Status and prospects of rare kaon decay experiments

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On behalf of the NA62 Collaboration

RENCONTRES DU VIETNAM

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WINDOWS ON THE UNIVERSE

Outline

- Kaon Physics key observables
- Kaon physics **@J-PARC** :
  - **KOTO** results and short-term prospects
  - Long term prospect **KOTO II**
- Charged **kaon factory @CERN :** the **NA62** experiment
  - Measurement of the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay
  - Precision measurements, χ_{PT} studies
  - LFUV, LFV, LNV studies → **See talk by A. Shaikhiev**
  - Dark sector with kaons → **See talk by A. Kleimenova**
- Future of kaon physics **@CERN** → **See talk by E. Goudzovski**

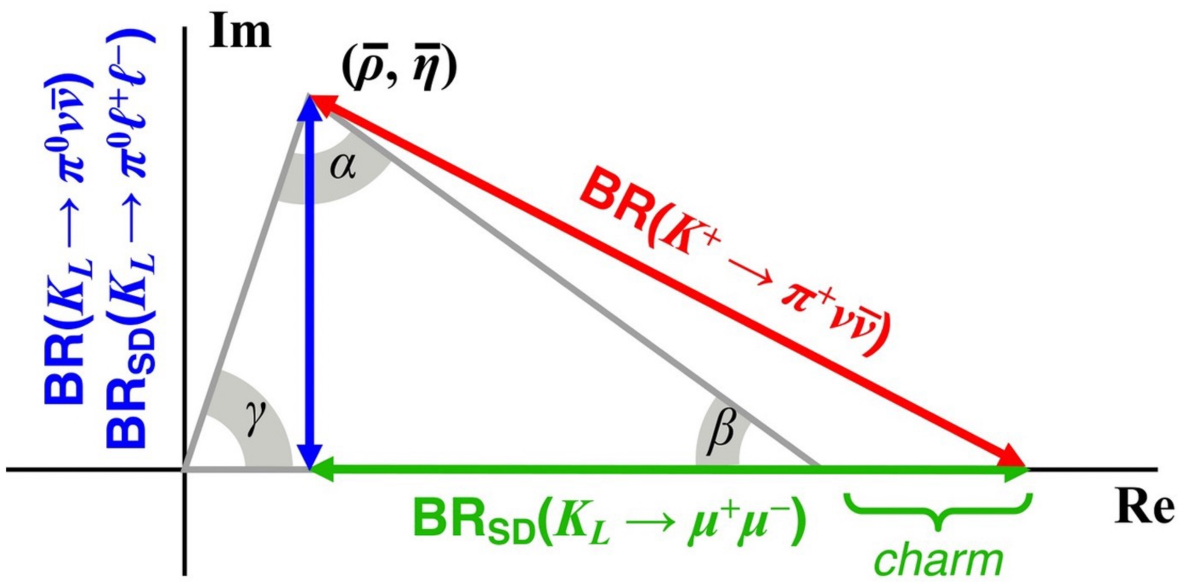
Kaon Physics key observables

Rare kaon decays:

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	< 300	KOTO	2019
$K^+ \to \pi^+\nu\bar{\nu}$	90%	4%	8.4 ± 1.0	10.6 ± 4.0	NA62	2021
$K_L \to \pi^0 e^+ e^-$	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

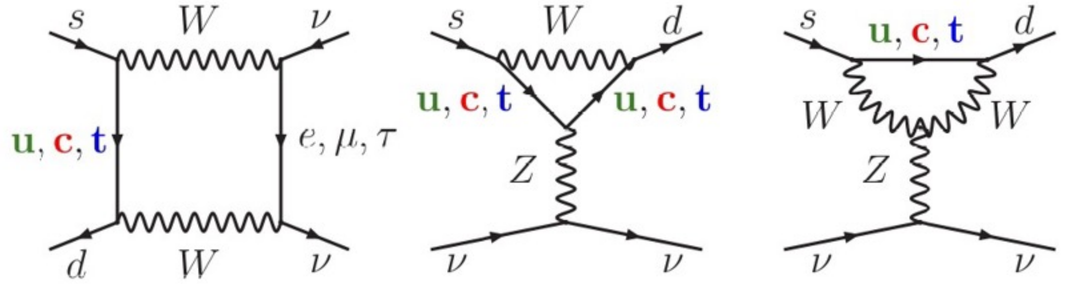
(see also arXiv:2203.09524)



- FCNC processes dominated by box and Z-penguin diagrams
- Highly GIM-suppressed with very small rates in SM
- SM rates determined by V_{CKM} with minimal non-parametric theory uncertainties
- The current focus is the Golden Mode $K \to \pi\nu\bar{\nu}$ uniquely clean theoretically and sensitive to new physics

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

Box and Penguin (one-loop) diagrams



- ✓ FCNC process forbidden at tree level
- ✓ s→d transition and highest CKM suppression
  → extremely rare process
- ✓ Theoretically clean: short distance contribution
- ✓ Hadronic matrix element evaluated experimentally using the precisely measured semileptonic BR(K_{l3})

SM Predictions (uncertainty mainly from CKM parameters) *[Buras et al., JHEP 11 (2015) 033]*

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

BR($K^0\rightarrow \pi^0\nu\bar{\nu}$) = $(3.4 \pm 0.6) \cdot 10^{-11}$

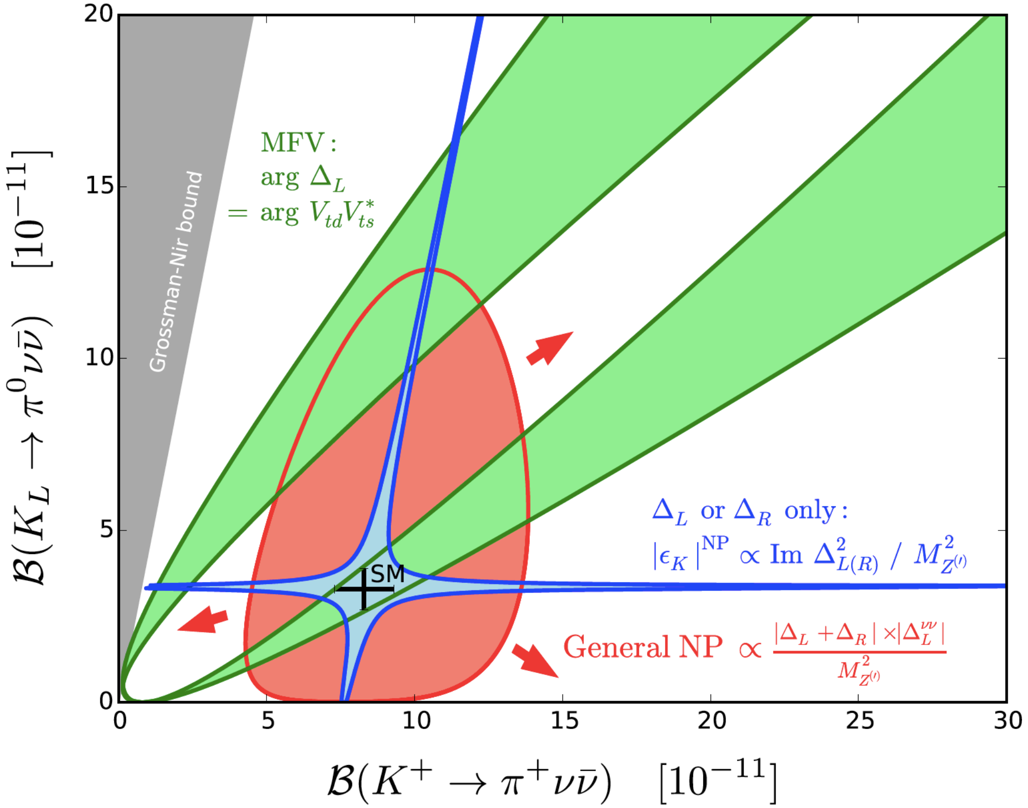
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

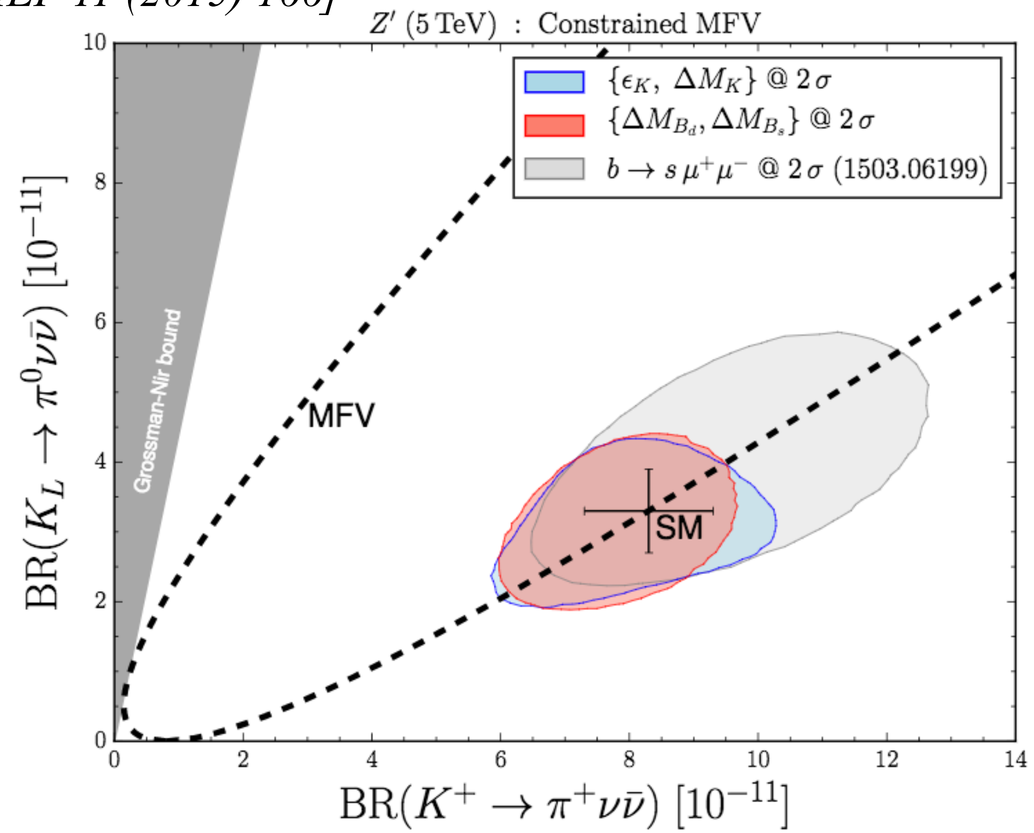
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{\sin(\gamma)}{\sin(73.2^\circ)}\right]^{2}$$

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

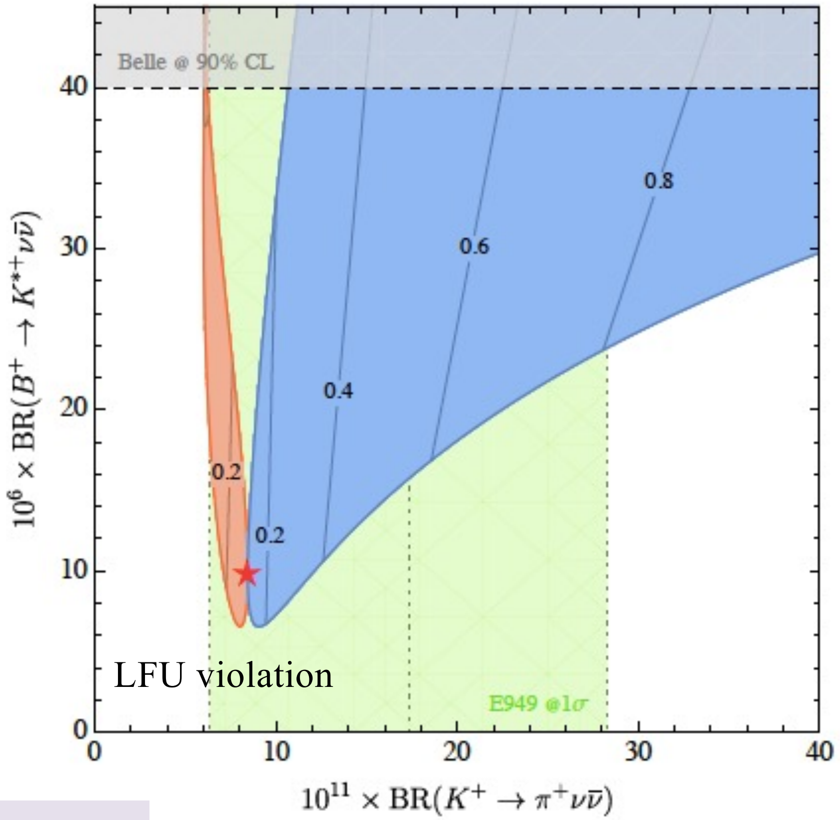
Indirect searches for NP with high precision studies of rare K decays

[Buras, Buttazzo, Knegjens., JHEP 11 (2015) 166]





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



High sensitivity to New Physics:

- Unique probe in flavour physics to reach a model independent $\mathcal{O}(100)$ TeV mass scale
- Correlations significantly change for different classes of NP models *[EPJ C76 (2016) no.4 182]*
- $\mathcal{O}(50\%)$ BR variations in many different models (Z', Little Higgs, Randall-Sundrum, non-MVF MSSM, LFUV leptoquark…)
- Measurement of both K^+ and K_L modes discriminate among different scenarios

