BEAUTY 2023

3-7 July 2023, Clermont-Ferrand, France

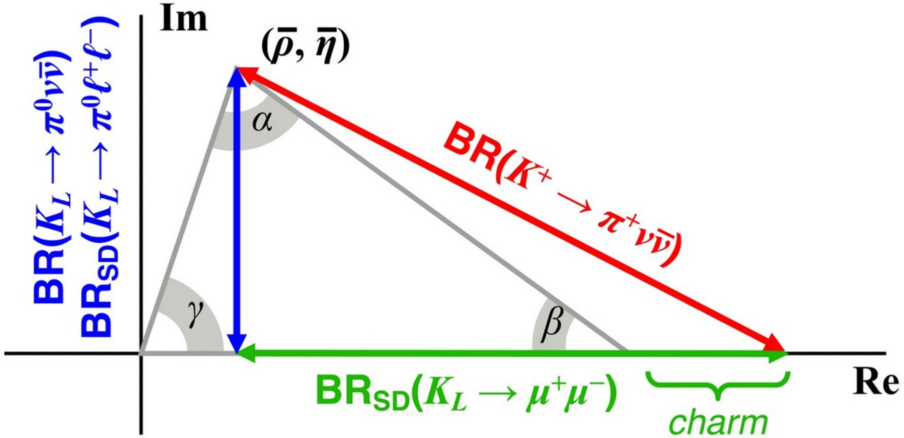
NA62 and KOTO: Status and Prospects

Angela Romano, University of Birmingham
on behalf of the NA62 collaboration

Rare Kaon Decays

Decay	Γ_{SD}/Γ	Theory Error*	SM BR x10^{11}	EXP BR x 10^{11}	EXPERIMENT	YEAR
$K_L \rightarrow \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300	KOTO	2019
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	10.6 ± 4.0	NA62	2021
$K_L \rightarrow \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	<28	KTeV	2004
$K_L \rightarrow \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	<38	KTeV	2000
$K_L \rightarrow \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000

(*) approximate error on LD-subtracted rate excluding parametric contributions

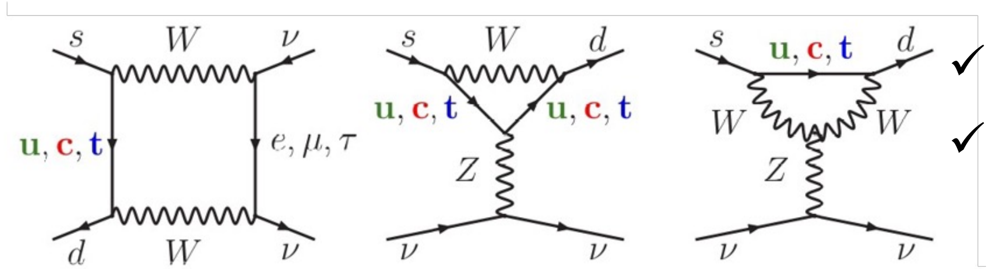


(see also arXiv:2203.09524)

- FCNC processes dominated by Z-penguin and box diagrams
- SM rates determined by V_{CKM}, with minimal non-parametric "theory" uncertainties
- Theory errors are being reduced [see talk from E. Stamou]
- The current focus is $K \rightarrow \pi\nu\bar{\nu}$: uniquely clean theoretically

$K \to \pi\nu\bar{\nu}$ in the Standard Model

Box & Penguin (one-loop) diagrams



- ✓ FCNC process forbidden at tree level
- ✓ Highly CKM suppressed (BR ~ $|V_{ts}^* V_{td}|^2$)
- ✓ Extraction of V_{td} with minimal (few %) non-parametric uncertainty

Theoretically very clean:

- ✓ dominant short-distance contribution
- ✓ hadronic matrix element extracted from precisely measured BR($K^+ \to \pi^0 e^+ \nu$)

SM Predictions, error CKM parametric [Buras et al., JHEP 1511 (2015) 033]:

BR($K^+ \to \pi^+\nu\bar{\nu}$) = $(8.4 \pm 1.0) \times 10^{-11}$	BR($K_L \to \pi^0\nu\bar{\nu}$) = $(3.4 \pm 0.6) \times 10^{-11}$

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

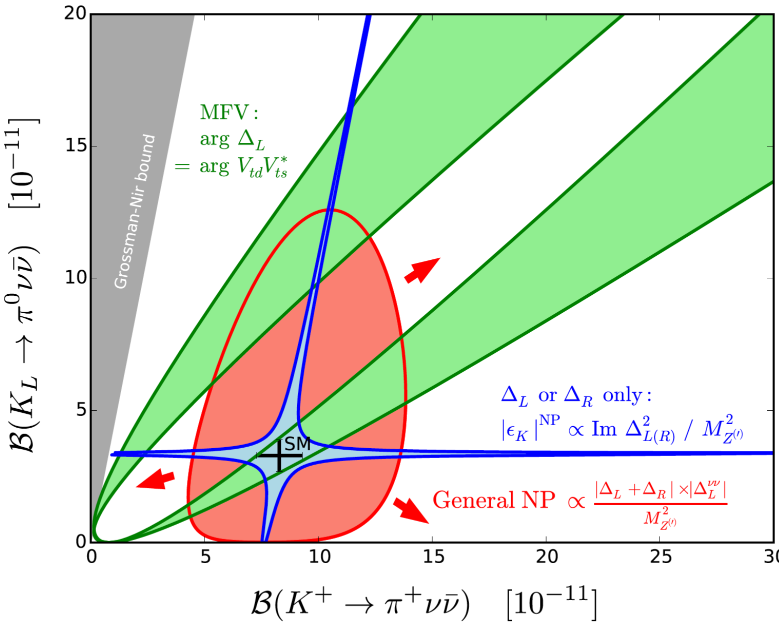
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{\sin(\gamma)}{\sin(73.2^\circ)}\right]^{2}$$

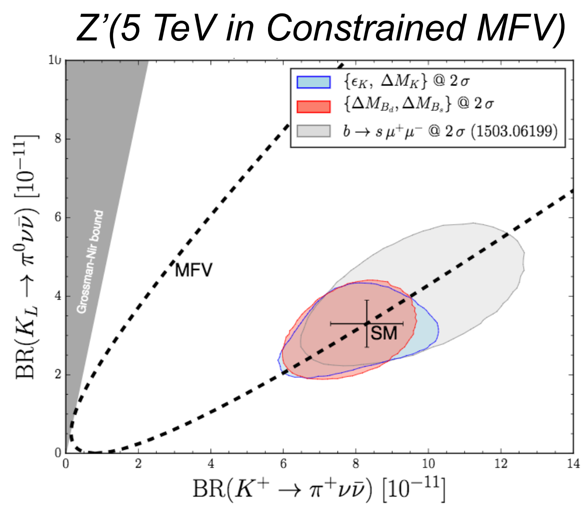
$K\to\pi\nu\bar{\nu}$ and New Physics

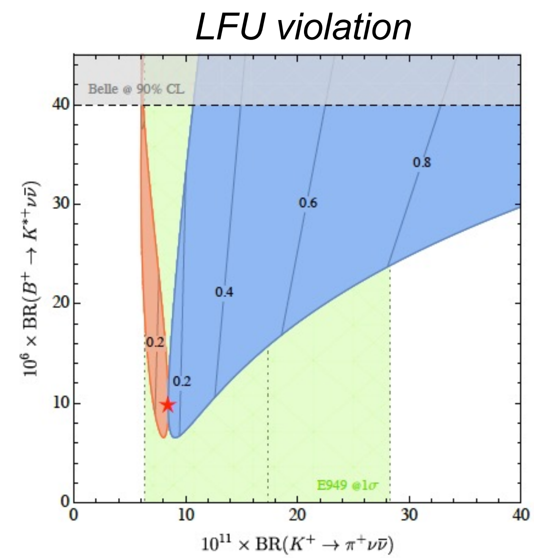
Indirect searches of NP with high precision studies of rare K decays

Measurement of charged ($K^+ \to \pi^+\nu\bar{\nu}$) and neutral ($K_L \to \pi^0\nu\bar{\nu}$) modes can **discriminate among different NP scenarios**

[Buras, Buttazzo, Knegjens, JHEP1511 (2015) 166]







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

Correlations significantly change for different classes of NP models

[EPJ C76 (2016) no.4 182]

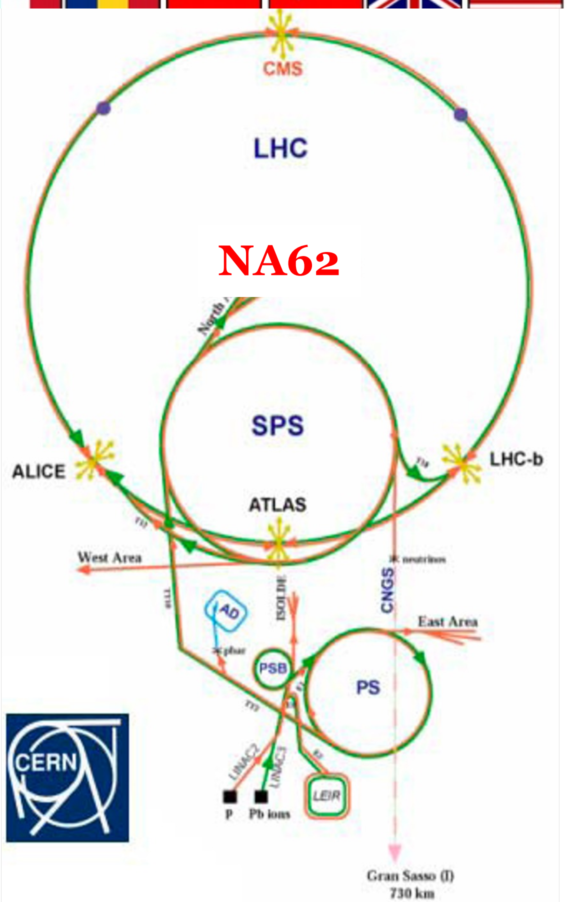
$K\to\pi\nu\bar{\nu}$ probes of unique sensitivity for NP models among B and K decays

(NP searches complementary/alternative to LHC)

The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS

~300 members from 31 institutions



NA62 Beam line & detectors

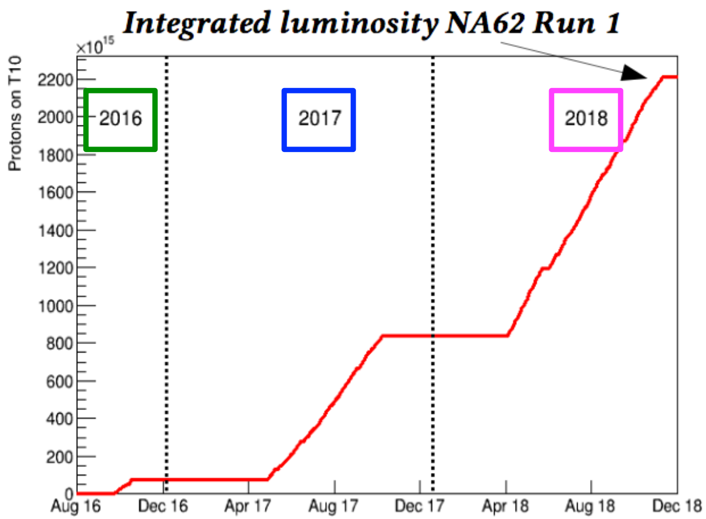
NA62 primary goal: Measure BR($K^+ \to \pi^+\nu\bar{\nu}$)

New: K^+ decay-in-flight technique

[PLB 791 (2019) 156, JHEP 11 (2020) 042, JHEP 06 (2021) 093]

NA62 Timeline & Datasets

2016 physics run: ~1.3 x 10^{12} ppp, 0.12 x 10^{12} K^+ decays
2017 physics run: ~1.9 x 10^{12} ppp, 1.5 x 10^{12} K^+ decays
2018 physics run: ~2.3 x 10^{12} ppp, 4 x 10^{12} K^+ decays
Run 1 (2016-2018): 2.2 x 10^{18} protons on target (T10) collected
Run 2 (2021 -) in progress: ~3 x 10^{12} ppp, approved till LS3



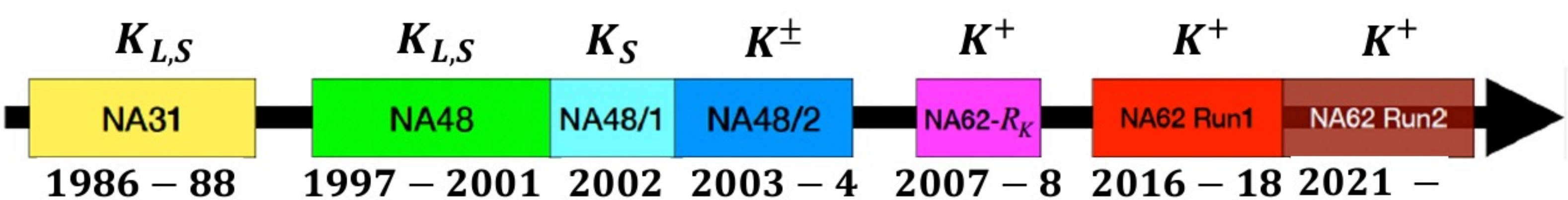
NA62 Timeline

Dec 2008 - Physics Approval

2009 - 2014: Detector R&D, Installation

2015 Commissioning
2016 - 2018: NA62 Run 1

2021 – LS3 NA62 Run 2



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Decay channel	Data set	
$K^+ \to \pi^+\mu^+\mu^-$	NA62 Run 1	JHEP 11 (2022) 11
$K^+ \to \pi^0 e^+\nu\gamma$	NA62 Run 1	arXiv:2304.12271
$K^+ \to \pi^+\gamma\gamma$	NA62 Run 1	Preliminary
$K^+ \to \pi^-\mu^+\mu^+$	NA62 Run 1	PLB 797 (2019) 134794
$K^+ \to \pi^-\mu^+e^+$	NA62 Run 1	PRL 127(2021) 131802
$K^+ \to \pi^+\mu^-e^+$	NA62 Run 1	PRL 127(2021) 131802
$\pi^0 \to \mu^-e^+$	NA62 Run 1	PRL 127(2021) 131802
$K^+ \to \pi^-e^+e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^-\pi^0e^+e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \mu^-\nu e^+e^+$	NA62 Run 1	PLB 838 (2023) 137679
Searches for hidden-sector mediator production in K^+ decays	NA62 Run 1	JHEP05(2019) 182 PLB 807(2020) 135599 PLB 816(2021) 136259 JHEP02(2021) 201 JHEP03(2021) 058
$A' \to \mu^+\mu^+$	NA62 2021 beam-dump	arXiv:2303.08666

NA62 Timeline

Dec 2008 - Physics Approval

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2015 Commissioning
2016 - 2018: NA62 Run 1

