Paolo Franzini and Juliet Lee-Franzini Memorial Symposium

Laboratori Nazionali di Frascati
19 April 2022

Rare kaon decays

Matthew Moulson
Laboratori Nazionali di Frascati

Paolo and Juliet at Columbia

Paolo.Franzini@lnf.infn.it — 22 October 1997 at 19:44
RE: Interest in KLOE
To: moulson, Cc: PAOLO@lnf.infn.it
Details

dear Matthew Moulson, perhaps I should just give you an idea of the immediate future of DAPHNE and KLOE according to the official lab schedule for the immediate future which as follows.

a. Machine commissioning has started, electrons have made 100 turns. By end of october positrons should also be in. Then machine will tune for luminosity at reduced number of bunches. Luminosity goal 1/10 max of 1/2 of final.
b. February 98 machine stops and KLOE rolls in, is raised, alligned, cryo connected, some debugging, machine restarts June 1, 98 at reduced luminosity, with KLOE solenoid on. That means, as far as luminosity, start from scratch.
c. After 3 months Dafne stops for installation of the other experiment, also with a magnet, same \int B d\ell.
d. Machine starts again before end 98.
e. Full luminosity ???

In the above c.) is somewhat nebulous, .d.) is driven by c.).
e.) depends on too many things, but I doubt
that we will begin CP before end 99. We have many other things to study in the meantime, so we are not very unhappy. We have a perfect magnet, all measured and by next week we disconnect the helium line and we have begun to install the calorimeter and electronics. The chamber still needs 5,000 wires out of 52,000.
Electronics and data acquisition is well ahead. Most DAQ software is complete as well as the production off line programs.
Getting the dector running with a new machine is always a major effort and we think we have a lot of interesting physics and work in 98 through at least 2002.
We are always happy to get new young people and I hope you can judge for yourself when it might be most convenient for you to come to Italy, vis a vis your thesis etc.

Sincerely,
Paolo Franzini

P.S. Did you ever resolve whether the Fano factor is seen in liquid xenon? I do not believe that there is such a thing, because it requires long, >>atomic size, correlations in the ionization energy losses in a medium.

My first contact from Paolo about KLOE

October 1997

Physics vs. luminosity: perspectives

0.5 fb^{-1} $5\times10^8\ K_SK_L$	**KLOE today**	Limit on $K_S \to 3\pi^0$ at 10^{-7} level A_S to 10^{-2} V_{us} from $K_{\ell 3}$ decays at few 10^{-3} level
2 fb^{-1} $2\times10^9\ K_SK_L$	**KLOE '04-'05**	Limit on $K_S \to 3\pi^0$ at 10^{-8} level A_S to 4×10^{-3} First studies of K_SK_L system with interference
40 fb^{-1} $4\times10^{10}\ K_SK_L$	**Original KLOE program**	Re ε'/ε at 10^{-4} level Im ε'/ε at 10^{-2} level from K_SK_L interference
200 fb^{-1} $2\times10^{11}\ K_SK_L$	**DAΦNE2**	High-precision studies of K_SK_L system via interference measurements Competitive measurement of Re δ from A_S BR($K_S \to 3\pi^0$) and BR($K_S \to \pi^0\ell\ell$) to 20%

$K^+ \to \pi^+\nu\nu$, $K_L \to \pi^0\nu\nu$, and $K_L \to \pi^0\ell^+\ell^-$ probably not within reach

“It took 35 years to measure $\mathrm{Re}\ \varepsilon'/\varepsilon$.

It will take 35 more to measure
one of the $K \to \pi\nu\nu$ branching ratios”

–Paolo, circa 2005

Rare kaon decays

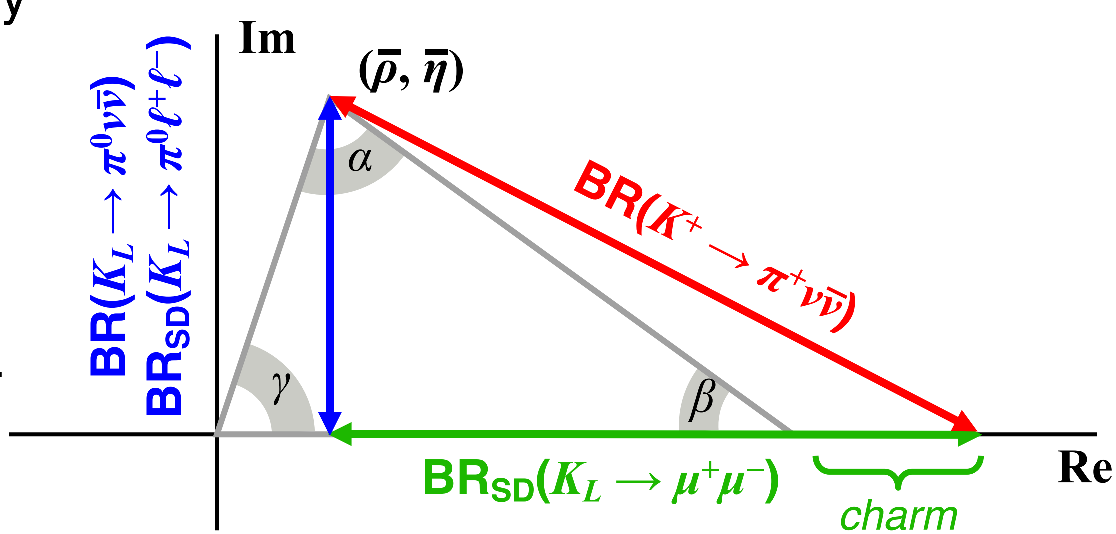
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11} (Sep 2019)
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	$< 28^\dagger$
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	$< 38^\dagger$
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	$< 18.5^\dagger$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

*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

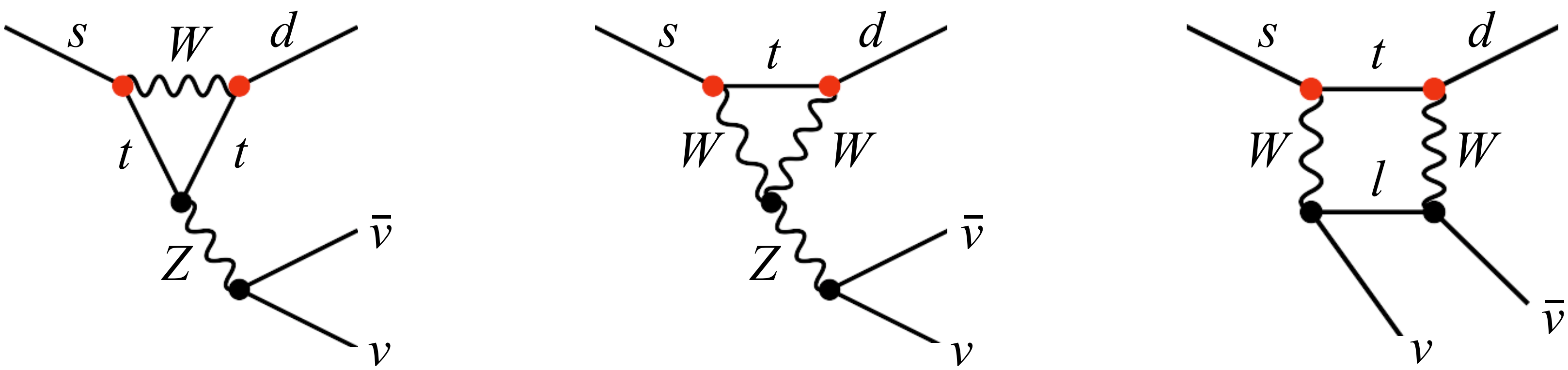
FCNC processes dominated by Z-penguin and box diagrams

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

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



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



Extremely rare decays with rates very precisely predicted in SM:

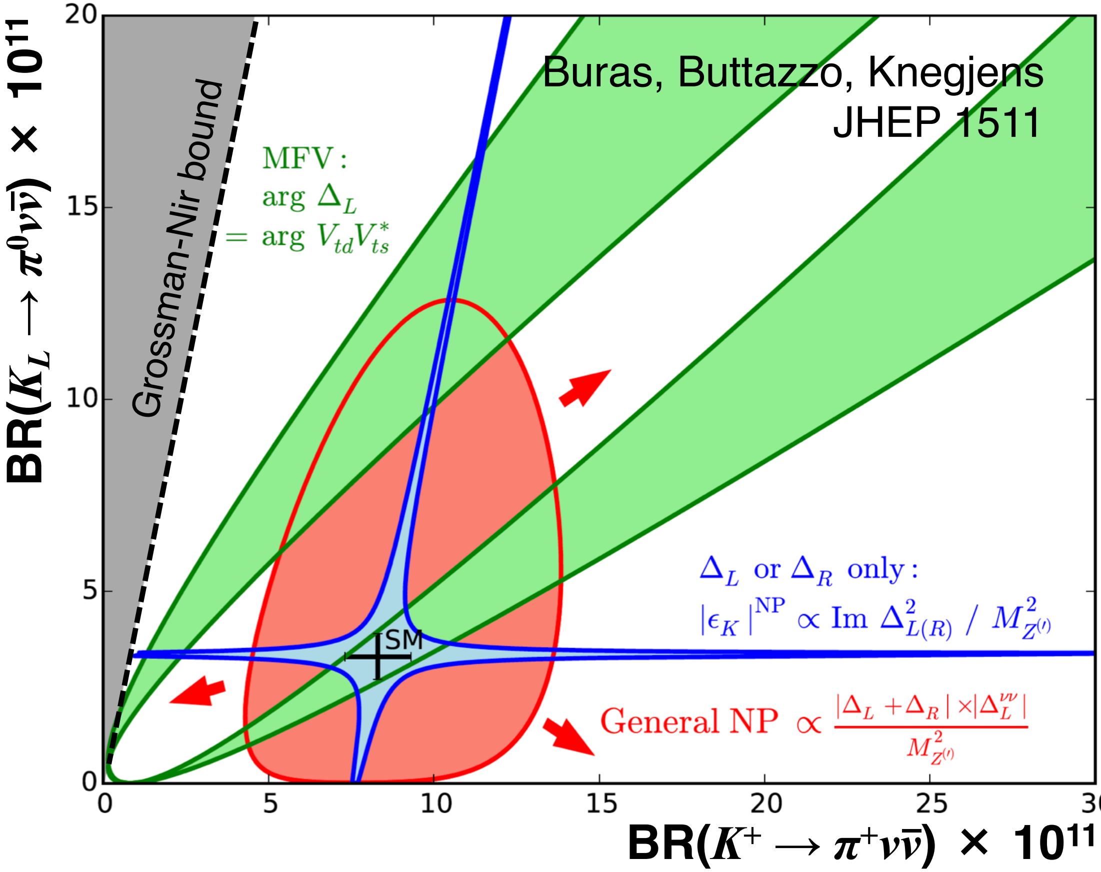
- Hard GIM mechanism + pattern of CKM suppression ($V_{ts}^* V_{td}$)
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

	SM predicted rates Buras et al, JHEP 1511*	**Experimental status** **(before Sep 2019)**
$K^+ \to \pi^+\nu\bar{\nu}$	**BR = (8.4 ± 1.0) × 10^−11^** → $\mathrm{BR} = (8.4 \pm 1.0) \times 10^{-11}$	$\mathrm{BR} = (17.3\,^{+11.5}_{-10.5}) \times 10^{-11}$ Stopped K^+, 7 events observed BNL 787/949, PRD79 (2009)
$K_L \to \pi^0\nu\bar{\nu}$	$\mathrm{BR} = (3.4 \pm 0.6) \times 10^{-11}$	$\mathrm{BR} < 300 \times 10^{-11}$ 90%CL KOTO, PRL122 (2019)

* Tree-level determinations of CKM matrix elements

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

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

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

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

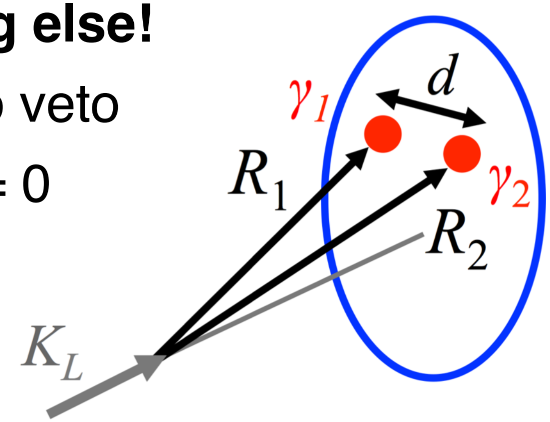
All other K_L decays have ≥ 2 extra γs or ≥ 2 tracks to veto

Exception: $K_L \to \gamma\gamma$, 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



