Rare kaon decays from NA62

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on behalf of the NA62 Collaboration

16th International Workshop on Meson Physics

17th - 20th May 2021

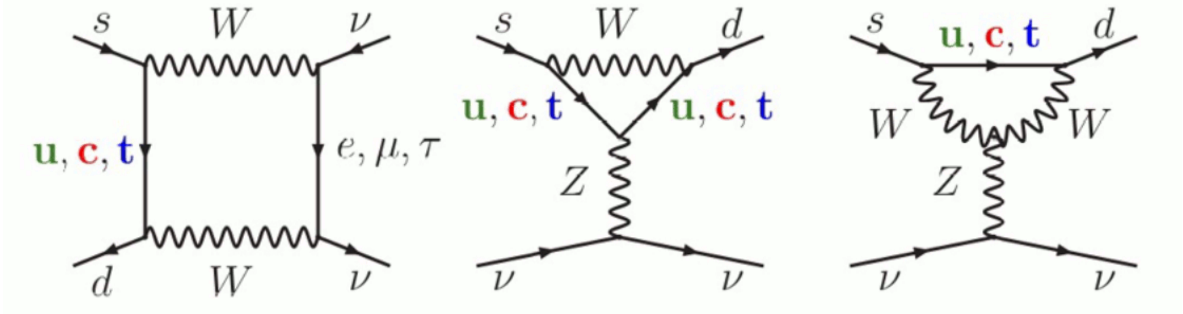
Historical foreword

Strange particles provided many building blocks of the Standard Model (SM):

- Strong production and weak decays $\rightarrow$ Flavor
- K0 –K0 oscillation $\rightarrow$ Flavor mixing
- θ/τ paradox $\rightarrow$ P-violation
- Universality of the weak interaction $\rightarrow$ Cabibbo theory
- Absence of FCNC $\rightarrow$ Four quarks (GIM)
- CP violation $\rightarrow$ Six quarks (KM)

Standard Model has been growing incorporating step by step all the new discoveries

Rare kaon decays: $K^+ \to \pi^+ \nu\bar{\nu}$ [Buras et al., JHEP11(2015)033]



- Flavour changing neutral current process with high CKM suppression
- Dominated by short distances: clean theoretical prediction
- Hadronic matrix element from semi-leptonic data

Making the dependence of the CKM explicit:

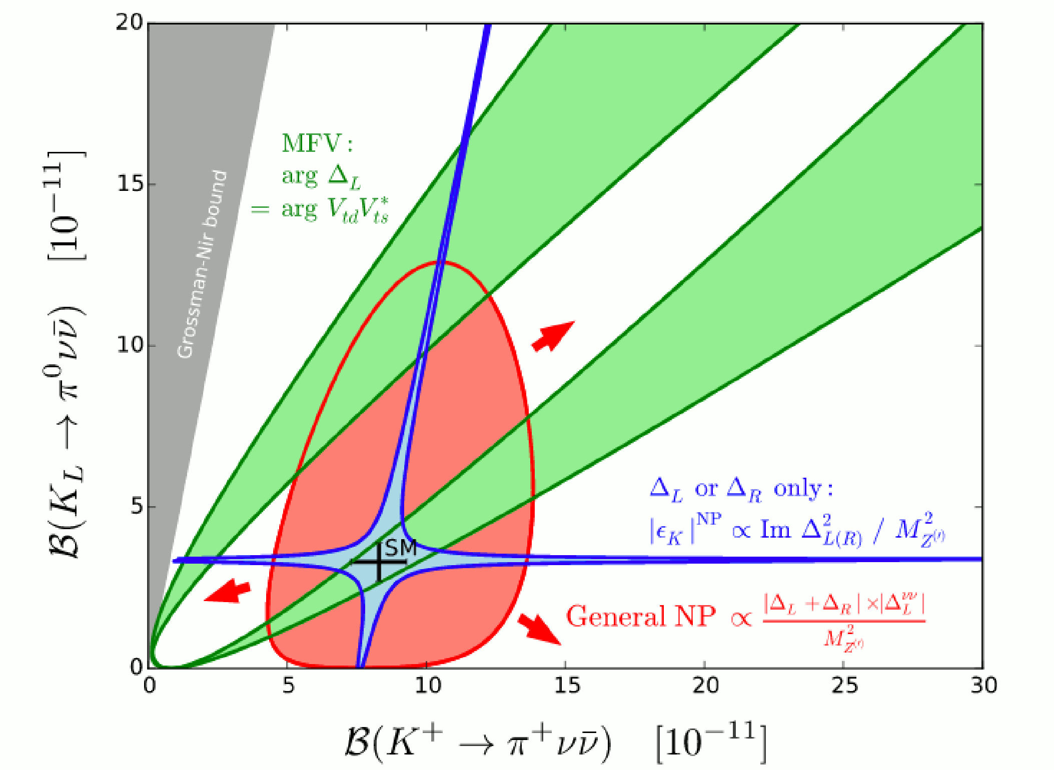
$$BR_{SM}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(0.839 \pm 0.030\right) \cdot 10^{-10} \cdot \left(\frac{|V_{cb}|}{40.7 \cdot 10^{-3}}\right)^{2.8} \cdot \left(\frac{\gamma}{73.2°}\right)^{0.74}$$

Taking $|V_{cb}|_{avg} = (40.7 \pm 1.4) \cdot 10^{-3}$, $|V_{ub}|_{avg} = (3.88 \pm 0.29) \cdot 10^{-3}$ and $\gamma = (73.2^{+6.3}_{-7.0})°$

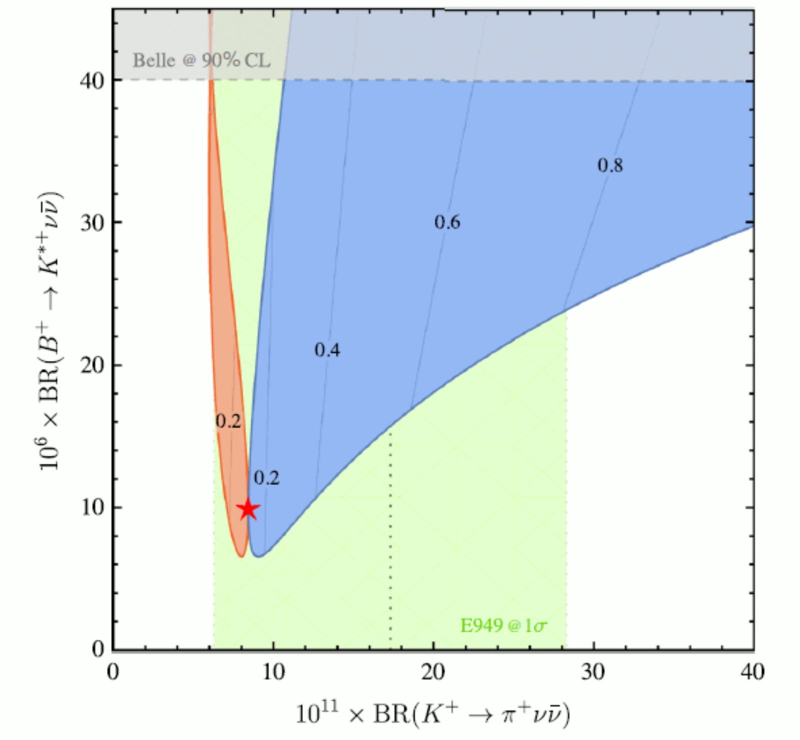
$$BR_{SM}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(0.84 \pm 0.10\right) \cdot 10^{-10}$$

Beyond the SM

[Buras et al., JHEP11 (2015) 166]



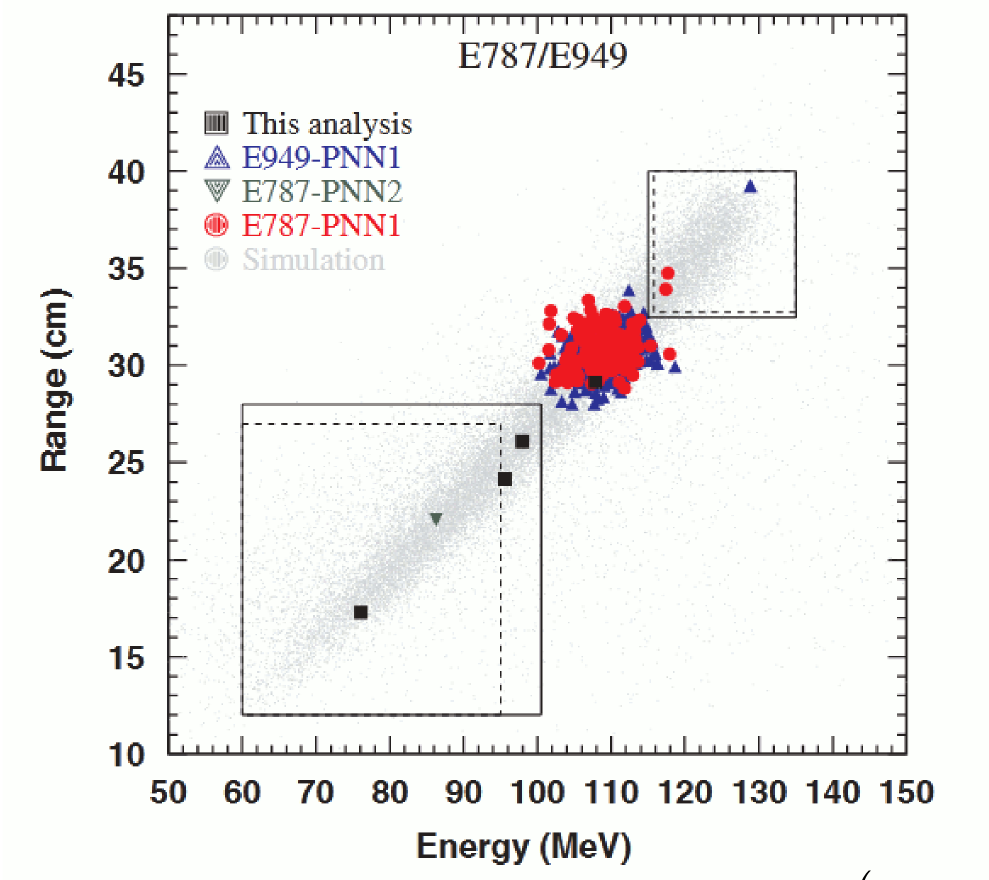
[Isidori et al., Eur.Phys.J. C (2017) 77: 618]



Most extensions of SM predict contributions to the branching ratio, e.g.:

MFV Simplified Z, Z'; LFU violation; Custodial Randall-Sundrum; MSSM; Littlest Higgs with T-parity; Leptoquarks

