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

Second Forum on Rare Kaon Decays
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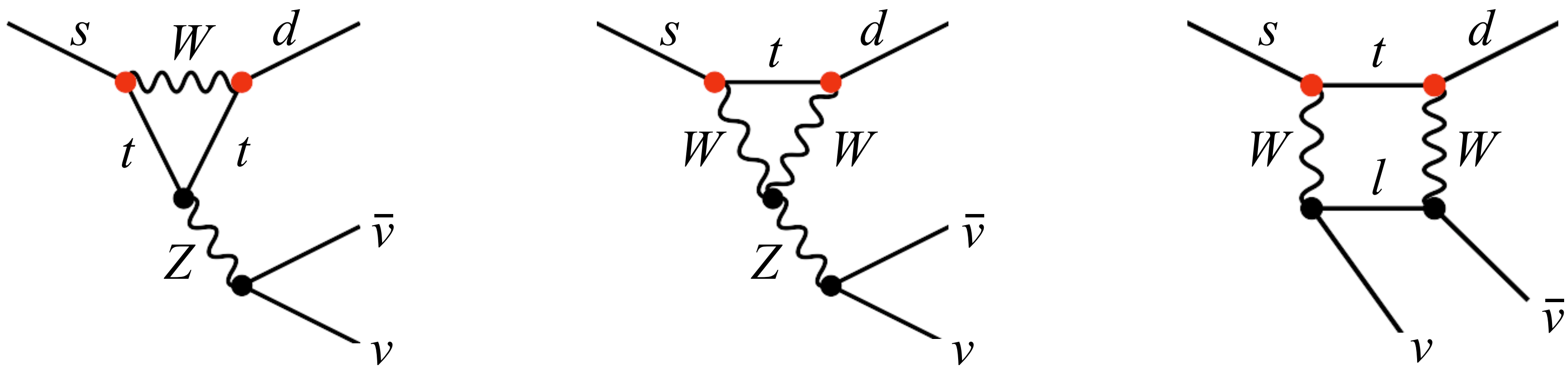
$K \to \pi\nu\bar{\nu}$ in the Standard Model

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 = $(8.4 \pm 1.0) \times 10^{-11}$**	**BR = $(17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$** Stopped K^+, 7 events observed BNL 787/949, PRD79 (2009)
$K_L \to \pi^0\nu\bar{\nu}$	**BR = $(3.4 \pm 0.6) \times 10^{-11}$**	**BR < 300×10^{-11} 90%CL** KOTO, PRL122 (2019)

* Tree-level determinations of CKM matrix elements

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

Dominant uncertainties for SM BRs are from CKM matrix elements

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

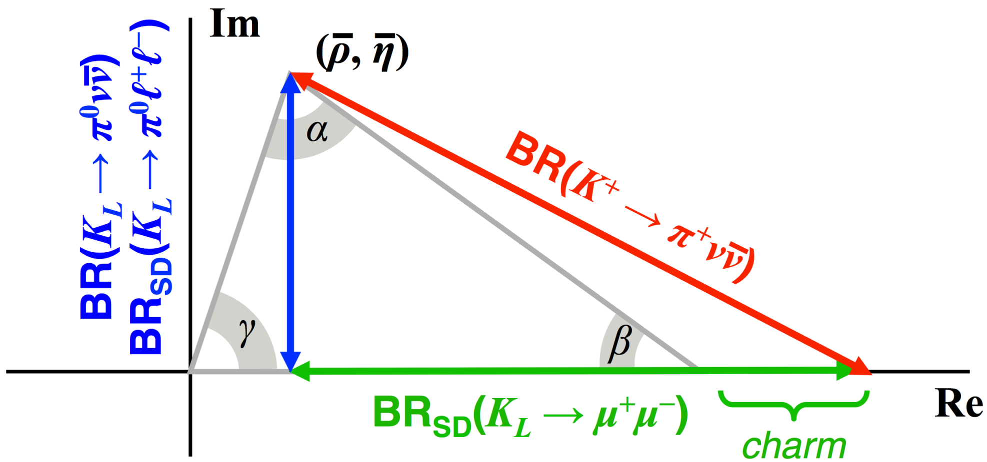
Buras et al., JHEP 1511

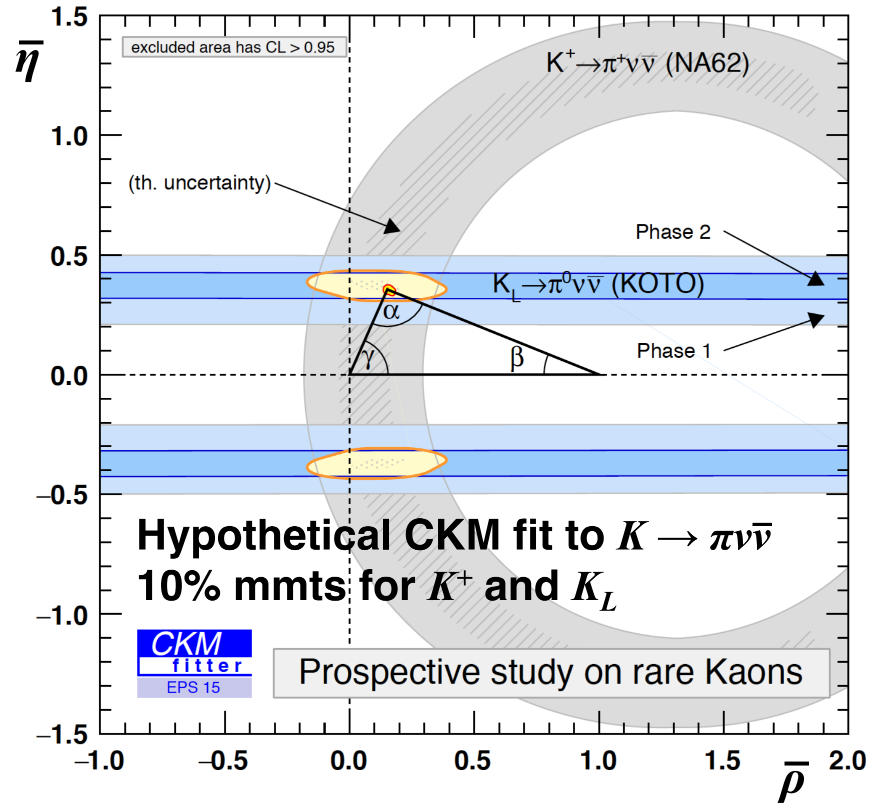
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

Intrinsic theory uncertainties ~ few percent

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

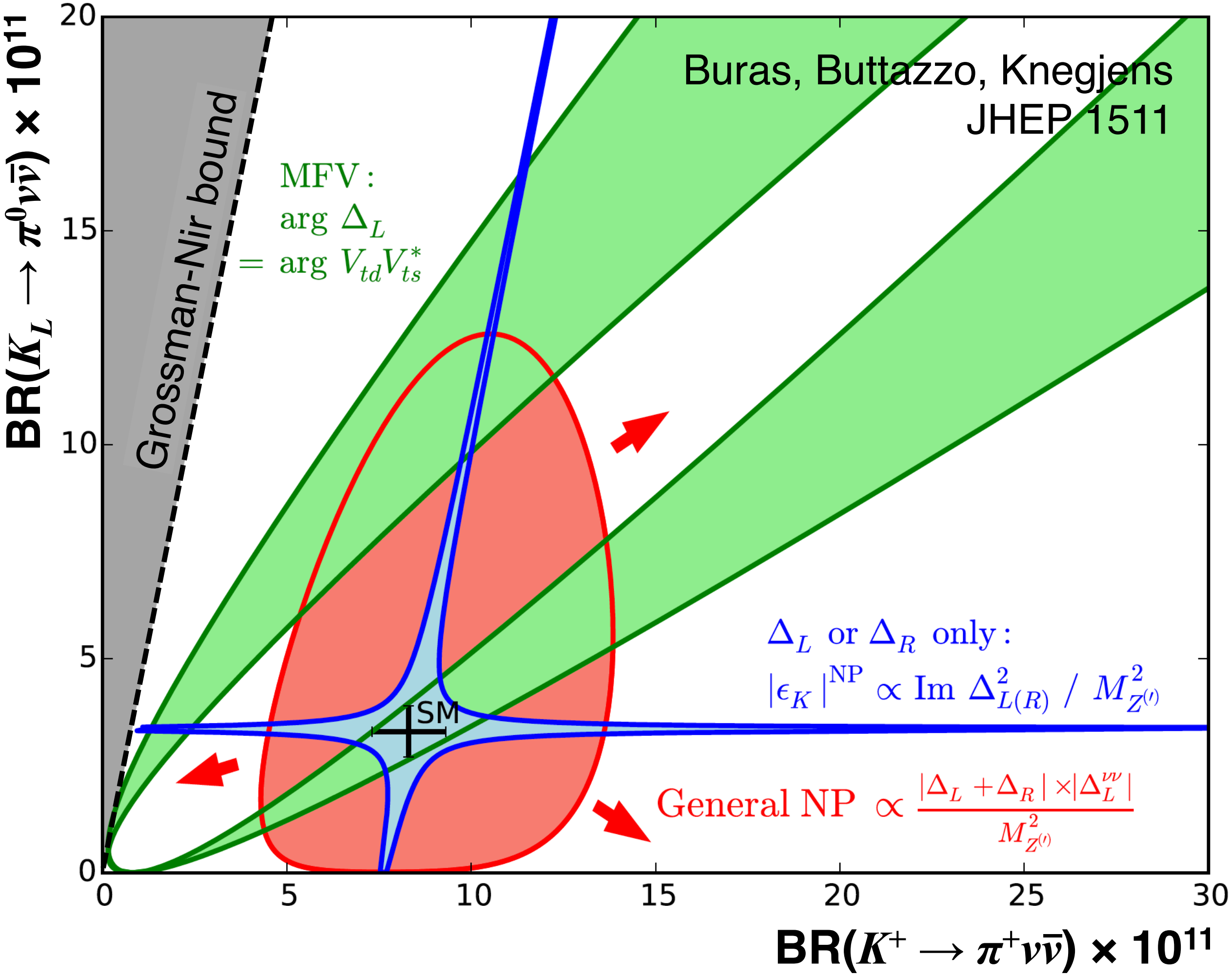
- Overconstrain CKM matrix → reveal NP?





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

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

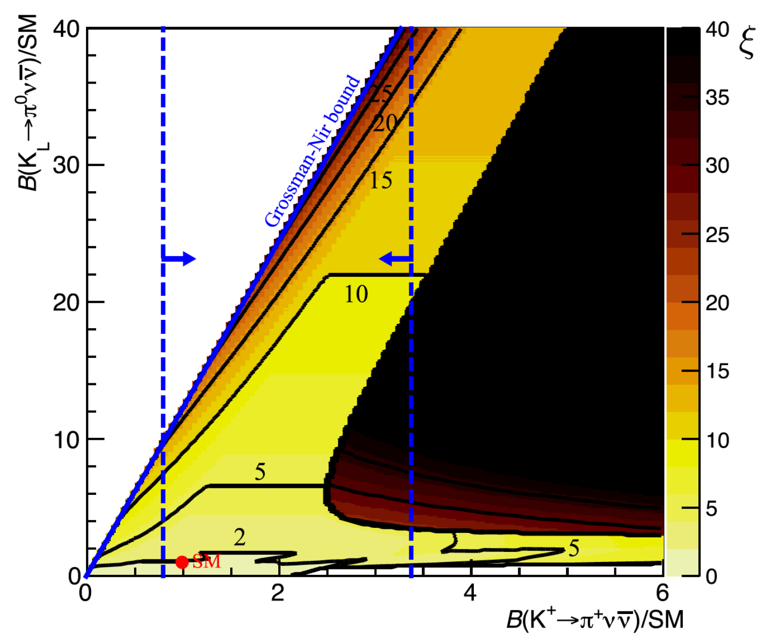
Endo et al. PLB771 (2017)

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

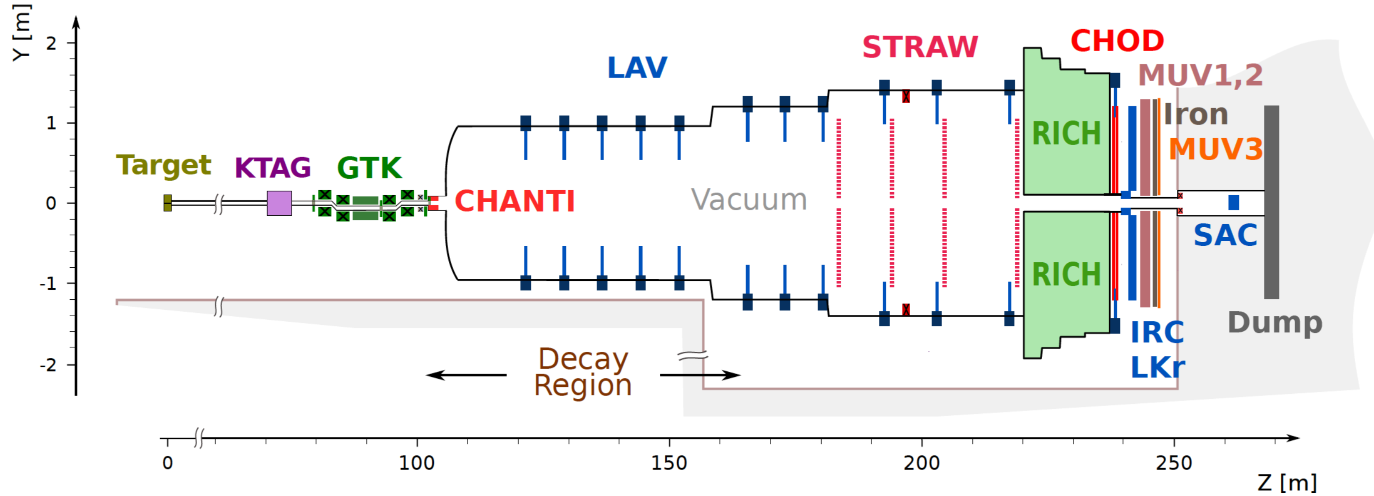
- Particularly in simplified scenarios: LH, RH, LRS
- With moderate tuning (cancellation of interference terms to 10%), large values for BR($K \to \pi\nu\nu$) are possible

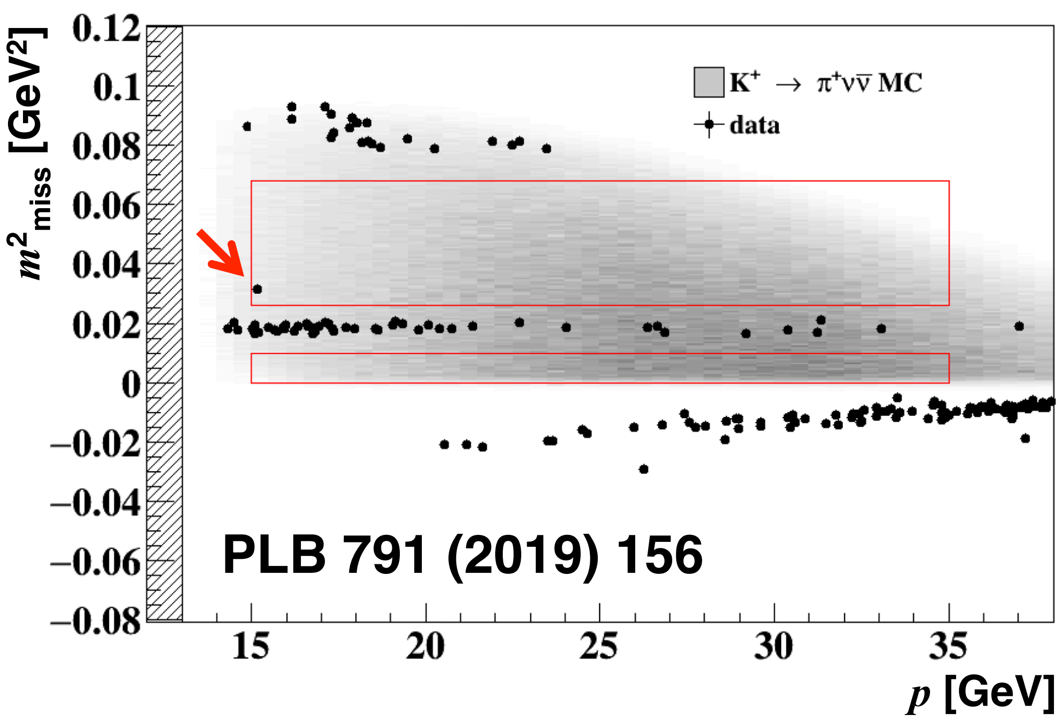


The NA62 experiment at the CERN SPS

BR($K^+ \to \pi^+ \nu\nu$) from 2016 data

- **High-rate, precision tracking**
- **Redundant PID and muon vetoes**
- **Hermetic photon vetoes**
- **High-performance EM calorimeter**





2016 data—1.21 × 10^{11} K^+ decays

SES = (3.15 ± 0.24) × 10^{-10}

Expected signal 0.267 ± 0.038

Expected background 0.15 ± 0.09

1 event observed in R2

BR($K^+ \to \pi^+\nu\nu$)

< 14 × 10^{-10} (95%CL)

< 10 × 10^{-10} (90%CL)

= 28^{+44}_{-23} × 10^{-11} (68% CL)

NA62 status and timeline

2016	Commissioning + 1st physics run
	First result presented in March 2018
	1 event observed
	BR($K^+ \rightarrow \pi^+\nu\nu$) < 14 × 10^{-10} (95%CL)
2017	Physics run (23 weeks at 60% nominal intensity)
	Better collection efficiency for physics data
	3 × 10^{12} K^+ decays recorded (> 20x more than 2016)
2018	Physics run (31 weeks at 60% nominal intensity)
	Better shielding of upstream background
	5 × 10^{12} K^+ decays recorded (> 40x more than 2016)
2019-2020	LS2 (LHC Long Shutdown 2)

Analysis of 2017-2018 data in progress

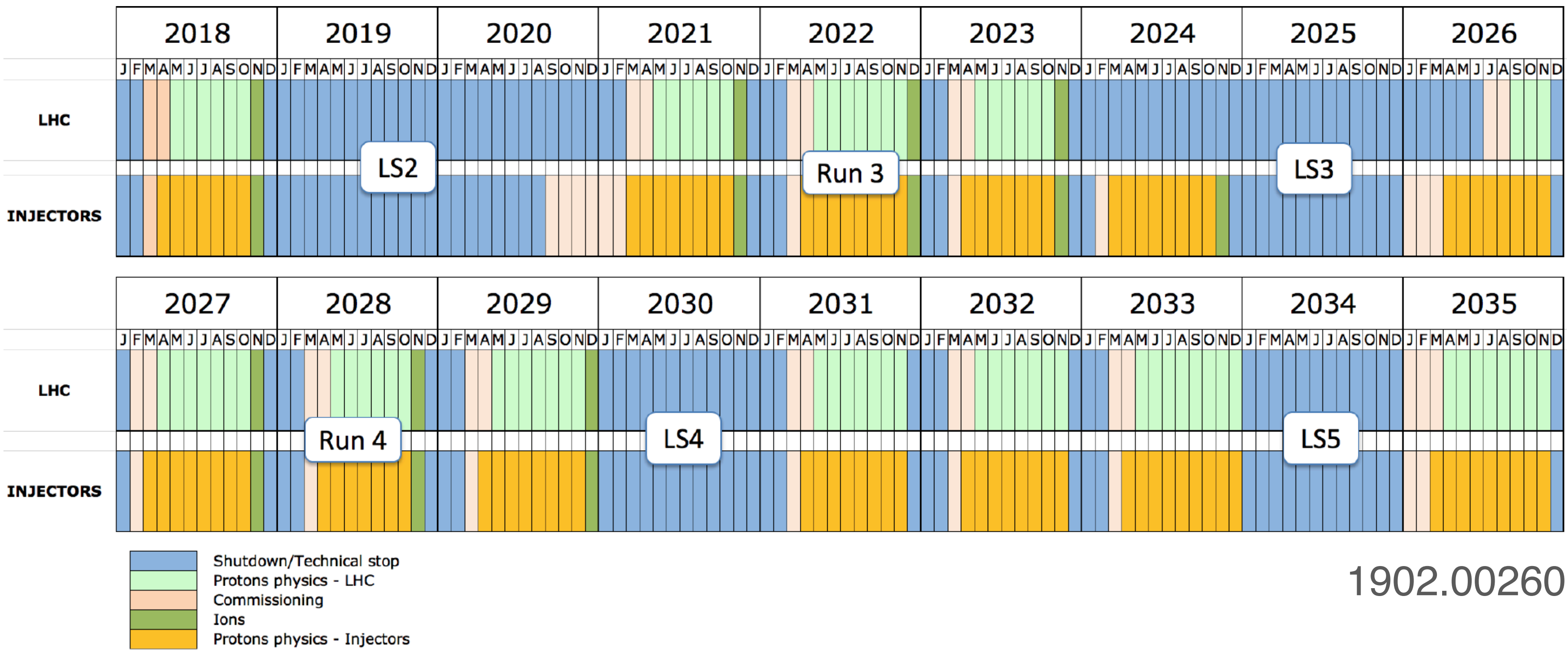
- Potential sensitivity = 15-20 SM $K^+ \rightarrow \pi^+\nu\nu$ events
- Solid extrapolation to ultimate sensitivity of NA62 achievable after LS2

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

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



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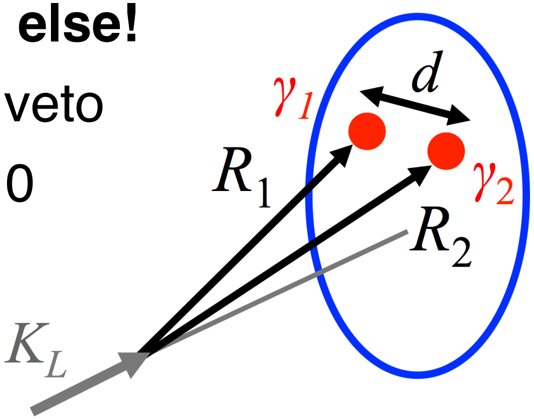
$K_L \to \pi^0 \nu\bar{\nu}$: Experimental issues

Essential signature: 2γ with unbalanced $p_\perp$ + nothing else!

