Physics beyond SM with Kaons from NA62

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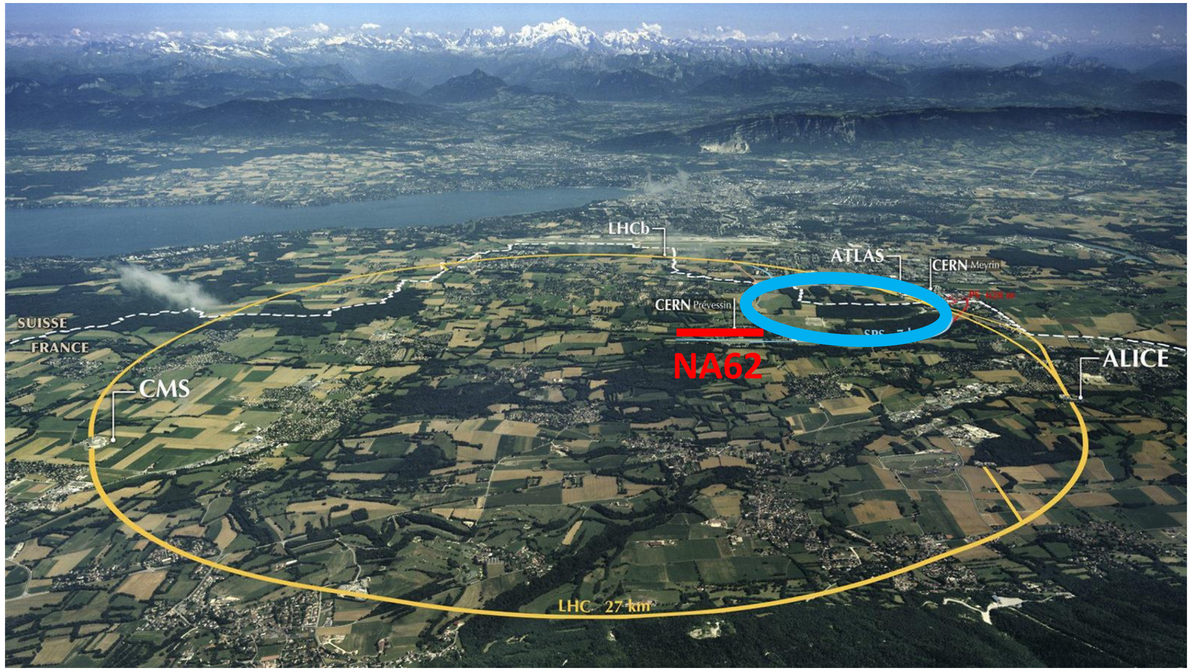
Outline

- Introduction: the NA62 experiment at CERN
- $K^+ \to \pi^+ \nu\bar{\nu}$
- Search for invisible vector bosons
- Search for LNV processes in kaon decays
- Conclusions

The NA62 experiment at CERN

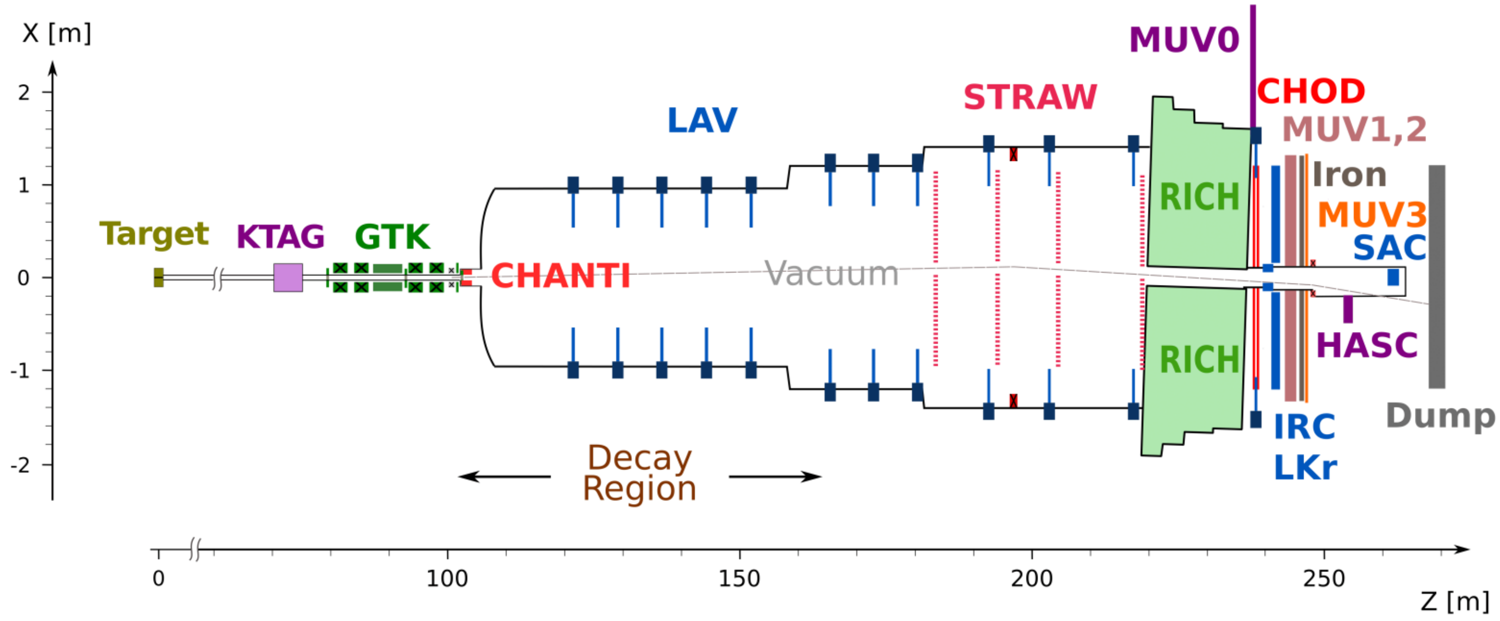
- Fixed target experiment
- Kaon decays in flight
- **Main goal:** measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) at 10% precision level



Primary beam of protons from SPS (400 GeV)

Secondary beam of hadrons (75 GeV, 800 MHz)
- Pions (70%)
- Protons (23%)
- Kaons (6%)
- Muons (0.7%)

