$K_L \to \pi^0 \nu\nu$: Results and prospects

Frontier Objects in Astrophysics and Particle Physics
Vulcano, 25 May 2018

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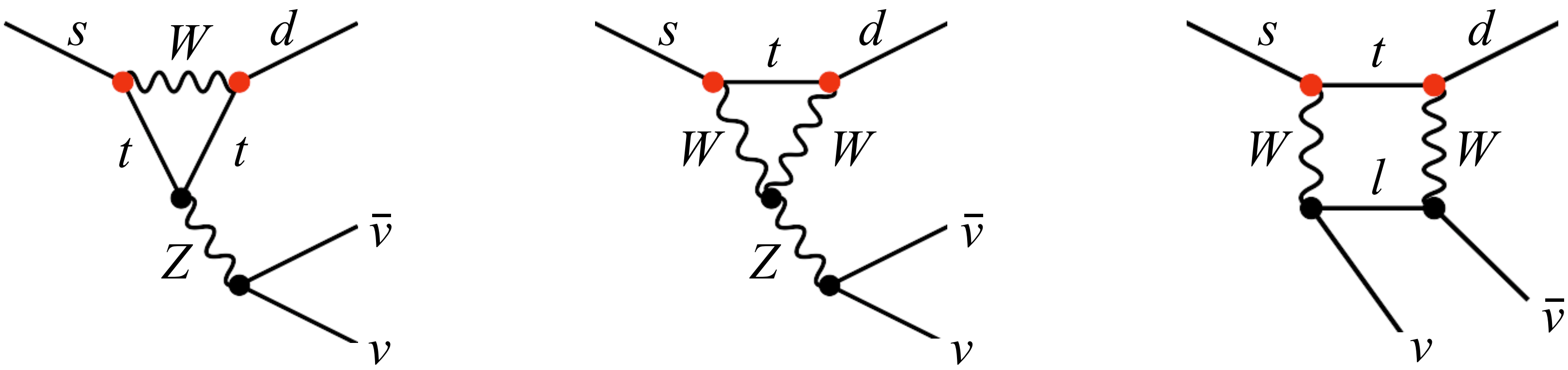
$K \to \pi\nu\bar{\nu}$ in the Standard Model

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

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

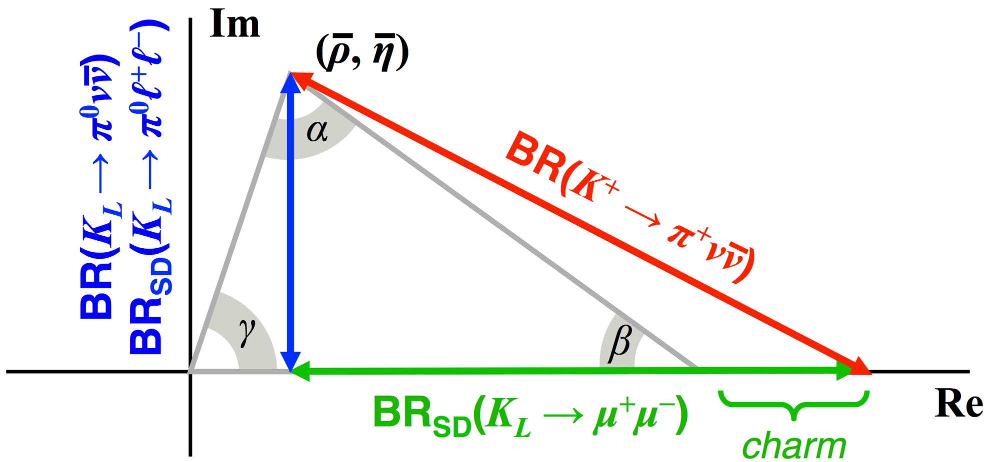
Buras et al., JHEP 1511

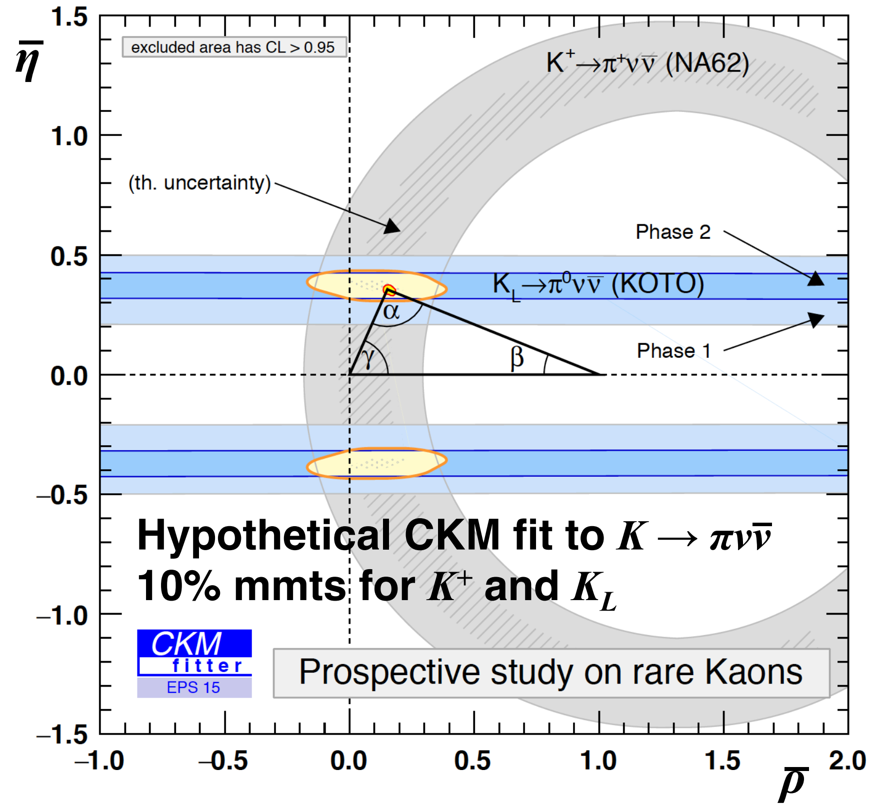
$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2°}\right]^{2}$$

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?

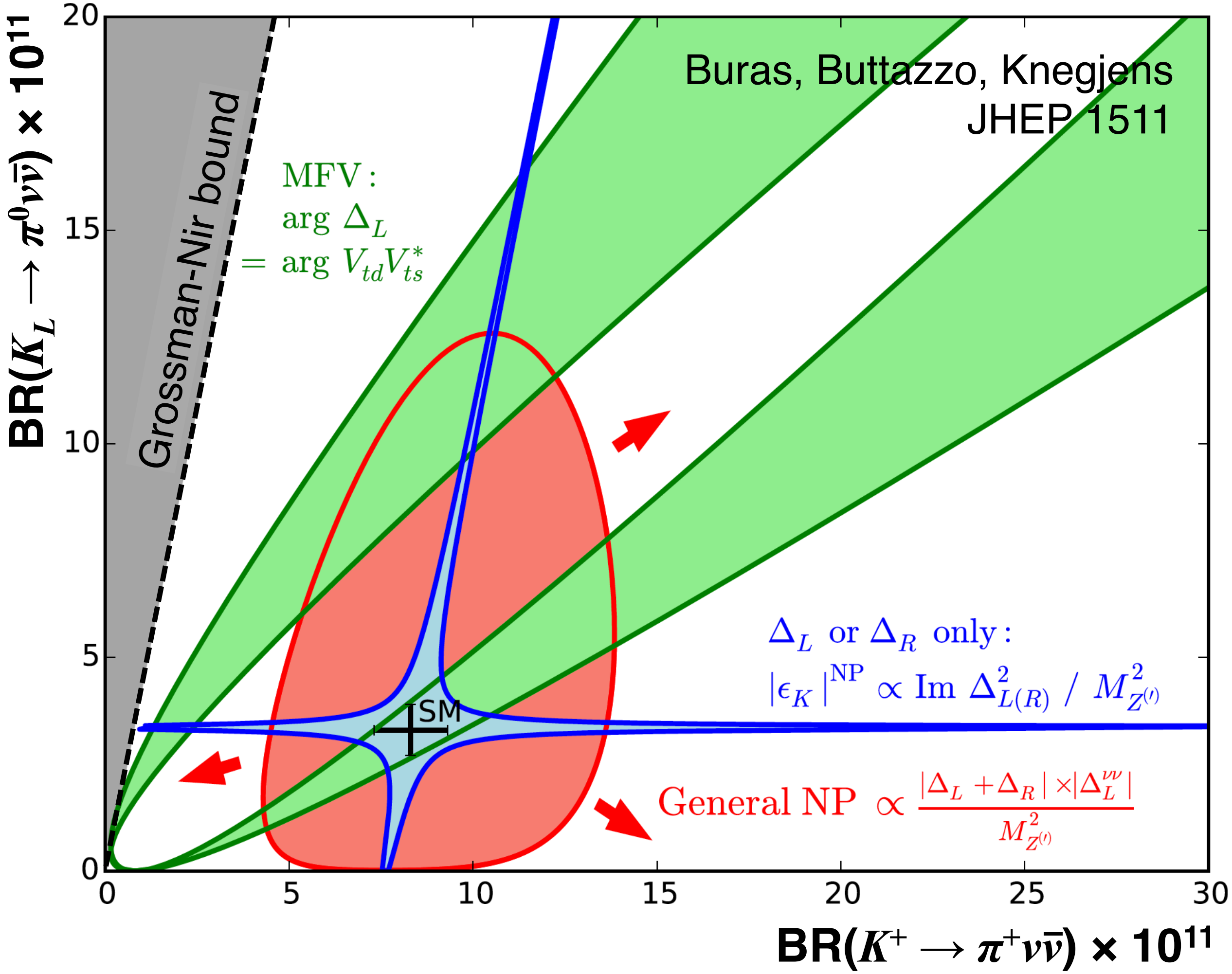




$K \to \pi\nu\bar{\nu}$ and new physics

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

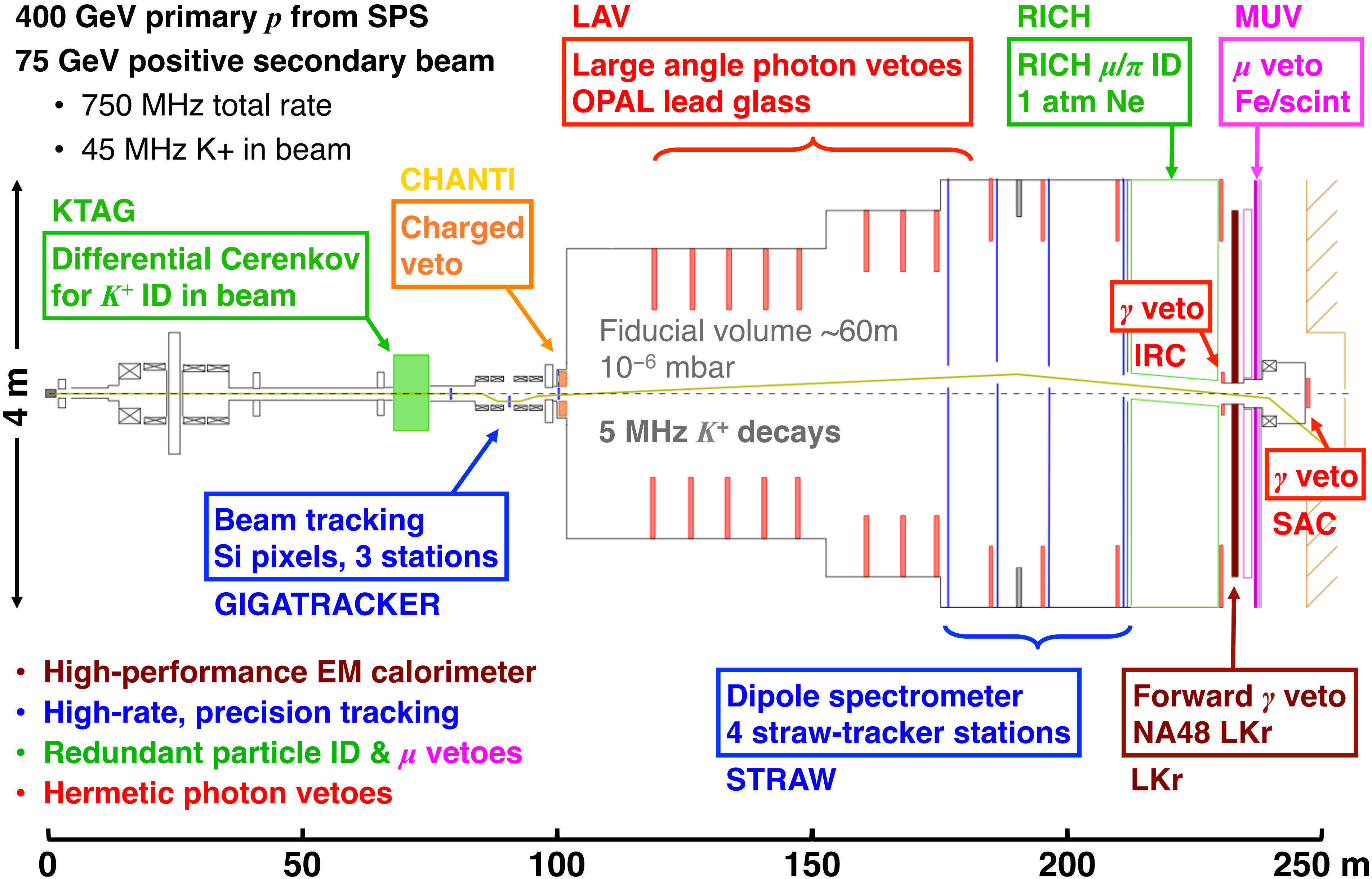
The NA62 experiment at the CERN SPS

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

See talk by G. Ruggiero

2014-2015	Pilot/commissioning runs
2016	Commissioning + 1st physics run SM sensitivity reached: BR ~ $O(10^{-10})$ **First result presented in March 2018**
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 $K^+ \rightarrow \pi^+ \nu\nu$ events

