High-Intensity Kaon Experiments at the CERN SPS

HIKE
High Intensity Kaon Experiments

Matthew Moulson
INFN Frascati

For the HIKE Collaboration

Workshop on status and perspectives of physics at high intensity
Laboratori Nazionali di Frascati, 11 November 2022

Rare kaon decays

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 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%	8.6 ± 0.4	$< 18.5^\dagger$
$K_L \rightarrow \pi^0 \nu\bar{\nu}$	>99%	2%	2.9 ± 0.2	$< 300^\dagger$

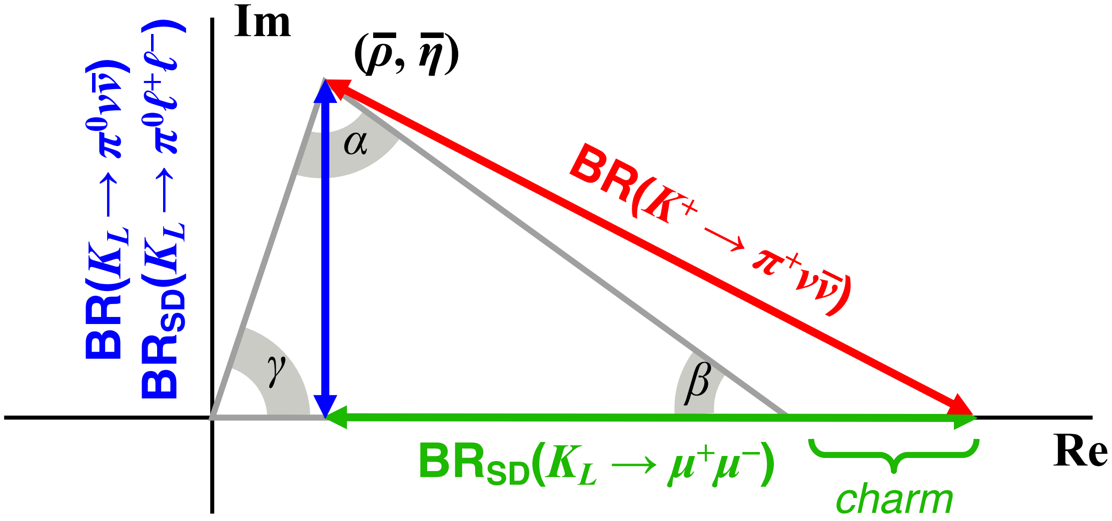
*Approx. error on LD-subtracted rate excluding parametric contributions

†90% CL

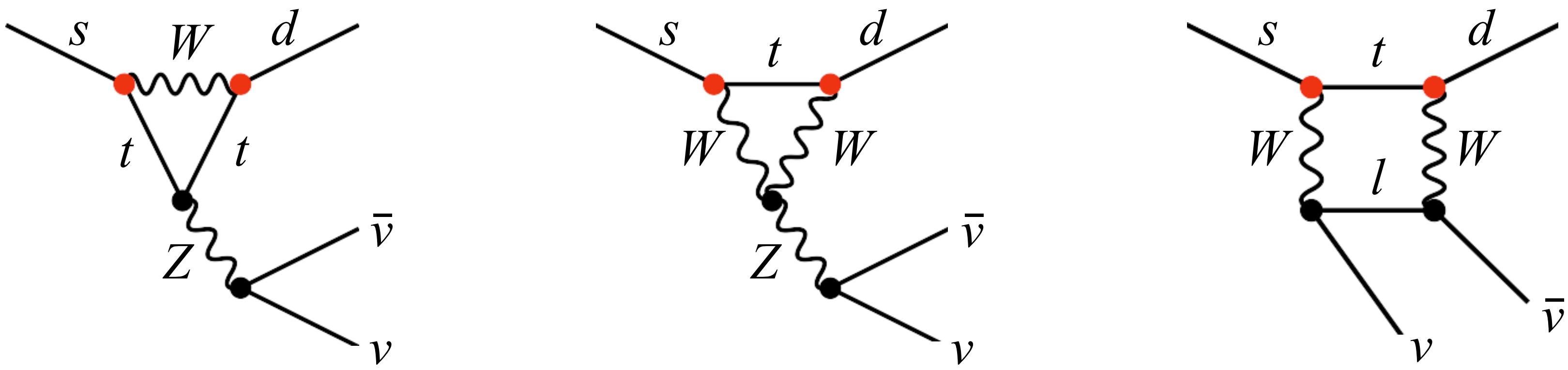
Flavor-changing processes with varying contributions from short-distance amplitudes

Highly suppressed in Standard Model

Rates related to CKM matrix elements with minimal non-parametric uncertainty



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



Extremely rare decays with rates very precisely predicted in SM:

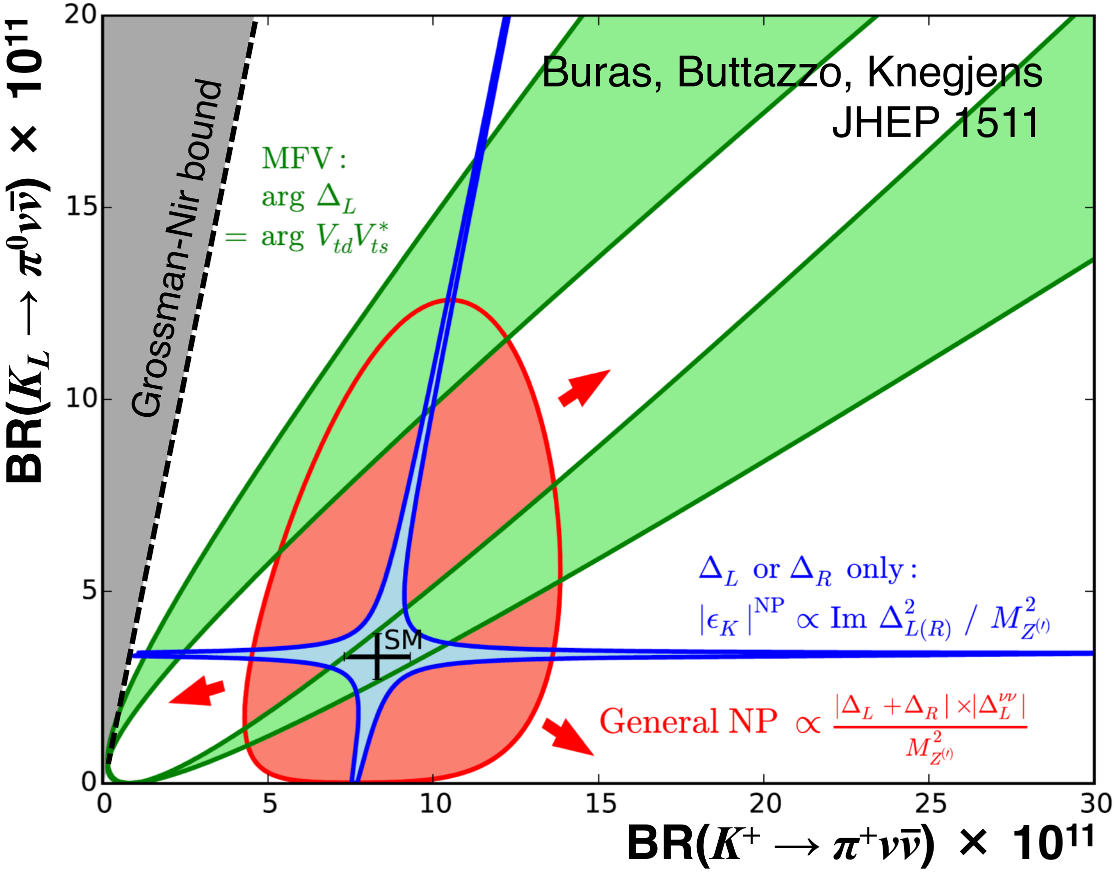
- Hard GIM mechanism + pattern of CKM suppression ($V_{ts}{}^{*}V_{td}$)
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

	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}**	**BR = (17.3 $^{+11.5}_{-10.5}$) × 10^{-11}** Stopped K^+, 7 events observed BNL 787/949, PRD79 (2009)
$K_L \to \pi^0\nu\bar{\nu}$	**BR = (3.4 ± 0.6) × 10^{-11}**	**BR < 300 × 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**

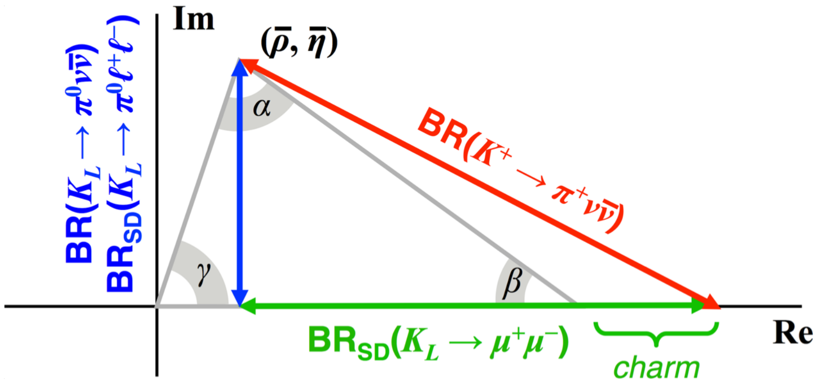
  Model-independent relation

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

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

BR($K_L \to \pi^0 \ell^+ \ell^-$) constrains height of UT like $K_L \to \pi^0 \nu\nu$

- 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



$$\mathrm{BR}_{\mathrm{SM}}(K_L \to \pi^0 e^+ e^-) = 3.54^{+0.98}_{-0.85} \times 10^{-11}\ \text{(constr.)}$$
$$= 1.56^{+0.62}_{-0.49} \times 10^{-11}\ \text{(destr.)}$$

$$\mathrm{BR}_{\mathrm{SM}}(K_L \to \pi^0 \mu^+ \mu^-) = 1.41^{+0.28}_{-0.26} \times 10^{-11}\ \text{(constr.)}$$
$$= 0.95^{+0.22}_{-0.21} \times 10^{-11}\ \text{(destr.)}$$

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

- SM prediction depends on sign of A($K_L \to \gamma\gamma$), which determines LD/SD interference
- **BR$_{\text{exp}}$($K_L \to \mu^+ \mu^-$) = (6.84 ± 0.11) × 10^{-9}**

  See e.g. BNL E871 result, PRL84 (2000)

$$\mathrm{BR}_{\mathrm{SM}}(K_L \to \mu^+ \mu^-) = 6.82^{+0.77}_{-0.24} \times 10^{-9}\ \text{(LD+)}$$
$$= 8.04^{+1.66}_{-0.97} \times 10^{-9}\ \text{(LD−)}$$

Further theoretical progress expected, including on lattice

$K^+ \to \pi^+\ell^+\ell^-$ and lepton universality

LD dominated, mediated by $K^+ \to \pi^+\gamma^*$

Vector form factor:

$$V_+(z) = a_+ + b_+ z + \underset{\substack{\uparrow \\ K_{3\pi}\text{ loop term}}}{V_+^{\pi\pi}(z)}$$

$$z = m_{\ell\ell}^2/m_K^2$$

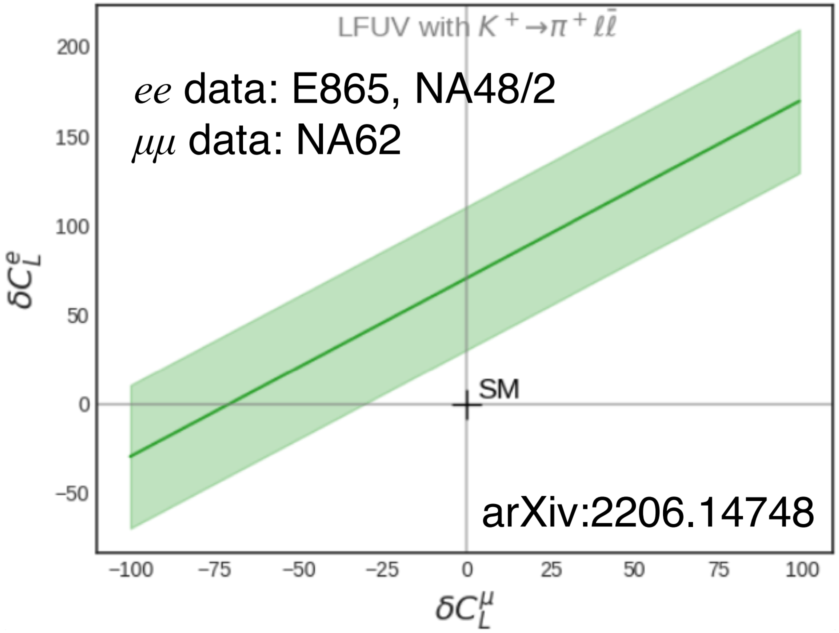
LD effects in a_+, b_+ purely universal

LD contribution to difference cancels out: sensitive only to short-distance effects

$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td}V_{ts}^*(C_9^\mu - C_9^e)\right]$$

Lepton universality predicts same a_+, b_+ for $\ell = e, \mu$

Closest analogue to R_K in B physics



ee data: E865, NA48/2

$\mu\mu$ data: NA62

arXiv:2206.14748

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

$$O_9^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu\ell)$$

$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

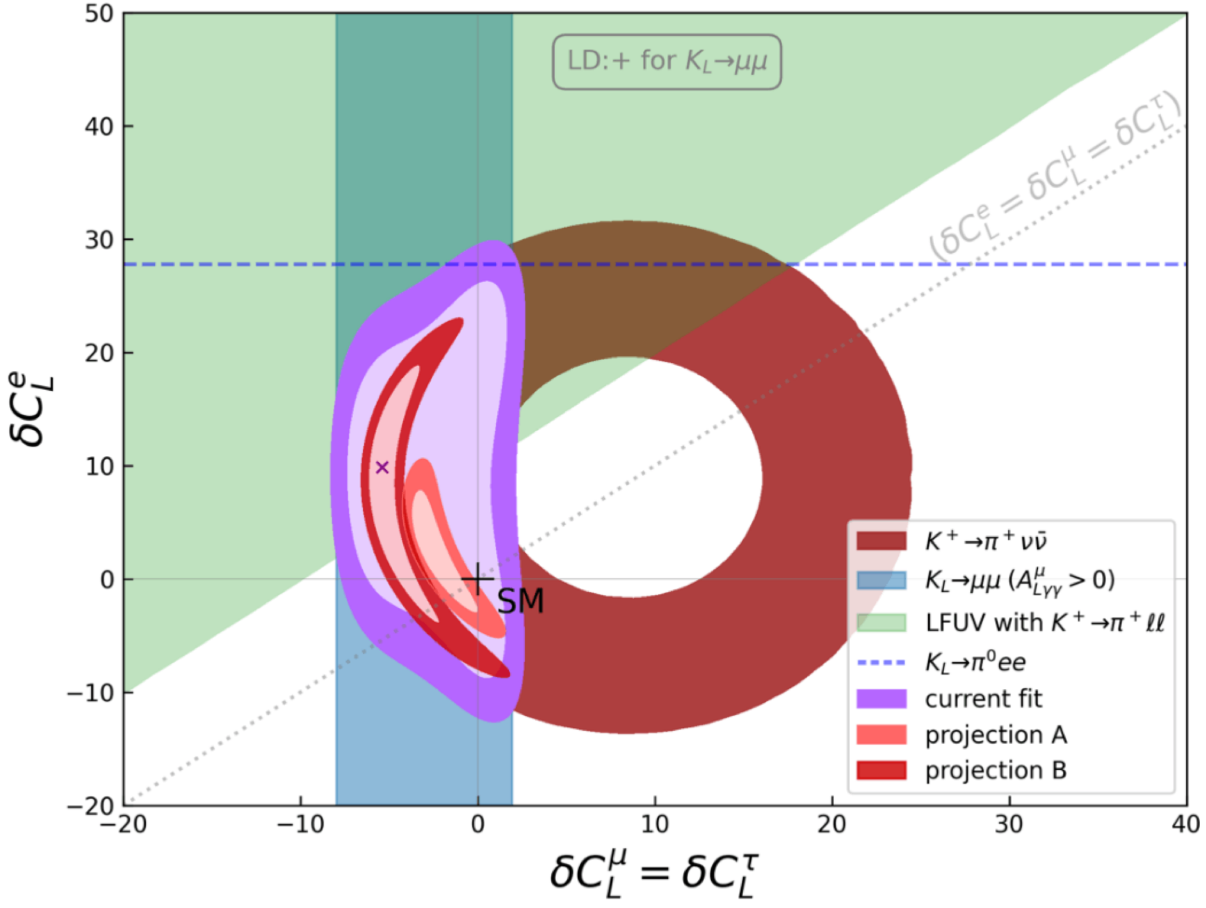
$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

$$C_k^\ell = C_{k,\text{SM}}^\ell + \delta C_k^\ell$$

Global fit to kaon observables

Deviation of Wilson coefficients from SM, for NP scenarios with LH quark currents

arXiv:2206:14748



Current data:

- $K^+ \to \pi^+ \nu\nu$
- $K_L \to \mu\mu$ (LD+)
- $K^+ \to \pi^+ \ell\ell$
- $K_L \to \pi^0 ee$ (CL90)

Fit to current data

Projection A:

- $K^+ \to \pi^+ \nu\nu$, $K_L \to \mu\mu$, $K^+ \to \pi^+ \ell\ell$ mmts confirmed at target precision
- $K_L \to \pi^0 ee$ assume SM value ± 100% unc

Projection B:

- All mmts give best fit values with target precision

The role of HIKE

Studies of the kaon sector are complementary to studies of the B and D sectors

Kaons provide different (in some cases higher) NP sensitivity than B, D mesons

NP scenarios	Process
Z-FCNC	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, ε'/ε
Z′	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, ε'/ε, ΔM_K
Simplified models	$K_L \to \pi^0 \nu\bar{\nu}$, ε'/ε
LHT	All K decays
331 models	Small effects in $K \to \pi\nu\bar{\nu}$
Vector-like quarks	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, ΔM_K
Supersymmetry	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
2HDM	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
Universal extra dimensions	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
Randall-Sundrum models	All rare K decays
Leptoquarks	All rare K decays
SMEFT	Several processes in K system
SU(8)	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
Diquarks	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, ε_K
Vector-like compositeness	$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, ε_K

arXiv:2203.09524

Many NP models predict effects on kaon observables

Main limitation to constraining these models is from experimental precision of kaon measurements

HIKE will:

- **Improve the precision of these measurements to match and challenge theory predictions**
- Study and measure for the first time channels not yet observed
- Search for kaon decays forbidden by the SM with unprecedented sensitivity

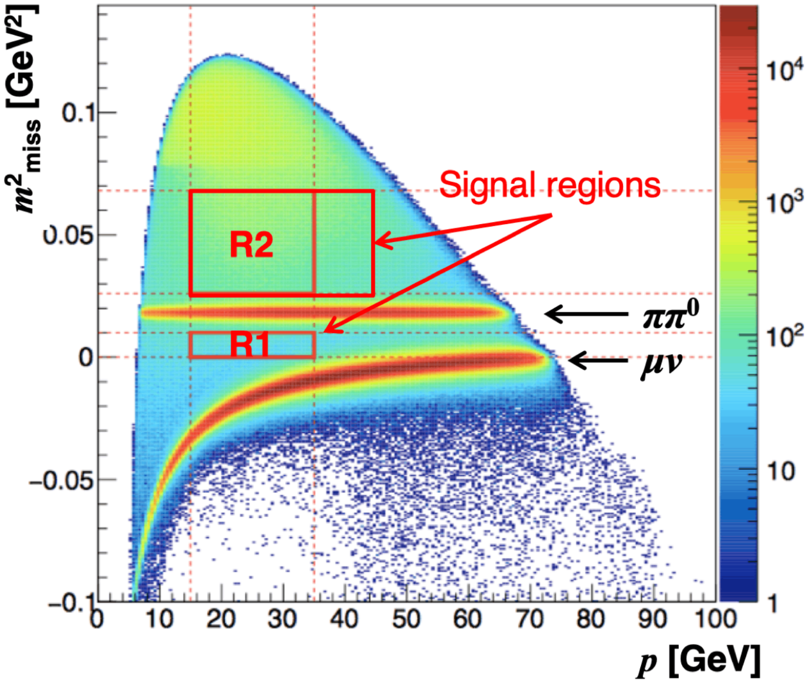
The NA62 experiment at the CERN SPS

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

Signal:

BR = (8.6 ± 0.4) × 10^{-11}

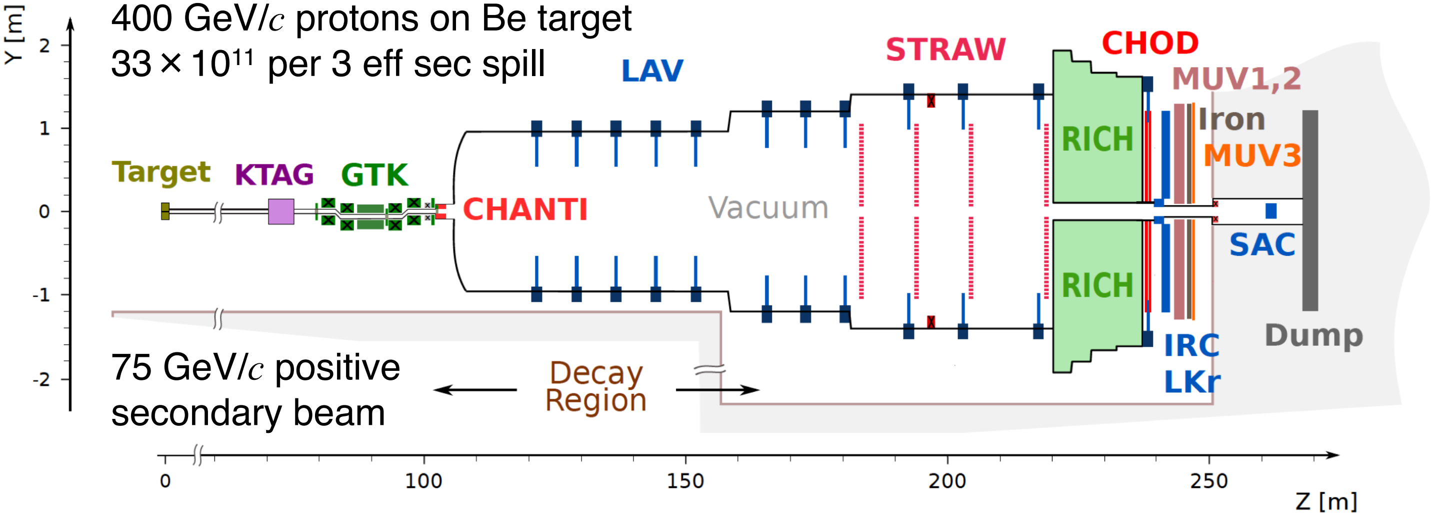
- K track in
- π track out
- No other particles in final state
- $M^2_{\text{miss}} = (p_K - p_\pi)^2$



Main K^+ backgrounds:

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

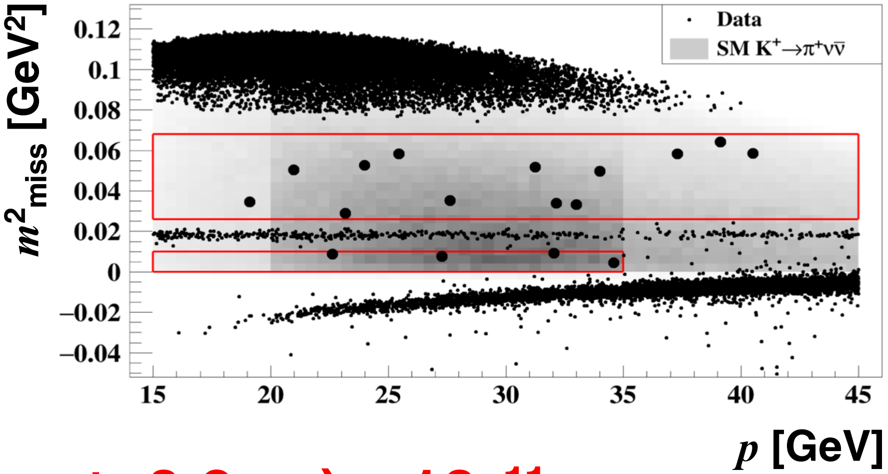
- **High-rate, precision tracking: 750 MHz at GTK**
- **Redundant PID and muon vetoes**
- **Hermetic photon vetoes**
- **High-performance EM calorimeter**



NA62 through 2025

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

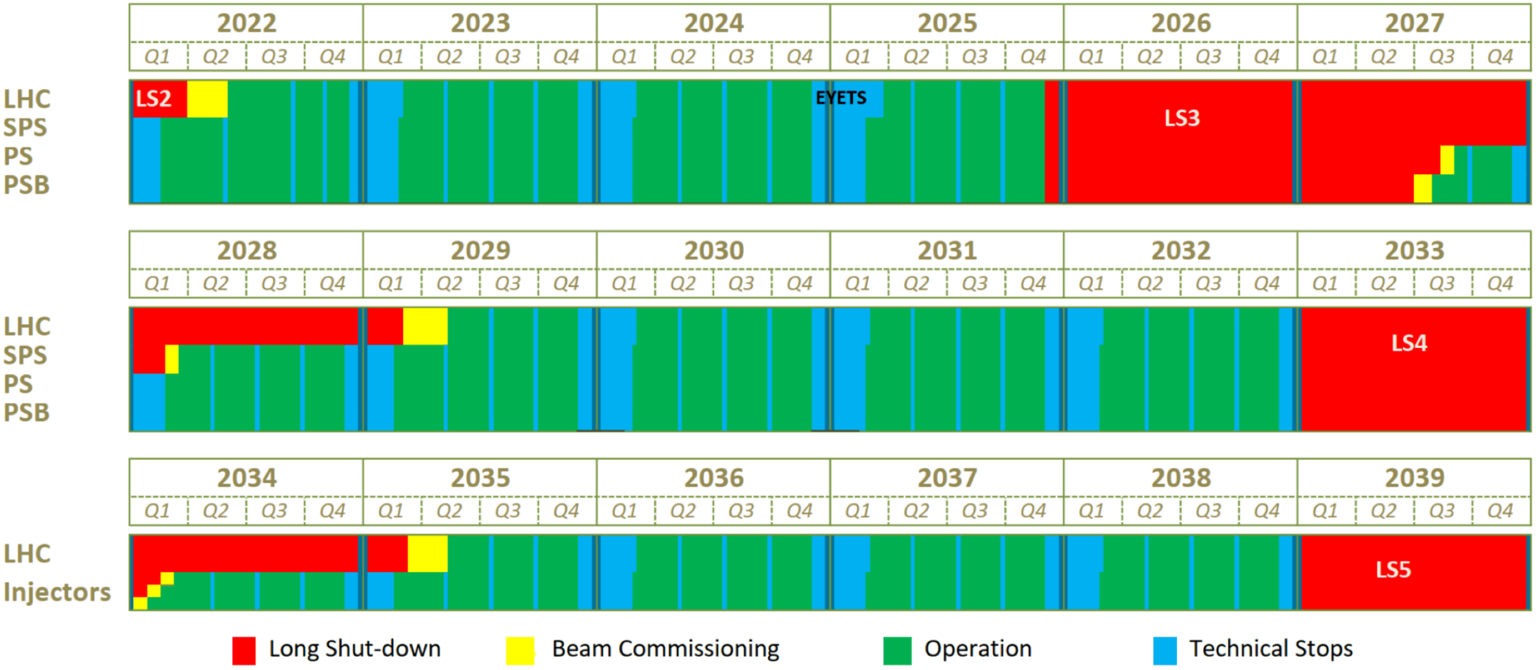
Key modifications to reduce background from upstream decays and interactions:

- Rearrangement of beamline elements around GTK achromat
- 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% → 100%)

Expect to measure BR($K^+ \to \pi^+\nu\nu$) to ~10% by LS3 (end 2025)

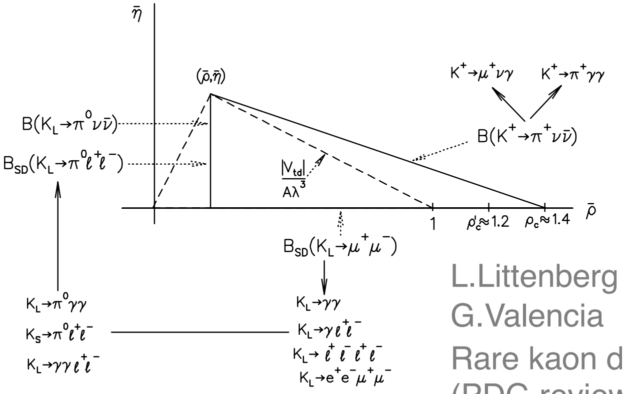
Fixed target runs at the SPS



IEFC working baseline, March 2022 – https://indico.cern.ch/event/1134440/

Fixed target runs foreseen through 2040
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)

The HIKE program

Phase 1: High-intensity K^+ experiment to measure BR($K^+ \to \pi^+\nu\nu$) to ~5%

- Also study lepton universality/number/flavor violation:

  $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$, $K^+ \to \pi^+\ell\ell$, $K^+ \to \pi^-\ell^+\ell^+$, $K^+ \to \pi^+\mu e$
- Radiative and Dalitz decays, chiral parameters, precision measurements

Phase 2: Experiment for rare K_L decays with charged particles

- K_L beamline, as in KLEVER
- Tracking and PID for secondary particles, as in NA62
- $K_L \to \pi^0\ell^+\ell^-$

  Excellent π^0 mass resolution – look for signal peak over Greenlee background
- Lepton universality/number/flavor violation in K_L decays
- Radiative K_L decays and precision measurements
- Measurement of K_L, n, and Λ fluxes and halo to prepare for K_L phase

During 1&2: Periodic runs with dumped beam, collect up to 5×10^{19} pot

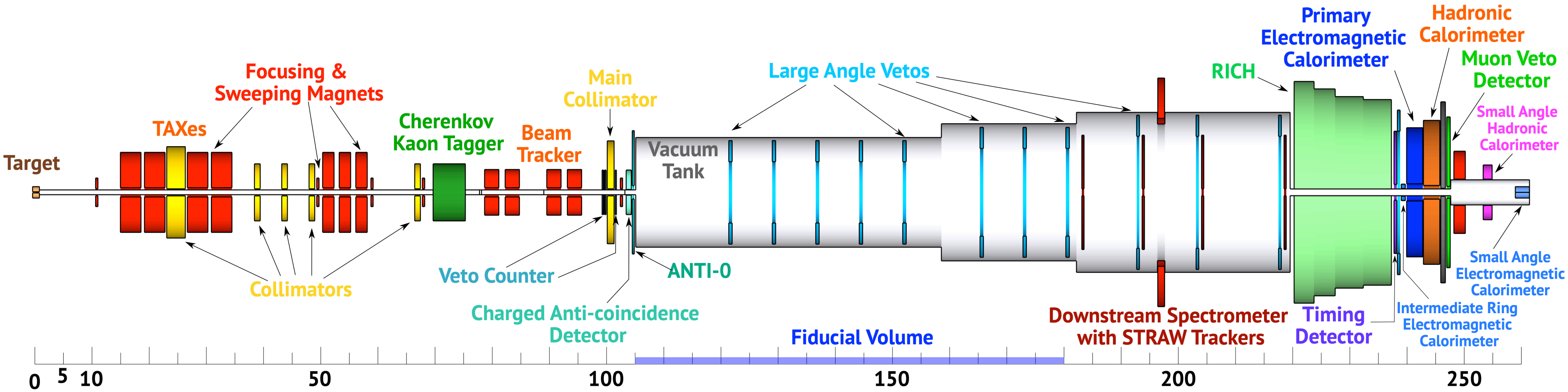
Phase 3: Measurement of BR($K_L \to \pi^0\nu\nu$) to ~20%: KLEVER

Phase 1: $K^+ \to \pi^+ \nu\nu$ at high-statistics

Goal: Measure BR($K^+ \to \pi^+ \nu\nu$) to within ~5%

Requires **4x** increase in intensity → requires major beam upgrades!

Basic design of NA62 will work at high intensity



1.2×10^{13} ppp = 4x NA62

Key challenges:

- Require **4x** better time resolution to keep random veto rate under control
- Must maintain other key performance specifications at high-rate:
  Space-time reconstruction, material budget, single photon efficiencies, etc.

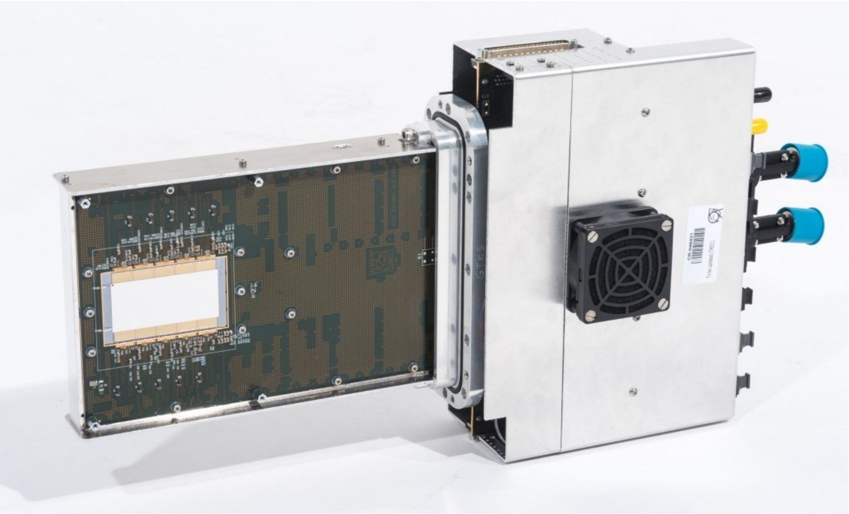
These characteristics are necessary for rare K_L decays as well

- Calorimeter, photon vetoes, and readout reused for K_L experiments

Experimental challenges: GTK

At 4x intensity GTK will track 3 GHz!

