K_LEVER

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

Laboratori Nazionali di Frascati
21 June 2018

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For the KLEVER project

Precision physics and rare decays

How can we extend the search for new physics to high effective scales?

Energy frontier Direct search	**Intensity frontier** Indirect investigation
Create new degrees of freedom in lab Explore spectroscopy of new d.o.f. **Λ ~ 1-10 TeV**	Evidence of new degrees of freedom as alteration of SM rates Explore symmetry properties of new d.o.f **Λ ~ 1-1000 TeV**

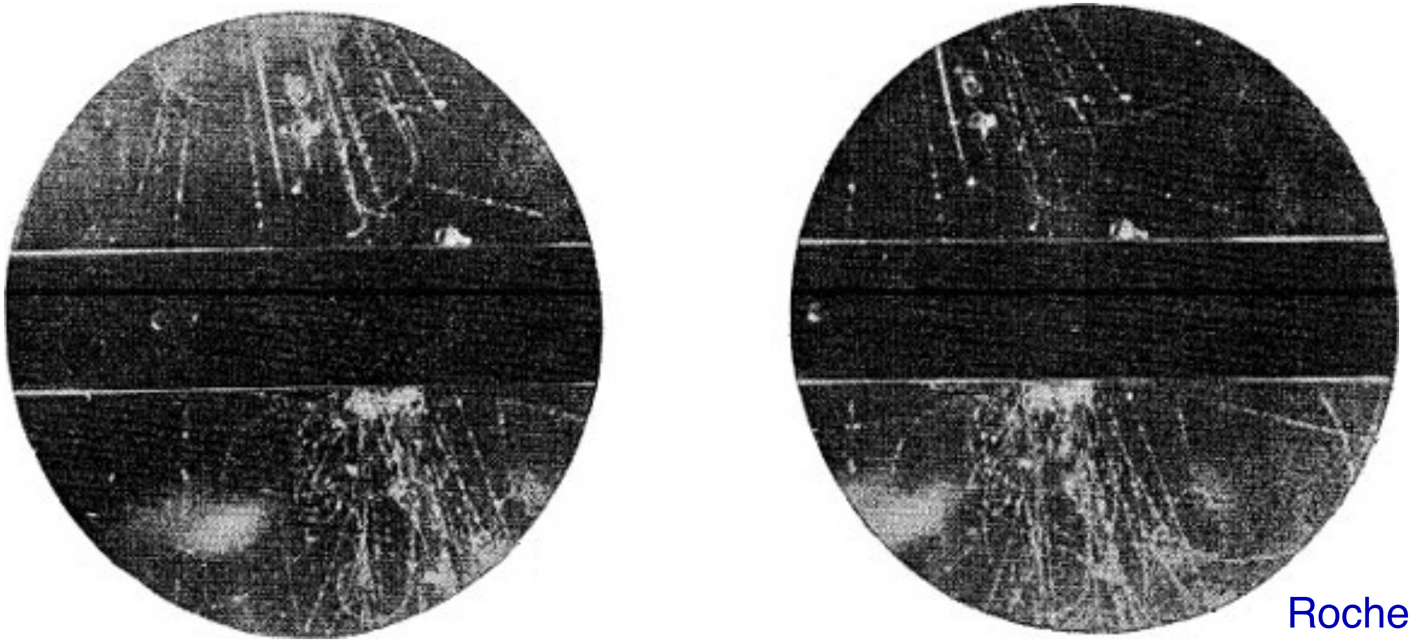
A rare decay is useful as an NP probe if:

- Process is (strongly) suppressed in the SM
- Parameter to be measured precisely calculated in SM
- There are specific predictions for NP contributions

Examples of what may be studied with rare decays:

- Explicit violations of the SM (e.g., lepton flavor violation)
- Tests of fundamental symmetries such as CP and CPT
- Search for new d.o.f. in the flavor sector, e.g., in FCNC processes
- Strong interaction dynamics at low energy using exclusive processes

What have kaons taught us?



Rochester & Butler
Nature 160 (1947)

Strangeness, concept of flavor quark model

τ-θ puzzle: hint of P violation, confirmation of weak $V-A$ structure

CP violation in mixing of neutral kaons

Suppression of $K_L \to \mu^+\mu^-$: GIM mechanism and the charm quark

Direct CP violation in $K \to \pi\pi$ and the CKM paradigm

Quiet successes of confirmation: conservation of lepton flavor, V_{us}, etc.

Kaons have been fundamental in the development of the SM flavor sector

Rare kaon decays

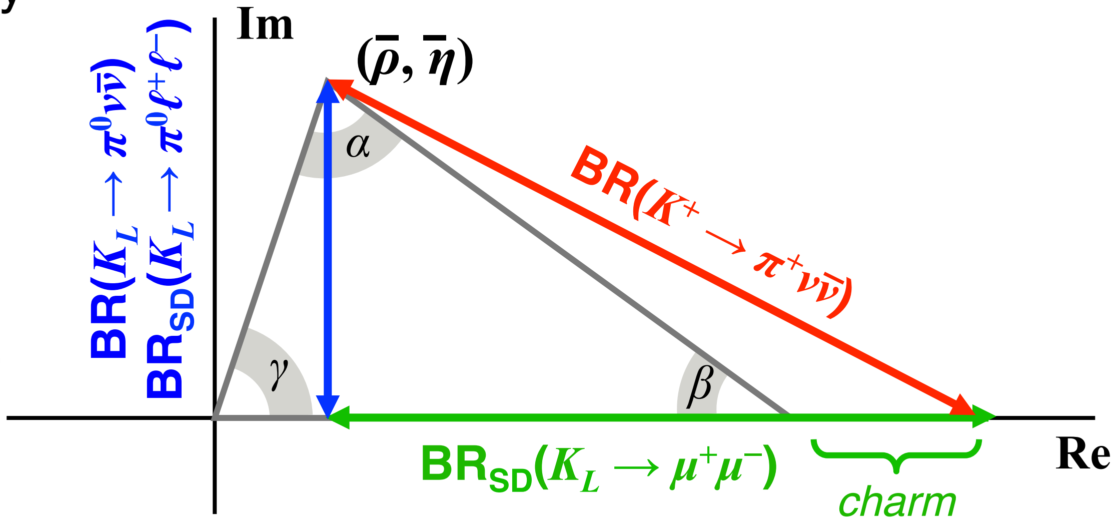
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	17 ± 11
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 2600†

*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

FCNC processes dominated by Z-penguin and box diagrams

Rates related to V_{CKM} with minimal non-parametric uncertainty

V_{CKM} overconstrained: look for NP in specific channels



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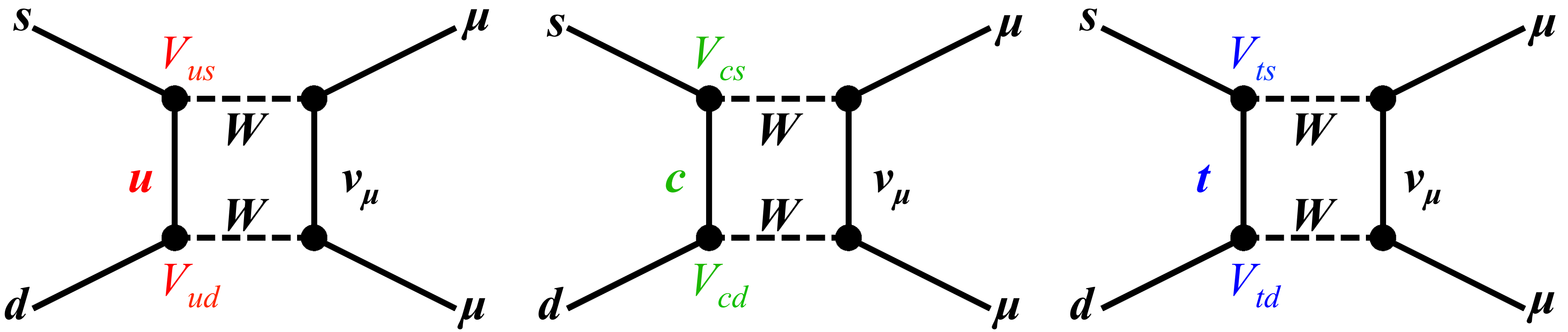
Rates for FCNC decays are suppressed by GIM mechanism:



$$\mathbf{V^\dagger V = 1} \qquad V_{us}^{*}V_{ud}\,L(x_u) + V_{cs}^{*}V_{cd}\,L(x_c) + V_{ts}^{*}V_{td}\,L(x_t) \approx 0$$

$$x_q = m_q^2/m_W^2$$

$$L(x_q) \sim x_q \ln x_q \quad (x_q \to 0)$$

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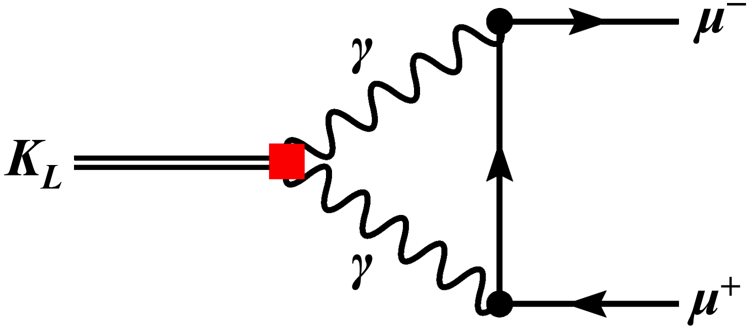
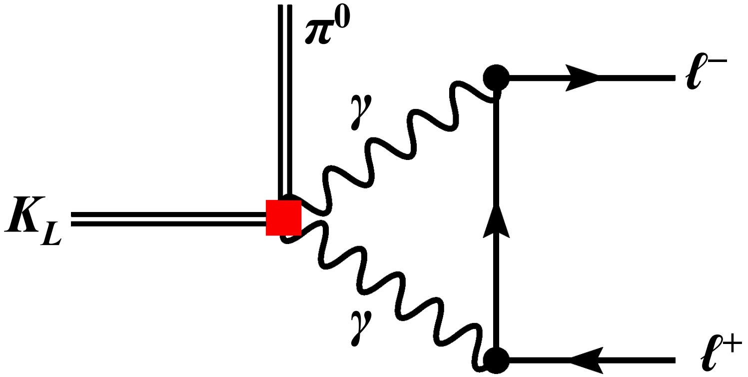
No LD contributions from states with intermediate γs for $K \to \pi\nu\bar{\nu}$

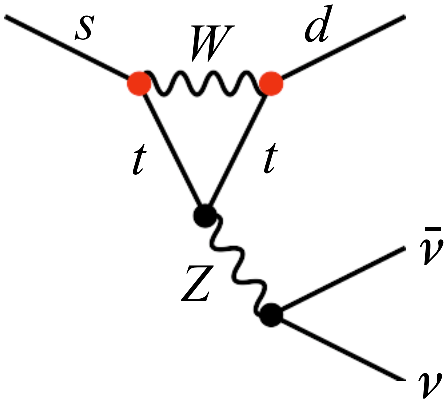


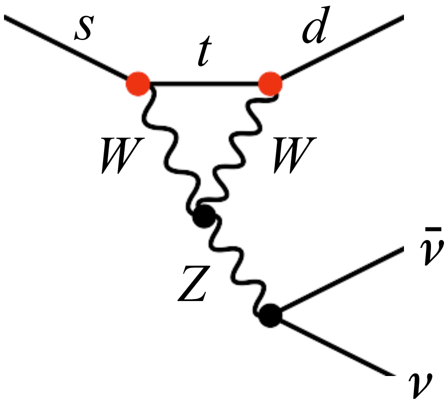
$K_L \to \mu^+\mu^-$

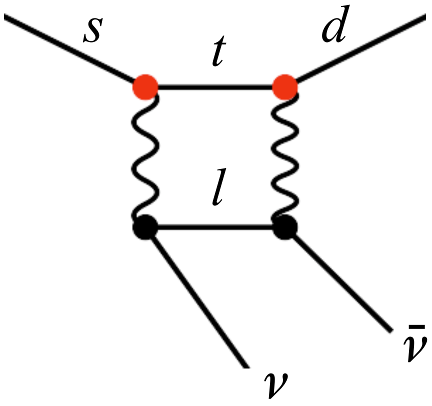


$K_L \to \pi^0\ell^+\ell^-$

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







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

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$
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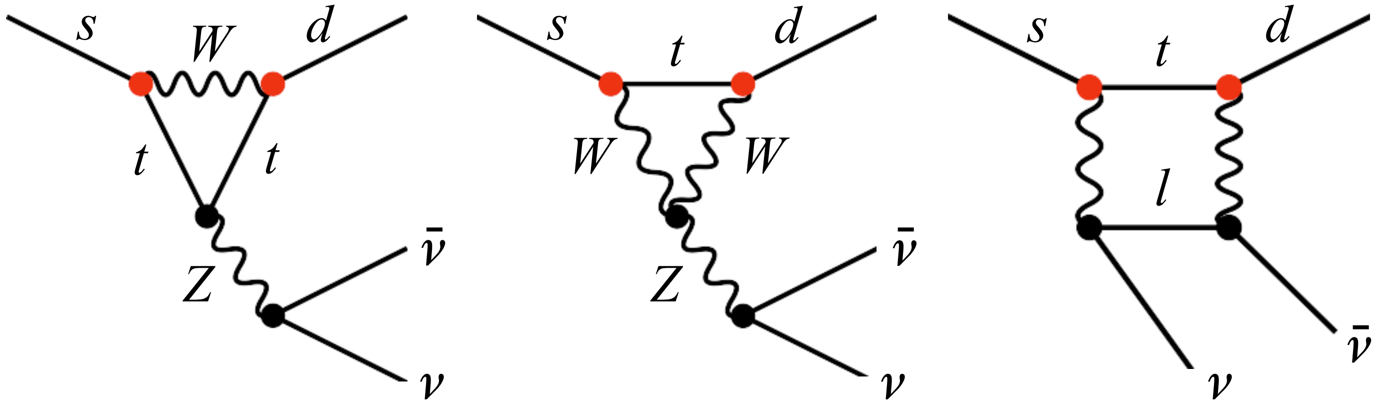

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Loop functions favor top contribution

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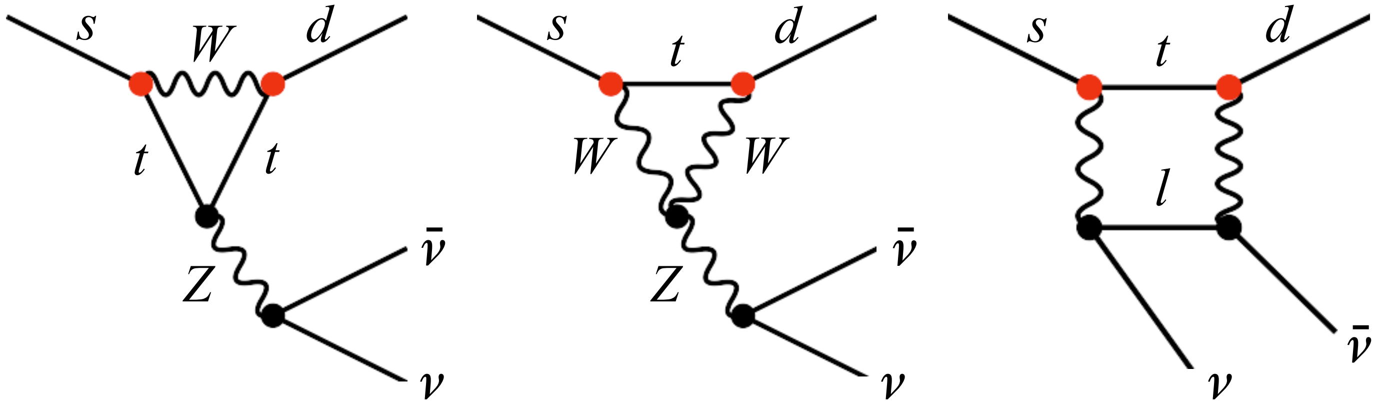

