Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay at CERN SPS

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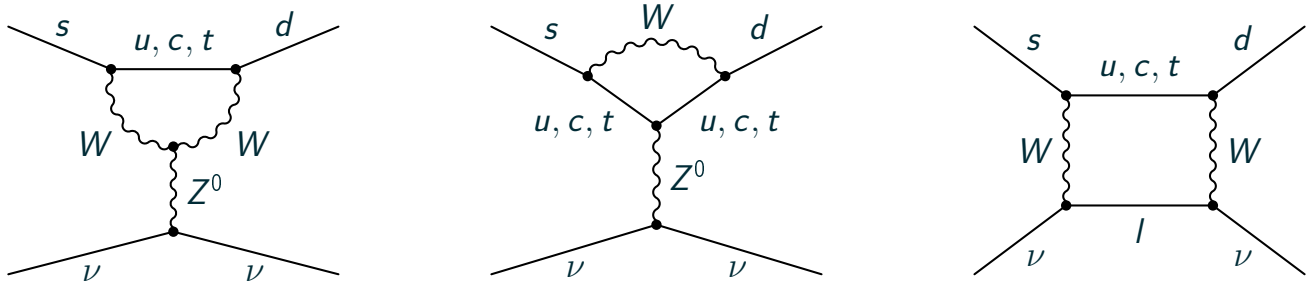
$K^+ \to \pi^+ \nu\bar{\nu}$ – In the Standard Model

Can be represented by penguin and box diagrams:



It is a Flavor Changing Neutral Current: the decay is extremely suppressed.

Theoretical uncertainties well under control: QCD and electroweak corrections, hadronic matrix element related to the $K^+ \to \pi^0 e^+ \nu_e$ decay.

[F. Mescia, C. Smith, 07'] [J. Brod, M. Gorbahn, 08'] [J. Brod, M. Gorbahn, E. Stamou, 11']

In terms of the CKM parameters:

$$\mathcal{B}_{\mathrm{SM}}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.39 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

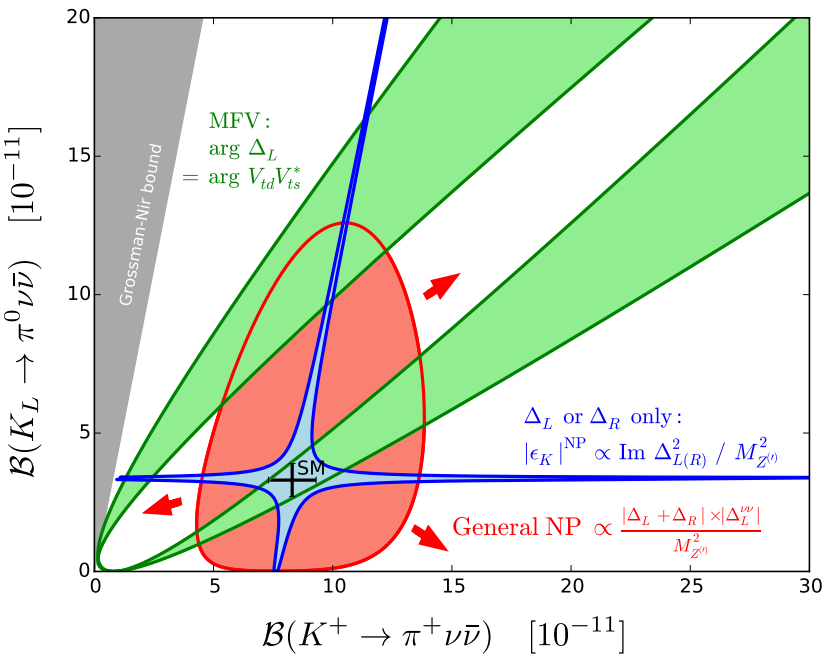
$$= (8.4 \pm 1.0) \times 10^{-11}$$

CKM uncertainties: $|V_{cb}| \approx 9.9\%$, $\gamma \approx 6.7\%$. [A. J. Buras et al, 15']

