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

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KLEVER

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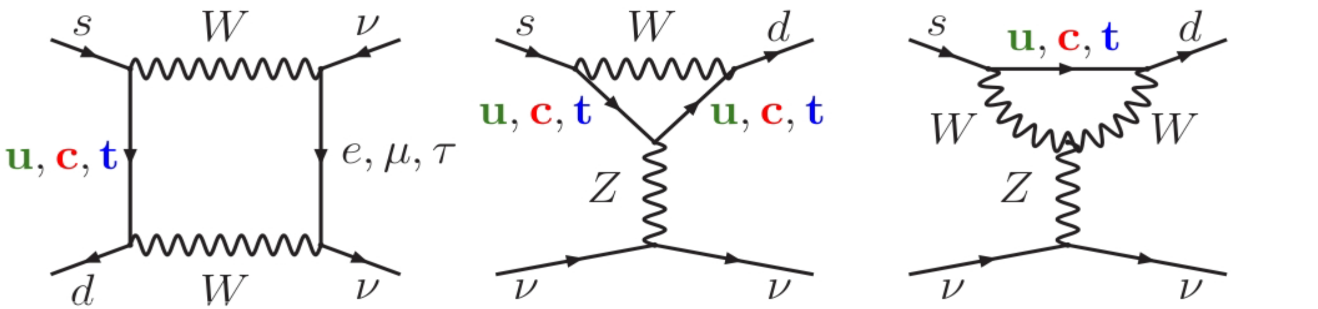
$K \to \pi\nu\bar{\nu}$ in the Standard Model

- **FCNC loop processes: s→d coupling and highest CKM suppression**

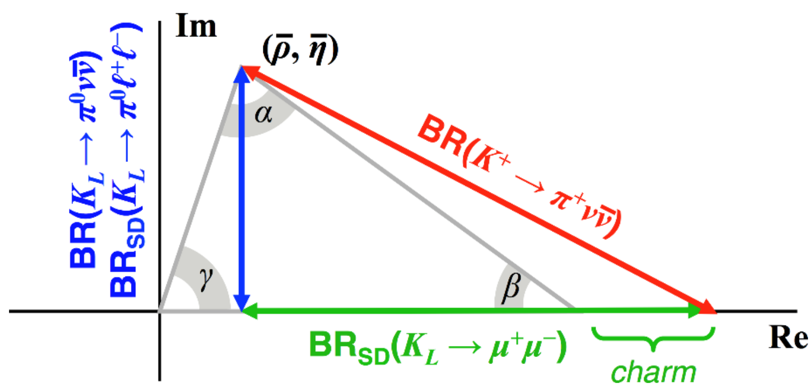


$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$

- **SD contributions dominate** $A_q \sim \frac{M_q^2}{M_W^2} V_{qs}^* V_{qd}$
- **Hadronic matrix element related to the precisely measured BR(K_{e3})**
- **SM prediction rates [Buras et al, JHEP 1511]:**

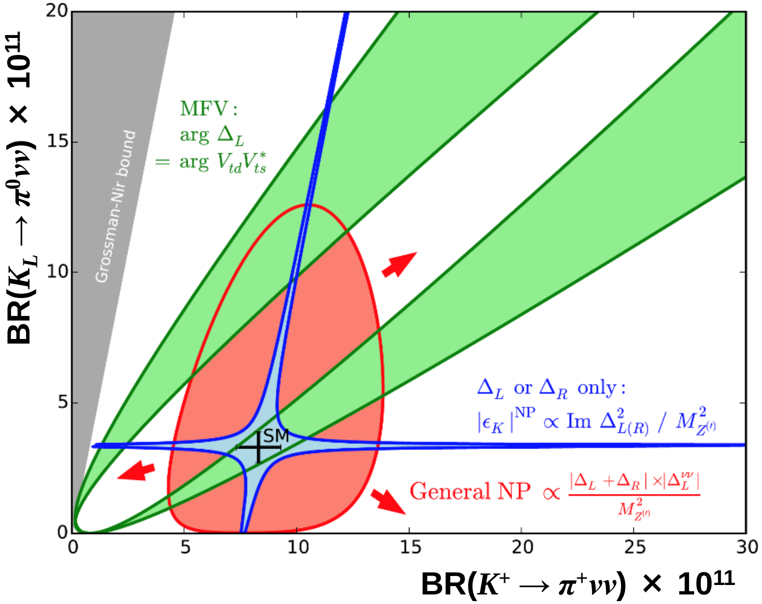
BR($K^+ \to \pi^+ \nu\bar{\nu}$) = $(8.4 \pm 1.0) \times 10^{-11}$ **BR($K_L \to \pi^0 \nu\bar{\nu}$) = $(3.4 \pm 0.6) \times 10^{-11}$**

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



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

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

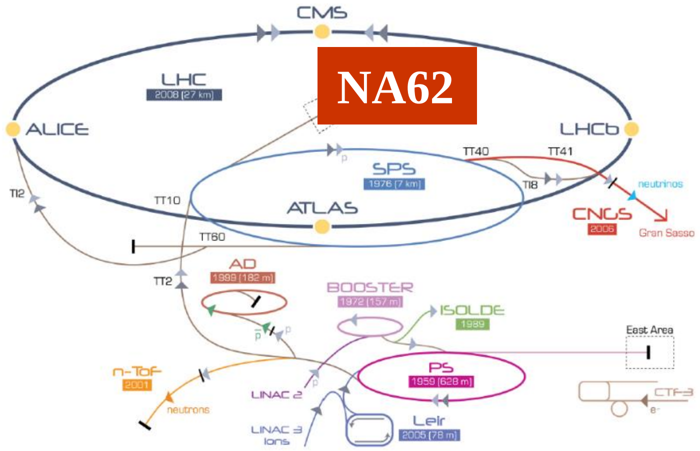


- **Models with CKM-like flavor structure**
  - **Models with MFV**
- **Models with new flavor-violating interactions in which either LH or RH couplings dominate**
  - ***Z/Z′* models with pure LH/RH couplings**
  - **Littlest Higgs with *T* parity**
- **Models without above constraints**
  - **Randall-Sundrum**

NP effects on $K \to \pi\nu\nu$ BRs with constraints from Re ε'/ε, ε_K, Δm_K, $K_L \to \mu\mu$

Model	Λ [TeV]	Effect on BR($K^+ \to \pi^+\nu\bar{\nu}$)	Effect on BR($K_L \to \pi^0\nu\bar{\nu}$)
Leptoquarks, most models	1–20	Very large enhancements; mainly ruled out	
Leptoquarks, U_1	1–20	+10% to +60%	+100% to +800%
Vector-like quarks	1–10	−90% to +60%	−100% to +30%
Vector-like quarks + Z'	10	−80% to +400%	−100% to 0%
Simplified modified Z, no tuning	1	−100% to +80%	−100% to −50%
General modified Z, cancellation to 20%	1	−100% to +400%	−100% to +500%
SUSY, chargino Z penguin	4–6 TeV		−100% to −40%
SUSY, gluino Z penguin	3–5.5 TeV	0% to +60%	−20% to +60%
SUSY, gluino Z penguin	10	Small effect	0% to +300%
SUSY, gluino box, tuning to 10%	1.5–3	±10%	±20%
LHT	1	±20%	−10% to −100%

NA62 status and timeline



2016 Commissioning + 1st physics run

First result presented in March 2018

1 event observed, BR($K^+ \to \pi^+ \nu\nu$) < 14 × 10^{-10} (95%CL)

2017 Physics run (23 weeks at 60% nominal intensity)

3 × 10^{12} K^+ decays recorded (> 10x more than 2016)

2018 Physics run (31 weeks at 80% nominal intensity and better shielding of upstream bkg)

5 × 10^{12} K^+ decays recorded (> 20x more than 2016)

