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An experiment to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) at the CERN SPS

First Forum on Rare Kaon Decays
University of Edinburgh, 22 February 2018

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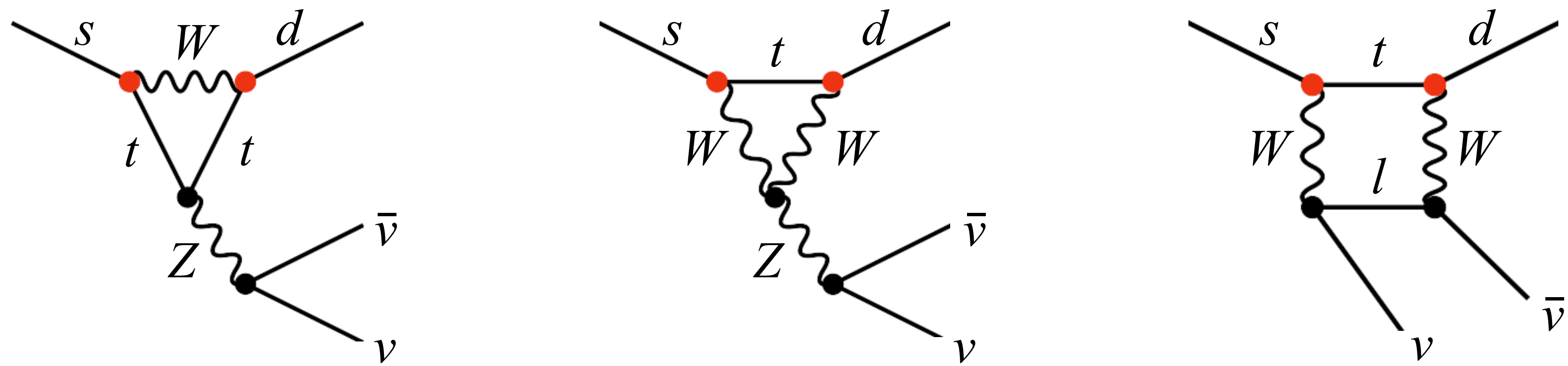
For the KLEVER project

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

FCNC processes dominated by Z-penguin and box amplitudes:



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**
$K^+ \to \pi^+\nu\bar{\nu}$	**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 < 2600 × 10^{-11} 90%CL** KEK 391a, PRD81 (2010)

* Tree-level determinations of CKM matrix elements

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

Dominant uncertainties for SM BRs are from CKM matrix elements

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

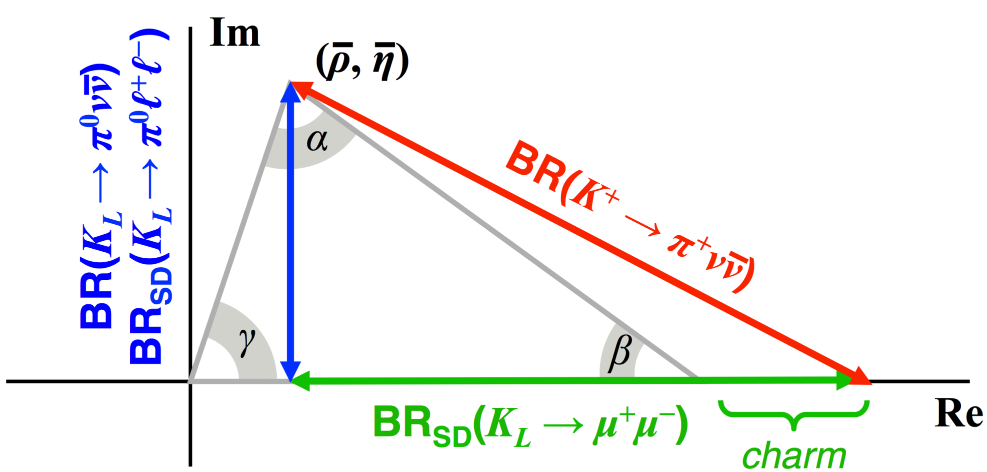
Buras et al., JHEP 1511

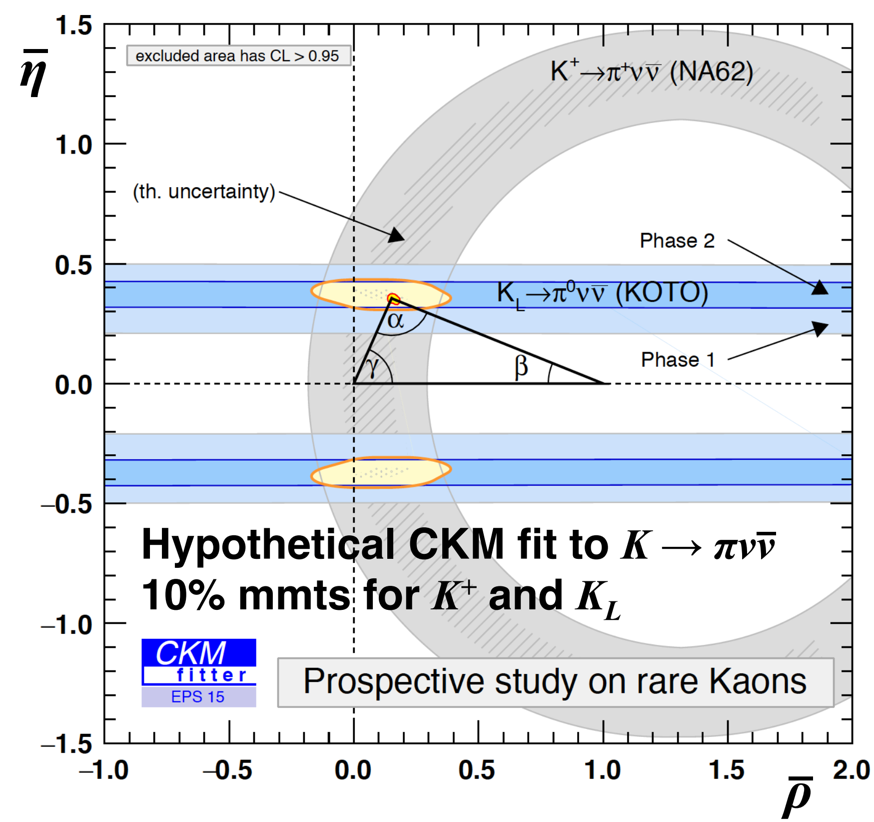
$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

Intrinsic theory uncertainties ~ few percent

Measuring both K^+ and K_L BRs can determine the unitarity triangle independently from B inputs

- Overconstrain CKM matrix → reveal NP?





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

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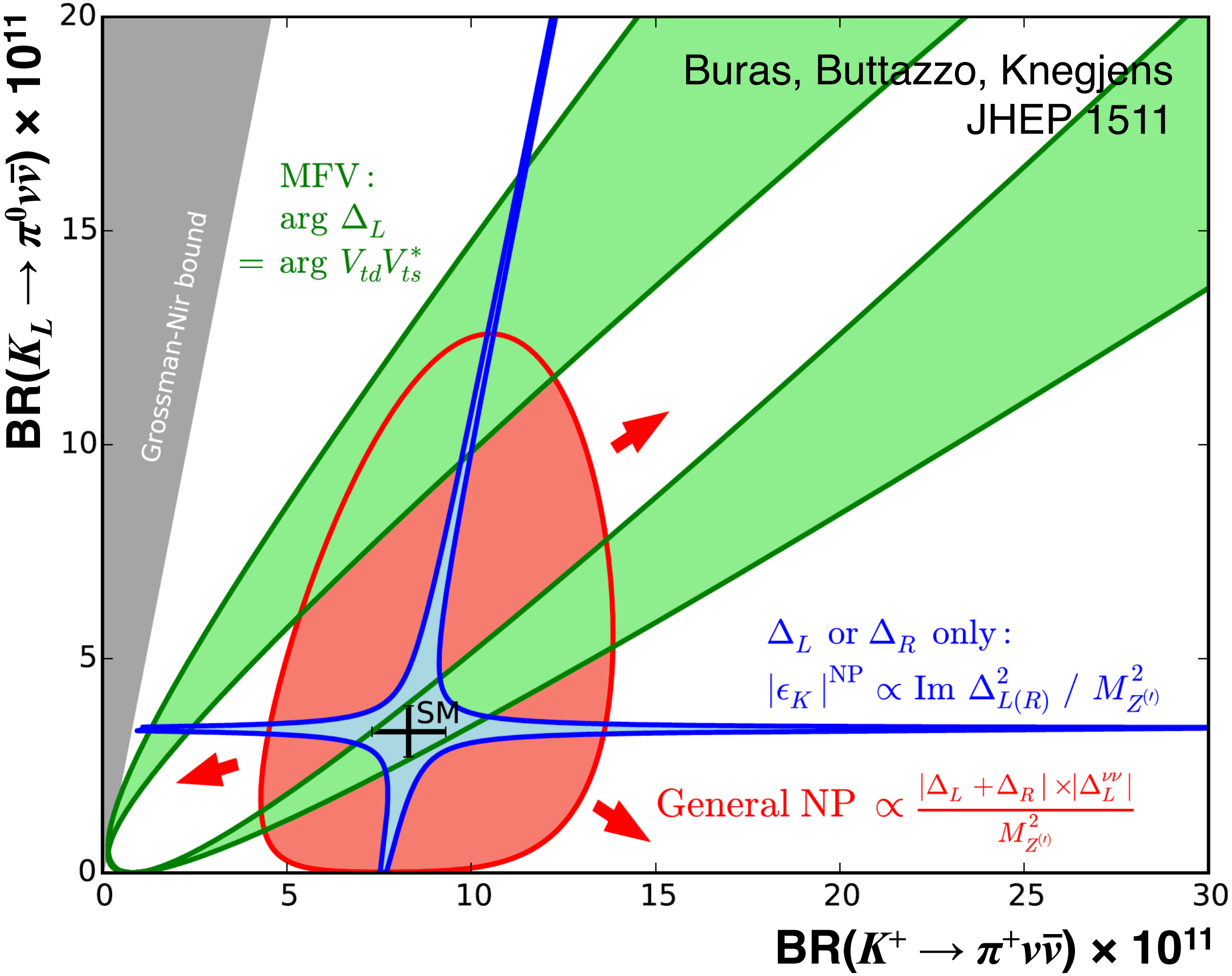
New physics affects BRs differently for K^+ and K_L channels

Measurements of both can discriminate among NP scenarios



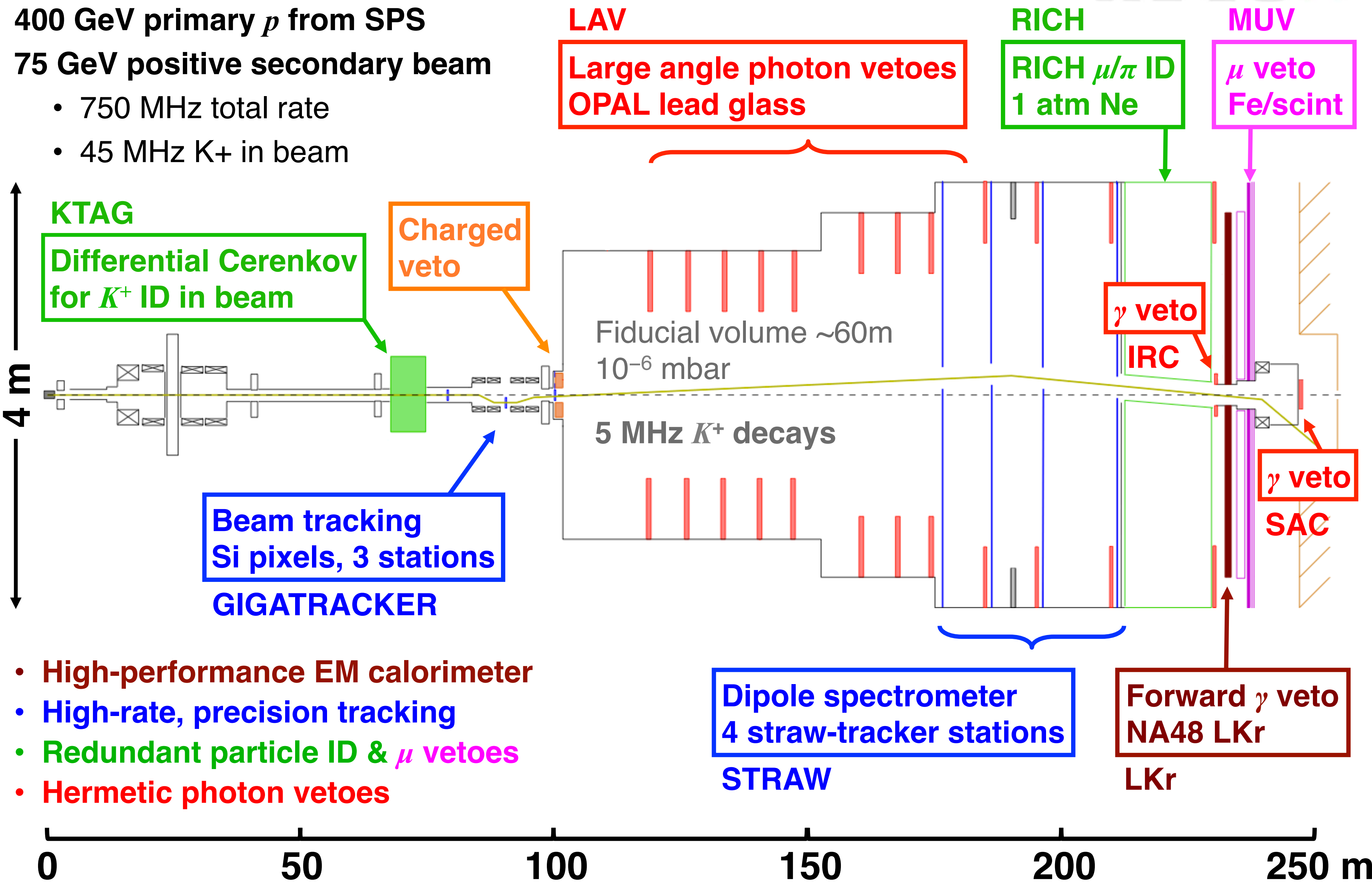
- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum

The NA62 experiment at the SPS

400 GeV primary p from SPS

75 GeV positive secondary beam

- 750 MHz total rate
- 45 MHz K+ in beam



- **High-performance EM calorimeter**
- **High-rate, precision tracking**
- **Redundant particle ID & μ vetoes**
- **Hermetic photon vetoes**

NA62 status and timeline

2014-2015	Pilot/commissioning runs
2016	Commissioning + 1st physics run SM sensitivity reached: BR ~ O(10^{-10})
2017	Physics run Will improve on current knowledge of BR($K^+ \to \pi^+\nu\nu$)
2018	31 weeks of data taking, starting 9 April
2019-2020	LS2 (Long Shutdown 2)

- **Assuming running is as smooth as in 2017, by the end of 2018 NA62 will reach a sensitivity of 20-30 SM $K^+ \to \pi^+\nu\nu$ events**
- Results from full 2016 data set will be presented in spring 2018
- Processing of 2017 data in progress

Fixed target runs at the SPS

2021 (Run 3):
- Continue data taking for $K^+ \rightarrow \pi^+ \nu\nu$
  O(100) SM events – measure BR to 10%
- Searches for hidden particles in beam-dump mode
  Dark photons, ALPs, heavy neutrinos, scalars…

2026 (Run 4): Turn focus to measurement of BR($K_L \rightarrow \pi^0 \nu\nu$) ➜ KLEVER

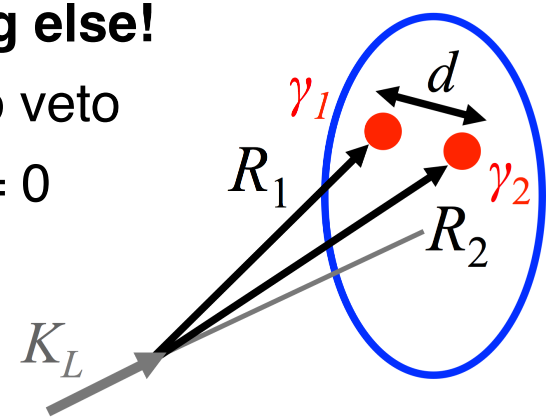
F. Bordry, presentation to HEPAP, Dec 2015

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

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

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

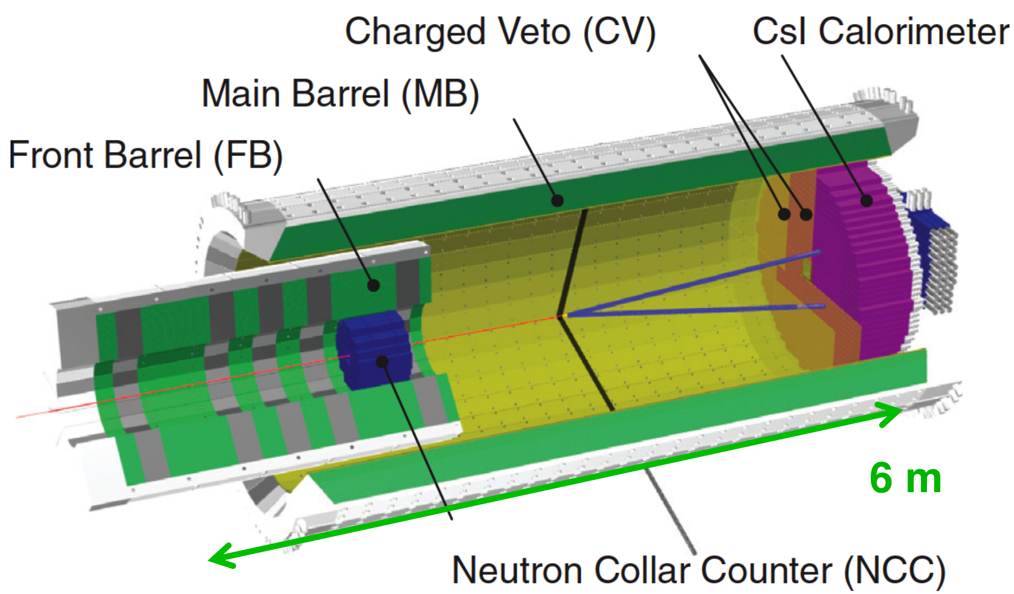
Main backgrounds:

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 + gas $\to X\pi^0$		High vacuum decay region

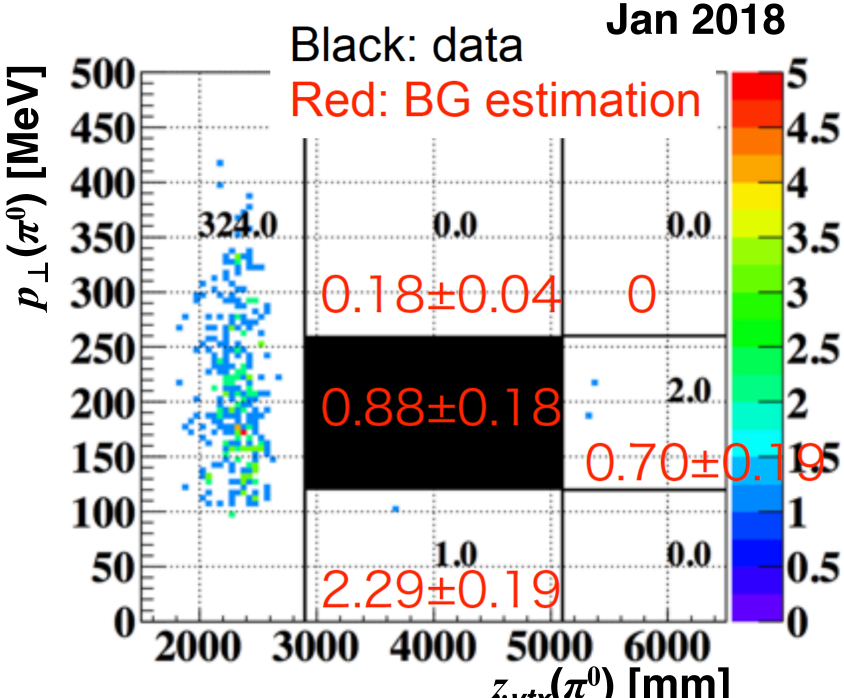
$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC

Primary beam: 30 GeV p
100 kW = 1.2 × 10^{14} p/6 s

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



J-PARC PAC
Jan 2018



- Preliminary results, all 2015 data:
  SES = 1.2 × 10^{-9}
  Expected bkg = 0.9 ± 0.2 events
  Signal box not yet unblinded
  Background still under study
- **Expect to reach SM sensitivity by 2021**
- Strong intention to upgrade to O(100) event sensitivity over long term, but no official Step 2 proposal yet

A $K_L \to \pi^0 \nu\nu$ experiment at the SPS?