BNL E787/E949: $K^+ \to \pi^+ \nu\bar{\nu}$ with decays at rest



Artamov AV, et al. (E949 Collab.) *Phys. Rev. D 77, 052003 (2008)*

Adler S, et al. (E949 and E787) Phys. Rev. D 79, 092004 (2009)

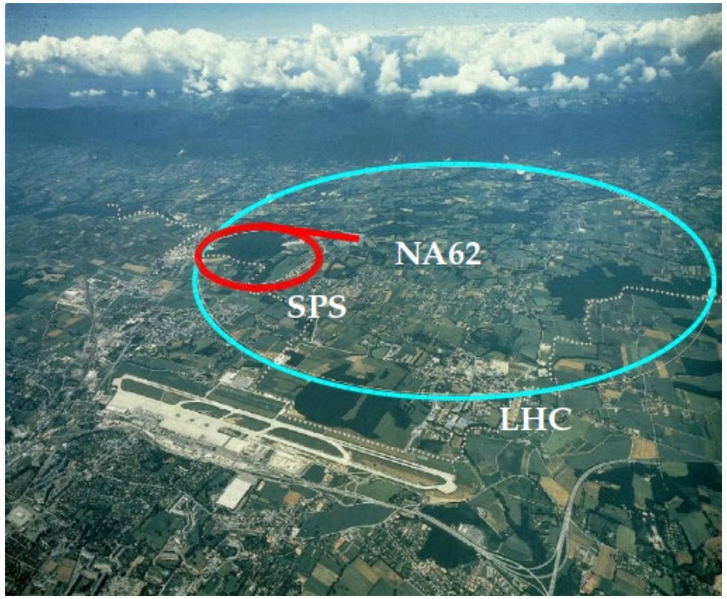
- *Kaon decay-at-rest technique*
- *Separated beam*
- *Full* $K^+ \to \pi^+ \to \mu^+ \to e^+$
- Small acceptance
- SES ≈ SM

$$BR_{BNL}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.73^{+1.15}_{-1.05}\right) \cdot 10^{-10}$$

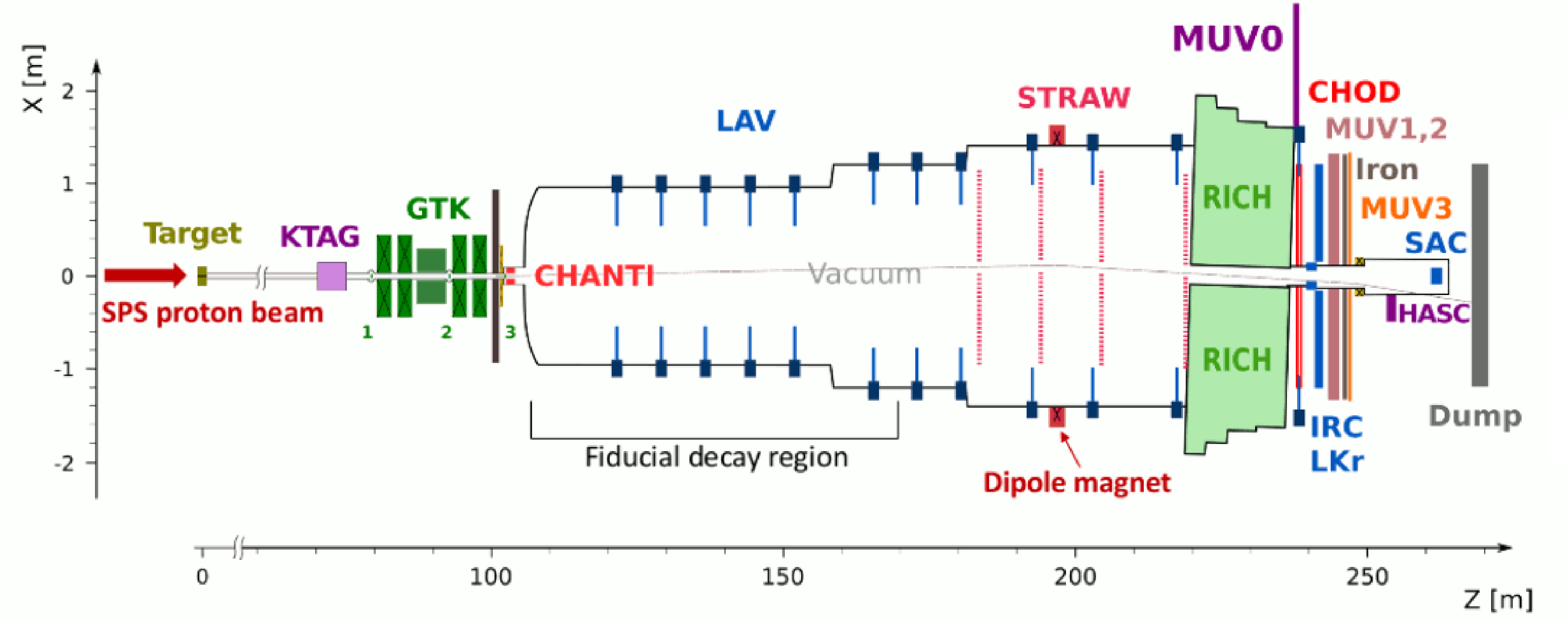
Decays in flight: NA62 @ CERN

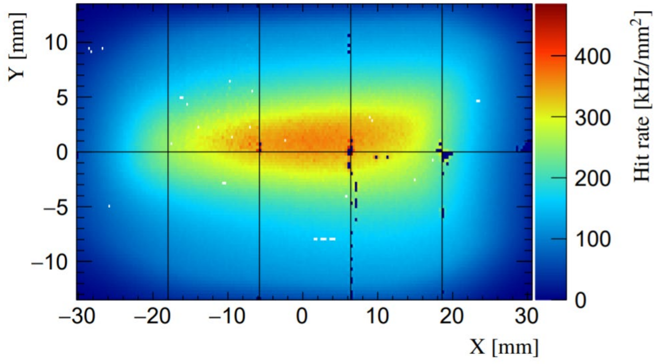
NA62 is installed in the CERN *North Area*

- 2016-2018: physics runs
- 2016 data: $K^+ \to \pi^+ \nu \nu$ result published
- 2017 data: $K^+ \to \pi^+ \nu \nu$ result published
- 2018 data (this talk): $K^+ \to \pi^+ \nu \nu$ result submitted for publication
- 2021-2024: physics runs



NA62 beam and detector *[2017 JINST 12 P05025]*



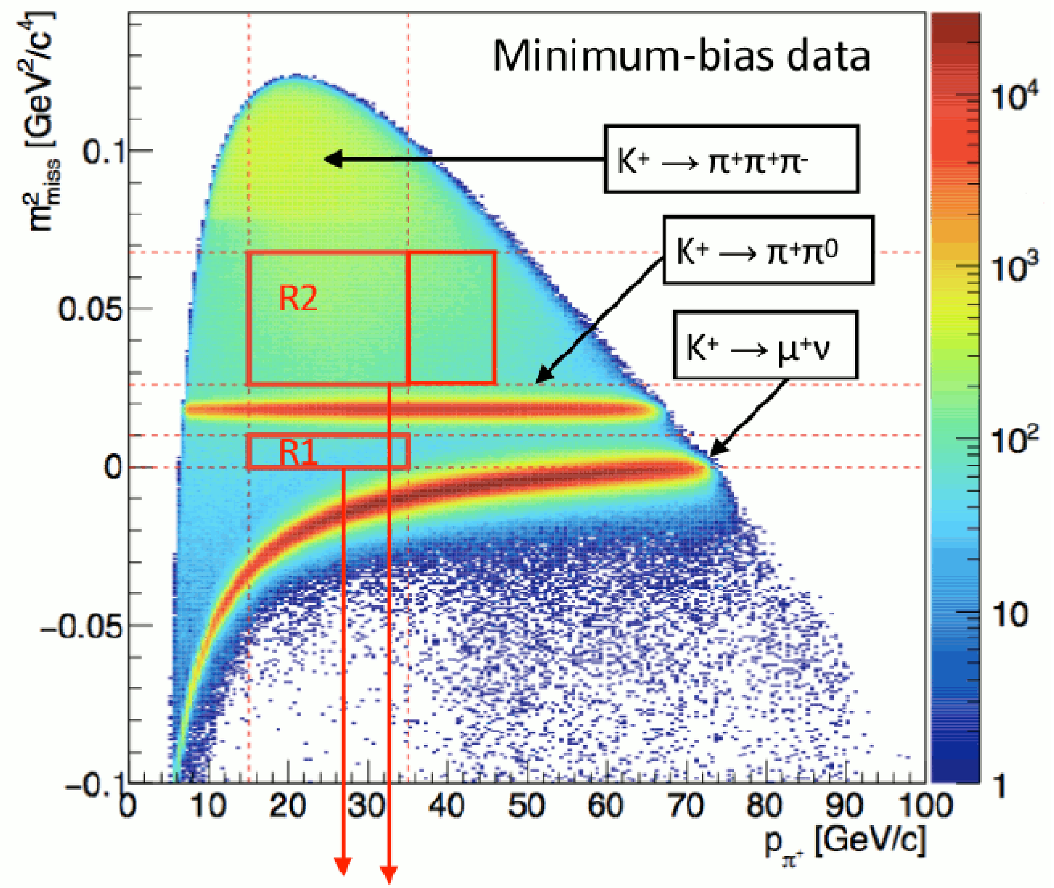


Illumination at GTK1

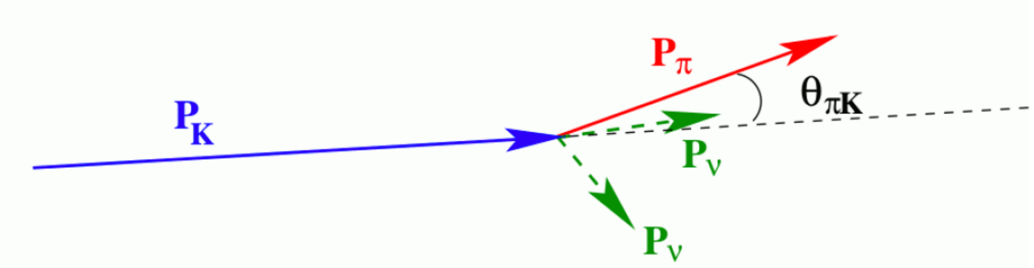
- SPS beam: 400 GeV/c proton on beryllium target
- Secondary hadron 75 GeV/c beam
- 70% pions, 24% protons, 6% kaons
- 60 m long fiducial region, ~ 5 MHz K^+ decay rate, vacuum ~ $O(10^{-6})$ mbar

