KLEVER

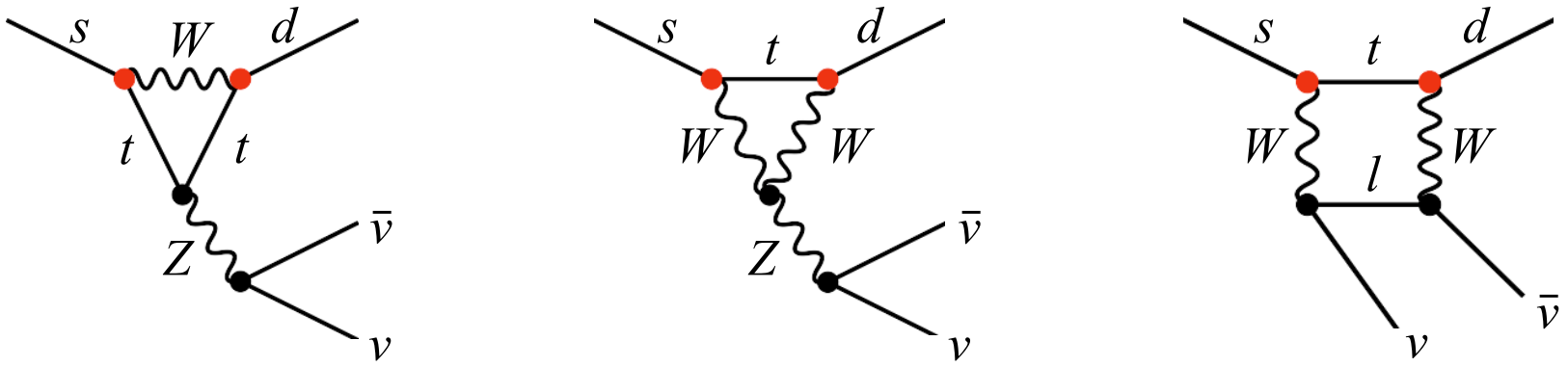
An experiment to measure BR($K_L \to \pi^0 \nu\bar{\nu}$) at the CERN SPS

International Conference on High-Energy Physics
Seoul, 7 July 2018

Matthew Moulson – INFN Frascati
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

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

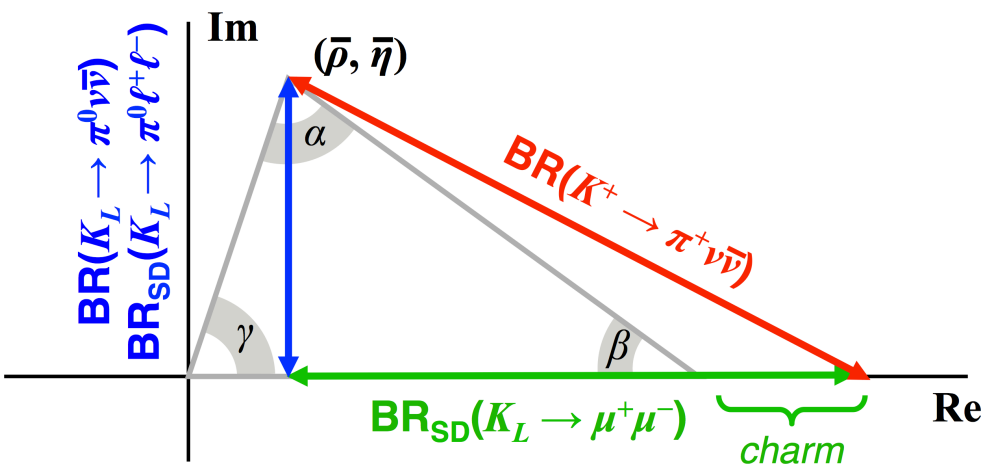
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

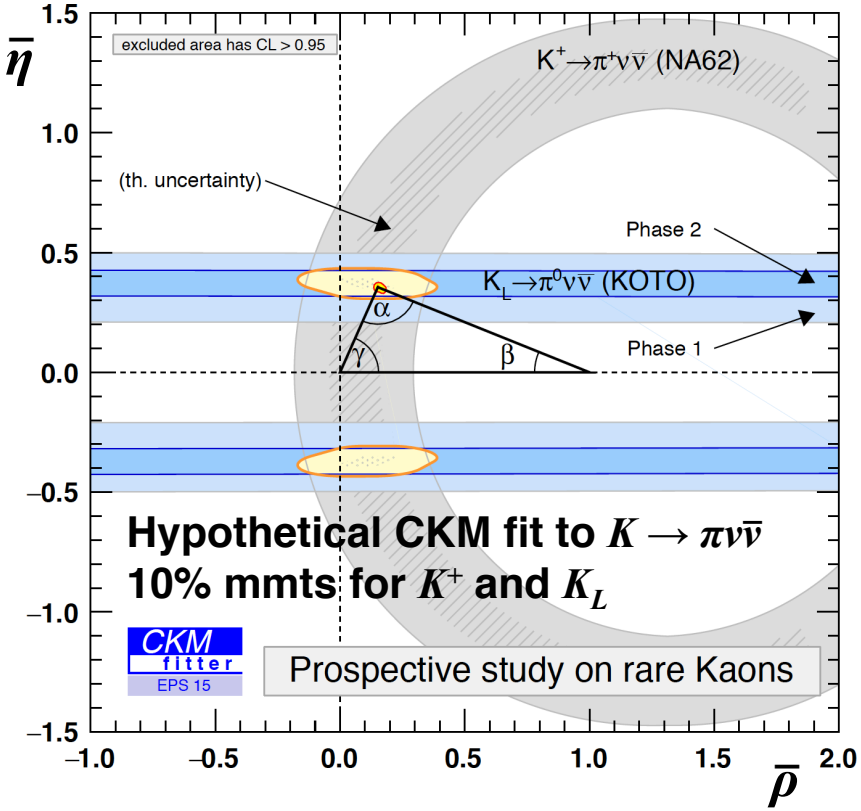
Buras et al., JHEP 1511

Intrinsic theory uncertainties ~ few percent

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

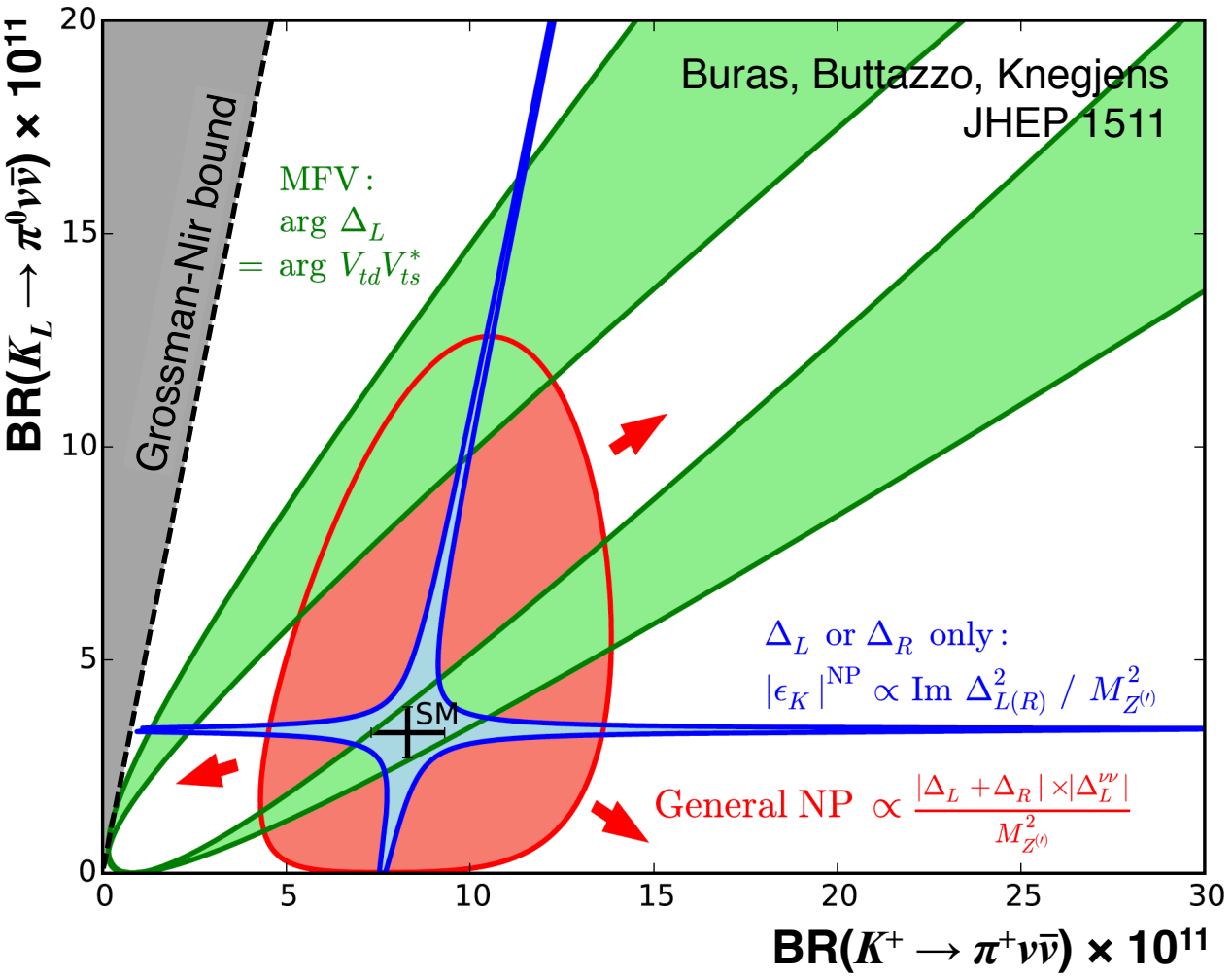
- Overconstrain CKM matrix → reveal NP?





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

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

LAV
Large angle photon vetoes
OPAL lead glass

RICH
RICH μ/π ID
1 atm Ne

MUV
μ veto
Fe/scint

CHANTI
Charged veto

KTAG
Differential Cerenkov for K^+ ID in beam

4 m

Fiducial volume ~60m
10^{-6} mbar

5 MHz K^+ decays

γ veto
IRC

γ veto
SAC

Beam tracking
Si pixels, 3 stations
GIGATRACKER

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

Dipole spectrometer
4 straw-tracker stations
STRAW

Forward γ veto
NA48 LKr
LKr

0 50 100 150 200 250 m

NA62 status and timeline

2016	Commissioning + 1st physics run
	Preliminary result presented in March 2018
	Expected 0.267 signal, 0.15 ± 0.09 background
	1 event observed
	BR($K^+ \to \pi^+ \nu\nu$) < 14 × 10^{-10} (95%CL)
2017	Physics run (23 weeks)
	20x more data than 2016 result
	Data processing in progress
2018	Physics run (31 weeks, started 9 April)
2019-2020	LS2 (LHC Long Shutdown 2)

By end of 2018 NA62 will reach a sensitivity of 20 SM $K^+ \to \pi^+ \nu\nu$ events

- Input to the European Strategy for Particle Physics
- Solid extrapolation to ultimate sensitivity of NA62 achievable after LS2

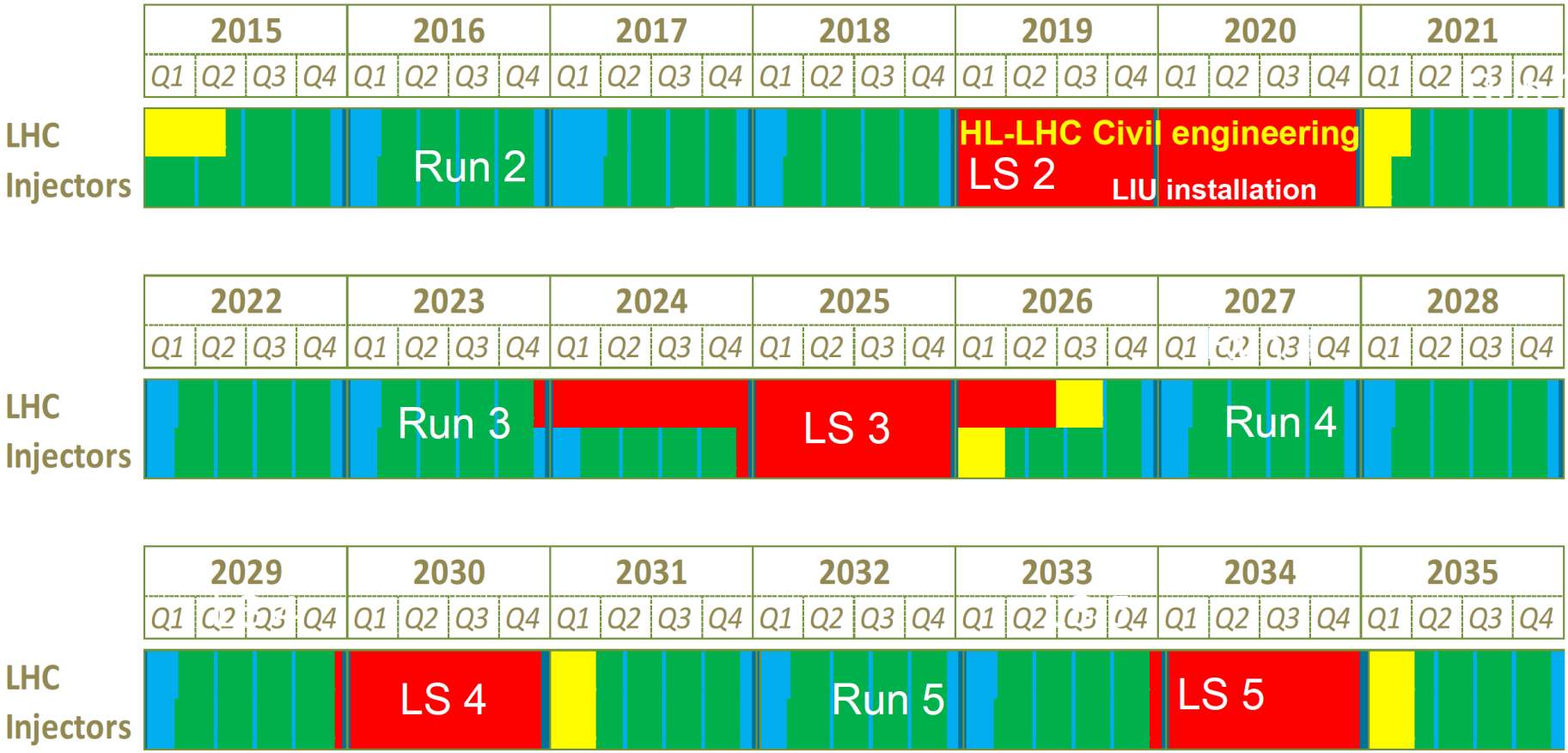
Fixed target runs at the SPS

2021 (Run 3): Intention to continue data taking with NA62

- Measure BR($K^+ \to \pi^+ \nu\nu$) with ultimate sensitivity
- Search for hidden particles in beam-dump mode