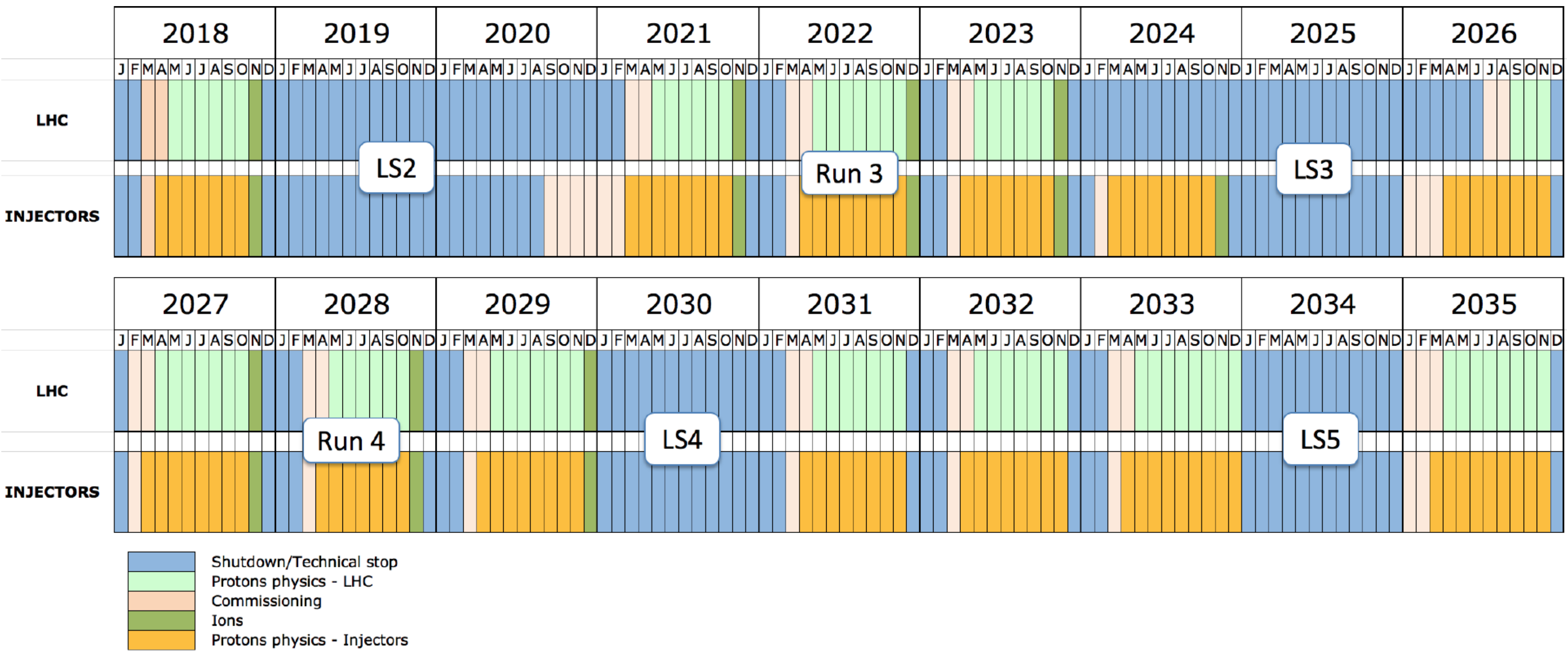
2019-2020 LS2 (LHC Long Shutdown 2)

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

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

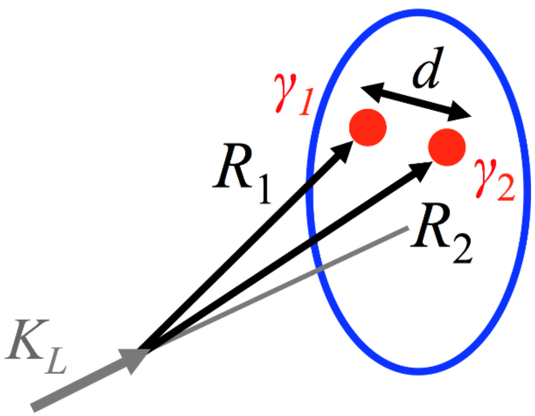


$K_L \to \pi^0 \nu\bar{\nu}$ experimental issues

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 $p_\perp = 0$



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

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

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

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

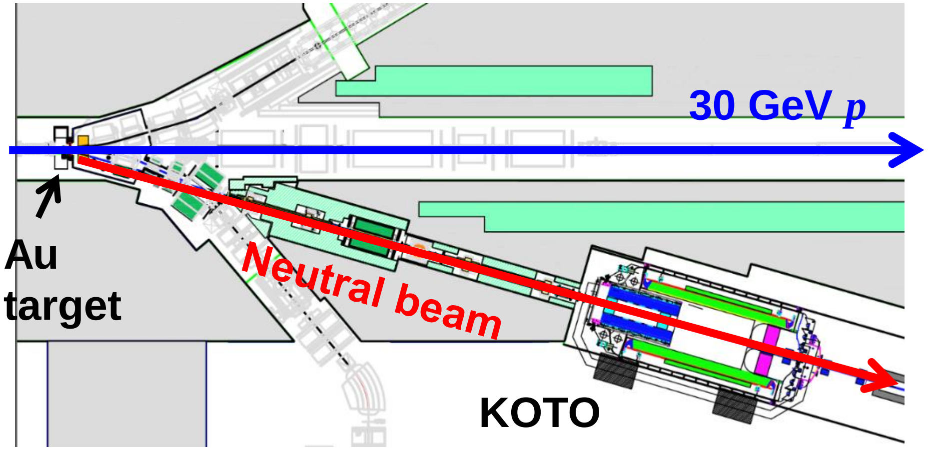
KOTO

Primary beam: 30 GeV *p*

100 kW = 1.2 × 10^{14} p/5.2 s

Neutral beam (16°)

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



2015 run (current result)

- BR($K_L \to \pi^0 \nu\nu$) < 3.0 × 10^{-9} (90%CL)
- SES = (1.30 ± 0.14) × 10^{-9}
- Expected bkg = 0.42 ± 0.18 events
- Zero events in signal box

2016-2018

- 1.4x more data than for 2015 collected
- Several important detector upgrades and analysis improvements
- SES = 8.2 × 10^{-10} [KOTO preliminary, Moriond 2019]
- Combined with 2015: SES ~ 5 × 10^{-10}

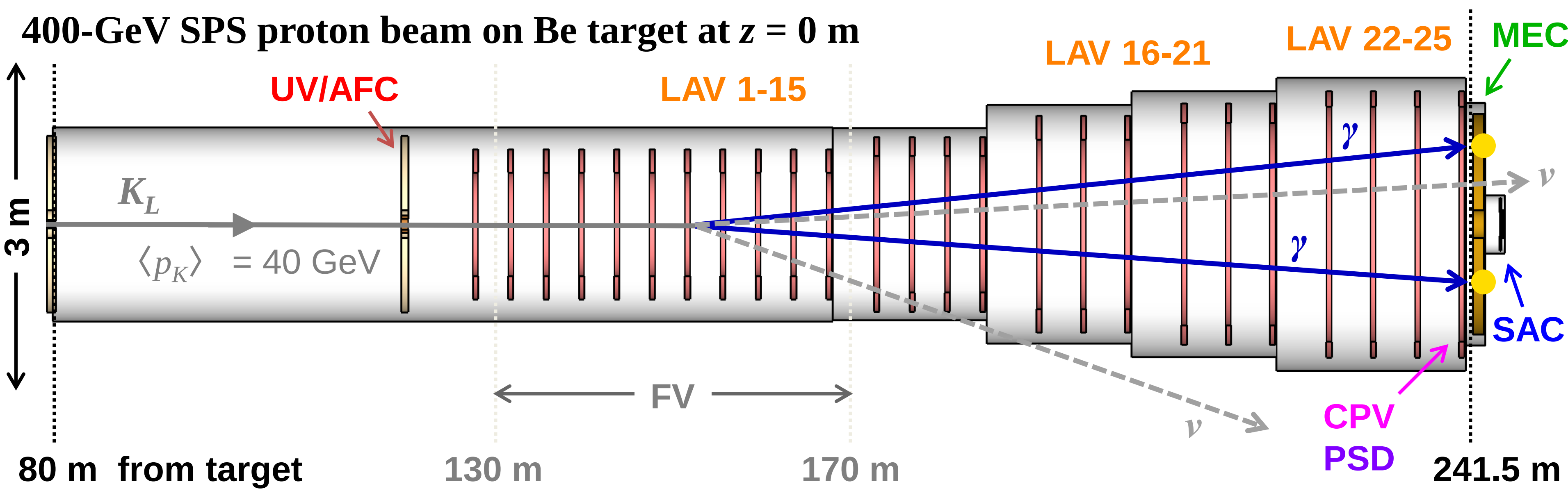
2019-2024

- 20+ months of additional running planned
- Beam power expected to increase 50→100 kW gradually by 2024
- Continuing program of detector upgrades
- SES for SM BR reached around 2025