NA62: Decay in flight

$$m^2_{miss} = (p_K - p_\pi)^2$$



Kinematic cuts to define signal regions R1 and R2



K^+ main (background) decays

Decay channel	Branching ratio
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	$(63.56 \pm 0.11) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^0$ ($K_{2\pi}$)	$(20.67 \pm 0.08) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$)	$(5.583 \pm 0.024) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4})	$(4.247 \pm 0.024) \cdot 10^{-5}$

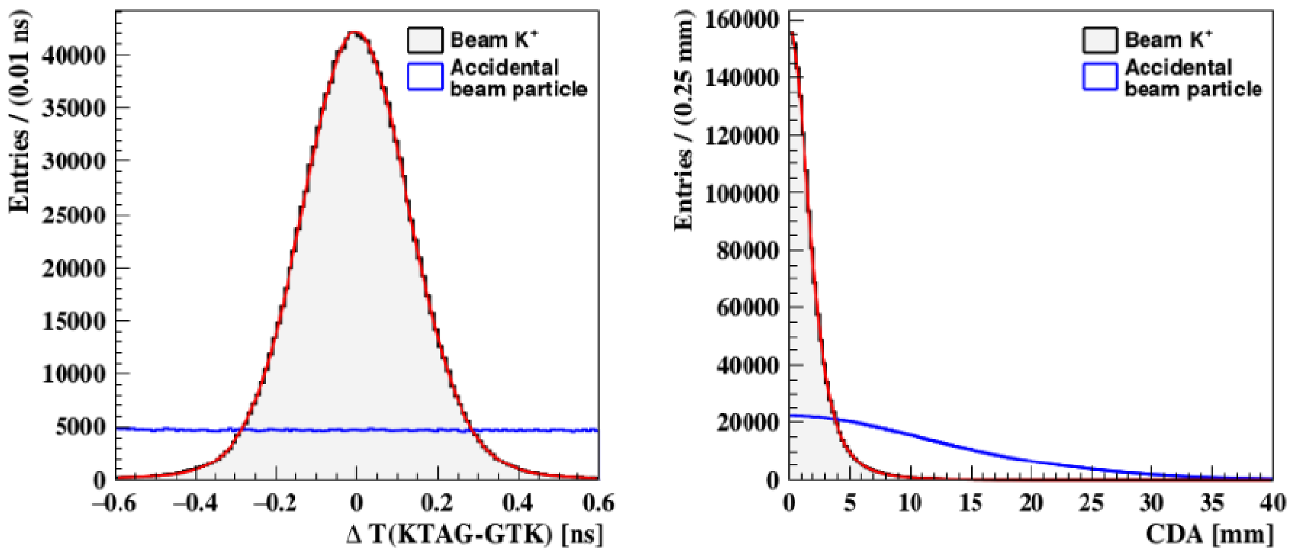
NA62: $K^+ \to \pi^+ \nu \bar{\nu}$ selection

Time – space association

Selection steps

- π^+ and K^+ tracks reconstruction
- K^+ - π^+ time matching: O(100 ps)
- decay vertex reconstruction
- π^+ identification (μ^+ rejection: > 10^7)
- photon rejection: > 10^7
- multi-track rejection
- kinematics rejection: O(10^4)

data - $K^+ \to \pi^+\pi^+\pi^-$ control sample

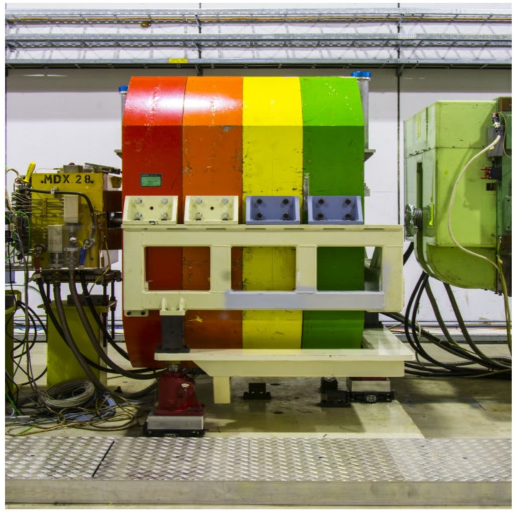


- KTAG: differential Cherenkov counter
- GTK: Gigatracker
- CDA: Closest Distance Approach

NA62: Upstream decays

OLD COL

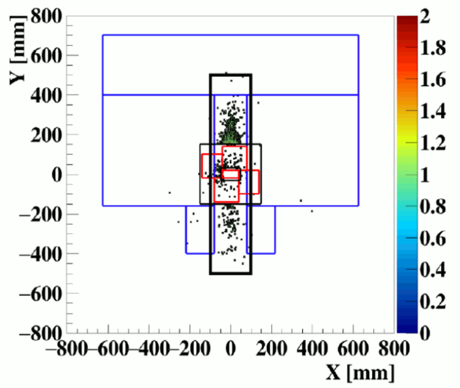
NEW COL (from June 2018)



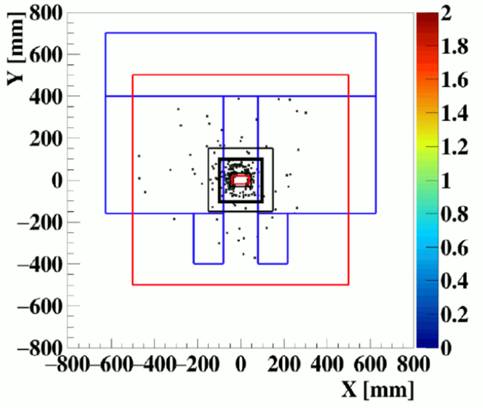
Track extrapolation at collimator in enriched sample of upstream events

Red boxes: collimator coverage

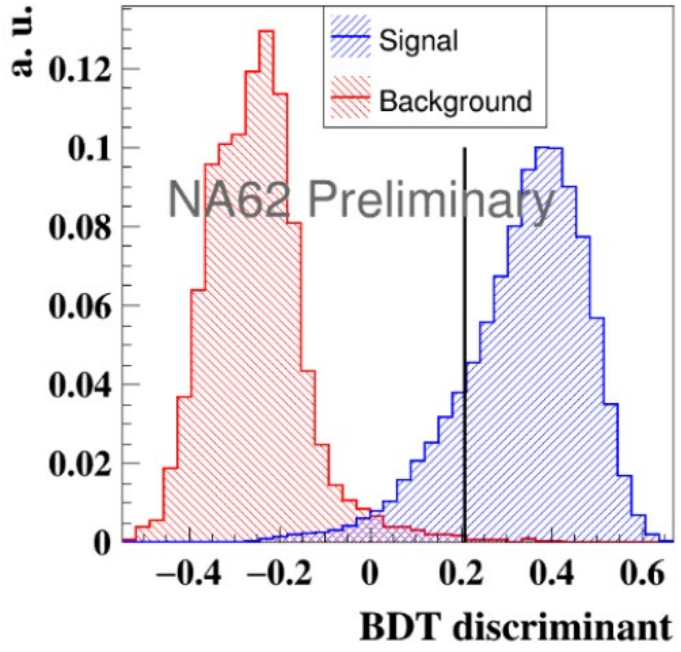
OLD COL



NEW COL



Both samples normalized to 1



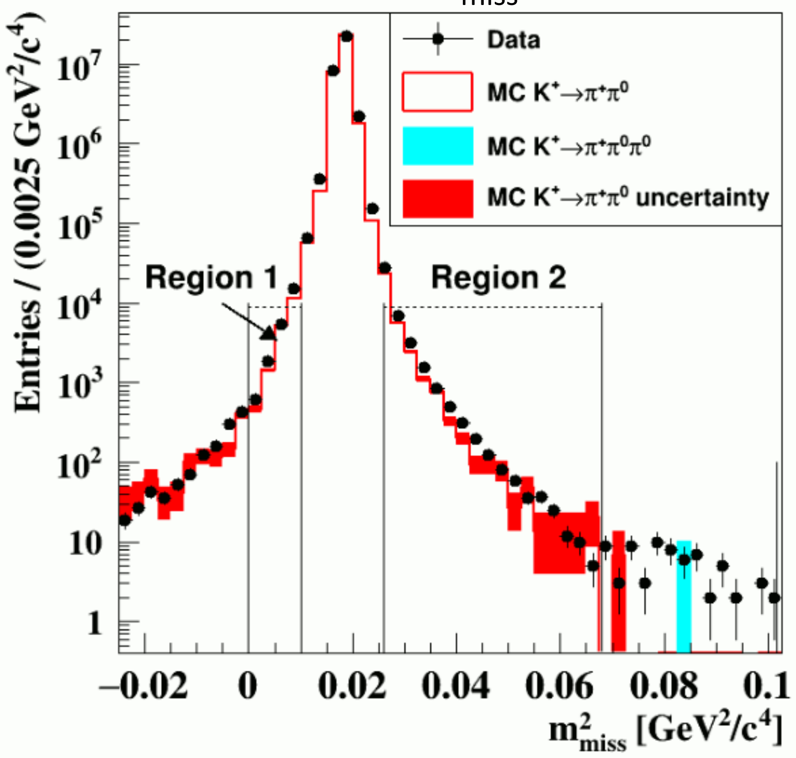
$\epsilon(sig) \sim 83\%$ @ $\epsilon(bkg) \sim 0.5\%$

BDT (NEW COL) based on:

- X,Y at Collimator
- Vertex
- Track slope

NA62: Background from standard K^+ decays

Control $K^+\to\pi^+\pi^0$ data used to study the tails of the m^2_{miss} distribution



events in $\pi^+\pi^0$ region after the $\pi\nu\nu$ selection

$$N^{exp}_{\pi\pi}(\text{region}) = N(\pi^+\pi^0)\cdot f^{kin}(\text{region})$$

expected $K^+\to\pi^+\pi^0$ events in signal region after the $\pi\nu\nu$ selection

fraction of $\pi^+\pi^0$ events in signal region measured in minimum bias sample

The pure sample to determine f^{kin} (region) is selected requiring $(P_K - P_0)^2$ to be consistent with $m^2_{\pi+}$, and P_0 is reconstructed using only LKr information

- Similar data driven methods for $K^+\to\pi^+\pi^+\pi^-$ and $K^+\to\mu^+\nu$
- Monte Carlo simulations for the rarer $K^+\to\pi^+\pi^- e^+\nu$ and $K^+\to\pi^+\gamma\gamma$