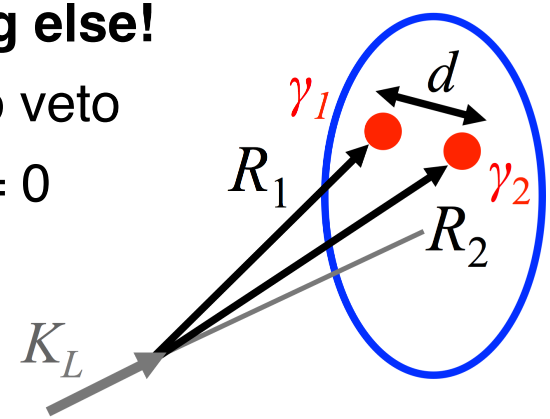
- Input to the European Strategy for Particle Physics
- Solid extrapolation to ultimate sensitivity of NA62 achievable after LS2

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

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

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

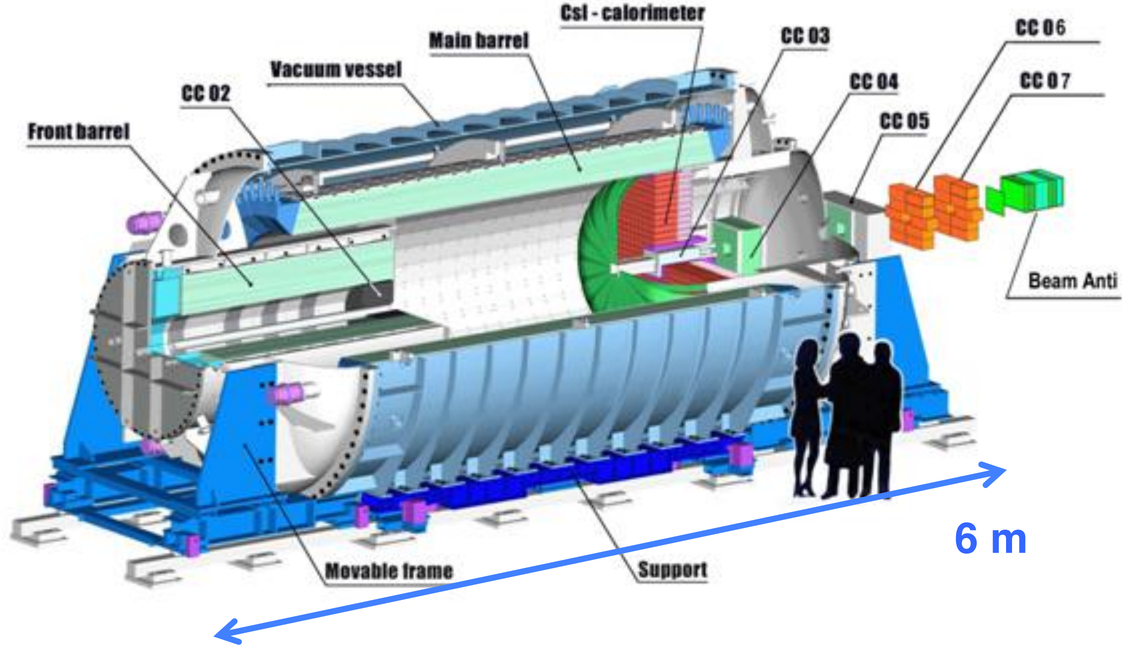
Main backgrounds:

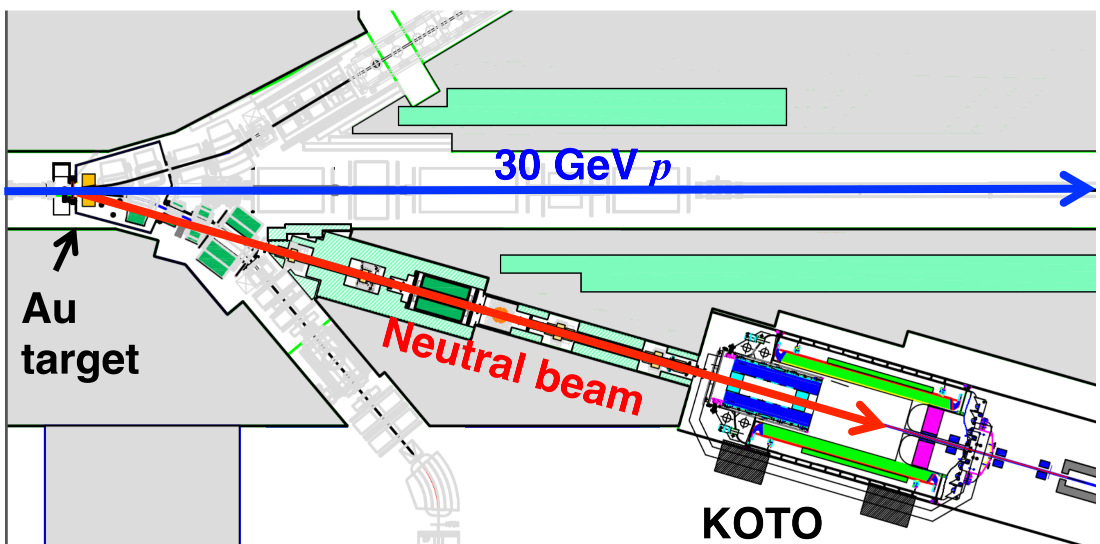
Mode	BR	Methods to suppress/reject
$K_L \to \pi^0\pi^0$	8.64 × 10^{-4}	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi^0\pi^0\pi^0$	19.52%	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi e \nu(\gamma)$	40.55%	Charged particle vetoes, π ID, γ vetoes
$\Lambda \to \pi^0 n$		Beamline length, $p_\perp$
n + gas $\to X\pi^0$		High vacuum decay region

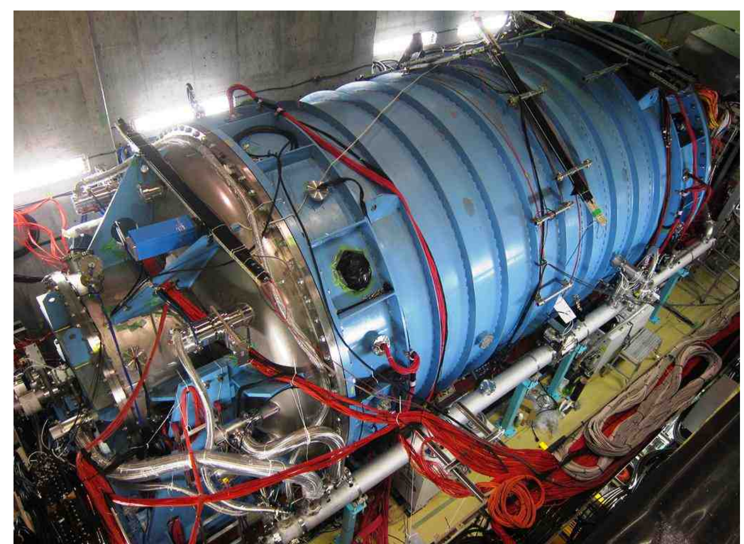
$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC

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

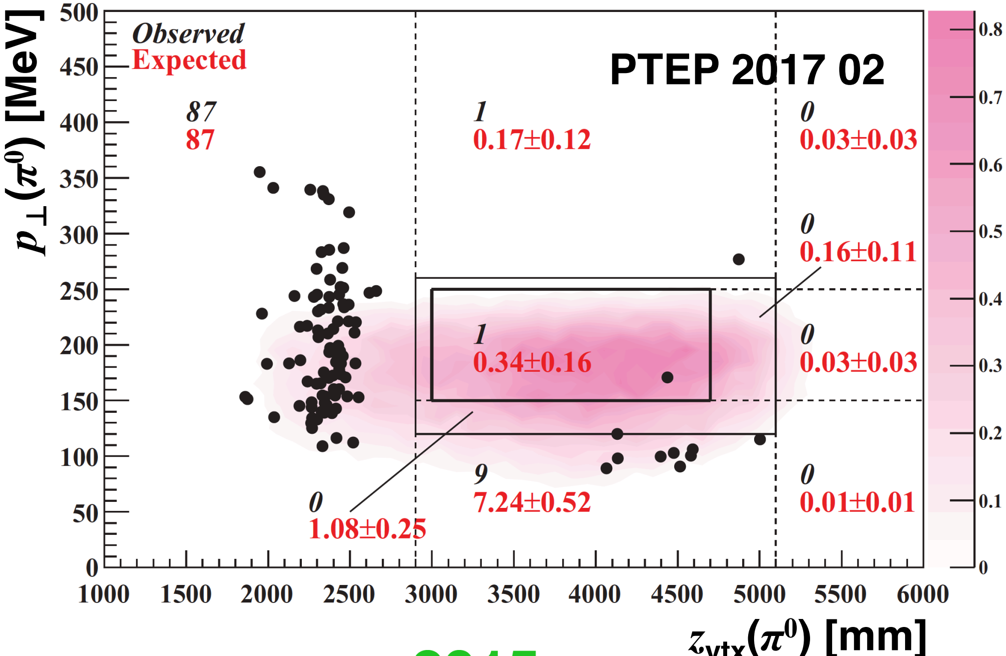
Neutral beam (16°)
$\langle p(K_L)\rangle$ = 2.1 GeV
50% of K_L have 0.7-2.4 GeV
8 µsr “pencil” beam

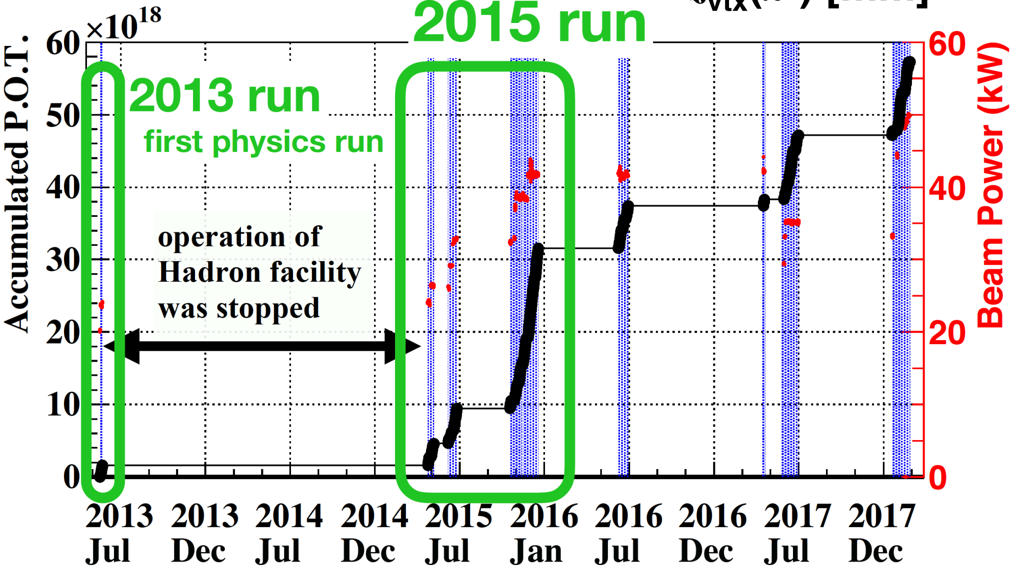






$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC





KOTO is based on KEK-E391a

E391a result = current exp. value:

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

KOTO run history:

2013 pilot run (100 hrs)

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

2015 run (result coming soon)

- **40 kW** of slow-extracted beam power
- 3e19 pot collected

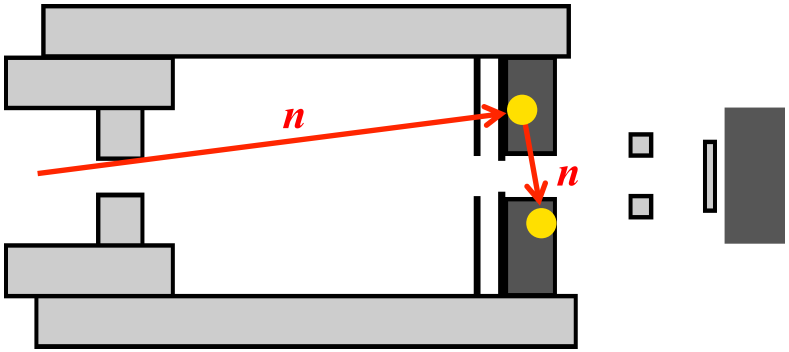
2016-2017

- Beam power increased to **50 kW**
- 3e19 pot collected (6e19 total)

Background rejection

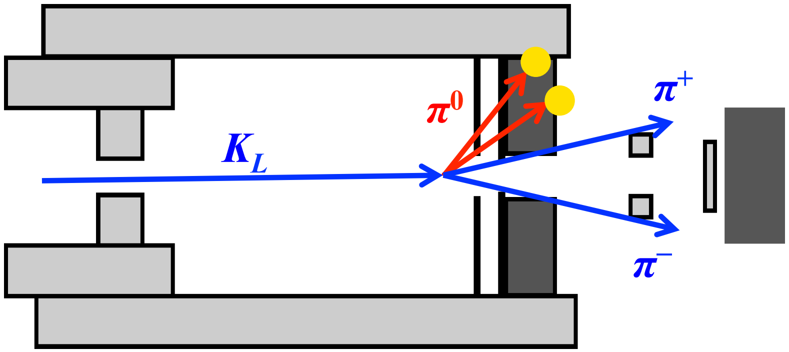
Lessons from 2013 run help to reject backgrounds other than $K_L \rightarrow \pi^0\pi^0$

