

NA62: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

and Searches for New Physics

Bob Velghe*, on behalf of the NA62 collaboration

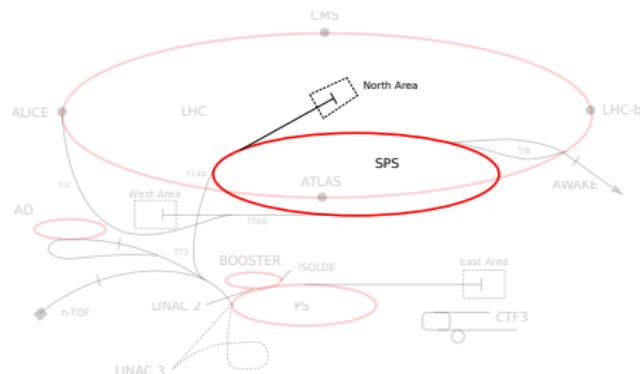
Lake Louise Winter Institute
Feb 16, 2019

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Goal: measure $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with a relative uncertainty around 10 %.

But also, lepton flavour/number violation, exotic physics searches, etc.

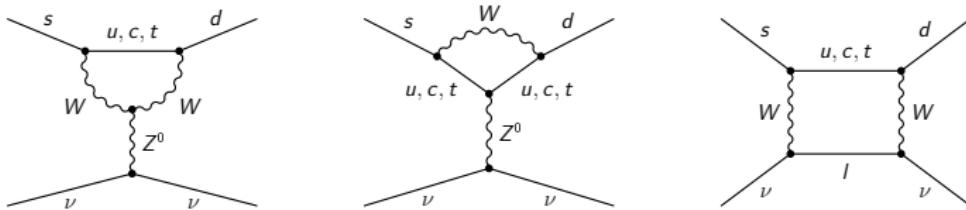
- ▶ 2005 Proposal,
- ▶ 2010 Technical design,
- ▶ 2014–15 Pilot runs,
- ▶ 2016–18 Physics runs,
- ▶ 2019–20 LS2, no beam.



Fixed target experiment, kaons decay in flight.

Primary proton beam (slow)-extracted from the SPS (≈ 5 s burst, 10^{12} p/s).

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ – In the Standard Model



Flavour Changing Neutral Current: decay extremely suppressed.

Clean theoretical prediction: QCD corrections, electroweak corrections, hadronic matrix element related to $K^+ \rightarrow \pi^0 e^+ \nu_e$ decay.

[arXiv:0705.2025], [arXiv:0805.4119], [arXiv:1009.0947]

In terms of the CKM parameters:

$$\begin{aligned} \mathcal{B}_{\text{SM}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= (8.39 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}} \right]^{2.8} \left[\frac{\gamma}{73.2^\circ} \right]^{0.74} \\ &= (8.4 \pm 1.0) \times 10^{-11} \end{aligned}$$

A. J. Buras et al [arXiv:1503.02693]

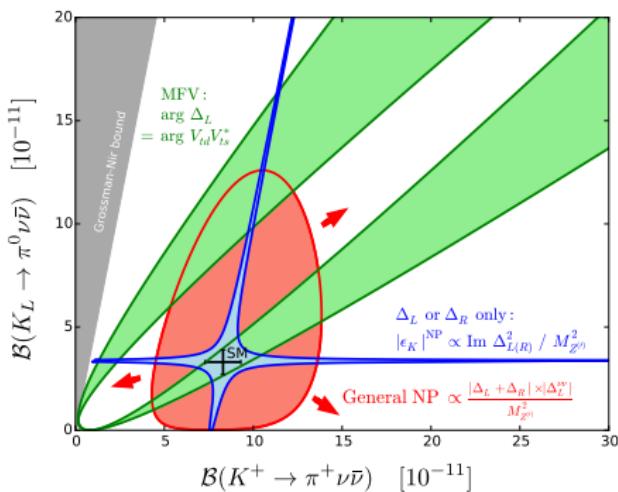
$$\mathcal{B}_{\text{Exp.}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

E787/949 Collaboration [arXiv:0808.2459]

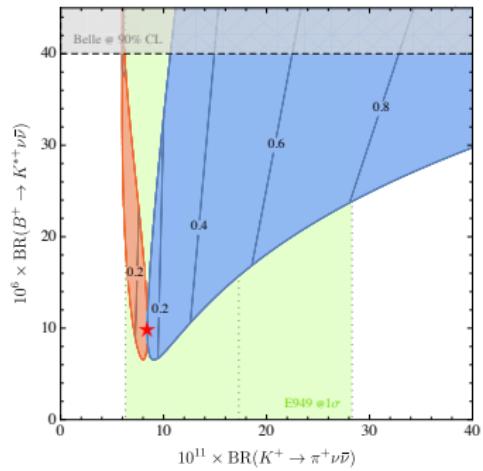
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - Beyond the Standard Model

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has been studied in many BSM scenarios. To name a few:

- ▶ **Z' models,** A. Buras et al [arXiv:1211.1896],[arXiv:1507.08672]
- ▶ **Randall and Sundrum models,** M. Blanke et al [arXiv:0812.3803]
- ▶ **Supersymmetry,** M. Tanimoto, K. Yamamoto [arXiv:1603.07960], T. Blažek, P. Maták [arXiv:1410.0055]
- ▶ **Lepton Flavour Violation models.** M. Bordone et al [arXiv:1705.10729]



A. J. Buras et al [arXiv:1507.08672]

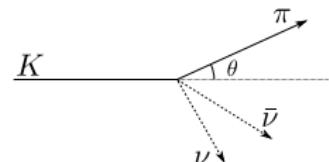


M. Bordone et al [arXiv:1705.10729]

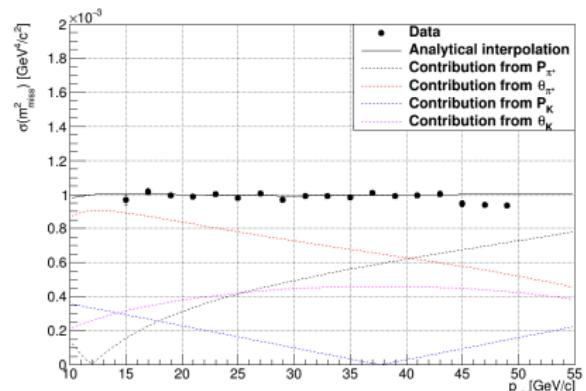
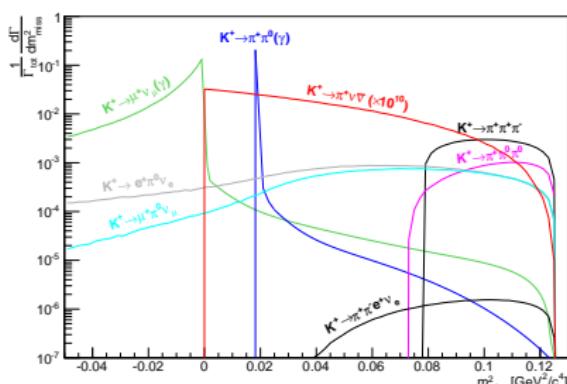
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - Measurement Principle

Signal: K^+ associated to a π^+ and missing energy.

- ▶ Identification of K and π ,
- ▶ Measurements of K and π momentum,
- ▶ Vetoos for γ and μ ,
- ▶ $\mathcal{O}(100 \text{ ps})$ timing capabilities for K - π matching.



