“New measurement of radiative decays at the NA62 experiment at CERN: $K_{e3\gamma}$”

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On behalf of the NA62 collaboration

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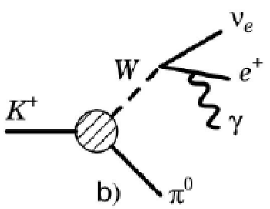
$K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$) decay



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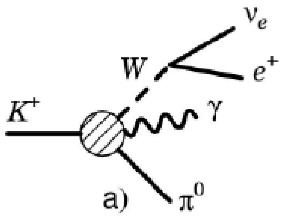
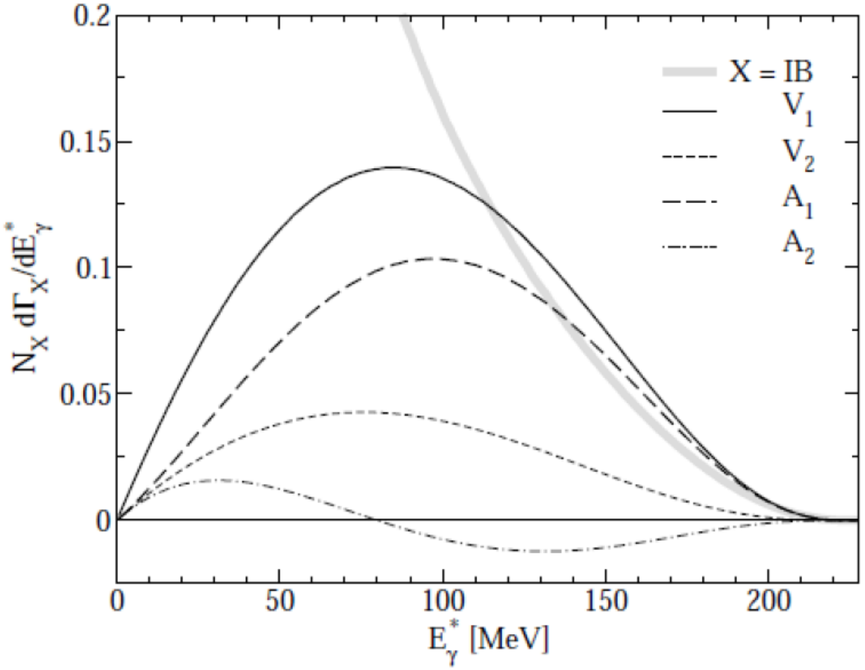


+ INT

IB

DE

- 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) about 1% of total amplitude
  - Calculation **up to order p^6** in **ChPT**
  - The error on the DE amplitude is dominated by unknown radiative corrections and higher-order chiral corrections



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

Branching ratio measurements: present status

$$R = \frac{Br\left(K_{e3\gamma}\right)}{Br\left(K_{e3}\right)} = \frac{Br\left(K^{+} \rightarrow \pi^{0} e^{+} \nu\gamma \left| E_{\gamma}^{cut}, \theta_{e,\gamma}^{cut} \right.\right)}{Br\left(K^{+} \rightarrow \pi^{0} e^{+} \nu(\gamma)\right)}$$

- Experimentally cuts on minimal photon energy and minimal photon-positron opening angle (in kaon rest frame) are applied.
- Theoretical predictions and experimental measurements are given for **three sets** of cuts.

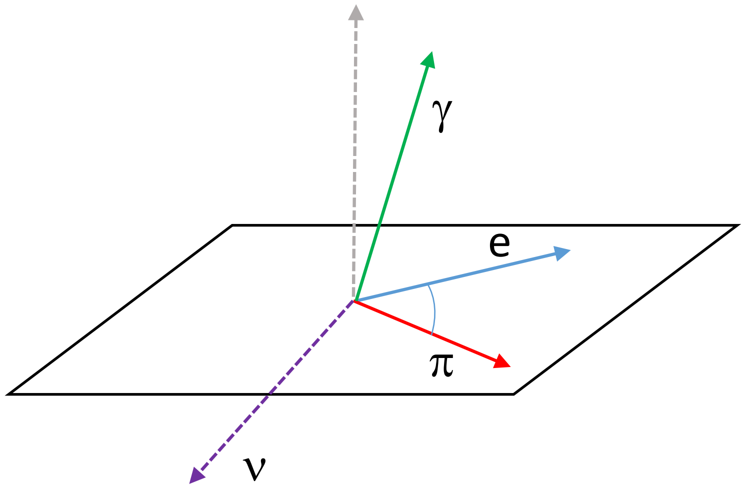
	E_γ cut	**$\theta_{e,\gamma}$ cut**	**ISTRA+ ($\times10^{-2}$)** *[Akimenko et al. PAN 70, 702 (2007)]*	**OKA ($\times10^{-2}$)** *[Polyarush et al. EPJ 81, 2, 161 (2021)]*	**$O(p^6)$ ChPT ($\times10^{-2}$)** *[Kubis et al., EPJ C50, 557 (2007)]*
R_1	$E_\gamma > 10$ MeV	$\theta_{e,\gamma} > 10°$	1.81 ± 0.03 ±0.07	1.990 ± 0.017 ±0.021	1.804 ± 0.021
R_2	$E_\gamma > 30$ MeV	$\theta_{e,\gamma} > 20°$	0.63 ± 0.02 ±0.03	0.587 ± 0.010 ±0.015	0.640 ± 0.008
R_3	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.47 ± 0.02 ±0.03	0.532 ± 0.010 ±0.012	0.559 ± 0.006

- Most recent calculation of $R_2=(0.56\pm0.02)\%$ *[Khriplovich et al., PAN 74, 1214 (2010)]*