Long-term upgrade plans:

- Intention to upgrade to 10-100 event sensitivity (no official step proposal yet)
- Increase beam power to >100 kW
- New neutral beamline and extension of hadron hall
- Complete rebuild of detector

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

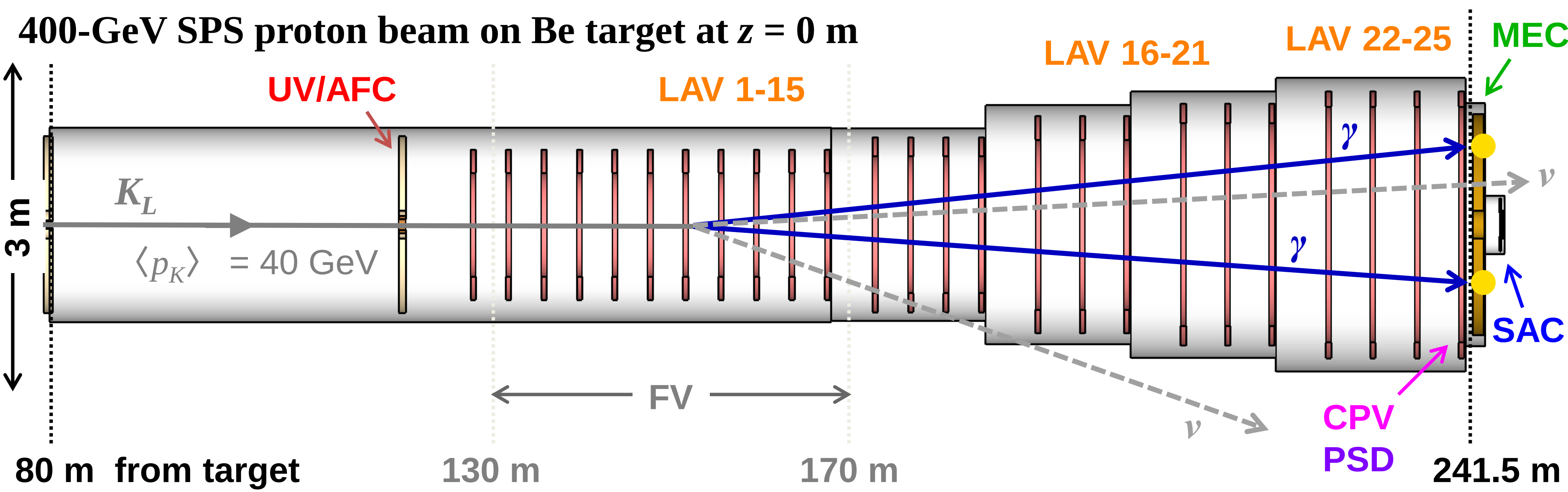


KLEVER

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 CERN SPS



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

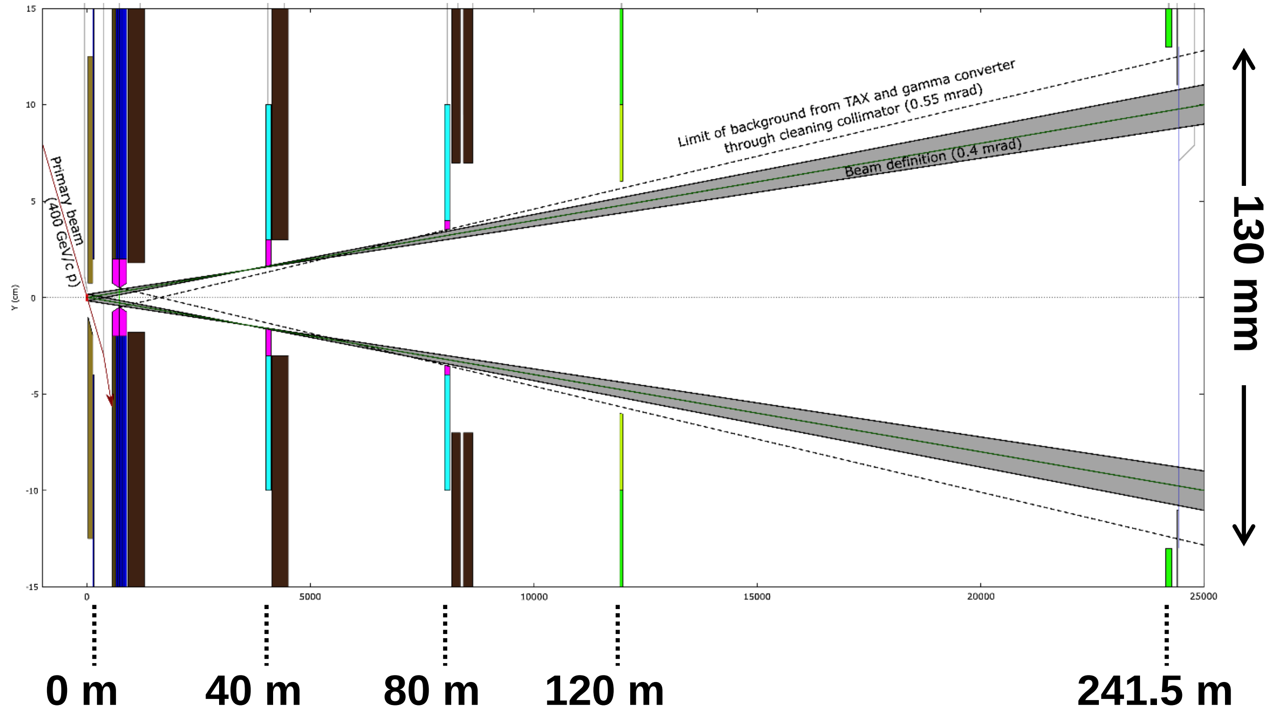
KLEVER target sensitivity:
5 years starting Run 4

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

δBR/BR($\pi^0 \nu\nu$) ~ 20%

Neutral beam and beamline

- **400 GeV *p* on 400 mm Be target**
- **Production angle $\theta = 8.0$ mrad**
- **Solid angle $\Delta\theta = 0.4$ mrad**
- **2.1×10^{-5} K_L/pot in beam**
- **$\langle p(K_L) \rangle = 40$ GeV**
- Probability for decay inside FV ~ 4%
- Acceptance for $K_L \to \pi^0 \nu\nu$ decays occurring in FV ~ 5%

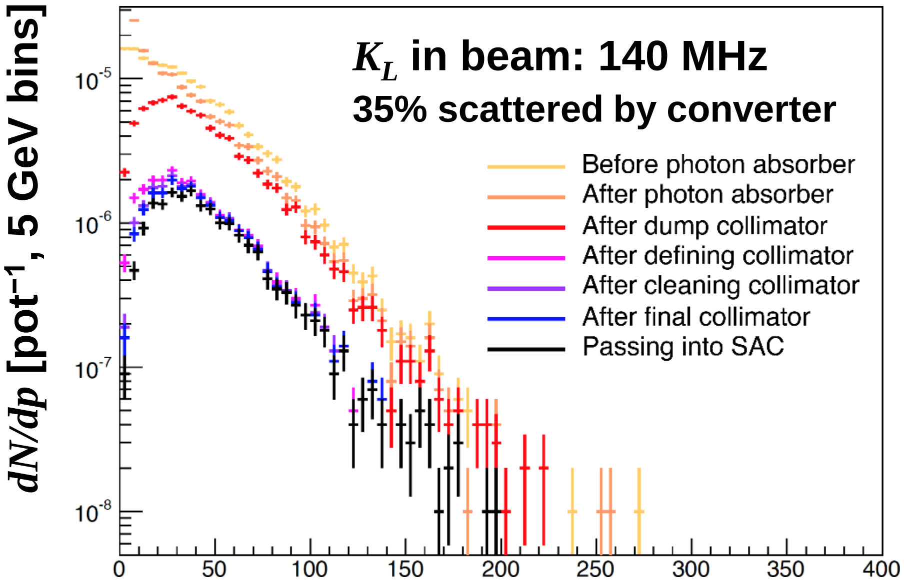


- **4 collimation stages** to minimize neutron halo, including beam scattered from absorber
- **Photon absorber** in dump collimator

