K_LEVER

Status and plans

Physics Beyond Colliders Annual Meeting
CERN, 21 November 2017

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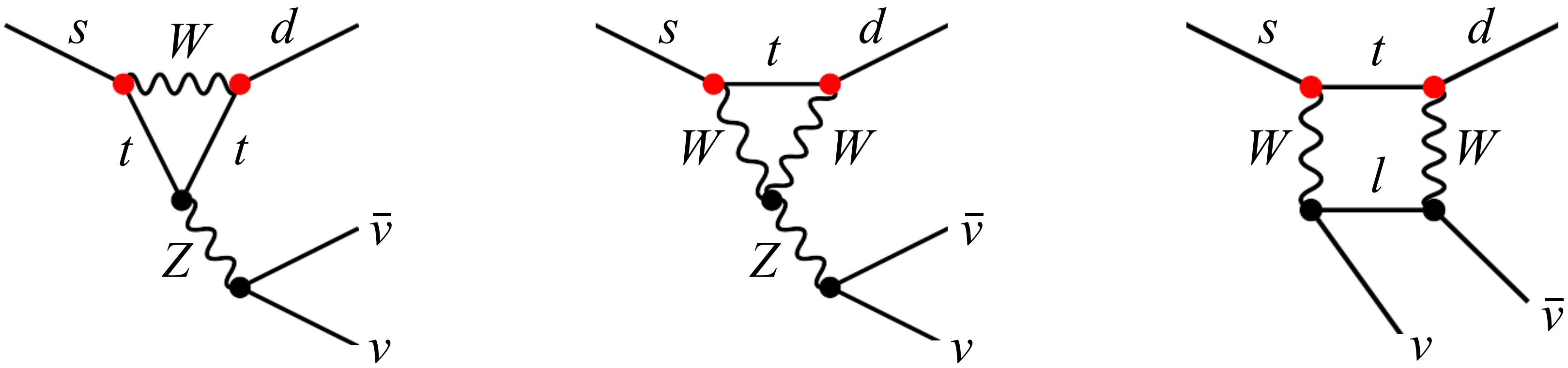
For the KLEVER project

$K \rightarrow \pi\nu\nu$ 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
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	BR = $(8.4 \pm 1.0) \times 10^{-11}$	BR = $(17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$ Stopped K^+, 7 events observed BNL 787/949, PRD79 (2009)
$K_L \rightarrow \pi^0 \nu\bar{\nu}$	BR = $(3.4 \pm 0.6) \times 10^{-11}$	BR < 2600×10^{-11} 90%CL KEK 391a, PRD81 (2010)

* Tree-level determinations of CKM matrix elements

$K \to \pi\nu\nu$ and new physics

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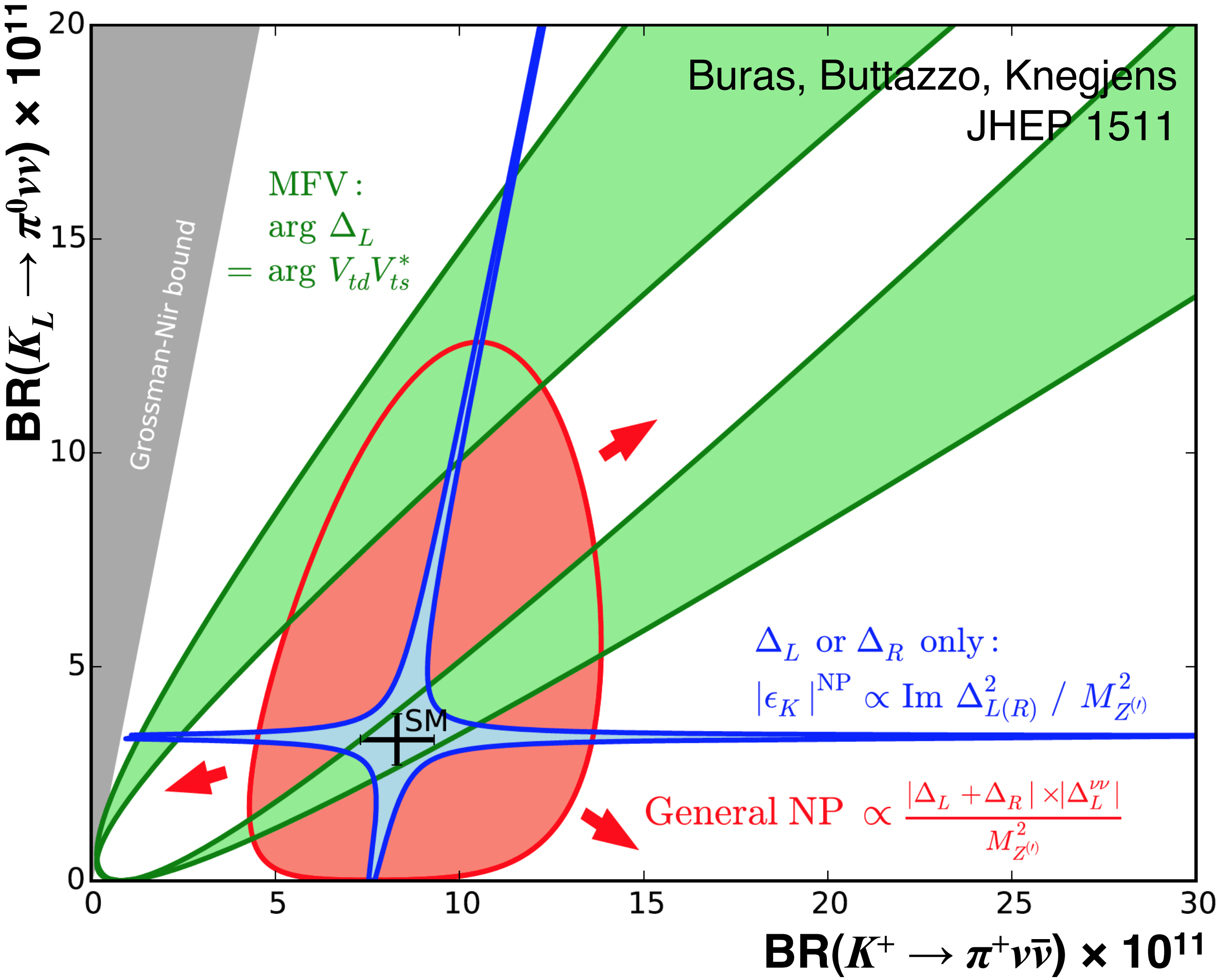
New physics affects BRs differently for K^+ and K_L channels
Measurements of both can discriminate among NP scenarios