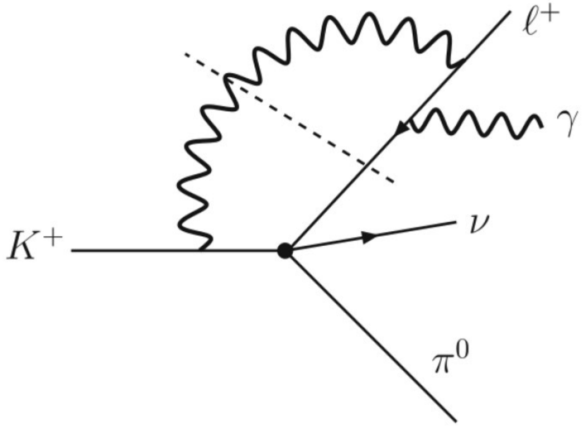
T-Asymmetry

- Even without measuring the lepton polarization, it’s possible to define a T-odd observable (in the kaon rest frame):

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

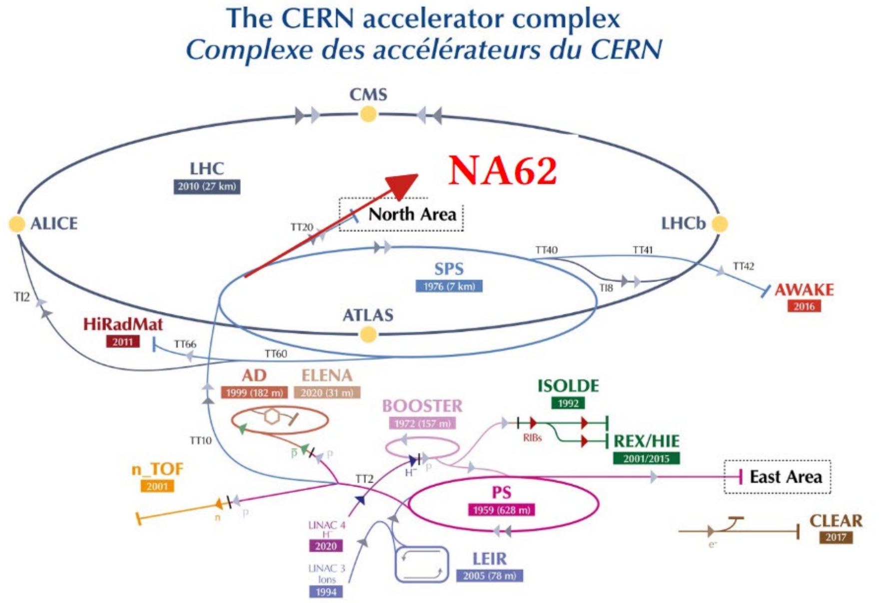


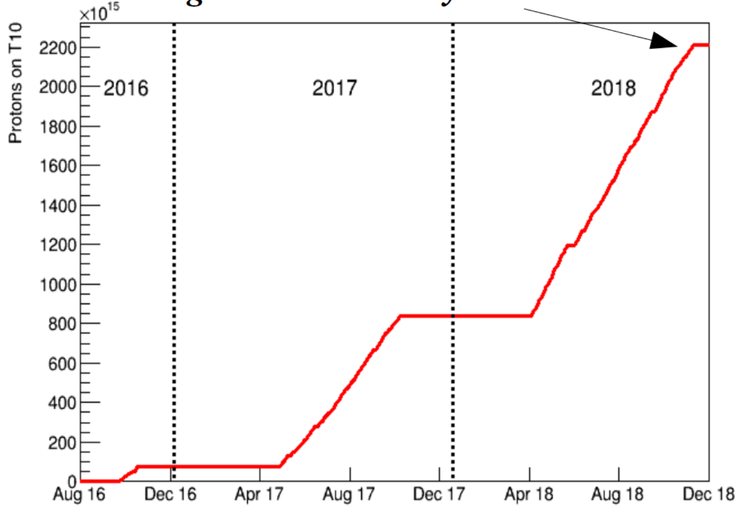
- In principle $A_\xi \neq 0$ is a indication of **T-violation**
  - Non-zero asymmetry could be due to one-loop (and higher order) electromagnetic and hadronic corrections *[Muller et al., EPJ C48, 427]*
  - $A_\xi = -0.59 \times 10^{-4}$ (electromagnetic) and $A_\xi = 0.9 \times 10^{-6}$ (O(p^6) SD contribution)
  - No strong dependence on the experimental cut on E_γ and $\theta_{e,\gamma}$

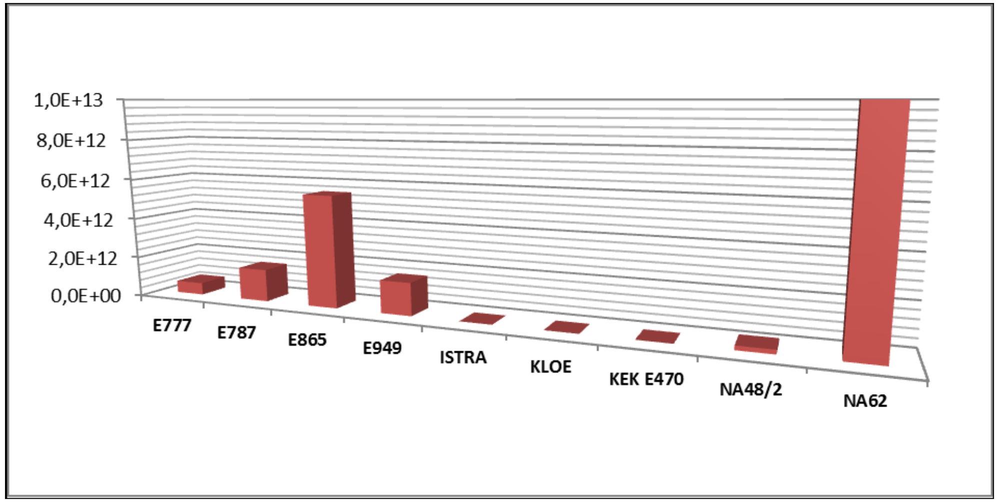


The NA62 experiment @CERN

- **NA62** is a fixed target experiment at CERN SPS
- Detector installation completed in 2016
  - 2016, 2017 and 2018 of physics runs
  - Data taking **re-started** in July 2021
  - Data taking approved **up to CERN LS3**
- Main goal: **Br($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)** measurement
  - Measurement from full 2016+2017+2018 data se recently published *[JHEP 06 (2021) 093]*
  - Broad physics program thanks to unprecedented statistics for many decay modes