NP searches complementary/alternative to LHC

Kaon physics @ JPARC

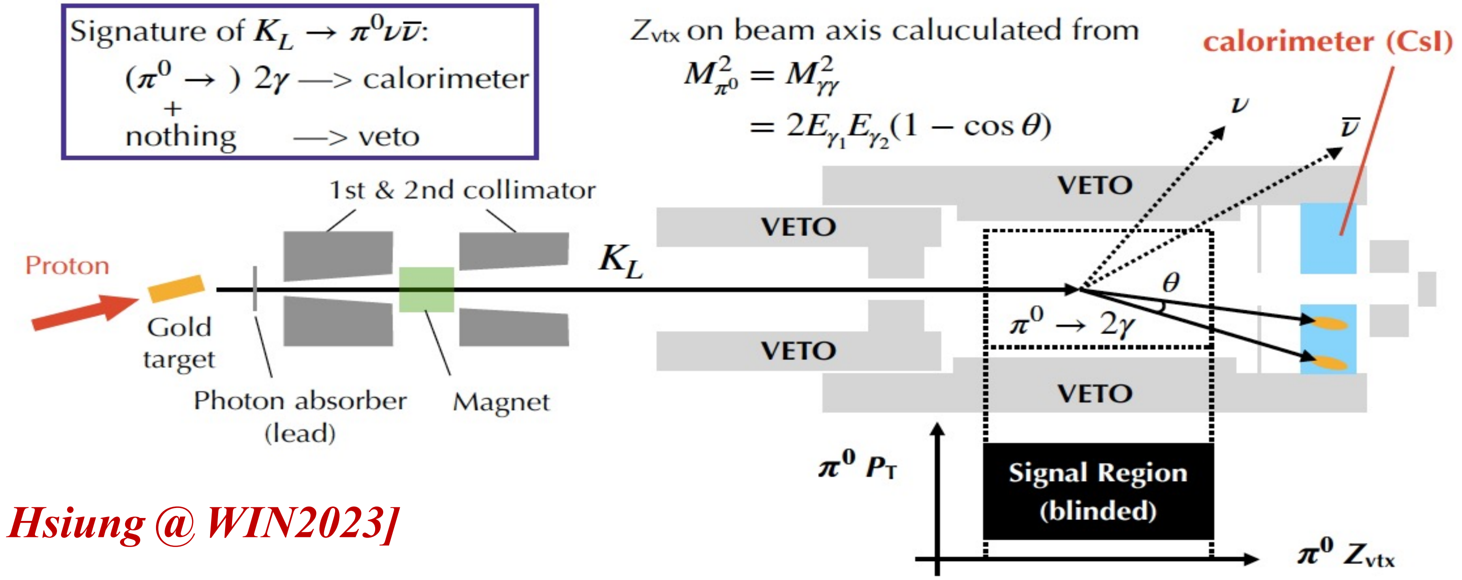
The KOTO experiment

Study of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ @ J-PARC in Ibaraki, Japan

→ GOAL: to observe few SM events

[PRL 122 (2019) 021802, PRL 126 (2021) 121801]

Extremely challenging measurement



[Yee Bob Hsiung @ WIN2023]

Primary beam:

- 30 GeV/c protons on gold target
- 2s spill length

Secondary beam:

- neutral beam: K_L / n / γ
- **2016–2018:**
  - p_K = 1.4 GeV/c (peak momentum)
  - K_L flux: 2.1 x 10^{-7} K_L per PoT

Signature:

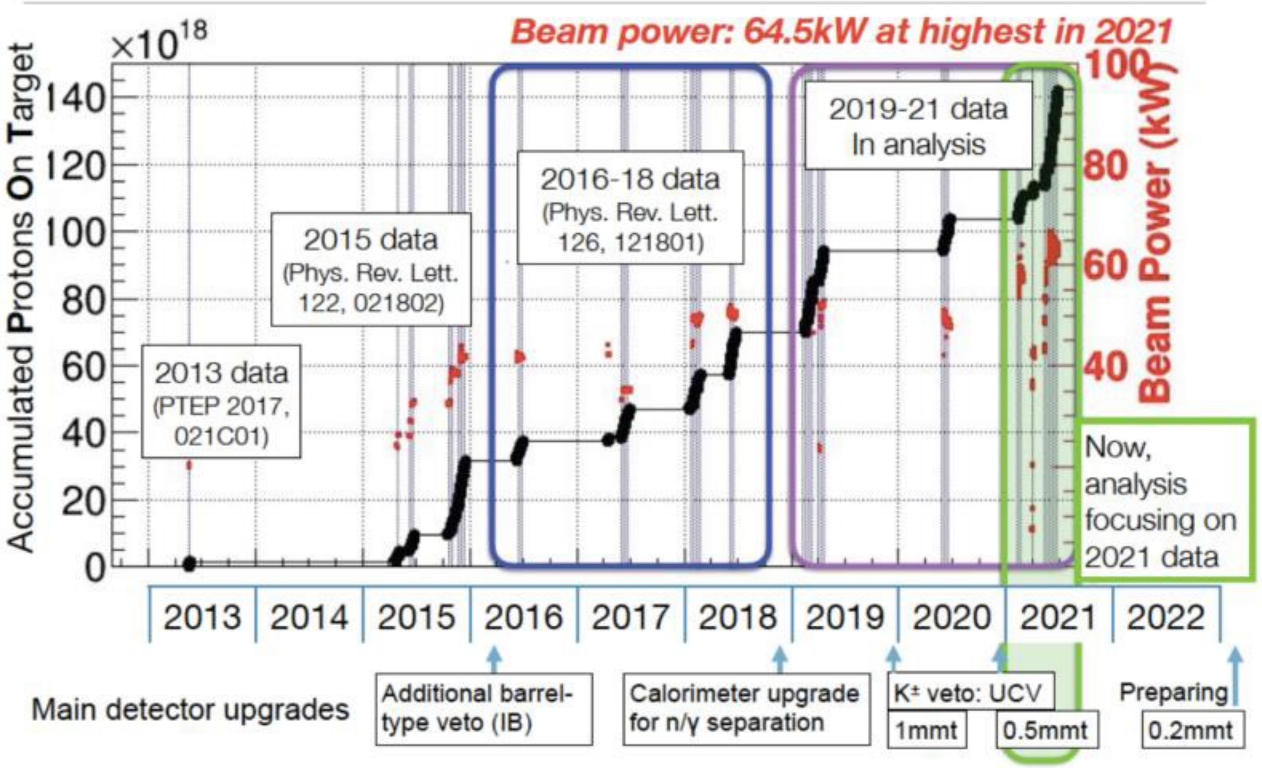
2γ + missingP_T + nothing

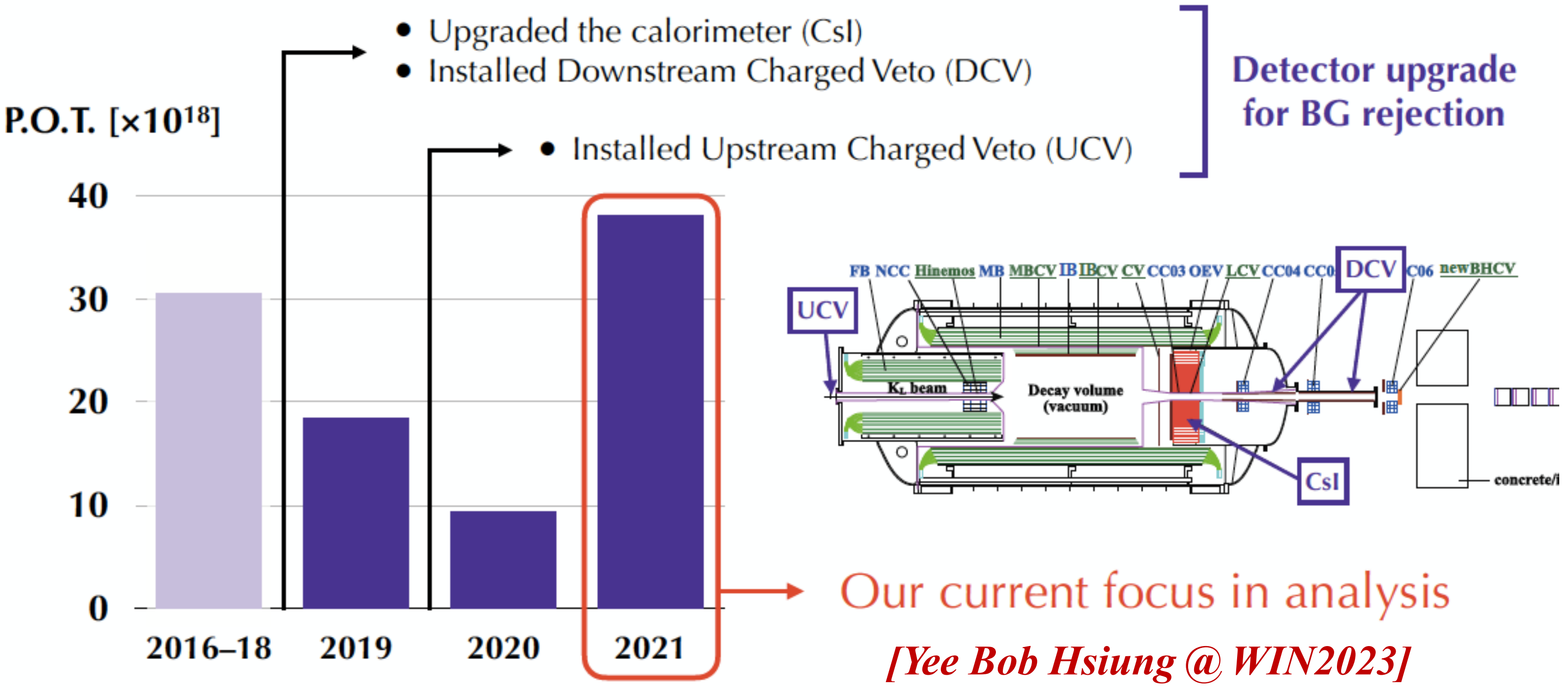
- CsI calorimeter to measure 2γ
- Hermetic veto to ensure nothing else

KOTO Keystones

- Well collimated neutral beam (precise P_T)
- Good photon detection
- Hermetic vetoes in decay region and in beam region after the EM calo

KOTO physics runs





2015 physics run: 24-42 kW beam power, 2.2×10^{19} PoT
BR($K_L \rightarrow \pi^0 \nu\bar{\nu}$)$<3.0\times10^{-9}$ (90% CL) *[PRL 122 (2019) 021802]*

2016-2018 physics runs: 31-51 kW beam power, 3.05×10^{19} PoT
BR($K_L \rightarrow \pi^0 \nu\bar{\nu}$)$<4.9\times10^{-9}$ (90% CL) *[PRL 126 (2021) 121801]*

2019-2021 physics run: 64.5 kW max beam power
- Twice the 2016-2018 data set
- Lower backgrounds

Detector improvements in 2019-2021

- Multi-Pixel Photon Counters (MPPCs)
- Downstream Charged Veto counter (DCV)
- Upstream Charged Veto counter (UCV)

Upgrade completed in 2020
→ focus on the analysis of the 2021 data set

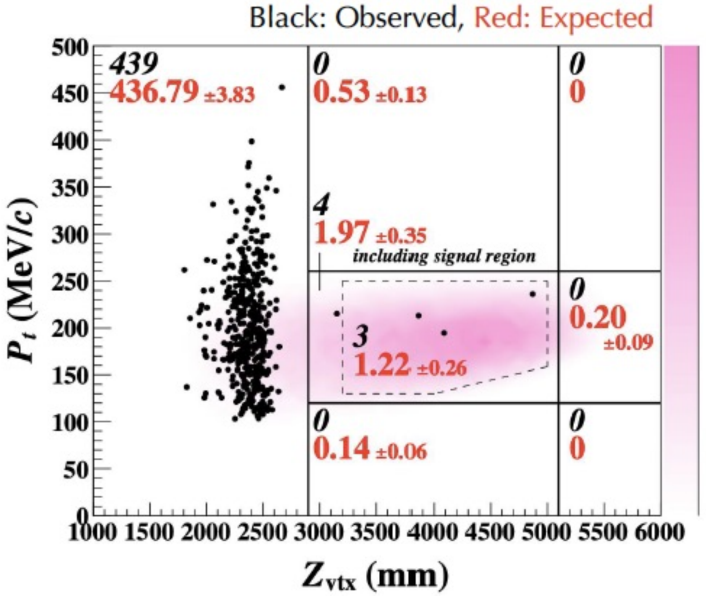
KOTO Data Analysis

2016-2018 Data Analysis

Background Table

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

Total #BG = 1.22 ± 0.26



Acceptance($K_L \to \pi^0 \nu \bar{\nu}$) from MC:
Decay in FV: 3.3%
Overall acceptance: 0.6%

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

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

→ **Expected:** 0.04 signal + 1.22 background events
Observed: 3 events in the signal box

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

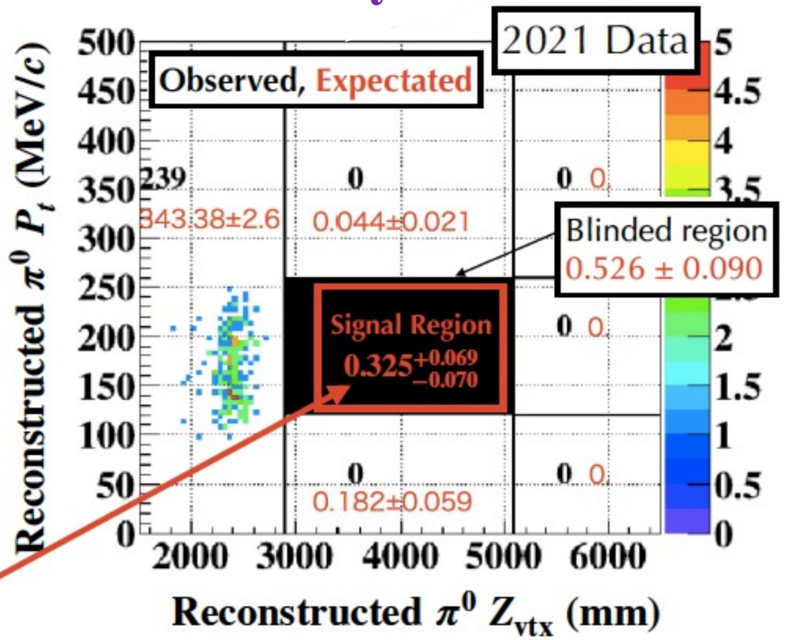
[PRL 126 (2021) 121801]