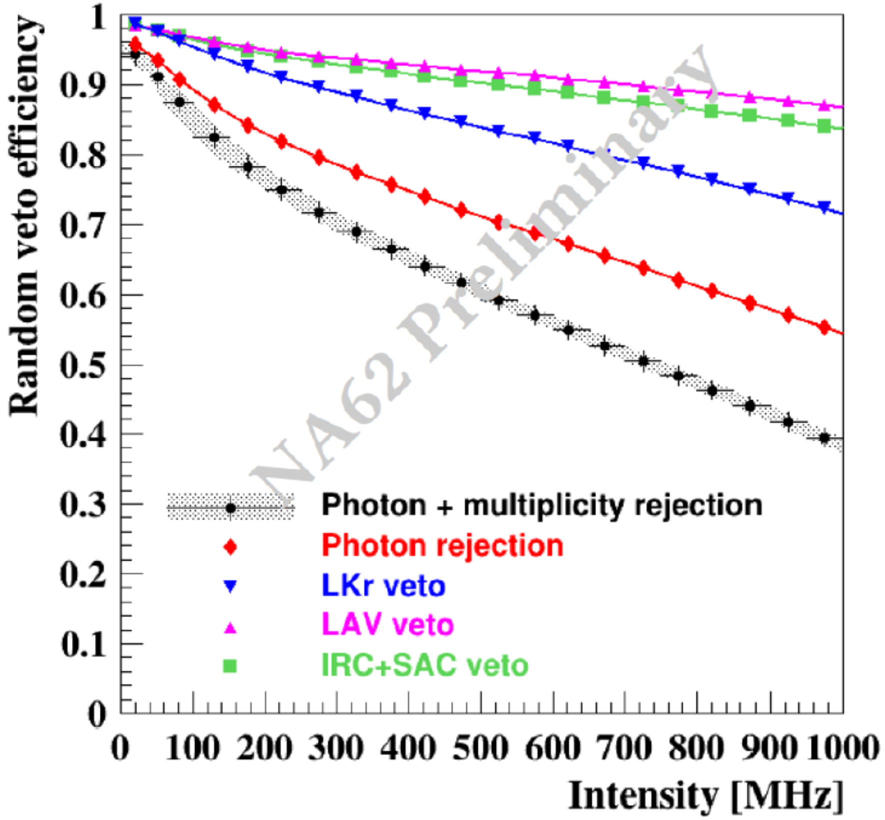
NA62 2018: Single Event Sensitivity

$$SES = \frac{1}{N_K \cdot \sum_j \left(A^j_{\pi\nu\nu} \cdot \varepsilon^j_{trig} \cdot \varepsilon^j_{RV} \right)} = (1.11 \pm 0.07) \cdot 10^{-11}$$

- N_K : effective number of K^+ decays

$$N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR_{\pi\pi}}$$

- $N_{\pi\pi}$: number of $K^+ \rightarrow \pi^+\pi^0$ decays from downscaled trigger
- D : down-scaling factor
- $A_{\pi\nu\nu}$, $A_{\pi\pi}$: signal, normalization selection acceptance (from MC)
- $BR_{\pi\pi}$: normalization decay branching ratio
- ε_{trig} : trigger efficiency
- ε_{RV} : random trigger efficiency
- j : bins of π^+ momentum

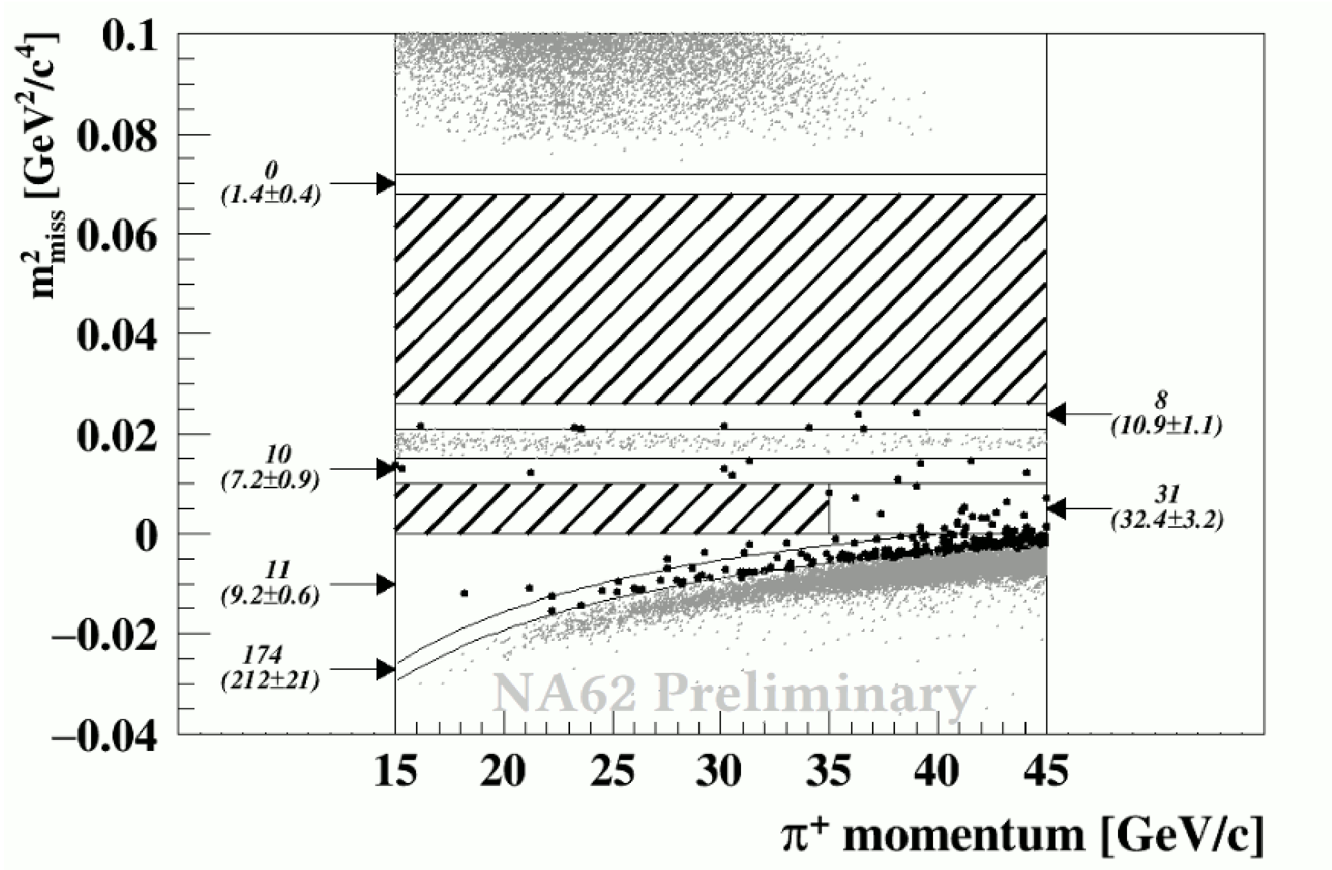


NA62 2018 Data: Summary of backgrounds

Process	**Expected events in $\pi\nu\nu$ signal regions**
$K^+ \rightarrow \pi^+\nu\nu$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{exp}$
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	0.75 ± 0.04
$K^+ \rightarrow \mu^+\nu(\gamma)$	0.49 ± 0.05
$K^+ \rightarrow \pi^+\pi^- e^+\nu$	0.50 ± 0.11
$K^+ \rightarrow \pi^+\pi^+\pi^-$	0.24 ± 0.08
$K^+ \rightarrow \pi^+\gamma\gamma$	< 0.01
$K^+ \rightarrow l^+\pi^0\nu_l$	< 0.001
Upstream background	$3.30^{+0.98}_{-0.73}$
Total background	$5.28^{+0.99}_{-0.74}$

NA62 2018 Data: Control regions

Observed (expected) events in control regions. Signal regions blinded.



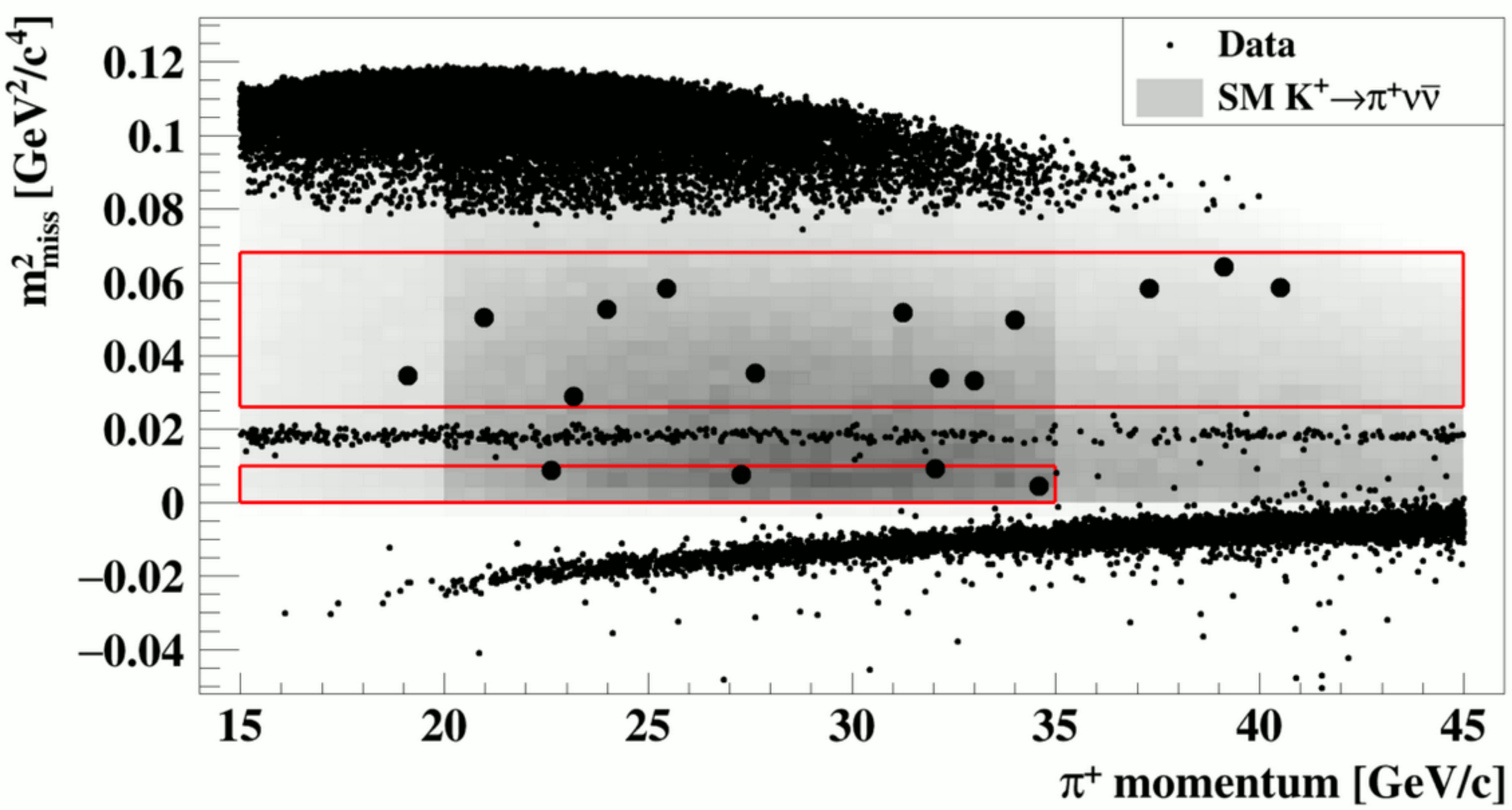
NA62 2018 Data: Signal efficiency

Sizeable improvements in 2018 data analysis (hardware and software)