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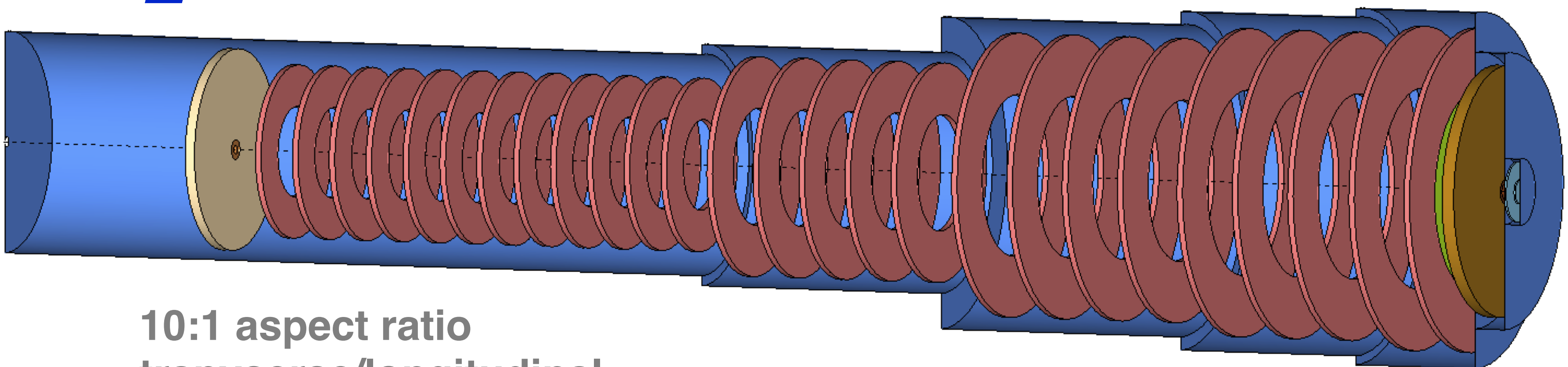
K_L Experiment for VEry Rare events

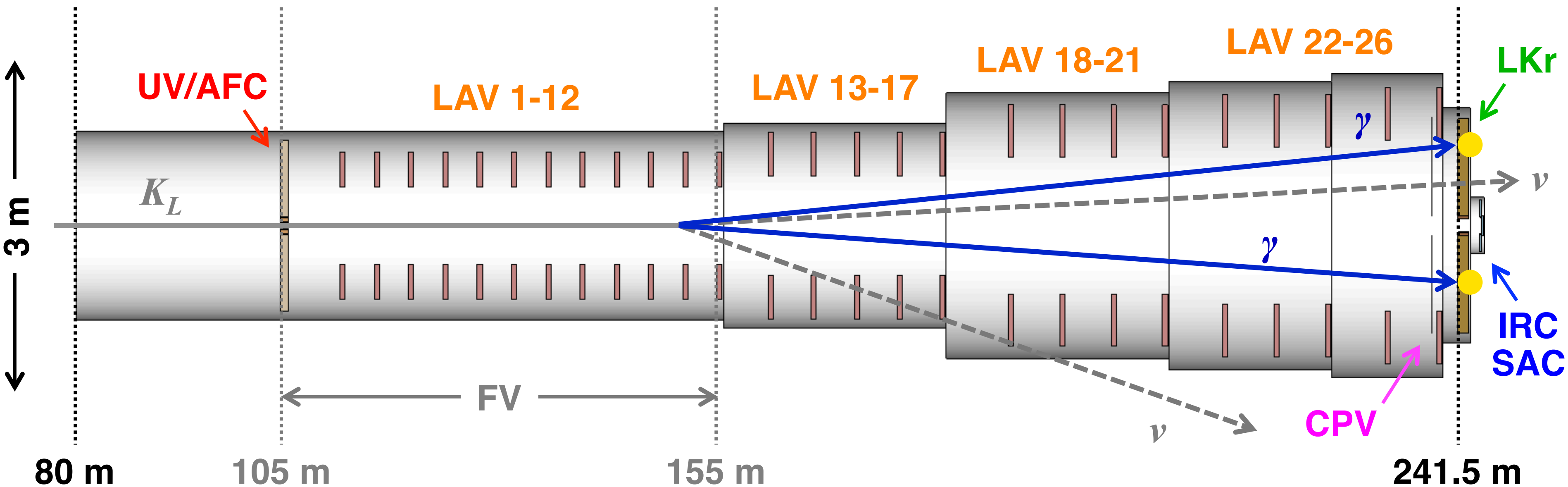


10:1 aspect ratio
tranvserse/longitudinal

Interesting features:

- High-energy experiment: Complementary approach 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
- Possible to re-use LKr calorimeter, NA62 experimental infrastructure?

An experiment to measure $K_L \to \pi^0 \nu\bar{\nu}$ KLEVER



Main detector/veto systems:

UV/AFC	Upstream veto/active final collimator
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 liquid krypton calorimeter
IRC/SAC	Small-angle vetoes
CPV	Charged particle veto

Required intensity for $K_L \to \pi^0 \nu\bar{\nu}$

Assumptions:

- BR($K_L \to \pi^0 \nu\bar{\nu}$) = 3.4×10^{-11}
- Acceptance for decays occurring in FV ~ 10%

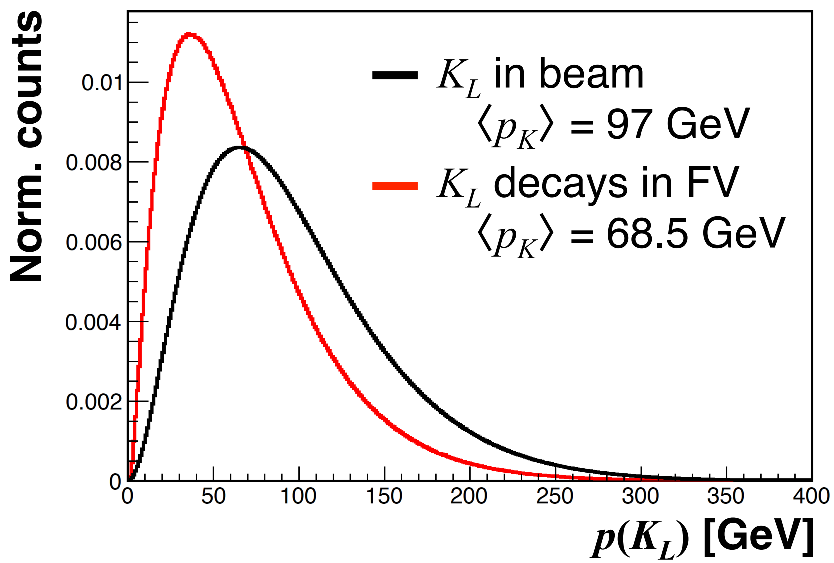
→ **3×10^{13} K_L decay in FV for 100 signal evts**

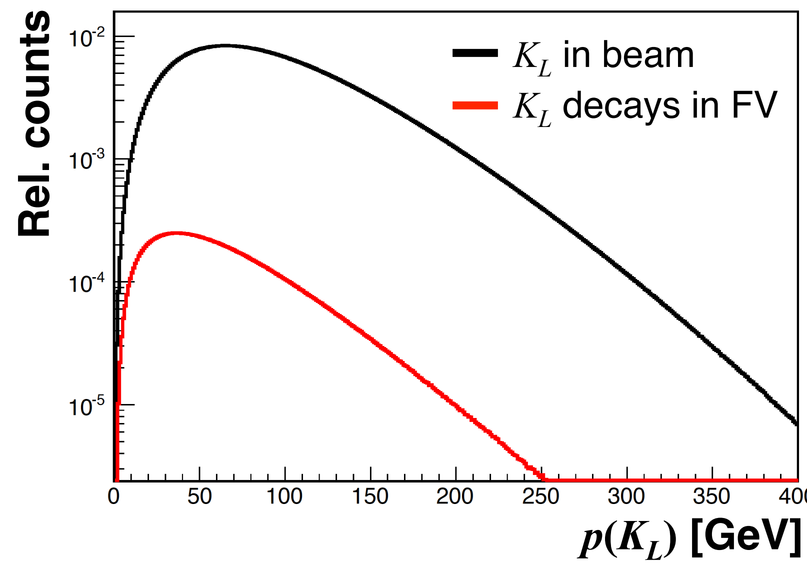
Beam parameters:

- **400 GeV p on 400 mm Be target**
- Production at **2.4 mrad** to optimize (K_L in FV)/n

→ **2.8×10^{-5} K_L in beam/pot**

Probability for decay inside FV **~ 2%**





Required total proton flux = 5×10^{19} pot

10^{19} pot/year (= 100 eff. days)
E.g.: 2×10^{13} ppp/16.8 s

Feasibility of intensity upgrade

2×10^{13} p/16.8 s = 6× increase in intensity relative to NA62

Tight neutral beam collimation

Longer K_L lifetime ($\tau_L/\tau_+ \sim 5$)

Max. intensity from SPS to North Area (TT20): 4×10^{13} ppp

Must be divided among users: T2 + T4 + T6

2×10^{13} ppp not currently available on any North Area target

Target area and transfer lines will require upgrades

- Minimization of consequences of beam loss
- Additional shielding against continuous small losses
- Study issues of equipment survival, e.g., TAX motors
- Ventilation, zone segmentation, etc.

Detailed solutions and meaningful cost estimates are under study by the CERN Accelerator & Technology Sector

We are collaborating through the Physics Beyond Colliders Conventional Beam Working Group to better define available intensity & related issues

Neutral beamline layout (2.4 mrad)

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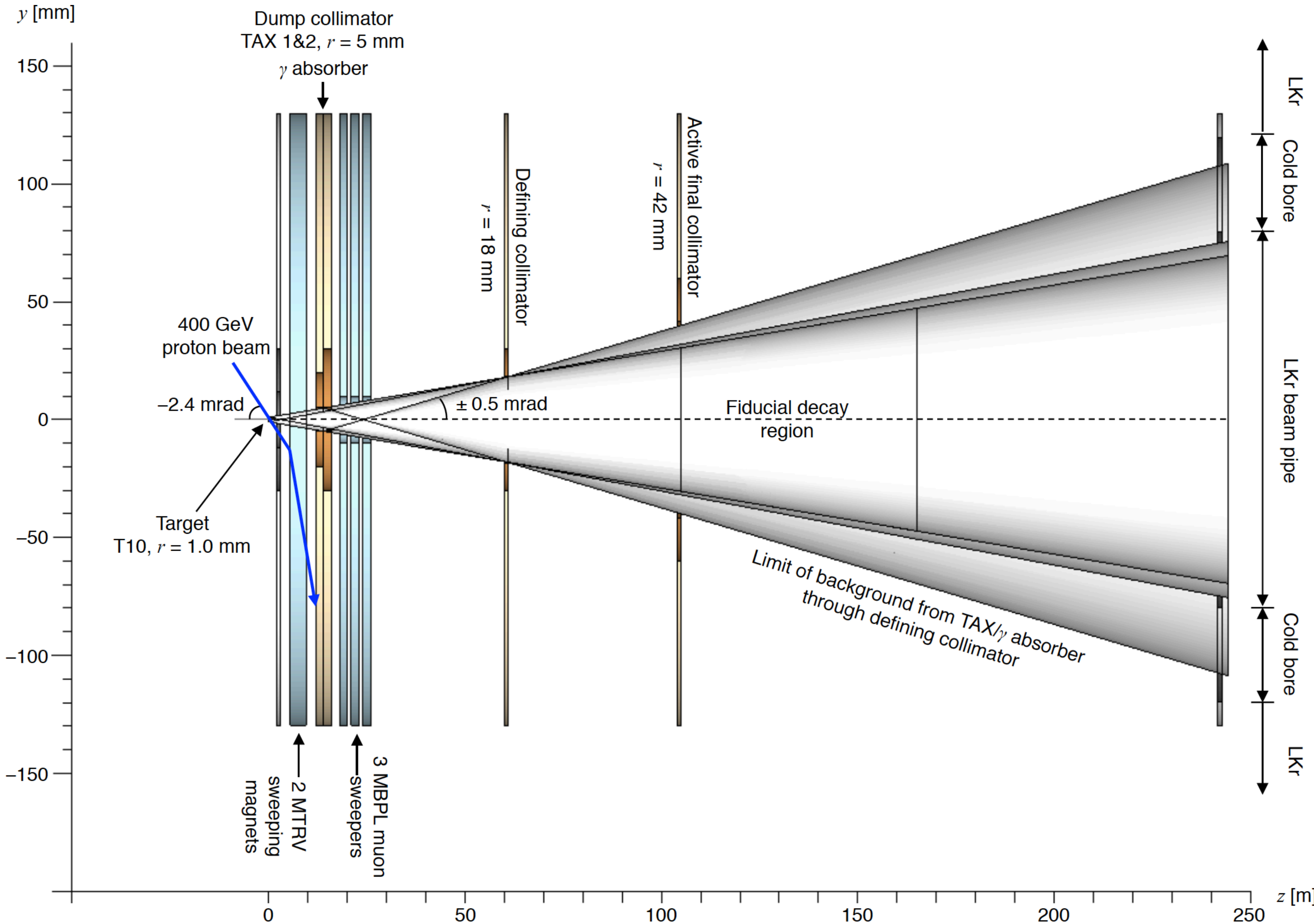
400-mm Be rod target, r = 1 mm
Production at θ = 2.4 mrad

3 collimation stages: $\Delta\theta$ = 0.3 mrad
Total length of beamline + experiment = 250 m



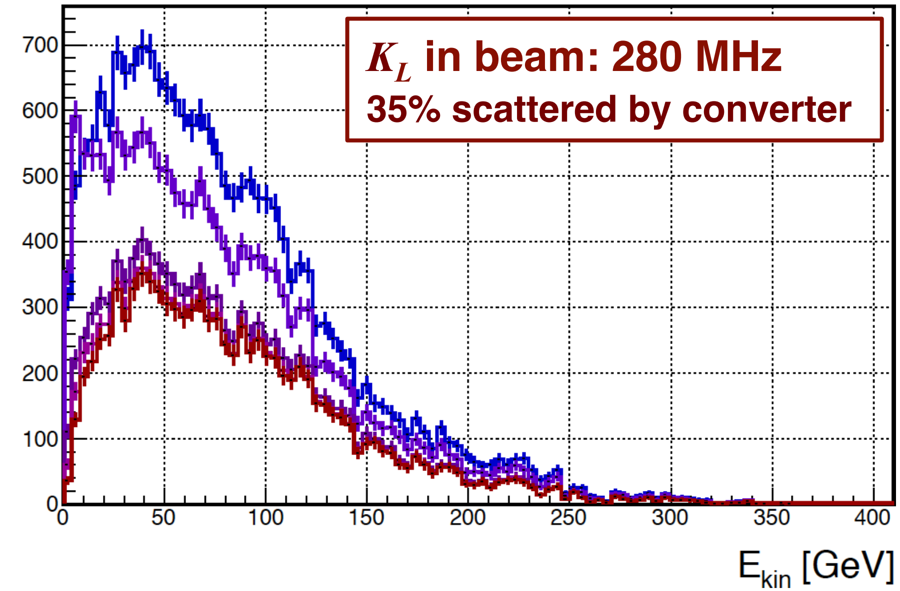
Neutral beam simulation

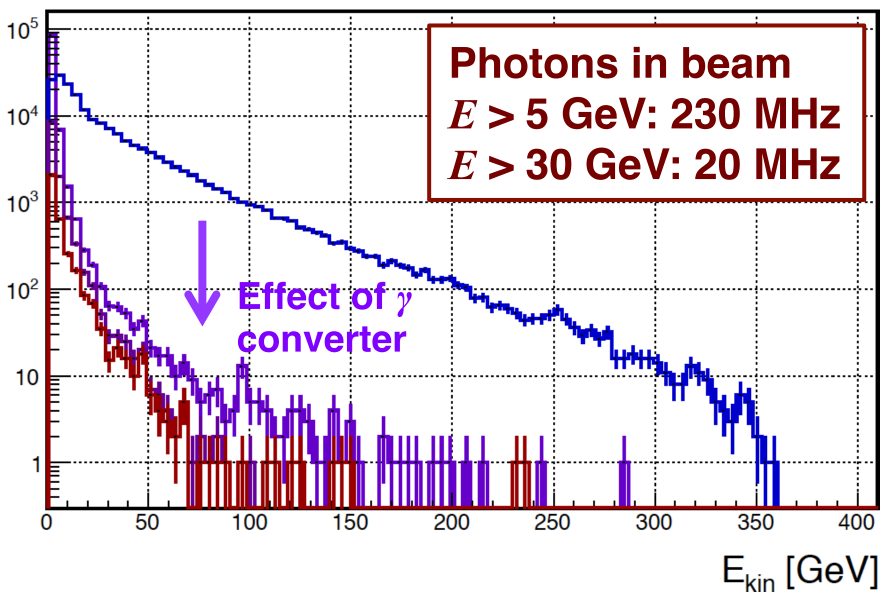
FLUKA simulation of 400 GeV p on 400-mm Be target

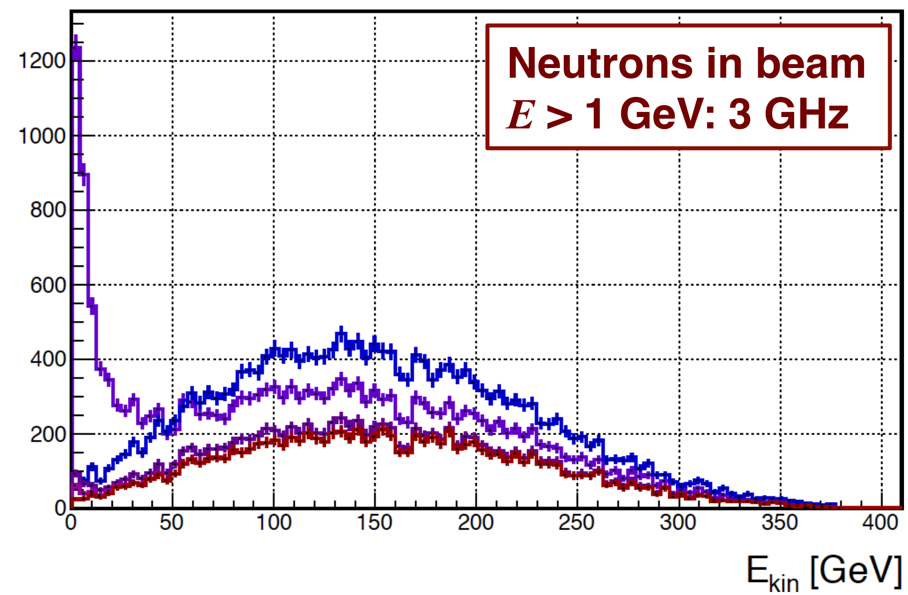
Geant4 simulation of beamline

- 3 collimators, $\Delta\theta = 0.3$ mrad
- 30-mm Ir photon converter in dump collimator

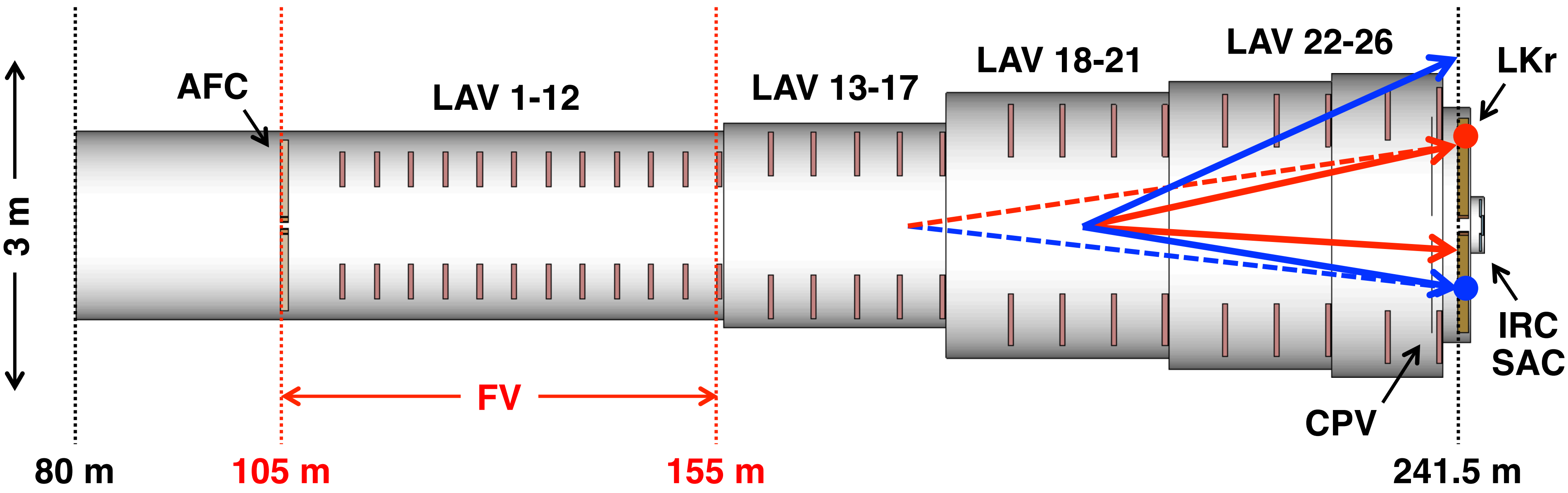
gen
After absorber
After dump collimator
After defining collimator
After final collimator