NA62 schematic layout



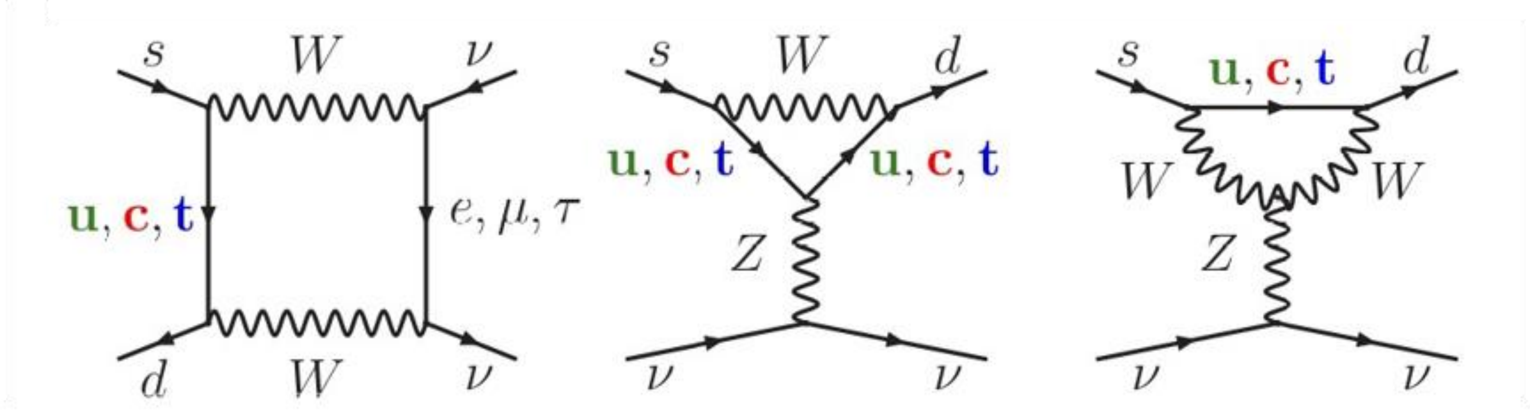
Keystones:

- O(100 ps) timing between sub-detectors
- O(10^4) kinematic background suppression
- $> 10^7$ muon suppression
- $> 10^7$ π^0suppression

More details here: https://arxiv.org/abs/1703.08501

Theoretical motivation for $K^+ \to \pi^+ \nu\bar{\nu}$ search

$K^+ \to \pi^+ \nu\bar{\nu}$ is a FCNC process, very suppressed by CKM



Short distance contributions, dominated by t loop

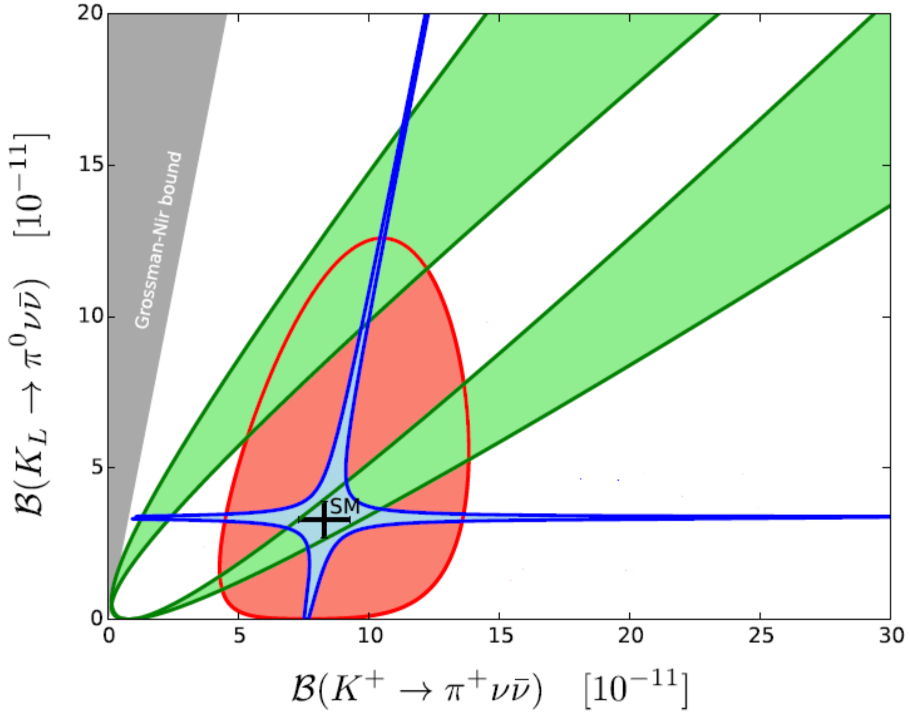
Theoretical prediction [Buras et al. , JHEP 1511 (2015)]:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

Theoretical motivation for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ search

$K \rightarrow \pi\nu\bar{\nu}$ decays are very sensitive to New Physics (NP) beyond Standard Model

The correlation between these branching ratios is predicted by different models like:



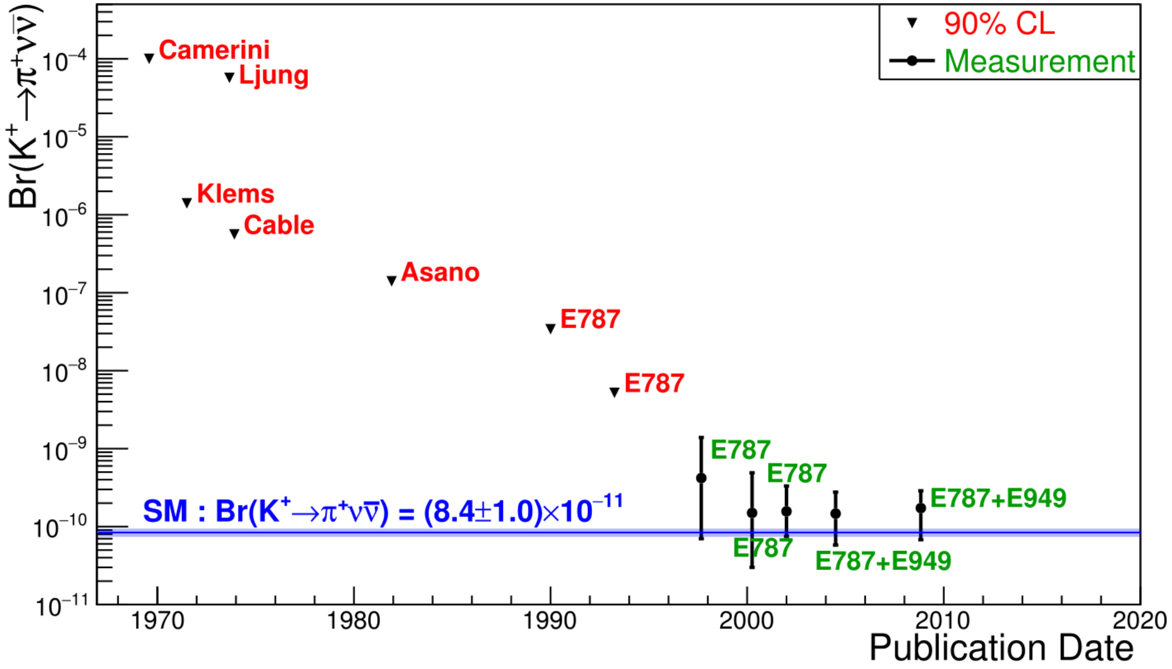
- Randall-Sundrum
- Littlest Higgs with T parity
- Minimal Flavour Violation

$K \rightarrow \pi\nu\bar{\nu}$ decays are very powerful tools to probe NP sector

$K^+ \to \pi^+ \nu\bar{\nu}$ experimental state of the art

Measured value [Phys. Rev. D 79, 092004 (2009)]:

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$$

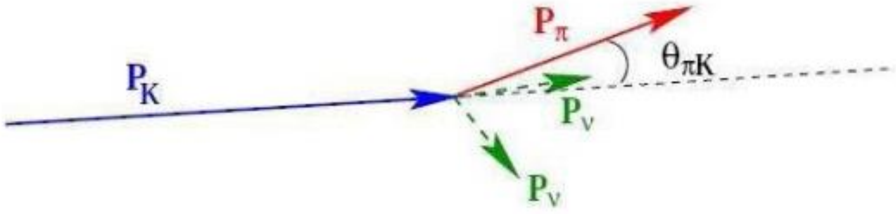


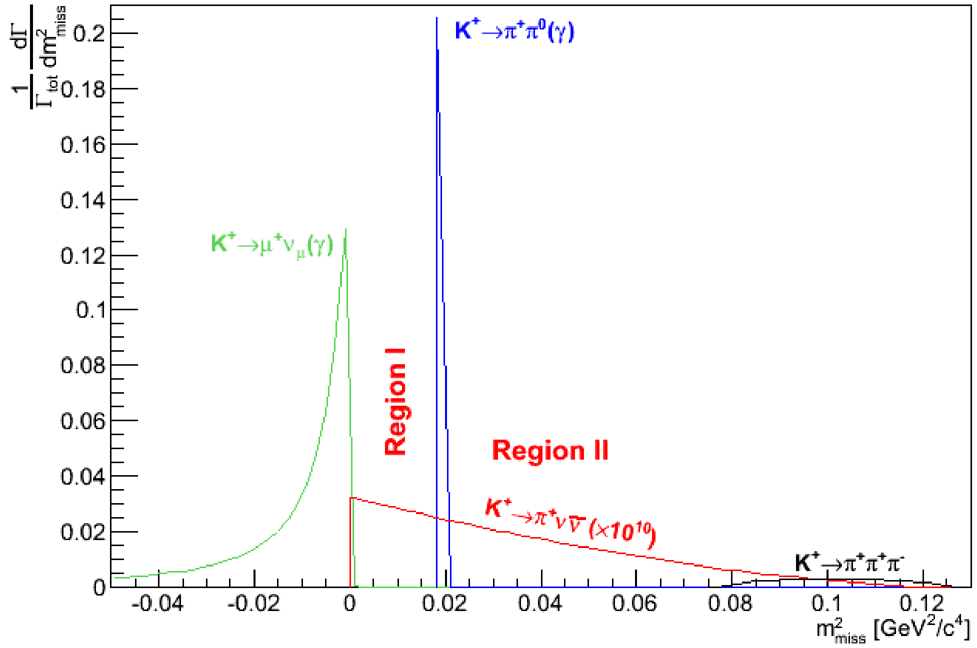
All the measurements have been performed using stopped kaons

$K^+ \to \pi^+\nu\bar{\nu}$ analysis strategy

Decay in flight technique

$$m^2_{miss} = (P_K - P_\pi)^\mu (P_K - P_\pi)_\mu$$





Blind analysis based on:

- Kinematic rejection
- $15\ GeV/c < P_\pi < 35\ GeV/c$
- π ID
- Photon veto

Single Event Sensitivity (SES) in 2016 dataset

$$SES = \frac{1}{N_K} \cdot \frac{1}{\epsilon_{\pi\nu\bar{\nu}}} = \frac{A_{\pi\pi} BR_{\pi\pi}}{N_{\pi\pi} D} \cdot \frac{1}{A_{\pi\nu\nu}\epsilon_{trigger}\ \epsilon_{RV}}$$

$K^+ \to \pi^+\pi^0$ sample used for normalization

Acceptance

Trigger efficiency

Random veto

$N_K = (1.21 \pm 0.02) \times 10^{11}$

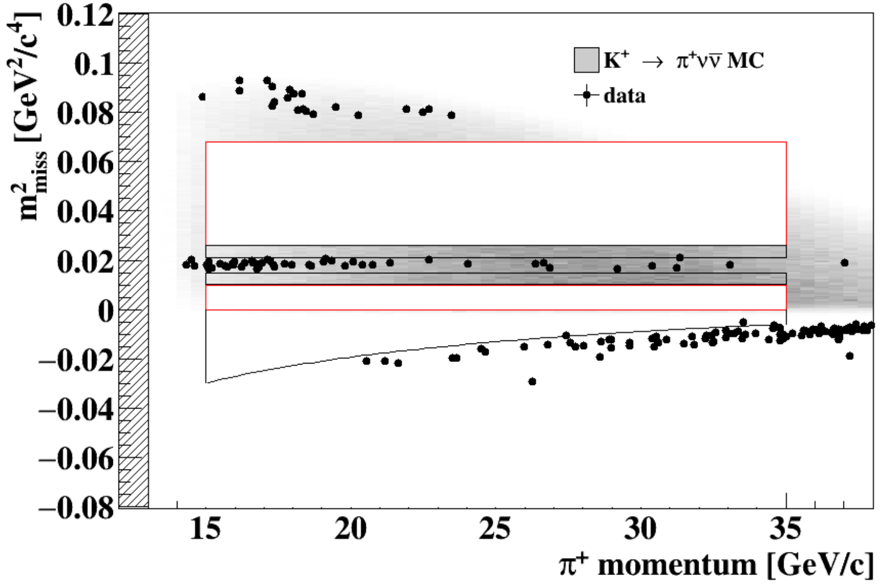
$SES = \left(3.15 \pm 0.01_{stat} \pm 0.24_{syst}\right) \times 10^{-10}$

$N_{\pi\nu\nu}^{exp} = 0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

Source	$\delta SES\ (10^{-10})$
Random veto	0.17
N_K	0.05
Trigger efficiency	0.04
Definition of $\pi^+\pi^0$ region	0.10
Momentum spectrum	0.01
Simulation of π^+ interactions	0.09
Extra activity	0.02
GTK Pile up	0.02
Total	**0.24**

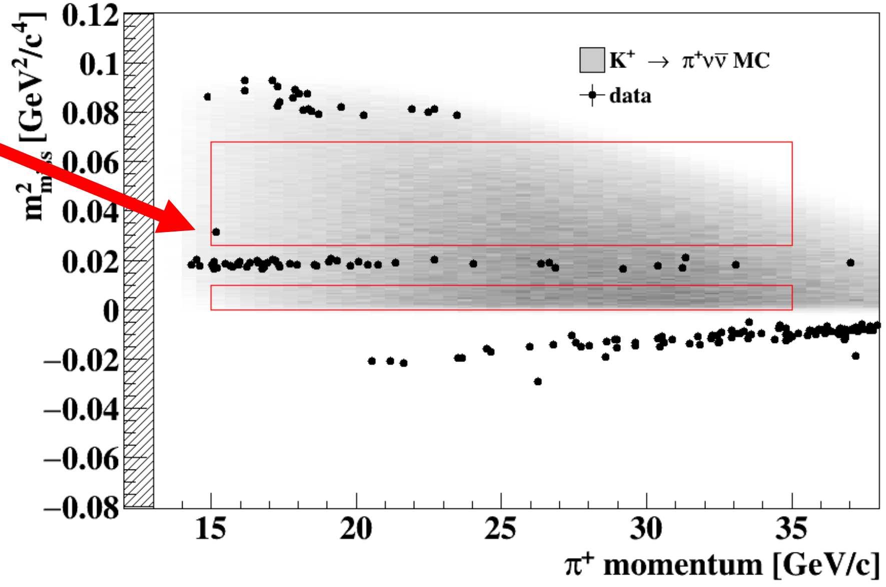
Results from 2016 analysis

Process	Number of expected events
$K^+ \to \pi^+ \nu\bar{\nu}$ **(SM)**	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total expected background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+\pi^0(\gamma)$	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{stat}$



