidden by (accidental) symmetries of the SM

- Lepton Number (LN) and Lepton Flavour (LF) violating decays see Artur Shaikhiev's talk

Search for new interactions in the hidden sector

- Dark photons
- Heavy Neutral Leptons  see Artur Shaikhiev's talk
- Axions/Axion-like Particles

# NA62: the CERN kaon factory



**Kaon physics at CERN:**

- ✓ Fixed target experiments at CERN SPS
- ✓ Kaon decay-in-flight

**Currently in NA62:**

~ 200 participants, ~ 30 institutions

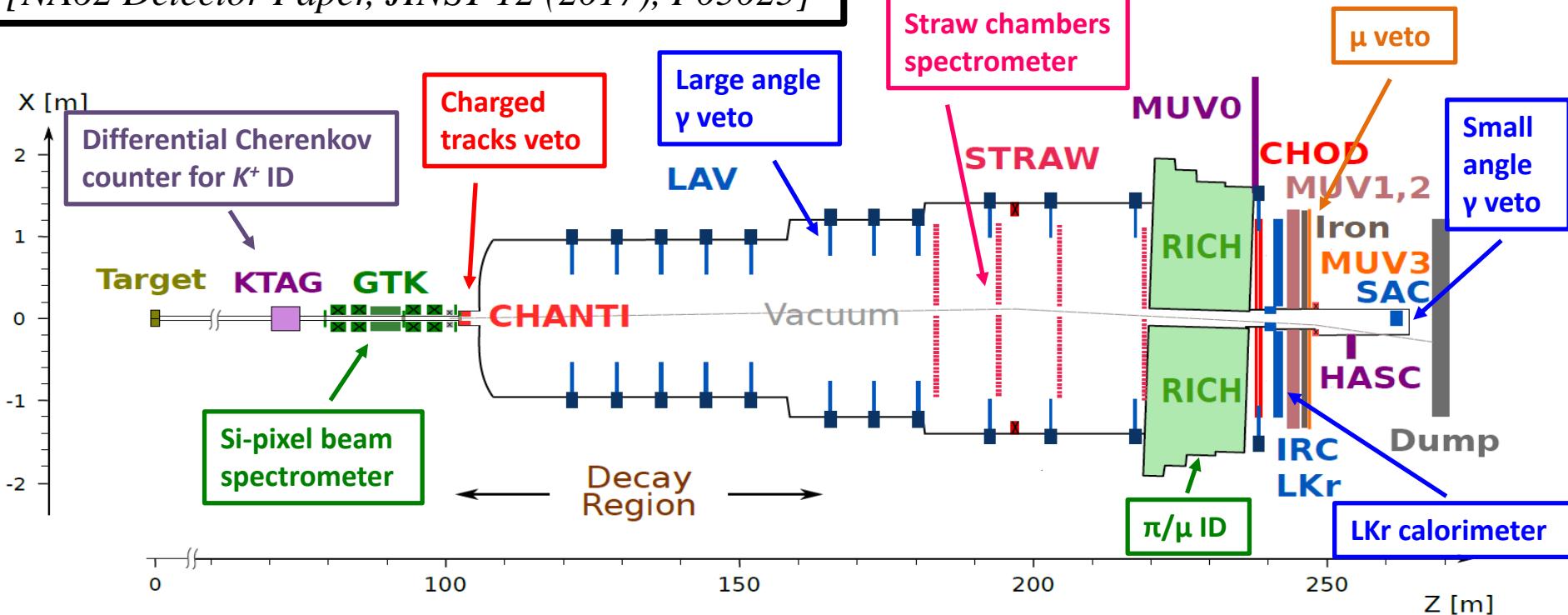
**Main goal:  $\text{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$  measurement with  $\mathcal{O}(10\%)$  precision**

**Run1: 2016-2018 with  $2.2 \times 10^{18}$  proton on target and  $6.8 \times 10^{12} K^+$  decays in flight**

**Run2: in progress, from 2021 till LS3**

# NA62 layout

[NA62 Detector Paper, JINST 12 (2017), P05025]



## SPS protons:

400 GeV/c on beryllium  
target  
 $10^{12}$  POT/sec on spill  
3 sec effective spill length

## Unseparated secondary beam:

75 GeV/c, 1% bite  
100  $\mu$ rad divergence  
 $60 \times 30$  mm<sup>2</sup> transverse size  
 $K^+(6\%)/\pi^+(70\%)/p(24\%)$   
Beam particle rate: 750 MHz at GTK3

## Kaon decay region:

60 m long  
 $\sim 5$  MHz kaon decays rate  
Vacuum  $\mathcal{O}(10^{-6})$  mbar

# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ theory overview

- Sensitive to new physics, LFU test together with electron channel
- FCNC decay described in the scope of ChPT, mediated by one virtual photon exchange with long distance hadronic contributions [*Nucl. Phys. B291 (1987) 692–719*], [*Phys. Part. Nucl. Lett. 5 (2008) 76–84*]

$$K^+ \rightarrow \pi^+ \gamma^* \rightarrow \pi^+ \mu^+ \mu^-$$

- Two Dalitz variables:  $z = m_{\mu^+ \mu^-}^2 / M_K^2$  and  $x = m_{\mu^+ \pi^+}^2 / M_K^2$
- Full differential decay width ( $r_i = \frac{m_i}{M_K}$ ) :

$$\frac{d^2\Gamma(x,z)}{dx dz} = \frac{\alpha^2 M_K}{8\pi(4\pi)^4} [(2x + z - 2 - 2r_\mu^2)(-2x - z + 2r_\pi^2 + 2r_\mu^2) + z(z - 2 - 2r_\pi^2)] |\mathbf{W}(z)|^2 (1 + \delta(x, z))$$