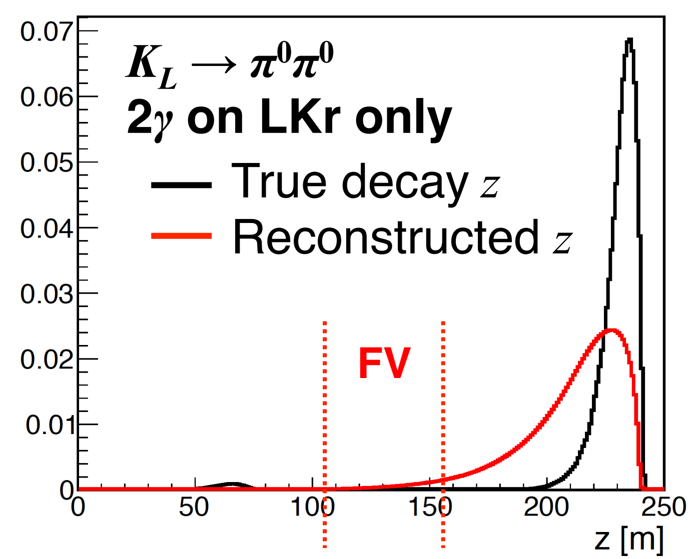
Detector layout for $K_L \to \pi^0 \nu\bar{\nu}$



Vacuum tank layout and FV similar to NA62

90-m distance from FV to LKr significantly helps background rejection

- Most $K_L \to \pi^0\pi^0$ decays with lost photons occur just upstream of the LKr
- "π^0s" from mispaired γs are mainly reconstructed downstream of FV



Suitability of LKr calorimeter

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Study and confirm LKr performance with NA62 data

- Photon detection efficiency
- Two-cluster separation

In parallel with efforts by NA62

Explore possibilities to improve time resolution with faster readout

- Signal π^0 candidates all have $E_{\gamma\gamma} > 20$ GeV

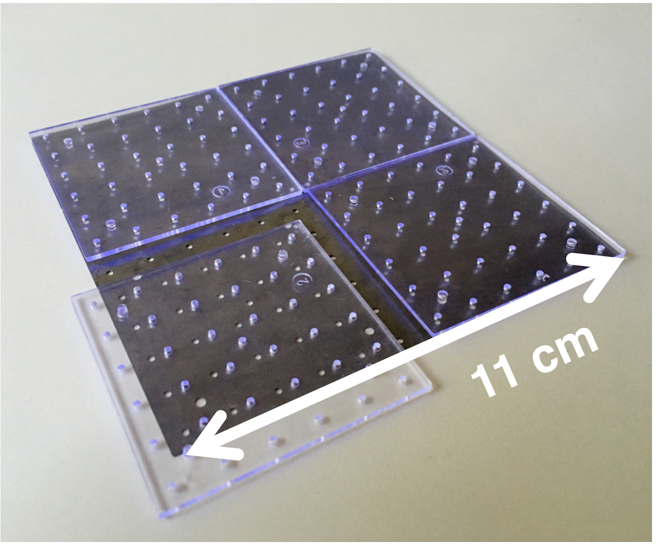
  $\sigma_t = 2.5$ ns/$\sqrt{E}$ (GeV) → 500 ps or better
- Needs improvement – SAC may have ~100 MHz accidental rate
- Simulating readout upgrades to estimate effect on time resolution:

  Shorter shaping time, faster FADCs

Evaluate long-term reliability of LKr (2018 → 2030):

- Identify support systems needing replacement or upgrade
- Effect of dead cells, prospects for repair

Shashlyk-based alternatives to LKr



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

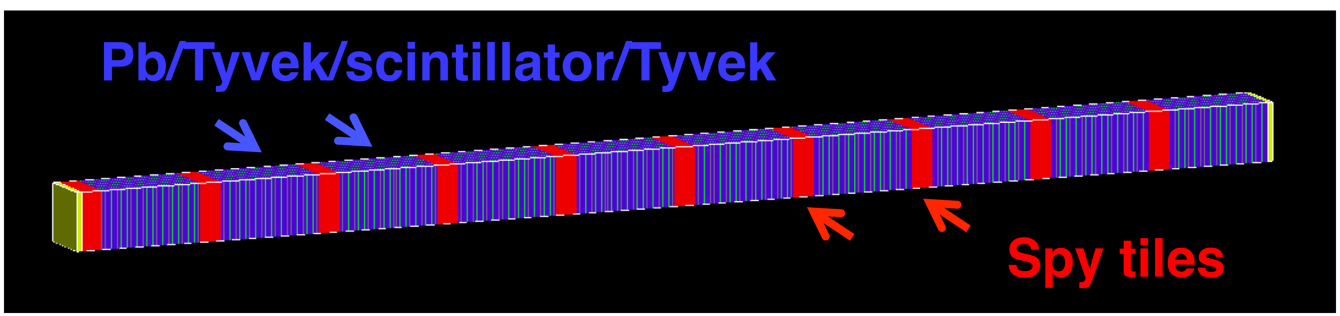
0.275 mm Pb + 1.5 mm scintillator

$\boldsymbol{\sigma_E/\sqrt{E}}$ **~ 3%** $/\sqrt{E}$ (GeV)
$\boldsymbol{\sigma_t}$ **~ 72 ps** $/\sqrt{E}$ (GeV)
$\boldsymbol{\sigma_x}$ **~ 13 mm** $/\sqrt{E}$ (GeV)

PANDA, KOPIO prototypes

New for KLEVER: Longitudinal shower information from spy tiles

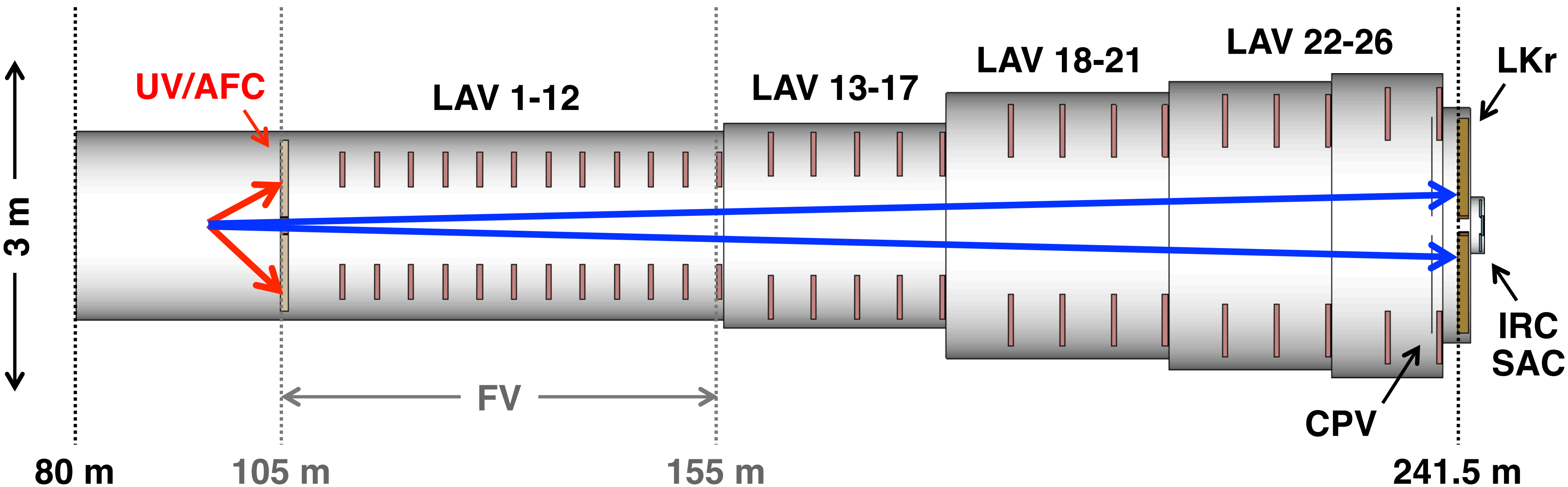
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



Thicker spy tiles (5-20 mm) with independent WLS fiber readout

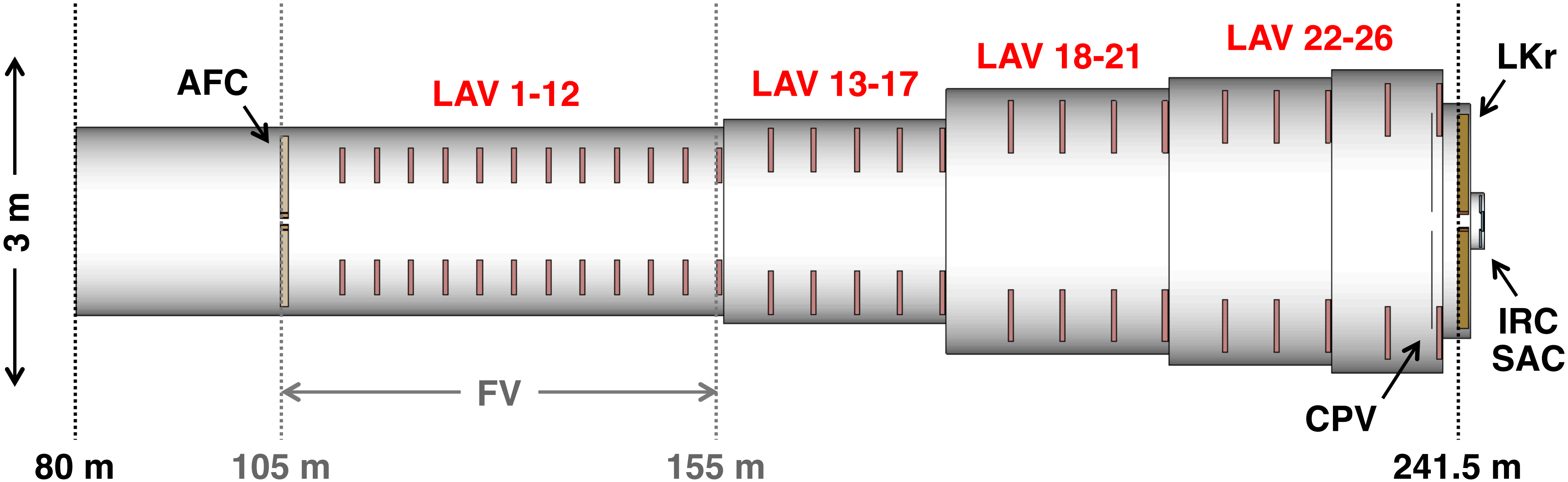
Simulation studies in progress (e.g., to choose spy tile thickness)

Vetoes for upstream K_L decays



- **25 m of vacuum upstream of final collimator**
  No obstruction for γs from decays with 80 m < z < 105 m
- **Upstream veto (UV):**
  Outer ring: Shashlyk calorimeter, lead/scintillator in 1:5 ratio
  10 cm < r < 1 m → 1/3 of total rate
- **Active final collimator (AFC):**
  Inner ring: LYSO collar counter, 80 cm deep, shaped crystals
  4.2 cm < r < 10 cm → 2/3 of total rate

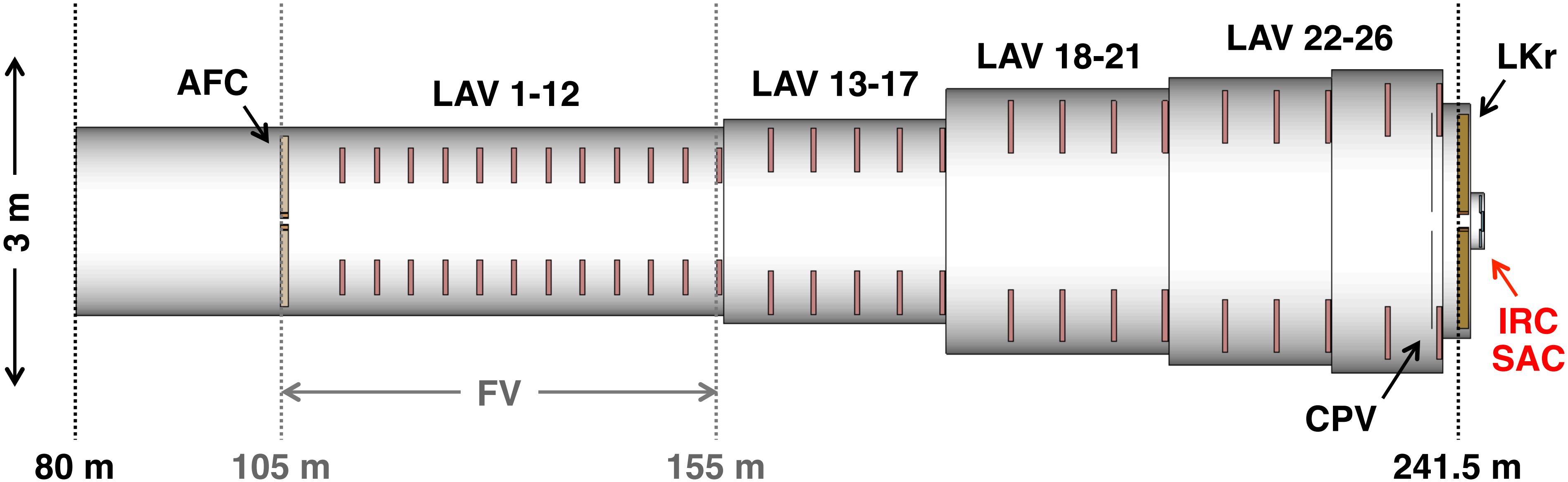
Large-angle photon vetoes



26 new large-angle photon veto stations (LAV)

- 5 sizes, sensitive radius 0.9 to 1.6 m, at intervals of 4 to 6 m
- Hermetic coverage out to 100 mrad for E_γ down to ~100 MeV
- Baseline technology: Lead/scintillator tile with WLS readout
  Based on design of CKM VVS
  Assumed efficiency based on E949 and CKM VVS experience

Small-angle photon vetoes



Small-angle photon veto systems (IRC, SAC)

- Reject high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 3 GHz of beam neutrons

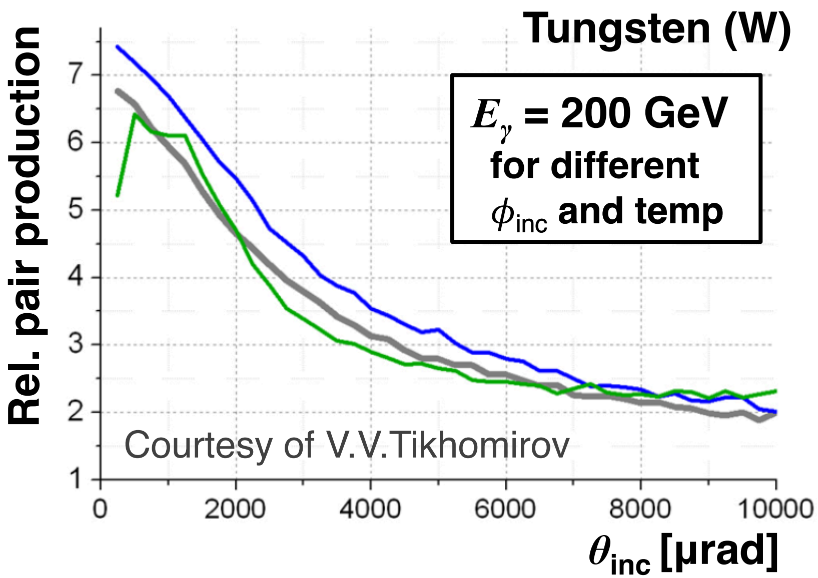
Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
γ, $E > 5$ GeV	**230**	**10^{-2}**
γ, $E > 30$ GeV	**20**	**10^{-4}**
n	**3000**	**–**

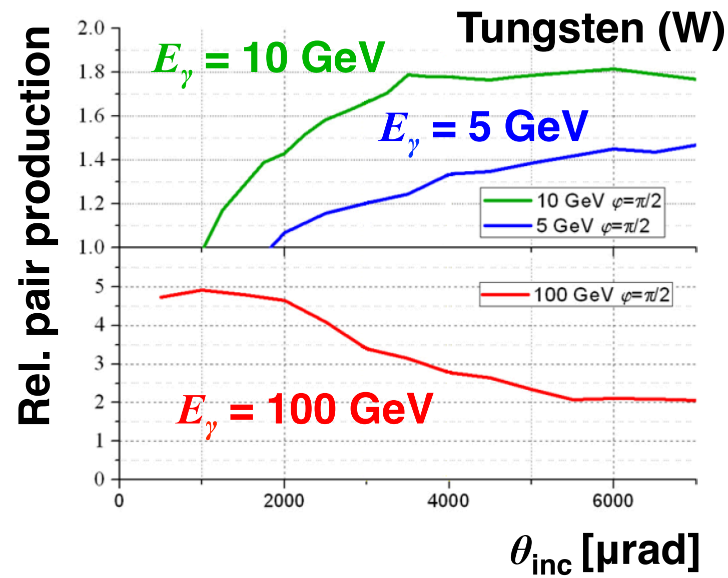
Baseline solution:

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber

Efficient γ conversion with crystals

Coherent effects in crystals enhance pair-conversion probability





Use coherent effects to obtain a converter with large effective λ_{int}/X_0:

1. **Beam photon converter in dump collimator**
   Effective at converting beam γs while relatively transparent to K_L
2. **Absorber material for small-angle calorimeter (SAC)**
   Must be insensitive as possible to ~GHz of beam neutrons while efficiently vetoing high-energy γs from K_L decays

Beam test of $\gamma \rightarrow e^+e^-$ in crystals

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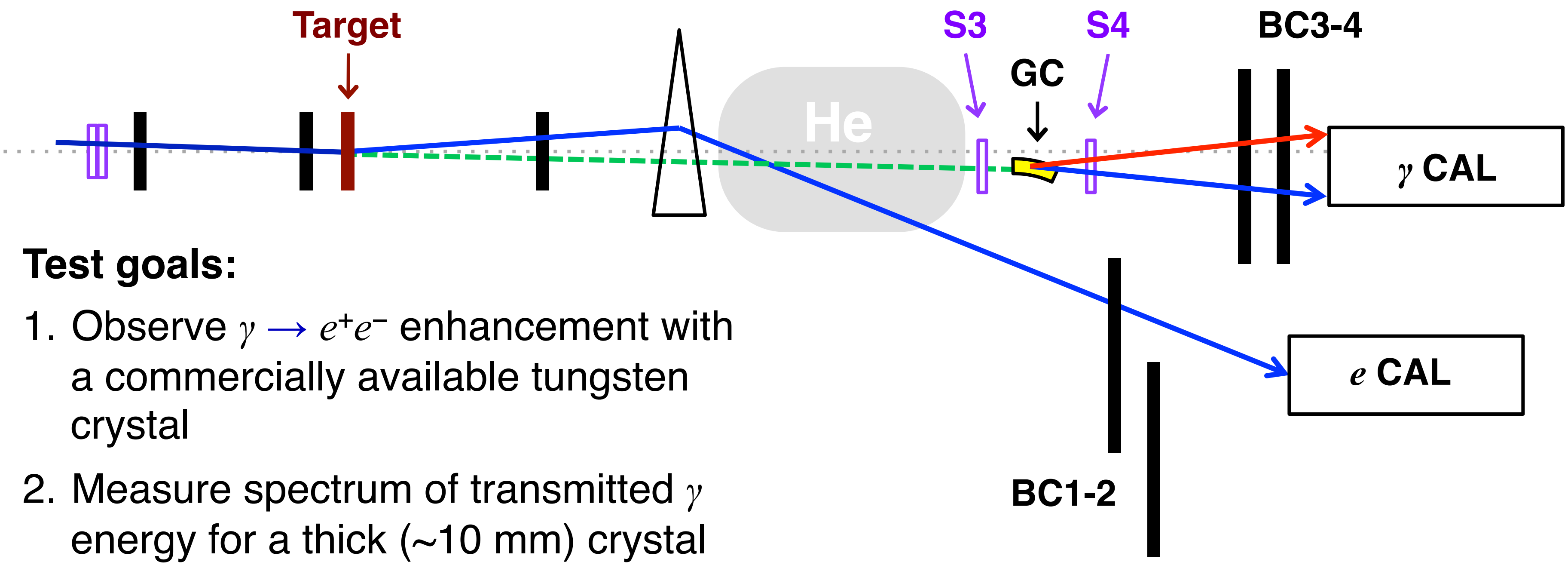
AXIAL group is collaborating with KLEVER on test beam measurement of pair-production enhancement in crystals