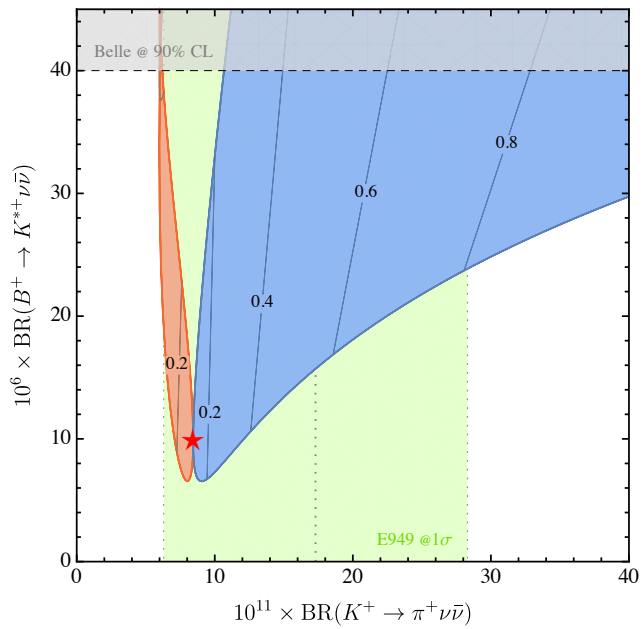
$K^+ \to \pi^+ \nu\bar{\nu}$ – Beyond the Standard Model

$K^+ \to \pi^+ \nu\bar{\nu}$ has been studied in many BSM scenarios. A few examples:

- *Z′ models*, [A. J. Buras, F. De Fazio, J. Girrbach, 13'] [A. J. Buras, D. Buttazzo, R. Knegjens, 15'] [J. Aebischer, A. J. Buras, J. Kumar, 20']
- *Leptoquark models*, [C. Bobeth, A. J. Buras, 18'] [S. Fajfer, N. Košnik, L. Vale Silva, 18']
- *Supersymmetry*, [G. Isodori et al, 06'] [T. Blažek, P. Maták, 14'] [M. Tanimoto, K. Yamamoto, 16']
- *Lepton Flavour Violation models*. [M. Bordone et al, 17']

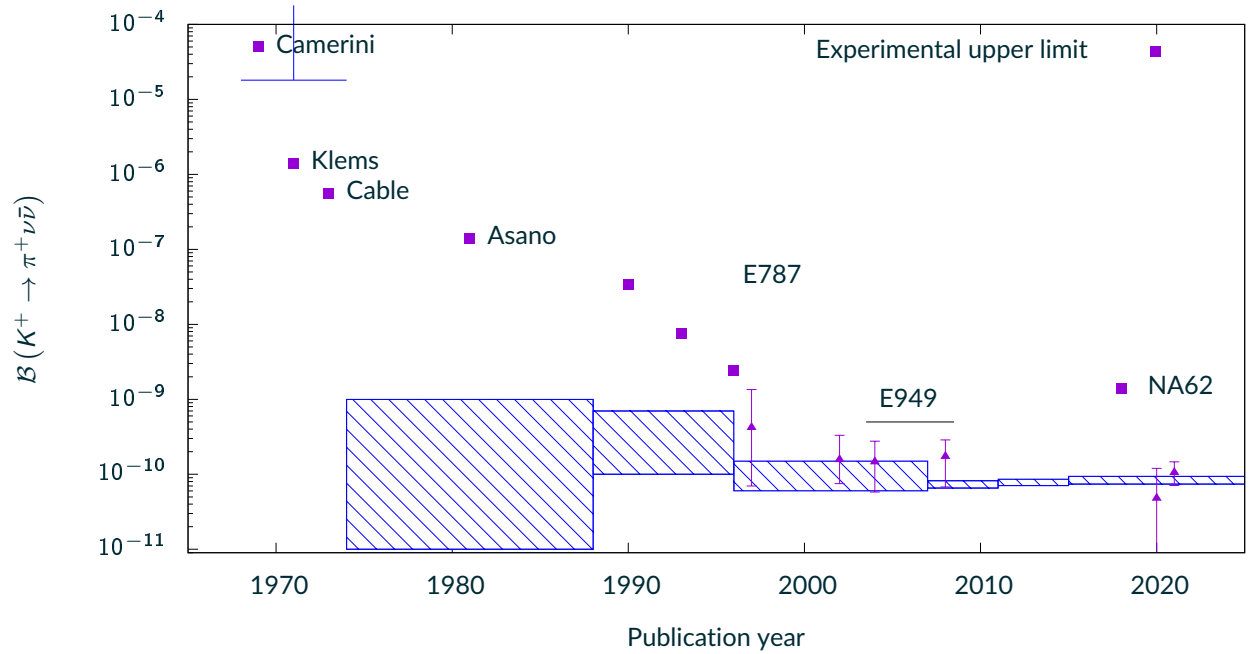


[A. J. Buras et al, 15']



[M. Bordone et al, 17']

$K^+ \to \pi^+ \nu\bar{\nu}$ – Experimental Program



$$\mathcal{B}_{\mathrm{Exp.}}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10} \text{ (E787/E949)}$$