Results from 2016 analysis

1 event observed



Process	Number of expected events
$\boldsymbol{K^+ \to \pi^+\nu\bar{\nu}}$ **(SM)**	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total expected background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
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$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

$BR(K^+ \to \pi^+\nu\bar{\nu}) < 11 \times 10^{-10}$ @90% CL
$BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @95% CL

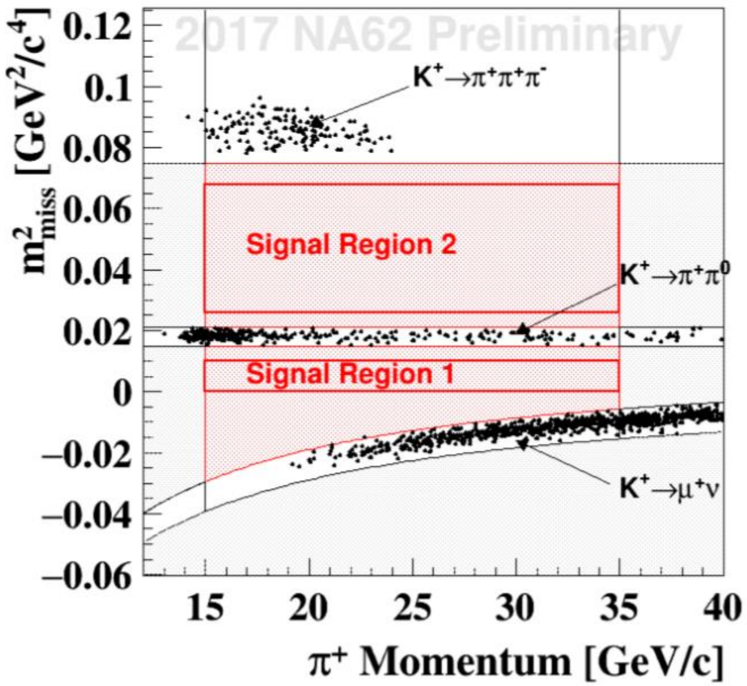
2017 dataset analysis

- Higher beam intensity
- 2016-like selection
- Improvements on:
  - Pile-up treatment in IRC/SAC
  - π^0 rejection
  - Usage of RICH variables

$N_K = (1.3 \pm 0.1) \times 10^{12}$

$SES = (0.34 \pm 0.04) \times 10^{-10}$

$N_{\pi\nu\nu}^{exp} = 2.5 \pm 0.4$



Process	Expected events in signal regions
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	$0.012 \pm 0.012_{syst}$
Upstream Background	Analysis on–going

Search for invisible vector bosons

Possible extension to SM with a new U(1) symmetry mediated by A’ **(dark photon)**

Search for A’ through the decay chain:

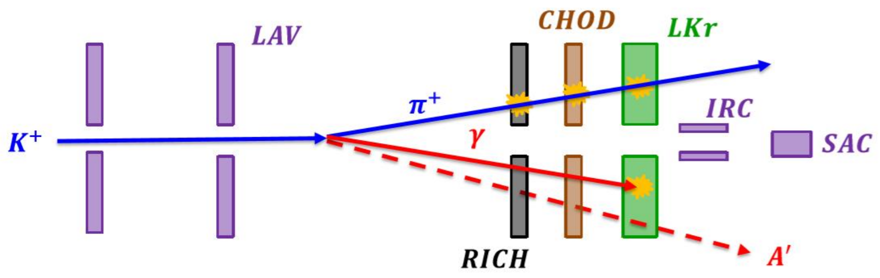
$$K^+ \to \pi^+\pi^0$$
$$\pi^0 \to \gamma A'$$

Master formula:

$$BR(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \times BR(\pi^0 \to \gamma\gamma)$$

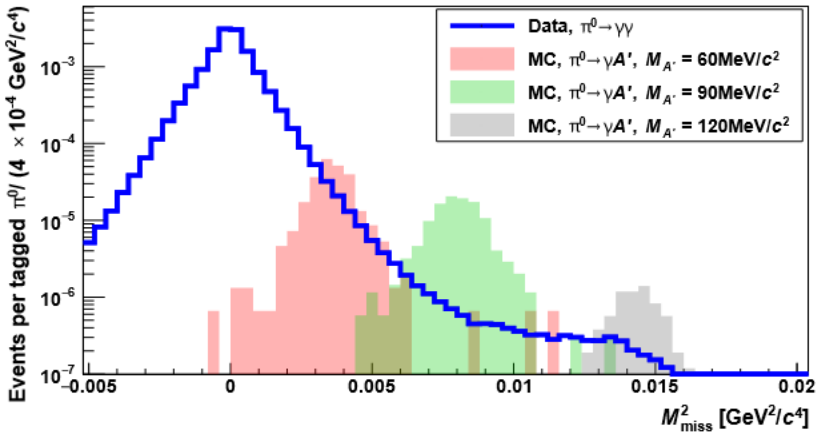
Signal selection

- Normalization: $K^+ \to \pi^+\pi^0$
- Main kinematic variable: $M^2_{miss} = \left(P_K - P_\pi - P_\gamma\right)^2$
- No in-time activity in LAV, IRC, SAC
- No extra activity in RICH e CHOD (photon conversions)



Main background:

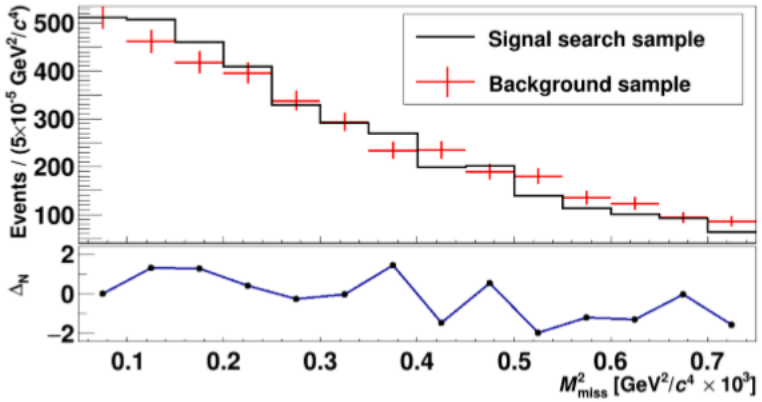
- $\pi^0 \to \gamma\gamma$ with a mis-reconstructed photon



Background evaluation

Sidebands to scale background:

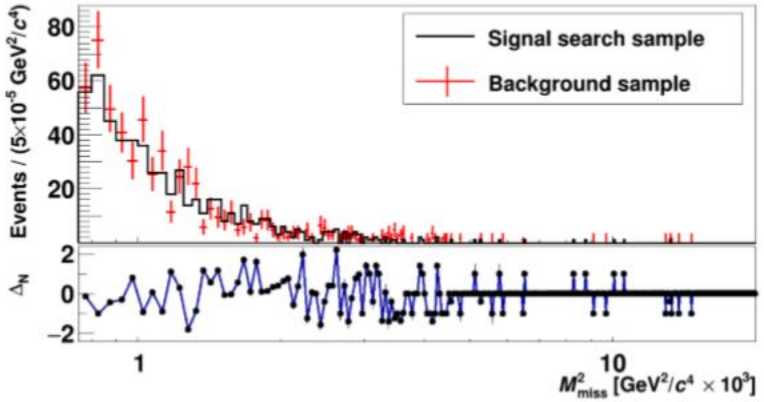
$$0.00005 < M^2_{miss} < 0.00075\ GeV^2/c^4$$



Signal region:

$$0.00075 < M^2_{miss} < 0.01765\ GeV^2/c^4$$

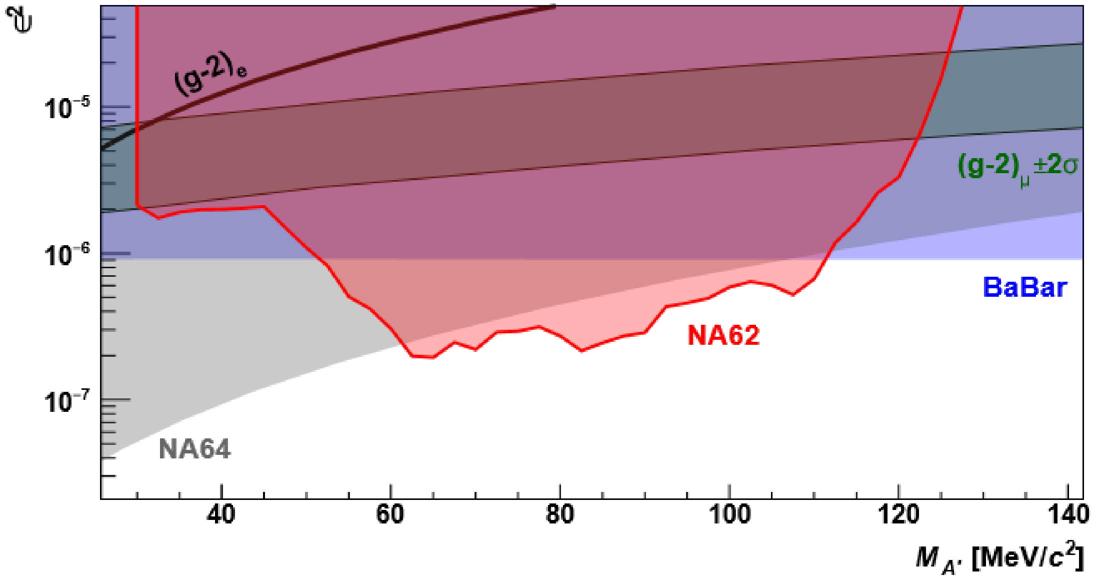
O(1) background events with $4 \times 10^8 \pi^0$ decays



Results

No statistically relevant excess has been found

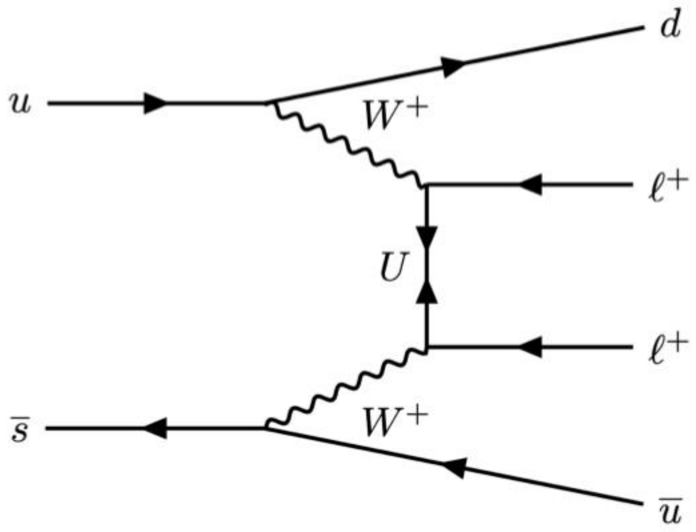
Improvement of previous limits in the range 60-110 $\mathrm{MeV/c^2}$ for A' mass



Search for lepton number violations

Lepton number conservation is an accidental symmetry that emerges from the SM

- Its violation by 2 units could indicate the presence of Majorana neutrinos
- LN violation search with kaons: $K^+ \to \pi^- l^+ l^+$, $l = (\mu, e)$ analogous to $0\nu\beta\beta$



Current limits (90% CL):

$BR(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10}$ BNL E865

$BR(K^+ \to \pi^- \mu^+ \mu^+) < 8.6 \times 10^{-11}$ CERN NA48/2

Signal selection

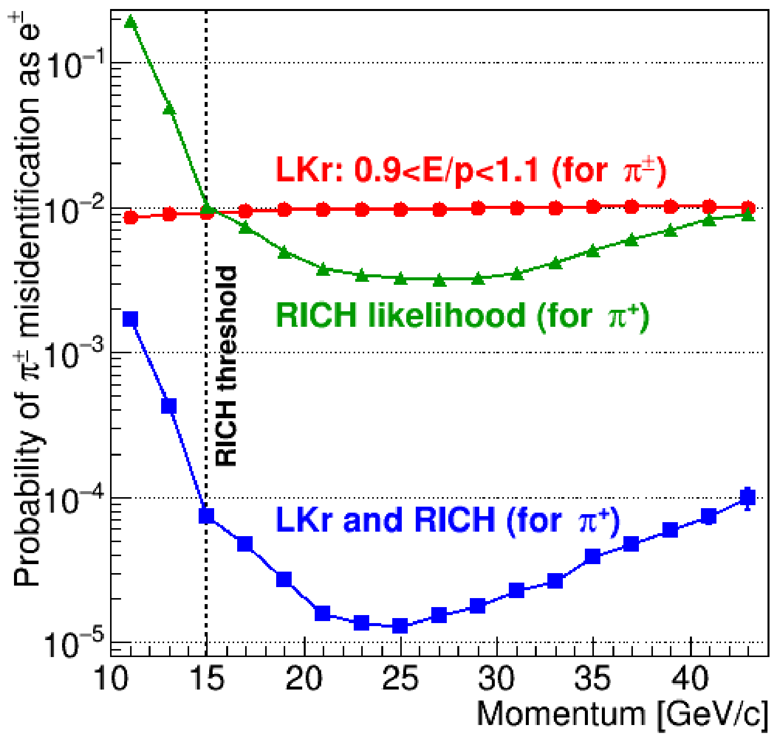
Normalization channels: SM decays $K^+ \to \pi^+ l^+ l^-$