	2017	2018-OLDCOL	2018-NEWCOL
N_K	$(1.5 \pm 0.2) \cdot 10^{12}$	$(0.8 \pm 0.1) \cdot 10^{12}$	$(1.9 \pm 0.2) \cdot 10^{12}$
$A_{\pi\nu\nu}$	$(3.0 \pm 0.3)\%$	$(4.0 \pm 0.4)\%$	$(6.4 \pm 0.6)\%$
ε_{RV}	0.64 ± 0.01	0.66 ± 0.01	0.66 ± 0.01
ε_{trig}	0.87 ± 0.03	0.88 ± 0.04	0.88 ± 0.04
$N_{\pi\nu\nu}^{exp}(SM)$	2.16 ± 0.29	1.56 ± 0.21	6.02 ± 0.82
B/S	~ 0.7	~ 0.7	~ 0.7

Increase of signal efficiency with the same B/S ratio

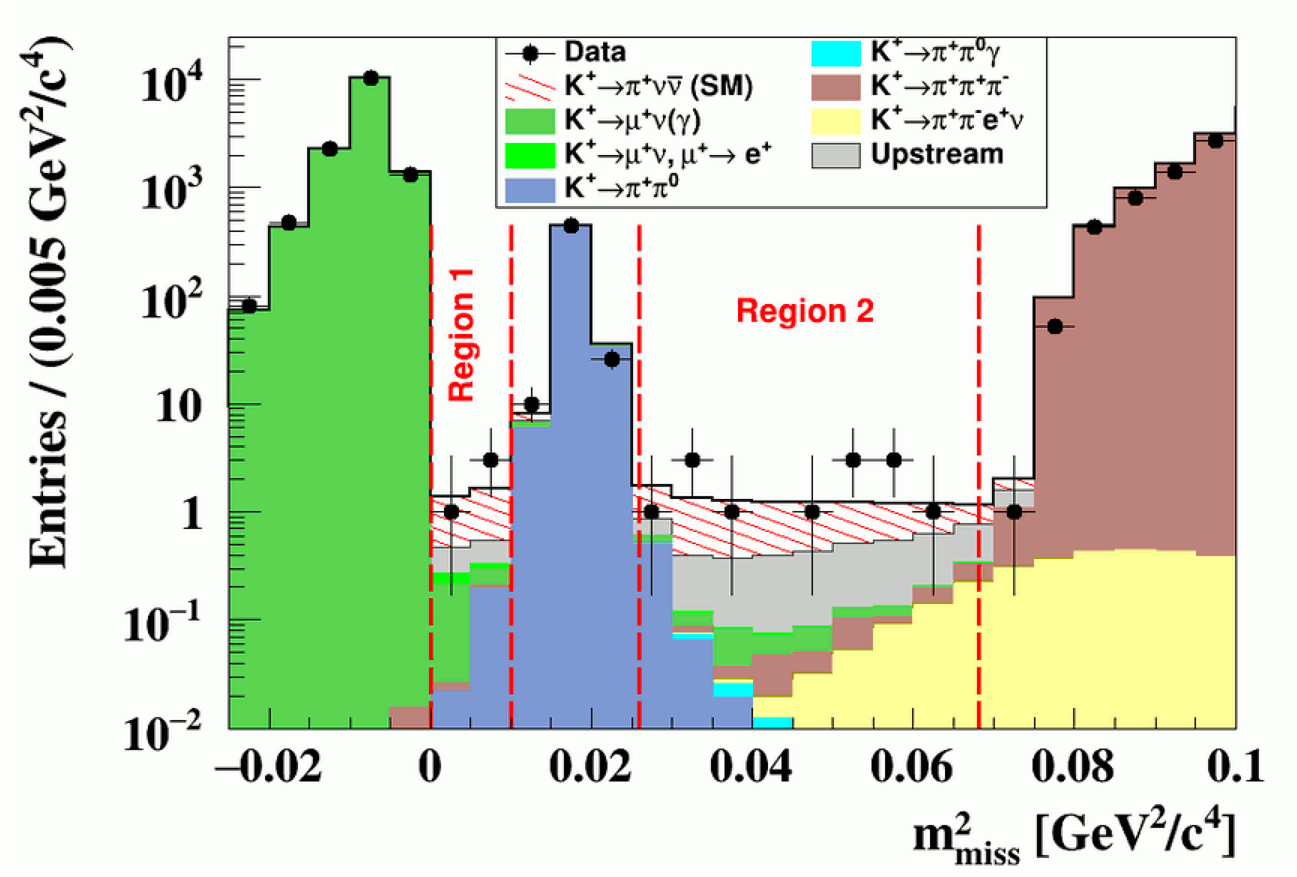
NA62 2018 Data: Box opened (ICHEP 2020)



Expected SM signal events: $7.58 \pm 0.40_{syst} \pm 0.75_{exp}$, expected background events: $5.28^{+0.99}_{-0.74}$

17 candidates observed

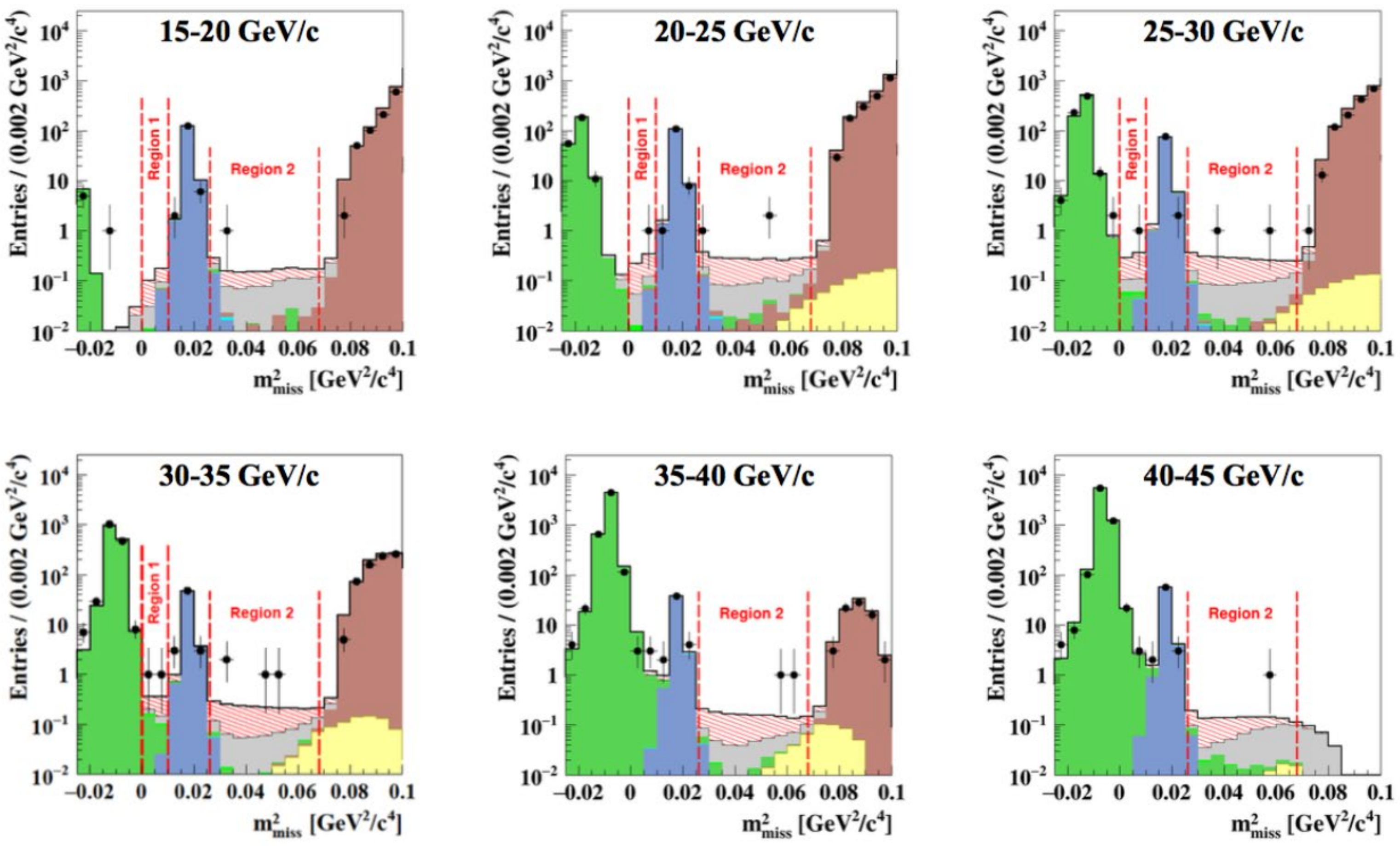
NA62 2018 Data: Box opened



NEW COL Data / MC comparison

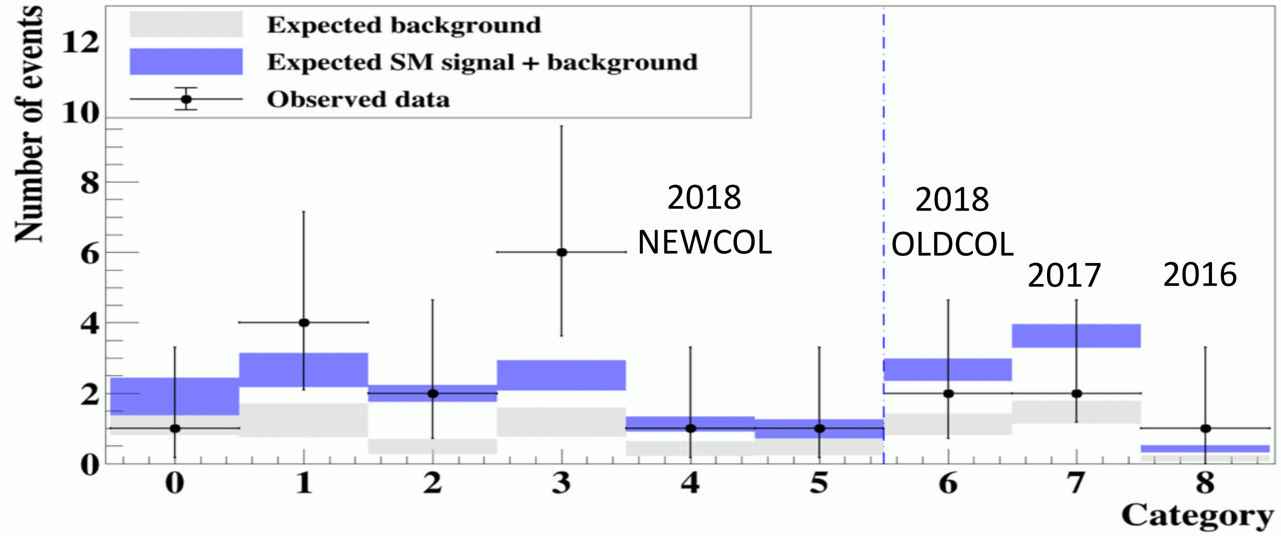
NA62 2018 Data: Momentum bins

π^+ momentum range (15-45 GeV/c) split in six bins (5 GeV/c size)