- **Time resolution < 50 ps per plane, no non-gaussian tails!**
- Smaller pixels to reduce occupancy: $< 300 \times 300$ µm^2
- Efficiency: > 99% (incl. fill factor)
- Reduced 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: 2.3×10^{15} n eq/cm^2/yr

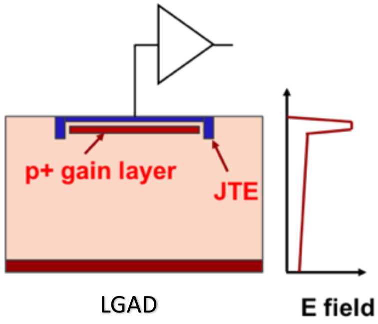


NA62 Gigatracker station

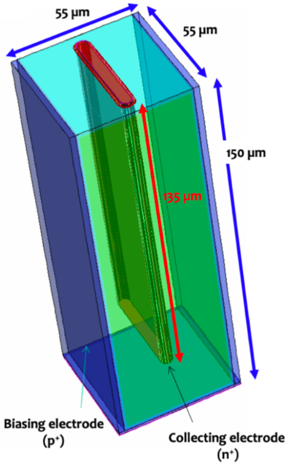
Continue to improve planar sensors while monitoring progress on new technologies

Possible synergies with ongoing development efforts:

LGAD: Low Gain Avalanche Detectors



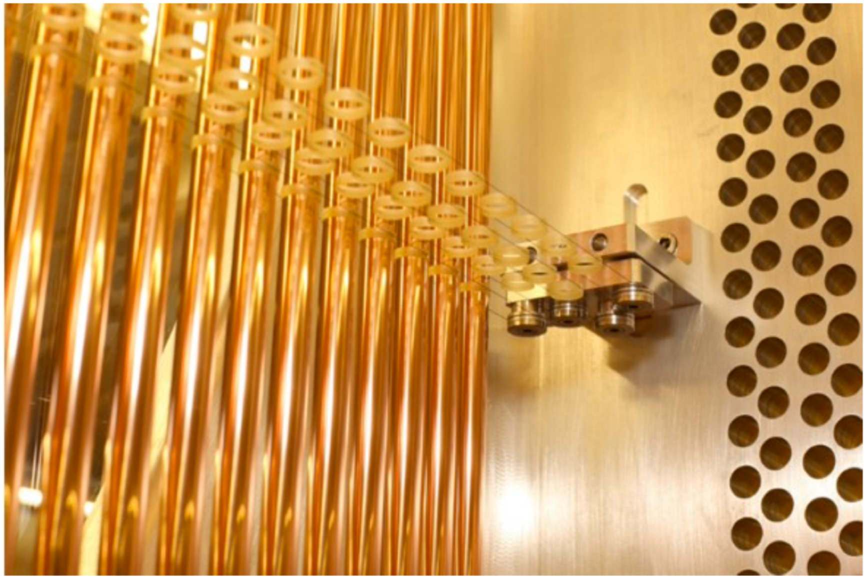
TimeSPOT: time-stamping 3D sensors



Experimental challenges: STRAW

For 4x intensity:

- **Increase rate capability**
  - Reduce straw diameter
  - Use fast shaping
- **Further improve momentum resolution**
  - Reduce material budget
  - Improve position resolution



Design studies in progress at CERN and Dubna

- **Straw diameter 9.8 → 5 mm**
- **Trailing-time resolution: 30 → 6 ns**
- **Maximum drift time: 150 → 80 ns**
- **Rate capability increased 6-8x**
- Layout: 4 chambers, ~21000 straws
- Decreased straw wall thickness: 36 → 20 µm
- Material budget: 1.7 → 1.4% X_0

First prototype
5 mm straws
from Dubna

NA48 LKr calorimeter in HIKE

Quasi-homogeneous ionization calorimeter: 27X_0 of LKr

Photon efficiency likely adequate even for K_L program

- NA48-era studies for NA62: $1 - \varepsilon < 10^{-5}$ for $E_\gamma > 10$ GeV
- High-energy efficiency confirmed with NA62 data

Time resolution

- $\sigma_t \sim 500$ ps for π^0 with $E_{\gamma\gamma} > 20$ GeV
- Would require 4x improvement in K^+ phase to hold accidental veto rate to current levels
- Critical for KLEVER: Accidental rate ~140 MHz!

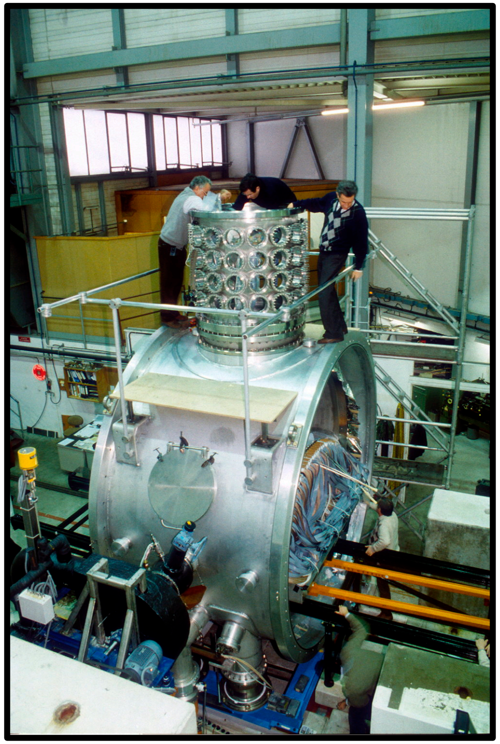
Consolidation work necessary

Investigating upgrade possibilities

- Increase operating voltage to increase drift velocity
- Faster digitizers and signal shaping

For K_L phase, LKr inner bore limits beam solid angle

- Cold bore $r = 80$ mm, inner sensitive radius $r = 120$ mm



LKr resolution:

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$

$$\sigma_t = \frac{2.5\text{ ns}}{\sqrt{E}}$$

Shashlyk calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

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

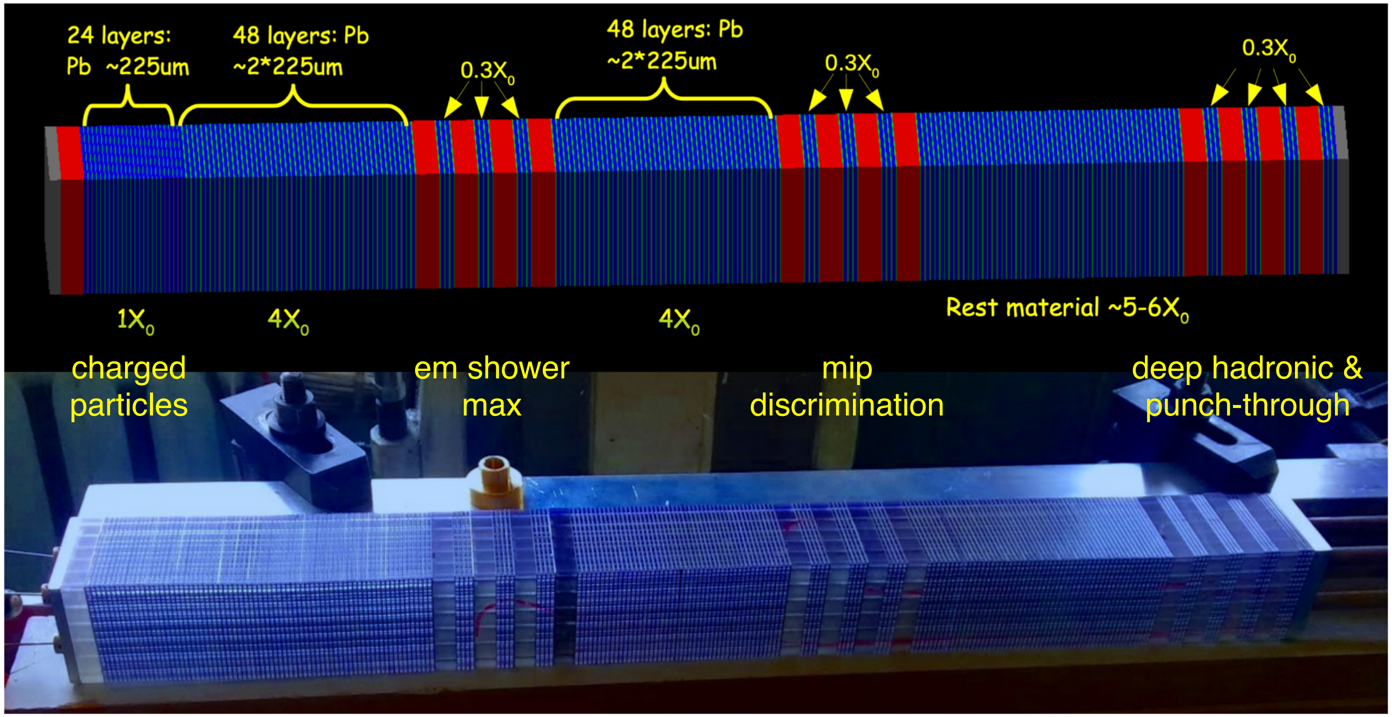
0.275 mm Pb + 1.5 mm scintillator

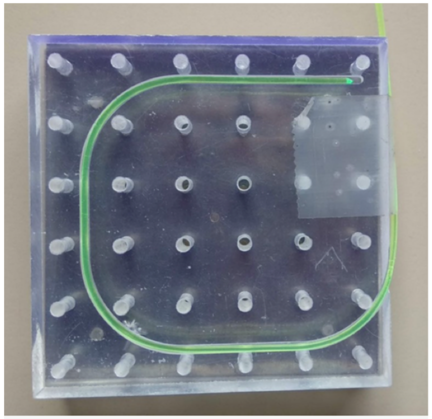
PANDA/KOPIO prototypes:

- $\sigma_E/\sqrt{E}$ **~ 3%** $/\sqrt{E}$ (GeV)
- σ_t **~ 72 ps** $/\sqrt{E}$ (GeV)
- σ_x **~ 13 mm** $/\sqrt{E}$ (GeV)

New for KLEVER: Longitudinal shower information from spy tiles

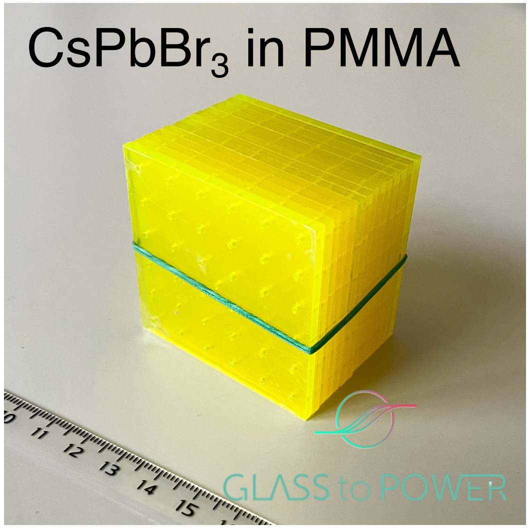
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers

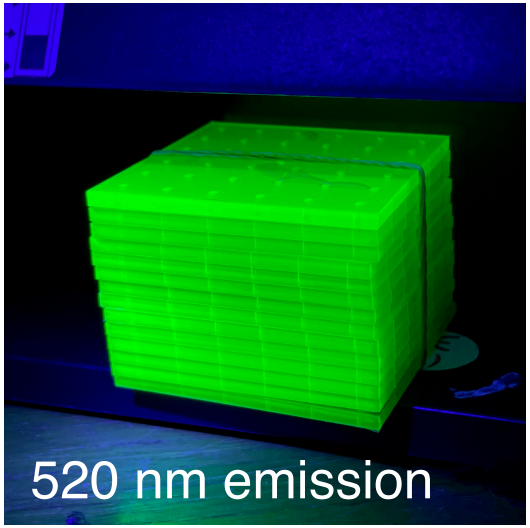




1st prototype assembled in Protvino and tested at OKA in April 2018 and DESY in Nov 2019

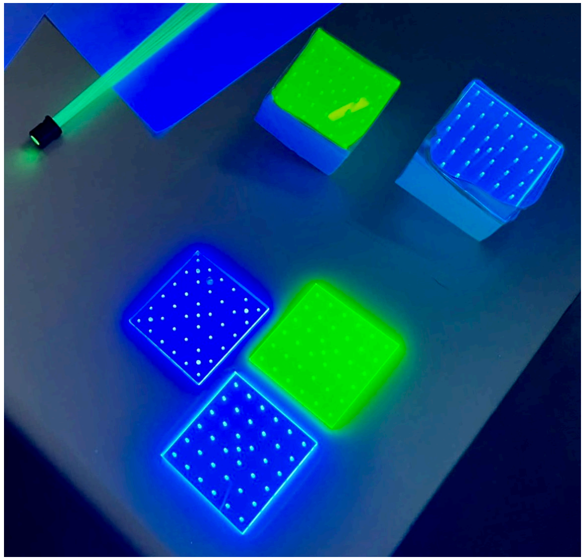
Innovative scintillators for shashlyk





Quantum dots used as emitters for bright, ultrafast, robust scintillators:

- Excellent candidate for HIKE shashlyk!
- Applications to timing planes



Trial production of tiles in Protvino format (55 x 55 mm^2)

R&D in synergy with NanoCal project

Realize first calorimeter with NC scintillators:

$CsPbBr_3$, 0.05% w/w in UV-cured PMMA

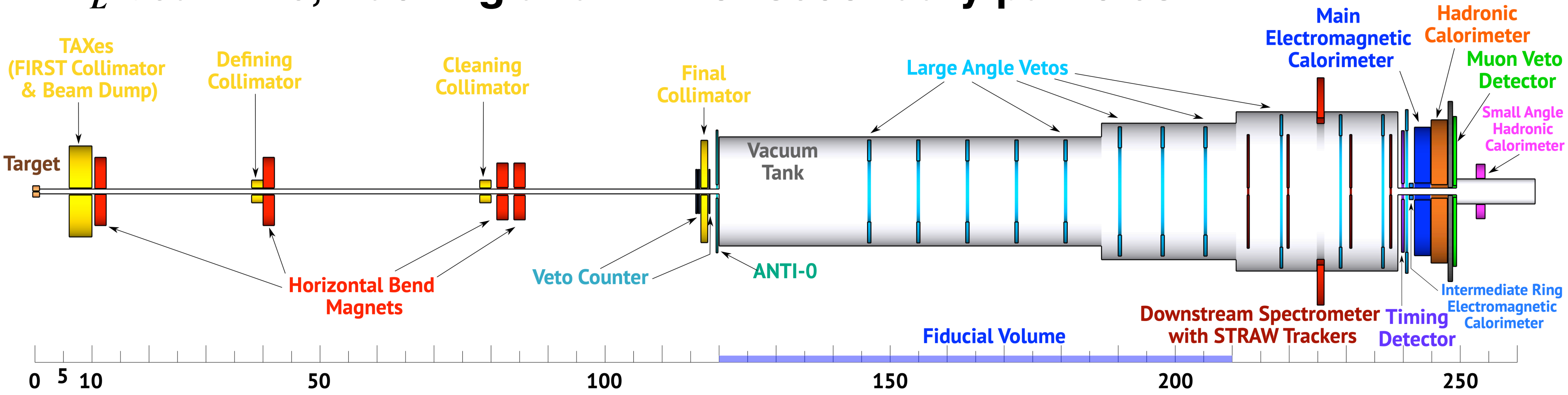
- Light yield O(few k) photons/MeV deposit
- 50% of light emitted in components with $\tau < 0.5$ ns
- Radiation hard to O(1 MGy)

Progress:

- **2022:** Component test at CERN this fall (fibers/tiles/SiPMs)
- **2023-2024**: Build and compare full-scale prototypes with conventional/NC scintillator

Phase 2: Rare K_L decays

K_L beamline, tracking and PID for secondary particles



2×10^{13} ppp = 6x NA62

Physics objectives:

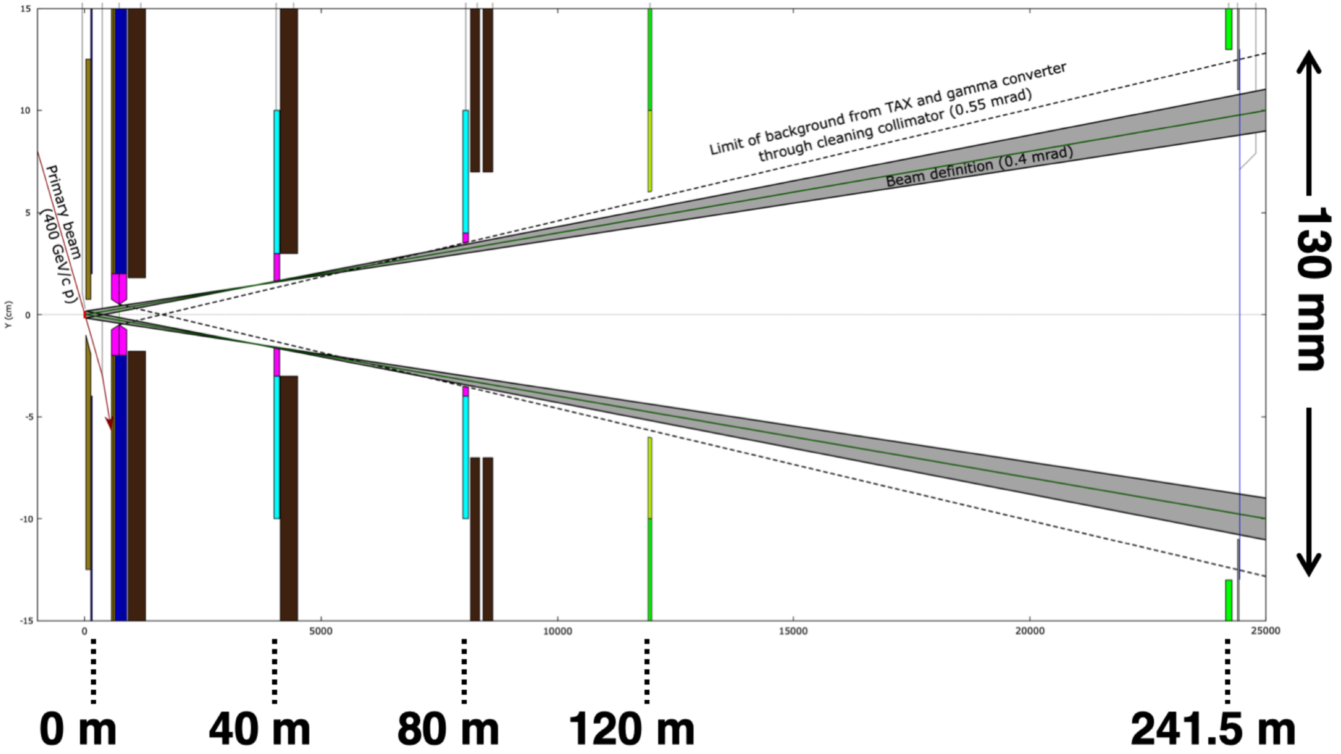
- $K_L \to \pi^0 \ell^+ \ell^-$, $K_L \to \mu^+ \mu^-$: Overconstrain UT with information on $s \to d\ell\ell$
- Lepton-flavor violation in K_L decays
- Radiative K_L decays and precision measurements
- K_L decays to exotic particles

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!