Decay at rest [E787/949 Collaboration, 08']

$$\mathcal{B}_{\mathrm{Exp.}}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(0.48^{+0.72}_{-0.48}\right) \times 10^{-10} \text{ (NA62 2016 + 2017)}$$

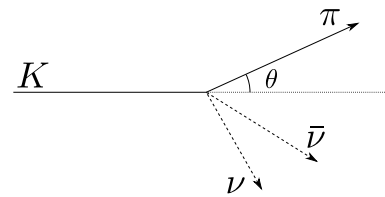
Decay in flight [NA62 Collaboration, 20']

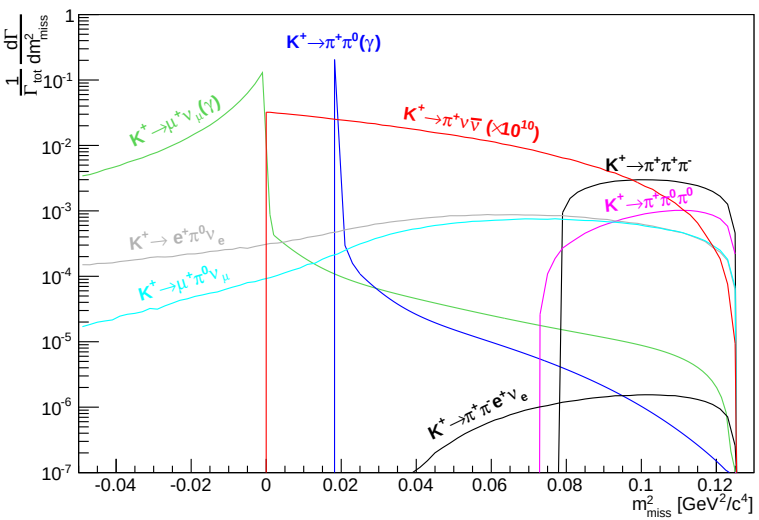
This talk: NA62 **2018** results [NA62 Collaboration, 21']

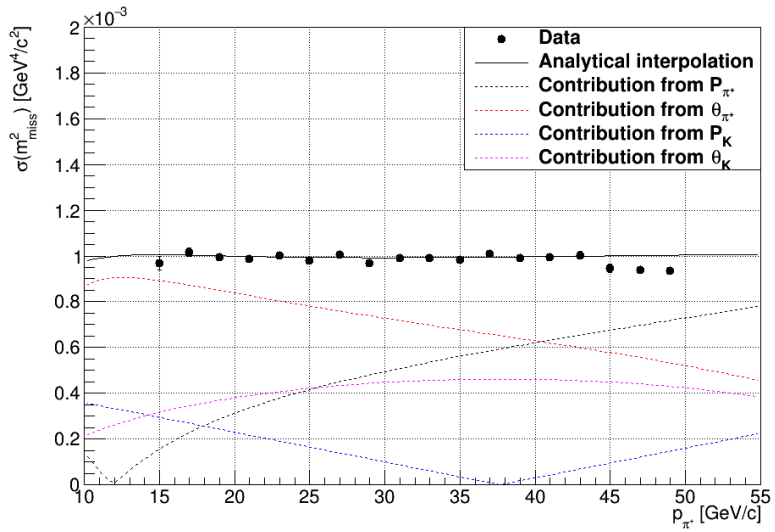
$K^+ \to \pi^+ \nu\bar{\nu}$ – Decay in Flight – Analysis Strategy

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

- Identification of K and π,
- Multi-track event rejection,
- Vetoes for γ and μ, rejection $> \mathcal{O}\left(10^7\right)$,
- $\mathcal{O}\left(100\ \mathrm{ps}\right)$ timing for K - π matching,
- Excellent kinematic reconstruction $\to m^2_{\mathrm{miss.}} = (P_{K^+} - P_{\pi^+})^2$.



