

Next-generation kaon experiments

Flavor Physics and CP Violation: FPCP 2021
Fudan University, Shanghai, 11 June 2021

Matthew Moulson – INFN Frascati

For the NA62 Collaboration and KLEVER Project

Rare kaon decays

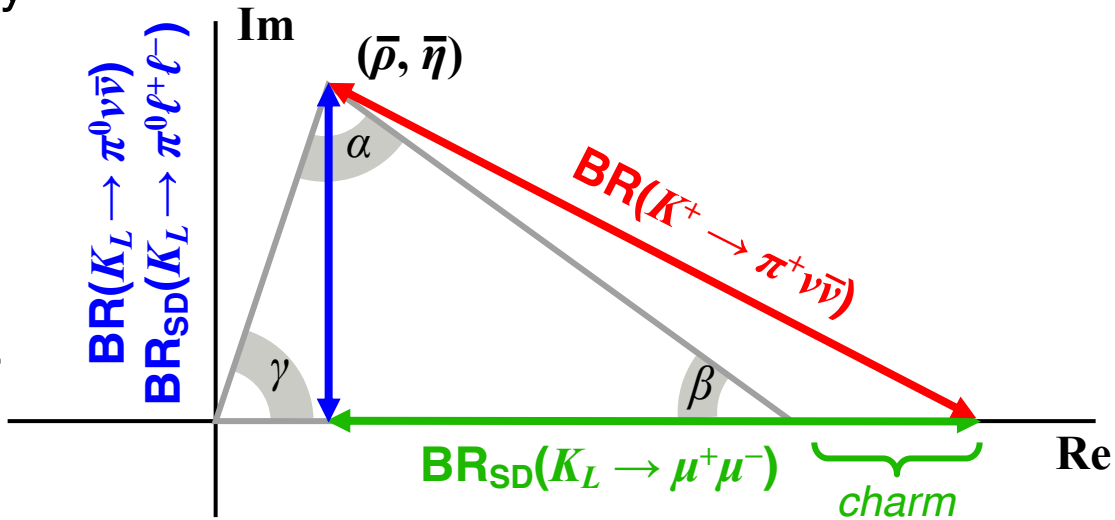
Decay	Γ_{SD}/Γ	Theory err.*	SM BR $\times 10^{11}$	Exp. BR $\times 10^{11}$ (Sep 2019)
$K_L \rightarrow \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \rightarrow \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	$< 28^\dagger$
$K_L \rightarrow \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	$< 38^\dagger$
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	90%	4%	8.4 ± 1.0	$< 18.5^\dagger$
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	$> 99\%$	2%	3.4 ± 0.6	$< 300^\dagger$

*Approx. error on LD-subtracted rate excluding parametric contributions $^\dagger 90\%$ CL

FCNC processes dominated by Z-penguin and box diagrams

Rates related to V_{CKM} with minimal non-parametric uncertainty

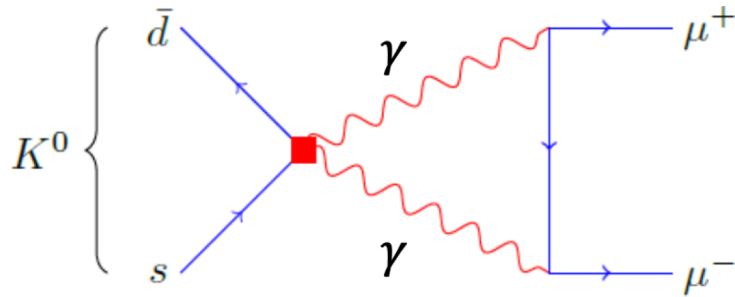
V_{CKM} overconstrained: look for NP in specific channels



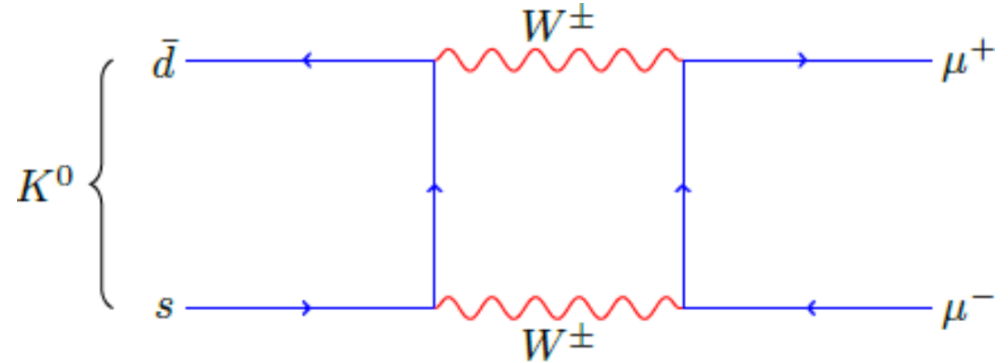
$$K_{S,L} \rightarrow \mu^+ \mu^-$$

$$\text{BR}_{\text{SM}}(K_{S,L} \rightarrow \mu^+ \mu^-) \propto |A_{S,L}^{LD} + A_{S,L}^{SD}|^2$$

Long distance (LD)



Short distance (SD)



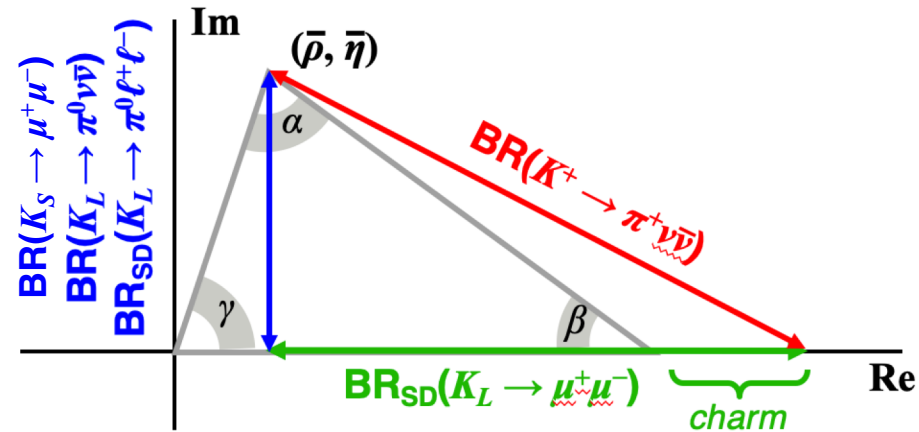
$$\text{BR}(K_L \rightarrow \mu^+ \mu^-) \rightarrow A_L^{SD} \propto (1 - \rho)$$

- SM prediction depends on sign of $A(K_L \rightarrow \gamma\gamma)$, which determines LD/SD interference
- $\text{BR}_{\text{exp}}(K_L \rightarrow \mu^+ \mu^-) = (6.84 \pm 0.11) \times 10^{-9}$
See e.g. BNL E871 result, PRL84 (2000)

$$\text{BR}(K_S \rightarrow \mu^+ \mu^-) \rightarrow A_S^{SD} \propto \eta$$

- $\text{BR}_{\text{SM}}(K_S \rightarrow \mu^+ \mu^-) = (5.0 \pm 1.5) \times 10^{-12}$
If $> 10^{-11}$ \rightarrow unambiguous sign of NP
Isidori, Unterdorfer '04

- Due to $K_S K_L$ interference, high sensitivity to NP and to sign of $A(K_L \rightarrow \gamma\gamma)$
see e.g. D'Ambrosio & Kitahara '17, Dery et al. '21



K_S decays at LHCb

$10^{13} K_S/\text{fb}^{-1}$ produced in LHCb acceptance

About 1 strange hadron per event!

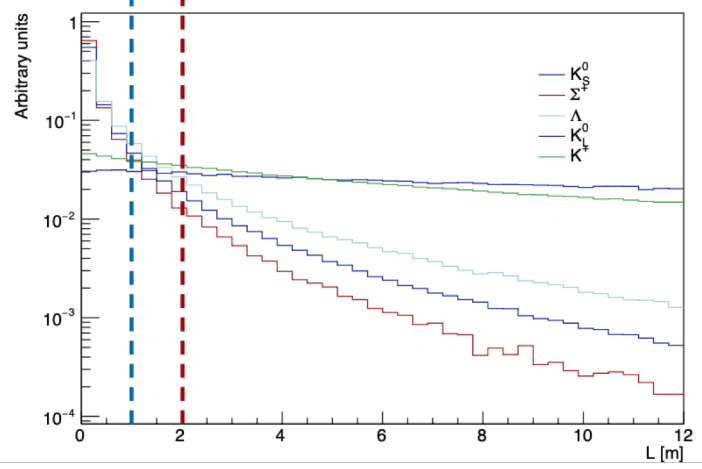
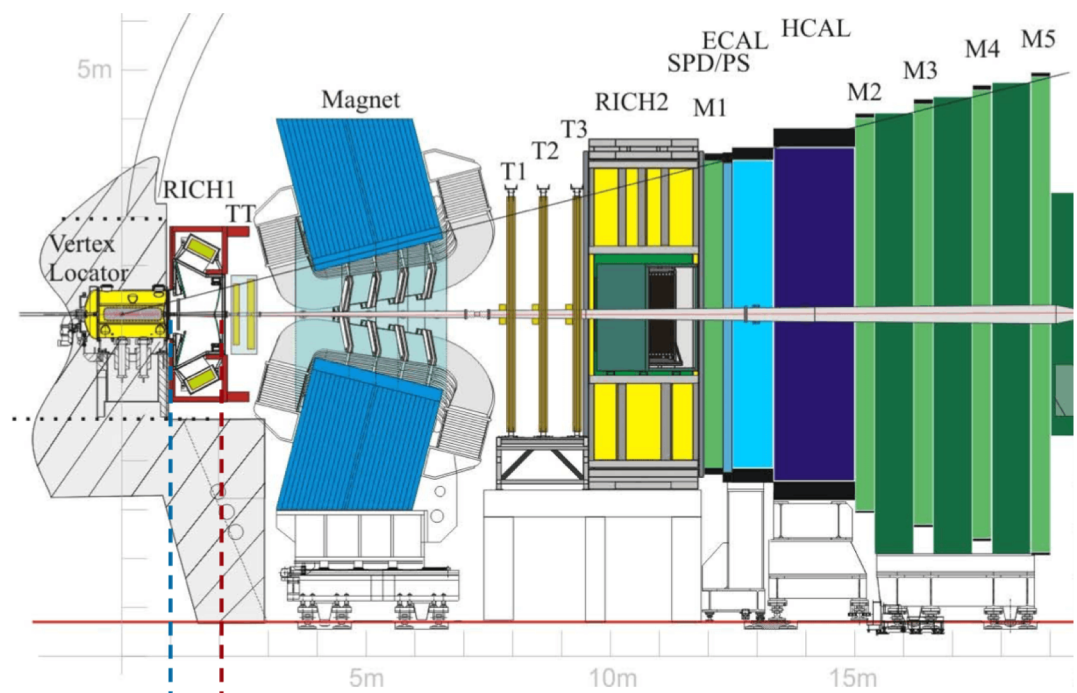
Production rate compensates for low trigger efficiency and long lifetime

Vast K program for Run 3:

- $K_{S,L} \rightarrow \mu^+\mu^-$
- $K_S \rightarrow \pi^0\mu^+\mu^-$
- $K_S \rightarrow \pi^+\pi^-e^+e^-$
- $K_S \rightarrow \ell^+\ell^-\ell^+\ell^-$
- $K^+ \rightarrow \pi^+\ell^+\ell^-$
- + others

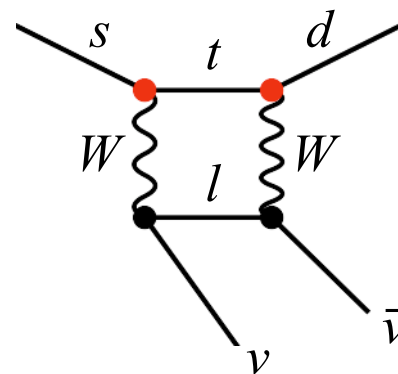
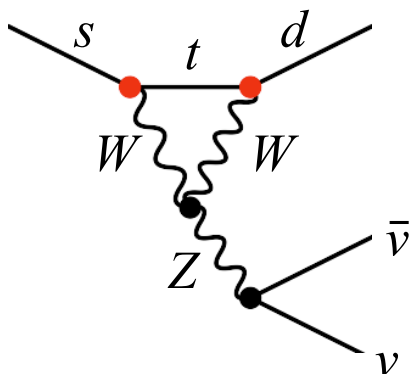
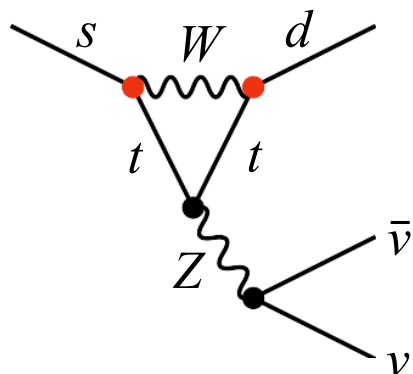
For example:

$\text{BR}(K_S \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$ (90%CL)
PRL125 (2020) 231801



See talk yesterday by R. Lollini

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



Extremely rare decays with rates very precisely predicted in SM:

- Hard GIM mechanism + pattern of CKM suppression ($V_{ts}^* V_{td}$)
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from $\text{BR}(K_{e3})$ via isospin rotation

SM predicted rates
Buras et al, JHEP 1511*

Experimental status
(before Sep 2019)

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

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

$\text{BR} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$
Stopped K^+ , 7 events observed
BNL 787/949, PRD79 (2009)