1. Hadron clusters on CsI



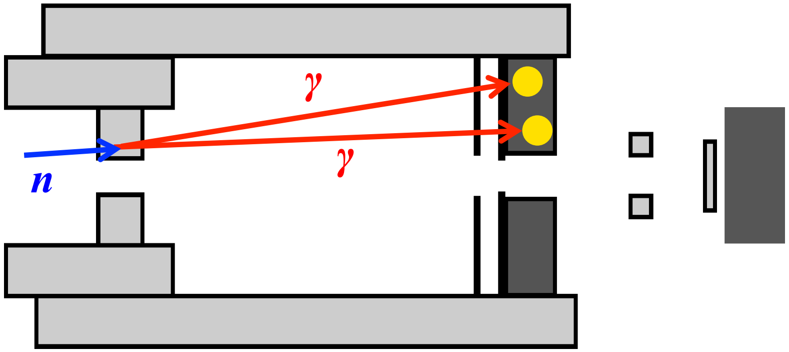
- Control sample with Al plate in beam
- Cluster and pulse shape analysis

2. $K_L \rightarrow \pi^+\pi^-\pi^0$ with $\pi^+\pi^-$ escape



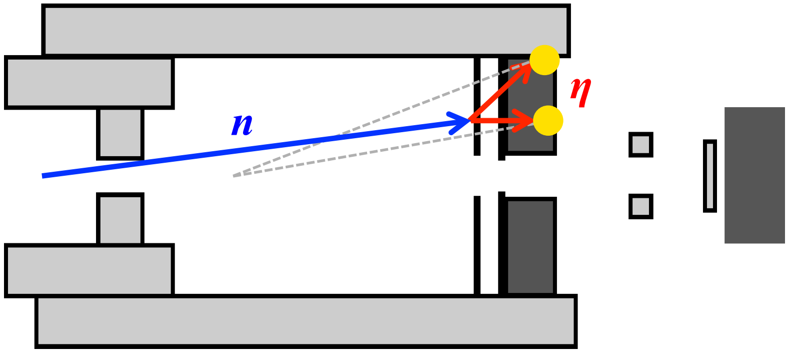
- New charged-particle vetoes lining beam exit

3. $n \rightarrow X\pi^0$ on collar (NCC)



- Beam profile monitor for better alignment
- Thinner vacuum window

4. $n \rightarrow X\eta$ on charged veto (CV)

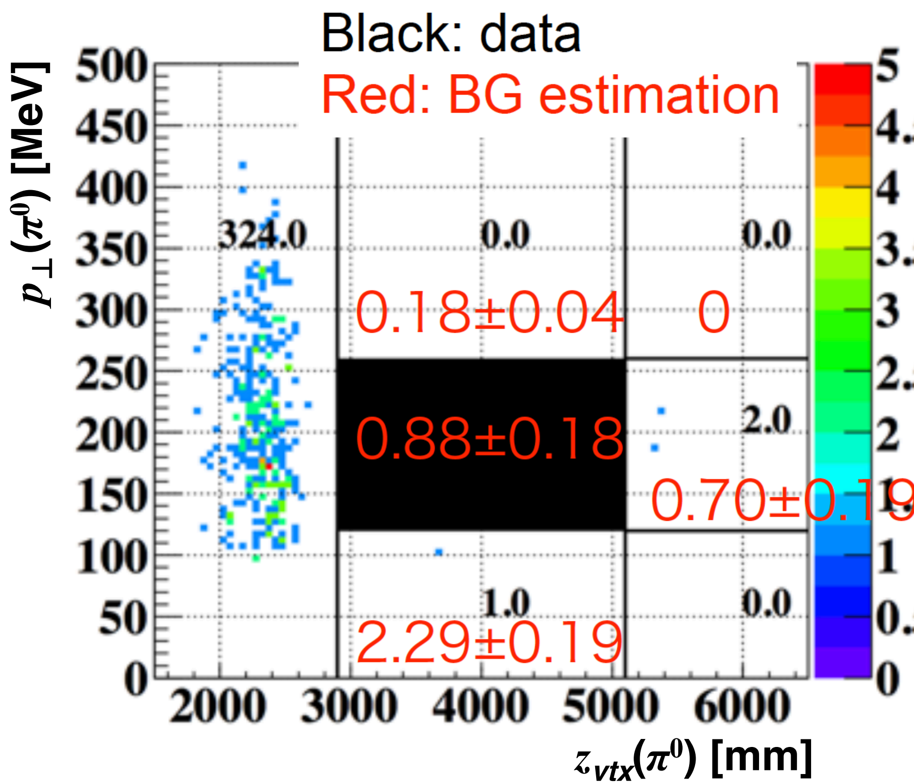


- Cluster shape (angle of incidence)

Sensitivity from 2015 data

J-PARC PAC, Jan 2018

Background	Expected counts
$K_L \to 2\pi^0$	0.07 ± 0.07
$K_L \to \pi^+\pi^-\pi^0$	0.18 ± 0.05
$K_L \to 3\pi^0$	0.17 ± 0.12
$K_L \to 2\gamma$	0.02 ± 0.02
Hadron cluster	0.26 ± 0.08
π^0 from NCC	0.13 ± 0.07
η from CV	0.05 ± 0.02
Total	**0.88 ± 0.18**



Preliminary sensitivity, all 2015 data:

SES = 1.2×10^{-9}

Expected bkg = 0.88 ± 0.18 events

Signal box to be opened summer 2018

K_L flux from $K_L \to 2\pi^0 = 4.62 \times 10^{12}$

$\pi^0\nu\nu$ acceptance from MC:

Decay in FV: 3.8%

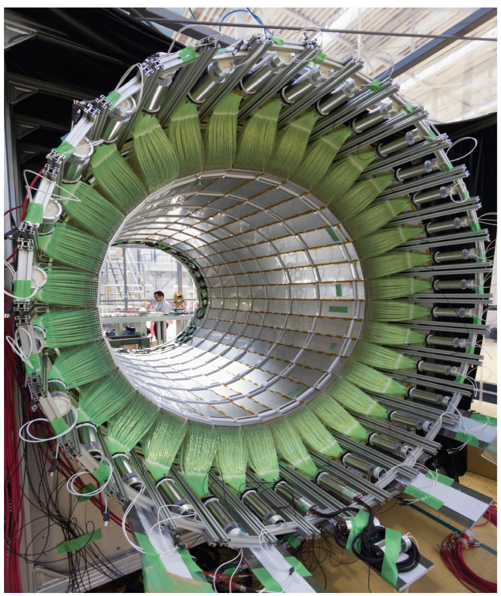
Overall acceptance: 1.8×10^{-4}

Upgrades to improve sensitivity

Signal: Need ~40x more flux × acceptance for 1 expected SM $\pi^0 \nu\nu$ event
- Beam power expected to increase 50 → 100 kW gradually by 2021
- 20+ months of additional running planned in 2018-2021

Background: Need ~40x more background rejection for S/B ~ 1
- Continuing program of detector upgrades

Inner barrel veto

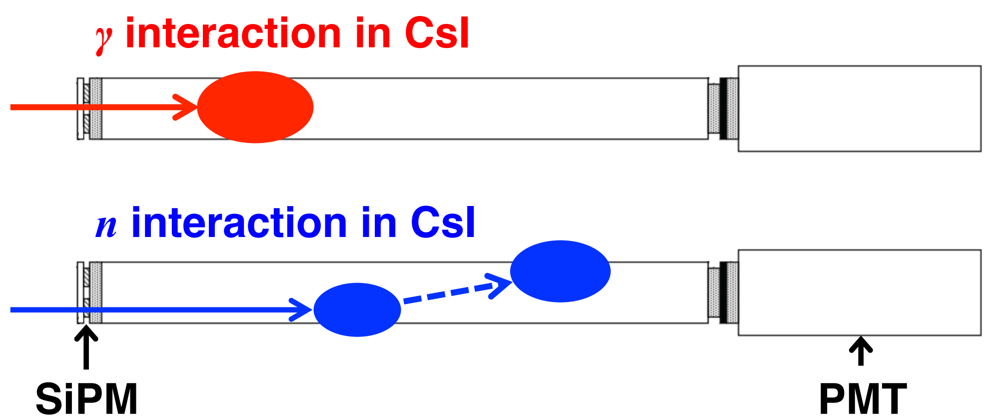


Increase barrel thickness 13.5 + 5 X_0

3x better rejection for $K_L \to 2\pi^0$

Installed April 2016

Dual side readout for CsI modules



Resolve γ/n interaction depth by reading light from front CsI face with SiPM

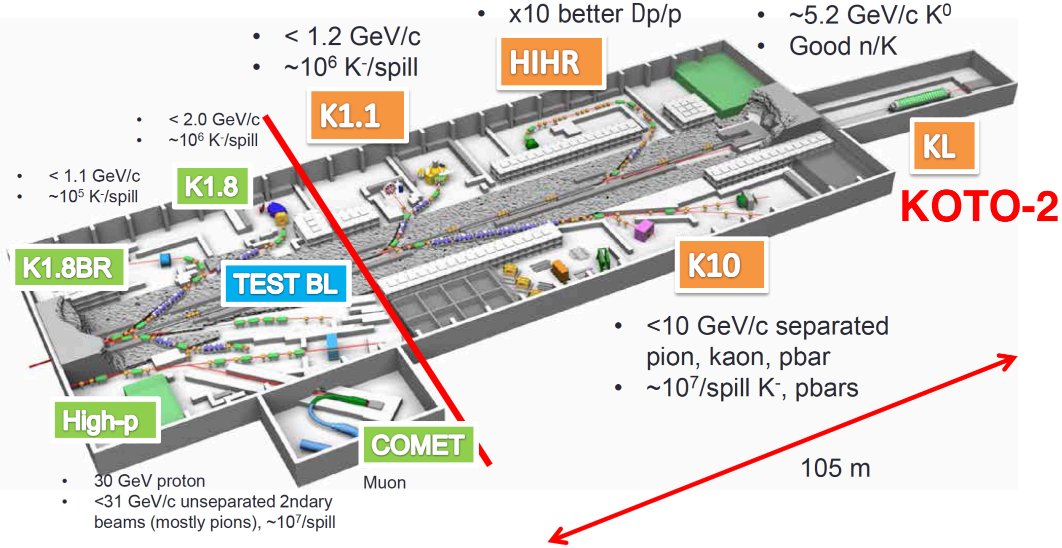
SiPMs to be installed summer 2018

Expect to reach SM sensitivity by 2021

$K_L \to \pi^0 \nu\bar{\nu}$: Long-term plans

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:

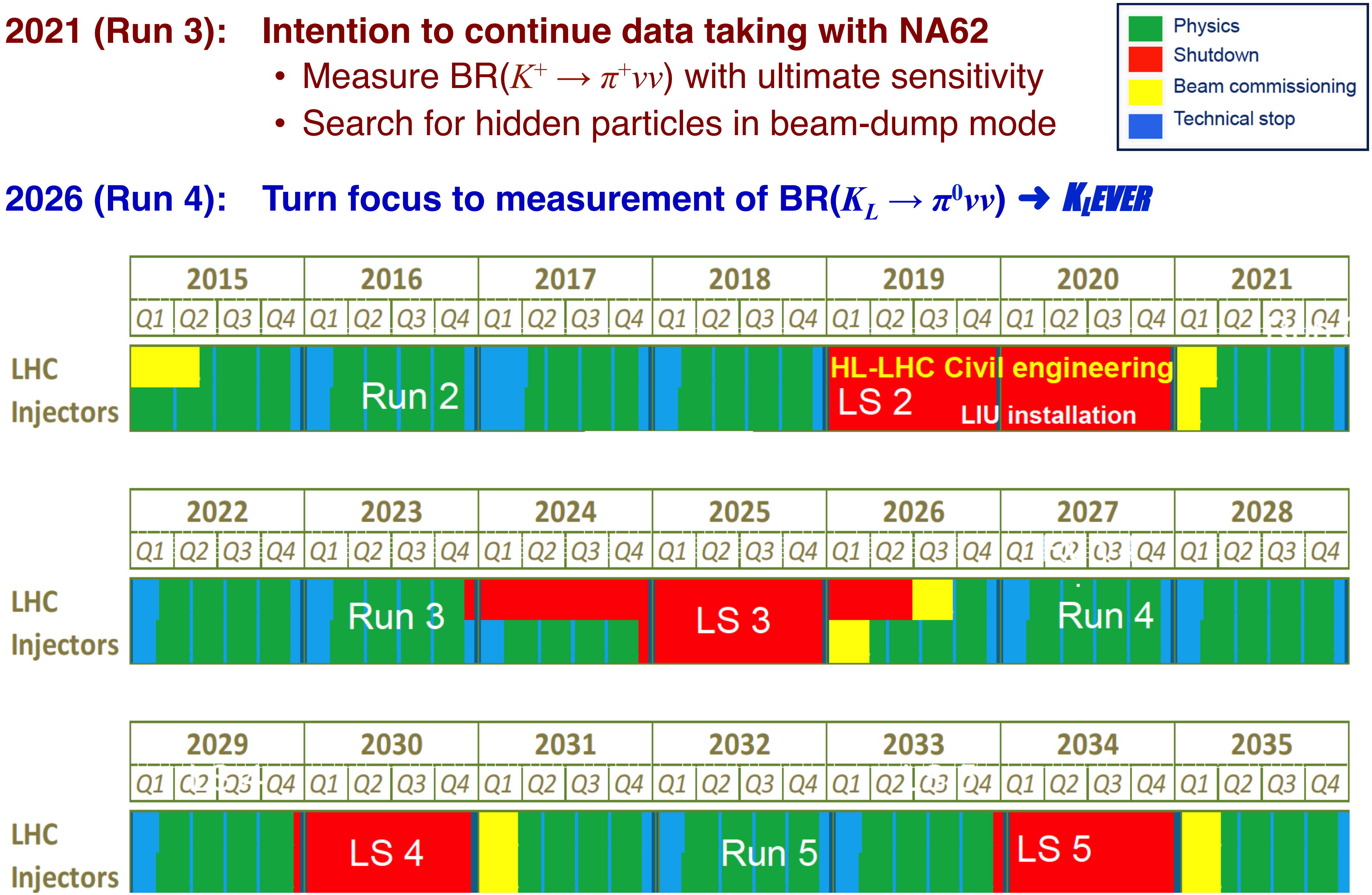
- No official Step 2 proposal yet (plan outlined in 2006 KOTO proposal)
- Scaling KOTO performance for smaller beam angle & larger detector:
  ~10 SM evts/year per 100 kW beam power?
- Exploring possibilities for machine & detector upgrades to further increase sensitivity