2021 – LS3 NA62 Run 2

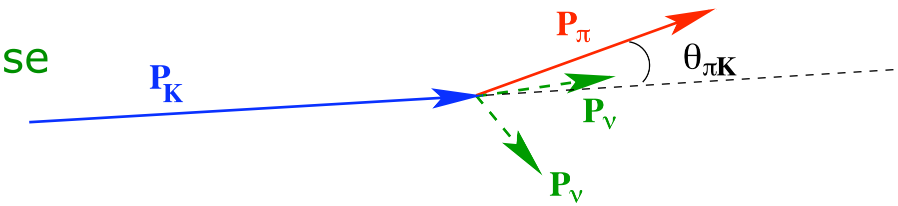
Broad physics programme beyond $K^+ \to \pi^+\nu\bar{\nu}$
Precision measurements
Rare and forbidden decays: LN and LF violation
Exotics searches: dark photon, heavy neutral leptons, axion-like particles

$K^+ \to \pi^+ \nu\bar{\nu}$ Signal and Backgrounds

$$m^2_{miss} \approx m^2_K\left(1-\frac{|p_\pi|}{|p_K|}\right) + m^2_\pi\left(1-\frac{|p_K|}{|p_\pi|}\right) - |p_K||p_\pi|\theta^2_{\pi K}$$

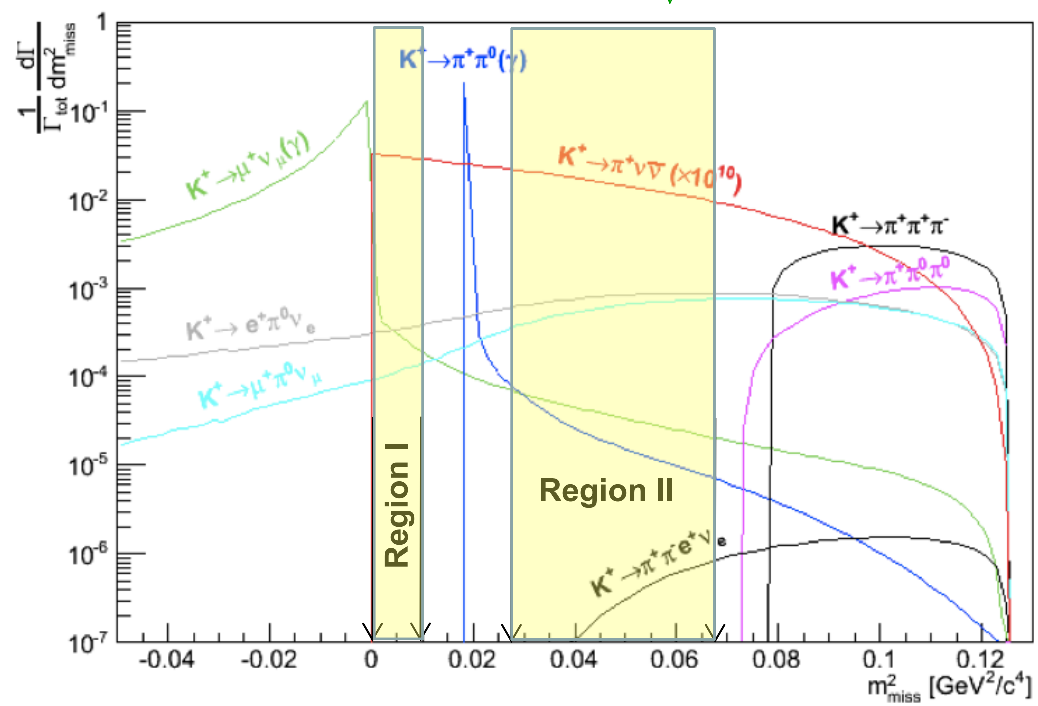
$K^+ \to \pi^+\nu\bar{\nu}$ signature:

Kaon track + Pion track + nothing else



Main kaon decay backgrounds

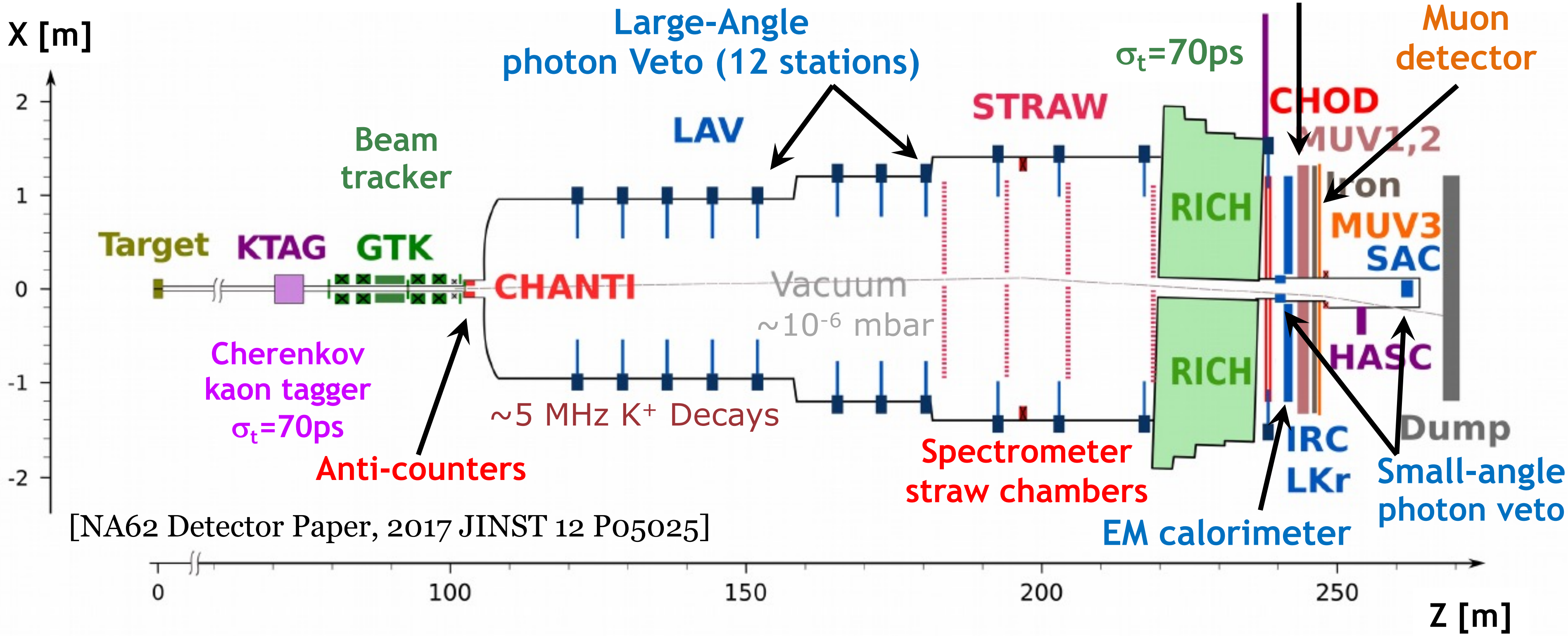
Process	Branching ratio
$K^+ \to \mu^+\nu_\mu(\gamma)$	63.5%
$K^+ \to \pi^+\pi^0(\gamma)$	20.7%
$K^+ \to \pi^+\pi^+\pi^-$	5.6%
$K^+ \to \pi^+\pi^-e^+\nu_e$	4.3×10^{-5}



Sign & Bkg control regions kept blind throughout the analysis

Background rejection relies on **Kinematics** (15GeV/c < P_π < 35GeV/c ; m^2_{miss}) used in conjunction with **Particle ID**, **Veto systems** and **sub-ns timing**

NA62 Beam and Detector



[NA62 Detector Paper, 2017 JINST 12 P05025]

- SPS protons on Be target (PoT): 400 GeV/c, ~10^{12} PoT/sec , 3.5 sec/spill
- Un-separated hadron beam: π^+(70%)/K^+(6%)/p(24%)
- K^+: 75GeV/c (±1%), divergence < 100μrad, (60 x 30) mm² transverse size
- 750MHz nominal beam rate @GTK (~5MHz K^+ decays in 60 m fiducial volume)
- 2016, 2017, 2018 beam rates in Run 1 [MHz]: ~300,~500,~600

Measurement Strategy

NA62 Performance keystones:

- O(100ps) Timing
- $\geq 10^3$ Kinematic bkg rejection
- $\geq 10^8$ Muon suppression (from $K^+ \to \mu^+ \nu$)
- $\geq 10^8$ $\pi^0 \to \gamma\gamma$ suppression (from $K^+ \to \pi^+ \pi^0$)

Signal selection:

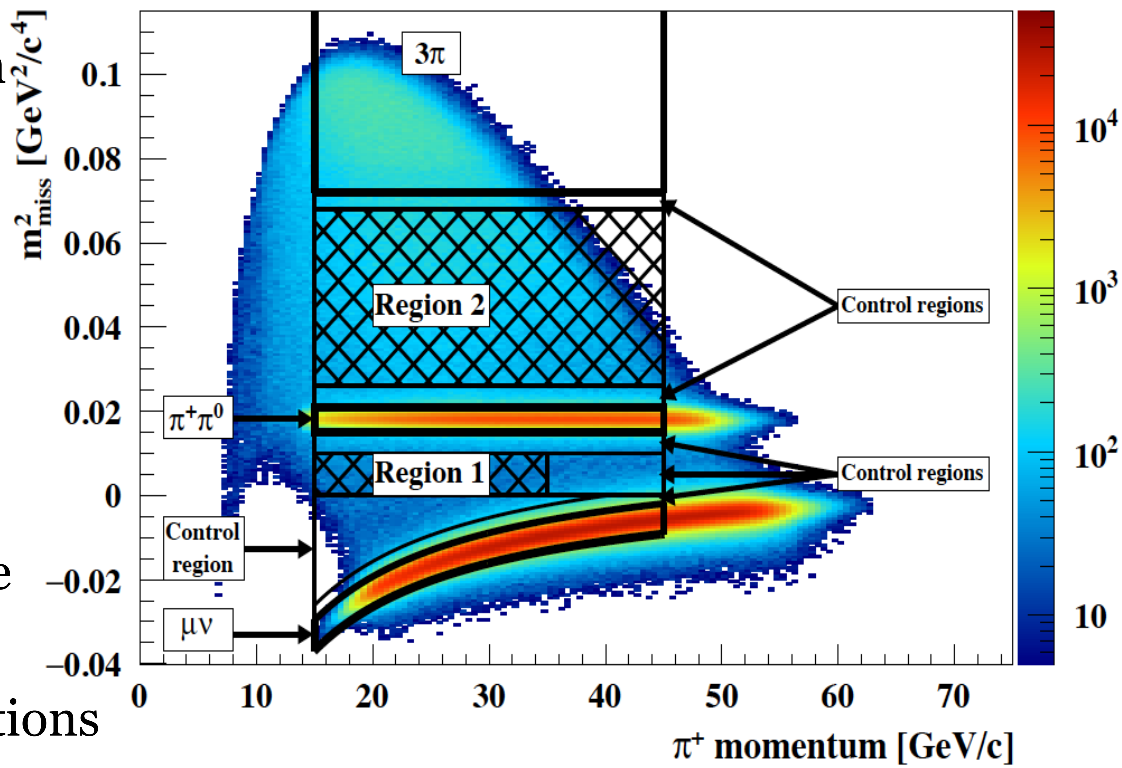
K^+ decays with 1 track in final state

Definition of Region 1, Region 2

PID, photon and multi-track rejections

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

m_π mass hypothesis



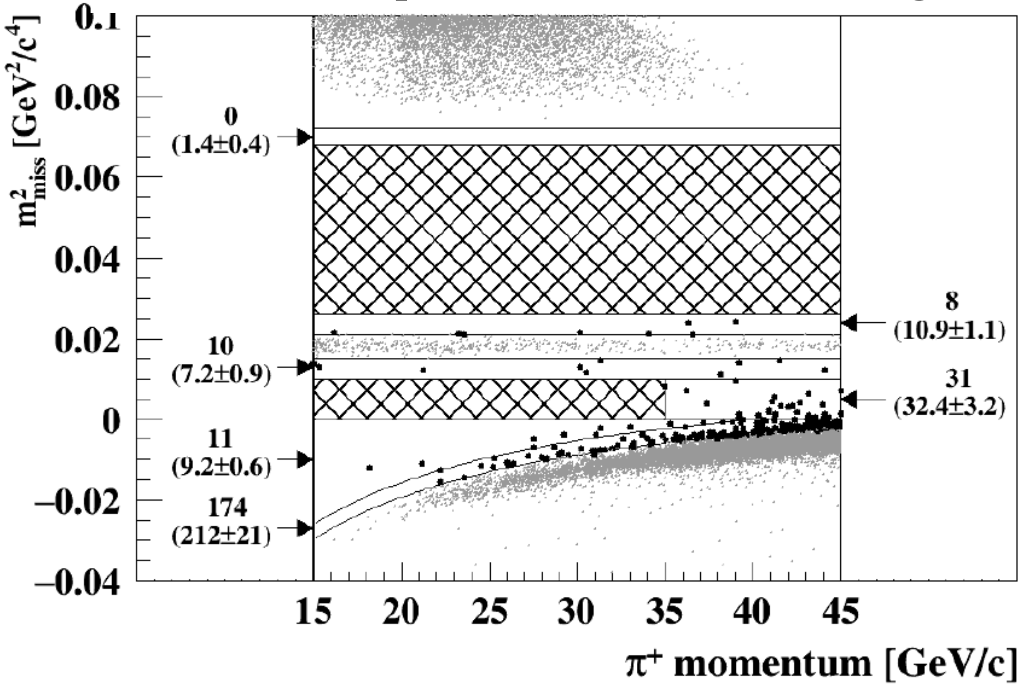
Signal and Control kinematic regions blinded during the analysis