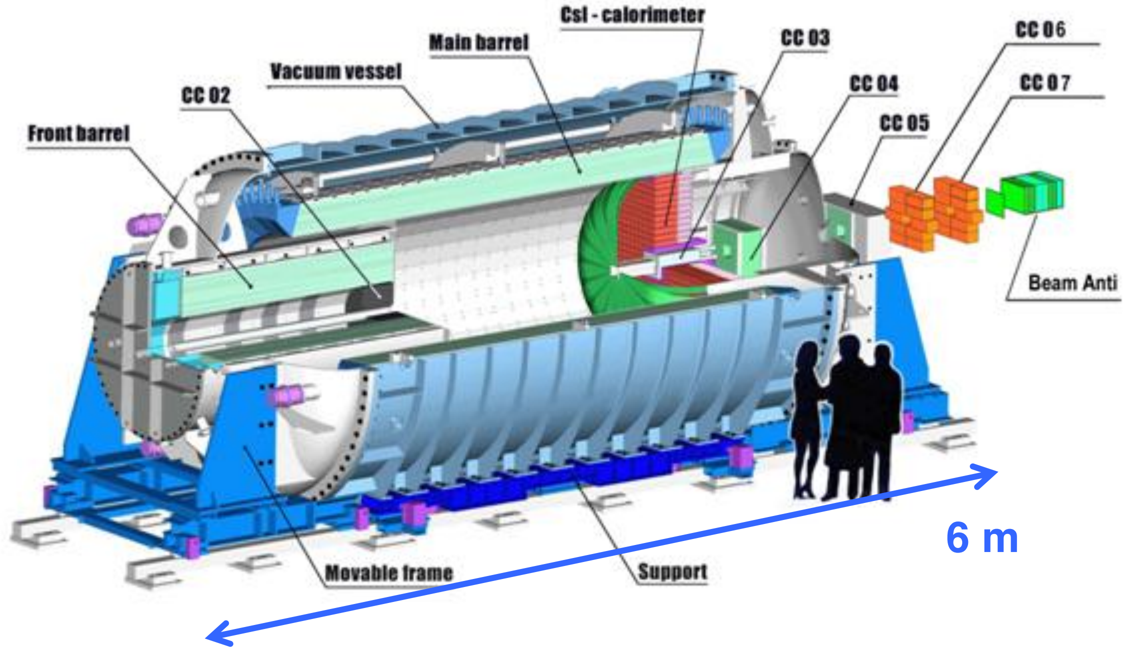
$$m_{\pi^0}^2 = 2E_1E_2\,(1 - \cos\theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

Main backgrounds:

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

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



Primary beam: 30 GeV p

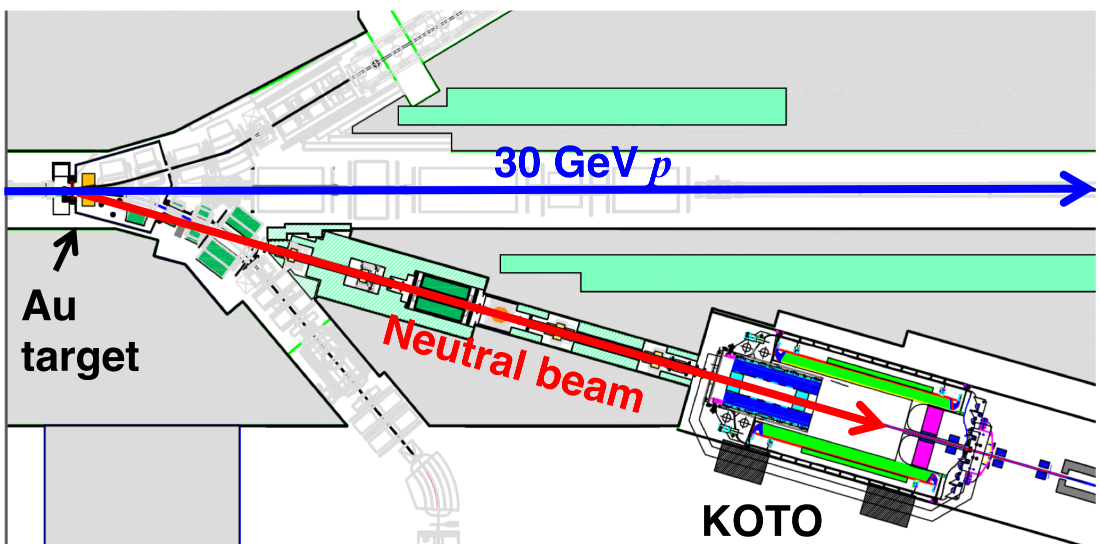
50 kW=5.5 × 10^{13} p/5.2 s (2019)

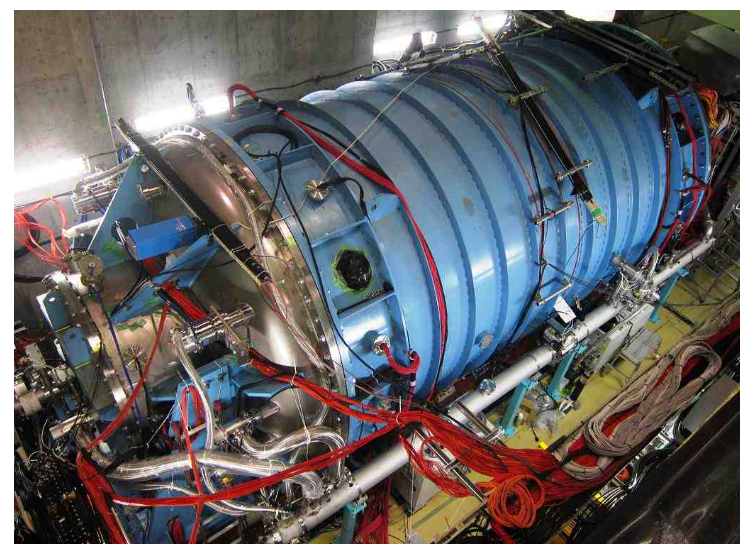
Neutral beam (16°)

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

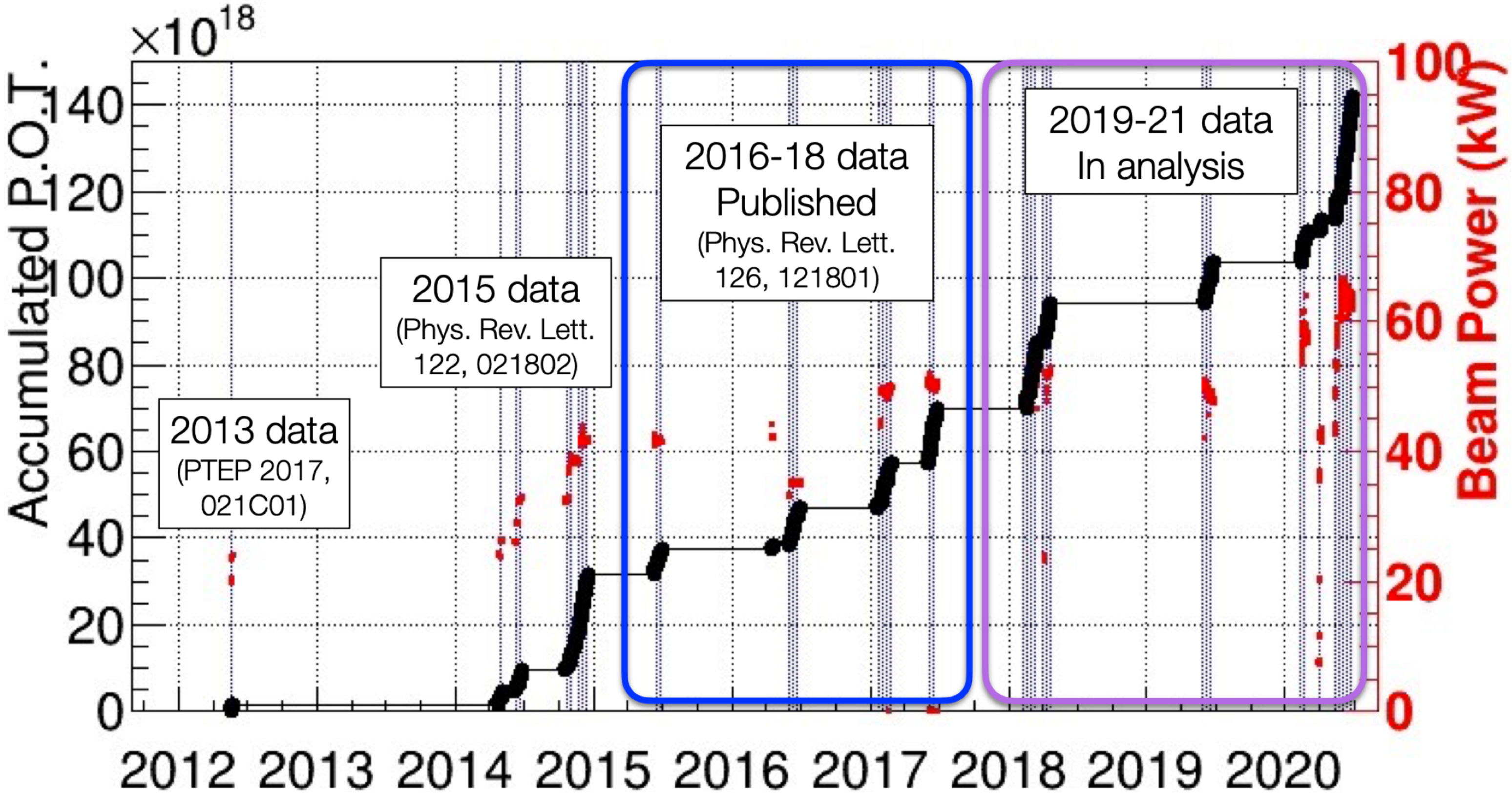
50% of K_L have 0.7-2.4 GeV

8 μsr "pencil" beam





KOTO status and timeline



2015 run

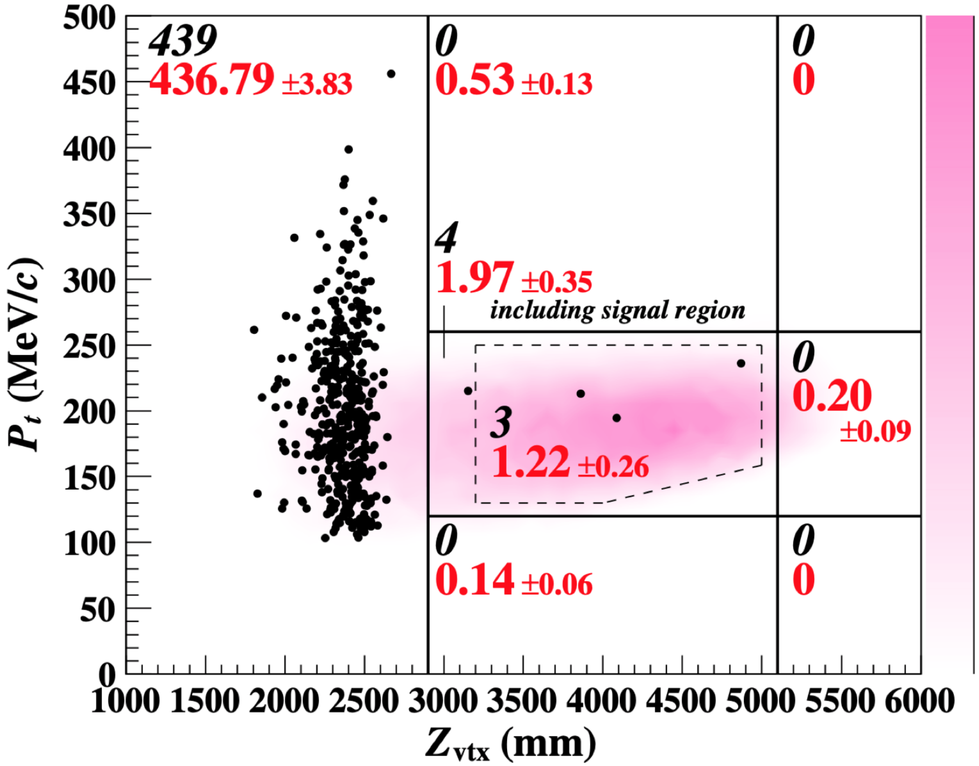
- Reached **40 kW** slow-extracted beam power
- 2.2 × 10^{19} pot collected
- **BR($K_L \to \pi^0 \nu\nu$) < 3.0 × 10^{-9} (90%CL)**
  PRL 122 (2019) 021802

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)
$K_L \to \pi^0\pi^0\pi^0$	0.01 ± 0.01
$K_L \to \gamma\gamma$ halo	**0.26 ± 0.07**
Other K_L decays	0.005 ± 0.005
$K^\pm_{e3} + K^\pm_{\mu 3} + K^\pm_{\pi 2}$	**0.87 ± 0.25**
n interaction in CsI	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($K_L \to \pi^0\nu\nu$) < 4.9 × 10^{-9} (90%CL)