- 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

$K \rightarrow \pi\nu\nu$ and new physics

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

Indirect probes to explore high mass scales is even more interesting

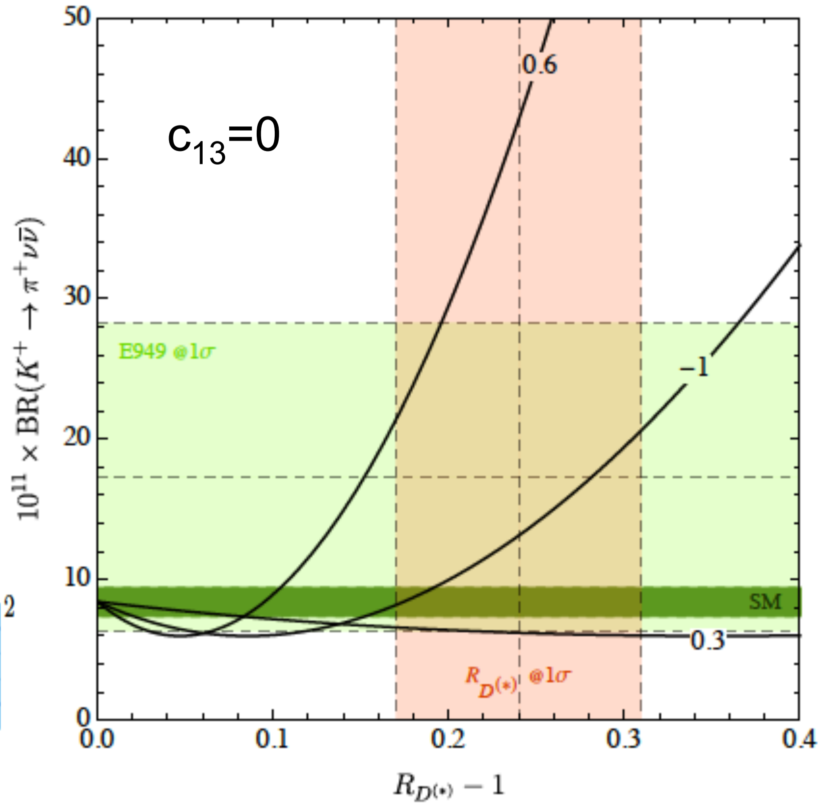
$K \rightarrow \pi\nu\nu$ is uniquely sensitive to high mass scales ~*O*(10^3 TeV)

Model within EFT recently developed to accommodate anomalies in B sector (R_K, P_5', $R_{D(*)}$, etc.) and suggests sizable effect for $K \rightarrow \pi\nu\nu$ decays

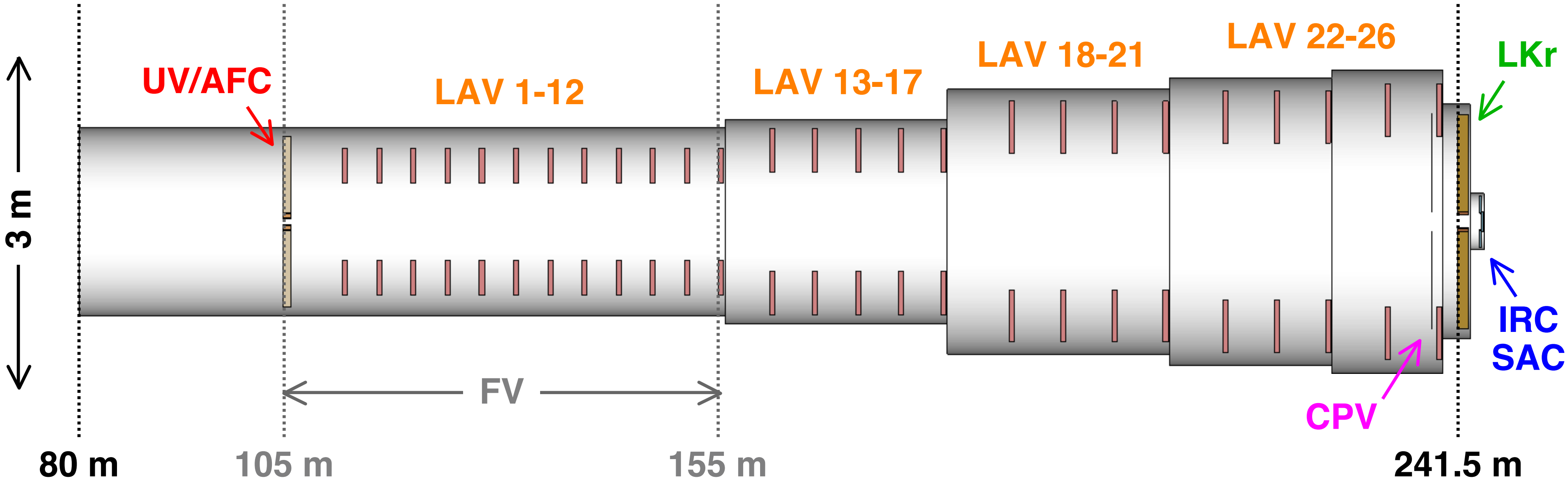
[Buttazzo et al. 1706.07808 and Bordone et al. 1705.10729]