Selection optimized in bins of π^+ momentum

Backgrounds: 2018 Data

Background expectations validated using control regions

Observed (expected) events in control regions

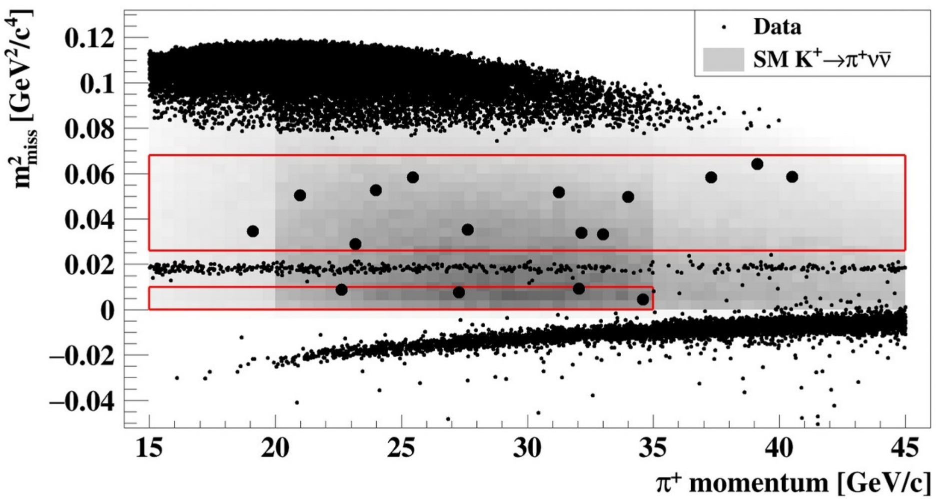


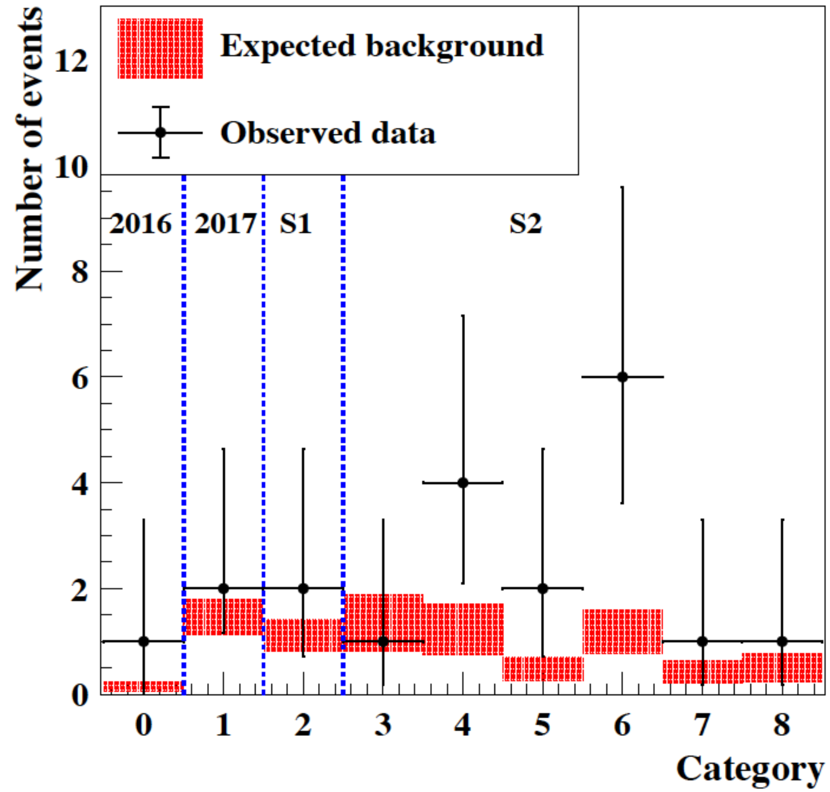
Background estimates summed over Region 1 and Region 2

Background	Subset S1	Subset 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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
$BR_{SES} \times 10^{10}$	**0.54±0.04**	**0.14±0.01**
$N^{exp}_{\pi\nu\bar{\nu}}$	**1.56±0.21**	**6.02±0.82**

Dominant background is not due to K⁺ decays in the vacuum tank
Improvement of beam line layout and new upstream veto detectors installed after 2018
to bring the Run 2 measurement into a low-background regime

NA62 Result: 2016-2018





2018 Data

Exp: 7.6 signal + 5.4 background events

Obs: 17 $K^+\to\pi^+\nu\bar{\nu}$ candidates

[JHEP 06 (2021) 093]

Combined NA62 Result with 2016-2018 data

- 20 events observed in signal regions
- P(only bkg) = 3.4 x 10^{-4}
- corresponding to 3.4σ significance

SES = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$

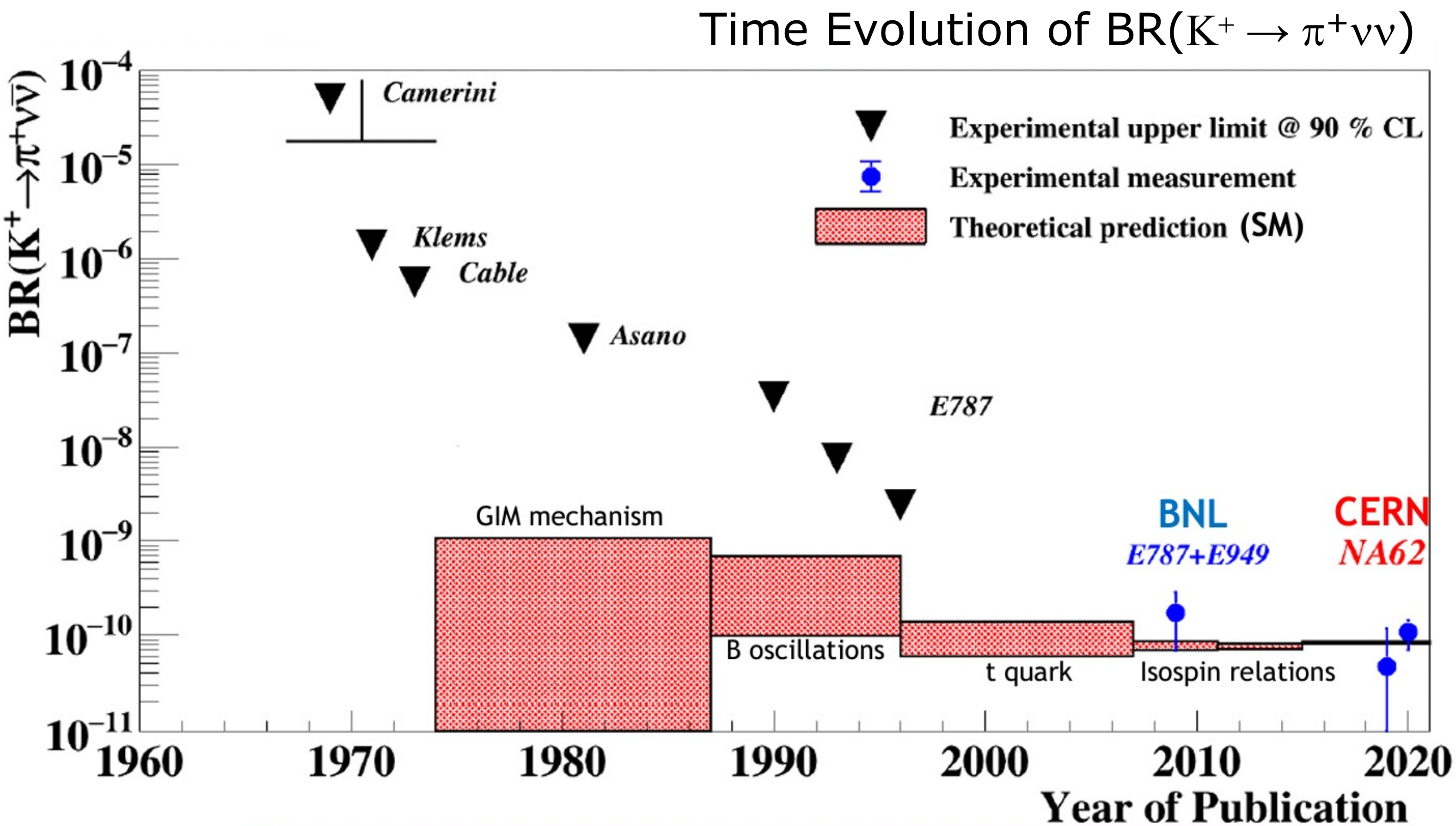
Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

Expected bkg: $7.03^{+1.05}_{-0.82}$

Observed: 20 (1+2+17) events

$$BR(K^+\to\pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

History of $K^+ \to \pi^+ \nu\bar{\nu}$ Measurements

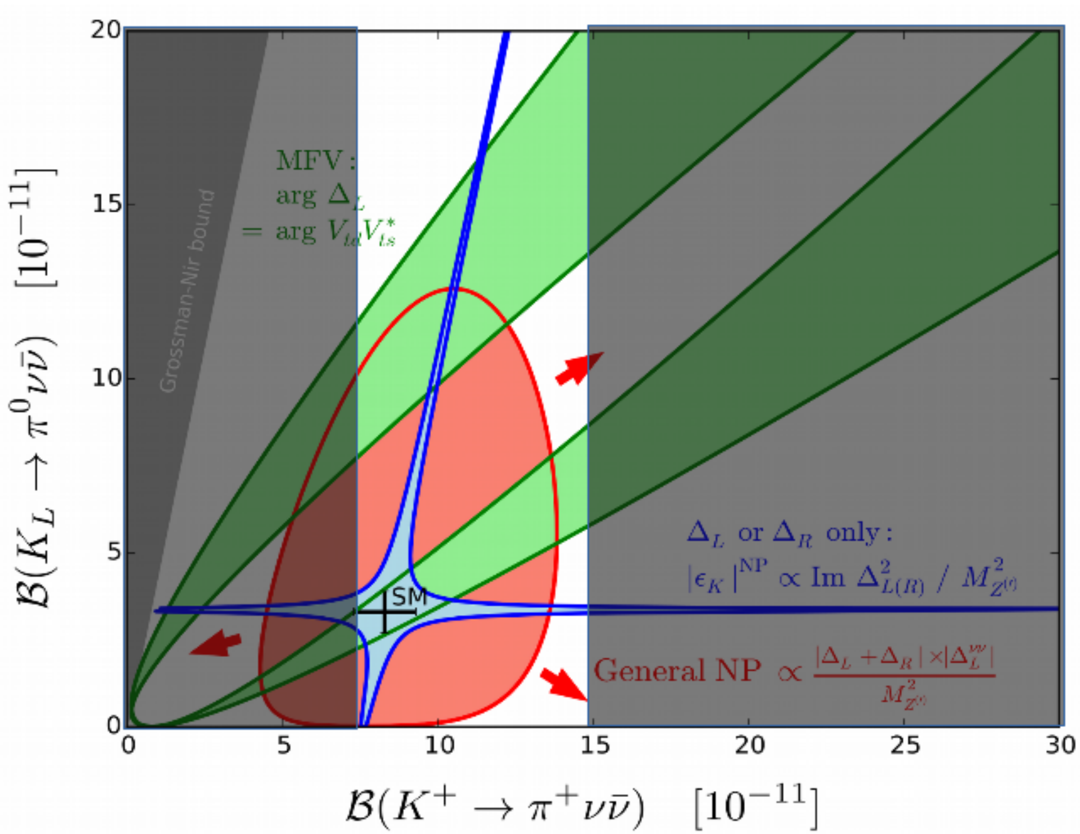


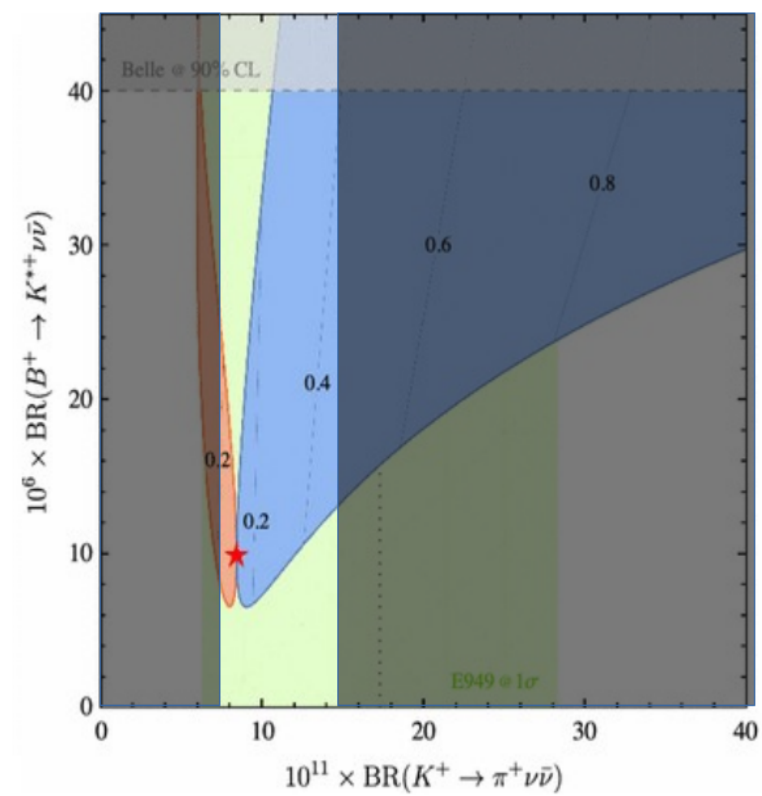
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$

3.4σ significance, most precise measurement to date!

Implication of NA62 Result on New Physics

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$





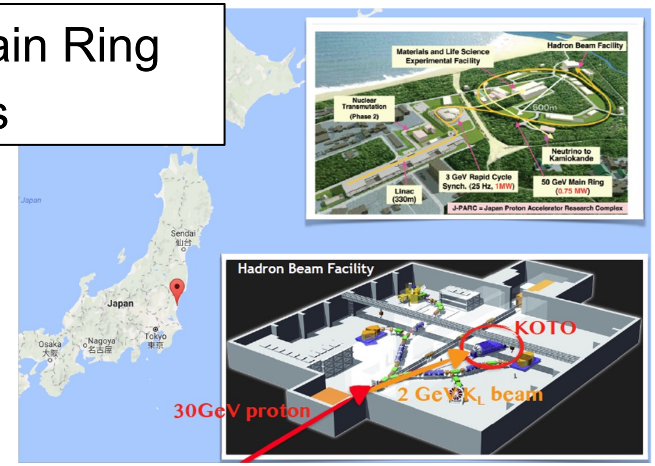
Large BR($K^+ \to \pi^+\nu\bar{\nu}$) values with respect to SM expectation start to be excluded: high precision measurement needed!