$K_L \rightarrow \pi^0 \nu \bar{\nu}$

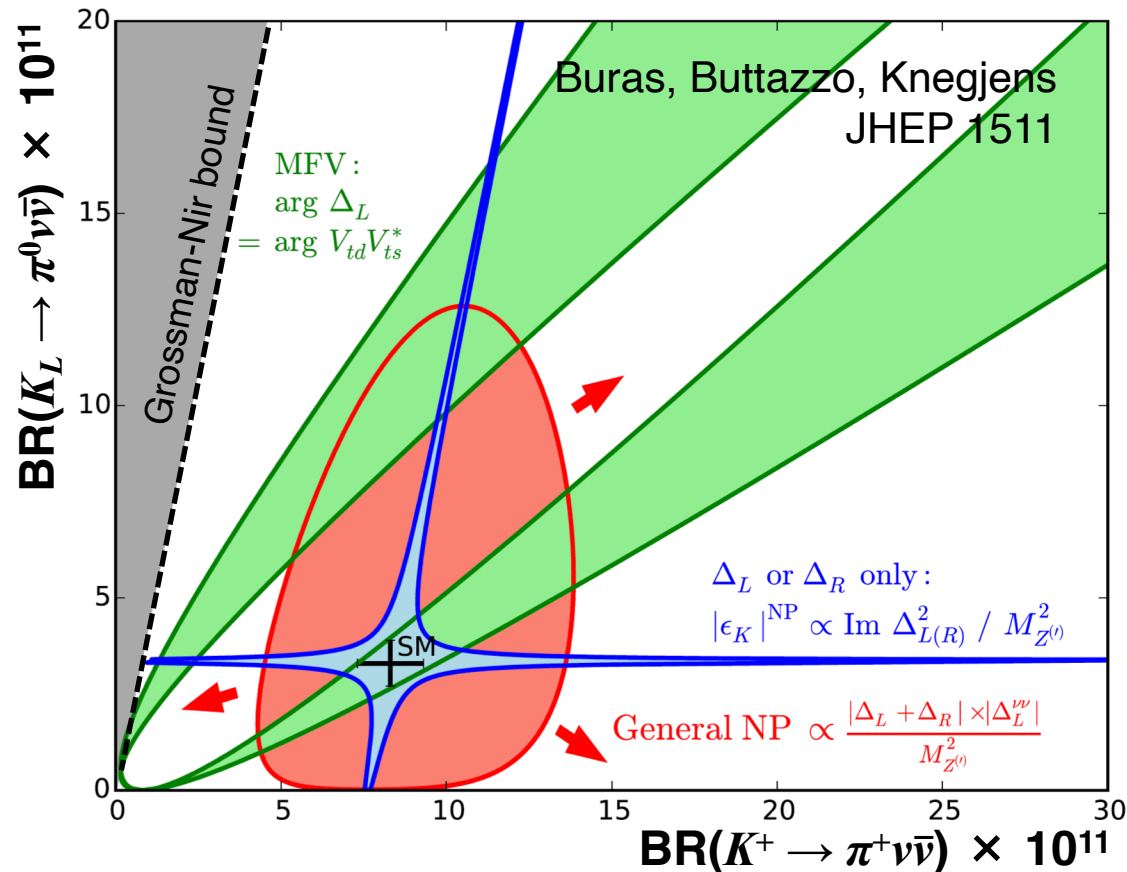
$\text{BR} = (3.4 \pm 0.6) \times 10^{-11}$

$\text{BR} < 300 \times 10^{-11}$ 90%CL
KOTO, PRL122 (2019)

* Tree-level determinations of CKM matrix elements

$K \rightarrow \pi \nu \bar{\nu}$ and new physics

New physics affects K^+ and K_L BRs differently
 Measurements of both can discriminate among NP scenarios



- **Models with CKM-like flavor structure**
 - Models with MFV
- **Models with new flavor-violating interactions in which either LH or RH couplings dominate**
 - Z/Z' models with pure LH/RH couplings
 - Littlest Higgs with T parity
- **Models without above constraints**
 - Randall-Sundrum
- **Grossman-Nir bound**
 Model-independent relation

$$\frac{\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})}{\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

$K_L \rightarrow \pi^0 \nu \bar{\nu}$: Experimental issues

Essential signature: 2γ with unbalanced p_\perp + nothing else!

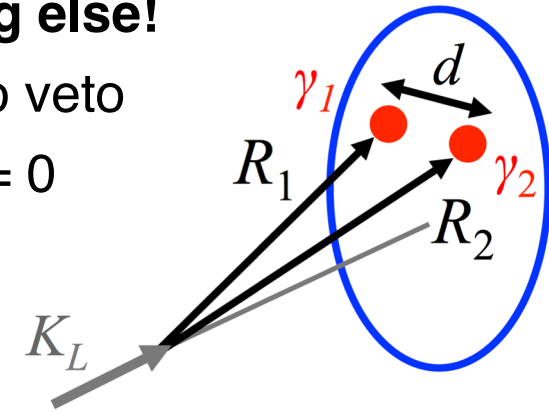
All other K_L decays have ≥ 2 extra γ s or ≥ 2 tracks to veto

Exception: $K_L \rightarrow \gamma\gamma$, but not a big problem since $p_\perp = 0$

K_L momentum generally is not known

$M(\gamma\gamma) = m(\pi^0)$ is the only sharp kinematic constraint

Generally used to reconstruct vertex position



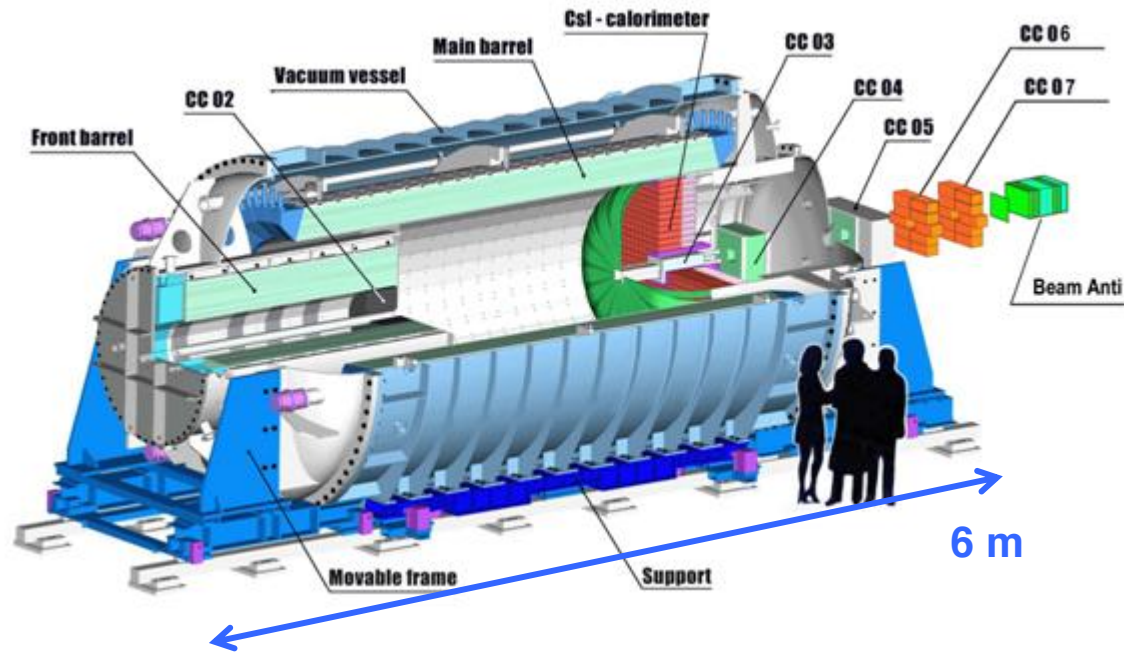
$$m_{\pi^0}^2 = 2E_1 E_2 (1 - \cos \theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1 E_2}}{m_{\pi^0}}$$

Main backgrounds:

Mode	BR	Methods to suppress/reject
$K_L \rightarrow \pi^0 \pi^0$	8.64×10^{-4}	γ vetoes, π^0 vertex, p_\perp
$K_L \rightarrow \pi^0 \pi^0 \pi^0$	19.52%	γ vetoes, π^0 vertex, p_\perp
$K_L \rightarrow \pi e \nu(\gamma)$	40.55%	Charged particle vetoes, π ID, γ vetoes
$\Lambda \rightarrow \pi^0 n$		Beamline length, p_\perp
$n + A \rightarrow X \pi^0$		High vacuum decay region

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC



Primary beam: 30 GeV p

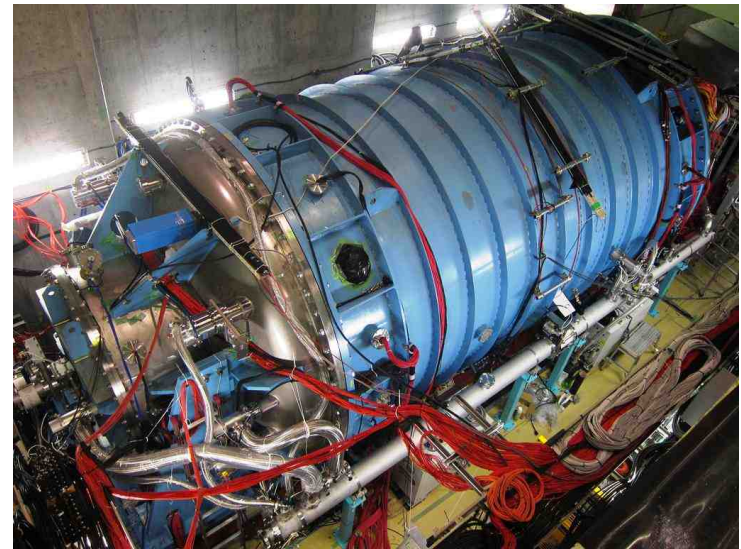
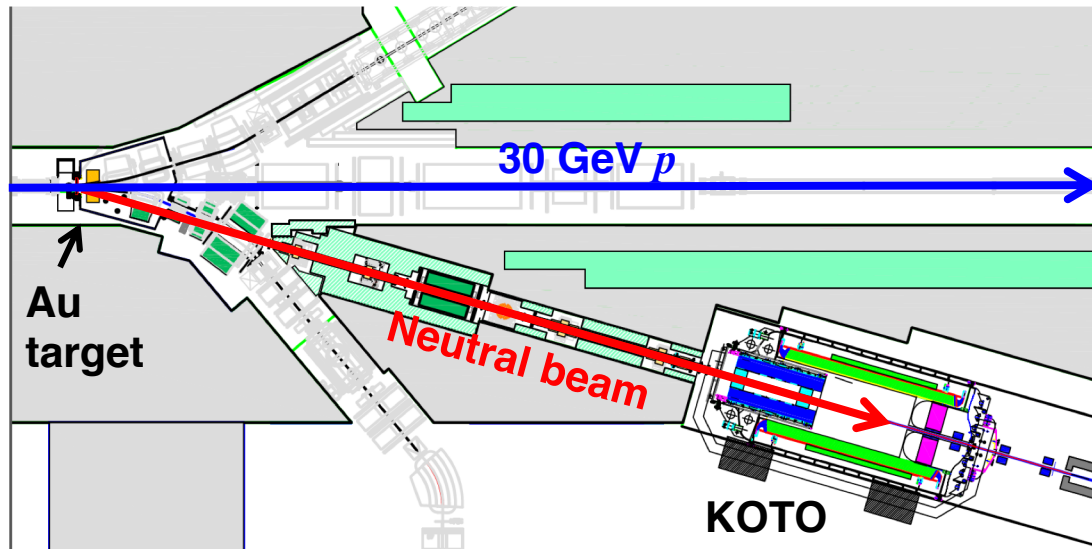
50 kW = 5.5×10^{13} p/5.2 s (2019)

Neutral beam (16°)