Tagged photon test beam setup:

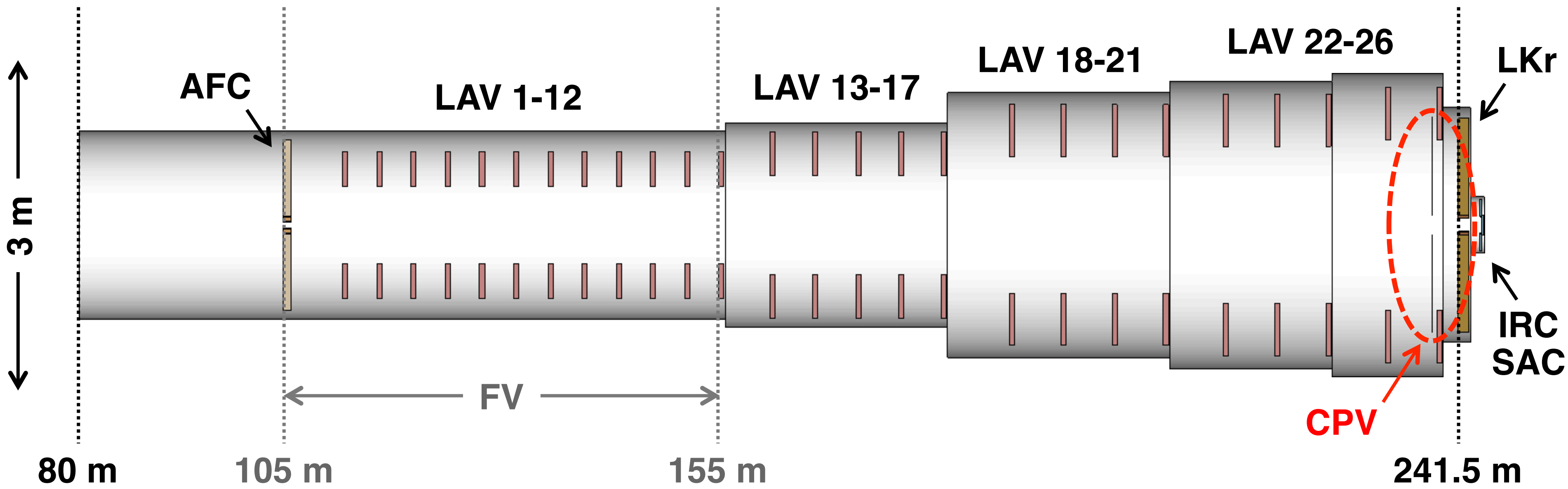


Test goals:

1. Observe $\gamma \rightarrow e^+e^-$ enhancement with a commercially available tungsten crystal
2. Measure spectrum of transmitted γ energy for a thick (~10 mm) crystal
3. Measure pair conversion vs. E_γ, θ_{inc} for $5 < E_\gamma < 150$ GeV
4. Obtain information to assist MC development for beam photon converter and SAC

- **Nearly all detectors and DAQ system available for use from AXIAL**
- **1 week of beam H2 beam time in August 2018**

Charged particle rejection



Most dangerous mode: K_{e3}

- BR = 40%
- Easy to mistake $e \leftrightarrow \gamma$ in LKr
- Acceptance $\pi^0 \nu\nu / K_{e3}$ = 30

➜ Need 10^{-9} suppression!

Charged particle veto (CPV)

- Scintillating tiles, just upstream of LKr

Calorimetric ID for μ and π

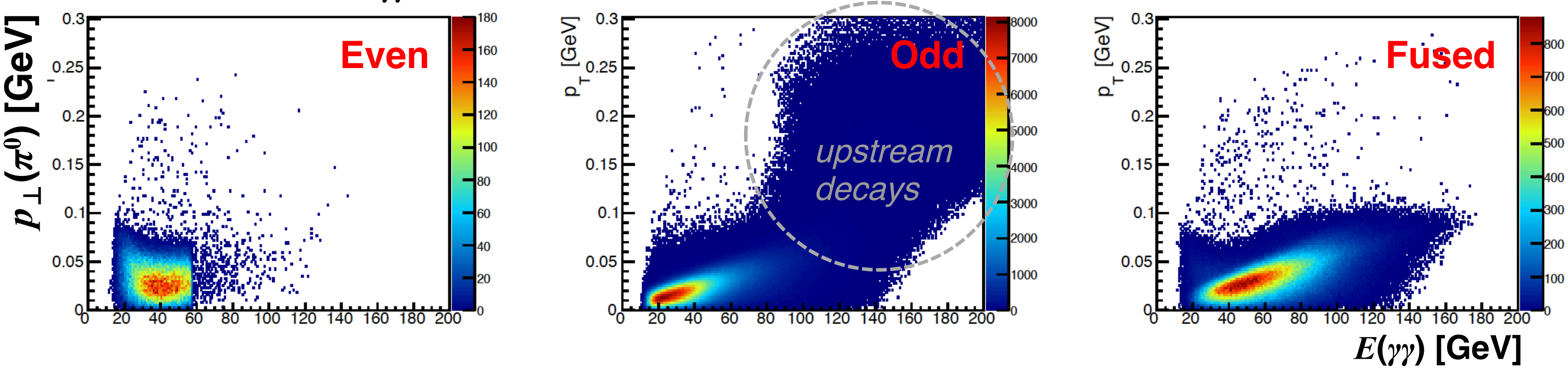
- Shower profile in LKr
- Re-use NA62 hadronic calorimeters MUV1/2 (not shown), downstream of LKr

$K_L \to \pi^0\pi^0$ rejection

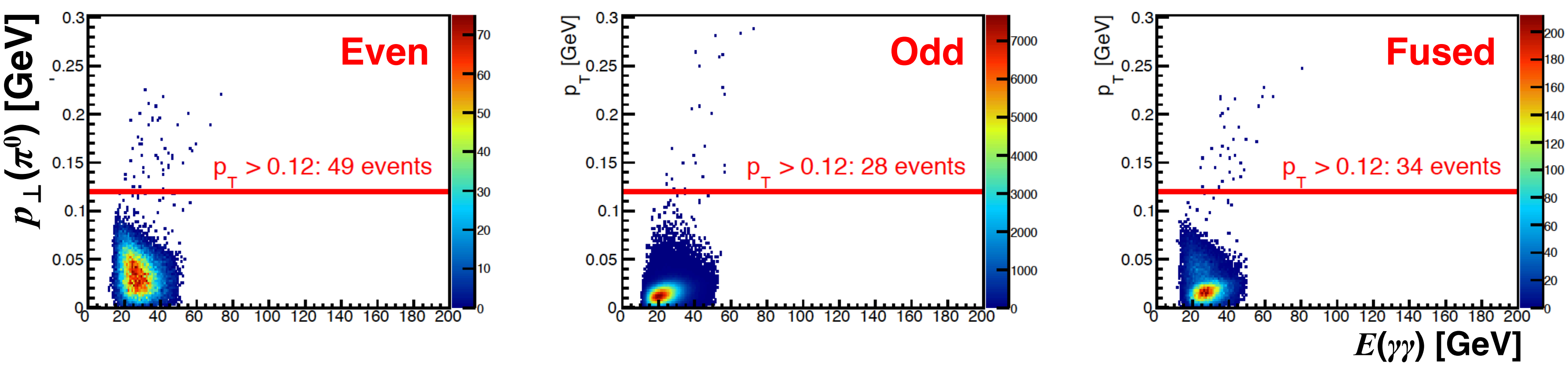
$K_L \to \pi^0\pi^0$ simulated with fast MC (5 yr equivalent statistics)

- Accept only events with 2 γs in LKr and no hits in AFC, LAV, IRC/SAC
- Distinguish between even/odd pairs and events with fused clusters

1. Require $z_{\text{rec}}(m_{\gamma\gamma} = m_{\pi 0})$ in fiducial volume (105 m < z < 155 m)



2. Require r_{min} > 35 cm on LKr and $p_\perp(\pi^0)$ > 0.12 GeV



22 $\pi^0\pi^0$ evts/year About 50% with 1γ with 100 < θ < 400 mrad, E < 50 MeV

$K_L \to \pi^0 \nu\bar{\nu}$ acceptance

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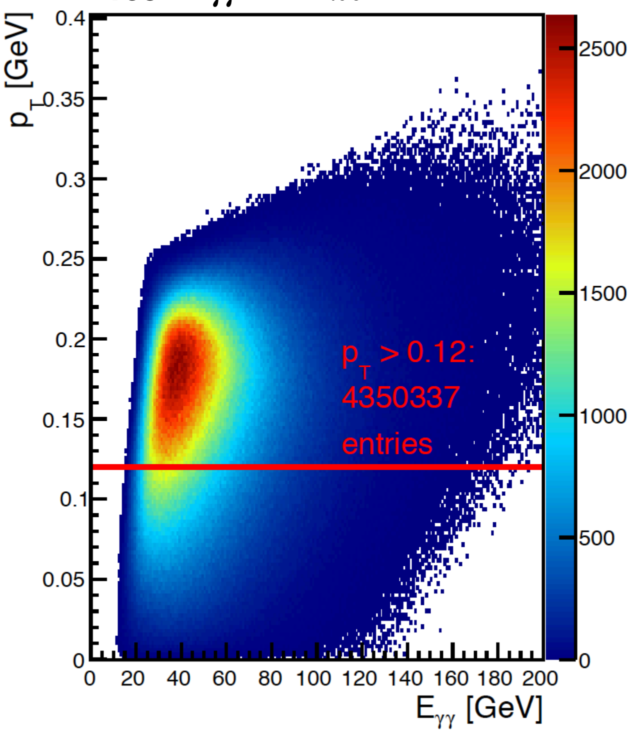
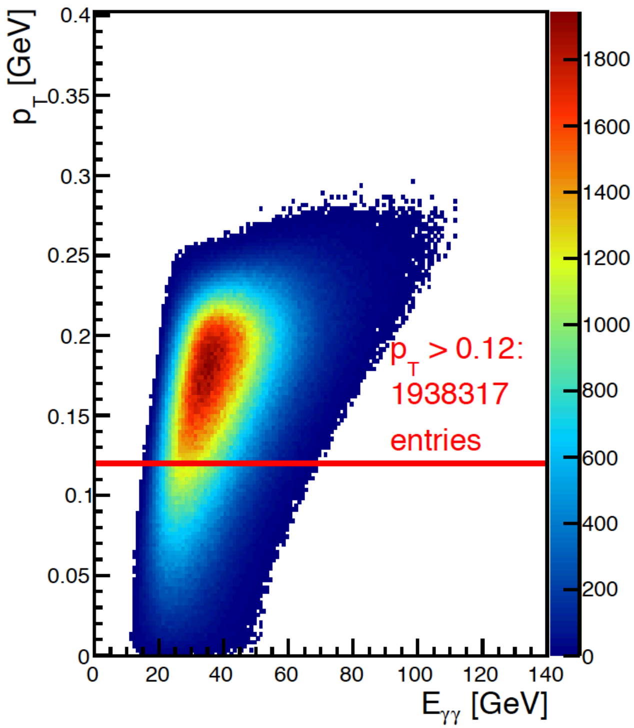
Cut stage	Cut eff.	Cuml. eff.
$K_L \to \pi^0 \nu\bar{\nu}$ evts with 2γ on LKr	2.0%	2.0%
$z_{\rm rec}(m_{\gamma\gamma} = m_{\pi 0})$ in FV	31%	0.62%
$r_{\rm min} > 35$ cm on LKr	42%	0.26%
$p_\perp(\pi^0) > 0.12$ GeV	78%	0.20%

Alternatively:
- 2.2% K_L decay in FV
- 27% $\pi^0 \nu\bar{\nu}$ with 2γ on LKr

$z_{\rm rec}(m_{\gamma\gamma} = m_{\pi 0})$ in FV



$r_{\rm min}$ and $p_\perp(\pi^0)$ cuts



With:
- 10^{19} pot/year
- 2.8×10^{-5} K_L/pot
- BR = 3.4×10^{-11}
- $\varepsilon_{\rm total}$ = 0.20%

19.4 $\pi^0 \nu\bar{\nu}$ evts/year

excluding transmission losses from γ converter

$K_L \to \pi^0 \nu\bar{\nu}$ sensitivity summary

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Channel	Simulated statistics	Events found	Expected in 5 yrs*
$K_L \to \pi^0 \nu\bar{\nu}$	100k yr	1.94M	**97**
$K_L \to \pi^0\pi^0$	5 yr	111	**111**
$K_L \to \pi^0\pi^0\pi^0$ All bkg evts from cluster fusion Upstream decays not yet included	1 yr	3	**15**
$K_L \to \gamma\gamma$ $p_\perp$ cut very effective	3 yr	0	**0**
$K_L \to$ **charged**	**thought to be reducible**		

*Must subtract 35% for K_L losses in dump γ converter

~ 60 SM $K_L \to \pi^0 \nu\bar{\nu}$ in 5 years with S/B ~ 1

Background study incomplete!

π^0 from interactions of halo neutrons on residual gas, detector materials

Radiative K_L decays, **K_S/hyperon decays**

Background from $\Lambda \to n\pi^0$

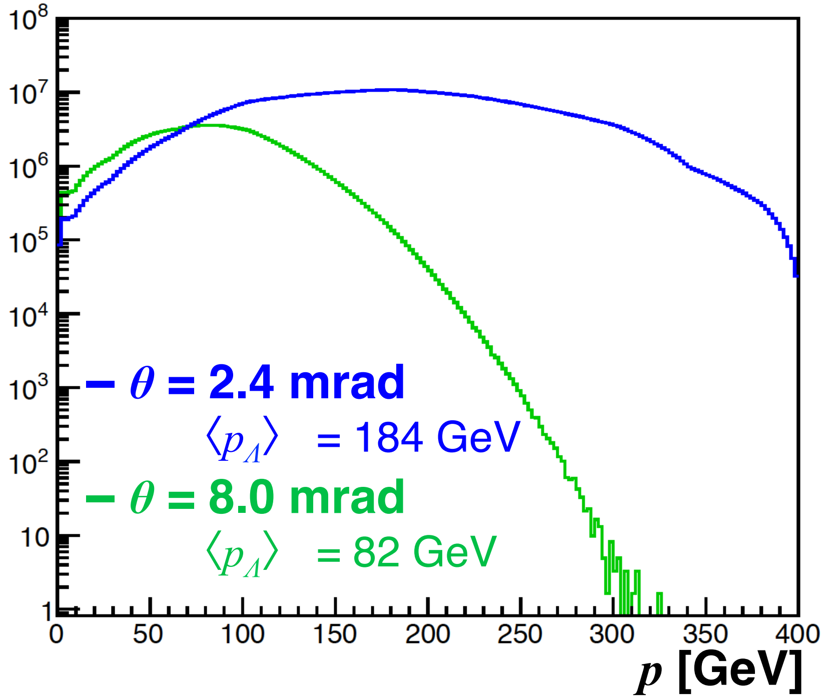
Λ and K produced in similar numbers: O(10^{15}) Λ in beam in 5 years

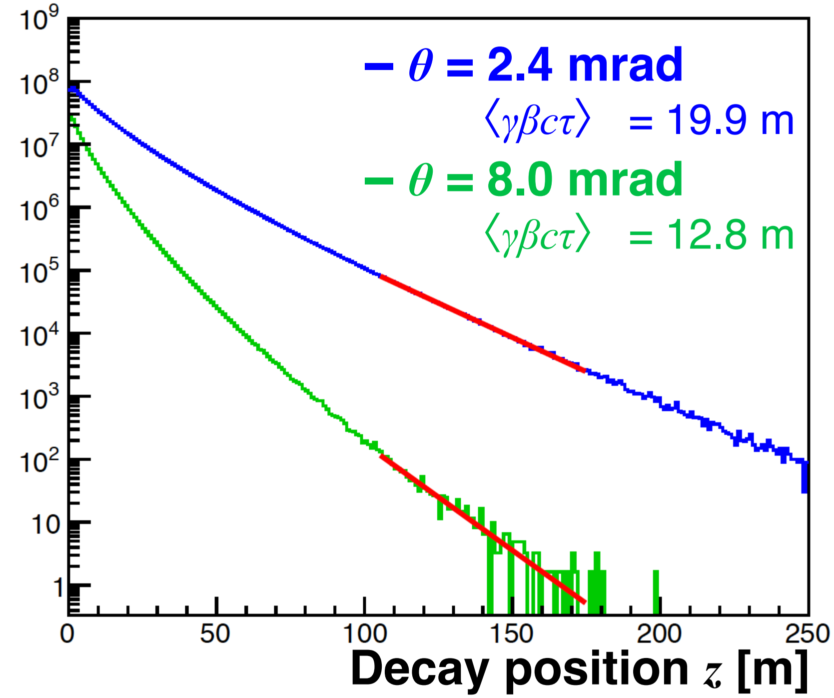
Small but significant fraction of Λ decay in fiducial volume

- $c\tau_\Lambda$ = 7.89 cm, but Λ is forward produced: hard momentum spectrum

$\Lambda \to n\pi^0$ (BR = 35.8%) can mimic signal decay

- $p_\perp$ cut partially effective: $p^*(\Lambda \to n\pi^0)$ = 105 MeV





Move from θ = 2.4 → 8 mrad production angle looks promising

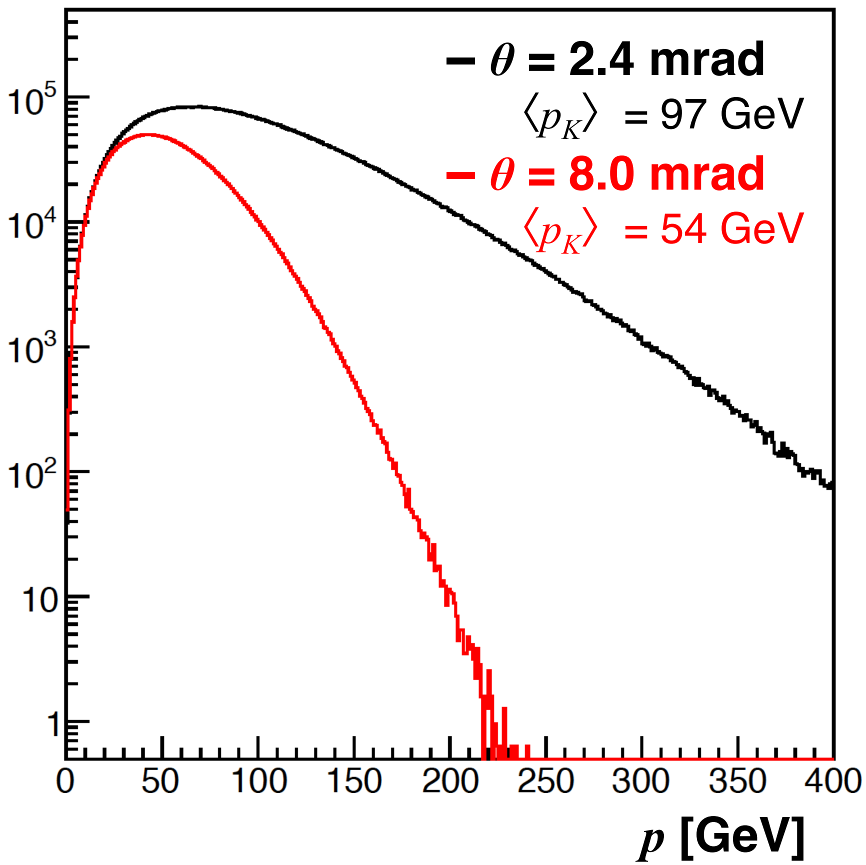
➜ Decrease Λ flux in beam and soften Λ momentum spectrum