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

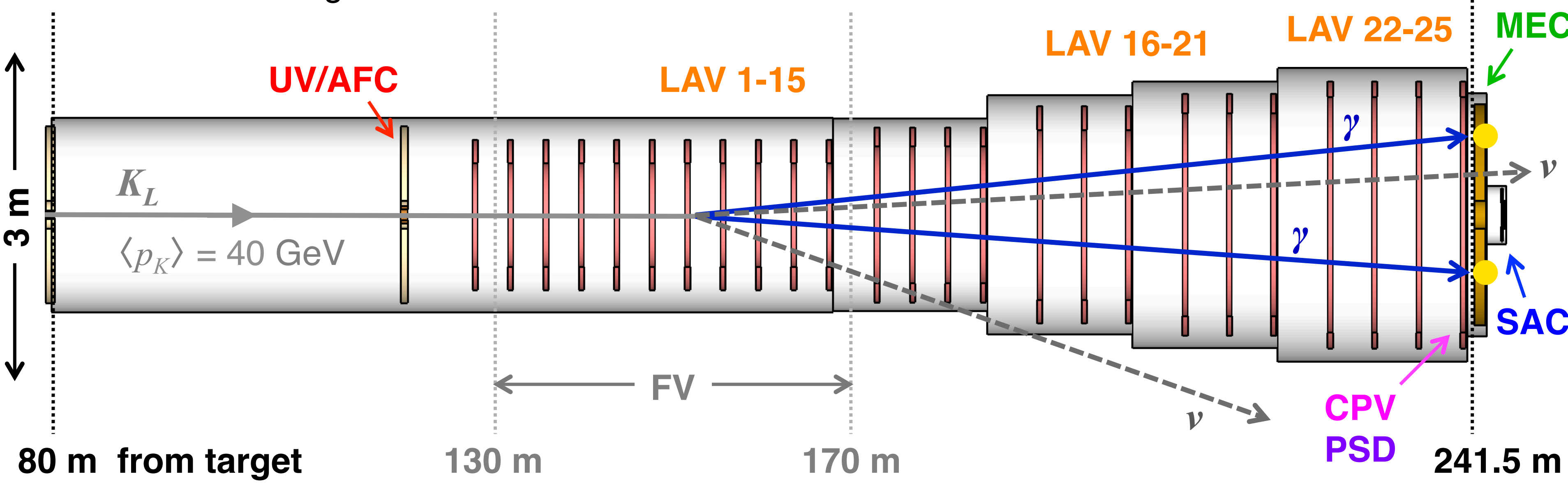
2026 (Run 4): Turn focus to measurement of BR($K_L \to \pi^0\nu\nu$) ➜ K_LEVER



F. Bordry, presentation to HEPAP, Dec 2015

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

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



KLEVER

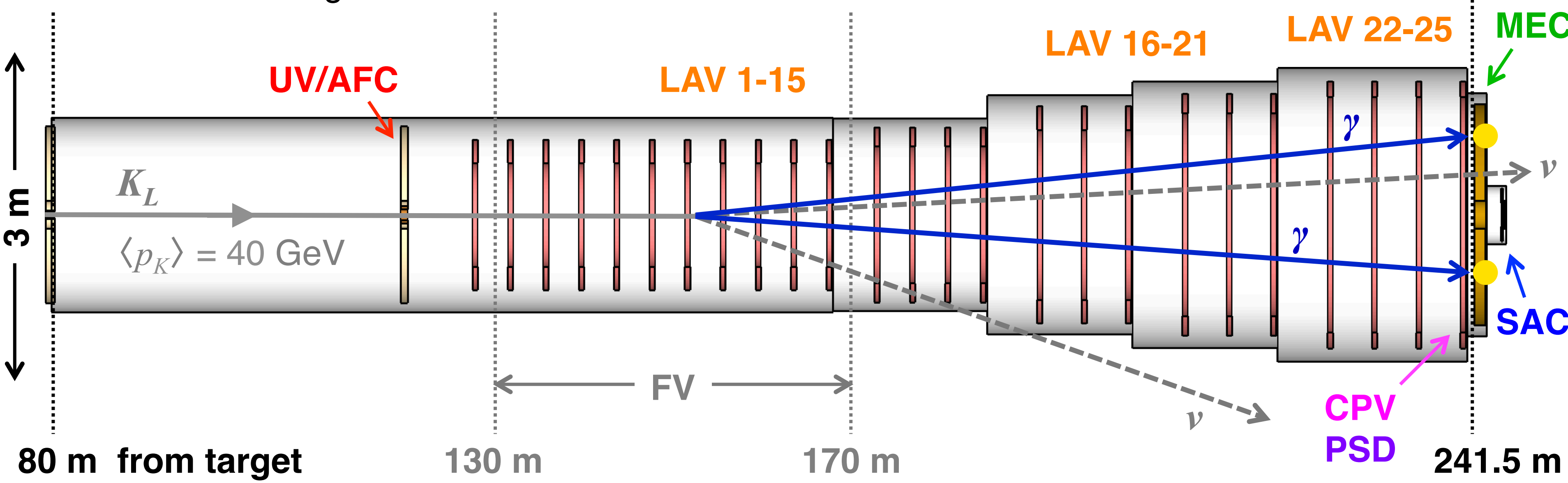
K_L Experiment for
VEry Rare events

- 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

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



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:

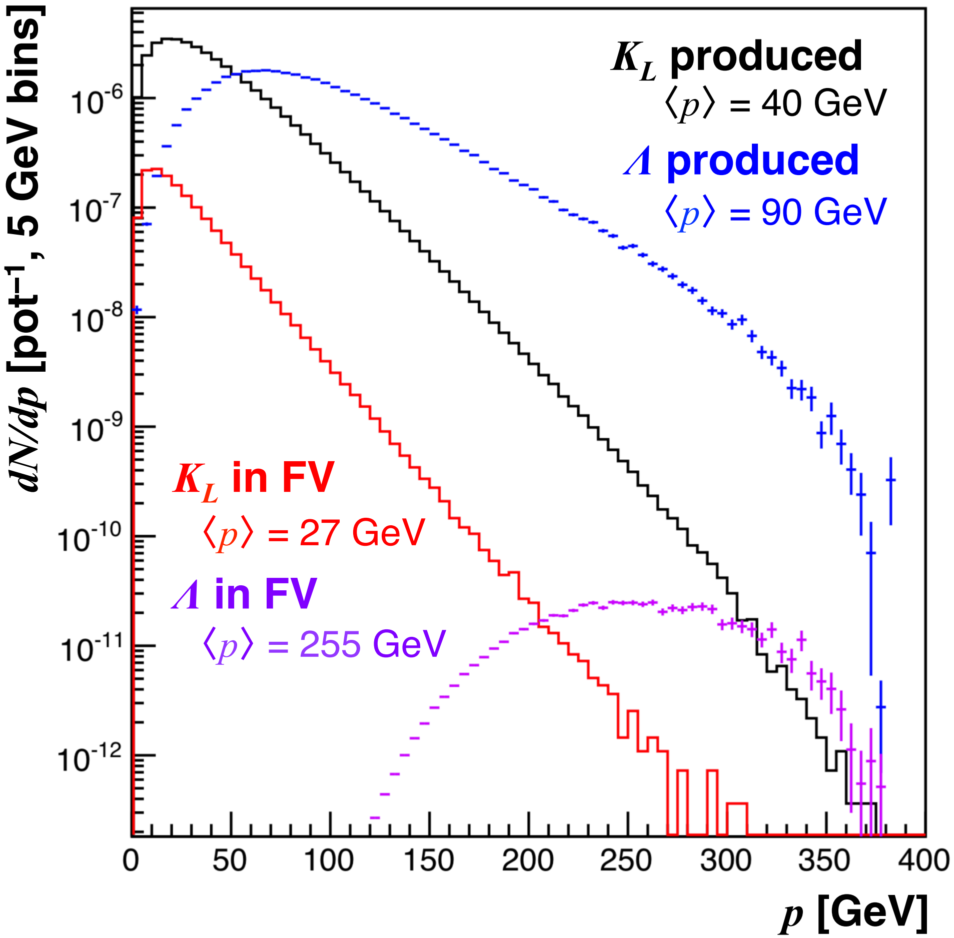
UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector

Beam and intensity requirements

K_LEVER

K_L and Λ fluxes in beam

FLUKA simulation

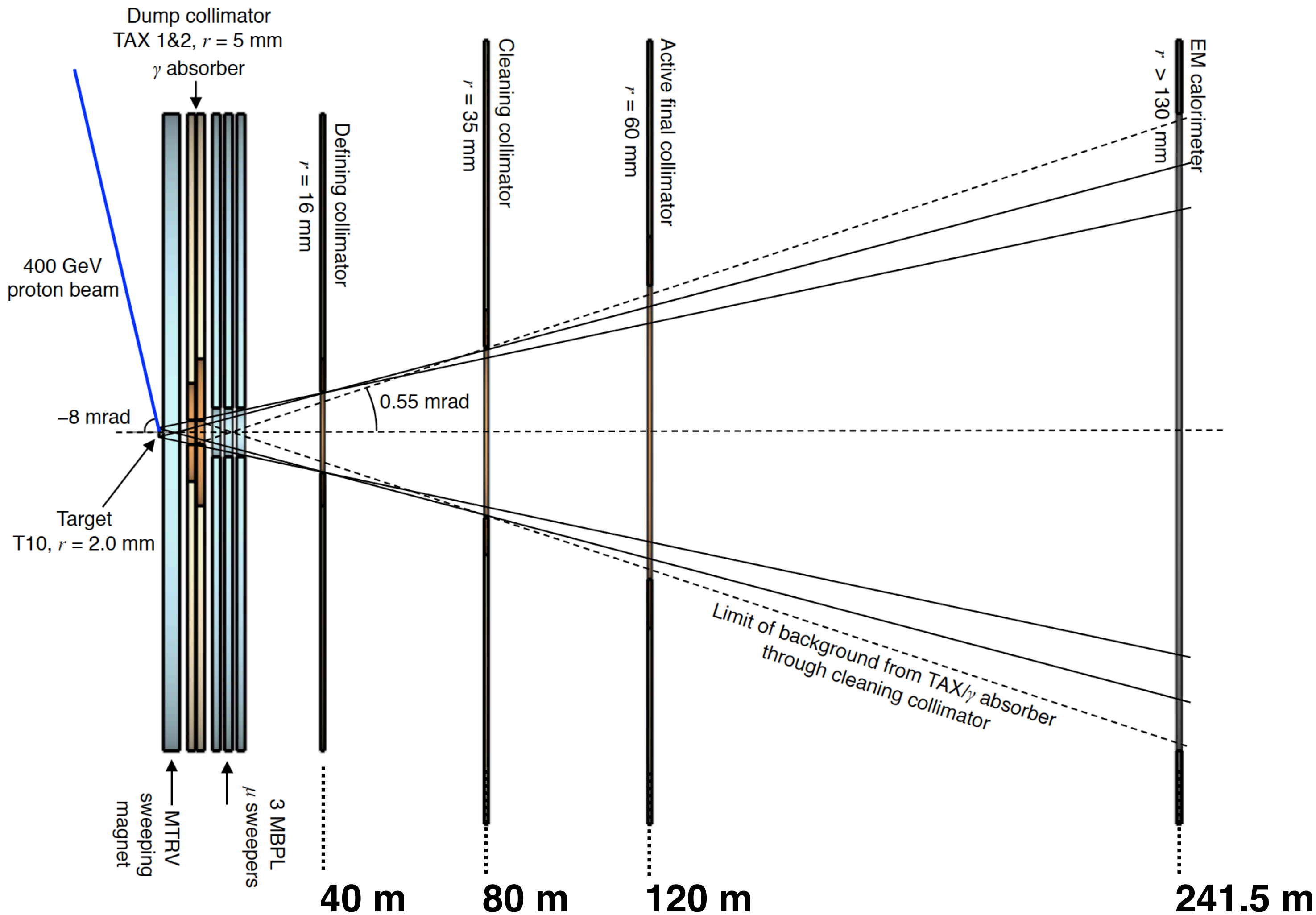


- **400 GeV p on 400 mm Be target**
- **Production at $\theta = 8.0$ mrad:**
  - As much K_L production as possible
  - Low ratio of n/K_L in beam ~ 3
  - Reduce Λ production and soften momentum spectrum
- **Solid angle $\Delta\theta = 0.4$ mrad**
  - Large $\Delta\theta$ = high K_L flux
  - Maintain 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