Blind analysis technique

- 3-tracks vertex, Q=1, $|p_{3trks} - p_K| < 2.5$ GeV/c
- Upstream K identification
- **Key point: PID (mostly E/p and RICH but also MUV3)**
- Main background: $K^+ \to \pi^+\pi^+\pi^-$ through
  - particle misID
  - decay in flight

For πee channel: $M(ee) > 140\ \mathrm{MeV/c^2}$ to reject $K^+ \to \pi^+\pi^0_D$

and $K^+ \to \pi^0_D e^+ \nu$ $(\pi^0_D\!: \ \pi^0 \to e^+e^-\gamma)$



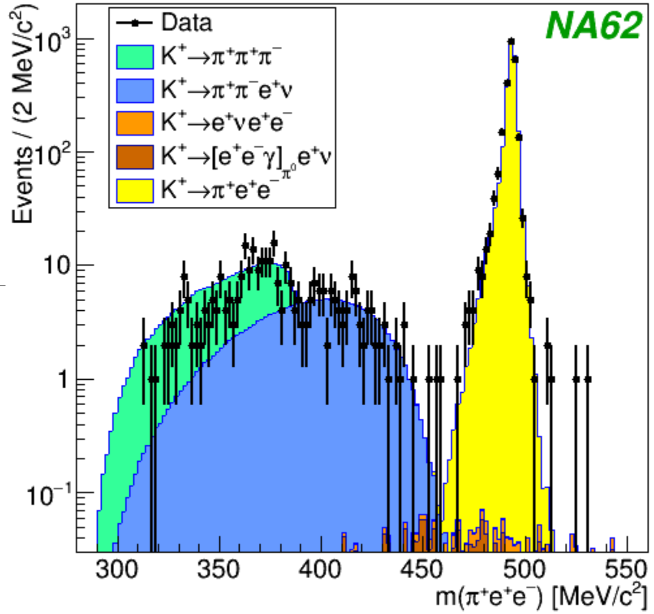
Search for $\mathrm{K}^{+} \rightarrow \pi^{-}e^{+}e^{+}$

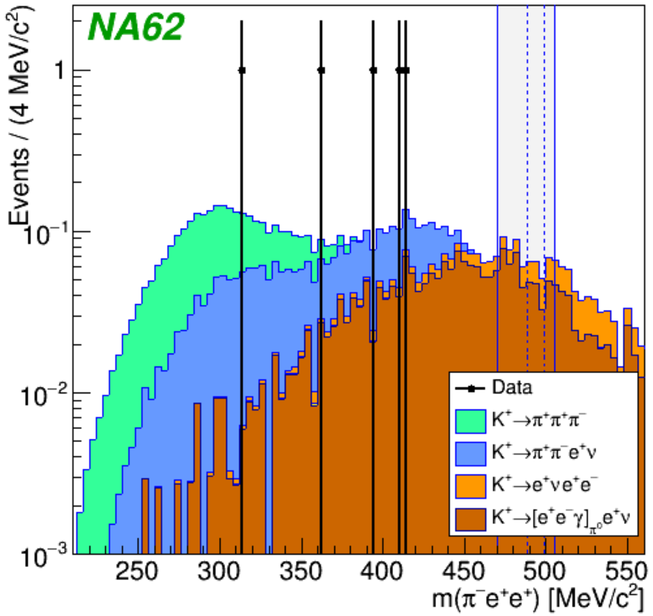
$$N_K = (2.14 \pm 0.07) \times 10^{11}$$

Signal acceptance: 4.98%
Expected background events in signal region:
0.16 ± 0.03
Observed events: 0

Upper limit (90% CL):

$$BR(K^{+} \rightarrow \pi^{-}e^{+}e^{+}) < 2.2 \times 10^{-10}$$



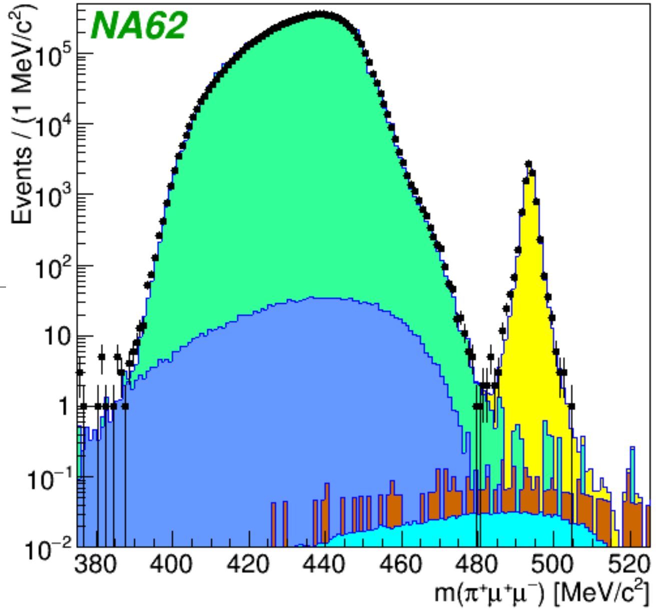


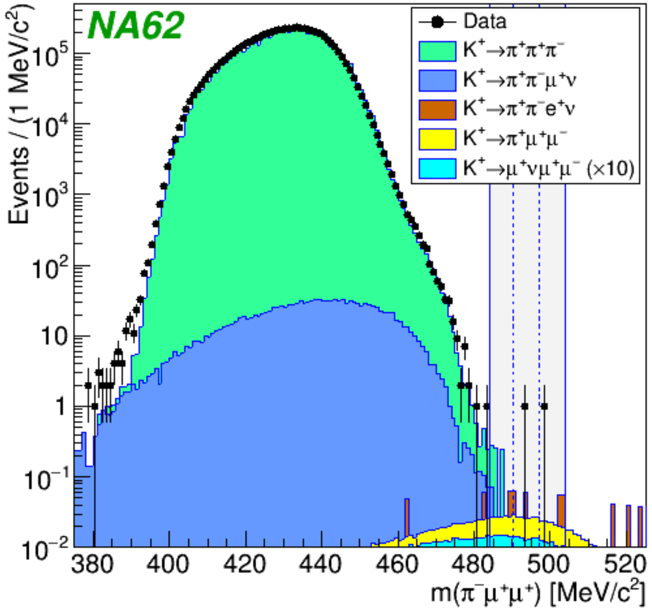
Search for $\mathrm{K}^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$

$$N_K = (7.94 \pm 0.23) \times 10^{11}$$

Acceptance: 9.81%
Expected background events in signal region:
0.91 ± 0.41
Observed events: 1

Upper limit (90% CL):
$$BR(K^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}) < 4.2 \times 10^{-11}$$