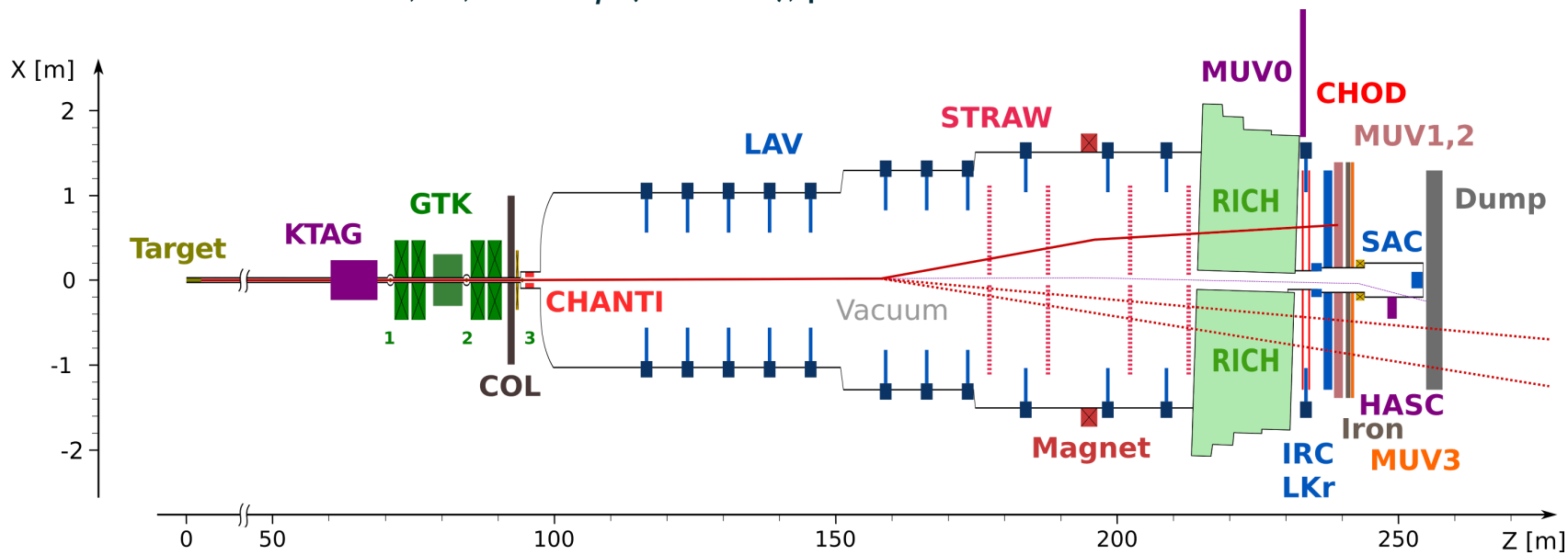




The main kaon backgrounds are $K^+ \to \mu^+\nu_\mu\,(\gamma)$, $K^+ \to \pi^+\pi^0\,(\gamma)$, $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^+\pi^- e^+\nu_e$.

NA62 Experiment at the CERN SPS – In 2018

Beam: 75 GeV/c $\pm$ 1%, K, π and p (6:70:23), particle rate $\approx$ 500 MHz.