The KOTO Experiment

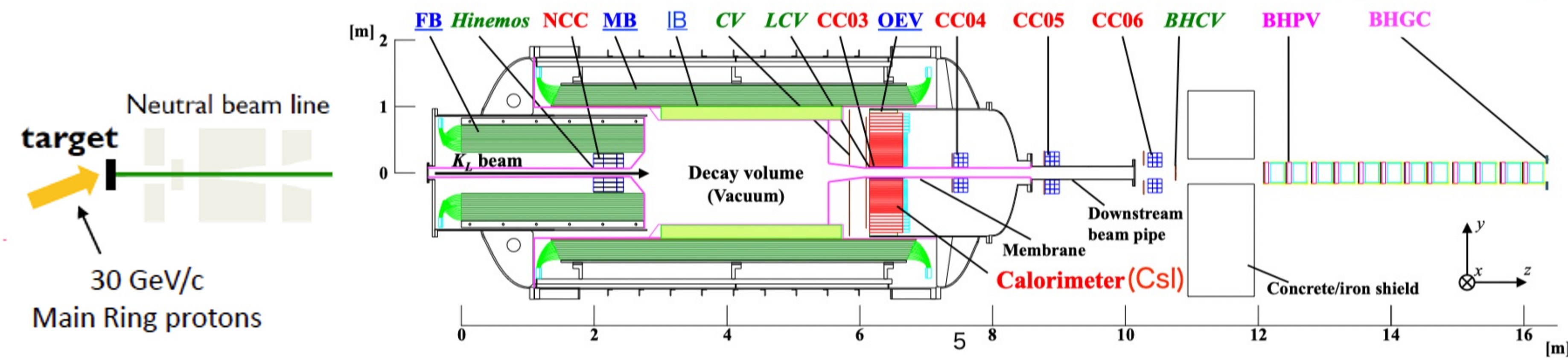
Study of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ @ JPARC 30GeV Main Ring
Goal is to observe few SM events

Primary 30 GeV/c protons on gold target
- Intensity in 2021: 60 kW = 6.6×10^{13} p/5.2 s

Secondary neutral beam (K_L, neutron, photons)
- beam angle ~16°, 8 μsr "pencil" beam
- $\langle p(K_L) \rangle$ = 2.1 GeV, 50% in [0.7-2.4] GeV/c range
- Fiducial decay region ~3 m



Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga & Yamagata

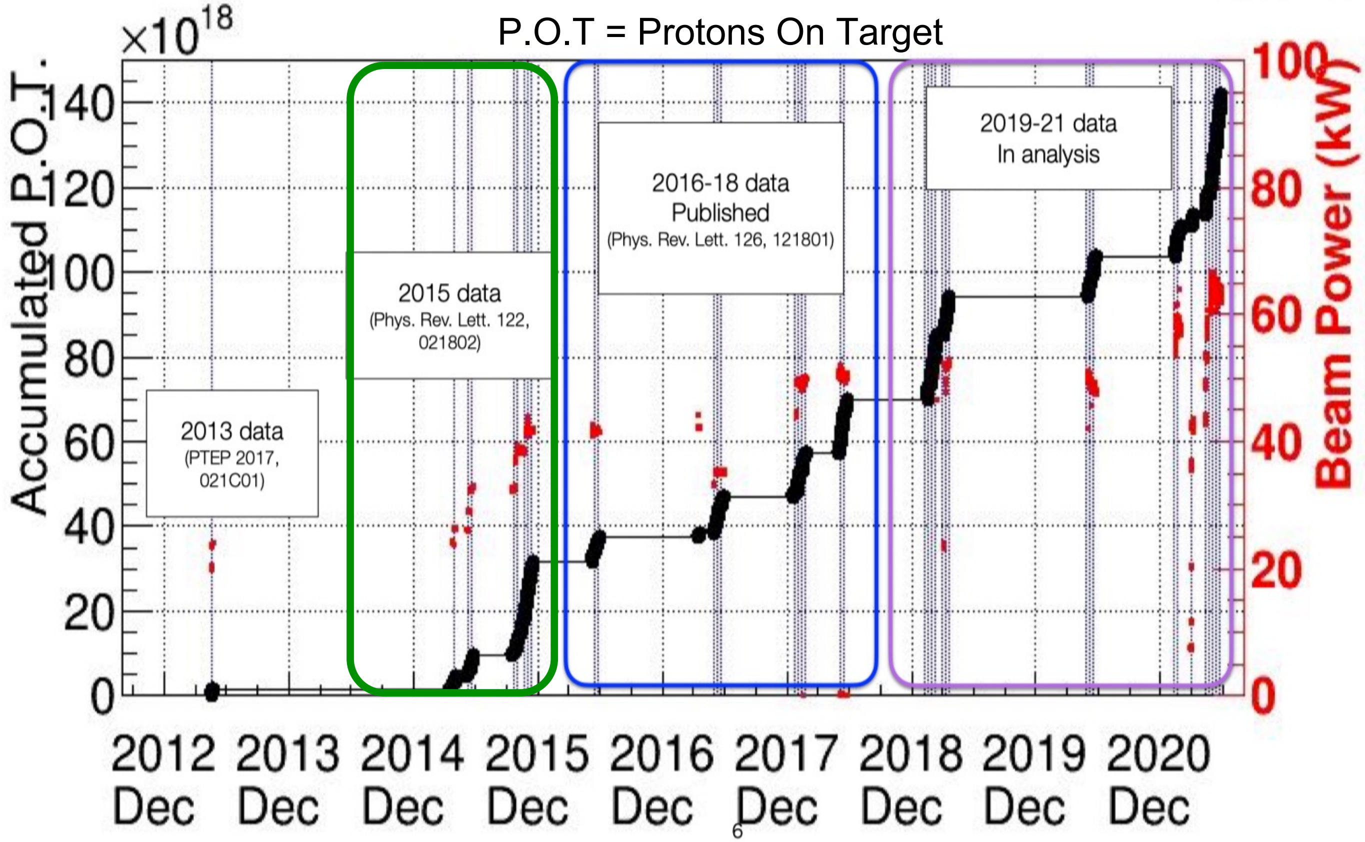


Lead-scintillator sandwich
Plastic scintillator counter
CsI Calorimeter from KTeV

} **Hermetic Veto Systems** → To suppress $K_L \rightarrow \pi^0 \pi^0$

KOTO Timeline & Datasets

Physics runs and dataset history as shown at KAON 2022 (K. Shiomi)



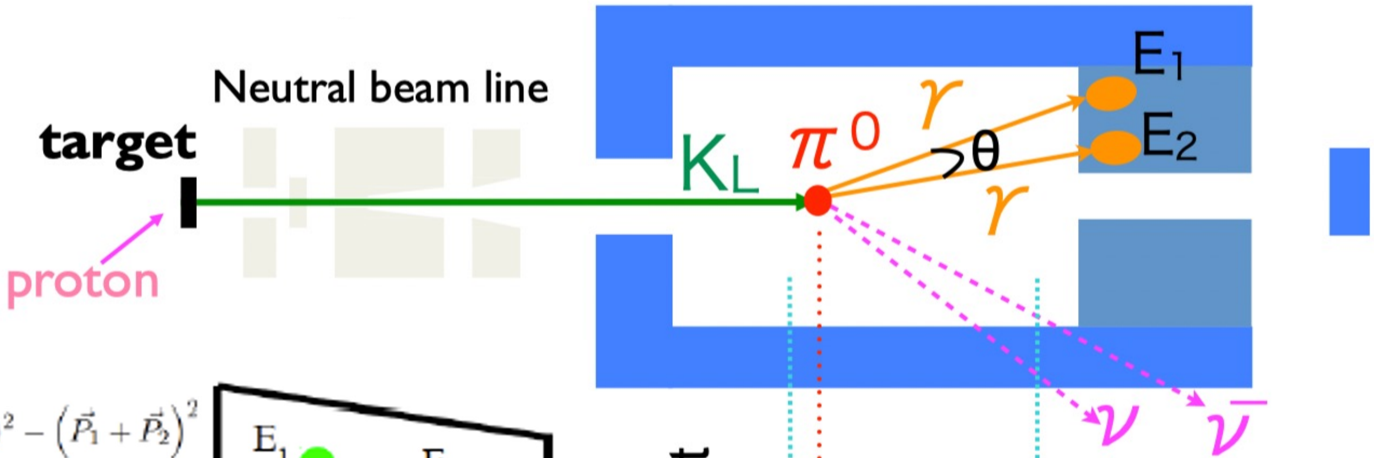
2015 physics run: 40 kW beam power, 3×10^{19} P.O.T
$BR(K_L \to \pi^0 \nu\bar{\nu}) < 3.0\times10^{-9}$ (90% CL) [PRL 122 (2019) 021802]

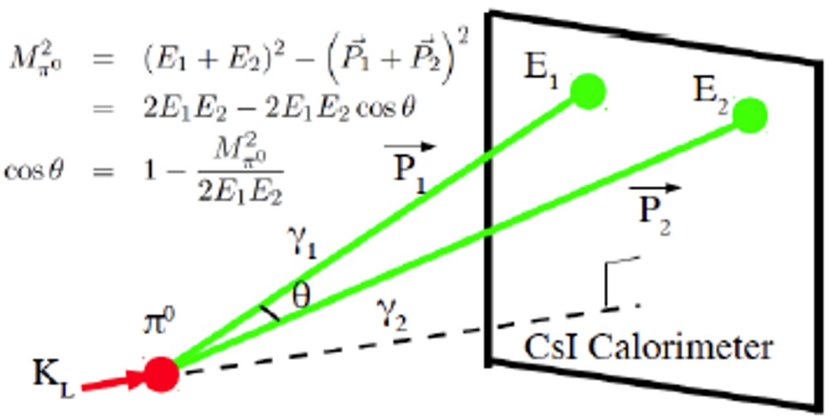
2016-2018 physics runs: 50 kW beam power, 4×10^{19} P.O.T
$BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.9\times10^{-9}$(90% CL) [PRL 126 (2021) 121801]

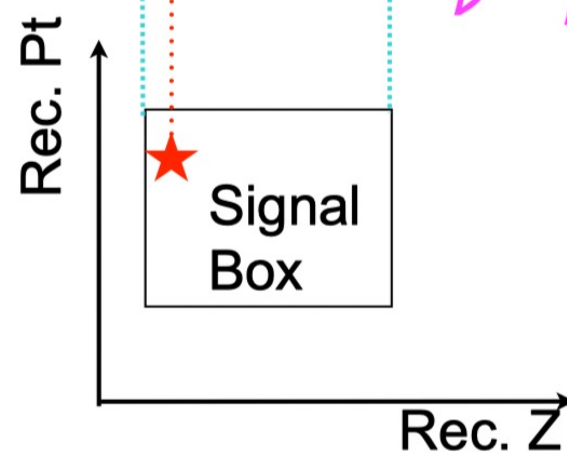
2019-21 physics runs: twice 2016-18 dataset, detector improvements, lower bkg

$K_L \to \pi^0 \nu \bar{\nu}$ signature: 2γs + missing P_t + nothing else

Signal $K_L \to \pi^0 \nu \bar{\nu}$ in KOTO detector:







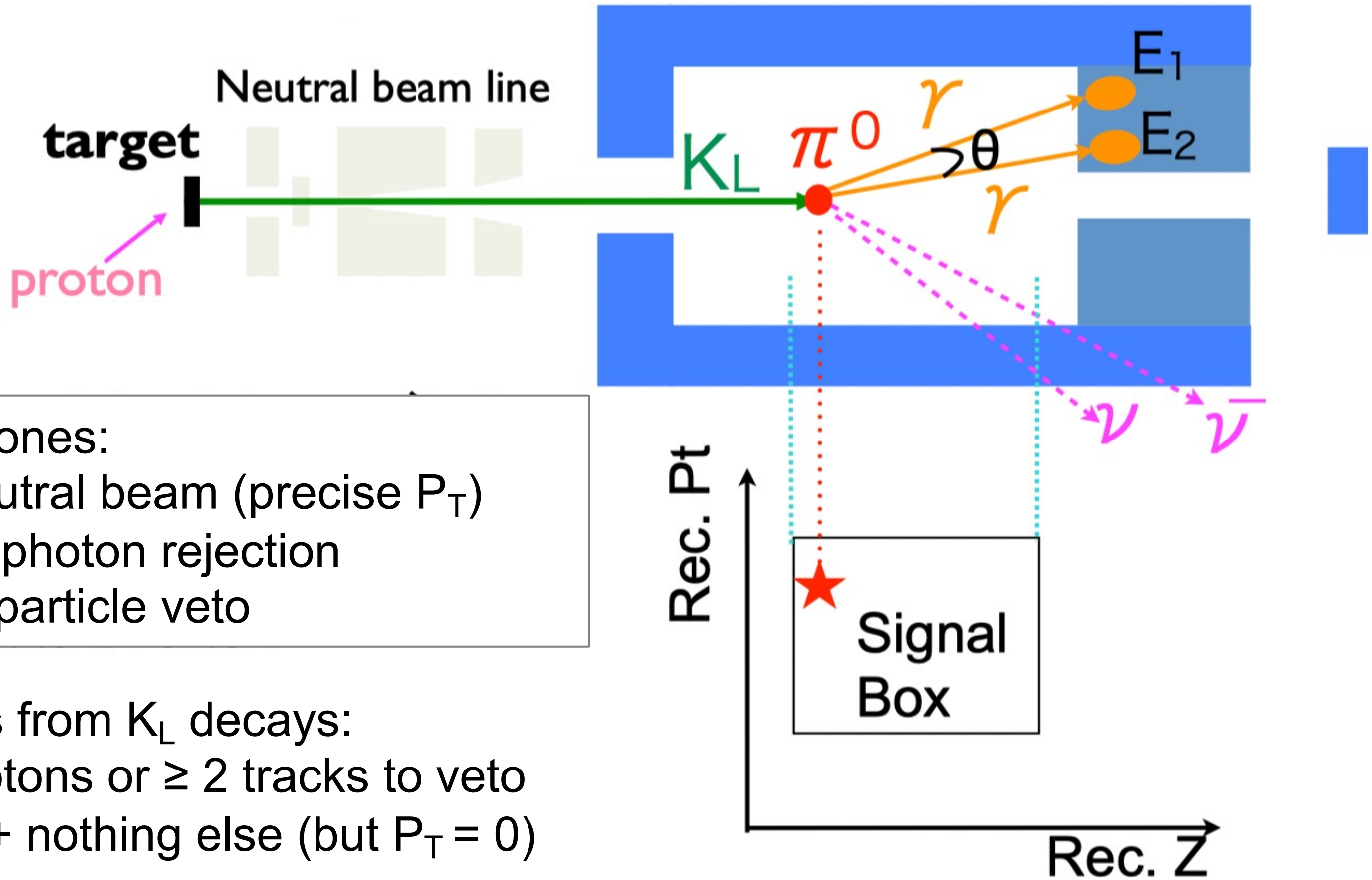
Assuming 2γ from π^0, calculate Z vertex

Signal region defined by π^0 Z and transverse momentum (P_t)

$K_L \to \pi^0 \nu\bar{\nu}$ Signal & Backgrounds

$K_L \to \pi^0 \nu\bar{\nu}$ signature: 2γs + missing P_t + nothing else

Signal $K_L \to \pi^0 \nu\bar{\nu}$ in KOTO detector:

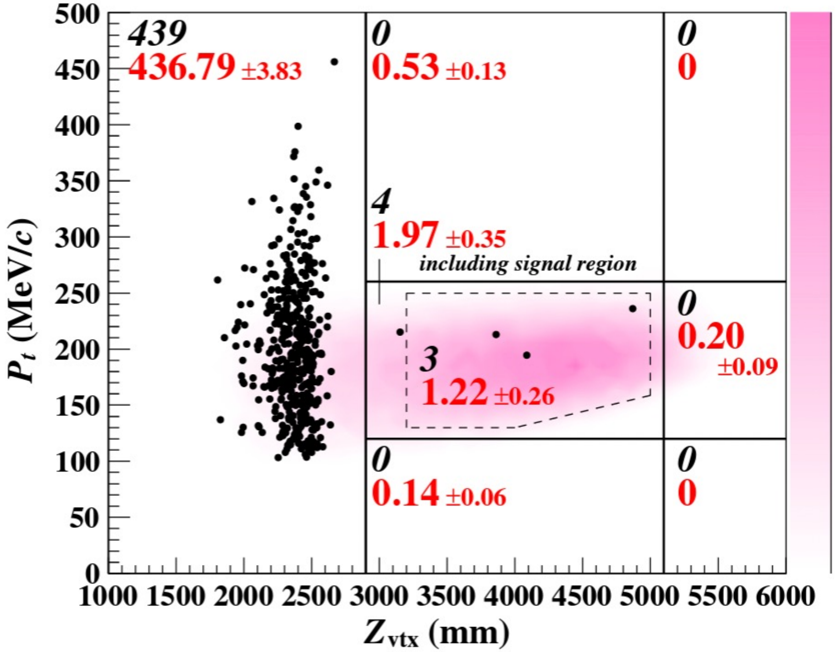


KOTO Keystones:
- Pencil neutral beam (precise P_T)
- Hermetic photon rejection
- Charged particle veto