2021 Data Analysis

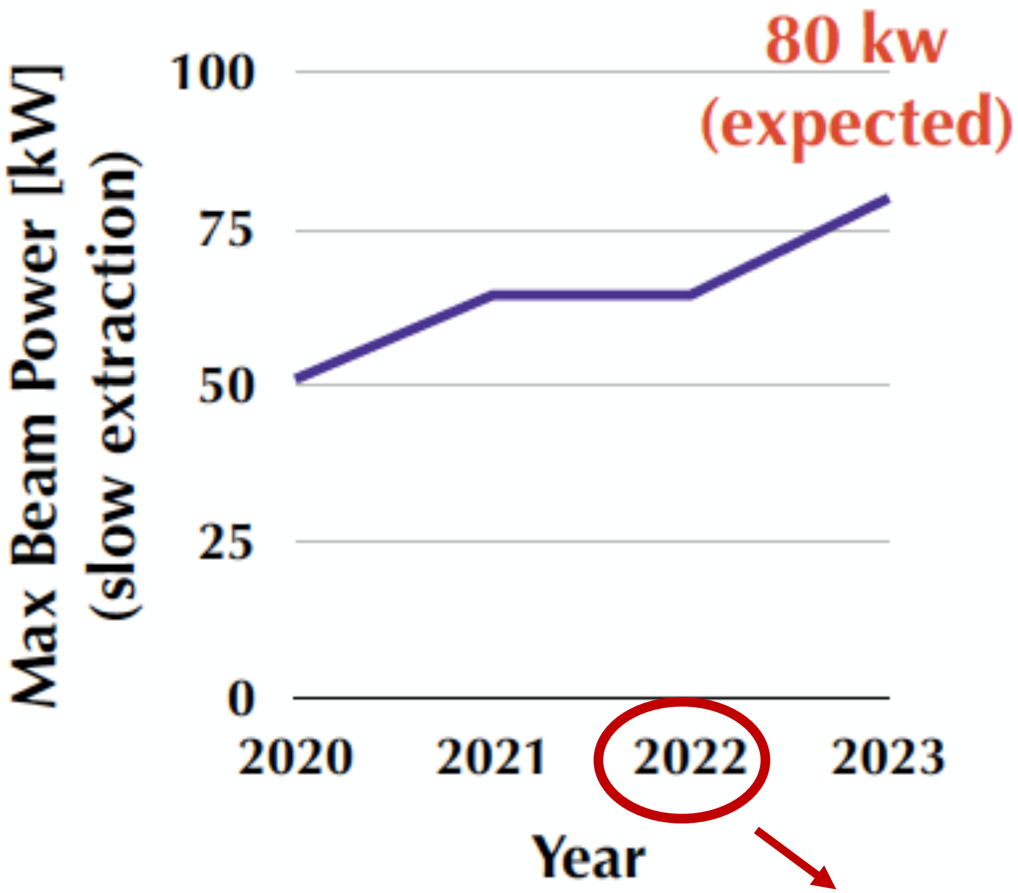
- Blind analysis
- Single Event Sensitivity: **SES = 7.9 x 10^{-10}**
- Expect to complete the analysis of 2021 data this year

Source	#BG in Signal Region
$K_L \to 2\pi^0$	0.141 ± 0.059
$K^{\pm}$	0.043 +0.016/-0.022
Hadron cluster	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 at CV	0.023 ± 0.010
Upstream π^0	0.02 ± 0.02
$K_L \to 3\pi^0$	0.019 ± 0.019
Total	**0.325 +0.069/-0.070**

Preliminary



[Yee Bob Hsiung @ WIN2023]



Main Ring: magnet power supplier upgrade during LS

J-PARC Main Ring upgrade

- Beam power increased to 80 kW (~100 kW in the future)
- Beam Time: 2023 - 2026

DAQ upgrade

- handle higher trigger rate
- introduce new triggers

DAQ Rate: ~10 k events/spill → 25 - 30 k events/spill

Expect to approach SM SES below 10^{-10} by 2025, operating in low-background regime

[Yee Bob Hsiung @ WIN2023]

KOTO II : measurement of the BR($K_L \rightarrow \pi^0 \nu\bar{\nu}$)

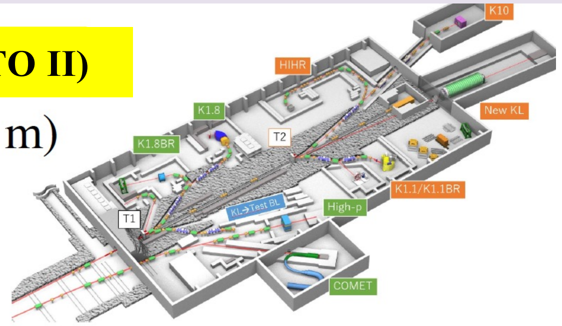
Design of KOTO II @ J-PARC

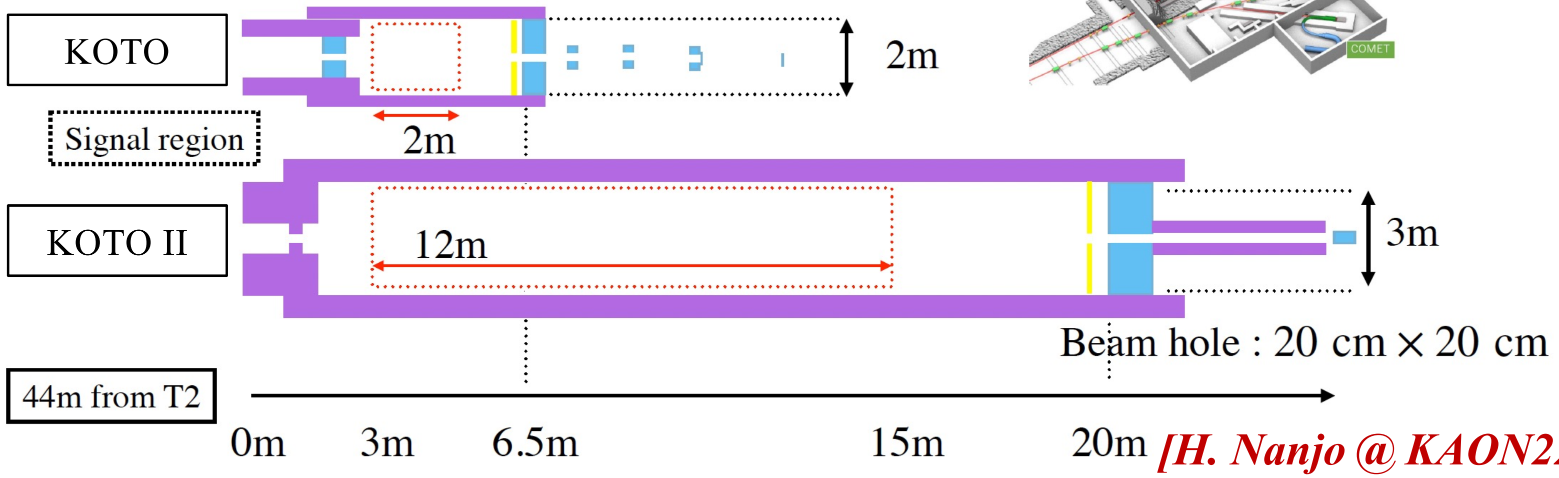
[arXiv 2110.04462 Extension of J-PARC Hadron Experimental Facility : Third White Paper]
[arXiv 2204.13394 Searches for new physics with high-intensity kaon beams]

Peak K_L momentum: 1.4 GeV/c (KOTO) → 3 GeV/c (KOTO II)

Possible to use longer decay volume (2 m → 12 m)

Larger diameter calorimeter (2 m → 3 m)





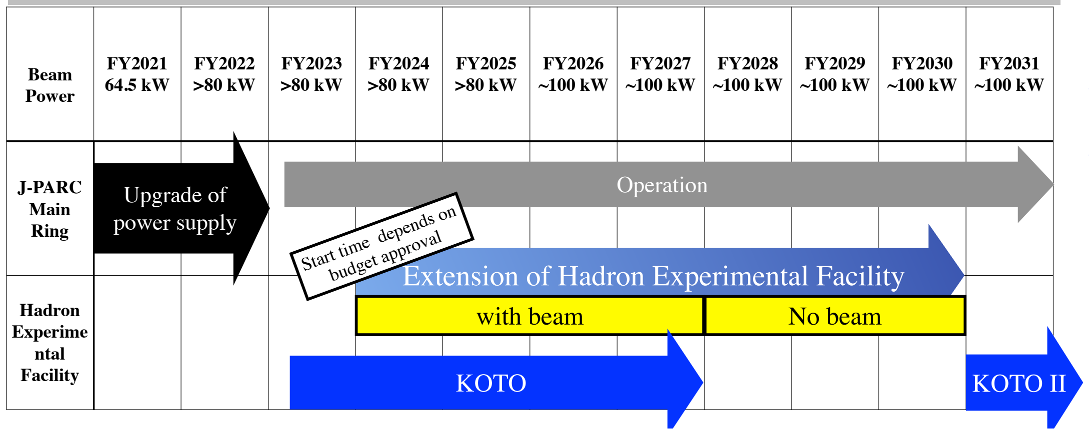
[H. Nanjo @ KAON22]

Upgrade to reach sensitivity $O(10^{-13})$

- Increase proton beam power → 100 kW
- Higher kaon momentum
- Higher K_L flux (keeping same ratio of n/K_L)
- Complete rebuild of the detector
- Require hadron hall extension (supported by KEK PIP 2022)

Design work is in progress

TIMELINE



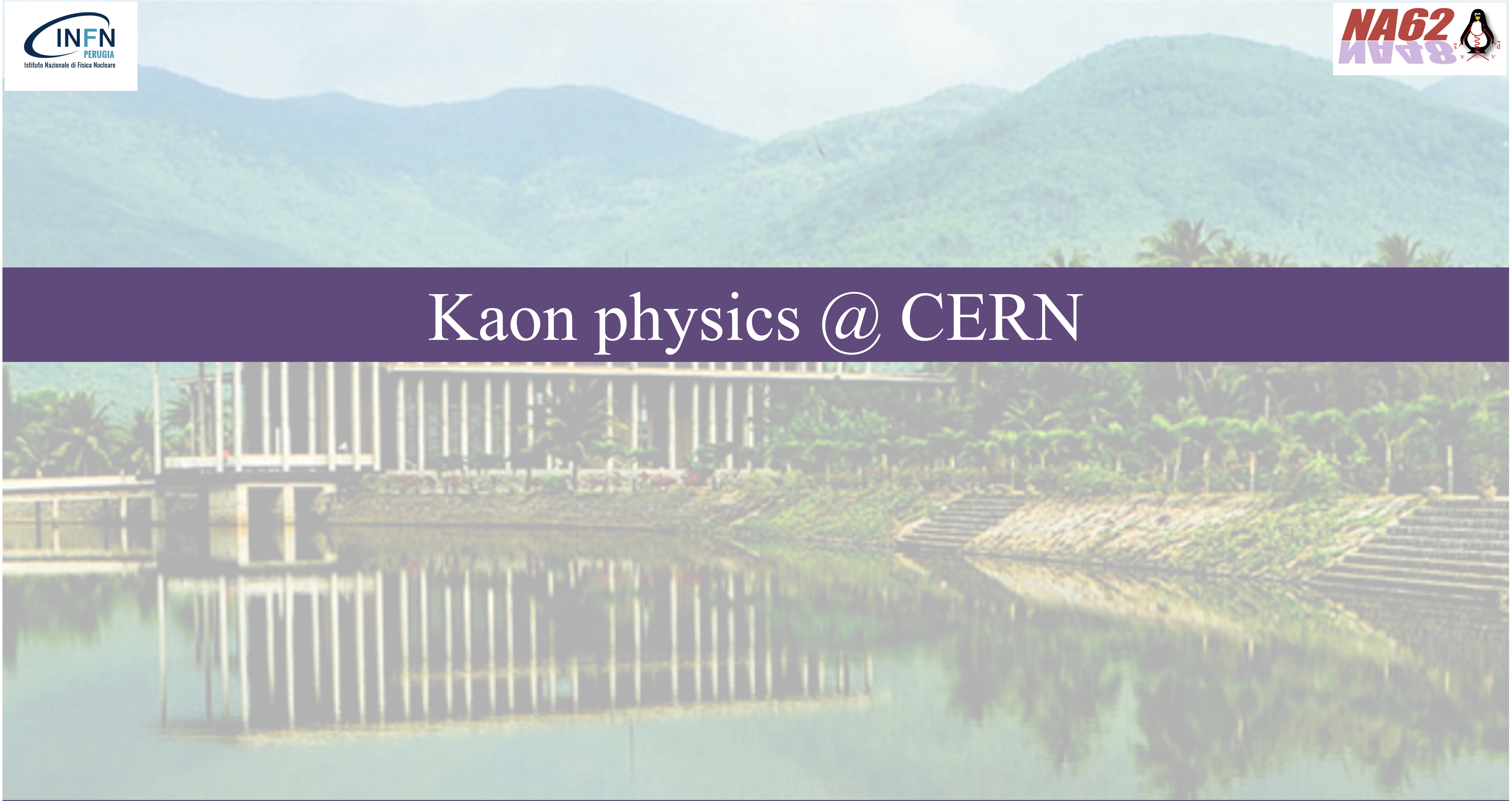
- Current baseline is 7-year construction
- Early realization of the hall extension

→Start of KOTO II in 2030s

[Courtesy of H. Nanjo]

Aim to observe ~ 40 SM events

- **BR measurement at 30% precision**
- **5 σ discovery of the decay**
- **Deviation from SM indicates new physics**



Kaon physics @ CERN

Kaons @ CERN

NA31 : $K_L + K_S$
Search for direct CPV : ε'/ε
→ **1986-1988**

NA48 : $K_L + K_S$
Search for direct CPV : ε'/ε
→ **1997-2001**

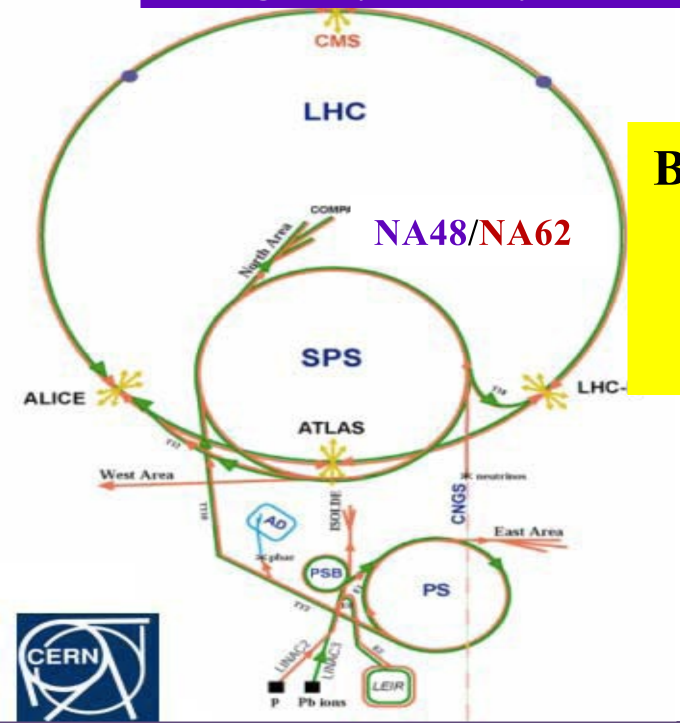
NA48/1 : K_S
Rare K_S/Hyperon decays, CPV tests
→ **2002**