30.5×10^{19} pot

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

0.04 signal + 1.22 background events expected

3 events in signal box

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

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

Decay in FV: 3.3%

Overall acceptance: 0.6%

PRL 126 (2021) 121801

Outlook after 2021

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

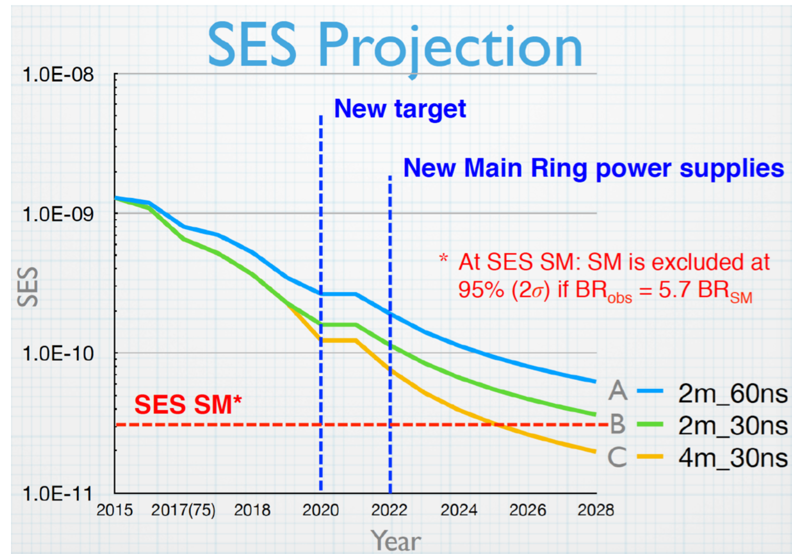
- Beam power expected to increase from 50 → 100 kW after 2022

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 rediual activity for the beam power upgrade

JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event	long shutdown ↔ (2020–2021)								
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 → (2020–2021)								
RF system upgrade			↔ (2022–2025)						
2nd harmonic rf system	→ (2020–2024)								
Collimator system		Add.colli. (3.5kW)							
Injection system FX system	Kicker PS improvement, Septa manufacture /test → (2020–2021)								
Beam Monitors (BPM circuits)	→ (2020–2024)								
SX Local sheild Diffuser/ Bent crystal/ VHF	↔ (2020–2025)								

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

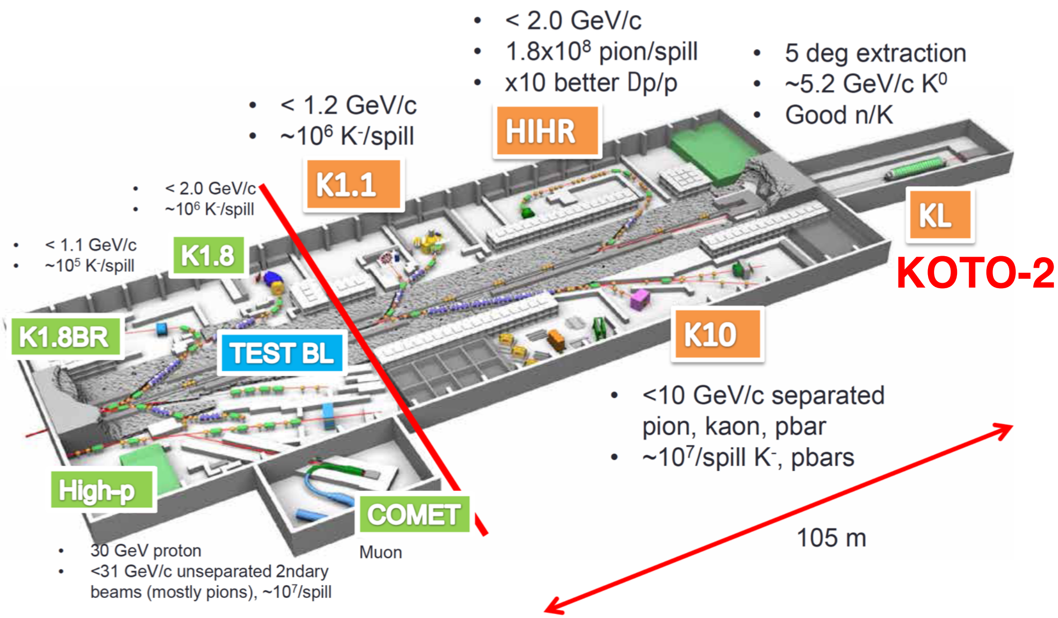
SES projection from 2018 and will be updated soon, but main conclusion unchanged:

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 design work for 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 12 m
  Complete rebuild of detector
- **Requires hadron-hall extension**

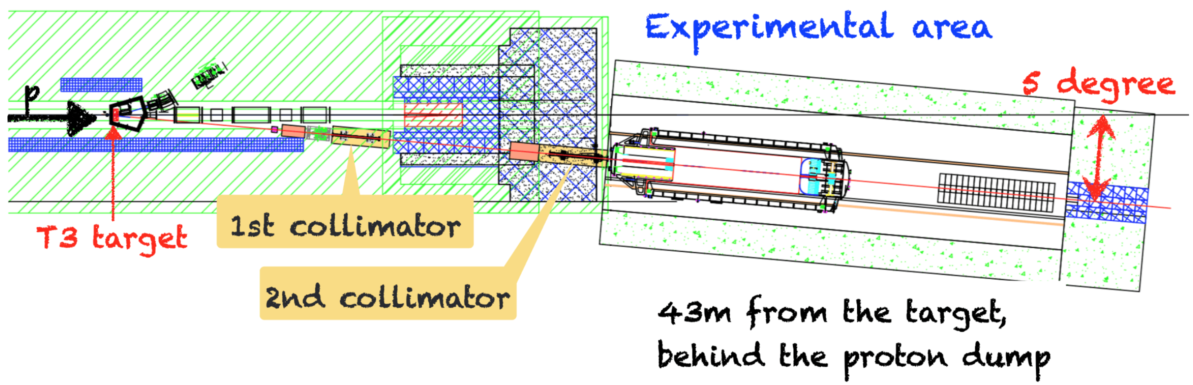


- Hadron-hall extension is a joint project with nuclear physics community
  KOTO Step-2 is a flagship project
- Described in KEK Road Map 2021 for research strategy 2022-2027
- Focused review conducted in Aug 2021, with KOTO providing Step-2 input

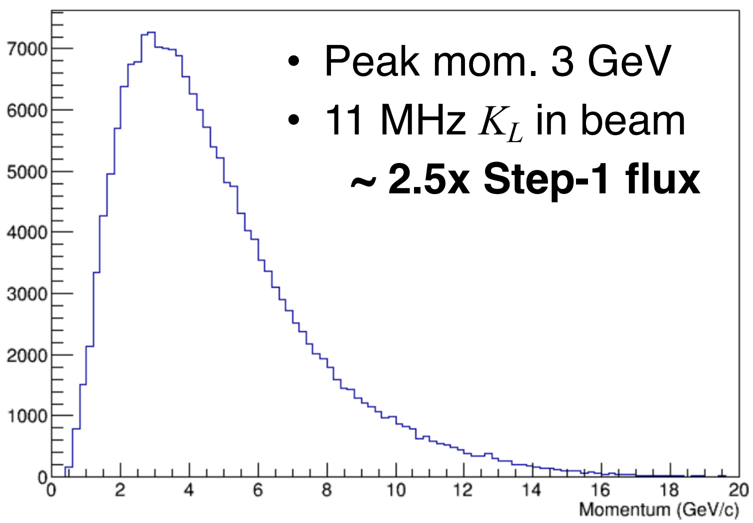
KOTO Step-2 detector

Step-2 beamline setup in hadron-hall extension

- Smaller angle (16° → 5 °)
- Longer beamline (20 → 43 m)
- 2 collimators

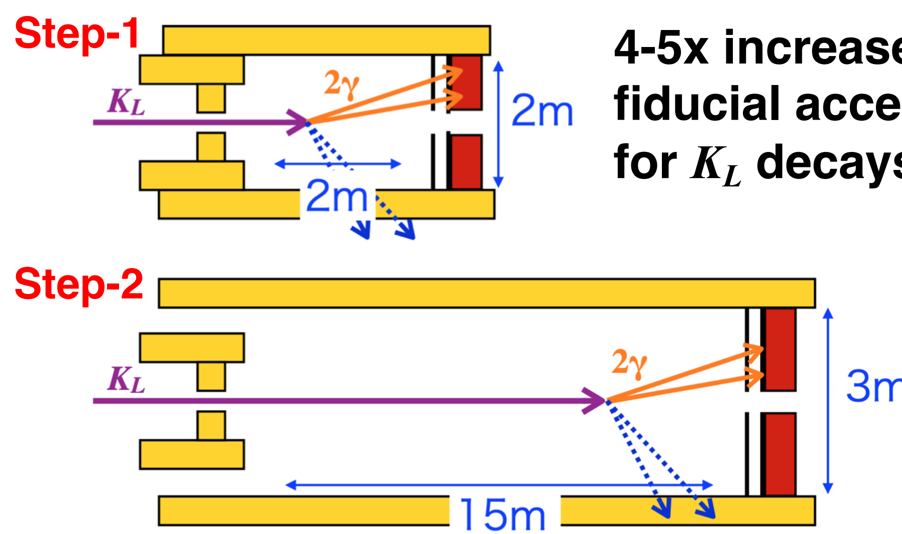


K_L spectrum at beam exit



- Peak mom. 3 GeV
- 11 MHz K_L in beam

~ 2.5x Step-1 flux



4-5x increased fiducial acceptance for K_L decays

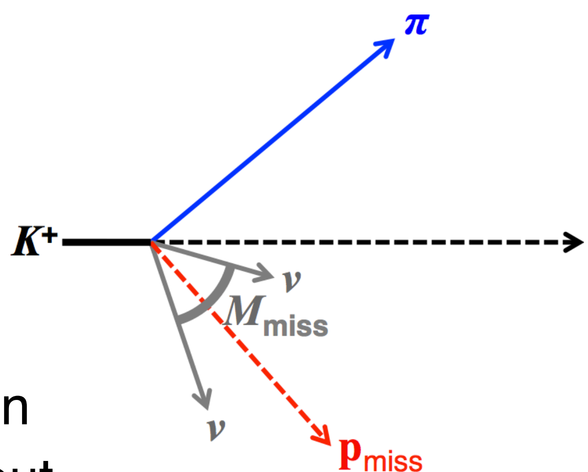
New sensitivity studies for smaller beam angle & larger detector:
~ 60 SM evts with S/B ~ 1 at 100 kW beam power (3×10^7 s)

The NA62 experiment at the CERN SPS

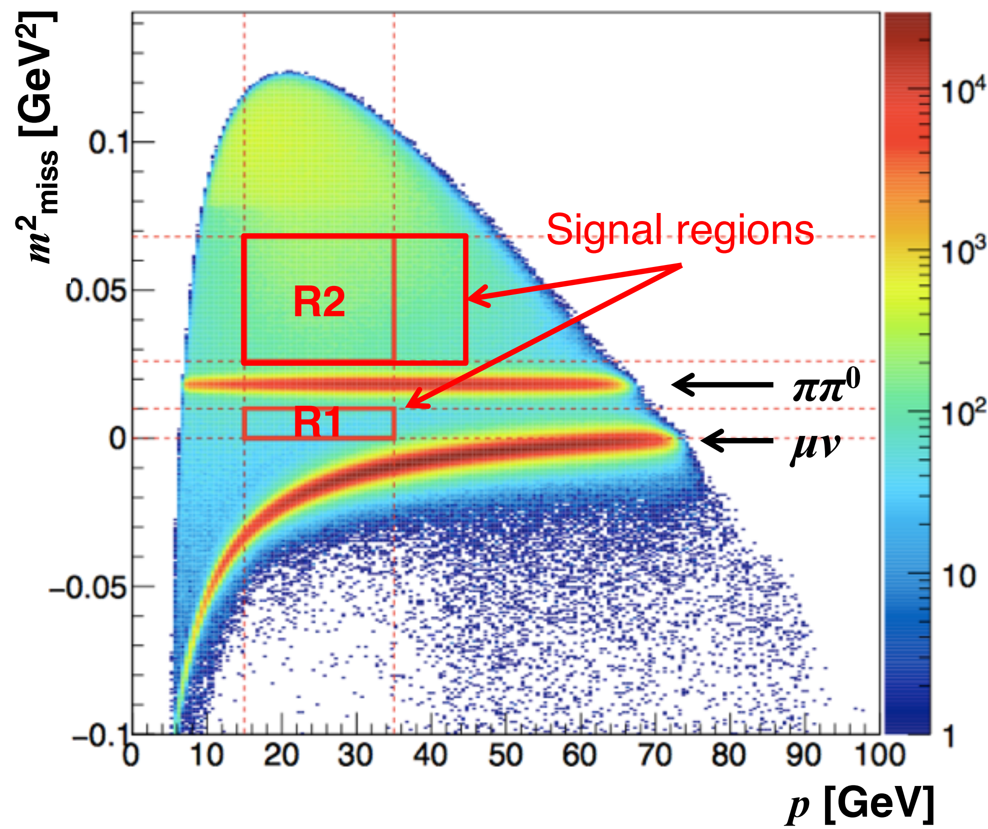
$K^+ \to \pi^+ \nu\bar{\nu}$ with decay in flight

Signal:

BR = (8.4 ± 1.0) × 10^{-11}



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



Selection criteria:

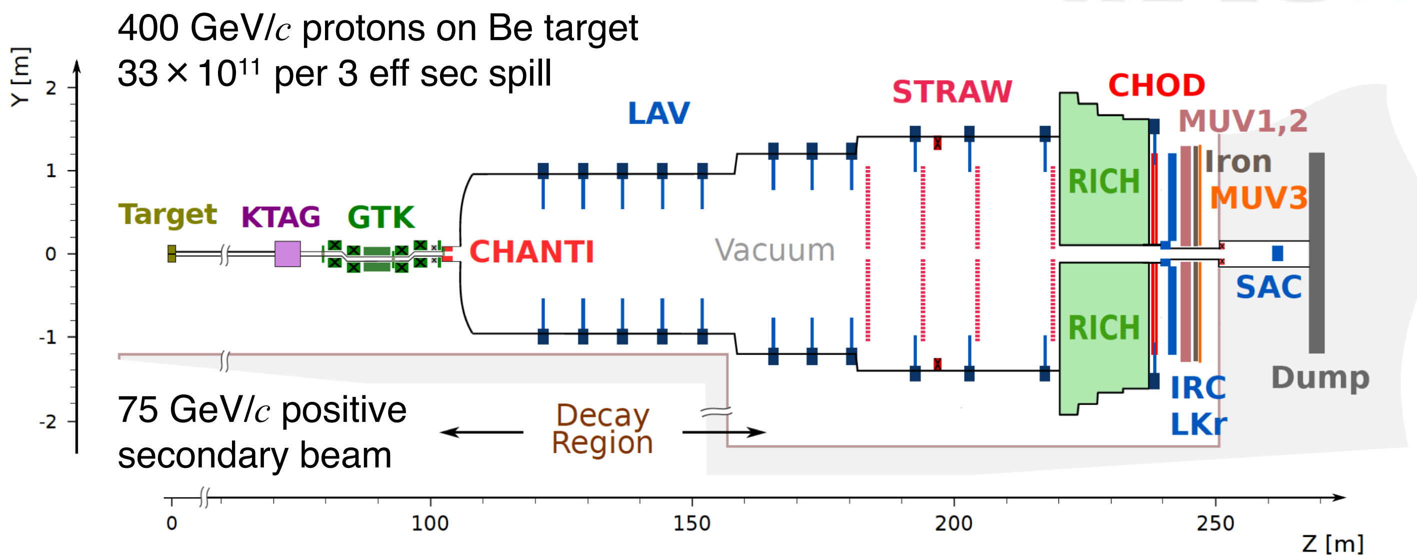
- K^+ beam identification
- Single track in final state
- π^+ identification ($\varepsilon_\mu \sim 1 \times 10^{-8}$)
- γ rejection ($\varepsilon_{\pi 0} \sim 3 \times 10^{-8}$)

Main backgrounds:

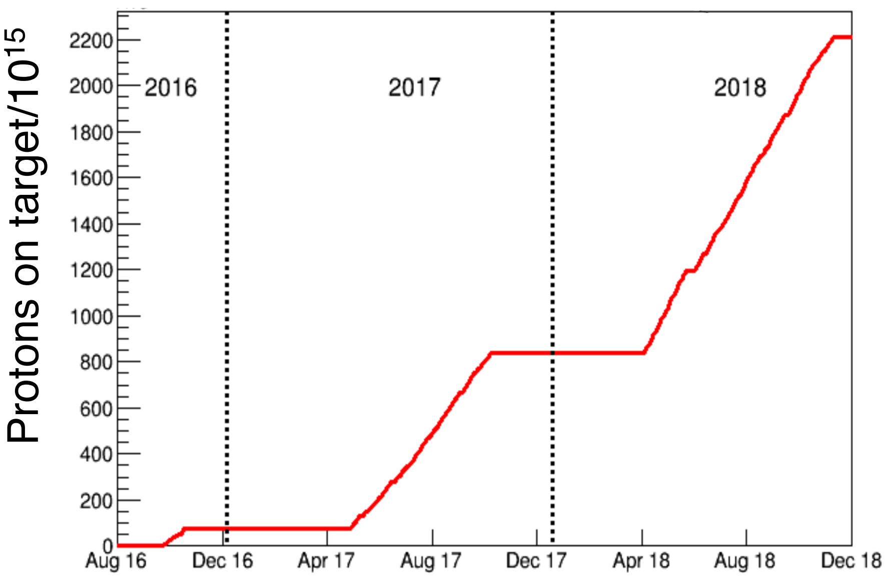
$K^+ \to \mu^+\nu(\gamma)$	**BR = 63.5%**
$K^+ \to \pi^+\pi^0(\gamma)$	**BR = 20.7%**

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
0.12×10^{12} K^+ decays in FV

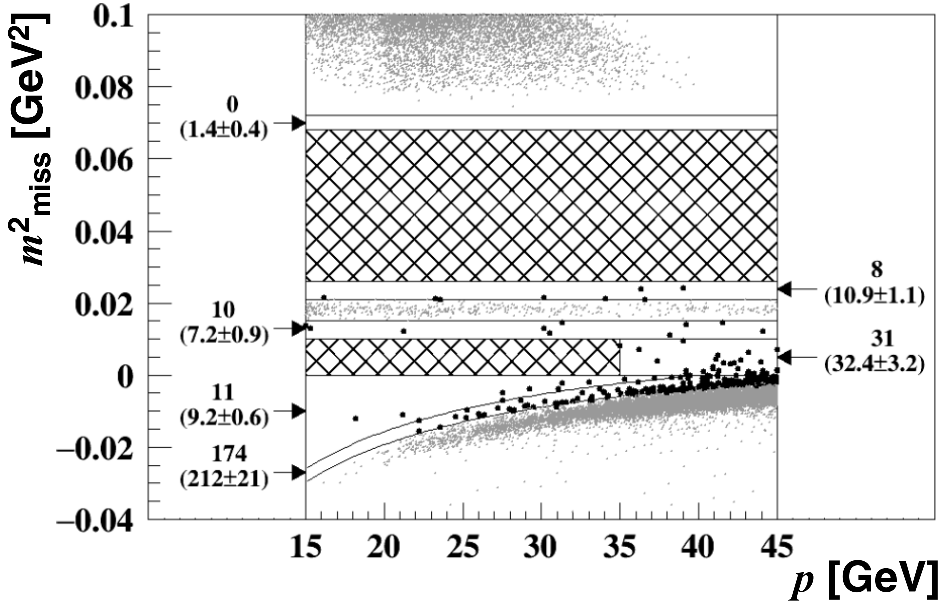
2017 60% of nominal intensity
1.5×10^{12} K^+ decays in FV

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

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

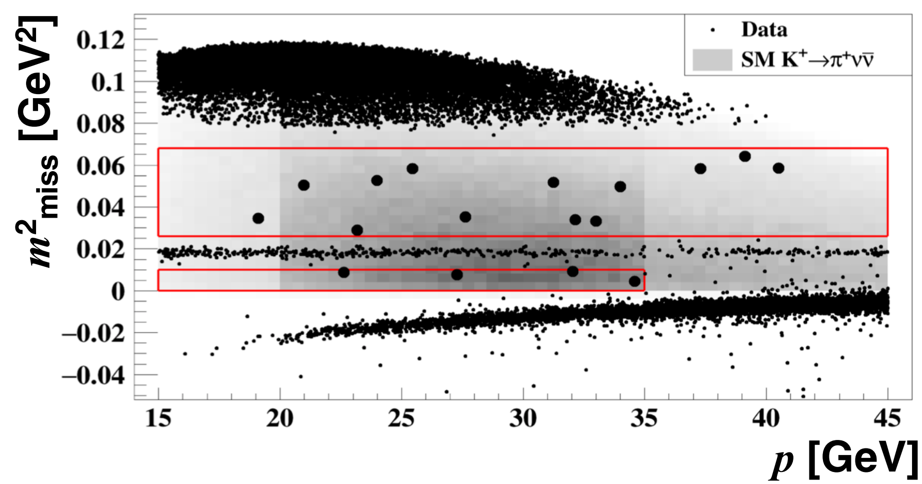
Final results: 2016-2018 data

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

17 signal candidates in 2018 data



NA62 2016-2018 data

JHEP 06 (2021) 093

- SES: $(8.39 \pm 0.53) \times 10^{-11}$
- Expected sig: $10.01 \pm 0.42_{sys} \pm 1.19_{ext}$
- Expected bkg: $7.03^{+1.05}_{-0.82}$ evts
- **20 events observed!**

NA62 through LS3

Summary of NA62 Run 1 (2016-2018):

- **Expected signal (SM): 10 events**
- **Expected background: 7 events**
- **Total observed: 20 events**
- 3.4σ signal significance
- Most precise measurement to date

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

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

NA62 resumed data taking in July 2021!

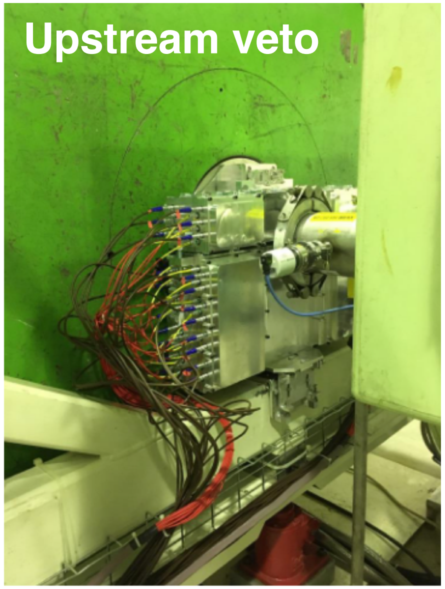
Key modifications to reduce background from upstream decays and interactions:

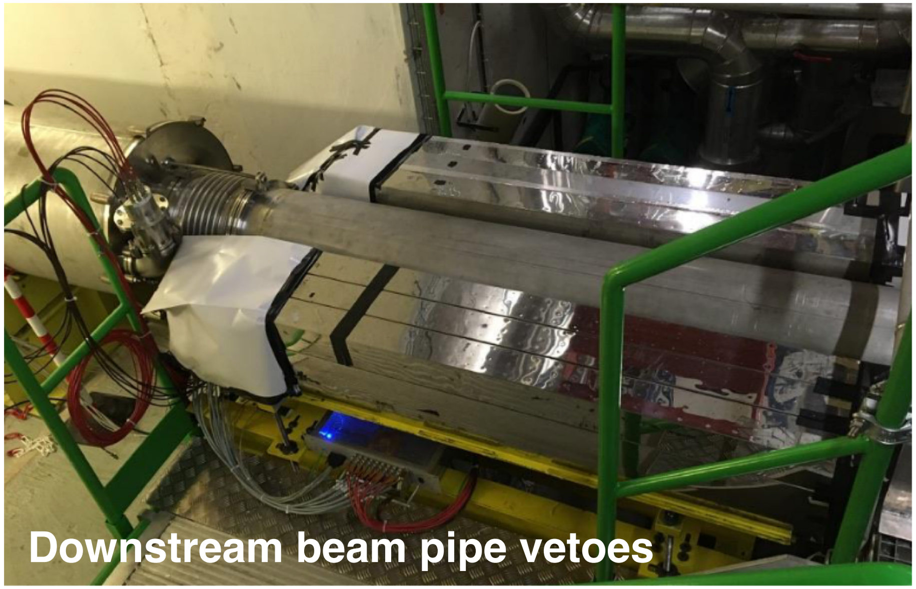
- Rearrangement of beamline elements around GTK achromat
- 4^{th} station added to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

Running at higher beam intensity (70% → 100%)