Neutral beam and beamline

- **400 GeV p on 400 mm Be target**
- **Production angle $\theta = 2.4—8.0$ mrad**
- **Solid angle $\Delta\theta = 0.4$ mrad**
- **4 collimation stages** minimize neutron halo, including beam scattered from absorber
- **Photon absorber** in dump collimator: Optimize thickness using aligned metal crystal



	θ = 2.4 mrad **Phase 2**	**θ = 8.0 mrad** **Phase 3**
Mean $p(K_L)$ at prod	79 GeV	39 GeV
Mean $p(K_L)$ in FV	46 GeV	26 GeV
K_L rate in beam	5.4×10^{-5}/pot	2.1×10^{-5}/pot

Phase 2 physics sensitivity

- Nearly 2 × 10^{14} kaon decays in FV in 5 years!
- Single-event sensitivities for $K_L \to \pi^0 \ell^+ \ell^-$ improved by more than two orders of magnitude
- Suppression of the $K_L \to \gamma\gamma\ell^+\ell^-$ background relies on excellent photon energy resolution of the HIKE EM calorimeter

Experimental status (KTeV):

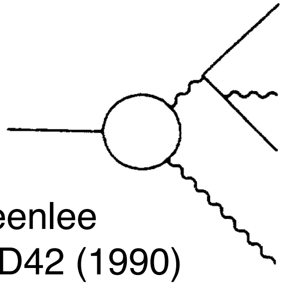
$\mathrm{BR}(K_L \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$

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

$K_L \to \gamma\gamma\ell$+ℓ−

$\mathrm{BR}(\gamma\gamma e^+ e^-) \sim 6 \times 10^{-7}$

$\mathrm{BR}(\gamma\gamma\mu^+\mu^-) \sim 10^{-8}$



Greenlee PRD42 (1990)

Mode	Assumed branching ratio	Acceptance	Signal yield in five years
$K_L \to \pi^0 e^+ e^-$	3.5×10^{-11}	2.1%	140
$K_L \to \pi^0 \mu^+ \mu^-$	1.4×10^{-11}	6.0%	160
$K_L \to \mu^+ \mu^-$	7×10^{-9}	17%	2.3×10^5
$K_L \to \mu^\pm e^\mp$	–	16%	–

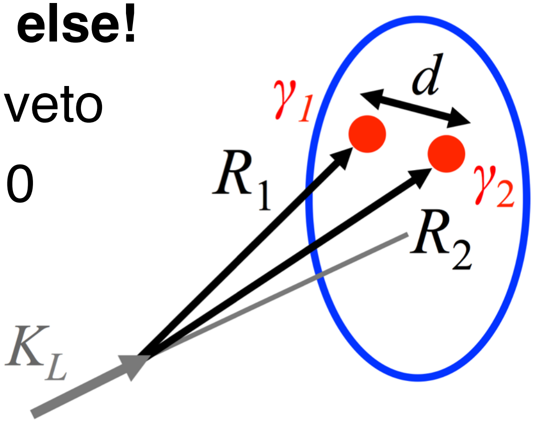
- **Likely first observation of $K_L \to \pi^0 \ell^+ \ell^-$** or sensitivity to BRs O(10^{-11})
- **$K_L \to \mu^+ \mu^-$ signal yield: BR with 0.2% statistical precision**
- Sensitivities of O(10^{-12}) for BR of a broad range of rare and forbidden K_L decays (e.g. 60x better than BNL-E871)

Phase 3: $K_L \to \pi^0 \nu\bar{\nu}$:

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

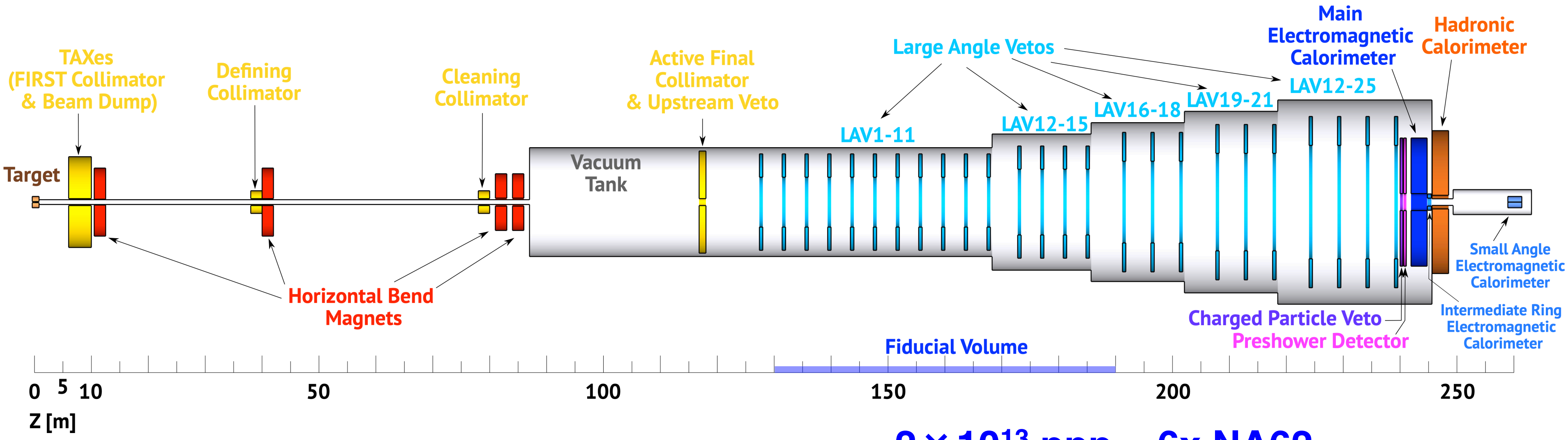
$$m^2_{\pi^0} = 2E_1E_2\,(1-\cos\theta)$$

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

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

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



2×10^{13} ppp = 6x NA62

KLEVER target sensitivity:
5 years: 6×10^{19} pot

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

δBR/BR($\pi^0 \nu\nu$) ~ 20%

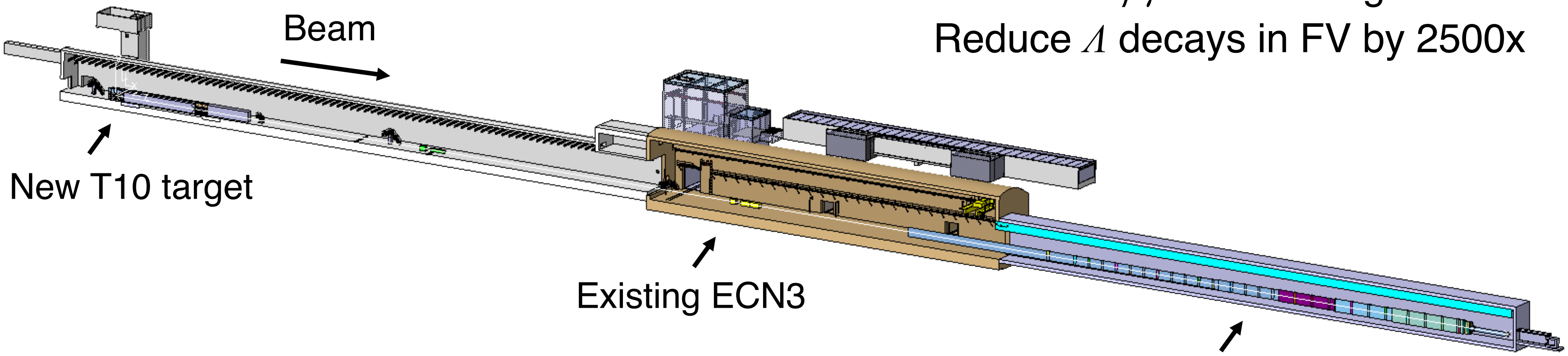
Studied in context of Physics Beyond Colliders

- 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 for other HIKE phases

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

Need to extend beamline 150 m (120 m → 270 m from target to UV/AFC)
Downstream extension of ECN3 hall

150 m ~ 8 $\beta\gamma c\tau$ for average Λ
Reduce Λ decays in FV by 2500x



New T10 target

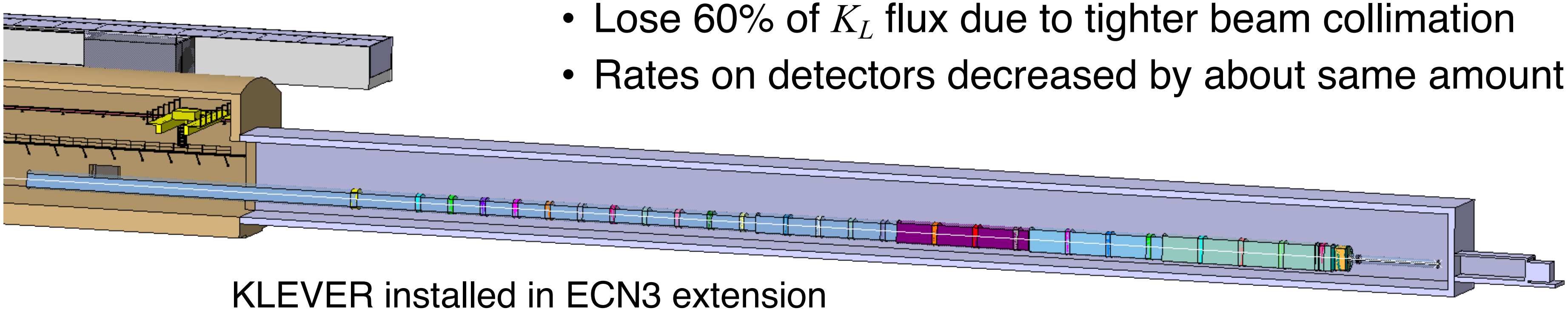
Existing ECN3

Hall extension
with overhead crane
150 x 7 x 9 m^3

Need for civil engineering a major factor in scheduling KLEVER after K^+ phase: Cost estimate in progress

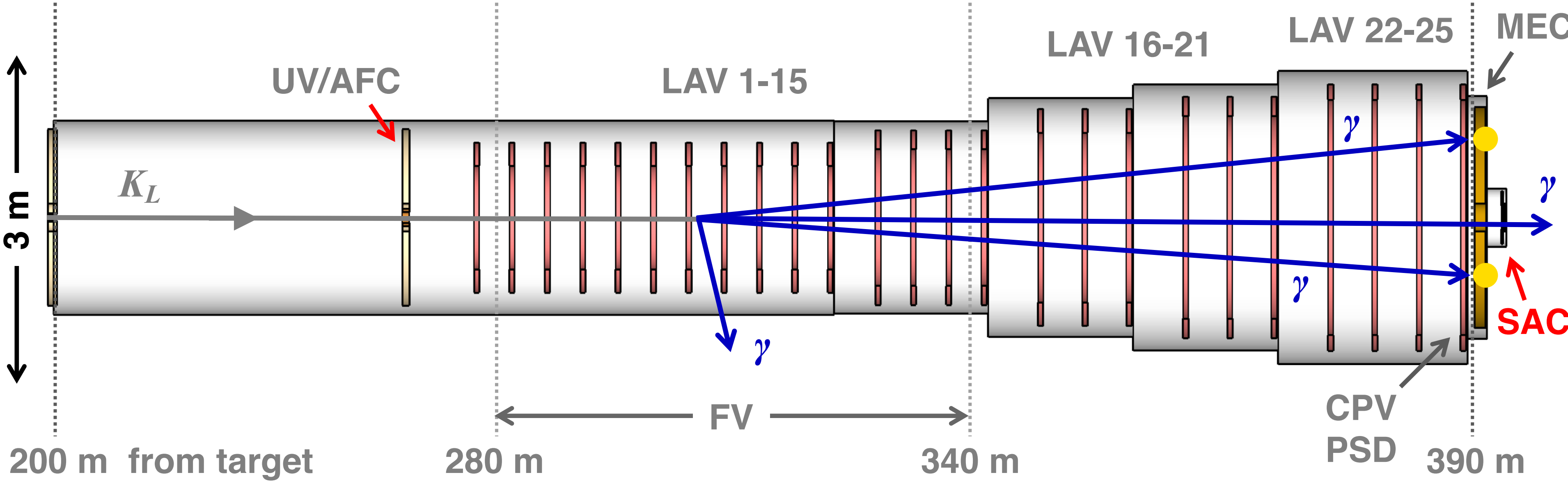
With longer beamline:

- Lose 60% of K_L flux due to tighter beam collimation
- Rates on detectors decreased by about same amount



KLEVER installed in ECN3 extension

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
- $\sigma_t < 100$ ps, 2-pulse separation at ~ 1 ns
- Radiation hard to 10^{13}-10^{14} n/cm^2 and 10^5-10^6 Gy