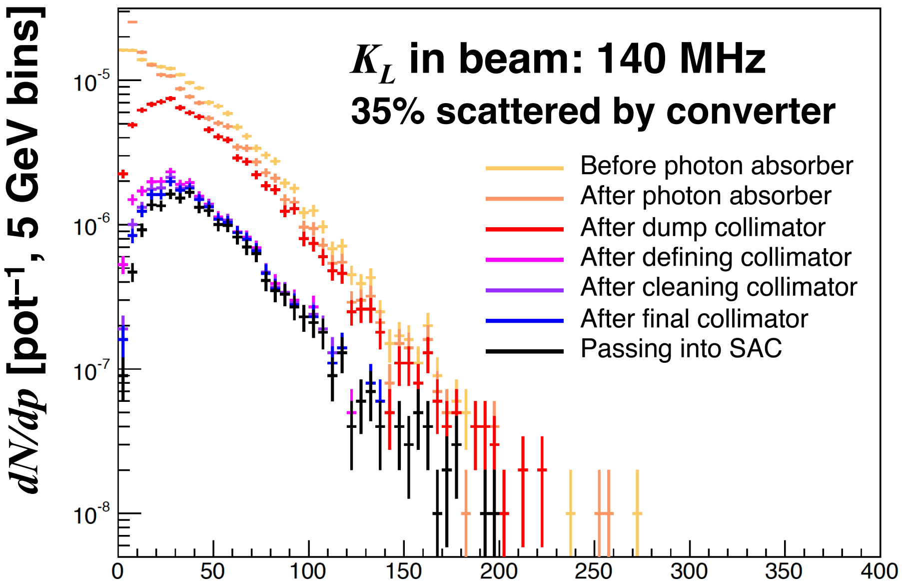
× 5 years ⇨ **60 $K_L \to \pi^0 \nu\nu$ events**

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

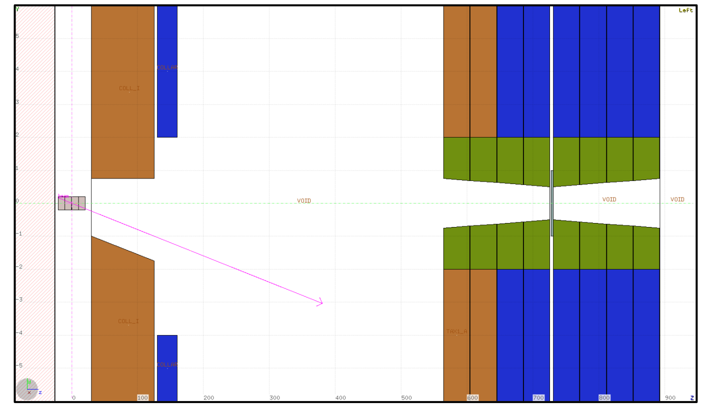
Neutral beam simulation

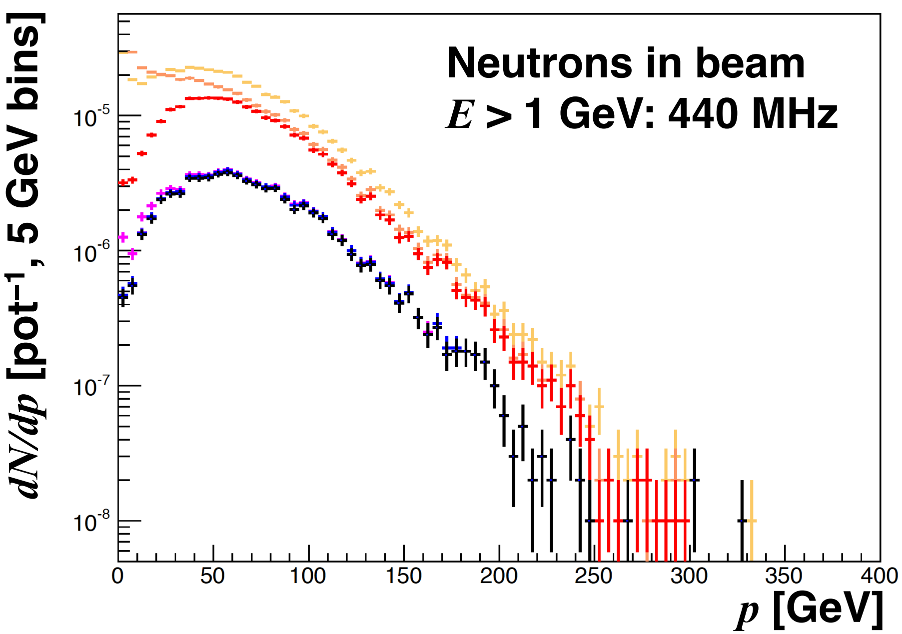


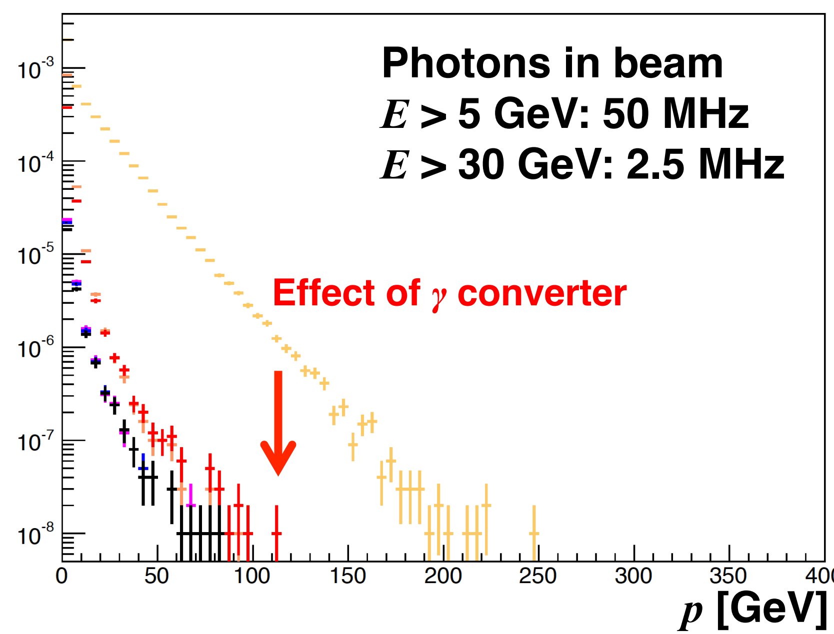
FLUKA simulation of beamline

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

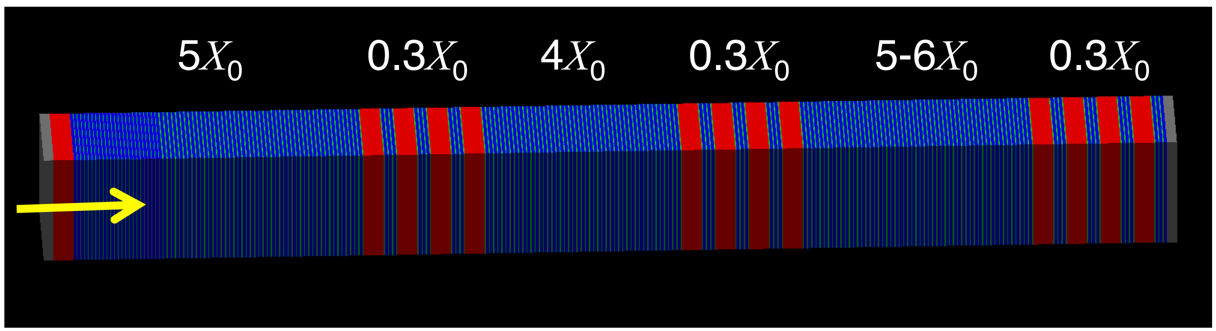
0.275 mm Pb + 1.5 mm scintillator

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)

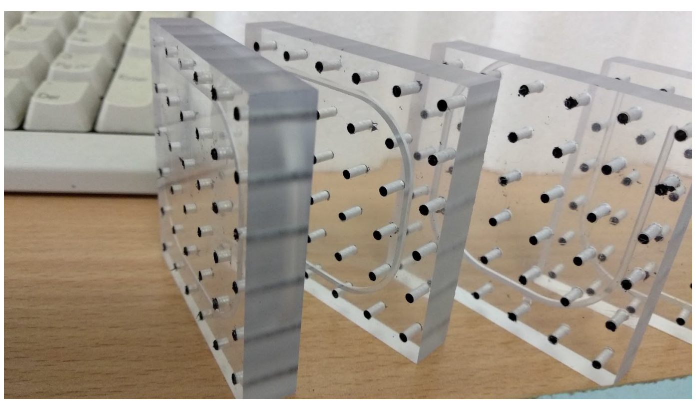
New for KLEVER: Longitudinal shower information from spy tiles

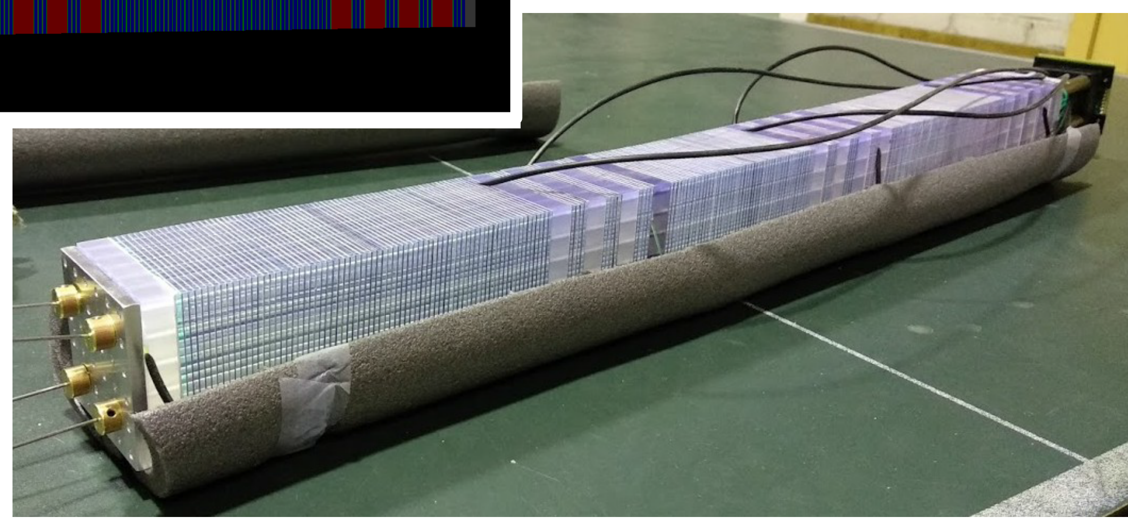
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



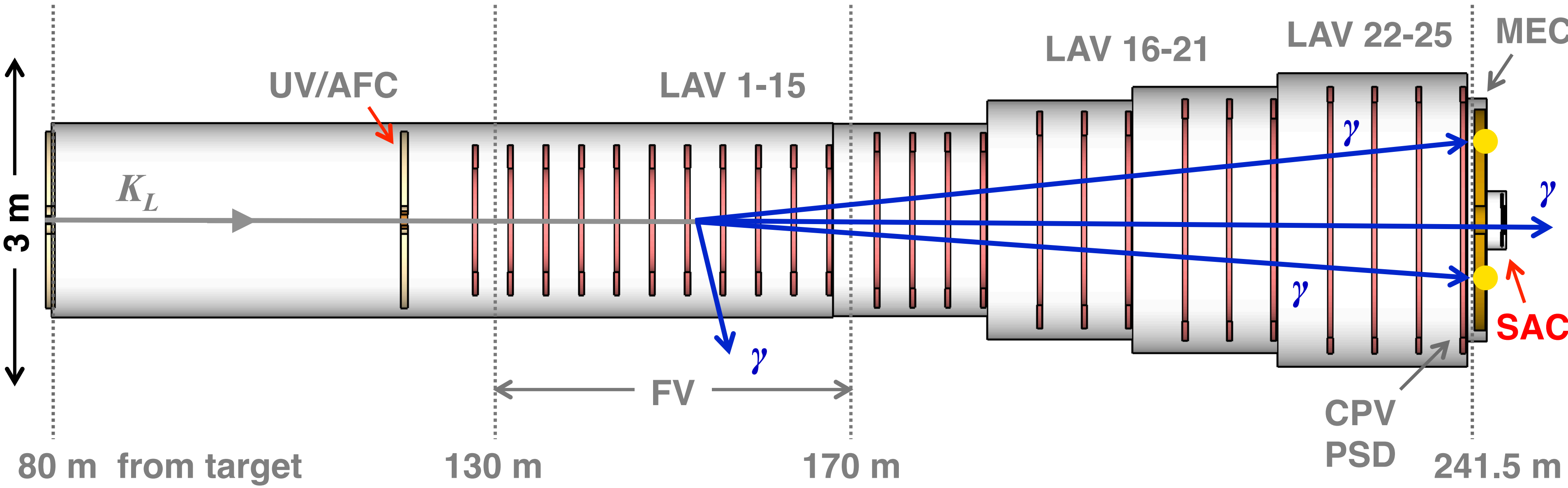
1st prototype assembled and tested at Protvino

OKA beamline, April 2018





Small-angle photon veto



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 430 MHz of beam neutrons

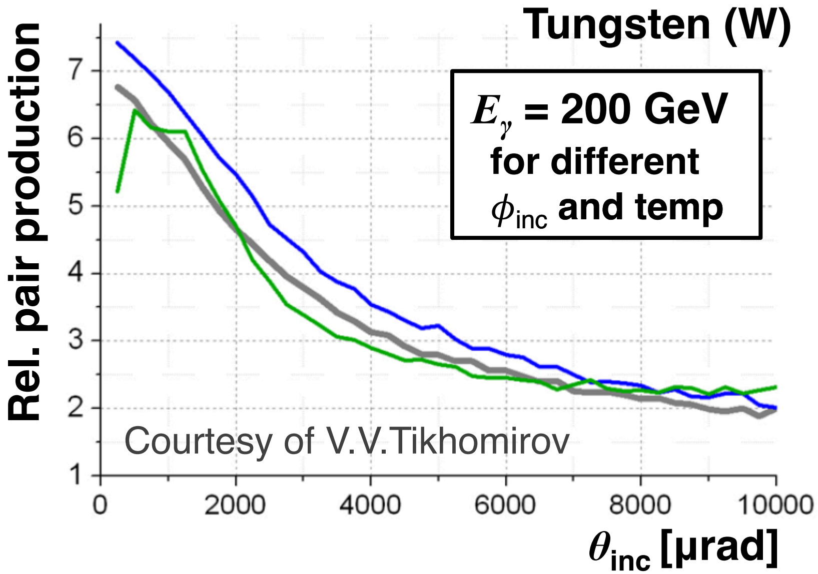
Beam comp.	Rate (MHz)	Req. $1-\varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

