Latest results from the NA62 experiment at CERN

On behalf of the NA62 collaboration

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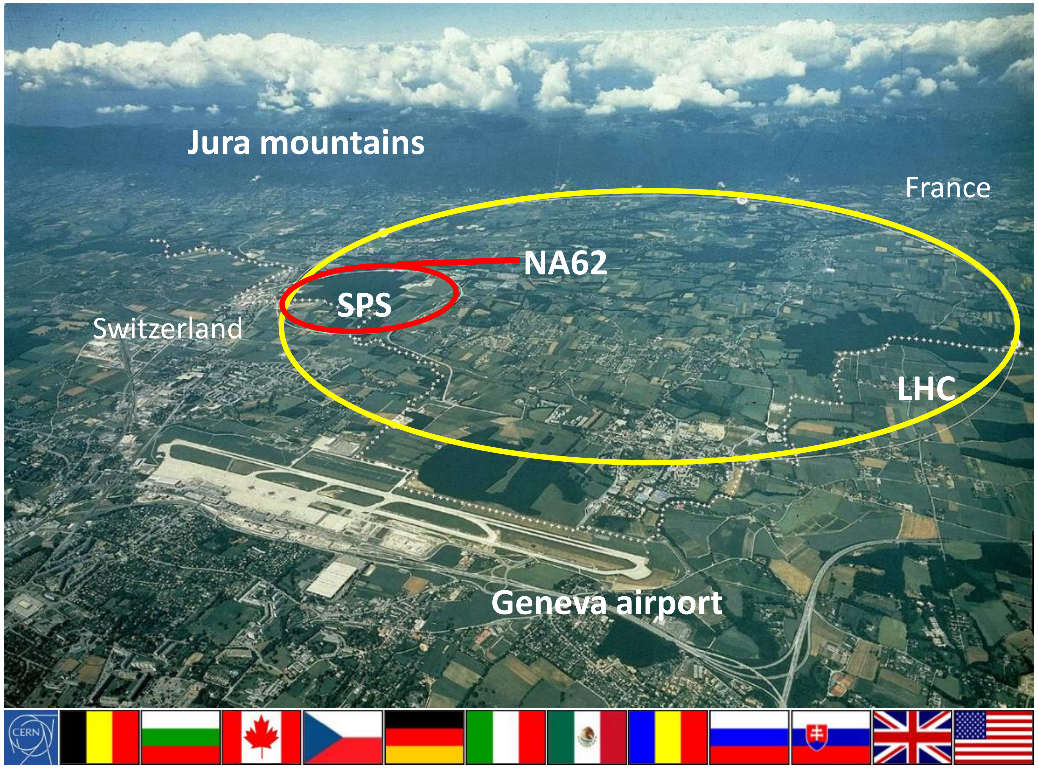
Outline

- The NA62 experiment and detector
- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ results
- LNV results
- Dark photon searches

The NA62 experiment and detector

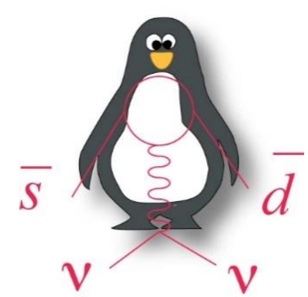
The NA62 Experiment

Fixed target Kaon experiment at CERN SPS

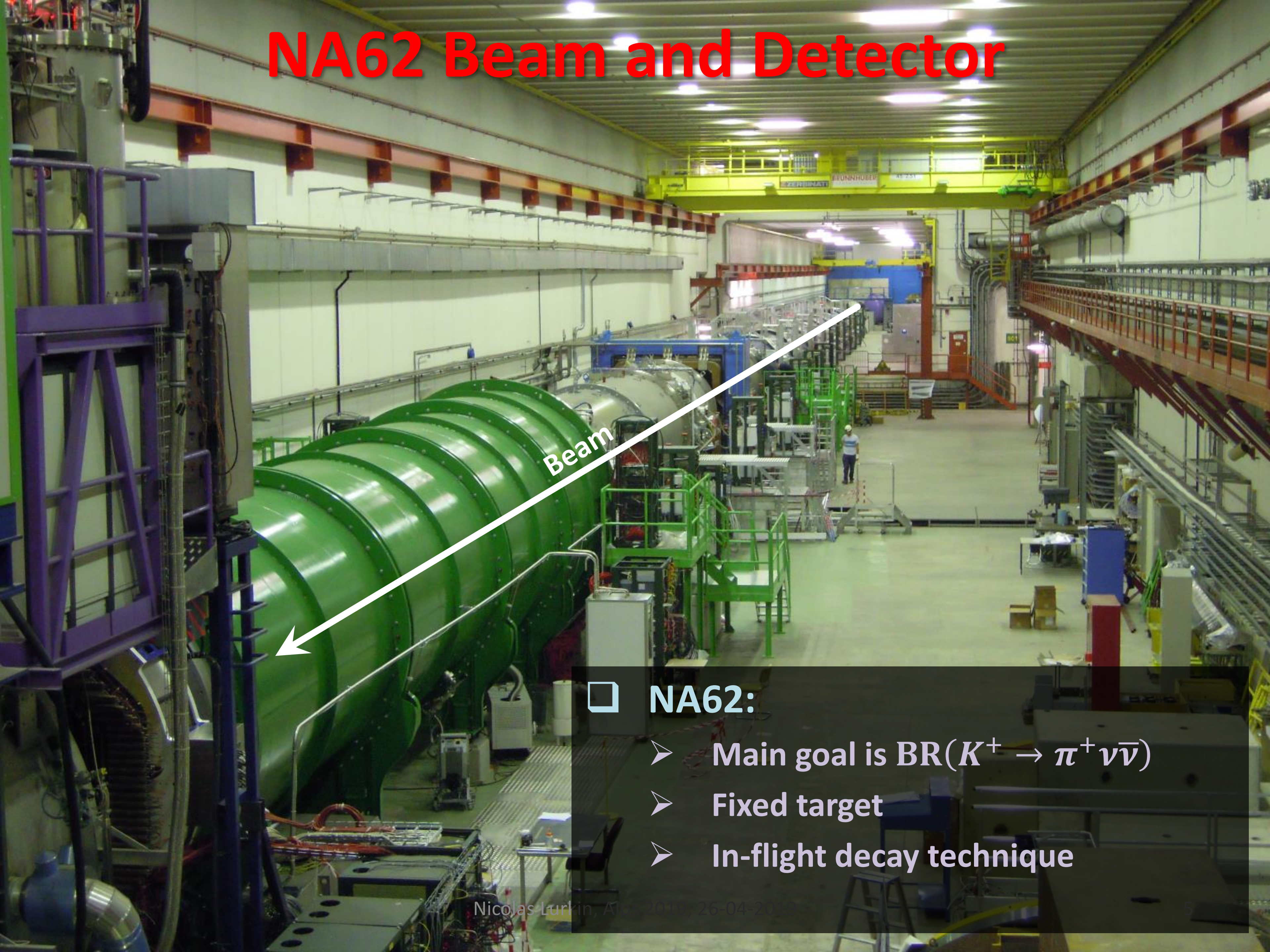


~ 200 participants: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain-La-Neuve, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

- **2008**: NA62 Approval
- **2009-2014**: Detector R&D and Installation
- **2014**: Pilot Run
- **2015**: Commissioning run
- **2016-2018**: Physics runs
- **2021-2023**: Future runs

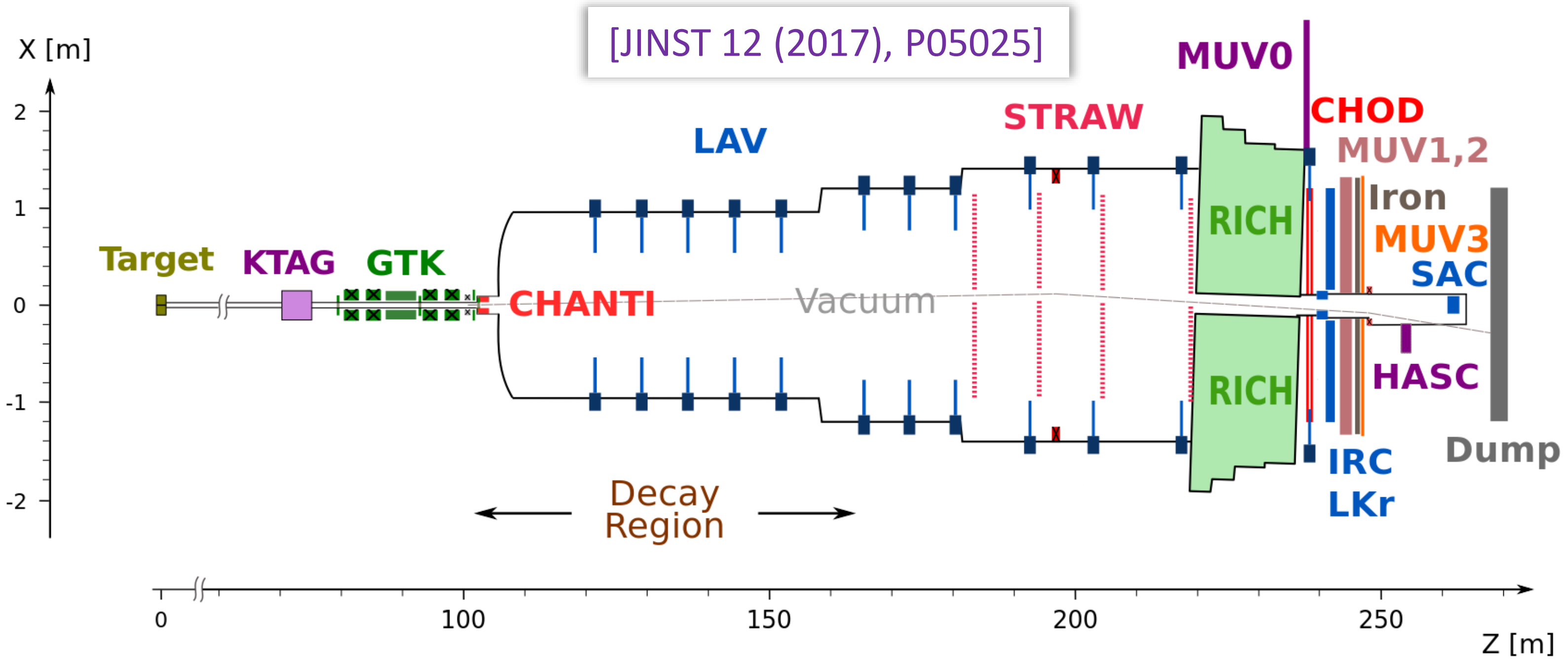


NA62 Beam and Detector



- **NA62:**
  - Main goal is $\mathrm{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
  - Fixed target
  - In-flight decay technique

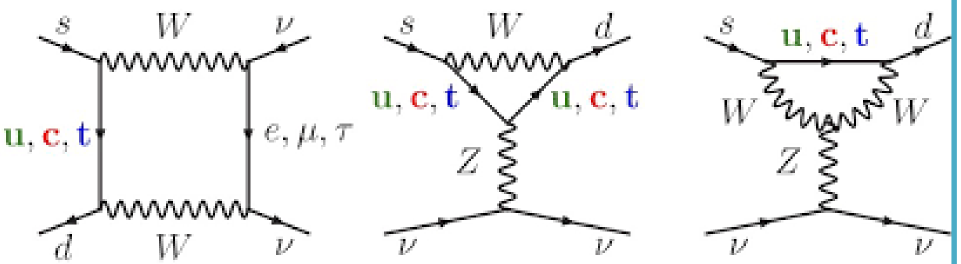
NA62 Beam & Detector



- **SPS Beam:**
  - 400 GeV/c protons
  - 2×10^{12} protons/spill
  - 3.5s spill
- **Secondary positive beam**
  - 75 GeV/c momentum, 1% bite
  - $100\ \mu\mathrm{rad}$ divergence (RMS)
  - $60 \times 30\ \mathrm{mm}^2$ transverse size
  - $K^+(6\%)/\pi^+(70\%)/p(24\%)$
  - 33×10^{11} ppp on T10 (750 MHz at GTK3)
- **Decay region**
  - 60 m long fiducial region
  - $\sim 5\ \mathrm{MHz}\ K^+$ decay rate
  - Vacuum $\sim\mathcal{O}(10^{-6})$ mbar

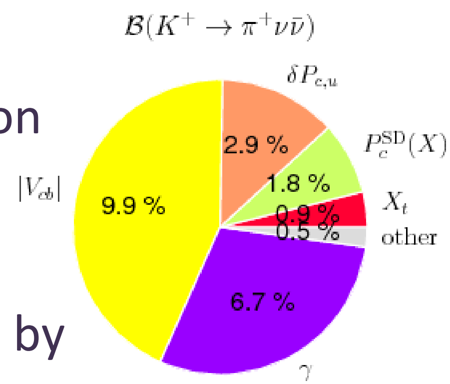
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results

The $K^+ \to \pi^+ \nu\bar{\nu}$ Process



- **Highly suppressed:**
  - FCNC process forbidden at tree level
  - CKM suppression ($s \to d$ coupling, $BR \sim |V_{ts}V_{td}|^2$)