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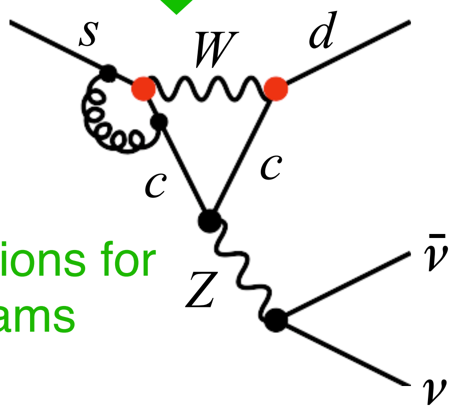
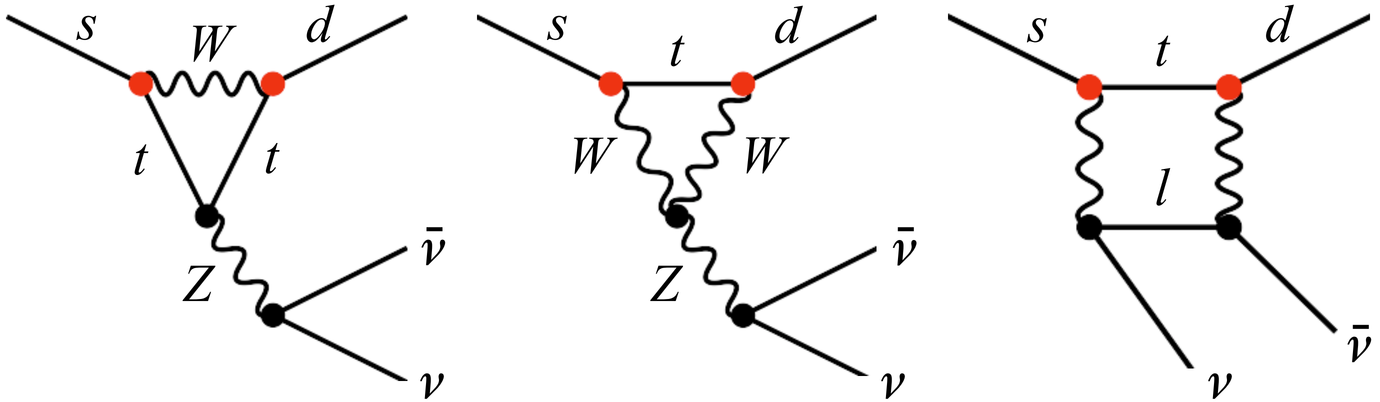


QCD corrections for charm diagrams contribute to uncertainty

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



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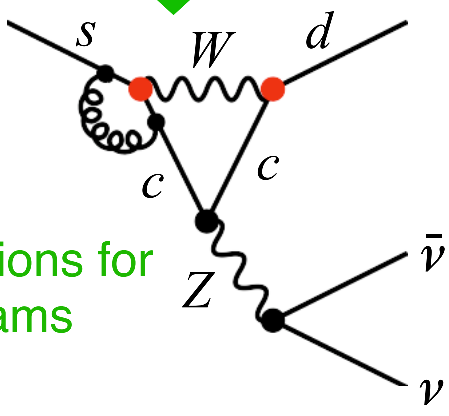
$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \cancel{CP}$$

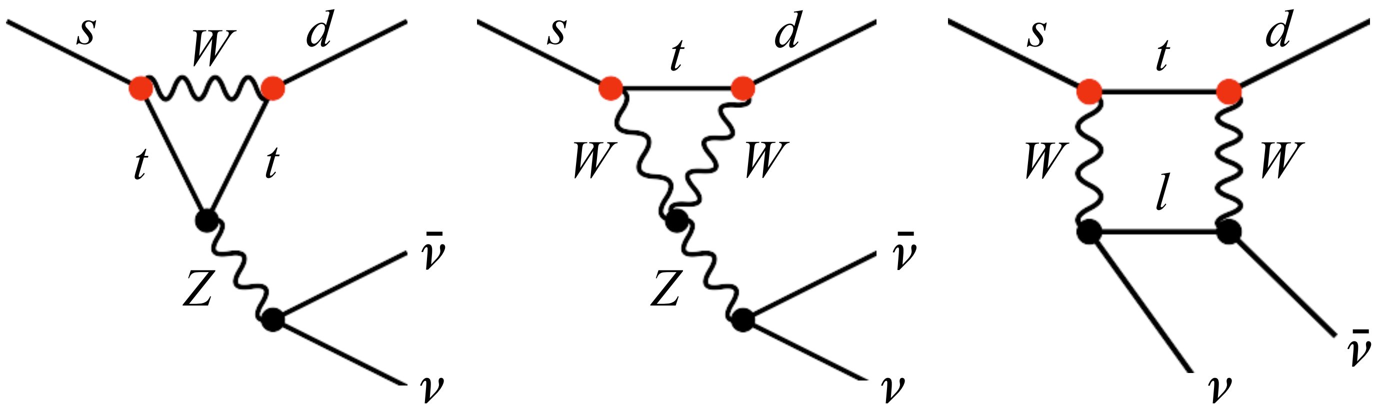
$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$

Hadronic matrix element obtained from $\mathrm{BR}(K_{e3})$ via isospin rotation



QCD corrections for charm diagrams contribute to uncertainty

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

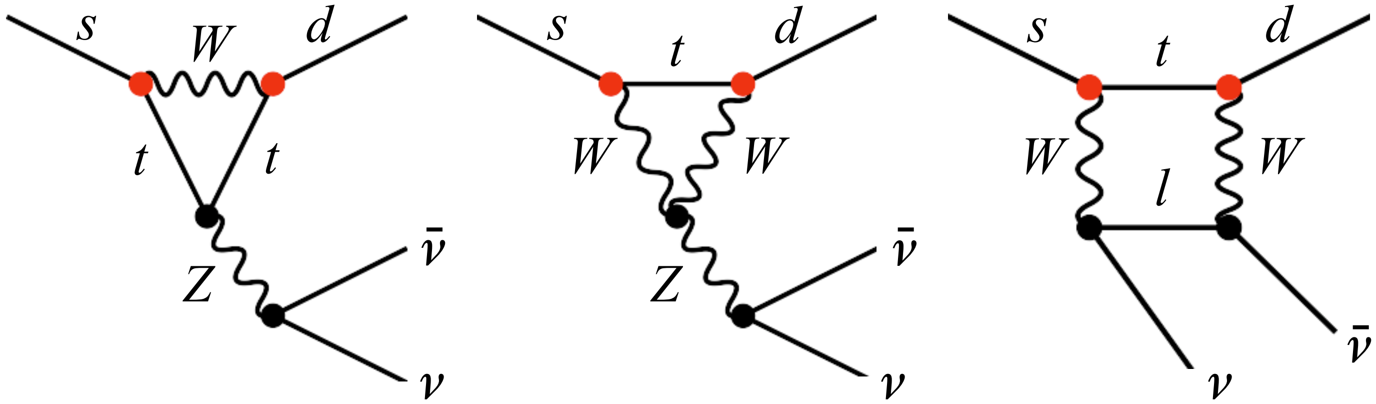


$$\begin{aligned}\lambda &= V_{us}\\ \lambda_c &= V_{cs}^* V_{cd}\\ \lambda_t &= V_{ts}^* V_{td}\end{aligned}$$