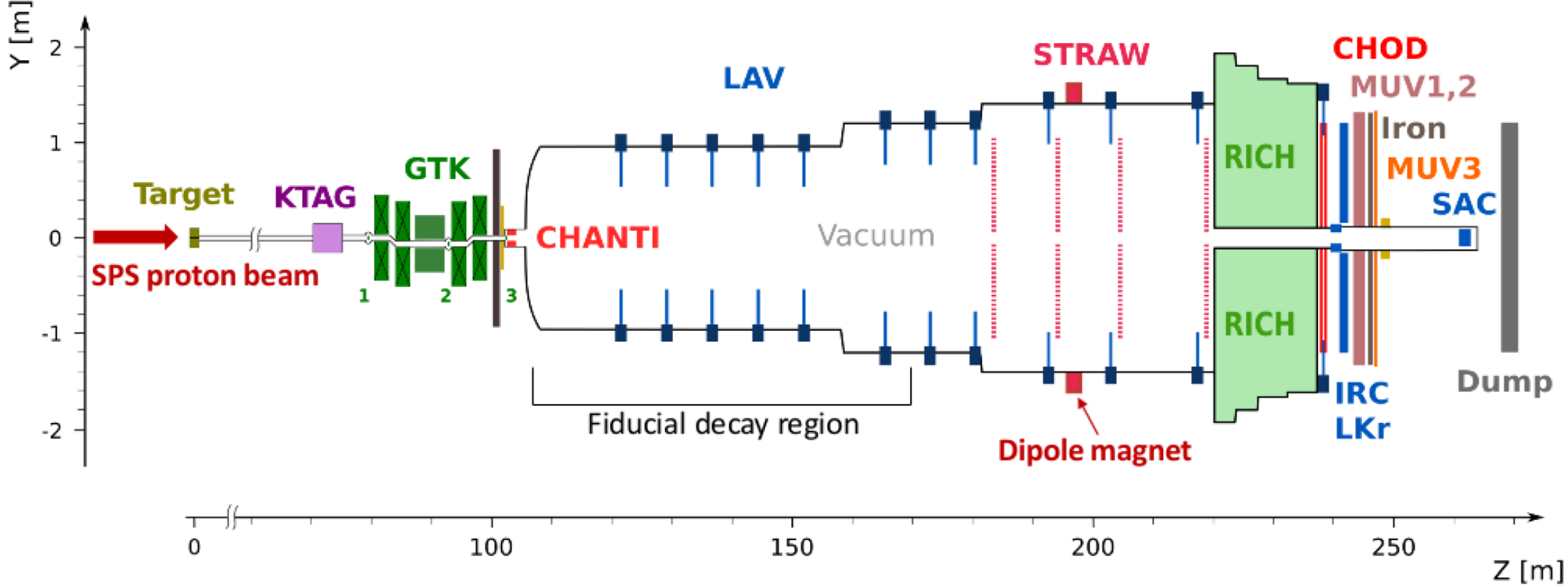

The CERN accelerator complex
Complexe des accélérateurs du CERN


Integrated luminosity NA62 Run 1



NA62 Detector postcard

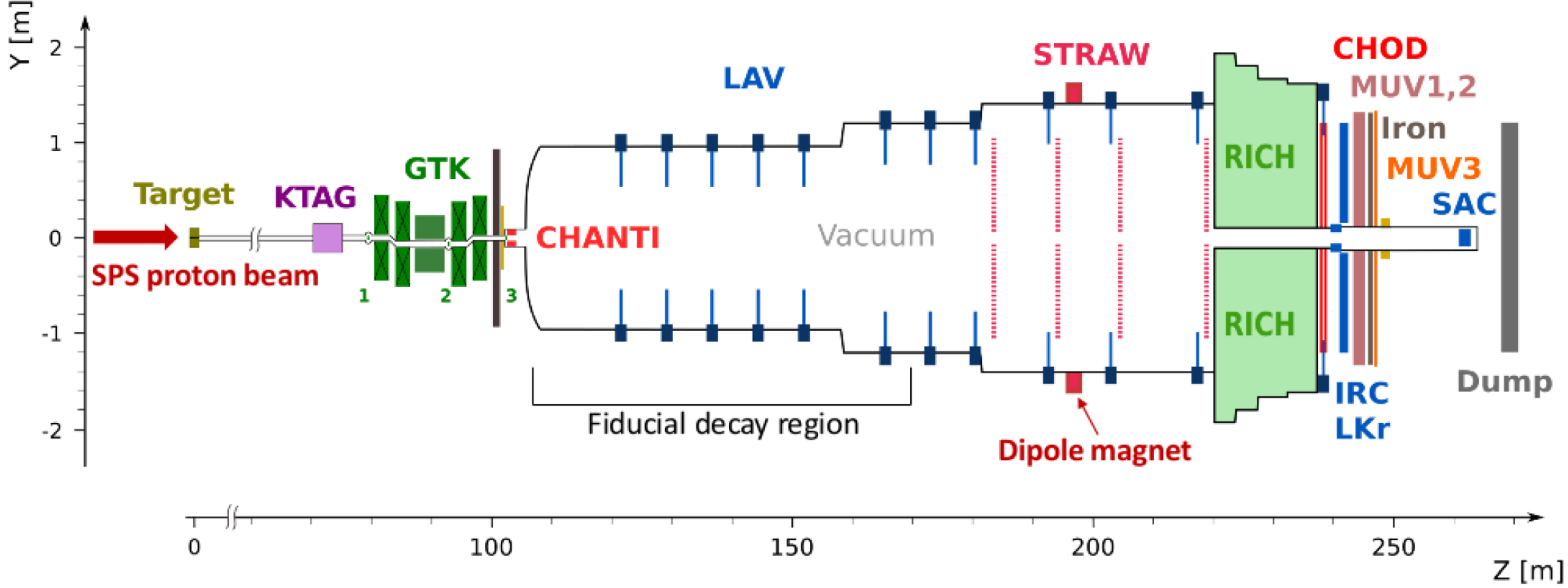
[JINST 12 P05025 (2017)]