Search for LNV: results

Channel	Previous limit	NA62 (2017 data)
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	2.2×10^{-10}
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}

x3 (2) improvement achieved in πee $(\pi\mu\mu)$ channel

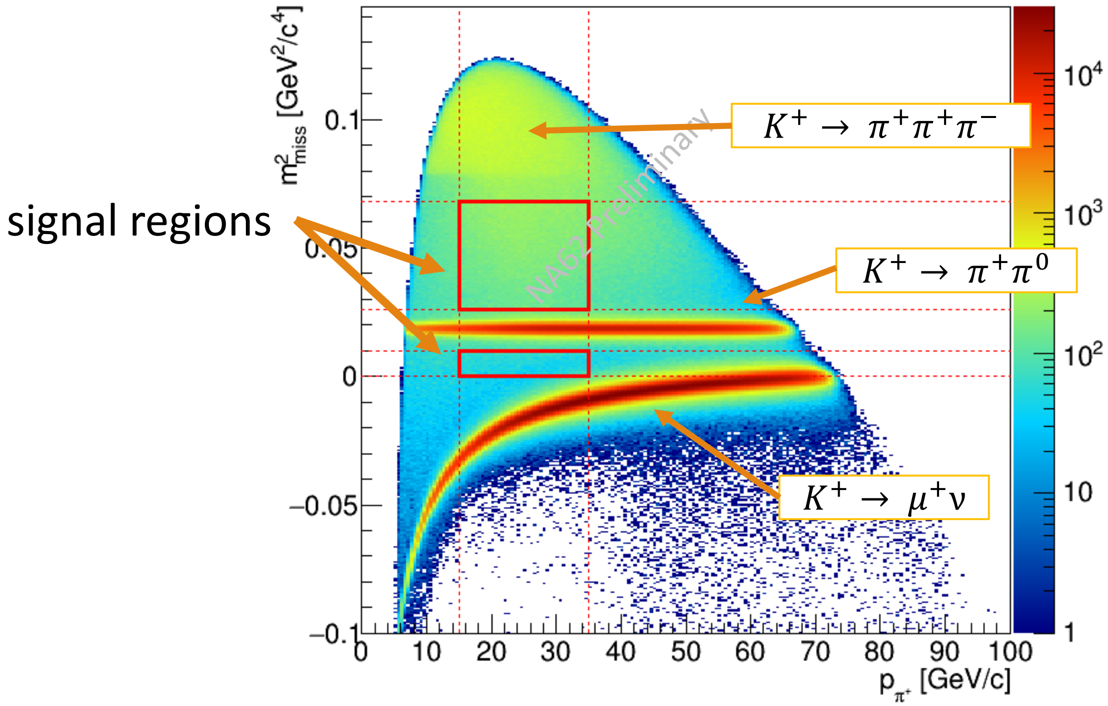
$\sim 1/3$ of the total 2017-2018 statistics analyzed

Conclusions

Broad physics program at NA62 to search for NP with kaons:

- $K^+ \to \pi^+ \nu \bar{\nu}$
  - one event observed in 2016 dataset, x10 statistics expected in 2017 sample
- Search for invisible vector bosons
  - limits improved in the range $60 < m_{A'} < 110\ \mathrm{MeV/c^2}$
- Search for LNV in kaon decays $K^+ \to \pi^- l^+ l^+$
  - x3 (2) improvement achieved in πee $(\pi\mu\mu)$ channel

$K^+ \to \pi^+ \nu\bar{\nu}$ analysis: signal selection

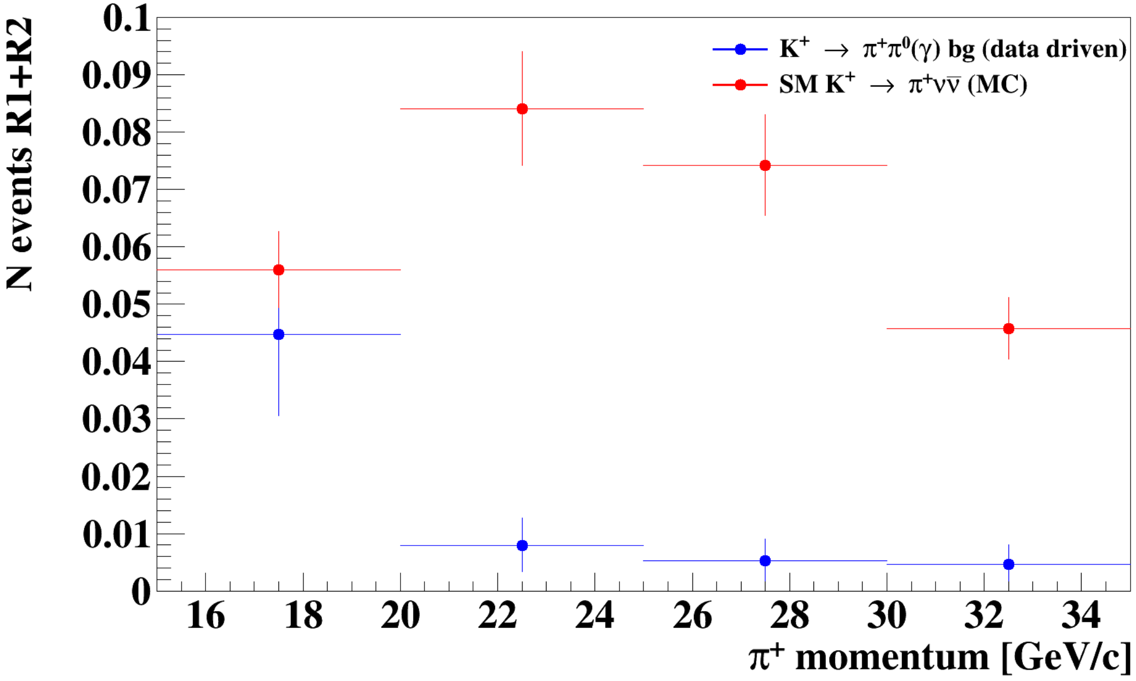


- 1 downstream track selection
- π^+ identification
- Photon and multi-track rejection

Selection performances:

- $\sigma(T) \sim O(100\text{ ps})$
- $\sigma(m^2_{miss}) = 10^{-3}\ \text{GeV}^2/\text{c}^4$
- $\epsilon_{\pi^0} = 3 \times 10^{-8}$
- $\epsilon_{\mu^+} = 10^{-8}$ with 64% π ID efficiency