All other K_L decays have ≥ 2 extra γs or ≥ 2 tracks to veto

Exception: $K_L \to \gamma\gamma$, but not a big problem since $p_\perp = 0$



K_L momentum generally is not known

$M(\gamma\gamma) = m(\pi^0)$ is the only sharp kinematic constraint

Generally used to reconstruct vertex position

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

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

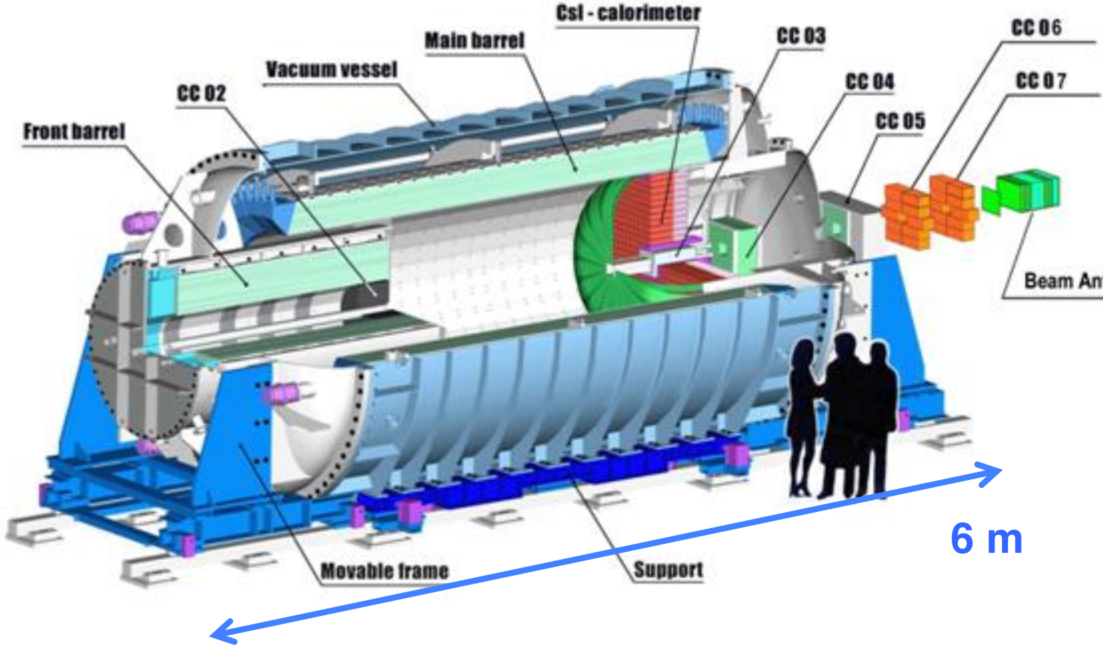
Main backgrounds:

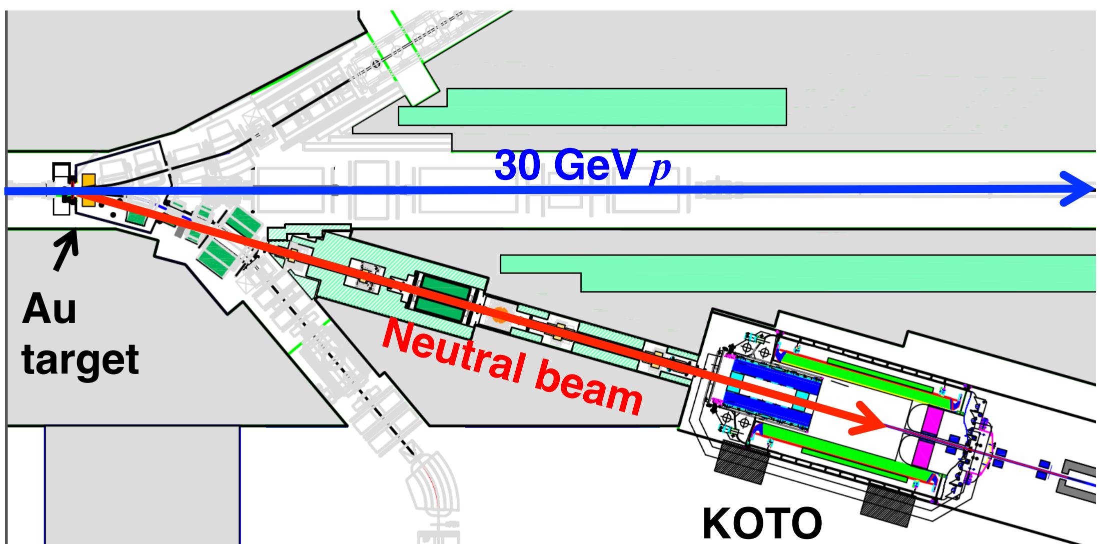
Mode	BR	Methods to suppress/reject
$K_L \to \pi^0\pi^0$	8.64×10^{-4}	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi^0\pi^0\pi^0$	19.52%	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi e\nu(\gamma)$	40.55%	Charged particle vetoes, π ID, γ vetoes
$\Lambda \to \pi^0 n$		Beamline length, $p_\perp$
n + gas $\to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

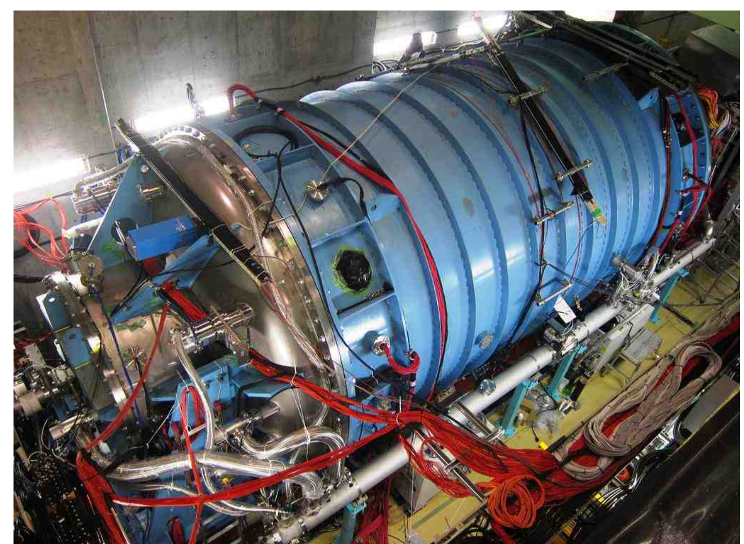
$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC

Primary beam: 30 GeV p
100 kW = 1.2×10^{14} p/5.2 s

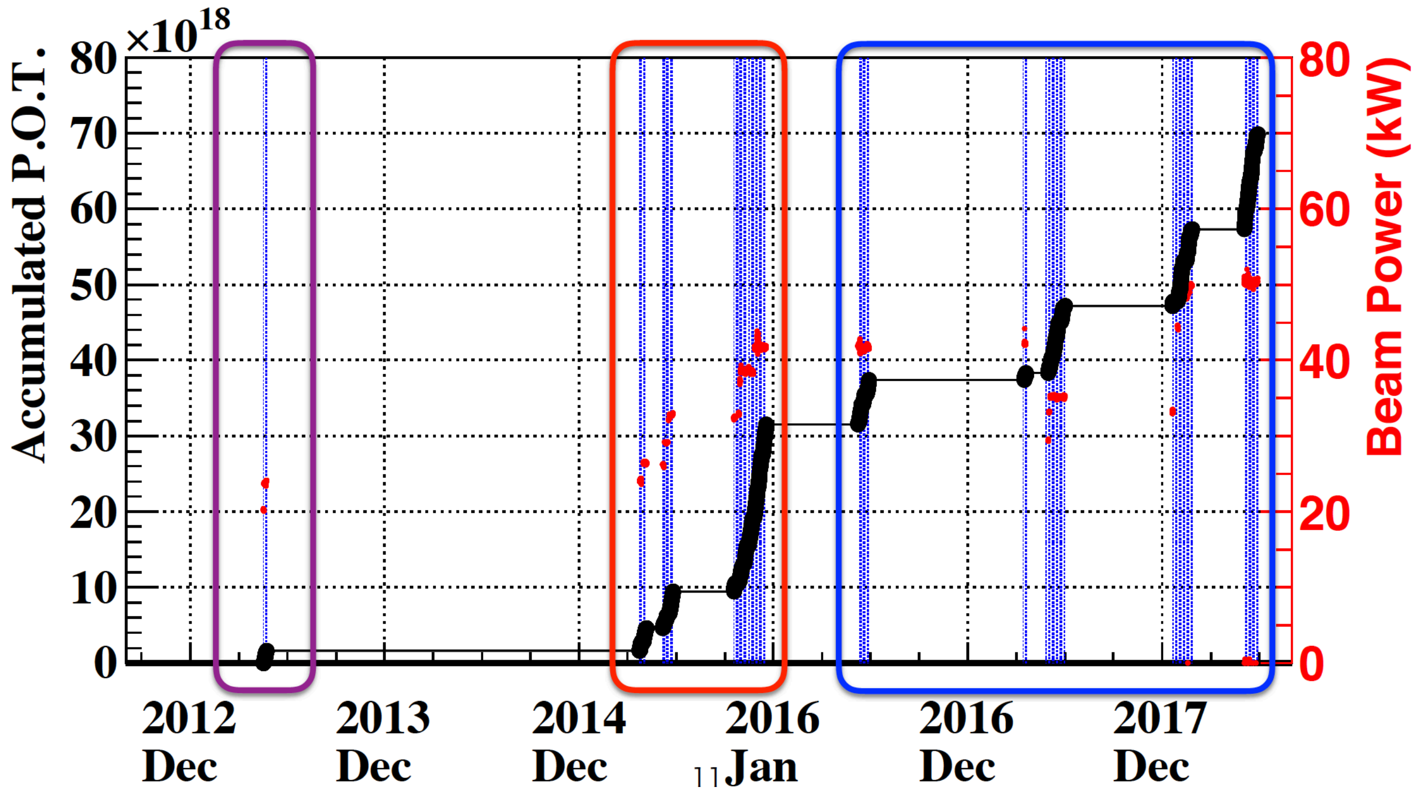
Neutral beam (16°)
$\langle p(K_L)\rangle$ = 2.1 GeV
50% of K_L have 0.7-2.4 GeV
8 μsr "pencil" beam







KOTO status and timeline



2013 pilot run (100 hrs)

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

2015 run (current result)

- Reached **40 kW** slow-extracted beam power
- 3 × 10^{19} pot collected

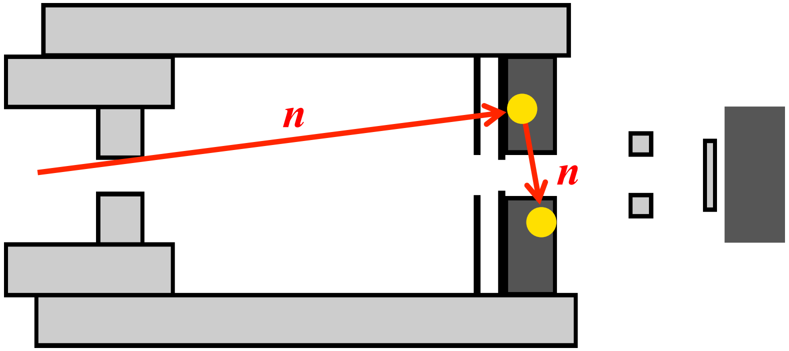
2016-2018

- Reached **50 kW beam power**
- 4 × 10^{19} pot collected
- With all 2015-2018 data, expected sensitivity below Grossman-Nir bound

Background rejection

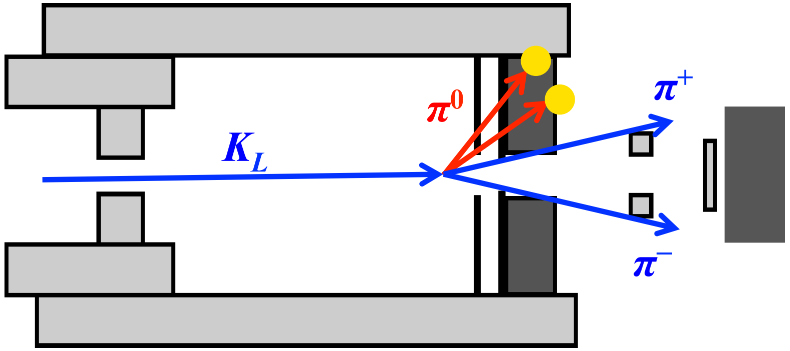
Lessons from 2013 run help to reject backgrounds other than $K_L \to \pi^0\pi^0$

1. Hadron clusters on CsI



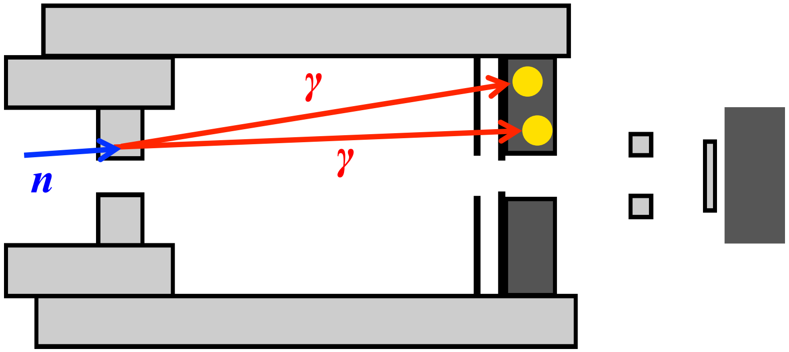
- Control sample with Al plate in beam
- Cluster and pulse shape analysis

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



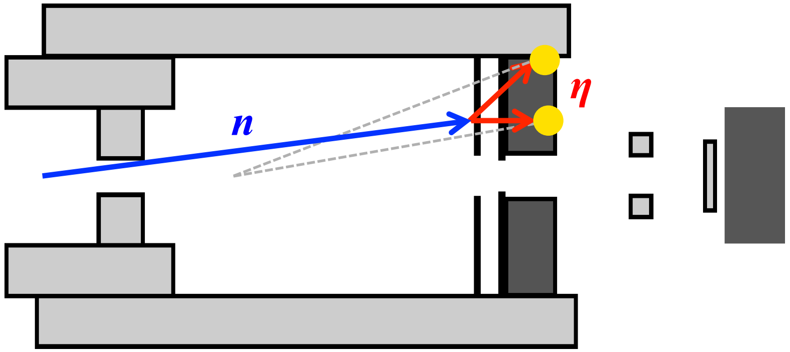
- New charged-particle vetoes lining beam exit

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



- Beam profile monitor for better alignment
- Thinner vacuum window

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

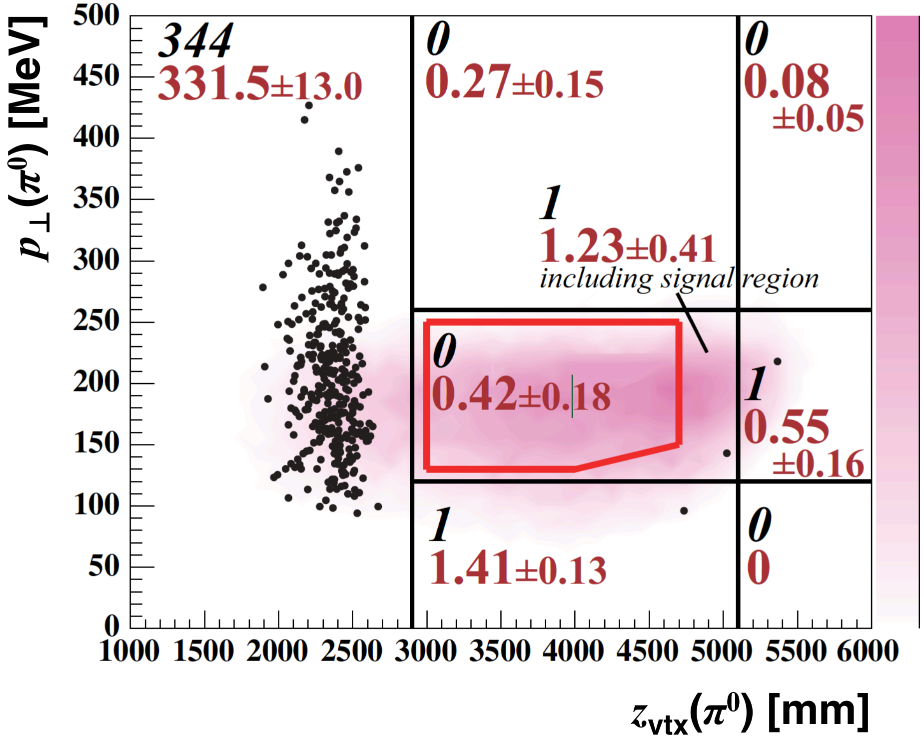


- Cluster shape (angle of incidence)

Result from 2015 data

Background	Expected counts
$K_L \to 2\pi^0$	0.02 ± 0.02
$K_L \to \pi^+\pi^-\pi^0$	0.05 ± 0.02
$K_L \to$ other	0.03 ± 0.01
Hadron cluster	0.24 ± 0.17
π^0 from NCC	0.04 ± 0.03
η from CV	0.04 ± 0.02
Total	**0.42 ± 0.18**

PRL 122 (2019) 021802



$BR(K_L \to \pi^0\nu\nu) < 3.0 \times 10^{-9}$ (90%CL)

2.2×10^{19} pot

SES = $(1.30 \pm 0.14) \times 10^{-9}$

Expected bkg = 0.42 ± 0.18 events

Zero events in signal box

K_L flux from $K_L \to 2\pi^0 = 4.6 \times 10^{12}$

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

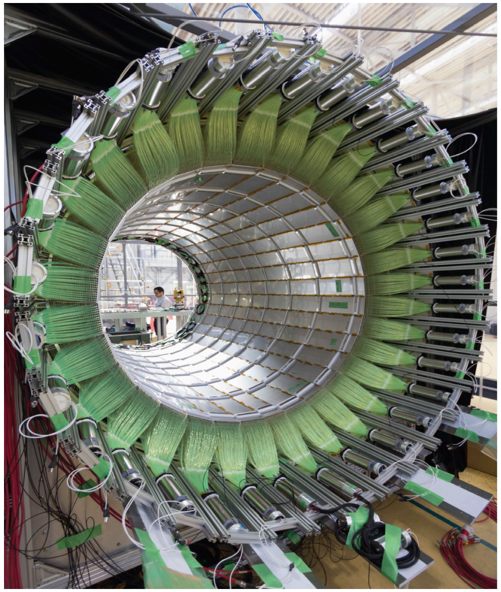
Decay in FV: 3.2%

Selection efficiency: 0.52%

Upgrades for 2016-2018

1.4x more data than for 2015 collected in 2016-2018
Several important detector upgrades and analysis improvements

Inner barrel veto



Increase barrel thickness
13.5 + 5 X_0

Installed April 2016

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

Trigger and readout upgrades

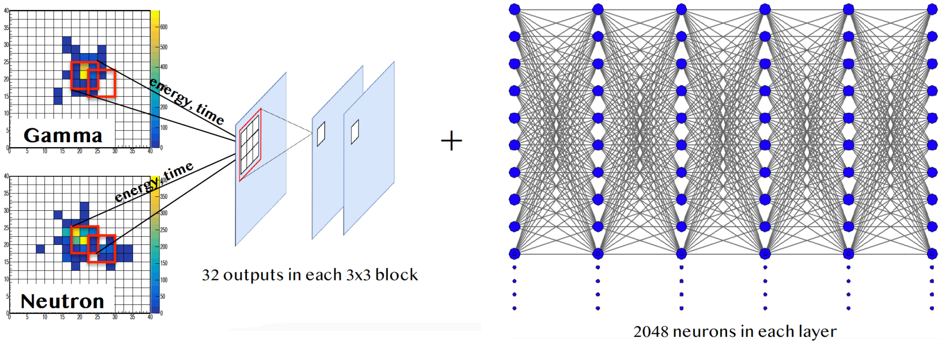
Online cluster counting at level-2

Neutron ID by pulse shape

- Hadronic pulse wider than EM pulse
- Fourier analysis of ADC waveforms
- **Reduces hadron cluster bkg ~3x**