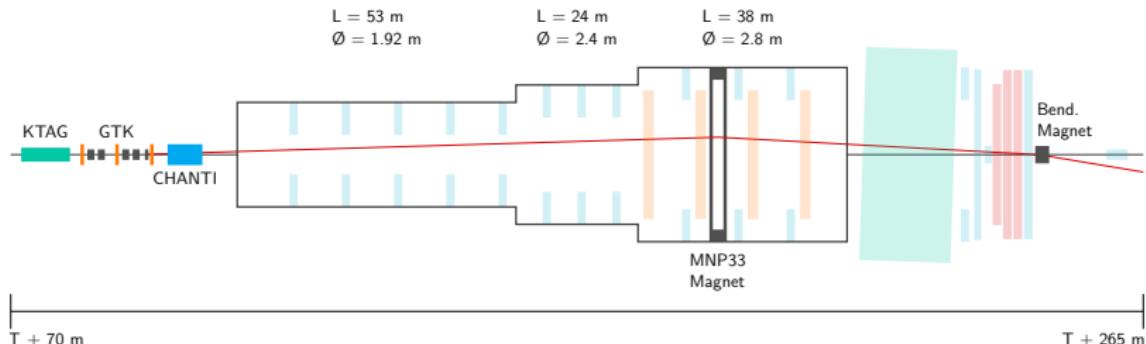
Excellent kinematic reconstruction is key $\rightarrow m_{\text{miss}}^2 = (p_k - p_\pi)^2$.



Main kaon backgrounds: $K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$, $K^+ \rightarrow \pi^+ \pi^0 (\gamma)$, $K^+ \rightarrow \pi^+ \pi^+ \pi^-$, $K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$.

NA62 / CERN SPS – Layout

Nominal beam: $75 \text{ GeV}/c \pm 1\%$, K, π and p (6:70:23), 750 MHz.



NA62 Collaboration [arXiv:1703.08501]

KTAG: Differential Cherenkov \rightarrow kaon ID,

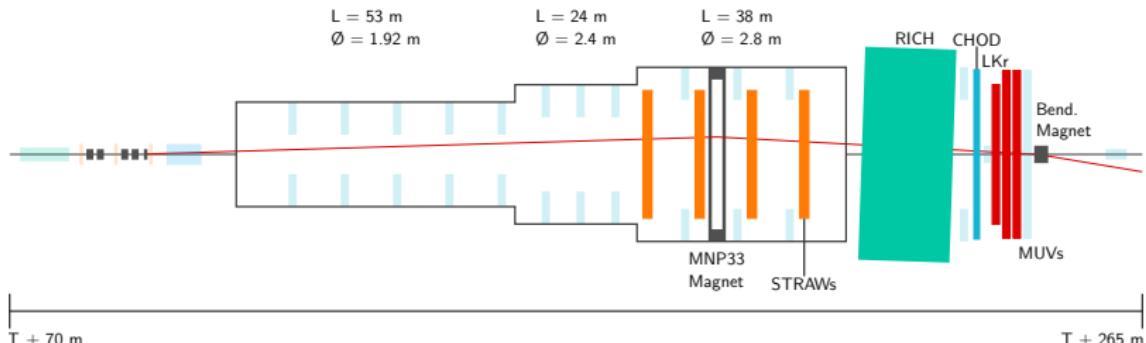
GigaTracker (GTK): Silicon pixel spectrometer \rightarrow beam part. momentum measurement,

CHANTI: Charged particle veto \rightarrow protects against beam induced backgrounds.

75 % K^+ reconstruction efficiency

NA62 / CERN SPS – Layout

Nominal beam: $75 \text{ GeV}/c \pm 1\%$, K, π and p (6:70:23), 750 MHz.



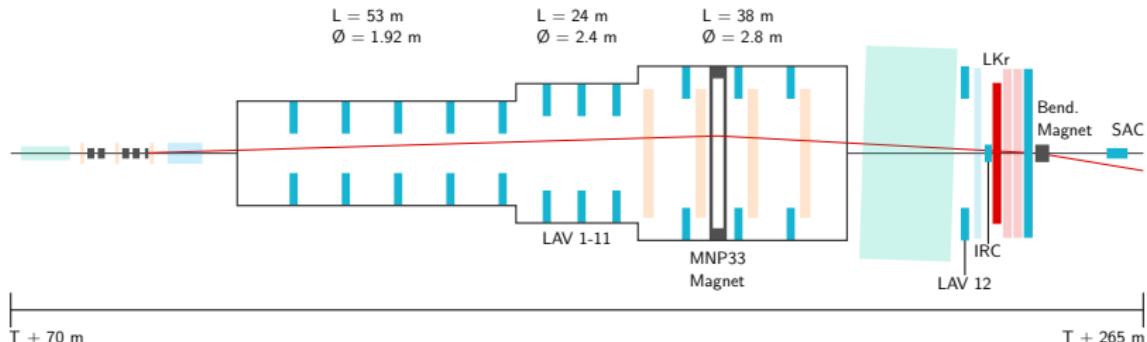
NA62 Collaboration [arXiv:1703.08501]

STRAW: Straw spectrometer → decay products momentum measurement,
RICH: Ring Imaging Cherenkov → particle ID,
CHOD: Hodoscope → event multiplicity,
LKr & MUVs: Calorimeters → particle ID.

$$\epsilon(\mu^+) = 1 \times 10^{-8} \text{ (64 \% } \pi^+ \text{ efficiency)}$$

NA62 / CERN SPS – Layout

Nominal beam: $75 \text{ GeV}/c \pm 1\%$, K, π and p (6:70:23), 750 MHz.



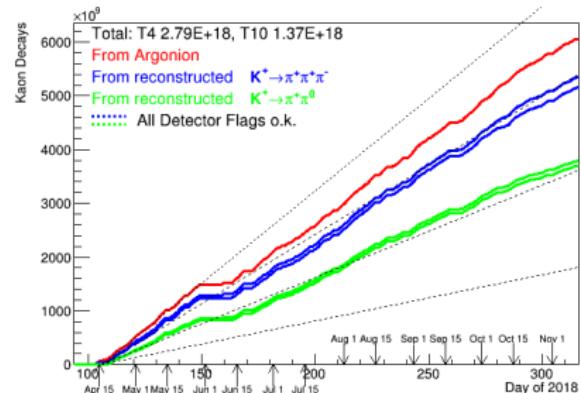
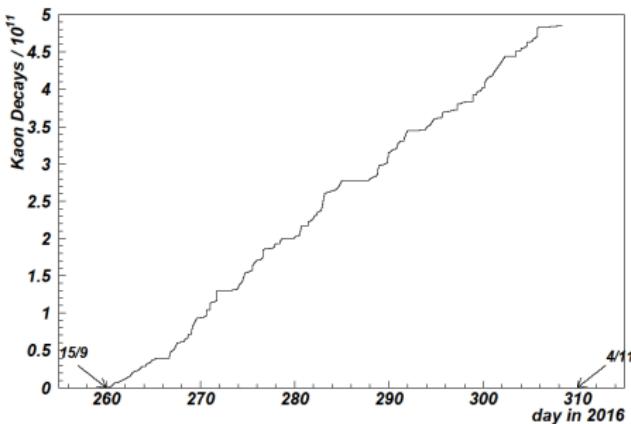
NA62 Collaboration [arXiv:1703.08501]

LAV: Lead glass block rings $\rightarrow \gamma$ veto ($8.5 < \theta < 50 \text{ mrad}$),
LKr: Liquid Krypton calo. $\rightarrow \gamma$ veto ($1 < \theta < 8.5 \text{ mrad}$),
IRC and SAC: Schaschlik calor. $\rightarrow \gamma$ veto ($< 1 \text{ mrad}$).

$$\epsilon(\pi^0) = 3 \times 10^{-8}$$

This talk: **2016 data**, 1 month of data taking at 35 – 40% of the design intensity.