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

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



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



Target sensitivity:

5 years starting Run 4

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

S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

Main detector/veto systems:

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

High-intensity neutral beam issues

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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

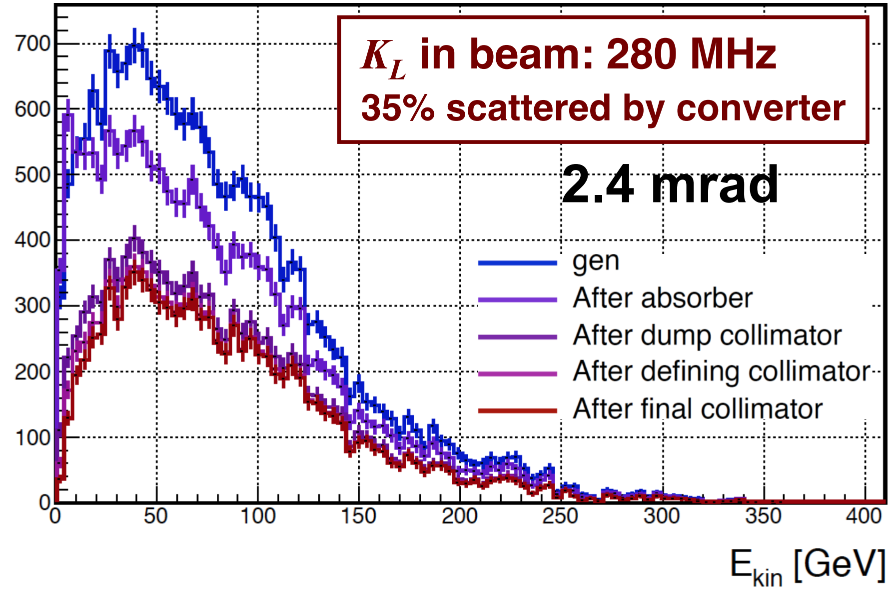
Preliminary analysis of critical issues by Secondary Beams & Areas group

Issue	Approach
Extraction losses	Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) Slow extraction workshop: https://indico.cern.ch/event/639766/
Beam loss on T4	Vertical by-pass to increase transmission to T10
Equipment protection	Maybe SIS interlock to stop extraction during P0Survey 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

Beamline simulation

Previous results, θ = 2.4 mrad:

- **FLUKA simulation of 400 GeV p on 400-mm Be target**
- **Geant4 beamline simulation**
  - 3 collimators, $\Delta\theta$ = 0.3 mrad
  - Photon converter in first collimator



Work in progress with SBA group:

✔ **Refine and improve FLUKA & Geant4 simulation**
- Reproduced previous results with FLUKA
- Good agreement between FLUKA, Geant4, experimental data
- Extending simulations to include full beamline

➜ **Understand neutral beam halo from photons and neutrons**

➜ **Complete muon halo studies**

➜ **Simulate beam-gas interaction (e.g. $nn \rightarrow nn\pi^0$)**
- Evaluate background, level of vacuum needed in decay volume

Work in progress: KLMC simulation

Full MC with realistic detector simulation under development:

- KLMC analysis framework (MC + reconstruction + analyzers)

New detectors added to KLMC since March:

- Active final collimator/Upstream veto (AFC/UV)
- Large-angle vetoes (LAV)
- Charged particle veto (CPV)

New generators added to KLMC:

- K_L and Λ production and decays
- Generalized exotic decay generator framework from NA62: ALPs, dark photons, etc

Working on complete survey of backgrounds from broad variety of sources

- First results from short-lived beam components are being analyzed $(\Lambda \rightarrow n\pi^0)$

LKr calorimeter

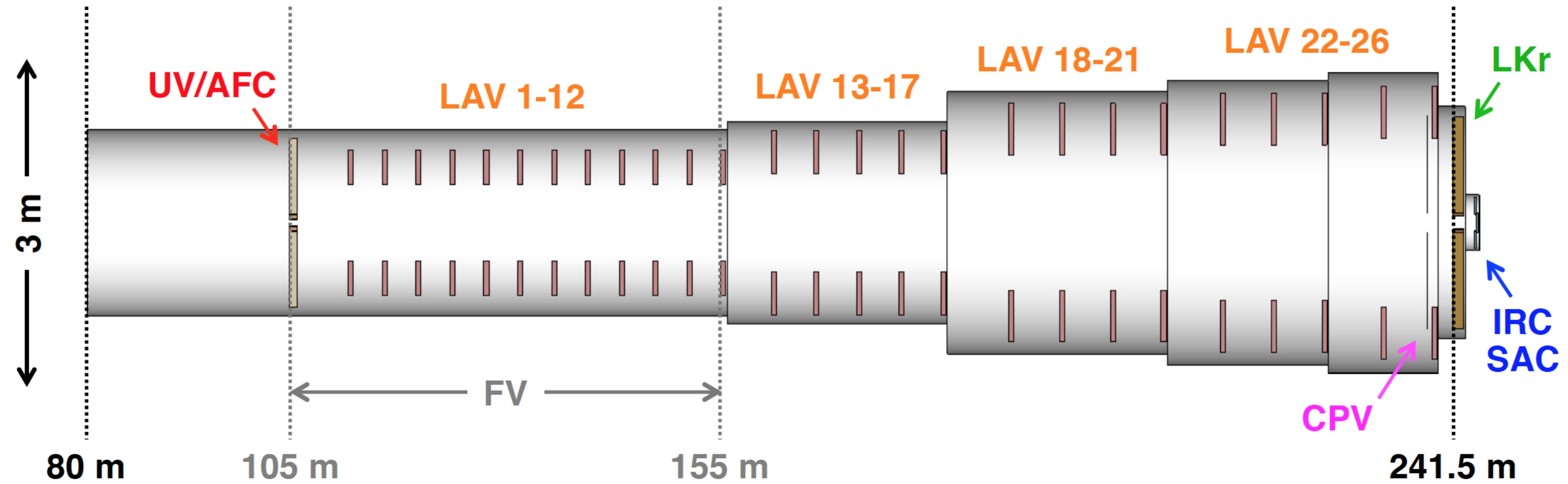
Baseline design uses NA48 LKr calorimeter:

In parallel with NA62:

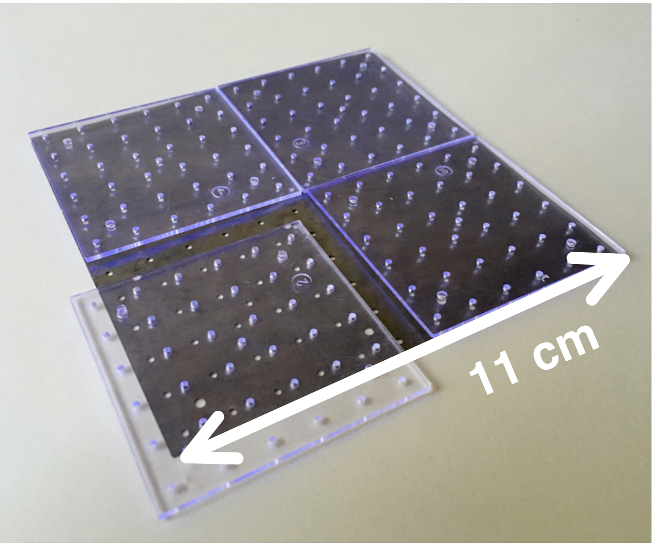
- Study and confirm LKr performance with NA62 data
- Explore possibilities to improve time resolution with faster readout
- Evaluate long-term reliability of LKr (2024 → 2030+)

Begin to evaluate possible alternatives to using LKr

- Longitudinally-segmented shashlyk calorimeter?
- Same technology as Upstream Veto (UV)



Longitudinally-segmented shashlyk



Based on PANDA forward EM calorimeter produced at Protvino

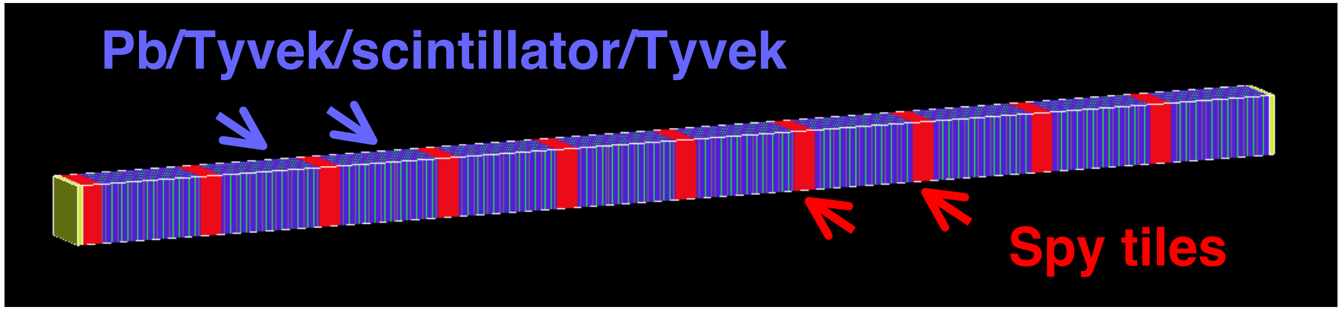
Fine-sampling shashlyk
0.275 mm Pb + 1.5 mm scintillator

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

PANDA, KOPIO prototypes

New for KLEVER: Longitudinal shower information from spy tiles

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



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

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

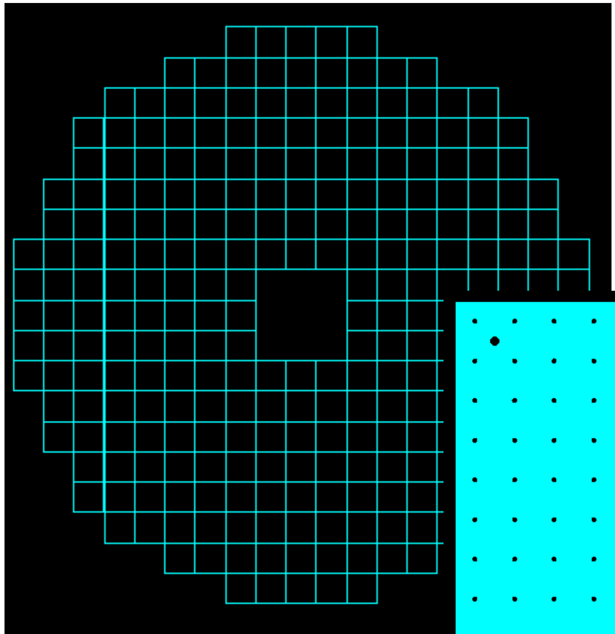
Upstream decays

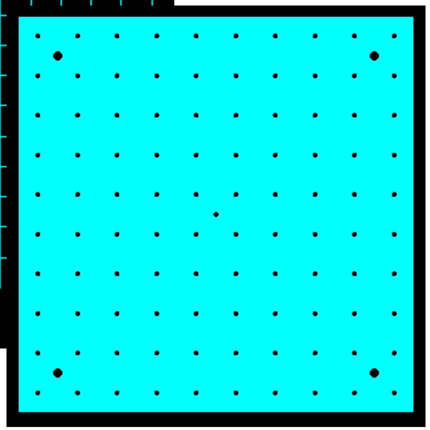
Rejects $K_L \to \pi^0\pi^0$ from upstream of final collimator (80 m < z < 105 m)