- **Theoretically clean:**
  - Dominant short-distance contribution
  - Hadronic matrix element extracted from $BR(K^+ \to \pi^0 e^+ \nu)$
  - Theoretical error budget dominated by CKM parameters



- **Many BSM models predict deviations**

[Buras et al., JHEP1511 (2015) 033]

- **Previous exp. determination:**

$BR(K^+ \to \pi^+ \nu\bar{\nu})$
E787/E949 at BNL
$(17.6^{+11.5}_{-10.5}) \times 10^{-11}$

- **SM Predictions:**

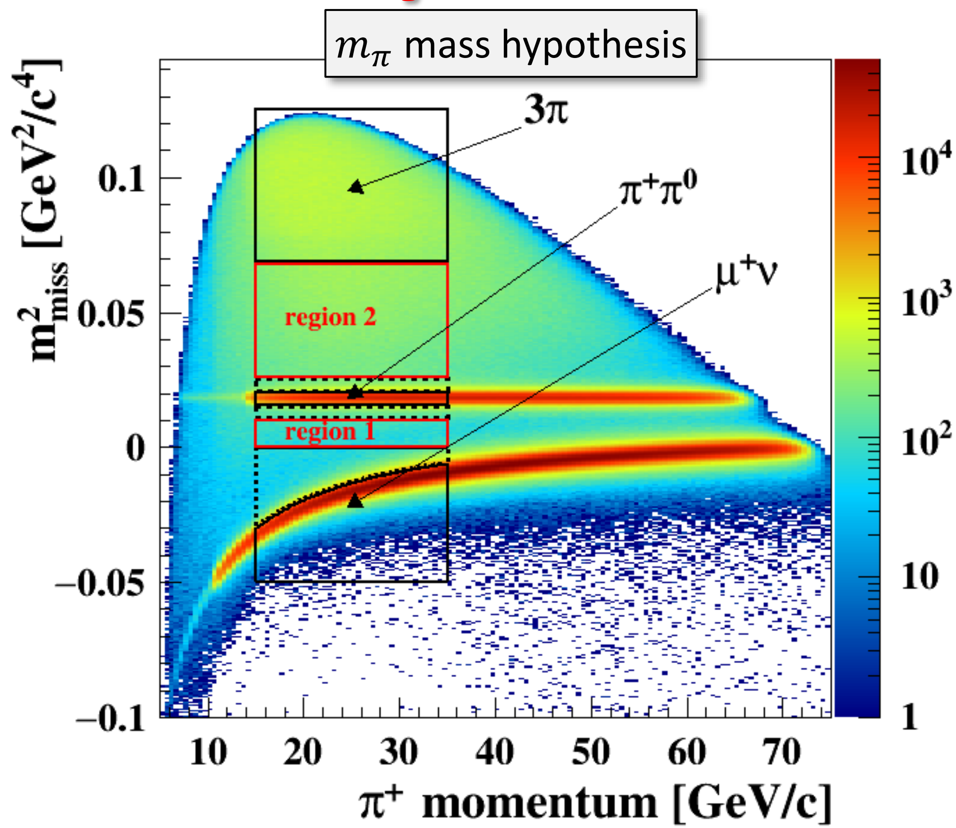
$BR(K^+ \to \pi^+ \nu\bar{\nu})$
$(8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{\lvert V_{cb}\rvert}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$
$(8.4 \pm 1.0) \times 10^{-11}$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Analysis

- **Selection criteria**
  - Single track topology
  - π^+ identification
  - Photon rejection
  - Multi-track rejection

- **Performances**
  - $\varepsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
  - $\varepsilon_{\pi^0} = 3 \cdot 10^{-8}$
  - $\sigma(\mathrm{m}^2_{\mathrm{miss}}) = 1 \cdot 10^{-3}\ \mathrm{GeV}^2/c^4$
  - $\sigma_t \sim \mathcal{O}(100\ \mathrm{ps})$

- **Signal region**
  - $15 < P_{\pi^+} < 35 \mathrm{GeV}/c$
  - $\boldsymbol{m^2_{\mathrm{miss}}} = (\mathbf{P_K} - \mathbf{P_\pi})^2$ in 3 ways:
    - $m^2_{\mathrm{miss}}(\mathrm{STRAW}, \mathrm{GTK})$
    - $m^2_{\mathrm{miss}}(\mathrm{RICH}, \mathrm{GTK})$
    - $m^2_{\mathrm{miss}}(\mathrm{STRAW}, \mathrm{beam})$



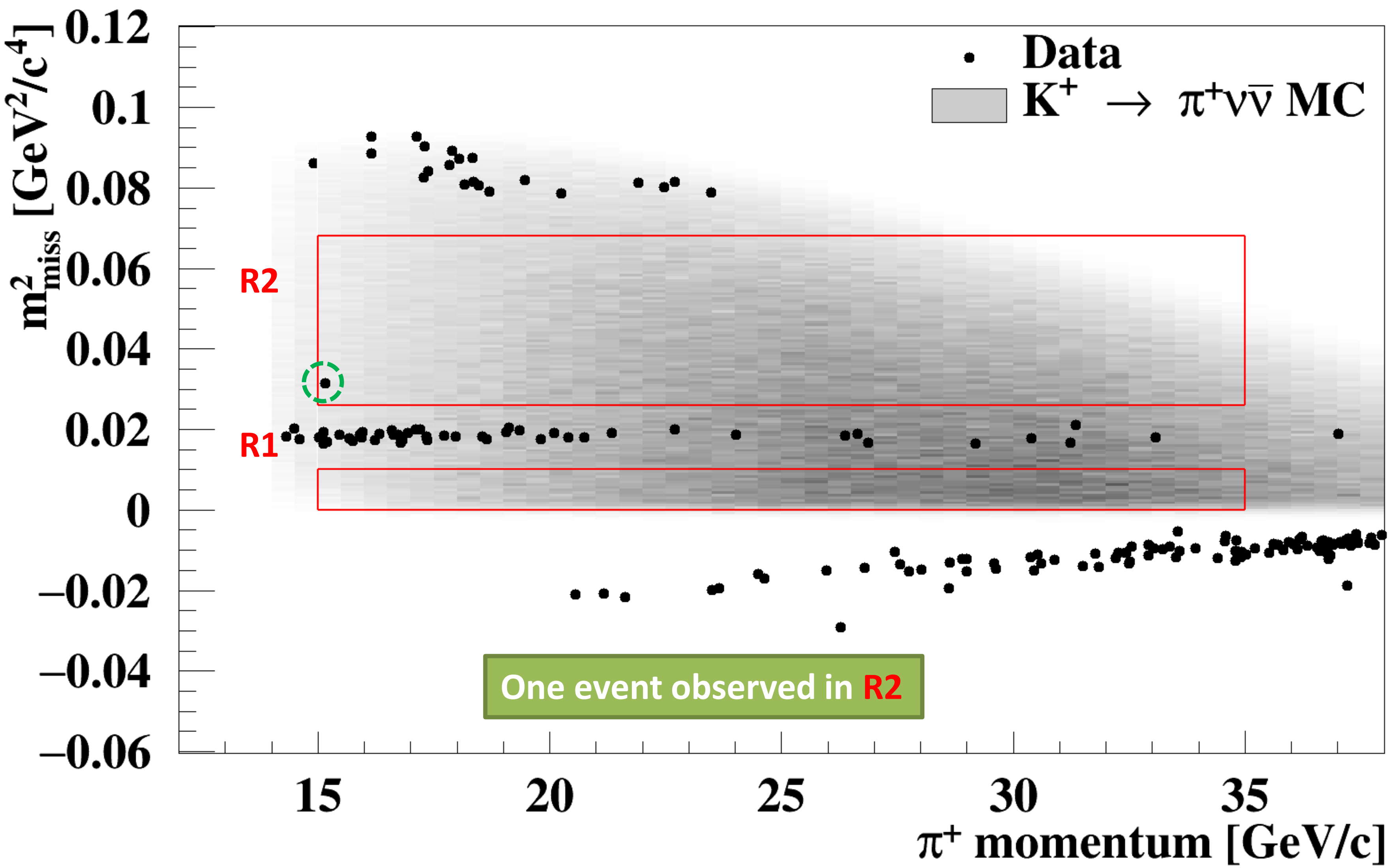
- **Signal acceptance: 4%**
- **Normalization** $K^+ \rightarrow \pi^+ \pi^0$
  - Number of kaon decays in the FV: $N_K = 1.21(4) \times 10^{11}$
- **Single event sensitivity**
  - $SES = (3.15 \pm 0.01_{\mathrm{stat}} \pm 0.24_{\mathrm{syst}}) \cdot 10^{-10}$

$K^+ \to \pi^+ \nu \bar{\nu}$ Background Summary

- $K^+ \to \pi^+ \pi^0 (\gamma)$ (Data driven)
  - Control region: 1 observed
    $1.46 \pm 0.16_{stat} \pm 0.06_{syst}$ expected
- $K^+ \to \mu^+ \nu_\mu (\gamma)$ (Data driven)
  - Control region: 2 observed
    $1.02 \pm 0.16_{stat} \pm 0.31_{syst}$ expected
- $K^+ \to \pi^+ \pi^- e^+ \nu_e$ (MC)
  - 600M MC decays
  - Good agreement across 5 validation samples
- **Upstream background (accidental and interactions)**
  - Data driven
  - Geometrical and Kaon-pion matching cuts effective
  - Addition of a copper block in the beam line in 2017
  - Installation of a new final collimator in 2018

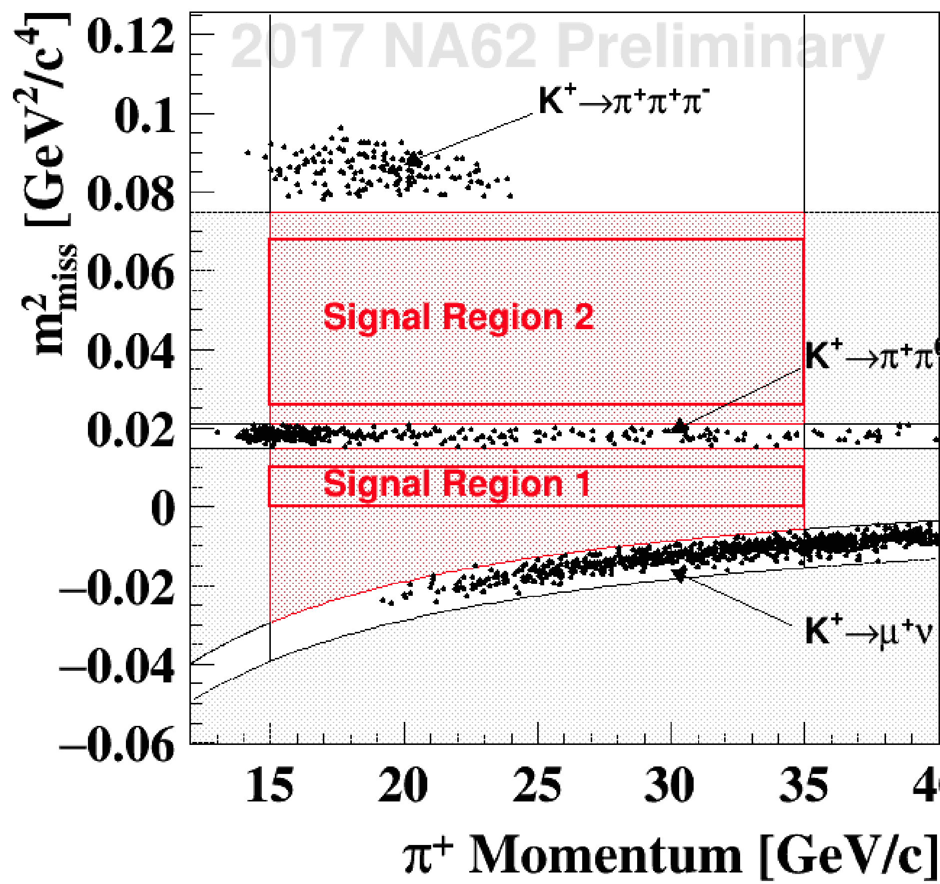
Process	Expected events (R1+R2)
$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.152^{+0.092}_{-0.033}\big\vert_{stat} \pm 0.013_{syst}$
$K^+ \to \pi^+ \pi^0 (\gamma)$	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+ \nu (\gamma)$	$0.020 \pm 0.003_{stat} \pm 0.006_{syst}$
$K^+ \to \pi^+ \pi^+ \pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.013^{+0.017}_{-0.012}\big\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^0 \ell^+ \nu \ (\ell = \mu, e)$	< 0.001
$K^+ \to \pi^+ \gamma\gamma$	< 0.002
Upstream background	$0.050^{+0.090}_{-0.030}\big\vert_{stat}$

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Results



$K^+ \to \pi^+ \nu\bar{\nu}$ 2017 update

- ❑ **Higher beam intensity**
- ❑ **2016-like selection**
  - ➢ Comparable performances
  - ➢ Better pileup treatment in IRC/SAC
  - ➢ Improved LKr reconstruction
  - ➢ 40% better π^0 rejection (does not depend on intensity)
  - ➢ Slightly improved usage of RICH variables
    No effect from intensity on π efficiency and μ rejection.