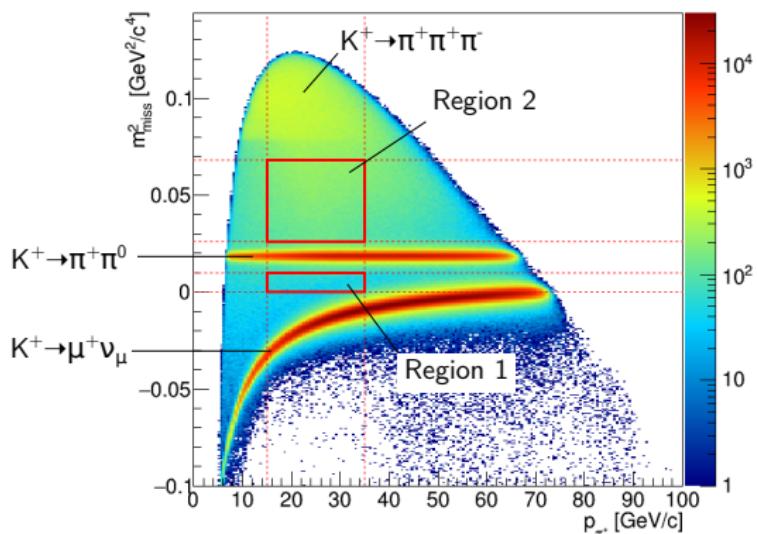
2017-18 data 6/7 months/year of data taking at 60 – 65% of the design intensity, higher data quality.



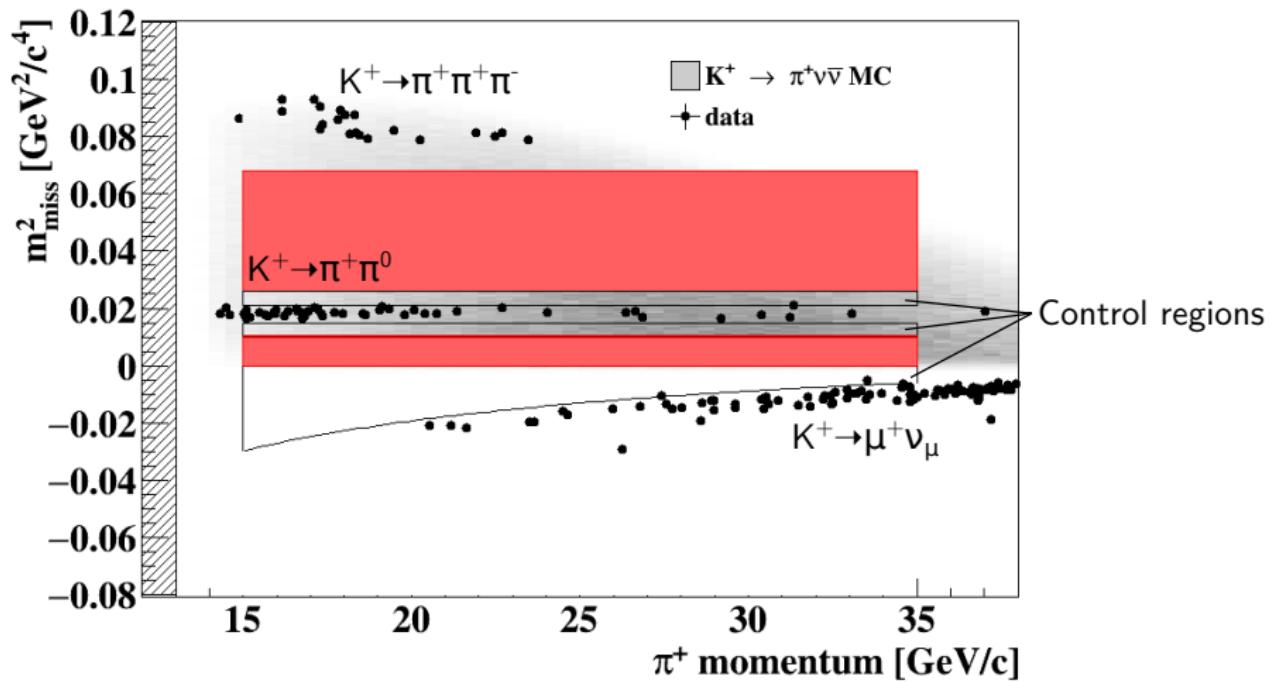
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - Analysis Strategy

Signal selection sketch: K^+ - π^+ association, $15 < P_\pi^+ < 35$ GeV/c, decay vertex in fiducial volume (≈ 65 m long), no photon / muon / upstream activity.

Signal and background control regions were blinded. Data-driven background estimation.



After the Signal Selection



Single Event Sensitivity (SES)

$K^+ \rightarrow \pi^+ \pi^0$ (from control data) used as normalization channel.

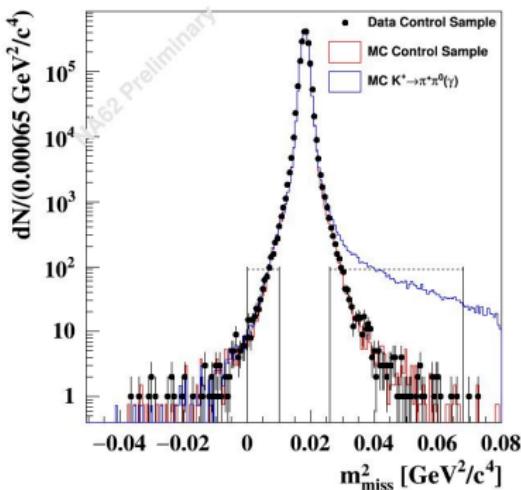
N_K	$(1.21 \pm 0.02) \times 10^{11}$
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ acceptance (MC)	$(4.0 \pm 0.1) \times 10^{-2}$
Random veto efficiency	0.76 ± 0.04
Trigger efficiency	0.87 ± 0.02

$$\text{SES} = \frac{1}{N_K \cdot \epsilon_{\pi\nu\nu}} = (3.15 \pm 0.01_{\text{stat.}} \pm 0.24_{\text{syst.}}) \times 10^{-10}$$

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

Background Evaluation Example: $K^+ \rightarrow \pi^+\pi^0(\gamma)$

Assume that π^0 rejection cuts and kinematic cuts are independent, kinematic rejection measured on $\pi^+\pi^0$ with tagged π^0 ($\gamma\gamma$ in LKr).