Radiative corrections [*Eur. Phys. J. C70 (2010) 219–231*]

Form factor (FF) parametrized at NLO in ChPT [*JHEP 08 (1998) 004*]

$$W(z) = G_F M_K^2 (\color{red}{a} + \color{blue}{b}z) + W^{\pi\pi}$$



FF parameters



Pion loop term from  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$

# $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ normalization sample

## Normalization decay channel $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ :

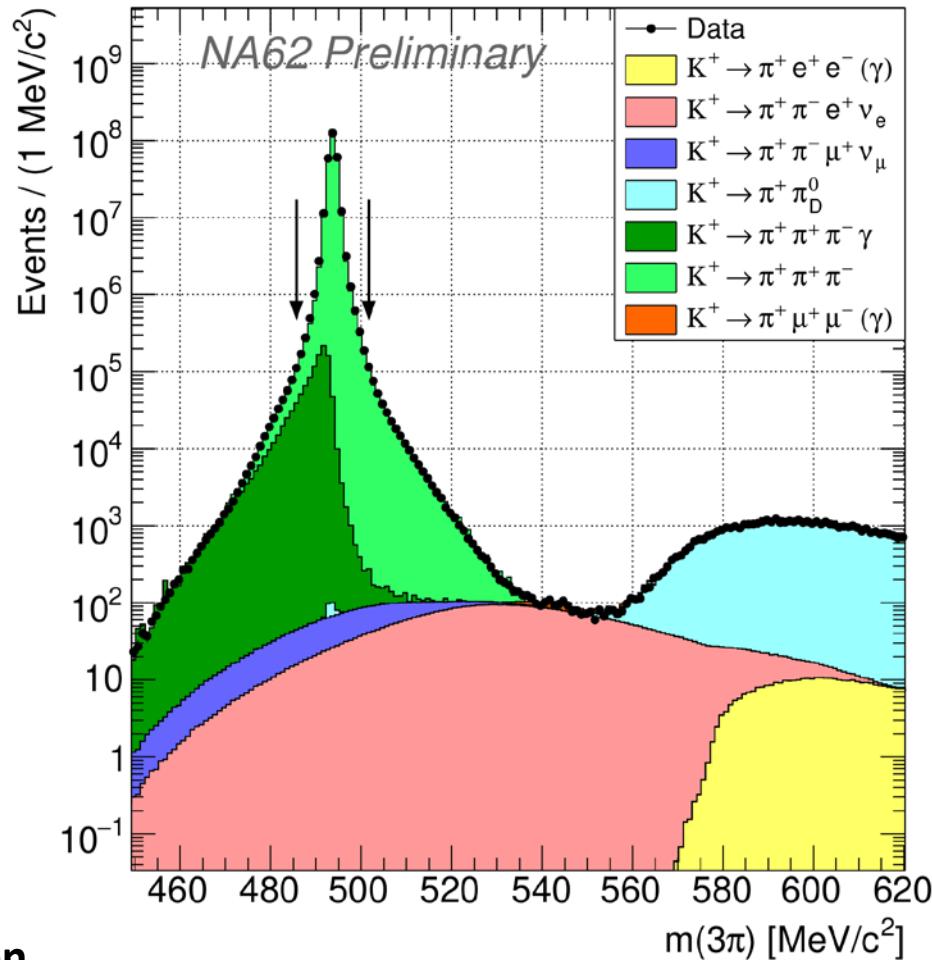
- Abundant: BR  $\sim 5\%$
- Kinematically similar to  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$

## Generic 3-track event selection:

- Three track vertex topology  
-> Straw tracker
- Timing cuts  
-> CHOD, NA48-CHOD, KTAG, RICH
- Suppression of  $e^\pm$  background  
-> Straw tracker and LKr ( $E/p < 0.9$ )

## $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ sample:

- $|m(3\pi) - M_K| < 8 \text{ MeV}/c^2$
- MC: Acceptance  $A(3\pi) \sim 7\%$
- Data  $N(3\pi) \sim 2.78 \times 10^8$ ,  
with  $\sim 0.3\% K^+ \rightarrow \pi^+ \pi^+ \pi^- \gamma$  contamination



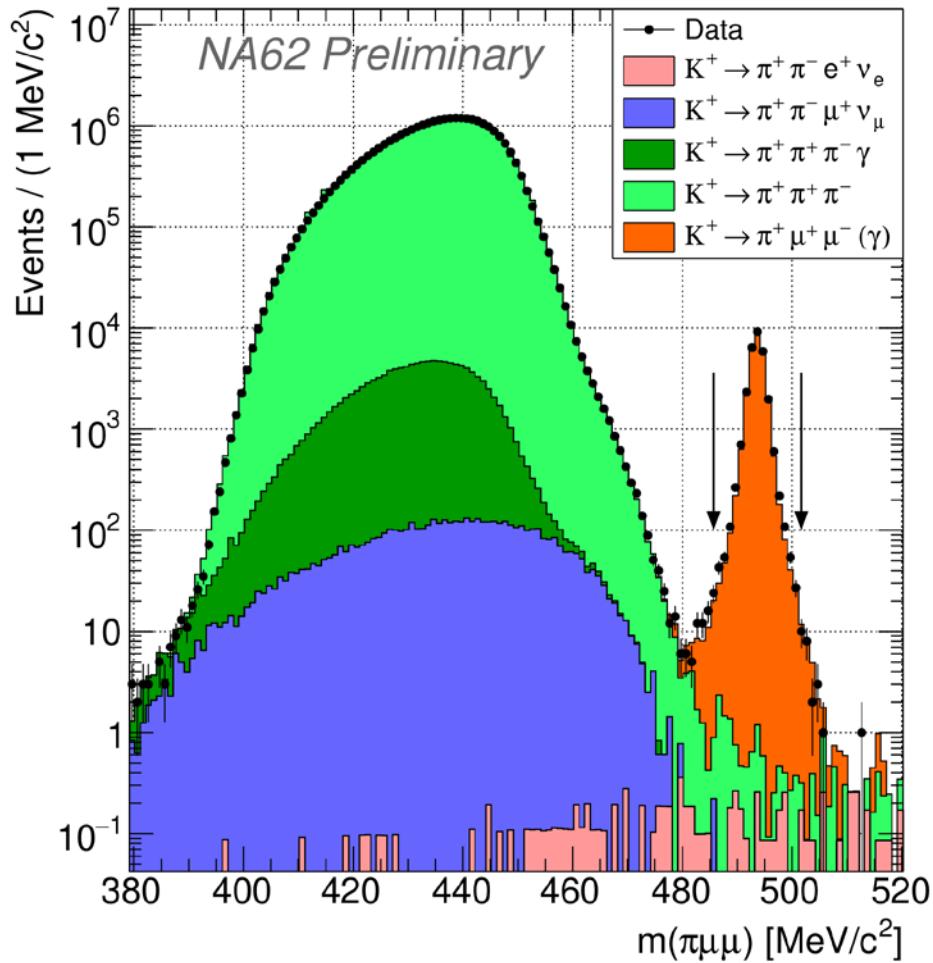
# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ signal sample