Backgrounds from K_L decays:
≥ 2 extra photons or ≥ 2 tracks to veto
$K_L \to \gamma\gamma$: 2γs + nothing else (but $P_T = 0$)

Background rejection relies on **kinematics**, **photon** and **particle veto systems**

KOTO Result: 2016-2018



PRL 126 (2021) 121801

Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25[a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

Background sources studied after looking inside the blind signal region

Acceptance($K_L \to \pi^0 \nu\bar{\nu}$) from MC:

Decay in FV: 3.3%

Overall acceptance: 0.6%

K_L flux from $K_L \to \pi^0\pi^0 = 6.8 \times 10^{12}$

$$\text{SES} = \frac{1}{A_{sig} N_{K_L}} = (7.20 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$$

→ **Expected:** 0.04 signal + 1.22 background events

Observed: 3 events in the signal box

BR($K_L \to \pi^0 \nu\bar{\nu}$) < 4.9 × 10^{-9} (90% CL)

$K \to \pi\nu\bar{\nu}$ Experimental Status

Decay	Γ_{SD}/Γ	Theory Error*	SM BR x10[11]	EXP BR x 10[11]	EXPERIMENT	YEAR
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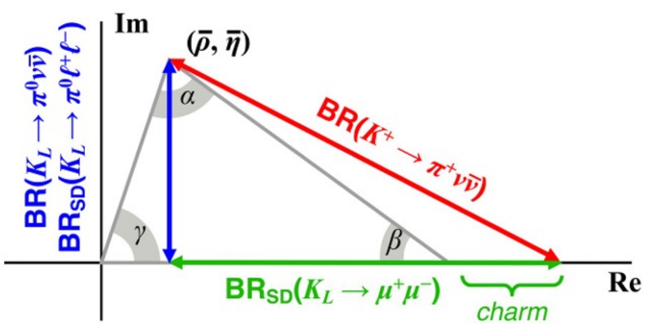
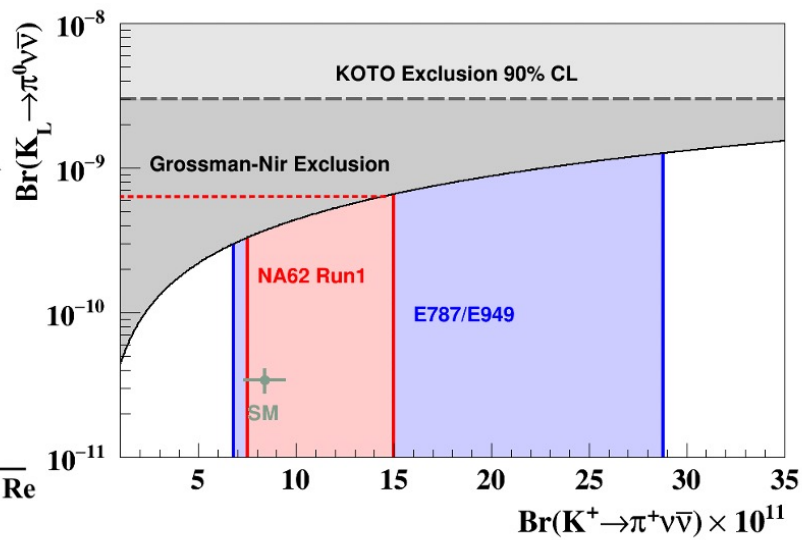
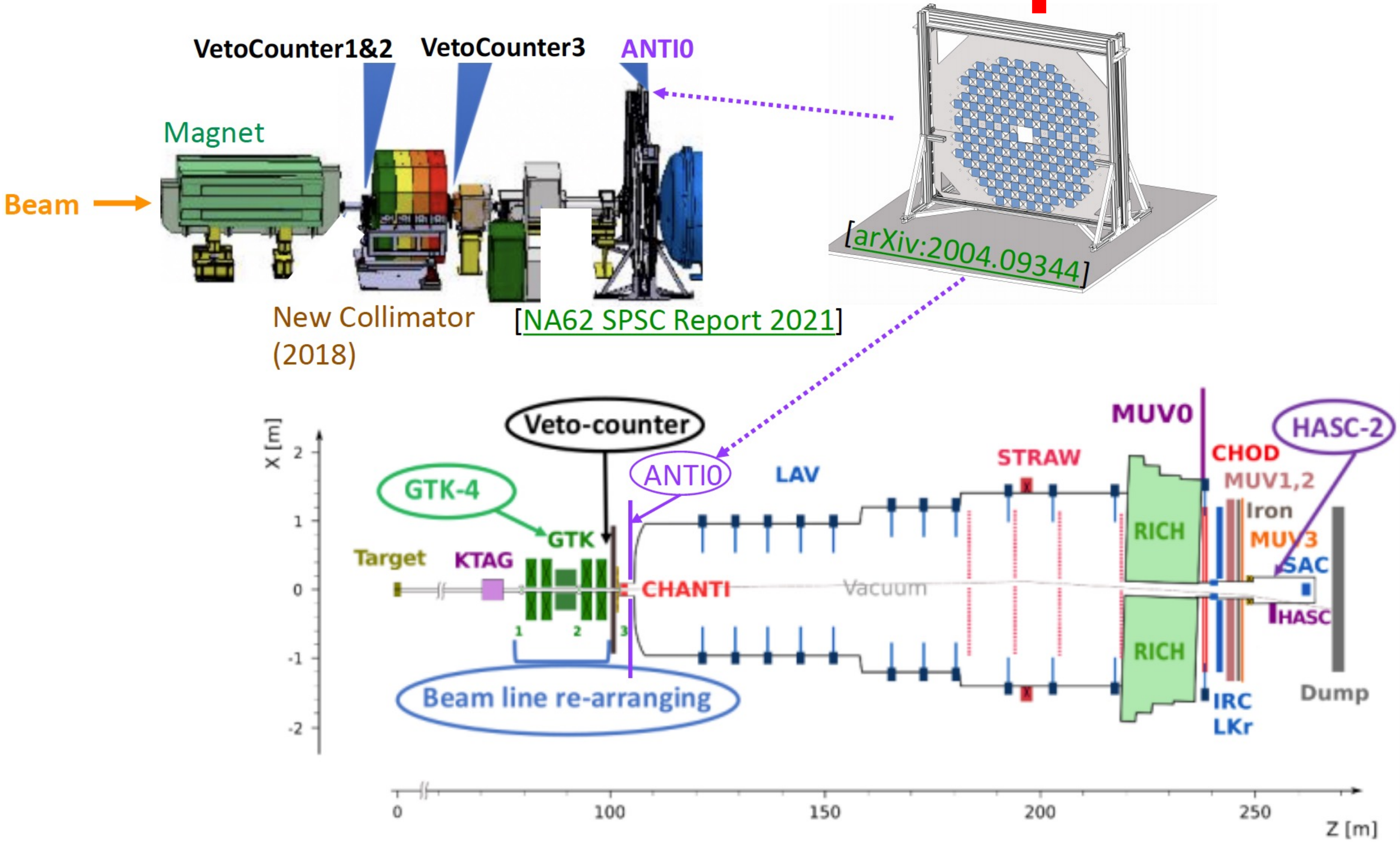




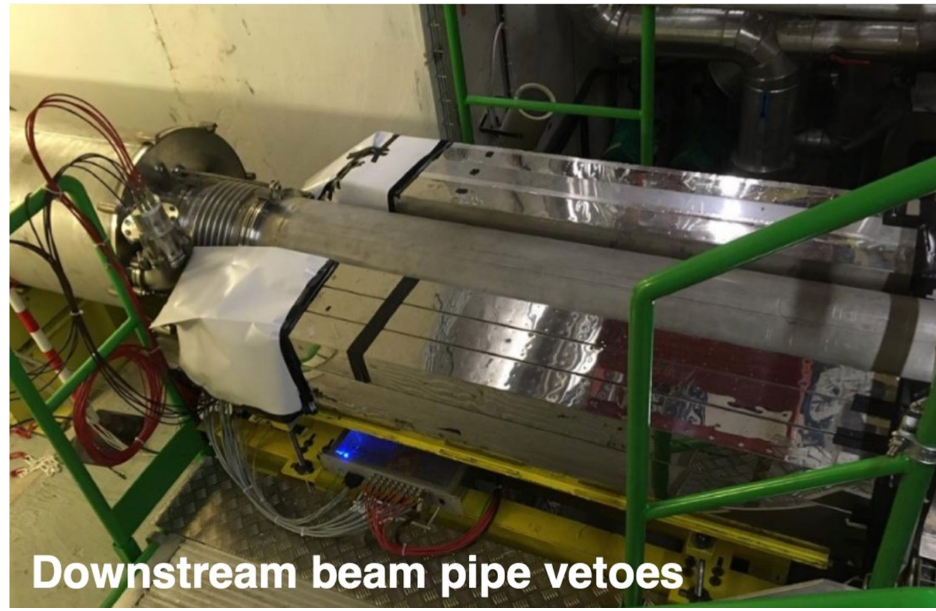
NA62 Short Term Prospects



Strategy for reduction of most dominant background in 2016-2018 analysis:

- Additional 4th kaon beam tracker station (GTK-4)
- Rearrangement of beam line elements around GTK achromat
- New veto hodoscopes upstream of decay volume (Veto-counter, ANTI0)
- Additional veto counters around downstream beam pipe (HASC-2)

NA62 Short Term Prospects



New detectors installed for NA62 Run2 (2021 – 2025)

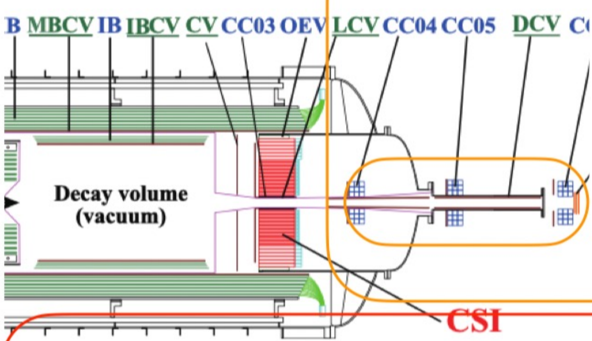
- The kaon decay-in-flight technique is firmly established
- Improved trigger: beam intensity increased by ~40% wrt Run 1
- $K^+ \to \pi^+\nu\bar{\nu}$ measurement in a low-background, high-acceptance regime
- Analysis of 2021-2022 combined datasets is ongoing

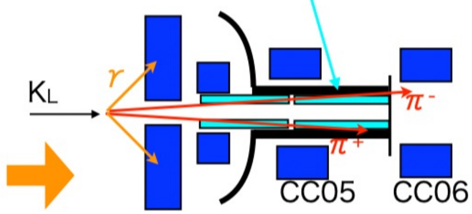
Expect to measure BR($K^+ \to \pi^+\nu\bar{\nu}$) at O(15%) precision by LS3

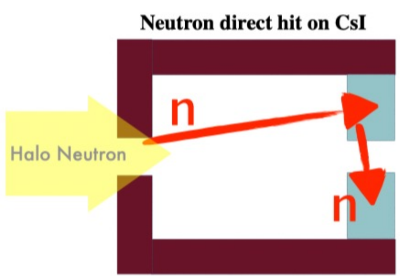
KOTO Short Term Prospects

- Downstream charged veto(DCV)

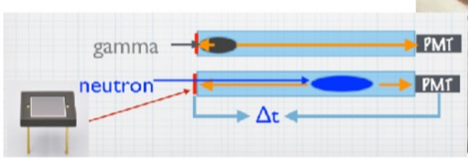
Installed in the vacuum to detect charged particles before hitting the down stream beam pipe



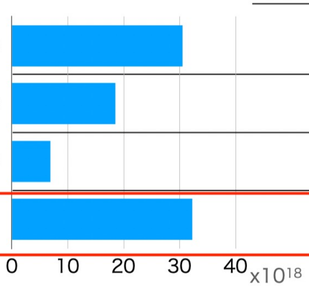




- Calorimeter's both-end readout against Hadron cluster background



K. Shiomi @ KAON2022



	Calorimeter Upgrade (Hadron cluster BG)	Downstream Charged Veto ($K_L \to \pi^+\pi^-\pi^0$ BG)	Upstream Charged Veto ($K^\pm$ BG)
2016-2018			
2019	✔	✔	
2020	✔	✔	Prototype
2021	✔	✔	✔

DCV: suppress background from $K_L \to \pi^0\pi^+\pi^-$ and allow extension of signal region

Calorimeter upgrade: suppress background from neutrons

KOTO Short Term Prospects

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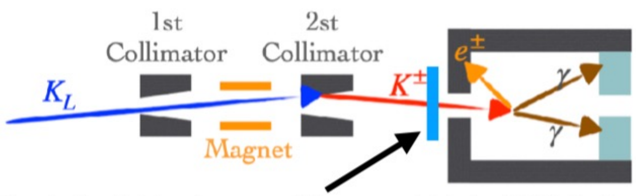
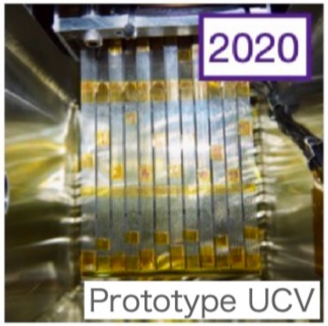
Strategy for reduction of most dominant background sources in 2016-2018 analysis

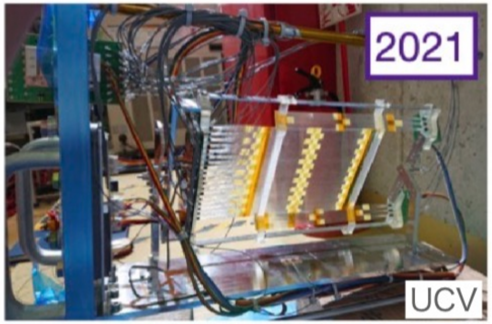
K± BG ($K^{\pm} \rightarrow \pi^0 e^{\pm} \nu$)



- Installed Upstream Charged Veto(UCV) for K± detection
- A plane of square scintillation fibers read by MPPC