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

NA62 through LS3





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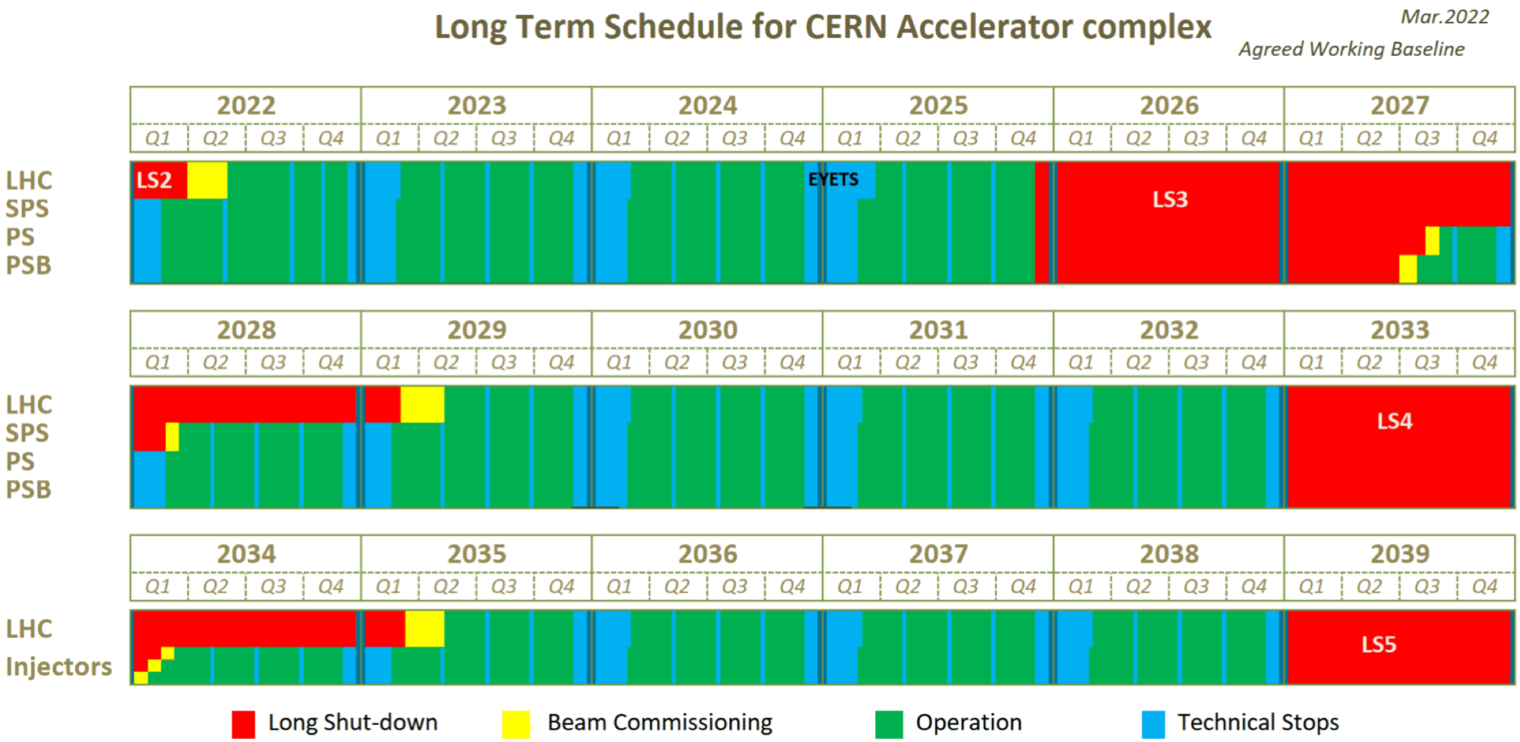
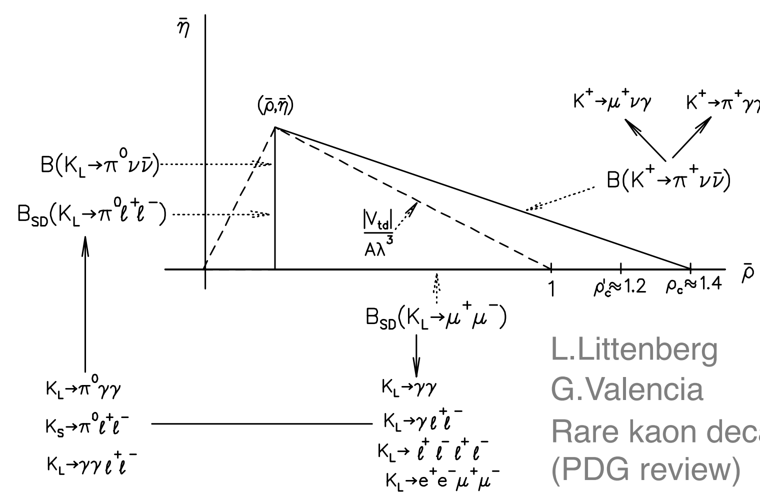
Fixed target runs at the SPS



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)

High-intensity kaon beams at the SPS

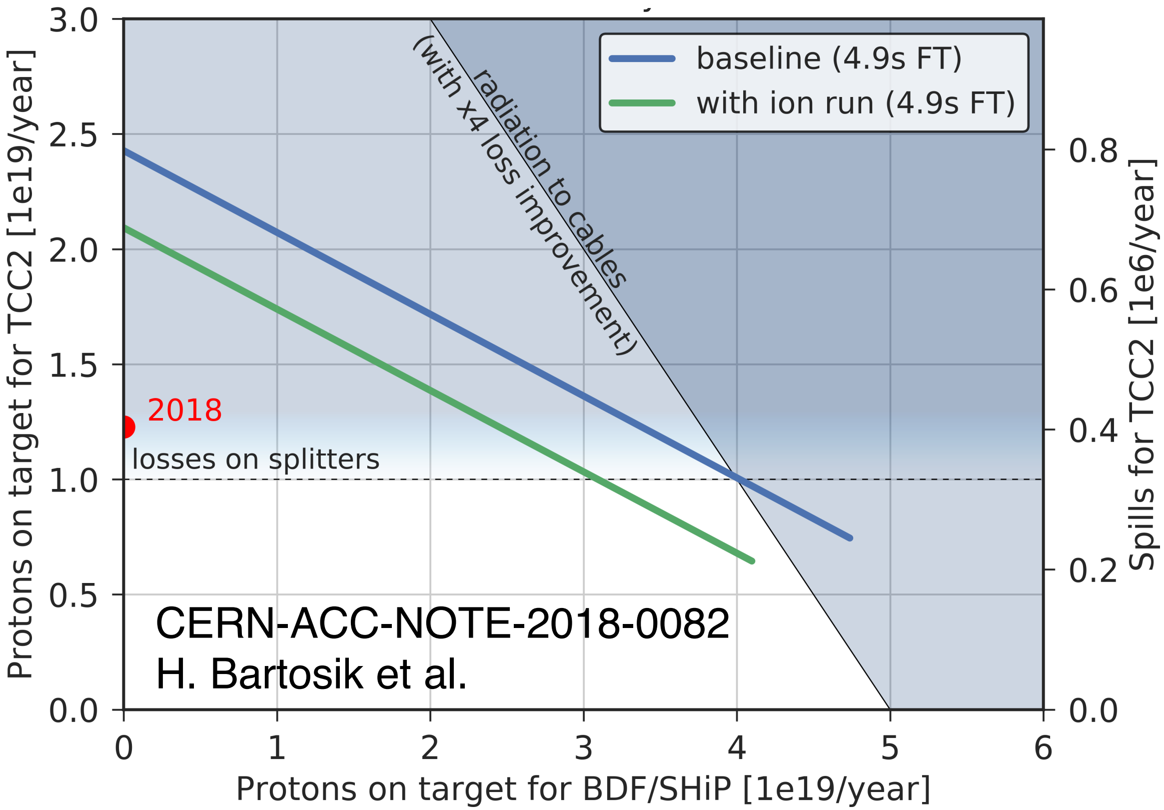
Operational scenarios and limits on the intensity deliverable to the North Area targets were studied in context of the BDF proposal as part of Physics Beyond Colliders

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

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

$K^+ \to \pi^+ \nu\nu$ 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 BR($K^+ \to \pi^+ \nu\nu$) to within ~5%!

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

Basic design of experiment will work at high intensity

Key challenges:

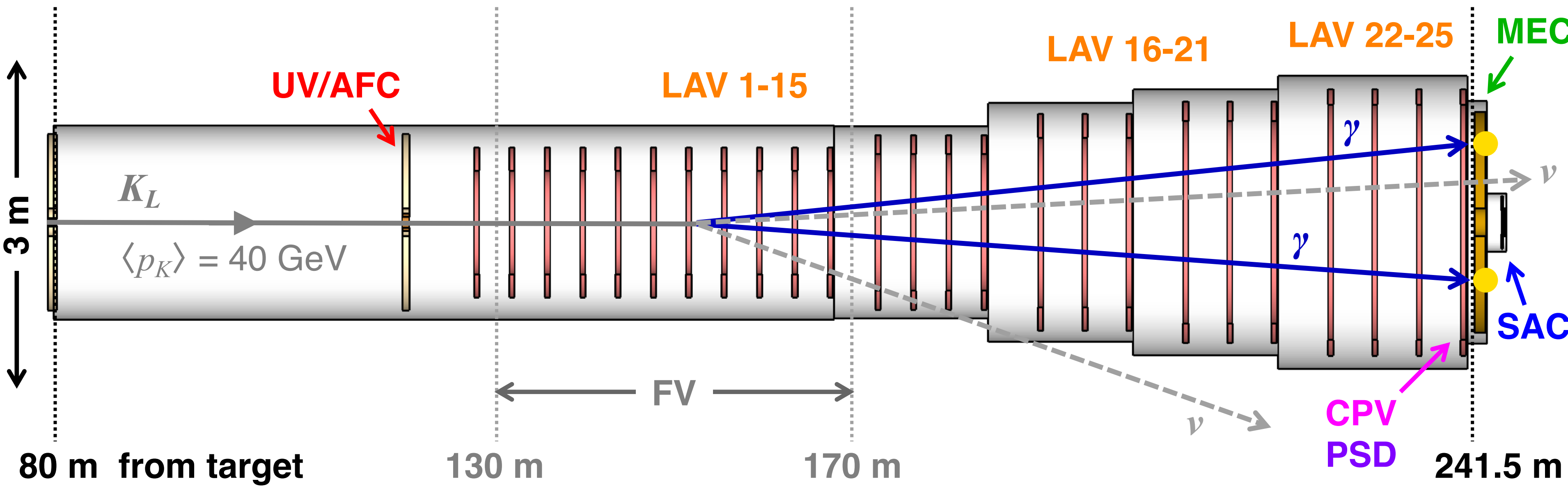
- Require much improved time resolution to keep random veto rate under control
- Must maintain other key performance specifications at high-rate:
  - Space-time reconstruction, low material budget, single photon efficiencies, control of non-gaussian tails, etc.

Synergies to be explored:

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

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

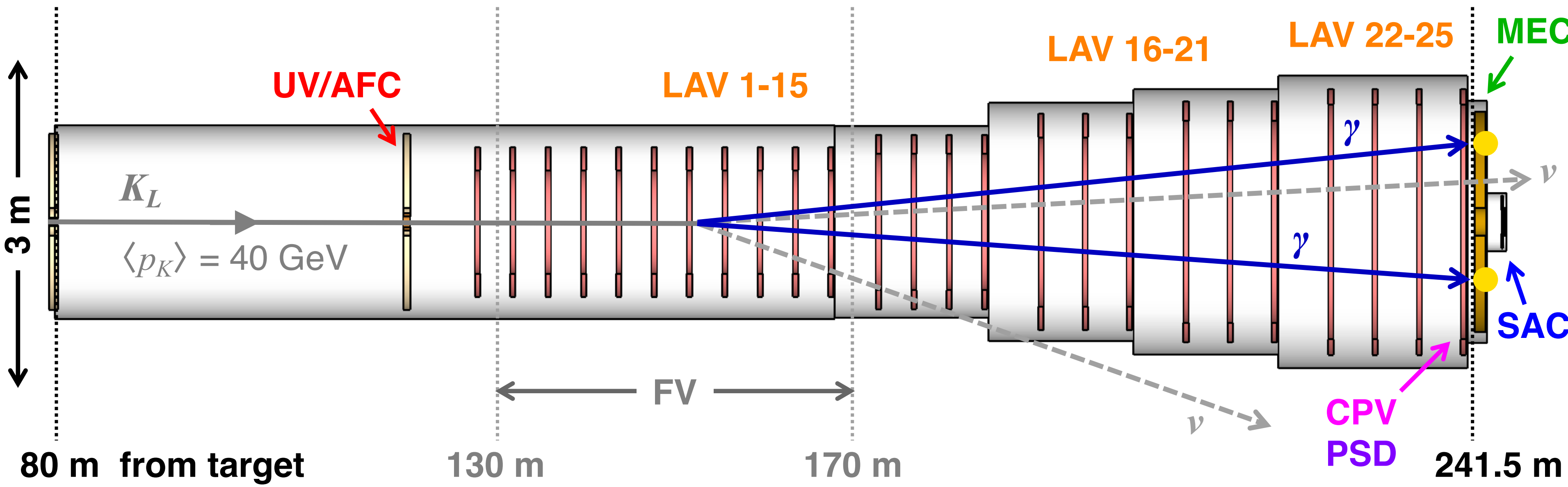
~ 60 SM $K_L \rightarrow \pi^0 \nu\nu$
S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

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

A $K_L \to \pi^0 \nu\bar{\nu}$ 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 $K_L \to \pi^0 \nu \nu$
S/B ~ 1

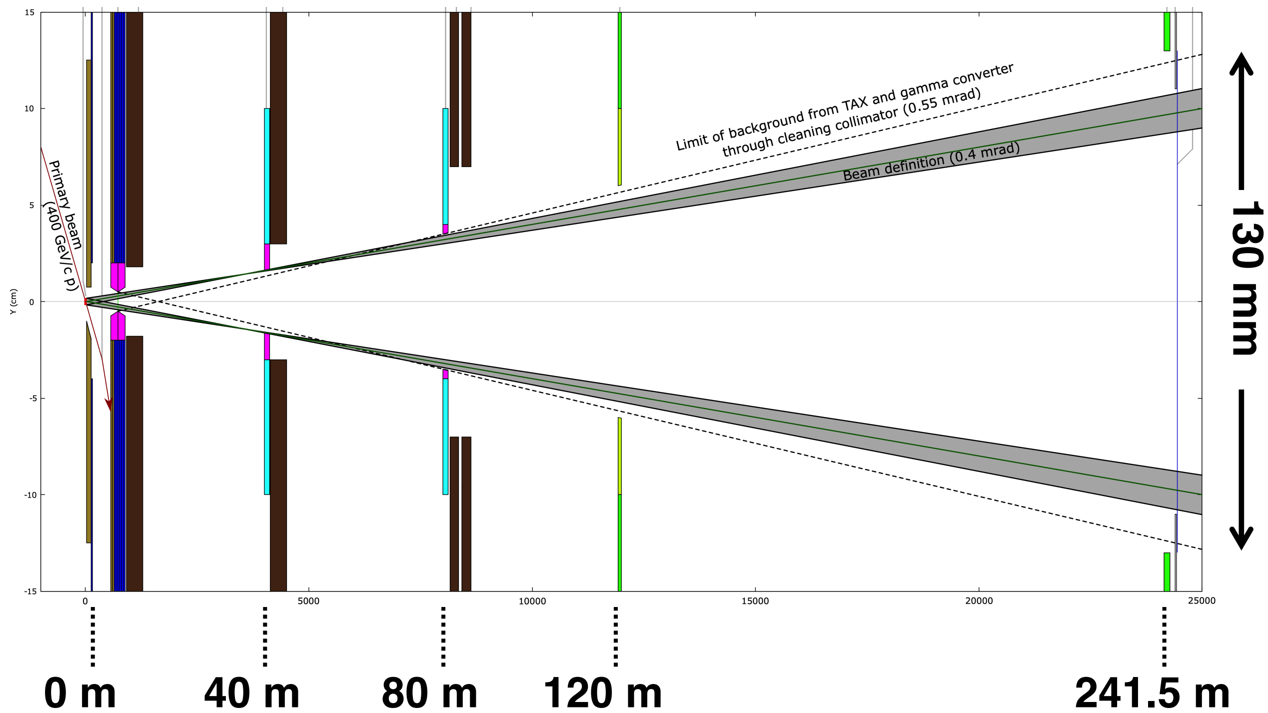
δBR/BR($\pi^0 \nu \nu$) ~ 20%

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 θ = 8.0 mrad**
- **Solid angle $\Delta\theta$ = 0.4 mrad**
- **2.1×10^{-5} K_L/pot in beam**
- **$\langle p(K_L) \rangle$ = 40 GeV**
- Probability for decay inside FV ~ 4%
- Acceptance for $K_L \to \pi^0 \nu\nu$ decays occurring in FV ~ 5%