NA48/2 : $K^+ + K^-$
Search for direct CPV :
charge asymmetry measurement
→ **2003-2004**

2007-2008 ← **NA62-R_K :** $K^+ + K^-$
$R_K = K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ measurement

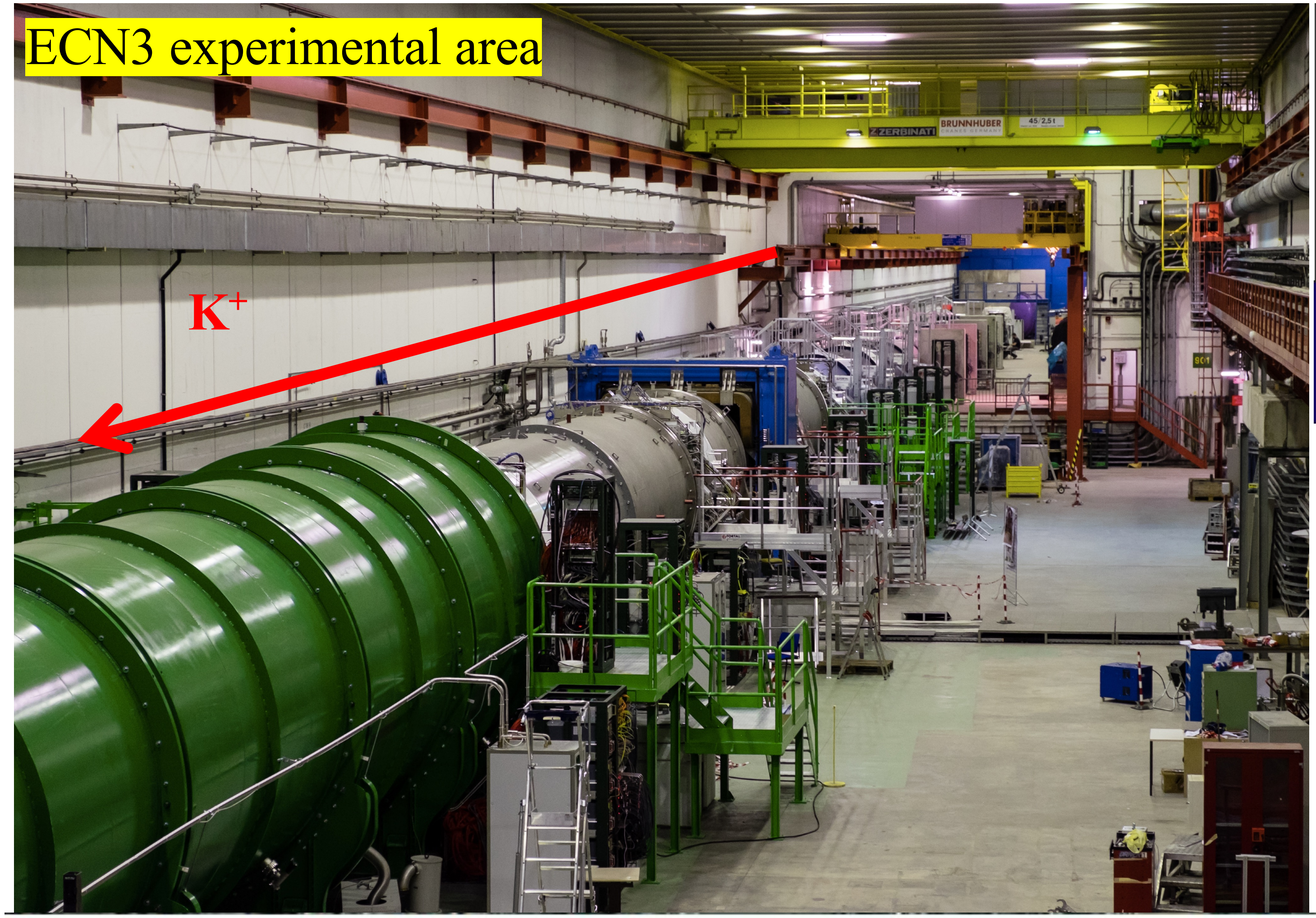
2016-2018 ← **NA62-RUN1 :** K^+
Measurement of $K^+ \rightarrow \pi^+\nu\bar{\nu}$

2021-2025 ← **NA62-RUN2 :** K^+
Measurement of $K^+ \rightarrow \pi^+\nu\bar{\nu}$



Broad physics programme thanks to unprecedented statistics for many decay modes

The NA62 experiment



MAIN GOAL:

Measurement of BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) @ 10% accuracy

→ novel K^+ decay in flight technique

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

2008	2009-2015	2015	2016-2018	2021-2025
NA62 Approval	Detector R&D Installation	Commissioning	Physics RUN1 (~407 days)	Physics RUN2 (started July 2021)

RUN2 2021-LS3

- Complete $\pi^+ \nu \bar{\nu}$ measurement
- Broad physics programme
  - Precision measurements
  - Rare and forbidden decays, LFV and LNV
  - Dump mode → Exotic searches (Dark Photons, FIPs, etc)

NA62 Collaboration ~300 participants from 31 institutions

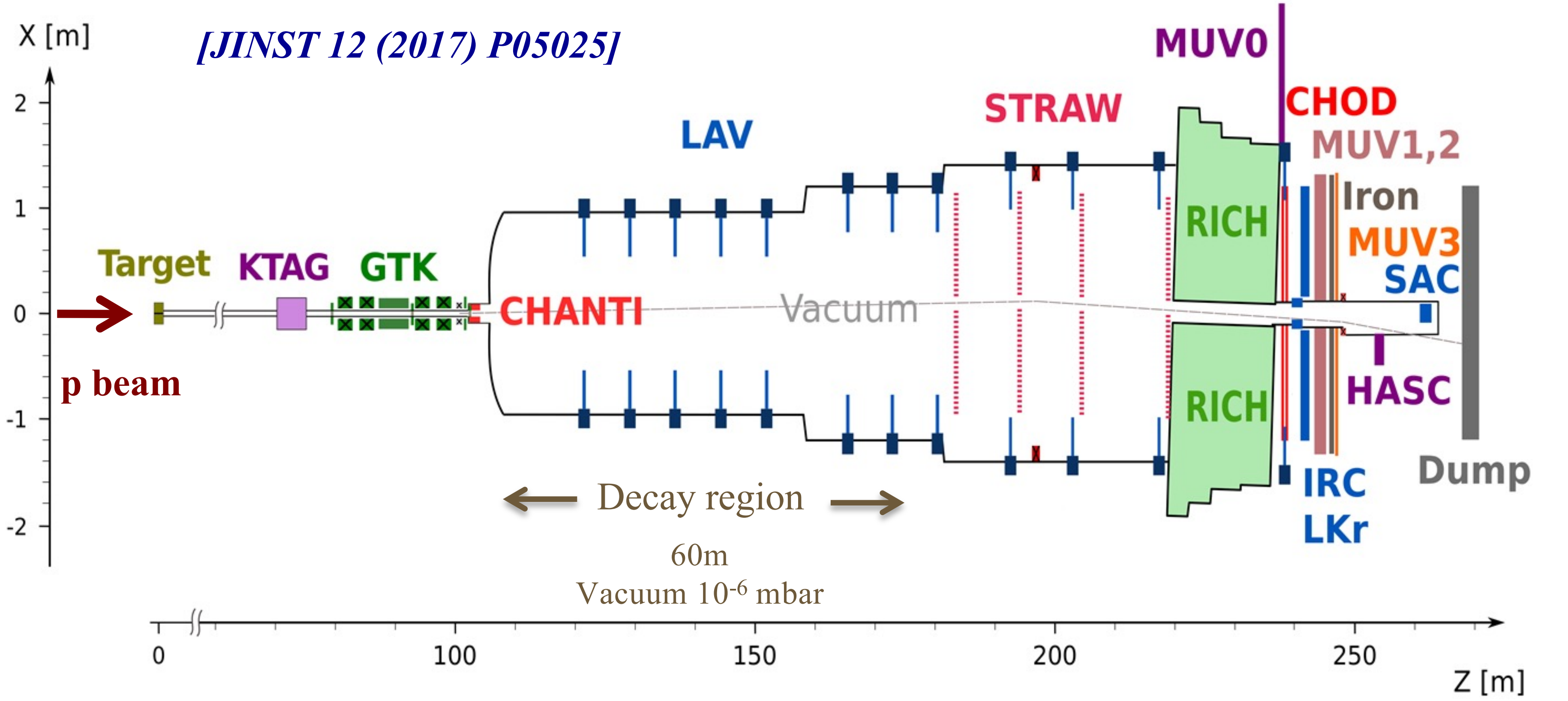
NA62 beam and detector

Primary beam: CERN SPS protons

- 400 GeV/c protons on beryllium target
- ~ 10^{12} ppp; ~3.5 s spill

Secondary beam:

- unseparated positive beam π(70%) / K(6%) / p(23%)
- p_K = 75 GeV/c (Δp/p ~ 1%)
- Nominal beam rate = 750 MHz@GTK
- Beam rates in RUN1: 2016 2017 2018
  ~300 ~500 ~600 MHz
- ~5 MHz K^+ decays in 60m fiducial volume



UPSTREAM DETECTORS (K^+)

- GTK: Silicon pixel beam tracker
- KTAG: Differential Cherenkov for K^+ ID (σ_t~70ps)
- CHANTI: against inelastic beam/GTK interactions

Tracking

PID

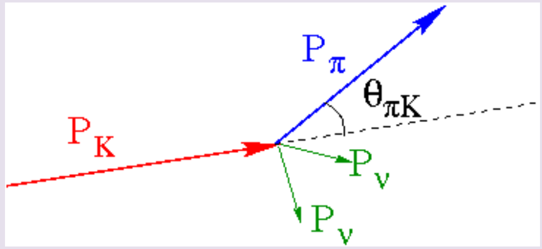
Veto

DOWNSTREAM DETECTORS (π^+)

- STRAW: Track momentum spectrometer
- CHOD: plastic scintillators for fast charged trigger
- RICH: Cherenkov counter for π/μ/e ID (σ_t~70ps)
- LKR/MUV1-2: calorimetric system
- LAV/IRC/SAC: photon veto detectors
- MUV3: muon veto

NA62: $K^+ \to \pi^+ \nu\bar{\nu}$ RUN1 analysis

- **Decay in flight technique**
- **High-momentum Kaon beam** $15 < p_\pi < (35)\ 45$ GeV/c
- **High intensity**
- **High signal efficiency**

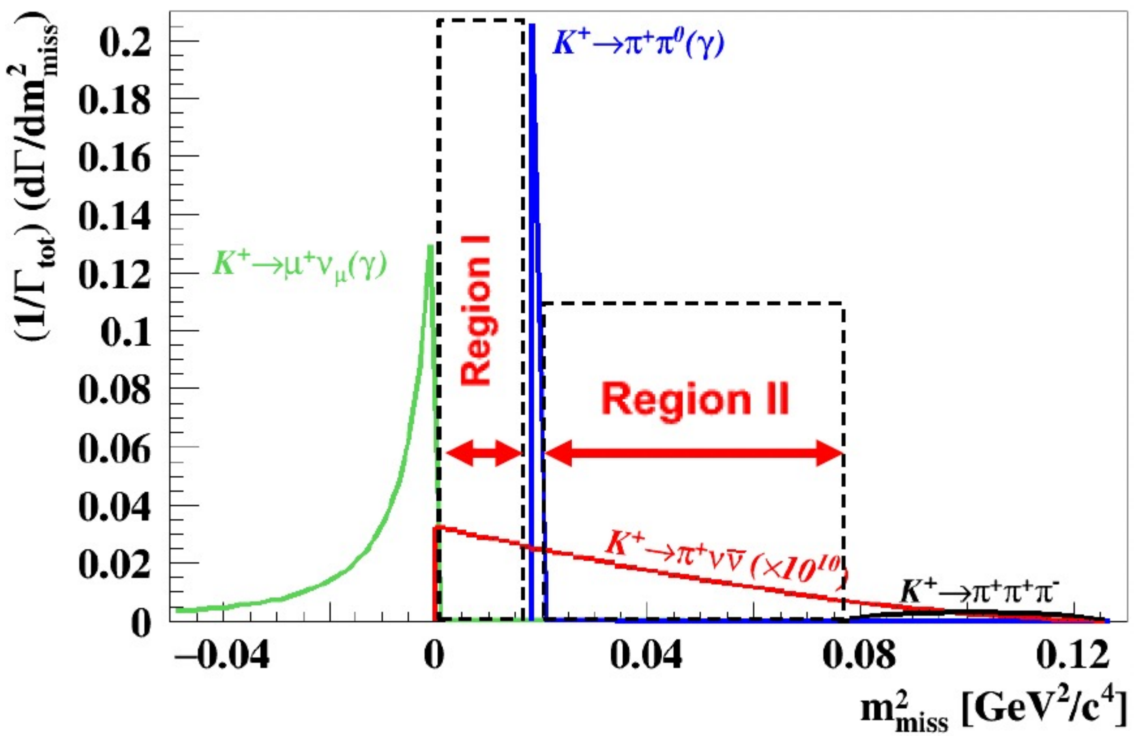


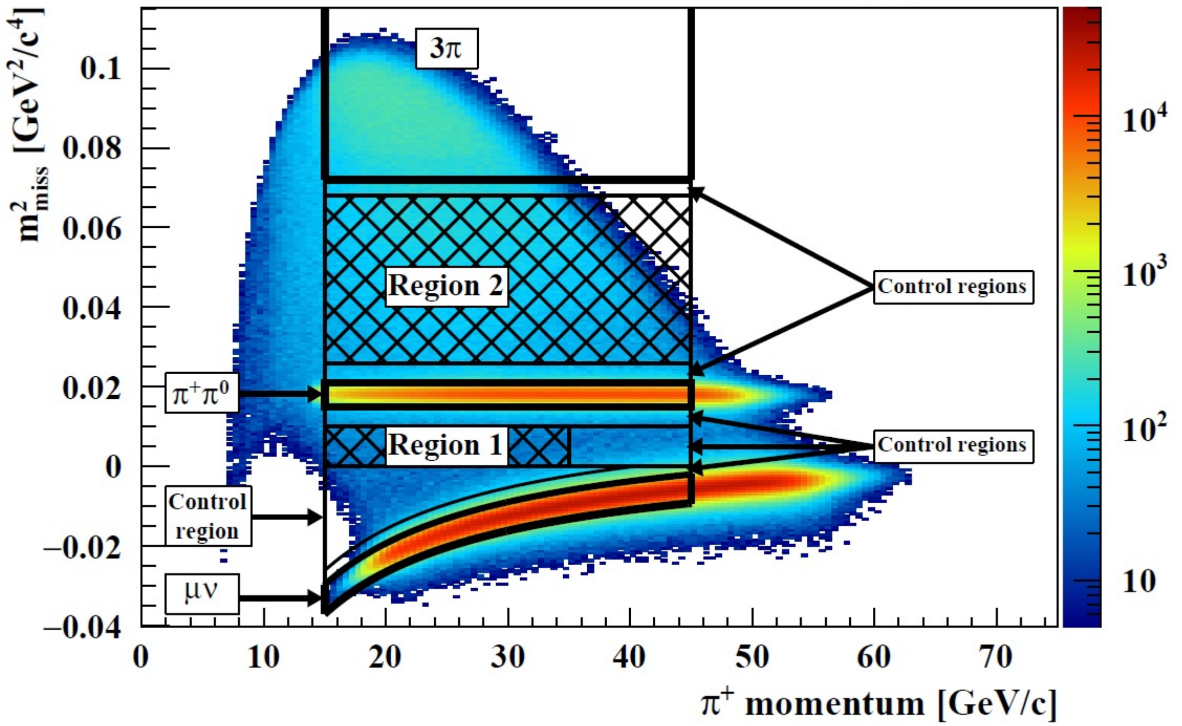
→ Kinematic selection based on $\mathbf{m^2_{miss}} = (\mathbf{P_K} - \mathbf{P_\pi})^2$