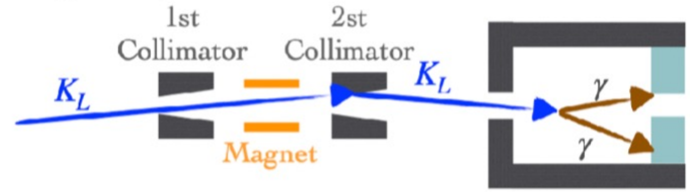
1mm-square fibers



0.5 mm-square fibers
tilted 25 degree

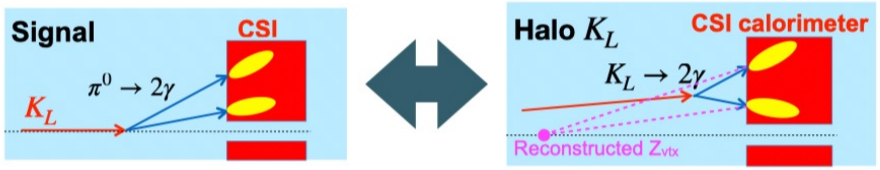
Reduction of $K^{\pm}$ background by 95%

Halo $K_L \rightarrow 2\gamma$



- Developed new cuts based on the difference of kinematical distributions or shower shape

Shower shape Likelihood



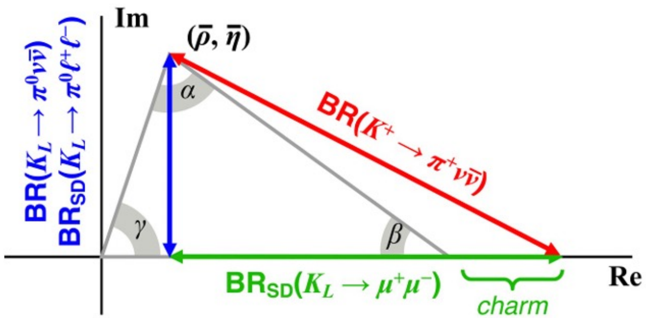
Reduction of $K_L \rightarrow 2\gamma$ background by 94%

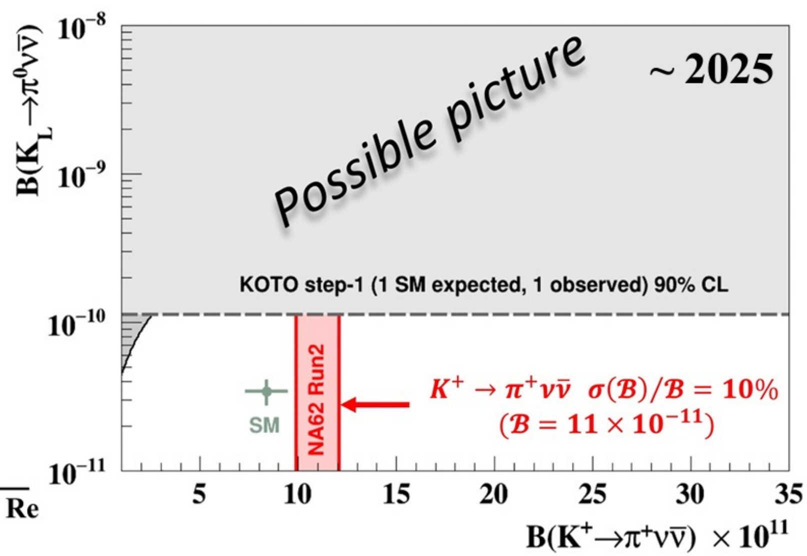
Reachable SES with 2021 data is (6~8) x 10^{-10} → 2021 data analysis in progress
In 2023 beam power increased from ~60 → 80 kW (later: 100 kW)
Expect to approach SM SES O(10^{-11}) by 2025, operating in low-background regime

$K\to\pi\nu\bar{\nu}$ Short Term Prospects

Decay	Γ_{SD}/Γ	Theory Error*	SM BR x10^{11}	EXP BR x 10^{11}	EXPERIMENT	YEAR
$K_L \to \pi^0\nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	~ SM SES	KOTO	~2025
$K^+ \to \pi^+\nu\bar{\nu}$	90%	4%	8.4 ± 1.0	~10% precision	NA62	~2025
$K_L \to \pi^0 e^+e^-$	40%	10%	3.2 ± 1.0	<28	KTeV	2004
$K_L \to \pi^0\mu^+\mu^-$	30%	15%	1.5 ± 0.3	<38	KTeV	2000
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000

(*) approximate error on LD-subtracted rate excluding parametric contributions



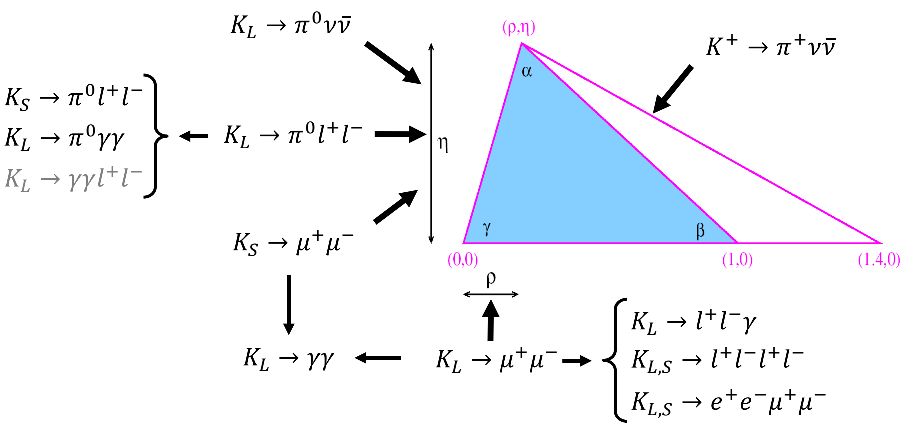


Long Term Plan: High Intensity Kaon Experiments (HIKE) at CERN

Long-term kaon physics programme proposed at CERN SPS (after LS3)

Charged and Neutral rare K decay modes can give clear insight about NP flavour structure [arXiv:1408.0728]

Snowmass paper: arXiv:2204.13394; LoI: arXiv:2211.16586



Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.6 ± 0.4
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.9 ± 0.2 <

*Approx. error on LD-subtracted rate excluding parametric contributions

Importance of kaon physics highlighted in the last European Strategy: findings of the last European Particle Physics Strategy Group in the deliberation document **CERN-ESU-014** "**Rare kaon decays at CERN** and KEK" mentioned in Section 4 as "**Other essential activities**"

Long Term Plan: High Intensity Kaon Experiments (HIKE) at CERN

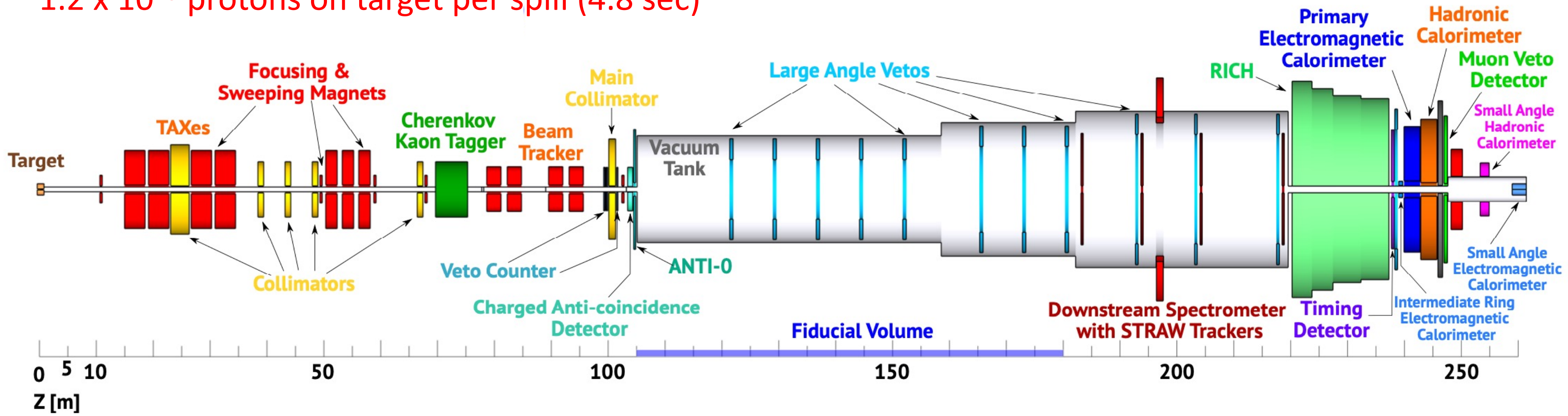
A multi-purpose high-intensity kaon decay-in-flight experiment at CERN SPS

High-intensity beams at CERN North Area after LS3 with x 4 current NA62 nominal would allow for a kaon comprehensive programme

HIKE K^+ and K_L phases share detectors and infrastructure of ECN3 experimental area

Feasibility studies within CERN Physics Beyond Colliders initiative show that high-intensity facility is feasible for operation from Run4 from beam delivery point of view

1.2 x 10^{13} protons on target per spill (4.8 sec)



<u>HIKE Proposal for Phases 1 and 2: to be submitted in 2023</u>

Phase 1 ($K^+ \to \pi^+ \nu\bar{\nu}$ at ~5% precision), Phase 2 ($K_L \to \pi^0 l^+ l^-$ at ~20% precision)

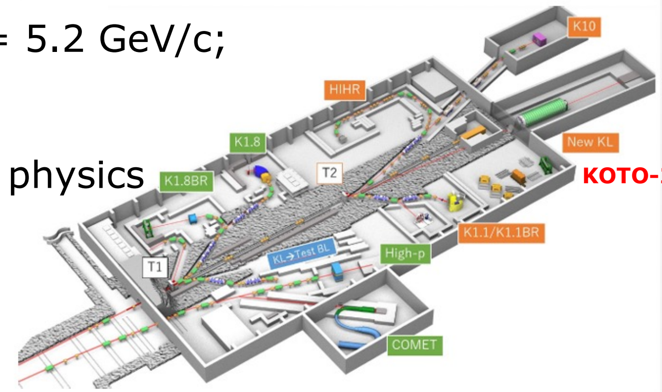
Technological solutions exist for all detectors

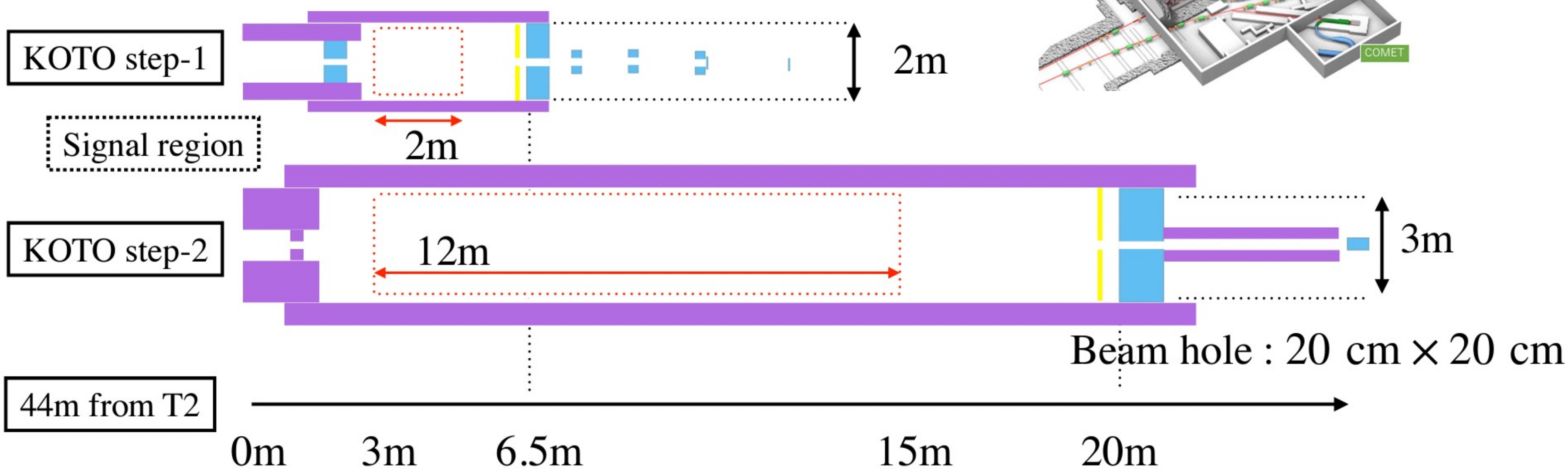
KOTO Long Term Prospects

H. Nanjo @ KAON2022

KOTO Step-2:

- ✓ Upgrade to reach sensitivity $O(10^{-13})$
- ✓ Increase proton beam power → 100 kW;
- ✓ New neutral beamline at 5° → larger K_L yield, <p(KL)> = 5.2 GeV/c;
- ✓ Increase fiducial decay volume from 2m to 12m;
- ✓ Complete rebuild of the detector;
- ✓ Require hadron hall extension: joint project with nuclear physics community;
- ✓ Design work is in progress.





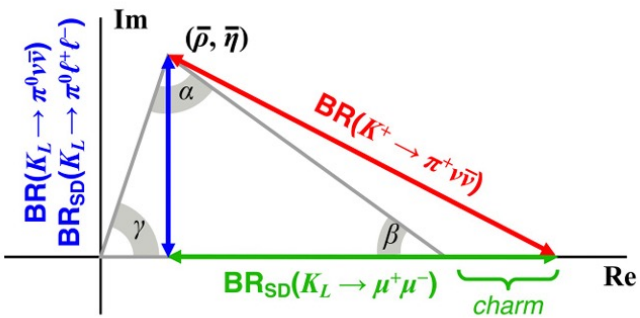
New sensitivity studies for smaller beam angle & larger detector: ~ 60 SM evts with S/B ~ 1 at 100 kW beam power (3×10^7 s)

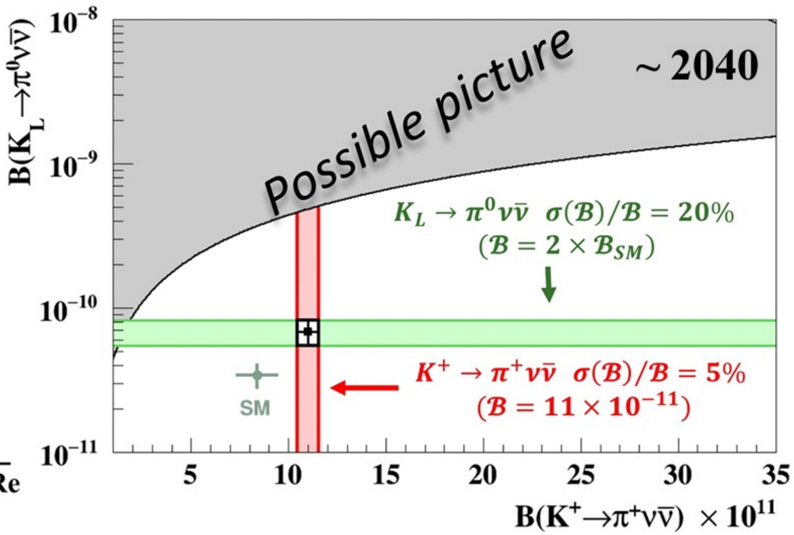
KOTO Step-2: aim at ~5σ SM $K_L \rightarrow \pi^0 \nu\bar{\nu}$ discovery