- High energy kaons decay **in-flight** technique in ~60 m decay region
- 75 GeV/c hadron beam from 400 GeV/c primary proton beam impinging on beryllium target
- Unseparated secondary beam (70% pions, 24% protons, **6% kaons**)
- Nominal total rate (on GTK3) 750 MHz, O(10^{12}) pot per spill, ~3.5 s effective spill
- Average beam particle rate during 2018 data-taking: **450-500 MHz**

NA62 Detector postcard

[JINST 12 P05025 (2017)]



- Beam spectrometer (**GTK**)
- Particle identification system (**KTAG, RICH, MUVs**)
- Decay products spectrometer (**STRAW**)
- Electromagnetic Calorimeter (**LKR**)
- Veto system (**LAV, IRC, SAC, CHANTI, MUV0, HASC**)
- Multi level (L0, L1, L2) **trigger**

R_j measurement strategy

Observed events

background events

Trigger efficiencies

$$R_j = \frac{Br(K_{e3\gamma})}{Br(K_{e3})} = \frac{N_{sign}^{obs} - N_{sign}^{bkg}}{N_{norm}^{obs} - N_{norm}^{bkg}} \cdot \frac{A_{norm}}{A_{sign}} \cdot \frac{\epsilon_{norm}}{\epsilon_{sign}}$$

Acceptances

- The signal ($K^+ \to \pi^0 e^+ \nu\gamma$) and the normalization ($K^+ \to \pi^0 e^+ \nu$) share most of the selection criteria → first-order-cancellation of systematics effects.
- Acceptances evaluated with GEANT4 based MC
- Trigger efficiencies measured with data
  - Same trigger selection for signal and normalization
- Preliminary results based on full **2017** and **2018** data sets

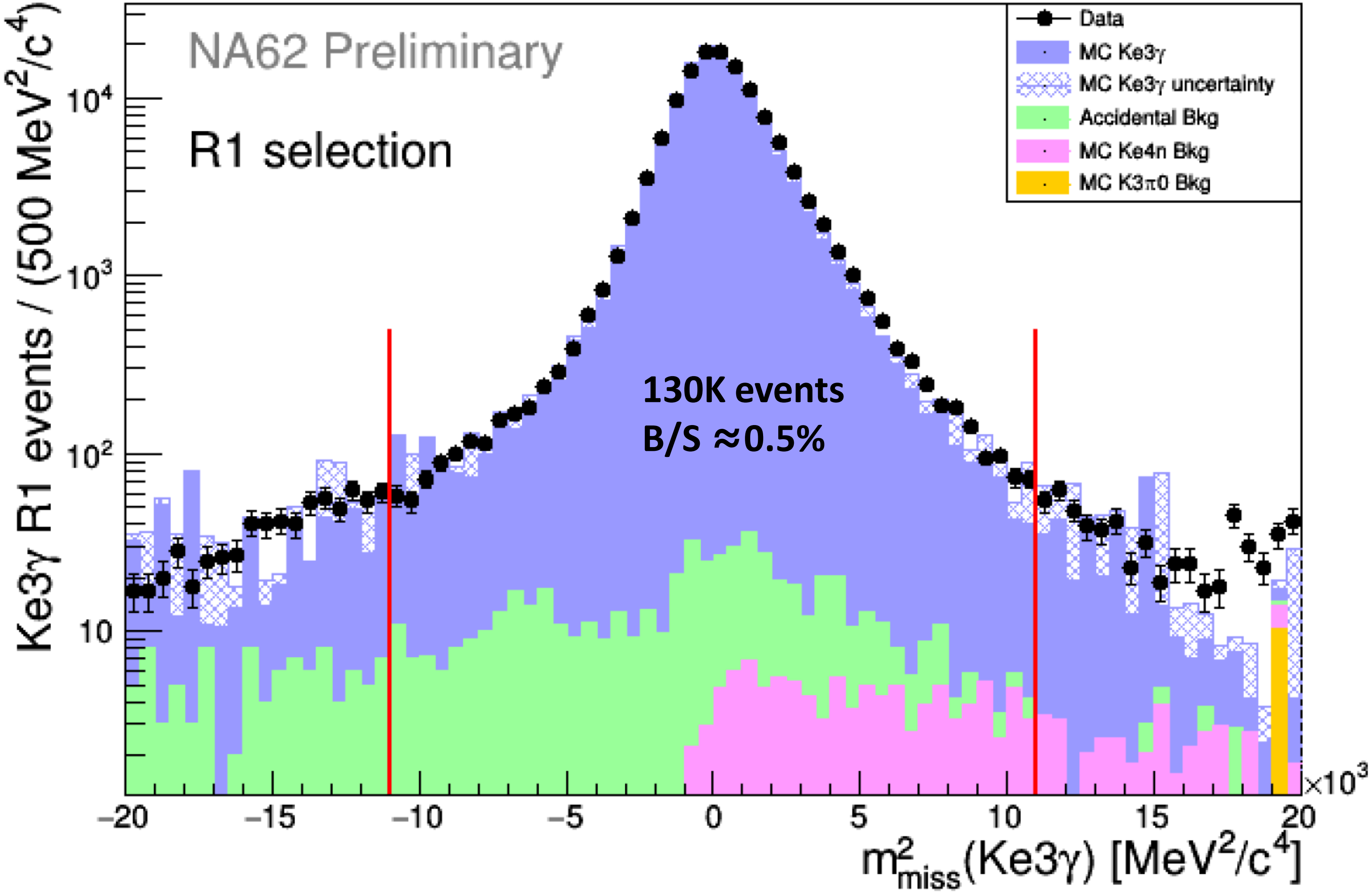
$K_{e3\gamma}$ selection

- K^+ momentum reconstructed in GTK, positron momentum reconstructed in STRAW: decay vertex identified by K^+ and positron tracks;
- K^+ positively identified with KTAG;
- Positron PID with RICH ring radius and LKr-STRAW E/p (π^+ and μ^+ rejection);
- $\pi^0 \rightarrow \gamma\gamma$ identified selecting two γs in LKr and reconstructing the invariant mass;
- Radiative γ identified selecting in-time additional isolated cluster in LKr;
- In-time extra activity in Veto system 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;
- Final kinematic selection based on the missing mass (→neutrino) both for signal and normalization