## Specific $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ event selection:

- Generic 3-track event selection
- MUV3 and LKr based PID
  - >  $\mu^\pm$ : in-time MUV3 response,  $E/p < 0.2$
  - >  $\pi^+$ : no in-time MUV3 response,  $E/p < 0.9$
- Additional kinematics cuts applied to reject  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  background

## $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ sample:

- $|m(\pi\mu\mu) - M_K| < 8 \text{ MeV}/c^2$
- MC: Acceptance  $A(\pi\mu\mu) \sim 9.40\%$
- Data  $N(\pi\mu\mu) = 28011$ 
  - > 9x more than NA48/2
  - [*Phys. Lett. B 697 (2011) 107-115*]
- > Expected background:  
 $12.5 \pm 1.7_{\text{stat}} \pm 12.5_{\text{syst}}$



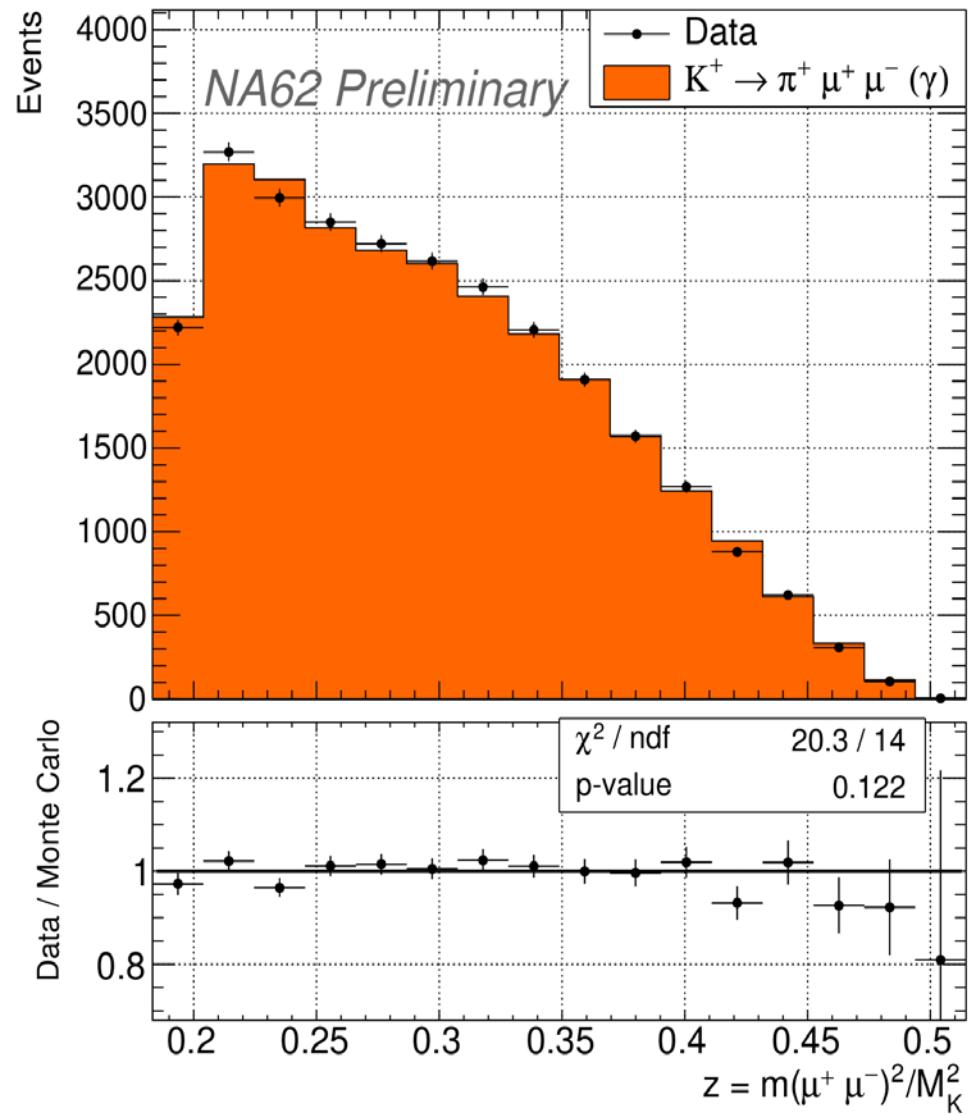
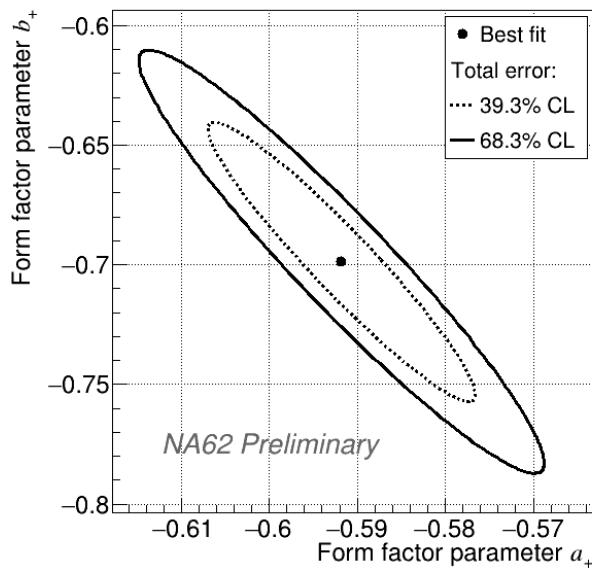
# Fit of the form factor parameters