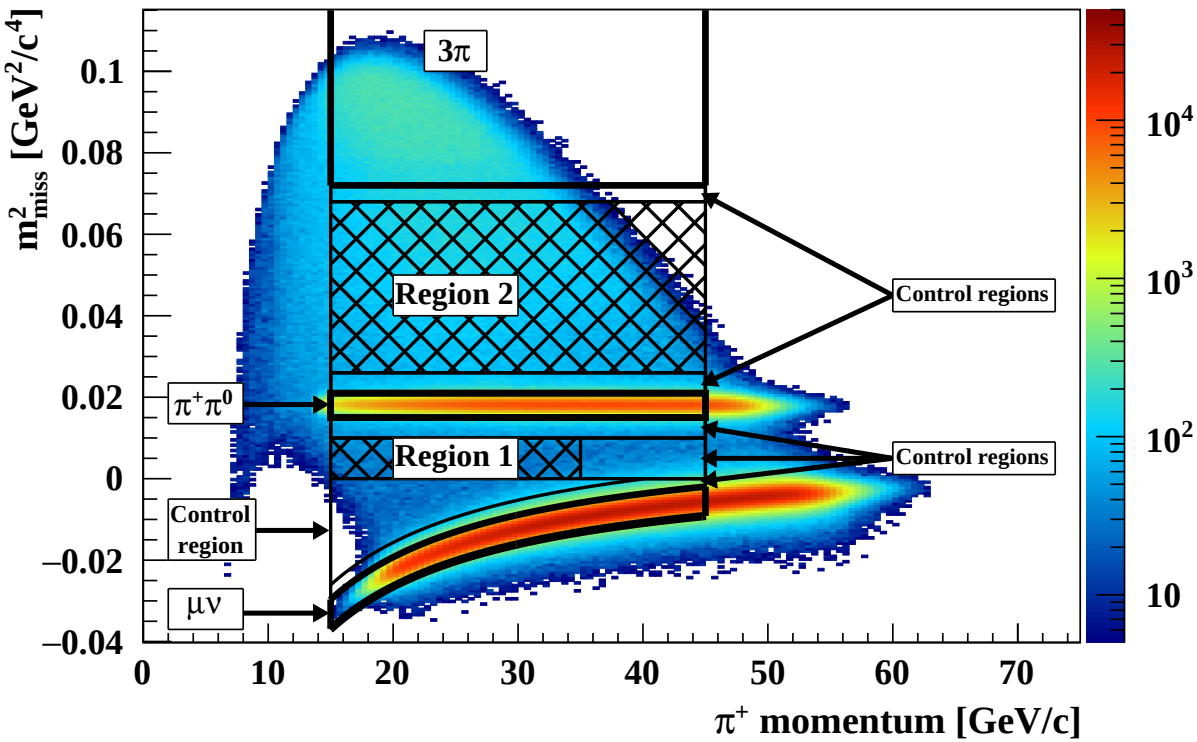


KTAG →	Kaon tagging,	CHOD →	Event multiplicity,
GTK →	Beam tracker,	LKr, MUV1, MUV2 →	Particle ID,
CHANTI →	Charged particles veto,	LAV, IRC, SAC →	Photon vetos,
STRAW →	Spectrometer,	MUV3 →	Muon vetos,
RICH →	Particle ID,	MUV0, HASC →	Off-acceptance vetos.

Note: 2018 data set divided into two subsets: S1 (20%) w/o COL and S2 (80%) w/ COL.

For details about the detector, see [NA62 collaboration, 17']

K^+ decay selection without PID and photon/multi-track rejection:



Pion momentum restricted to $15 < p_{\pi^+} < 35\ \mathrm{GeV}/c$ (region 1) and $15 < p_{\pi^+} < 45\ \mathrm{GeV}/c$ (region 2). The analysis of the S2 subset has been done in $5\ \mathrm{GeV}/c$ bins.

$K^+ \to \pi^+\pi^0$ from the *control* trigger chain are used for normalization.

$$\mathrm{SES} = \frac{\mathcal{B}\left(K^+ \to \pi^+\pi^0\right) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{\mathrm{RV}} \cdot \epsilon_{\mathrm{trig.}}^{\mathrm{PNN}}} \propto \frac{1}{N_K \cdot \epsilon_{\pi\nu\nu}}$$

The expected number of signal events is then

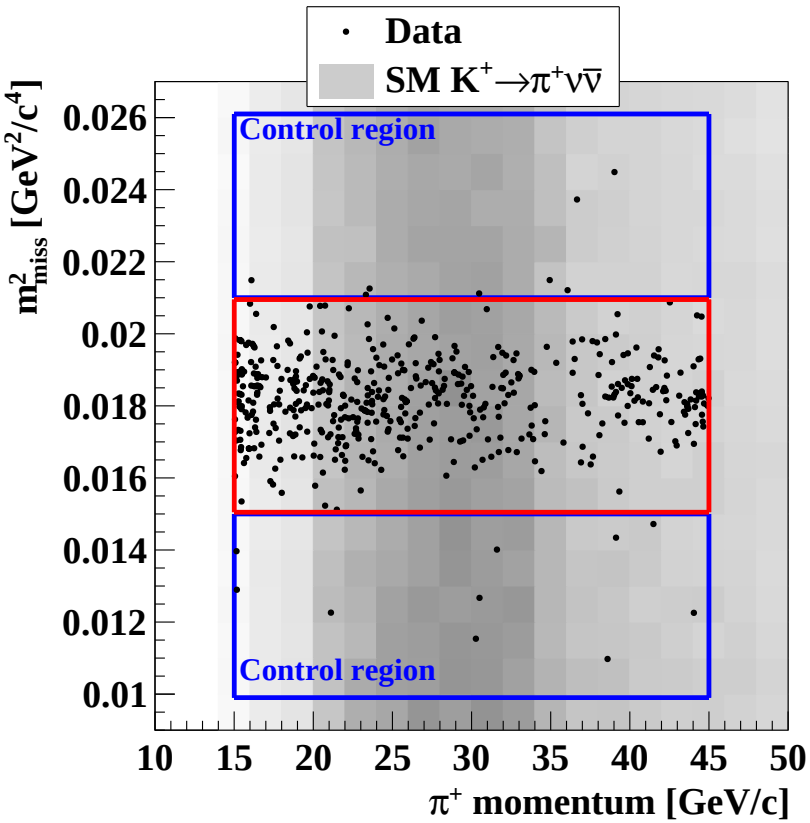
$$N_{\pi\nu\bar{\nu}}^{\mathrm{exp.}} = \frac{\mathcal{B}_{\mathrm{SM}}\left(K^+ \to \pi^+\nu\bar{\nu}\right)}{\mathrm{SES}}$$