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**

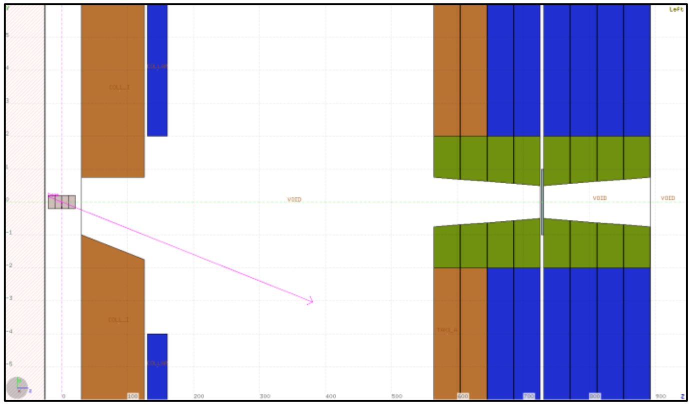
Neutral beam simulation

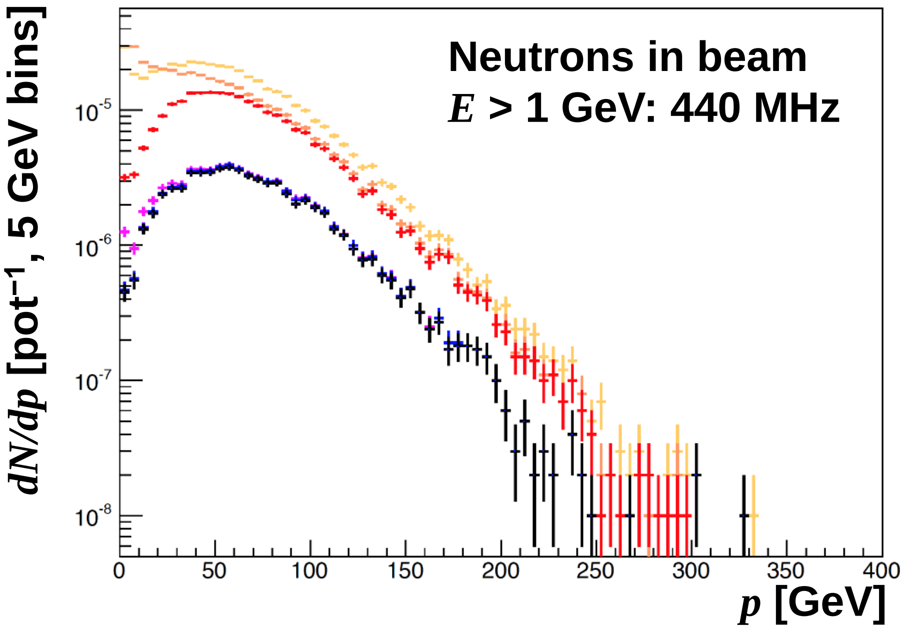


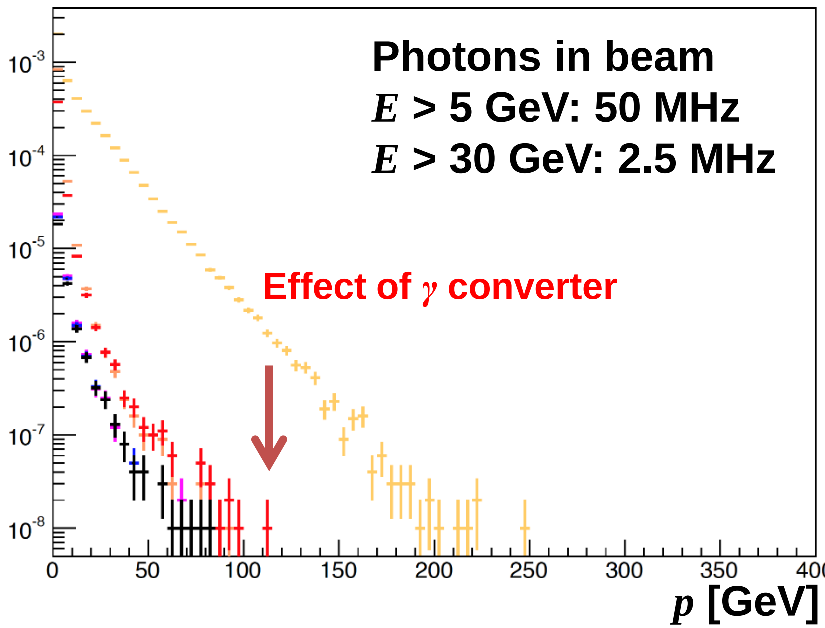
FLUKA simulation of beamline

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

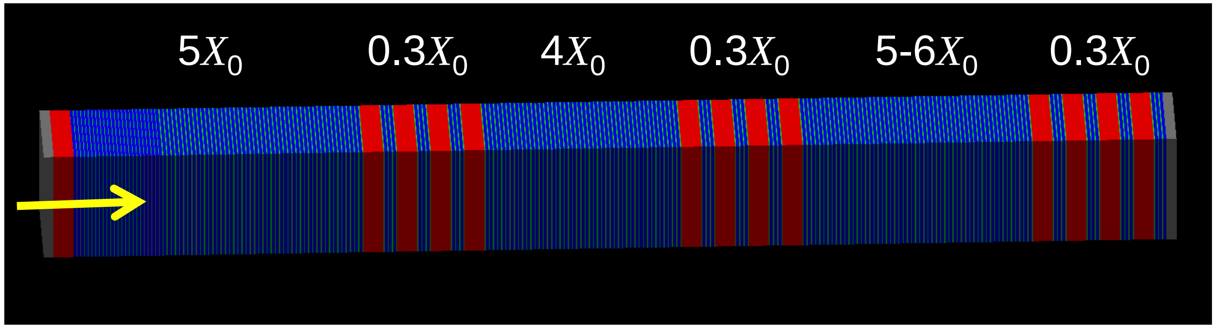
0.275 mm Pb + 1.5 mm scintillator

PANDA/KOPIO prototypes:

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

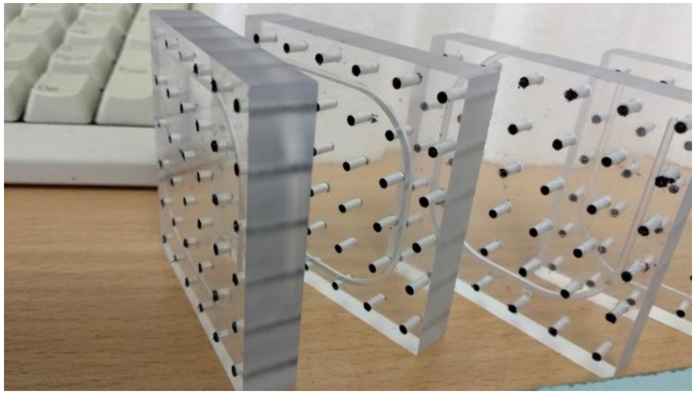
New for KLEVER: Longitudinal shower information from spy tiles