Upstream veto (UV):

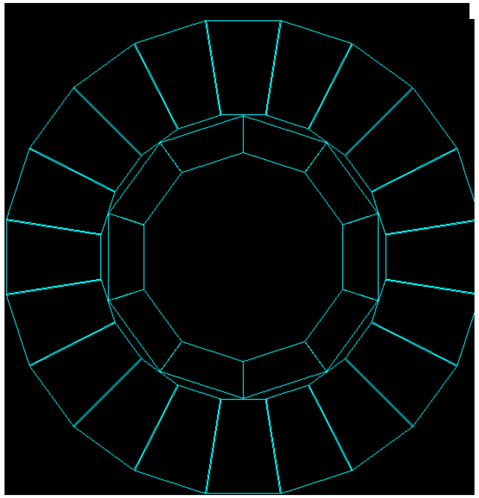
- 10 cm < r < 1 m:
- Shashlyk calorimeter modules à la PANDA/KOPIO

As implemented in KLMC:





Active final collimator (AFC):



- 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

Charged particle rejection & tracking K_LEVER

Use simulation to add detail to design of charged particle vetoes

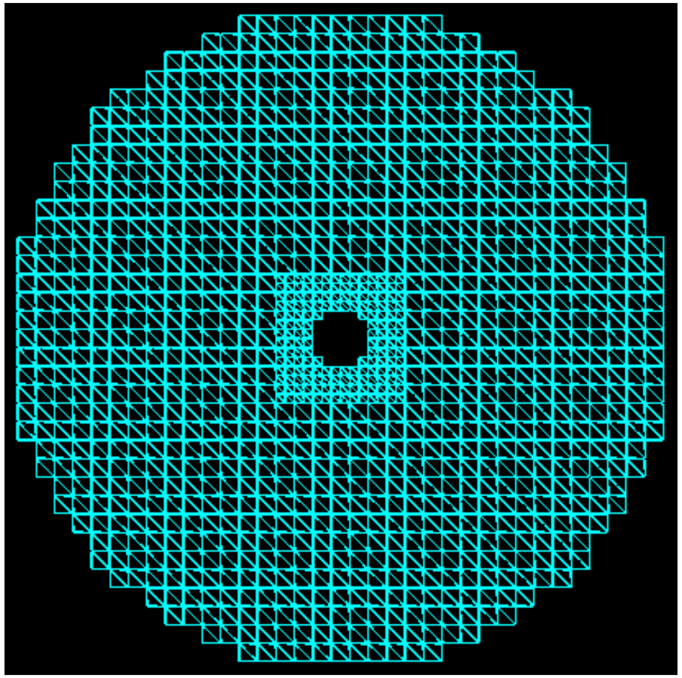
Current description (CPV):

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



As implemented in KLMC

Charged particle rejection with hadron calorimeters

- Study of HAC (MUV1/2) response in NA62 data
- Parameterization of HAC response for fast simulation

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

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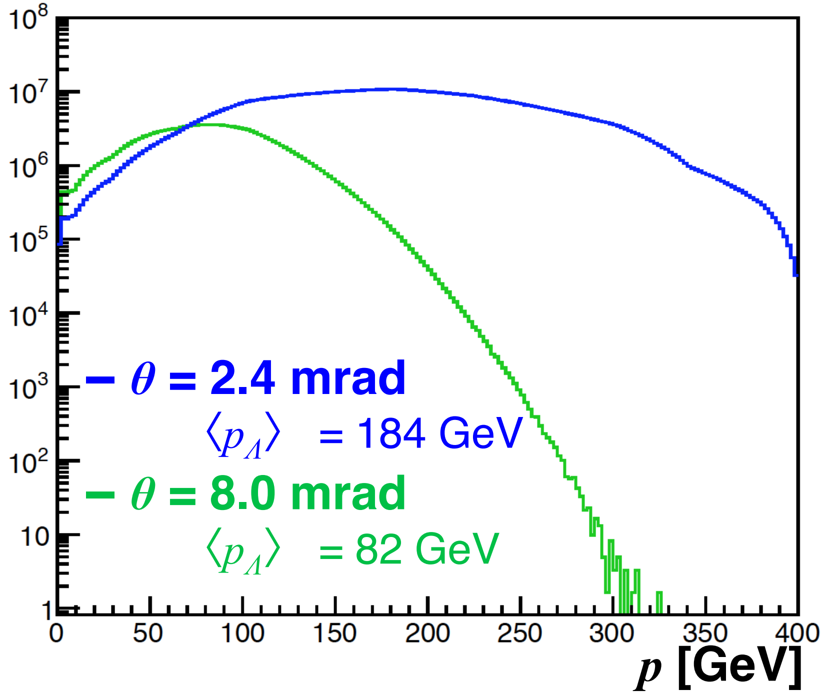
Λ and K produced in similar numbers: O(10^{15}) Λ in beam in 5 years