Physics
Shutdown
Beam commissioning
Technical stop

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



F. Bordry, presentation to HEPAP, Dec 2015

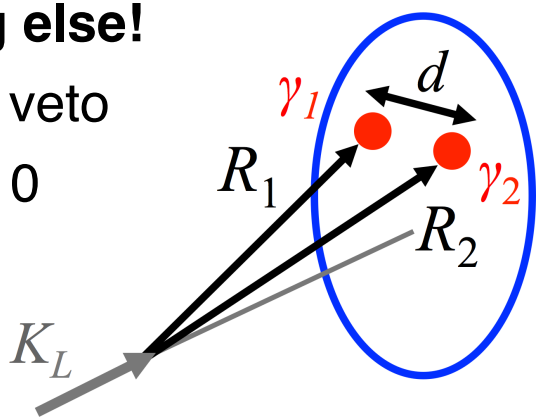
$K_L \to \pi^0 \nu\bar{\nu}$: Experimental issues

KLEVER

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

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

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

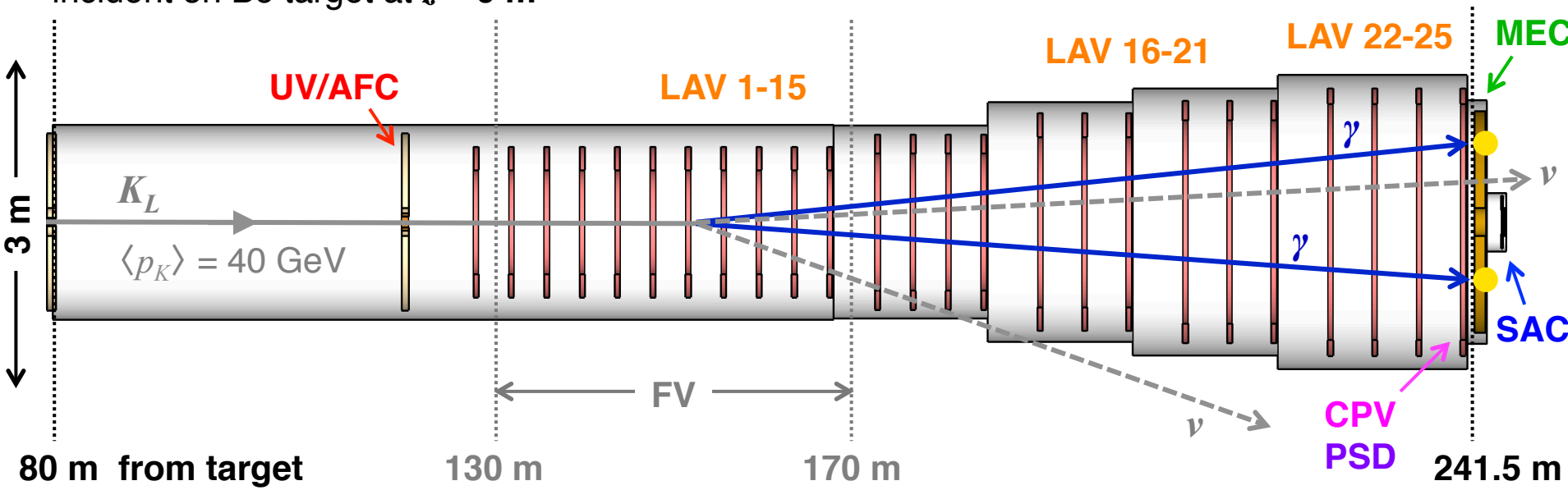
Main backgrounds:

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

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

KLEVER

400-GeV SPS proton beam (2×10^{13} pot/16.8 s)
incident on Be target at z **= 0 m**



KLEVER

K_L Experiment for VEry Rare events

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

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

KLEVER

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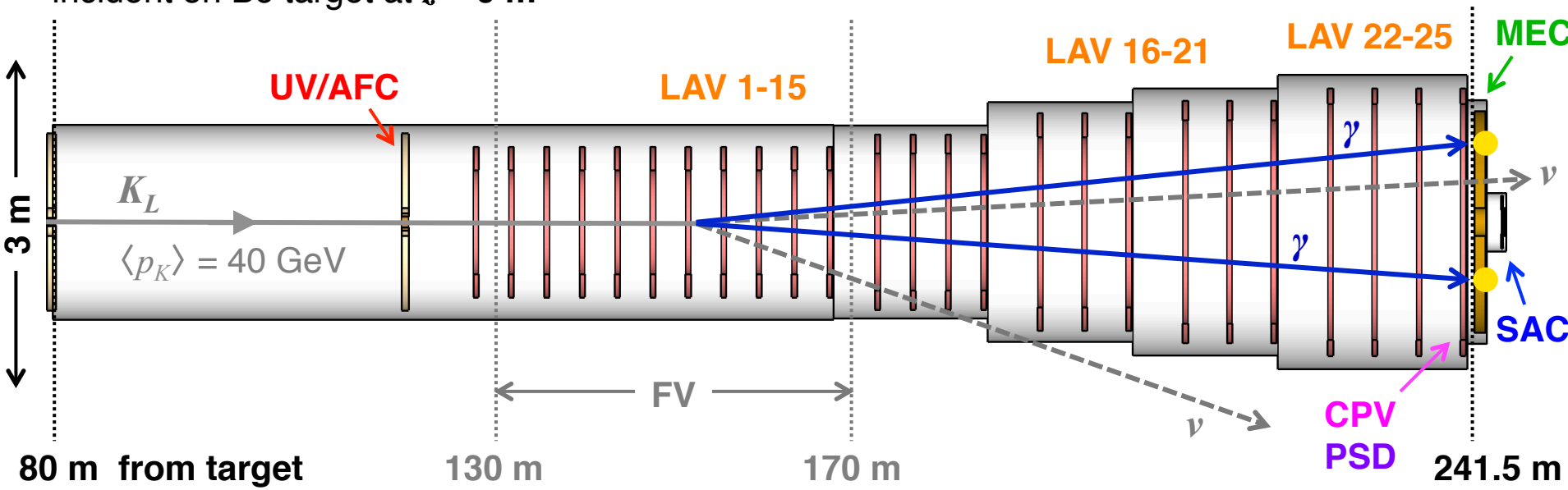


KLEVER target sensitivity:

5 years starting Run 4

60 SM $K_L \to \pi^0 \nu\nu$

$S/B \sim 1$

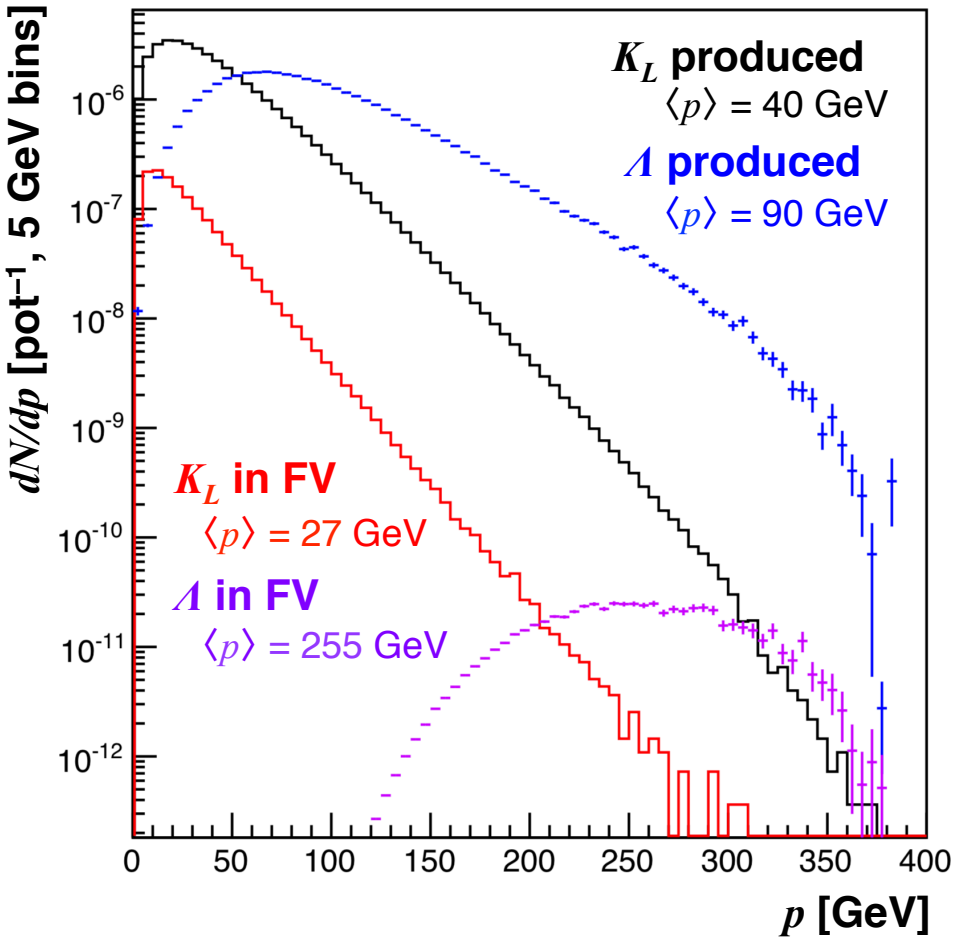
δBR/BR($\pi^0 \nu\nu$) ~ 20%

Main detector/veto systems:

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

Beam and intensity requirements

K_L and Λ fluxes in beam
FLUKA simulation

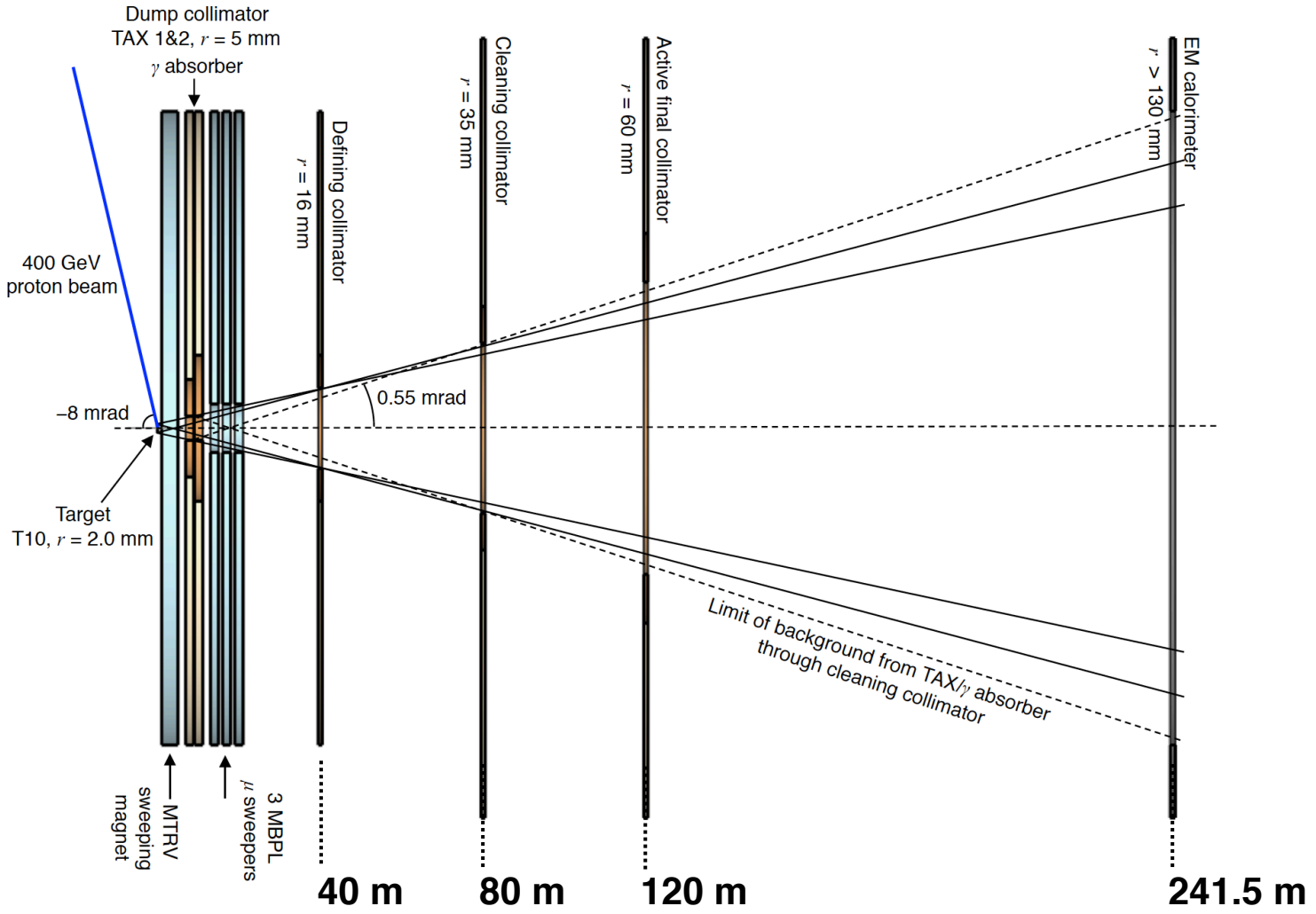


- **400 GeV p on 400 mm Be target**
- **Production at θ = 8.0 mrad:**
  - As much K_L production as possible
  - Low ratio of n/K_L in beam ~ 3
  - Reduce Λ production and soften momentum spectrum
- **Solid angle $\Delta\theta$ = 0.4 mrad**
  - Large $\Delta\theta$ = high K_L flux
  - Maintain tight beam collimation to improves $p_\perp$ constraint for background rejection
- **2.1 × 10^{-5} K_L in beam/pot**
- Probability for decay inside FV ~ 2%
- Acceptance for $K_L \to \pi^0\nu\nu$ decays occurring in FV ~ 10%

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

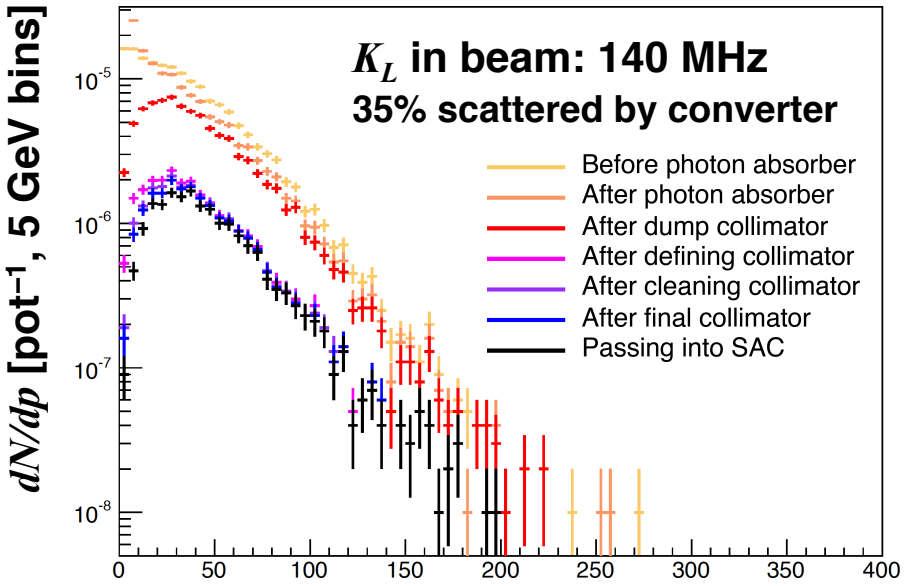
× 5 years ⇨ **60 $K_L \to \pi^0\nu\nu$ events**

Neutral beamline layout



- Compact primary beam sweeping
- Photon absorber in dump collimator
- 4 collimation stages to minimize neutron halo, including beam scattered from absorber
- Active final collimator in LYSO

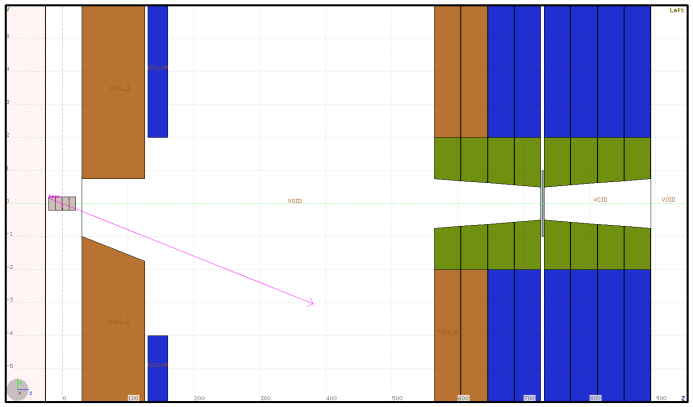
Neutral beam simulation

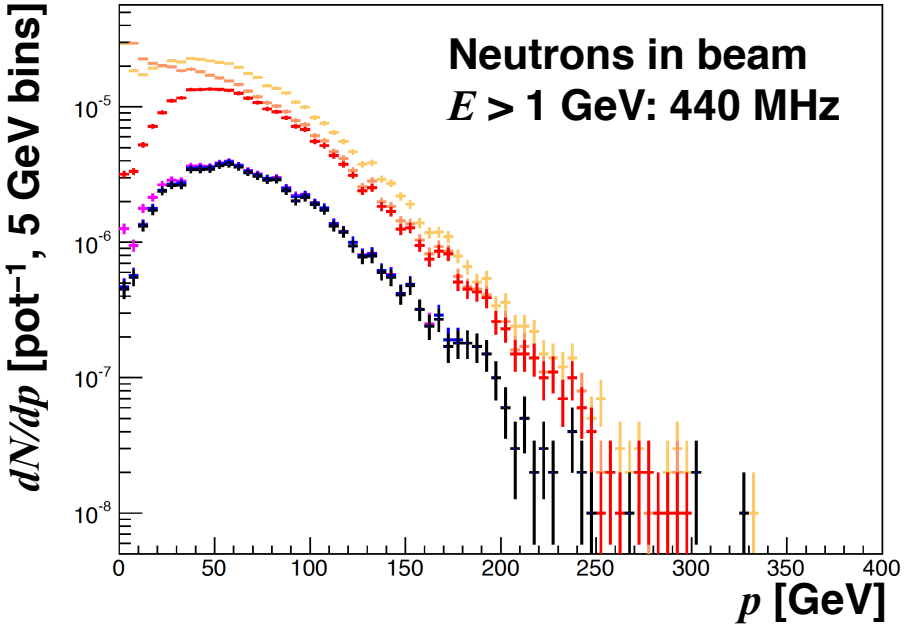


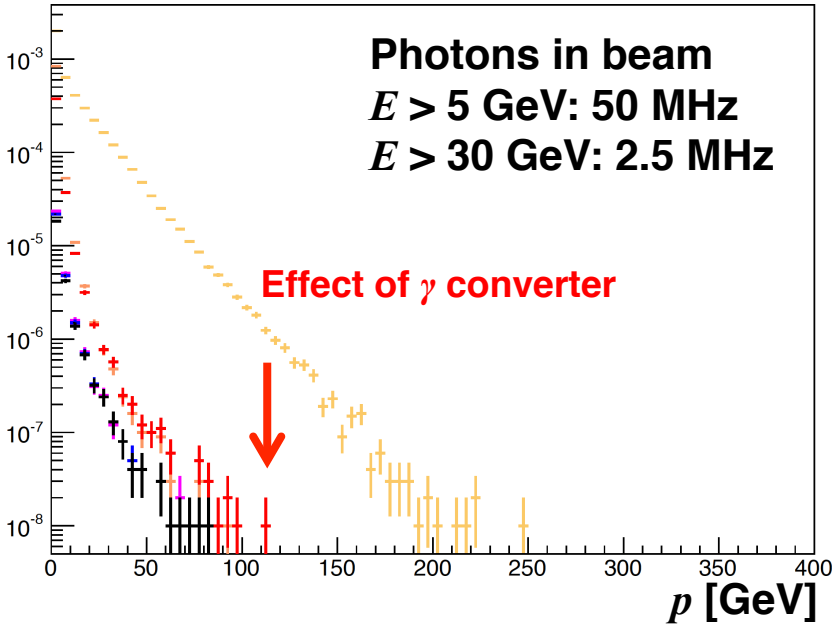
FLUKA simulation of beamline

32-mm tungsten coverter ($9X_0$)

Detail of target and dump collimator:







Shashlyk calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

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

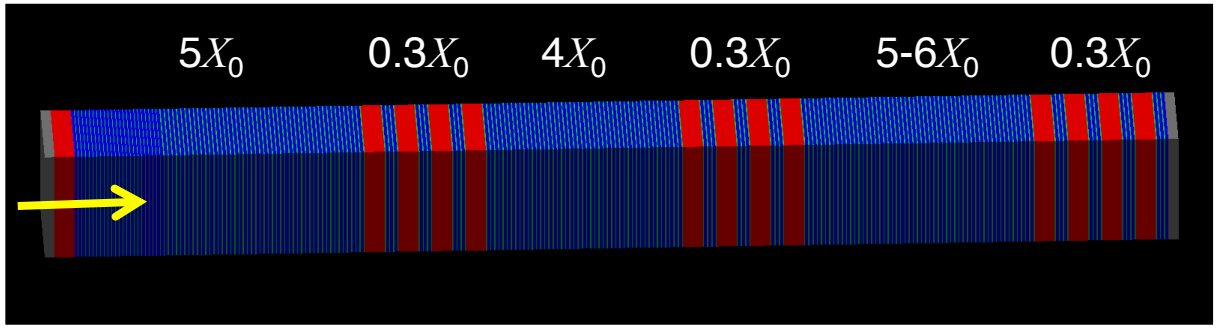
0.275 mm Pb + 1.5 mm scintillator

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)

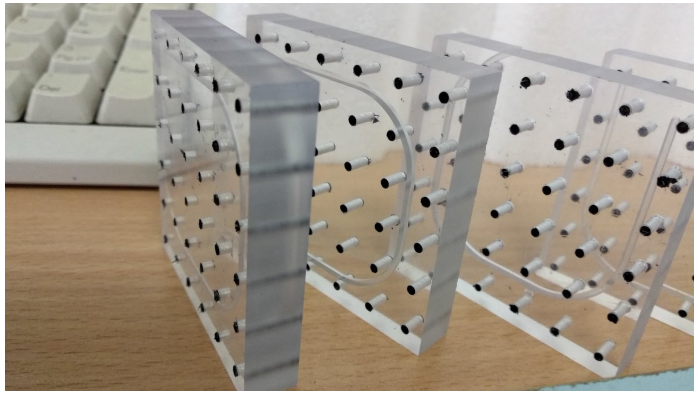
New for KLEVER: Longitudinal shower information from spy tiles

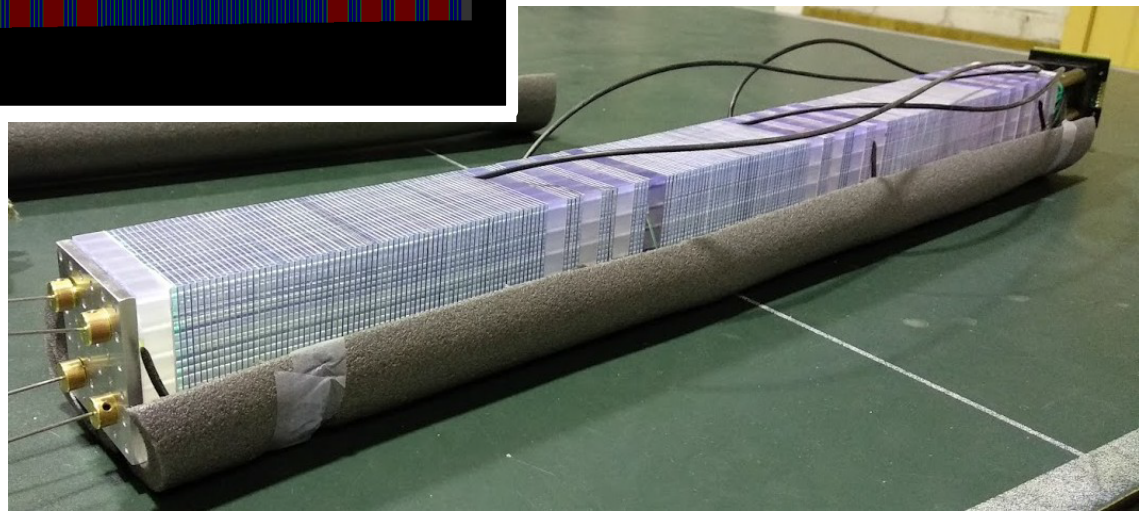
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