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

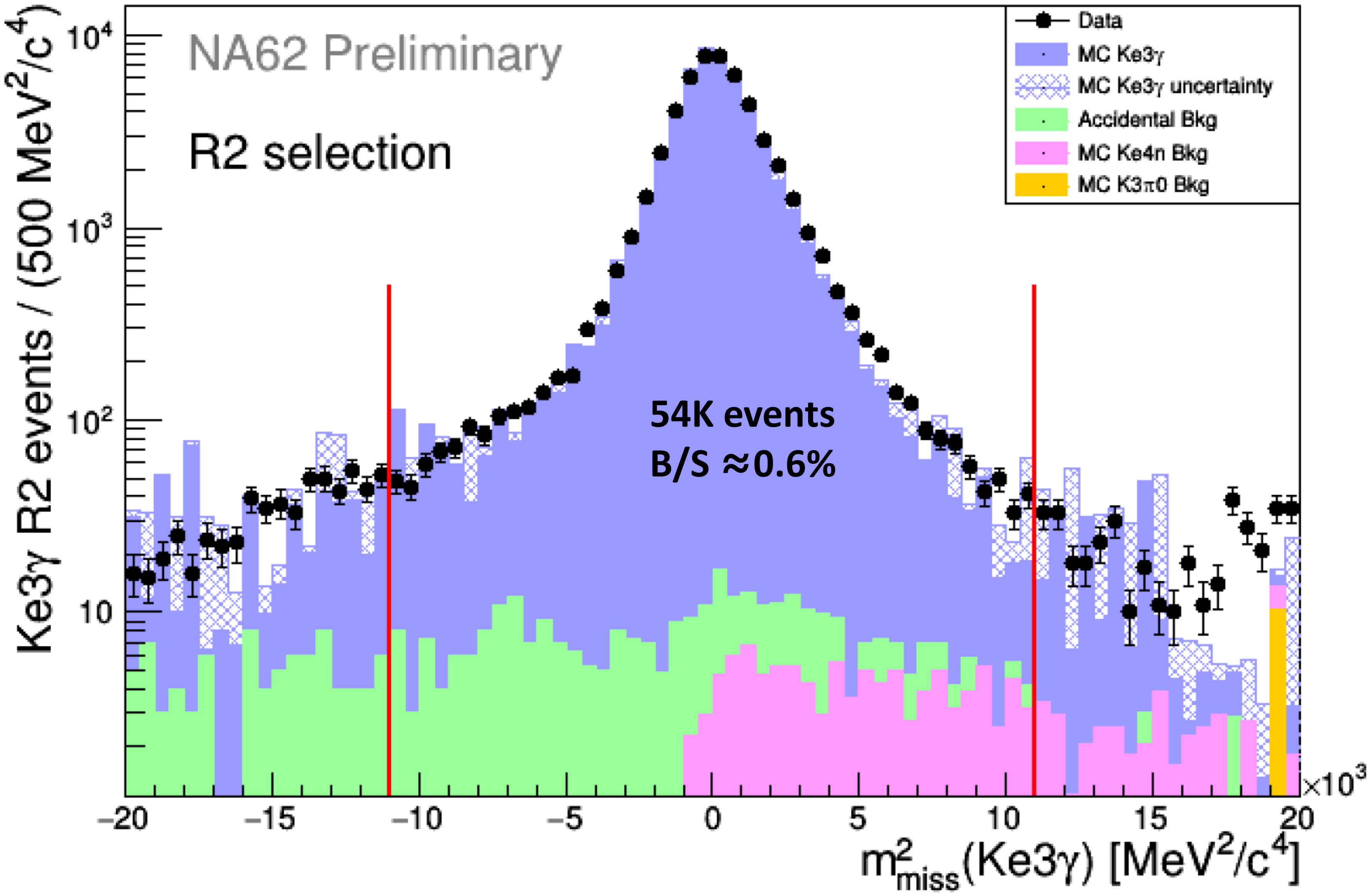
- E_γ and $\theta_{e,\gamma}$ cuts applied after the selection (R_1, R_2, R_3 samples)