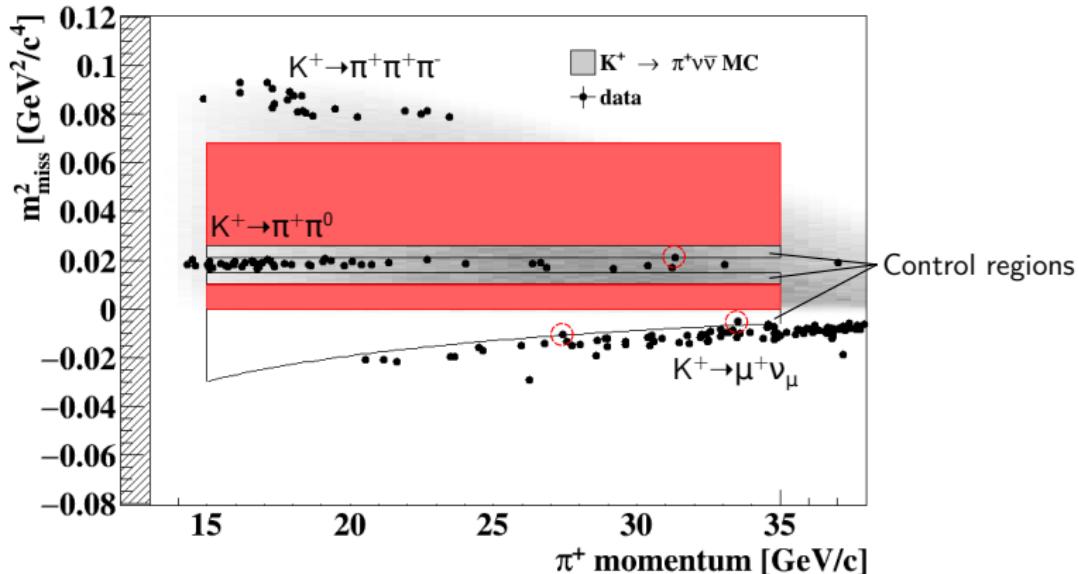
- ▶ Radiative tail in R2 estimated from MC,
- ▶ Single- γ veto efficiency measured on data.

Radiative tail $\times 6$ resolution tail but rejection $\times 30$ thanks to the extra γ .

Region	$N_{\pi\pi}^{\text{exp.}}$
R1	$0.022 \pm 0.004 \pm 0.002$
R2	$0.037 \pm 0.006 \pm 0.003$

Region	$N_{\pi\pi\gamma}^{\text{exp.}}$
R1	0
R2	$0.005 \pm 0.005_{\text{syst.}}$

Backgrounds – Control Regions



Region	$N_{\pi\pi\gamma}^{\text{exp.}}$	$N_{\pi\pi\gamma}^{\text{obs.}}$
CR1	$0.52 \pm 0.08 \pm 0.03$	0
CR2	$0.94 \pm 0.14 \pm 0.05$	1

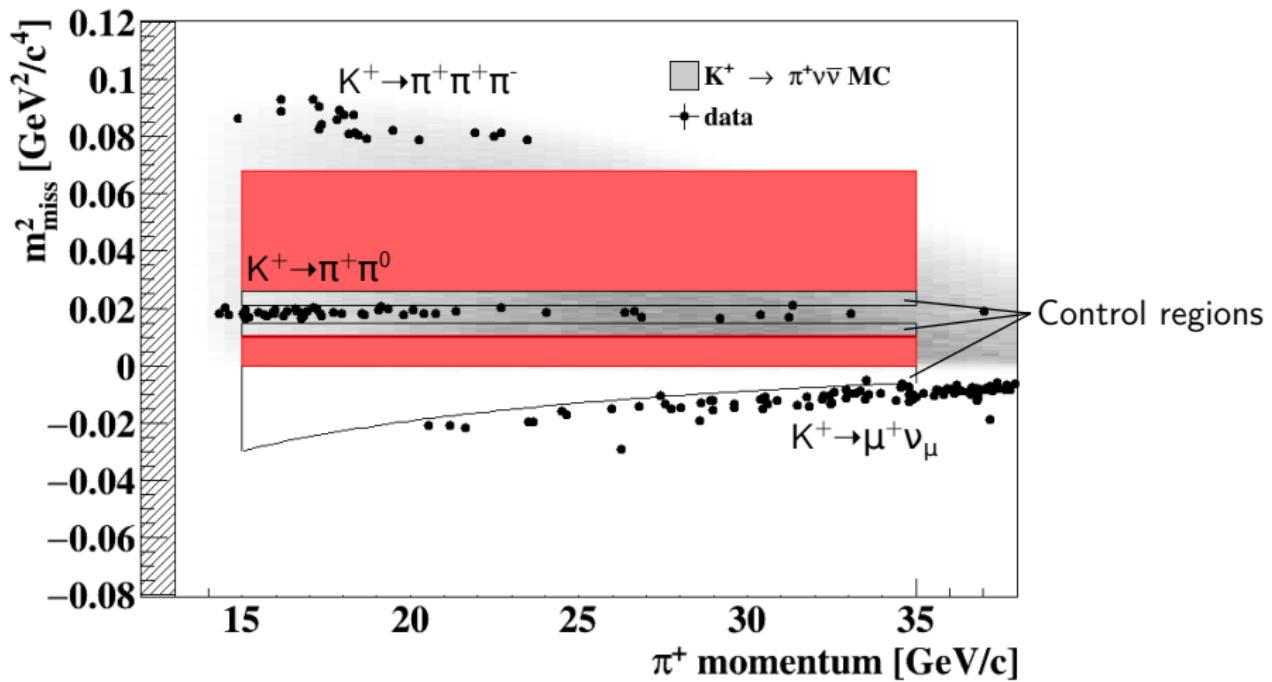
Region	$N_{\mu\nu(\gamma)}^{\text{exp.}}$	$N_{\mu\nu(\gamma)}^{\text{obs.}}$
CR	1.02 ± 0.16	2