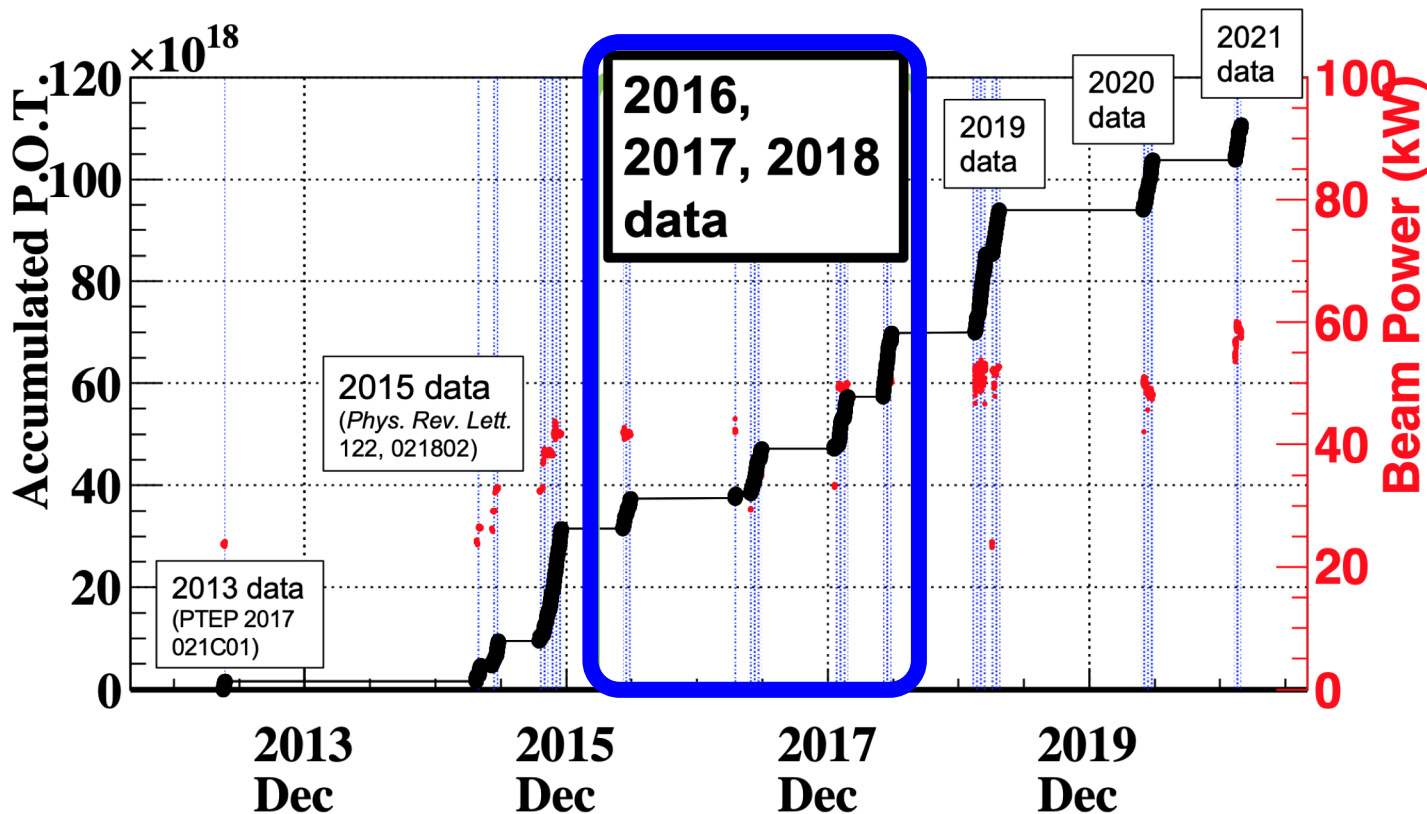
$\langle p(K_L) \rangle = 2.1$ GeV

50% of K_L have 0.7-2.4 GeV

8 μ sr “pencil” beam



KOTO status and timeline



2015 run

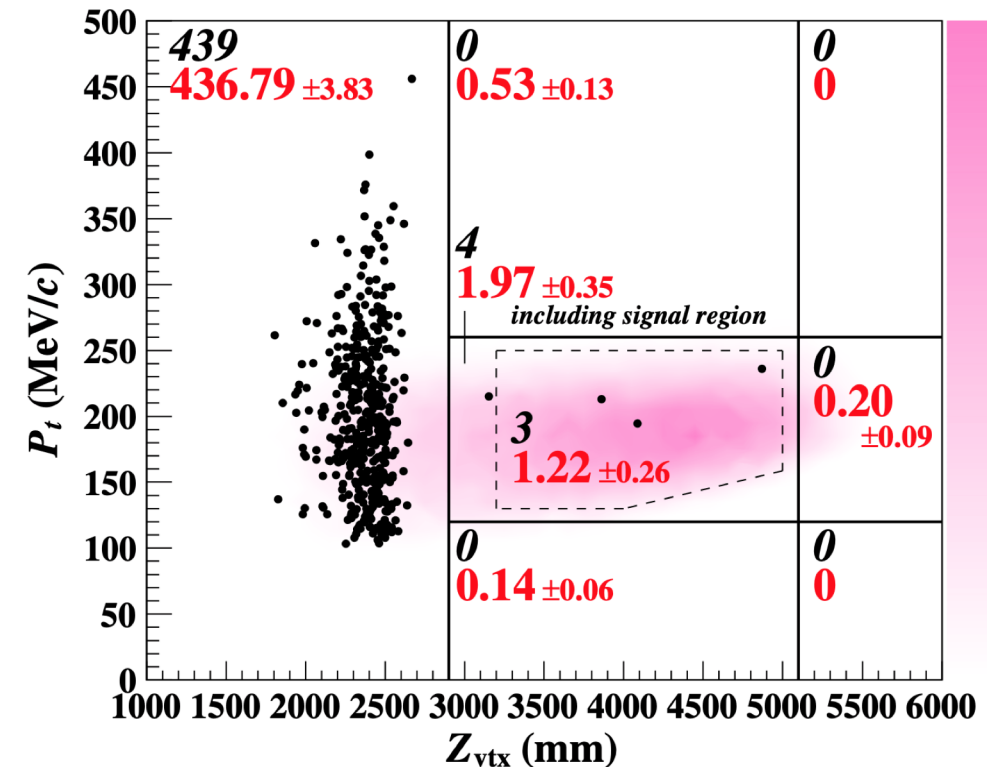
- Reached **40 kW** slow-extracted beam power
- 2.2×10^{19} pot collected
- **$\text{BR}(K_L \rightarrow \pi^0 \nu \nu) < 3.0 \times 10^{-9}$ (90%CL)**
PRL 122 (2019) 021802

2016-2018 runs

- Reached **50 kW** beam power
- 3.1×10^{19} pot collected
- **Results recently published!**

2019-2021 runs: Work in progress

Final result: 2016-2018 data



Expected backgrounds

Source	Expected (68%CL)
$K_L \rightarrow \pi^0 \pi^0 \pi^0$	0.01 ± 0.01
$K_L \rightarrow \gamma \gamma$ halo	0.26 ± 0.07
Other K_L decays	0.005 ± 0.005
$K^+_{e3} + K^+_{\mu 3} + K^+_{\pi 2}$	0.87 ± 0.25
n interaction in Csl	0.017 ± 0.002
η from n in CV	0.03 ± 0.01
π^0 from upstream int.	0.03 ± 0.03
Total	1.22 ± 0.26

* Newly evaluated source since KAON 2019

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

30.5×10^{19} pot

$SES = (7.20 \pm 0.05_{\text{stat}} \pm 0.66_{\text{syst}}) \times 10^{-10}$

0.04 signal + 1.22 background events expected

3 events in signal box

K_L flux from $K_L \rightarrow 2\pi^0 = 6.8 \times 10^{12}$

$\pi^0 \nu \nu$ acceptance from MC:

Decay in FV: 3.3%

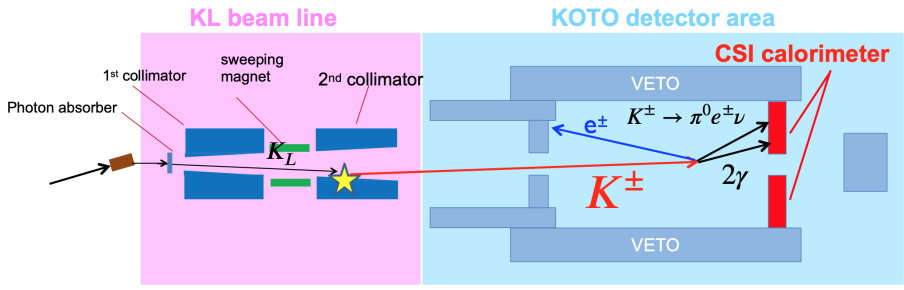
Overall acceptance: 0.6%

PRL 126 (2019) 121801

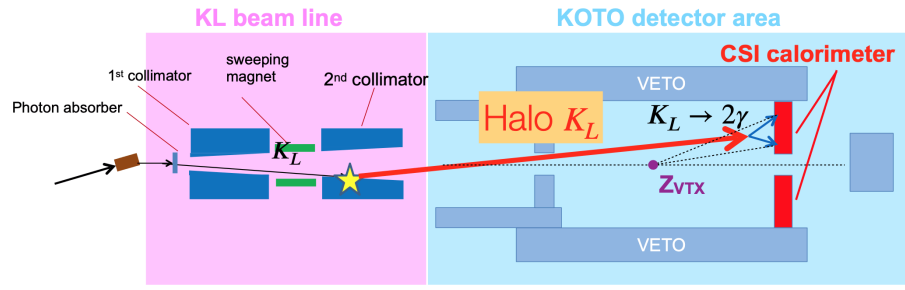
Background studies for 2016-2018



K^+ decays (charge exchange)

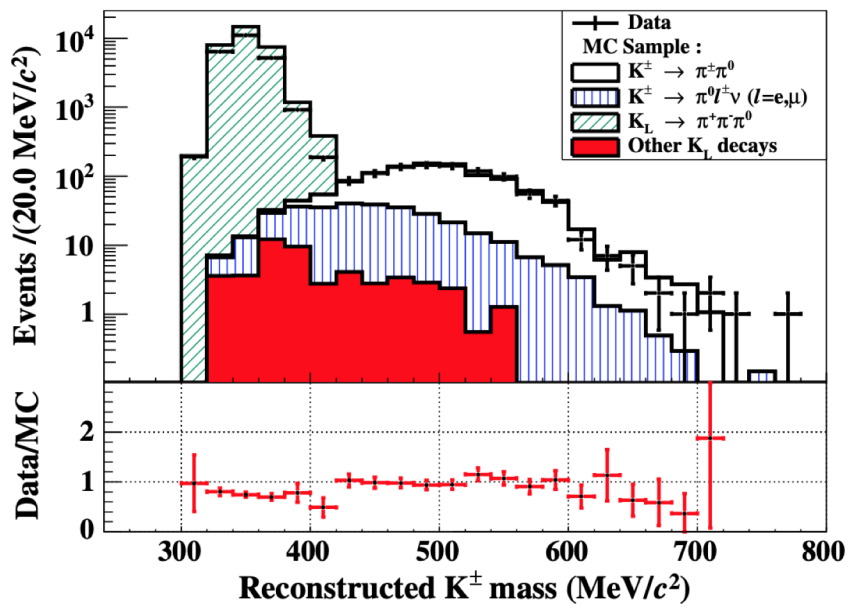


$K_L \rightarrow \gamma\gamma$ (scattered K_L)

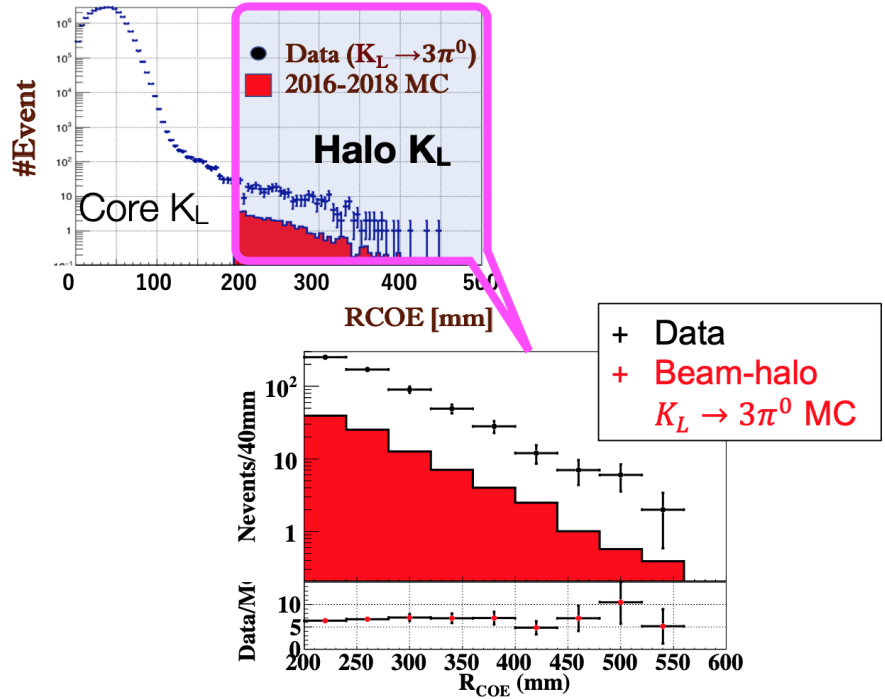


Dedicated data taking June 2020:

- Measure K^+ flux with 3-cluster sample ($\pi^+\pi^0$ reconstruction hypothesis)



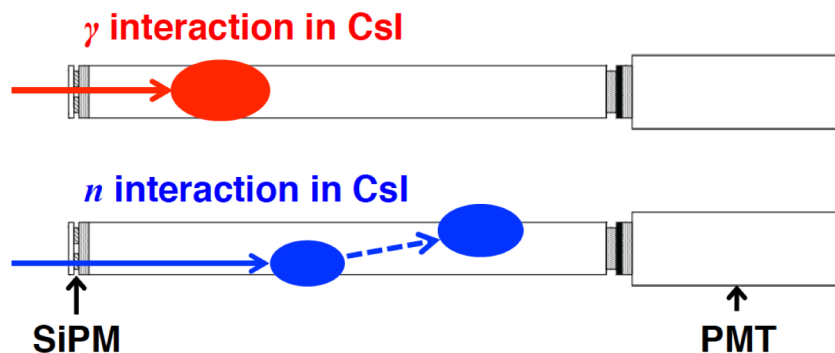
- $K_L \rightarrow 3\pi^0$ events reconstructed by center of energy to calibrate K_L halo in MC



Improvements for 2019-2021

Dual side readout for CsI modules

Installed for 2019 run



Resolve γ/n interaction depth by reading light from front CsI face with SiPM

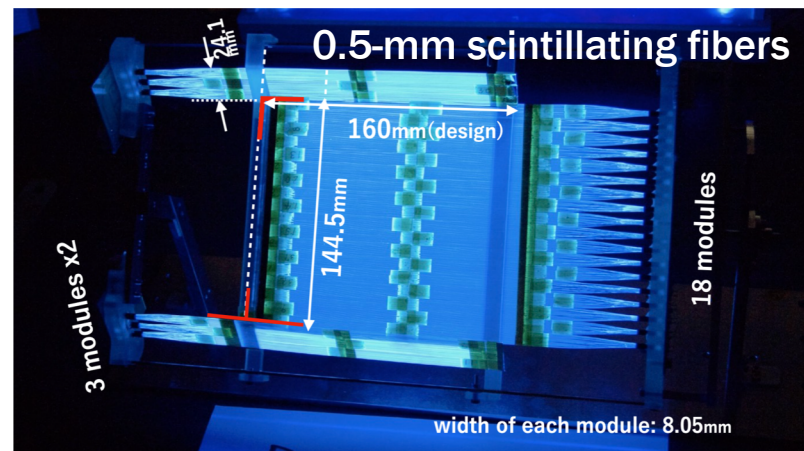
Reduces neutron background $\sim 50x$

Run	pot [10^{18}]	UCV
2016-2018	30.5	No
2019	18.5	No
2020	2.5	No
	6.9	Yes
2021 (in progress)	9.8	Yes

Upstream charged-particle veto

Prototype installed for 2020 run

Final version available in 2021



Reduces K^+ background $\sim 20x$

- **May-June 2021 run currently in progress**
- **Expect data set of comparable size to 2016-2018 by end**

Outlook after 2021

Signal: Need ~20x more (flux × acceptance) to reach SM SES

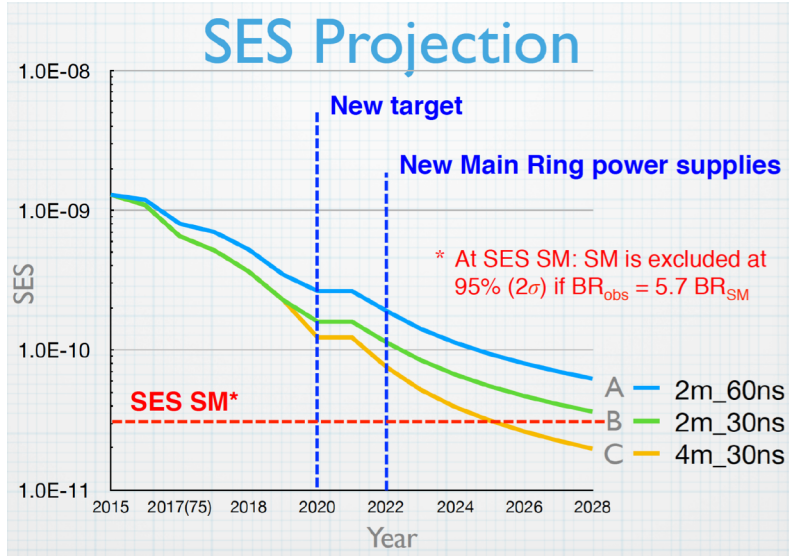
- Beam power expected to increase from 50 → 100 kW after 2022