Neutral beam at 8 mrad

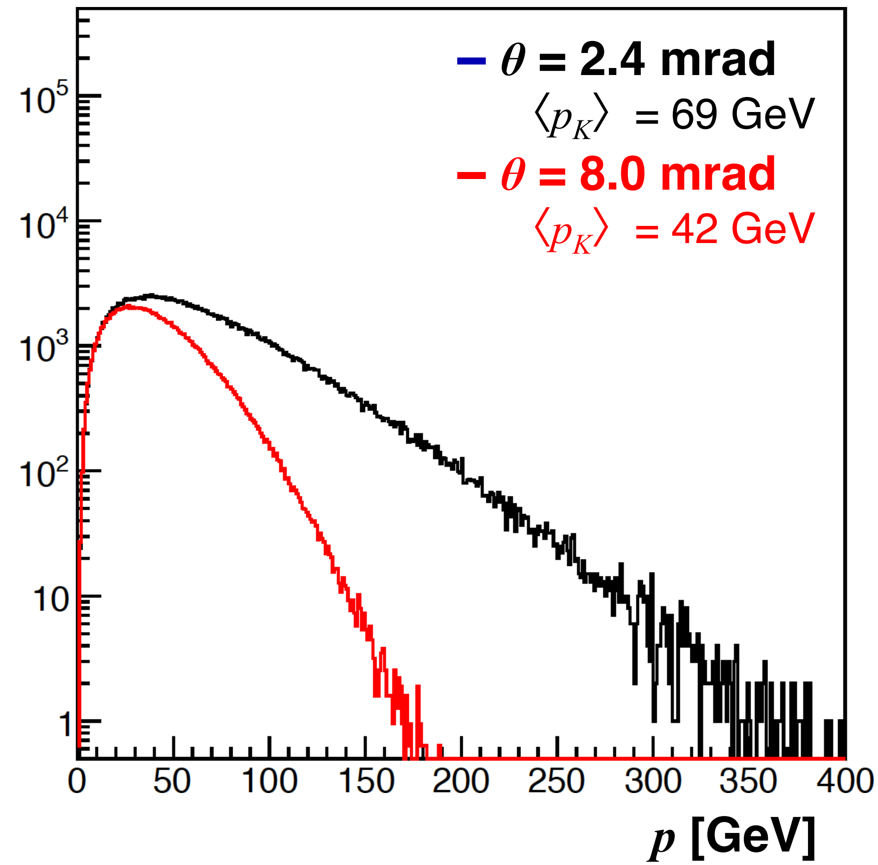
KLEVER

Implications of changing production angle: θ = 2.4 → 8 mrad

All K_L in beam



K_L decays in FV (105 < z < 155 m)



- 3× decrease in K_L production, mainly for high-energy K_L
- $K_L \to \pi^0 \nu\nu$ acceptance and S/B ratio $\pi^0\nu\nu/\pi^0\pi^0$ not significantly affected

Neutral beam at 8 mrad

K_LEVER

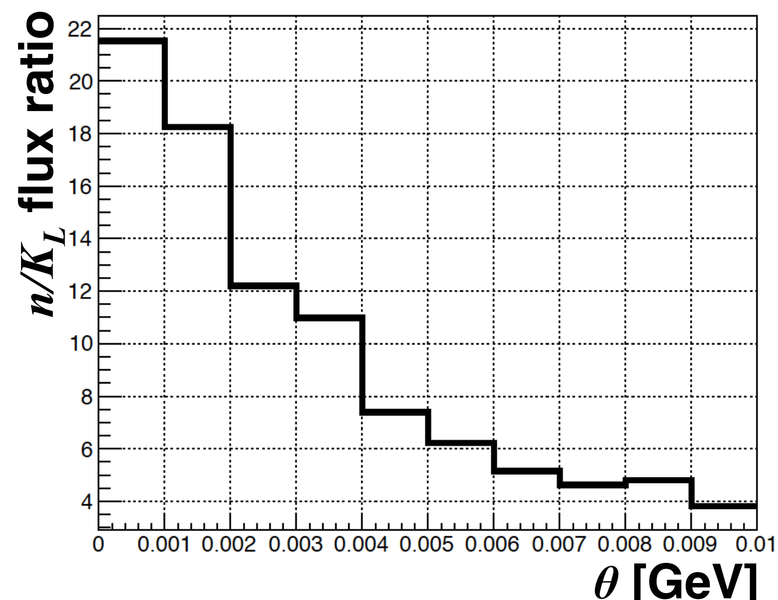
Implications of changing production angle and moving FV downstream:

- 3× decrease in K_L production
  No net change in acceptance for K_L
- 15× decrease in Λ production
  1000× decrease in Λ acceptance
- 2× decrease in S/B ratio from $K_L \to \pi^0\pi^0$

θ:	2.4 mrad	→	**8 mrad**
z **FV min:**	105 m	→	**130 m**
z **FV max:**	155 m	→	**170 m**

Advantages to moving to larger angle:

- 7× decrease in neutron flux
  Much less demanding rates on SAC
  Possible to use thinner absorber in beam?



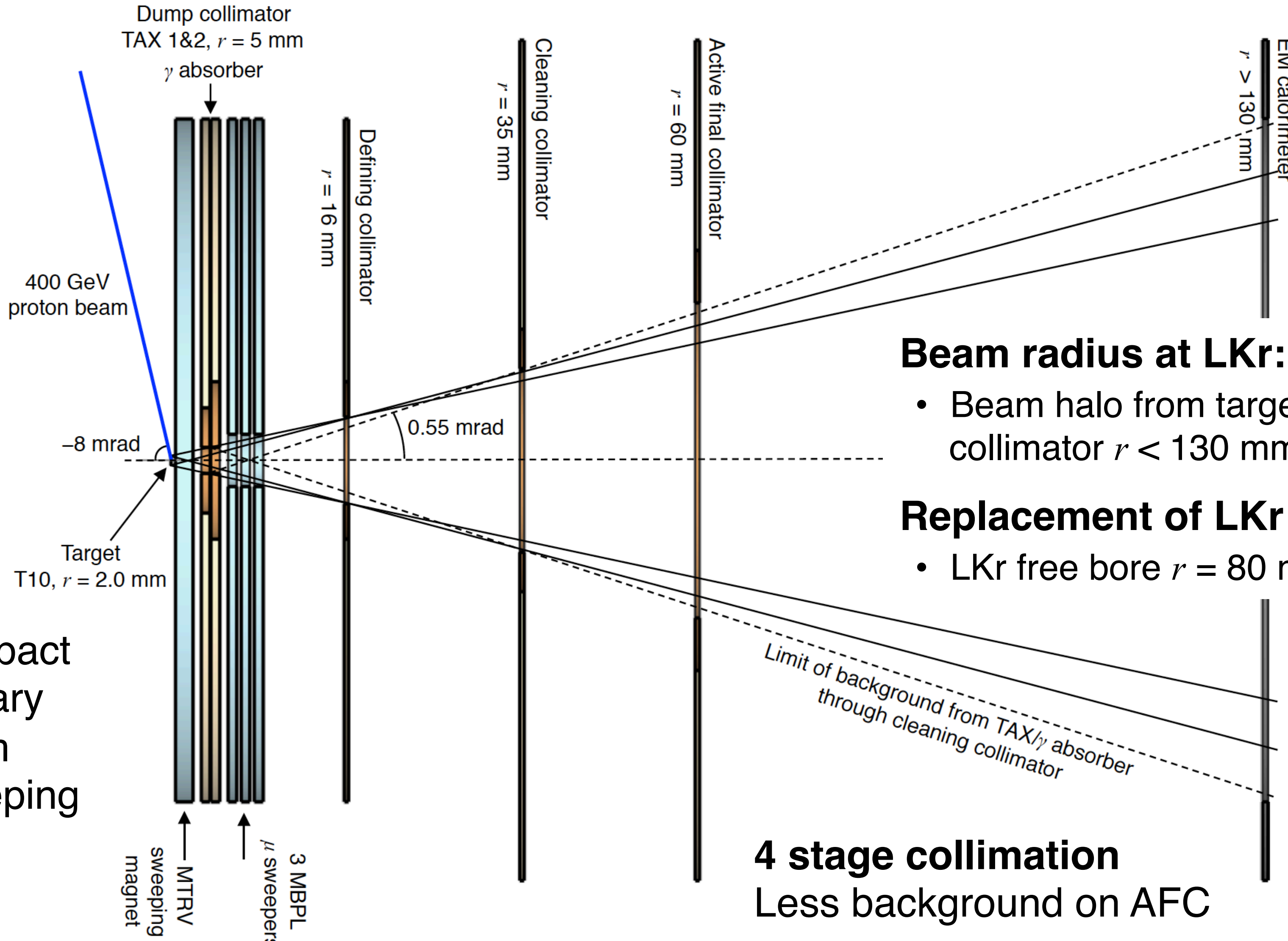
Next steps:

- **Finish optimization studies**
  Better quantify Λ rejection from $p_\perp$ cut
- **New 8.0 mrad beamline design with increased solid angle to compensate for decreased K_L production**

Neutral beamline layout (8 mrad)

KLEVER

Increase solid angle to compensate for decreased K_L production
$\Delta\theta$ = 0.3 → 0.4 mrad gives 1.8× increase in beam flux



Compact primary beam sweeping

Beam radius at LKr:
- Beam halo from target/dump collimator r < 130 mm

Replacement of LKr needed!
- LKr free bore r = 80 mm

4 stage collimation
Less background on AFC

Additional ideas to pursue

KLEVER

Add a tracking system for charged particles?

Advantages

- Expand physics scope of experiment:
  $K_L \to \pi^0 \ell^+ \ell^-$, $K_L \to \ell^+ \ell^- \ell^+ \ell^-$, etc.
- Facilitate calibration and efficiency measurements

Issues

- Potential complications for $K_L \to \pi^0 \nu\nu$
  - Simulate impact of material budget on photon veto efficiency
  - Evaluate impact of magnet on photon veto coverage

Add a preshower detector in front of LKr?

Advantages

- Redundancy for rejection for $K_L \to \pi^0 \pi^0$
  - 20-30% reduction in background overall
  - Most background is from even pairs
- Partial event reconstruction for calibration channels
- Sensitivity for exotics searches
  $K_L \to \pi^0 X$, $X \to \gamma\gamma$ with displaced vertex

Issues

- Require at least 1 conversion for signal events → cost in signal?
  - $0.5X_0$ converter → 50% of pairs have at least 1 conversion
- Same complications as for adding tracking
  - As close as possible to main calorimeter, like CPV

Preshower background rejection

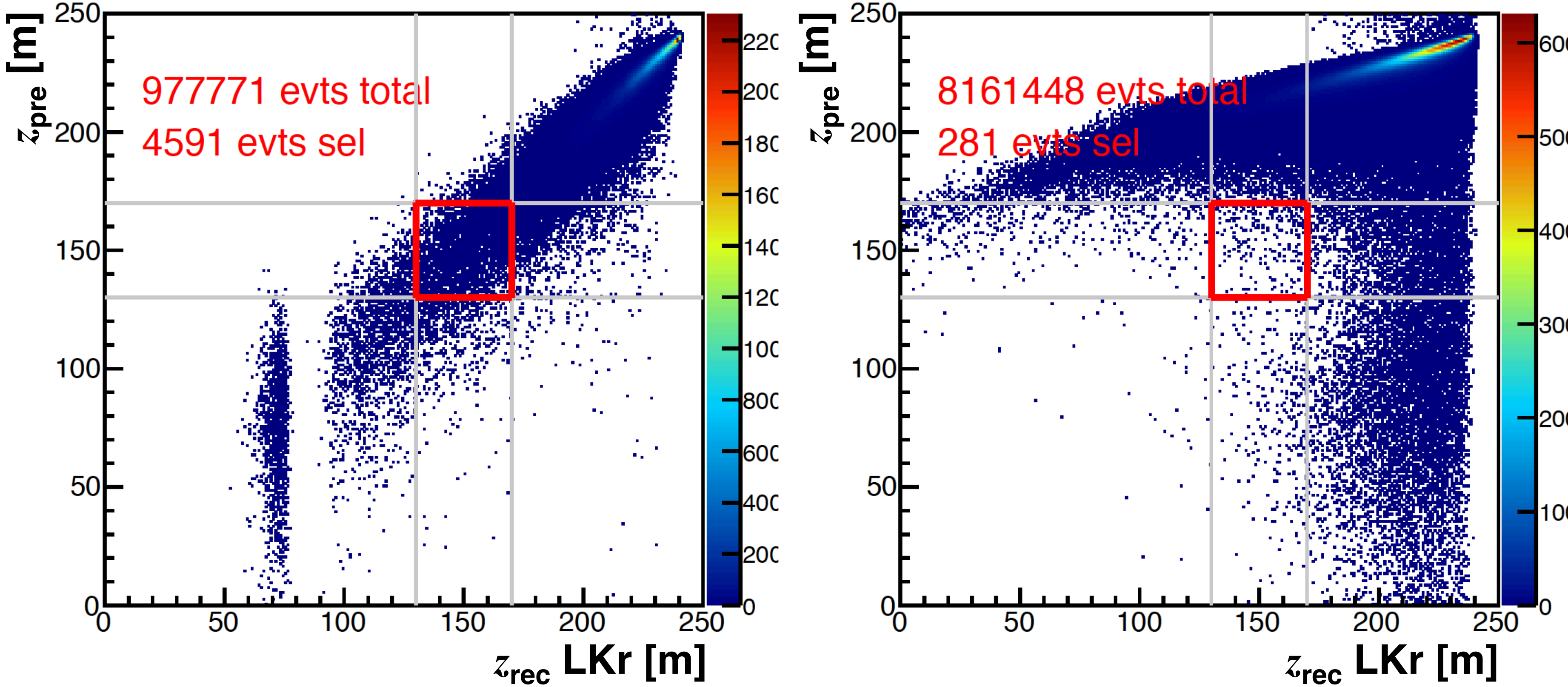
Preshower vertex z_{pre} vs. LKr vertex z_{rec}

z_{rec} reconstructed by imposing $M(\gamma\gamma) = m_{\pi 0}$

- $K_L \rightarrow \pi^0\pi^0$, 1 year eqiuvalent
- No cuts on FV, $p_\perp$, r_{min}

Even pairs (2 γ from same π^0)
1 γ converts in preshower

Odd pairs (2 γs from different π^0)
1 γ converts in preshower



Status and timeline

Project timeline – target dates:

2017-2018 **Project consolidation and proposal**
- Beam test of crystal pair enhancement
- Consolidate design

2019-2021 **Detector R&D**

2021-2025 **Detector construction**
- Possible K12 beam test if compatible with NA62

2024-2026 **Installation during LS3**

2026- **Data taking beginning Run 4**

- Most groups participating in NA62 have expressed interest in KLEVER

  We are actively seeking new collaborators!
- KLEVER is represented in the CERN Physics Beyond Colliders study
- An Expression of Interest to the CERN SPSC is in preparation and will also be submitted as input to the European Strategy for Particle Physics

Summary and outlook

Flavor will play an important role in identifying new physics, even if new physics is found at the LHC

- $K \to \pi\nu\bar{\nu}$ is a uniquely sensitive indirect probe for high mass scales
- Need precision measurements of both K^+ and K_L decays

Preliminary design studies indicate that an experiment to measure BR($K_L \to \pi^0\nu\bar{\nu}$) can be performed at the SPS in Run 4 (2026-2029)

- Many issues still to be addressed!
- Expected sensitivity: ~ 60 SM events with S/B ~ 1
- Comparable in precision to KOTO Step 2, with complementary technique (high vs. low energy) and different systematics

$K_L \to \pi^0\nu\bar{\nu}$ is a difficult measurement

- 2 efforts are justified to ensure precision measurement of the BR!

An Expression of Interest to the CERN SPSC is in preparation

- Many aspects of the experiment still need to be better defined
- **The time to get involved in KLEVER is now!**

Additional information

Matthew Moulson – Frascati

For the KLEVER project

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

General agreement of flavor observables with SM → invocation of MFV
- Long before recent flavor results from LHC

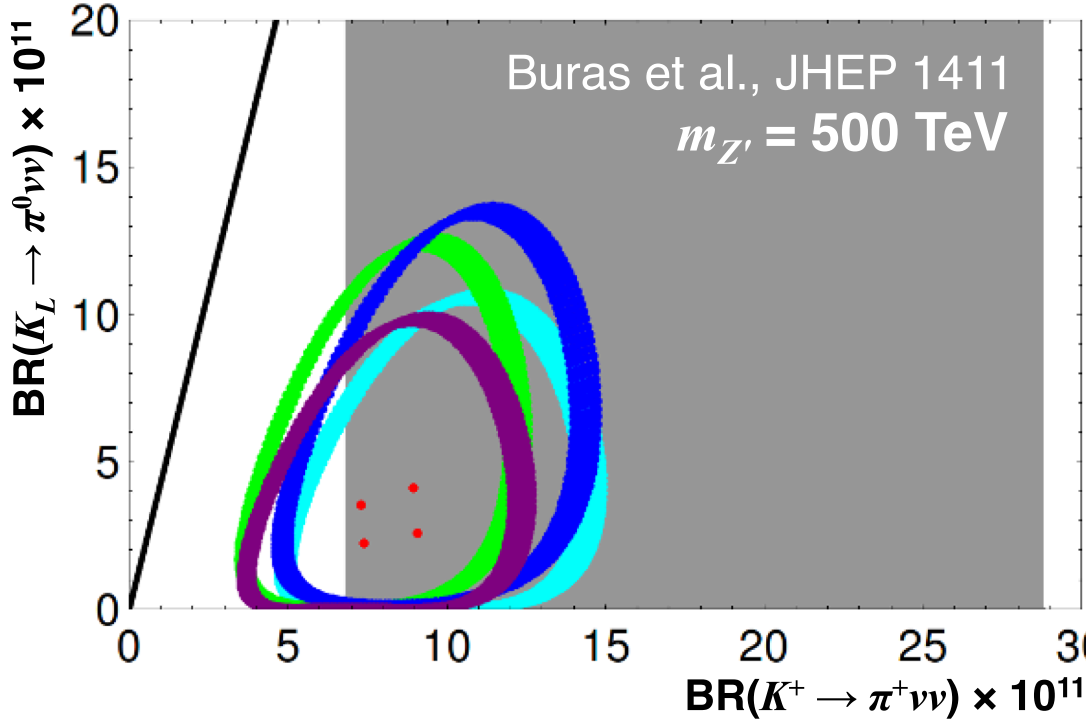
But NP may simply occur at a higher mass scale
- Null results from direct searches at LHC so far

Indirect probes to explore high mass scales become very interesting!

$K \to \pi\nu\bar{\nu}$ is uniquely sensitive to high mass scales

Tree-level flavor changing Z'
LH+RH couplings

- Some fine-tuning around constraint from ε_K
- $K \to \pi\nu\bar{\nu}$ sensitive to mass scales up to 2000 TeV
  - Up to tens of TeV even if LH couplings only
- Order of magnitude higher than for B decays

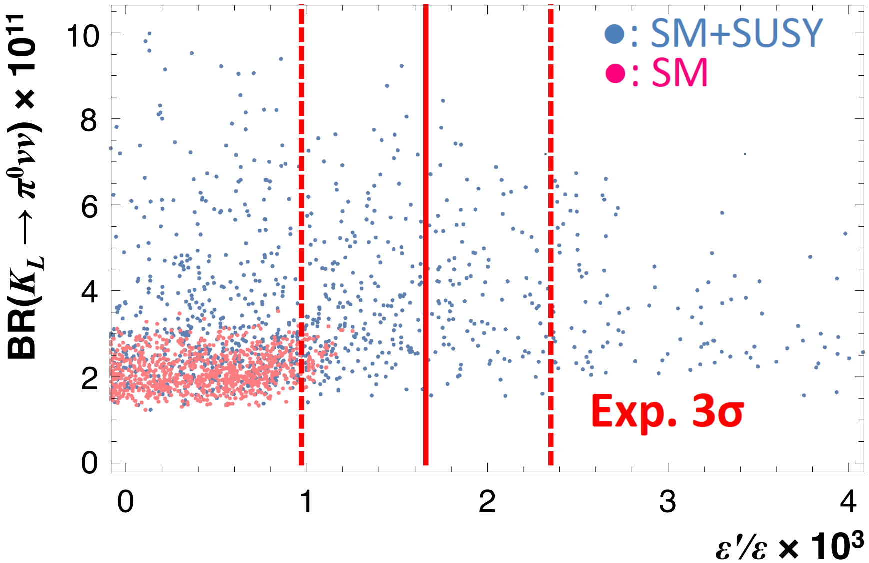


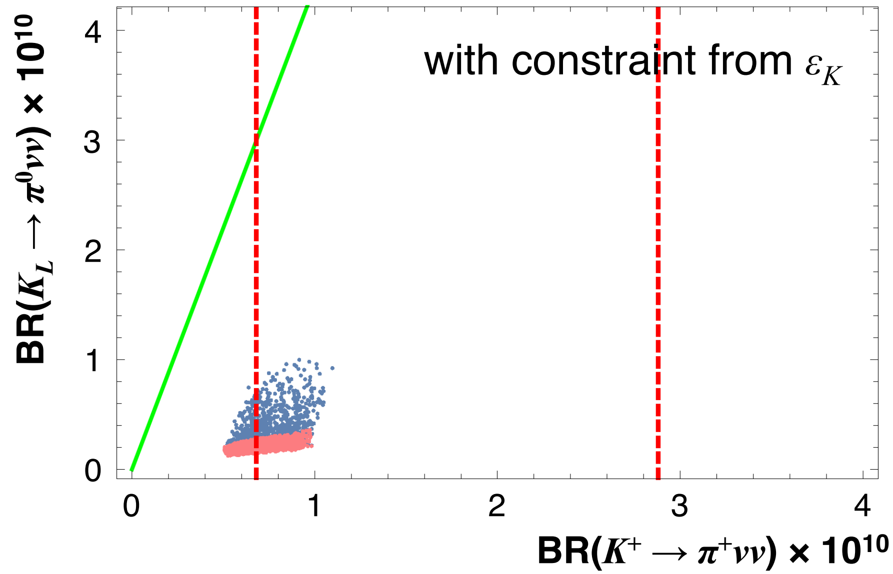
$K \to \pi\nu\bar{\nu}$ and large-scale SUSY

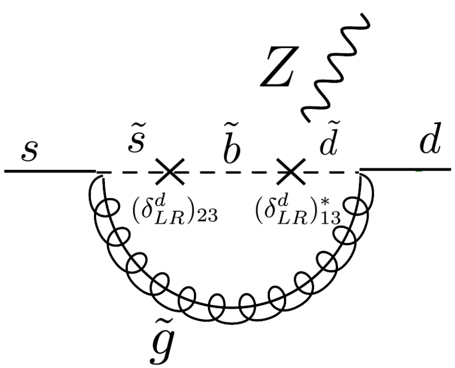
KLEVER

SUSY with m_{stop} ~ 10 TeV

Tanimoto & Yamamoto, PTEP 2016







Possible to choose Zsd couplings such that gluino Z penguin simultaneously enhances ε'/ε and BR($K_L \to \pi^0\nu\nu$)

BR($K_L \to \pi^0\nu\nu$) up to 1 × 10^{10} possible with experimental bounds on ε'/ε satisfied

$K \to \pi\nu\bar{\nu}$ and other kaon observables

KLEVER

What about constraints from Re ε'/ε, ε_K, Δm_K, $K_L \to \mu\mu$?