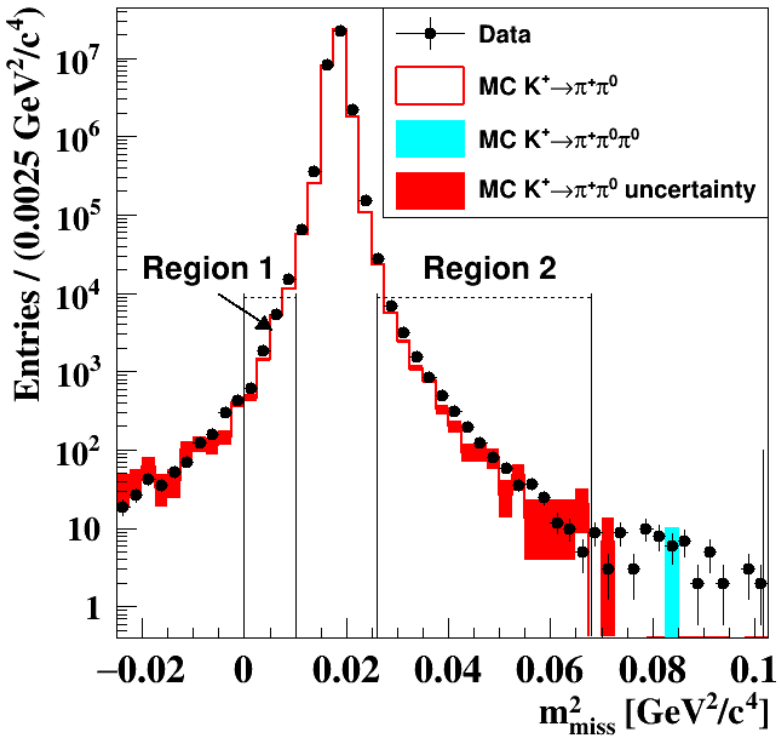
		Subset S1 (w/o COL)	Subset S2 (w/ COL)
CTRL Trig. downscale	D	400	400
	$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
Acceptance (MC)	$A_{\pi\pi} \times 10^2$	7.62 ± 0.77	11.77 ± 1.18
Acceptance (MC)	$A_{\pi\nu\bar{\nu}} \times 10^2$	3.95 ± 0.40	6.37 ± 0.64
Trig. efficiency	$\epsilon_{\mathrm{trig}}^{\mathrm{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
Random veto	ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
	$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
	$N_{\pi\nu\bar{\nu}}^{\mathrm{exp}}$	$1.56 \pm 0.10 \pm 0.19_{\mathrm{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\mathrm{ext}}$

ϵ_{RV} encodes the random vetos caused by accidental activity in the detector.

Background – Kaon Decays – $K^+ \to \pi^+\pi^0$

Data driven estimation: $N^{\mathrm{exp.}}_{\mathrm{decay}} = N_{\mathrm{bkg.}} \cdot f_{\mathrm{kin.}}\,(\mathrm{region})$ where $N_{\mathrm{bkg.}}$ is the number of event in bkg. region after the signal selection and $f_{\mathrm{kin.}}$ the kinematic rejection factor for a given control/signal region.