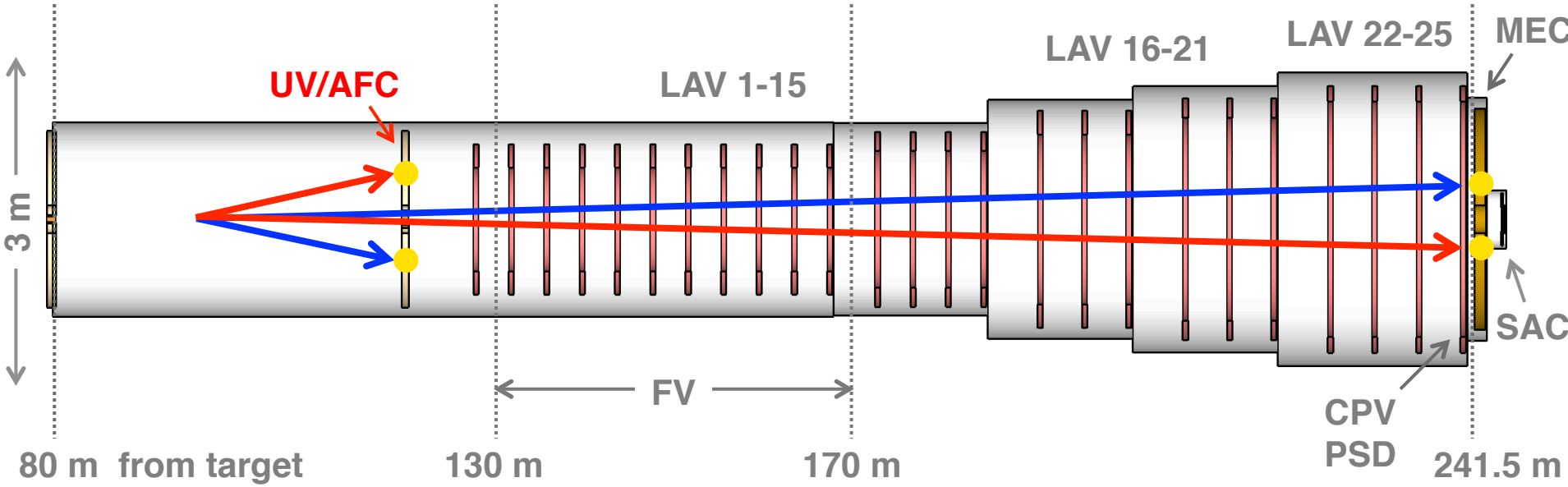
1st prototype assembled and tested at Protvino

OKA beamline, April 2018



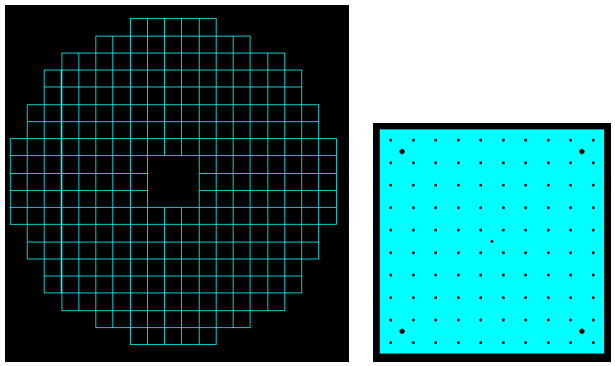


Vetoes for upstream $K_L \to \pi^0\pi^0$

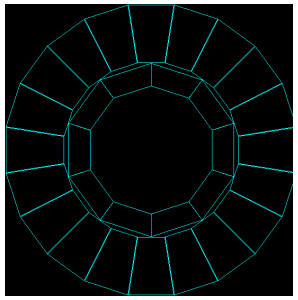


Upstream veto (UV):

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



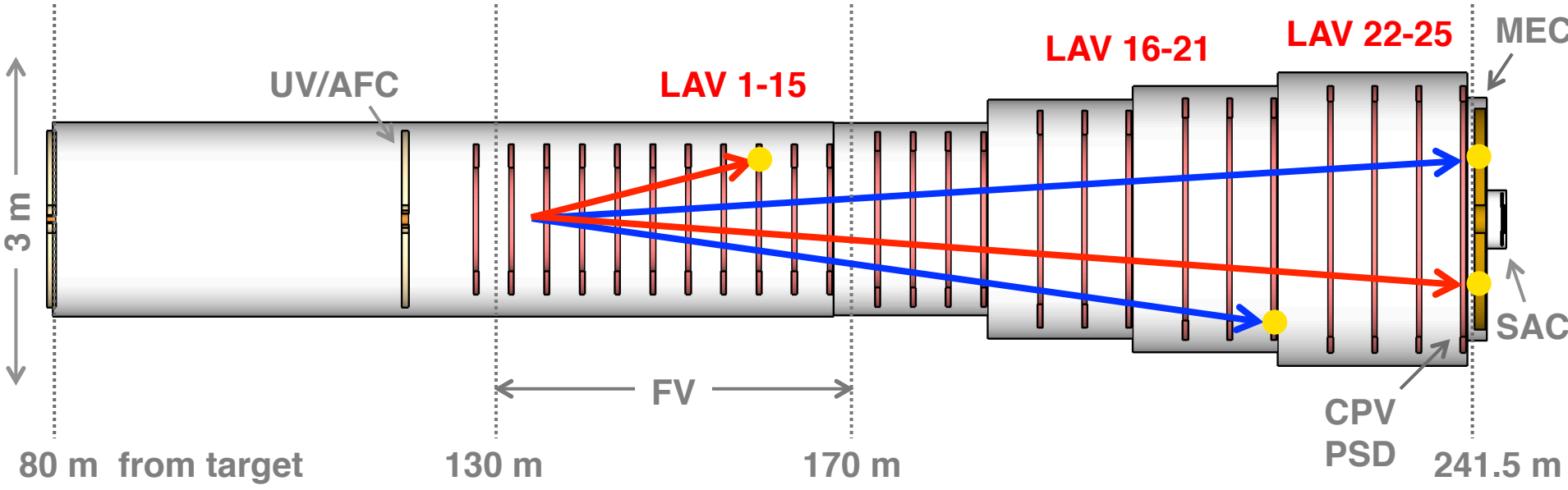
Active final collimator:



- 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 $K_L \to \pi^0\pi^0$ in transit through collimator

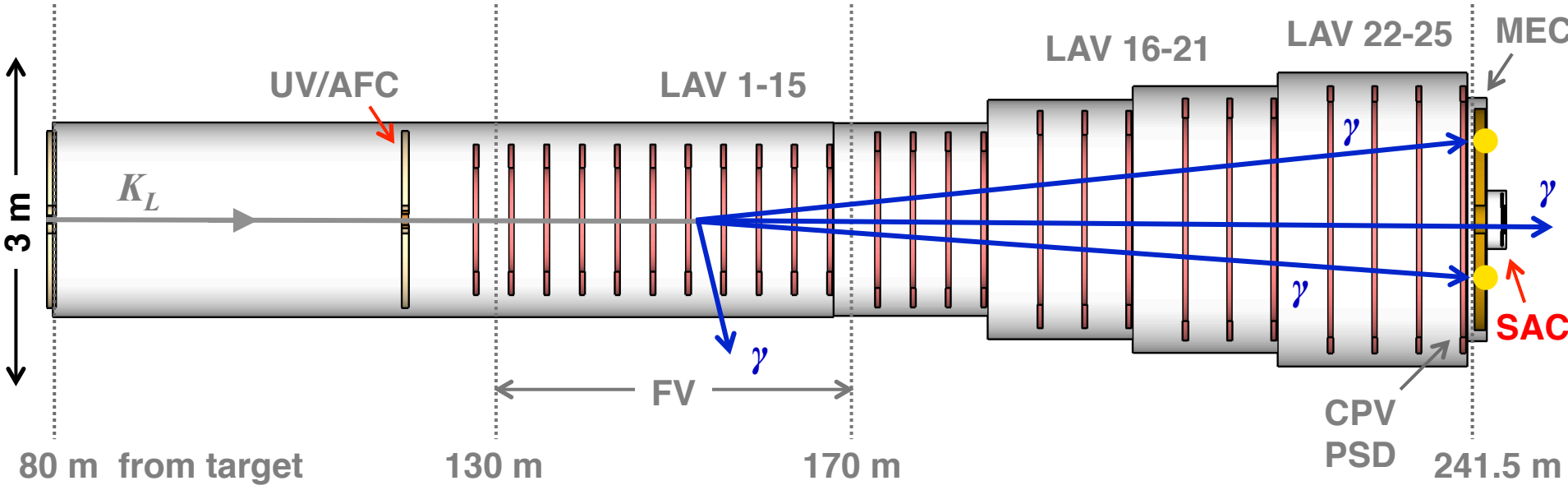
Large-angle photon vetoes



25 new large-angle photon veto stations (LAV)

- 5 sizes, sensitive radius 0.85 to 1.5 m, at intervals of 4 to 5 m
- Hermetic coverage out to 100 mrad
  Need good detection efficiency at low energy ($1 - \varepsilon \sim 0.5\%$ at 20 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 veto



Small-angle photon calorimeter system (SAC)

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

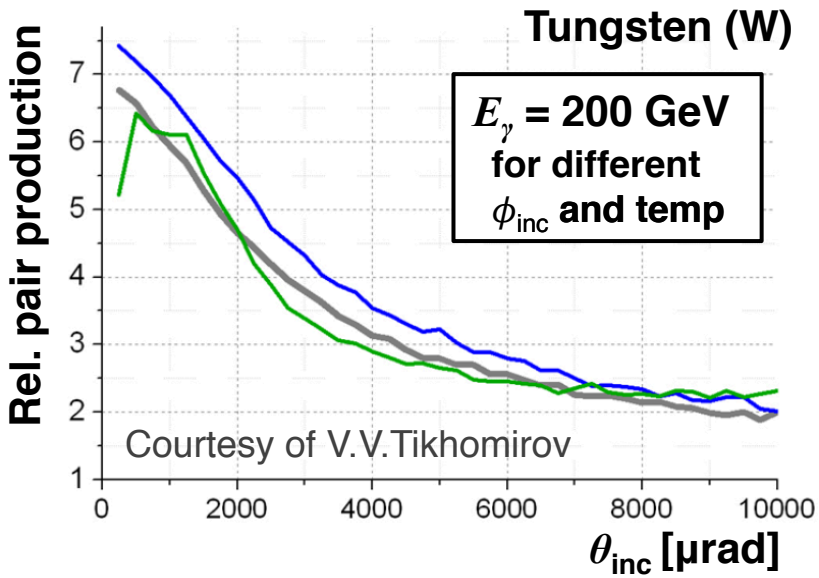
Beam comp.	Rate (MHz)	Req. $1-\varepsilon$
$\gamma, E > 5$ GeV	**50**	**10^{-2}**
$\gamma, E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

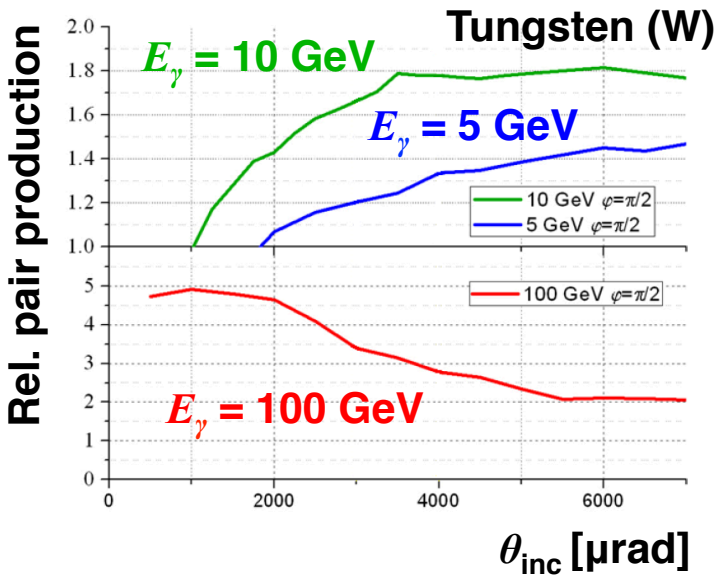
Baseline solution:

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

Efficient γ conversion with crystals

Coherent effects in crystals enhance pair-conversion probability





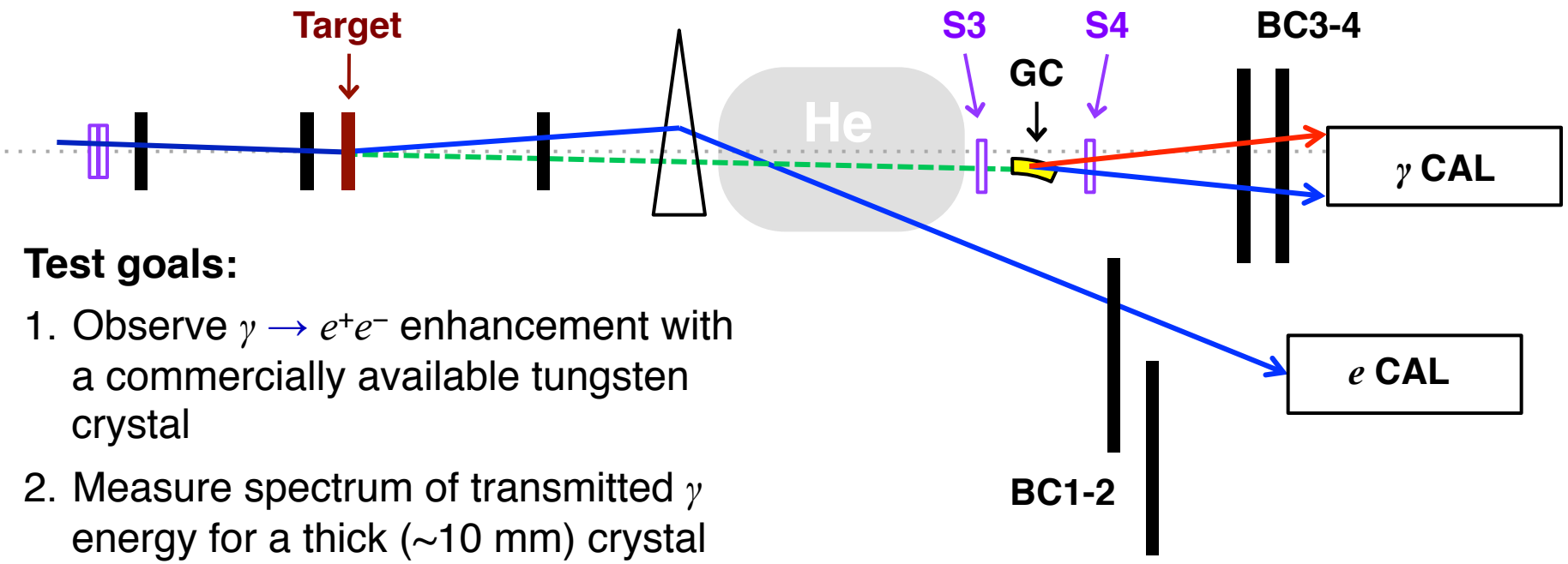
Use coherent effects to obtain a converter with large effective λ_{int}/X_0:

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 high flux of beam neutrons while efficiently vetoing high-energy γs from K_L decays

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

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

Tagged photon test beam setup:

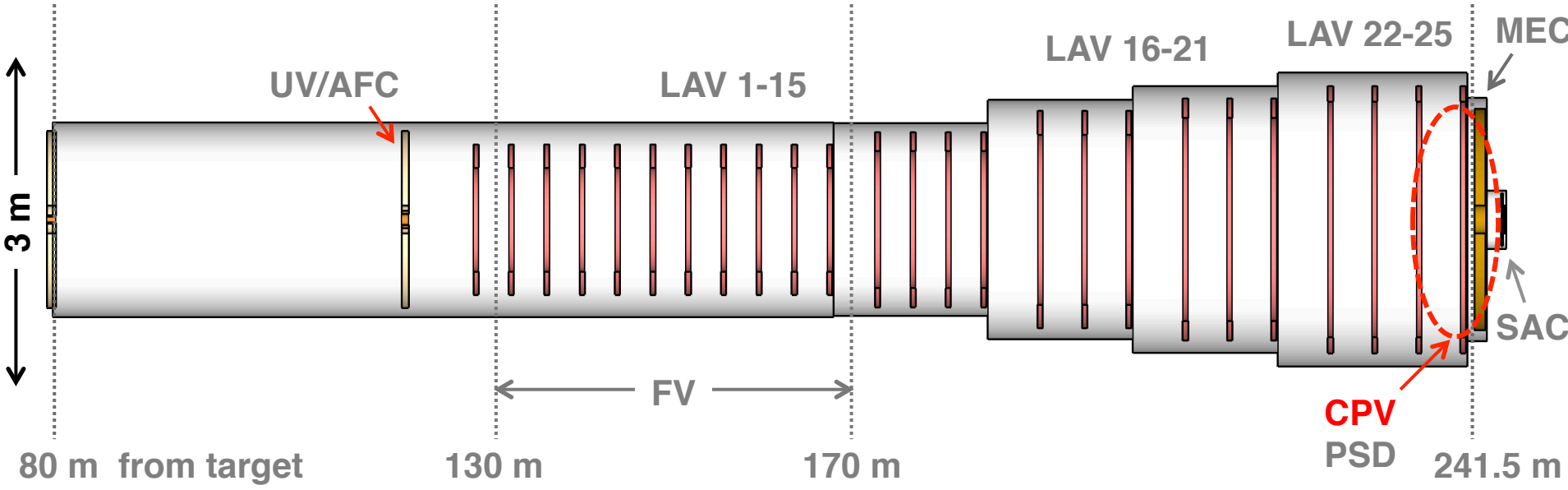


Test goals:

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 H2 beam 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!**

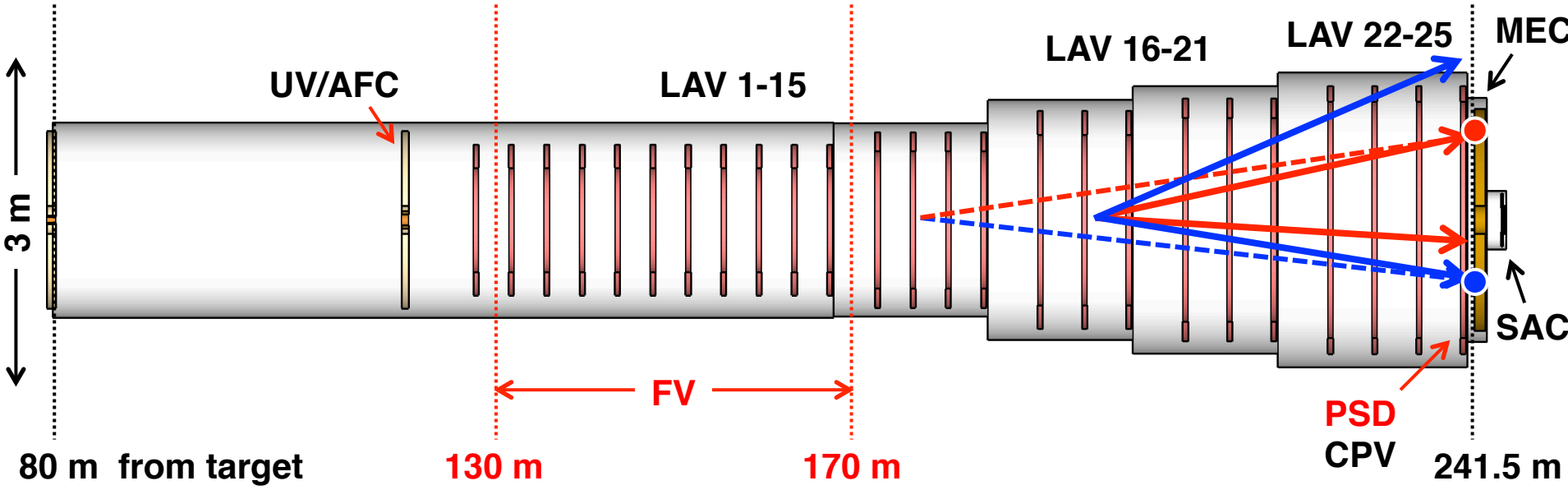
Charged particle veto (CPV)

- Scintillating tiles, just upstream of MEC

Calorimetric ID for μ and π

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

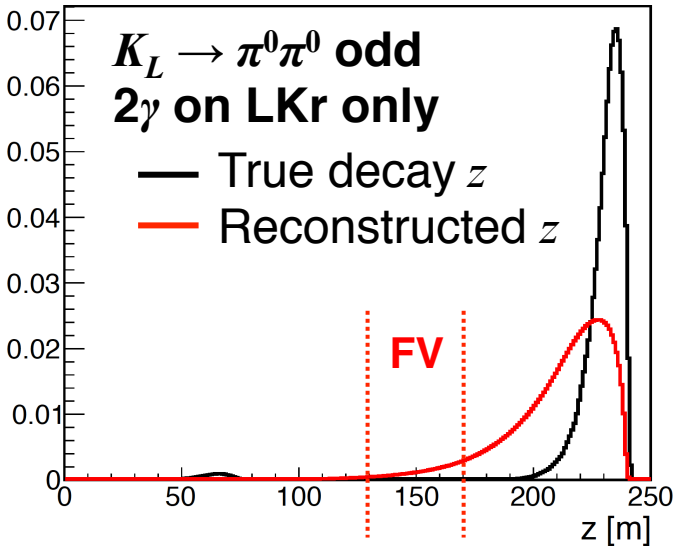
Mispaired $K_L \to \pi^0\pi^0$ events



Distance from FV to LKr significantly helps for rejection of "odd" background from $K_L \to \pi^0\pi^0$

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

Preshower detector (PSD) is particularly effective against downstream decays



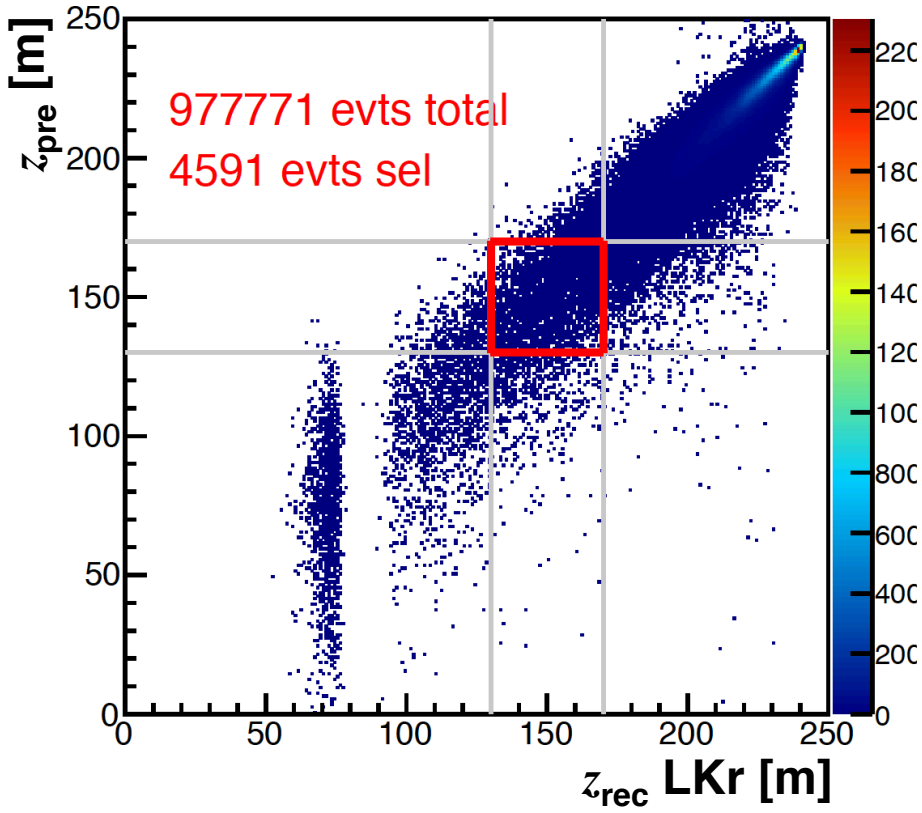
Preshower background rejection

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

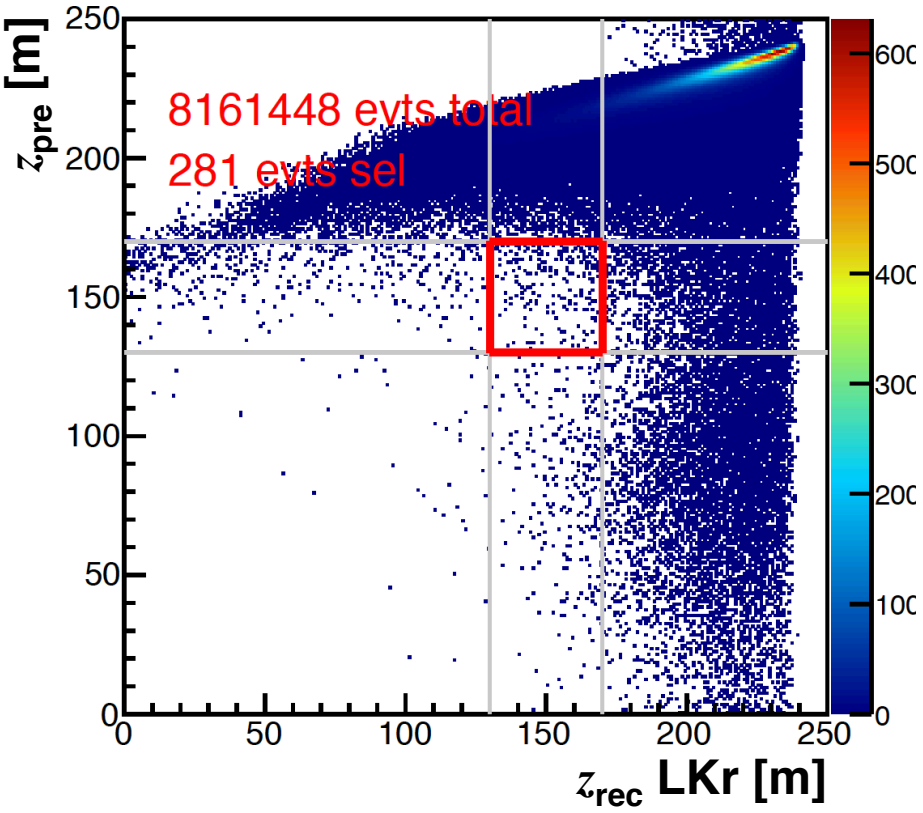
z_{rec} reconstructed by imposing $M(\gamma\gamma) = m_{\pi 0}$