$K \to \pi\nu\bar{\nu}$ Long Term Prospects

Decay	Γ_{SD}/Γ	Theory Error*	SM BR x10^{11}	EXP BR x 10^{11}	EXPERIMENT	YEAR
$K_L \to \pi^0\nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	20% precision	KOTO-2	start ~2030
$K^+ \to \pi^+\nu\bar{\nu}$	90%	4%	8.4 ± 1.0	5% precision	HIKE	start ~2030
$K_L \to \pi^0 e^+e^-$	40%	10%	3.2 ± 1.0	<28	KTeV	2004
$K_L \to \pi^0\mu^+\mu^-$	30%	15%	1.5 ± 0.3	<38	KTeV	2000
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000

(*) approximate error on LD-subtracted rate excluding parametric contributions





Conclusions

NA62 and KOTO: current primary focus on $K \to \pi\nu\bar{\nu}$

Status:

➢ Recent results from KOTO ($K_L \to \pi^0\nu\bar{\nu}$) and NA62 ($K^+ \to \pi^+\nu\bar{\nu}$) presented

$BR(K_L \to \pi^0\nu\bar{\nu}) < 4.9 \times 10^{-9}$ (90% CL)	$BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\,_{stat} \pm 0.9_{syst}) \times 10^{-11}$

Prospects:

➢ Short-term (< ~2025) clear strategy defined for $K \to \pi\nu\bar{\nu}$

❖ Reduce current main sources of background

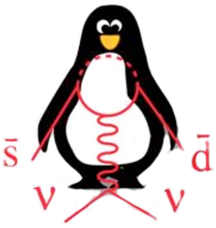
❖ Run at higher beam intensity

❖ Expect KOTO to reach SM SES and NA62 to reach O(15%) precision

➢ Long-term (> ~2030) next-generation of kaon experiments

❖ J-PARC: Plans for KOTO-2 to measure $BR(K_L \to \pi^0\nu\bar{\nu})$

❖ CERN: Proposal for high-intensity K^+ and K_L experiments



BEAUTY 2023

3-7 July 2023, Clermont-Ferrand, France

SPARES

Angela Romano, University of Birmingham (axr@hep.ph.bham.ac.uk)

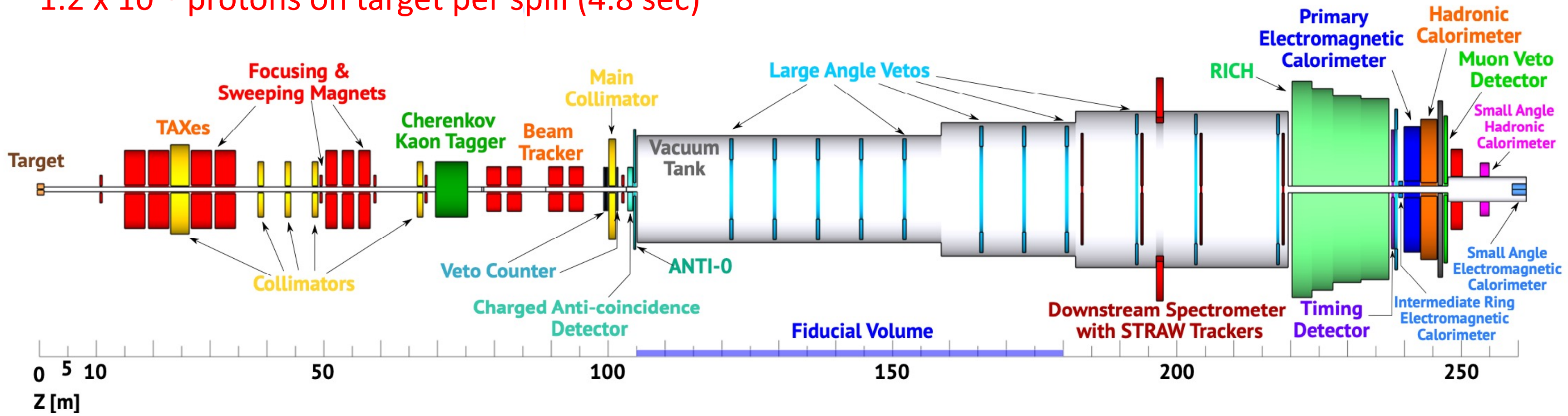
Long Term Plan at CERN SPS: The HIKE Detector

- Decay in flight technique, experience from NA62 and similar layout
- Essential K^+ ID, momentum, space and time
- High-rate, precision particle tracking
- Minimize material
- Highly efficient PID for photons, pions, electrons and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, time, granularity)

Improved timing is the crucial element to be able to increase intensity 4 x NA62

Technological solutions exists for all detectors

1.2 x 10^{13} protons on target per spill (4.8 sec)



Challenge: 20-40 ps time resolution for key detectors, while maintaining all other NA62 specs
Technology challenges aligned with HL-LHC projects and future flavour/dark matter experiments

Breakdown of backgrounds

BG table

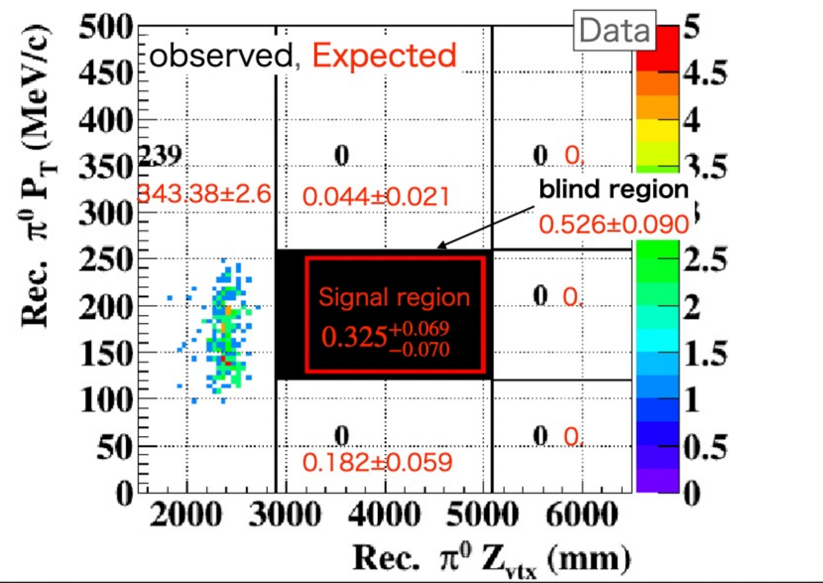
source	#BG in the signal box
$K_L \to 2\pi^0$	0.141±0.059
K^+	$0.043^{+0.016}_{-0.022}$
Hadron cluster BG	0.042±0.007
Halo $K_L \to 2\gamma$	0.013±0.006
Scattered $K_L \to 2\gamma$	0.025±0.005
η production in CV	0.023±0.010
Upstream π^0	0.02±0.02
$K_L \to 3\pi^0$	0.019±0.019
Sum	$0.325^{+0.069}_{-0.070}$

Single Event Sensitivity(S.E.S.):7.9×10^{-10}

c.f. 2016-2018 analysis:7.2×10^{-10}

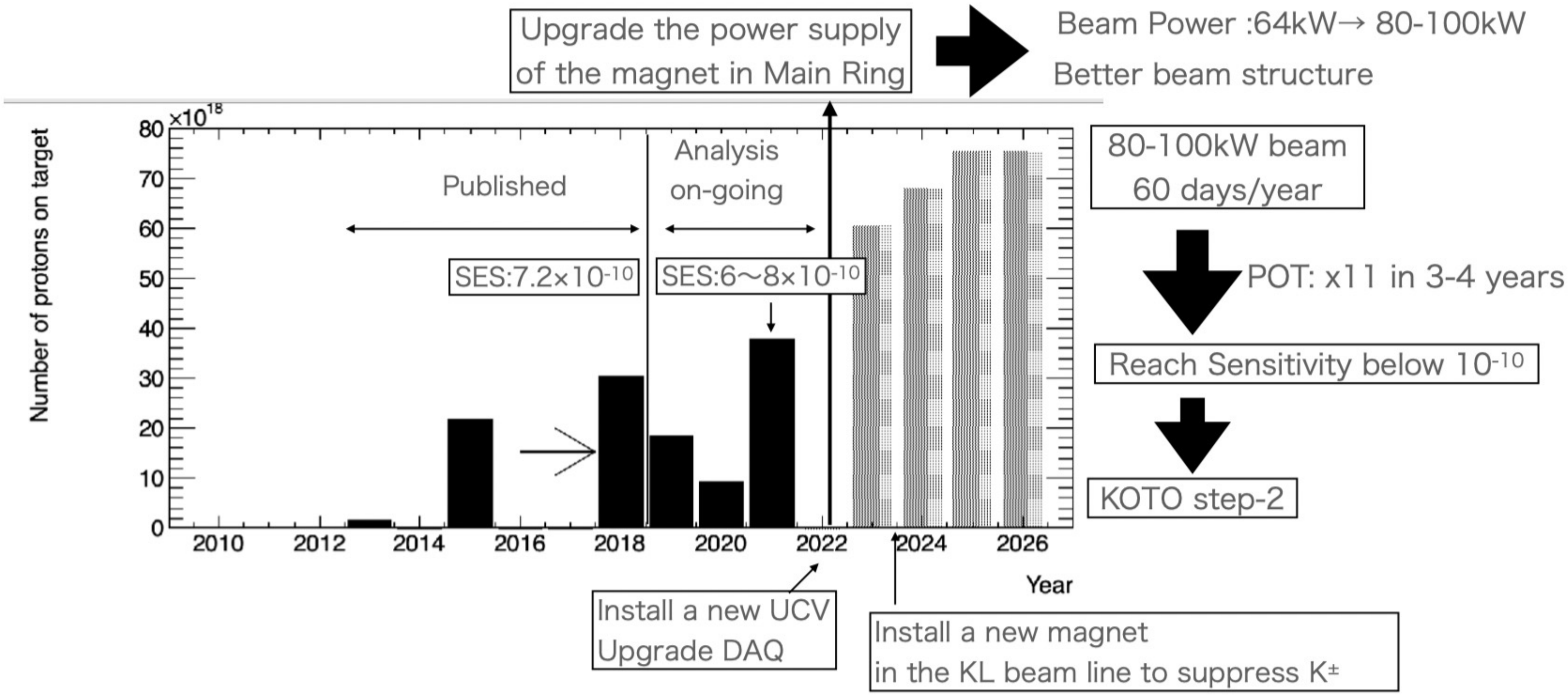
BG Estimation

c.f. 2016-2018 analysis:1.23±0.26



Reachable S.E.S with the 2021 data is (6~8) x 10^{-10}

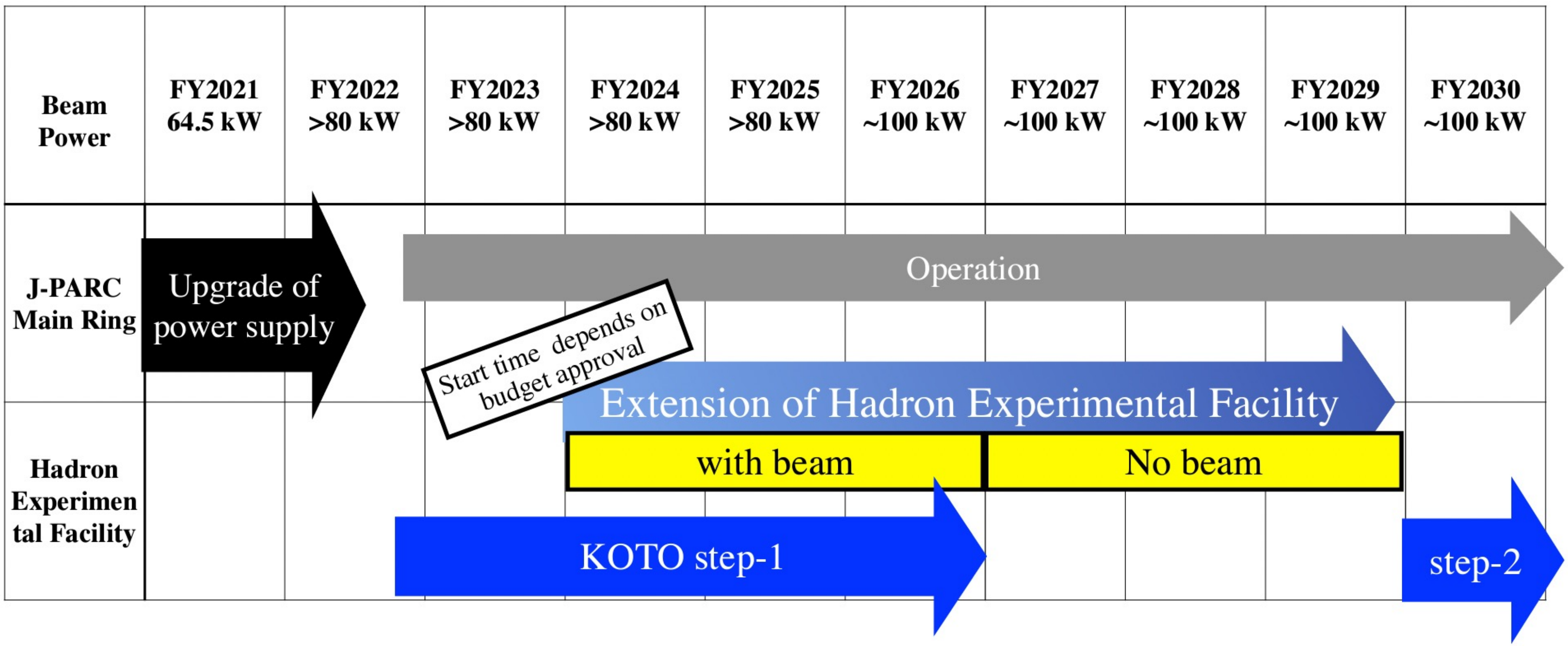
Prospects for future run



KOTO Beam Line Upgrade

Time line

H. Nanjo @ KAON2022

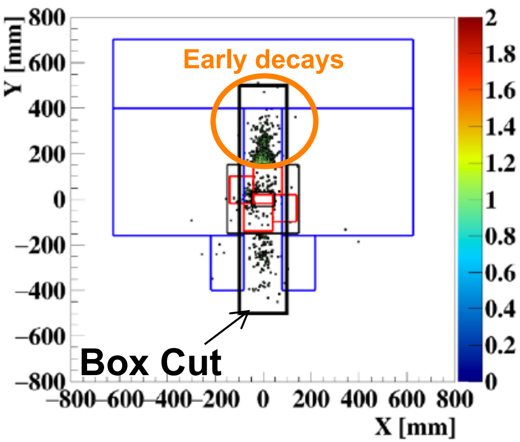


Early realization of extension of hall → Start of KOTO step-2 in 2030s

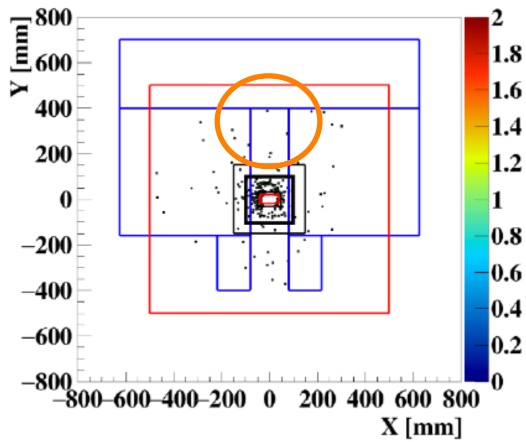
Upstream Background

- Kaon decays in upstream region (e.g. interactions with GTK stations)
- π^+ enters fiducial volume (FV) and scatters in first STRAW chamber
- Beam pileup particle (in GTK) generates a fake decay vertex inside the FV
- In 2018 collimator was replaced to remove early decays mechanism
- Data sample split in subsets S1 (OLD COL) and S2 (NEW COL)