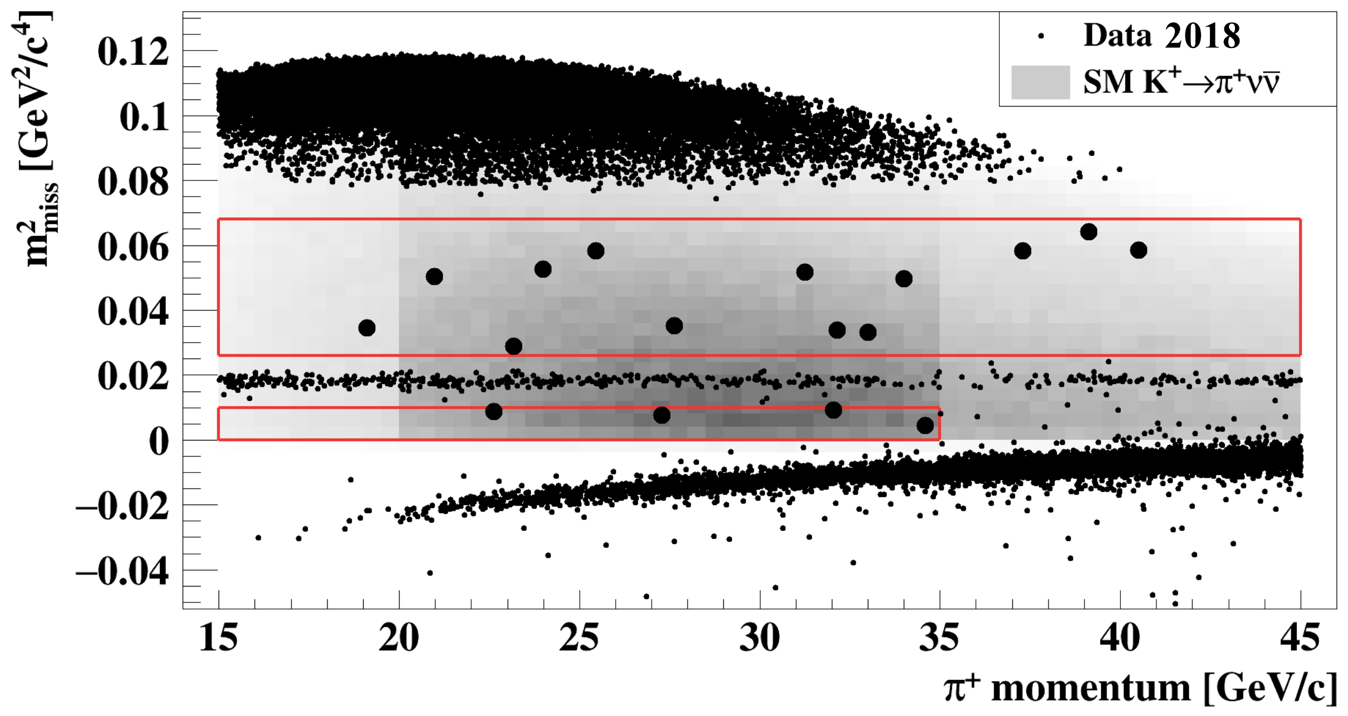
Performance keystones

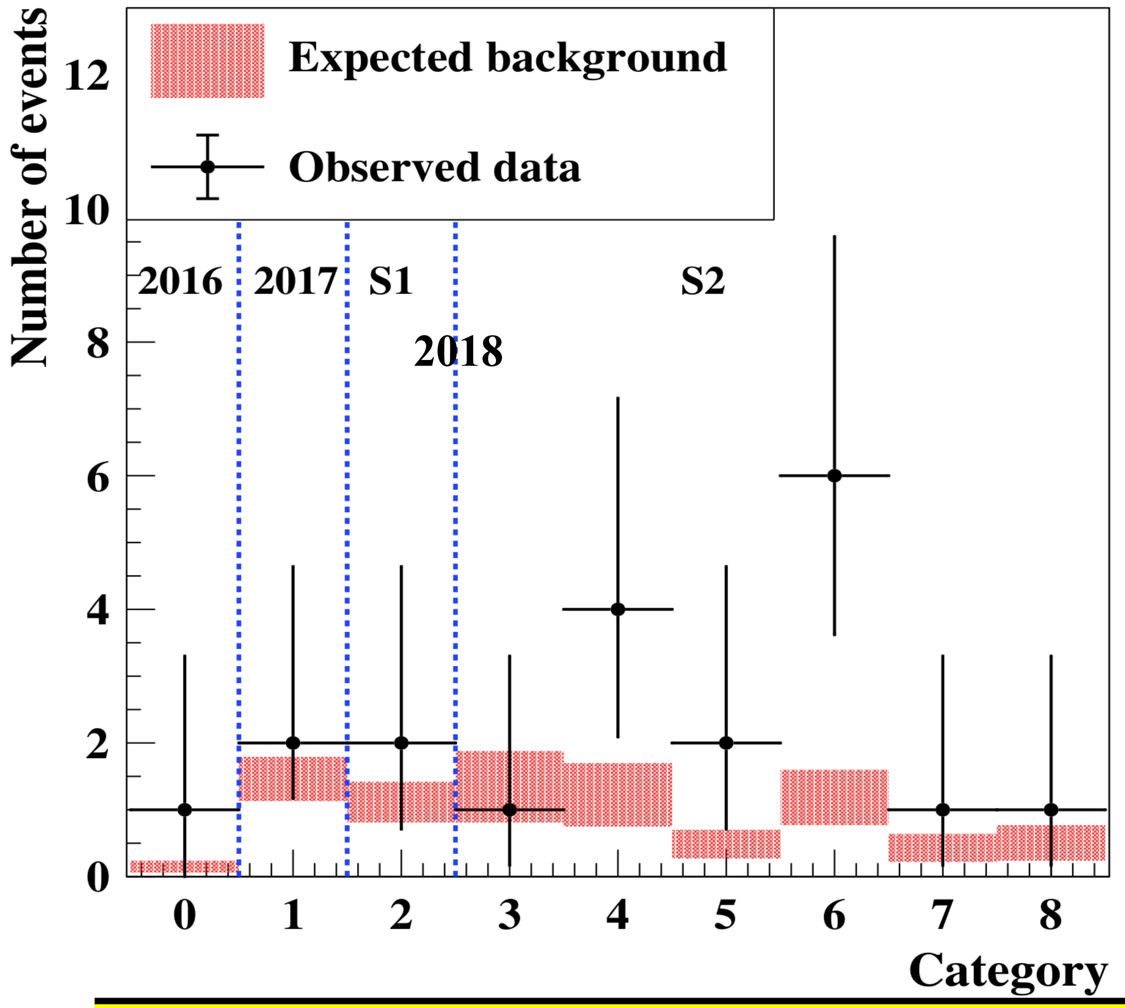
- Precise timing between subdetectors $O(100\text{ ps})$
- Kinematic background suppression $\geq 10^3$
- Particle-ID
- π^0 suppression (from $K^+ \to \pi^+\pi^0$) $\geq 10^8$
- Muon suppression $\geq 10^8$

- MVA techniques for PID and accidental background suppression
- Normalization from $K^+ \to \pi^+\pi^0$
- Selection optimized in bins of π^+ momentum
- Data-Driven estimation of background from K^+ decays and accidentals
- Background estimation validated in control regions
- Two signal regions in m^2_{miss}
- Blind analysis :
  Signal and Control kinematic regions masked during the analysis









Combined NA62 results 2016+2017+2018

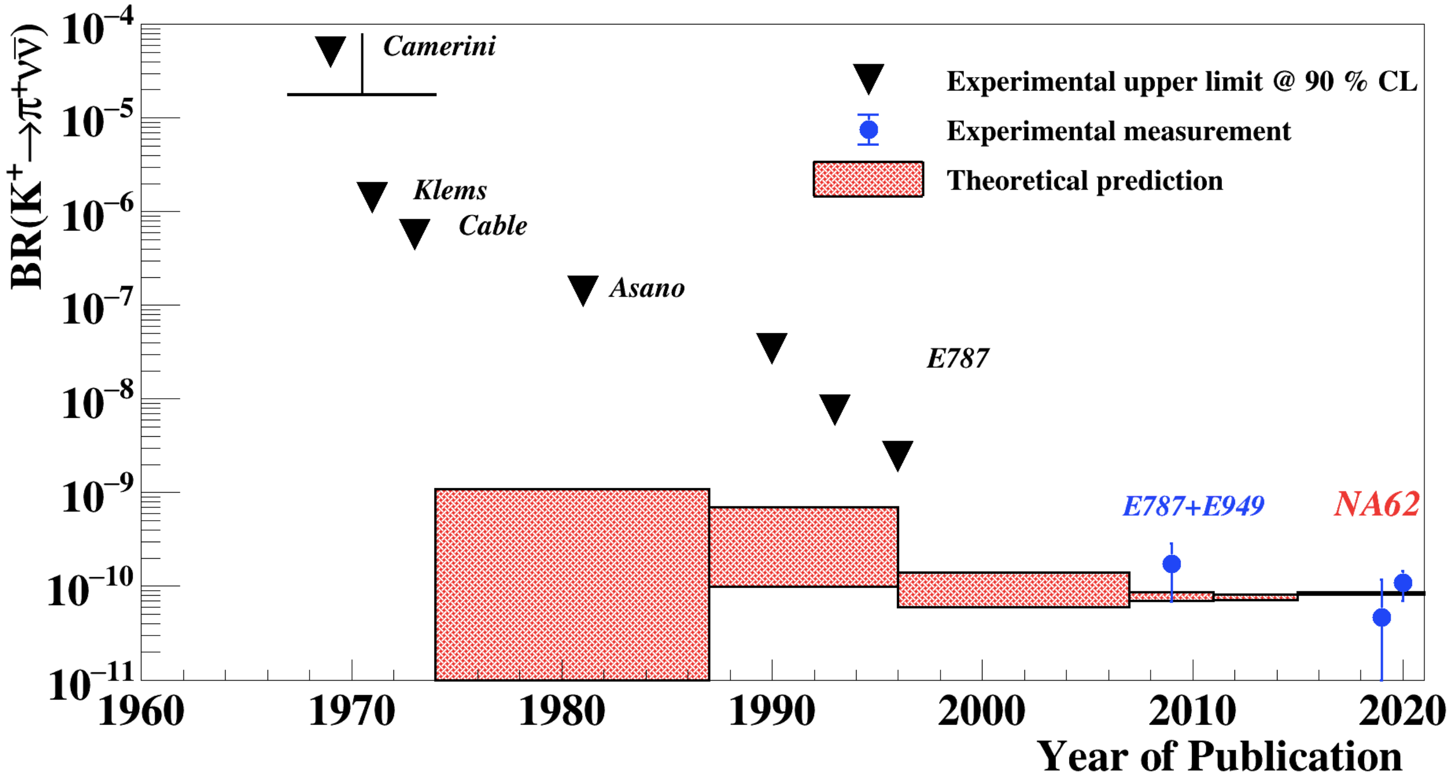
- SES = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$
- Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected backg: $7.03^{+1.05}_{-0.82}$
- 20 events observed in signal regions
- P(bkg only) = 3.4×10^{-4}
- 3.4σ significance

N. events/Year	2016	2017	2018
Observed events	1	2	17
Expected signal	0.267 ± 0.038	2.16 ± 0.29	7.58 ± 0.85
Exp. background	0.152 ± 0.090	1.46 ± 0.33	$5.42^{+0.99}_{-0.75}$