## Fitting procedure:

- $z$  spectrum of  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  MC reweighted to best fit the data

## Best fit of FF parameters:

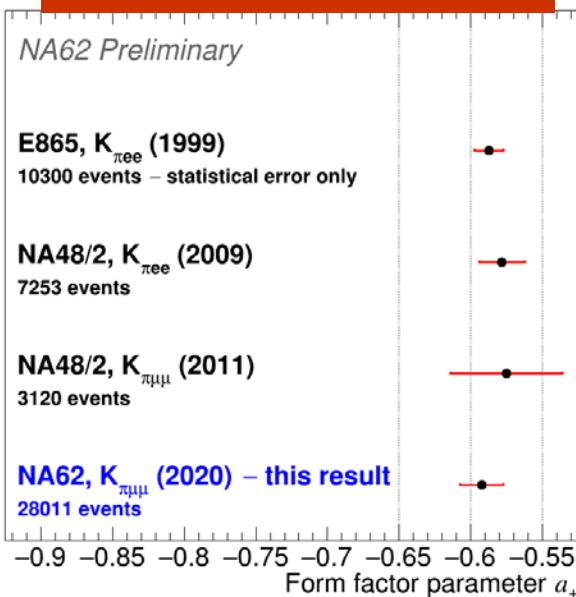
- $a = -0.592 \pm 0.013_{\text{stat}}$
- $b = -0.699 \pm 0.046_{\text{stat}}$
- Goodness of fit:  
 $\chi^2 / \text{ndf} = 20.3 / 14$ ,  $p\text{-value} = 0.122$



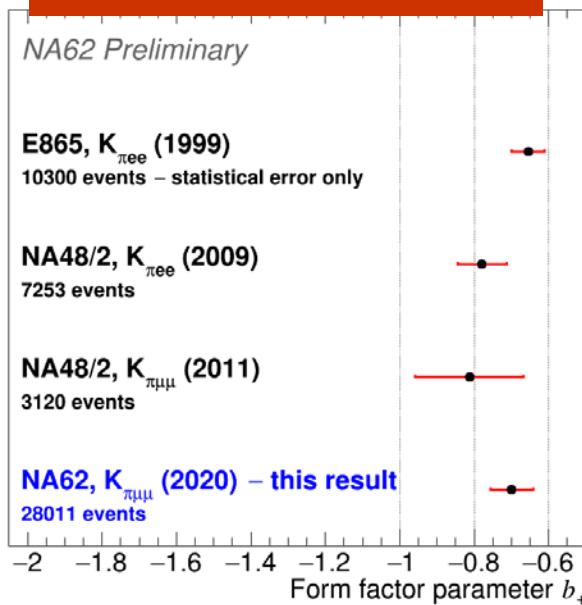
# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ results (2017+2018 data set)

Model-dependent  $BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-)$  by integrating the differential decay width

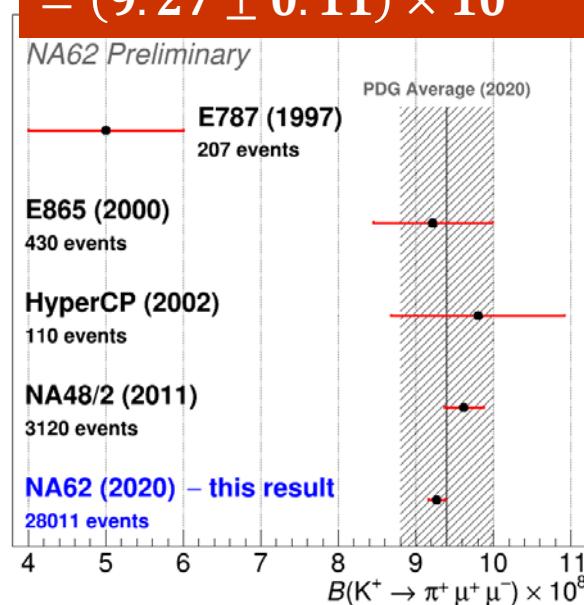
$$a = -0.592 \pm 0.015$$



$$b = -0.699 \pm 0.058$$



$$BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-) = (9.27 \pm 0.11) \times 10^{-8}$$