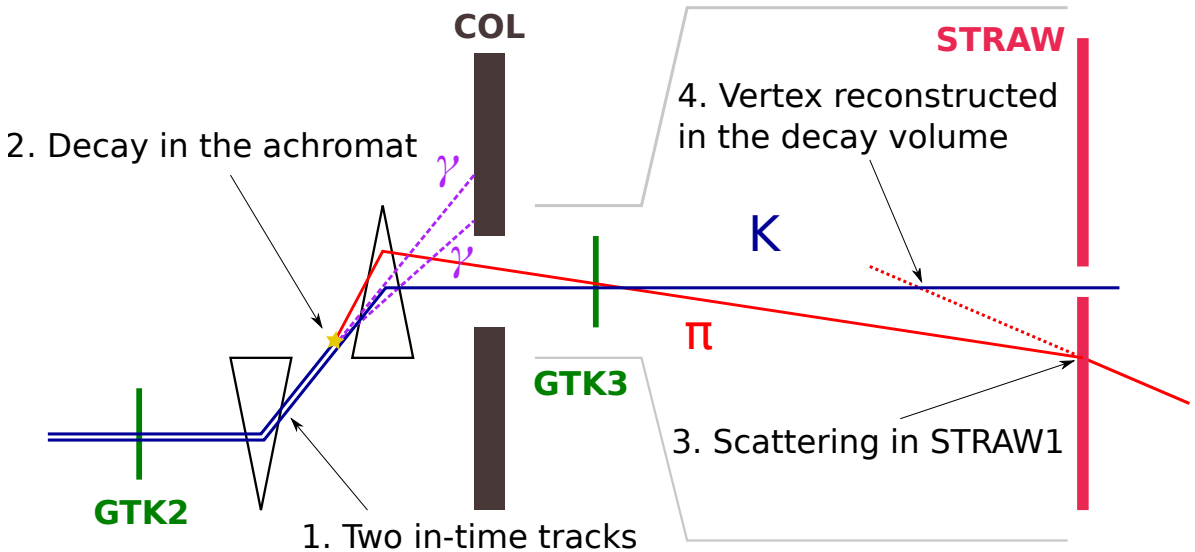


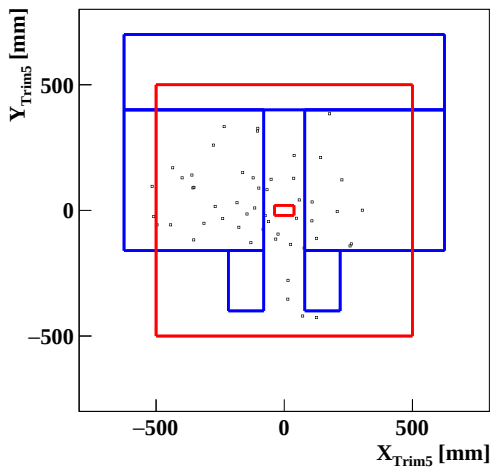


This approch is used for the $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^+\pi^-$ † modes. $K^+ \to \pi^+\pi^- e^+\nu_e$ and other less problematic decays rely on MC simulations.

† In the case of $K^+ \to \pi^+\pi^+\pi^-$ $f_{\mathrm{kin.}}$ is estimated from MC.

Data-driven estimation: $K^+ \to \pi^+ \nu\overline{\nu}$ selection except for no π/K association and distance of closest approach (CDA) > 4 mm.

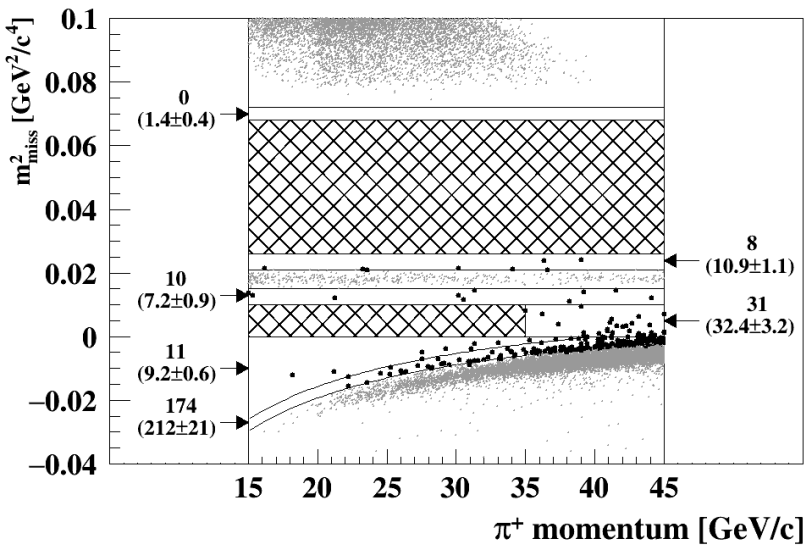




This family of processes is controlled by a "box" cut in the collimator plane (subset S1) / a specialized boosted decision tree (BDT) (subset S2).