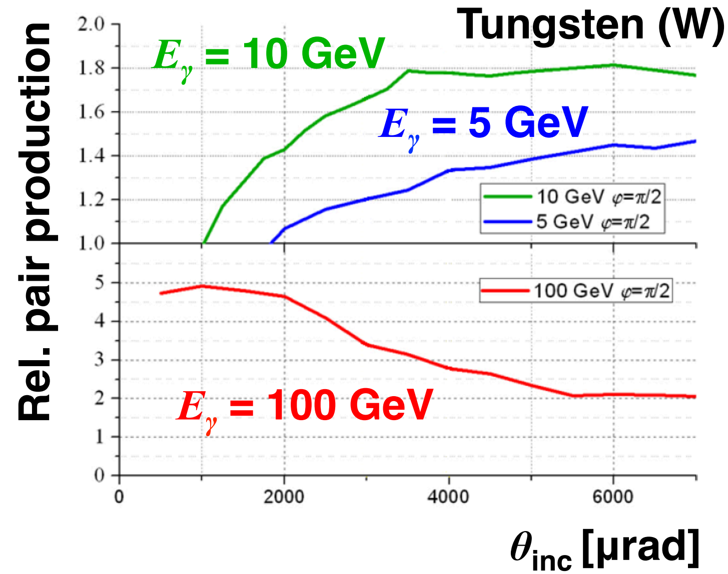
Baseline solution:

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

Efficient γ conversion with crystals

Coherent effects in crystals enhance pair-conversion probability





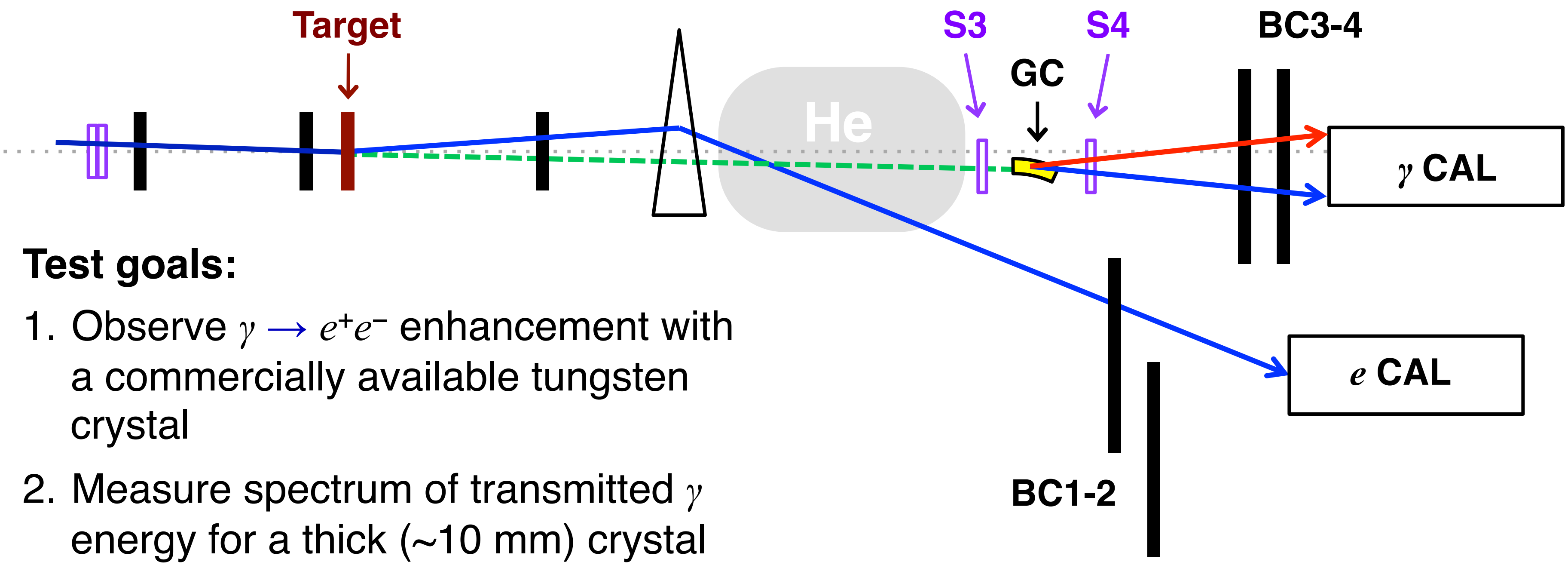
Use coherent effects to obtain a converter with large effective λ_{int}/X_0:

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:



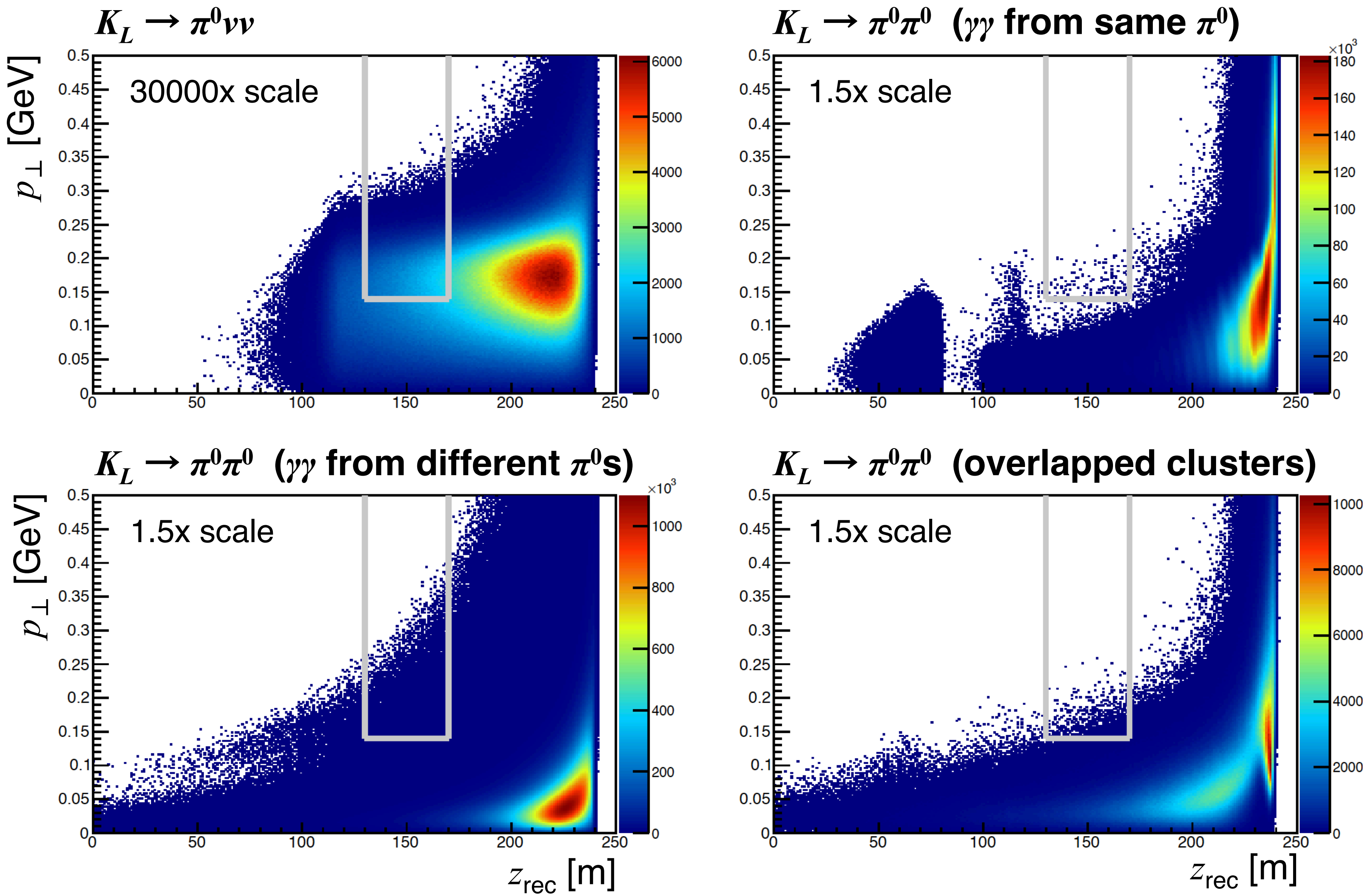
Test goals:

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 beam H2 beam time in August 2018**

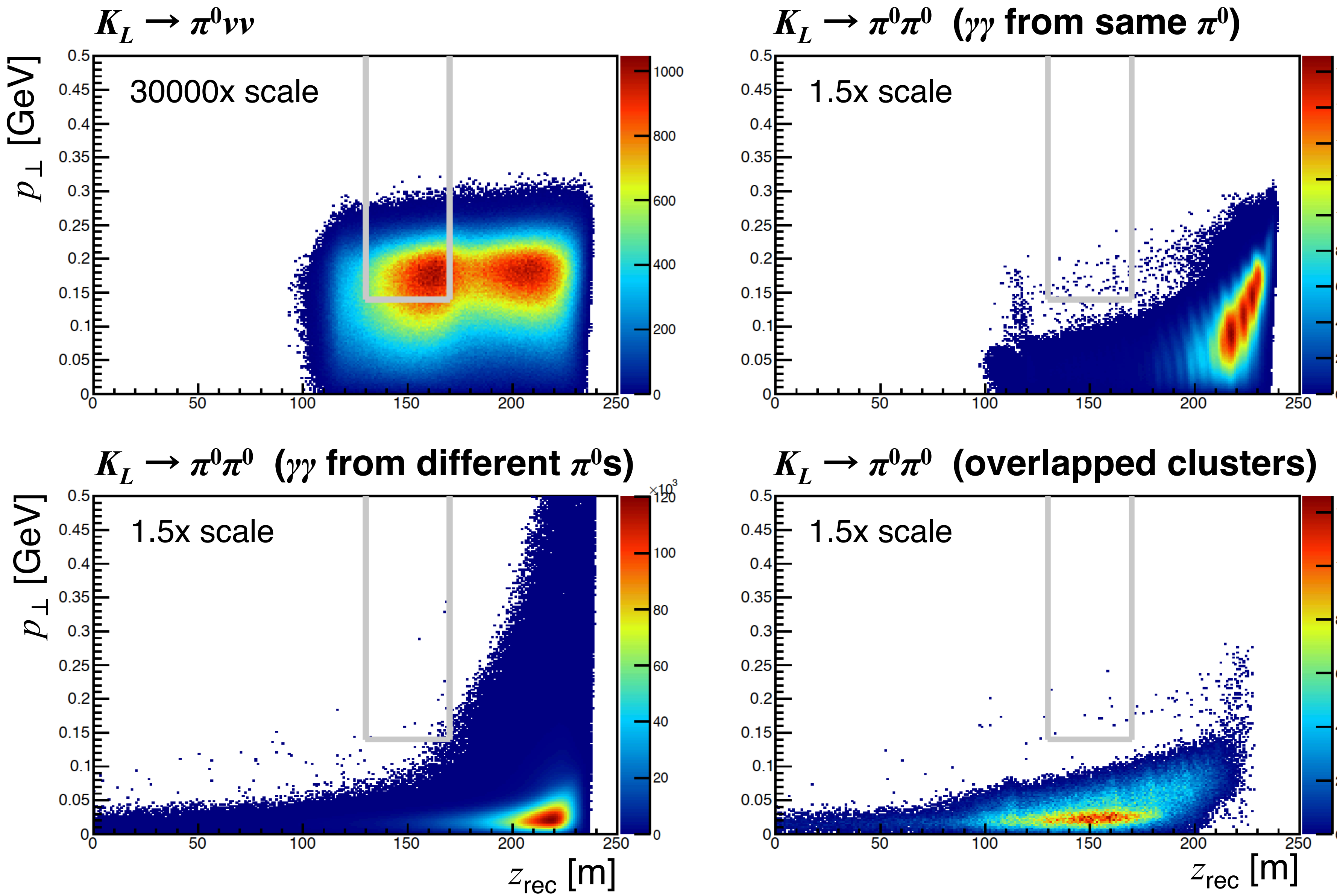
Basic signal selection

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



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**

- **KLEVER is 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

$K_L \to \pi^0 \nu\bar{\nu}$: 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 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 ~ 1
- KLEVER is preparing Expression of Interest to CERN SPSC and will provide input to European Strategy for Particle Physics

Additional information

Frontier Objects in Astrophysics and Particle Physics
Vulcano, 25 May 2018

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$K \to \pi\nu\bar{\nu}$ 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