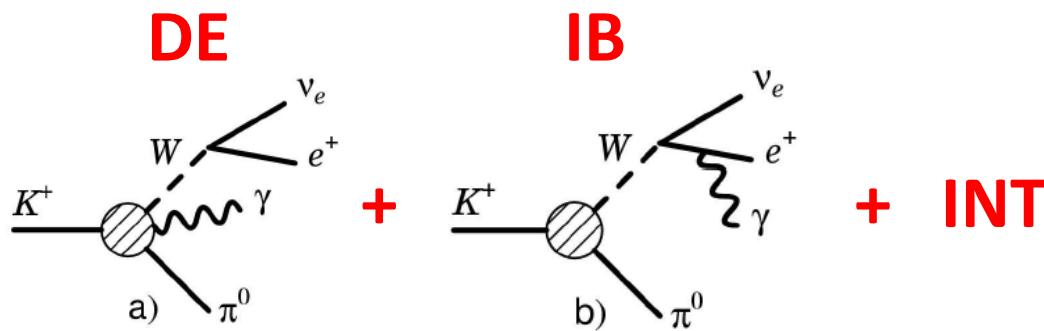


Preliminary  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  result consistent with  $K^+ \rightarrow \pi^+ e^+ e^-$  FF parameters -> no tension in LFU observed (paper in preparation)

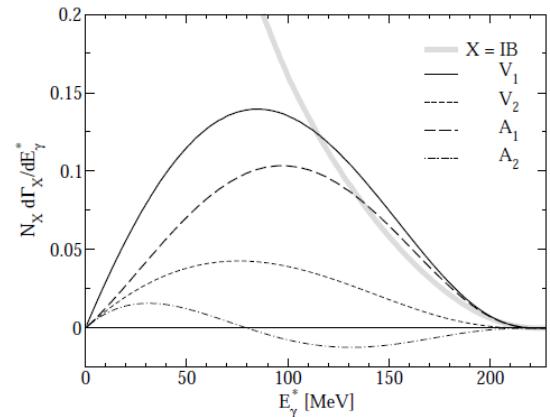
Revised, more stringent trigger for di-muon and di-electron in 2021

# $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ theory overview

Inner Bremsstrahlung (IB) decay amplitude divergent for  $E_\gamma \rightarrow 0$  and  $\theta_{e,\gamma} \rightarrow 0$



[Kubis et al., EPJ C 50, 557]



Theoretical predictions and experimental measurements for 3 sets of cuts: minimal  $E_\gamma$  and  $\theta_{e,\gamma}$  (in  $K^+$  rest frame)

$$R_j = \frac{BR(K^+ \rightarrow \pi^0 e^+ \nu \gamma | E_\gamma^j, \theta_{e,\gamma}^j)}{BR(K^+ \rightarrow \pi^0 e^+ \nu(\gamma))}$$

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

Most recent calculation of  $R2 = (0.56 \pm 0.02)\%$  [Khriplovich et al., PAN 74, 1214 (2010)]

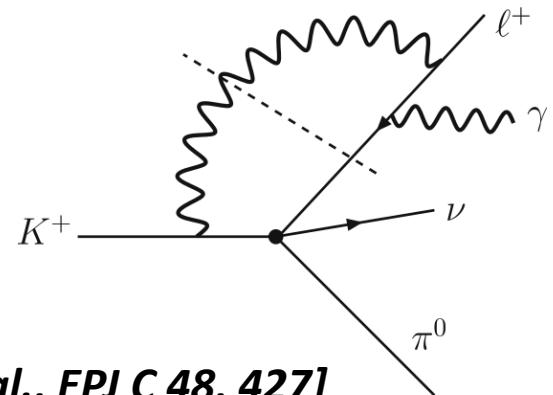
# $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ theory overview: T-asymmetry

T-odd observable (in the kaon rest frame):

$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{m_K^3}; \quad A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

Non-zero  $A_\xi$  values due to NLO  
(one-loop) electromagnetic  
corrections

$$|A_\xi^{SM \text{ and beyond}}| < 10^{-4}$$



[Muller et al., EPJ C 48, 427]

## Experimental status

- $A_\xi^{ISTRAP}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- No measurements for  $R_1$  and  $R_2$

# $R_j$ measurement strategy

$$R_j = \frac{BR(Ke3\gamma^j)}{BR(Ke3)} = \frac{N_{Ke3\gamma^j}^{obs} - N_{Ke3\gamma^j}^{bkg}}{N_{Ke3}^{obs} - N_{Ke3}^{bkg}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma^j}} \cdot \frac{\epsilon_{Ke3}^{trig}}{\epsilon_{Ke3\gamma^j}^{trig}}$$

- Background estimation performed using both data and MC.
- Acceptances: evaluated by MC.
- Signal ( $Ke3\gamma$ ) and normalization ( $Ke3$ ) channels share most of the selection criteria (except for the radiative photon): first-order-cancellation of systematics effects.
- Trigger efficiencies: measured with data. Almost equal for signal and normalization (within per mill precision) since trigger conditions refer to the presence of the  $e^+$  only.
- Only statistical uncertainty of  $N_{Ke3\gamma^j}^{obs}$  and  $N_{Ke3}^{obs}$  is propagated as statistical uncertainty to the  $R_j$  measurement, all the rest is considered as systematic.
- Full 2017 and 2018 data sets have been analyzed -> preliminary results presented.