R_1: E_γ>10 MeV and $\theta_{e,\gamma}$>10°



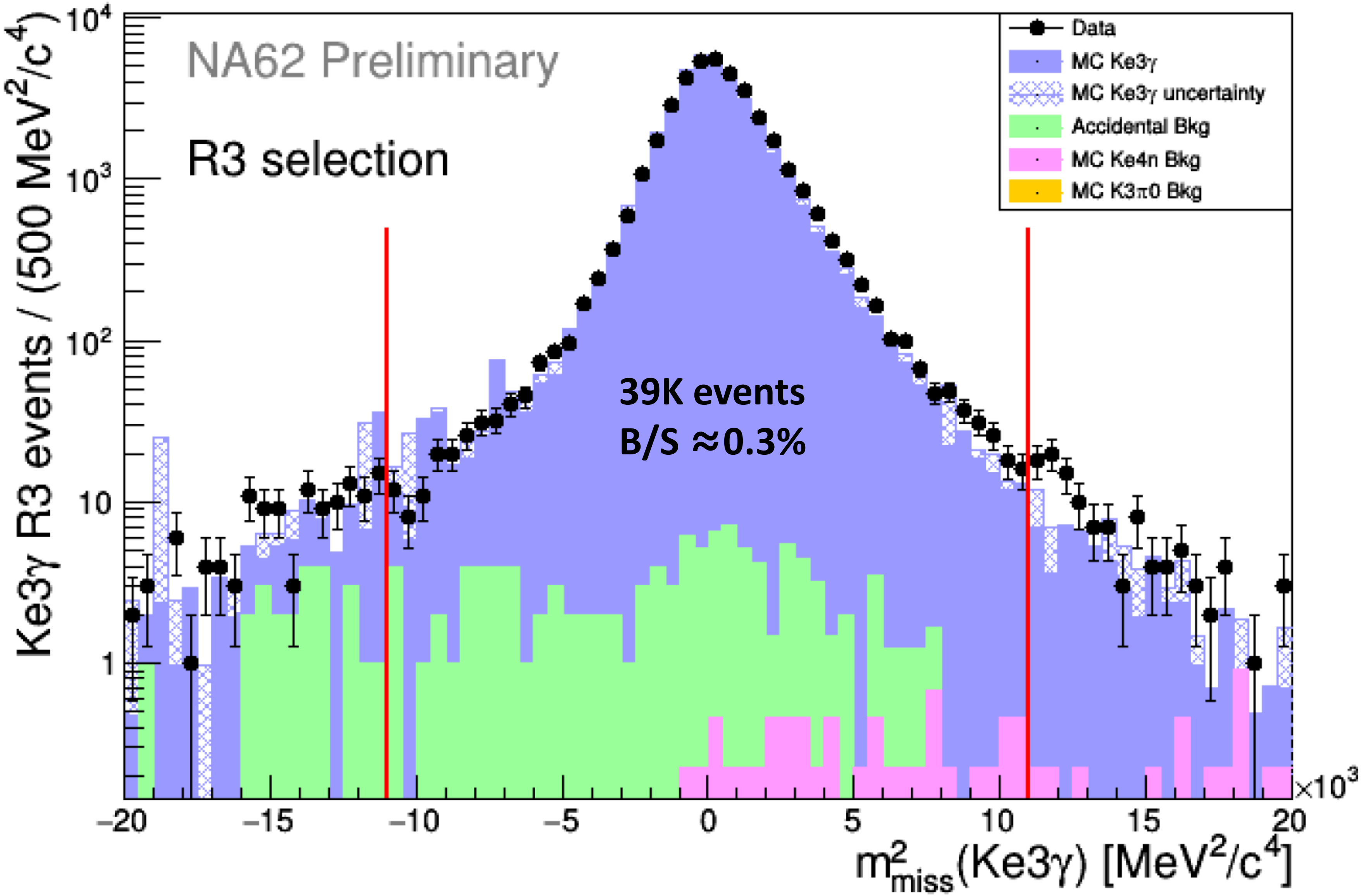
130K events
B/S ≈0.5%

R_2: E_γ>30 MeV and $\theta_{e,\gamma}$>20°

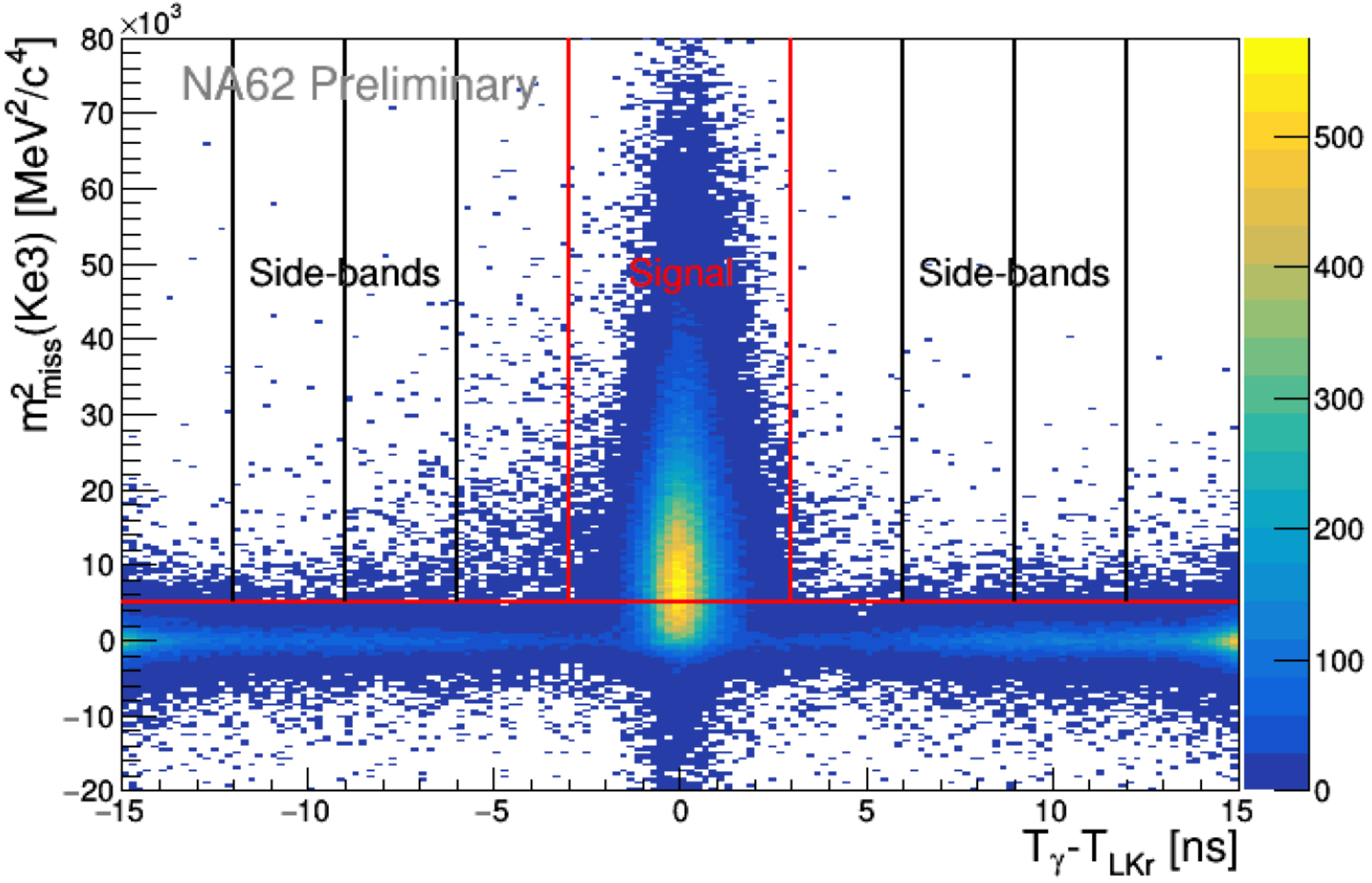


54K events
B/S ≈0.6%

R_3: E_γ>10 MeV and 0.6<cos $\theta_{e,\gamma}$<0.9

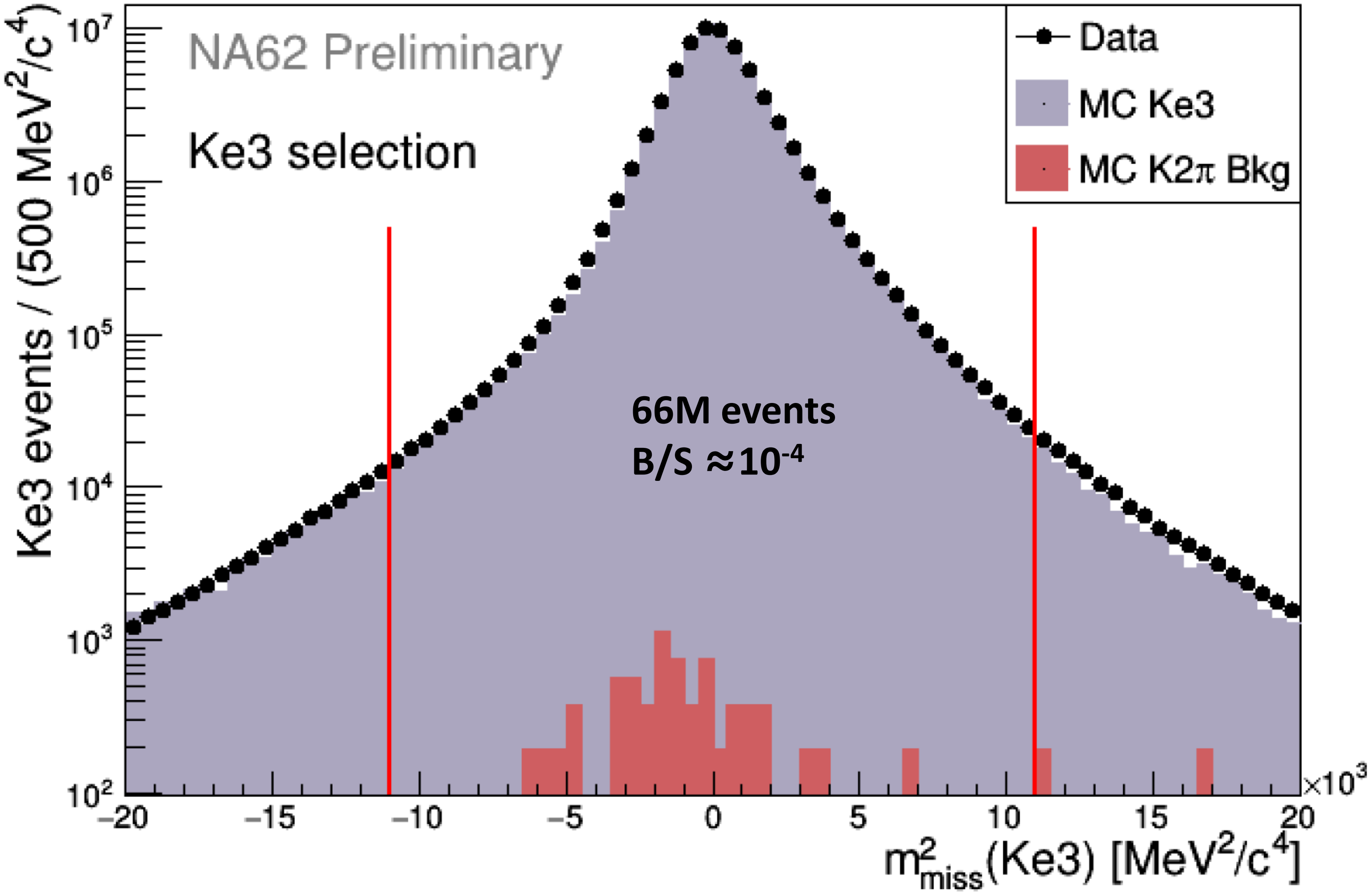


Backgrounds



- In-time accidental LKr cluster superimposed with $K^+ \rightarrow \pi^0 e^+ \nu$ or $K^+ \rightarrow \pi^+ \pi^0$ (with mis-ID π^+)
- Background valuated with out-of-time side-bands in dedicated study
- Other backgrounds evaluated with MC

Normalization: K_{e3}



Final statistics

	N^{obs}	Uncertainty	Acceptance [%]
Ke3 (norm)	$66.378 \cdot 10^6$	0.01%	3.839±0.002
Ke3γ (R1)	$129.6 \cdot 10^3$	0.3%	0.443±0.001