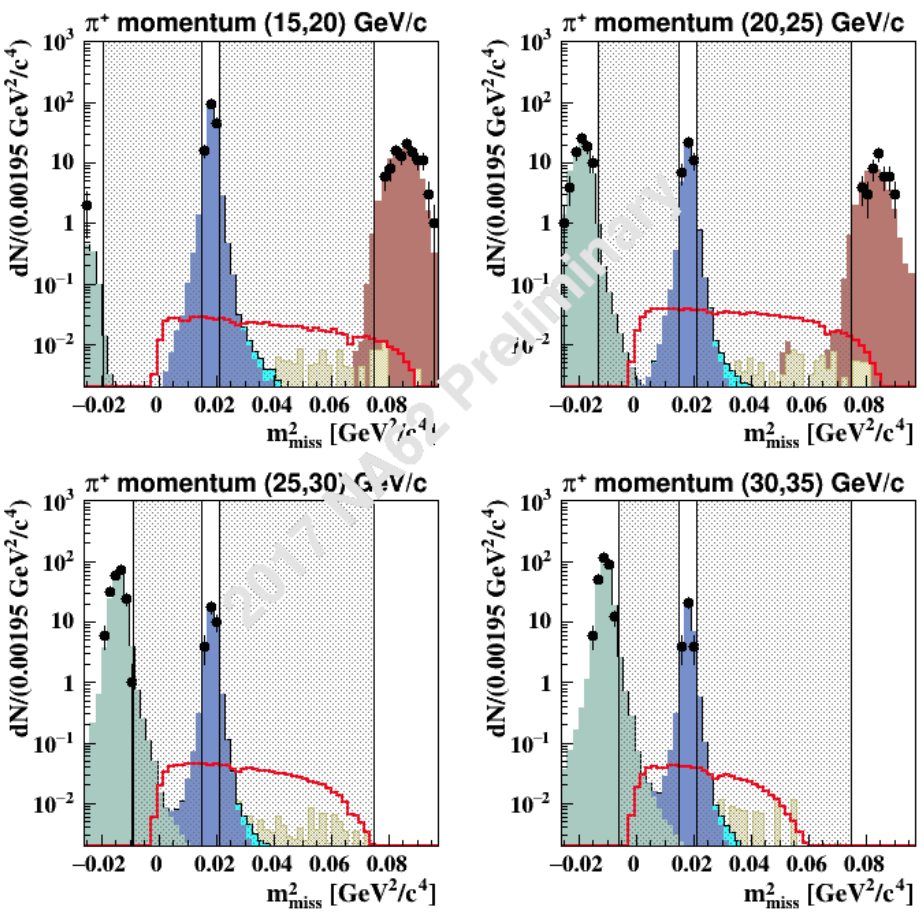


- ❑ **Expectations**
  - ➢ $N_K = 1.3(1) \times 10^{12}$ $(\sim 10 \times 2016)$ from $\pi^+\pi^0$
  - ➢ $SES = (0.34 \pm 0.04) \times 10^{-10}$ (scales linearly with intensity)
  - ➢ Expected SM $K^+ \to \pi^+\nu\bar{\nu}$ events: 2.5 ± 0.4

$K^+ \to \pi^+ \nu \bar{\nu}$ 2017 update

- Background studies ongoing, including possible intensity related effects

Process	Expected events
$K^+ \to \pi^+ \pi^0 (\gamma)$	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+ \nu (\gamma)$	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+ \pi^+ \pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^0 \ell^+ \nu$ $(\ell = \mu, e)$	$0.012 \pm 0.012_{syst}$
$K^+ \to \pi^+ \gamma\gamma$	$0.005 \pm 0.005_{syst}$
Upstream Bckg.	Ongoing



- **Detailed comparison of data and background models**
  - Shape depends on pion momentum
  - Background distributions normalised separately to background regions. Signal normalised to expected SM events .

$K^+ \to \pi^+\nu\bar{\nu}$ Summary

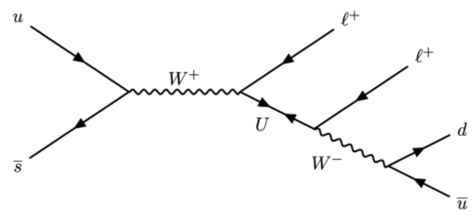
- **One event observed in Region 2 in 2016**
- **The result is compatible with the Standard Model**
  - $BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL
  - **Published in** [Phys. Lett. B 791 (2019) 156-166]
- **Decay in flight technique is working!**

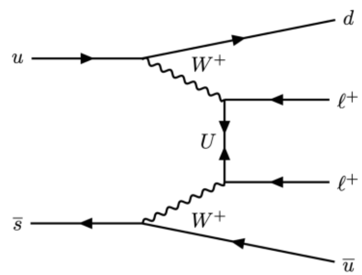
- **Analysis of 2017 data is ongoing.**
  - Analysis largely similar to 2016
  - Expect about a factor 10 of improvement (from statistics)
  - Signal-over-background ratio do not degrade with intensity

LNV results

LNV processes $K^+ \to \pi^- \ell^+ \ell^+$

- **Violation of lepton number predicted by some BSM models (e.g. Majorana Neutrino)**

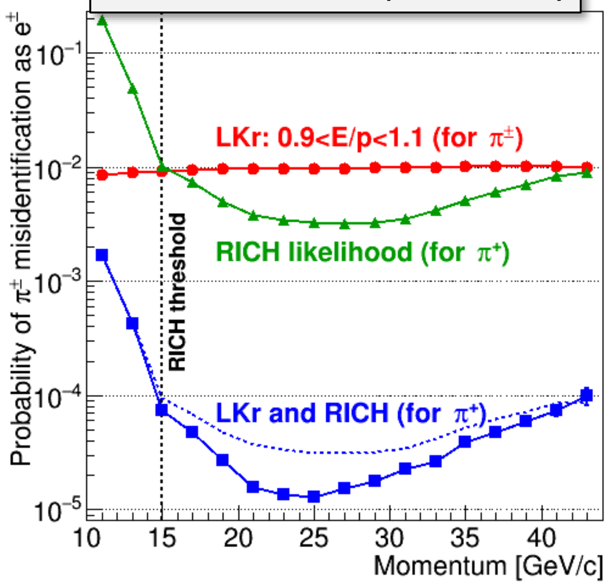




- Previous exp. results (@90% CL):
  - BNL E865: [PRL 85 2877 (2000)]
    $\mathcal{B}(K^+ \to \pi^- e^+ e^+) < 6.4 \cdot 10^{-10}$
  - NA48/2: [Phys. Lett. B769 67 (2017)]
    $\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) < 8.6 \cdot 10^{-11}$

- **NA62 search:**
  - Subset of 2017 data: ~3 months of data taking
  - Blind analysis procedure
  - Normalization from equivalent SM channels
  - Main source of background from π^+ mis-identification and π^+ decays in flight
    - Special MC with enriched decay in flight + data-driven approach

$\pi^+ \to e^+$ mis-id probability



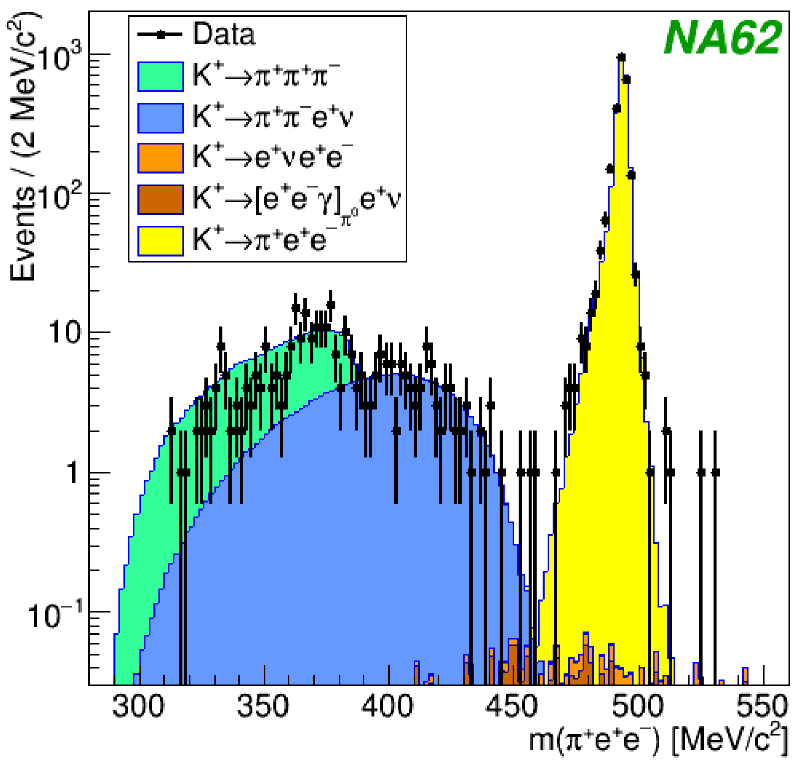
Search for $K^+ \to \pi^- e^+ e^+$

- Upper limit at 90% CL using CLs treatment
  - Signal acceptance: 4.98%
  - $N_K = (2.14 \pm 0.07) \times 10^{11}$
  - $SES = (0.94 \pm 0.03) \times 10^{-10}$
  - $\mathcal{B}(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$

Process	Expected in Sig. Region
$K^+ \to e^+ \nu e^+ e^-$	0.12 ± 0.02
$K^+ \to [e^+ e^- \gamma]_{\pi^0} e^+ \nu$	0.04
Total	$\mathbf{0.16 \pm 0.03}$

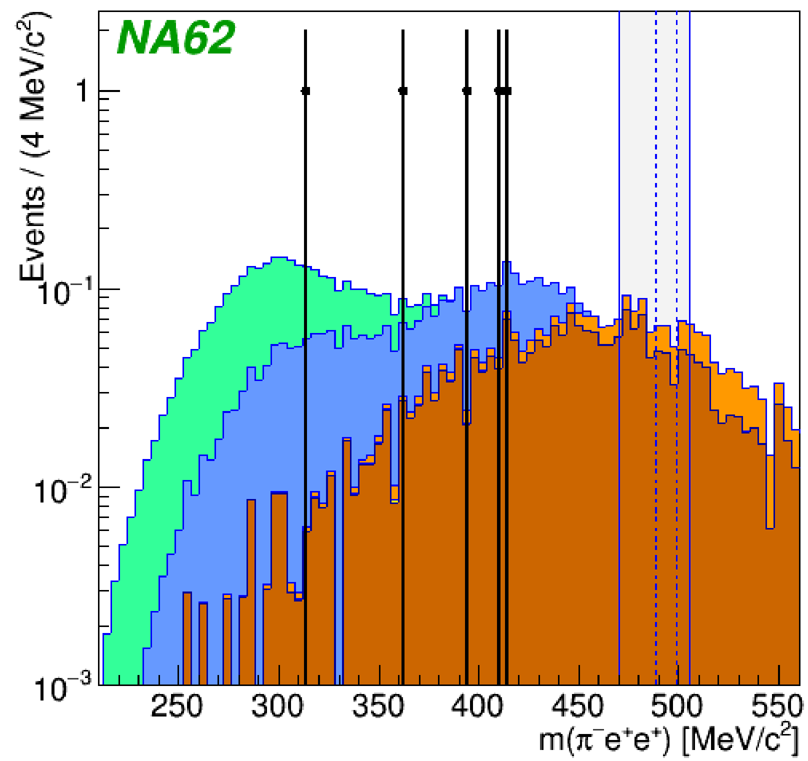
SM channel ($K^+ \to \pi^+ e^+ e^-$) ($m_{ee} > 140$ MeV$/c^2$)