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

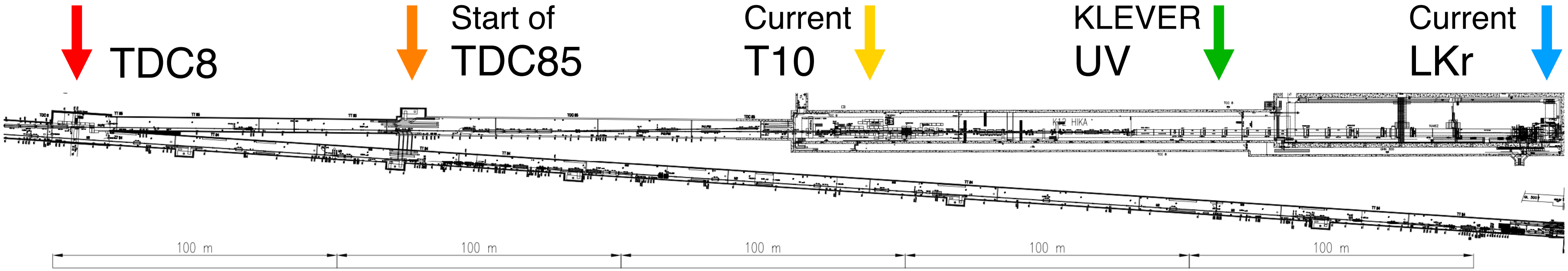
NB: Changes to beamline configuration and experimental layout under study to decrease rate of $\Lambda \to n\pi^0$ decays in detector

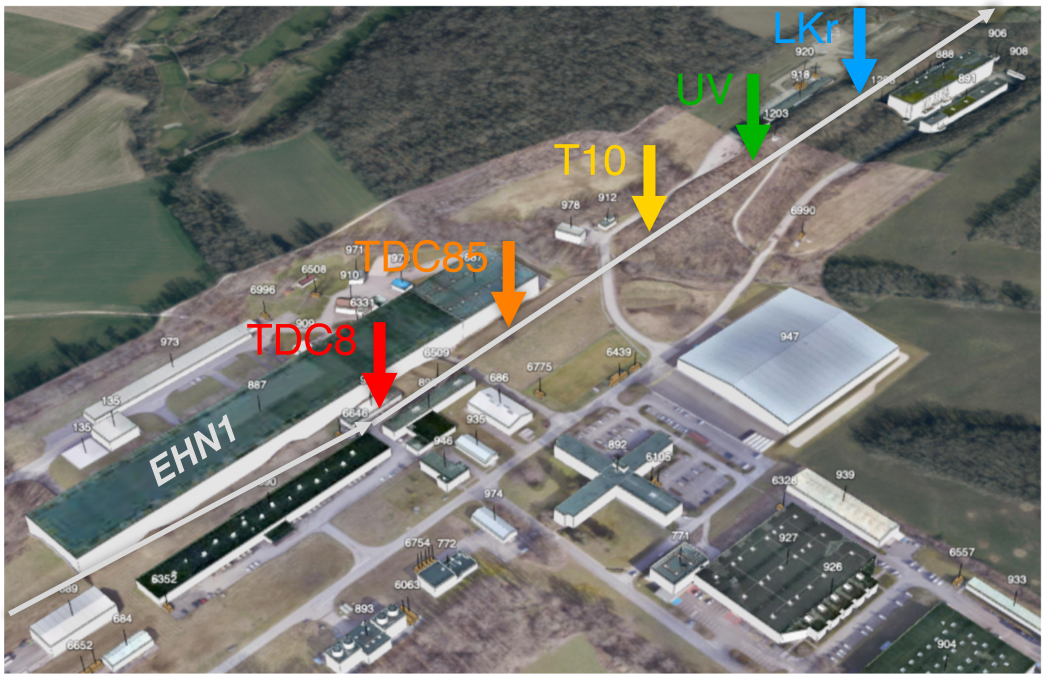
Long beamline to suppress $\Lambda \to n\pi^0$

KLEVER

Maintain θ = 8 mrad and increase length of beamline

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



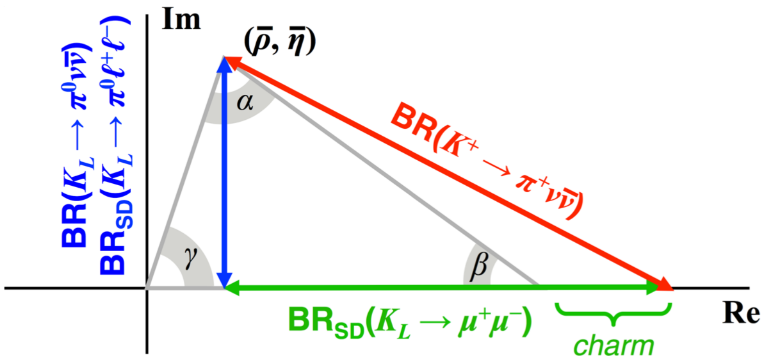


- Maintain K_L momentum
  - Fewer design changes for KLEVER
- Preserve K_L flux per solid angle
  - Still lose 2x in K_L flux due to tighter beam collimation
- Infrastructure work needed
- RP issues for area downstream of TDC85 to be investigated
- **Alternatively, ECN3 extension would solve problem**

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

$K_L \to \pi^0 \ell^+ \ell^-$ vs $K \to \pi \nu \nu$:

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



$K_L \to \pi^0 \ell^+ \ell^-$ CPV amplitude constrains UT in same way as BR($K_L \to \pi^0 \nu\nu$)

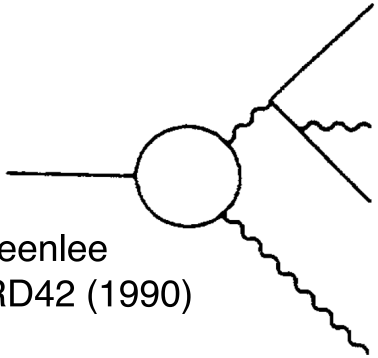
Experimental status:

BR($K_L \to \pi^0 e^+ e^-$) < 28 × 10^{-11} Phys. Rev. Lett. 93 (2004) 021805

BR($K_L \to \pi^0 \mu^+ \mu^-$) < 38 × 10^{-11} Phys. Rev. Lett. 84 (2000) 5279–5282

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

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



Greenlee PRD42 (1990)

BR($K_L \to e^+ e^- \gamma\gamma$) = (6.0 ± 0.3) × 10^{-7} $E_\gamma^* > 5$ MeV

BR($K_L \to \mu^+ \mu^- \gamma\gamma$) = 10^{+8}_{-6} × 10^{-9} $m_{\gamma\gamma} > 1$ MeV

K_S decays at LHCb

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

About 1 strange hadron per event!

Production rate compensates for low trigger efficiency and long lifetime

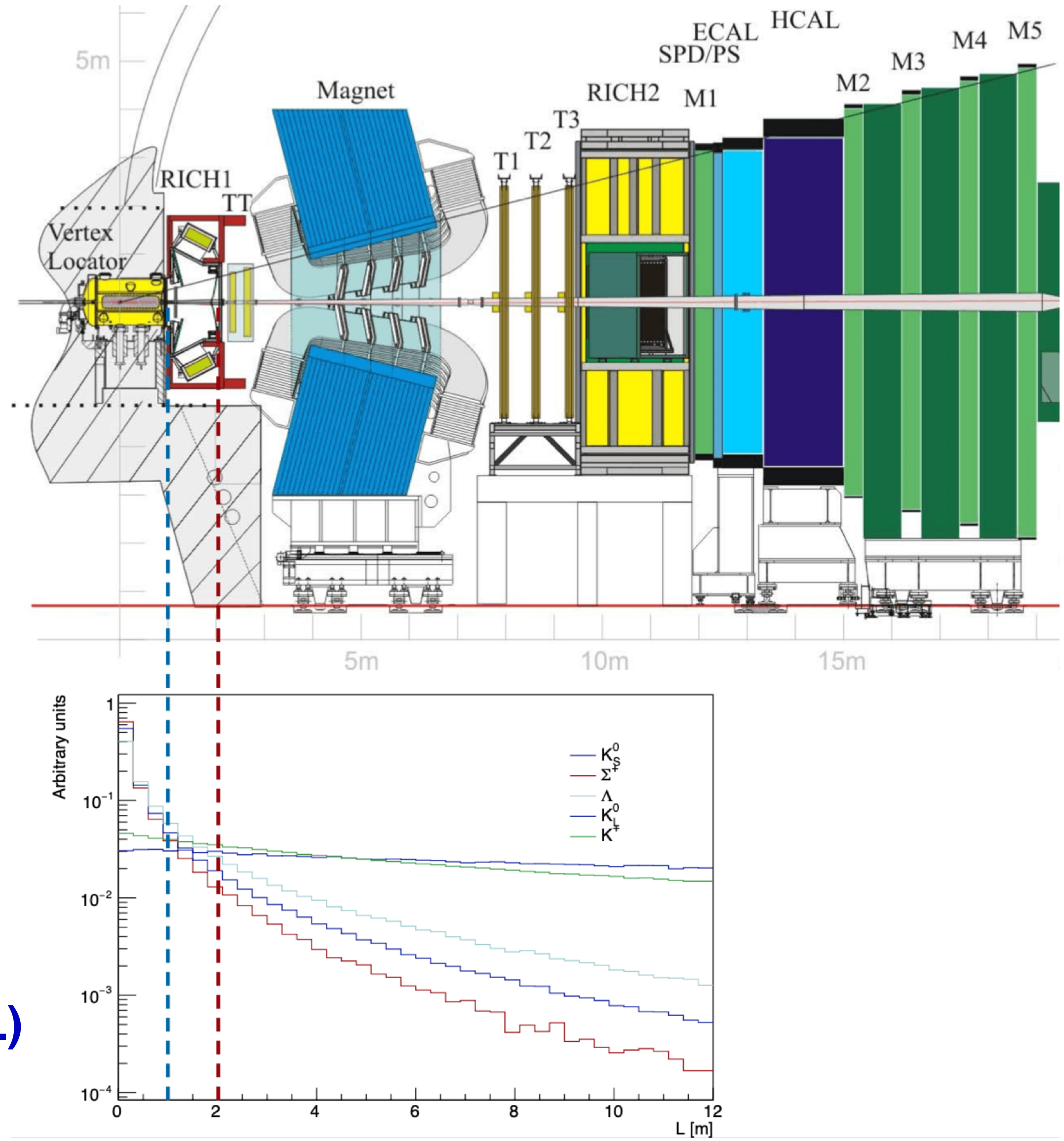
Vast K program for Run 3:

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

For example:

BR($K_S \to \mu^+\mu^-$) < 2.1 × 10^{-10} (90%CL)

PRL125 (2020) 231801



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:

- $K_L \to \pi^0 \ell^+ \ell^-$
  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

$K \to \pi \nu \nu$ 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!

- NA62 will improve on current knowledge of BR($K^+ \to \pi^+ \nu \nu$) in short term, ultimately reaching O(10%) precision
- KOTO is making significant progress in background reduction and will reach SM sensitivity to BR($K_L \to \pi^0 \nu \nu$) by 2025
- LHCb BR measurements for decays such as $K_{S,L} \to \mu^+ \mu^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ will help with theoretical systematics (e.g., separate LD/SD contributions)

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

This **multi-generational effort** is in mid-course, with plans extending possibly to 2040, 35 years

“It took 35 years to measure $\mathrm{Re}\ \varepsilon'/\varepsilon$.