Particular interest in constraints from Re ε'/ε

- 2015 result demonstrates Re ε'/ε is accessible to lattice QCD
- Lattice QCD value 2.1σ lower than experimental value

PDG average: NA48 + KTeV

Re ε'/ε = (16.6 ± 2.3) × 10^{-4}

RBC/UKQCD PRL115 (2015)

Re ε'/ε = 1.38(5.15$_{st}$)(4.59$_{sy}$) × 10^{-4}

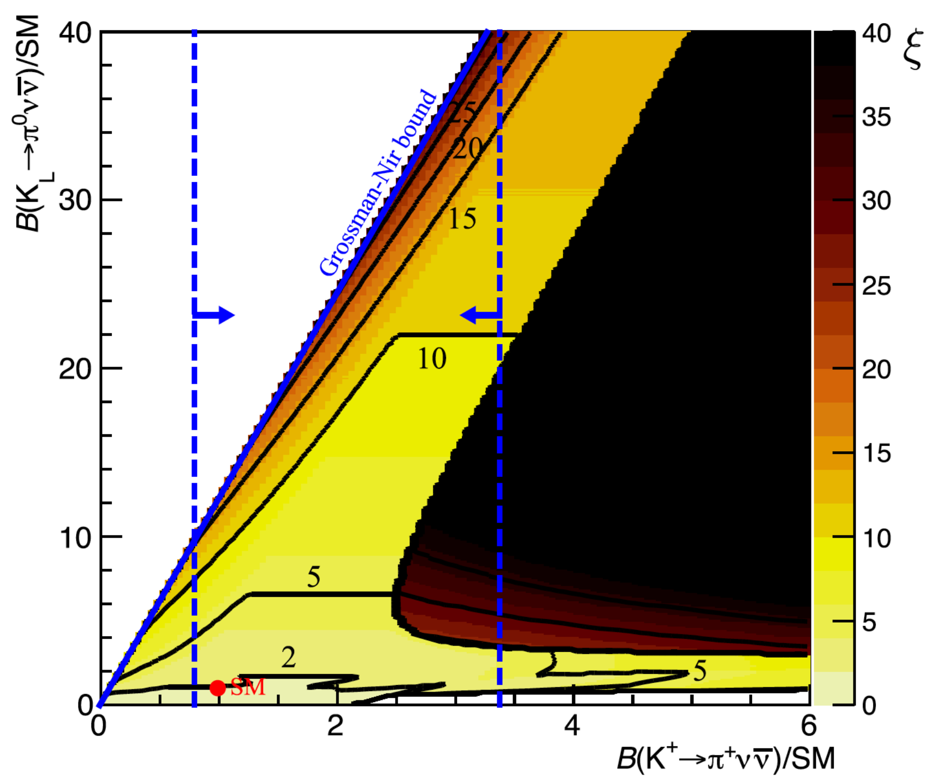
Endo et al. PLB771 (2017)

General Z scenario with modified couplings, Λ = 1 TeV

- Because of interference between SM and NP amplitudes, if all constraints satisfied including "discrepancy" in Re ε'/ε:

  BR($K \to \pi\nu\nu$) ~ 0.5 SM BR

- Particularly in simplified scenarios: LH, RH, LRS
- With moderate tuning (cancellation of interference terms to 10%), large values for BR($K \to \pi\nu\nu$) are possible

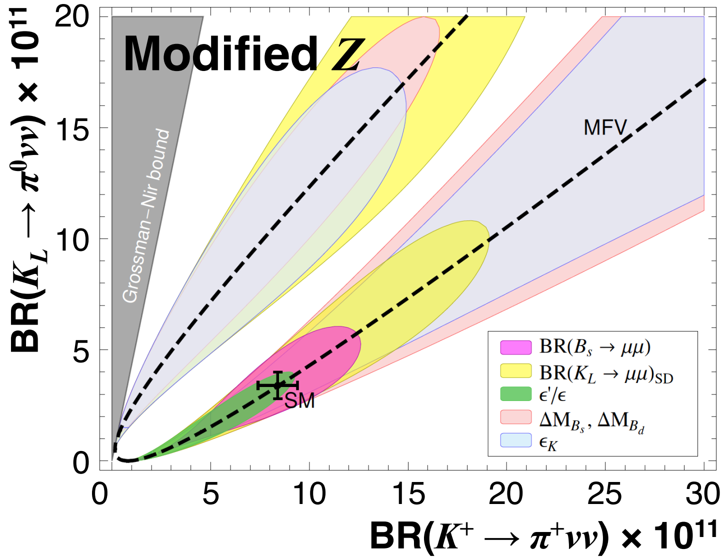


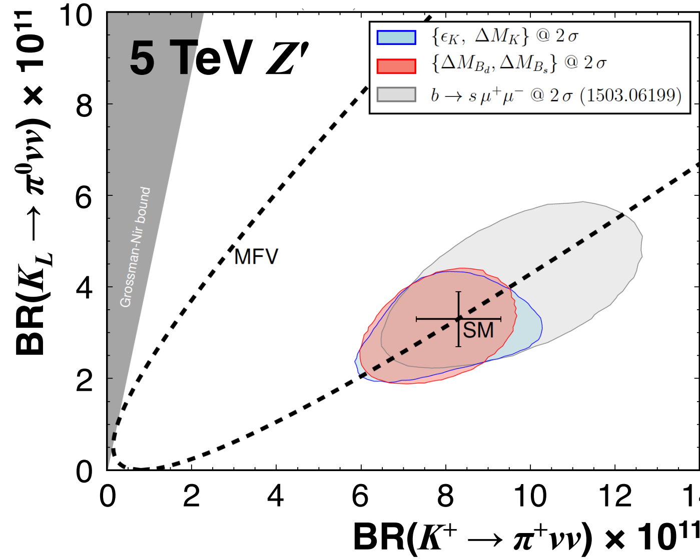
$K \to \pi\nu\bar{\nu}$ and other flavor observables KLEVER

Simplified Z, Z' model used as paradigm Buras, Buttazzo, Knegjens, JHEP 1511

CMFV hypothesis:

Constraints from B and K observables

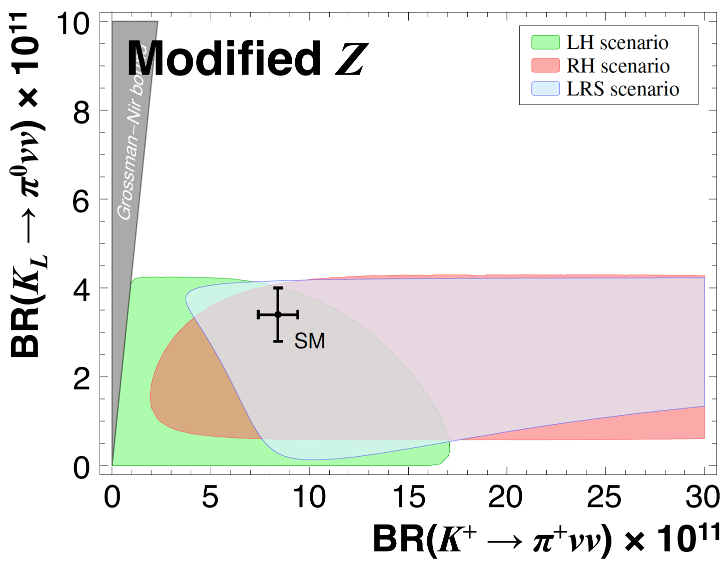


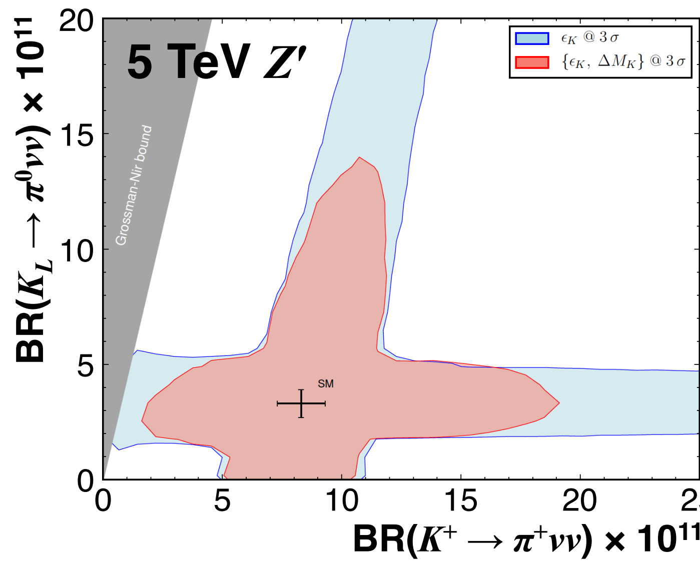


LH and RH couplings allowed:

Constraints from K observables:

- ε_K, ΔM_K
- ε'/ε, $K \to \mu\mu$ (for modfied Z)





$K \to \pi\nu\bar{\nu}$ and other flavor observables KLEVER

New ideas relating $K \to \pi\nu\nu$ to B-sector LFU anomalies:

R_K, P_5': μ/e LFU in $B \to K\ell\ell$, $B \to K^*\ell\ell$

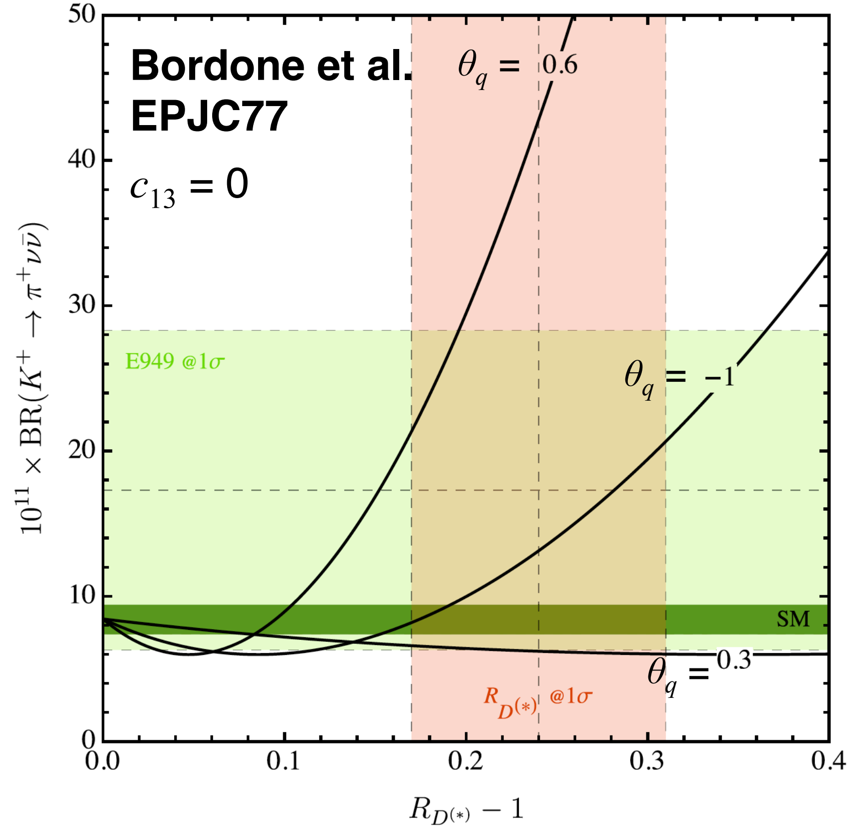
$R_{D(*)}$: $\tau/(\mu, e)$ LFU in $B \to D^{(*)}\ell\nu$

Coherent explanation from NP coupled predominantly to 3rd generation LH quarks and leptons, e.g., mediated by vector leptoquark

- **Di Luzio et al. PRD 96 (2017)**
- **Buttazzo et al. JHEP 1711**

EFT studies suggest large effect for $K \to \pi\nu\nu$

- **Bordone et al. EPJC77 (2017)**



$$R_0 = \frac{1}{\Lambda^2}\frac{1}{\sqrt{2}G_F}$$

$$\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}) = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})_{\rm SM}\left|1 + R_0\left(1 - \theta_q e^{-i\phi_q}\right)\right|^2$$

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = 2\mathcal{B}(K_L \to \pi^0\nu_e\bar{\nu}_e)_{\rm SM} + \mathcal{B}(K_L \to \pi^0\nu_\tau\bar{\nu}_\tau)_{\rm SM}\left|1 - \frac{R_0\,\theta_q^2(1 - c_{13})}{(\alpha/\pi)(X_{\rm t}/s_{\rm W}^2)}\right|^2$$

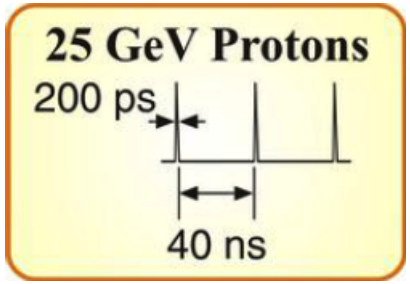
Extra constraints for $K_L \to \pi^0 \nu\bar{\nu}$

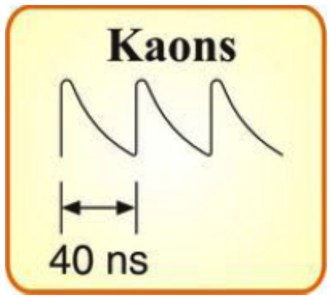
KOPIO

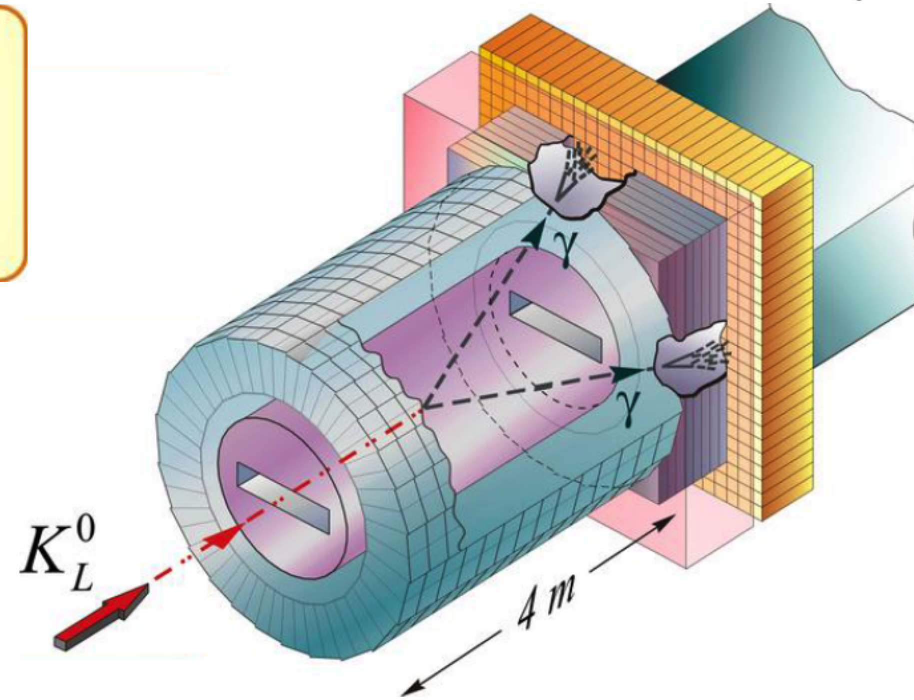
Brookhaven AGS
Cancelled 2005

Primary: 26 GeV p
10^{14} p/7.2 s

Neutral beam (43°)
$\langle p(K_L)\rangle$ = 0.9 GeV
50% of K_L have
0.5-1.2 GeV







Microbunched beam from AGS:
200 ps every 40 ns, 10^{-3} extinction

Flat beam to increase K_L flux
Solid angle 360 μsr = 1 m wide!