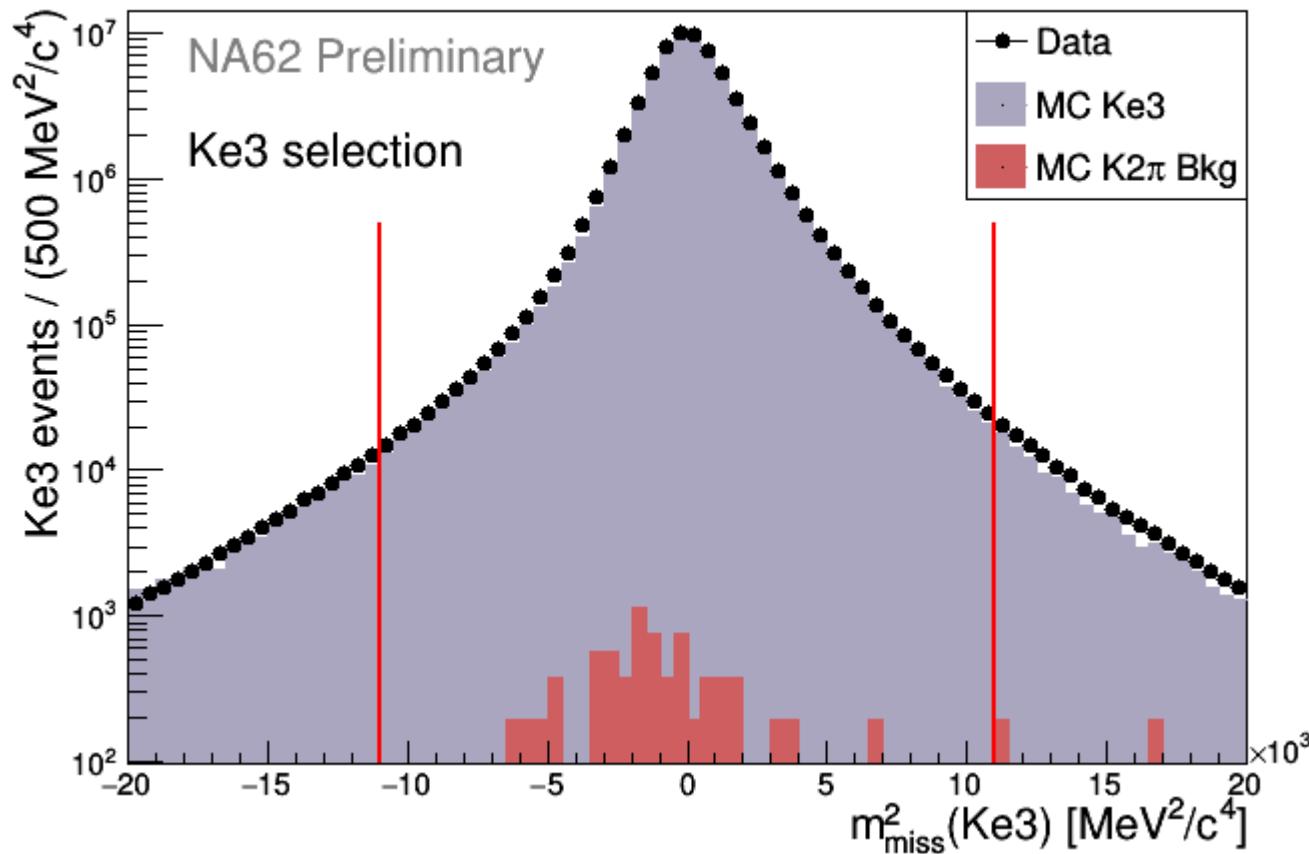
# $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ selection criteria

- $K^+$  track reconstructed in GTK, positively identified in KTAG,  $e^+$  track reconstructed in STRAW, identified using associated signals in RICH and LKr
- $\pi^0 \rightarrow \gamma\gamma$  identified selecting two energy clusters in LKr
- Radiative  $\gamma$  identified selecting an in-time isolated energy cluster in LKr
- In-time extra activity in photon veto system (LKr, LAV, IRC, SAC) not allowed
- In-time signal in MUV3 not allowed
- Dedicated kinematic cuts to reject  $K^+ \rightarrow \pi^+ \pi^0 \pi^0$  and  $K^+ \rightarrow \pi^+ \pi^0$  backgrounds
- Kinematic selection using the two main observables:

$$m_{miss}^2(Ke3\gamma) = (P_K - P_e - P_{\pi^0} - P_\gamma)^2$$

$$m_{miss}^2(Ke3) = (P_K - P_e - P_{\pi^0})^2$$

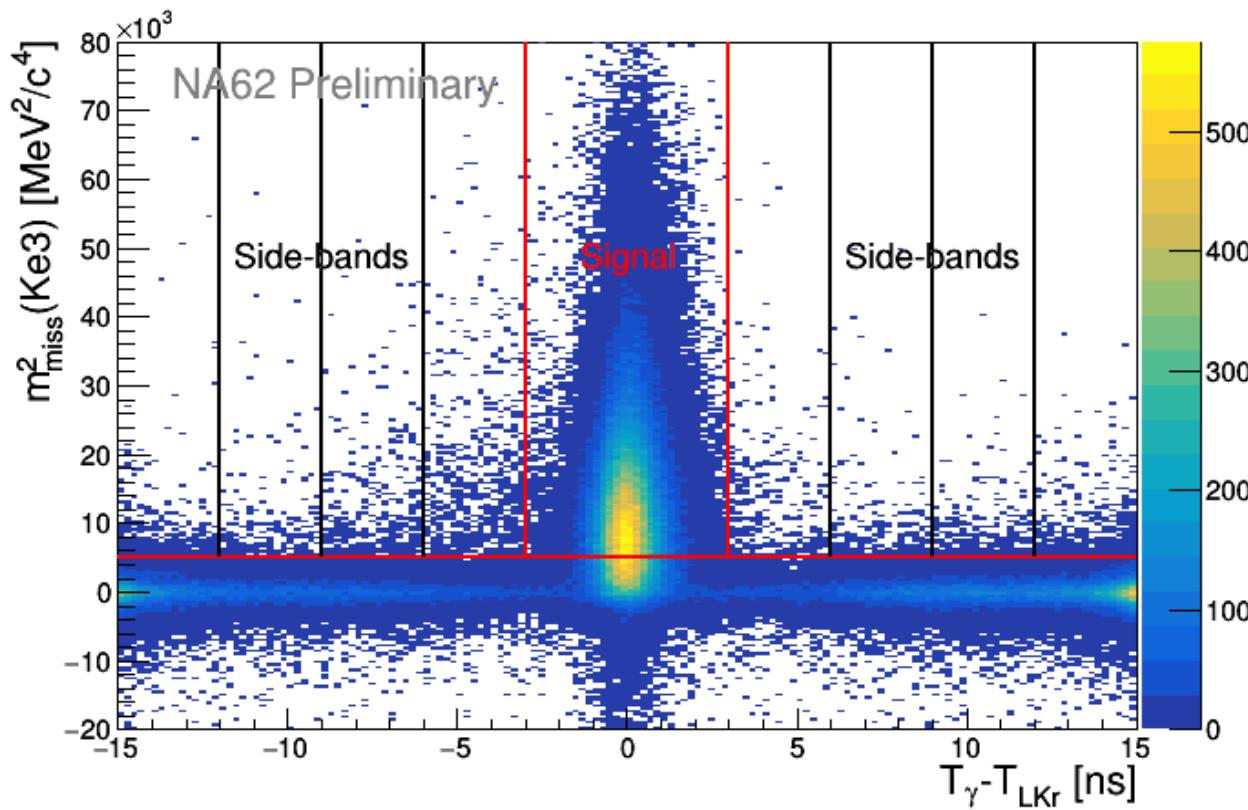
# Normalization selected events *Ke3*



- **66M selected events**
- **Almost background free: B/S  $\sim 10^{-4}$**

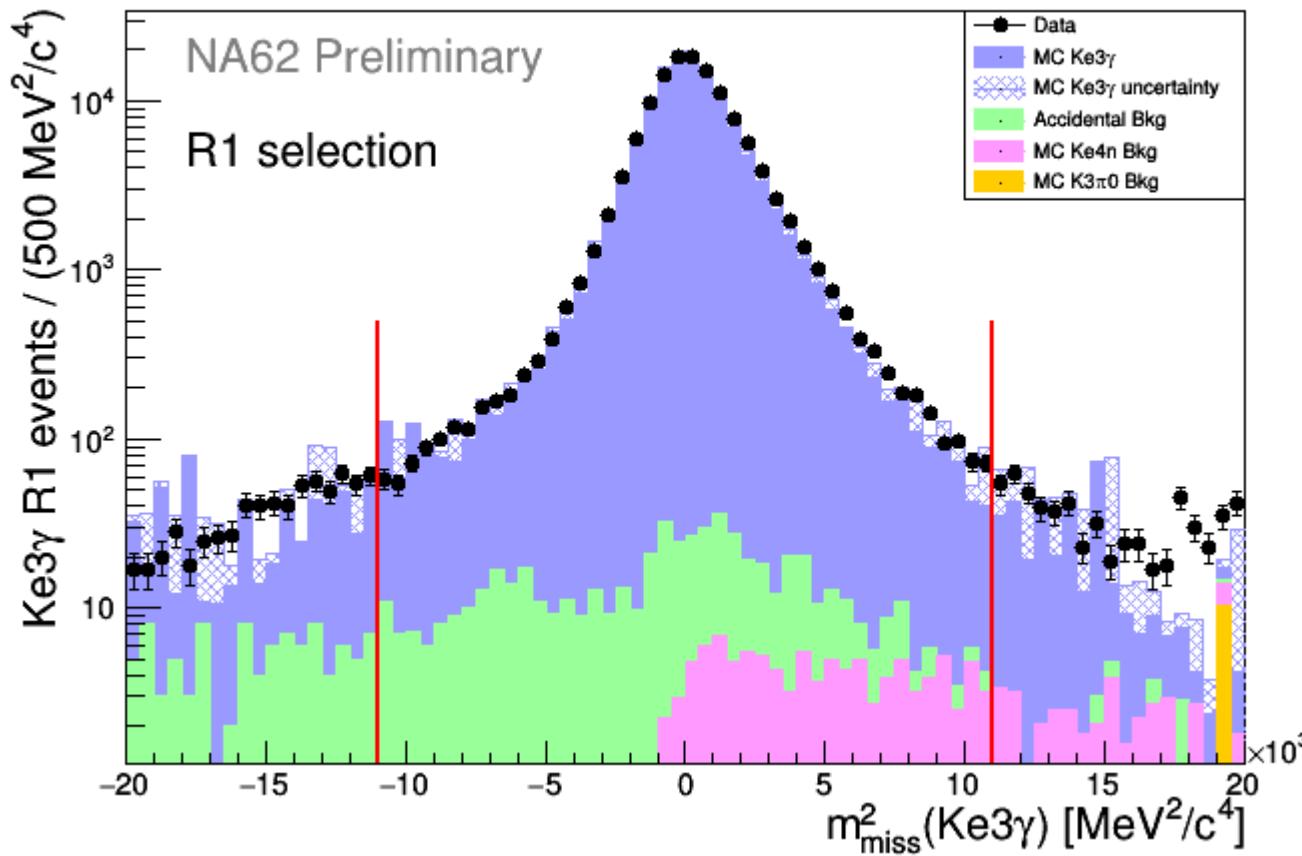
# Main background of $Ke3\gamma$ : accidentals

Accidental event:  $K^+ \rightarrow \pi^0 e^+ \nu$  decay (or  $K^+ \rightarrow \pi^+ \pi^0$  with  $\pi^+$  mis-ID) + additional LKr cluster that mimics the radiative photon



- Dedicated cut in signal selection using  $m_{miss}^2(Ke3)$  observable
- Background in signal region estimated with data from the out-of-time side-bands