Ke3γ (R2)	$53.6 \cdot 10^3$	0.4%	0.513±0.002
Ke3γ (R3)	$39.1 \cdot 10^3$	0.5%	0.431±0.002

- Factor 3 improvement with respect to previous results on statistical uncertainty
- Uncertainties on acceptance limited by statistics in MC samples

- B/S < 1%
- Small contribution to the uncertainty of the final R_j measurements

Bkg Source	R_1	R_2	R_3
Accidentals	$(4.9\pm0.2\pm1.3)\cdot 10^2$	$(2.3\pm0.2\pm0.3)\cdot 10^2$	$(1.1\pm0.1\pm0.5)\cdot 10^2$
$K^+ \to \pi^0\pi^0 e^+\nu$	$(1.1\pm1.1)\cdot 10^2$	$(1.1\pm1.1)\cdot 10^2$	$(0.07\pm0.07)\cdot 10^2$
$K^+ \to \pi^+\pi^0\pi^0$	< 20	< 20	< 20
$K^+ \to \pi^+\pi^0\gamma$	< 2	< 2	< 2
Total	$(5.9\pm1.7)\cdot 10^2$	$(3.4\pm1.1)\cdot 10^2$	$(1.1\pm0.6)\cdot 10^2$
B/S	0.46%	0.64%	0.29%