Cluster shape discrimination

- Convolutional neural net with energies and times in groups of 3x3 cells
- **Reduces hadron cluster bkg ~5x**



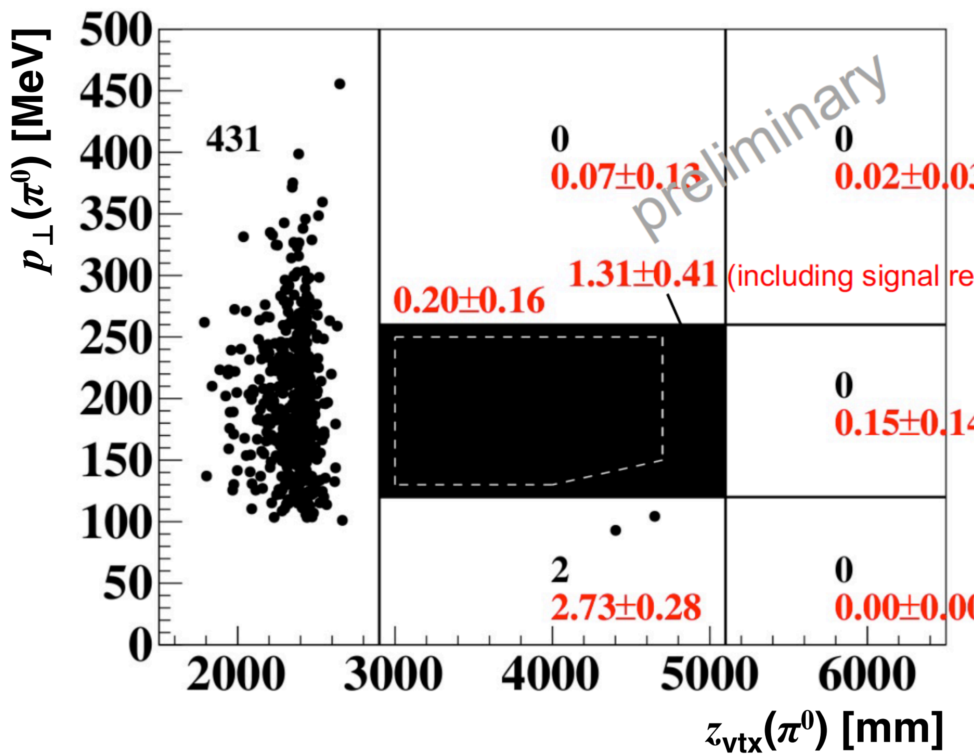
Sensitivity for 2016-2018 data

1.4x more data than for 2015 collected in 2016-2018
Several important detector upgrades and analysis improvements

KOTO preliminary 2016-2018 data, Moriond 2019

SES = 8.2 × 10^{-10}

Background	**Expected counts**
$K_L \to 2\pi^0$	0.09 ± 0.09
$K_L \to \pi^+\pi^-\pi^0$	0.02 ± 0.02
Hadron cluster	0.07 ± 0.13
π^0 from NCC	< 0.19
η from CV	0.02 ± 0.01
Total	**0.20 ± 0.16**



Combined with 2015 result SES ~ 5 × 10^{-10}

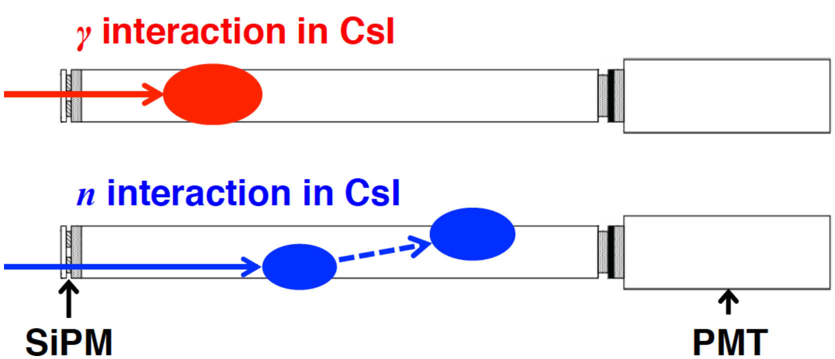
New results expected summer 2019!

Path to SM single-event sensitivity

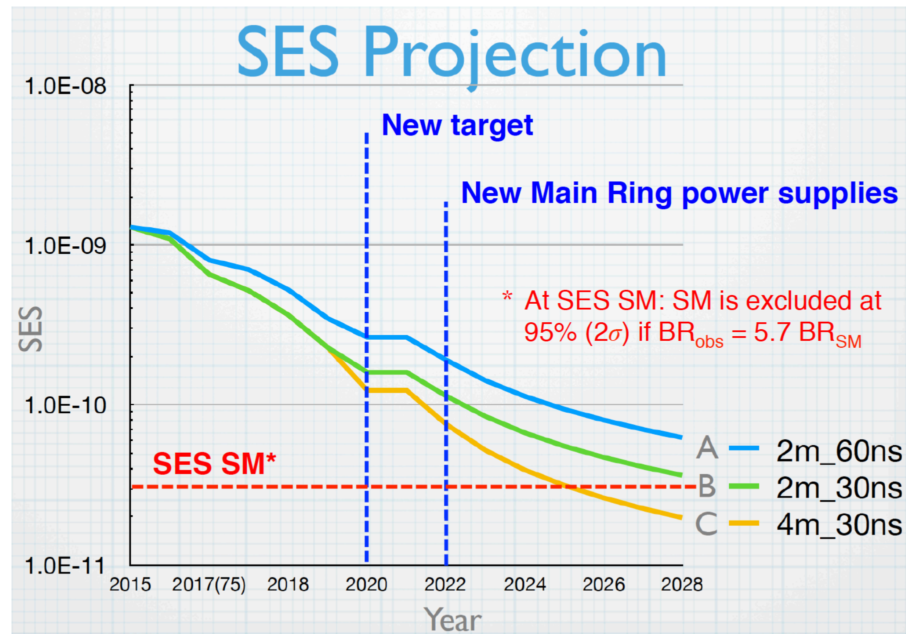
Signal: Need ~15x more (flux × acceptance) to reach SM SES
- Beam power expected to increase 50 → 100 kW gradually by 2024
- 20+ months of additional running planned in 2019-2024

Background: Need ~5x more background rejection to get S/B ~ 1 at SM SES
- Continuing program of detector upgrades

Dual side readout for CsI modules
Installed at end of 2018 run



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

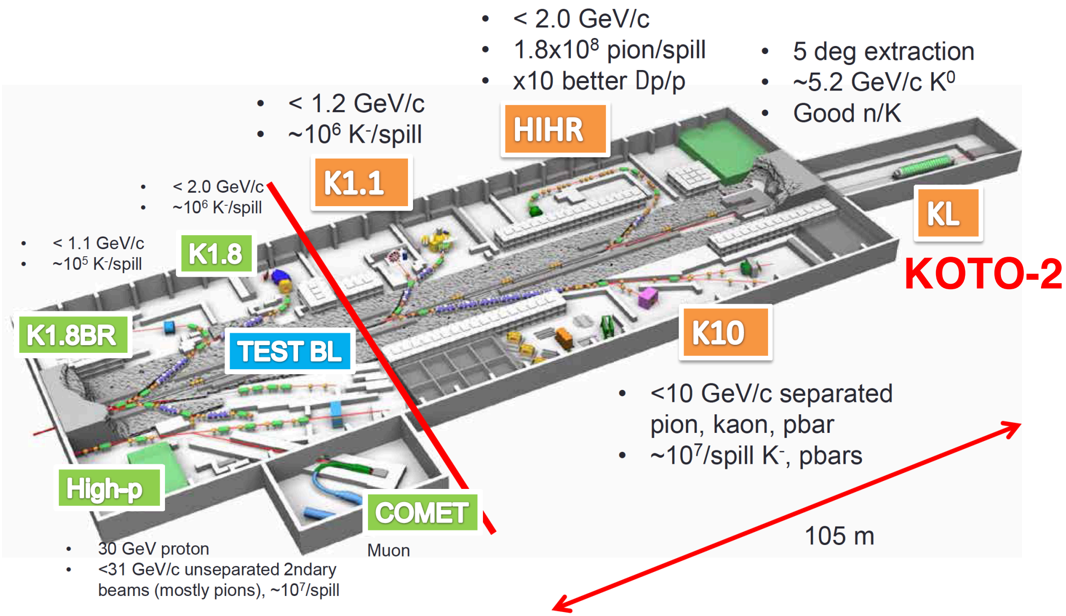


Single-event sensitivity for SM BR reached around 2025

Long-term upgrade 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

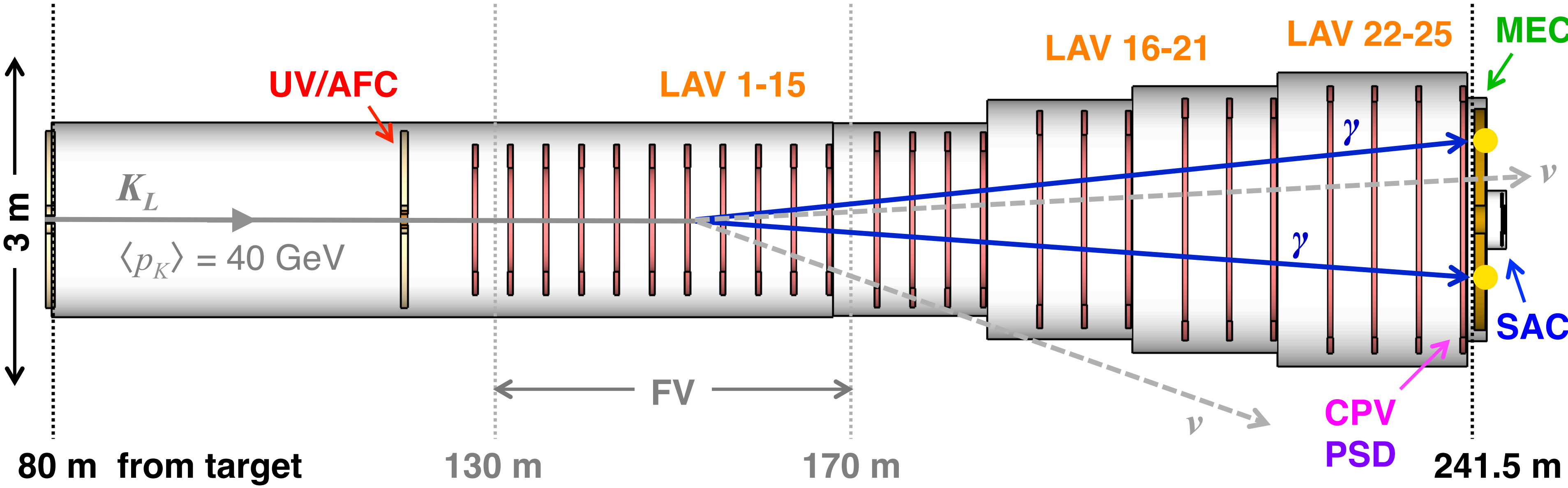


Strong intention to upgrade to 10-100 event sensitivity over long term:

- 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 (10^7 s) at 100 kW beam power?
- Exploring possibilities for machine & detector upgrades to further increase sensitivity

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

400-GeV SPS proton beam on Be target at z = **0 m**



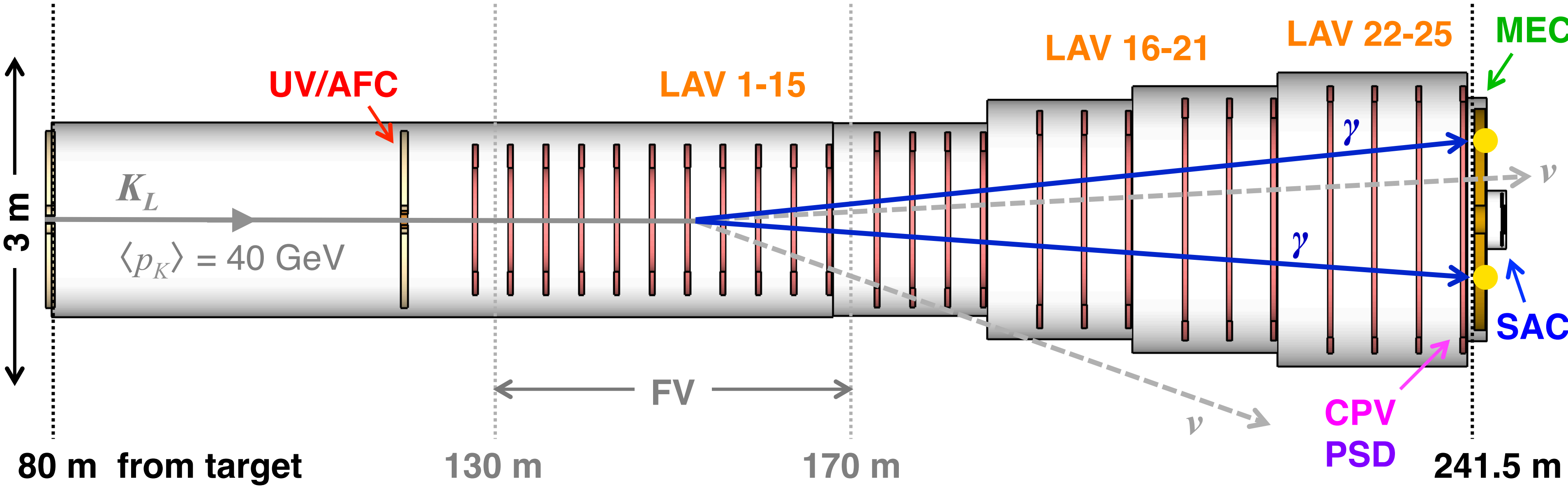
K_L Experiment for VEry Rare events

- 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 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 ~ 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

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

KLEVER

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%

60 $K_L \to \pi^0\nu\nu$ events at SM BR
60 background events

$$\text{Signif.} \approx \frac{S_{\text{obs}} - S_{\text{SM}}}{\sqrt{S_{\text{obs}} + B_{\text{obs}}}}$$

If BR($K_L \to \pi^0\nu\nu$) is:

- Suppressed to 0.25 BR_{SM} ➡ **5σ**
- Enhanced to 2 BR_{SM} ➡ **5σ**
- Suppressed to 0.5 BR_{SM} ➡ **3σ**

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($K_L \to \pi^0\nu\bar{\nu}$)
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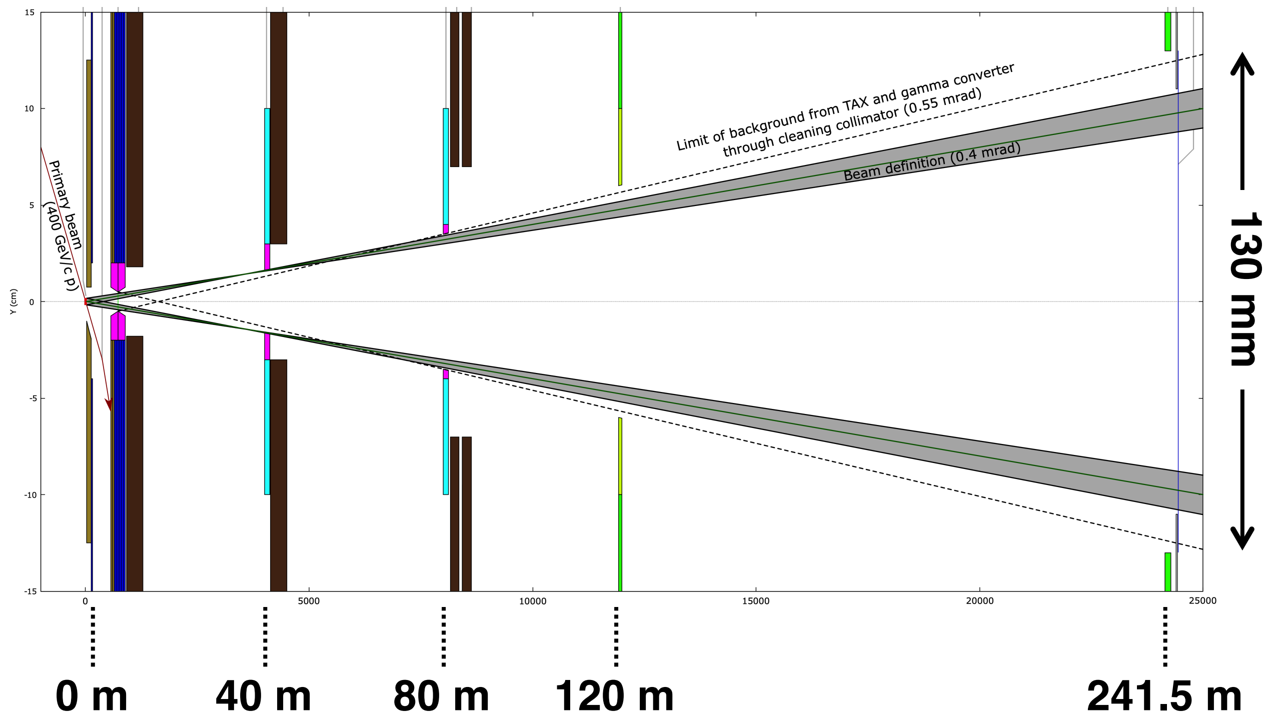
SUSY, gluino Z penguin	10	Small effect	0% to +300%
SUSY, gluino box, tuning to 10%	1.5–3	±10%	±20%
LHT	1	±20%	−10% to −100%

Neutral beam and beamline

KLEVER

- **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%



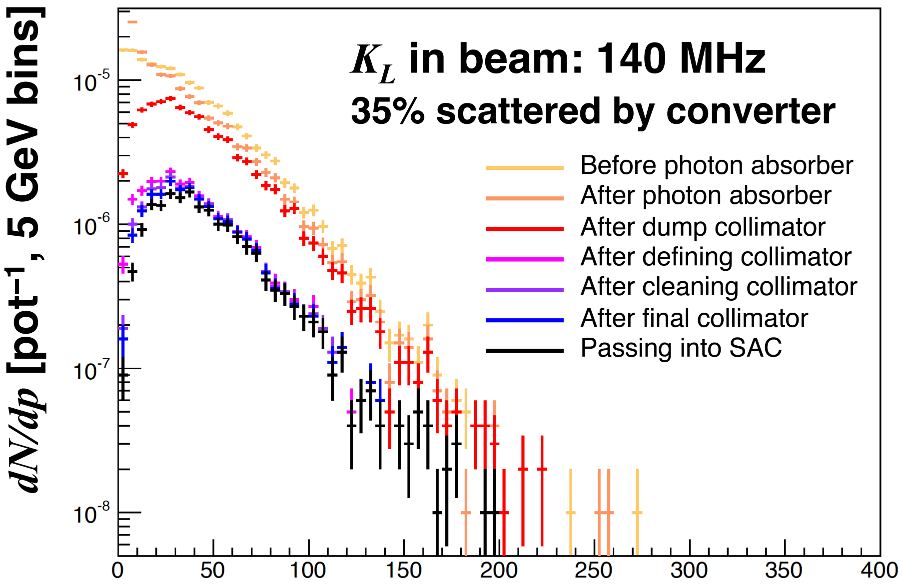
- **4 collimation stages** to minimize neutron halo, including beam scattered from absorber
- **Photon absorber** in dump collimator