$$x_q \equiv m_q^2/m_W^2$$

	SM predicted rates Buras et al, JHEP 1511*	**Experimental status**
$K^+ \rightarrow \pi^+\nu\nu$	**BR = $(8.4 \pm 1.0) \times 10^{-11}$**	**BR = $(17.3\ ^{+11.5}_{-10.5}) \times 10^{-11}$** Stopped K^+, 7 events observed Brookhaven 787/949, PRD79 (2009)
$K_L \rightarrow \pi^0\nu\nu$	**BR = $(3.4 \pm 0.6) \times 10^{-11}$**	**BR < 2600×10^{-11} 90%CL** Low energy, decay in flight KEK 391a, PRD81 (2010)

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



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$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

Grossman-Nir limit on BR($K_L \to \pi^0\nu\nu$):

$$\frac{\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

Current experimental value

Brookhaven E787/949 '09 – Stopped K^+

BR($K^+ \to \pi^+\nu\nu$) = $(17.3^{+11.5}_{-10.5}) \times 10^{-11}$

BR($K_L \to \pi^0\nu\nu$) ≤ 1.4×10^{-9}

BR($K \to \pi\nu\bar{\nu}$) and the CKM matrix

Uncertainty on SM predictions for $K \to \pi\nu\bar{\nu}$ BRs mostly from $\mathbf{V}_{\mathbf{CKM}}$

$\mathrm{BR}_{\mathrm{SM}}(K_L \to \pi^0\nu\bar{\nu}) \times 10^{11}$
$3.36 \pm 0.59_{\mathrm{par}} \pm 0.05_{\mathrm{th}}$

V_{ub}	0.50	15%
γ	0.24	7%
V_{cb}	0.24	7%
X_t + other	0.05	1.5%

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V_{cb}	0.83	10%
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$P_c^{\mathrm{SD}} + \delta P_{c,u}$	0.39	5%
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Buras, et al. JHEP 1511

CKM constraints from:

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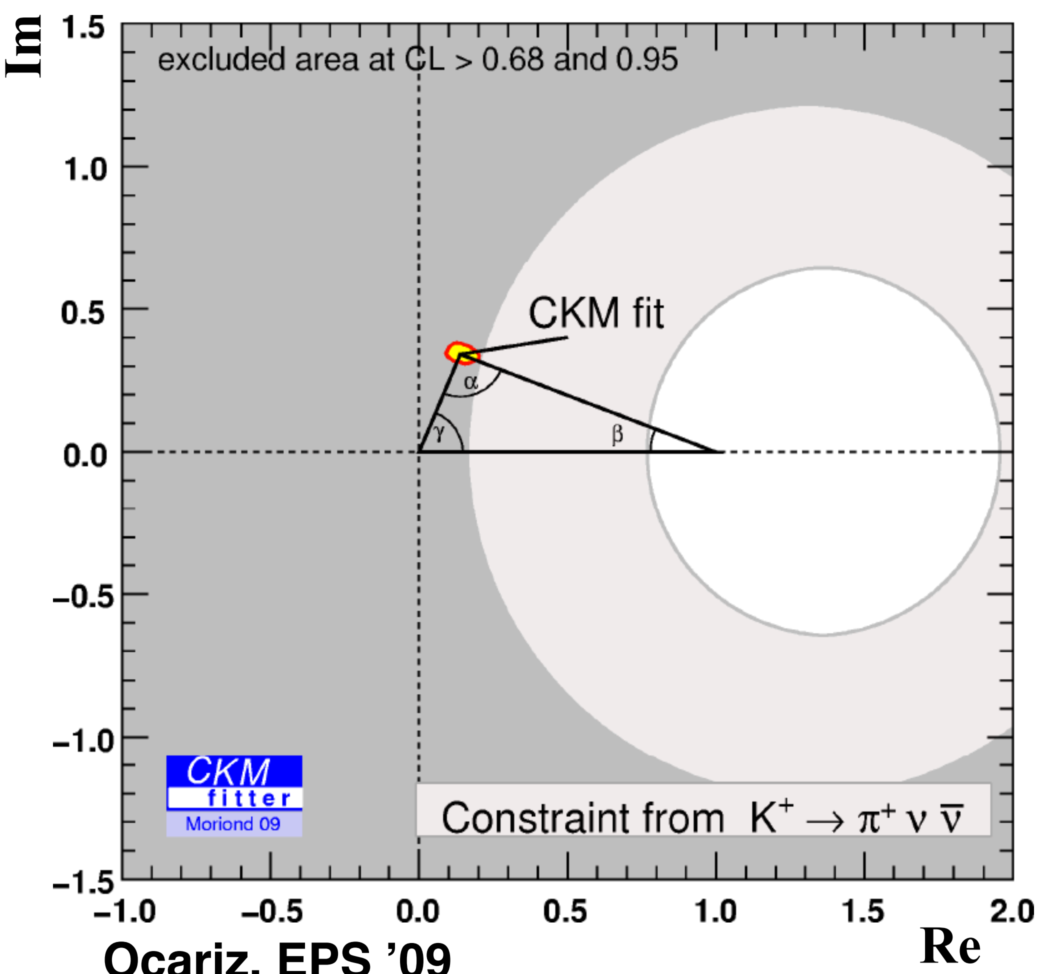

Ocariz, EPS ’09

BR($K \to \pi\nu\bar{\nu}$) and the CKM matrix

K_LEVER

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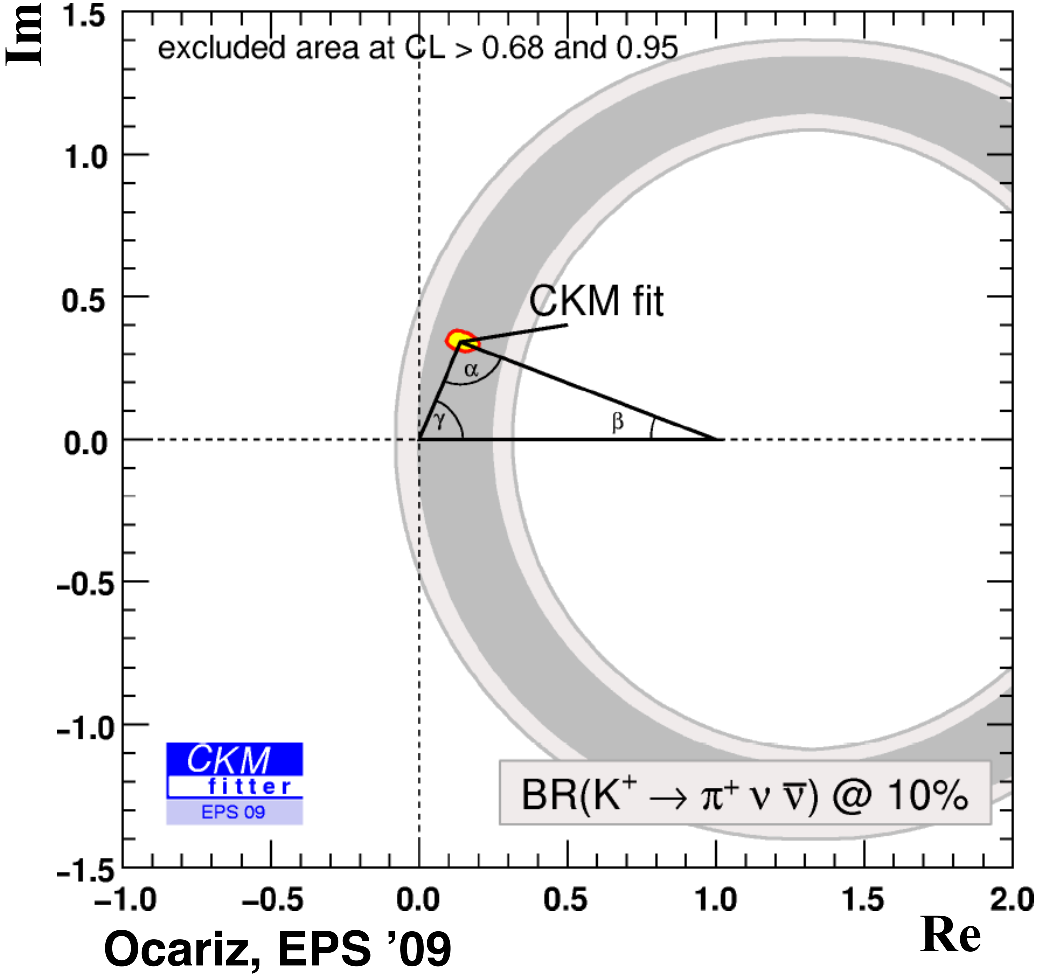
CKM constraints from:

Hypothetical BR($K^+ \to \pi^+\nu\bar{\nu}$) to ±10%



Ocariz, EPS '09

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CKM constraints from:

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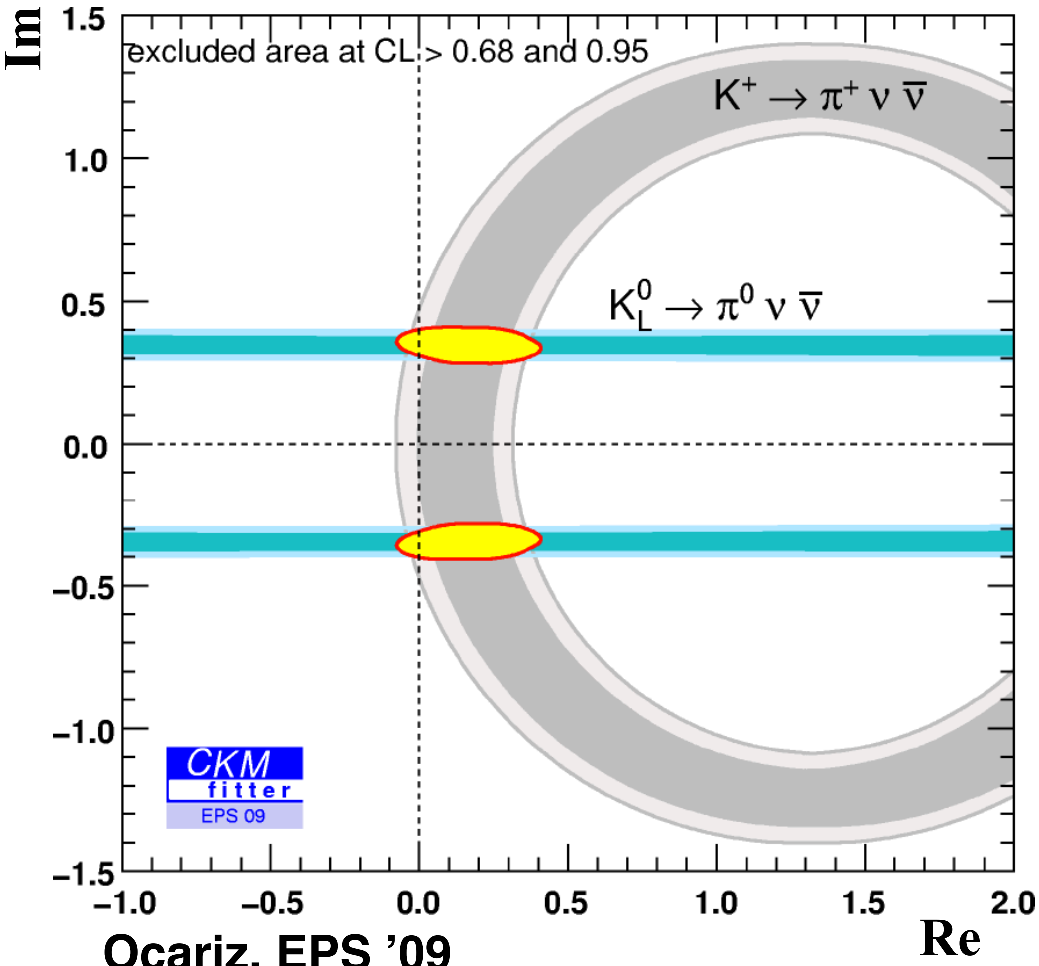
Hypothetical BR($K_L \to \pi^0\nu\bar{\nu}$) to ±15%



Ocariz, EPS '09

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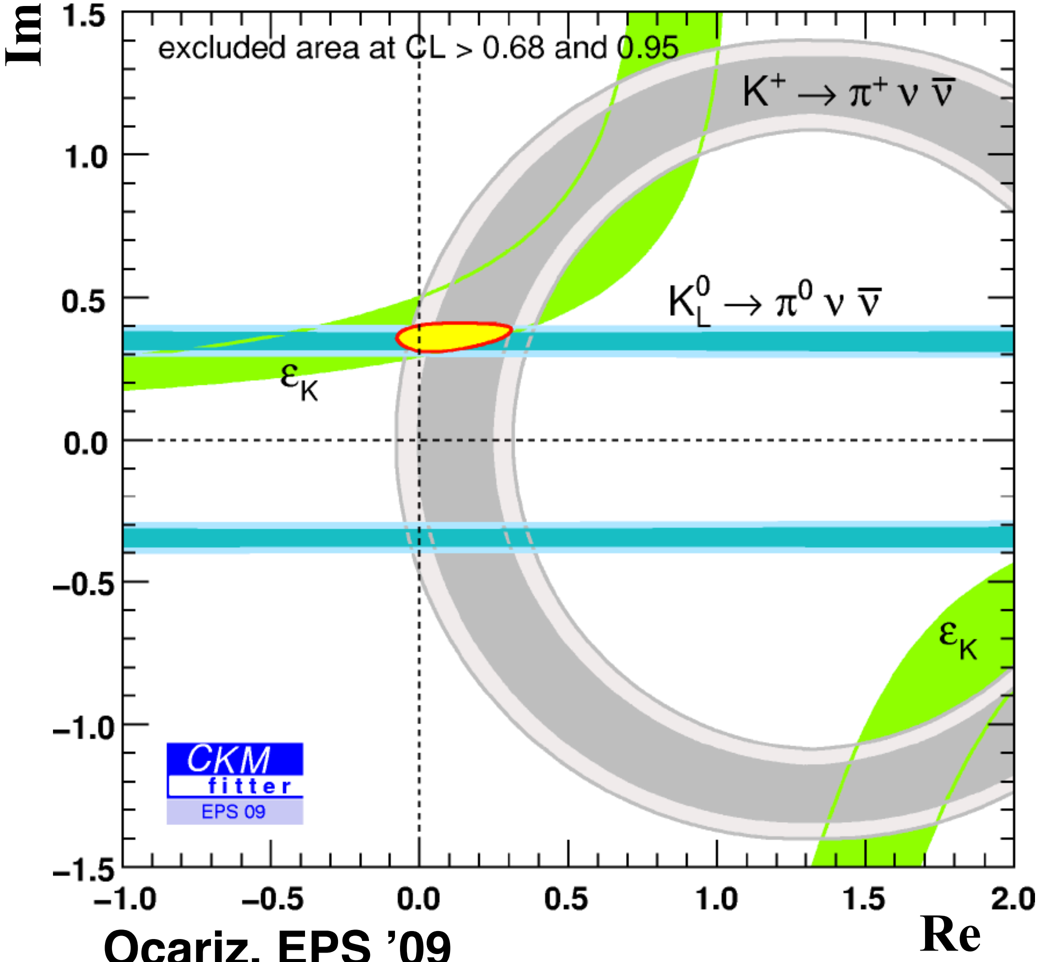
Buras, et al. JHEP 1511