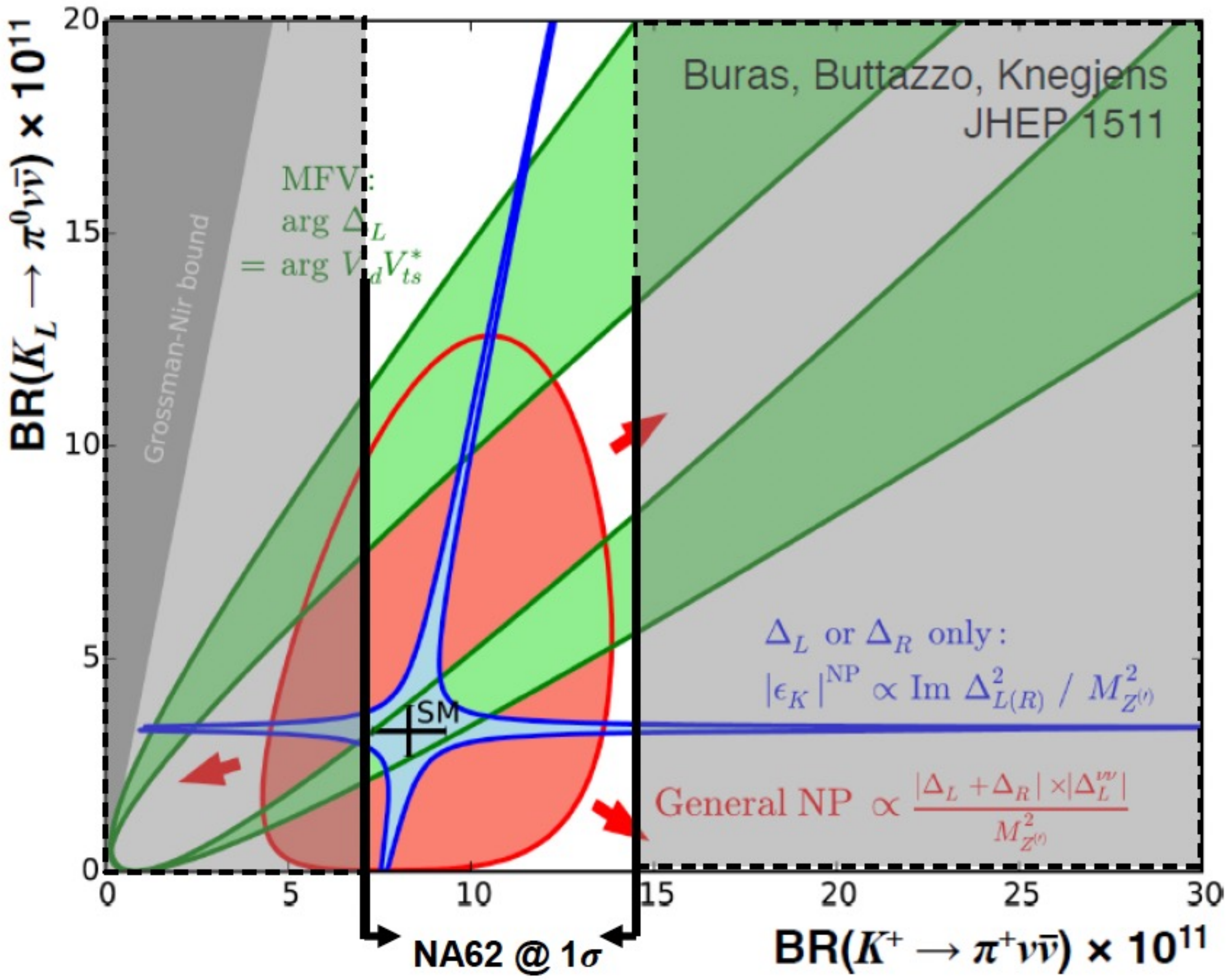
$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ at 68% CL

[JHEP 06 (2021) 096]

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ at 68% CL



NOT-SUSY models *[See also arXiv:2006.01138]*



- **Most precise measurement of the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay rate to date**
- **Strongest evidence so far (3.4 σ) for its existence**
- **Part of parameter space already ruled out: large BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) deviations from SM excluded**

Next target:

improved precision to match theoretical uncertainty by the end of RUN2

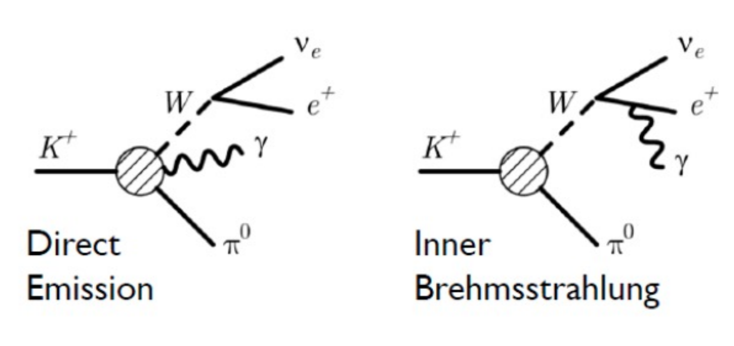
$K^+ \to \pi^0 e^+ \nu\gamma$ precision measurement

Decay described in ChPT

- $BR(K^+ \to \pi^0 e^+ \nu\gamma)$ strongly depends on E_γ and $\theta_{e\gamma}$ in the K^+ rest frame

	$E^j_\gamma,\ \theta^j_{e\gamma}$	$\mathcal{O}(p^6)$ ChPT [EPJ C 50 (2007)]	ISTRA+ [PAN 70 (2007)]	OKA [EPJ C 81 (2021)]
$R_1 \times 10^2$	$E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
$R_2 \times 10^2$	$E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
$R_3 \times 10^2$	$E_\gamma > 10$ MeV, $0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

ChPT LD dominated

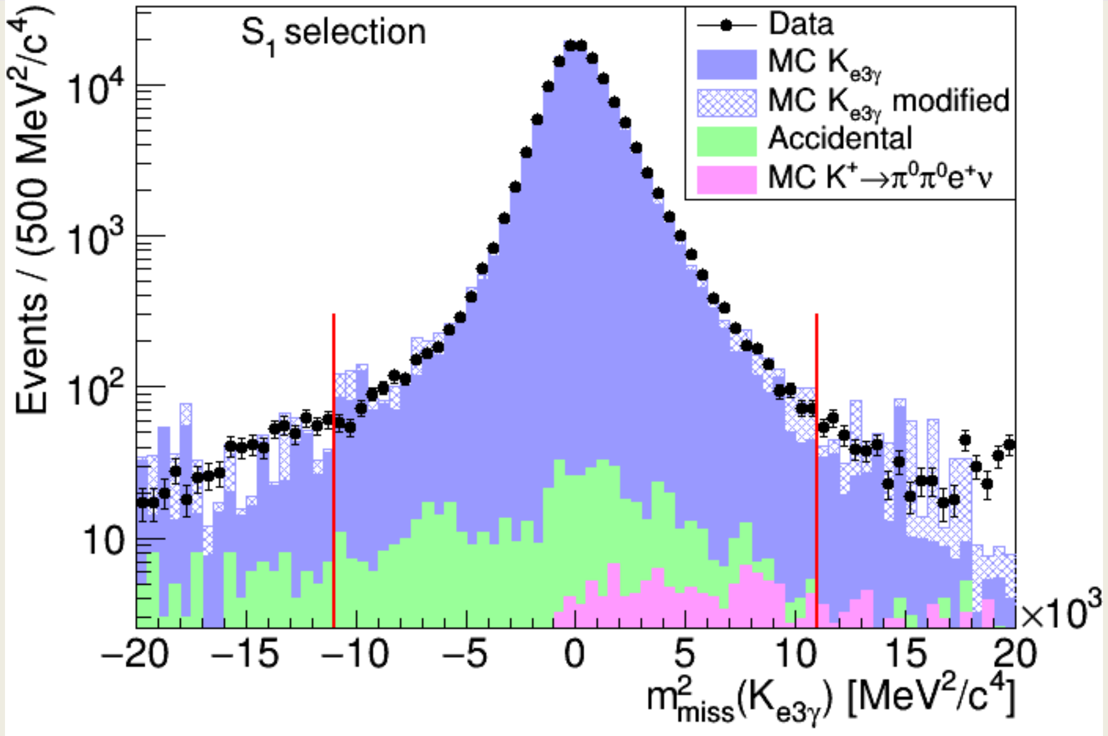


GOAL

- Measurement of normalized BR in three kinematic regions (R_1, R_2, R_3)
- Test of T-conservation through the T-odd observable ξ and its asymmetry A_ξ

$$R_j = \frac{\mathcal{B}(K_{e3\gamma^j})}{\mathcal{B}(K_{e3})} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E^j_\gamma,\ \theta^j_{e\gamma})}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{(M_K \cdot c)^3}, \quad A_\xi = \frac{N_{\xi>0} - N_{\xi<0}}{N_{\xi>0} + N_{\xi<0}}$$



Analysis on RUN1 data:

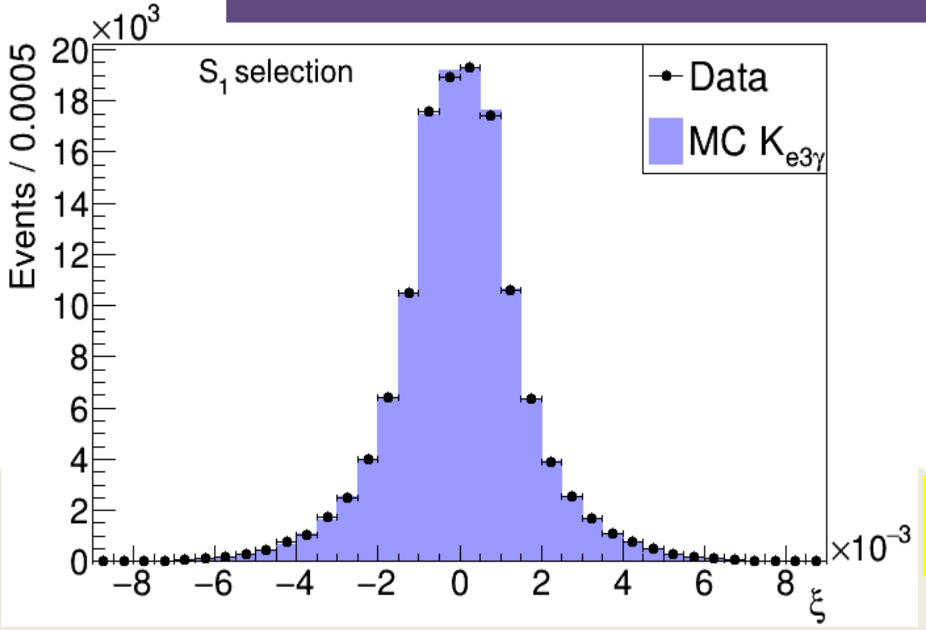
Signal: $K^+ \to \pi^0 e^+ \nu\gamma$

- e^+ track matching K^+ track; e^+ PID
- 2 EM calorimeter γ from π^0 + 1 radiative γ
- Veto of additional photons
- Conditions on $m^2_{miss}(K_{e3\gamma}) = (P_K - P_e - P_\pi - P_\gamma)^2$

Normalization: $K^+ \to \pi^0 e^+ \nu$

- Selected as signal without radiative γ
- Minimal differences in signal and normalization ⇒ reduced systematic effects

$K^+ \to \pi^0 e^+ \nu \gamma$ precision measurement



	Normalization	S_1	S_2	S_3
Selected candidates	6.6420×10^7	1.2966×10^5	0.5359×10^5	0.3909×10^5
Acceptance	$(3.842 \pm 0.002)\%$	$(0.444 \pm 0.001)\%$	$(0.514 \pm 0.002)\%$	$(0.432 \pm 0.002)\%$
Accidental	—	$(4.9 \pm 0.2 \pm 1.3) \times 10^2$	$(2.3 \pm 0.2 \pm 0.3) \times 10^2$	$(1.1 \pm 0.1 \pm 0.5) \times 10^2$
$K^+ \to \pi^0\pi^0 e^+\nu$	—	$(1.1 \pm 1.1) \times 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(0.1 \pm 0.1) \times 10^2$
$K^+ \to \pi^+\pi^0\pi^0$	—	< 20	< 20	< 20
$K^+ \to \pi^+\pi^0$	$(1.0 \pm 1.0) \times 10^4$	—	—	—
Total background	$(1.0 \pm 1.0) \times 10^4$	$(6.0 \pm 1.8) \times 10^2$	$(3.4 \pm 1.2) \times 10^2$	$(1.2 \pm 0.6) \times 10^2$

RESULTS *[arXiv: 2304.12271 (2023), submitted to JHEP]*

$$R_1 \times 10^2 = 1.715 \pm 0.005_{\text{stat}} \pm 0.010_{\text{syst}} = 1.715 \pm 0.011$$
$$R_2 \times 10^2 = 0.609 \pm 0.003_{\text{stat}} \pm 0.006_{\text{syst}} = 0.609 \pm 0.006$$
$$R_3 \times 10^2 = 0.533 \pm 0.003_{\text{stat}} \pm 0.004_{\text{syst}} = 0.533 \pm 0.004$$

$$A_\xi(S_1) \times 10^3 = -1.2 \pm 2.8_{\text{stat}} \pm 1.9_{\text{syst}}$$
$$A_\xi(S_2) \times 10^3 = -3.4 \pm 4.3_{\text{stat}} \pm 3.0_{\text{syst}}$$
$$A_\xi(S_3) \times 10^3 = -9.1 \pm 5.1_{\text{stat}} \pm 3.5_{\text{syst}}$$

Sistematics:

A_ξ MC statistics

R_j EM calorimeter response modelling, acceptance correction, theoretical model, MC statistics

Results comparison

	NA62	ChPT	ISTRA+	OKA
$R_1 \times 10^2$	1.715 ± 0.011	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
$R_2 \times 10^2$	0.609 ± 0.006	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
$R_3 \times 10^2$	0.533 ± 0.004	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$
$A_\xi(S_1) \times 10^3$	$-1.2 \pm 2.8 \pm 1.9$	/	/	$-0.1 \pm 3.9 \pm 1.7$
$A_\xi(S_2) \times 10^3$	$-3.4 \pm 4.3 \pm 3.0$	/	/	$+7.0 \pm 8.1 \pm 1.5$
$A_\xi(S_3) \times 10^3$	$-9.1 \pm 5.1 \pm 3.5$	/	/	$-4.4 \pm 7.9 \pm 1.9$

- **NA62 measurements of Rj smaller than $O(p^6)$ ChPT by 5% relative (3 standard deviation disagreement)**
- **Improvement on the experimental precision of Rj by a factor > 2**
- **The T-asymmetry measurements at an improved precision are compatible with no asymmetry**

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

$K^\pm \to \pi^\pm l^+ l^-$ decays (l = e,μ)

Crivellin et al. PRD 93074038 (2016)
D'Ambrosio et al. JHEP 02049 (2019)

- Heavily suppressed FCNC transition, LD dominated: $K^\pm \to \pi^\pm \gamma^* \to \pi^\pm l^+ l^-$
- Main kinematic variable $z = m^2_{l+l-}/m^2_K$
- Form Factor of the $K^\pm \to \pi^\pm \gamma^*$ transition: $W(z)$ parameterized in ChPT at $O(p^6)$ as

$$W(z) = G_F\, m^2_K\, (a_+ + z\, b_+) + W^{\pi\pi}(z)$$

with real parameters a_+, b_+ and (known) complex function $W\pi\pi(z)$

GOAL

- Model independent measurement of **BR($K^+ \to \pi^+\mu^+\mu^-$)**
- Measurement of $|W(z)|^2$ and determination of FF parameters a_+, b_+