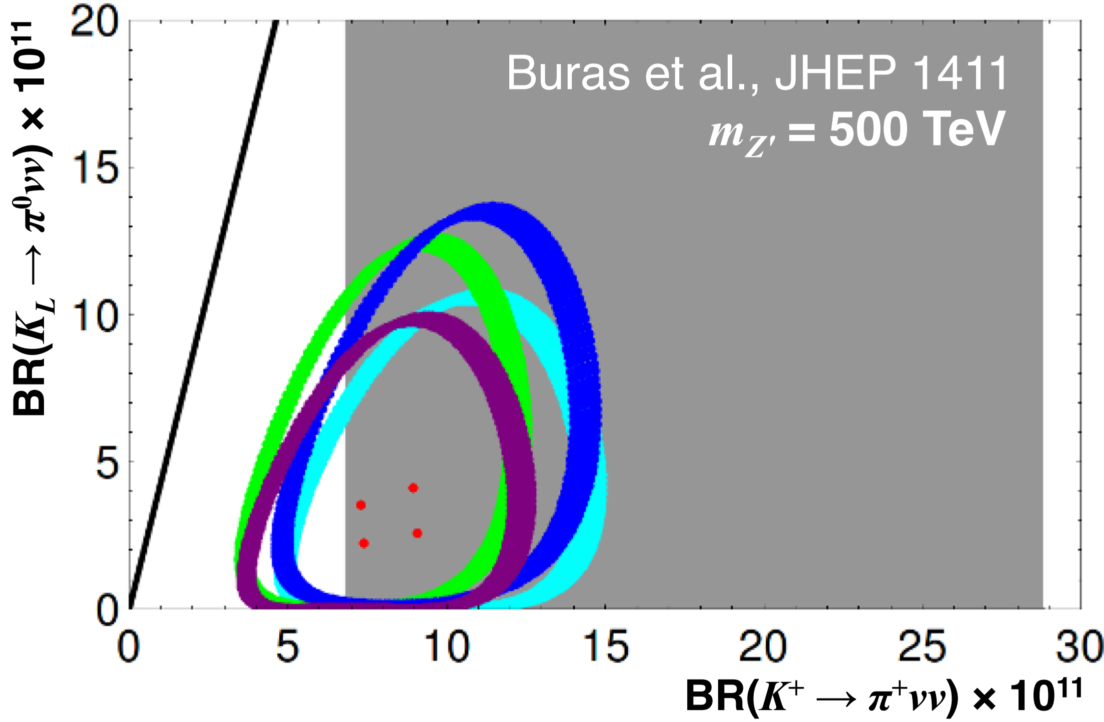
– Null results from direct searches at LHC so far

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 other kaon observables

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

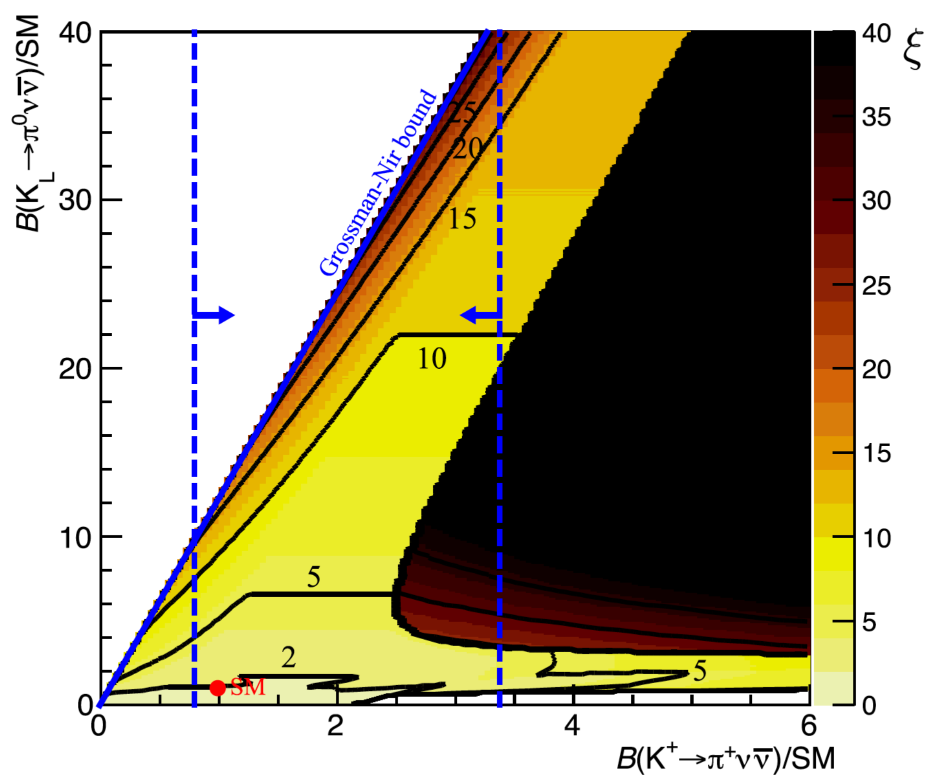
PDG average: NA48 + KTeV
Re ε'/ε = (16.6 ± 2.3) × 10^{-4}

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

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

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

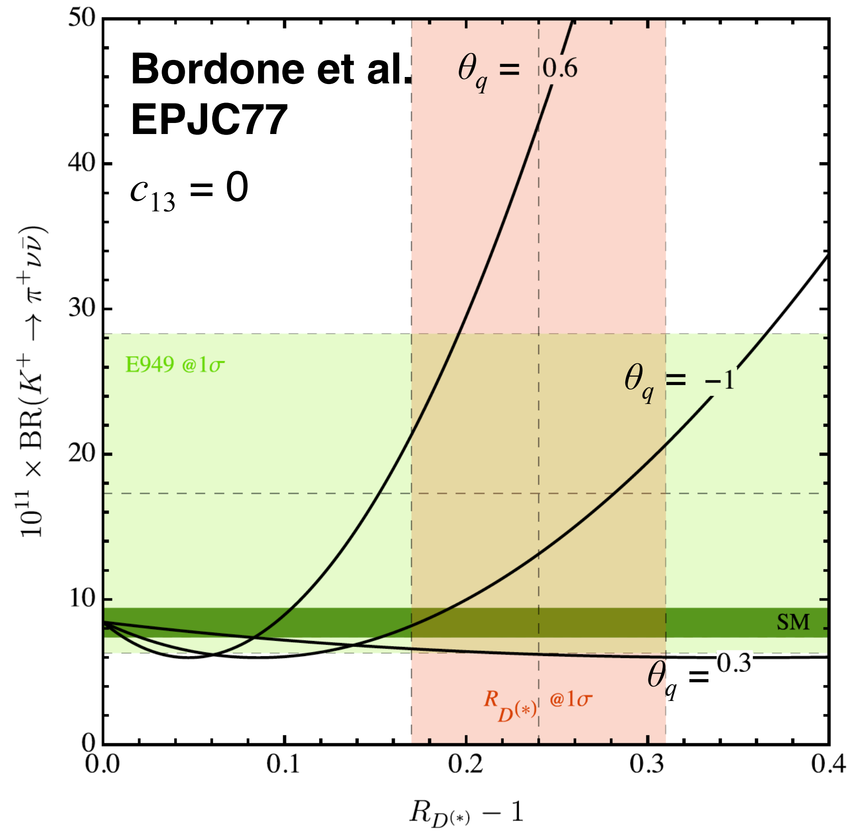
$R_{D(*)}$: $\tau/(\mu, e)$ LFU in $B \to D^{(*)}\ell\nu$

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)**



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

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

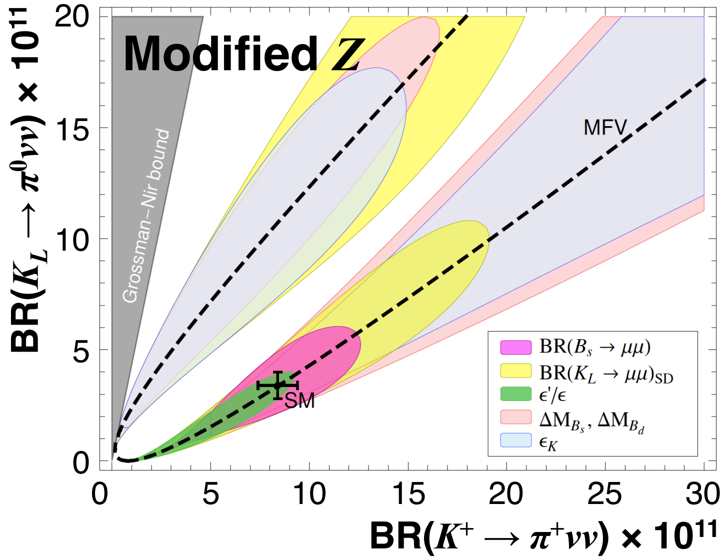
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = 2\mathcal{B}(K_L \to \pi^0\nu_e\bar{\nu}_e)_{\mathrm{SM}} + \mathcal{B}(K_L \to \pi^0\nu_\tau\bar{\nu}_\tau)_{\mathrm{SM}}\left|1 - \frac{R_0\,\theta_q^2(1 - c_{13})}{(\alpha/\pi)(X_t/s_W^2)}\right|^2$$

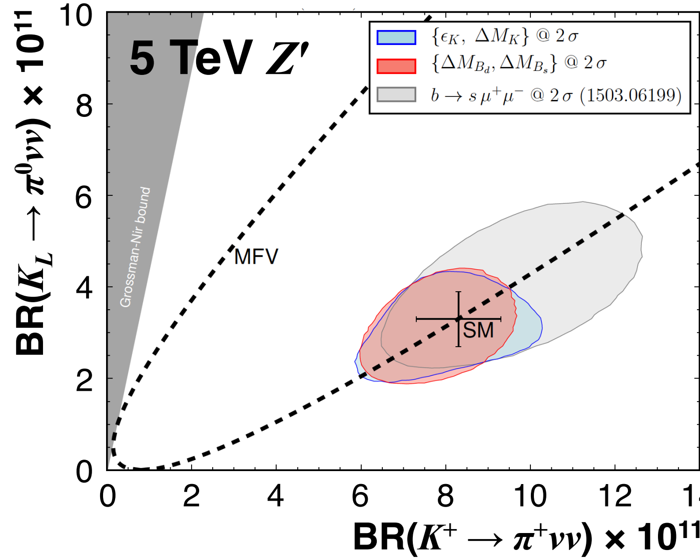
$K \to \pi\nu\bar{\nu}$ and other flavor observables

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

CMFV hypothesis:

Constraints from B and K observables

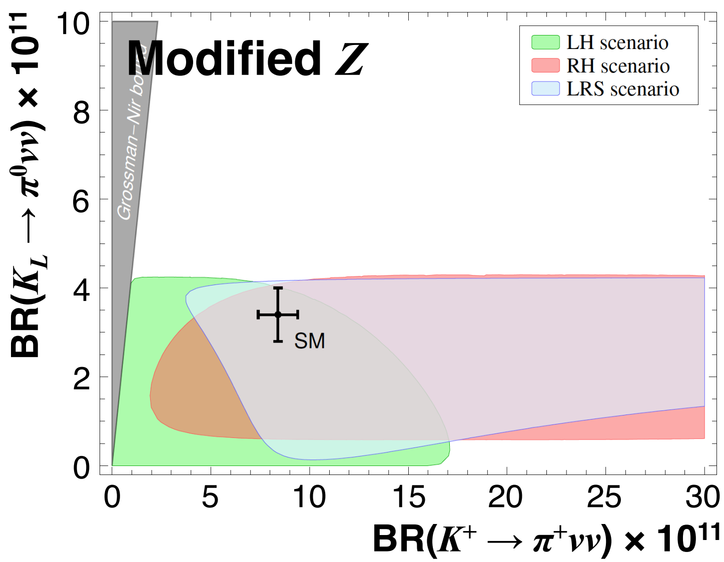


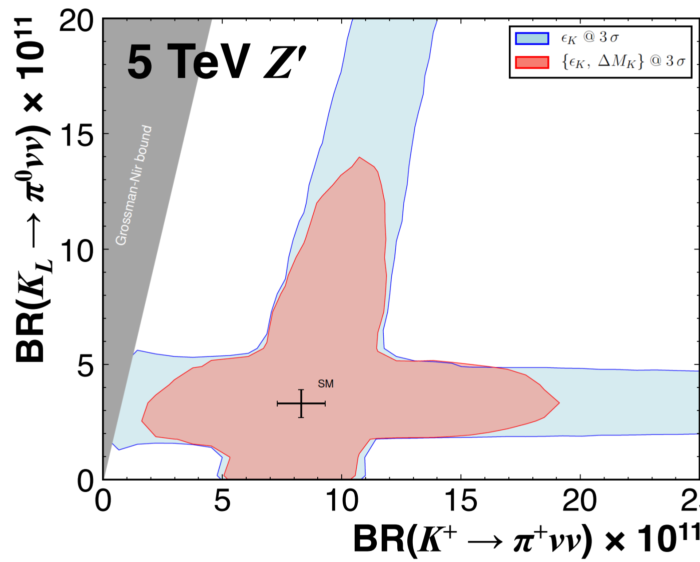


LH and RH couplings allowed:

Constraints from K observables:

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



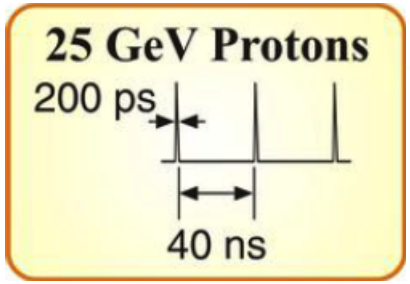


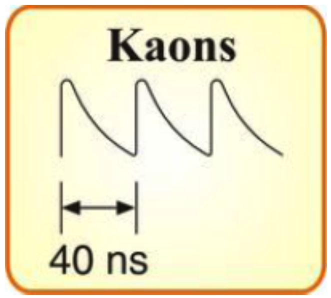
Extra constraints for $K_L \to \pi^0 \nu\bar{\nu}$