CKM constraints from:

Hypothetical BR($K^+ \to \pi^+\nu\bar{\nu}$) to ±10%

Hypothetical BR($K_L \to \pi^0\nu\bar{\nu}$) to ±15%

Current ε_K to resolve ambiguities

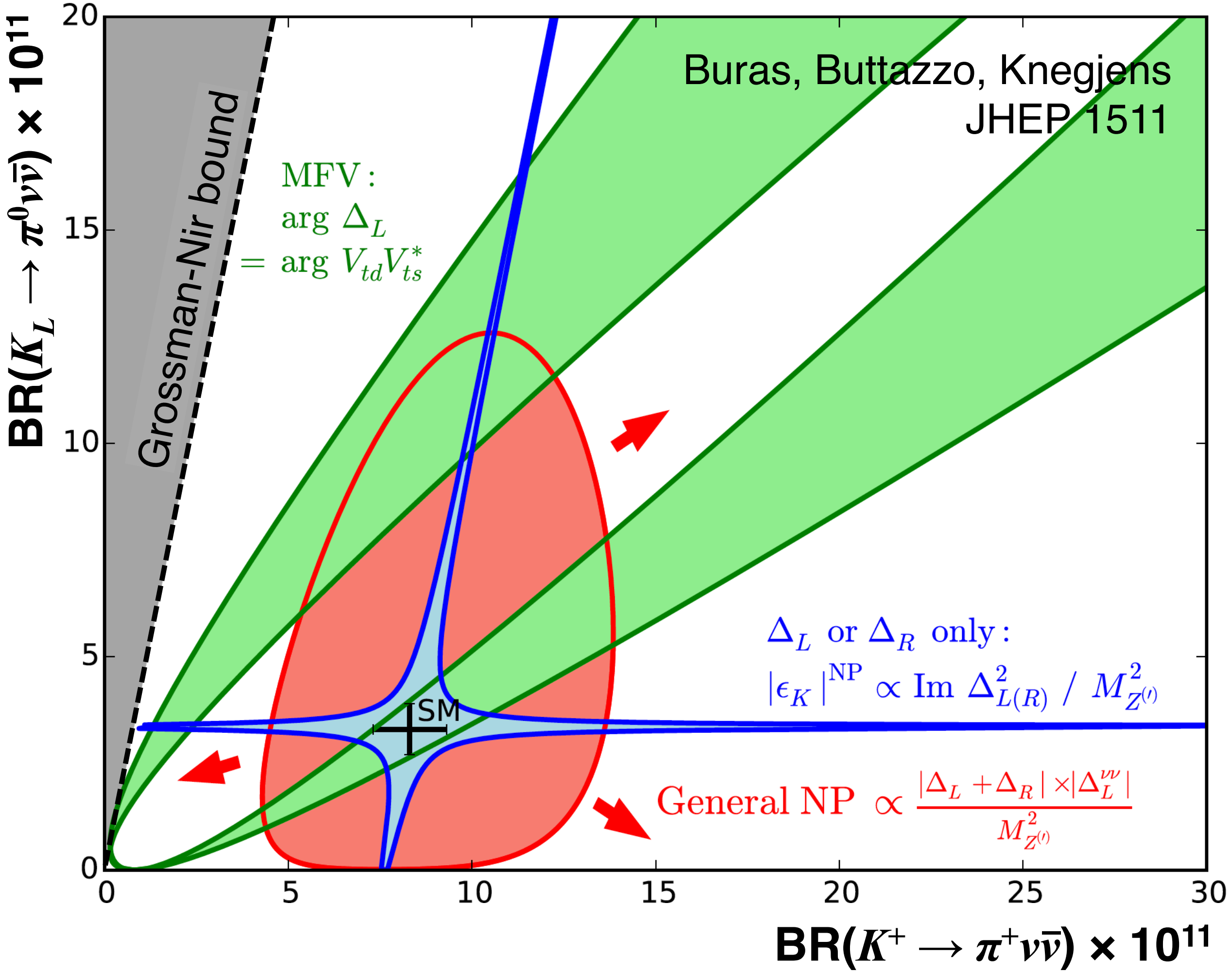


Ocariz, EPS '09

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

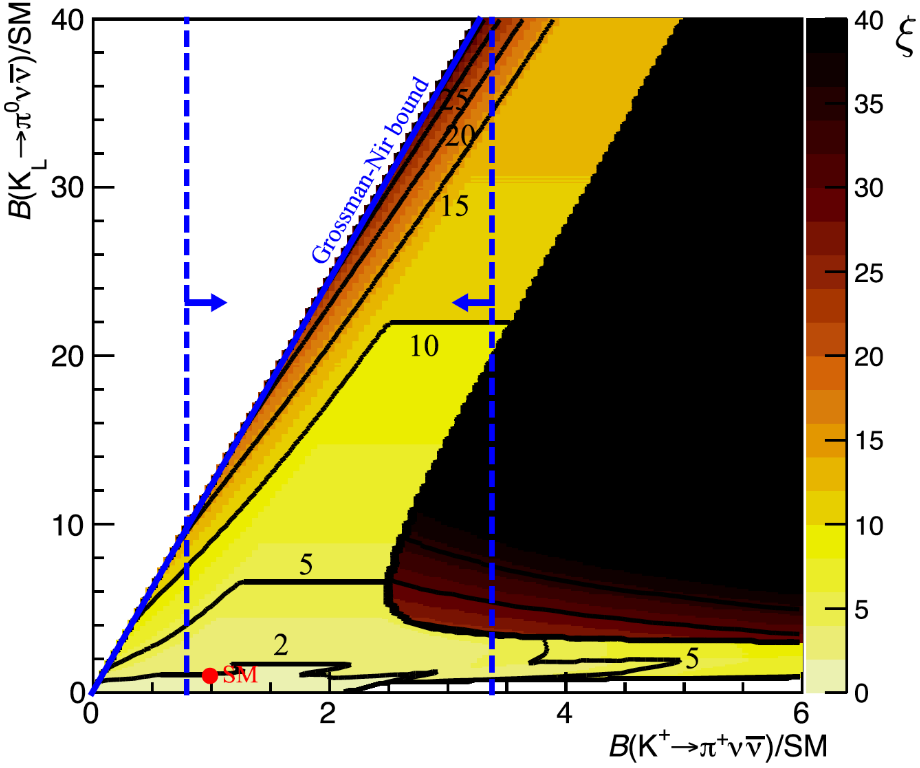
Model	Effect	Refs
Vector-like quarks	K_L suppressed, K^+ possibly enhanced	Bobeth et al. '16
Leptoquarks	Large effects for both K_L, K^+: possibly ruled out?	Bobeth, Buras '17
Simplified *Z*	K_L suppressed 30%, K^+ enhanced up to 2x	Endo et al. '17
SUSY	K^+ and K_L enhanced 10-20% for $\Lambda_{\text{SUSY}}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