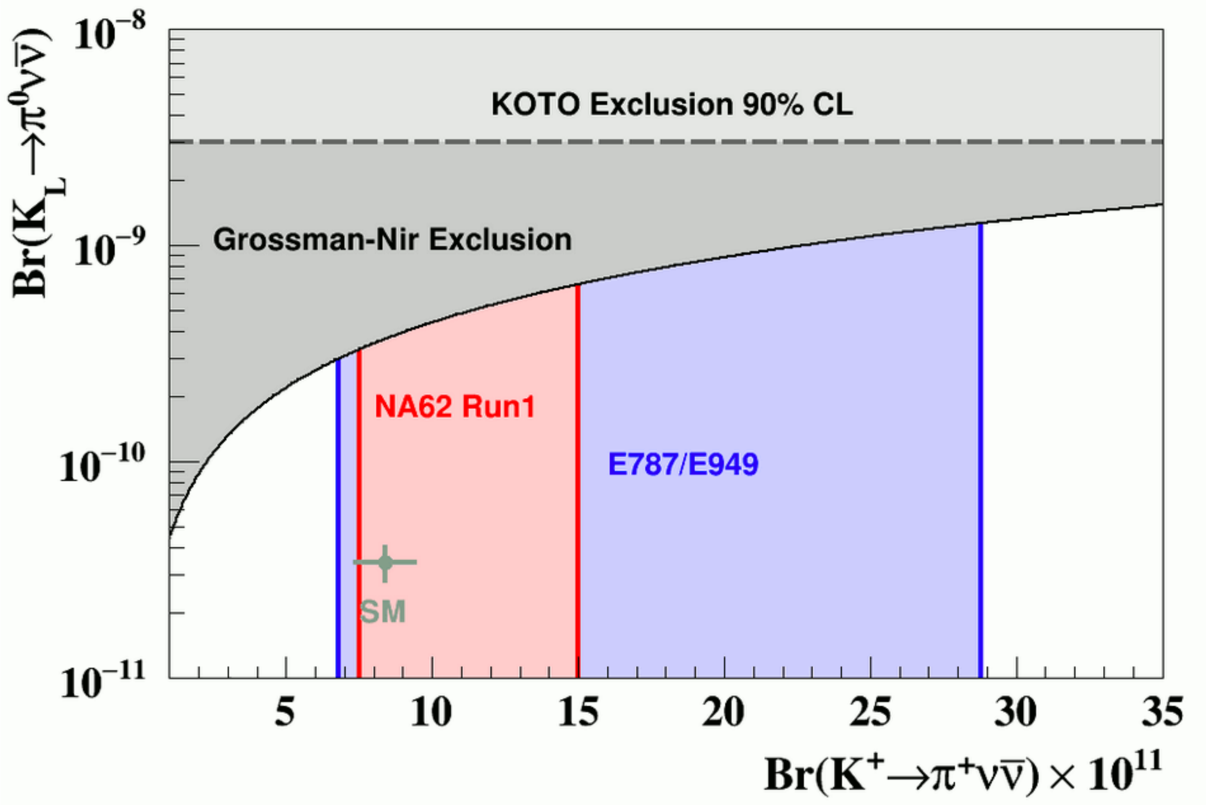
NA62: Combined results

	2016 data	2017 data	2018 data
SES	$(3.15 \pm 0.24)\cdot 10^{-10}$	$(0.39 \pm 0.02)\cdot 10^{-10}$	$(0.111 \pm 0.007)\cdot 10^{-10}$
Expected SM signal	0.27 ± 0.04	2.16 ± 0.29	7.58 ± 0.85
Expected background	0.15 ± 0.09	1.50 ± 0.31	$5.28^{+0.99}_{-0.74}$
	1	2	17



$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(11.0^{+4.0}_{-3.5}(stat) \pm 0.3(syst)\right) \cdot 10^{-11}$(3.5 σ significance)

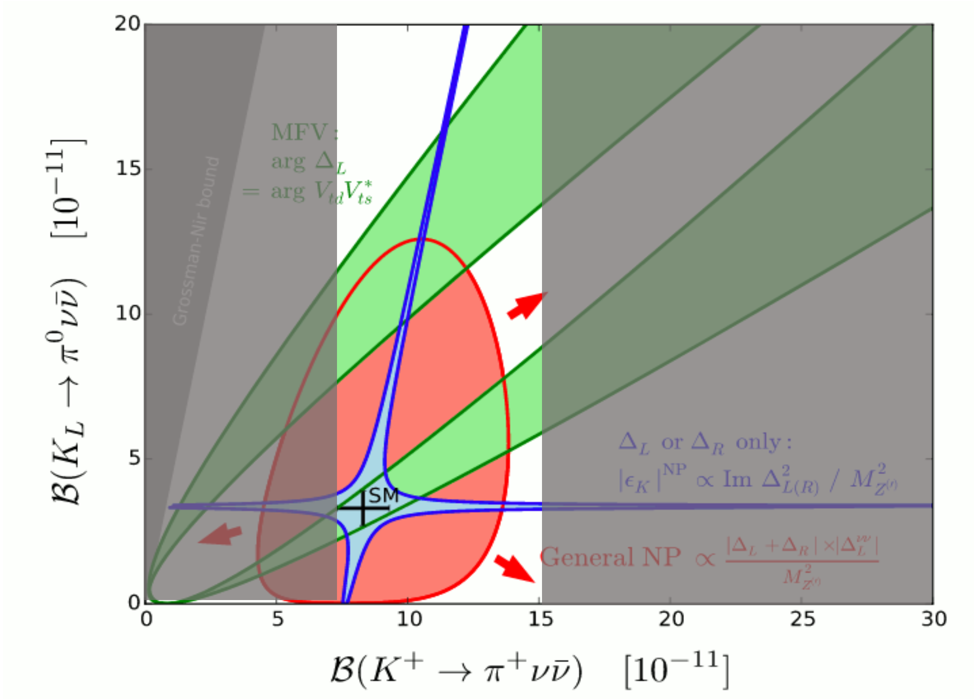
Grossman-Nir bound *[PBL 398 163 (1997)]*

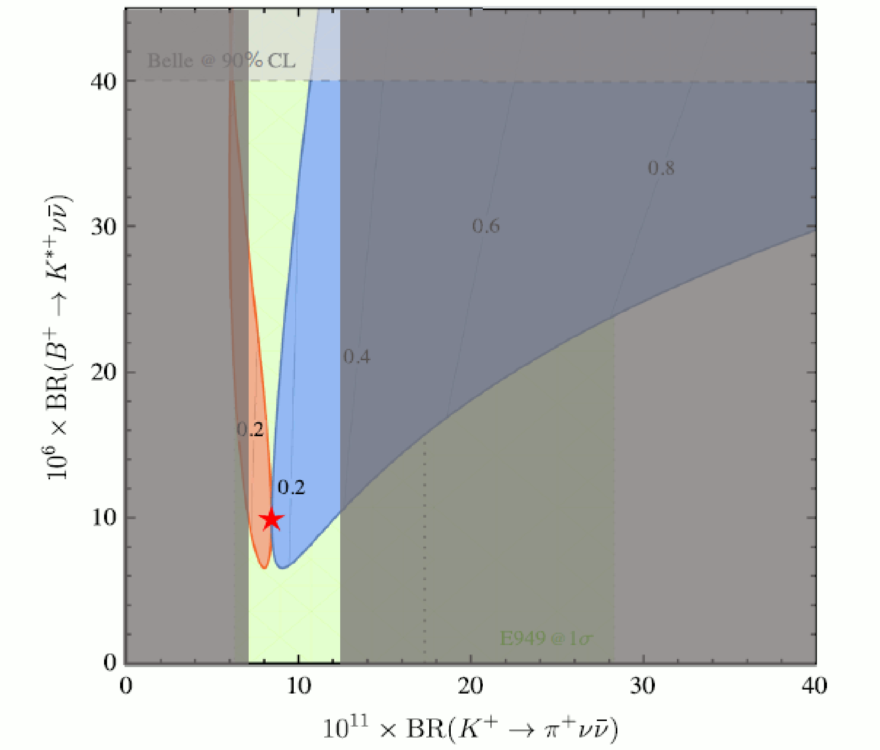


Model independent limit assumes that the $K_L \to \pi^0 \nu\bar{\nu}$ is entirely CP-violating:

BR($K_L \to \pi^0 \nu\bar{\nu}$) $<$ 4.4 BR($K^+ \to \pi^+ \nu\bar{\nu}$)

New BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement from NA62 and BSM scenarios





- Large BR($K^+ \to \pi^+ \nu\bar{\nu}$) values with respect to the SM expectation start to be excluded
- High precision measurement needed

Some NA62 byproducts

- Search for invisible bosons $K^+ \to \pi^+ X$
- Search for invisible π^0 decays
- Lepton Flavour Violation
- Lepton Number Violation
- Lepton Universality
- Search for Heavy Neutral Leptons