It will take 35 more to measure one of the $K \to \pi\nu\nu$ branching ratios”

–Paolo, circa 2005

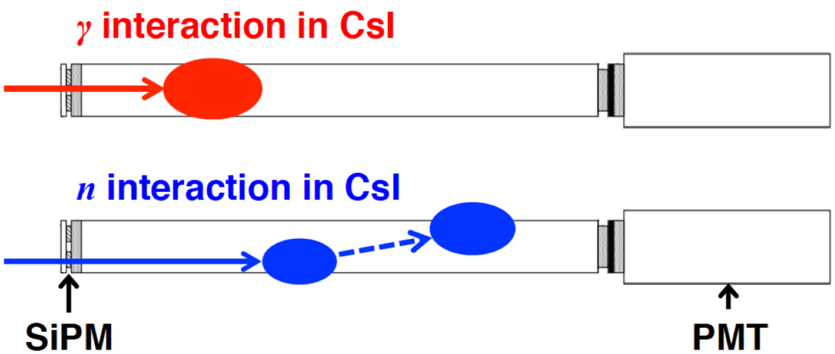
Paolo, predictably, is turning out to be correct

We are learning very much and doing a lot of great physics along the way!

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

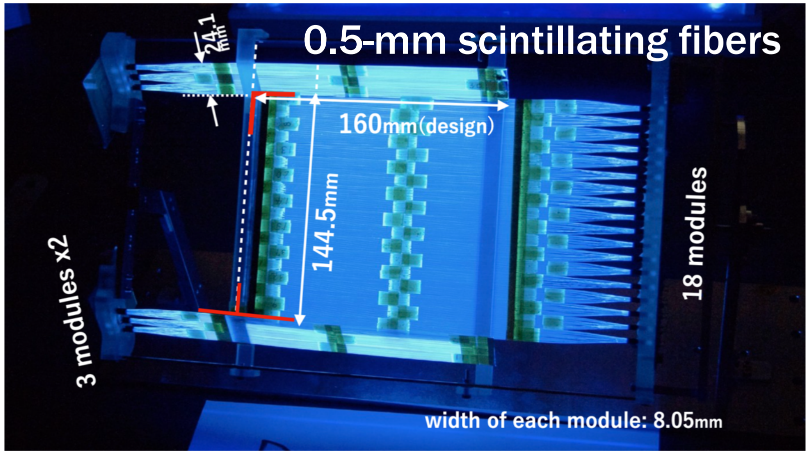
Reduces neutron background ~ 50x

Run	pot [10^{18}]	UCV
2016-2018	30.5	No
2019	18.5	No
2020	2.5	No
	6.9	Yes
2021 (in progress)	~ 35	Yes

Upstream charged-particle veto

Prototype installed for 2020 run

Final version available in 2021



Reduces K^+ background ~ 20x

- **May-June 2021 run recently completed**
- Data set of comparable size to 2016-2018 under analysis

Paolo Franzini and Juliet Lee-Franzini Memorial Symposium

Laboratori Nazionali di Frascati
19 April 2022

Additional information

Matthew Moulson
Laboratori Nazionali di Frascati

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

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

Buras et al., JHEP 1511

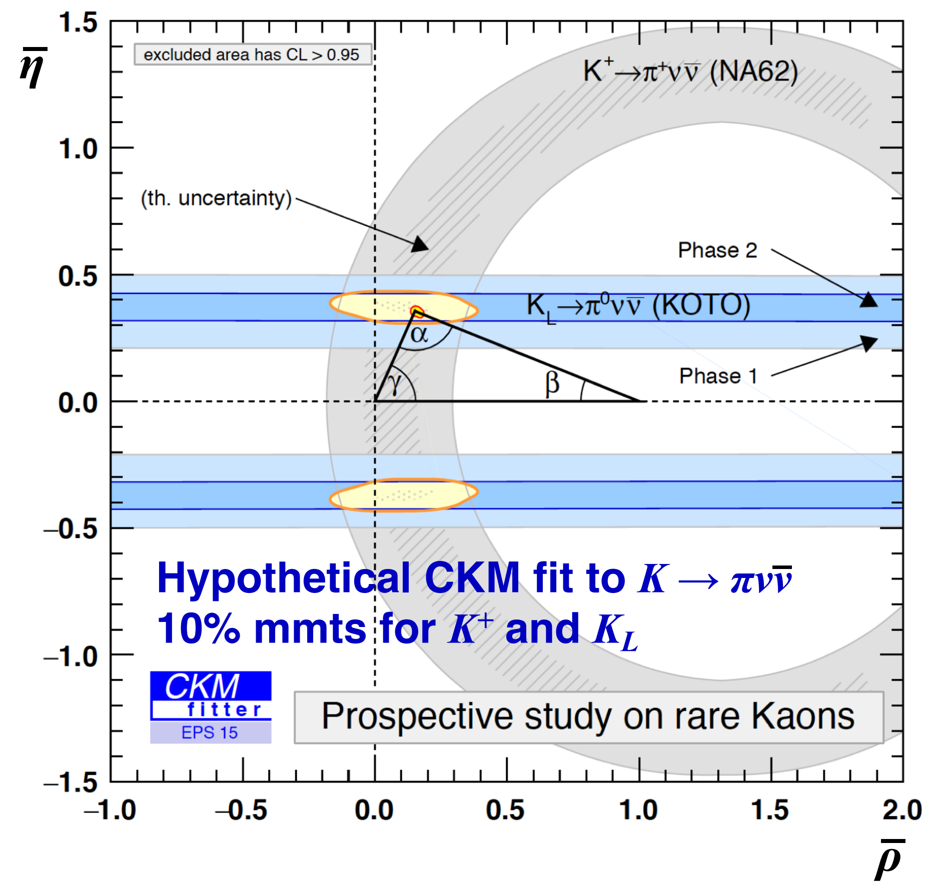
$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

Dominant uncertainties for SM BRs are from CKM matrix elements

Intrinsic theory uncertainties 1.5-3.5%

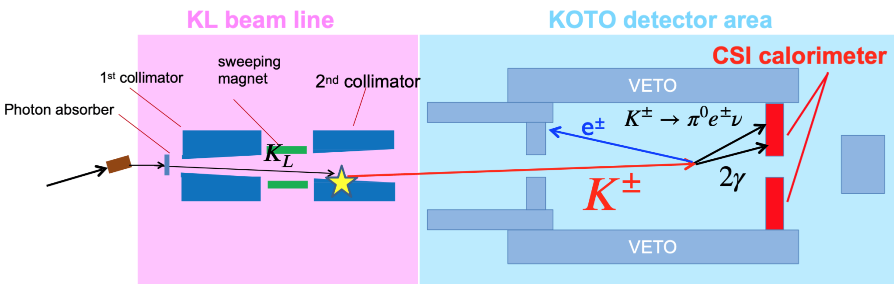
Measuring BRs for both $K^+ \to \pi^+\nu\nu$ and $K_L \to \pi^0\nu\nu$ can determine the CKM unitarity triangle independently from B inputs:

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



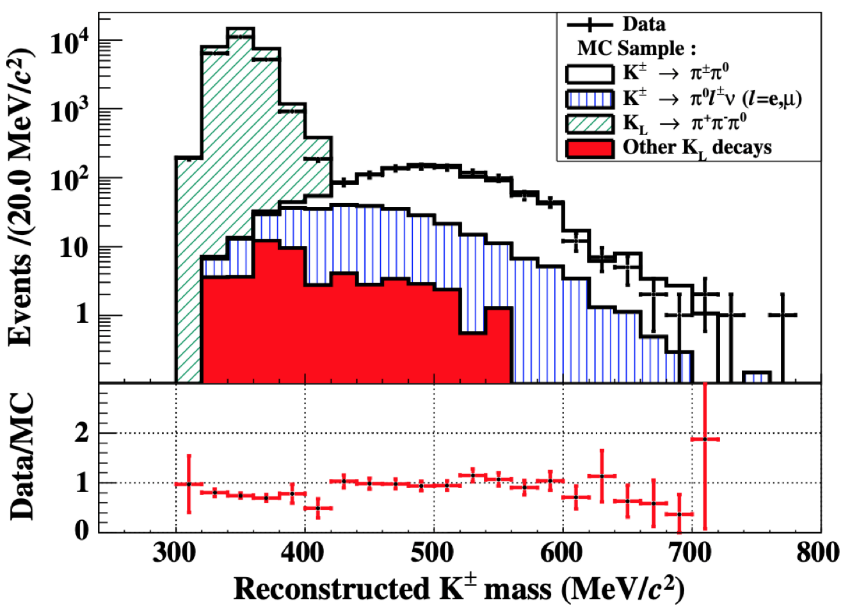
Background studies for 2016-2018

K^+ decays (charge exchange)

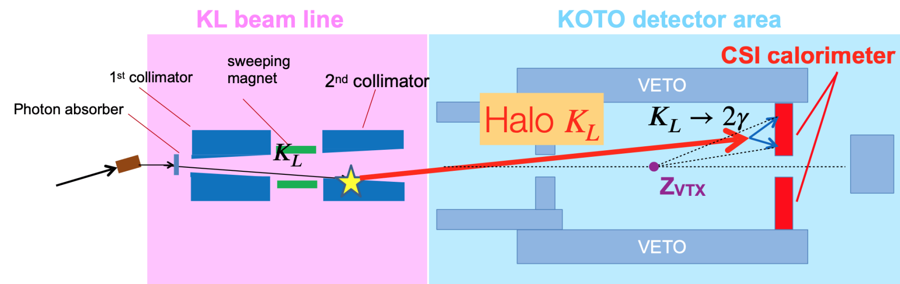


Dedicated data taking June 2020:

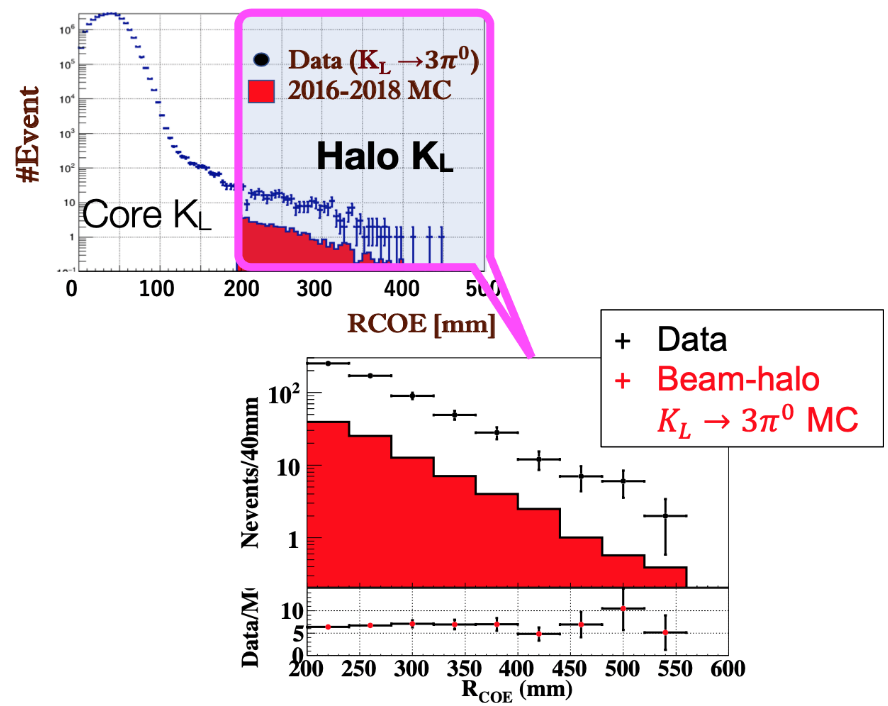
- Measure K^+ flux with 3-cluster sample ($\pi^+\pi^0$ reconstruction hypothesis)



$K_L \to \gamma\gamma$ (scattered K_L)

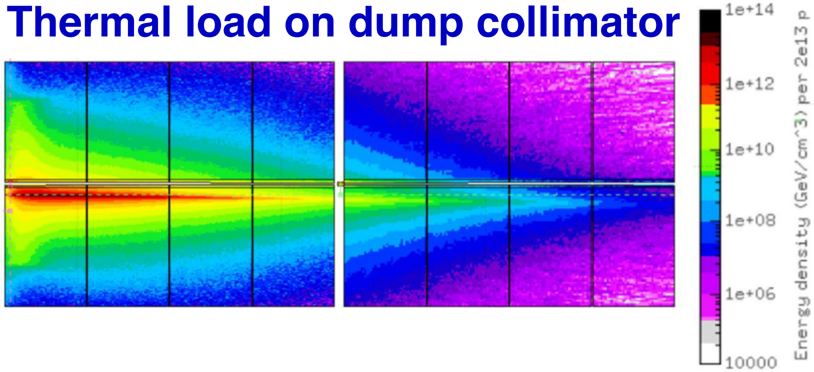


- $K_L \to 3\pi^0$ events reconstructed by center of energy to calibrate K_L halo in MC