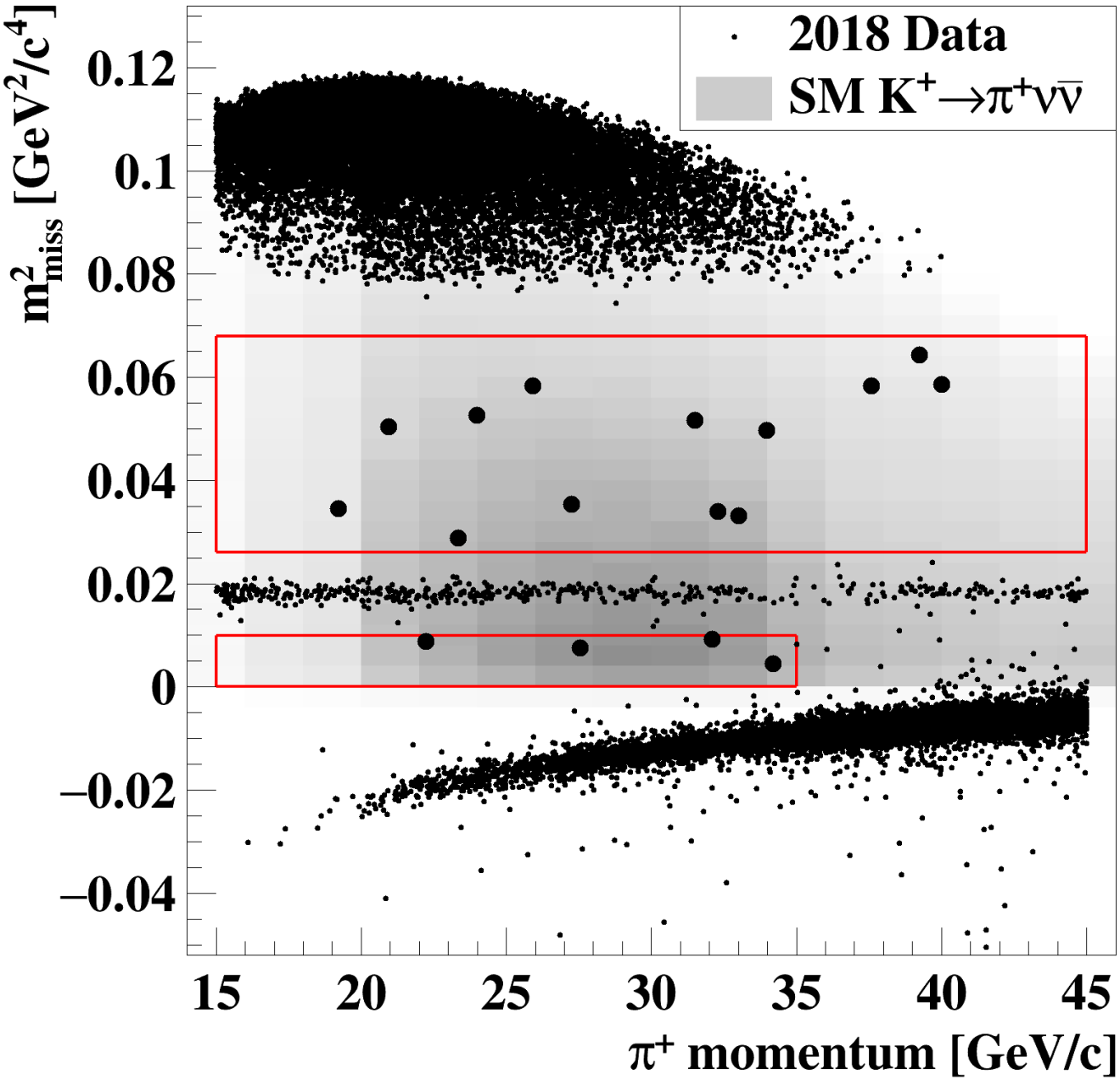
Background – Summary

The figure shows the (expected) and observed number of background events in the **control regions**, after the signal selection. Signal regions were masked during the analysis.



Background	Expected (S1)	Expected (S2)
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^- e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Observed $K^+ \to \pi^+ \nu\bar{\nu}$ Candidates



Conclusions

After unblinding the 16', 17' and 20' data sets, a total of 20 candidates were found, consistent with the expectations. The corresponding branching ratio is

$$\mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(10.6^{+4.0}_{-3.4}\Big|_{\text{stat.}} \pm 0.9_{\text{syst.}}\right) \times 10^{-11} \text{ at } 68\% \text{ CL} ,$$

in agreement with the SM value $(8.4 \pm 1.0) \times 10^{-11}$.

	Expected signal	Expected background	Observed candidates
2016	$0.267 \pm 0.20_{\text{syst.}} \pm 0.32_{\text{ext.}}$	0.15 ± 0.093	1
2017	$2.16 \pm 0.13_{\text{syst.}} \pm 0.26_{\text{ext.}}$	1.46 ± 0.30	2
16' + 17' + 18'	$10.01 \pm 0.42_{\text{syst.}} \pm 1.19_{\text{ext.}}$	$7.03^{+1.05}_{-0.82}$	20

Data taking will resume in July 2021. The beam line was modified during LS2 to suppress the dominant upstream background processes.

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

Other talks at Pheno2021:

- Roberta Volpe, Long-lived feebly interacting particle, Today at 16.30 in Axions & ALPs II
- Joel C. Swallow, Lepton flavour and lepton number violation, Tuesday at 14.45 in Flavor III
- Marco Mirra, Heavy neutral leptons, Tuesday at 16.30 in Neutrino I