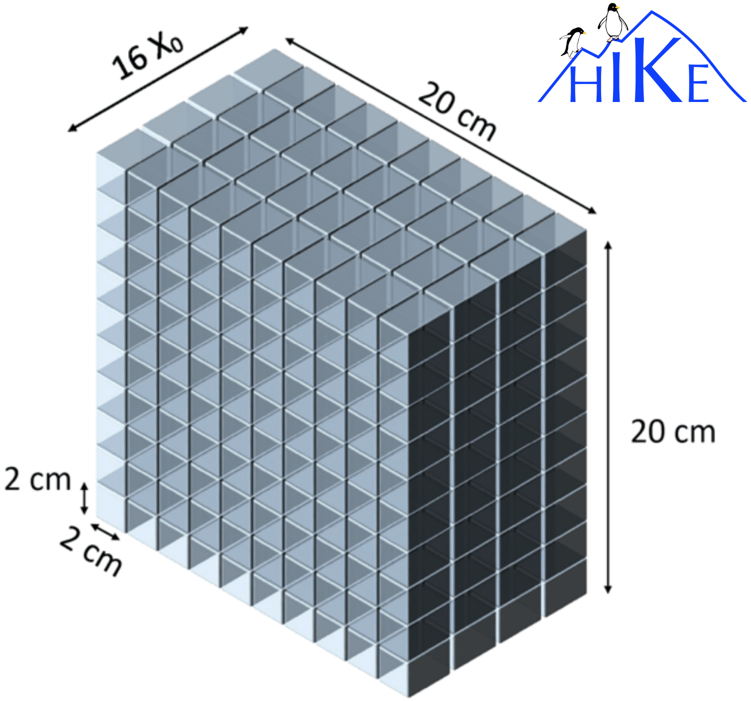
Efficiency requirements

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

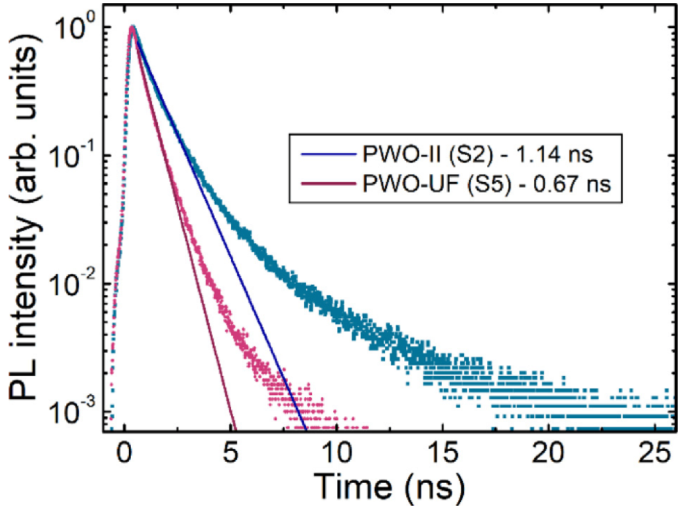
Small-angle photon veto

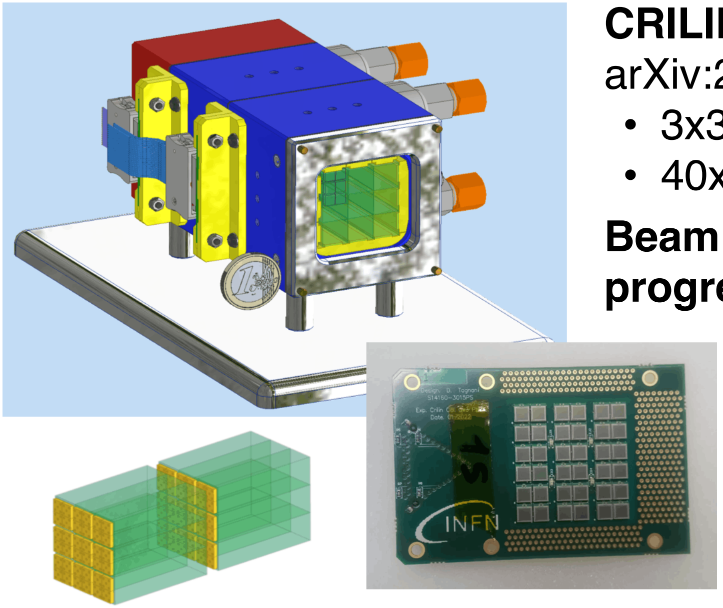
Proposed solution:
Ultra-fast, high-Z crystal calorimeter

- Cerenkov radiator like PbF_2 or ultra-fast scintillator such as PWO-UF
- Transverse and longitudinal segmentation for γ/n discrimination
- Exploit coherent interactions in crystals to reduce thickness



PWO-UF (ultra-fast):
Dominant emission with $\tau < 0.7$ ns
M. Korzhik et al., NIMA 1034 (2022) 166781





CRILIN prototype:
arXiv:2206.05838

- 3x3x2 crystals
- 40x10x10 mm^3

Beam tests in progress!

Summary of HIKE physics program

Observable	Target	Motivation
K^+ phase		
$K^+ \to \pi^+ \nu\nu$	BR to ~5%	New physics in FCNC decays
$K^+ \to \pi^+ \ell\ell$	Form factors at ~1% level	LFUV
$K^+ \to \pi\mu e$, $\pi^- \ell^+ \ell^+$	O(10^{-12}) sensitivity	LFV, LNV
$R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$	R_K to ~0.1%	LFUV
$K^+ \to \pi^+ \gamma\gamma$, $\pi^+ \pi^0 \gamma$, $\pi^+ \pi^0 ee$	As best as possible	Chiral parameters (LECs)
Hybrid phase		
$K_L \to \pi^0 \ell\ell$	Observation	New physics in FCNC decays
$K_L \to \mu\mu$	BR to < 1%	New physics in FCNC decays
$K_L \to \mu e$, $\pi^0 \mu e$	O(10^{-12}) sensitivity	LFV
$K_L \to \gamma\gamma$, $\pi^0 \gamma\gamma$	As best at possible	Ancillary to $K_L \to \mu\mu$, LECs
K_L phase (*K_LEVER*)		
$K_L \to \pi^0 \nu\nu$	BR to ~20%	New physics in FCNC decays

Plus periodic runs with dumped beam to accumulate at least 10^{19} pot to search for exotic, long-lived particles

Exotic, long-lived particles in HIKE

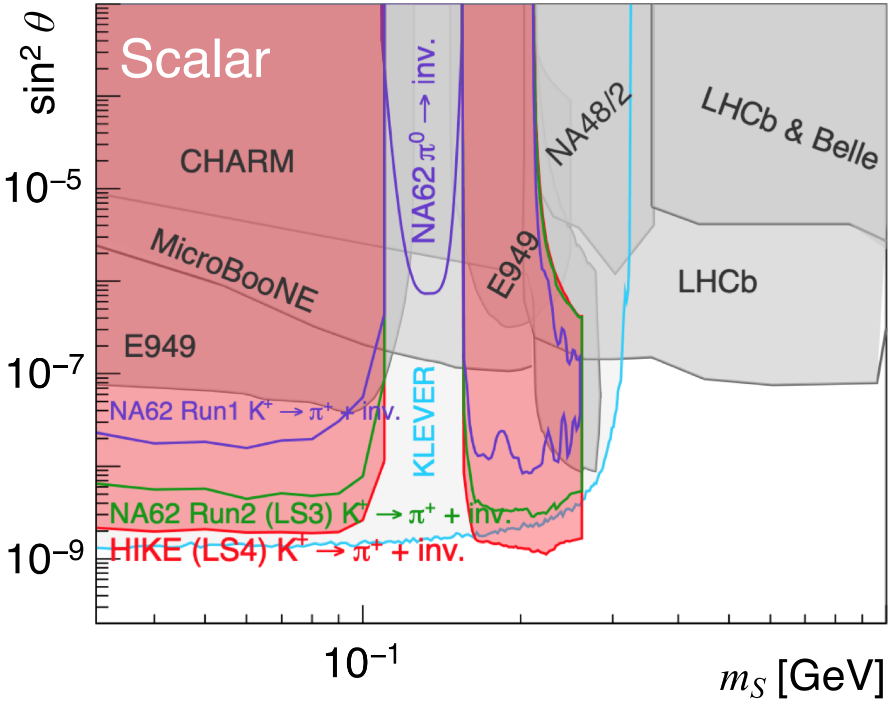
Searches for visible decays in beam-dump mode

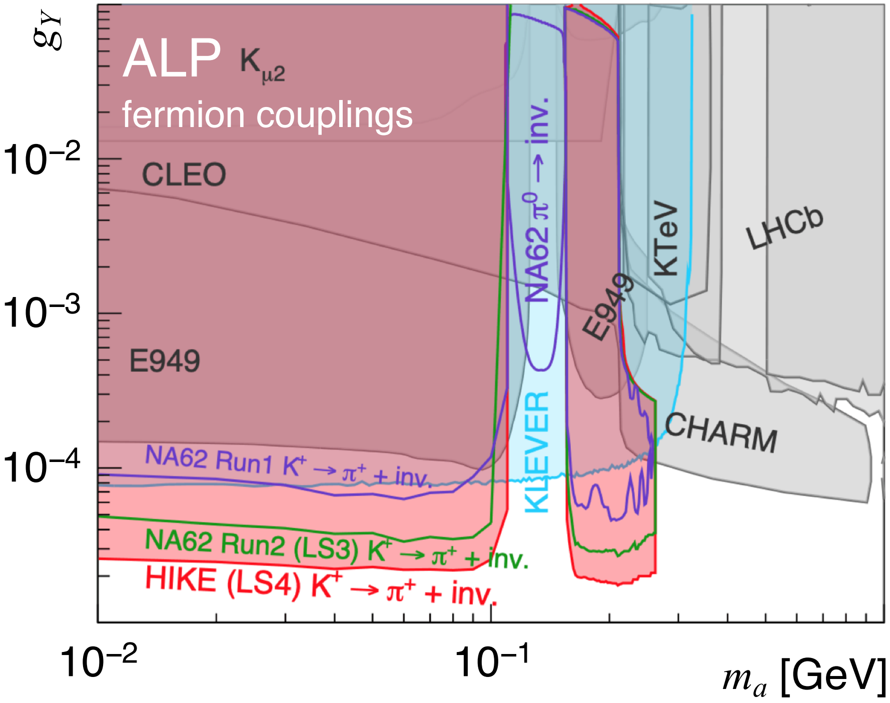
- Low rate in detector allows for potentially much higher beam intensity
- 10x statistics of 2021-2025 data (at least 10^{19} pot)
- Sensitive to forward processes, complimentary to off-axis experiments

  E.g., SHADOWS, an off-axis experiment proposed to run concurrently in ECN3

Searches for invisible decays during kaon running: $K \to \pi X$

- Projected sensitivities to scalars and ALPs for HIKE K^+ and K_L programs





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

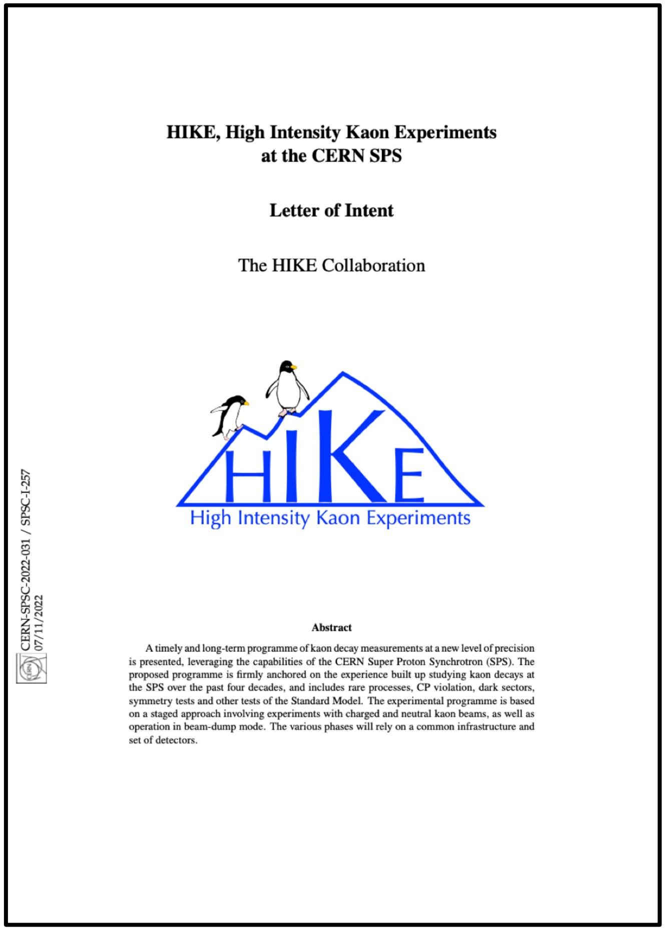
Need precision measurements of both rare K^+ and K_L decays!

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

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

HIKE—an **integrated program** of K^+ and K_L experiments—is taking shape at the CERN SPS

Letter of Intent SPSC-I-257
7 November 2022



CERN-SPSC-2022-031 / SPSC-I-257
07/11/2022

**HIKE, High Intensity Kaon Experiments
at the CERN SPS**

Letter of Intent

The HIKE Collaboration

High Intensity Kaon Experiments

Abstract

A timely and long-term programme of kaon decay measurements at a new level of precision is presented, leveraging the capabilities of the CERN Super Proton Synchrotron (SPS). The proposed programme is firmly anchored on the experience built up studying kaon decays at the SPS over the past four decades, and includes rare processes, CP violation, dark sectors, symmetry tests and other tests of the Standard Model. The experimental programme is based on a staged approach involving experiments with charged and neutral kaon beams, as well as operation in beam-dump mode. The various phases will rely on a common infrastructure and set of detectors.

High-Intensity Kaon Experiments at the CERN SPS

Additional information

Workshop on status and perspectives of physics at high intensity
Laboratori Nazionali di Frascati, 11 November 2022

High-intensity beams at the SPS

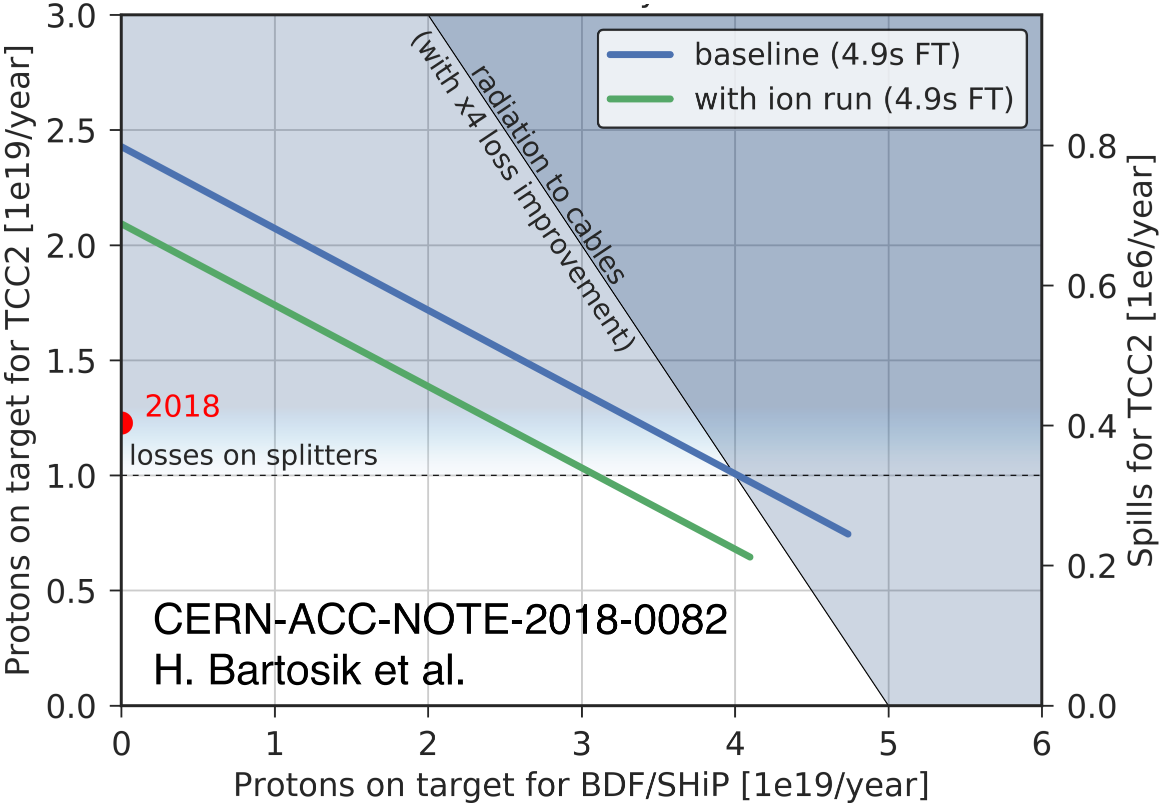
Operational scenarios and limits on the intensity deliverable to the North Area targets were studied in context of the BDF proposal as part of Physics Beyond Colliders

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)



CERN-ACC-NOTE-2018-0082
H. Bartosik et al.