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

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



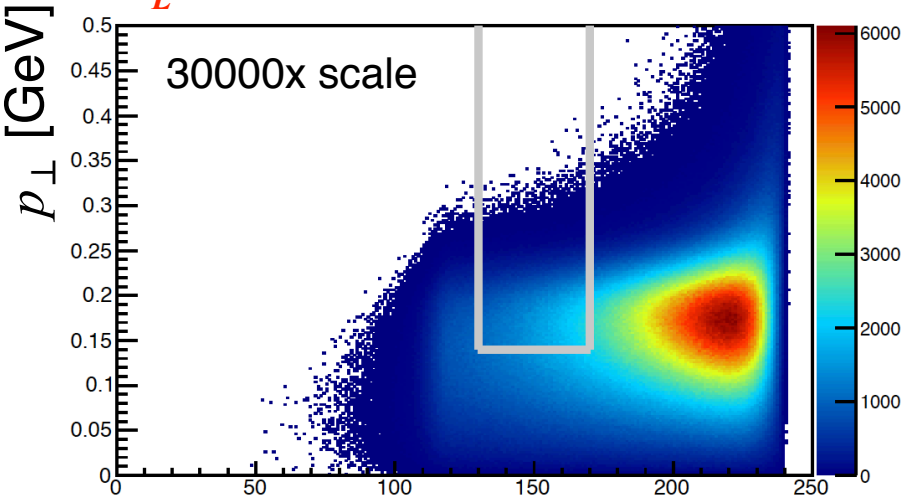
Odd pairs (2 γs from different π^0)
1 γ converts in preshower



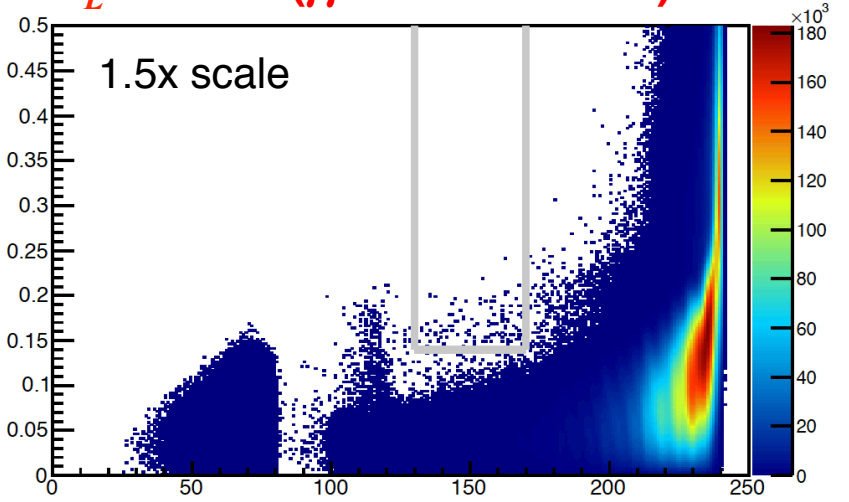
Basic signal selection

No hits in UV, AFC, LAV, SAC + fiducial volume (FV) and $p_\perp$ cuts

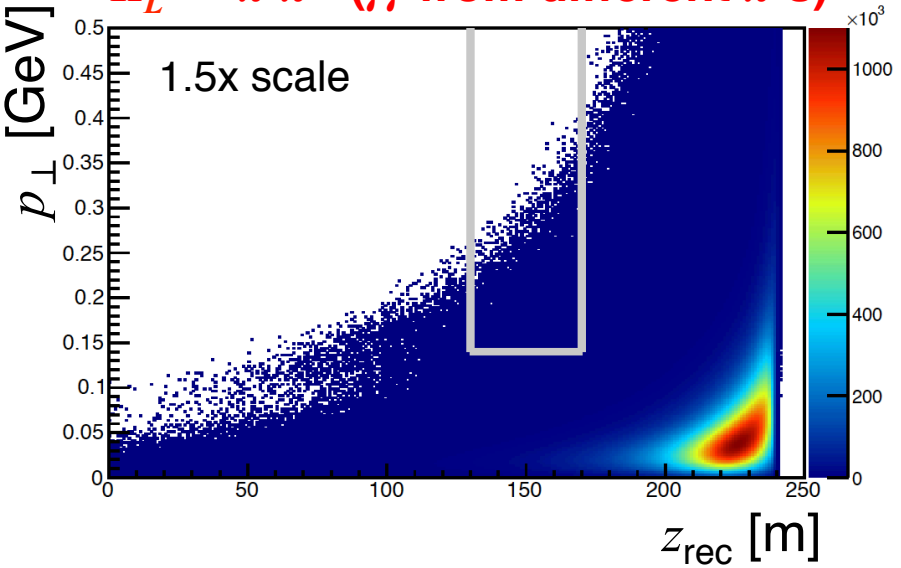
$K_L \to \pi^0\nu\nu$



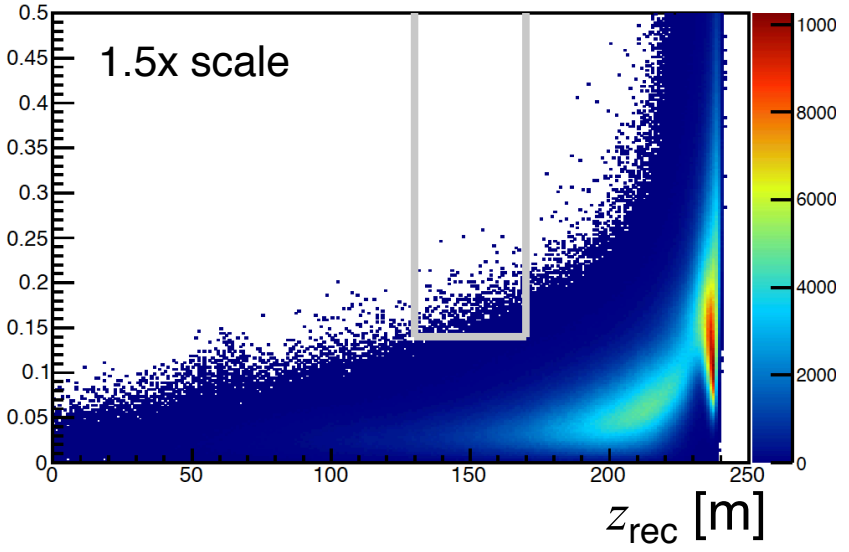
$K_L \to \pi^0\pi^0$ ($\gamma\gamma$ from same π^0)



$K_L \to \pi^0\pi^0$ ($\gamma\gamma$ from different π^0s)



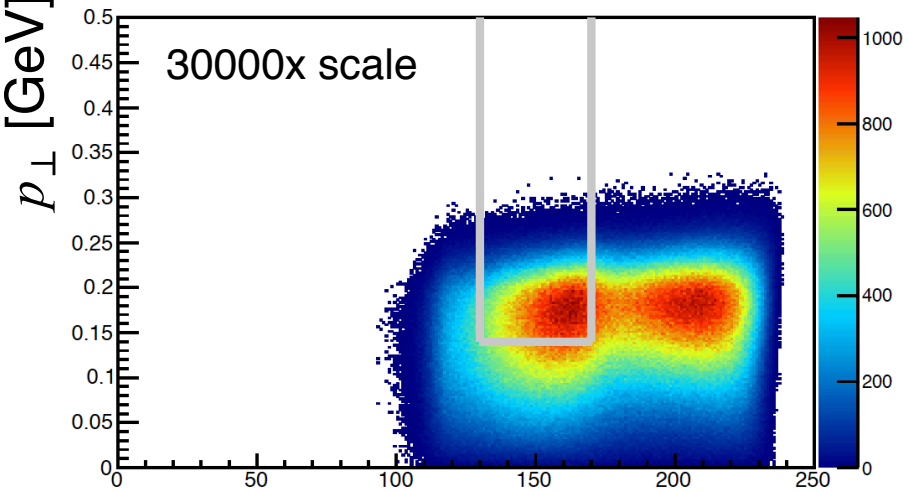
$K_L \to \pi^0\pi^0$ (overlapped clusters)



Additional background rejection

Cluster radius r_{MEC} > 35 cm – Require z_{PSD} in FV if PSD hit available

$K_L \to \pi^0\nu\nu$



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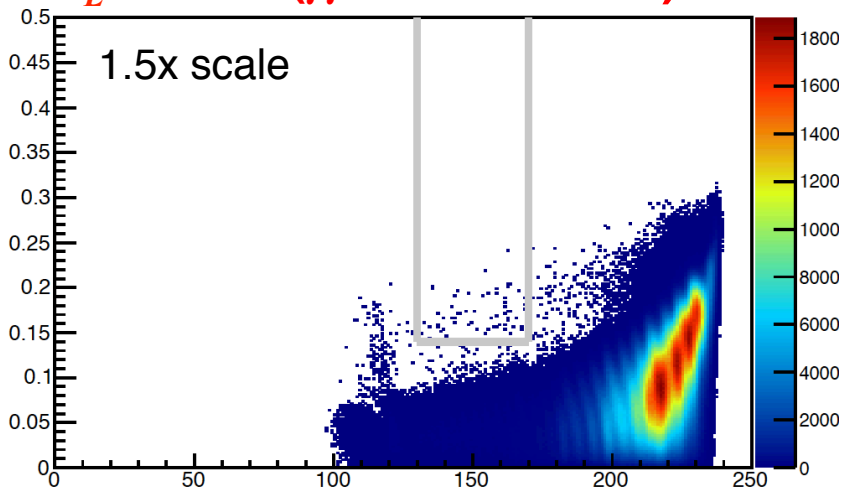
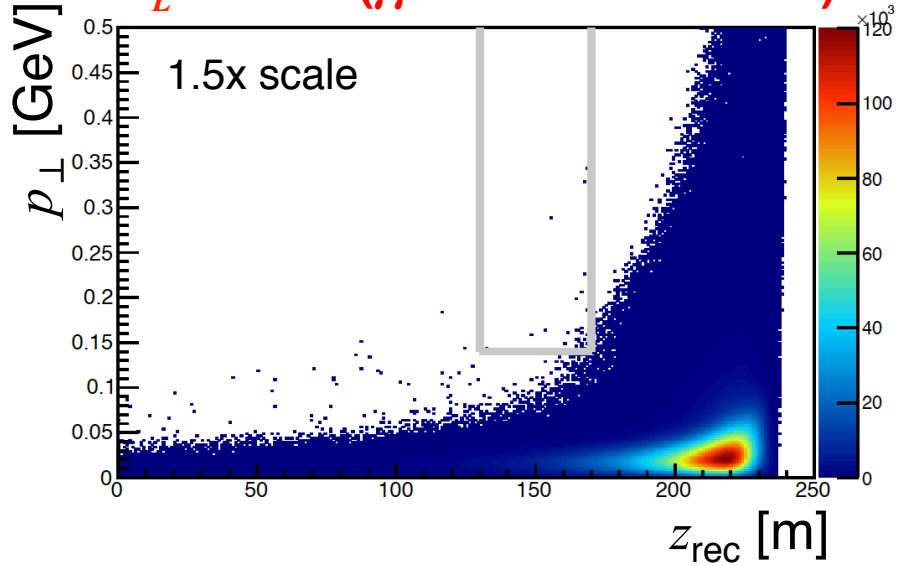
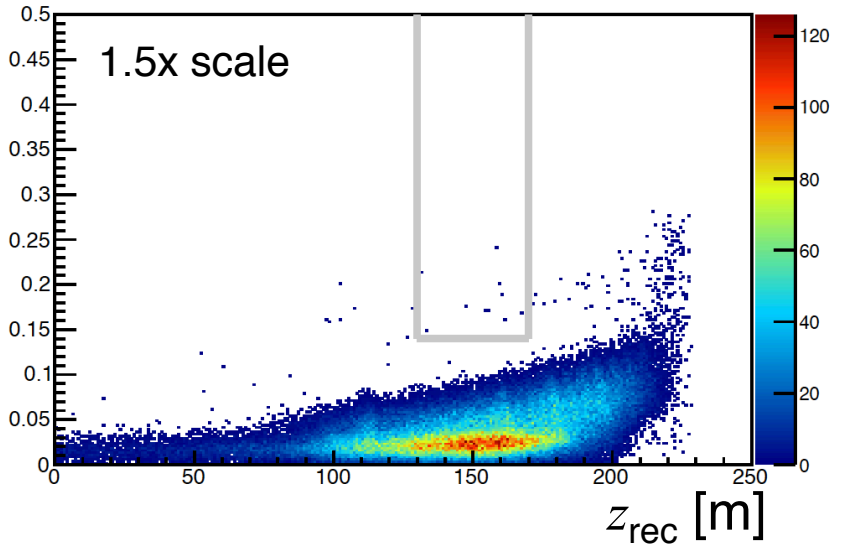


$K_L \to \pi^0\pi^0$ ($\gamma\gamma$ from different π^0s)



$K_L \to \pi^0\pi^0$ (overlapped clusters)



Status and timeline

Project timeline – target dates:

2017-2018	**Project consolidation and proposal** • Participation in Physics Beyond Colliders • Beam test of crystal pair enhancement • Input to European Strategy for Particle Physics • Expression of Interest to CERN SPSC
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!