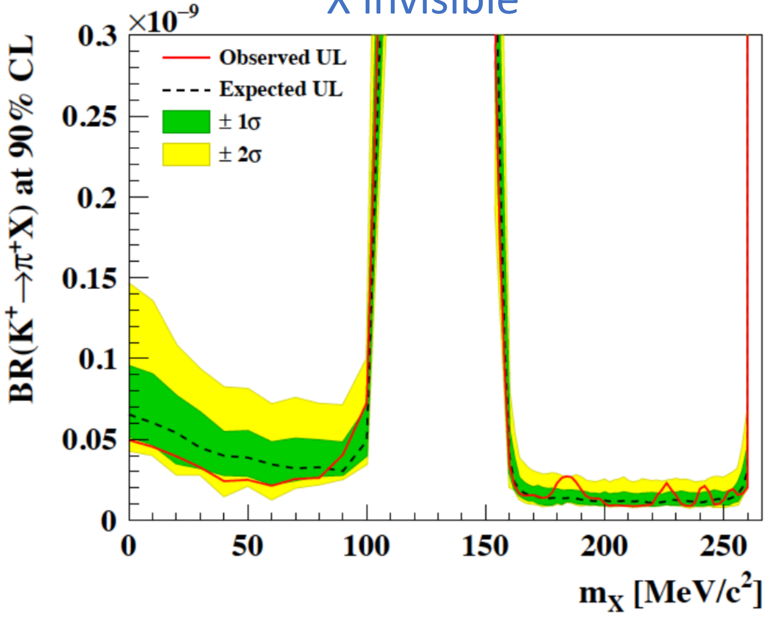
Search for $K^+ \to \pi^+ X$

Fleebly interacting particle X in $K^+ \to \pi^+ X$ foreseen in several models:

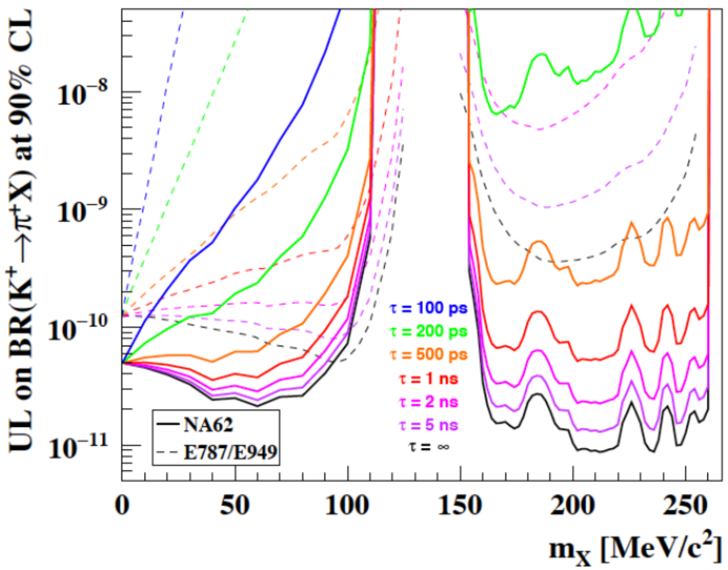
- Dark scalar mixing with the Higgs
- Pseudo scalar (APLs, QCD axion, Axiflavon) mediating interactions between SM and hidden sector fields

Selection, normalisation and bgk evaluation are identical to that used for the $K^+ \to \pi^+ \nu\bar{\nu}$ measurement
Bkg contributions are the same as for the $K^+ \to \pi^+ \nu\bar{\nu}$ analysis with the addition of the $K^+ \to \pi^+ \nu\bar{\nu}$ itself

X invisible



X decaying to visible SM particles



Comparison with BNL result

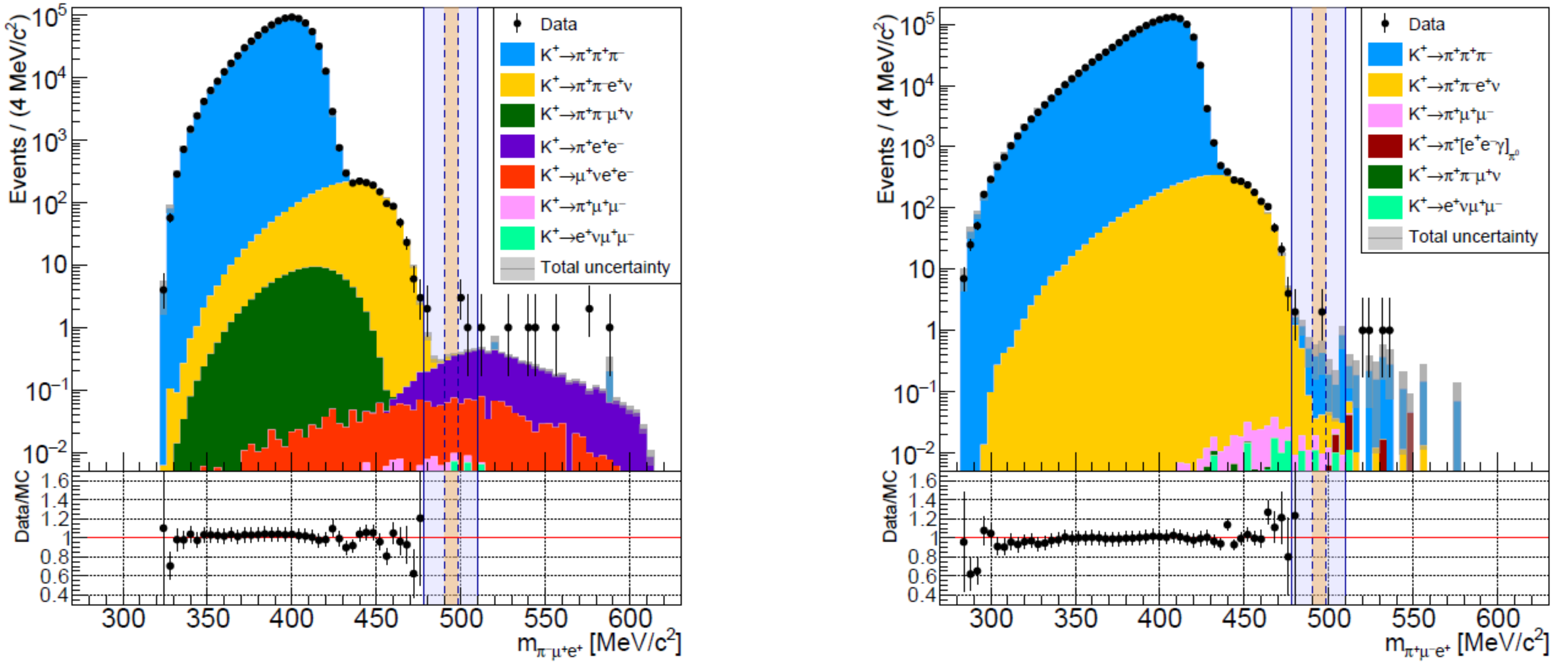
Full 2016-2018 data set
arXiv:2103.15389[hep-ex]
submitted to JHEP

Lepton Flavour and Lepton Number Violation

New physics models which explain experimental observations such as neutrino oscillations or the possible flavour anomalies in B-physics can introduce LN and LF violation

Search for the LN violating $K^+ \to \pi^- \mu^+ e^+$ decay and the LF violating $K^+ \to \pi^+ \mu^- e^+$ and $\pi^0 \to \mu^- e^+$ decays

$BR(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$ @ 90% $C.L.$ $BR(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$ @ 90% $C.L.$



N. Bkg expected: 1.07±0.20, Observed 0 **N. Bkg expected: 0.92±0.34, Observed 2**

2017-2018 data set
arXiv:2105.06759[hep-ex]
submitted to PRL

Improving on previous searches by one order of magnitude

Conclusions

- Strong kaon program continues to help building the SM
- Moving from exploration to precision in rare K decays
- Short term goals (2025):
  - BR($K^+ \to \pi^+ \nu\bar{\nu}$) to 10% (NA62)
  - BR($K_L \to \pi^0 \nu\bar{\nu}$) to SM SES (KOTO)
- Longer term goal:
  - BR($K^+ \to \pi^+ \nu\bar{\nu}$) to 5% ?
  - BR($K_L \to \pi^0 \nu\bar{\nu}$) to 20% ?
- Compelling byproducts: LFV, LNV, Exotics, HNL,…

Spares

Rare kaon decays: $K_L \to \pi^0 \nu \bar{\nu}$

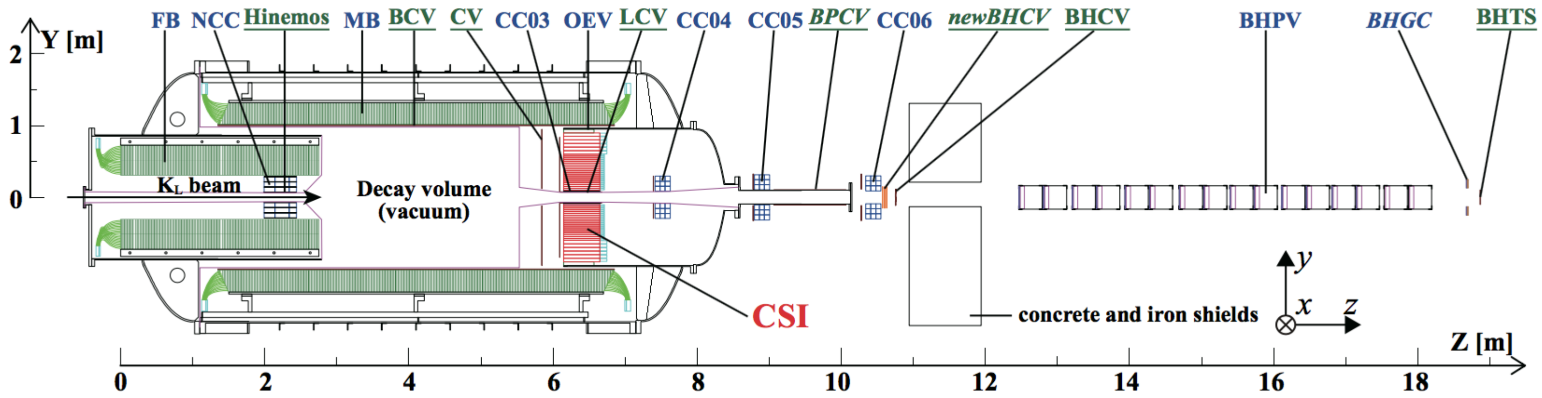
- The BR($K_L \to \pi^0 \nu\bar{\nu}$) depends only on the square of the imaginary part of the top loop which is CP-violating
- The charm contributions drop out because K_L^0 is modtly an odd linear combination of K^0 and $\overline{K^0}$
- This makes the theoretical prediction for the K_L^0 rate even cleaner than the K^+ one: $\sim$ 1.5%