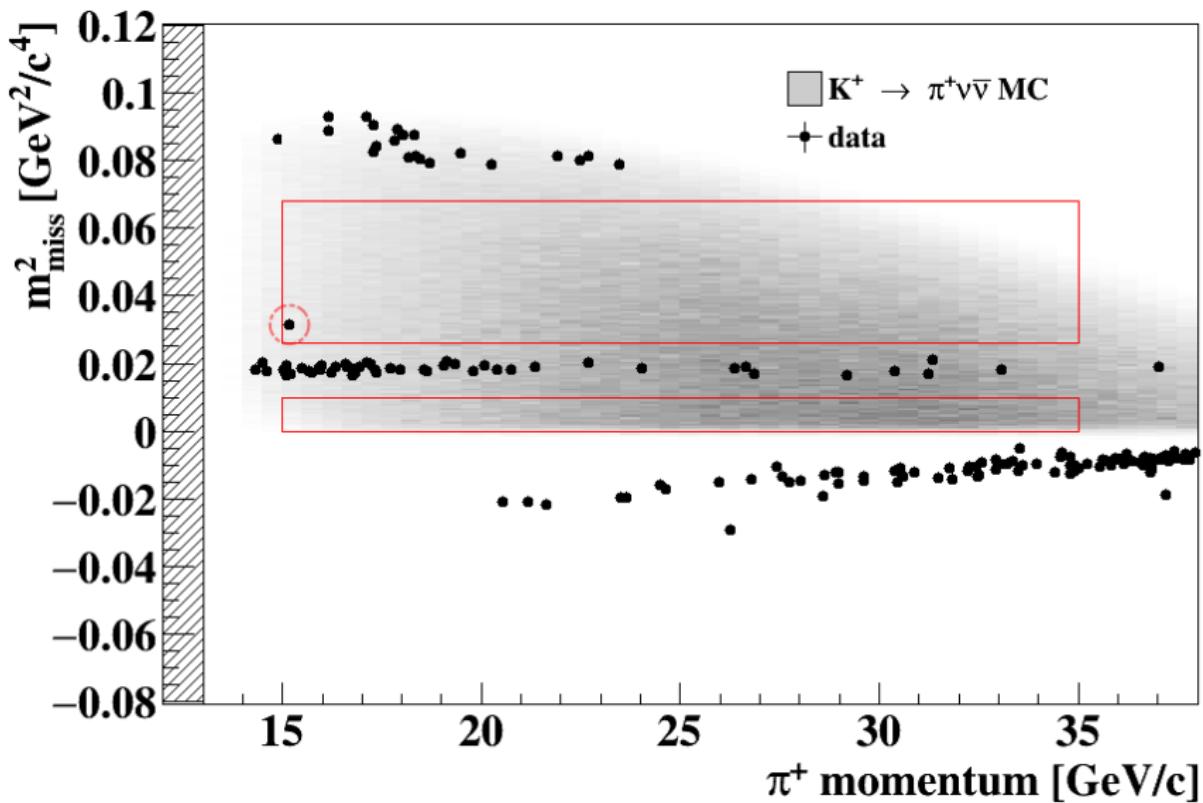
Backgrounds – Summary

Process	Expected events		
	R1	R2	R1+R2
$K^+ \rightarrow \pi^+ \pi^0 (\gamma)$	0.022	0.042	$0.064 \pm 0.007 \pm 0.006$
Upstream backgrounds(*)	-	-	$0.050^{+0.090}_{-0.030}$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	0	0.018	$0.018^{+0.024}_{-0.017} \pm 0.009$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0	0.002	$0.002 \pm 0.001 \pm 0.002$
$K^+ \rightarrow \mu^+ \nu (\gamma)$	0.019	0.001	$0.020 \pm 0.003 \pm 0.003$
Total backgrounds	-	-	$0.152^{+0.092}_{-0.033} \pm 0.013$
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (SM)	0.069	0.198	$0.267 \pm 0.001 \pm 0.020 \pm 0.032$

(*) A copper block (2017) and a new final collimator (2018) were installed to reduce the upstream backgrounds.

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ - 2016 Data Set

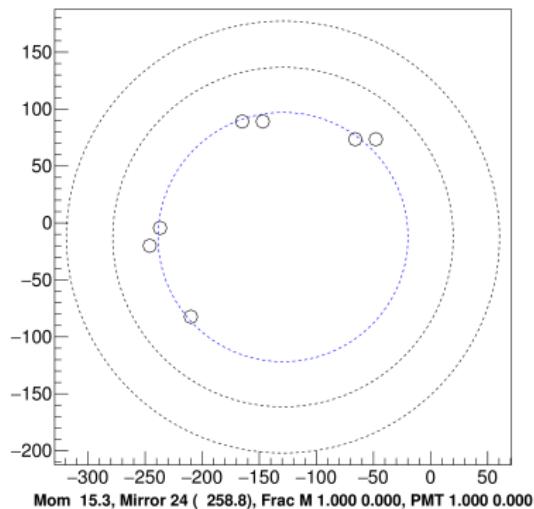


$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ - 2016 Data Set

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ - 2016 Data Set

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \text{ 95% C.L.}$$

NA62 collaboration [arXiv:1811.08508] (submitted to PLB)

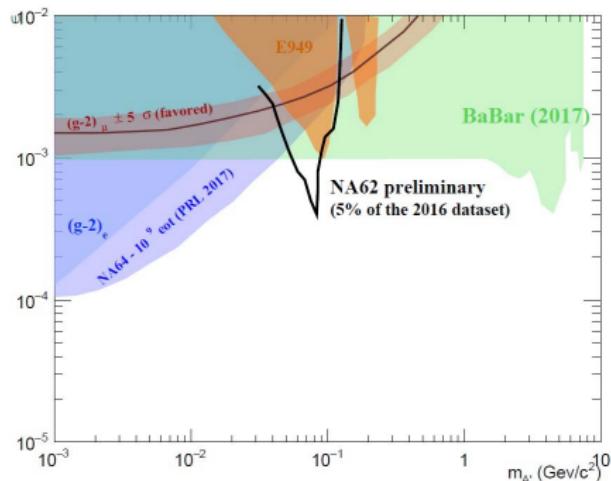


Candidate	1
N_K	$(1.21 \pm 0.02) \times 10^{11}$
SES	$(3.15 \pm 0.01 \pm 0.24) \times 10^{-10}$
Expected SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$0.267 \pm 0.001 \pm 0.020 \pm 0.032_{\text{ext.}}$
Expected background	$0.152^{+0.092}_{-0.033} \pm 0.013$

Broader Physics Program

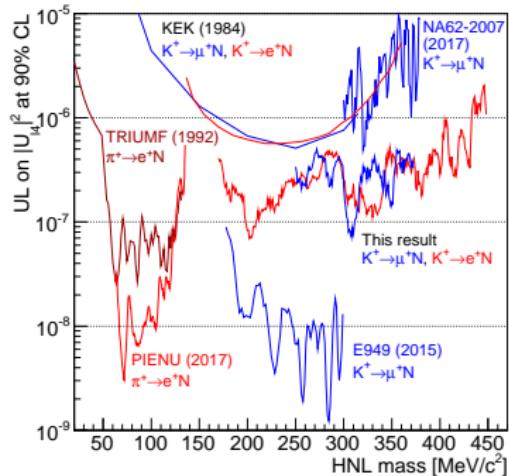
Two examples of peak searches in the missing mass squared spectra:

Search for $\pi^0 \rightarrow \gamma(A' \rightarrow \text{invisible})$



Paper in preparation

Search for Heavy Neutral Leptons



$10^{-6} - 10^{-7}$ limits on $|U_{14}|^2$ in the $(170-448) \text{ MeV}/c^2$ mass range.

Phys. Lett. B778(2018)137

Summary and Prospects

2016 data set: one candidate $\rightarrow \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10}$ 95% C.L.

- ▶ Data quality greatly improved in 2017/2018,
- ▶ Higher beam intensity (40–45% \rightarrow 60–65% of design value),
- ▶ More sophisticated data analysis (cut base \rightarrow multivariate).

Run I: $\approx 8.5 \times 10^{12}$ K^+ decays on tape \rightarrow about 20 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ SM events expected.

Rich complementary program: searches for dark photons, heavy neutral leptons, beam dump mode, etc.

Running after the LS2 will allow us to reach the full physics potential of the experiment.



$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ – Theoretical Error Budget (I)

The branching ratio, summing over the three neutrino flavours reads

[arXiv:hep-ph/0405132]:

$$\begin{aligned} \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+ (1 + \Delta_{\text{EM}}) & \left[\left(\frac{\text{Im } \lambda_t}{\lambda^5} X_t(x_t) \right)^2 \right. \\ & \left. + \left(\frac{\text{Re } \lambda_c}{\lambda} [P_c + \delta P_{c,u}] + \frac{\text{Re } \lambda_t}{\lambda^5} X_t(x_t) \right)^2 \right], \quad (1) \end{aligned}$$

where $\lambda_i = V_{is}^* V_{id}$, $x_t = m_t^2/M_W^2$. The parameter $\Delta_{\text{EM}} \approx -0.3\%$ encodes the QED long distance radiative corrections [arXiv:0705.2025v2].

$$\kappa_+ = (0.5173 \pm 0.0025) \times 10^{-10} \left(\frac{|V_{us}|}{0.225} \right)^8, \quad (2)$$

summarises the long-distance contributions extracted from the $K^+ \rightarrow \pi^0 e^+ \nu_e$ decay [arXiv:0705.2025v2].