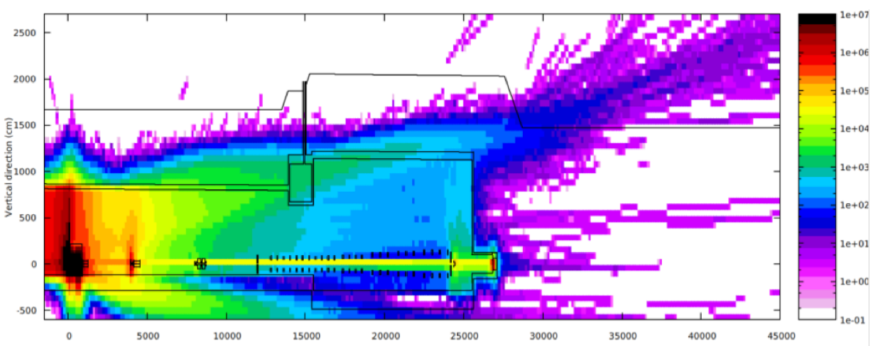
Beam and target simulations

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

Experimental challenges: STRAW

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

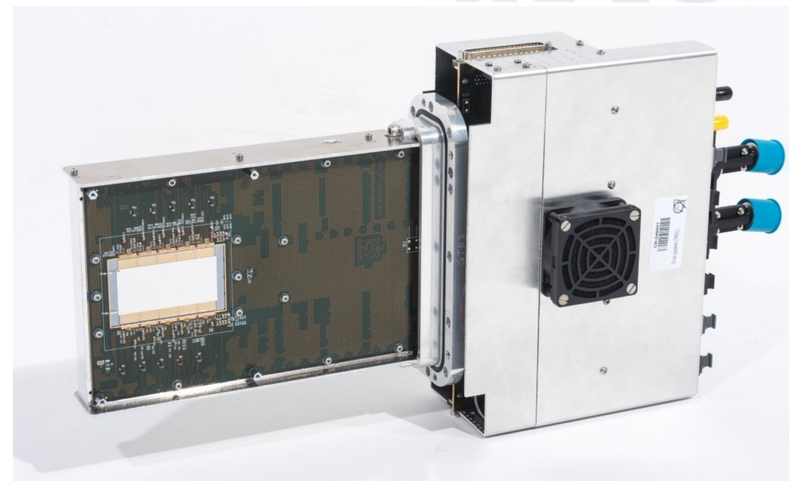
- **Main feature: Straw diameter ~5 mm**
- **Improved trailing-time resolution: ~6 ns (per straw)**
- **Smaller maximum drift time: ~80 ns**
- **Rate capability increased 6-8x**
- Layout: 4 chambers, ~21000 straws
- Decreased straw wall thickness: ~20 µm, with copper and gold plating
- Material budget: 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 μm^2
- Efficiency: > 99% (incl. fill factor)
- Material budget: 0.3-0.5% X_0
- Beam intensity: 3 GHz over ~ 3x6 cm^2
- Maximum local intensity: 8 MHz/mm^2
- Radiation resistance: 2.3x10^{15} n eq/cm^2/yr

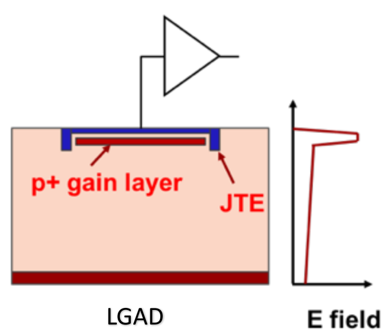


NA62 Gigatracker station

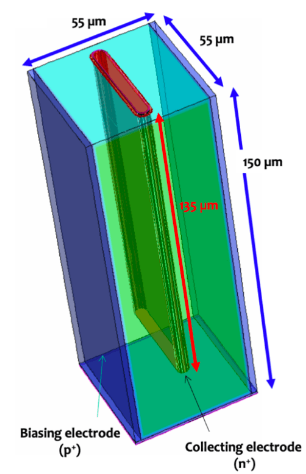
Continue to improve planar sensors while monitoring progress on new technologies

Possible synergies with ongoing development efforts:

LGAD: Low Gain Avalanche Detectors



TimeSPOT: time-stamping 3D sensors



Shashlyk calorimeter with spy tiles

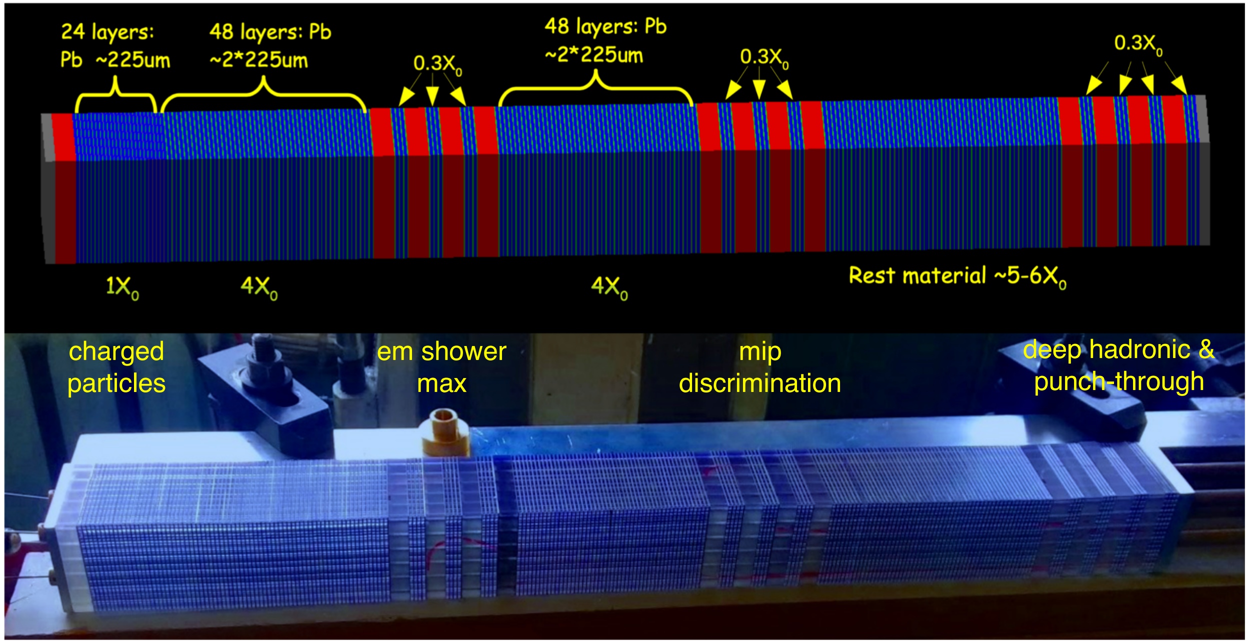
Requirements for main electromagnetic calorimeter (MEC):

Excellent efficiency, time resolution ~ 100ps, good 2-cluster separation

LKr calorimeter from NA62:

Photon detection efficiency probably adequate

Time resolution ~ 500 ps for π^0 with $E_{\gamma\gamma}$ > 20 GeV → 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:

$\sigma_E/\sqrt{E}$ **~ 3%** $/\sqrt{E}$ (GeV)

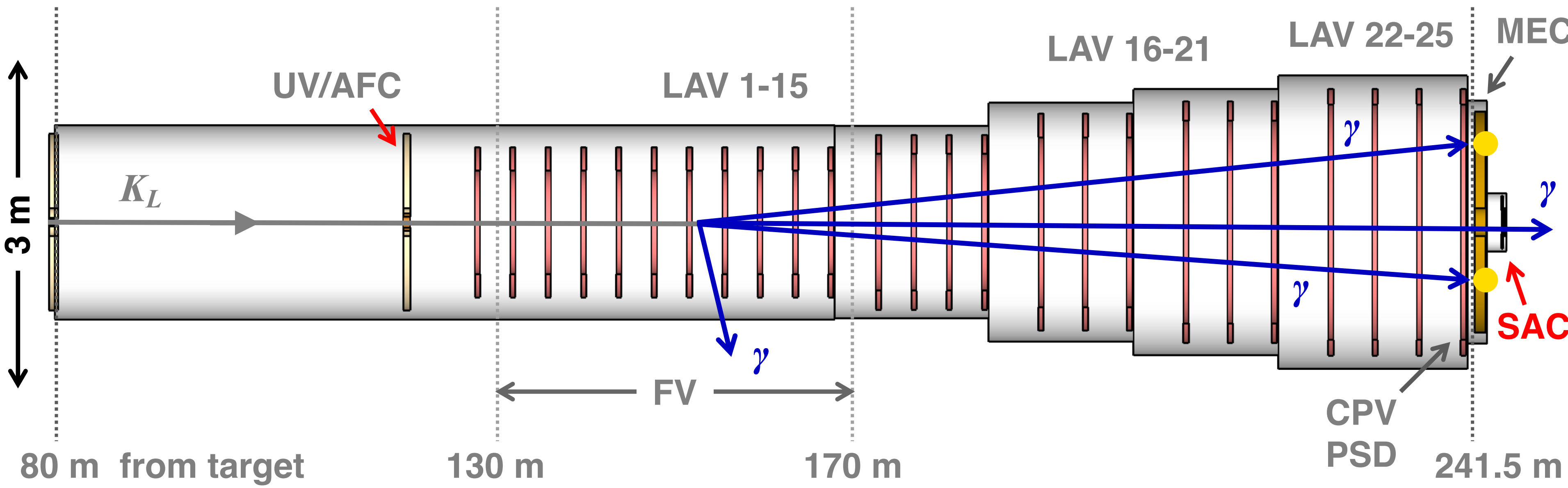
σ_t **~ 72 ps** $/\sqrt{E}$ (GeV)

σ_x **~ 13 mm** $/\sqrt{E}$ (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 γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

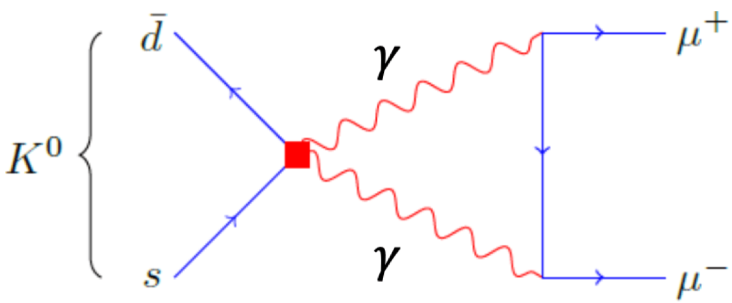
Possible solutions:

- 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

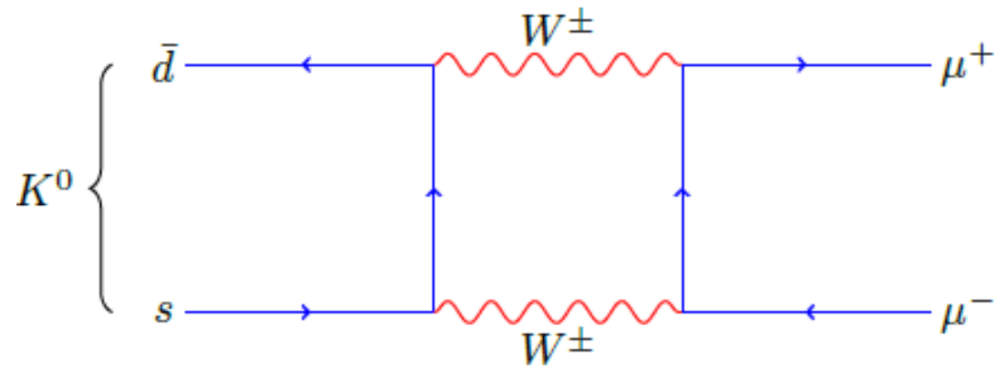
$K_{S,L} \to \mu^+\mu^-$

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

Long distance (LD)

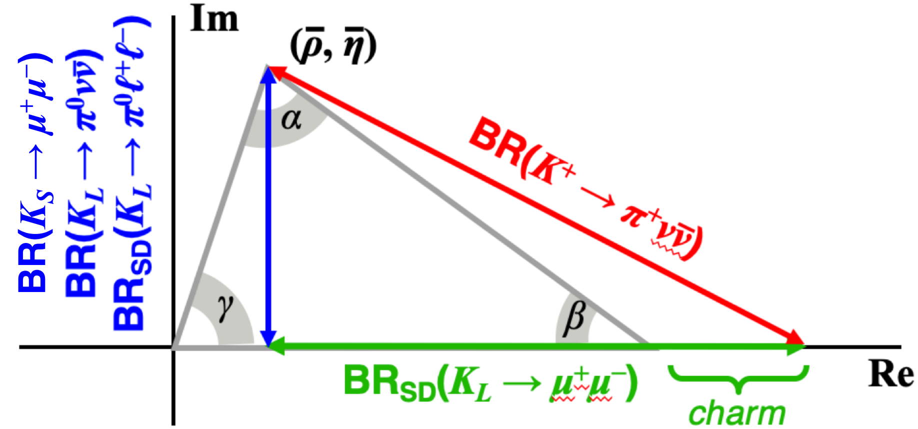


Short distance (SD)



$\mathrm{BR}(K_L \to \mu^+\mu^-) \;\to\; A_L{}^{SD} \propto (1 - \rho)$

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



$\mathrm{BR}(K_S \to \mu^+\mu^-) \;\to\; A_S{}^{SD} \propto \eta$

- **$\mathrm{BR}_{\mathrm{SM}}(K_S \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$**
  If $>10^{-11} \to$ unambiguous sign of NP
  Isidori, Unterdorfer ’04
- Due to **$K_S K_L$ interference**, high sensitivity to NP and to sign of A($K_L \to \gamma\gamma$)
  see e.g. D’Ambrosio & Kitahara ’17, Dery et al. ’21