Track extrapolation at collimator in enriched sample of upstream events (data)



OLD COL



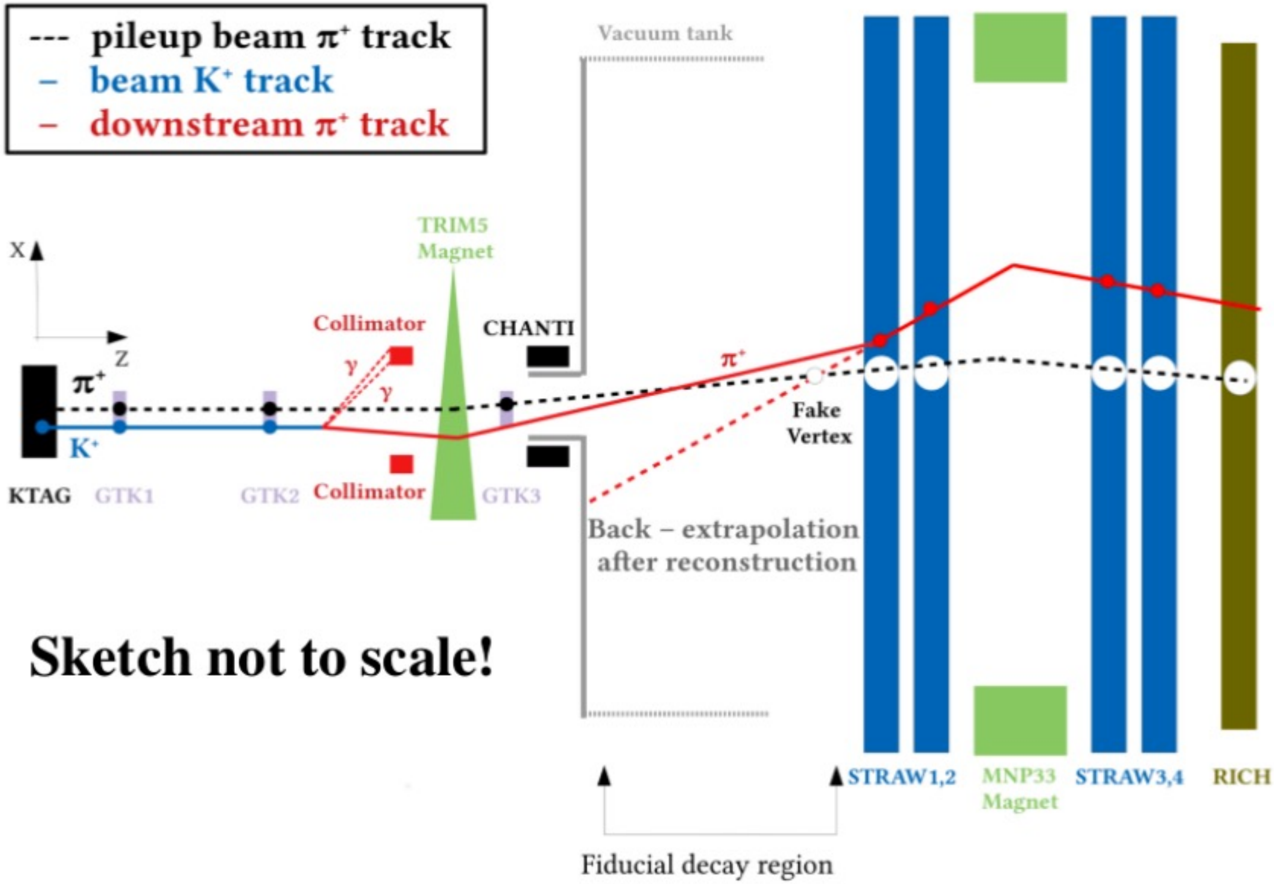
NEW COL

Dipole Magnet
CHANTI acceptance
Collimator

Background	Subset S1	Subset 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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Background estimates summed over Region 1 and Region 2

Upstream Background



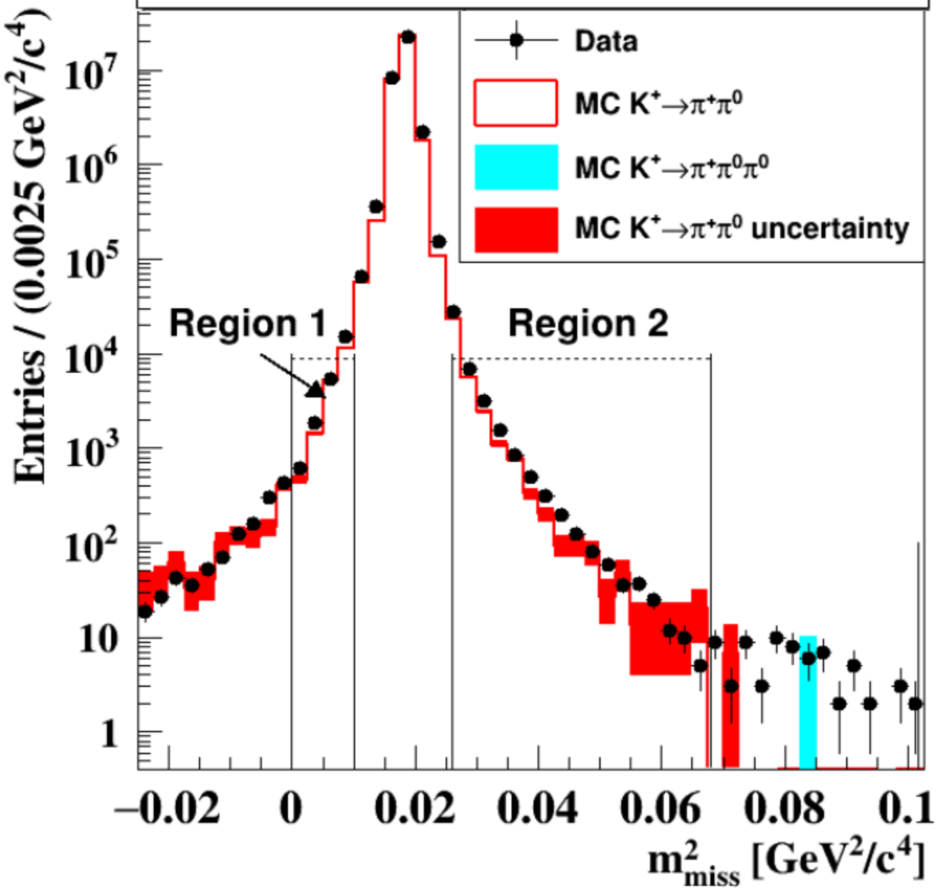
Kaon decays upstream the FV

→ only π^+ enters FV and scatters in first STRAW chamber

In-time pileup beam particle (in GTK) generates a fake decay vertex inside the FV

Background from Kaon decays

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



Background	Subset S1	Subset 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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Data Driven estimation

Number of events in $\pi^+\pi^0$ regions after $\pi\nu\nu$ selection

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

Expected number of $\pi^+\pi^0$ events in signal region after $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ events in signal region measured from control data

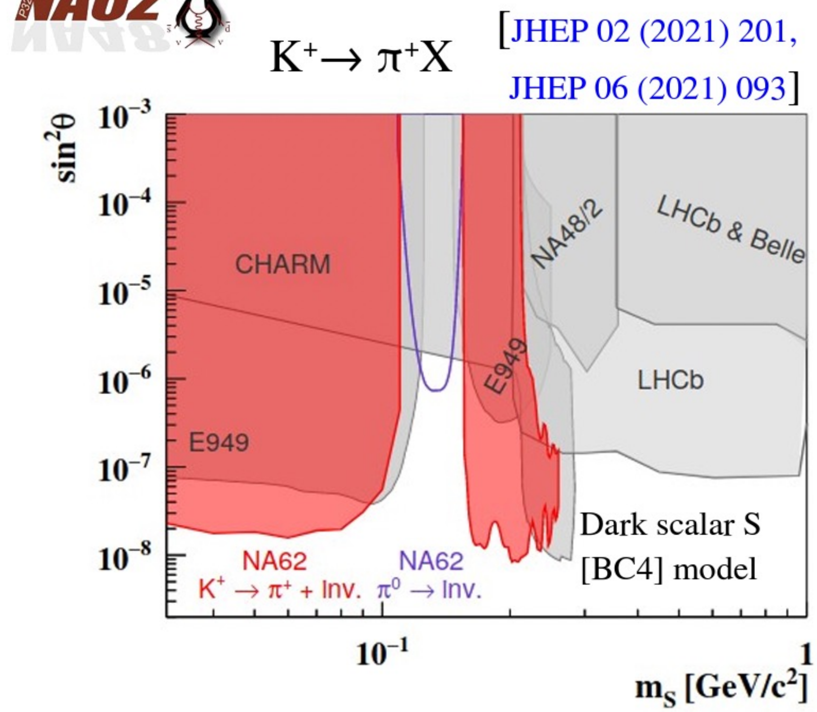
K physics: not only golden modes!

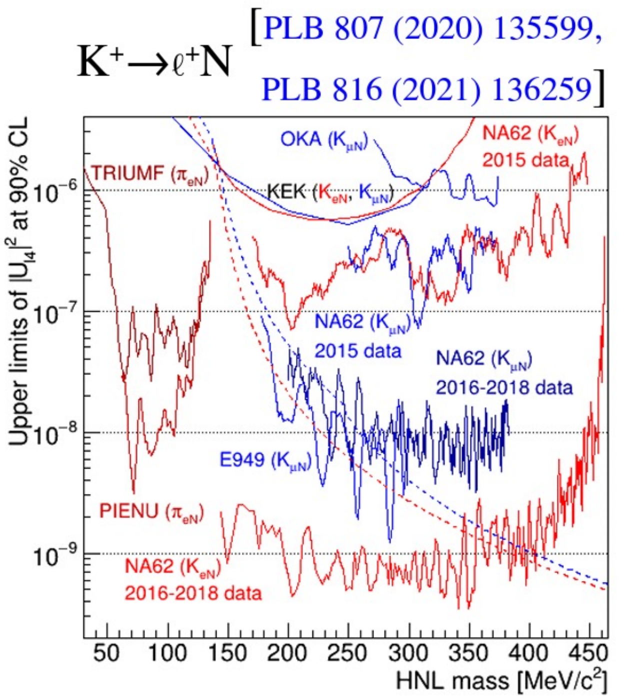
Production of on-shell BSM particles in K decays:

$K^+ \to \pi^+ X$, $K^+ \to \ell^+ N$

+ peak searches in states with $\ell^+\ell^-$ pair

$K^+ \to \pi^+\ell^+\ell^-$, $K_{L,S} \to \pi^0\ell^+\ell^-$, $K^+ \to \ell_1^+ \nu \ell_2^+ \ell_2^-$, $K_{L,S} \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$, …

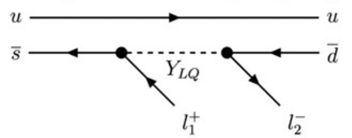




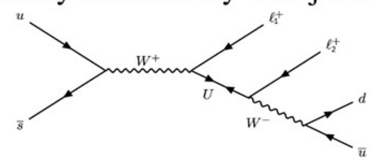
K physics: not only golden modes!

Lepton Number/Flavor Violation: many decay modes, forbidden in SM

LFV possibly mediated by leptoquark:

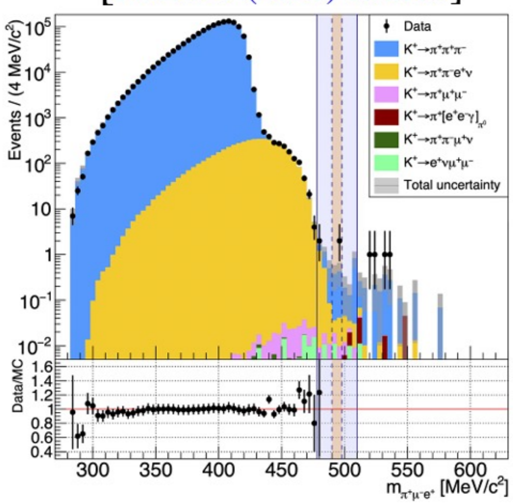


LNV possibly mediated by a Majorana neutrino:



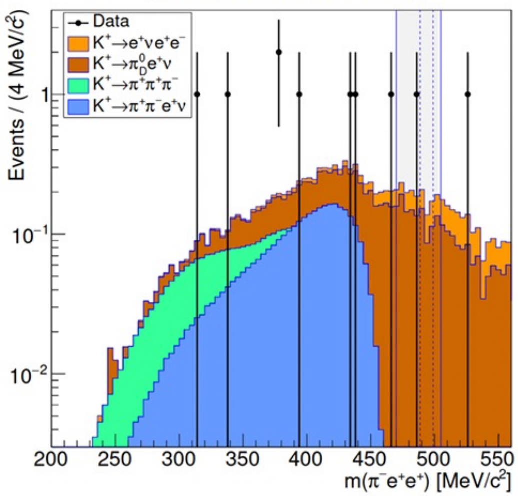
$K^+ \to \pi\mu e$

[PRL 127 (2021) 131802]



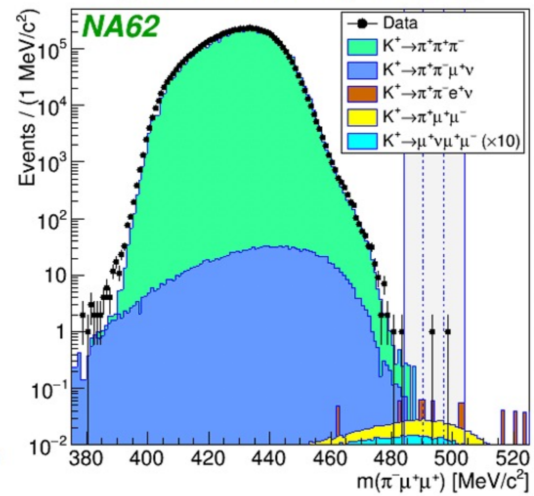
$K^+ \to \pi^- e^+ e^+$

[arXiv:2202.00331]



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

[PLB 797 (2019) 134794]



Obtained Upper Limits on BRs ~ O(10^{-11})