Summary and outlook

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

$K \to \pi\nu\nu$ is a uniquely sensitive indirect probe for high mass scales

- Need precision measurements of both K^+ and K_L decays

NA62 will improve on current knowledge of BR($K^+ \to \pi^+\nu\nu$) in the short term, ultimately reaching ~100 event sensitivity

KOTO will reach SM sensitivity to BR($K_L \to \pi^0\nu\nu$) by 2021

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

- Many issues still to be addressed!
- Expected sensitivity: ~ 60 SM events with $S/B \sim 1$

KLEVER is actively seeking new collaborators

- Expression of Interest to SPSC and input to ESPP in preparation
- Small contributions now can have a big impact!

Additional information

International Conference on High-Energy Physics
Seoul, 7 July 2018

Matthew Moulson – INFN Frascati
For the KLEVER project

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

Do constraints from Re ε'/ε, ε_K, Δm_K, $K_L \to \mu\mu$ limit size of effects on $K \to \pi\nu\nu$ BRs?

Model	Effect	Refs
Vector-like quarks	K_L suppressed, K^+ possibly enhanced	Bobeth et al. '16
Leptoquarks	Large effects for both K_L, K^+: possibly ruled out?	Bobeth, Buras '17
Simplified Z	K_L suppressed 30%, K^+ enhanced up to 2x	Endo et al. '17
SUSY	K^+ and K_L enhanced 10-20% for $\Lambda_{SUSY} \sim 3$ TeV	Kitahara et al. '16

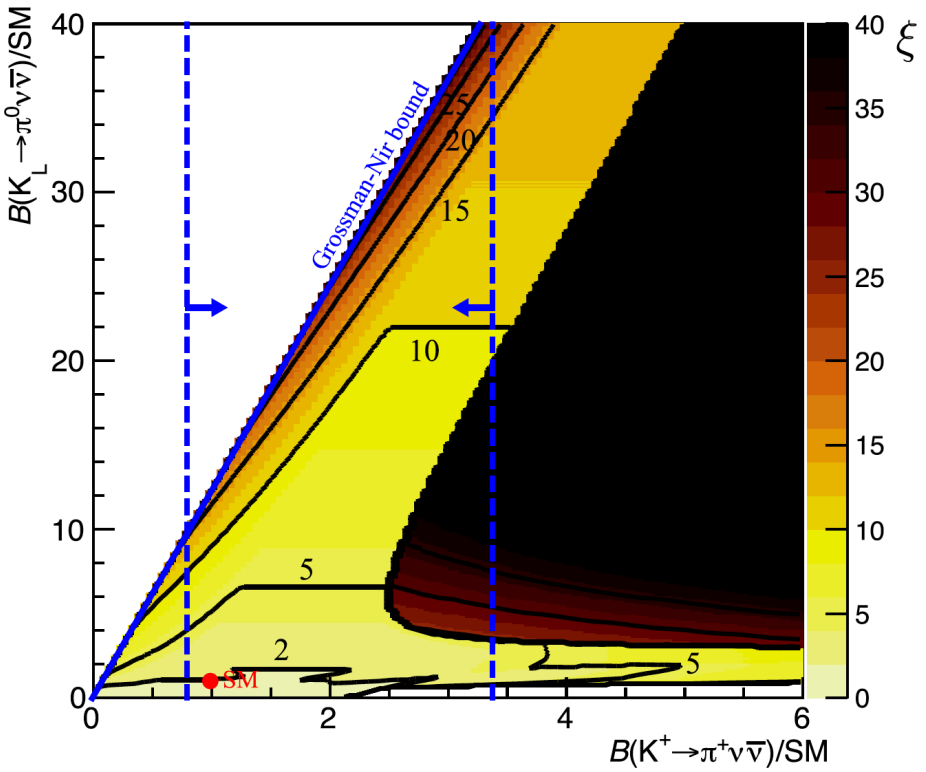
Endo et al. PLB771 (2017)

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($K_L \to \pi^0\nu\nu$) ~ 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

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

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

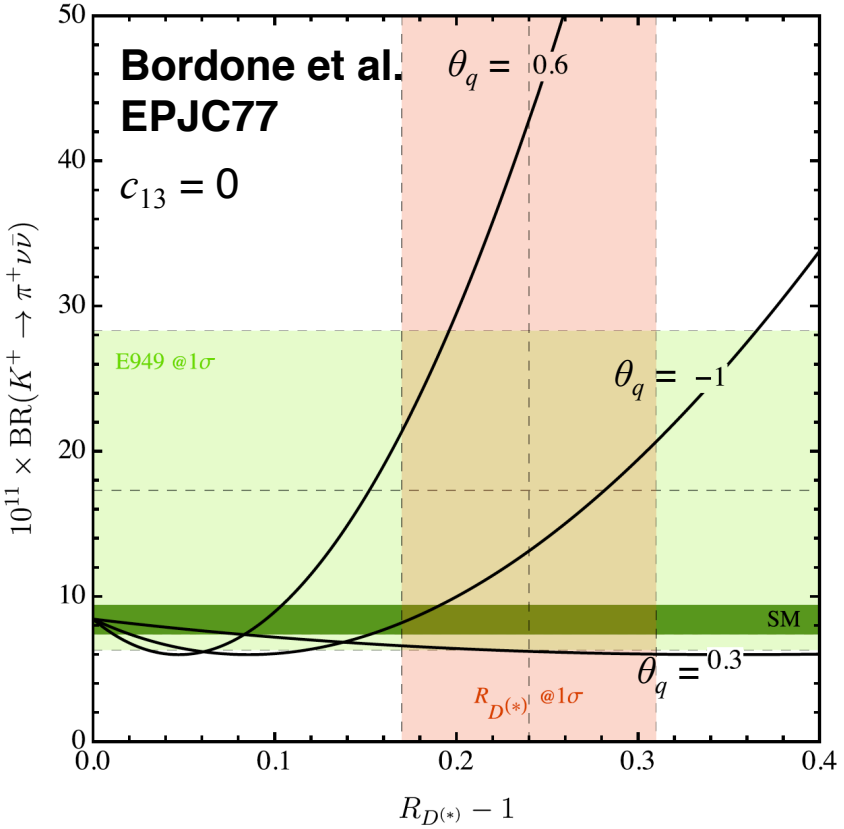
$R_{D^{(*)}}$: $\tau/(\mu, e)$ LFU in $B \to D^{(*)}\ell\nu$

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)**



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

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

High-intensity proton beam issues

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 Physics Beyond Colliders

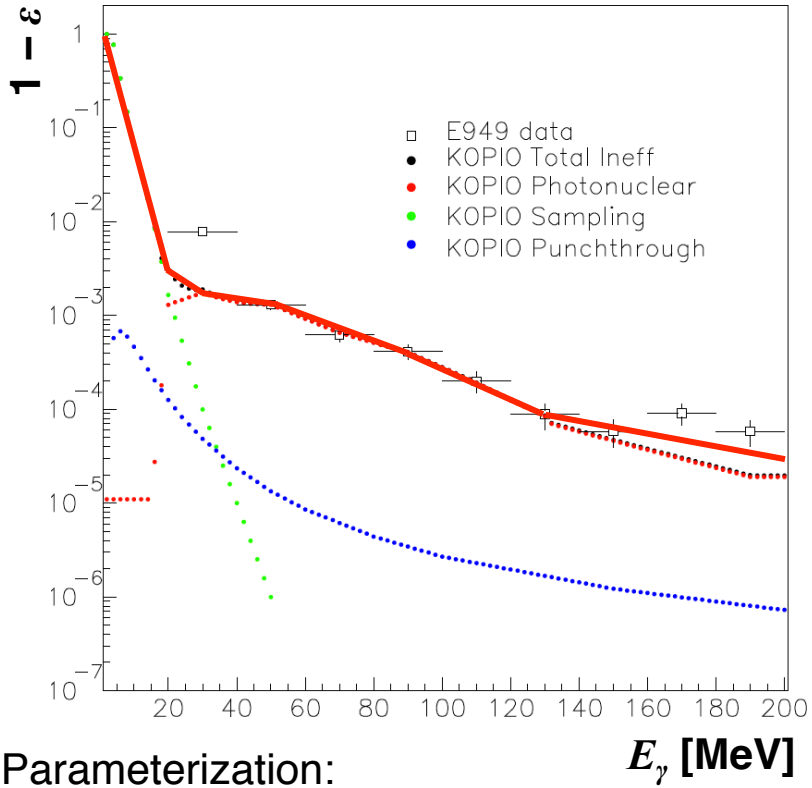
Preliminary analysis of critical issues by Secondary Beams & Areas group

Issue	Approach
Proton availability	SHiP supercycle = 4 × 10^{19} pot/yr with 1 × 10^{13} ppp for users KLEVER requires 1 × 10^{19} pot/yr (25% of SHiP)
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 transmission to T10
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
Background fluxes	Starting simulations for prompt background above target 8 mrad vertical targeting angle should help to mitigate

Large-angle photon vetoes

Need good detection efficiency at low energy ($1 - \varepsilon \sim 0.5\%$ at 20 MeV)

Baseline technology: CKM VVS
Scintillating tile with WLS readout

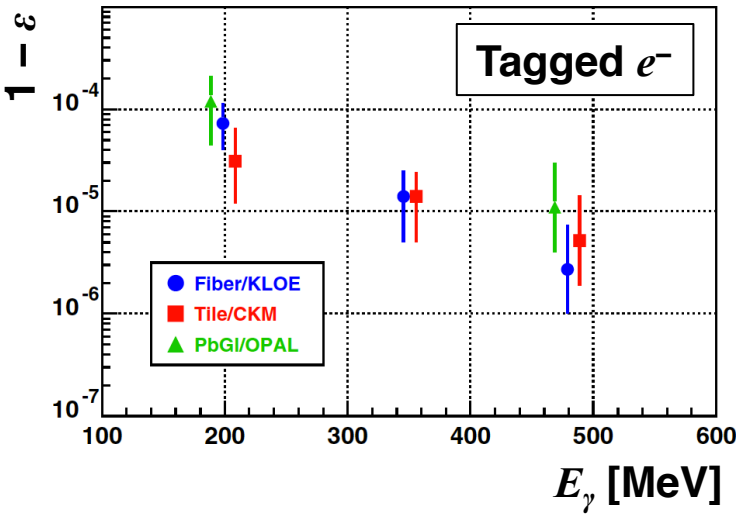


Parameterization:
- 1-129 MeV: KOPIO (E949 barrel)
- 203-483 MeV: CKM VVS

Good efficiency assumptions based on E949 and CKM VVS experience

E949 barrel veto efficiencies
Same construction as CKM

Tests for NA62 at Frascati BTF

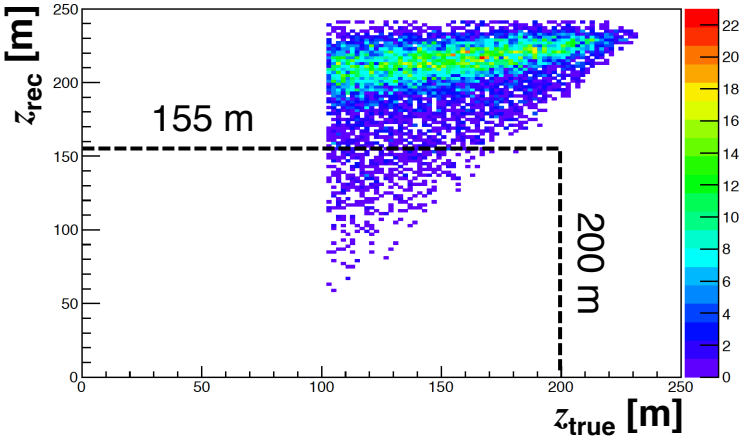


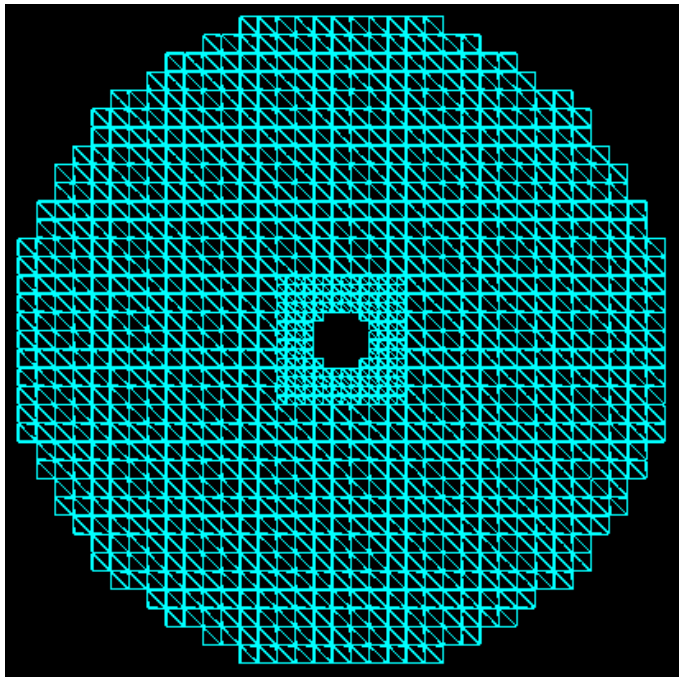
Tests at JLAB for CKM:
- $1 - \varepsilon \sim 3 \times 10^{-6}$ at 1200 MeV

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 $z_{rec} < 200$ 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