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

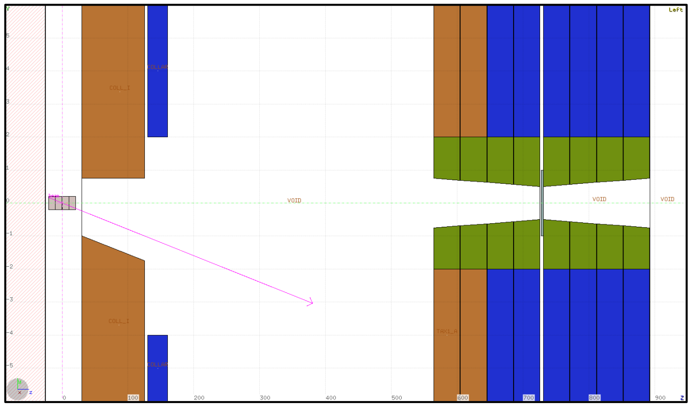
KLEVER

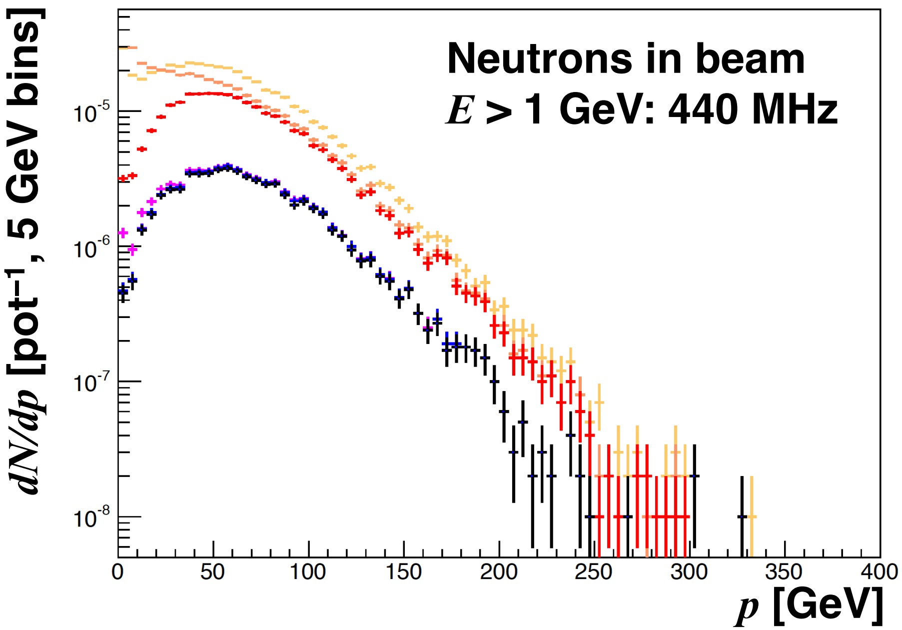


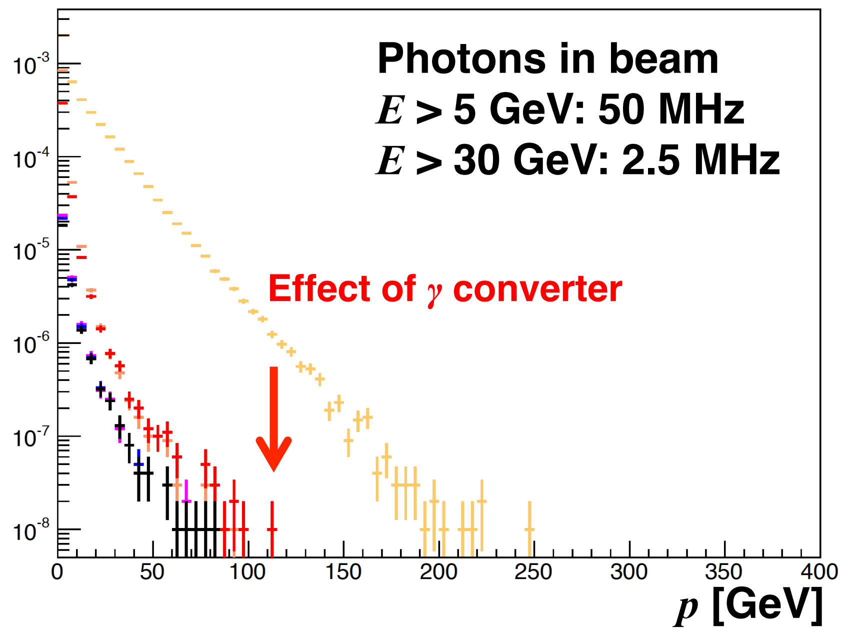
FLUKA simulation of beamline

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

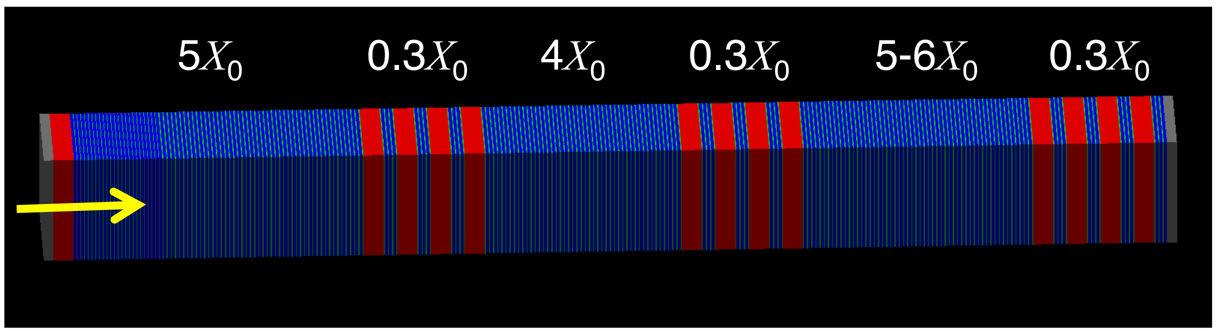
0.275 mm Pb + 1.5 mm scintillator

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)

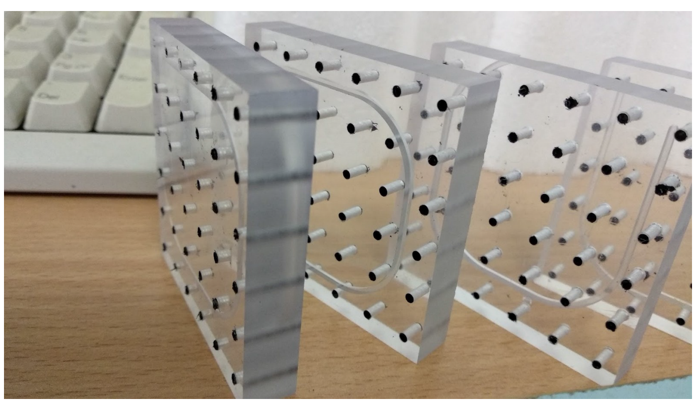
New for KLEVER: Longitudinal shower information from spy tiles

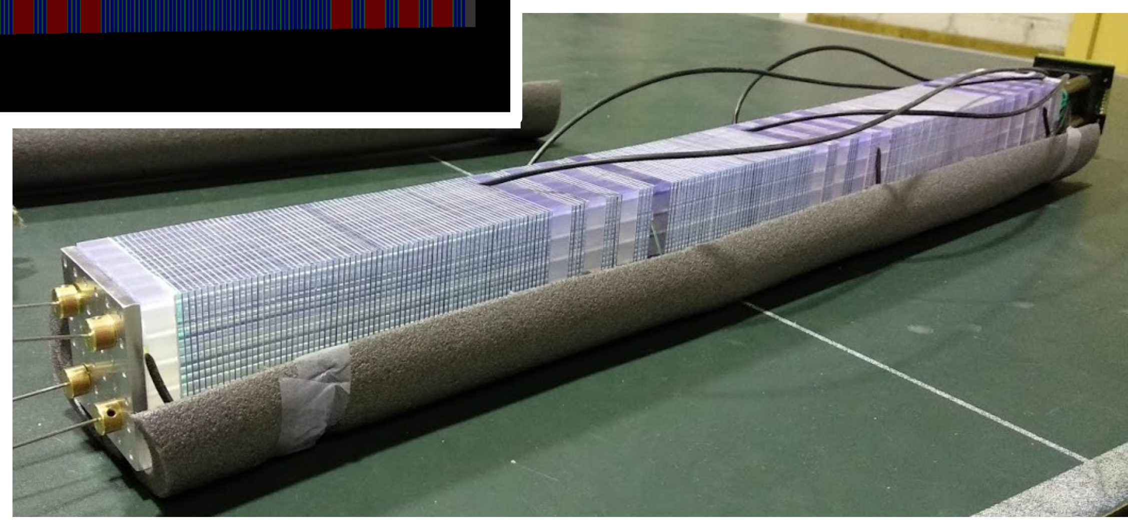
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



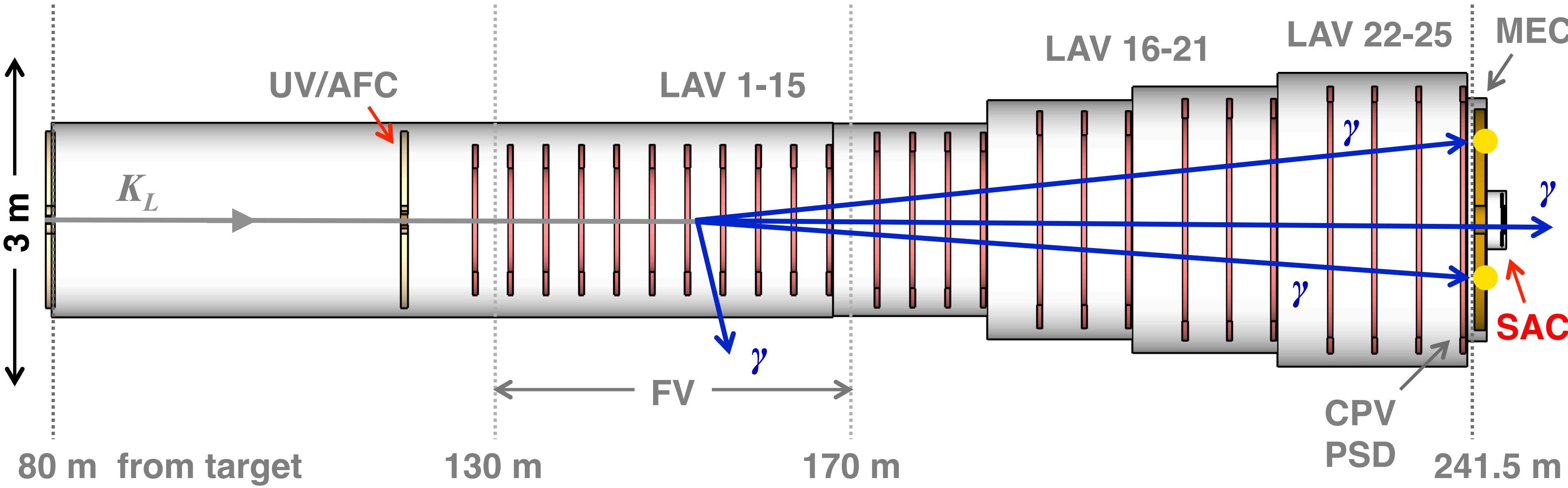
1st prototype assembled and tested at Protvino

OKA beamline, April 2018





Small-angle photon veto



Small-angle photon 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

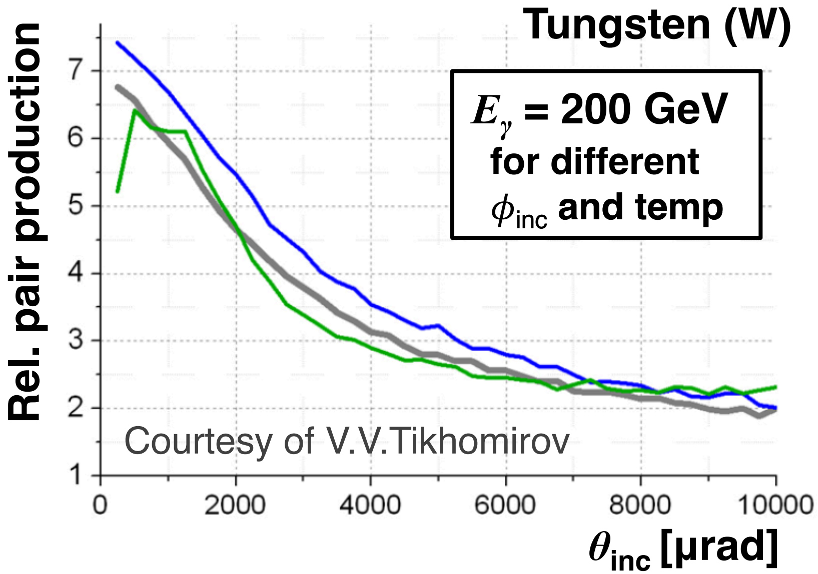
Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

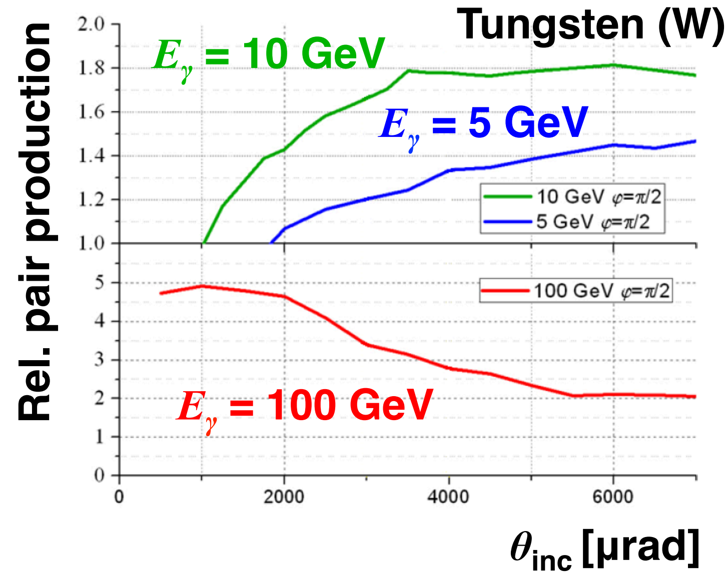
Baseline solution:

- 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:

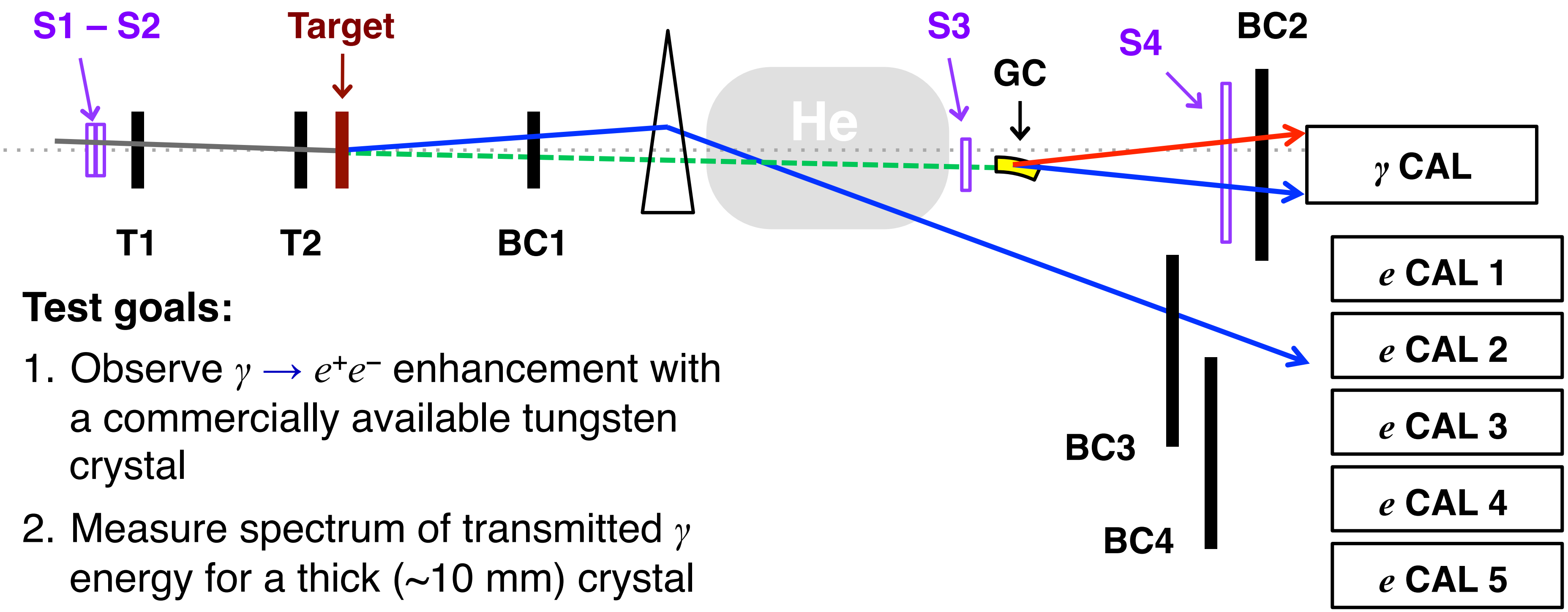
1. **Beam photon converter in dump collimator**
   Effective at converting beam γs while relatively transparent to K_L
2. **Absorber material for small-angle calorimeter (SAC)**
   Must be insensitive as possible to high flux of beam neutrons while efficiently vetoing high-energy γs from K_L decays

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

KLEVER

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

Test beam setup for tagged photons from 120 GeV e^-:



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}
4. Obtain information to assist MC development for beam photon converter and SAC

- **Nearly all detectors and DAQ system made available by AXIAL**
- **1 week H2 of beam: 8-15 August 2018**

First look at test beam data

Preliminary results
Data analysis in progress!

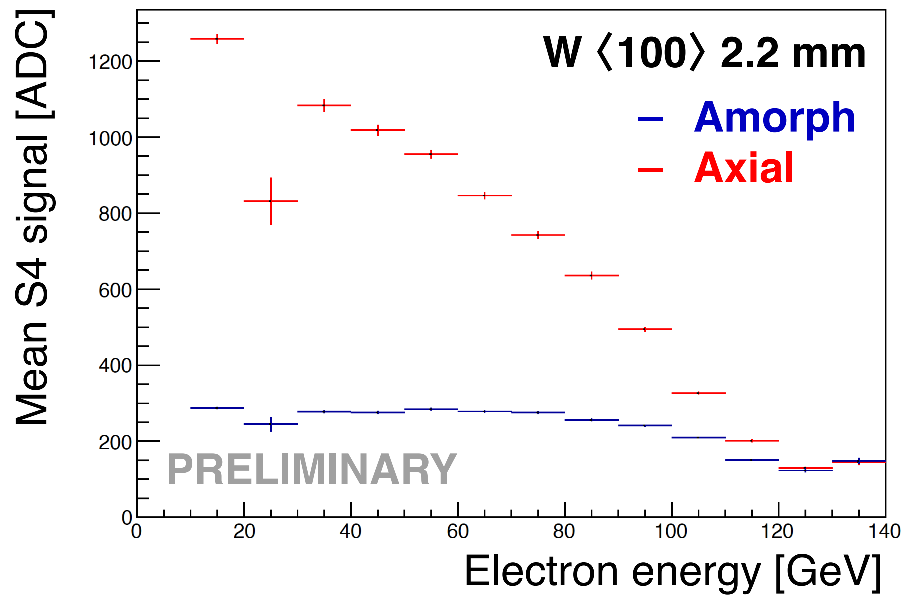
- Cuts to tag photons pointing at crystal sample
- Record charged particle multiplicity produced in crystal (at S4)
- Compare on- and off-axis measurements

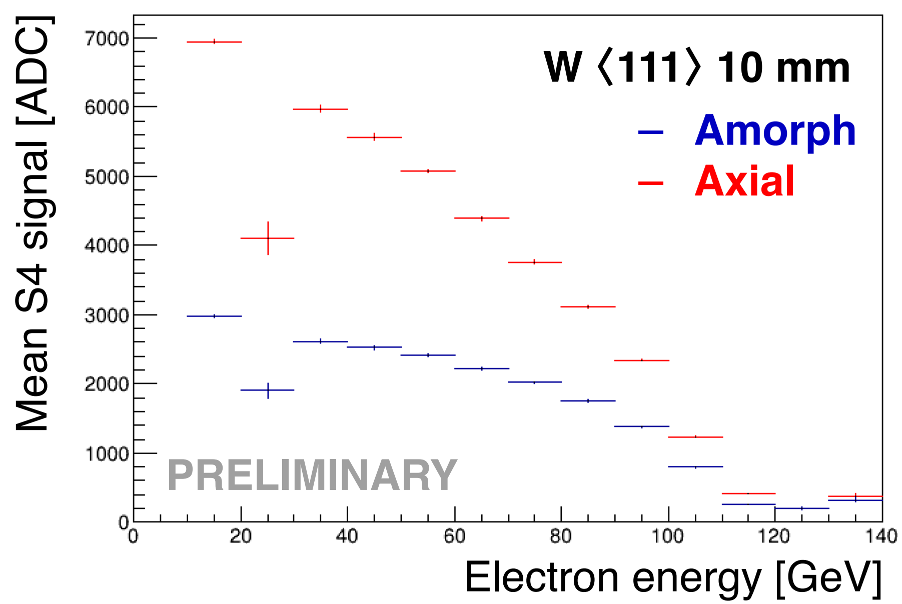
W ⟨100⟩ Moscow (2.2 mm)

- Charged multiplicity increased 6x at high photon energy
- Angular range for enhancement 1-2 mrad

W ⟨111⟩ Princeton (10 mm)