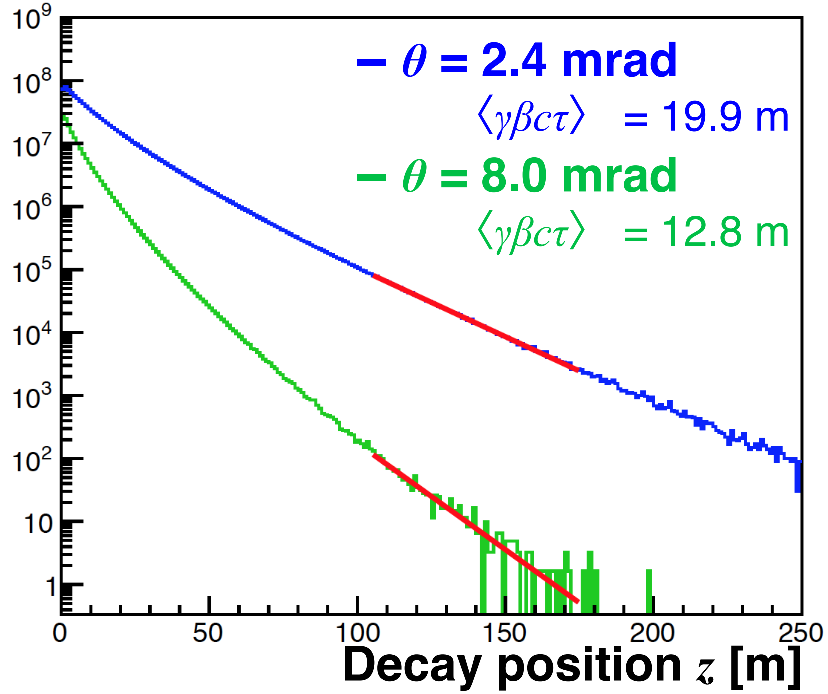
Small but significant fraction of Λ decay in fiducial volume

- $c\tau_\Lambda$ = 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

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

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Implications of changing production angle θ = 2.4 → 8.0 mrad:

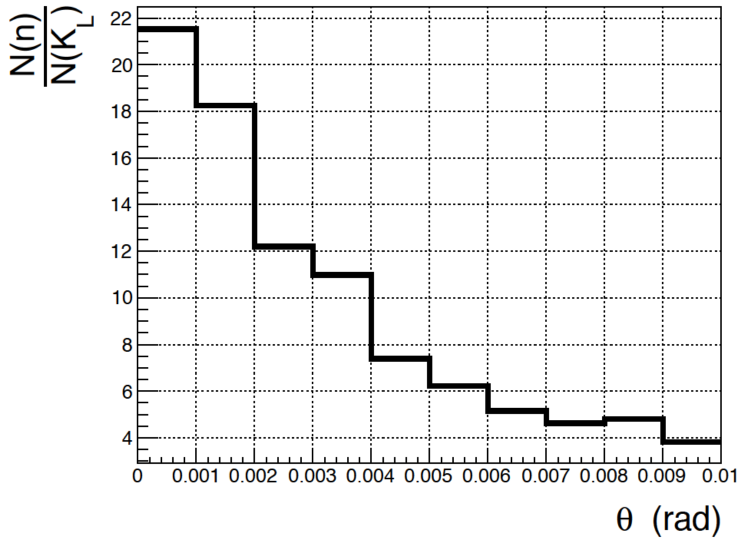
- 3x decrease in K_L decays in fiducial volume
- To reject more Λs, can move FV downstream by 25 m with no additional loss of K_L
- S/B ratio from $K_L \to \pi^0\pi^0$ decreased by factor 2

Advantages to moving to larger angle:

- Neutron flux decreased by factor ~7

  Much less demanding rates on SAC

  Possible to use thinner absorber in beam?



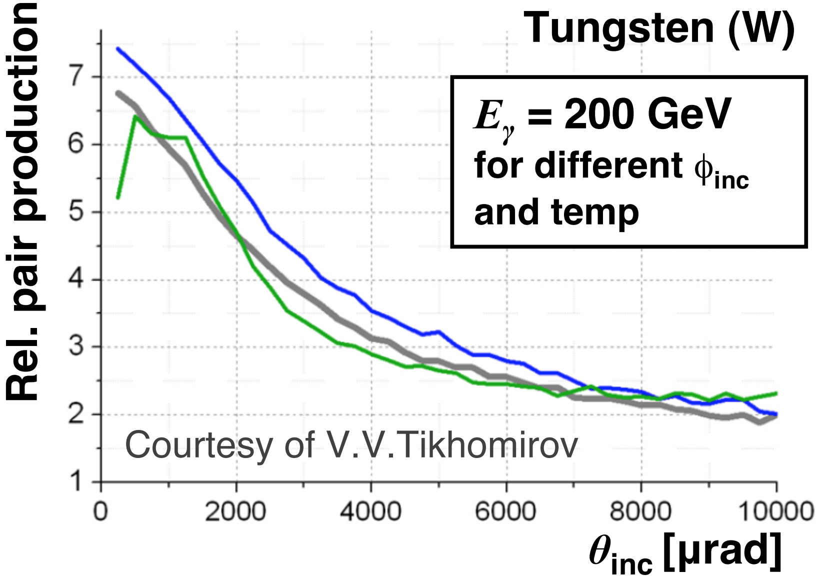
Next steps:

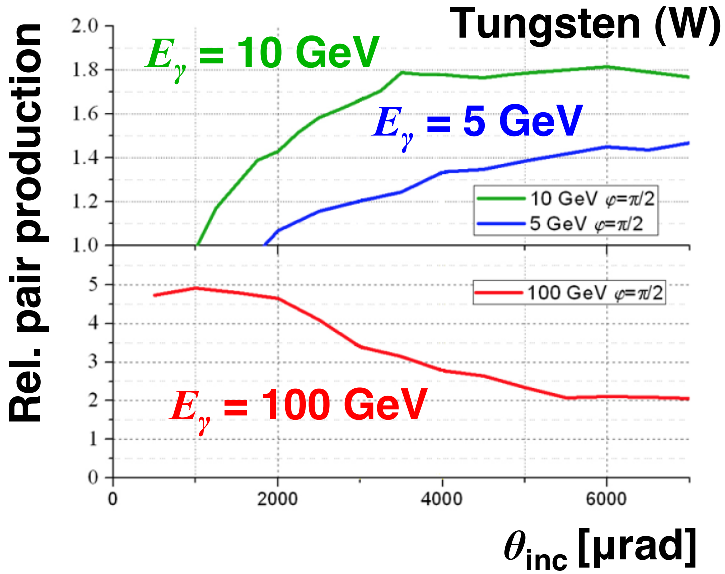
- Optimization studies in greater detail (K_L vs background)
- Identify possible solutions to further reduce Λ background

  Study effect of using heavier target (Be → Cu or Pb)

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

KLEVER is collaborating with INFN groups with experience with coherent phenomena in crystals for test beam measurement of pair-production enhancement

E. Bagli, L. Bandiera, V. Guidi, A. Mazzolari, M. Romangnoni, A. Sytov (Ferrara); D. DeSalvador (LNL); V. Mascagna, M. Prest (Milano Bicocca); E. Vallazza (Trieste).