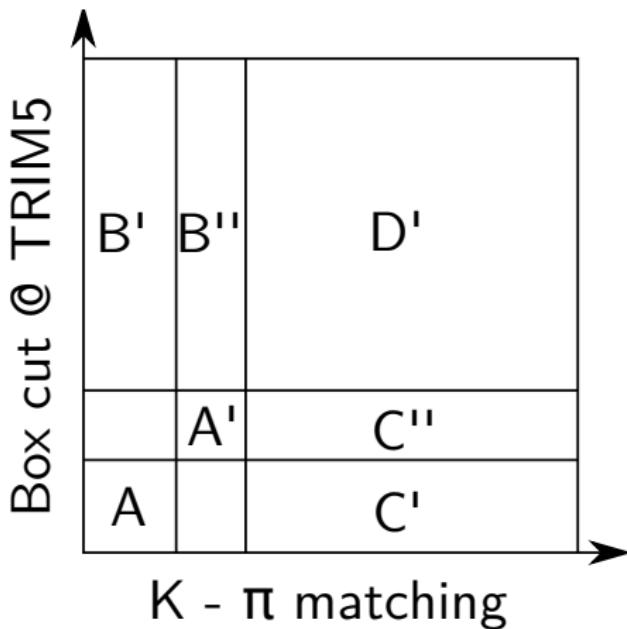
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ - Theoretical Error Budget (II)

Table: Error budget of the parameters entering the $K \rightarrow \pi \nu \bar{\nu}$ branching ratio computation [arXiv:1503.02693].

Quantity	Error budget (%)	Comment
$ V_{cb} $	9.9	-
γ	6.7	-
P_c	1.8	Charm quark contribution
$\delta P_{c,u}$	2.9	Long distance charm-quark contribution
X_t	0.9	Top-quark contribution
Other	0.5	-

Bifurcation Analysis

Estimate the number of background events in the signal region (A) using control regions B' , C' and D' :



A : signal region

A' : control region, B' , B'' , C' , C'' and
 D' : control samples.

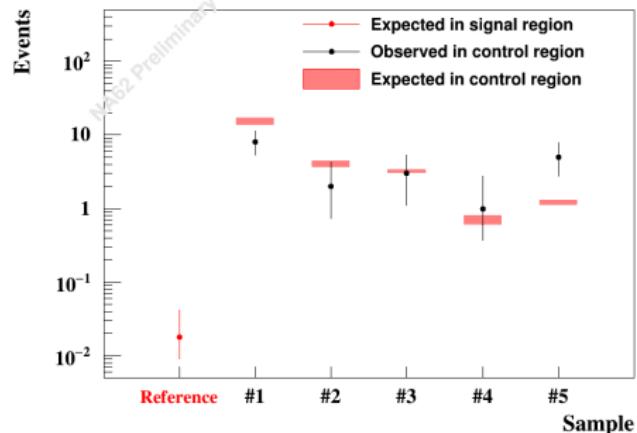
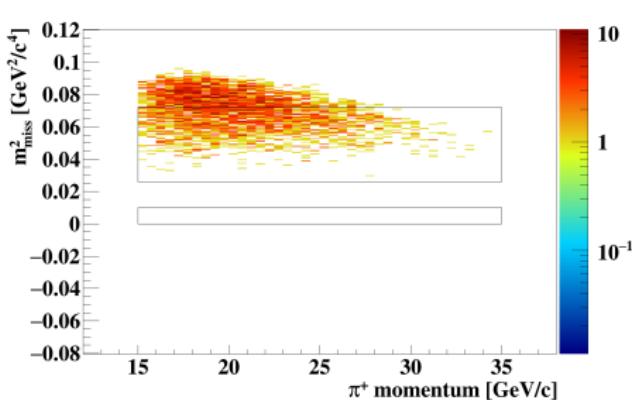
If the two cuts are independent:

$$\rightarrow A = \frac{B' C'}{D'}$$

$$\rightarrow A' = \frac{B'' C''}{D'}$$

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

Estimated using MC, $\approx 4 \times 10^8$ events generated.



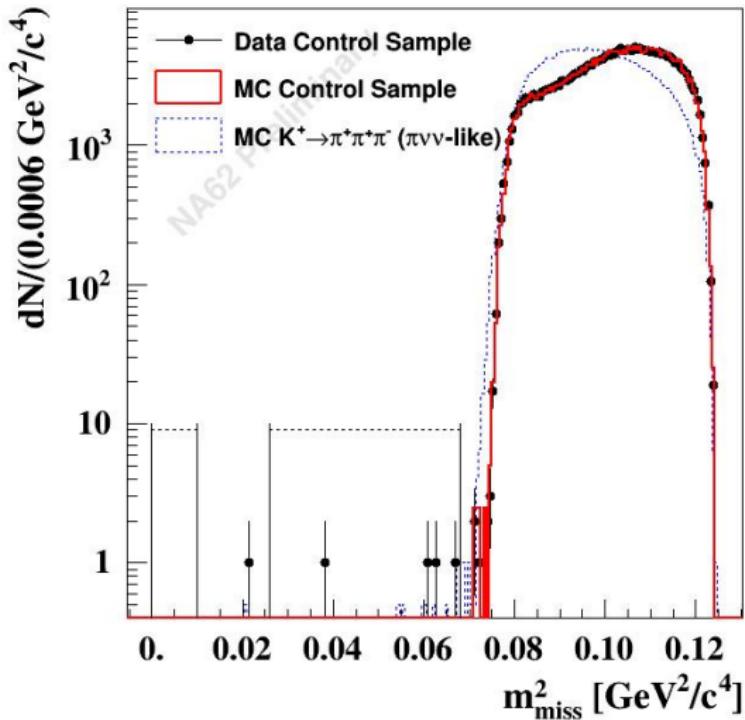
$0.026 < m_{\text{miss}}^2 < 0.072$ GeV $^2/c^4$ region used for validation, free from other background processes.