Mid-term Plan of MR

FX: The higher repetition rate scheme : Period 2.48 s → 1.32 s for 750 kW.
 (= shorter repetition period) → 1.16 s for 1.3 MW
SX: Mitigation of the residual activity for the beam power upgrade

JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event		long shutdown							
FX power [kW]	515	-	>700	800	900	>1000	>1100	>1200	1300
SX power [kW]	55	60~70	>80	>80	>80	>80	~100	~100	~100
Cycle time for Fast Extraction	2.48s		1.32s	1.32s	1.32s	1.32s	<1.32s	<1.32s	1.16s
New Magnet PS		Mass Production installation/Test							
RF system upgrade									
2 nd harmonic rf system									
Collimator system		Add.colli. (3.5kW)							
Injection system		Kicker PS improvement, Septa manufacture/test							
FX system									
Beam Monitors (BPM circuits)									
SX Local shield									
Diffuser/ Bent crystal/ VHF									

T. Yamanaka, J-PARC PAC, Jul 2018



- July 2021** Shutdown for MR magnet PS upgrade
Increase power, better spill structure
- June 2022** Tuning for FX
- Fall 2022** FX beam for users
SX beam tuning → 80 kW SX for users

SES projection from 2018 and will be updated soon, but main conclusion unchanged:

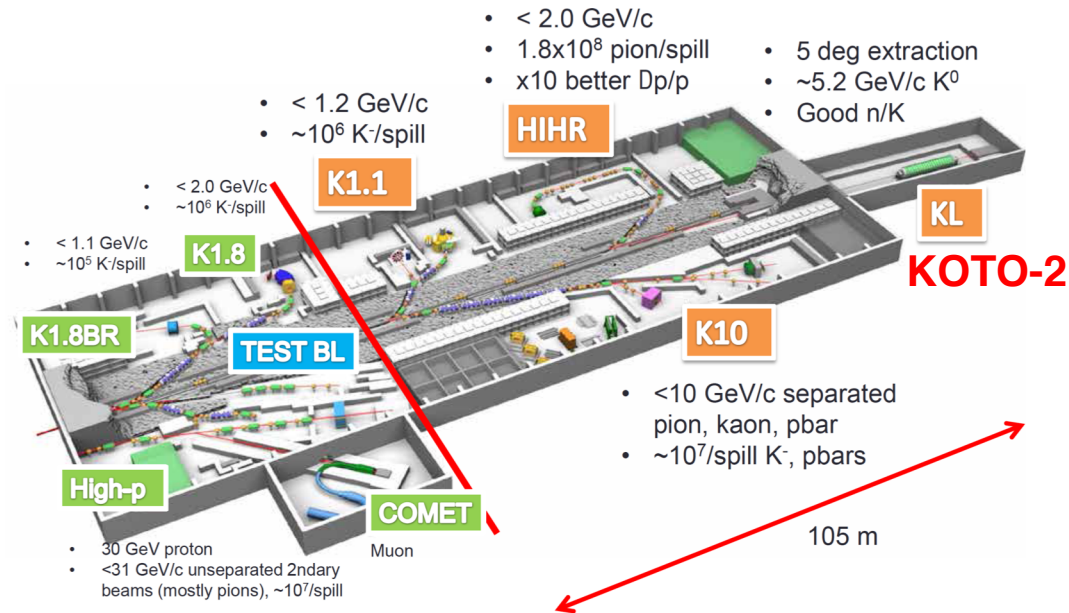
Expect to approach SM SES by mid-decade

KOTO long-term plans: Step-2



- Plan outlined in 2006 proposal to upgrade to O(100) SM event sensitivity over the long term
- Now beginning to seriously consider a new experiment to achieve this sensitivity

- Increase beam power to > 100 kW
- New neutral beamline at 5°
 $\langle p(K_L) \rangle = 5.2$ GeV
- Increase FV from 2 m to 13 m
 Complete rebuild of detector
- **Requires hadron-hall extension**

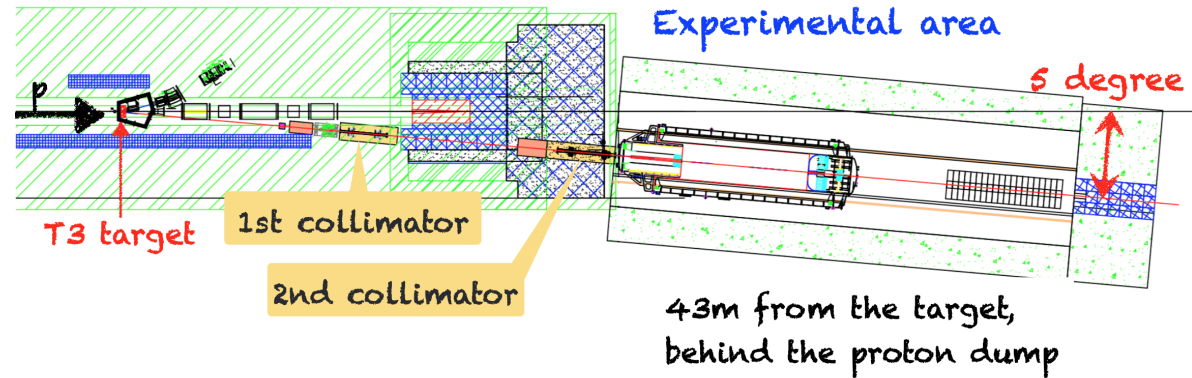


- Hadron-hall extension is a joint project with nuclear physics community
 KOTO Step-2 is a flagship project
- Described in KEK Road Map 2021 for research strategy 2022-2027
- Review planned for August 2021, with KOTO providing Step-2 input

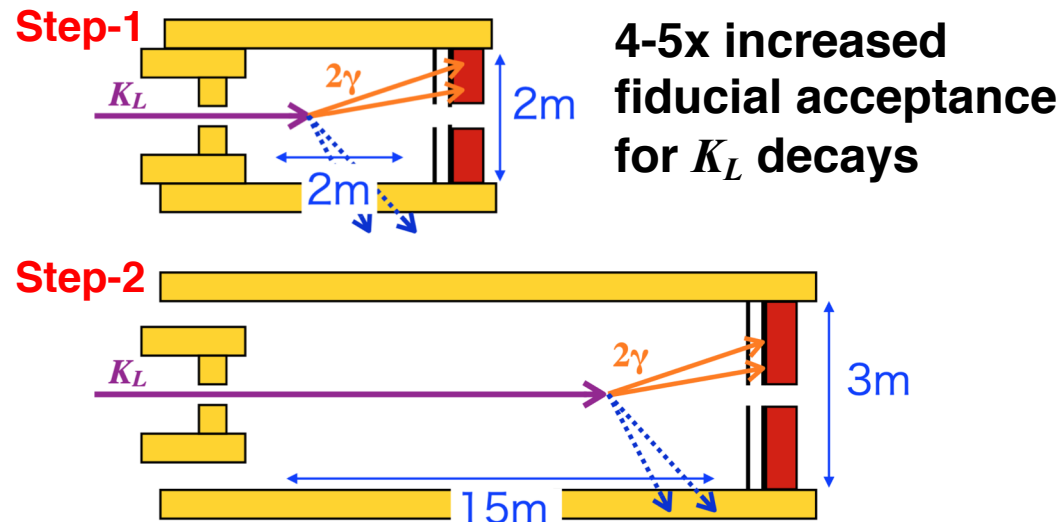
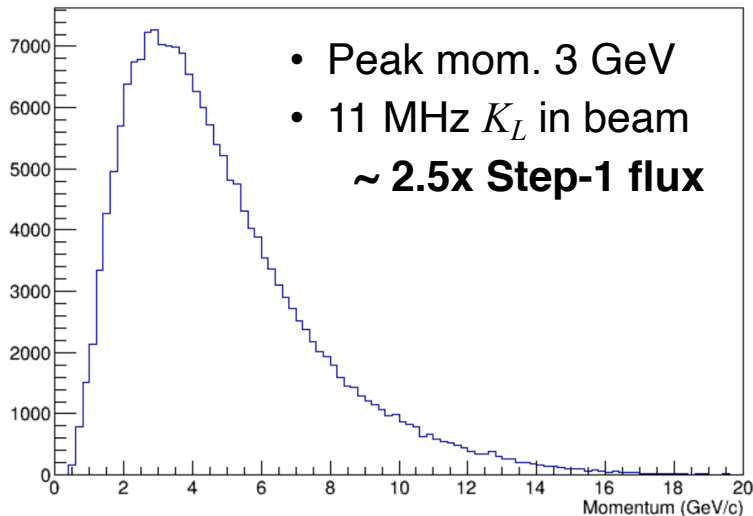
KOTO Step-2 detector

Step-2 beamline setup in hadron-hall extension

- Smaller angle ($16^\circ \rightarrow 5^\circ$)
- Longer beamline (20 \rightarrow 43 m)
- 2 collimators



K_L spectrum at beam exit



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

The NA62 experiment at the CERN SPS

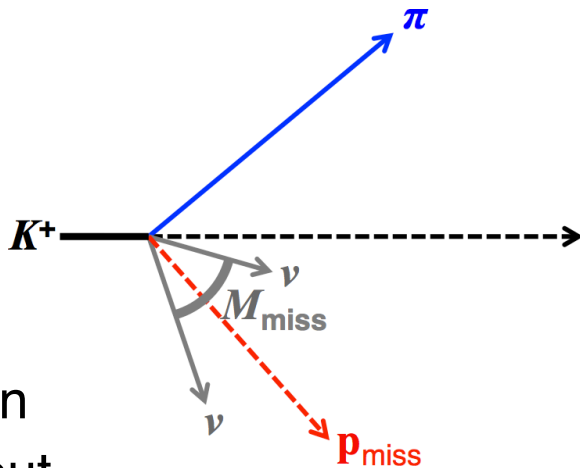


$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with decay in flight

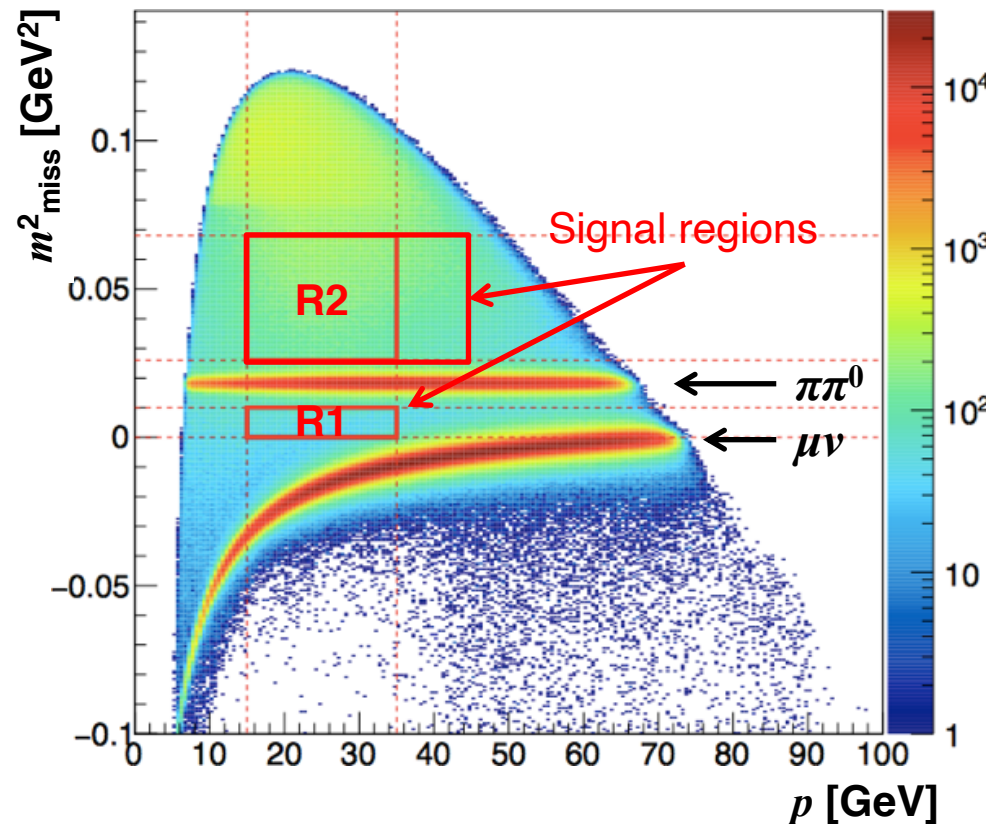


Signal:

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



- K track in
- π track out
- No other particles in final state
- $M_{\text{miss}}^2 = (p_K - p_\pi)^2$



Selection criteria:

- K^+ beam identification
- Single track in final state
- π^+ identification ($\epsilon_\mu \sim 1 \times 10^{-8}$)
- γ rejection ($\epsilon_{\pi^0} \sim 3 \times 10^{-8}$)

Main backgrounds:

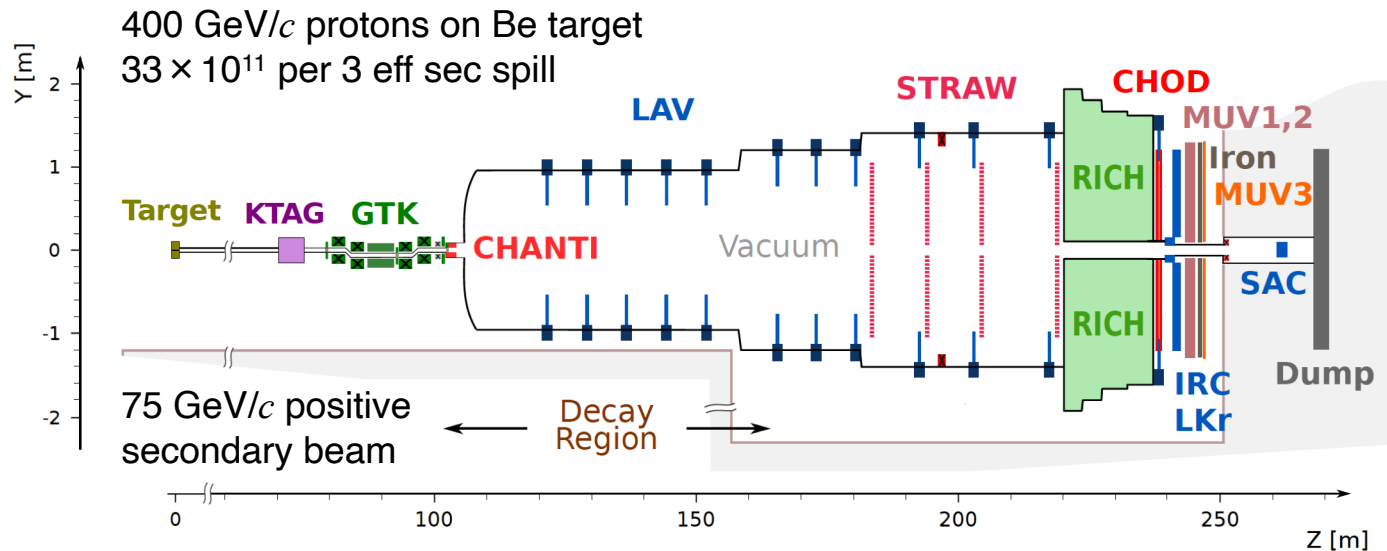
$$K^+ \rightarrow \mu^+ \nu(\gamma) \quad \text{BR} = 63.5\%$$

$$K^+ \rightarrow \pi^+ \pi^0(\gamma) \quad \text{BR} = 20.7\%$$

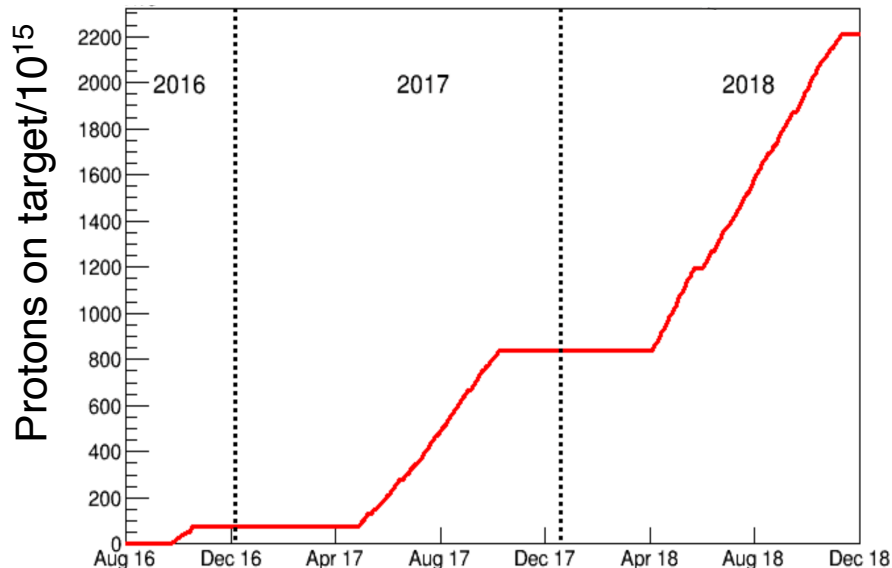
NA62 status and timeline



- High-rate, precision tracking: 750 MHz at GTK
- Redundant PID and muon vetoes
- Hermetic photon vetoes
- High-performance EM calorimeter



NA62 data taking:



2016 40% of nominal intensity
 $0.12 \times 10^{12} K^+$ decays in FV

2017 60% of nominal intensity
 $1.5 \times 10^{12} K^+$ decays in FV

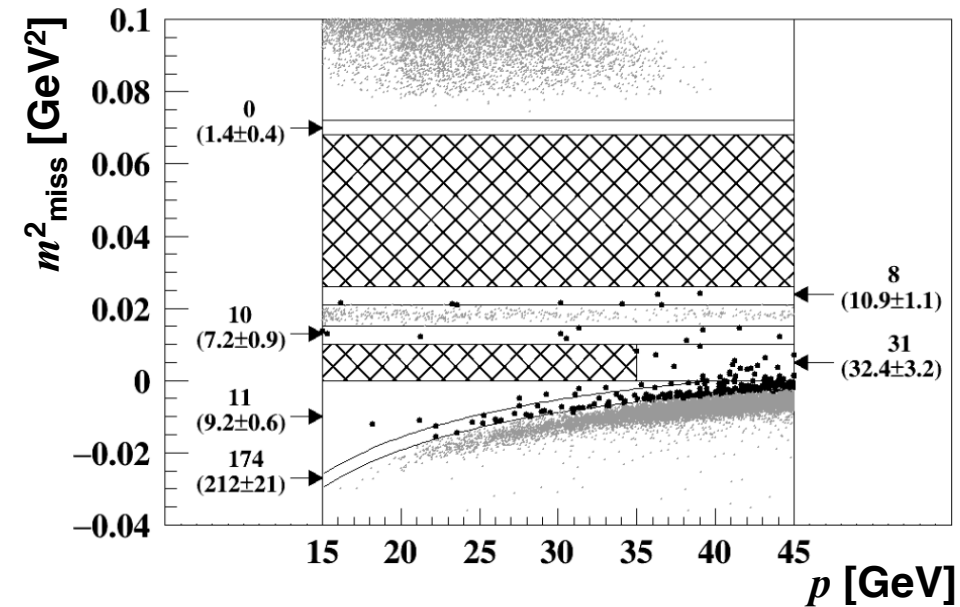
Combined result, 2016-2017 data:
 $BR(K^+ \rightarrow \pi^+ \nu \nu) < 1.78 \times 10^{-10}$ (90% CL)
3 events observed JHEP11 (2020) 042

2018 60-70% of nominal intensity
 $2.6 \times 10^{12} K^+$ decays in FV

Final results: 2016-2018 data



Background estimates for 2018



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
$\pi^0l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

NA62 2016-2018 data

2103.15389 (accepted by JHEP)

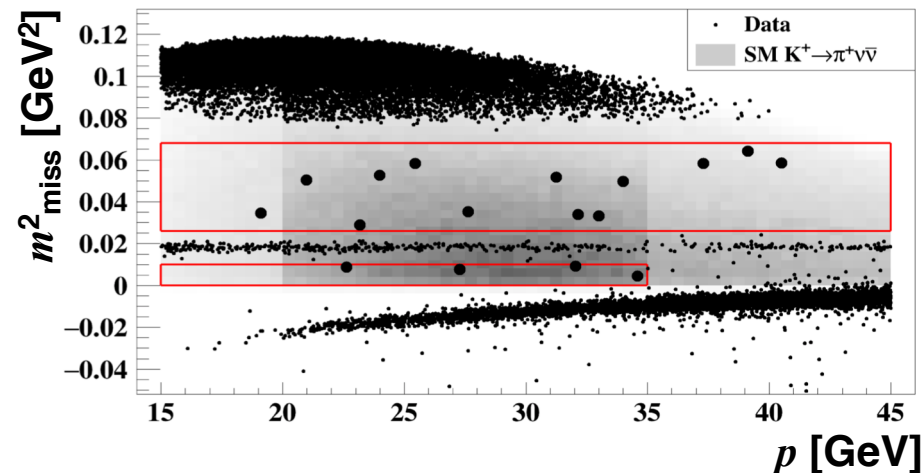
SES: $(8.39 \pm 0.53) \times 10^{-11}$

Expected sig: $10.01 \pm 0.42_{\text{sys}} \pm 1.19_{\text{ext}}$

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

20 events observed!

17 signal candidates in 2018 data



NA62 through LS3



Summary of NA62 Run 1 (2016-2018):

- **Expected signal (SM): 10 events**
- **Expected background: 7 events**
- **Total observed: 20 events**
- 3.5σ signal significance
- Most precise measurement to date

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

Plans for NA62 Run 2 (from LS2 to LS3):

NA62 to resume data taking in July 2021!

Key modifications to reduce background from upstream decays and interactions:

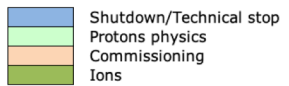
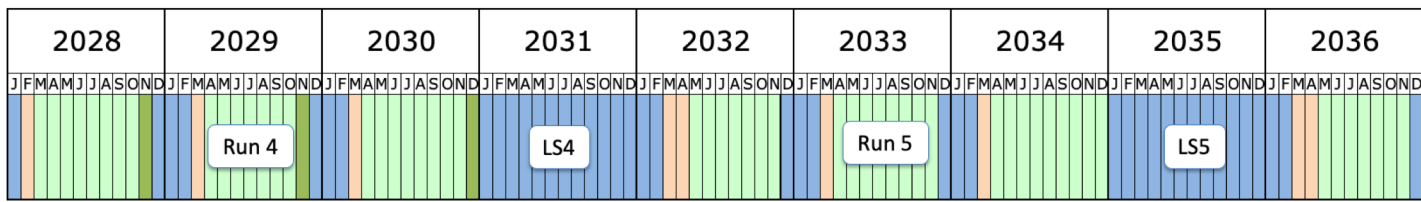
- Rearrangement of beamline elements around GTK achromat
- Add 4th station to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

Run at higher beam intensity (70% \rightarrow 100%)

Expect to measure $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ to O(10%) by LS3

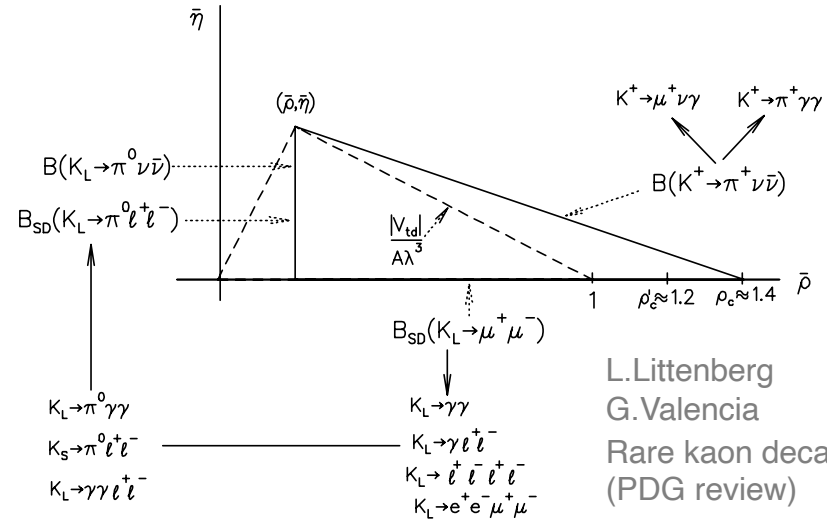
Fixed target runs at the SPS

Fixed target runs planned to accompany LHC running through 2036



<https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm>

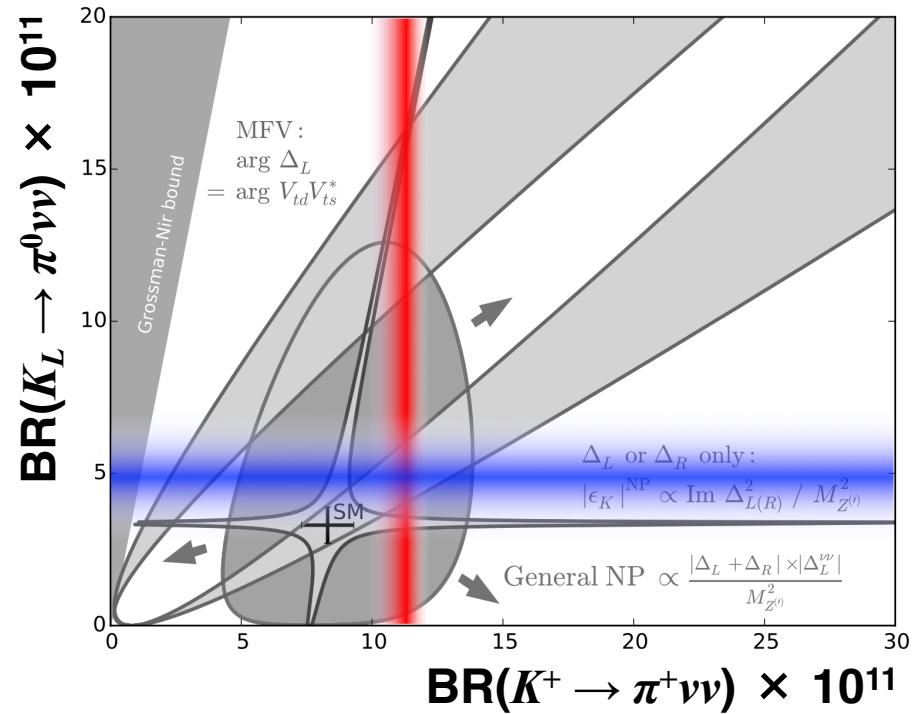
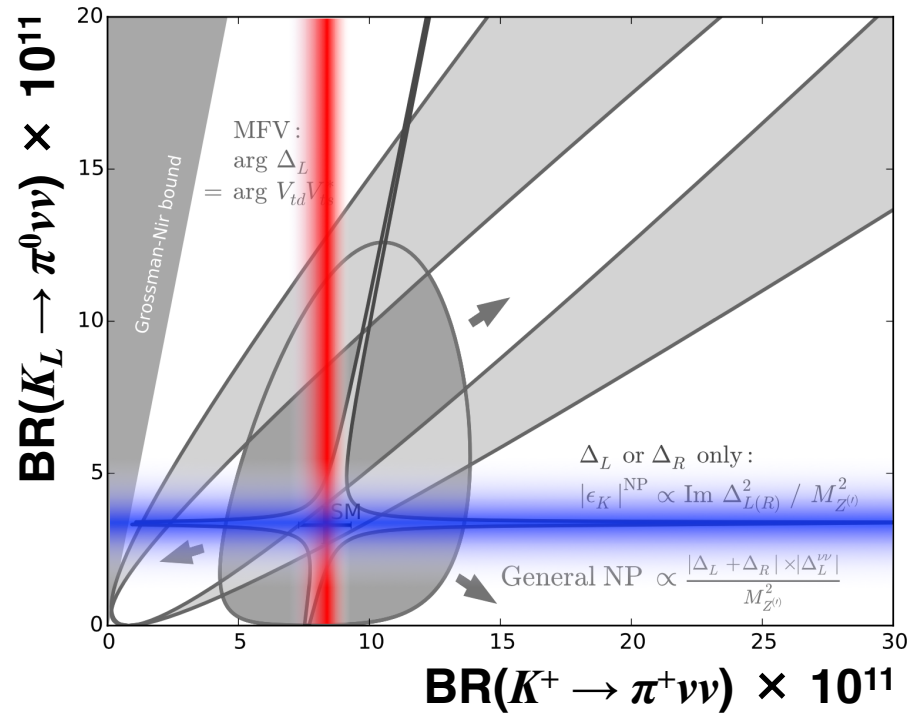
There is an opportunity at the SPS for an **integrated program** to pin down new physics in kaon decays
 Measurement of all rare kaon decay modes — **charged and neutral** — to give clear insight into the flavor structure of new physics