$K^+ \to \pi^+ \nu\bar{\nu}$ analysis: $K^+ \to \pi^+\pi^0(\gamma)$ background

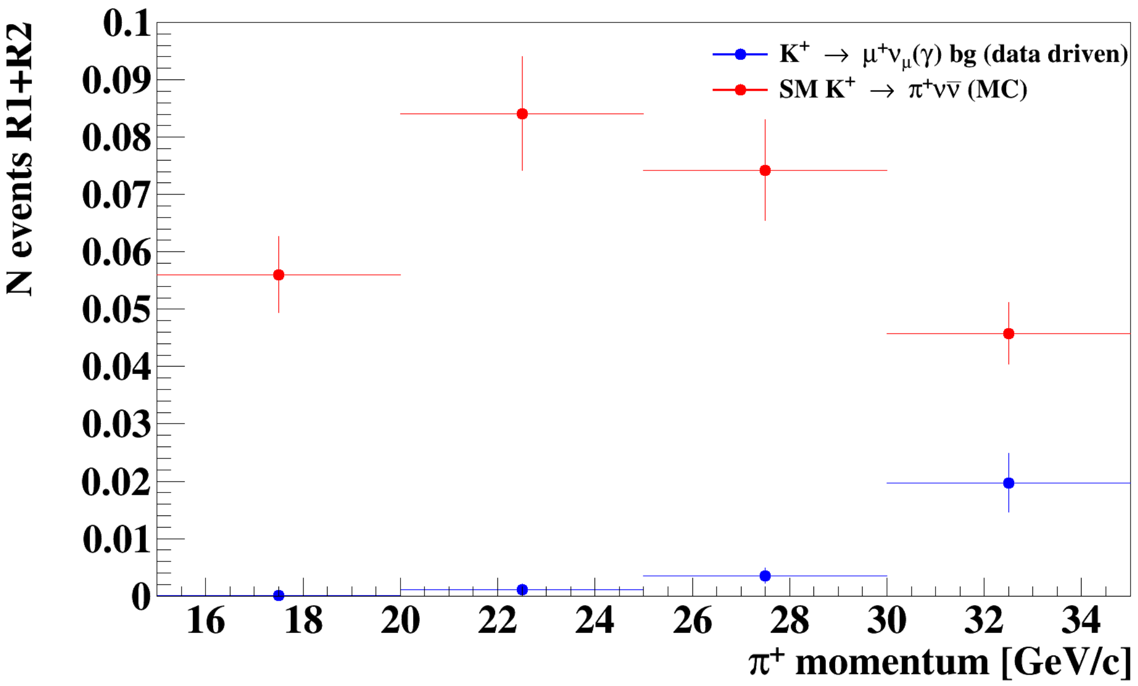


Data-driven background estimation

$$N^{bg}_{\pi\pi(\gamma)} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$$

1 event found in control regions (1.5 expected)

$K^+ \to \pi^+ \nu\bar{\nu}$ analysis: $K^+ \to \mu^+\nu(\gamma)$ background

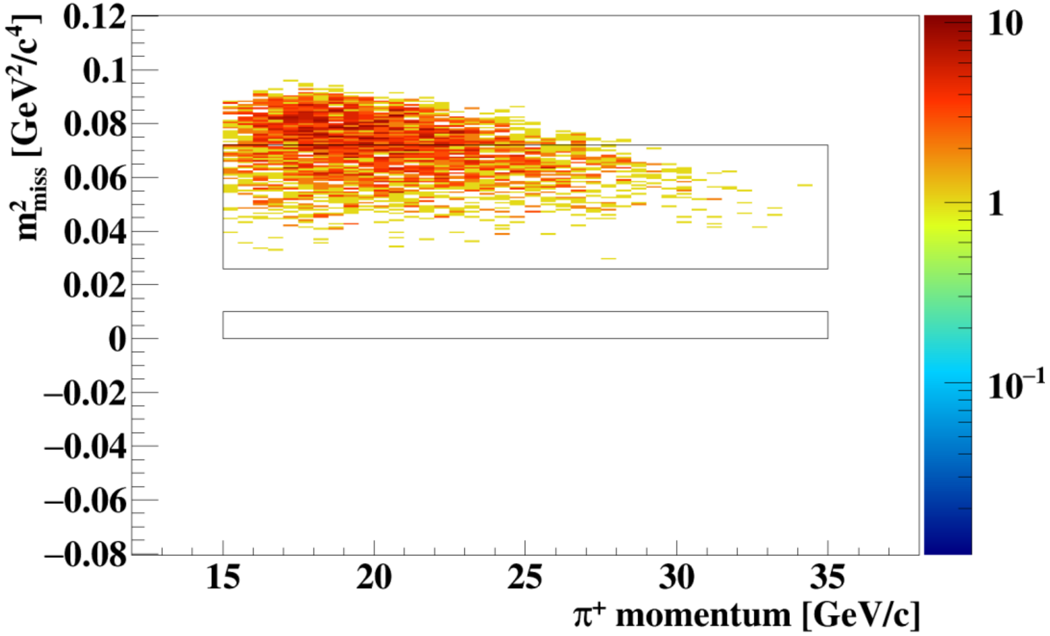


Data-driven background estimation

$$N^{bg}_{\mu\nu(\gamma)} = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}$$

2 events found in control region (1.1 expected)

$K^+ \to \pi^+ \nu\bar{\nu}$ analysis: $K^+ \to \pi^+\pi^- e^+ \nu$ background



Background estimated with MonteCarlo simulation

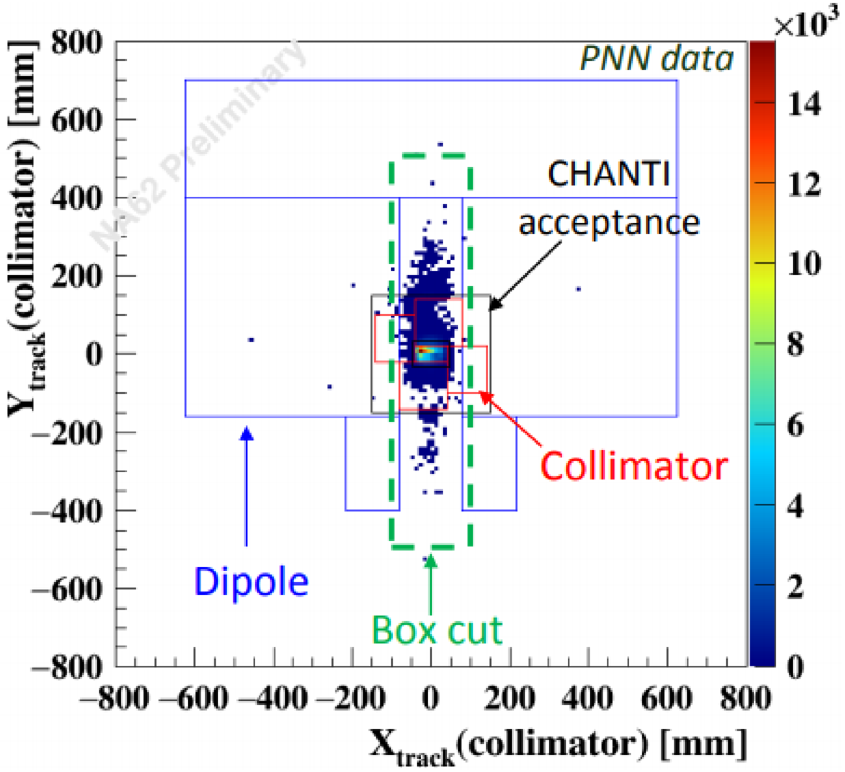
400 M simulated events, 5 validation regions

Validation region	N Expected	N observed
1	15.5(4)	8
2	4.0(4)	2
3	3.2(3)	3
4	0.7(1)	1
5	1.2(1)	5

$$N_{Ke4}^{bg} = 0.018^{+0.024}_{-0.017}|_{stat} \pm 0.009_{syst}$$

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ analysis: Upstream background

- Decays along the beamline
- Interactions in GTK3
- Random tracks matched in GTK



Several ways to reject this background:

- $K - \pi$ matching
- CHANTI
- Z_{vertex}
- «Box cut»