2484 SM candidates



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

No events observed

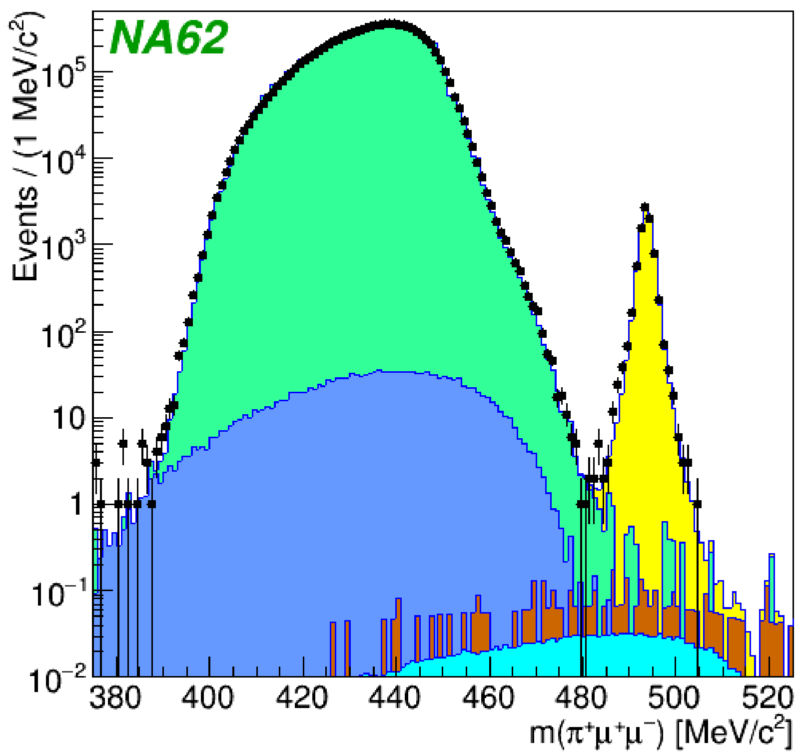


Search for $K^+ \to \pi^- \mu^+ \mu^+$

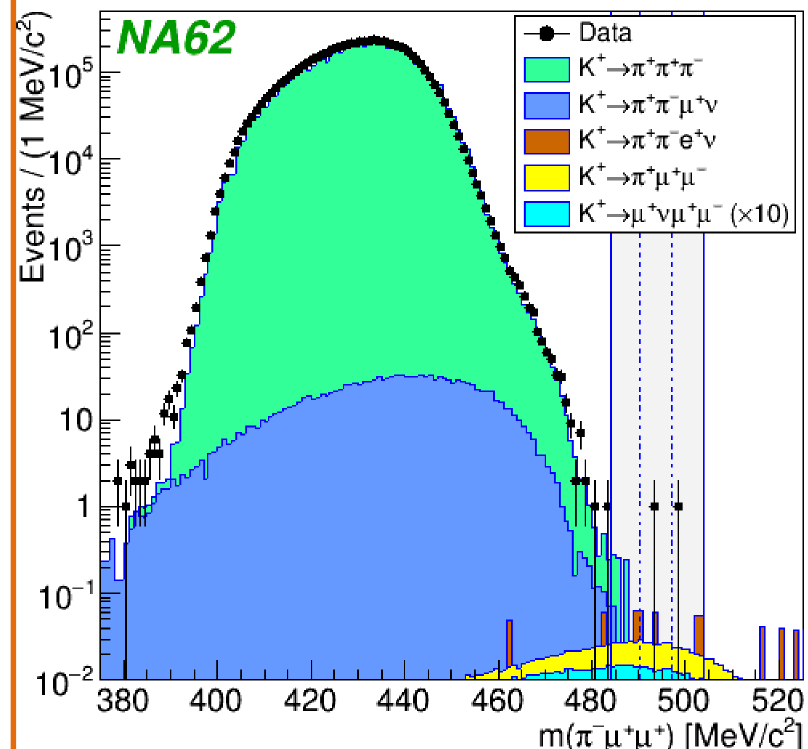
- Upper limit at 90% CL using CLs treatment
  - Signal acceptance: 9.81%
  - $N_K = (7.94 \pm 0.23) \times 10^{11}$
  - $SES = (1.23 \pm 0.03) \times 10^{-11}$
  - $\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$

Process	Expected in Sig. Region
$K^+ \to \pi^+\pi^+\pi^-$	0.70 ± 0.40
$K^+ \to \pi^+\pi^-\ell^+\nu$	0.06 ± 0.05 (μ), 0.07 ± 0.05 (e)
$K^+ \to \pi^+\mu^+\mu^-$	0.08 ± 0.02
$K^+ \to \mu^+\nu\mu^+\mu^-$	0.01
Total	$\mathbf{0.91 \pm 0.41}$

SM channel ($K^+ \to \pi^+\mu^+\mu^-$)
8357 SM candidates



LNV channel ($K^+ \to \pi^-\mu^+\mu^+$)
1 event observed



LNV Summary

- **Improved world limit for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$ decays in subset of 2017 data**
  - Very low background (<1) searches in both cases
  - $\mathcal{B}(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ (previously 6.4×10^{-10} E865)
  - $\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ (previously 8.6×10^{-11} NA48/2)

Dark photon searches

Hidden sector

- **From cosmological observations, there must be a dark sector**
  - Not observed so far $\Longrightarrow$ interacting with SM only through a gauge-mediator
  - Different possibilities: neutrino (HNL), axial (ALP), scalar, vector.

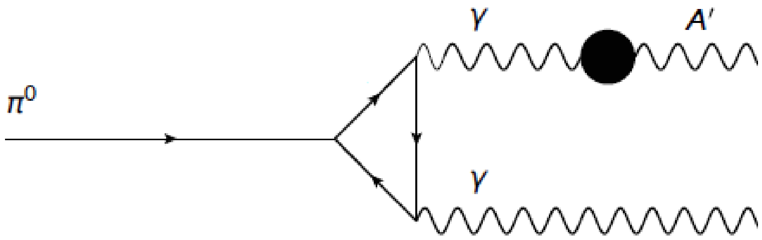
[Phys. Lett. B166 (1986) 196]

- **Dark photon A'** [PRD 80, 095024 (2009)]
  - Simplest model with one extra $U(1)$ gauge symmetry
  - Kinetic mixing between QED and new $U(1)$

$$\mathcal{L}_{\text{mix}} = -\frac{\varepsilon}{2} F_{\mu\nu}^{\text{QED}} F_{\text{dark}}^{\mu\nu}$$

  - Use $\pi^0 \rightarrow \gamma A'$ transition

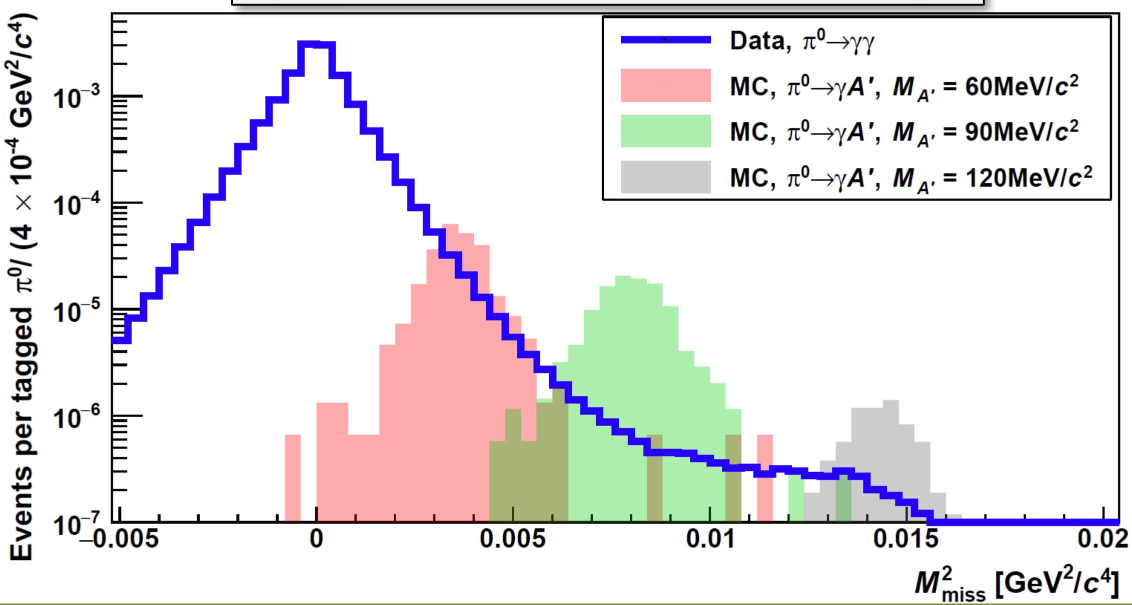
$$\frac{\mathcal{B}(\pi^0 \rightarrow \gamma A')}{\mathcal{B}(\pi^0 \rightarrow \gamma\gamma)} = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3$$



Analysis principle

- Select sample of tagged π^0 from $K^+ \rightarrow \pi^+\pi^0$ decays, with exactly one γ detected
- Peak search in the $m^2_{\text{miss}} = \left(\text{P}_\text{K} - \text{P}_\pi - \text{P}_\gamma\right)^2$ distribution
  - Sliding m^2_{miss} window of width $\pm 1\sigma_{m^2_{\text{miss}}}$ to count n_{sig} for each $m_{A'}$ hypothesis.
  - Use $K^+ \rightarrow \pi^+\pi^0$ as normalization

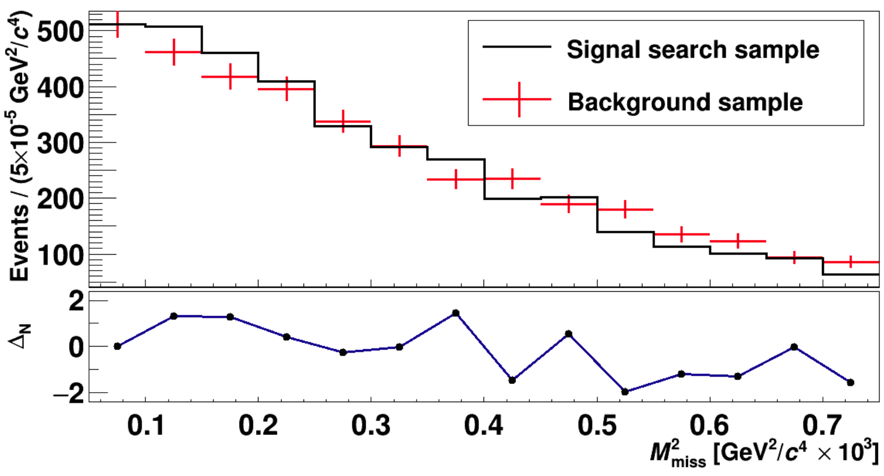
m^2_{miss} distribution for Data and simulated signal



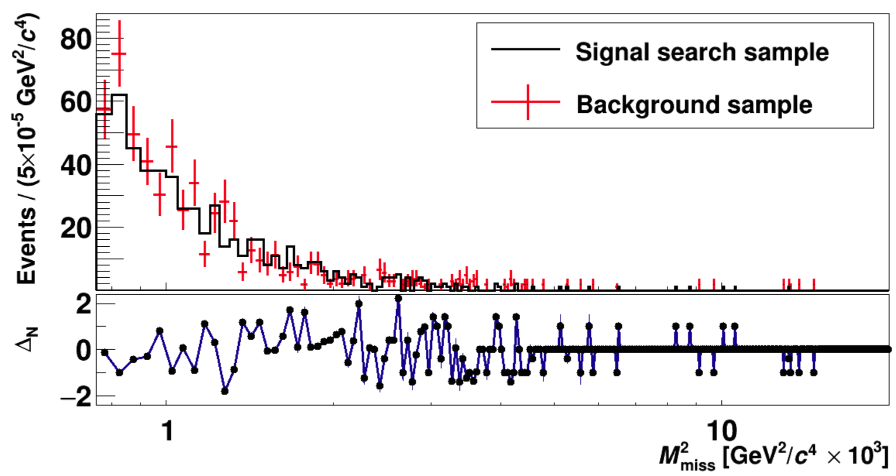
Background evaluation

- Most abundant background from $\pi^0 \to \gamma\gamma$ with one γ not detected
- Data-driven approach
  - Select sample with one γ converting into e^+e^- upstream (bckg sample)
  - Scale the bckg sample to the signal sample in a side-band not overlapping with the search region

Side band: $5 \cdot 10^{-5} < m^2_{\text{miss}} < 75 \cdot 10^{-5}\ \text{GeV}/c^4$



Search region: $75 \cdot 10^{-5} < m^2_{\text{miss}} < 1765 \cdot 10^{-5}\ \text{GeV}/c^4$

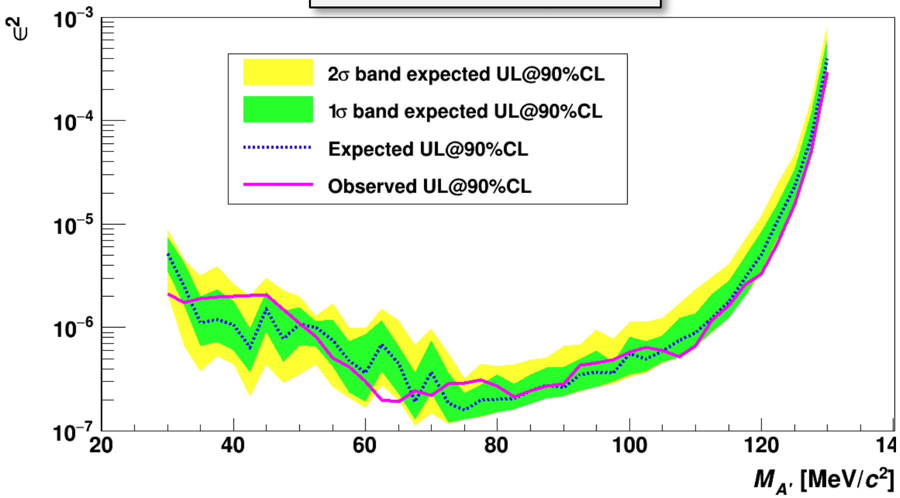


Dark photon result

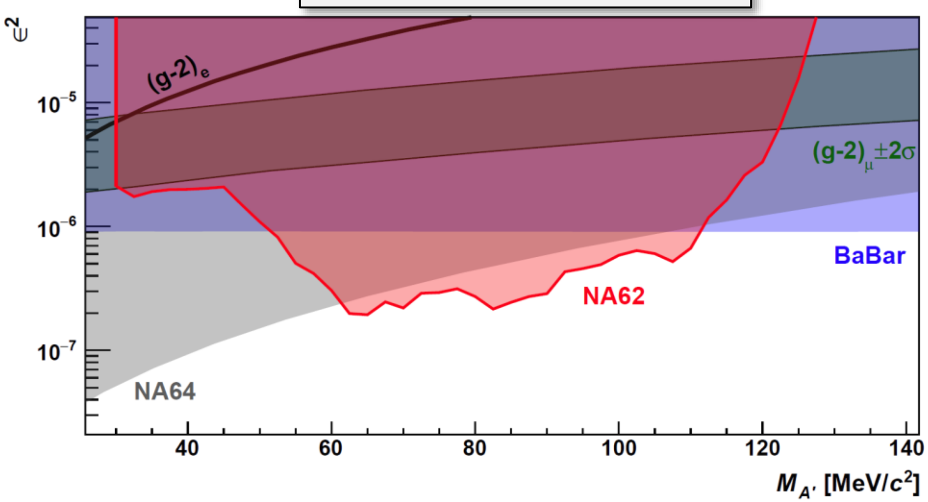
- CLs statistical treatment on a subset of the 2016 data sample (~1% of the total 2016-2018 data sample)
- No statistically significant excess is detected
  - Upper limits at 90% CL compatible with fluctuations from the background-only hypothesis
  - Improvement on previous limits over the mass range $60 - 110\ \mathrm{MeV}/c^2$