Example: single π^- events, full $\pi\nu\bar{\nu}$ selection, STRAW multiplicity cuts inverted.

$$N_{\pi\pi e\nu}^{\text{exp.}} = 0.018^{+0.024}_{-0.017} \pm 0.009$$

$$K^+ \rightarrow \pi^+\pi^+\pi^-$$

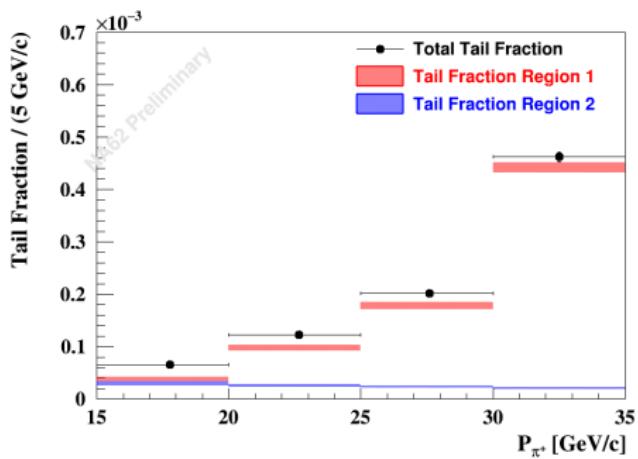
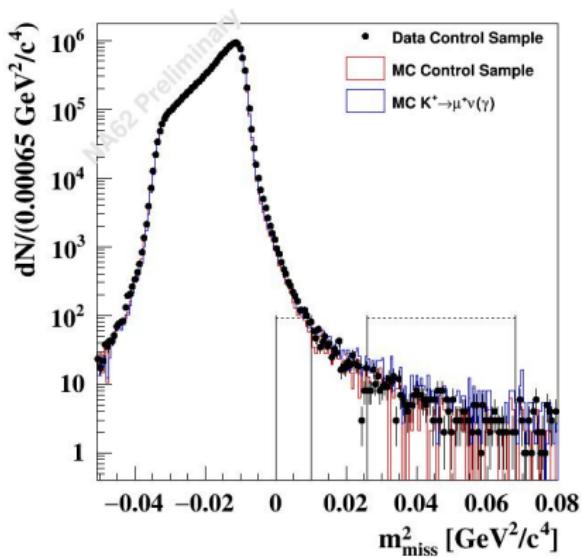
Kinematic rejection in $R2 \leq 10^{-4}$, corrected for selection bias using the MC.



$$N_{\pi\pi\pi}^{\text{exp.}} = 0.002 \pm 0.001 \pm 0.002$$

$$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$$

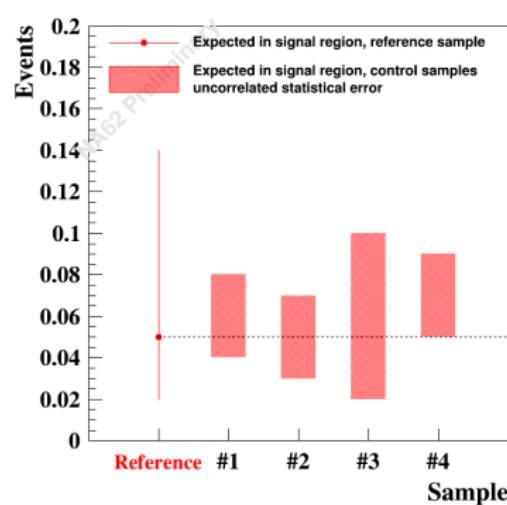
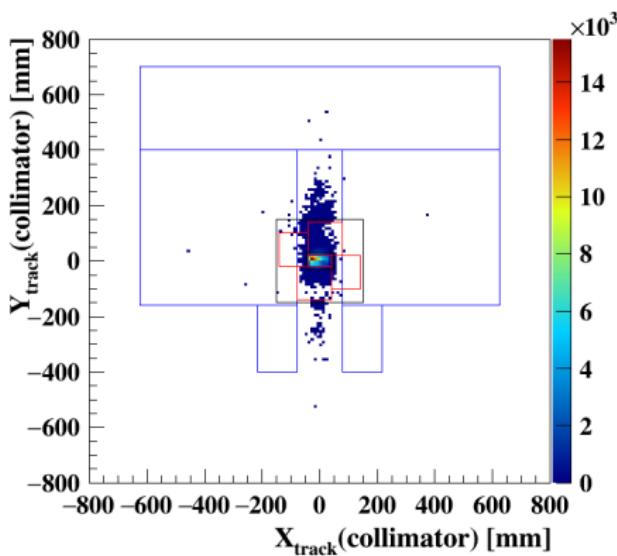
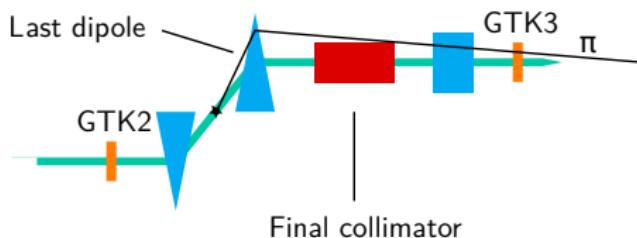
Same approach as $K^+ \rightarrow \pi^+ \pi^0 (\gamma)$, assume that PID rejection cuts and kinematic cuts are independent. Kinematic rejection measured on $\mu^+ \nu_\mu$ sample, applying the γ rejection.



Region	$N_{\mu\nu(\gamma)}^{\text{exp.}}$
R1	$0.019 \pm 0.003 \pm 0.003$
R2	$0.0012 \pm 0.0002 \pm 0.0006$

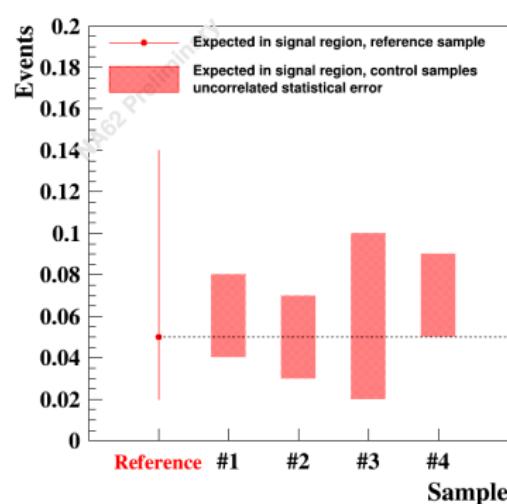
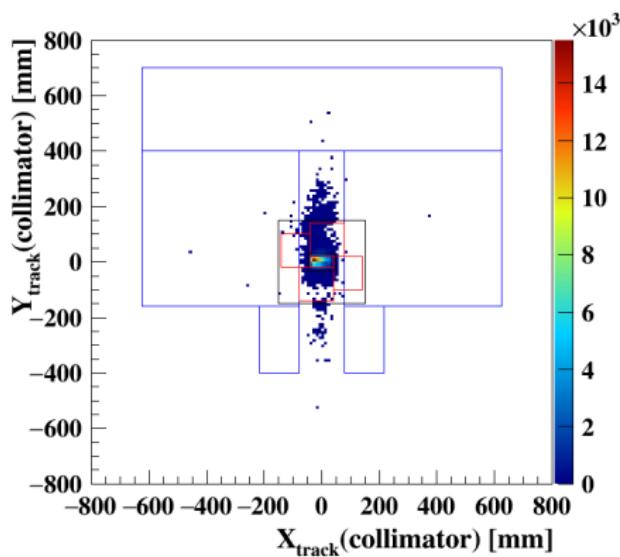
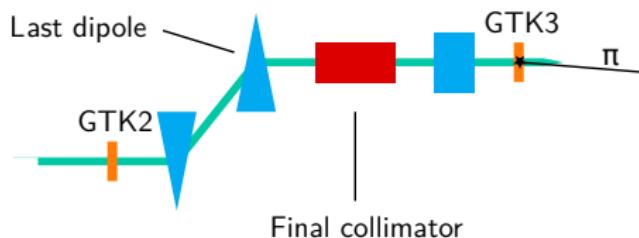
Upstream Backgrounds

Estimation based on a “bifurcation” analysis.