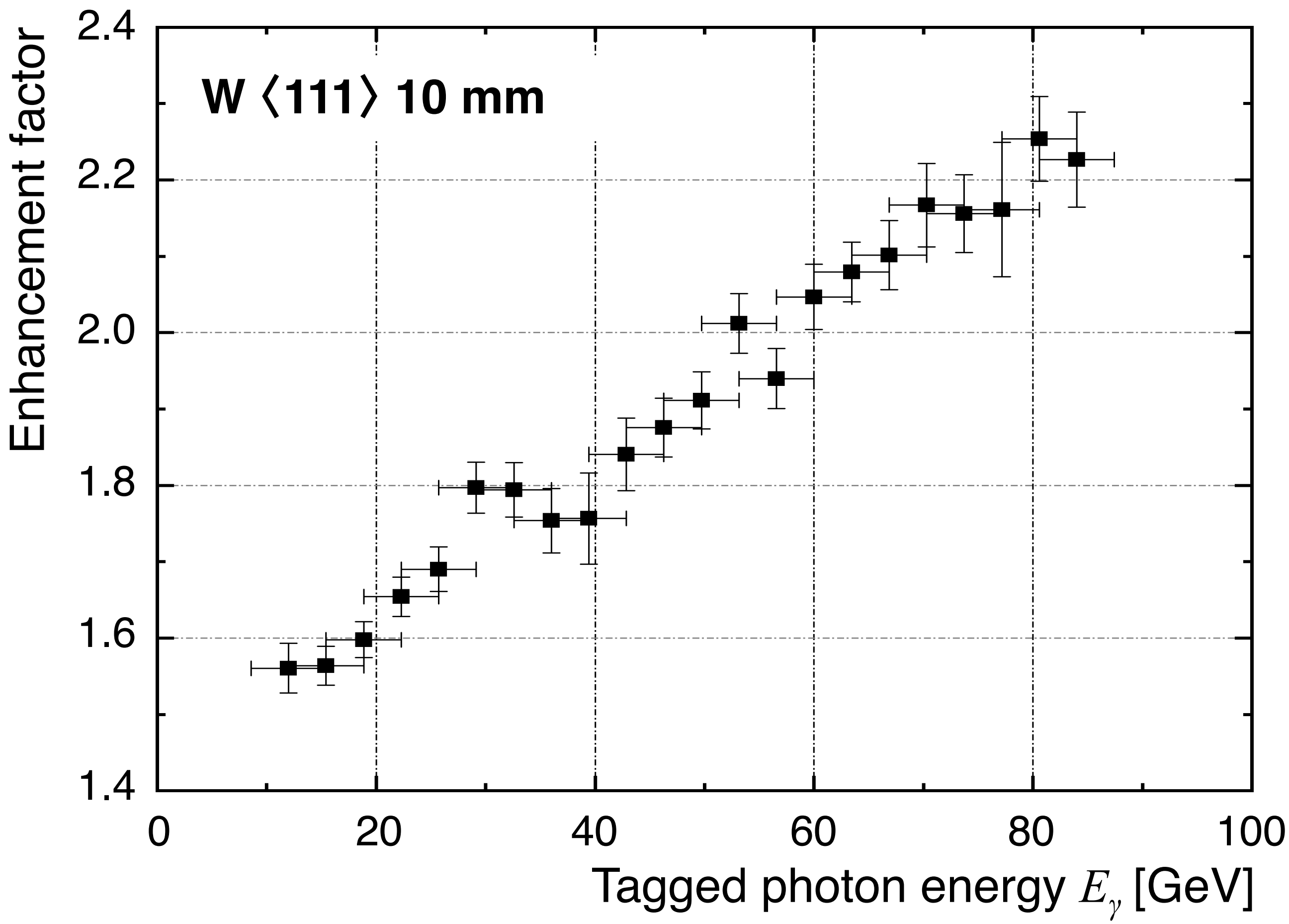
- Charged multiplicity increased 2x at high photon energy
- Angular range for enhancement several mrad





First look at test beam data

Enhancement of mean charged multiplicity (S4), axial/amorphous



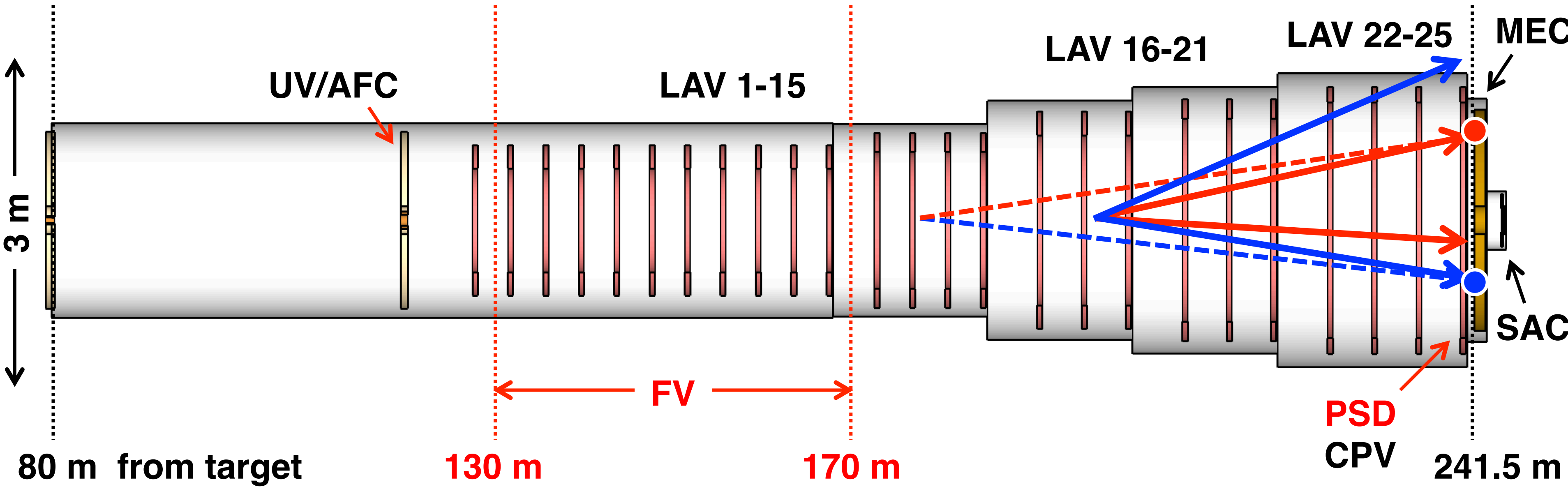
Charged multiplicity enhanced > 2x for E_γ ~ 80 GeV

1 extra shower generation in 10 mm → X_0 reduced by 33%

No sign of saturation up to E_γ ~ 80 GeV

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

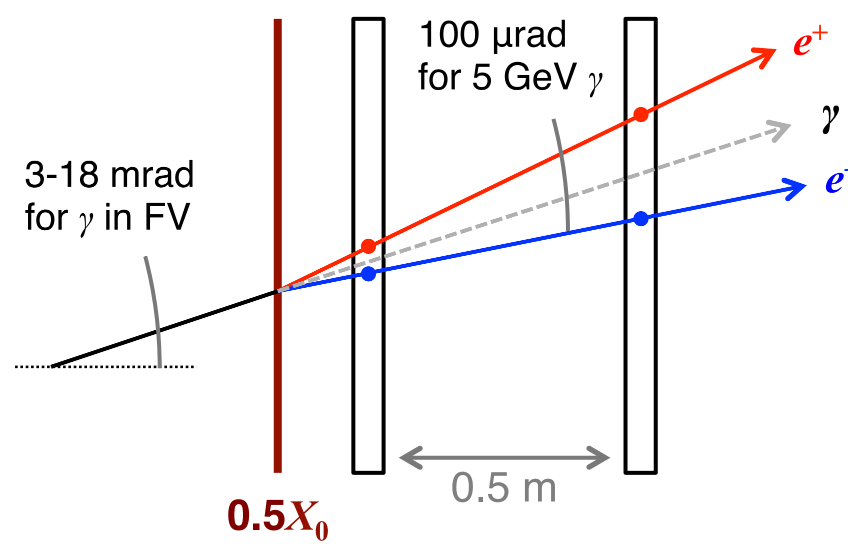
KLEVER



Distance from FV to LKr 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



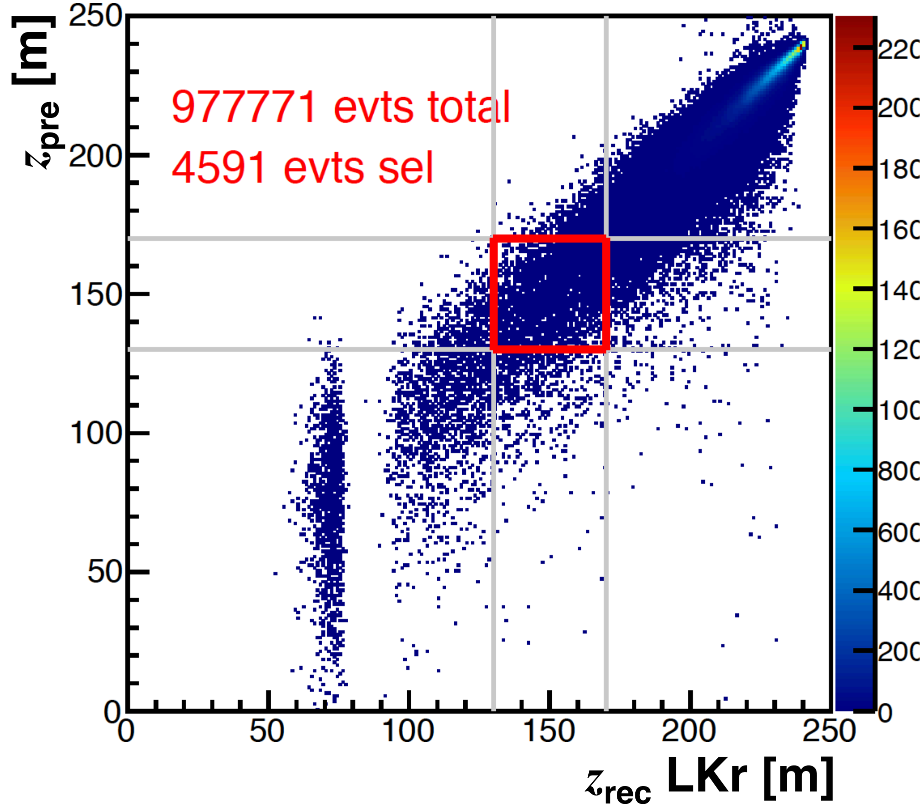
Preshower background rejection

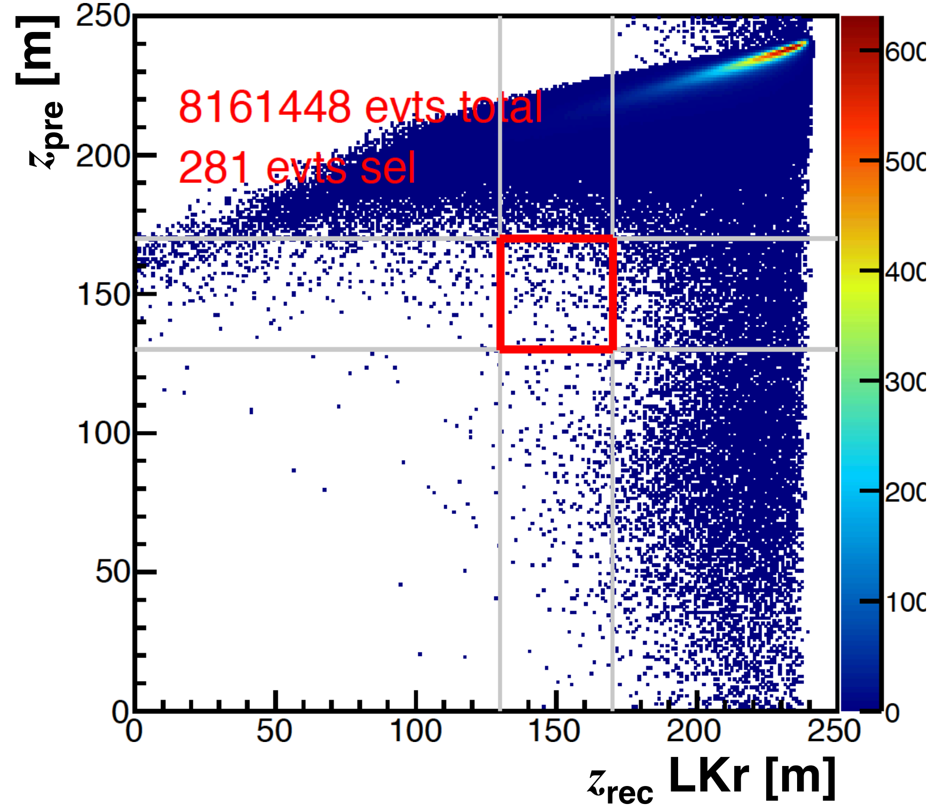
Preshower vertex z_{pre} vs. LKr vertex z_{rec}
z_{rec} reconstructed by imposing $M(\gamma\gamma) = m_{\pi 0}$

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

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

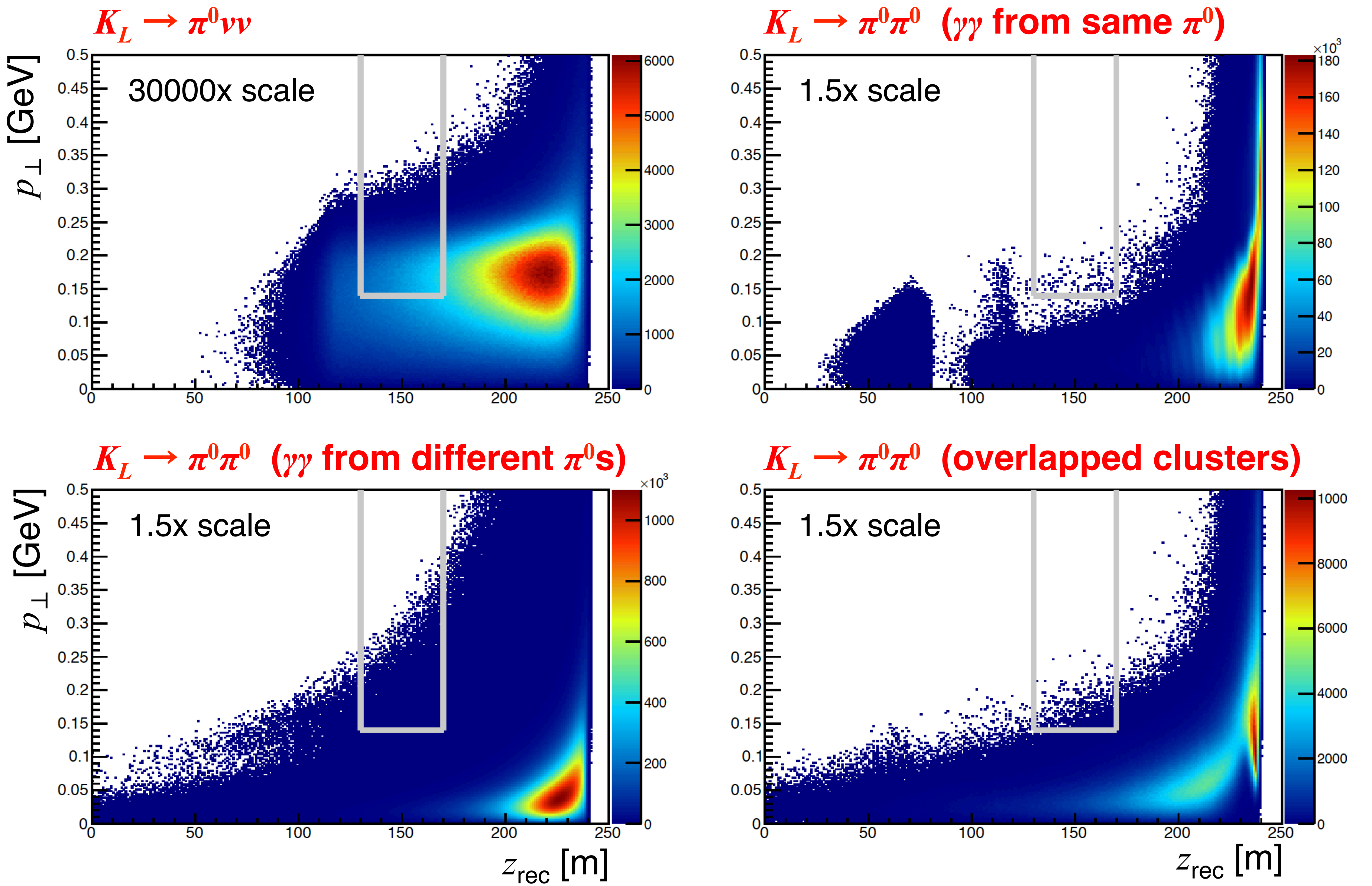
Odd pairs (2 γs from different π^0)
1 γ converts in preshower





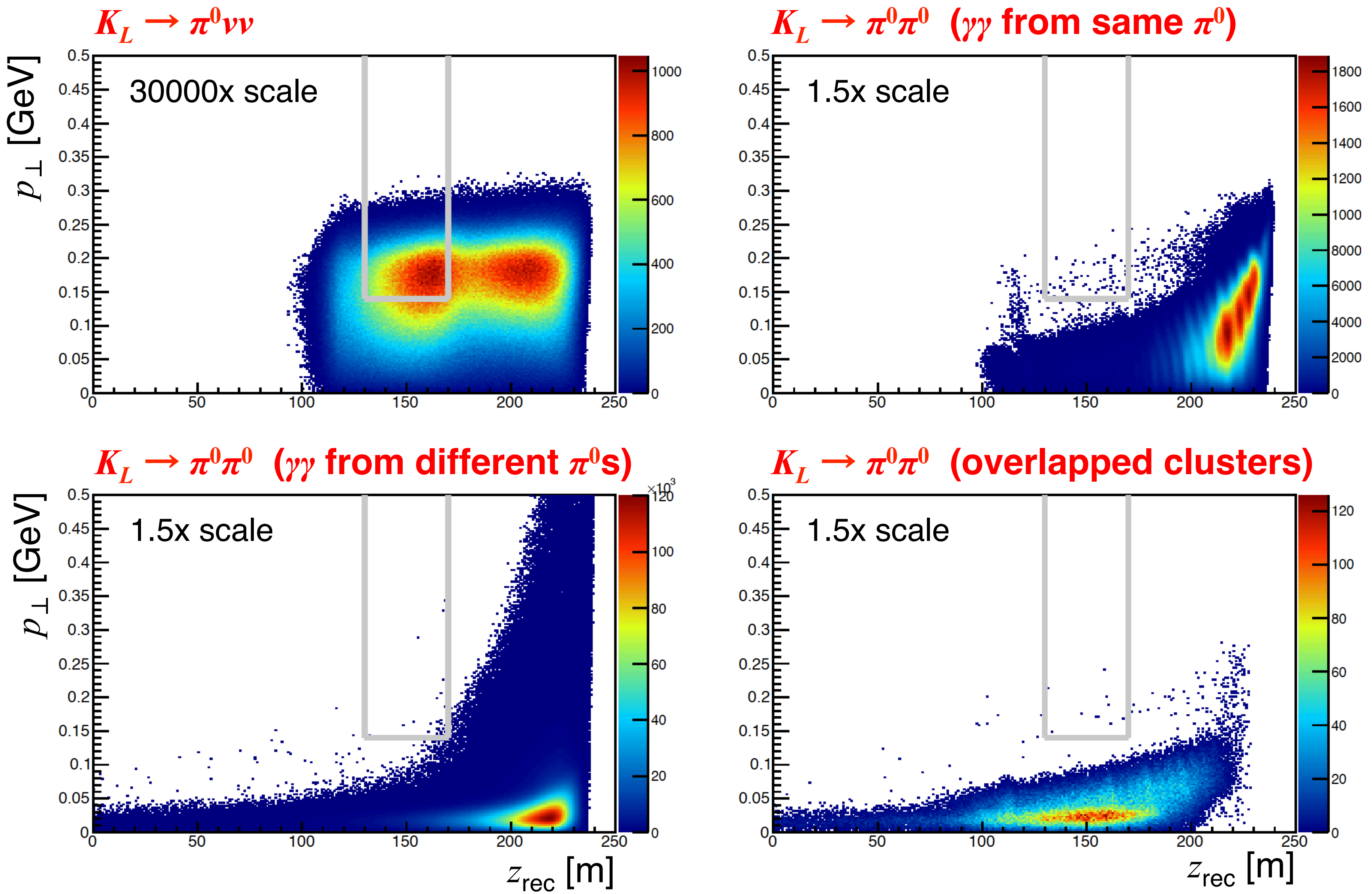
Basic signal selection

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



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**
- Participation in Physics Beyond Colliders
- Beam test of crystal pair enhancement
- Input to European Strategy for Particle Physics

2019 Q2 **Expression of Interest to CERN SPSC** (in preparation)

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

2025 **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 $S/B \sim 1$
- KLEVER is preparing Expression of Interest to CERN SPSC and is actively seeking new collaborators