NA62 preliminary R_j measurements

	O(p6) ChPT ($x10^{-2}$)	ISTRA+ ($x10^{-2}$)	OKA ($x10^{-2}$)	**NA62 Prelim. ($x10^{-2}$)**
R_1	1.804 ± 0.021	1.81 ± 0.03 ±0.07	1.990 ± 0.017 ±0.021	**1.684 ± 0.005 ±0.010**
R_2	0.640 ± 0.008	0.63 ± 0.02 ±0.03	0.587 ± 0.010 ±0.015	**0.599 ± 0.003 ±0.005**
R_3	0.559 ± 0.006	0.47 ± 0.02 ±0.03	0.532 ± 0.010 ±0.012	**0.523 ± 0.003 ±0.003**

- Preliminary results based on 2017+2018 data set
- Improved precision with respect to the previous measurements
- Relative discrepancy with the theory of 6-7% in all three measurements
- NA62 for R_2 is half way between the two latest theoretical predictions
  - (0.640±0.008)% *[Kubis et. Al., EPJ C 50, 557 (2007)]*
  - (0.56±0.02)% *[Khriplovich et al., PAN 74, 1214 (2010)]*

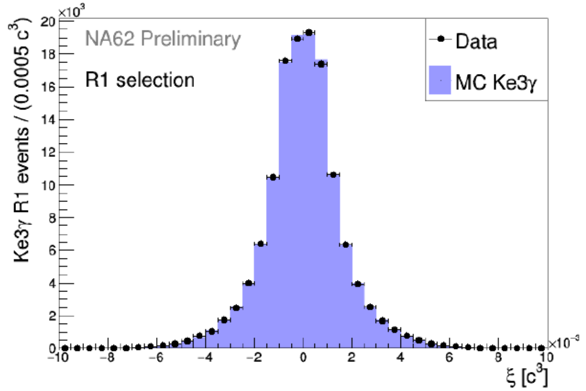
	$\delta R_1/R_1$	$\delta R_2/R_2$	$\delta R_3/R_3$
Statistical	0.3%	0.5%	0.6%
Acceptance from MC	0.3%	0.4%	0.4%
Background estimation	0.1%	0.2%	0.1%
LKr response modeling	0.5%	0.6%	0.5%
Theoretical model	0.1%	0.5%	0.1%
Total systematic	0.6%	0.9%	0.6%
Total stat+syst	0.7%	1.0%	0.8%

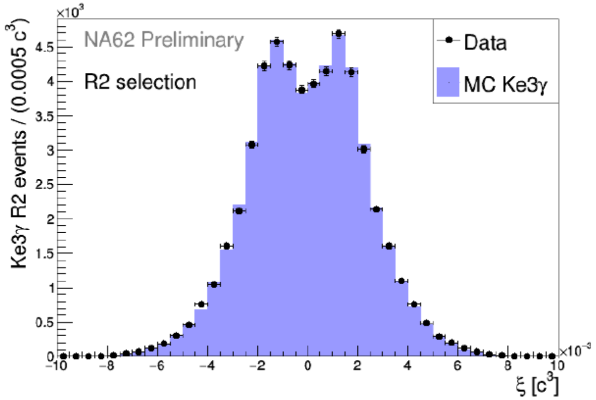
NA62 preliminary A_ξ measurements

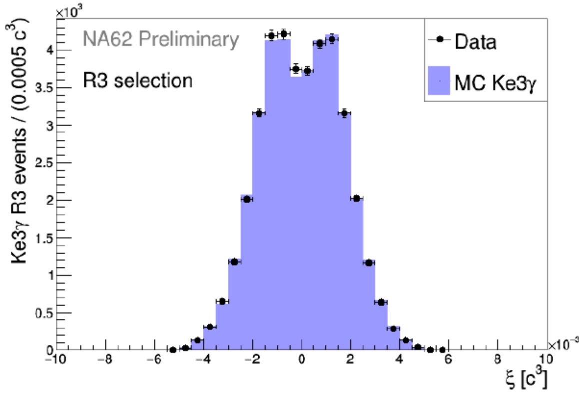
$$A_\xi = A_\xi^{Data} - \left(A_\xi^{MCreco} - A_\xi^{MCgene}\right) \simeq A_\xi^{Data} - A_\xi^{MCReco}$$

	R1 (x10^{-2})	**R2 (x10^{-2})**	**R3 (x10^{-2})**
$\boldsymbol{A_\xi^{Data}}$	0.2±0.3	0.1±0.4	-0.6±0.5
$\boldsymbol{A_\xi^{MCgene}}$	-0.01±0.01	0.00±0.02	-0.01±0.02
$\boldsymbol{A_\xi^{MCreco}}$	0.3±0.2	0.4±0.3	0.3±0.5
$\boldsymbol{A_\xi}$	-0.1±0.3$_{stat}$±0.2$_{MC}$	-0.3±0.4$_{stat}$±0.3$_{MC}$	-0.9±0.5$_{stat}$±0.4$_{MC}$

- Precision of R_3 asymmetry improved by a factor greater than 3
  - $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \cdot 10^{-2}$
- First measurements ever performed for R_1 and R_2 T-asymmetry







Conclusions

- New preliminary results from the NA62 experiment on $K^{+} \rightarrow \pi^{0} e^{+} \nu\gamma$ based on data collected in 2017 and 2018 are presented;
- Experimental relative precision on R_j measurements improved by a factor ~3 with respect to the previous measurements;
- The relative uncertainty is <1%;
- The measurements show a 6-7% relative discrepancy with ChPT $O(p^6)$ calculations;
- T-asymmetry measured for the first time for R_1 and R_2, improvement by a factor greater than 3 for R_3;
- The T-asymmetry measurement is compatible with zero within the experimental sensitivity. Still two order of magnitude from the theoretical expectation.

SPARES

T-asymmetry in log scale