Preradiator in front of calorimeter
Reconstruct angle of incidence for γs

Sensitivity: 180 SM evts in ~4 yr

Advantages:
- $p(K_L)$ from time of flight
- Vertex position from preradiator
- Redundant constraints

Disadvantages:
- Difficult to veto low-energy γs
- Much lower K_L flux at high angle

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

KOTO

Primary beam: 30 GeV p

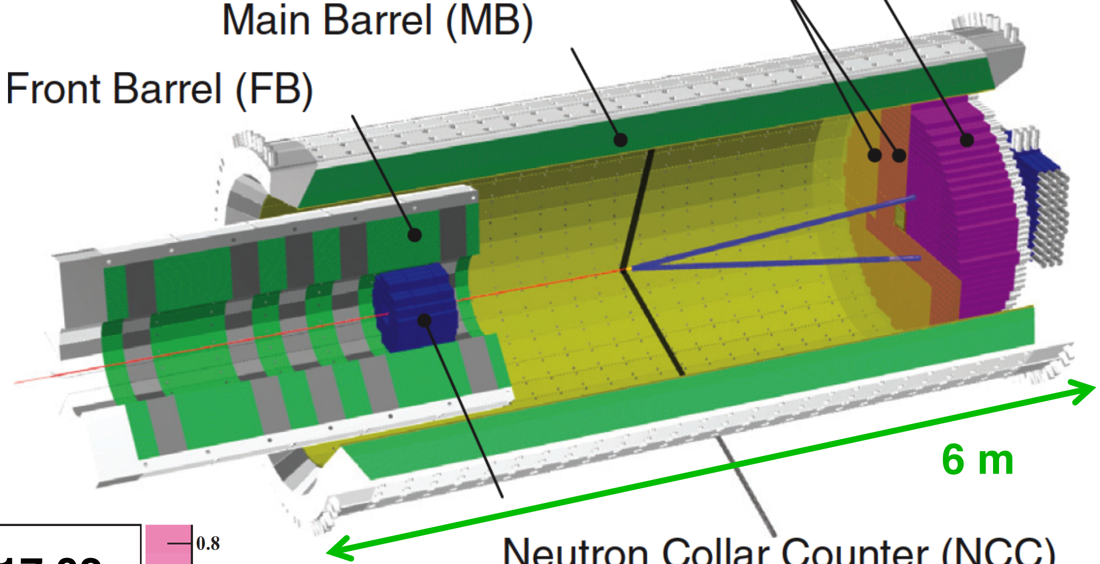
100 kW = 1.2 × 10^{14} p/6 s

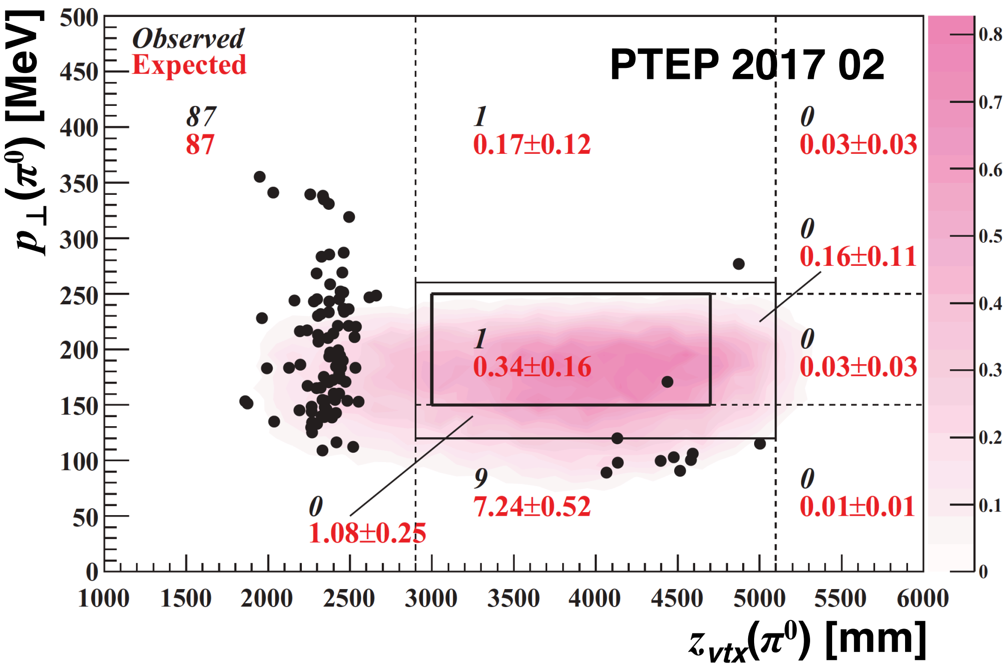
Neutral beam (16°)

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

50% of K_L have 0.7-2.4 GeV

8 μsr “pencil” beam





Based on KEK-391a:

Current experimental value

BR($K_L \to \pi^0 \nu\nu$) ≤ 2.6 × 10^{-8} (90%CL)

100-hour KOTO pilot run in 2013:

BR($K_L \to \pi^0 \nu\nu$) ≤ 5.1 × 10^{-8} (90%CL)

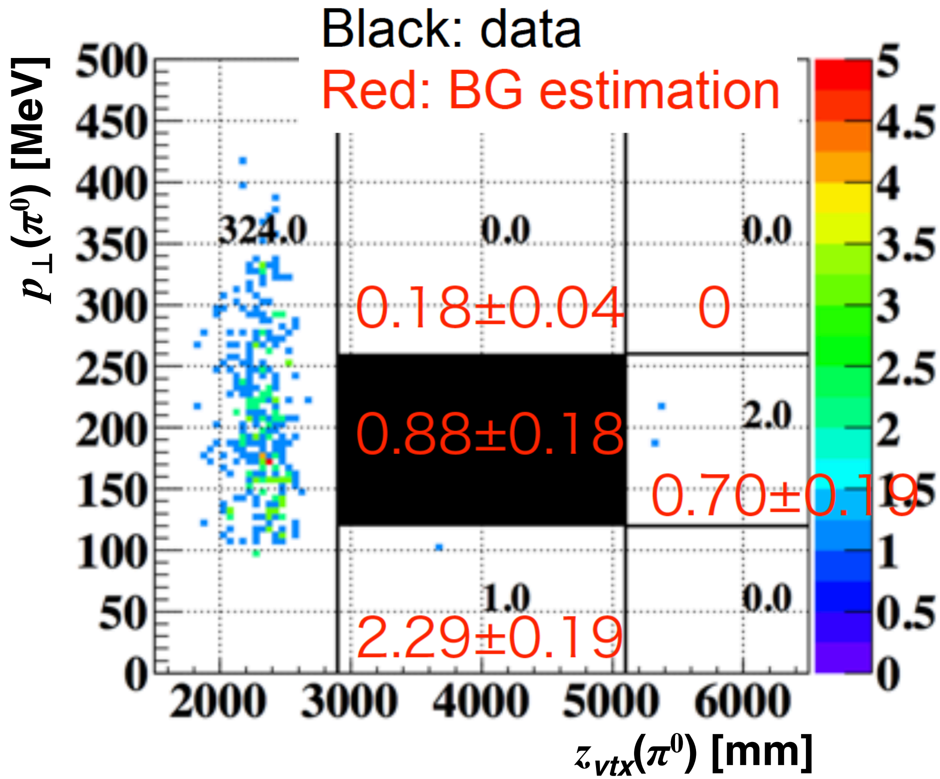
Taking data since 2015

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

Current status:

- Reached **44 kW** of slow-extracted beam power in 2017
- Preliminary results, all 2015 data:
  SES = 1.2 × 10^{-9}
  Expected bkg = 0.9 ± 0.2 events
  Signal box not yet unblinded
  Bkg estimate still under study
- With all 2015-2017 data, expected sensitivity below Grossman-Nir limit
- In 2018 beam power will increase to **50 kW**

J-PARC PAC, Jan 2018

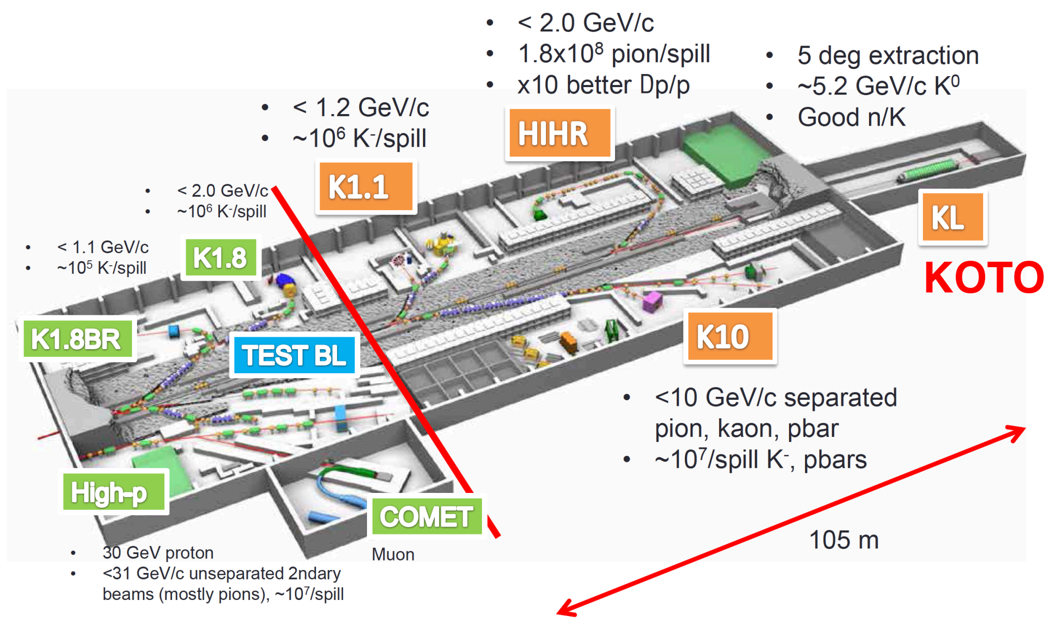


- Continuing program of upgrades to reduce background:
  New barrel veto (2016), both-end readout for CsI crystals (2018)
- **Expect to reach SM sensitivity by 2021**

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

KOTO Step-2 upgrade:

- 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 11 m
  Complete rebuild of detector
- Requires extension of hadron hall



Strong intention to upgrade to O(100) event sensitivity over long term:

- No official Step 2 proposal yet (plan outlined in 2006 KOTO proposal)
- Scaling from 2006 estimates: **~10 SM evts/yr per 100 kW beam power**
- Exploring possibilities for machine & detector upgrades to further increase sensitivity
- Indicative timescale: data taking starting 2025?

High-intensity neutral beam issues

KLEVER

10^{19} pot/yr × 5 years → 2 × 10^{13} ppp/16.8s = 6× increase relative to NA62

Feasibility/cost study a primary goal of our involvement in Conventional Beam WG

Preliminary analysis of critical issues by Secondary Beams & Areas group

Issue	Approach
Extraction losses	Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) Slow extraction workshop, 9-11 November: https://indico.cern.ch/event/639766/
Beam loss on T4	Vertical by-pass to increase transmission to T10
Equipment protection	Possibly use SIS interlock to stop extraction during P0Survey reaction time
Ventilation in ECN3	Need to understand better current safety margin May need comprehensive ventilation system upgrade
ECN3 beam dump	Significantly improved for NA62 Need to understand better current safety margin
Background fluxes	Detailed simulations getting started

NA48 liquid krypton calorimeter

KLEVER

Quasi-homogeneous ionization calorimeter

- 13248 channels
- Readout towers 2×2 cm^2
- Depth 127 cm = 27 X_0

NA48 performance:

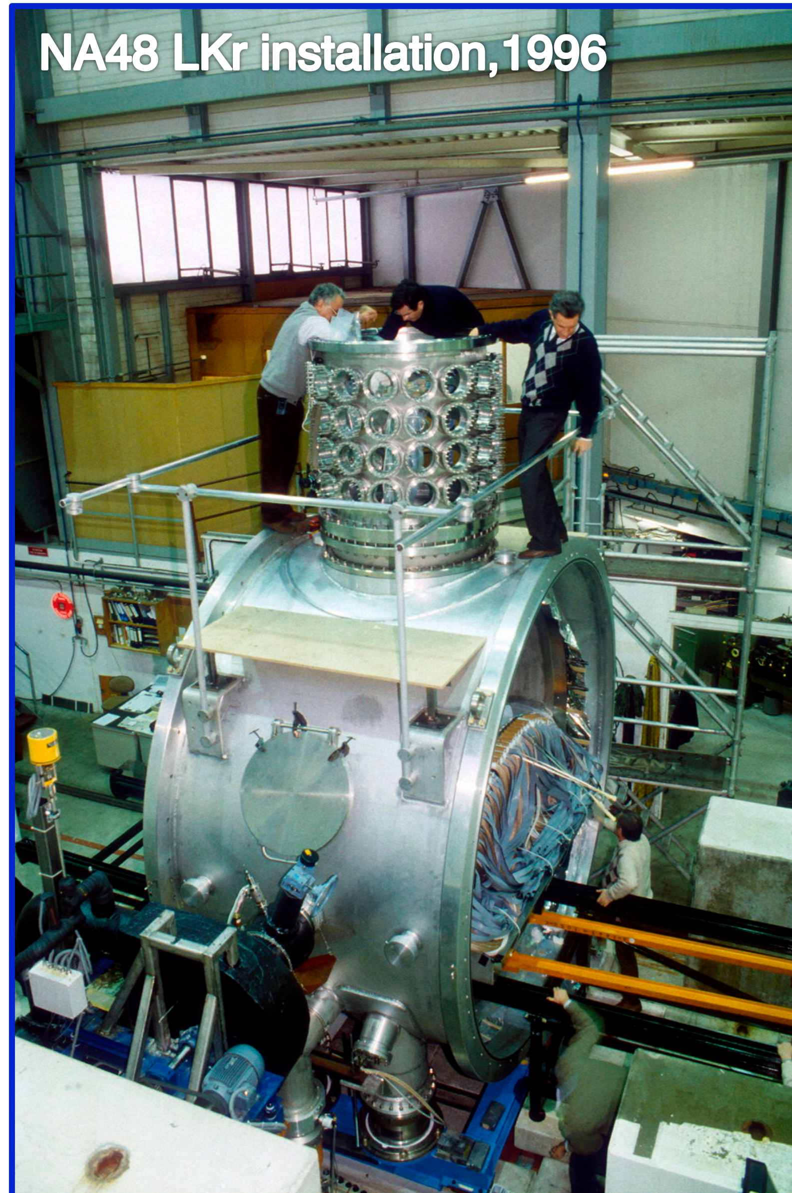
$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$

$$\sigma_x = \sigma_y = \frac{4.2\text{ mm}}{\sqrt{E}} \oplus 0.06\text{ mm}$$

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

New readout electronics for NA62:

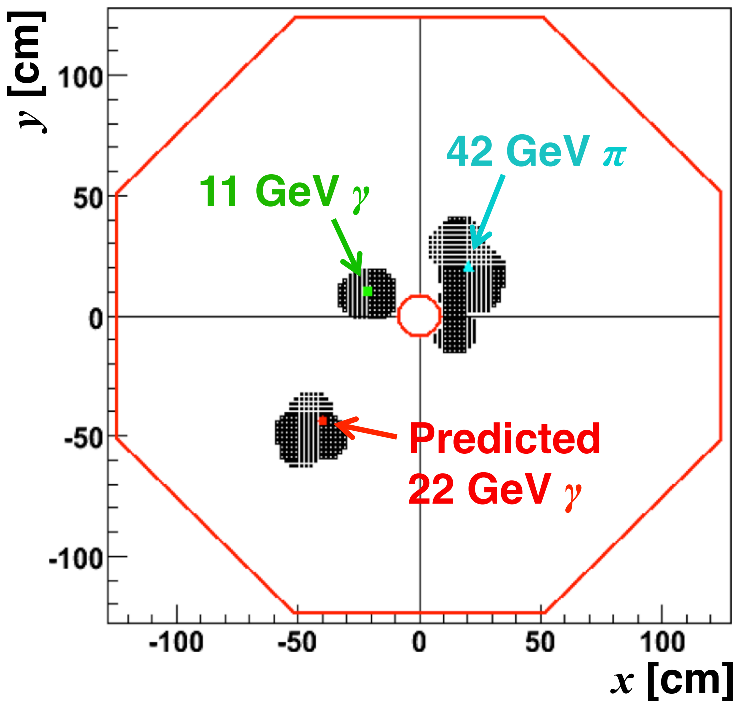
- 14-bit 40 MHz FADCs
- Large buffers to handle 1 MHz L0 rate



The NA48 LKr as a photon veto

Method 1: $K^+ \to \pi^+\pi^0$

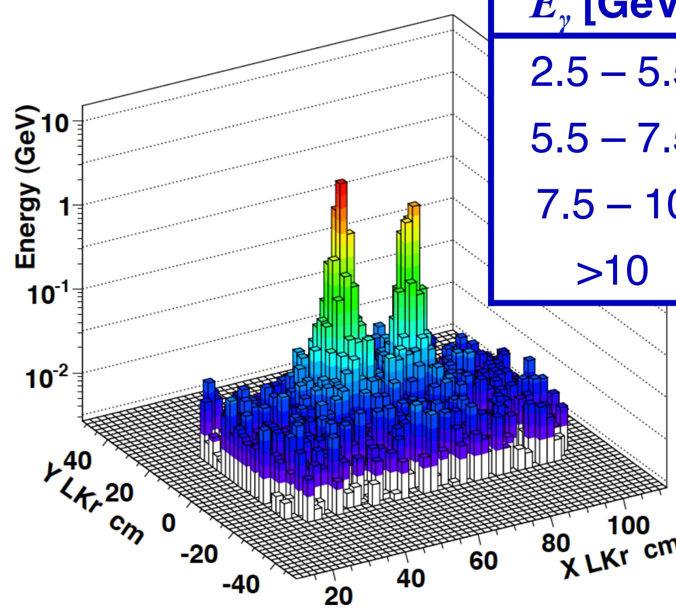
- Low-rate, p = 75 GeV run in 2004
- $K^+ \to \pi^+\pi^0$ selected using kinematics only
  - Tight topological and quality cuts
  - E/p cut and muon veto for track ID
- π^+ and lower energy γ are used to predict position of other γ



$1 - \varepsilon < 9 \times 10^{-6}$ 90% CL

Method 2: Tagged γ

- Test beam with e^- in 2006
- 25 GeV beam aimed at LKr
- Bremsstrahlung on material upstream of MNP33
- Beam deflected 12 cm, reconstruct e^- in LKr
- Nominal beam position = position of bremsstrahlung γ



E_γ [GeV]	$(1 - \varepsilon)$ 90% CL
2.5 – 5.5	$< 10^{-3}$
5.5 – 7.5	$< 10^{-4}$
7.5 – 10	$< 5 \times 10^{-5}$
>10	$< 8 \times 10^{-6}$

Vetoes for upstream K_L decays

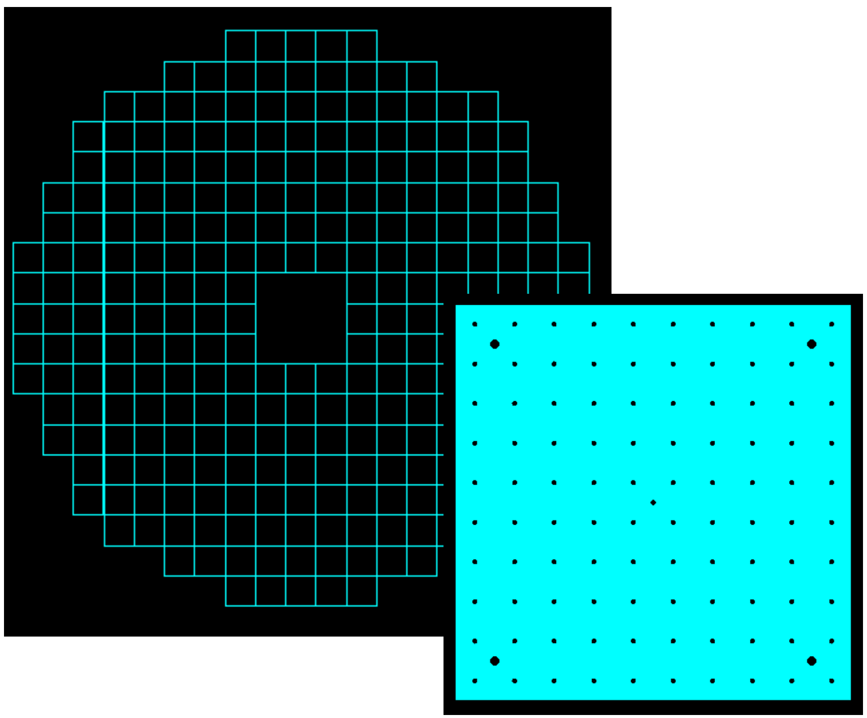
KLEVER

Rejects $K_L \to \pi^0\pi^0$ from upstream of final collimator (80 m < z < 105 m)

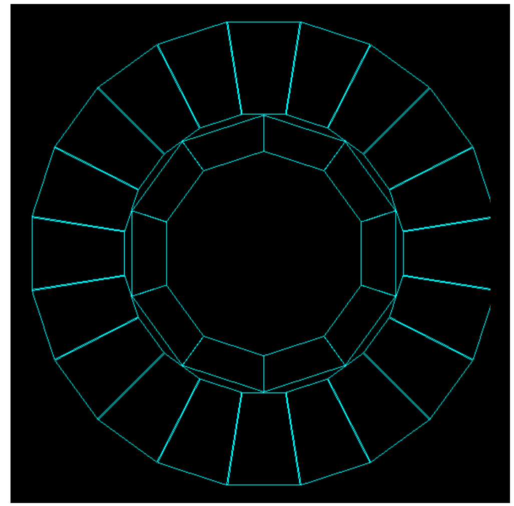
Upstream veto (UV):

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

As implemented in MC:



Active final collimator:



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

- Intercepts halo particles from scattering on defining collimator or γ absorber
- Active detector → better rejection for π^0 from n interactions

Residual background from upstream $K_L \to \pi^0\pi^0$:

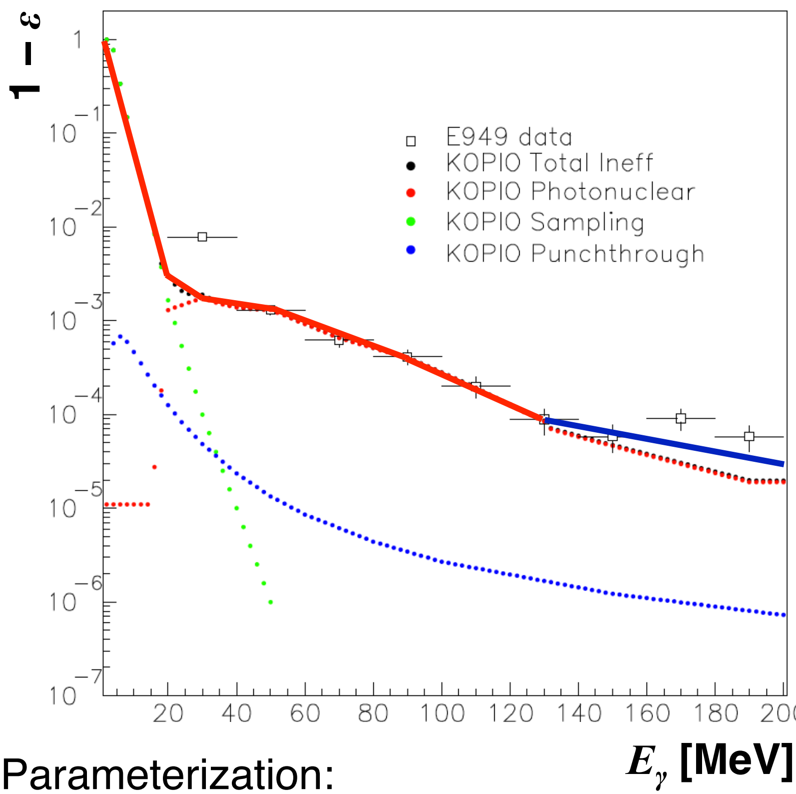
15 events/5 years

Large-angle photon vetoes

26 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

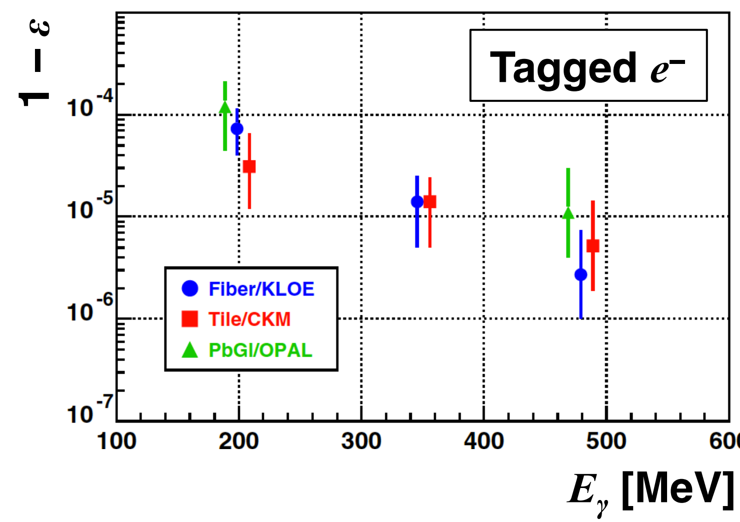
Good efficiency assumptions based on E949 and CKM VVS experience



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:

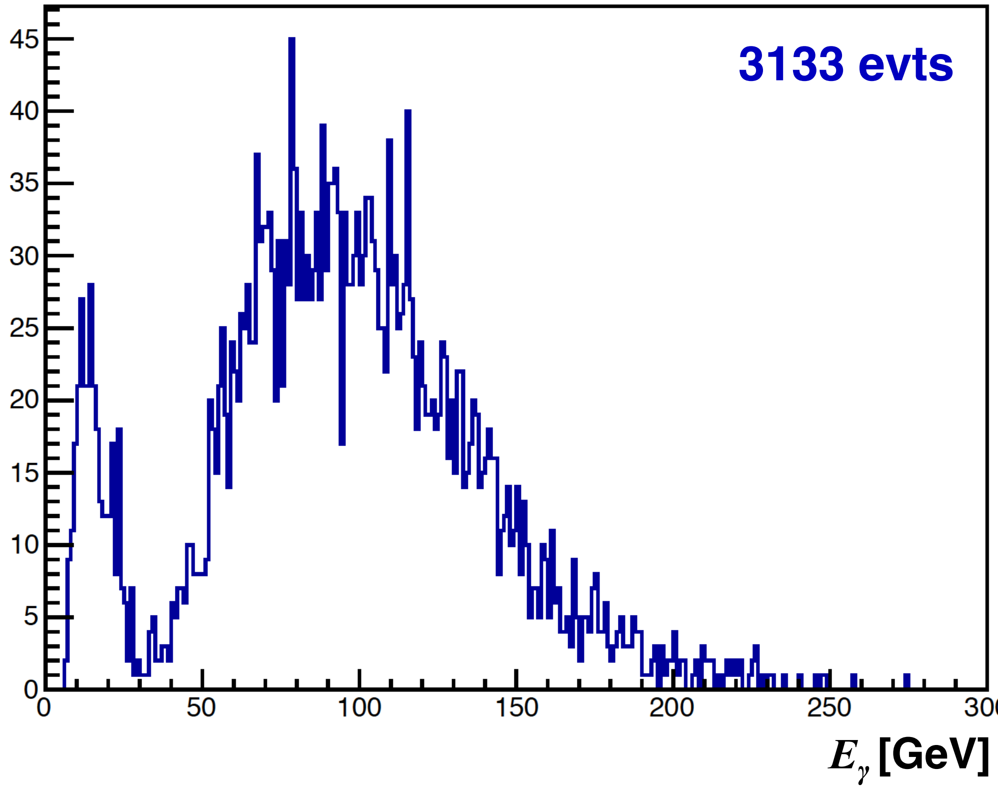
- $1 - \varepsilon \sim 3 \times 10^{-6}$ at 1200 MeV

Small-angle calorimeter

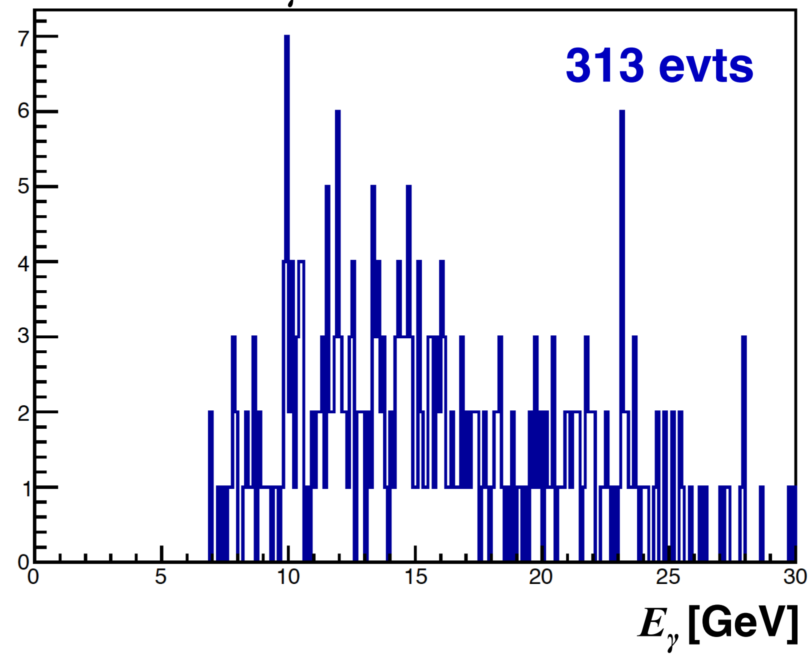
KLEVER

Energy of photons from $K_L \to \pi^0\pi^0$ on SAC after all cuts (5 years):

- 2γ on LKr
- No γs on LAV or IRC
- Cuts on z_{FV}, r_{min}(LKr), $p_\perp$



Detail for E_γ < 30 GeV



90% of γs from K_L on SAC have $30 < E_\gamma < 250$ GeV

- Need inefficiency < 10^{-4} for $E_\gamma > 30$ GeV
- Can tolerate 1% inefficiency for $E_\gamma < 30$ GeV
- Can be blind for $E_\gamma < 5$ GeV

Small-angle calorimeter

Proof-of-concept simulation for baseline solution:

- W-Si pad calorimeter, 14 layers × 1 mm crystal absorber, θ_{inc} = 2 mrad
  - Depth = 14X_0 for E_γ = 30 GeV, but only 4X_0 for E_γ = 5 GeV
- Naïve simulation of pair-conversion enhancement with Geant4:
  - Increase overall density as function of E_γ, instead of X_0

Photons

E_γ (GeV)	ρ/ρ_0	$1-\varepsilon$
350 GeV	3.5	**5×10^{-5}**
30 GeV	3.5	**1×10^{-4}**
10 GeV	1.5	**4.5%**
5 GeV	1.0	**20%**

Neutrons

50-300 GeV **$1-\varepsilon$ = 20%**

- E_{vis} thr. = 16 MeV chosen for E_γ = 30 GeV
- Inefficiency at small E_γ from punch through
- Need better treatment of coherent effects
- Need additional handles for γ/n separation

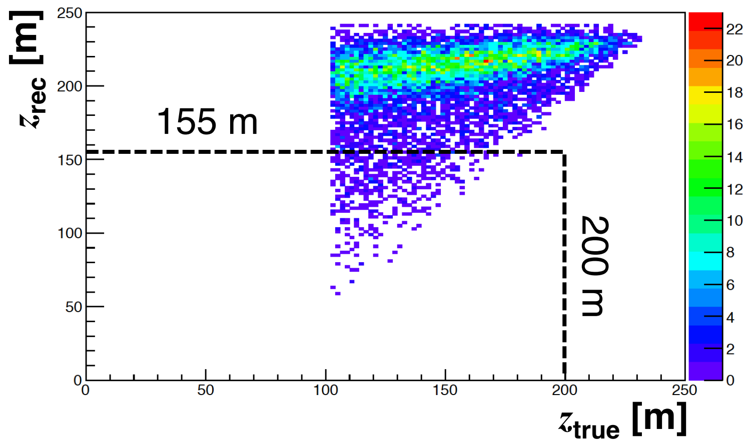
Work in progress:

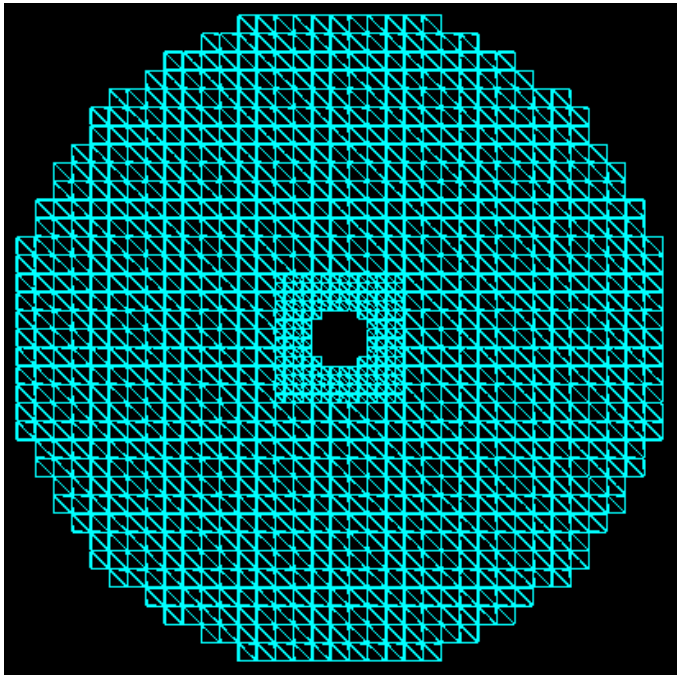
- Better simulation with X_0 for photons a function of E_γ and θ_γ
  - Benefit from effort by AXIAL collaborators to introduce into Geant4 detailed simulation of coherent effects in crystals
- Optimize transverse and longitudinal segmentation to increase γ/n separation

Charged particle veto

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

- 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





Using MC to add detail to design of CPV

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

- 2 planes → 3% X_0

Tile geometry: 4x4 cm² or 8x8 cm²

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

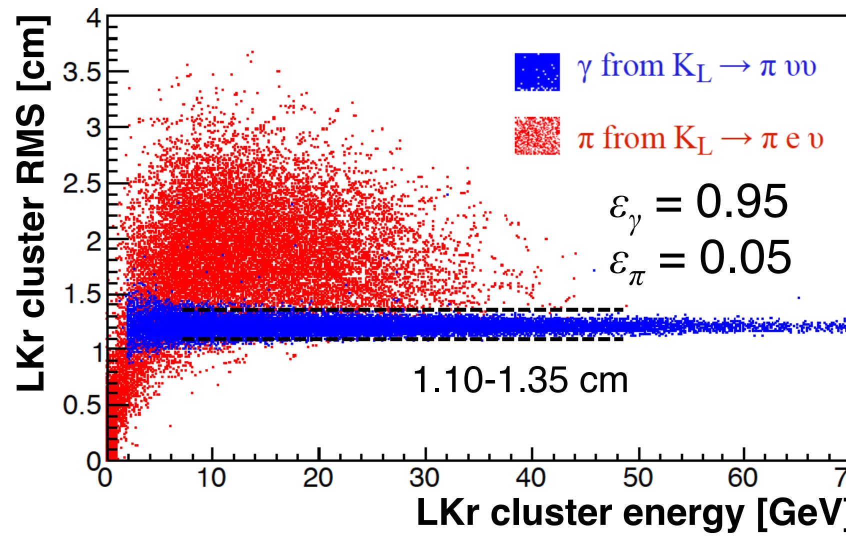
Charged particle rejection

$K_L \to \pi e \nu$ 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 pp0 events in NA62 data:
  $\varepsilon_\gamma = 0.95$
  $\varepsilon_\pi = 0.05$

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

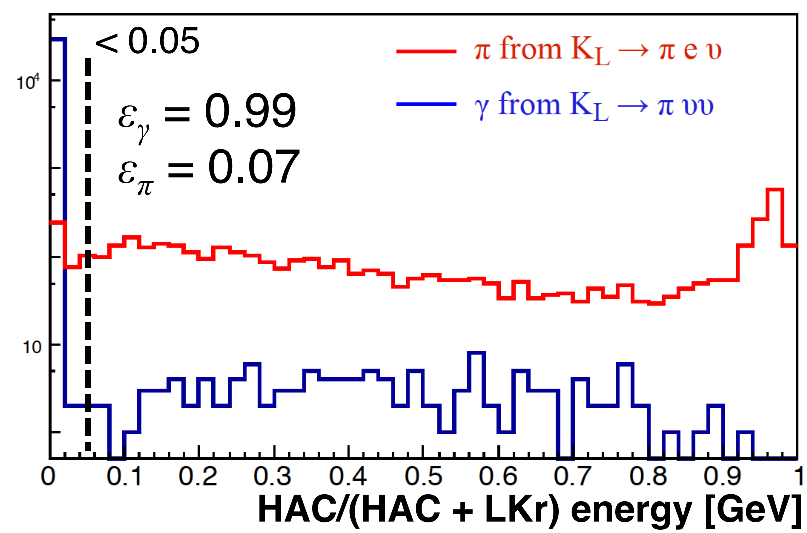


Ratio of hadronic/total energy effective to identify π showers

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

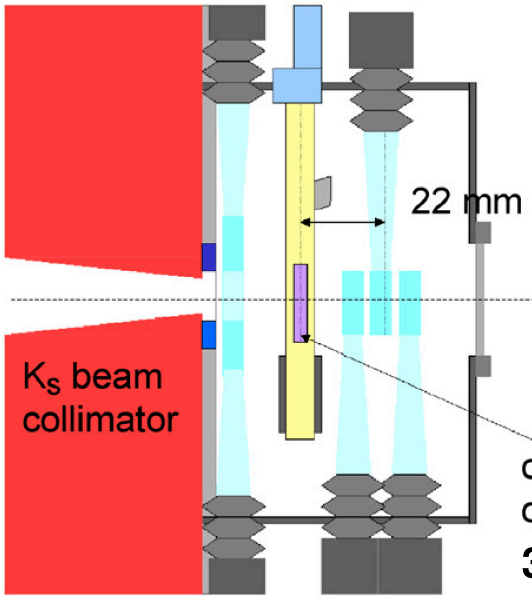
Study of HAC (MUV1/2) response in NA62 data in progress

- Parameterization of response for inclusion in fast simulation



Crystal converter for the NA48 AKS

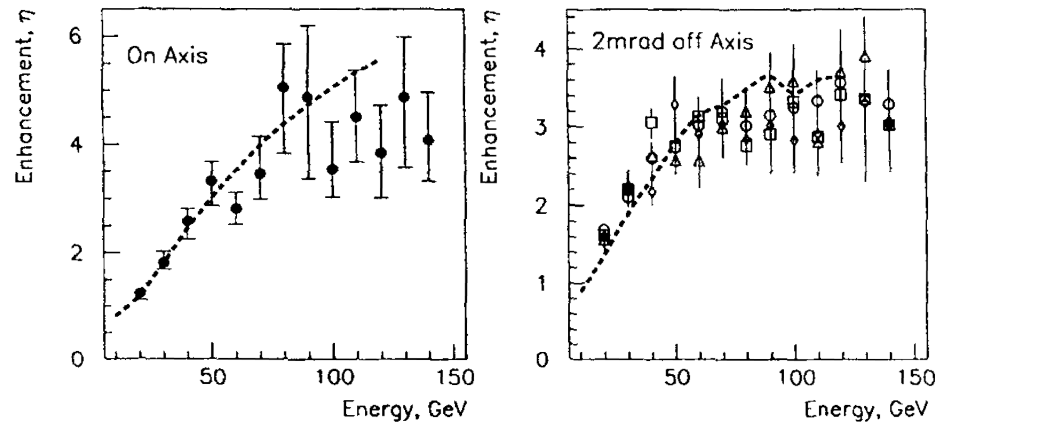
AKS used to define start of FV for $K_S \to \pi^0\pi^0$ decays in NA48



Pair-production enhancement from coherent interaction with crystal lattice was studied for AKS development

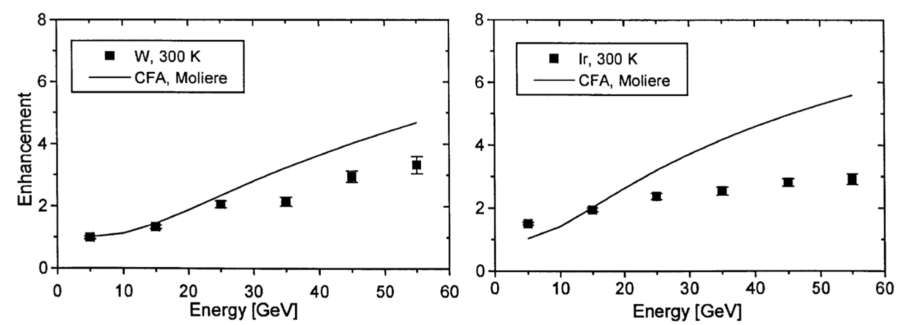
Pair prod. enhancement vs E_γ and θ_γ

Moore et al., NIMB 119, 149 (1996)



On–axis pair prod. enhancement for W and Ir

Kirsebom et al., NIMB 135, 248 (1998)

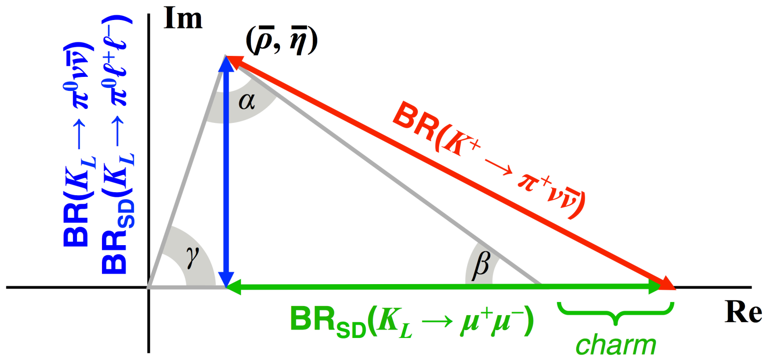


NA48 had use of high-quality crystals from MPI Stuttgart (mosaicity ~ 0.02 deg)
These crystals appear no longer to be commercially available!

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

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

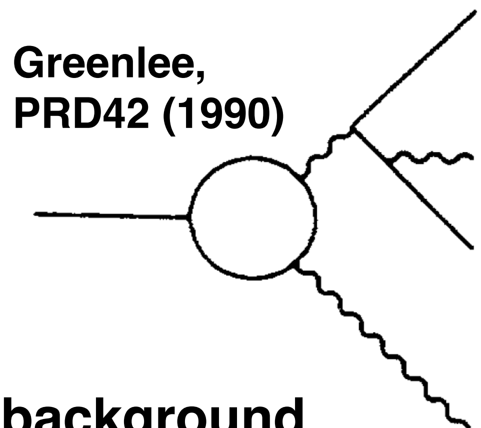


$K_L \to \pi^0 \ell^+ \ell^-$ CPV amplitude constrains UT in same way as $BR(K_L \to \pi^0 \nu\nu)$

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

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

Greenlee, PRD42 (1990)



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

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

$K_L \to \pi^0 e^+ e^-$ channel is plagued by $K_L \to e^+ e^- \gamma\gamma$ background

– Small acceptance because of tight cuts on Dalitz plot

$K_L \to \pi^0 \mu^+ \mu^-$ channel may be more tractable