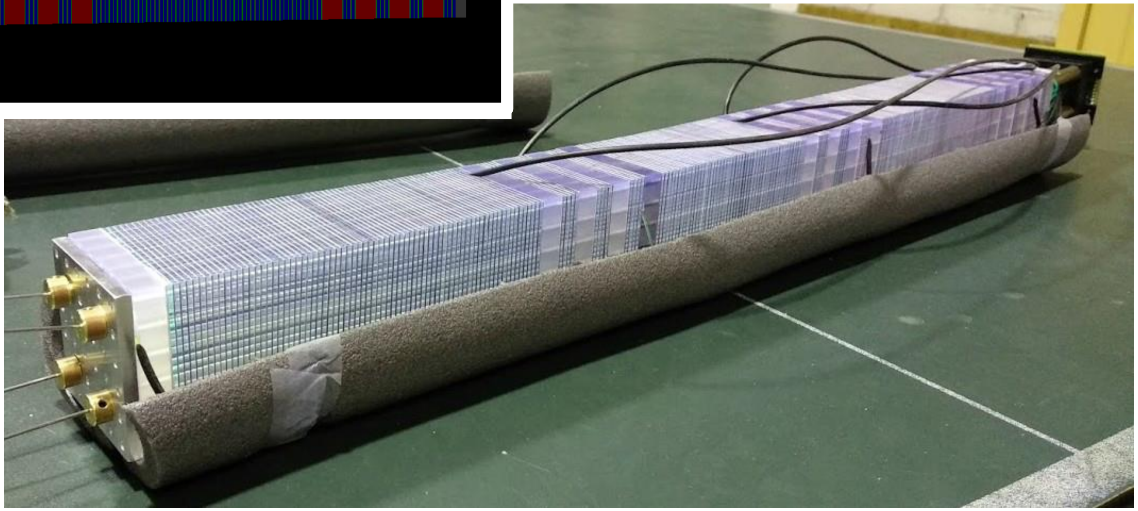
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



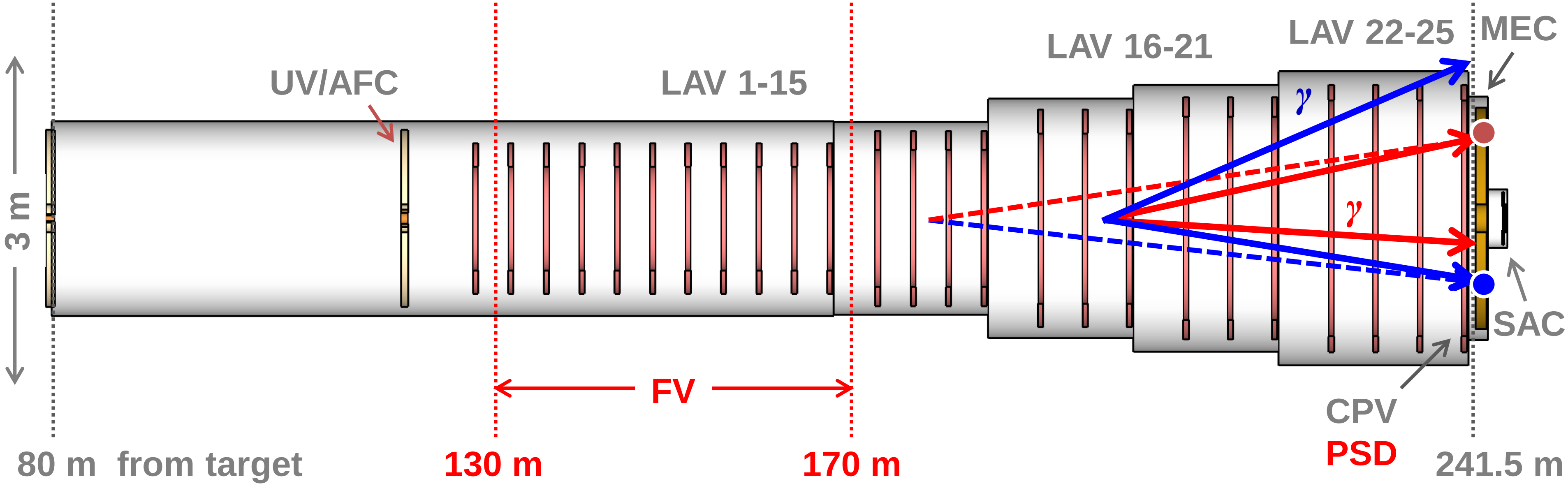
1st prototype assembled and tested at Protvino

OKA beamline, April 2018





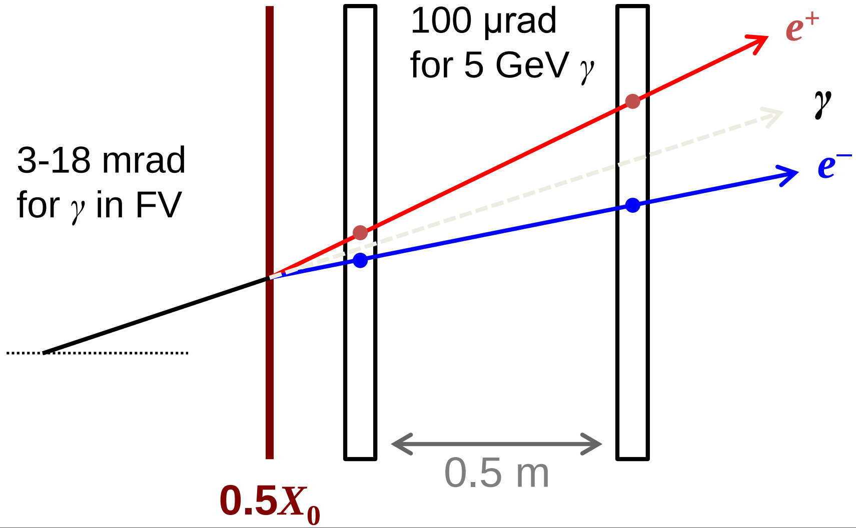
Mispaired $K_L \to \pi^0\pi^0$ events



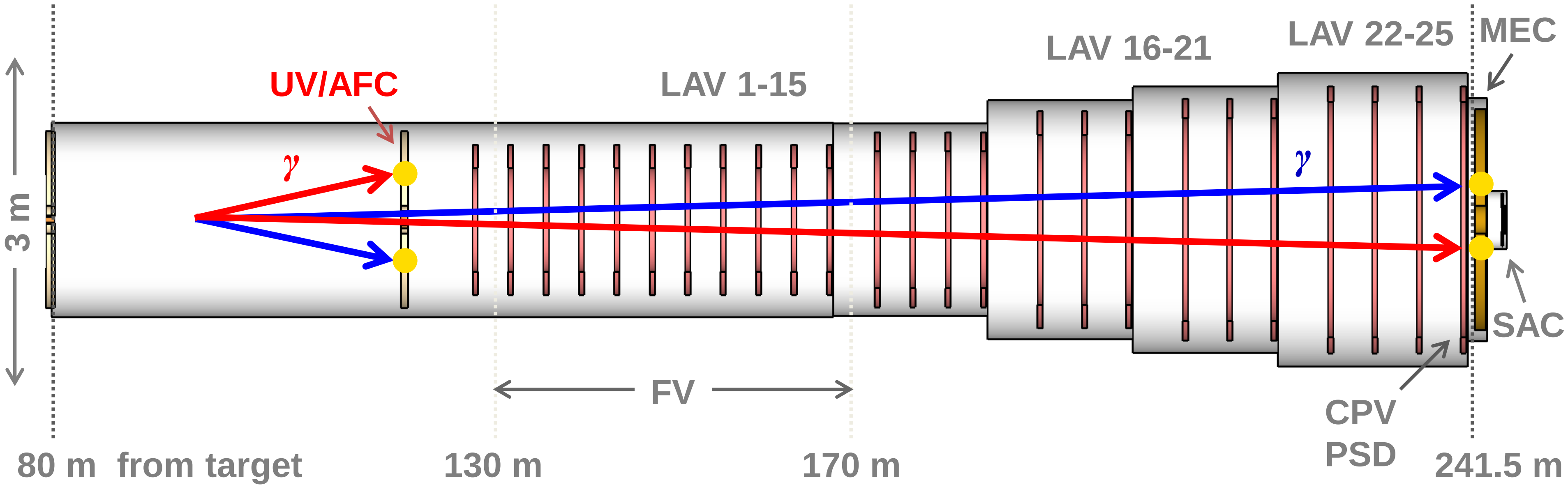
Distance from FV to MEC significantly helps for rejection of "odd" background

- 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

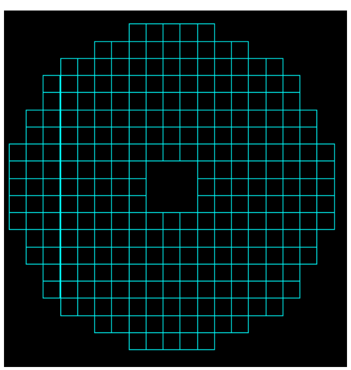


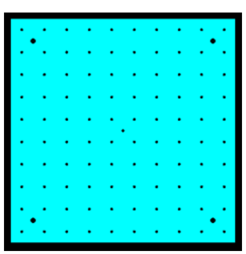
Vetoes for upstream $K_L \rightarrow \pi^0\pi^0$