Additional information

Second Forum on Rare Kaon Decays
Anacapri, 30 May 2019

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INFN Frascati

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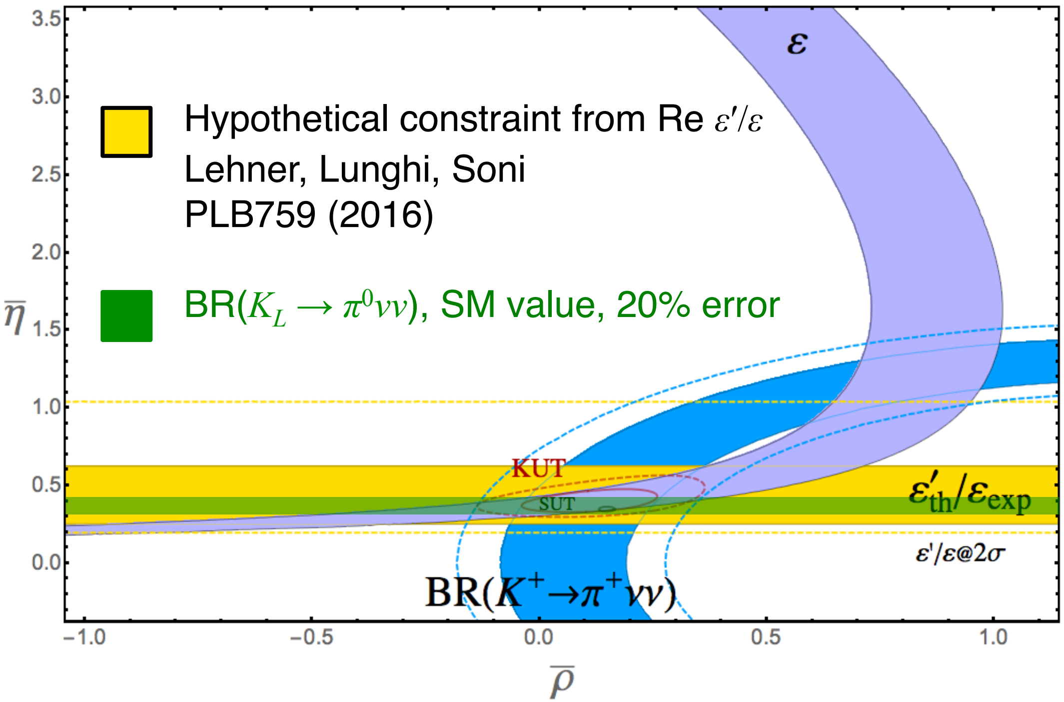
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Re ε'/ε vs BR($K_L \to \pi^0 \nu\bar{\nu}$)



Re ε'/ε constrains UT in same way as BR($K_L \to \pi^0 \nu\nu$)

Scenario assumes:

- Lattice value for Im A_0 in agreement with expt
- δ(Im A_0) = ~100% → 18%
  → δ(Re $\varepsilon'_{th}/\varepsilon$) = 1.6 × 10^{-4}
- BR($K^+ \to \pi^+ \nu\nu$) = SM value with 10% error

Calculations: Re ε'/ε × 10^4

RBC/UKQCD ’15	**1.38 ± 5.15 ± 4.59**
Gisbert & Pich ’17	15 ± 7

Measurements: Re ε'/ε × 10^4

KTeV	19.2 ± 1.1 ± 1.8
NA48	14.7 ± 1.7 ± 1.5
PDG fit	**16.6 ± 2.3 (S = 1.6)**

RBC/UKQCD value is 2.1σ lower than experimental value:

In progress: Increased statistics, larger volumes, additional lattice spacings

$K \to \pi\nu\bar{\nu}$ 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 $B \to K\ell\ell$, $B \to K^*\ell\ell$

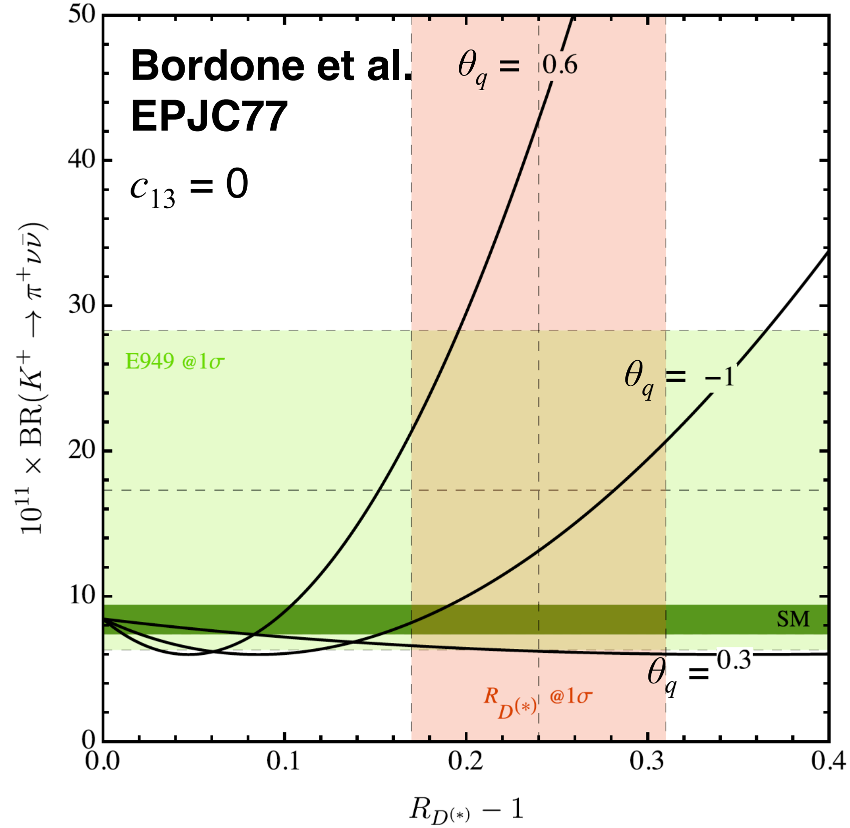
$R_{D(*)}$: $\tau/(\mu, e)$ LFU in $B \to D^{(*)}\ell\nu$

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)**



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

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

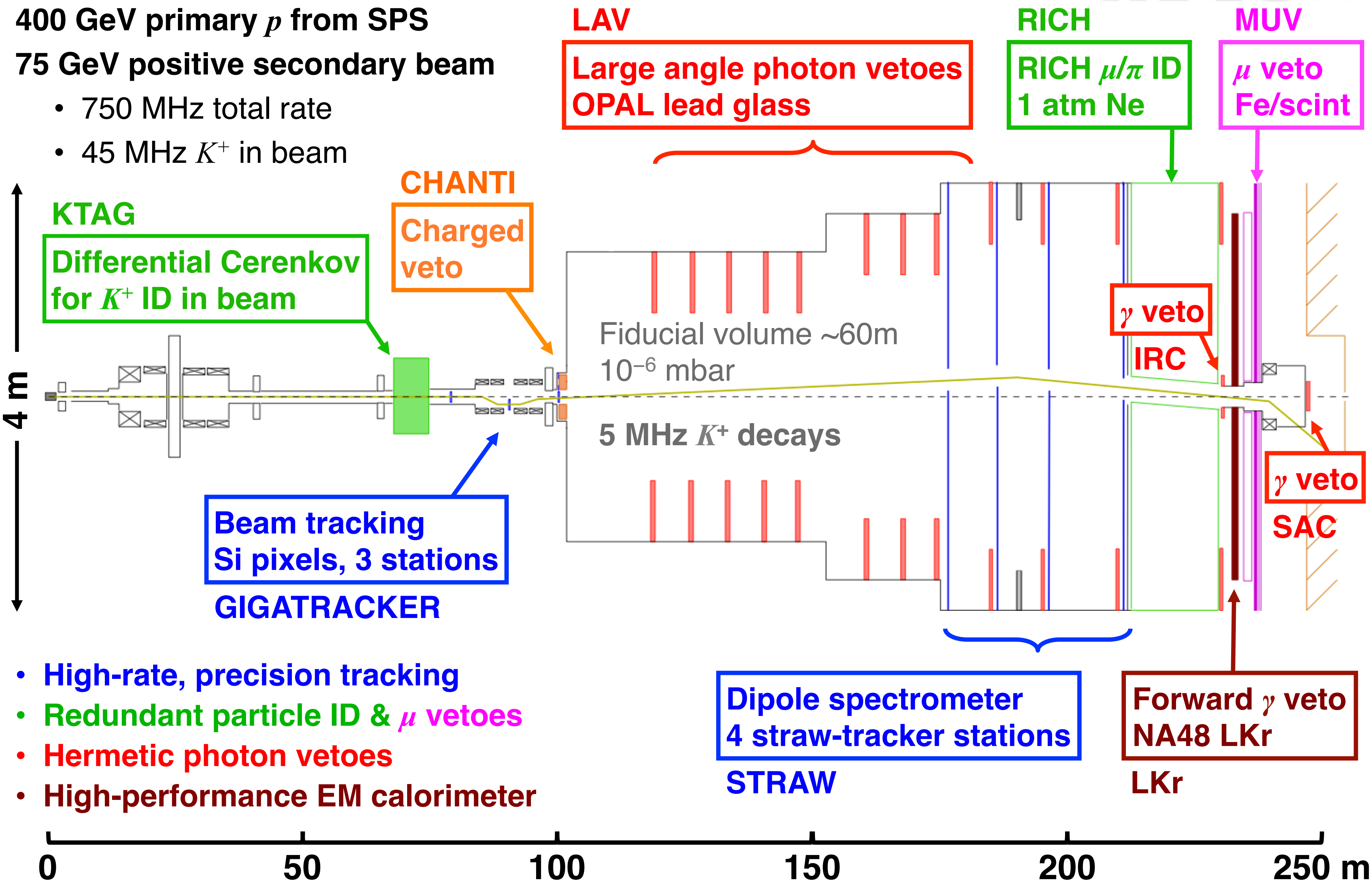
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = 2\mathcal{B}(K_L \to \pi^0\nu_e\bar{\nu}_e)_{\mathrm{SM}} + \mathcal{B}(K_L \to \pi^0\nu_\tau\bar{\nu}_\tau)_{\mathrm{SM}}\left|1 - \frac{R_0\,\theta_q^2(1 - c_{13})}{(\alpha/\pi)(X_t/s_W^2)}\right|^2$$

The NA62 experiment at the SPS

400 GeV primary p from SPS

75 GeV positive secondary beam

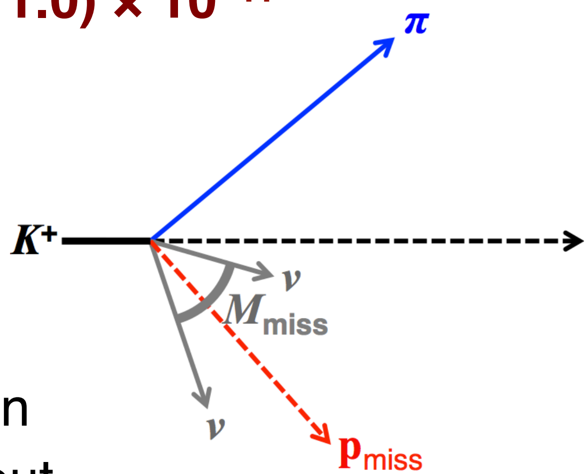
- 750 MHz total rate
- 45 MHz K^+ in beam



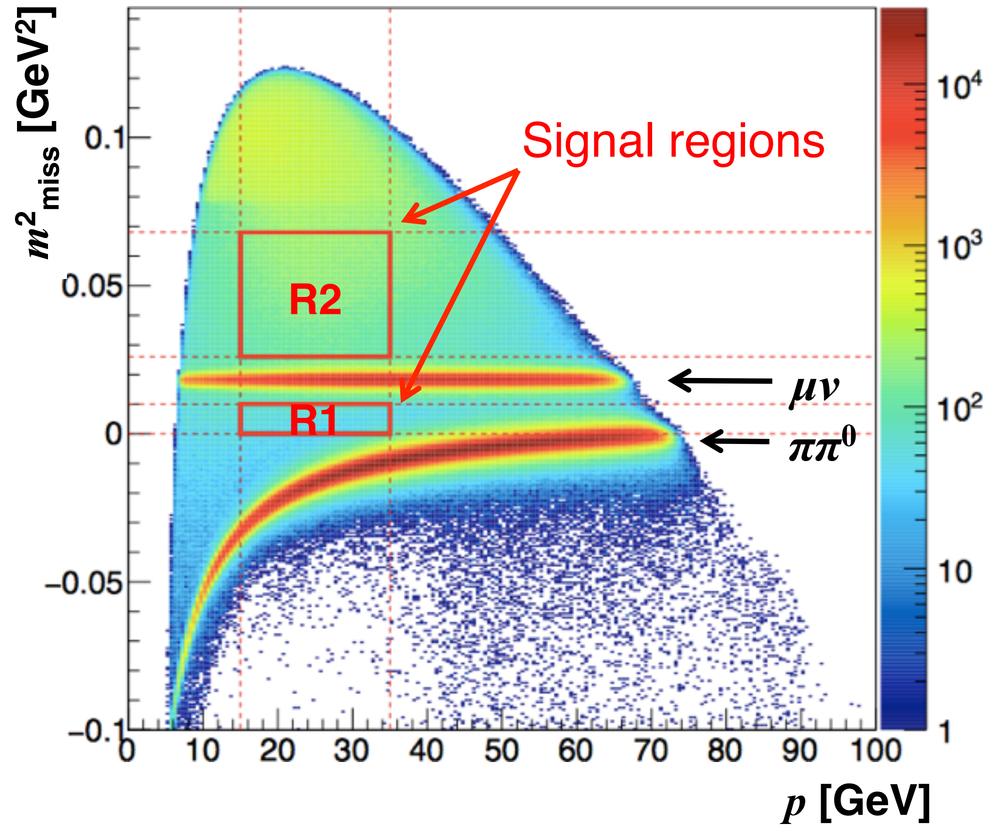
- **High-rate, precision tracking**
- **Redundant particle ID & μ vetoes**
- **Hermetic photon vetoes**
- **High-performance EM calorimeter**

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ with decay in flight

Signal:
BR = (8.4 ± 1.0) × 10^{-11}



- K track in
- π track out
- No other particles in final state
- $M^2_{\text{miss}} = (p_K - p_\pi)^2$



Main backgrounds:

$K^+ \rightarrow \mu^+\nu(\gamma)$	BR = 63.5%
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	BR = 20.7%

Selection criteria:

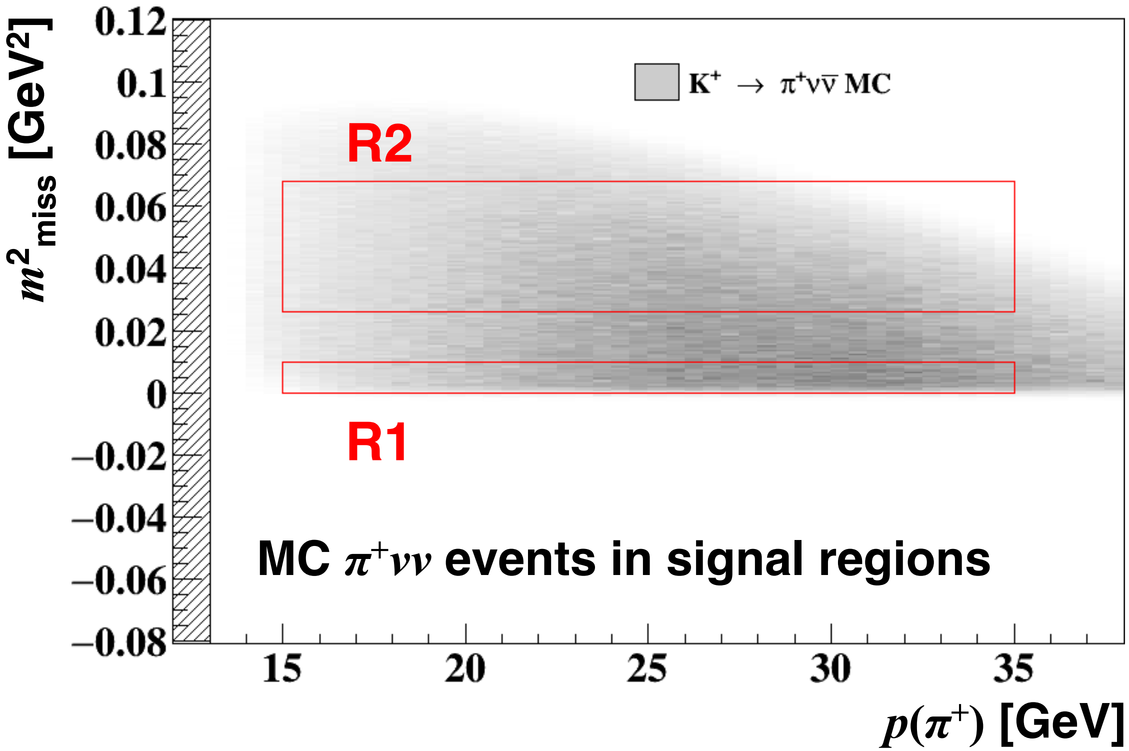
- K^+ beam identification
- Single track in final state
- π^+ identification ($\varepsilon_\mu \sim 1 \times 10^{-8}$)
- γ rejection ($\varepsilon_{\pi 0} \sim 3 \times 10^{-8}$)

$K^+ \to \pi^+ \nu\bar{\nu}$ sensitivity, 2016 data

2014-2015 Pilot/commissioning runs

2016 Commissioning + 1st physics run
40% of nominal intensity

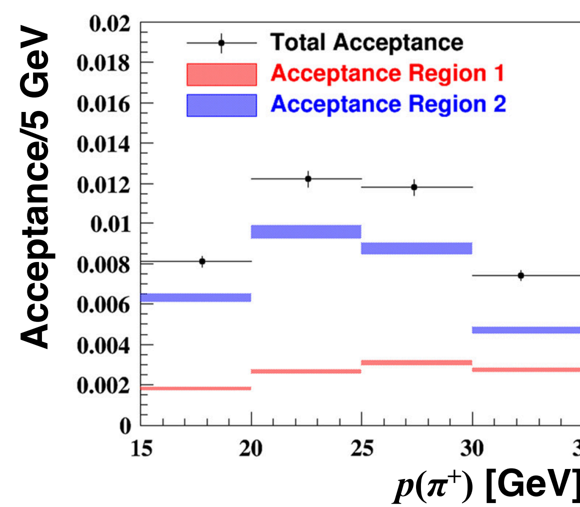
First result presented in March 2018
PLB 791 (2019) 156



Signal acceptance 4.0%

- 15 GeV < $p(\pi^+)$ < 35 GeV
- m^2_{miss} cuts to define R1, R2

Analysis in 4 bins of $p(\pi^+)$



Normalization to $K \to \pi\pi^0$

- 1.2×10^{11} K^+ decays recorded

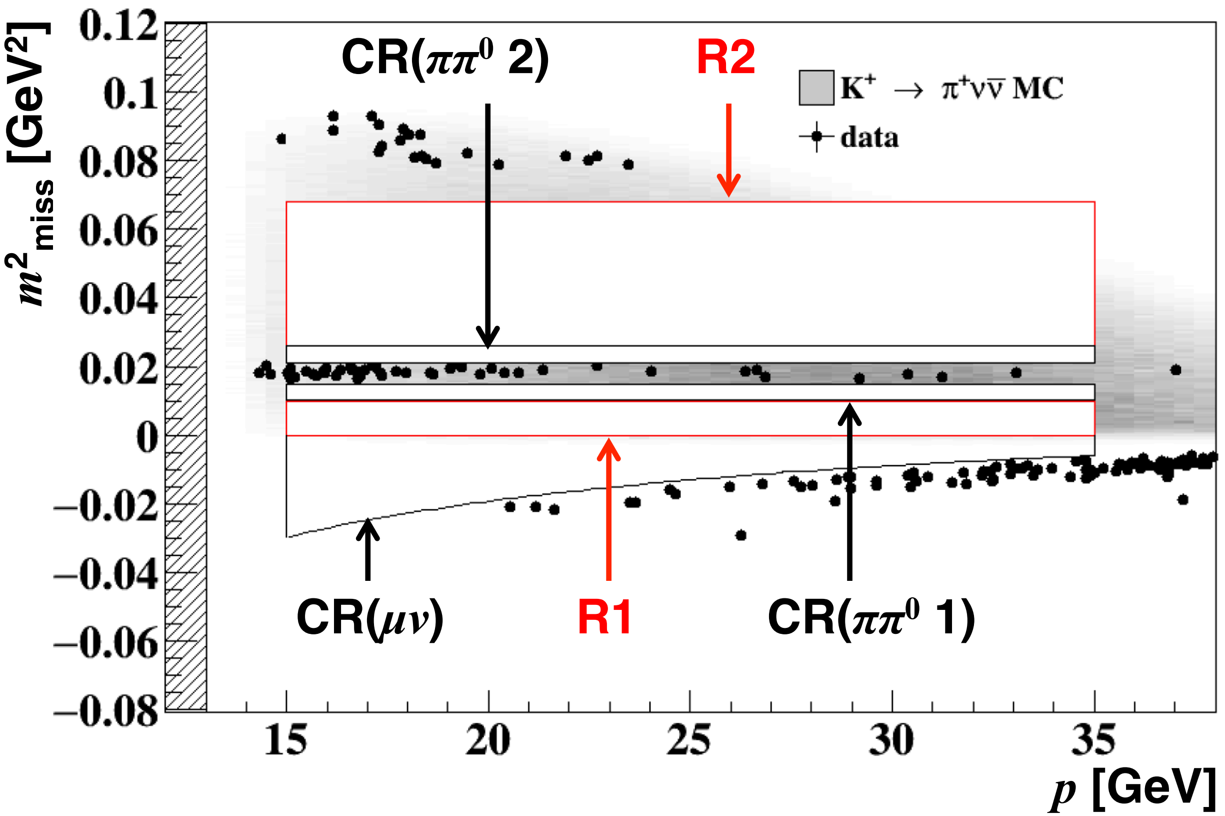
SES = $(3.15 \pm 0.01_{stat} \pm 0.24_{sys}) \times 10^{-10}$