[arXiv:1903.0876]

Limits on dark photon



Dark photon limits summary



Conclusions

- **One $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ event observed in Region 2 in 2016**
  - $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL
  - Published in [Phys. Lett. B 791 (2019) 156-166]
- **Analysis of 2017 data is ongoing.**
  - Expect about a factor 10 of improvement (from statistics)
- **Searches for LNV processes**
  - $\mathcal{B}(K^+ \rightarrow \pi^- e^+ e^+) < 2.2 \times 10^{-10}$
  - $\mathcal{B}(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$

- **Dark photon searches**
  - No statistically significant excess is detected
  - Upper limits at 90% CL compatible with fluctuations from the background-only hypothesis
  - Improvement on previous limits over the mass range $60 - 110\ \mathrm{MeV}/c^2$
- **Huge amount of data still to analyse. Stay tuned for more results!!!**

Backup

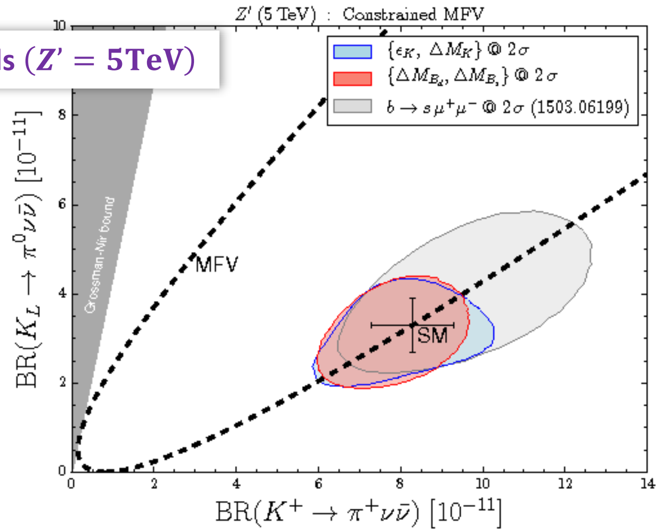
$K^+ \to \pi^+ \nu\bar{\nu}$ in New Physics Scenarios

- Custodial Randall-Sundrum
  - [JHEP 0903 (2009) 108]
- MSSM analyses [JHEP 0608 (2006) 064]
  - [Int.J.Mod.Phys A29 (2014) no.27, 1450162]
- Simplified Z, Z' models
  - [JHEP 1511 (2015) 166]
- Littlest Higgs with T-parity
  - [Eur.Phys.J. C76 (2016) 182]
- LFU violation models
  - [Eur.Phys.J. C77 (2017) no.9 618]

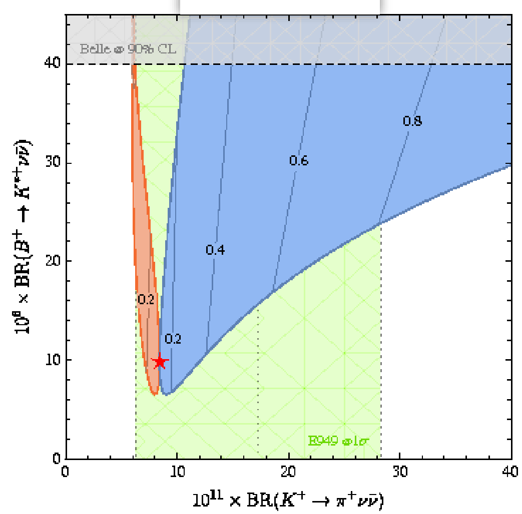
Combine measurement of with other channels

- Strong constraints on NP models

Z' models ($Z' = 5$TeV)



LFU violation



NA62 Analysis Strategy

Signal and background regions are kept blind throughout the analysis

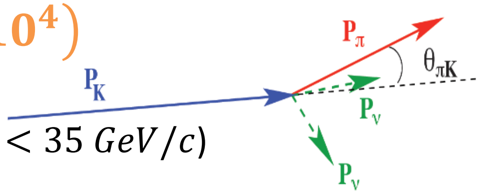
Decay backgrounds	
Decay mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^+\pi^-e^+\nu$	4.2×10^{-5}
Other backgrounds	
Beam-gas interactions	
Upstream interactions	

Time resolution $\sim\mathcal{O}(100\text{ ps})$

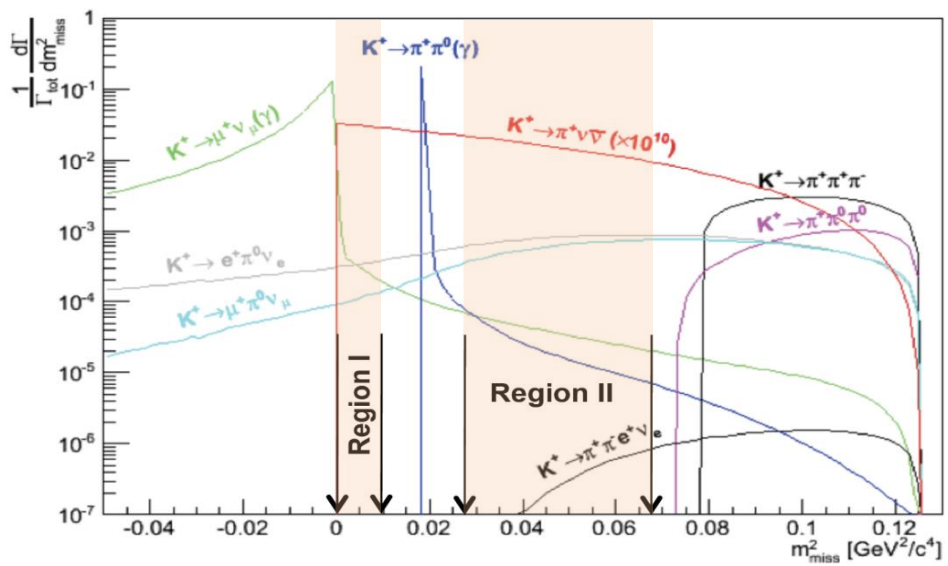
Matching of upstream-downstream activity

Kinematic suppression $\sim\mathcal{O}(10^4)$

- Kaon momentum
- π momentum ($15\ GeV/c < P_\pi < 35\ GeV/c$)



$$m^2_{miss} \cong m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\theta^2_{\pi K}$$



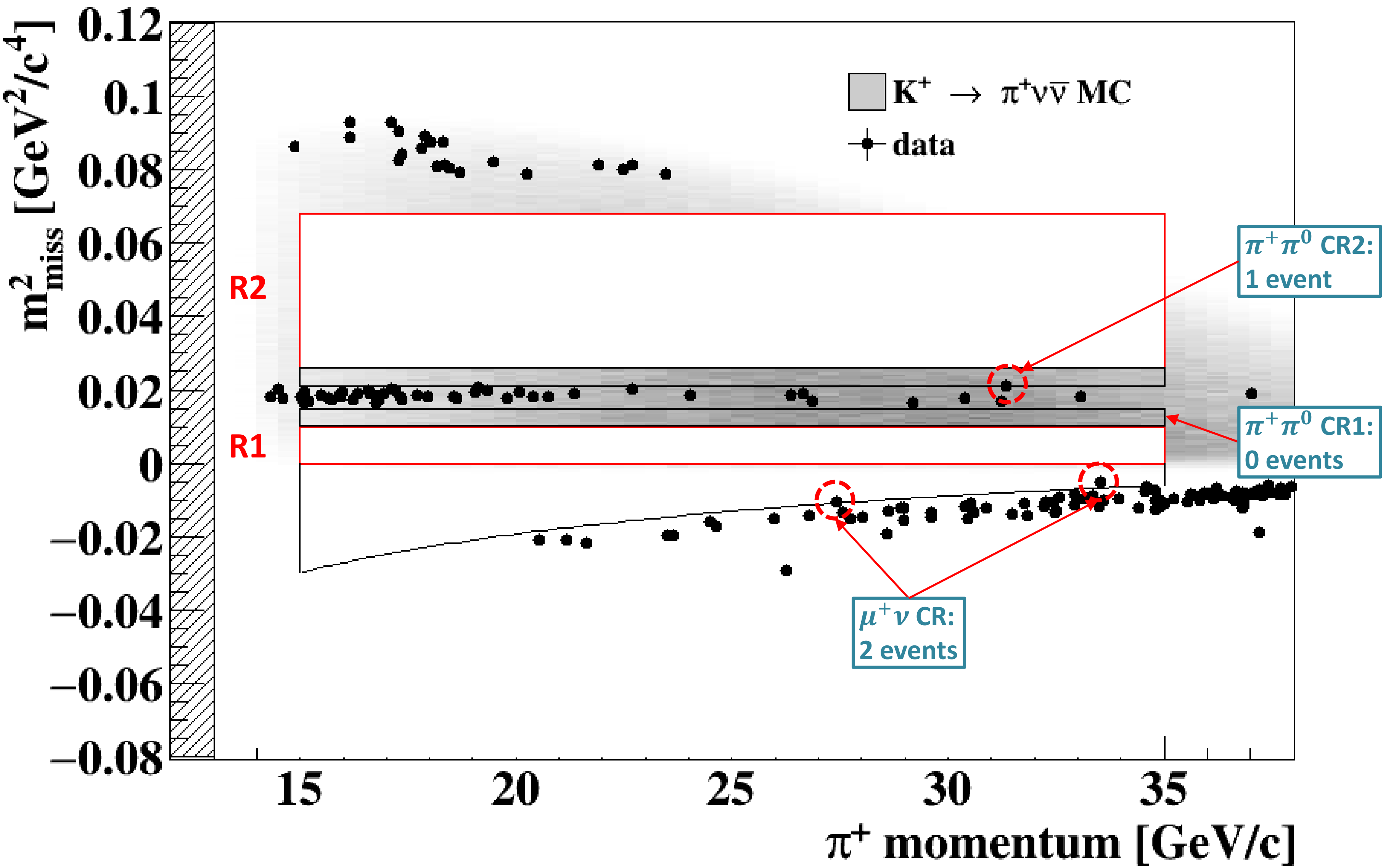
PID and high efficiency Veto systems

Muon suppression $> 10^7$

π^0 suppression $> 10^7$

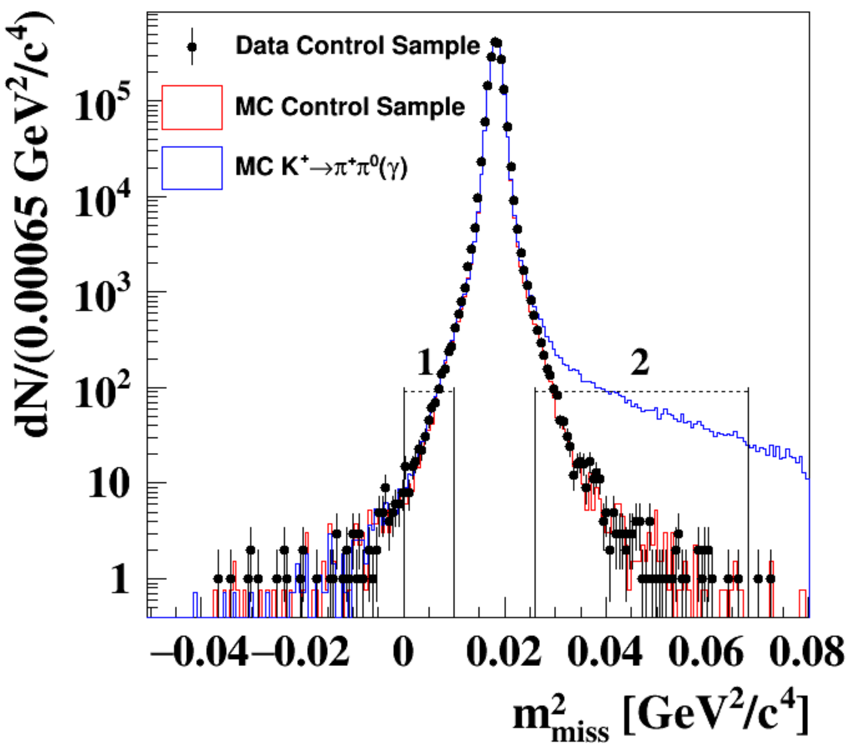
- Particle ID (Cherenkov + calorimeters)
- Photon veto