L.Littenberg
 G.Valencia
 Rare kaon decays
 (PDG review)

Physics opportunities in the kaon sector

Precision measurements of $K \rightarrow \pi \nu \nu$ BRs can provide model-independent tests for new physics at mass scales of up to $O(100 \text{ TeV})$



- $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) = \mathbf{BR_{SM}}$ with $\delta\text{BR} = \mathbf{5\%}$
- $\text{BR}(K_L \rightarrow \pi^0 \nu \nu) = \mathbf{BR_{SM}}$ with $\delta\text{BR} = \mathbf{20\%}$

- $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) = \mathbf{1.33 BR_{SM}}$ with $\delta\text{BR} = \mathbf{5\%}$
- $\text{BR}(K_L \rightarrow \pi^0 \nu \nu) = \mathbf{1.50 BR_{SM}}$ with $\delta\text{BR} = \mathbf{20\%}$

High-intensity kaon beams at the SPS

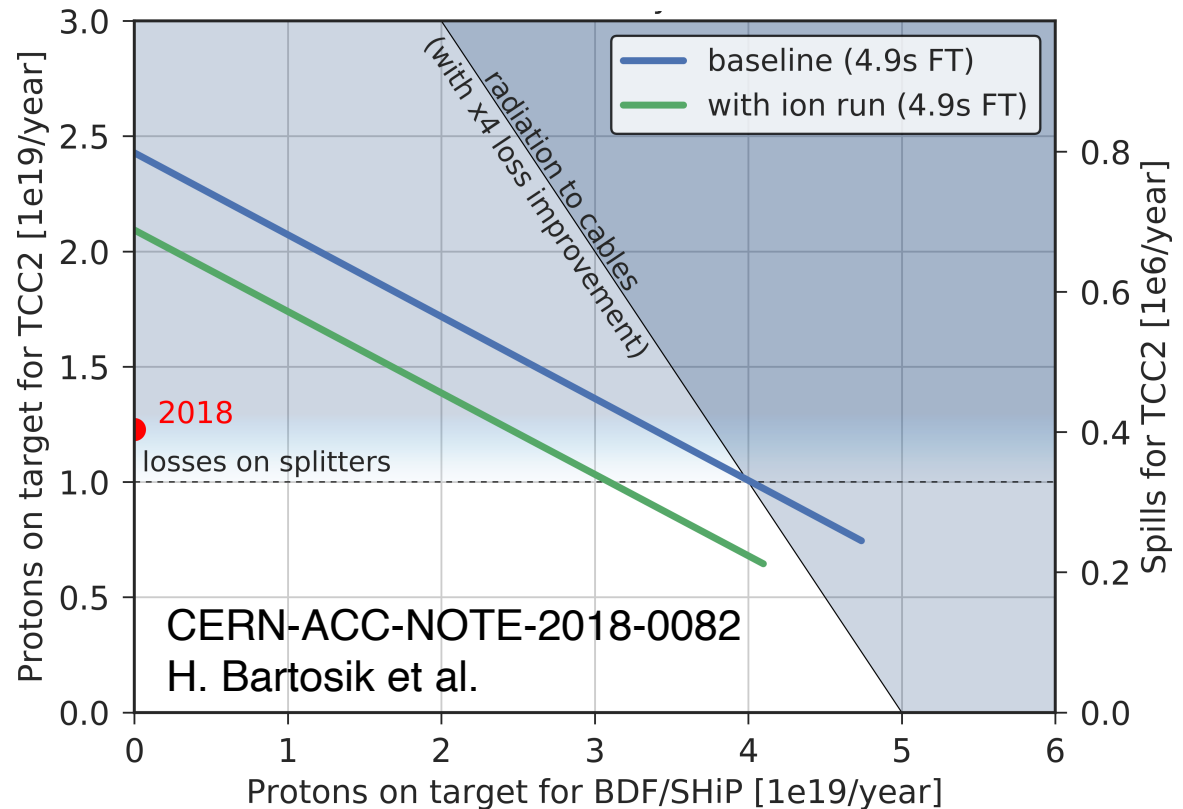
Operational scenarios and limits on the intensity deliverable to the North Area targets were studied in context of the BDF proposal as part of Physics Beyond Colliders

Experiments to measure $K \rightarrow \pi \nu \nu$ BRs at the SPS would require:

- $K^+ \rightarrow \pi^+ \nu \nu$
 6×10^{18} pot/year
4x increase
- $K_L \rightarrow \pi^0 \nu \nu$
 1×10^{19} pot/year
6x increase

increases with respect to present primary intensity

SPS proton sharing (4.9 sec flat top, 80% uptime)



A kaon experiment at 6x present intensity is compatible with a diverse North Area program

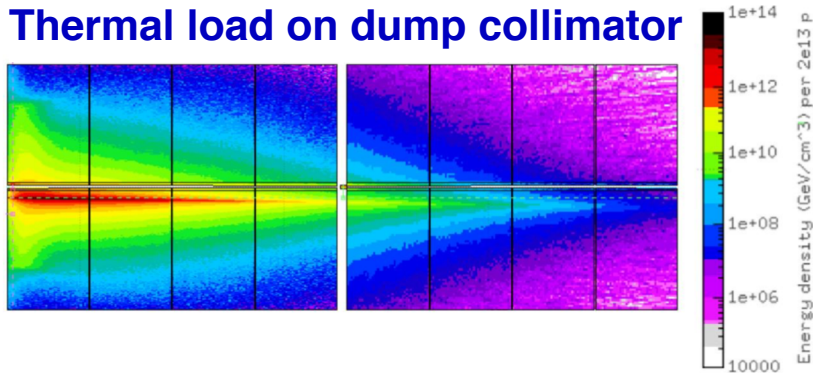
High-intensity proton beam study

Conclusions from PBC Conventional Beams working group

Issue	Approach
Extraction losses	Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) workshop, 9-11 November 2017: https://indico.cern.ch/event/639766/
Beam loss on T4	Vertical by-pass to increase T4 → T10 transmission to 80%
Equipment protection	Interlock to stop SPS extraction during P0Survey reaction time
Ventilation in ECN3	Preliminary measurements indicate good air containment Comprehensive ventilation system upgrade not needed
ECN3 beam dump	Significantly improved for NA62 Need to better understand current safety margin
T10 target & collimator	Thermal load on T10 too high → Use CNGS-like target? Dump collimator will require modification/additional cooling
Radiation dose at surface above ECN3	8 mrad vertical targeting angle should help to mitigate Preliminary results from FLUKA simulations Proposed target shielding scheme appears to be adequate Mixed mitigation strategy may be needed for forward muons

Beam and target simulations

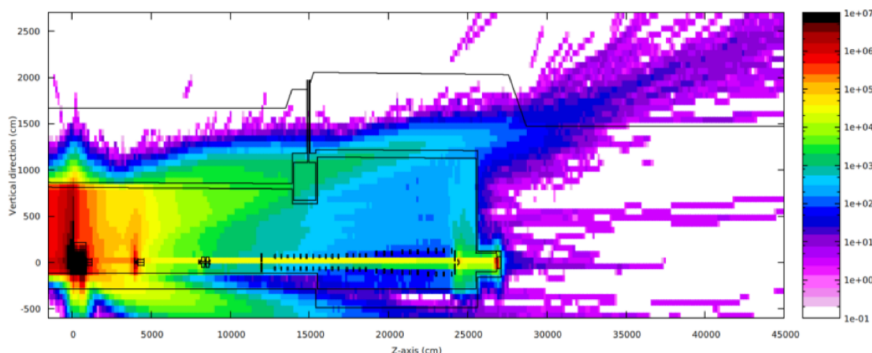
Thermal load on dump collimator



CNGS rod target



Dose rate simulation in ECN3, K_L beam



Thermal simulations of target and TAX dump collimator

- Identified upgrades needed for high-intensity beam
- Target: CNGS-like design: carbon-carbon supports, pressurized air cooling
- TAX: Cooling elements nearer to center of collimator, like for SPS beam dump

Neutral beam and prompt surface dose

- **Neutrons:** Shielding adequate to reduce surface dose; need access shaft airlock
- **Muons:** Additional shielding at target and/or at downstream end of ECN3

Complete evaluation of random veto and trigger rates with full FLUKA beamline simulation for all particles down to 100 MeV

- Random veto rate = 140 MHz

$K^+ \rightarrow \pi^+ \nu \nu$ at high-statistics



The NA62 decay-in-flight technique is now well established!

- Background estimates validated by in-depth study with data and MC
- Lessons learned in 2016-2018 will be put in action in 2021-2024

Possible next step:

An experiment at the SPS to measure $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ to within $\sim 5\%$!

Requires 4x increase in intensity \rightarrow matches present limit with charged secondary beam (after major upgrades)

Basic design of experiment will work at high intensity

Key challenges:

- Require much improved time resolution to keep random veto rate under control
- Must maintain other key performance specifications at high-rate:
 - Space-time reconstruction, low material budget, single photon efficiencies, control of non-gaussian tails, etc.

Synergies to be explored:

- Challenges often aligned with (sometimes more stringent than) High Luminosity LHC projects and next generation flavor/dark matter experiments

NA62 straw chambers

- Straw diameter: 9.8 mm
- Hit trailing-time resolution: ~ 30 ns
- Maximum drift time: ~ 150 ns
- Mylar straws: 36 wall μm thickness
- Material budget: 1.7% X_0



Straw chambers for 4x intensity

- **Main feature: Straw diameter ~ 5 mm**
- **Improved trailing-time resolution: ~ 6 ns (per straw)**
- **Smaller maximum drift time: ~ 80 ns**
- **Rate capability increased 6-8x**
- Layout: 4 chambers, ~ 21000 straws
- Decreased straw wall thickness: ~ 20 μm , with copper and gold plating
- Material budget: 1.4% X_0

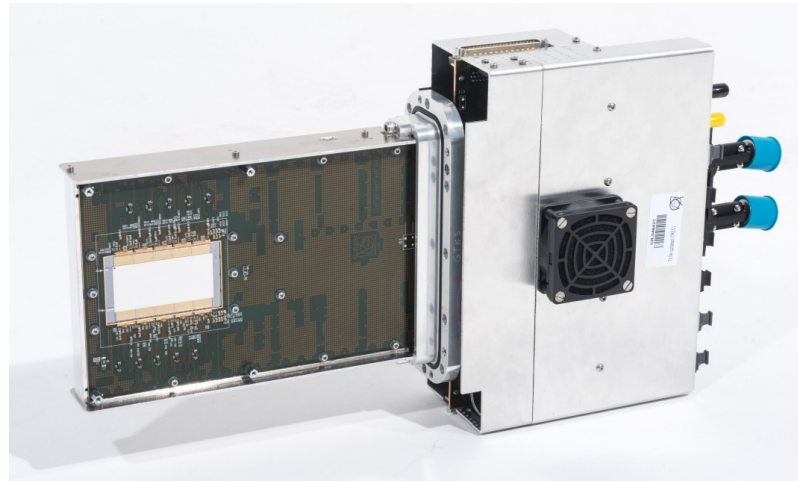
Design studies in progress at CERN and Dubna

Experimental challenges: GTK



GTK for 4x intensity

- Time resolution < 50 ps per plane, no non-gaussian tails!
- Pixel size: < 300 × 300 μm²
- Efficiency: > 99% (incl. fill factor)
- Material budget: 0.3-0.5% X₀
- Beam intensity: 3 GHz over ~ 3x6 cm²
- Maximum local intensity: 8 MHz/mm²
- Radiation resistance: 2.3x10¹⁵ n eq/cm²/yr

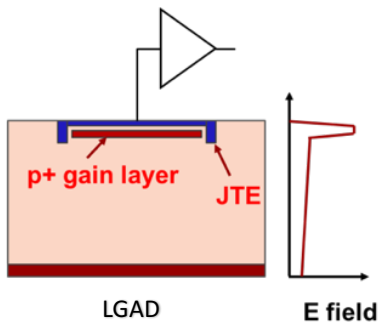


NA62 Gigatracker station

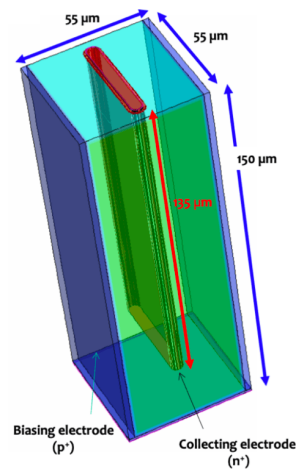
Continue to improve planar sensors while monitoring progress on new technologies

Possible synergies with ongoing development efforts:

LGAD: Low Gain Avalanche Detectors

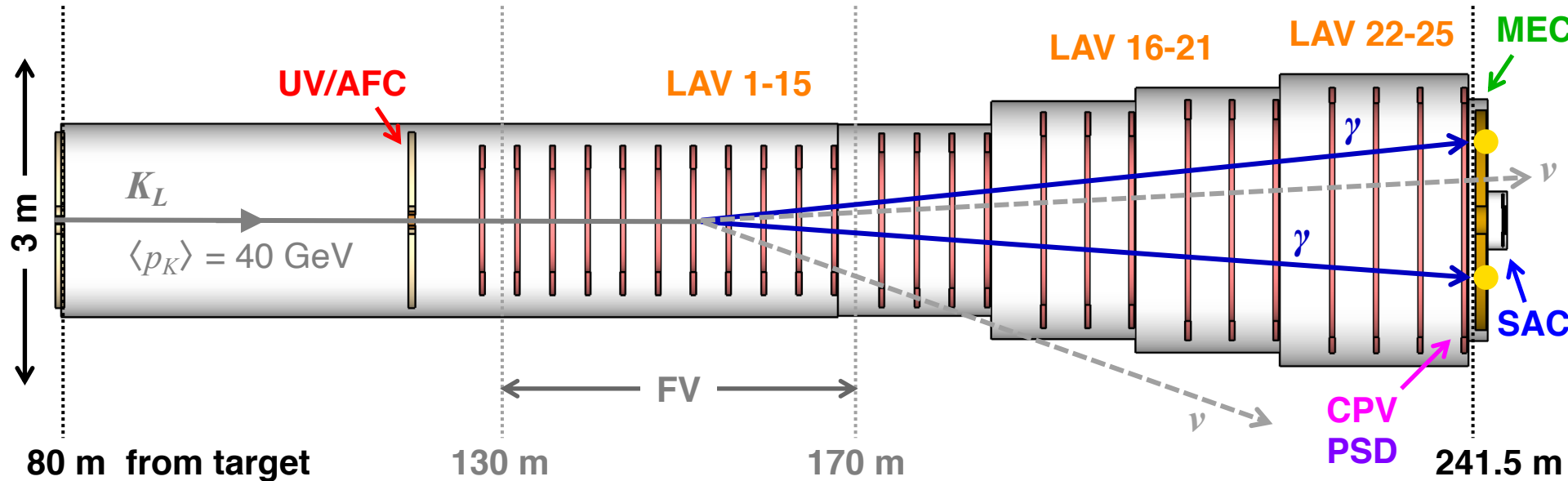


TimeSPOT: time-stamping 3D sensors



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

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



K_L EVER target sensitivity:

5 years starting Run 4

~ 60 SM $K_L \rightarrow \pi^0 \nu \bar{\nu}$

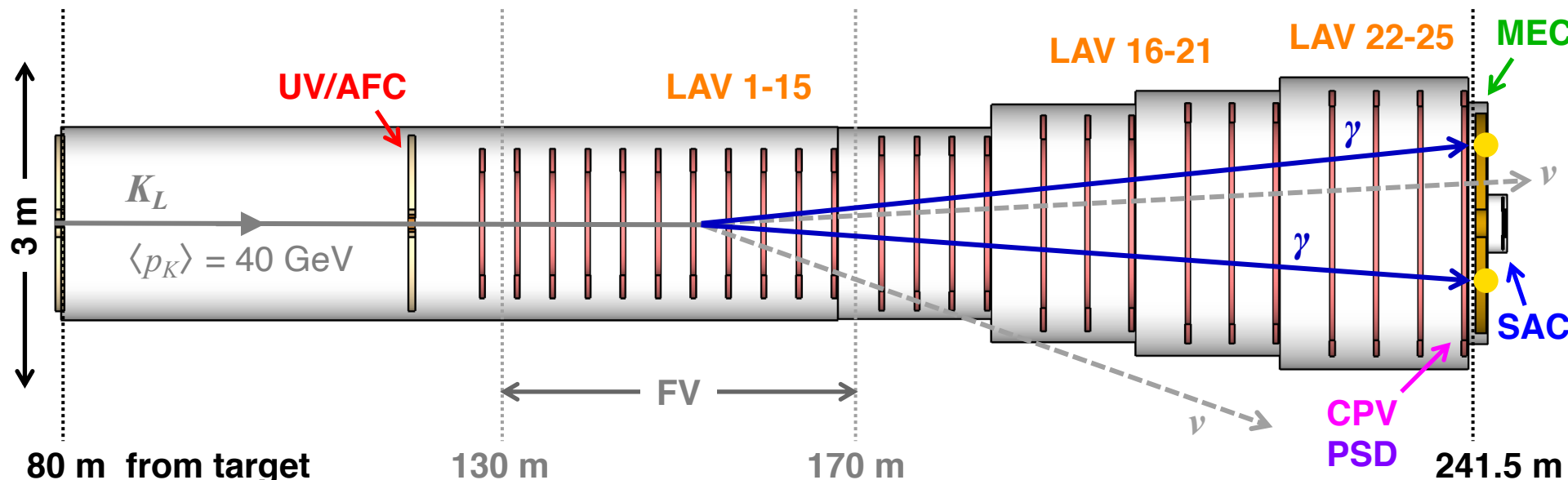
$S/B \sim 1$

$\delta BR/BR(\pi^0 \nu \bar{\nu}) \sim 20\%$

- 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

A $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiment at the SPS

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



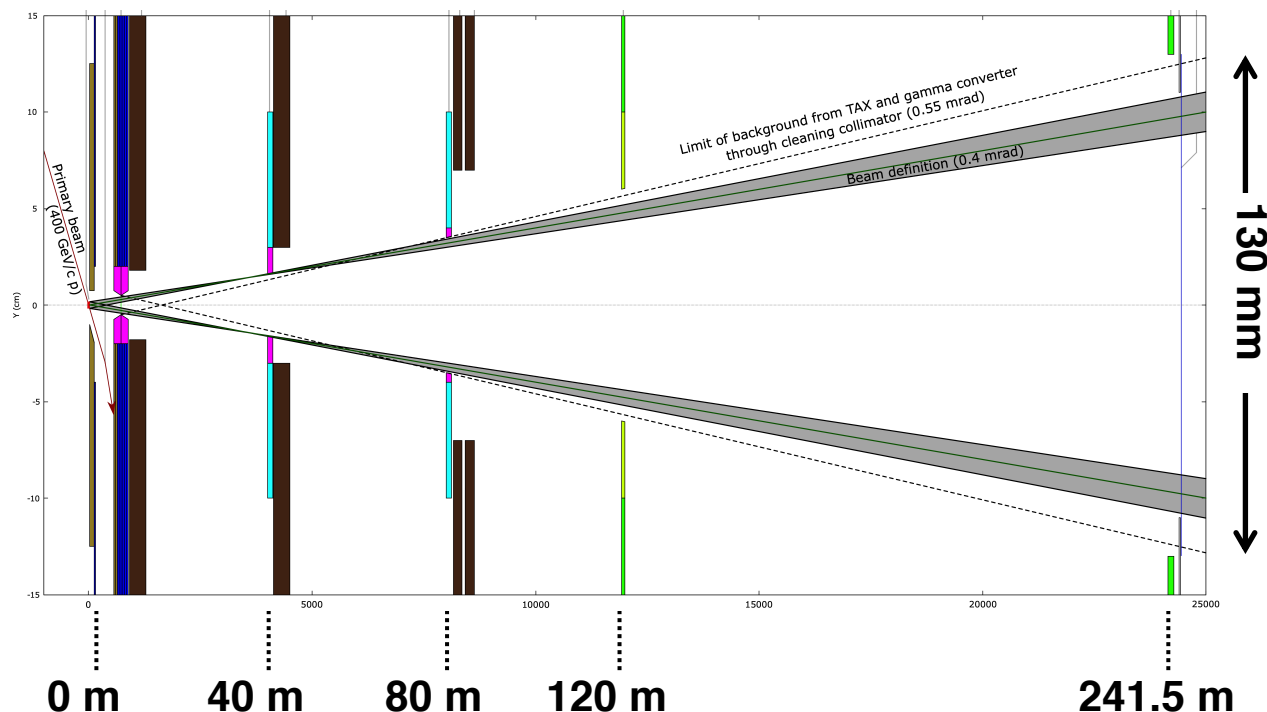
***KLEVER* target sensitivity:**
 5 years starting Run 4
 ~ 60 SM $K_L \rightarrow \pi^0 \nu \bar{\nu}$
 $S/B \sim 1$
 $\delta BR/BR(\pi^0 \nu \bar{\nu}) \sim 20\%$

Main detector/veto systems:

- UV/AFC** Upstream veto/Active final collimator
- LAV1-25** Large-angle vetoes (25 stations)
- MEC** Main electromagnetic calorimeter
- SAC** Small-angle vetoes
- CPV** Charged particle veto
- PSD** Pre-shower detector

Neutral beam and beamline

- 400 GeV p on 400 mm Be target
- Production angle $\theta = 8.0$ mrad
- Solid angle $\Delta\theta = 0.4$ mrad
- $2.1 \times 10^{-5} K_L/\text{pot}$ in beam
- $\langle p(K_L) \rangle = 40$ GeV
- Probability for decay inside FV $\sim 4\%$
- Acceptance for $K_L \rightarrow \pi^0 \nu \nu$ decays occurring in FV $\sim 5\%$



- **4 collimation stages** to minimize neutron halo, including beam scattered from absorber
- **Photon absorber** in dump collimator

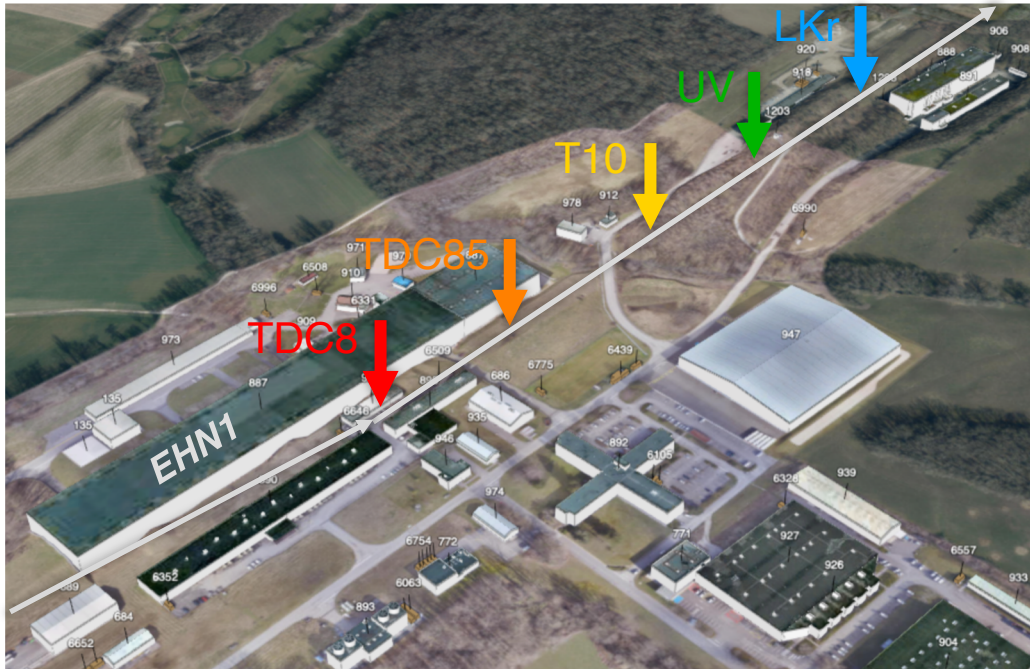
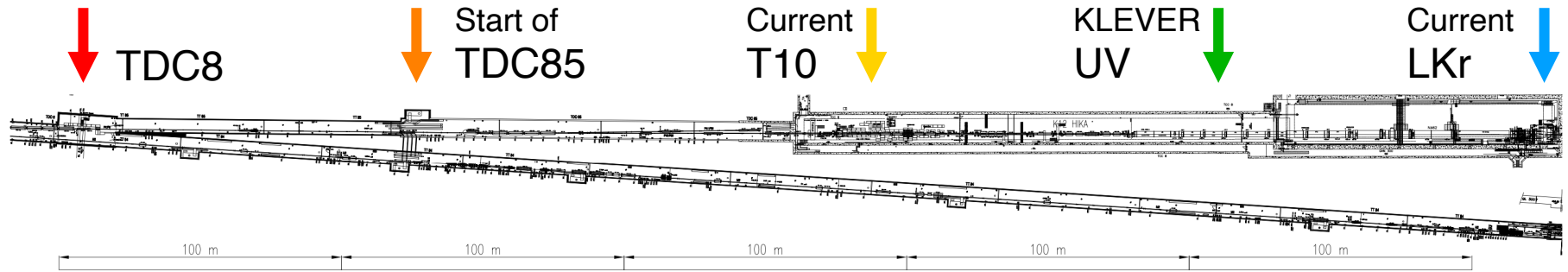
NB: Choice of higher production angle under study to decrease rate of $\Lambda \rightarrow n\pi^0$ decays in detector:

Possible changes to beamline configuration and experimental layout

Long beamline to suppress $\Lambda \rightarrow n\pi^0$ **KLEVER**

Maintain $\theta = 8$ mrad and increase length of beamline

E.g.: Move T10 from TCC8 to start of TDC85 (120 m \rightarrow 270 m from T10 to UV)



- Maintain K_L momentum
Fewer design changes for KLEVER
- Preserve K_L flux per solid angle
Still lose 2x in K_L flux due to tighter beam collimation
- Infrastructure work needed
- RP issues for area downstream of TDC85 to be investigated
- **Alternatively, ECN3 extension would solve problem**

Shashlyk calorimeter with spy tiles

Requirements for main electromagnetic calorimeter (MEC):

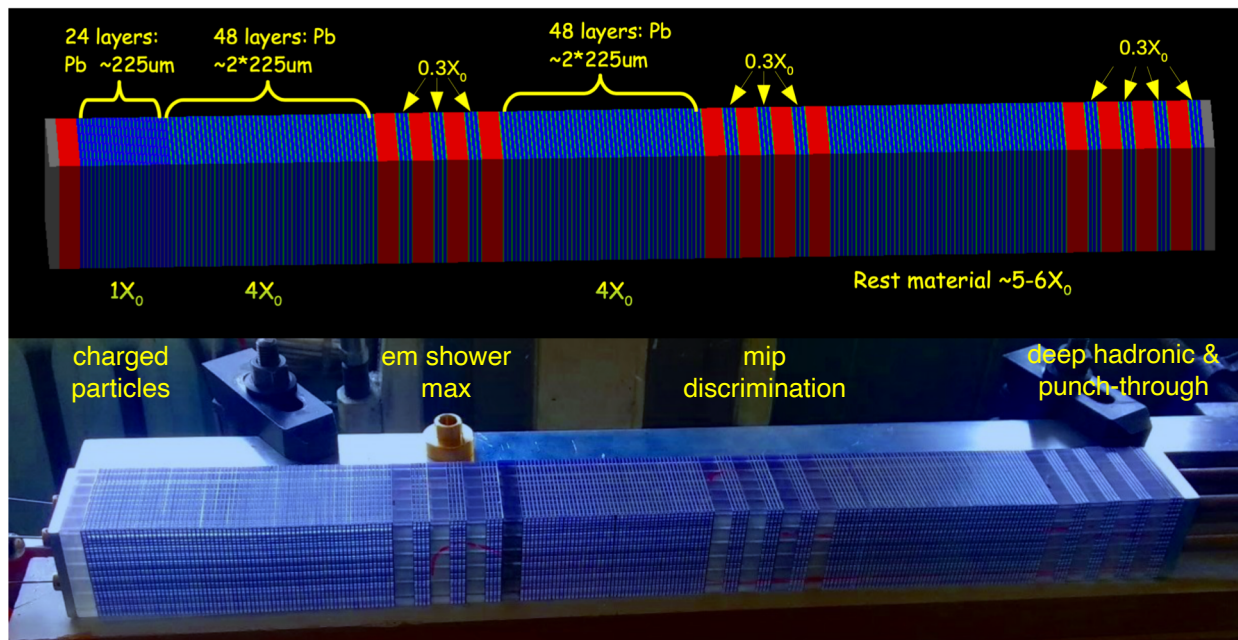
Excellent efficiency, time resolution $\sim 100\text{ps}$, good 2-cluster separation