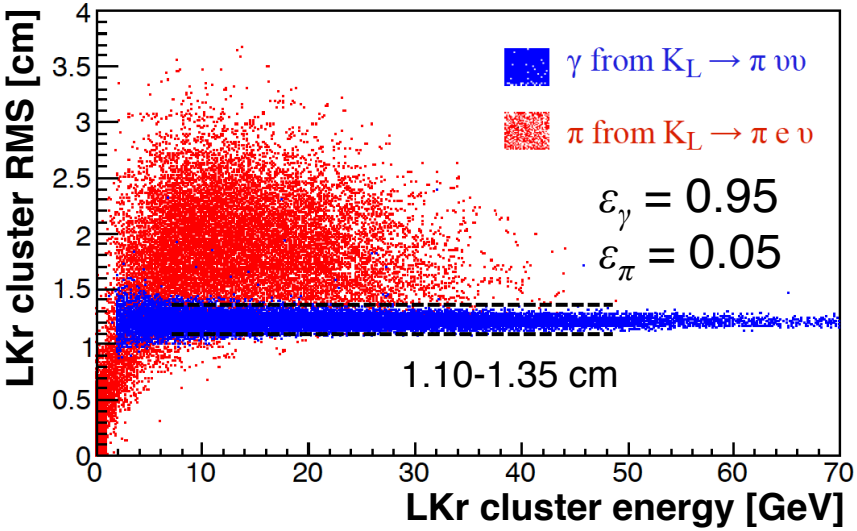
Charged particle rejection

$K_L \to \pi e \nu$ 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

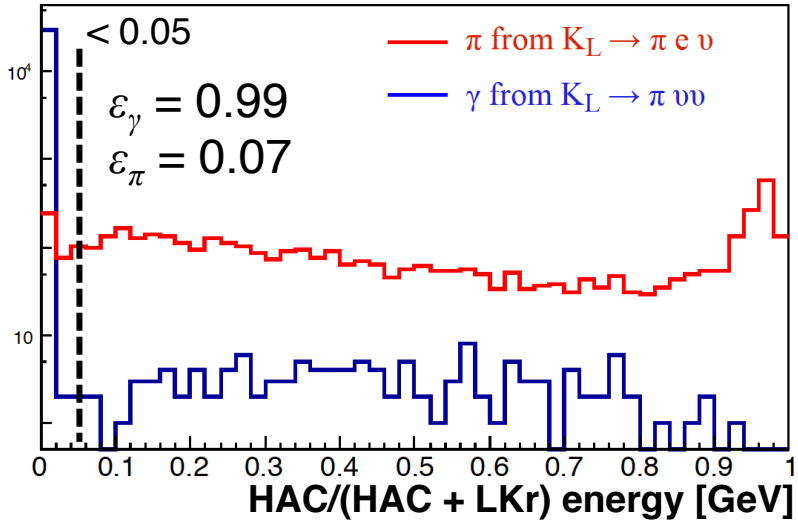


Ratio of hadronic/total energy effective to identify π showers

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

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

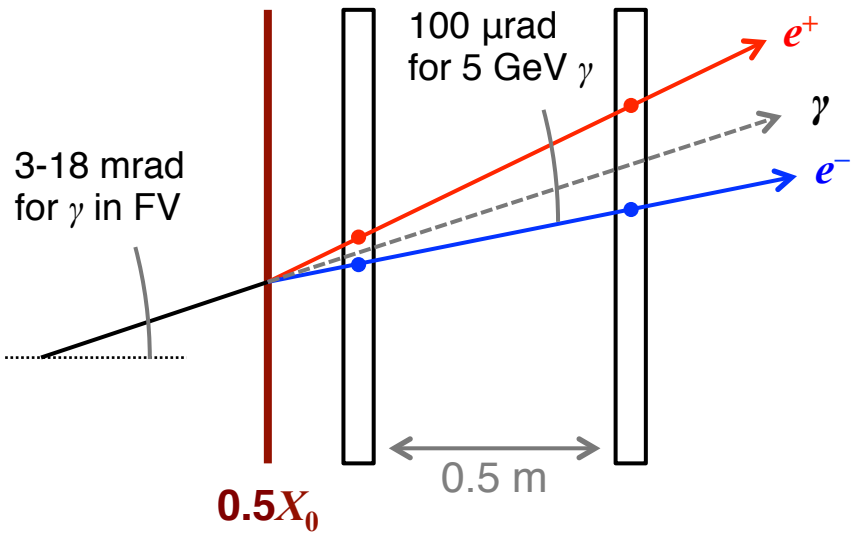
- Parameterization of response for inclusion in fast simulation



Concept for preshower detector

Advantages

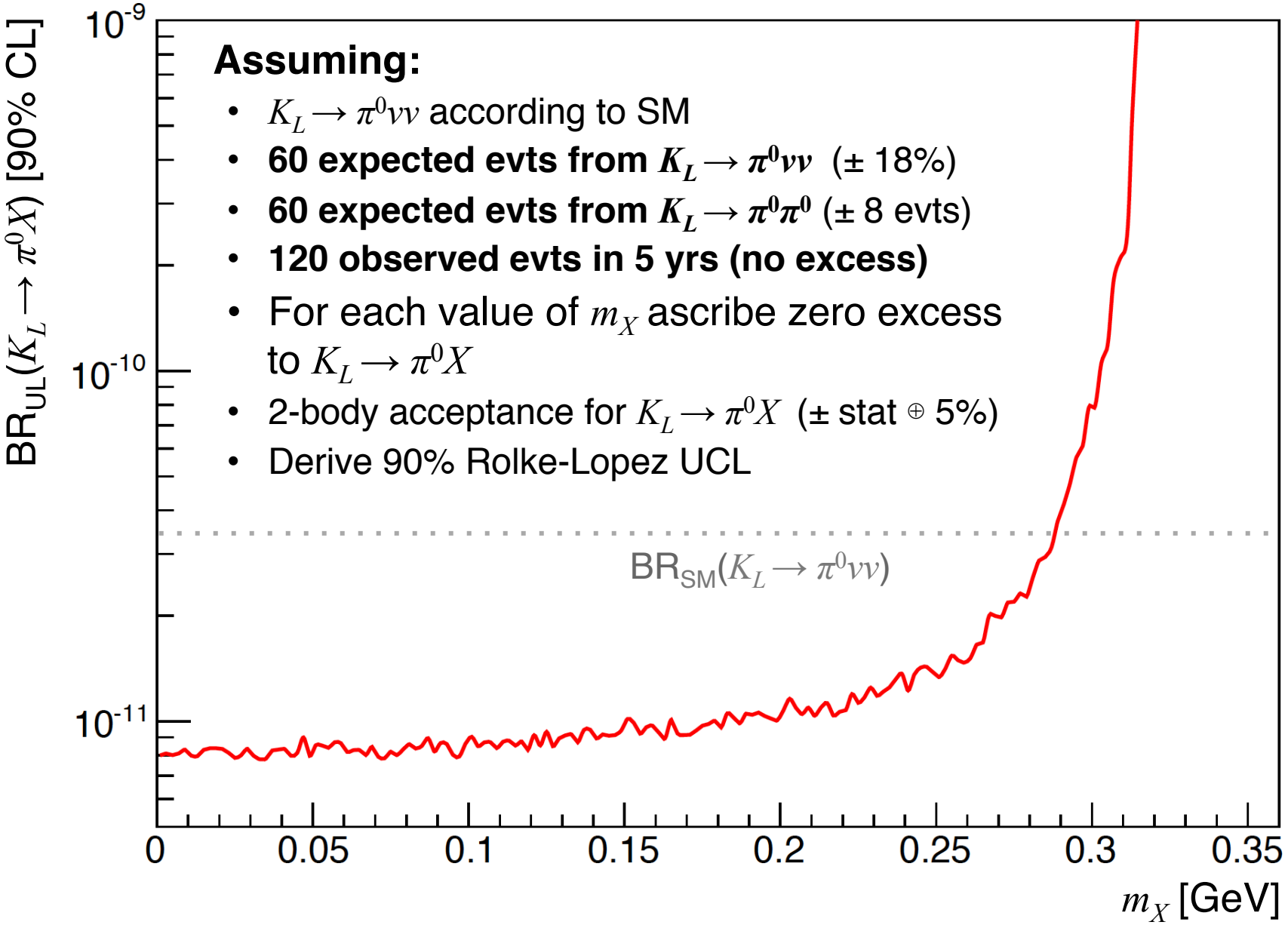
- Redundancy for rejection of $K_L \to \pi^0\pi^0$
- Partial event reconstruction for calibration channels
- Sensitivity for exotics searches
  e.g. $K_L \to \pi^0 X,\ X \to \gamma\gamma$ with displaced vertex



Issues

- Implications of extra material on MEC γ efficiency
  - Place material as close as possible to MEC, so energy from preshowering γs cannot escape
- Enough to establish partial redundancy if 50% of pairs have at least 1 conversion:
  $\to 0.5X_0$ converter
- Angular resolution for γs dominated by multiple scattering in converter if tracking planes have $\sigma_x < 100$ μm
  - $\sigma_\theta = 2$ mrad from MS
  - $\sigma_z \sim 10$ m and $\sigma_{m\gamma\gamma} < 25$ MeV
- Multi-pattern gas detectors to track conversion products?
  - Micromegas, μ-RWELL?
- Data condensation in front end: only active elements read out

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

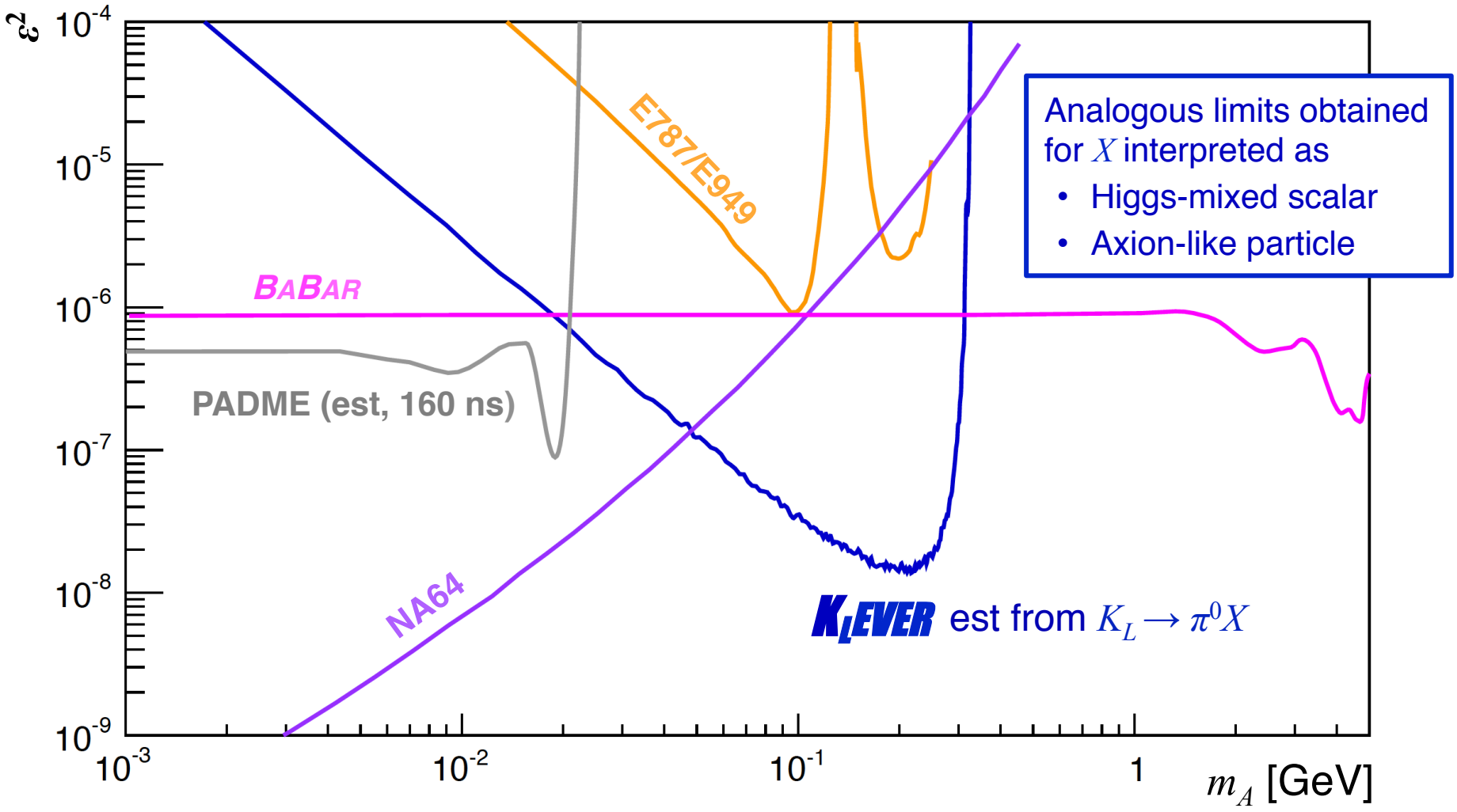


Limits on $K_L \to \pi^0 A'$ from $K_L \to \pi^0 \nu\nu$

For $K_L \to \pi^0 X$ interpret X as dark photon A' with no decays to SM particles

Obtain limits in ε^2 vs. m_A plane

ε^2 = kinetic mixing angle for A' and γ

As per Davoudiasl, Lee, Marciano 2014

Weaker limits obtain if A' also mixed with Z