Analysis on RUN1 data:

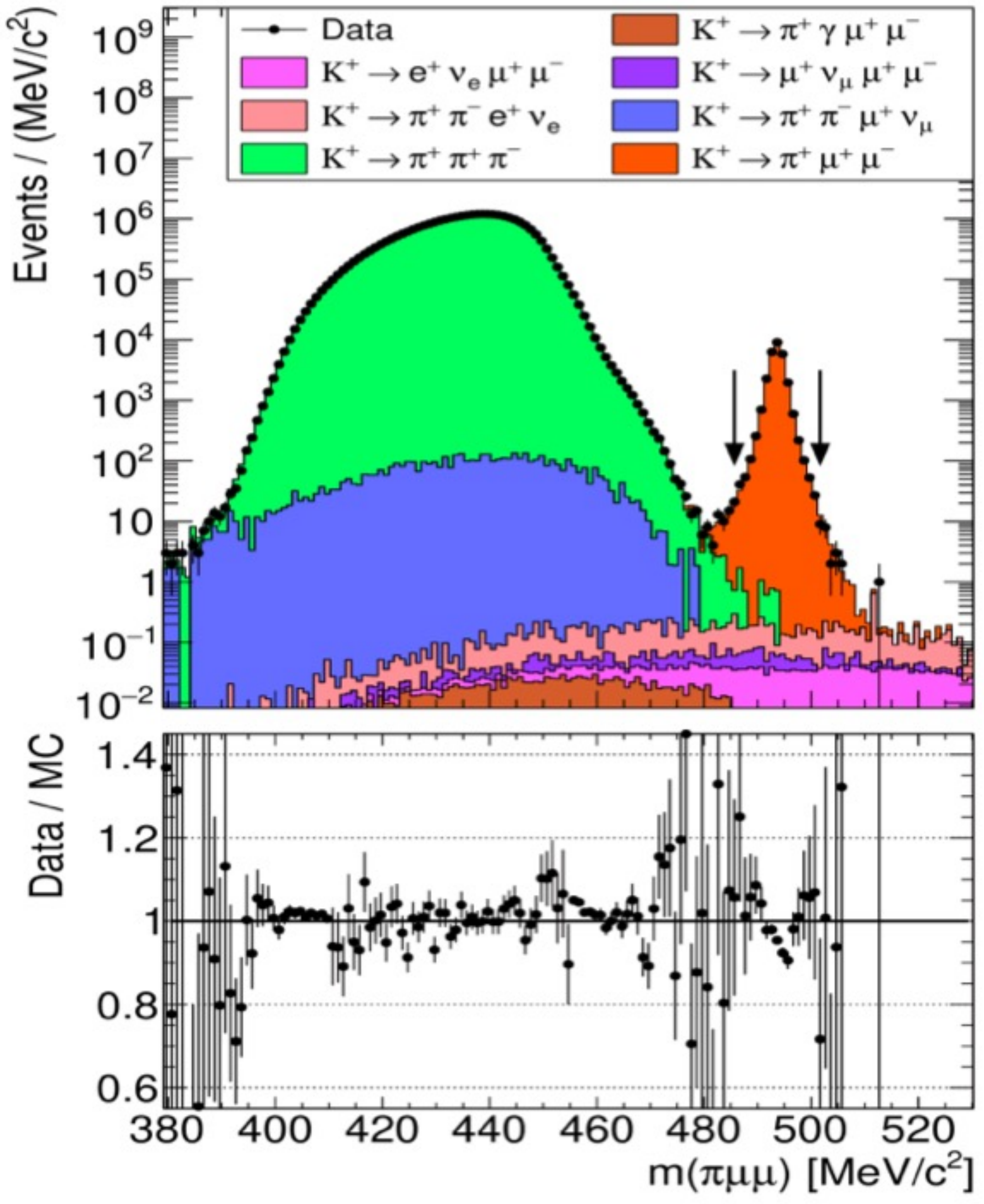
Signal: $K^+ \to \pi^+\mu^+\mu^-$
- 3-track vertex topology
- identified as $\pi^+\mu^+\mu^-$
- kinematic cuts on $m(\pi\mu\mu)$ to suppress $K_{3\pi}$ events

Normalization: $K^+ \to \pi^+\pi^+\pi^-$
- same 3-track selection as signal, but π-ID
- minimal differences in signal and normalization

⇒ reduced systematic effects

Lepton universality (LU) predicts same a,b for l= e,μ

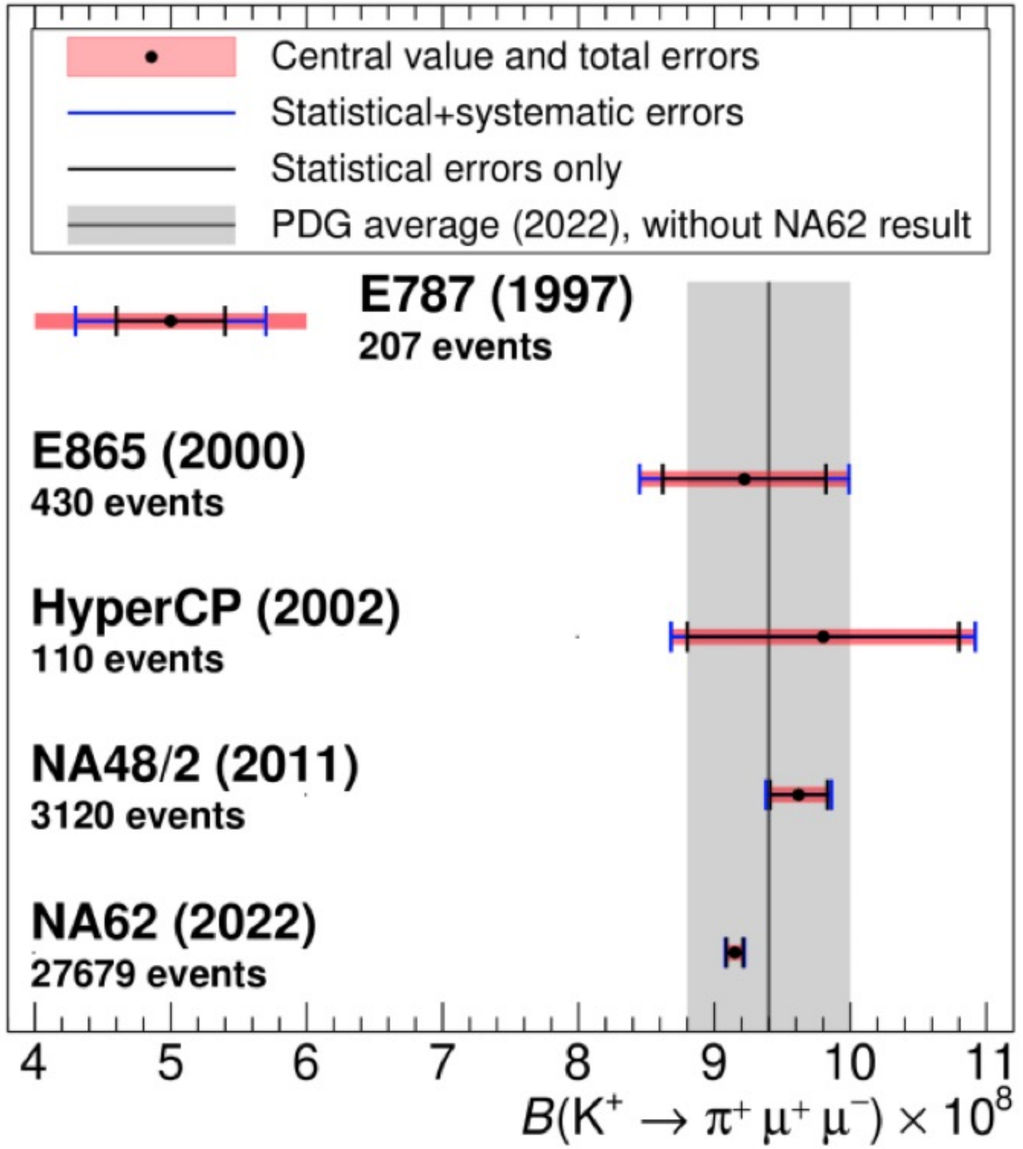
N_{events} after selection	
K^+ decays	$\sim 3.5 \times 10^{12}$
Signal	27679
Estimated bkg.	7.8 ± 5.6

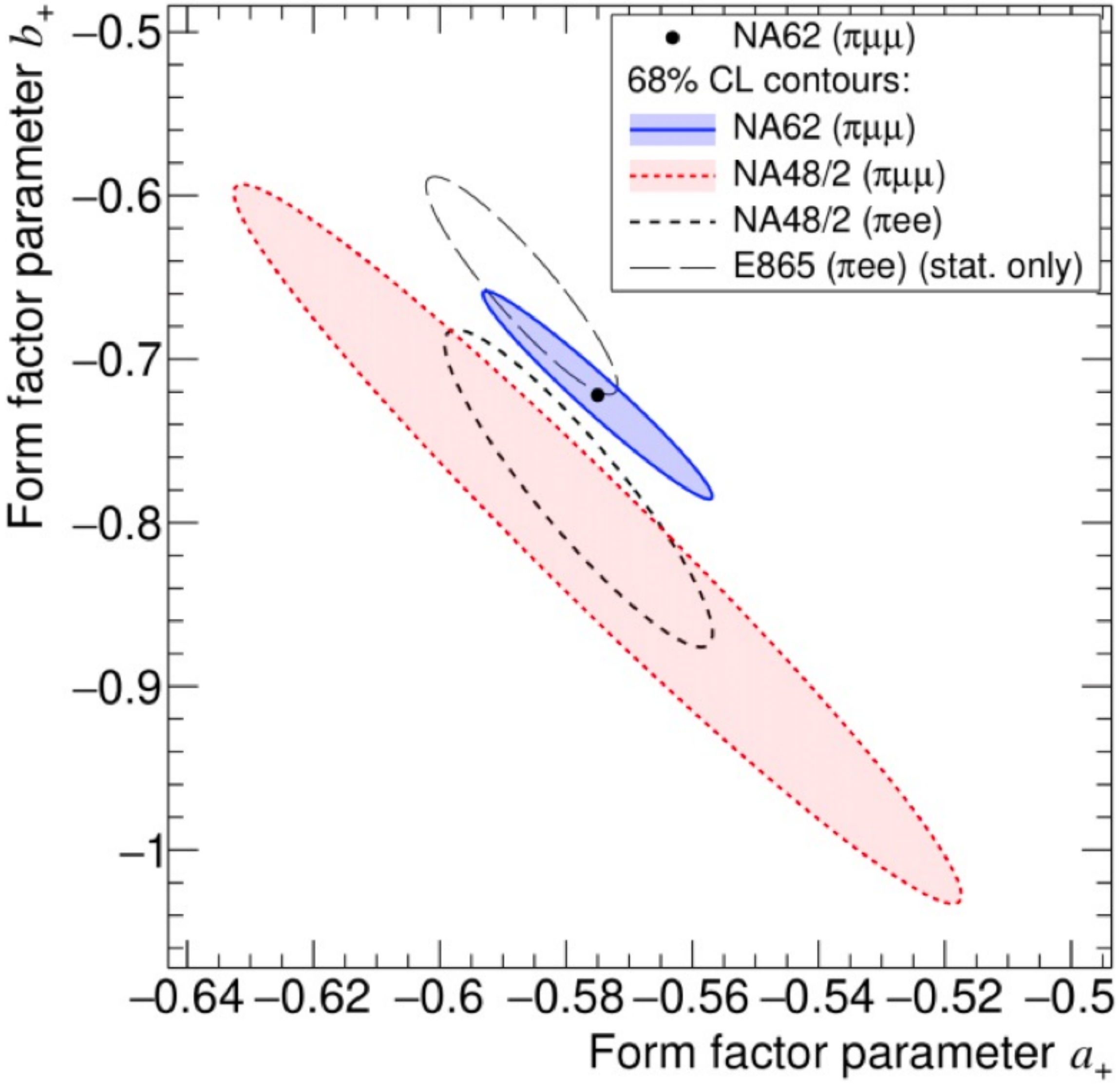


[JHEP 11 (2022) 011]

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

N^{obs} = 27679 with relative background contamination < 1% *[JHEP 11 (2022) 011]*





$BR(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$ at 68% CL

$a^+ = -0.575 \pm 0.013$
$b^+ = -0.722 \pm 0.043$

The $K^+ \to \pi^+\gamma\gamma$ decay

preliminary

- Crucial test of ChPT at $O(p^6)$, LD dominated *[D'Ambrosio, Portoles PLB 386403 (1996)]*
- Main kinematic variables: $z = m^2_{\gamma\gamma} / m^2_K$ and $y = P_K(P_{\gamma 1} - P_{\gamma 2}) / m^2_K$
- $BR(K^+ \to \pi^+\gamma\gamma)$ parameterized in ChPT by an unknown real parameter $\hat{c}$

GOAL: Measurement of **$BR(K^+ \to \pi^+\gamma\gamma)$** and **$\hat{c}$**

Analysis on RUN1 data:

Signal: $K^+ \to \pi^+\gamma\gamma$

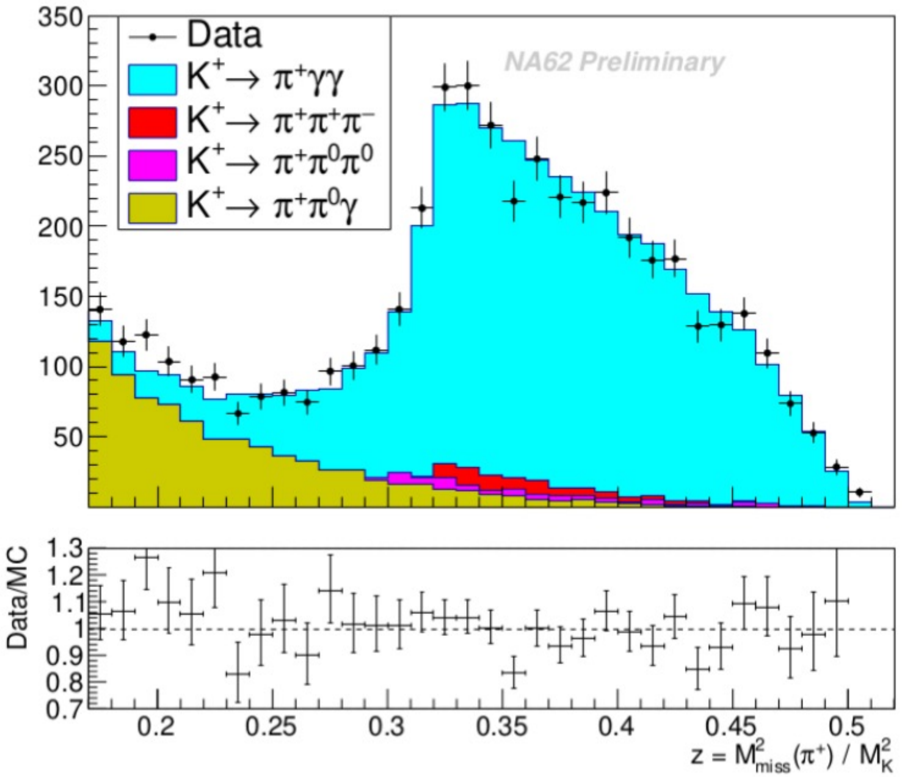
- π^+ track matching K^+ track
- EM calo clusters: $\gamma\gamma$ pair
- $z > 0.25$