July 2017 AXIAL data taking, H4 beamline
Run Coordinator: L. Bandiera

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

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

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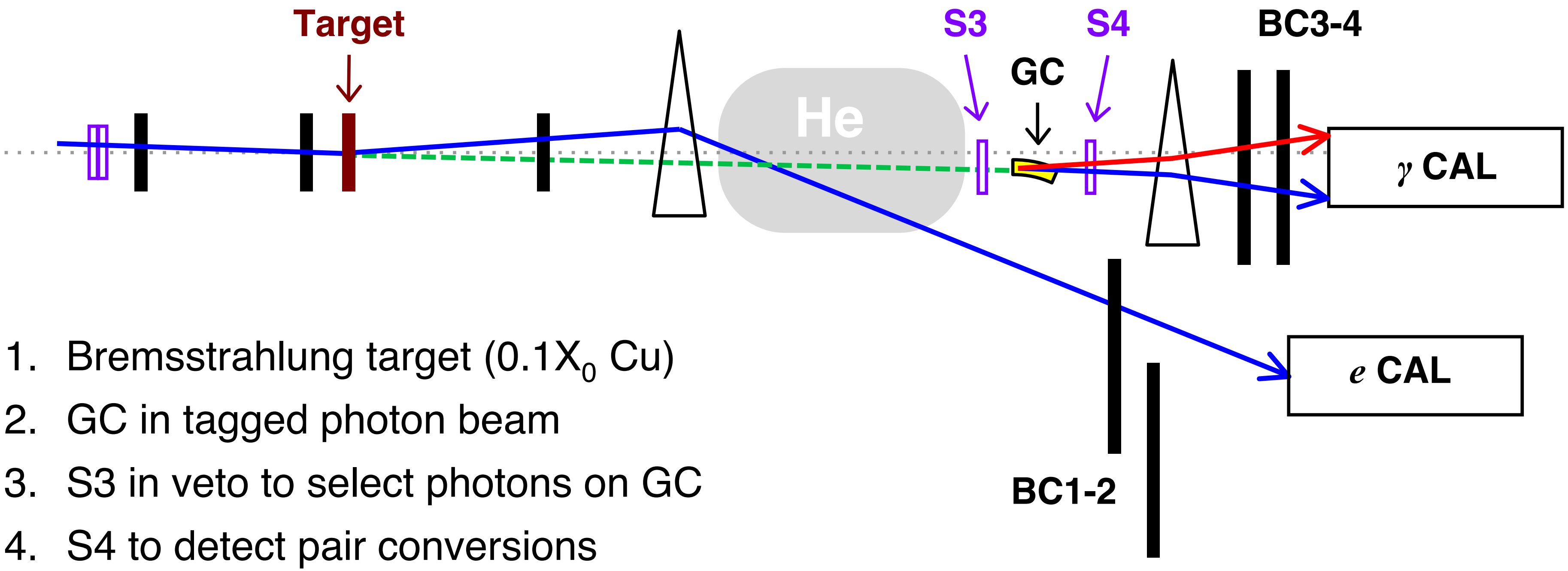
Tagged photon beam setup for H4 (or H2) test beam:



1. Bremsstrahlung target ($0.1X_0$ Cu)
2. GC in tagged photon beam
3. S3 in veto to select photons on GC
4. S4 to detect pair conversions
5. BC1-2: 9.5 × 9.5 cm^2 Si detectors to extend coverage of tagging system
6. Analysis magnet and BC3-4 to assist in reconstruction of e^+e^- pairs
7. He bag to reduce multiple scattering

- **Nearly all detectors and DAQ system available for use from AXIAL**
- **INFN has approved funds for crystal samples, etc.**
- **1 week of beam requested in 2018**

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

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Only preliminary investigations so far, plan to study it further with MC

Add a tracking system for charged particles?

- Expand physics scope of experiment: $K_L \to \pi^0 l{+}l{-}$, $K_L \to 4l$ *etc.*
- Facilitate calibration and efficiency measurements
- 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
- Non-destructive muon tracking downstream of LKr?

Add a preshower detector in front of LKr?

- Require at least 1 conversion for signal events → cost in signal?
- Similar complications as for adding tracking
- **Could allow 2γ vertex reconstruction for ALPs searches**

Status and timeline

Project timeline - target dates:

2017-2018	**Project consolidation** • Beam test of crystal pair enhancement • Consolidate the 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**

Expression of Interest to SPSC

- **Actively seeking new collaborators**
- **Institutes interested so far: Birmingham, Bristol, Charles U., Comenius U., Dubna, Ferrara, Florence, Frascati, George Mason U., Glasgow, La Sapienza, Louvain, Mainz, Moscow INR, Naples, Perugia, Pisa, Protvino, Sofia, Tor Vergata, Turin.**