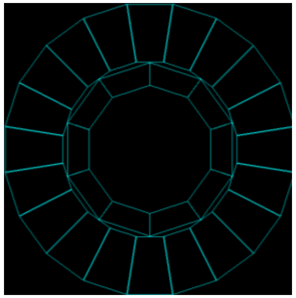
Upstream veto (UV):

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





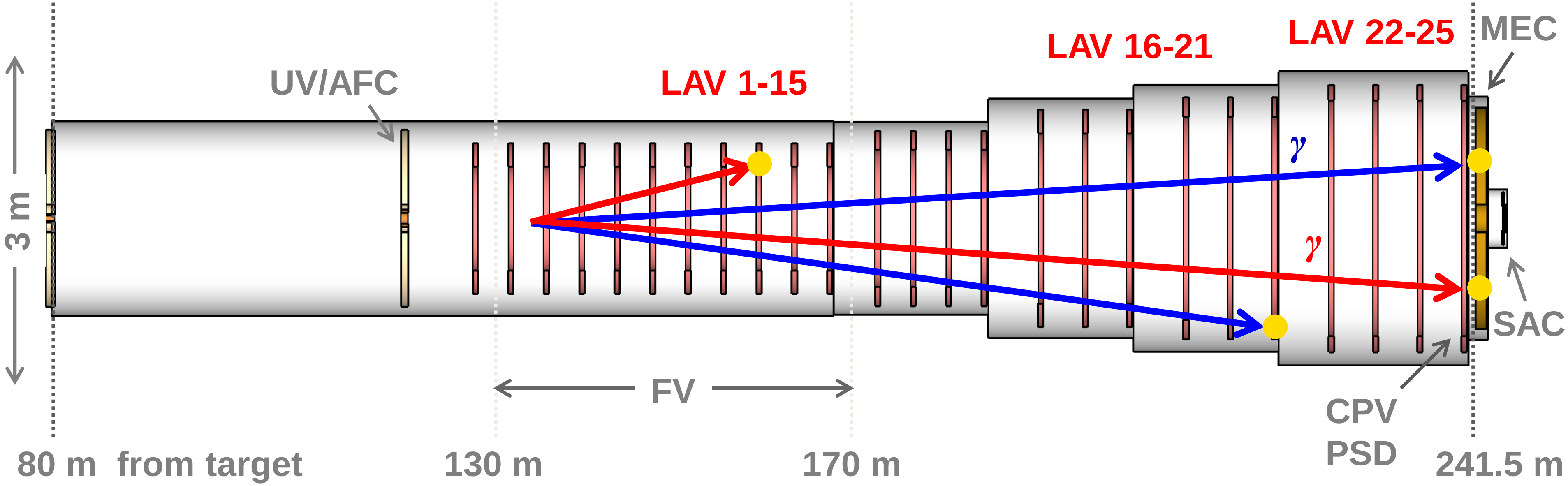
Active final collimator:



- 4.2 < r < 10 cm
- LYSO collar counter
- 80 cm long
- Internal collimating surfaces
- Intercepts halo particles from scattering on upstream collimators or γ absorber

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

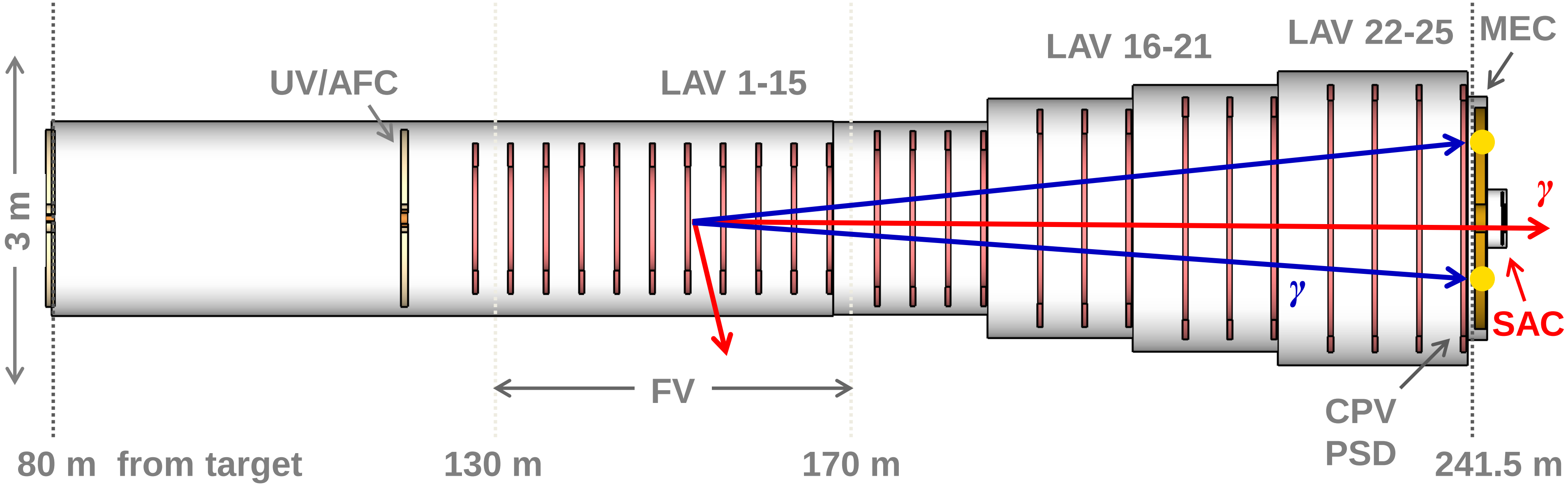
Large-angle photon vetoes



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

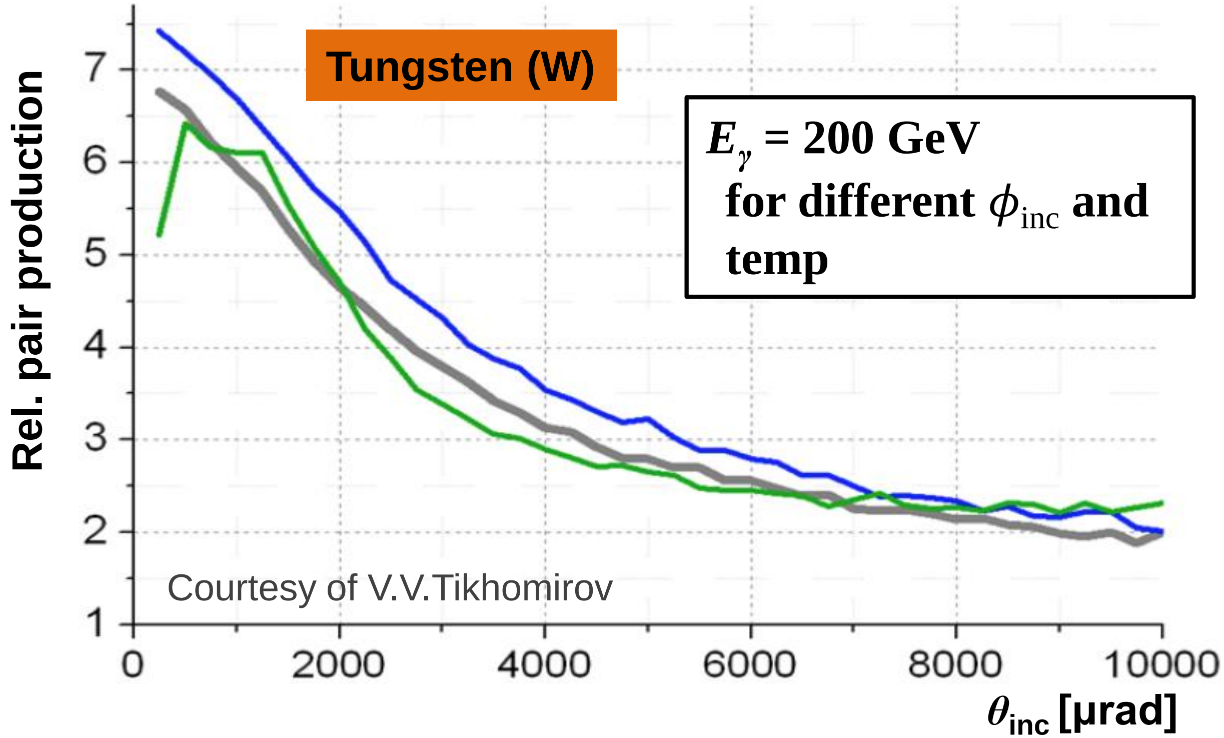
Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
γ, E > 5 GeV	**50**	$\mathbf{10^{-2}}$
γ, E > 30 GeV	**2.5**	$\mathbf{10^{-4}}$
n	**430**	**–**