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

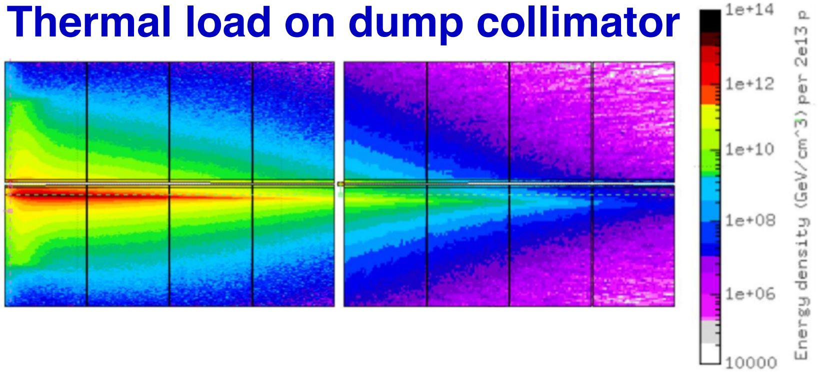
High-intensity proton beam in ECN3

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

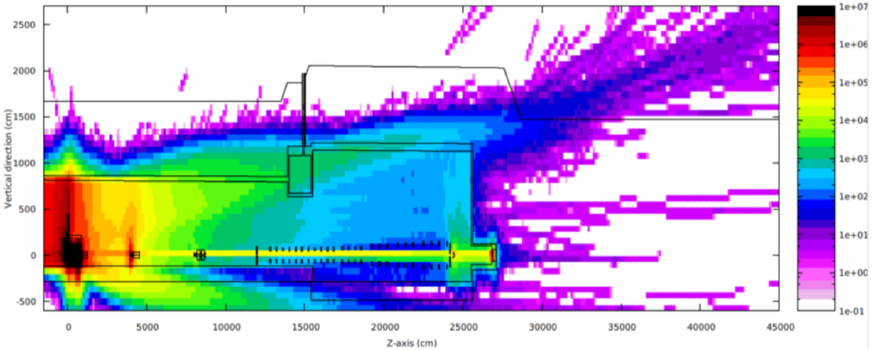
Beam and target simulations

Thermal load on dump collimator



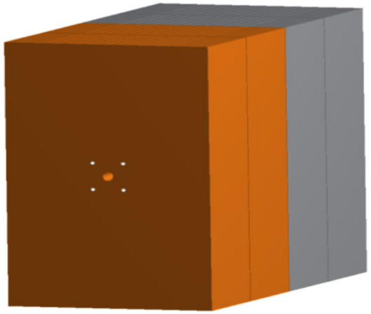
CNGS rod target

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



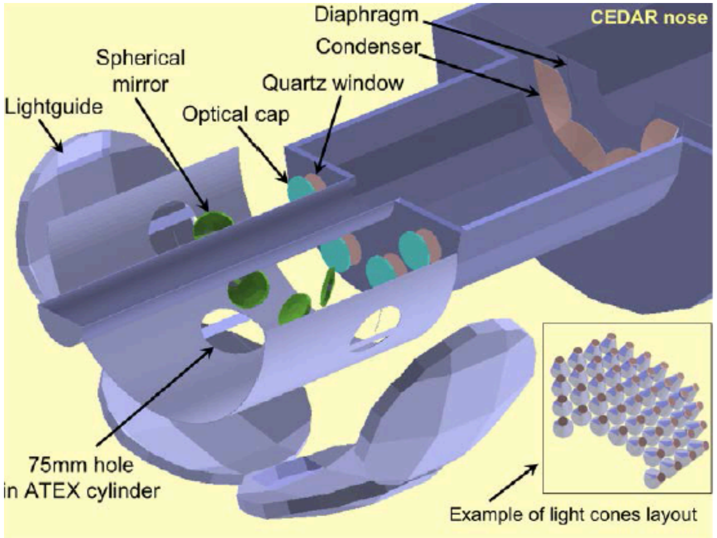
Neutral beam and prompt surface dose

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

Experimental challenges: KTAG

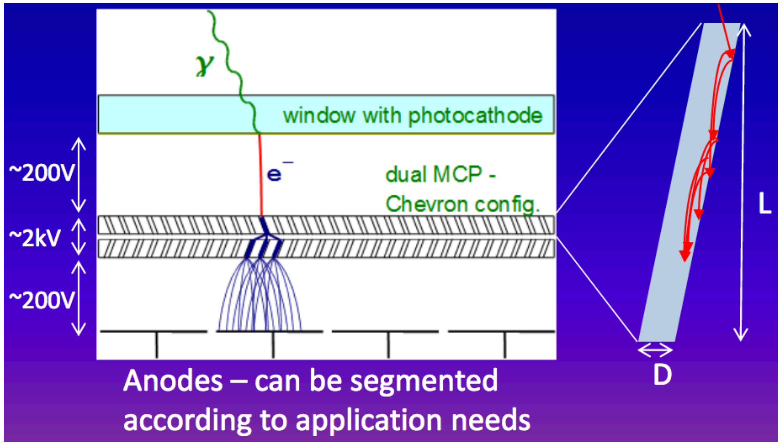
KTAG for 4x intensity:

- **Tag 200 MHz of K^+ in 3 GHz beam**
- **Need 4x better time resolution: ~20 ps!**
- Max detected photon rate: ~8 MHz/cm^2
- Single-photon capability with σ_t = 50-70 ps
- Good radiation resistance
- **Same vessel, new photodetectors**



Microchannel plate (MCP) PMTs

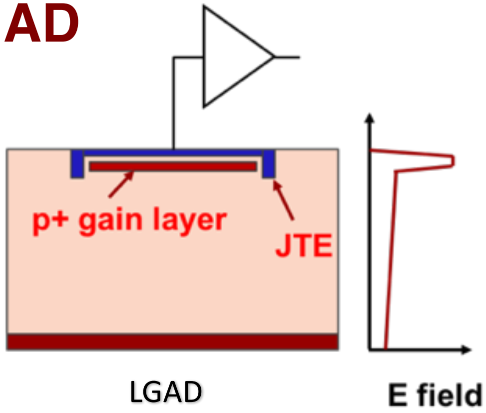
- Excellent time resolution (~20 ps)
- Low dark noise
- Single-photon sensitivity
- High gain, good QE
- Good filling factor
- Input rate capability ~MHz/cm^2



- **Susceptible to aging: QE drops due to to ion feedback to photocathode Effect of aging must be investigated and/or mitigated**

Experimental challenges: GTK

LGAD



Optimized for timing measurements

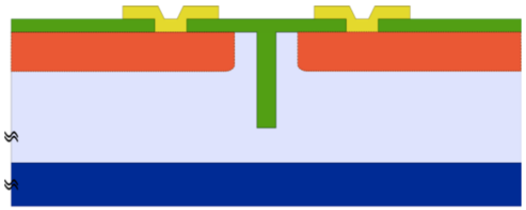
Add thin doped layer to conventional silicon detector to produce low, controlled multiplication

$$\sigma_t = \sigma_{\text{jitter}} \oplus \cancel{\sigma_{\text{time walk}}} \oplus \cancel{\sigma_{\text{TDC}}} \oplus \sigma_{\text{field}} \oplus \sigma_{\text{straggling}}$$

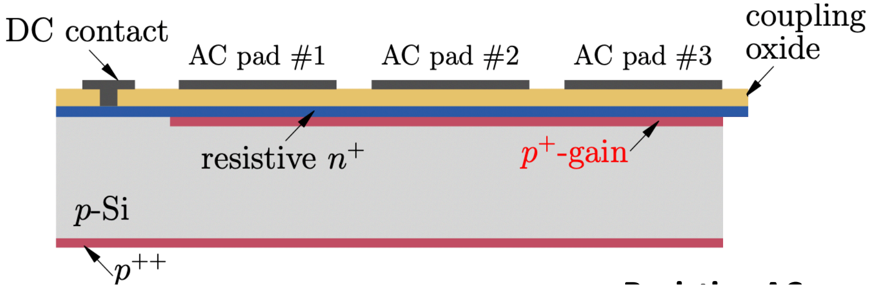
minimized by optimized readout electronics and correction techniques

- Excellent time resolution: 30-35 ps
- Thin sensors ~ 50 µm → reduced contribution to material budget
- Optimized gain layer design enhances reliability and radiation hardness
  No significant performance degradation up to 1.5×10^{15} n eq/cm^2
- New technologies to reduce impact of structures between readout pads
  (no-gain areas for signal)

Trench-isolated LGAD

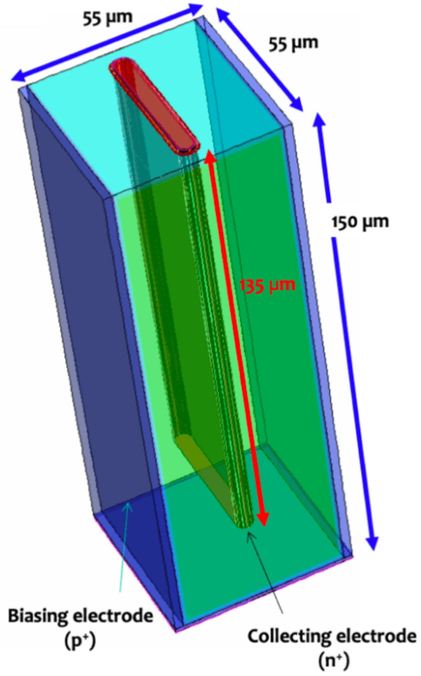


Resistive AC-coupled LGAD (RSD)



R. Arcidacono
NA62 Seminar
Feb 2020

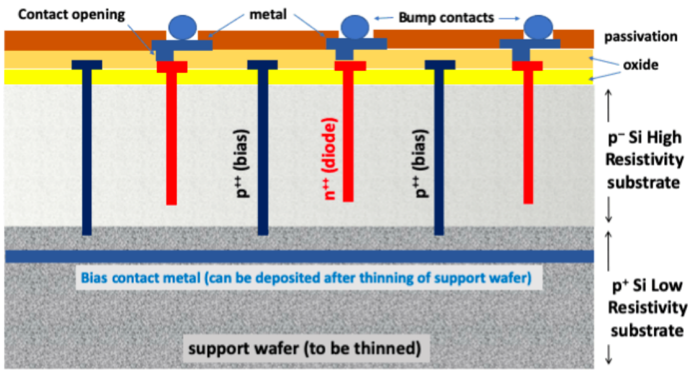
Experimental challenges: GTK



TimeSPOT

Trench geometry improves charge collection time uniformity

- Spatial resolution: O(10µm)
- Time resolution: ~30-50 ps/pixel seen in preliminary tests
- Radiation hardness $> 10^{16}\ n_{\mathrm{eq}}/\mathrm{cm}^2$
- Data throughput > 1 TB/s



- Use of 3D sensors for vertex detectors demonstrated

  ATLAS IBL Pixel Detector Upgrade
  NIMA694 2012

- Potential for timing not yet explored

Pros:

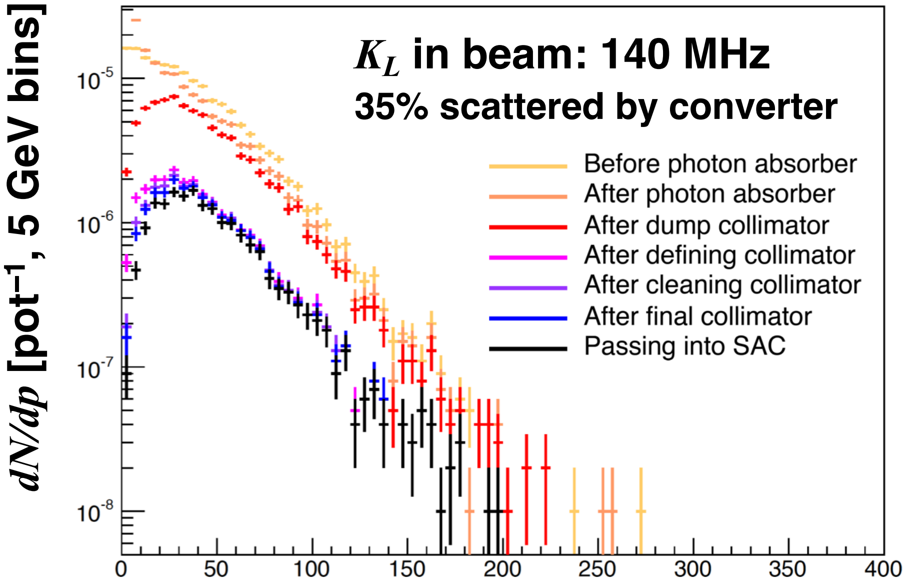
- **Unmatched radiation hardness**
- **Effect of Landau fluctuations mitigated by geometry**
- **Extremely fast signals**

Possible cons:

- Complexity of fabrication
- Geometric inefficiency (blind electrodes)
- Shape of time distribution (tail)?

See also:
A.Cardini
Detector Seminar
19 Jun 2020

Neutral beam simulation



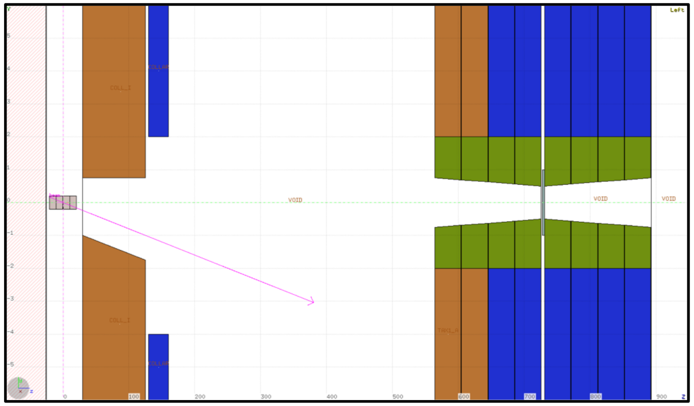
K_L in beam: 140 MHz

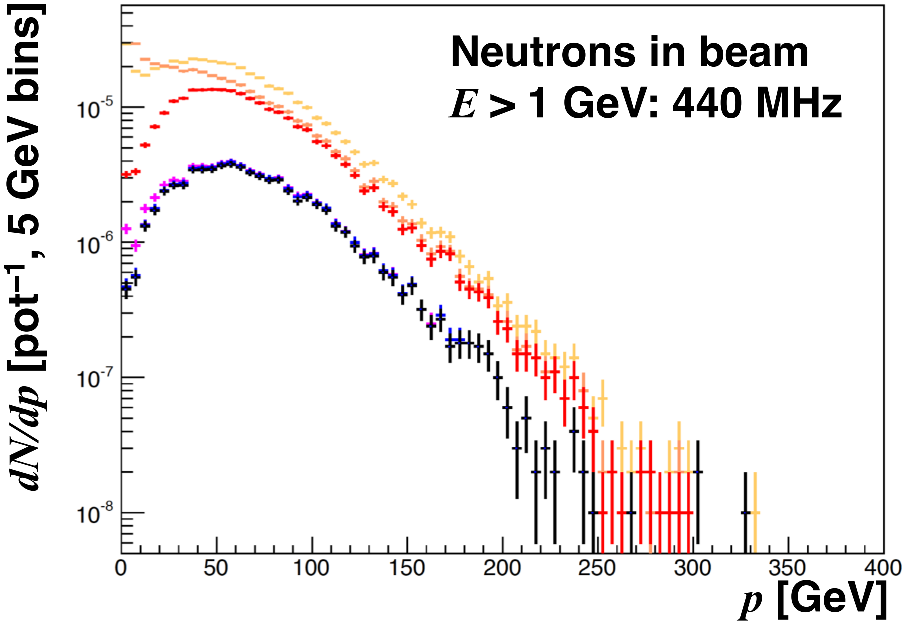
35% scattered by converter

FLUKA simulation of beamline

32-mm tungsten converter ($9X_0$)

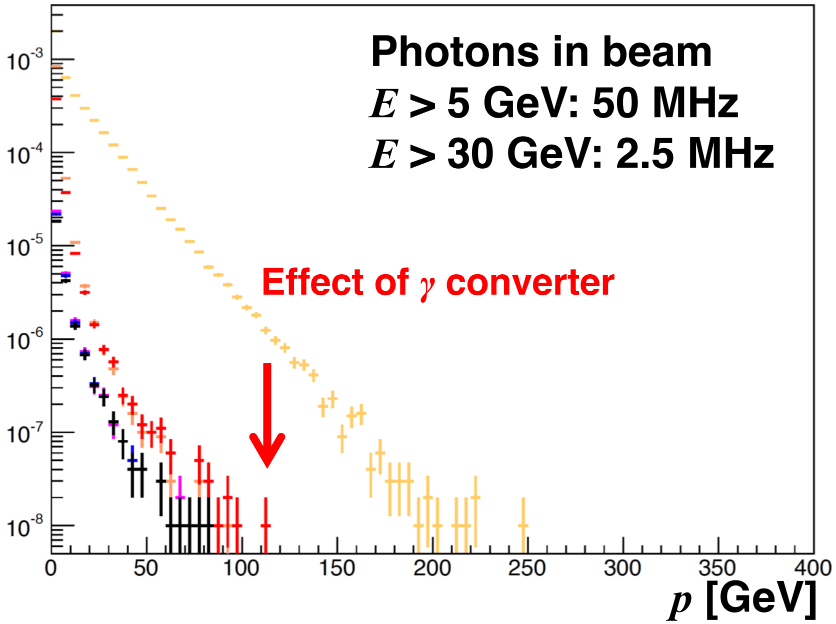
Detail of target and dump collimator:





Neutrons in beam

$E > 1$ GeV: 440 MHz



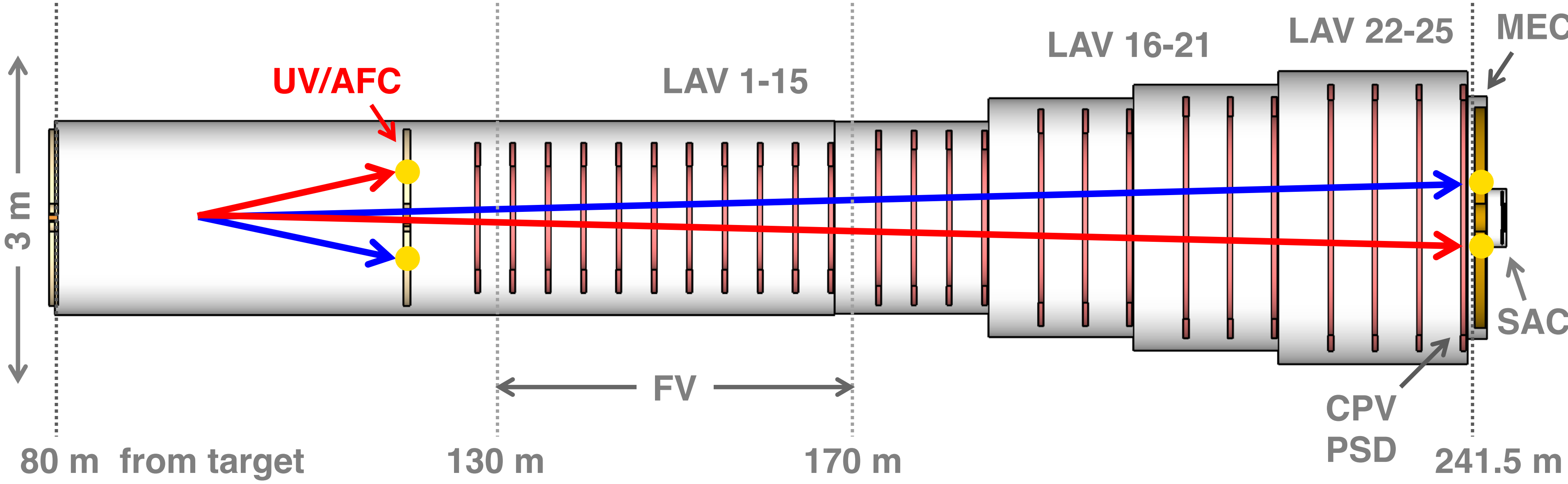
Photons in beam

$E > 5$ GeV: 50 MHz

$E > 30$ GeV: 2.5 MHz

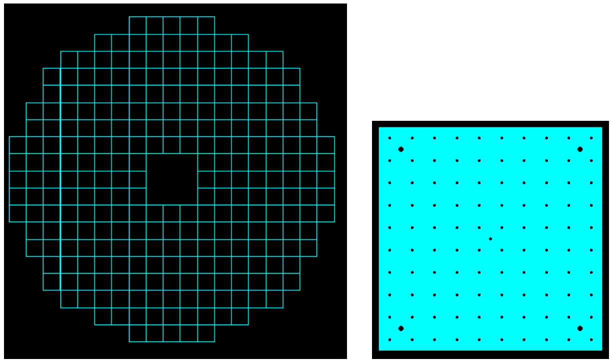
Effect of γ converter

Vetoes for upstream $K_L \rightarrow \pi^0\pi^0$

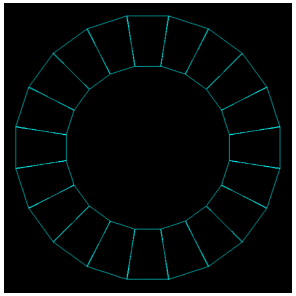


Upstream veto (UV):

- 10 cm < r < 1 m:
- Shashlyk calorimeter modules à la PANDA/KOPIO, like MEC



Active final collimator:



- 4.2 < r < 10 cm
- LYSO collar counter
- 80 cm long
- Internal collimating surfaces

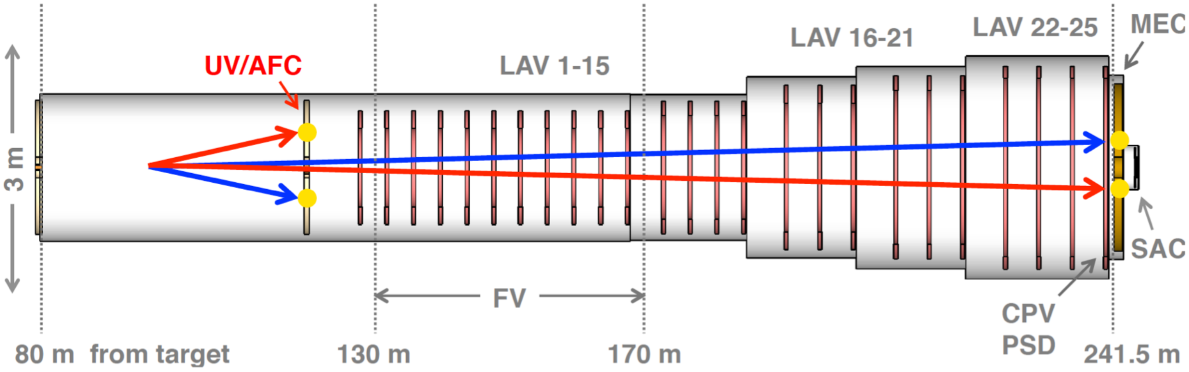
- Intercepts halo particles from scattering on upstream collimators or γ absorber

  Rejects π^0s from inelastic interactions
- Rejects $K_L \rightarrow \pi^0\pi^0$ in transit through collimator

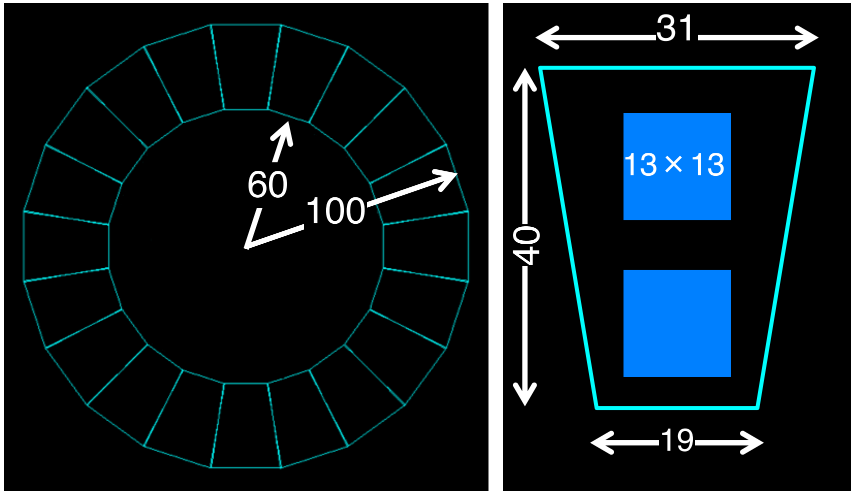
Active final collimator

- Intercepts halo particles from scattering on upstream collimators or γ absorber

  Rejects π^0s from inelastic interactions
- Rejects $K_L \to \pi^0\pi^0$ in transit through collimator



Design in progress:



- 60 mm $< r <$ 100 mm
- 80 cm long (3-4 consecutive rings)
- 20-24 crystals per ring

LYSO collar counter with internal collimating surfaces

- Fast (40 ns), bright (~ NaI), radiation hard (>10^6 Gy)

Crystals read out on back side with APDs

- Good coupling with LYSO and high quantum efficiency
- Simple signal and HV management
- E.g. RMD S1315 (13x13 mm^2)

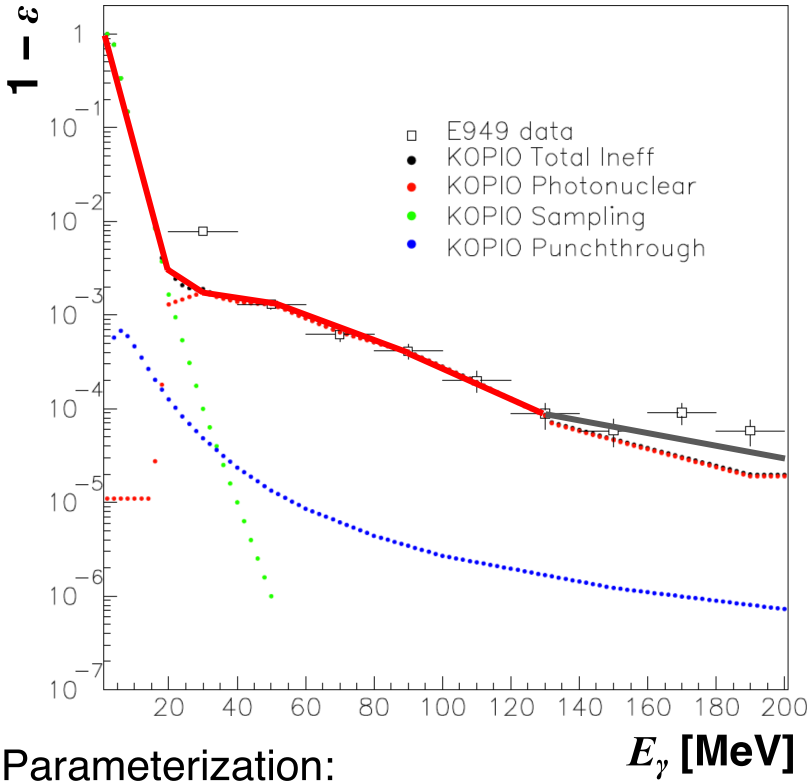
Expected light yield > 4000 p.e./MeV

Large-angle photon vetoes

25 new LAV detectors providing hermetic coverage out to 100 mrad
Need good detection efficiency at low energy ($1 - \varepsilon \sim 0.5\%$ at 20 MeV)

Baseline technology: CKM VVS
Scintillating tile with WLS readout

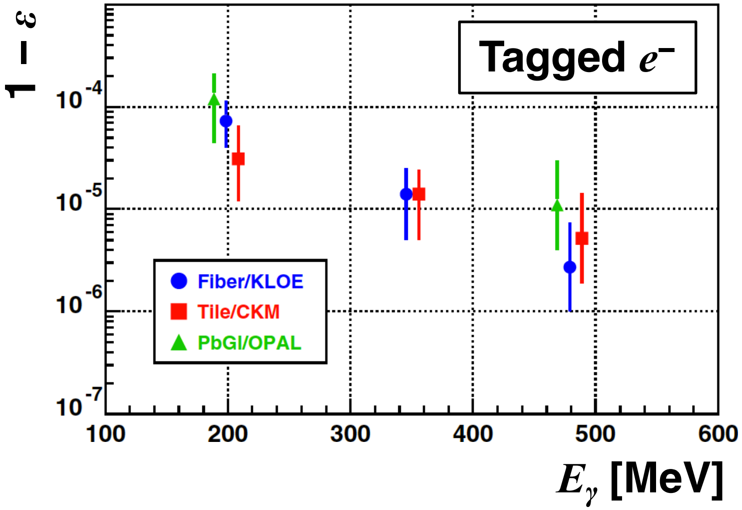
Good efficiency assumptions based on E949 and CKM VVS experience



Parameterization:
1-129 MeV: KOPIO (E949 barrel)
203-483 MeV: CKM VVS

E949 barrel veto efficiencies
Same construction as CKM

Tests for NA62 at Frascati BTF



Tests at JLAB for CKM:

- $1 - \varepsilon \sim 3 \times 10^{-6}$ at 1200 MeV

Large-angle vetoes

Time resolution for current LAVs ~ 1 ns

- Cerenkov light is directional
- Complicated paths to PMT with multiple reflections

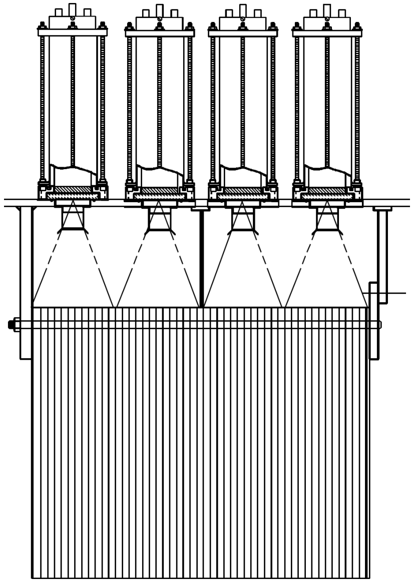
CKM Vacuum Veto System (VVS)

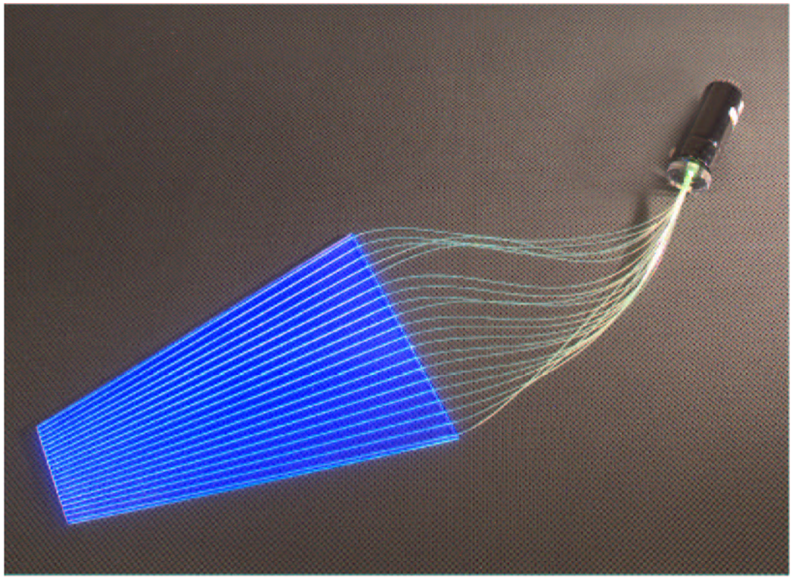
- Pb/scintillating tile
- 1 mm Pb + 5 mm scint
  $f_{\text{em}} \sim 36\%$
- WLS fiber readout

Light read out with PMTs in original design

$Y \sim 20$ p.e./MeV
cf NA62 ~ 0.3 p.e./MeV

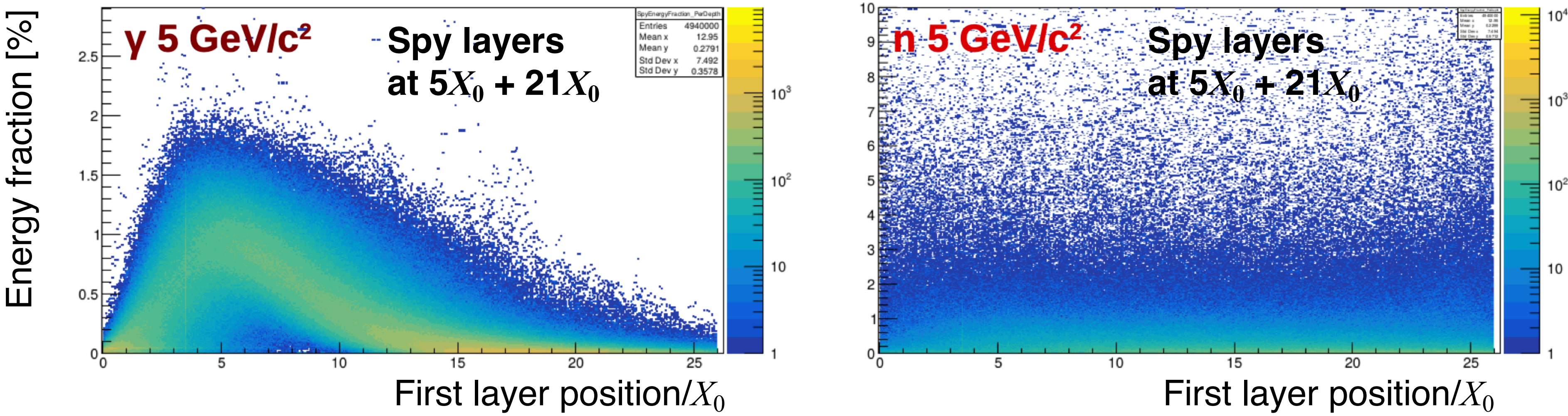
Modify design to use SiPM arrays

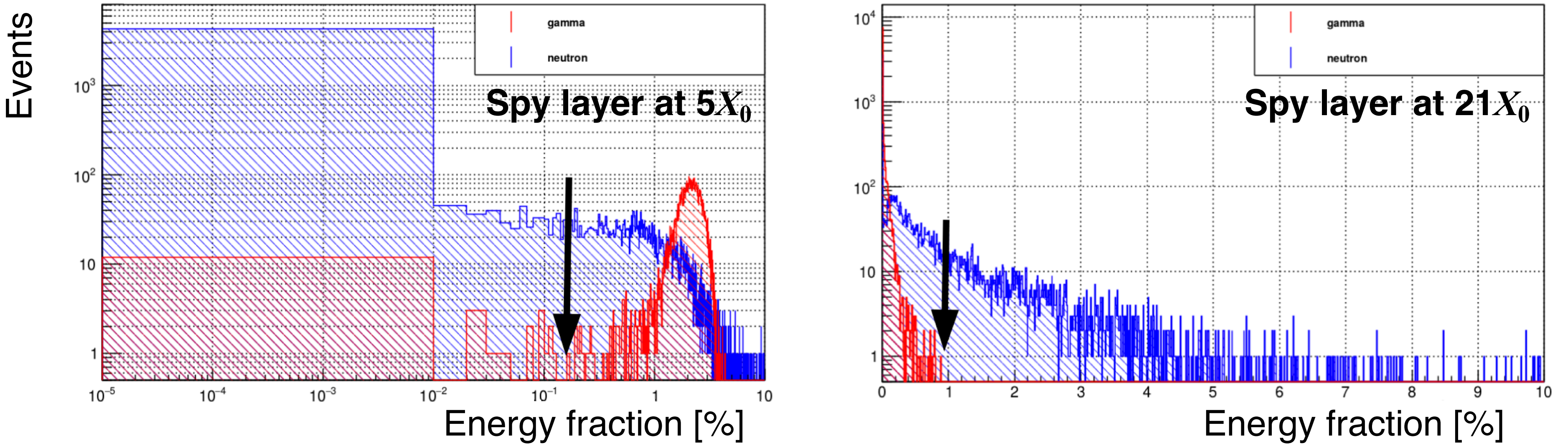




Simulation of γ/n separation

Energy fraction in spy group = energy deposited in spy tiles/deposited in shashlyk