THANK YOU

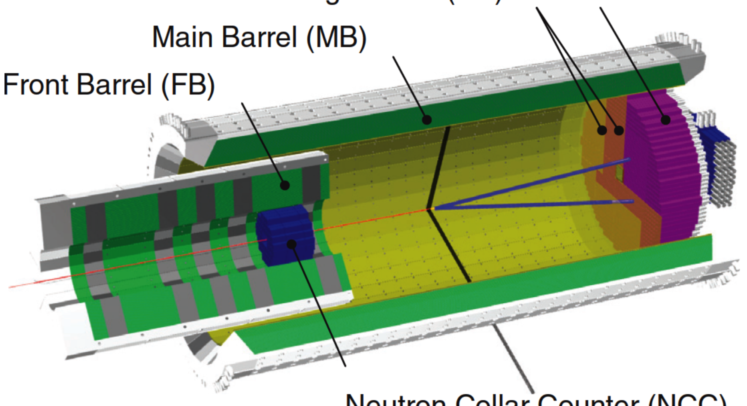
A special thanks to the CERN Secondary Beam and Areas group
for the help and support

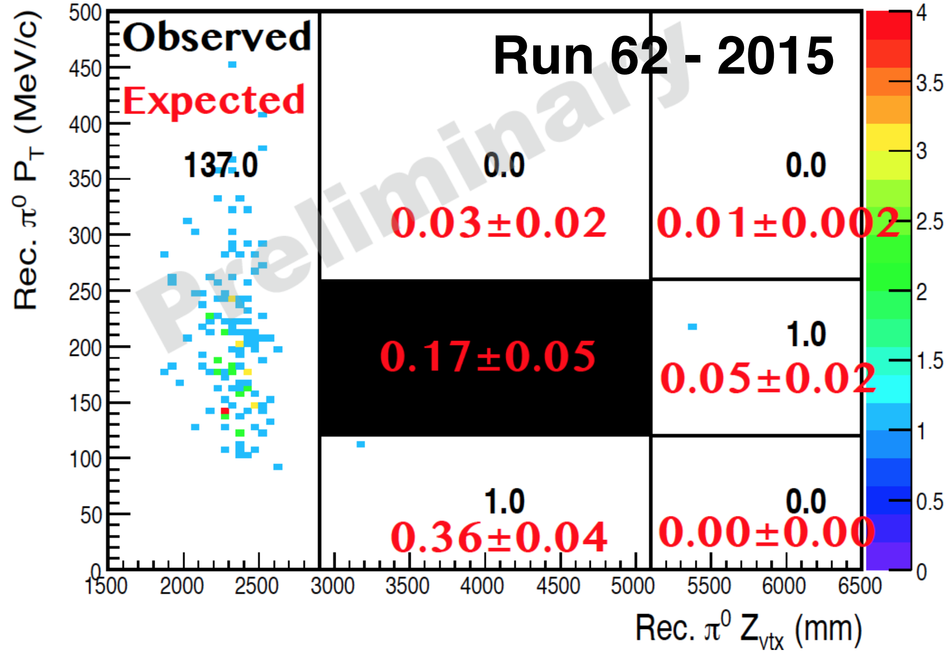
Additional slides

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

Primary beam: 30 GeV *p*

$\langle p_K \rangle$ = 2.1 GeV





Current status:

- Reached **42 kW** of slow-extracted beam power in 2016
  - Preliminary results: 10% of 2015 data

    SES = 5.9 × 10^{-9}

    Expected background = 0.17 events

    Background estimate still under study, signal box not yet unblinded

- Beam power will increase to **100 kW** by 2018
- Continuing upgrades to reduce background:

  New barrel veto (2016)

  Both-end readout for CsI crystals (2018)

Expect to reach SM sensitivity by 2021

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

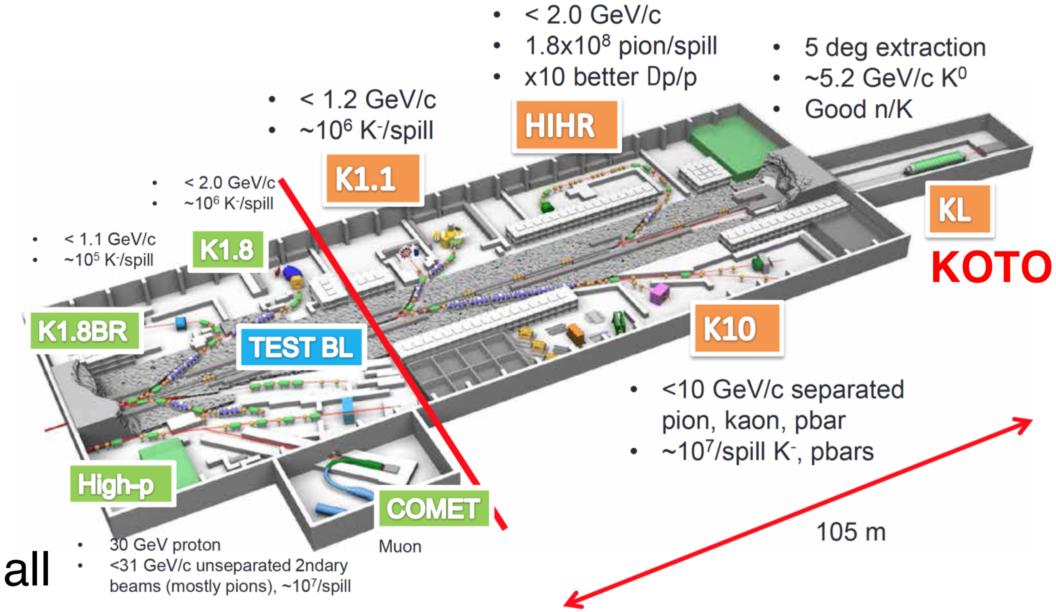
KOTO Step-2 upgrade:

•Increase beam power to >100 kW
(Originally 450 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



Long-term future: Strong intention to upgrade to O(100) event sensitivity

- 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 machine & detector upgrade possibilities to increase sensitivity
- Indicative timescale: data taking starting 2025?