# Signal selected events ( $Ke3\gamma - R_1$ )



- 130K selected events in  $R_1$  (54K in  $R_2$ , 39K in  $R_3$ )
- Background contamination:  $B/S(R_1) \sim 0.5\%$ ,  $B/S(R_2) \sim 0.6\%$ ,  $B/S(R_3) \sim 0.3\%$

# NA62 preliminary $R_j$ measurements

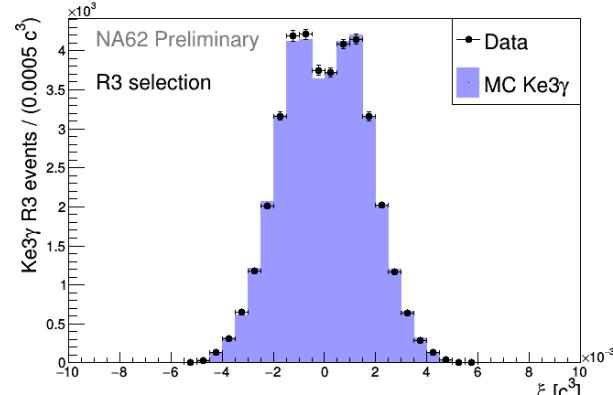
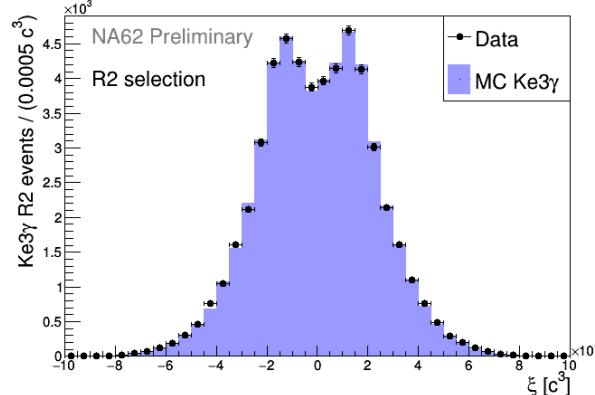
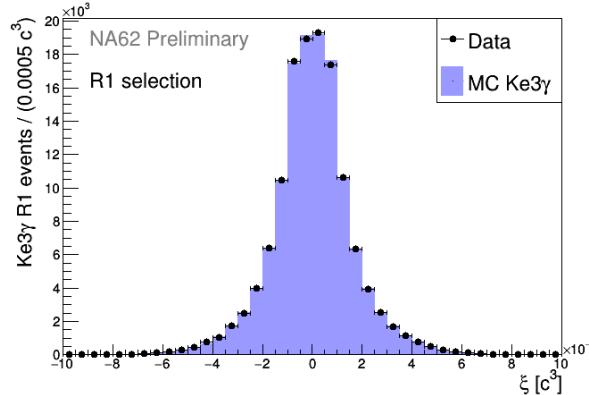
	$O(p^6)ChPT$	ISTRAP+	OKA	NA62 preliminary
$R_1 (\times 10^2)$	$1.804 \pm 0.021$	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
$R_2 (\times 10^2)$	$0.640 \pm 0.008$	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
$R_3 (\times 10^2)$	$0.559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

- $R_j$  measurement relative precision  $\leq 1\%$
- State of the art improved by a factor between 2.0 and 3.6
- Relative discrepancy with theory of 6-7% in all three measurements
- NA62 result for  $R_2$  is half way between the two latest theoretical predictions [Kubis et al., EPJ C 50, 557] and [Khriplovich et al., PAN 74, 1214]

Uncertainty source	$\delta R_1/R_1$	$\delta R_2/R_2$	$\delta R_3/R_3$
Statistical	0.3%	0.5%	0.6%
Acceptances from MC	0.2%	0.4%	0.4%
Background estimation	0.1%	0.2%	0.1%
LKr response modeling	0.5%	0.6%	0.5%
Theoretical model	0.1%	0.5%	0.1%
Total systematic	0.6%	0.9%	0.6%
Total stat+syst	0.7%	1.0%	0.8%

# NA62 preliminary $A_\xi$ measurements

$$A_\xi = A_\xi^{Data} - (A_\xi^{MCReco} - A_\xi^{MCgene}) \cong A_\xi^{Data} - A_\xi^{MCReco}$$



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

- $R_3$  T-asymmetry precision improved by a factor greater than 3:  
 $A_\xi^{ISTRAP}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- First measurements ever performed for  $R_1$  and  $R_2$  T-asymmetry

# Conclusions

- ✓ NA62 experiment at CERN collected a sample of  $\sim 6.8 \times 10^{12} K^+$  decays in flight during Run 1 in 2016-2018. Data taking restarted in 2021 (till LS3)
- ✓ Study of  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  decay with 2017+2018 dataset
  - Observed very clean sample of 28011  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  event candidates,  $\sim 9 \times$  more than NA48/2
  - Measured  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  form factor parameters  $a$  and  $b$ , and model-dependent  $BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-)$
  - Result consistent with  $K^+ \rightarrow \pi^+ e^+ e^-$  FF parameters -> no tension in LFU observed
- ✓ Study of the  $K^+ \rightarrow \pi^0 e^+ \nu \gamma$  process using 2017+2018 dataset
  - Measurements of  $K^+ \rightarrow \pi^0 e^+ \nu \gamma$  branching fraction ratio ( $R_j$ ) showed 6-7% relative discrepancy with ChPT  $O(p^6)$
  - Experimental relative precision of  $R_j$  measurements improved by a factor between 2.0 and 3.6, relative uncertainties  $\leq 1\%$
  - T-asymmetry measurements compatible with zero, experimental sensitivity far from the theoretical expectations. First T-asymmetry measurements for  $R_1$  and  $R_2$ , improvement by a factor greater than 3 for  $R_3$