Normalization: $K^+ \to \pi^+\pi^0$

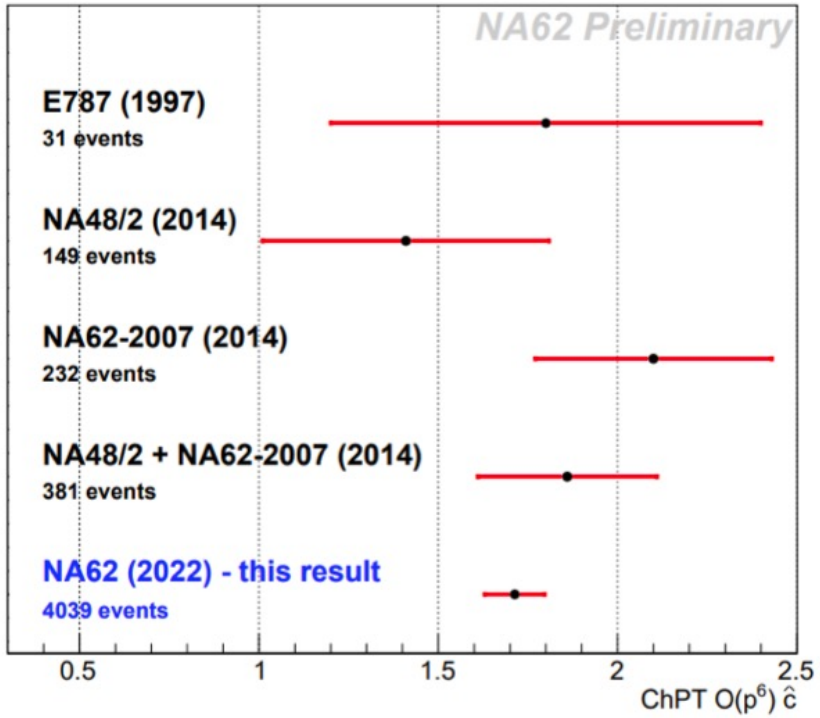
- minimal differences in signal and normalization
  - ⇒ reduced systematic effects

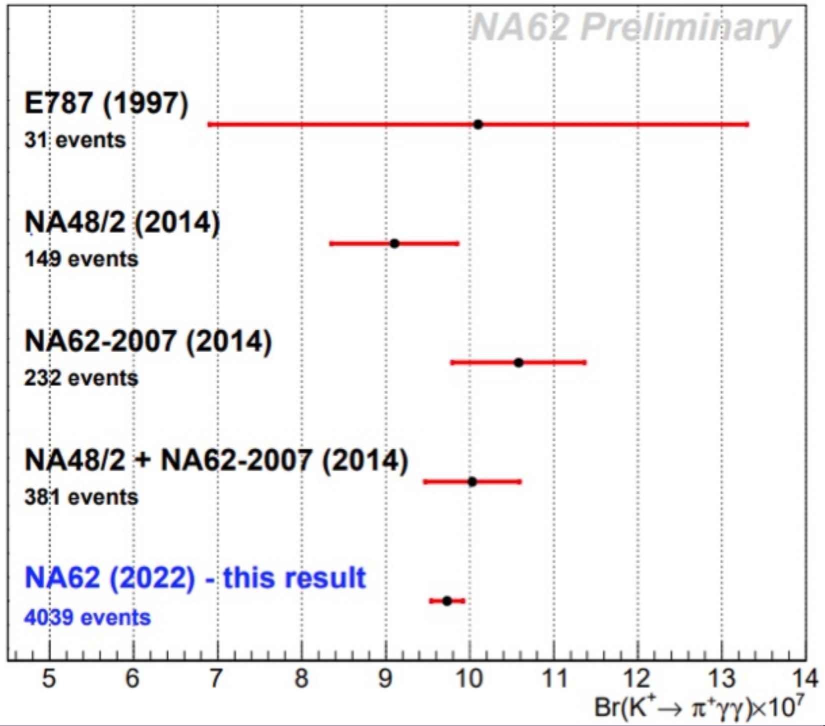
Main background: cluster merging in calorimeter

$K^+ \to \pi^+\pi^0\gamma$ or $K^+ \to \pi^+\pi^0\pi^0$ with $\pi^0 \to \gamma\gamma$



Signal.	4039 events
Exp. Bkg.	393 ± 20 events





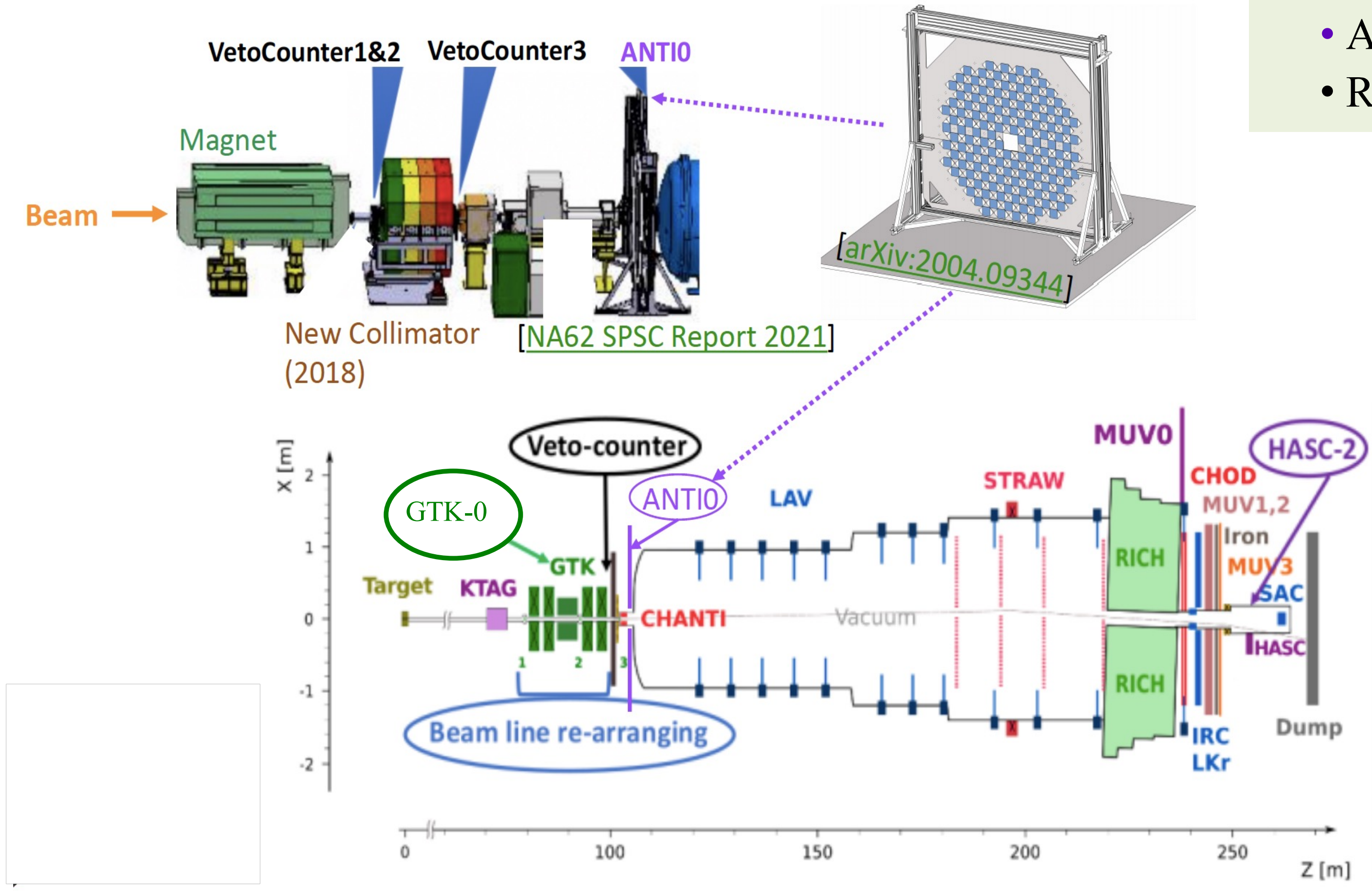
External parameters fixed:
Rev Mod Phys84 399 (2012),
Science 368 (2020), Nucl. Phys. B648 (2003)
Final result will use:
D'Ambrosio, Knech, Neshatpour, arXiv:2209.02143

$$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$$

$$BR(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7} \text{ at 68\% CL}$$

NA62 short term prospects: RUN2

RUN2: 2021 – LS3



MAIN GOAL:
Improve the **$BR(K^+\to\pi^+\nu\bar{\nu})$** measurement

Key modifications to reduce most dominant background in 2016-2018 data

- Add 4th station to **GTK** beam tracker (**GTK-0**, next to **GTK-1**)
- Rearrangement of beam line elements around GTK achromat
- New Veto-hodoscopes upstream the decay volume (**Veto-counter**, **ANTI0**)
- Additional veto counter downstream around the beam pipe (**HASC-2**)
- Replacement of CEDAR-N with **CEDAR-H**

Data taking foresee until LS3 (at least until 2025 included)

- 45-50% increase of intensity vs RUN1
- SES to SM $K^+\to\pi^+\nu\bar{\nu}$ events with 2022 data $\lesssim 10^{-11}$
- Mitigation of intensity relate effects
- Analysis optimization in progress to further increase performance

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

- Trigger upgrade to study new channels (e.g. $K^+\to\pi^+e^+e^-$)
- Continuing LNV/LFV and dark sector searches with K^+

$O(\%)$ LFUV tests. Lower UL (10^{-11} sensitivity)

- Data taking periods in dump mode

Expect 10^{18} POT in beam dump: dark photons/scalars, ALPs, HNLs

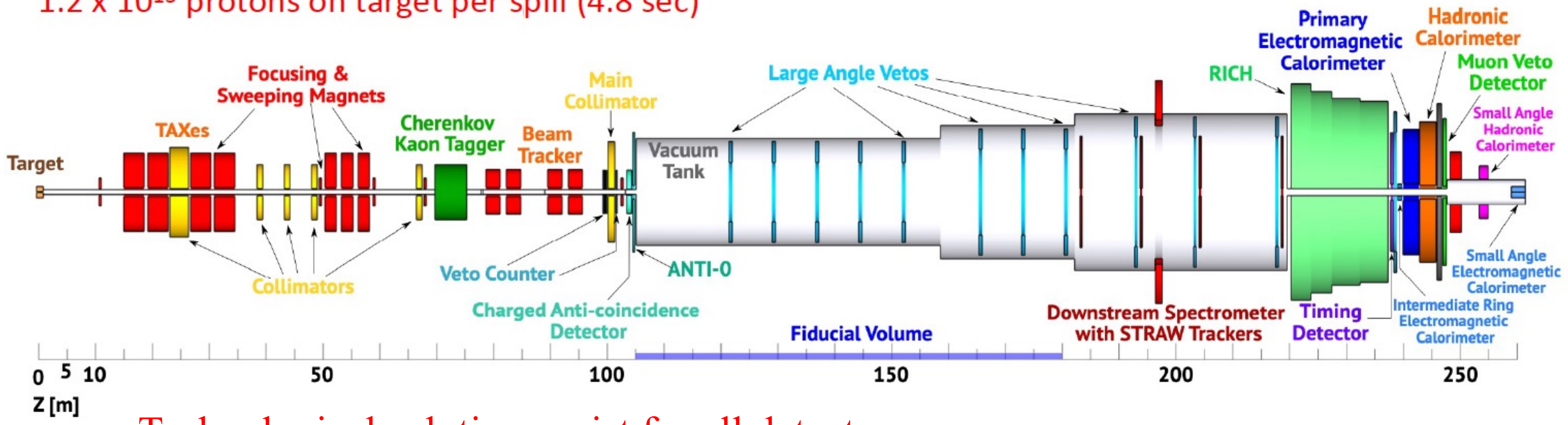
Kaons @ CERN long term plans

HIKE: High Intensity Kaon Experiments

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

[LoI-arXiv:2211.16586v1]
(proposal to SPSC in preparation)

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



Technological solutions exist for all detectors

Physics program

- $K^+ \to \pi^+ \nu\bar{\nu}$ approaching SM theory precision
- $K_L \to \pi^0 l^+ l^-$ observation and measurement of the BR
- LFUV tests with precision < %
- LFV –LNV searches with $O(10^{-12})$ sensitivity
- Measurement of V_{us} and main kaon decay modes
- Dump physics in synergy with Shadows proposal

- K^+ (Phase-1) and K_L (Phase-2) physics program at CERN SPS after LS3
- Beam line upgrade: intensity ×4 to ×6 larger than NA62
- Advanced detectors with O(20ps) time resolution
- Similar experimental layouts for charged and neutral beams: smooth transition between the two phases

→ **HIKE would allow for a kaon comprehensive program**

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

See talk by E. Goudzovski

Conclusions

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

Excellent prospects for kaon physics measurements with a broad program

Status:

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

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

$$BR(K_L \to \pi^0\nu\bar{\nu}) < 4.9 \times 10^{-9}$$

- Precision measurements of rare K^+ decays (NA62)

Prospects:

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

- ✓ Reduce current backgrounds
- ✓ 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 II to measure $BR(K_L \to \pi^0\nu\bar{\nu})$
- ✓ CERN: Proposal for high-intensity K^+ and K_L experiments