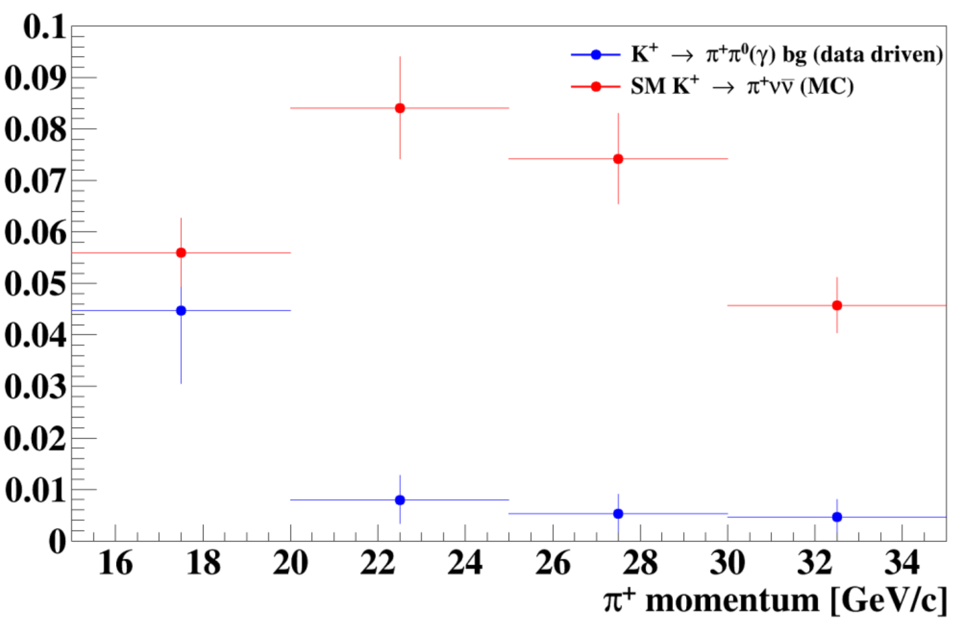
$K^+ \to \pi^+ \nu\bar{\nu}$ Background validation



Background $K^+ \to \pi^+\pi^0(\gamma)$

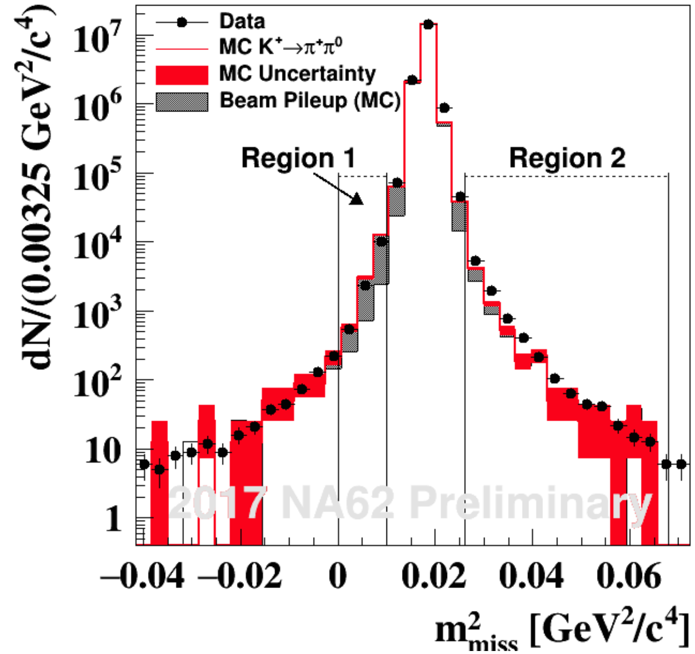
- **Data driven background estimation**
  - $N_{\pi\pi}^{CR1,2} = 1.46 \pm 0.16_{\text{stat}} \pm 0.06_{\text{syst}}$
  - $N_{\pi\pi}^{R1,2} = 0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$

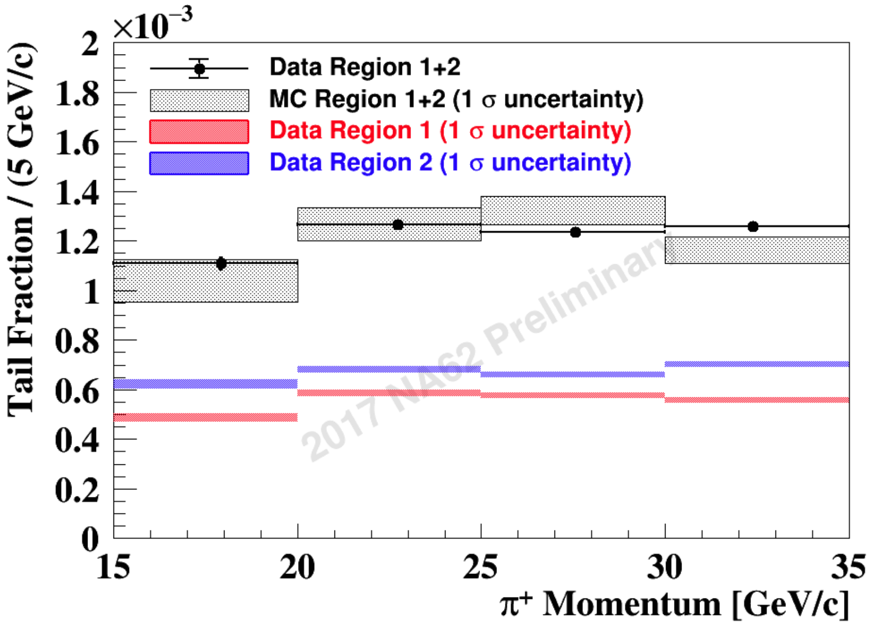


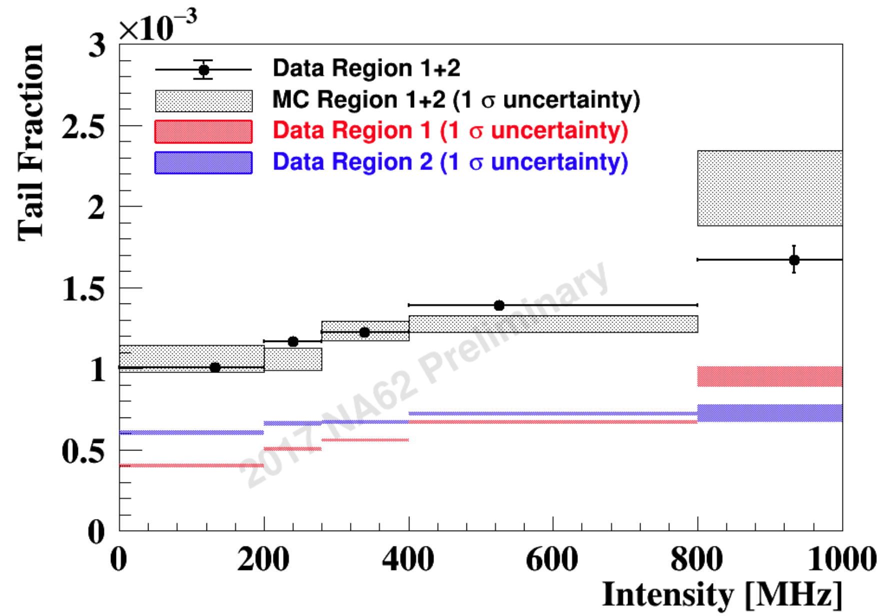


Background $K^+ \to \pi^+\pi^0(\gamma)$

- 2017 update
- Selected with π^0 tagging with 2 γ in LKr

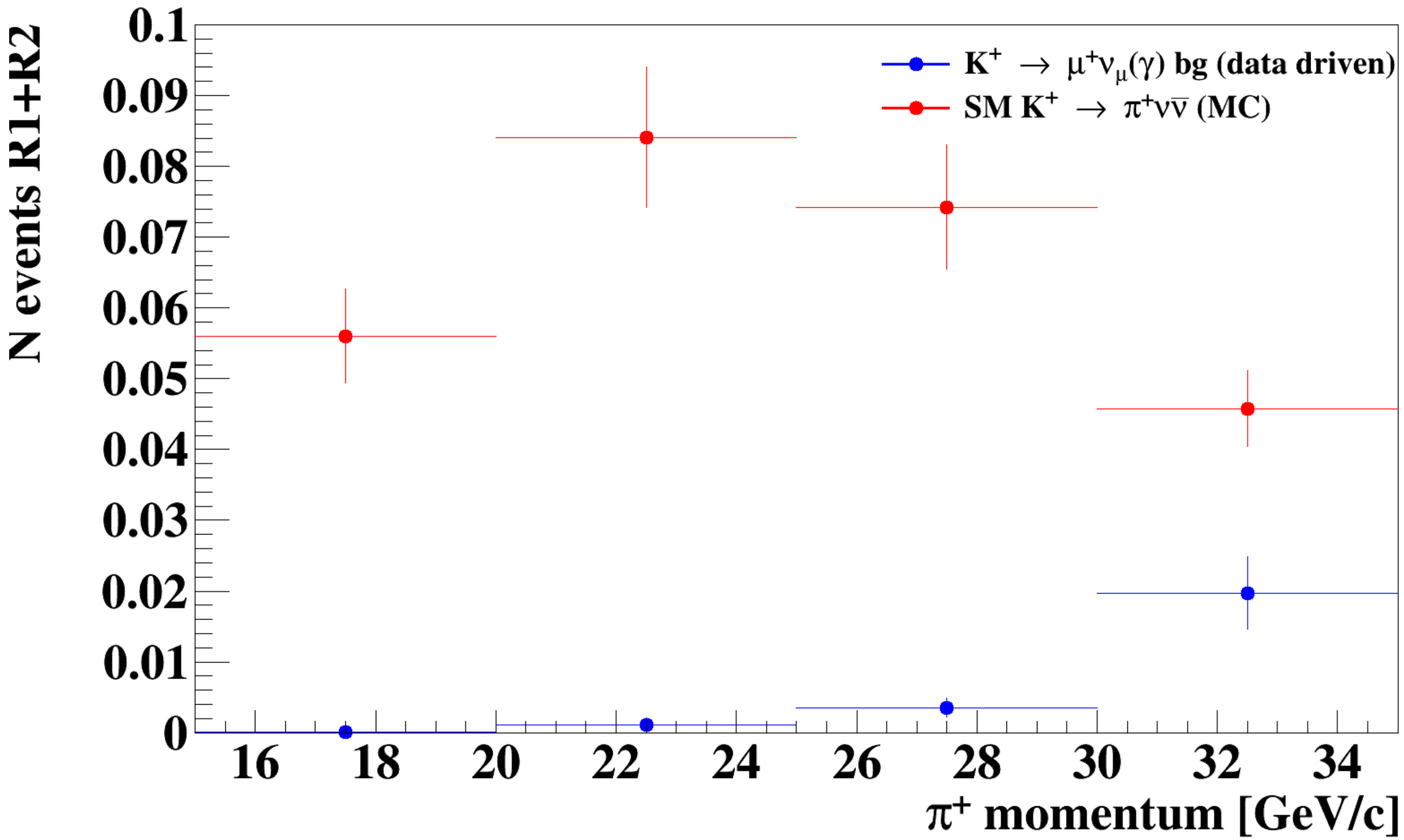






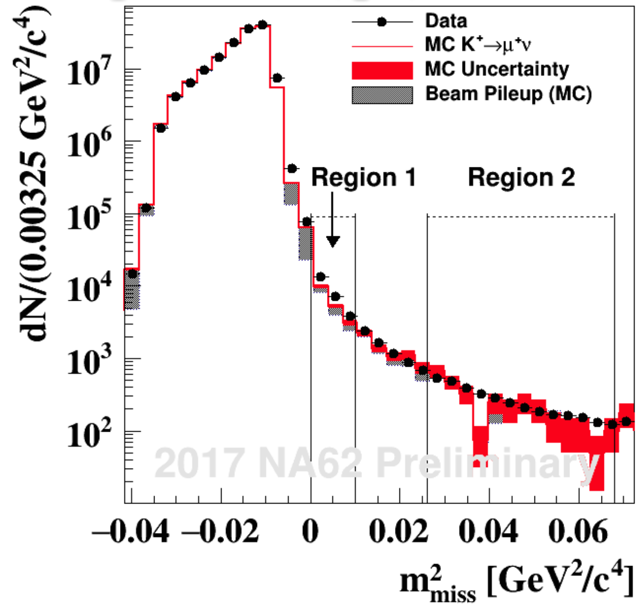
Background $K^+ \rightarrow \mu^+\nu(\gamma)$