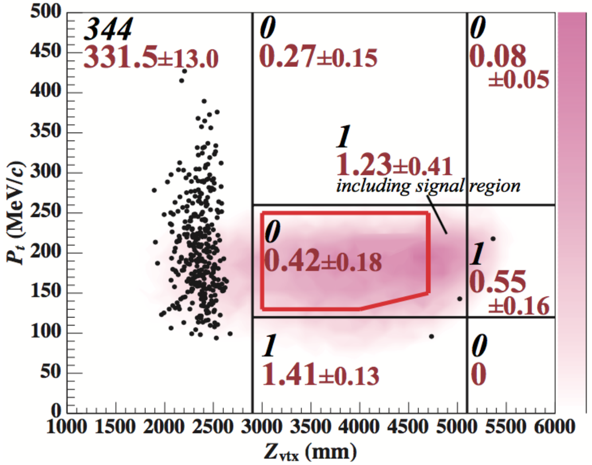
Inserting the numerical factors and making the dependence of the CKM explicit:

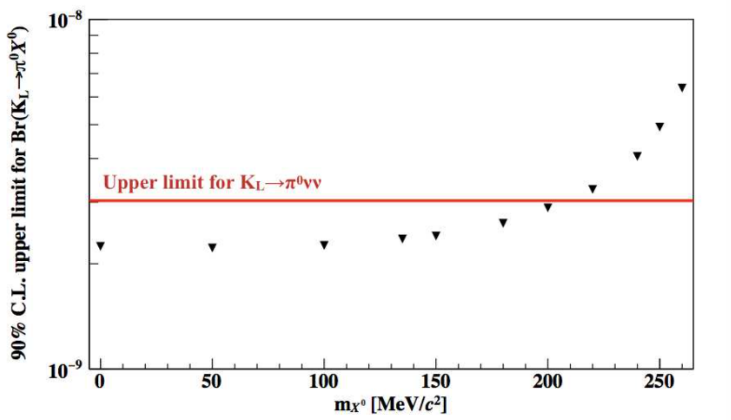
$$B(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^2 \left[\frac{sin\gamma}{\sin 73.2°}\right]^2$$

$$BR_{SM}(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

KOTO J-PARK: $K_L \to \pi^0 \nu \bar{\nu}$ PRL 122 (2019) 2 [arXiv1810.09655]







- Data 2015 (2.2×10^{19}, 30 GeV POT): $\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$ 90% CL
- Analysis of data 2016-2019 in progress

Preliminary results: 2016-2018 data

Several important detector upgrades and analysis improvements compared to 2015 data

KOTO preliminary (KAON, Sep 2019)

SES: 6.9 × 10^{-10} (0.05 SM evts)

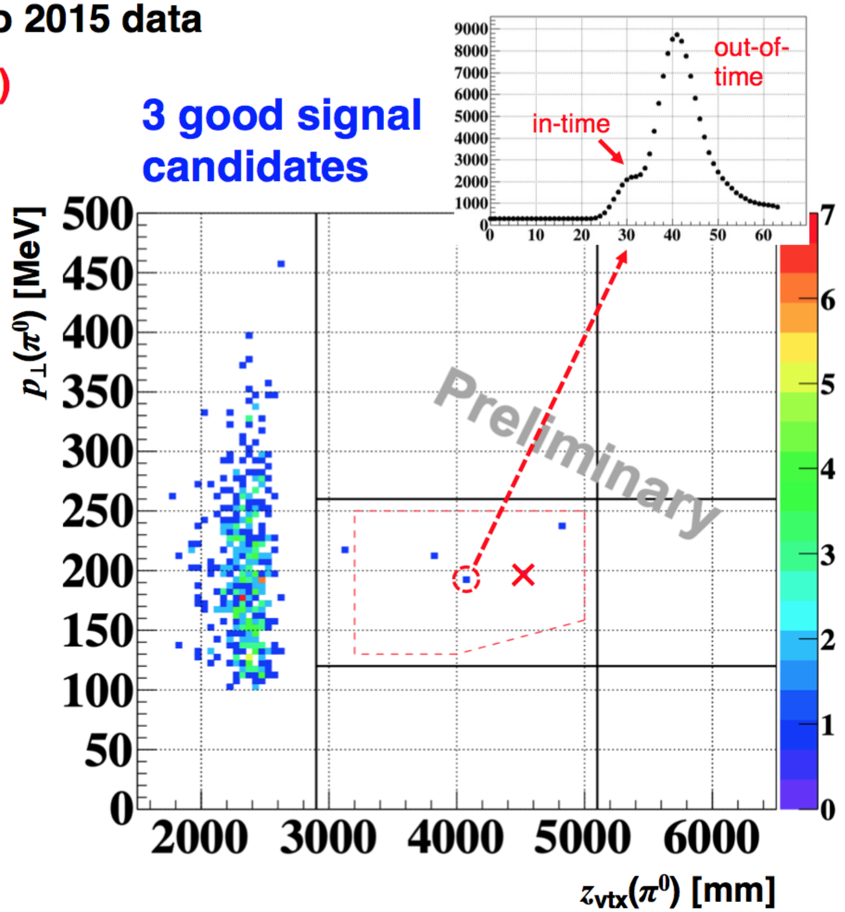
Expected bkg: 0.05 ± 0.02 evts

New background estimates

Preliminary (ICHEP 2020)

Source	**Expected (68%CL)**
$K_L \to \pi^0\pi^0$	< 0.05
$K_L \to \pi e \nu$ overlap pulse	< 0.05
$K_L \to ee\gamma$	< 0.05
$K_L \to \gamma\gamma$ core	< 0.06
$K_L \to \gamma\gamma$ halo	< 0.10
$K^+ \to \pi^0 e^+ \nu$	0.90 ± 0.27
$K^+ \to \pi^+\pi^0$	0.09 ± 0.09
$K^+ \to \pi^0 \mu^+ \nu$	< 0.12
π^0 from n in CV	< 0.05
Total	**1.05 ± 0.28**

3 good signal candidates

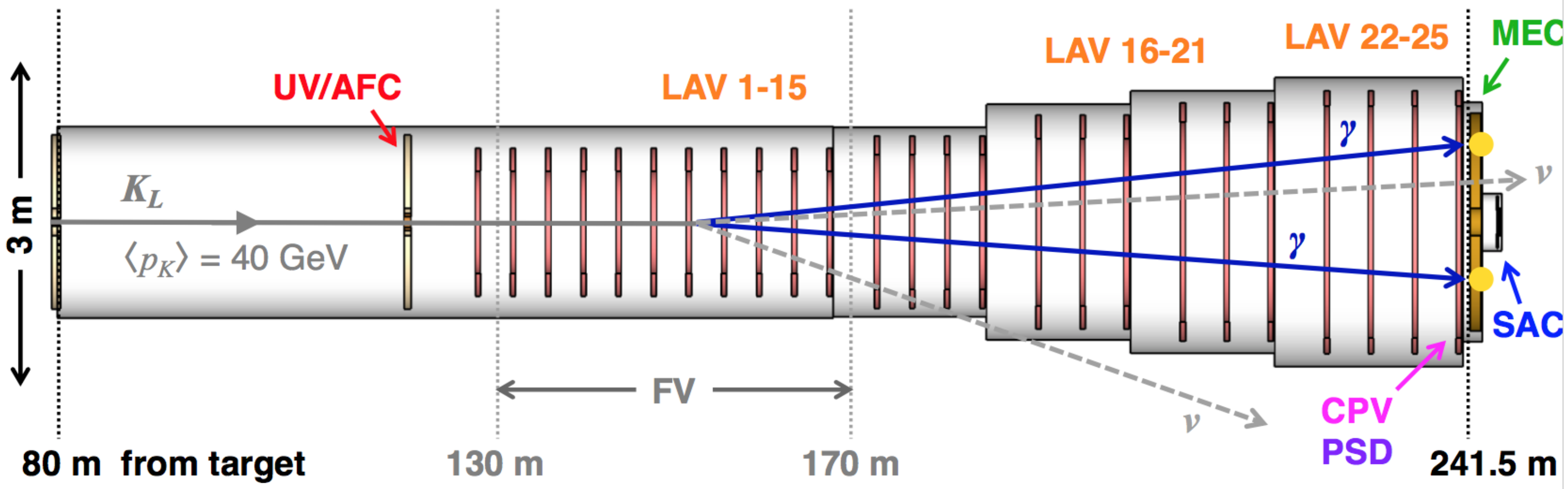


KOTO will reach SM SES by mid-decade: Step-2 required for BR mmt

Perspectives for high-intensity kaon physics at the SPS – M. Moulson (Frascati) – CERN Detector Seminar – 23 October 2020 32

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS? KLEVER

400-GeV SPS proton beam on Be target at z = **0 m**



KLEVER target sensitivity:
5 years starting Run 4

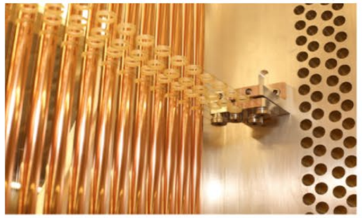
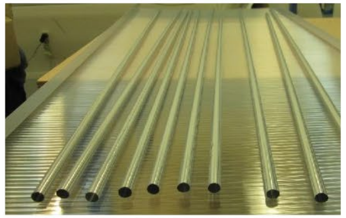
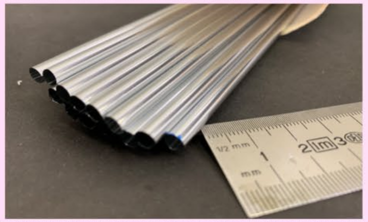
~60 SM $K_L \to \pi^0 \nu\nu$
S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

- High-energy experiment: Complementary to KOTO
- Photons from K_L decays boosted forward
  - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Roughly same vacuum tank layout and fiducial volume as NA62

Future of NA62: $BR(K^+ \to \pi^+\nu\bar{\nu})$ towards 5% ?

- Improved immunity upstream decays from 2021 onward
- Expect NA62 to reach a precision of ≈ 10% by 2025
- Experiment is currently limited by 65 ps time resolution of the beam tracker
- Developments for HL-LHC can lead to detectors with better timing (20 ps?)
- Not limited by beam intensity (target to be upgraded)
- Thinner straw tracker
- Reduce random veto

	NA62	COMET Phase-I	New Straw
Straw Wall Thickness	36 μm	20 μm	12 μm
Straw Diameter	9.8 mm	9.8 mm	4.8 mm
Metal Deposition	Cu+Au, 70nm	Al, 70 nm	Al, 70 nm
Photo			
Current Status	In Operation	Under Construction	Just Developed