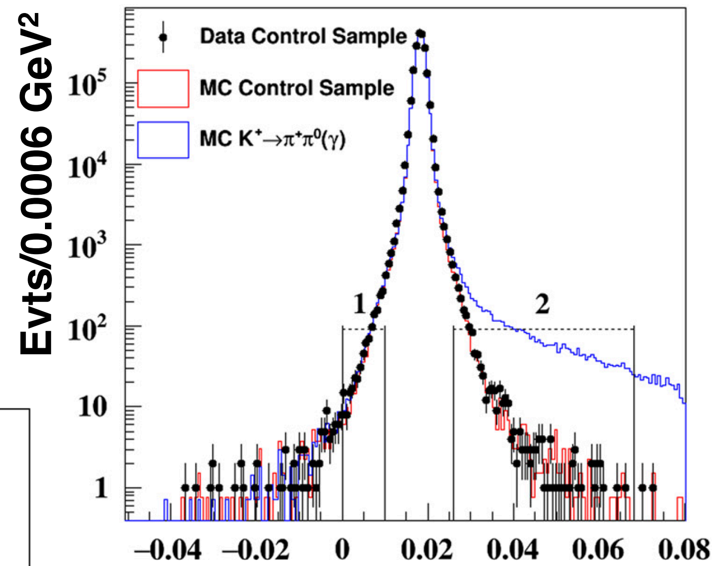
Expected signal events: $0.267 \pm 0.001_{stat} \pm 0.020_{sys} \pm 0.032_{ext}$

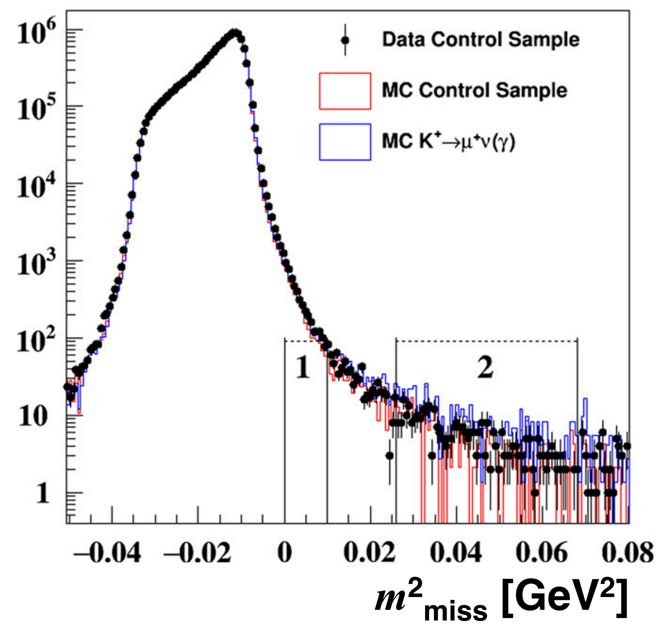
Background estimation

Estimate $K \to \mu\nu$ and $K \to \pi\pi^0$ background in signal regions R1, R2 from tails in m^2_{miss} distribution for control samples:

- $K \to \mu\nu$: 1-track selection like $\pi\nu\nu$ but with μ PID
- $K \to \pi\pi^0$: 1-track selection with reconstructed π^0

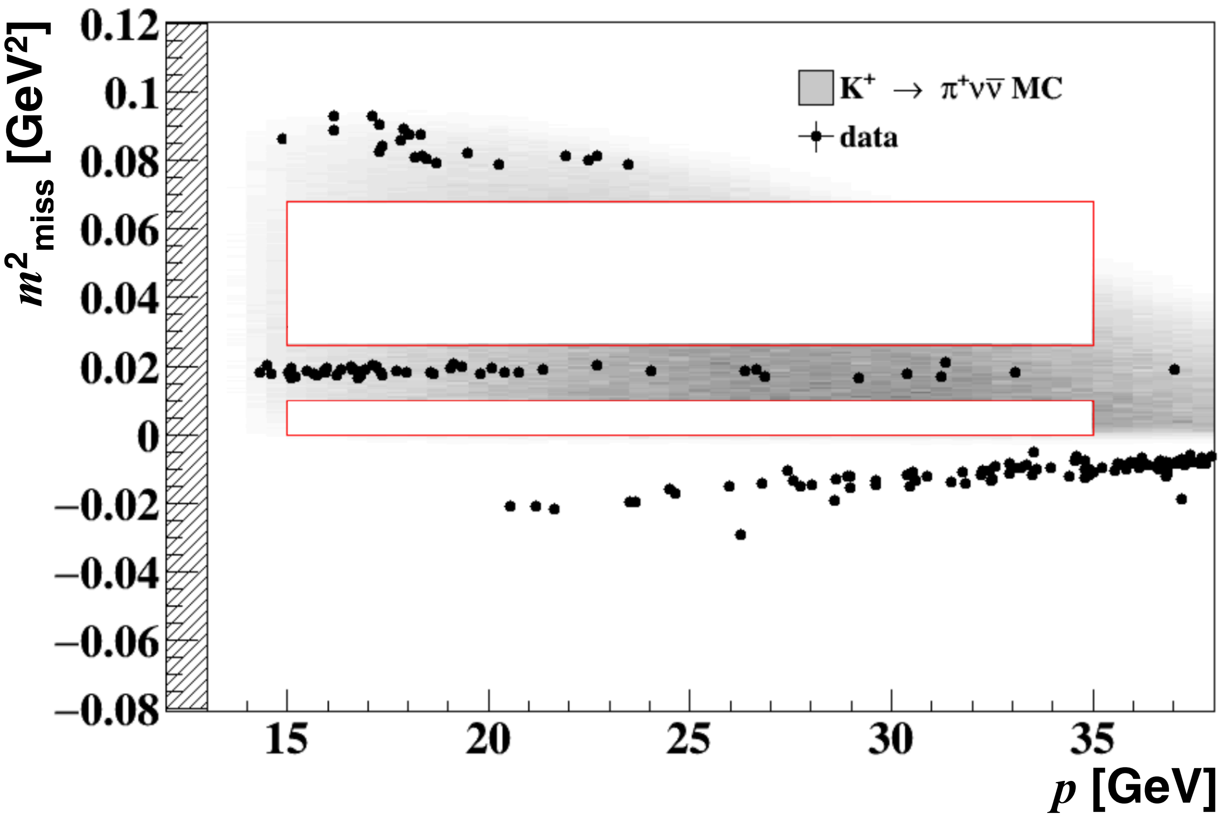


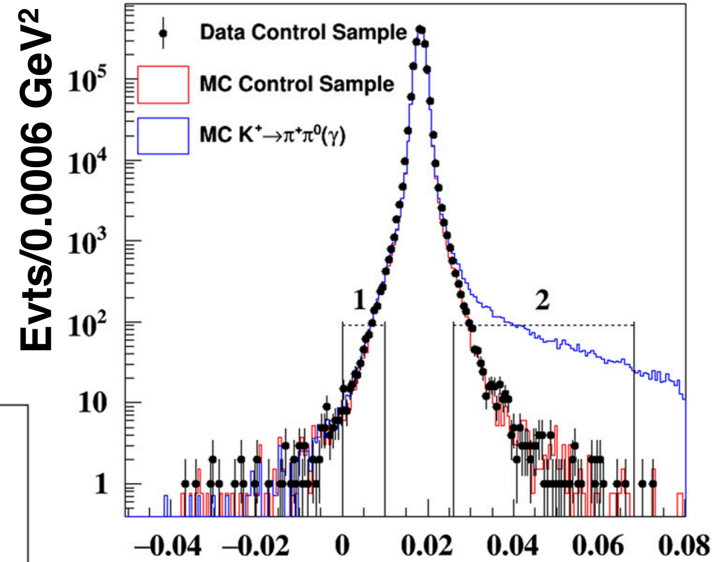


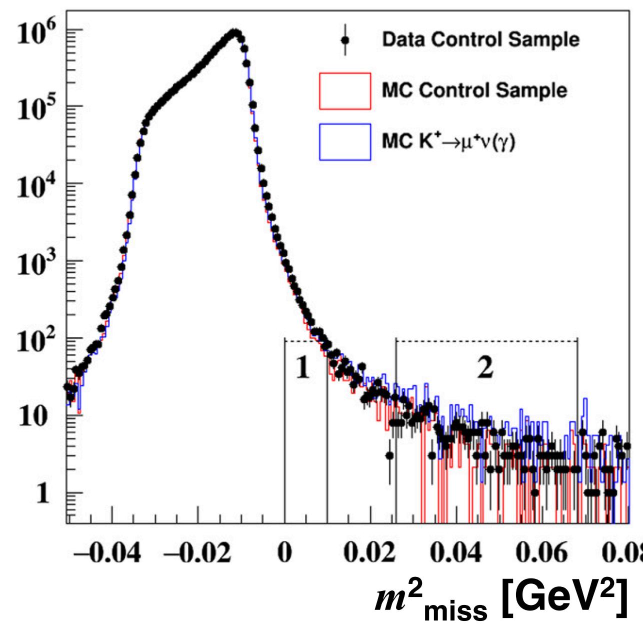


Background estimate validation

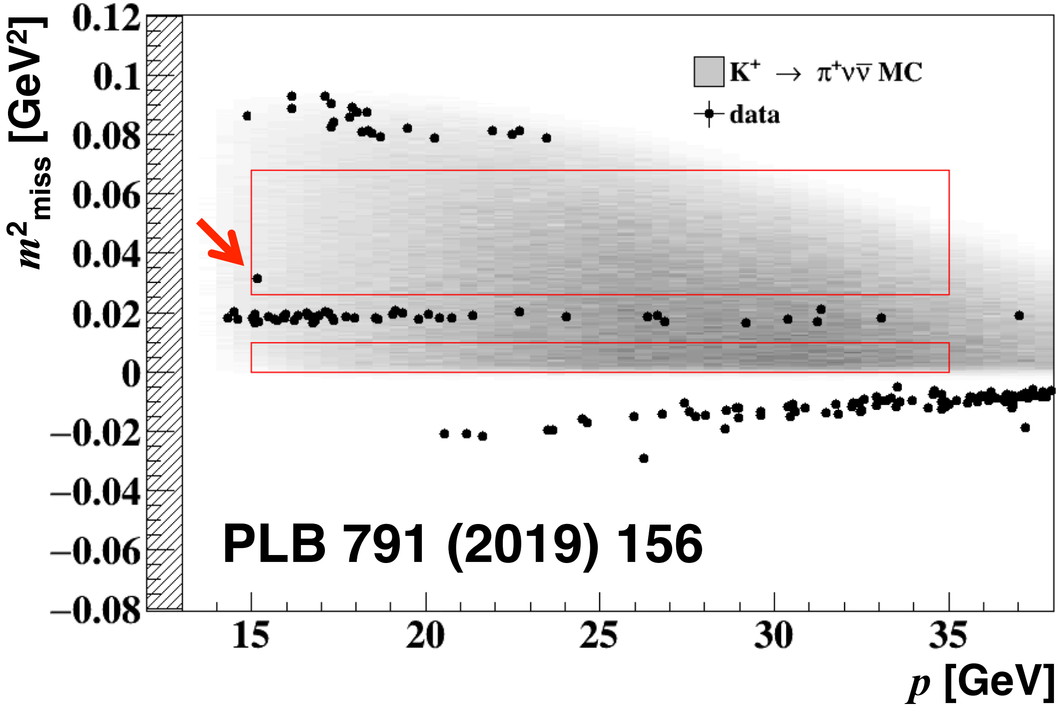
Region	Expected	Found
CR($\mu\nu$)	1.02 ± 0.16	2
CR($\pi\pi^0$ 1)	0.52 ± 0.08 ± 0.03	0
CR($\pi\pi^0$ 2)	0.94 ± 0.14 ± 0.05	1







BR($K^+ \to \pi^+ \nu\nu$) from 2016 data



2016 data—1.21 × 10^{11} K^+ decays

SES = (3.15 ± 0.24) × 10^{-10}

Expected signal 0.267 ± 0.038

Expected background 0.15 ± 0.09

1 event observed in R2

BR($K^+ \to \pi^+ \nu\nu$)

< 14 × 10^{-10} (95%CL)

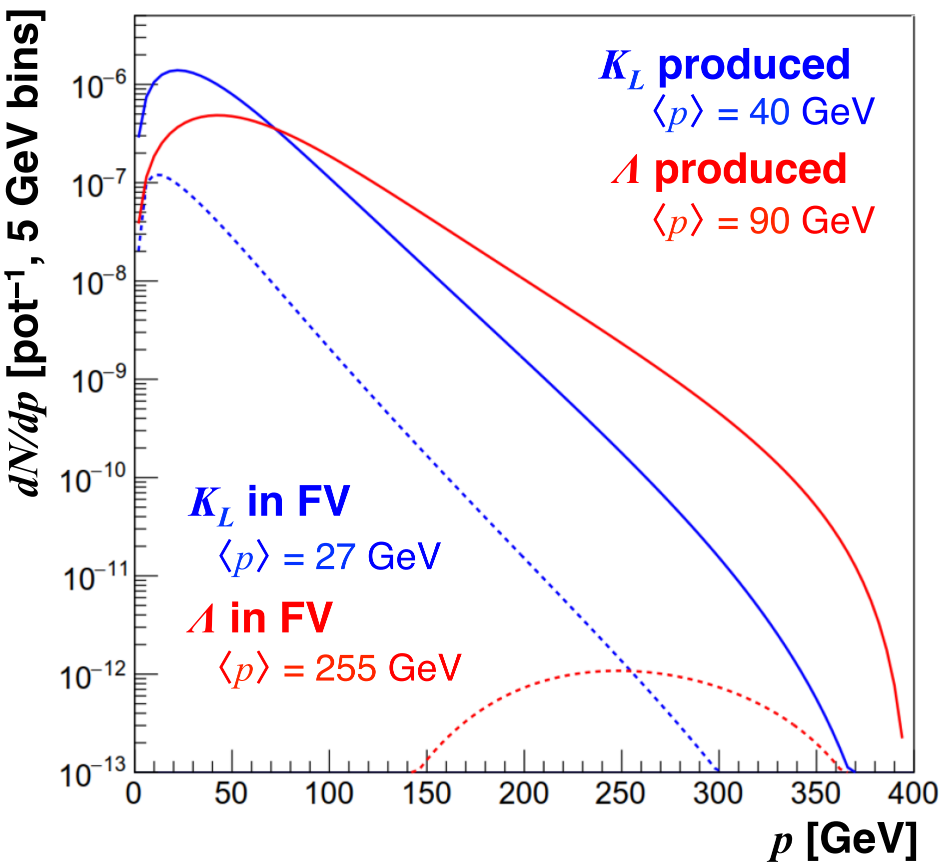
< 10 × 10^{-10} (90%CL)

= $28^{+44}_{-23} \times 10^{-11}$ (68% CL)

Background source	Expected events R1 + R2
$K^+ \to \pi^+ \nu\nu$ (SM)	**$0.267 \pm 0.001_{\text{stat}} \pm 0.029_{\text{sys}} \pm 0.032_{\text{ext}}$**
$K^+ \to \pi^+ \pi^0 (\gamma_{\text{IB}})$	$0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{sys}}$
$K^+ \to \mu^+ \nu (\gamma_{\text{IB}})$	$0.020 \pm 0.003_{\text{stat}} \pm 0.003_{\text{sys}}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.018\ ^{+0.024}_{-0.017}\ _{\text{stat}} \pm 0.009_{\text{sys}}$
$K^+ \to \pi^+ \pi^- \pi^+$	$0.002 \pm 0.001_{\text{stat}} \pm 0.002_{\text{sys}}$
Upstream background	$0.050 \pm\ ^{+0.090}_{-0.030}$
Total background	**$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{sys}}$**

Beam and intensity requirements

K_L and Λ fluxes, $\theta = 8.0$ mrad
Parameterized from 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 ~ 4%
- Acceptance for $K_L \to \pi^0 \nu\nu$ decays occurring in FV ~ 5%

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**

High-intensity neutral beam study

KLEVER

Conclusions from PBC Conventional Beams working 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 T4 → T10 transmission to 80%
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
T10 target & collimator	Thermal load on T10 too high → Use CNGS-like target? Dump collimator will require modification/additional cooling
Radiation dose at surface above ECN3	8 mrad vertical targeting angle should help to mitigate Preliminary results from FLUKA simulations Proposed target shielding scheme appears to be adequate Mixed mitigation strategy may be needed for forward muons

NA48 LKr calorimeter as MEC?

Quasi-homogeneous ionization calorimeter, 27X_0 of LKr

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\% \qquad \sigma_t = \frac{2.5\text{ ns}}{\sqrt{E}}$$

Photon detection efficiency probably adequate

- NA48-era studies for NA62: $1 - \varepsilon < 10^{-5}$ for $E_\gamma > 10$ GeV
- High-energy efficiency confirmed with NA62 data

Other concerns about LKr:

Time resolution

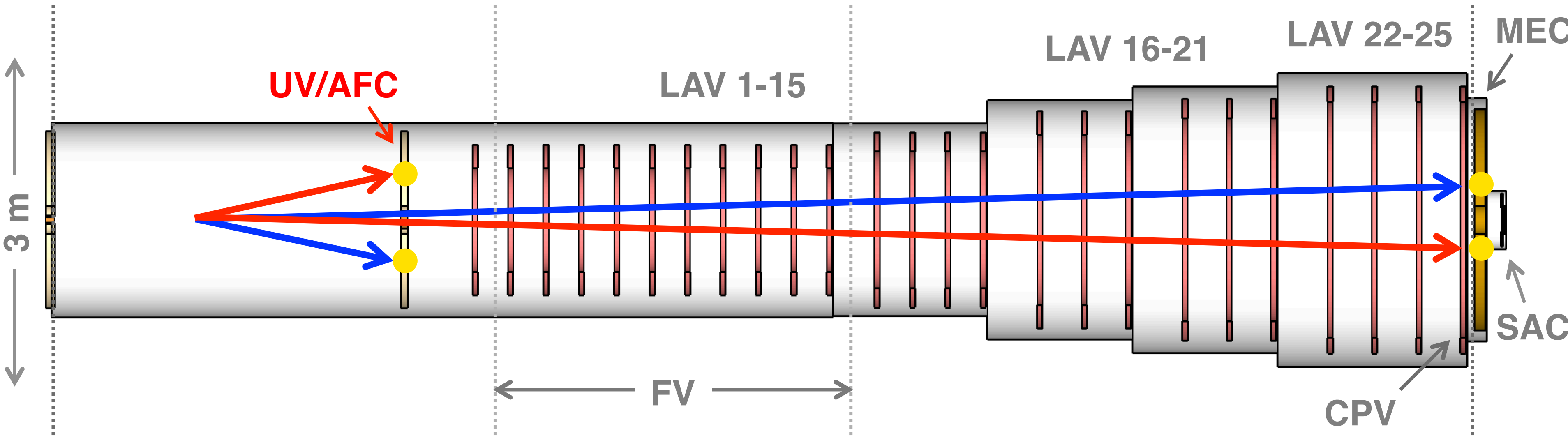
- $\sigma_t \sim 500$ ps for π^0 with $E_{\gamma\gamma} > 20$ GeV
- Would require improvement – SAC may have ~100 MHz accidental rate

Long-term reliability (1996 → 2018 → 2030?)