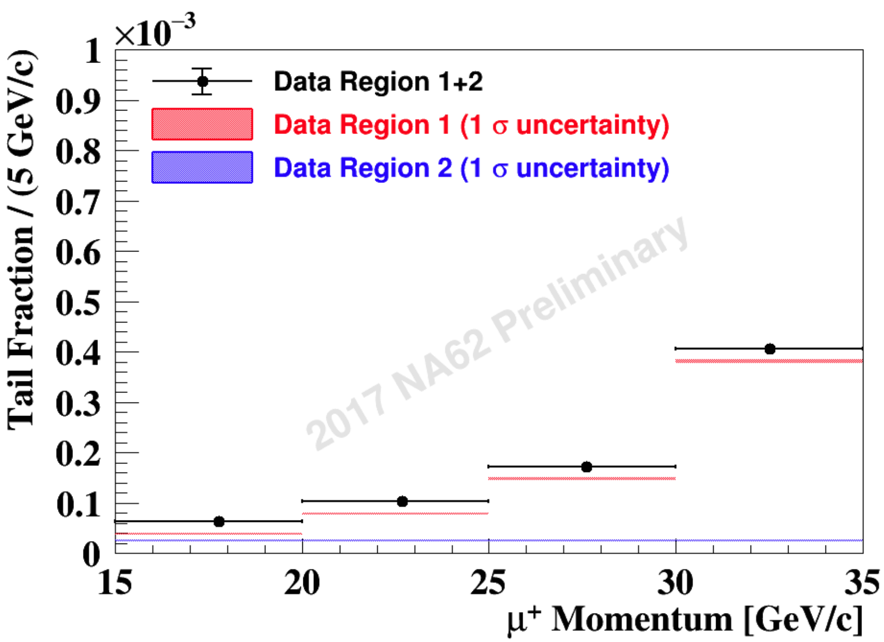
- **Data driven background estimation**
  - $N_{\mu\nu}^{R1,2} = 0.020 \pm 0.003_{\mathrm{stat}} \pm 0.006_{\mathrm{syst}}$

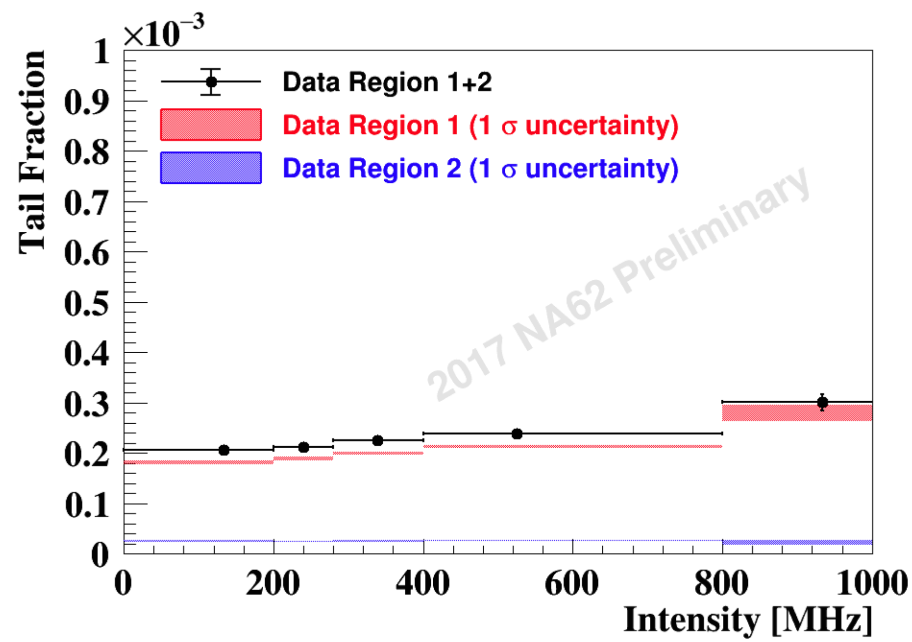


Background $K^+ \to \mu^+\nu(\gamma)$

- 2017 update
- Selected using MUV3 tagging



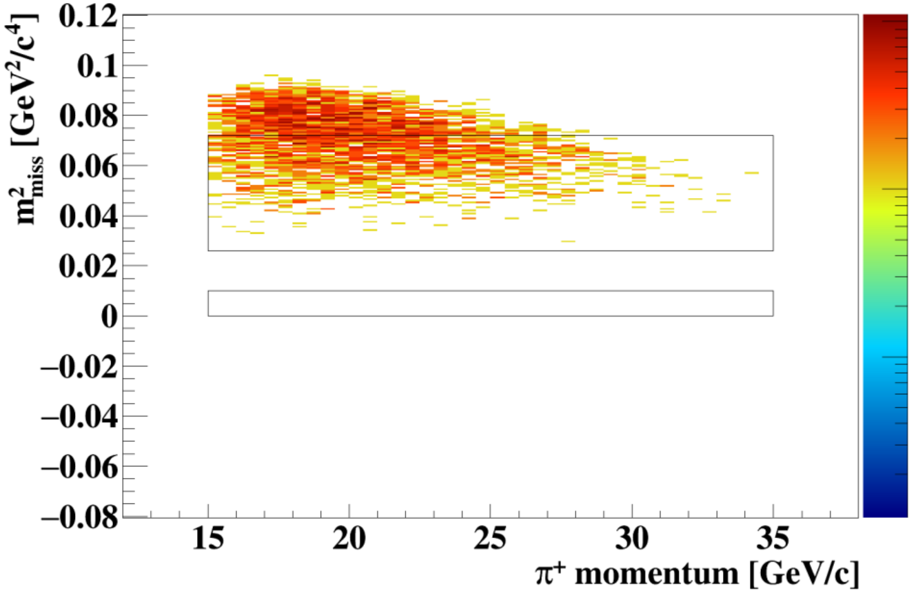


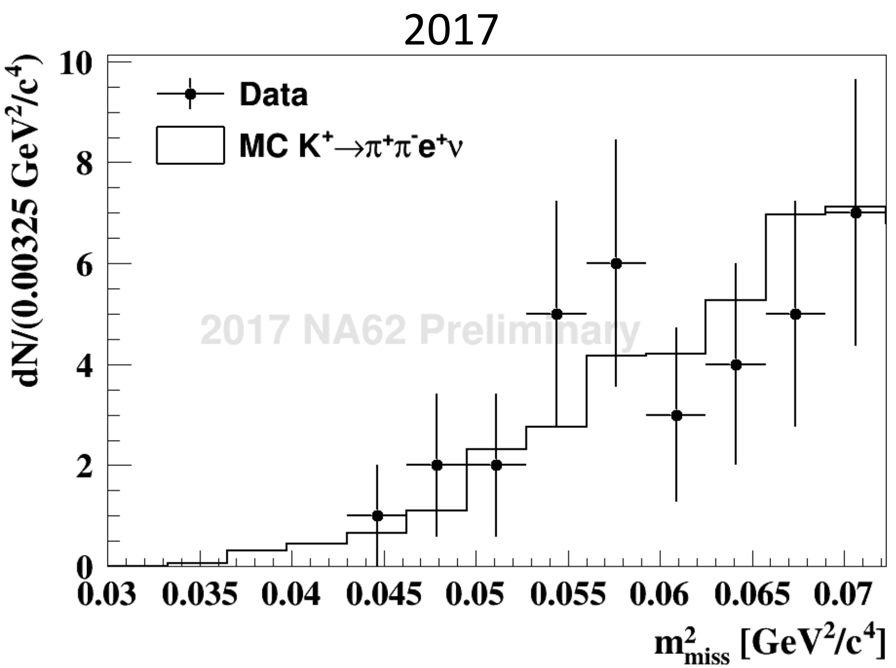


Background $K^+ \rightarrow \pi^+\pi^-e^+\nu$

MC estimation

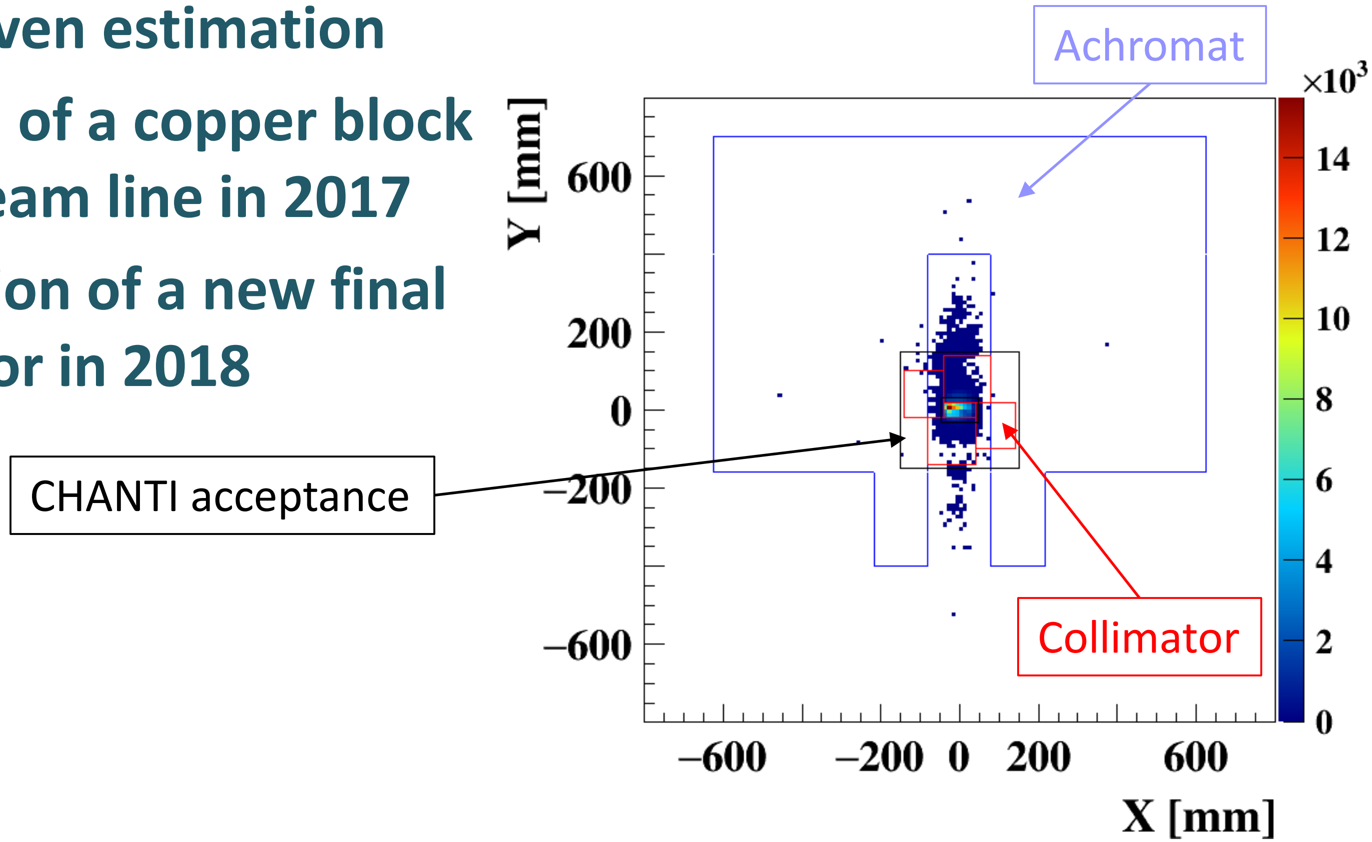
- 6×10^8 simulated decays, good agreement across 5 validation $K^+ \rightarrow \pi^+\pi^-e^+\nu$ enriched samples (invert multiplicity criteria)
- $N_{\pi\pi e\nu}^{R1,2} = 0.013^{+0.017}_{-0.012}|_{\text{stat}} \pm 0.009_{\text{syst}}$