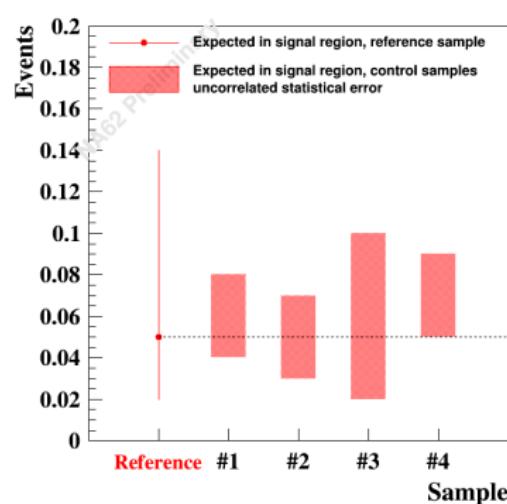
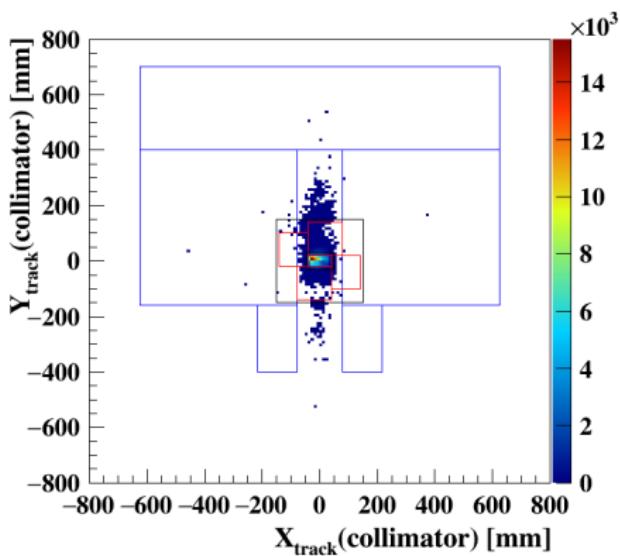
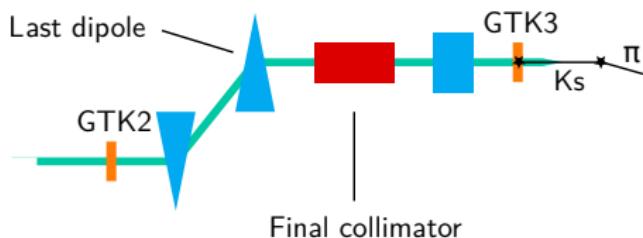
Upstream Backgrounds

Estimation based on a “bifurcation” analysis.



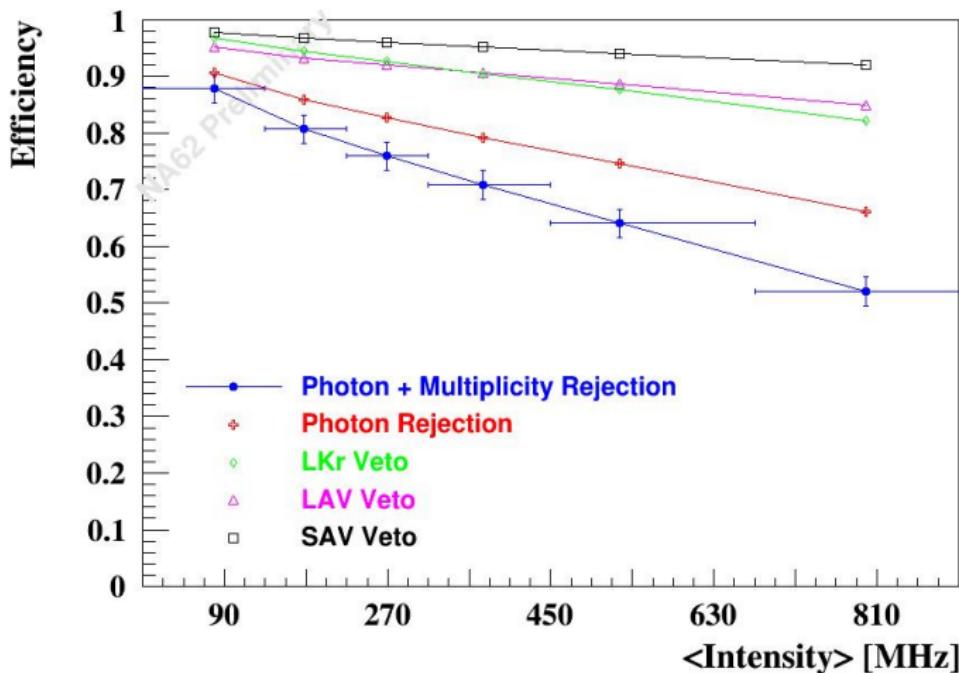
Upstream Backgrounds

Estimation based on a “bifurcation” analysis.



Random Veto Efficiency

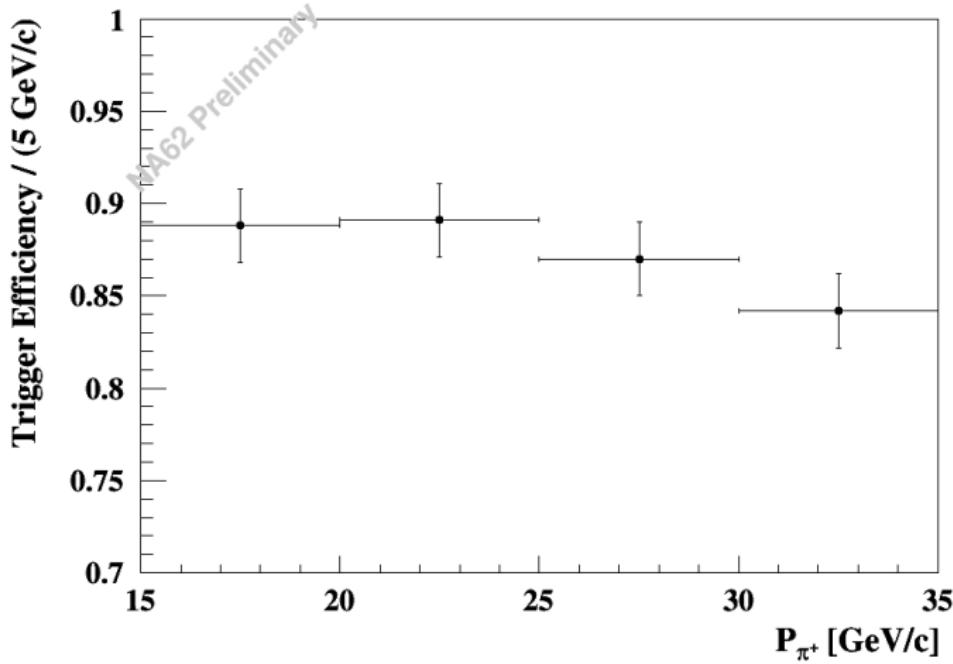
Accidental losses due to photon vetoes and multiplicity rejection, extracted from $K^+ \rightarrow \mu^+ \nu_\mu$.



$$\epsilon_{\text{RV}} = 0.76 \pm 0.04$$

Trigger Efficiency

Trigger efficiency extracted from $K^+ \rightarrow \pi^+\pi^0$ (control trigger), mainly due to L0, (L1 efficiency ≈ 0.97).



$$\epsilon_{\text{Trig.}} = 0.87 \pm 0.2$$