Baseline solution:

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber to exploit enhancement of photon conversion by coherent interaction with lattice

Efficient γ conversion with crystals

Coherent effects in crystals enhance pair-conversion probability



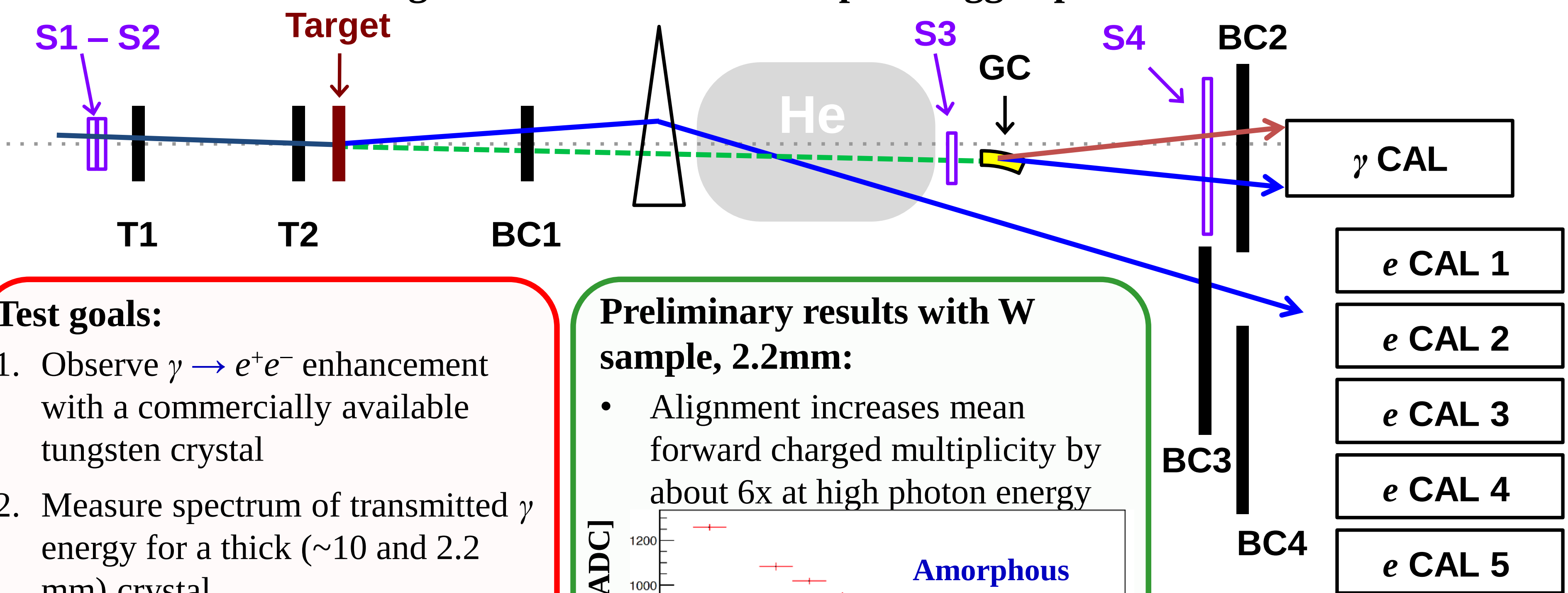
Use coherent effects to obtain a converter with large effective λ_{int}/X_0:

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 $\gamma \to e^+e^-$ in crystals

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

1 week of beam: 8-15 August 2018. Test beam setup for tagged photons from 120 GeV e^-:

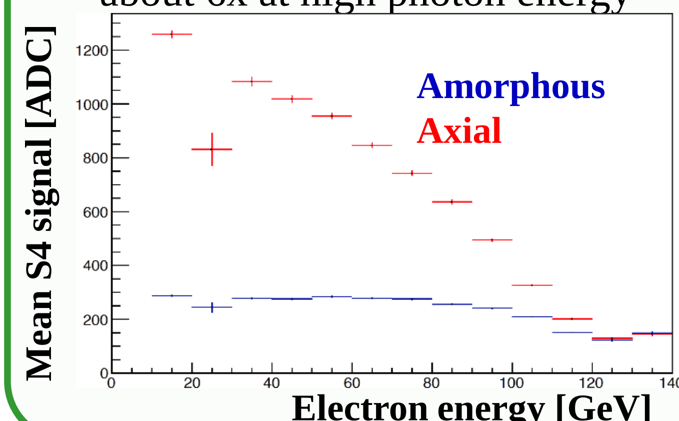


Test goals:

1. Observe $\gamma \to e^+e^-$ enhancement with a commercially available tungsten crystal
2. Measure spectrum of transmitted γ energy for a thick (~10 and 2.2 mm) crystal
3. Measure pair conversion vs. E_γ, θ_{inc}
4. Obtain information to assist MC development for beam photon converter and SAC

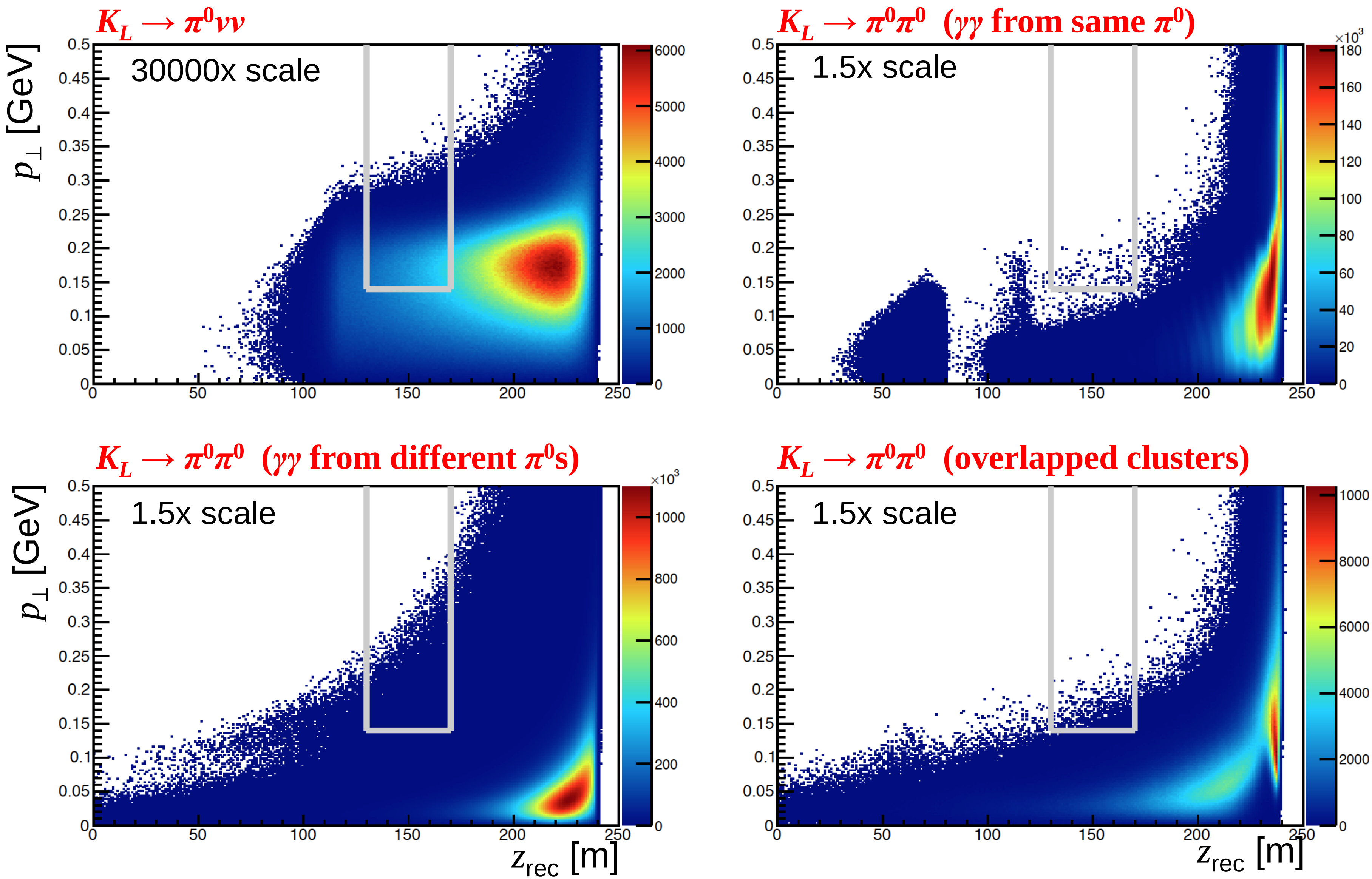
Preliminary results with W sample, 2.2mm:

- Alignment increases mean forward charged multiplicity by about 6x at high photon energy



Basic signal selection

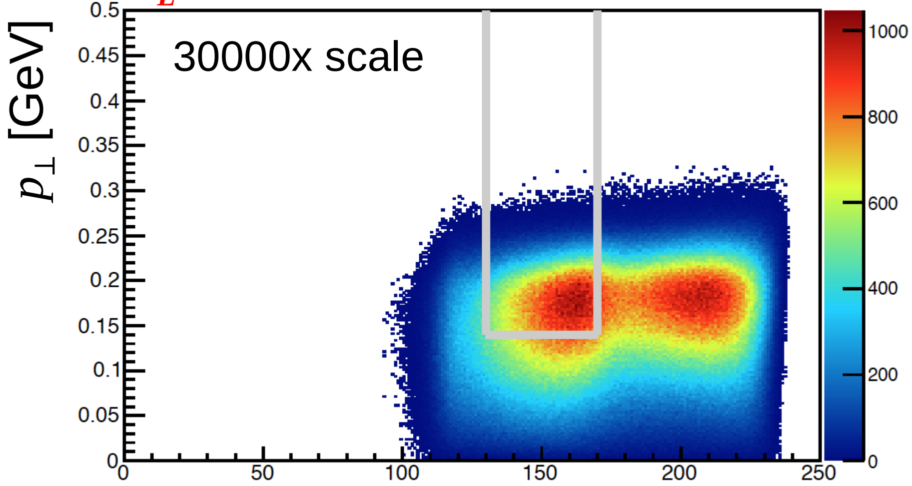
No hits in UV, AFC, LAV, SAC + fiducial volume (FV) and $p_\perp$ cuts



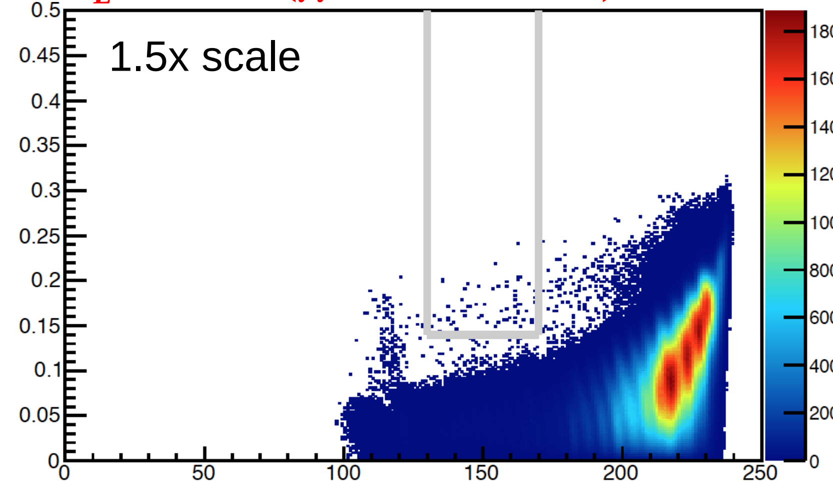
Additional background rejection

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

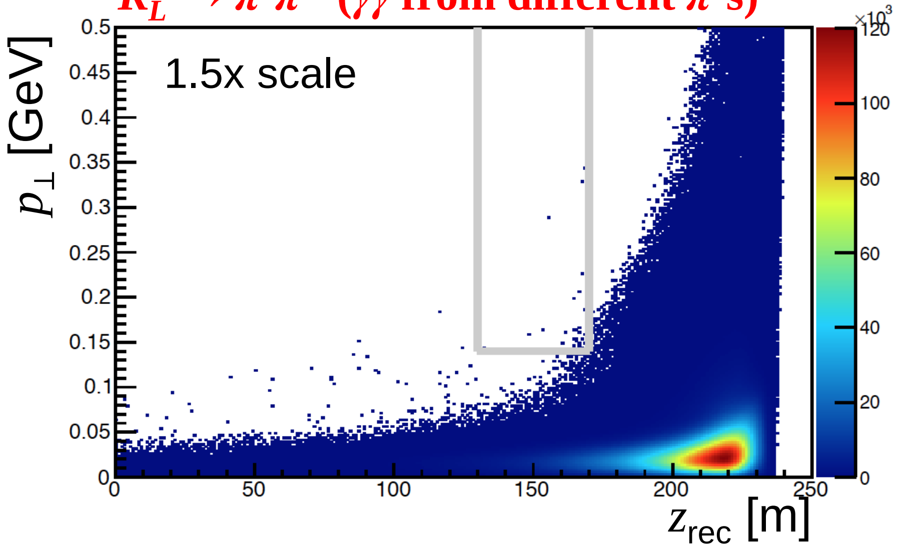
$K_L \to \pi^0 \nu\nu$



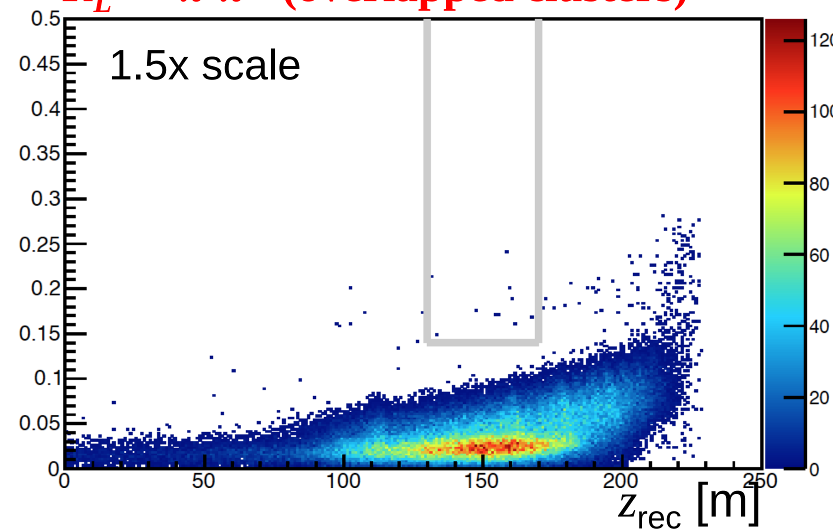
$K_L \to \pi^0\pi^0$ ($\gamma\gamma$ from same π^0)



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



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



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
2019 Q3	Expression of Interest to CERN SPSC
2020 Q2	Conclusion of European Strategy update KLEVER proposal
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

$K \to \pi\nu\nu$ 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 short term, ultimately reaching ~100 event sensitivity

KOTO is making significant progress in background reduction and will reach SM sensitivity to BR($K_L \to \pi^0\nu\nu$) by 2025

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)

- Many issues still to be addressed!
- Expected sensitivity: ~ 60 SM events with S/B ~ 1
- KLEVER is preparing Expression of Interest to CERN SPSC and is actively seeking new collaborators