LKr calorimeter from NA62:

Photon detection efficiency probably adequate

Time resolution $\sim 500\text{ ps}$ for π^0 with $E_{\gamma\gamma} > 20\text{ GeV}$ \rightarrow requires improvement



Main electromagnetic calorimeter (MEC):

Fine-sampling shashlyk based on PANDA forward EM calorimeter produced at Protvino

0.275 mm Pb + 1.5 mm scintillator

PANDA/KOPIO prototypes:

$$\sigma_E/\sqrt{E} \sim 3\% \sqrt{E} \text{ (GeV)}$$

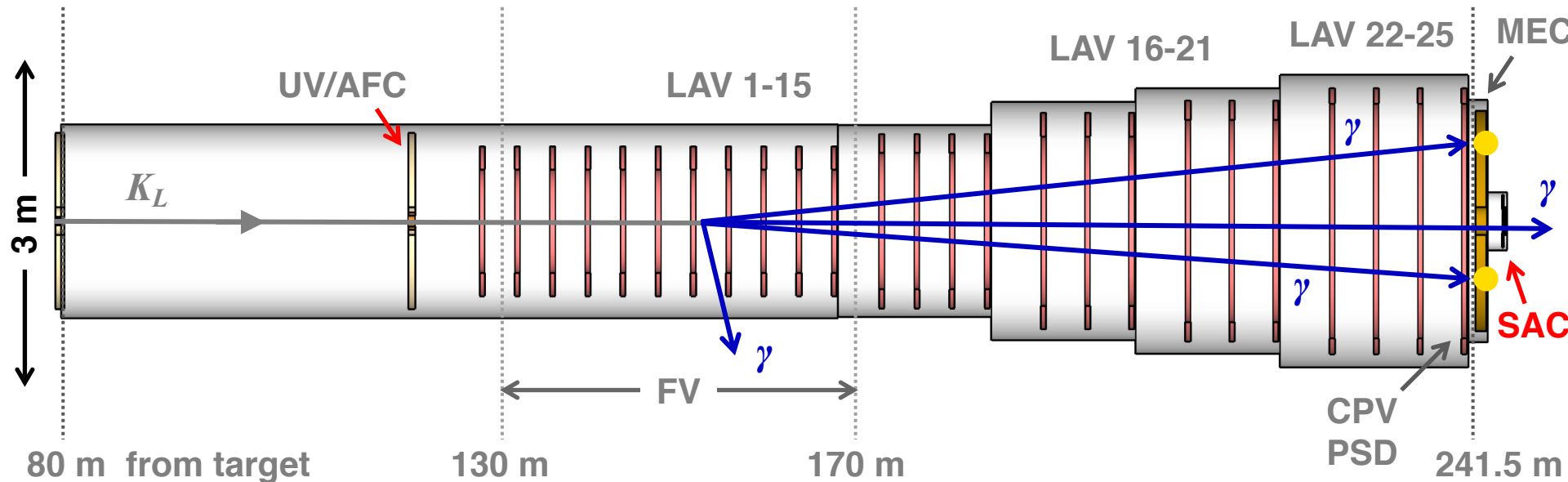
$$\sigma_t \sim 72 \text{ ps} \sqrt{E} \text{ (GeV)}$$

$$\sigma_x \sim 13 \text{ mm} \sqrt{E} \text{ (GeV)}$$

Longitudinal shower information from spy tiles

- PID information: identification of μ , π , n interactions
- Shower depth information: improved time resolution for EM showers

Small-angle photon veto



Small-angle photon calorimeter system (SAC)

- Rejects high-energy γ s from $K_L \rightarrow \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Beam comp.	Rate (MHz)	Req. $1 - \epsilon$
$\gamma, E > 5 \text{ GeV}$	50	10^{-2}
$\gamma, E > 30 \text{ GeV}$	2.5	10^{-4}
n	430	—

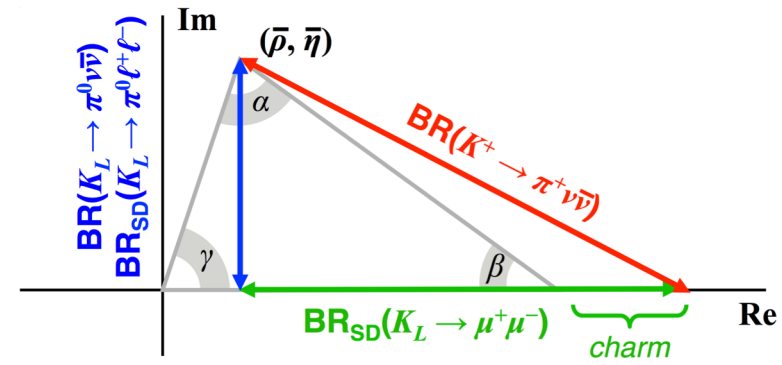
Possible solutions:

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber to exploit enhancement of photon conversion by coherent interaction with lattice
- Compact Cerenkov calorimeter with oriented crystals

What about $K_L \rightarrow \pi^0 \ell^+ \ell^-$?

$K_L \rightarrow \pi^0 \ell^+ \ell^-$ vs $K \rightarrow \pi \nu \bar{\nu}$:

- Somewhat larger theoretical uncertainties from long-distance physics
 - SD CPV amplitude: γ/Z exchange
 - LD CPC amplitude from 2γ exchange
 - LD indirect CPV amplitude: $K_L \rightarrow K_S$
- $K_L \rightarrow \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays



**$K_L \rightarrow \pi^0 \ell^+ \ell^-$ CPV amplitude
constrains UT in same way
as $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})$**

Experimental status:

$$\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) < 28 \times 10^{-11}$$

Phys. Rev. Lett. 93 (2004) 021805

$$\text{BR}(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$$

Phys. Rev. Lett. 84 (2000) 5279–5282

Main background: $K_L \rightarrow \ell^+ \ell^- \gamma \gamma$

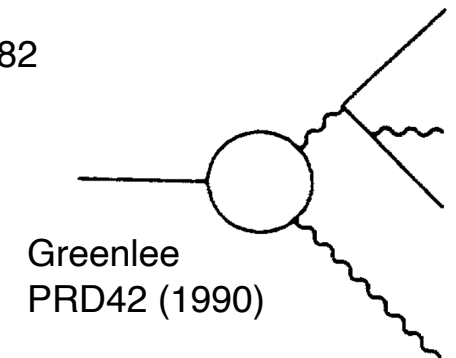
- Like $K_L \rightarrow \ell^+ \ell^- \gamma$ with hard bremsstrahlung

$$\text{BR}(K_L \rightarrow e^+ e^- \gamma \gamma) = (6.0 \pm 0.3) \times 10^{-7}$$

$$E_\gamma^* > 5 \text{ MeV}$$

$$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) = 10^{+8}_{-6} \times 10^{-9}$$

$$m_{\gamma\gamma} > 1 \text{ MeV}$$



Integrated program with K^+ and K_L beams

Availability of high-intensity K^+ and K_L beams at the SPS:

Important physics measurements at boundary of NA62 and KLEVER!

Example: Experiment for rare K_L decays with charged particles

- K_L beamline, as in KLEVER
- Tracking and PID for secondary particles, as in NA62

Physics objectives:

- $K_L \rightarrow \pi^0 \ell^+ \ell^-$
Excellent π^0 mass resolution – look for signal peak over Greenlee background
- Lepton-flavor violation in K_L decays
- Radiative K_L decays and precision measurements
- K_L decays to exotic particles

Will provide valuable information to characterize neutral beam

- Example: Measurement of K_L , n , and Λ fluxes and halo
- Experience from KOTO and studies for KLEVER show this to be critical!

Just getting started!

Summary and outlook

$K \rightarrow \pi\nu\nu$ and other rare kaon decays are uniquely sensitive indirect probes for new physics at high mass scales

Need precision measurements of both rare K^+ and $K_{S,L}$ decays!

LHCb BR measurements for decays such as $K_{S,L} \rightarrow \mu^+\mu^-$ and $K_S \rightarrow \pi^0\mu^+\mu^-$ will help with theoretical systematics (e.g., separate LD/SD contributions)

NA62 will improve on current knowledge of $\text{BR}(K^+ \rightarrow \pi^+\nu\nu)$ in short term, ultimately reaching O(10%) precision

KOTO is making significant progress in background reduction and will reach SM sensitivity to $\text{BR}(K_L \rightarrow \pi^0\nu\nu)$ by 2025

Next generation rare kaon experiments with high-intensity beams and cutting-edge detectors will provide a powerful tool to search for physics beyond the Standard Model

Planning has started for KOTO-2 at J-PARC to measure $\text{BR}(K_L \rightarrow \pi^0\nu\nu)$

An integrated program of K^+ and K_L experiments is taking shape at CERN

Additional information

Flavor Physics and CP Violation: FPCP 2021
Fudan University, Shanghai, 11 June 2021

Matthew Moulson – INFN Frascati

For the NA62 Collaboration and KLEVER Project

$K \rightarrow \pi \nu \bar{\nu}$ and the unitarity triangle

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407} \right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ} \right]^{0.74} \quad \text{Buras et al., JHEP 1511}$$

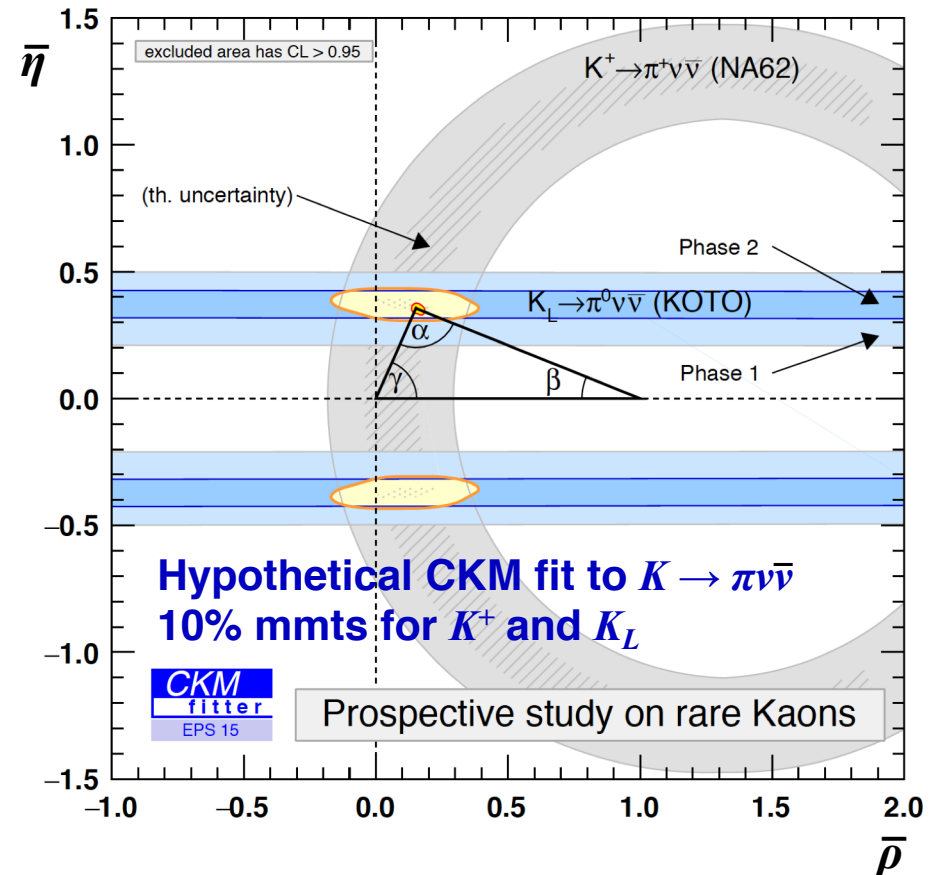
$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}} \right]^2 \cdot \left[\frac{|V_{cb}|}{0.0407} \right]^2 \cdot \left[\frac{\sin \gamma}{\sin 73.2^\circ} \right]^2$$

Dominant uncertainties for SM BRs are from CKM matrix elements

Intrinsic theory uncertainties 1.5-3.5%

Measuring BRs for both $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ can determine the CKM unitarity triangle independently from B inputs:

- Over-constrain CKM matrix \rightarrow reveal NP effects
- Sensitivity complementary to B decays



Dump mode after 2025



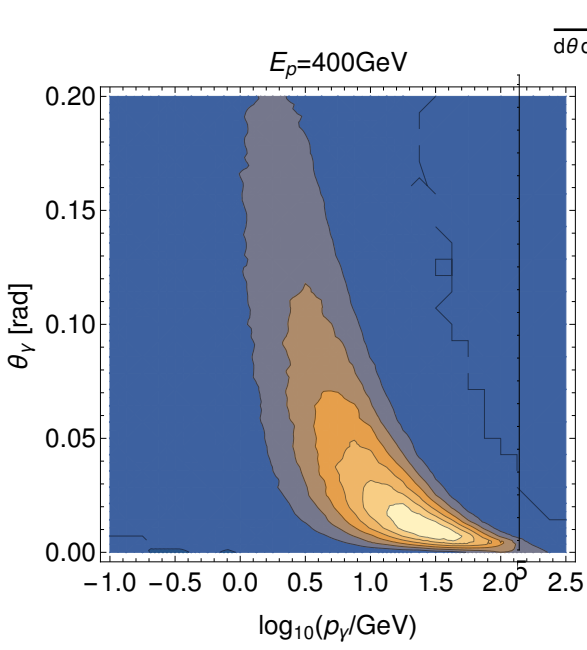
Search for visible decays feebly-interacting new-physics particles

- **10x improvement in statistics** expected with respect to 2021-2023 data taking
- If no signal and negligible background → **10x sensitivity improvement**

Dump mode is most sensitive to forward processes, complimentary to off-axis experiments

Distribution of photons from neutral pion decays in TAX: Primakov production

ALPs go in approx. same direction



Can capture distribution up to 5 mrad

Sensitivity to FIP lifetime depends on distance production-detector and length of detector (few ns, complimentary to other experiments)