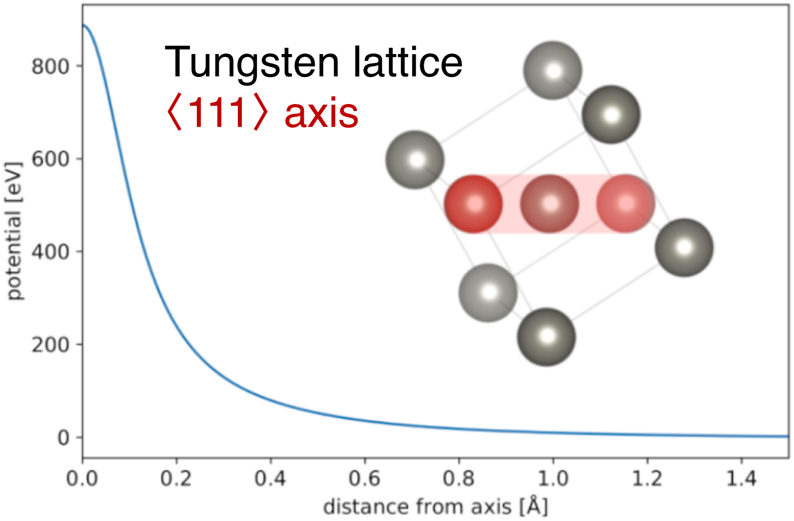


Information from spy tiles provides {
- 5-10x improvement in neutron rejection
- Overall neutron rejection at level of 10^3

Coherent effects in crystals

Coherent effects increase cross-section for electromagnetic shower processes (bremsstrahlung, pair production)

- **Decrease effective value of X_0**
- **Exploit coherent effects for calorimetry?**

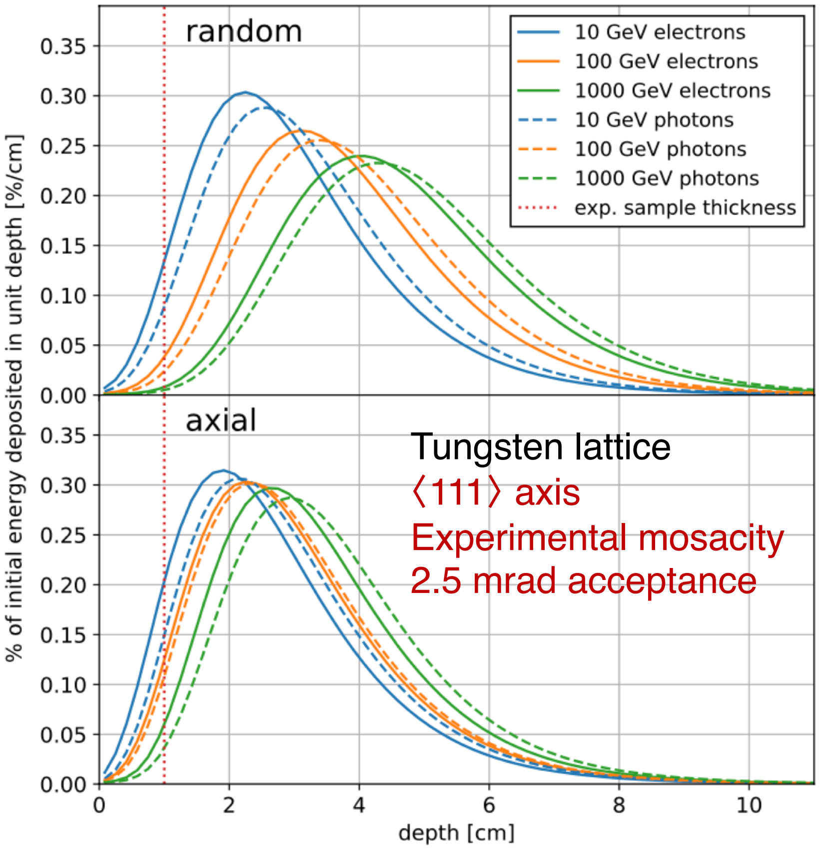


Coherent superposition of Coulomb fields

Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

Effective field $\varepsilon' = \gamma_{\text{eff}}$ ($\gamma_{\text{eff}} = E/m_e c$)

For $\varepsilon' \sim \varepsilon_0 = 2\pi m^2 c^3/eh$ virtual pairs disassociate



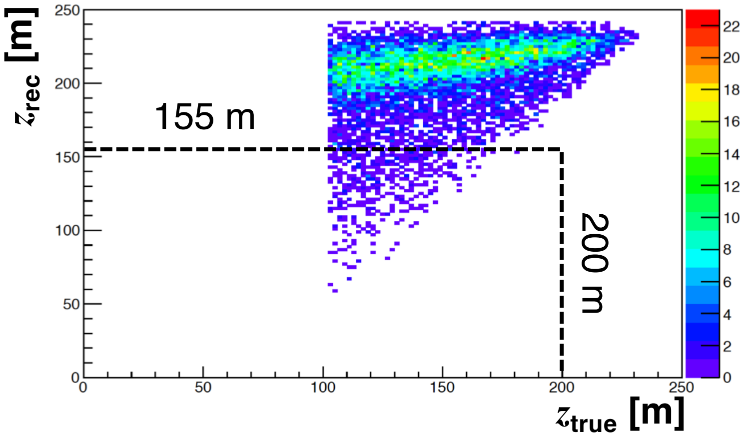
- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

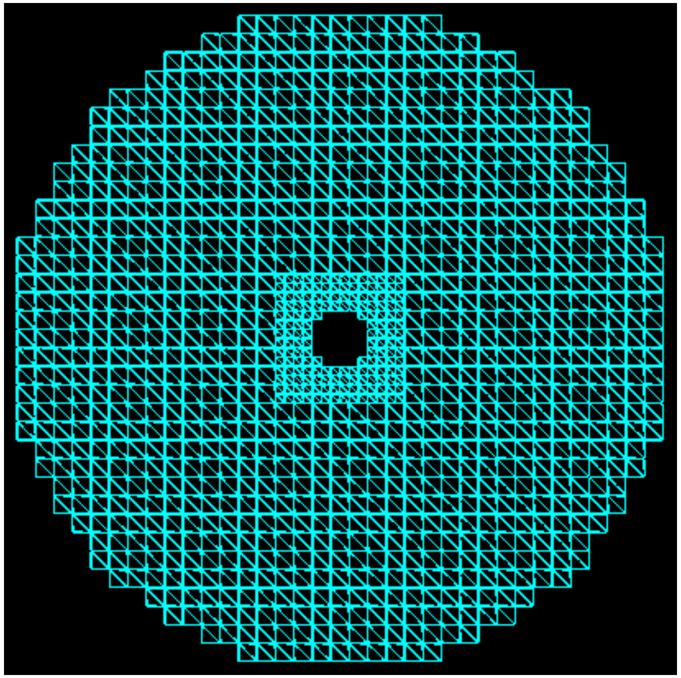
Pair production enhanced by coherent effects at small θ_γ and high E_γ

Charged particle veto

$K_L \to \pi e \nu$ can emulate signal when both π and e deposit energy in MEC

- Fake π^0 vertexes from πe all reconstructed downstream of true decay
  - π^+ deposits only a fraction of its energy
- K_{e3} decays with "π^0" reconstructed in FV have $z_{\text{rec}} < 200$ m
  - All within the acceptance of the CPV





Baseline CPV design

Square scintillator tiles, 5-mm thick, supported on carbon fiber membrane

- 2 planes → 3% X_0

Tile geometry: 4x4 cm^2 or 8x8 cm^2

- Smaller tiles near beam line
- Cracks staggered between planes
- 4 chamfered corners (45°) for direct SiPM coupling

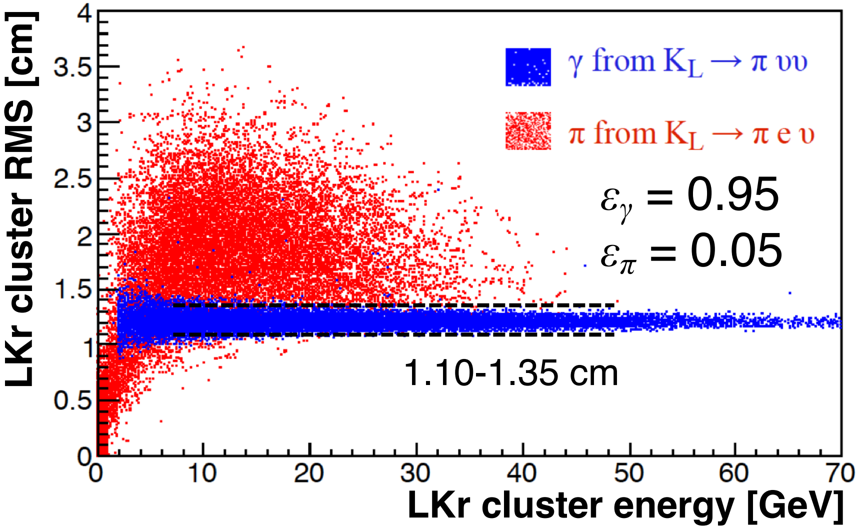
Charged particle rejection

$K_L \to \pi e \nu$ can emulate signal when both π and e deposit energy in LKr

Use cluster RMS in LKr to identify and reject π interactions

- Geant4 confirmed by preliminary analysis of $\pi\pi^0$ events in NA62 data:
  $\varepsilon_\gamma = 0.95$
  $\varepsilon_\pi = 0.05$

If LKr replaced by shashlyk, longitudinal shower profile information also available

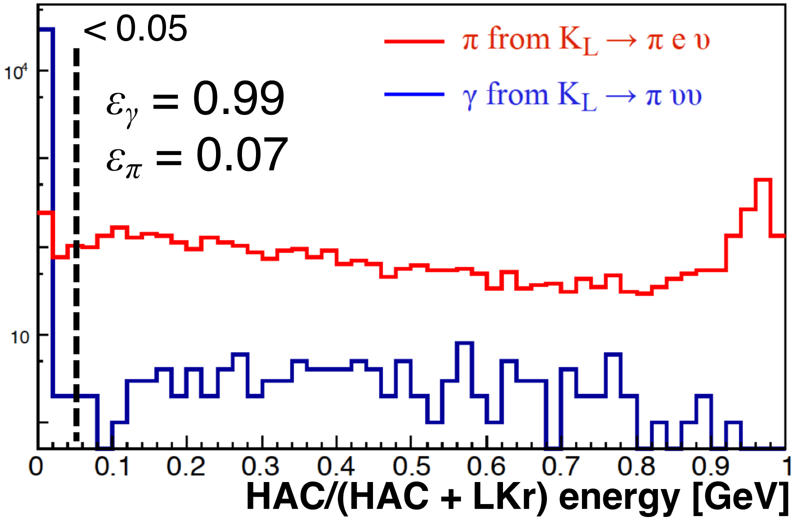


Ratio of hadronic/total energy effective to identify π showers

- Preliminary results based on Geant4:
  $\varepsilon_\gamma = 0.99$
  $\varepsilon_\pi = 0.07$

Study of HAC (MUV1/2) response in NA62 data in progress

- Parameterization of response for inclusion in fast simulation



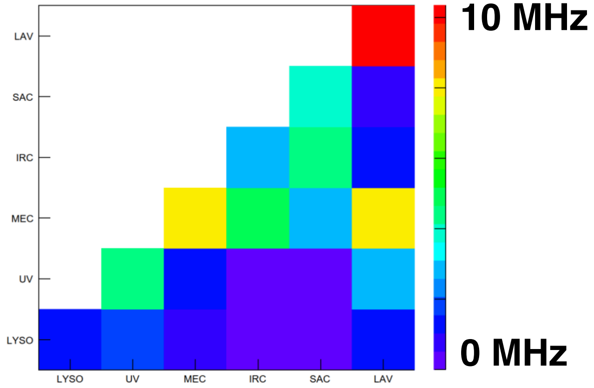
Trigger and veto rate simulations

Detector rates estimated with full FLUKA 120-m beamline simulation and idealized detector geometry

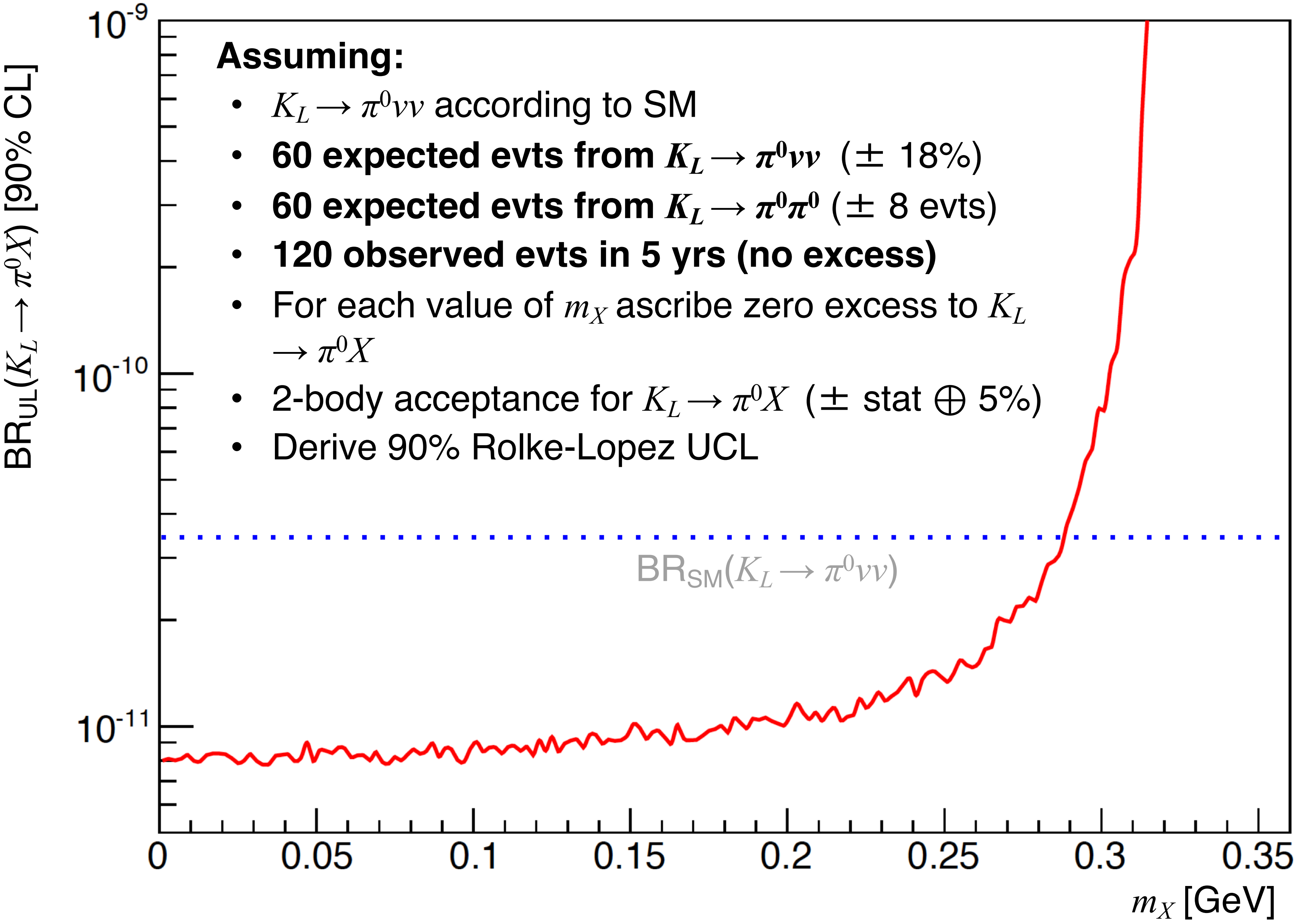
Event class	Rate [MHz]
Trigger rates	
Exactly 2 hits on MEC	4.8
Exactly 2 γ on MEC	1.0
Exactly 2 hits on MEC, no hits on UV or LAVs	3.1
Exactly 2γ on MEC, nothing else	0.007
Accidental rates	
Single hit	104
Multi hit	30

Detector	Hit rate [MHz]
AFC	2.3
UV	7.1
LAV	14
MEC	18
IRC	22
SAC	95

Simultaneous detector rates



Limits on $K_L \to \pi^0 X$ from $K_L \to \pi^0 \nu\bar{\nu}$



Assuming:

- $K_L \to \pi^0 \nu\nu$ according to SM
- **60 expected evts from $K_L \to \pi^0 \nu\nu$** (± 18%)
- **60 expected evts from $K_L \to \pi^0 \pi^0$** (± 8 evts)
- **120 observed evts in 5 yrs (no excess)**
- For each value of m_X ascribe zero excess to $K_L \to \pi^0 X$
- 2-body acceptance for $K_L \to \pi^0 X$ (± stat $\oplus$ 5%)
- Derive 90% Rolke-Lopez UCL