LKr cold bore r = 80 mm and start of sensitive volume r = 120 mm limits beam solid angle to $\Delta\theta < 0.3$ mrad → 40% less K_L flux

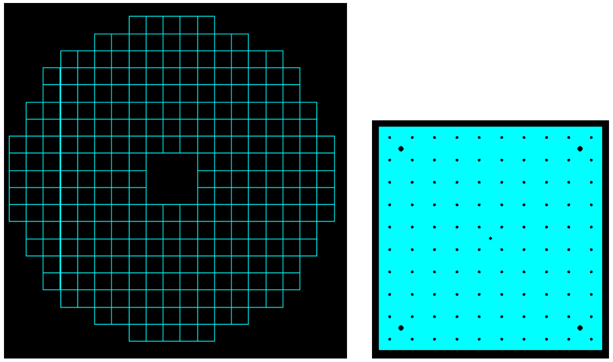
Baseline design calls for NA48 LKr to be replaced by new MEC

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

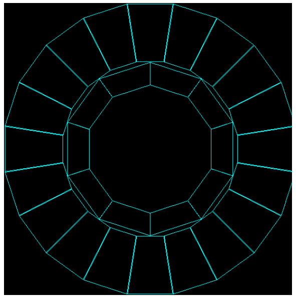


Upstream veto (UV):

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



Active final collimator:

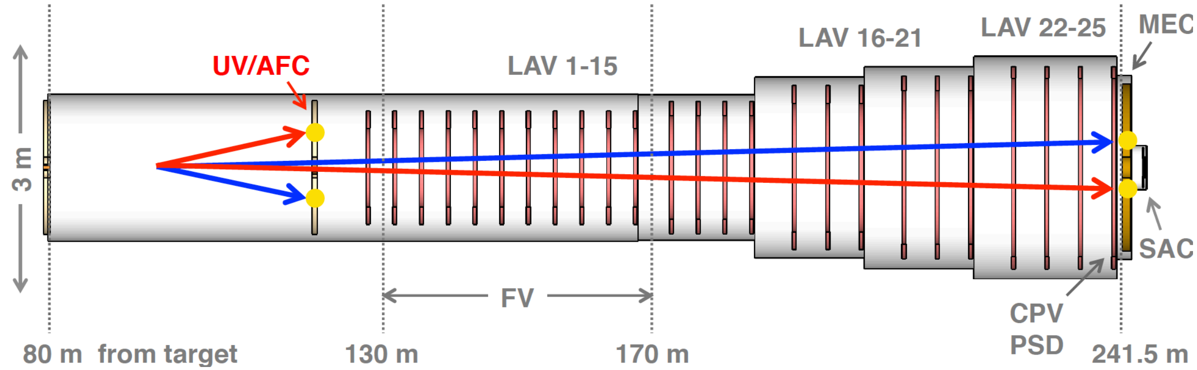


- 4.2 < r < 10 cm
- LYSO collar counter
- 80 cm long
- Internal collimating surfaces

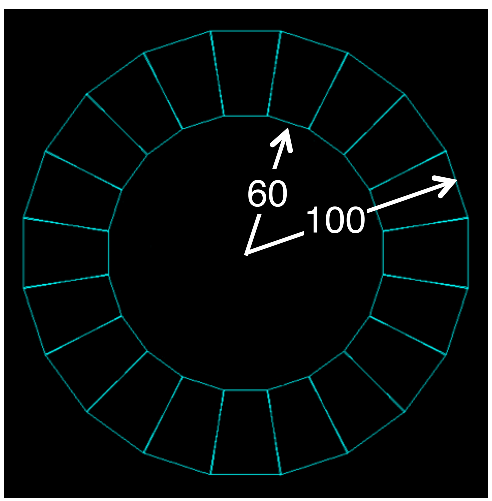
- Intercepts halo particles from scattering on upstream collimators or γ absorber
  Rejects π^0s from inelastic interactions
- Rejects $K_L \to \pi^0\pi^0$ in transit through collimator

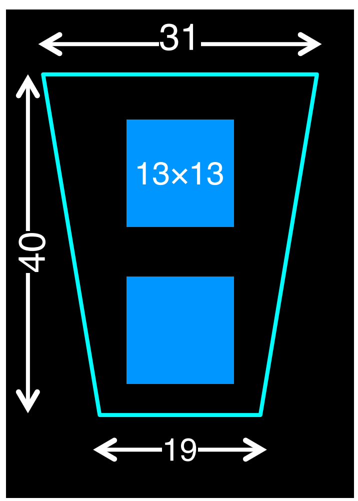
Active final collimator

- 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



Design in progress:





- 60 mm < r < 100 mm
- 80 cm long (3-4 consecutive rings)
- 20-24 crystals per ring

LYSO collar counter with internal collimating surfaces

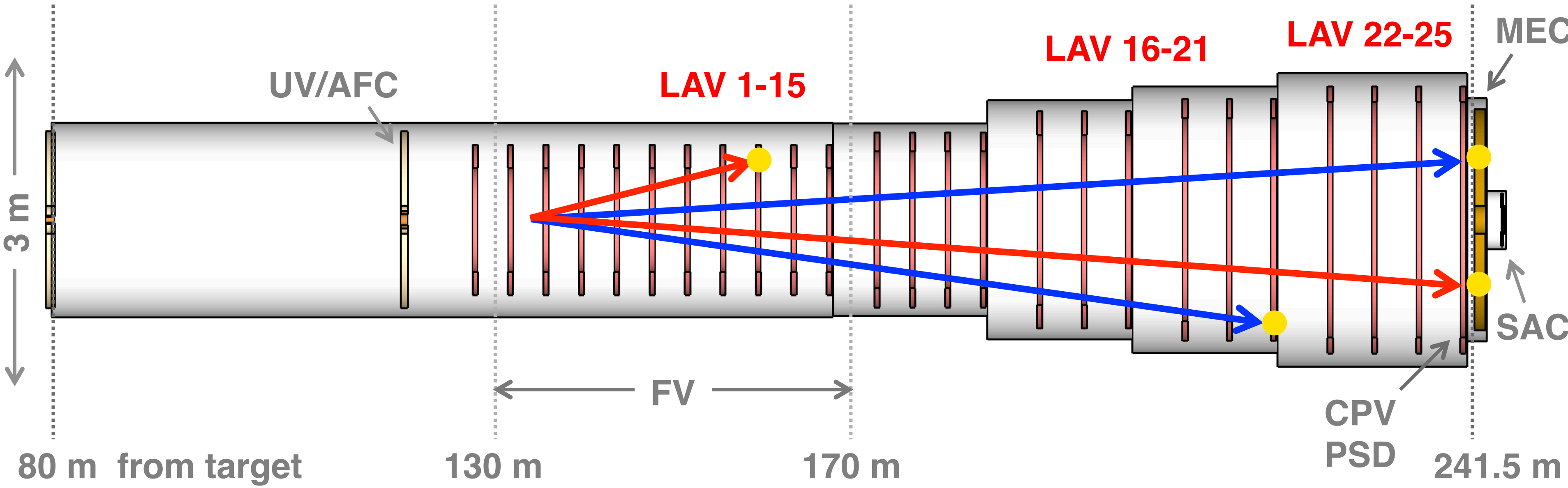
- Fast (40 ns), bright (~ NaI), radiation hard (>10^6 Gy)

Crystals read out on back side with APDs

- Good coupling with LYSO and high quantum efficiency
- Simple signal and HV management
- E.g. RMD S1315 (13x13 mm^2)

Expected light yield > 4000 p.e./MeV

Large-angle photon vetoes



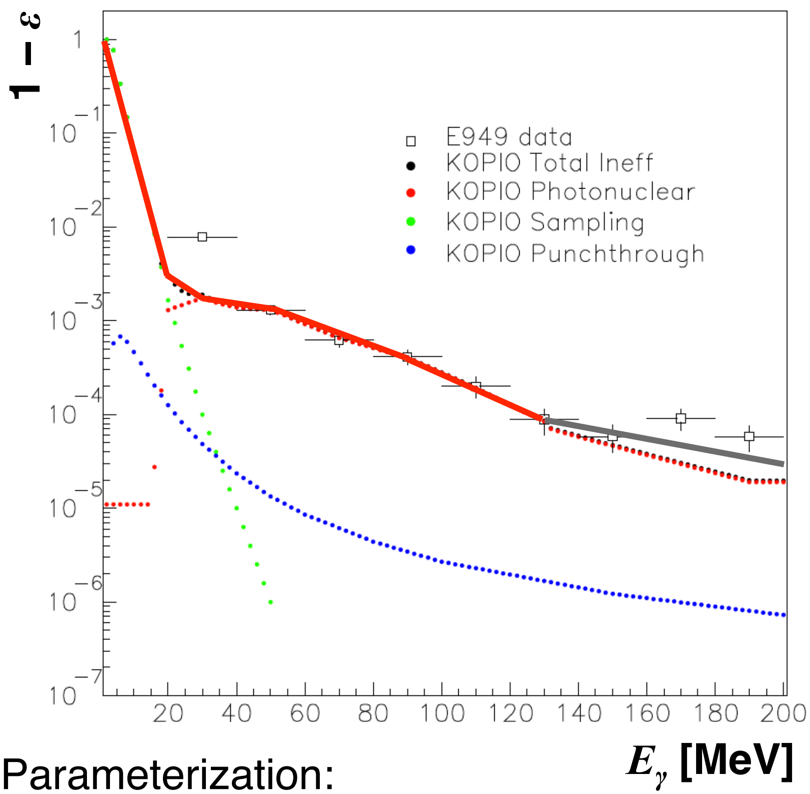
25 new large-angle photon veto stations (LAV)

- 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 – ε ~ 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

Large-angle photon vetoes

25 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

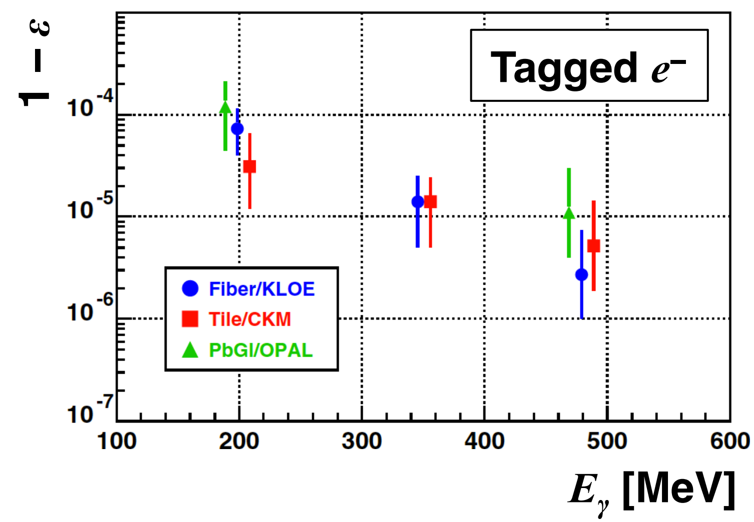


Parameterization:
- 1-129 MeV: KOPIO (E949 barrel)
- 203-483 MeV: CKM VVS

Good efficiency assumptions based on E949 and CKM VVS experience

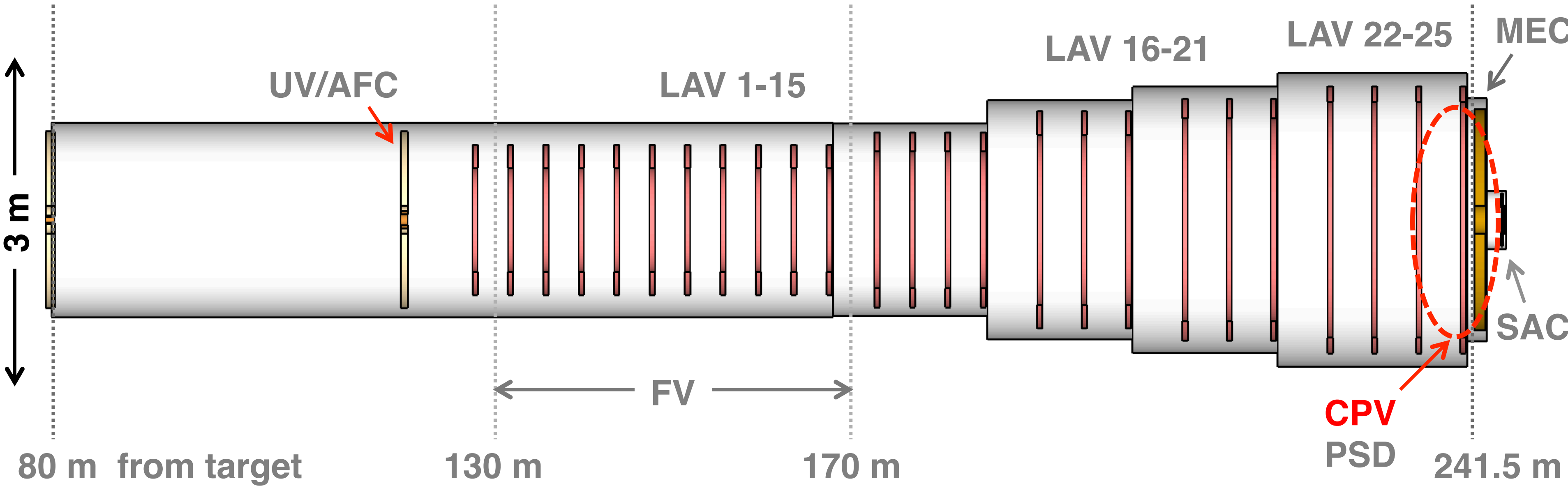
E949 barrel veto efficiencies
Same construction as CKM

Tests for NA62 at Frascati BTF



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

Charged particle 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!

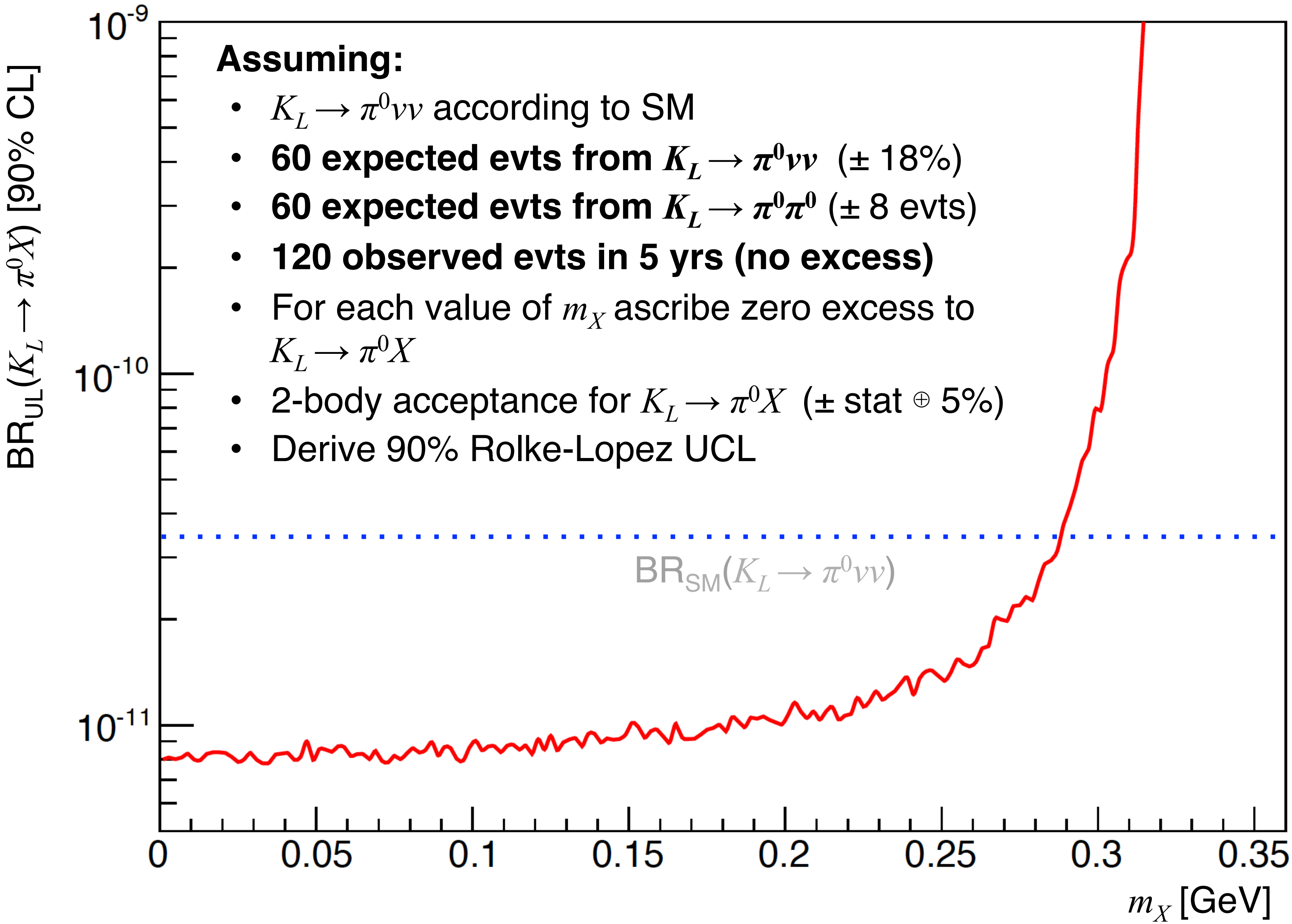
Charged particle veto (CPV)

- 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

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

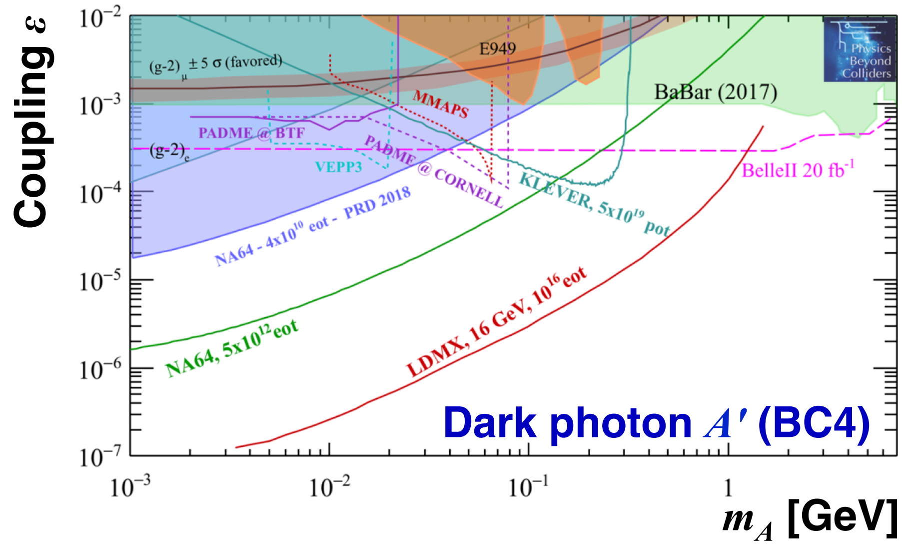


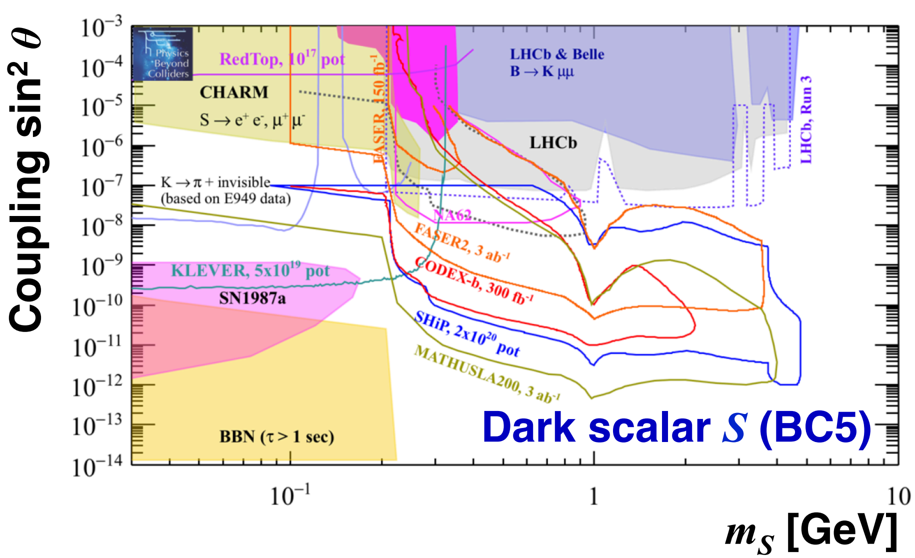
Exclusion potential from $K_L \to \pi^0 X$

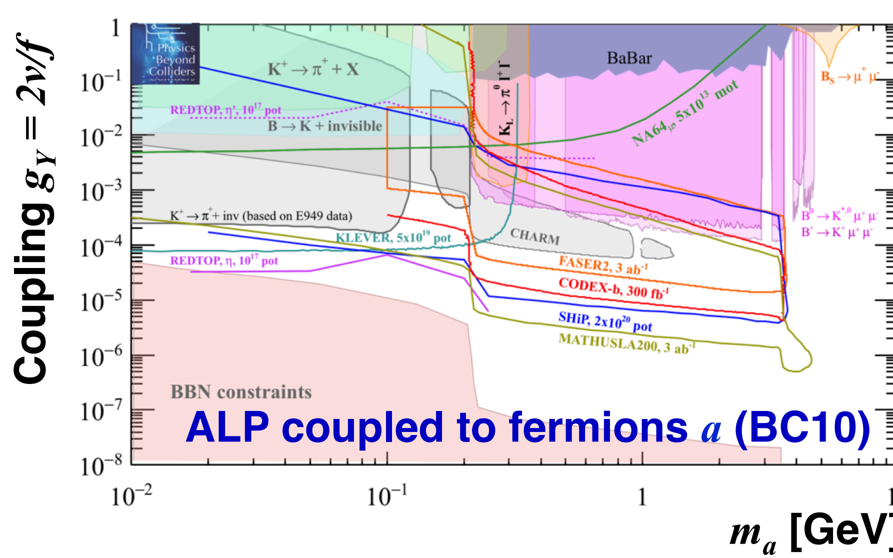
For $K_L \to \pi^0 X$, interpret X as:

- Invisible dark photon A' (BC2)
- Higgs-mixed scalar S (BC4)
- Axion-like particle a with fermion couplings (BC10)

Obtain limits in coupling vs. mass plane for each scenario*







* Calculation assumes that decaying particles escape the decay volume