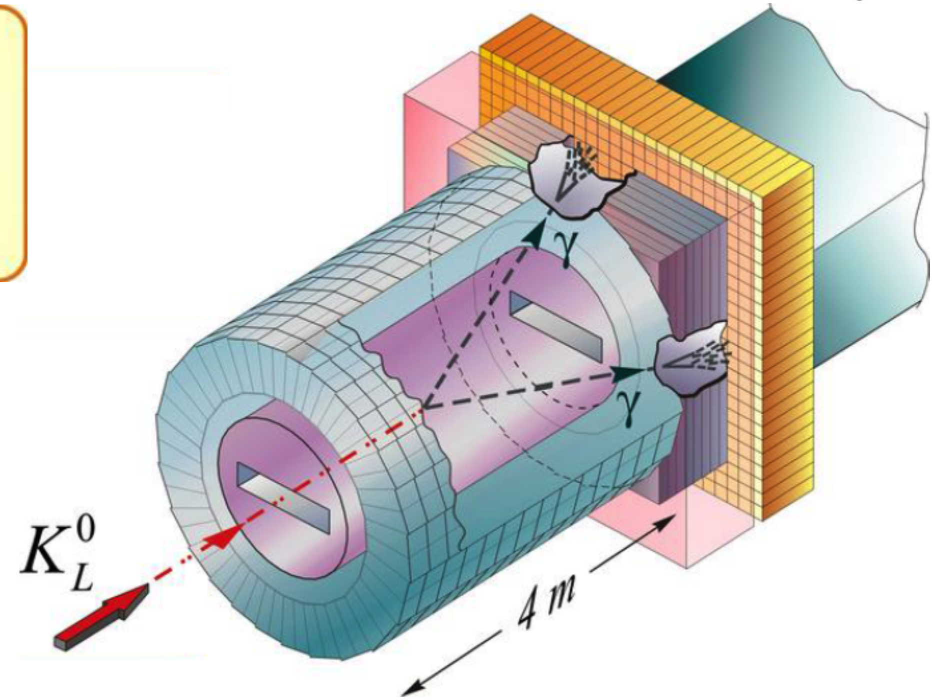
KOPIO
Brookhaven AGS
Cancelled 2005

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

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

Large-angle photon vetoes

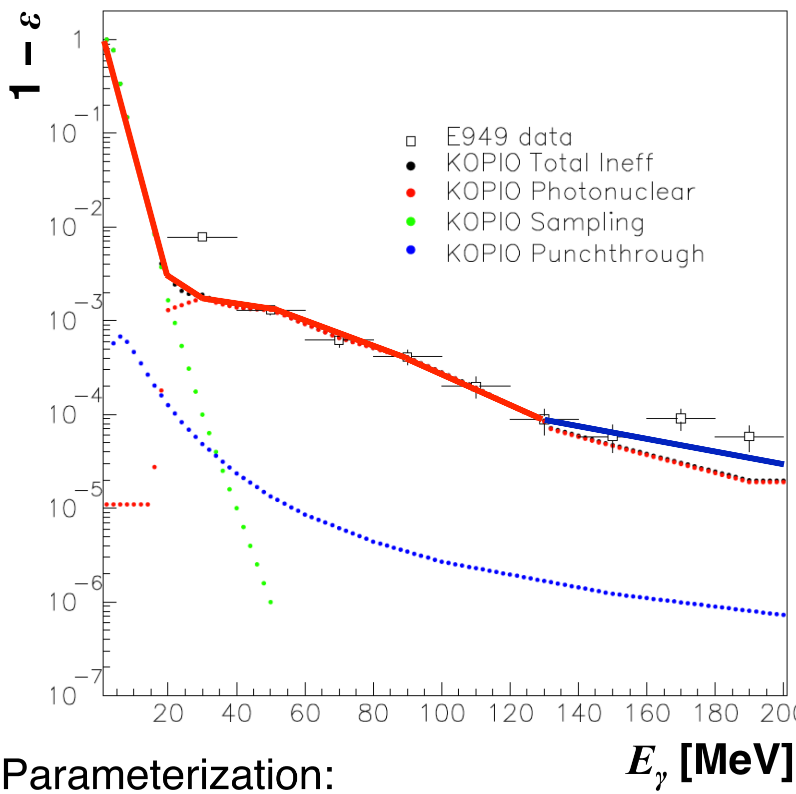
26 new LAV detectors providing hermetic coverage out to 100 mrad

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

Baseline technology: CKM VVS

Scintillating tile with WLS readout

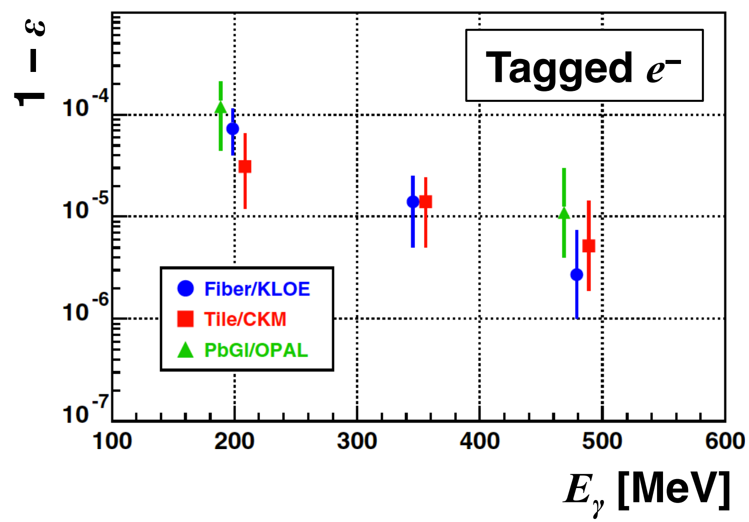
Good efficiency assumptions based on E949 and CKM VVS experience



E949 barrel veto efficiencies

Same construction as CKM

Tests for NA62 at Frascati BTF



Parameterization:

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

Tests at JLAB for CKM:

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

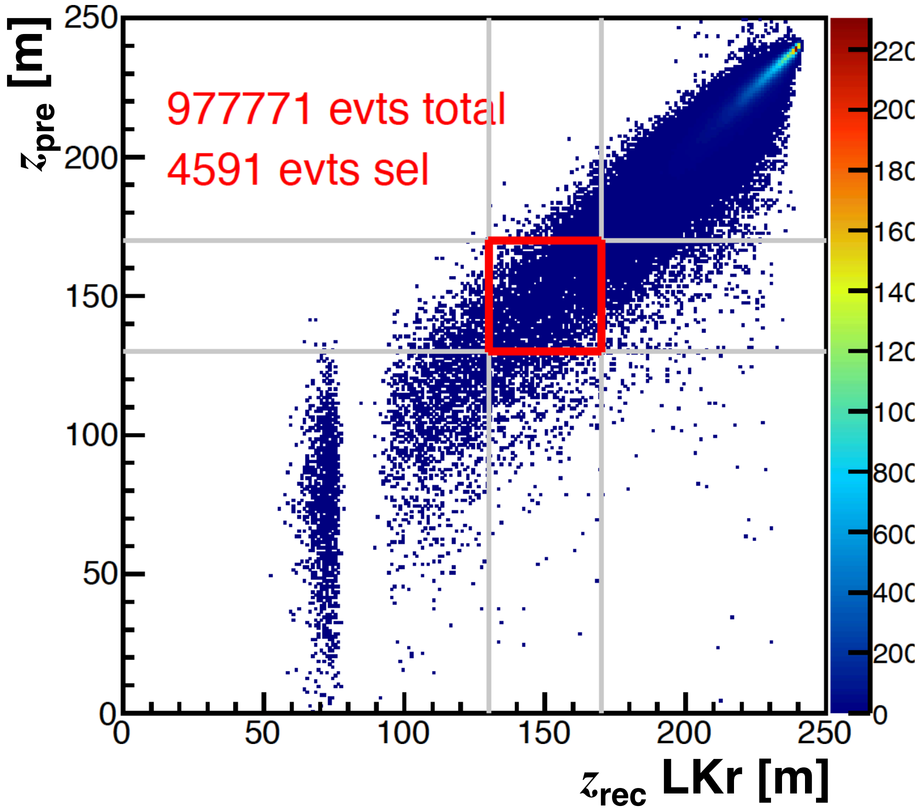
Preshower background rejection

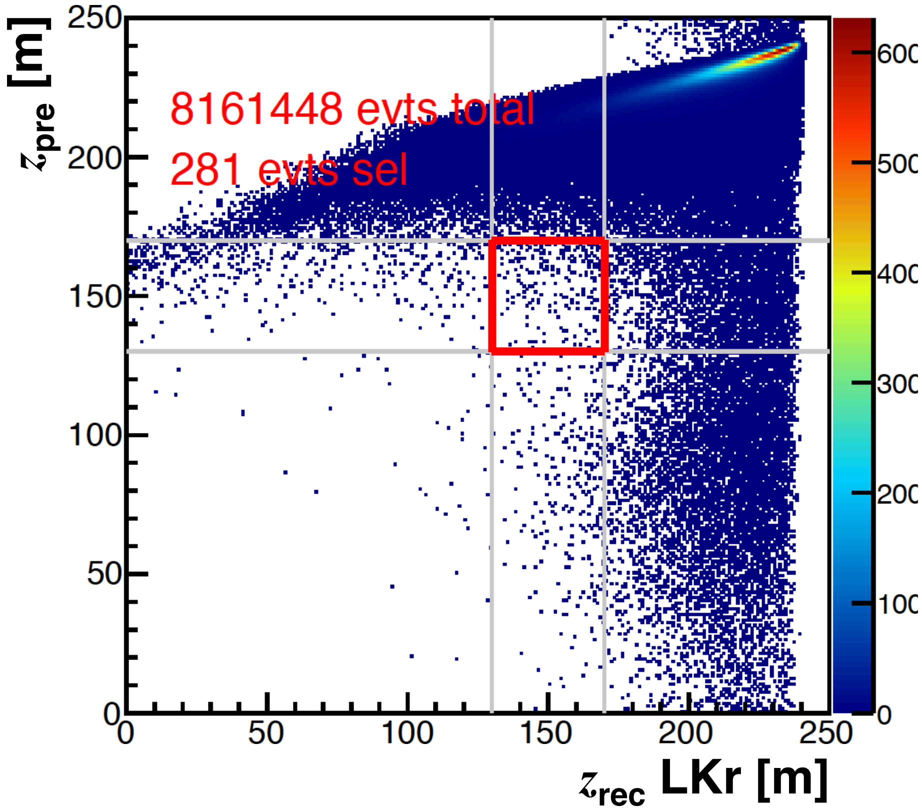
Preshower vertex z_{pre} vs. LKr vertex z_{rec}
z_{rec} reconstructed by imposing $M(\gamma\gamma) = m_{\pi 0}$

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

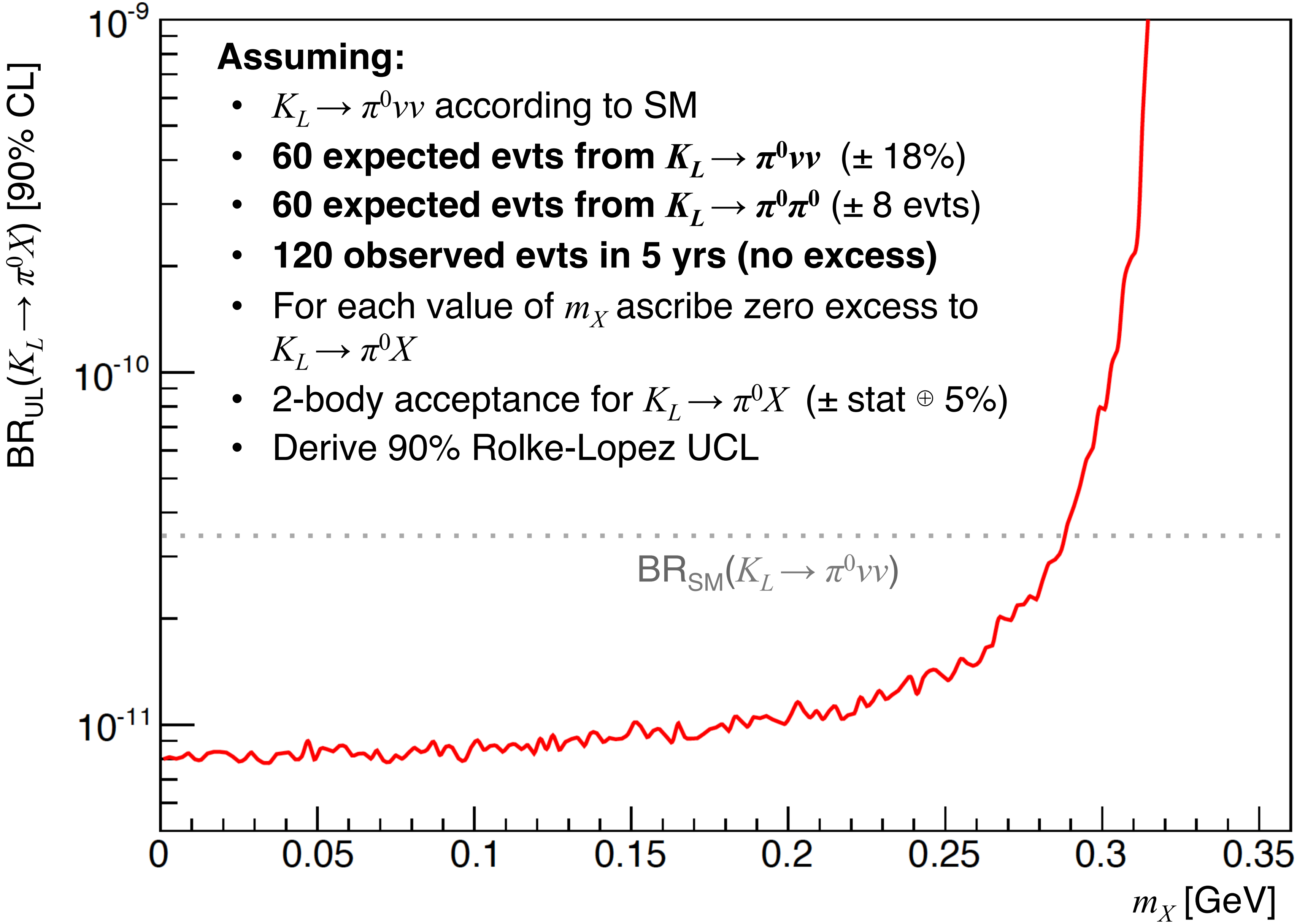
Even pairs (2 γ from same π^0)
1 γ converts in preshower

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





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



Limits on dark photon from $K_L \to \pi^0 \nu\nu$ KLEVER

Interpret X as dark photon and obtain limits in ε^2 vs. m_X plane

As per Davoudiasl, Lee, Marciano 2014 (analysis giving E787/E949 limits)