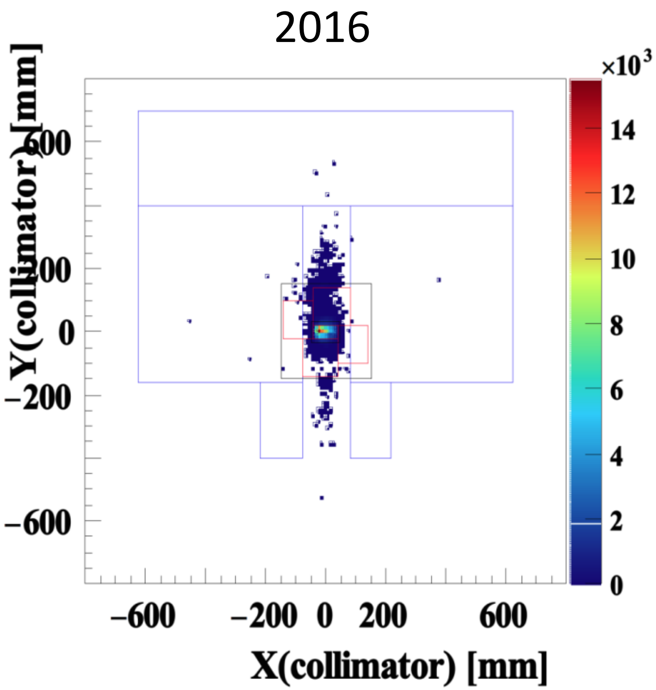


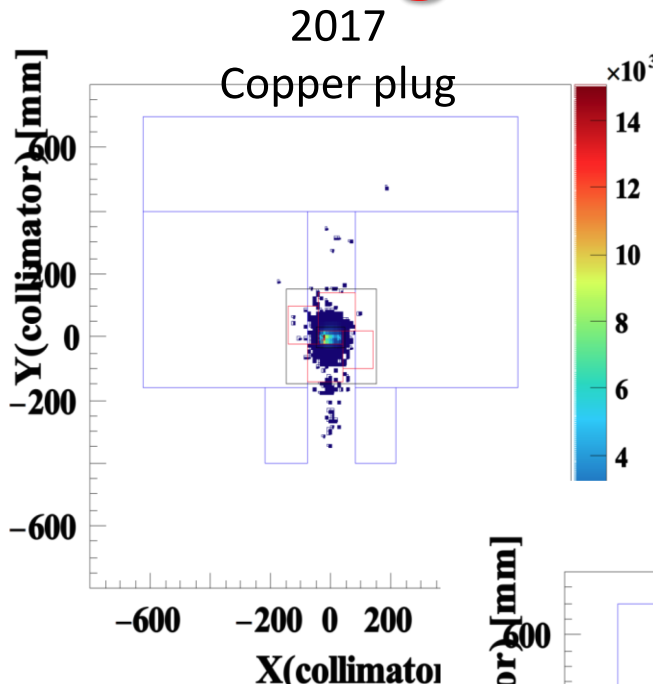
Upstream background

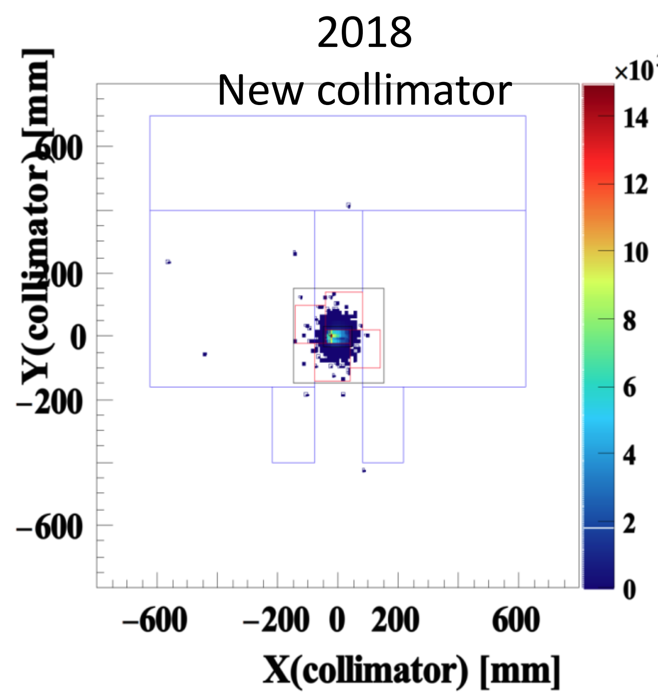
- Accidental particles from the beam line
- Pions from interactions with beam spectrometer material
- Kaon-pion matching and geometrical cuts effective
- Data-driven estimation
- Addition of a copper block in the beam line in 2017
- Installation of a new final collimator in 2018



Upstream background

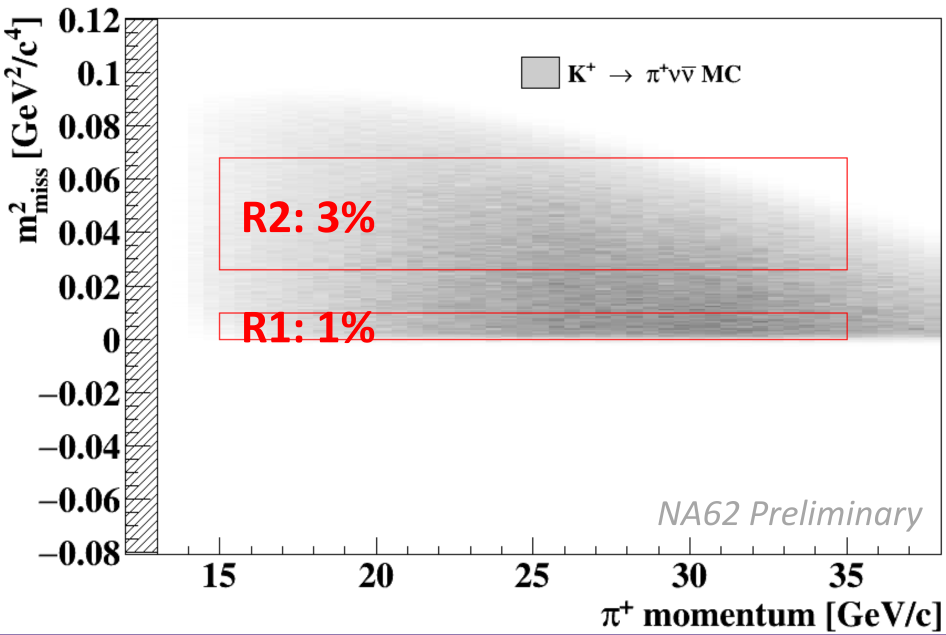






$K^+ \to \pi^+ \nu\bar{\nu}$ Single Event Sensitivity

- **Signal acceptance: 4%**
- **Normalization**
  - $K^+ \to \pi^+\pi^0$ on control trigger
  - Acceptance: 10%
  - Number of kaon decays in the fiducial volume: $\boldsymbol{N_K = 1.21(4) \times 10^{11}}$

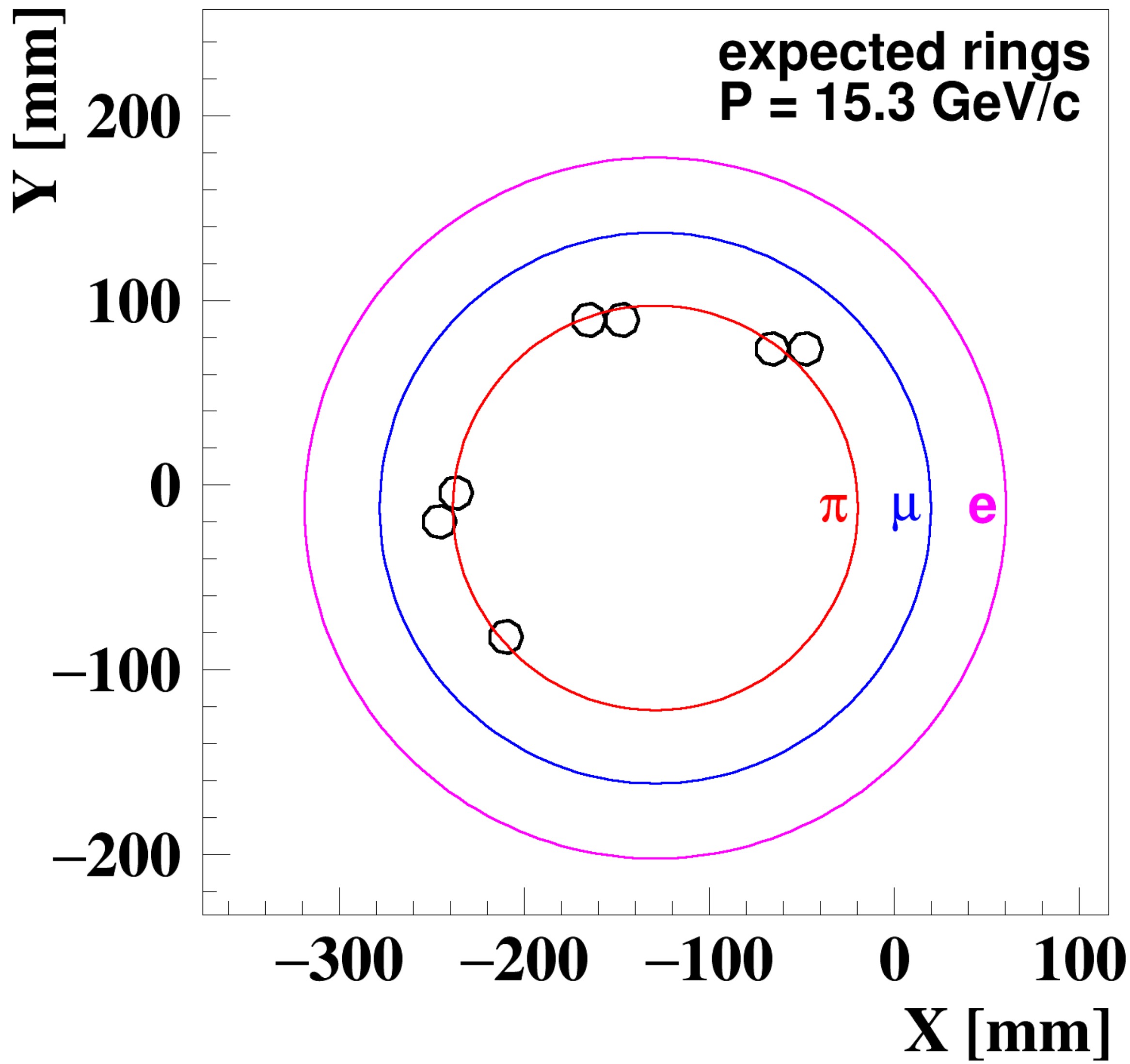


- **Uncertainties**

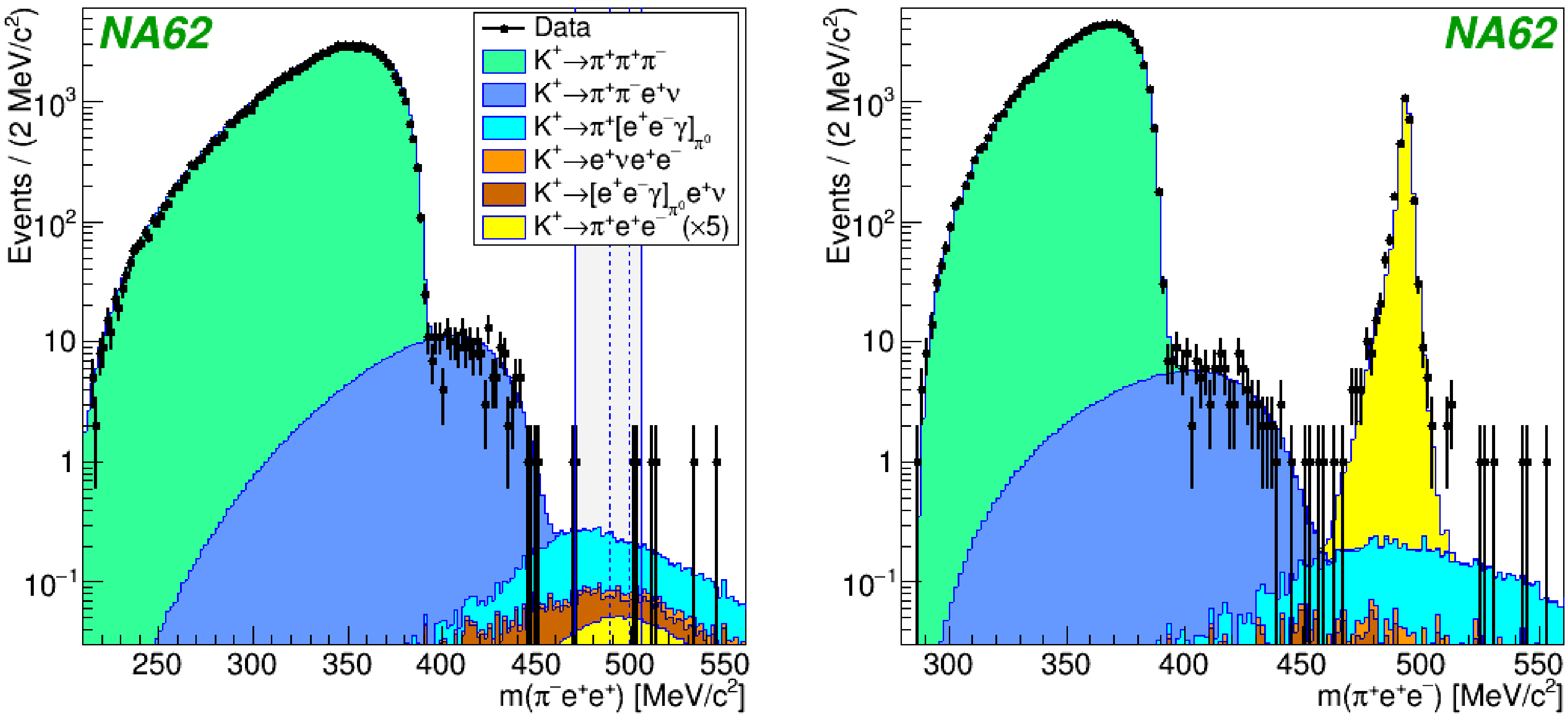
Source	$\delta SES\ (10^{-10})$
Random Veto	± 0.09
N_K	± 0.05
Trigger efficiency	± 0.04
Definition of $\pi^+\pi^0$ region	± 0.10
Momentum spectrum	± 0.01
Simulation of π^+ interactions	± 0.03
Extra activity	± 0.02
GTK Pileup simulation	± 0.02
Total	± 0.24

$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

RICH ring of π^+ of PNN candidate



LFV/LNV without RICH ID



$K^+ \to \pi^+ e^+ e^-$

- First observation of $K^+ \to \pi^+ e^+ e^-$ with $m_{ee} < 140\ \mathrm{MeV}/c^2$ without background
- Also first observation of $\pi^0 \to e^+ e^-$