Endo et al. PLB771 (2017)

General *Z* scenario with modified couplings, $\Lambda = 1$ TeV

- Because of interference between SM and NP amplitudes, if all constraints satisfied including "discrepancy" in Re ε'/ε:

  BR($K_L \to \pi^0\nu\nu$) ~ 0.5 SM BR
- Particularly in simplified scenarios: LH, RH, LRS
- With moderate tuning (cancellation of interference terms to 10%), large values for BR($K \to \pi\nu\nu$) are possible



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

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

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

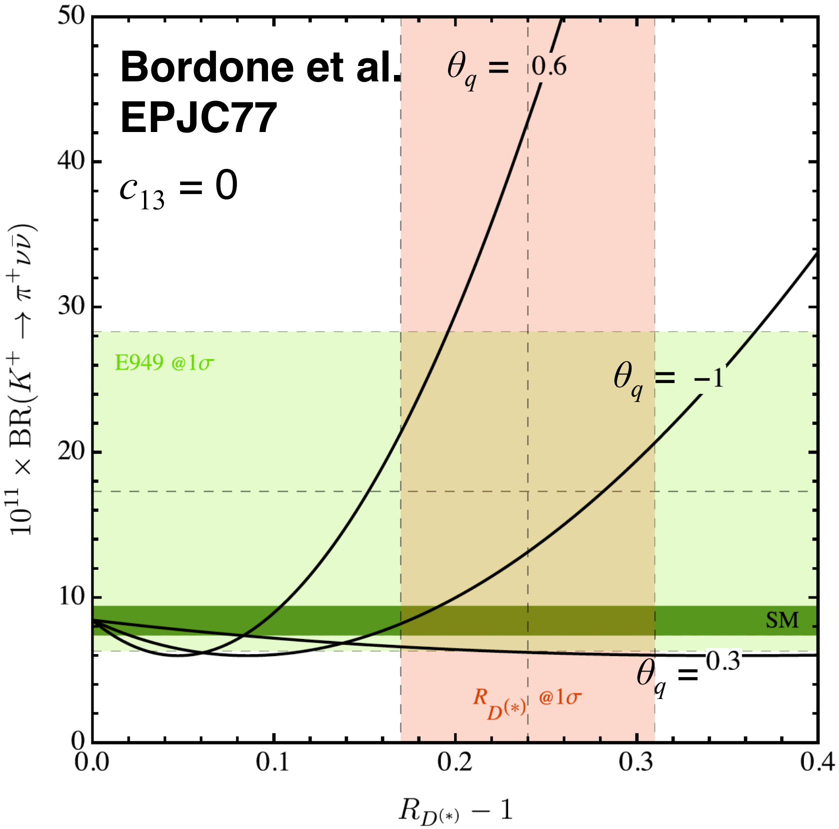
$R_{D(*)}$: $\tau/(\mu, e)$ LFU in $B \to D^{(*)}\ell\nu$

Coherent explanation from NP coupled predominantly to 3rd generation LH quarks and leptons, e.g., mediated by vector leptoquark

- **Di Luzio et al. PRD 96 (2017)**
- **Buttazzo et al. JHEP 1711**

EFT studies suggest large effect for $K \to \pi\nu\nu$

- **Bordone et al. EPJC77 (2017)**



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

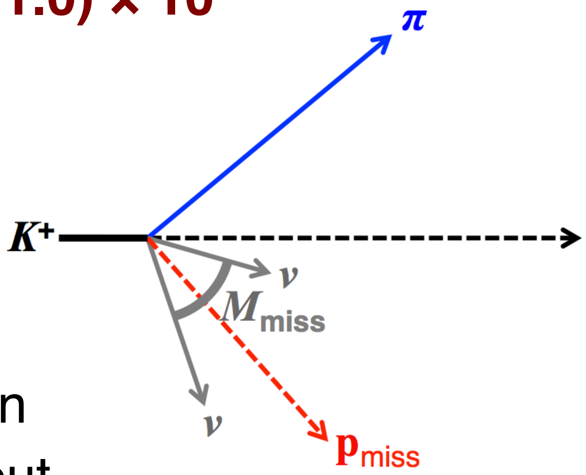
$$R_0 = \frac{1}{\Lambda^2} \frac{1}{\sqrt{2} G_F}$$

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

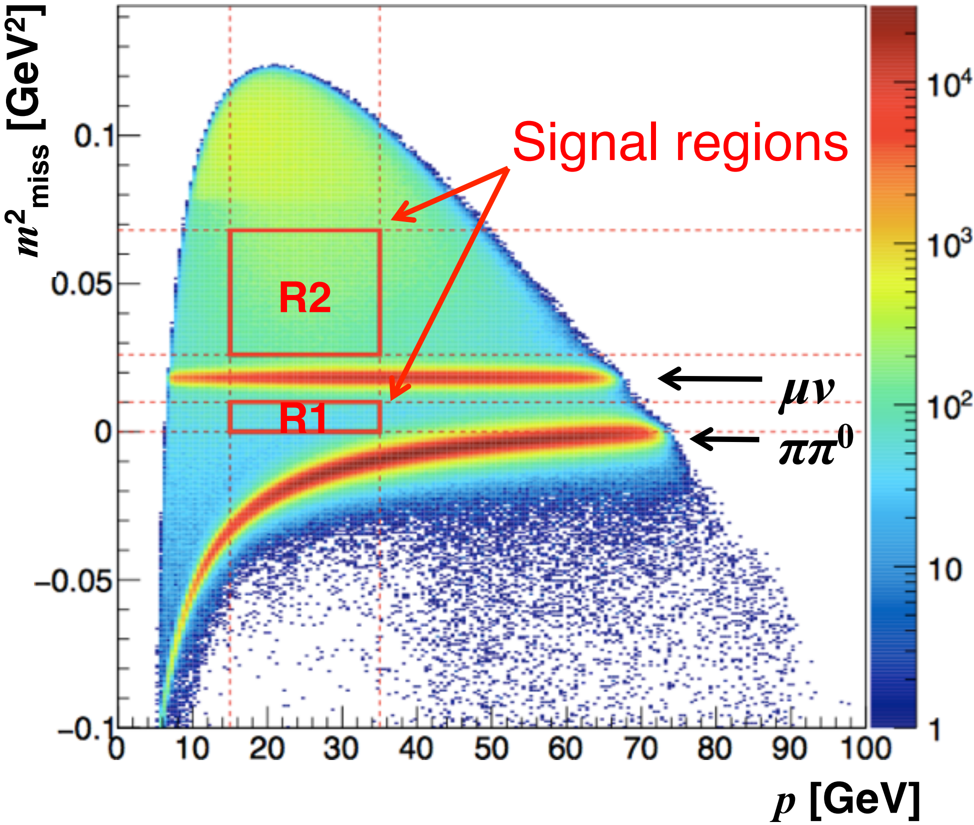
The NA62 experiment at the CERN SPS

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

Signal:
BR = $(8.4 \pm 1.0) \times 10^{-11}$



- 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:

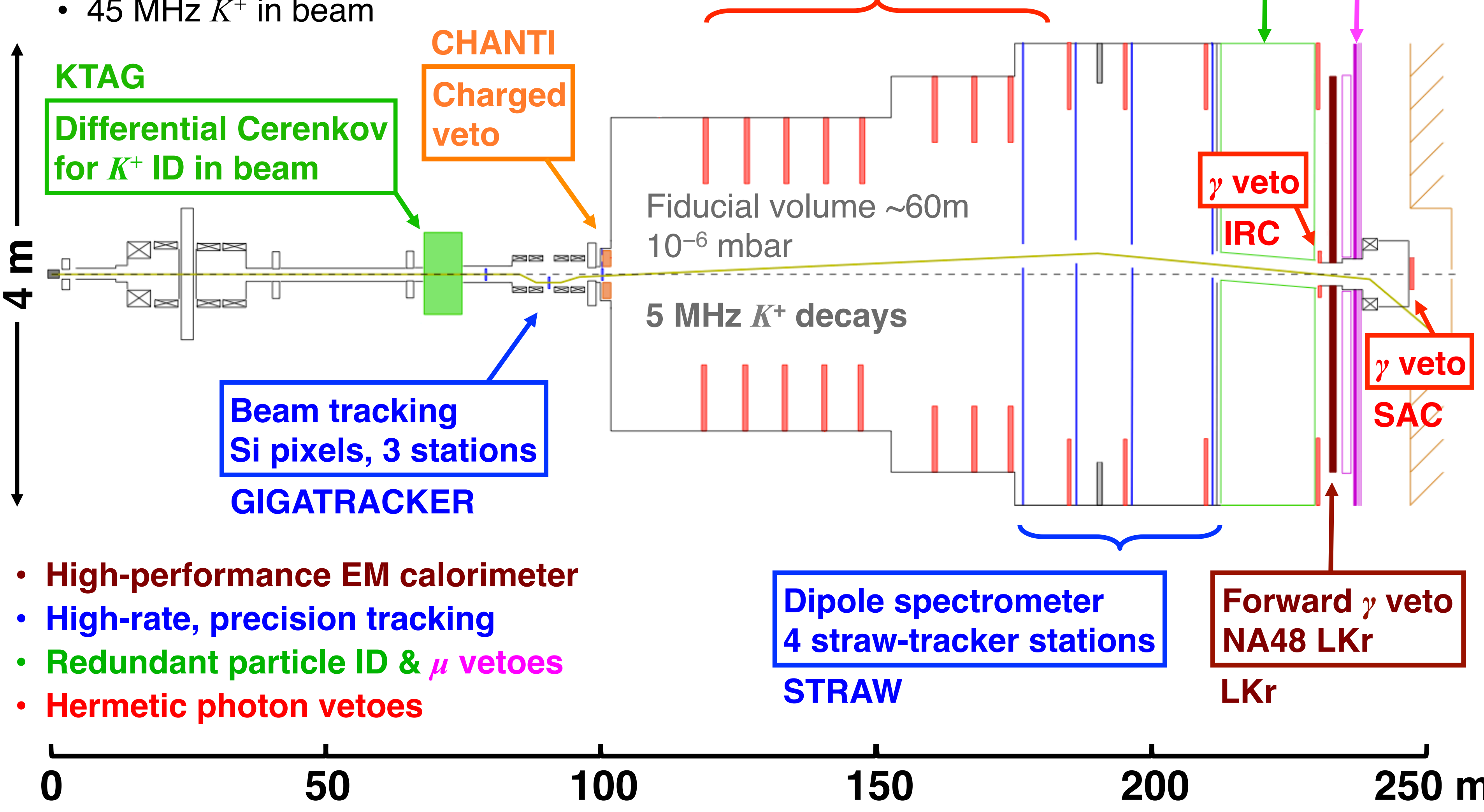
- K^+ beam identification
- Single track in final state
- π^+ identification ($\varepsilon_\mu \sim 1 \times 10^{-8}$)
- γ rejection ($\varepsilon_{\pi 0} \sim 3 \times 10^{-8}$)

The NA62 experiment at the SPS

400 GeV primary p from SPS

75 GeV positive secondary beam

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



LAV

Large angle photon vetoes
OPAL lead glass

RICH

RICH μ/π ID
1 atm Ne

MUV

μ veto
Fe/scint

CHANTI

Charged veto

KTAG

Differential Cerenkov for K^+ ID in beam

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

5 MHz K^+ decays

γ veto

IRC

γ veto

SAC

Beam tracking
Si pixels, 3 stations

GIGATRACKER

Dipole spectrometer
4 straw-tracker stations

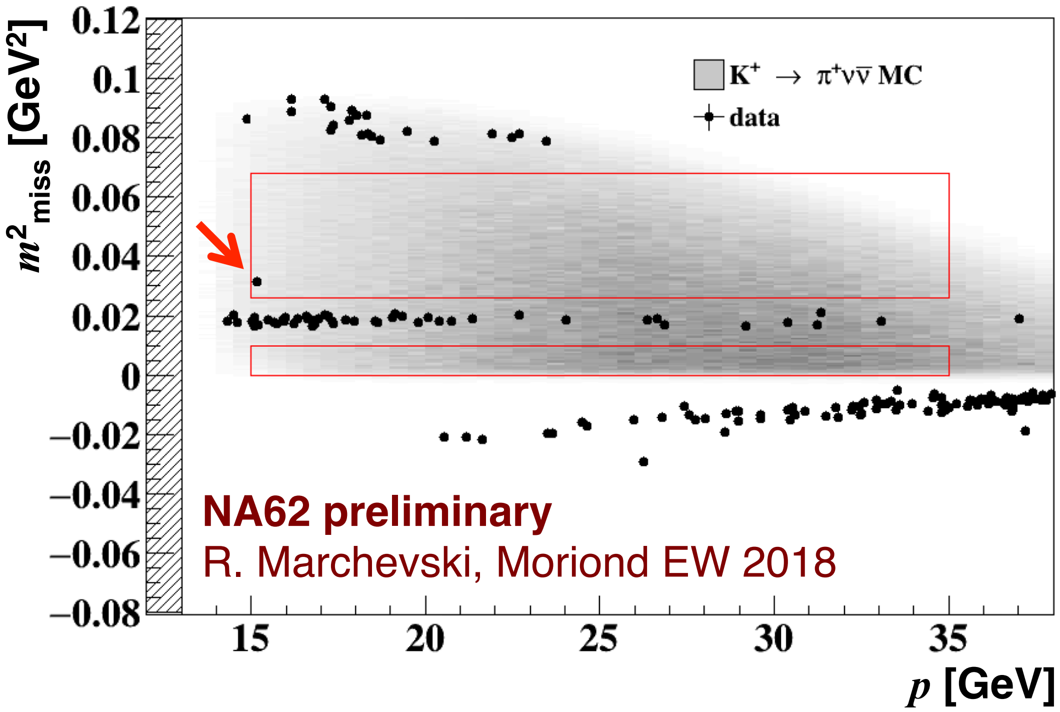
STRAW

Forward γ veto
NA48 LKr

LKr

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

2016 results for $K^+ \to \pi^+\nu\nu$



NA62 preliminary
R. Marchevski, Moriond EW 2018

NA62 preliminary – 2016 data

1.2×10^{11} K^+ decays

SES = $(3.15 \pm 0.24) \times 10^{-10}$

Expected signal 0.267 ± 0.038

Expected background 0.15 ± 0.09

1 event observed in R2

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

$< 14 \times 10^{-10}$ (95%CL)

$< 11 \times 10^{-10}$ (90%CL)

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

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	**$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{sys}}$**

NA62 status and timeline

2014-2015	Pilot/commissioning runs
2016	Commissioning + 1st physics run **Preliminary result presented in March 2018** **1 event observed** **BR($K^+ \to \pi^+\nu\nu$) < 14 × 10^{-10} (95%CL)**
2017	Physics run (23 weeks) 20x more data than 2016 result Data processing in progress
2018	Physics run (31 weeks, started 9 April)
2019-2020	LS2 (LHC Long Shutdown 2)

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

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

Fixed target runs at the SPS

- 🟩 Physics
- 🟥 Shutdown
- 🟨 Beam commissioning
- 🟦 Technical stop

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

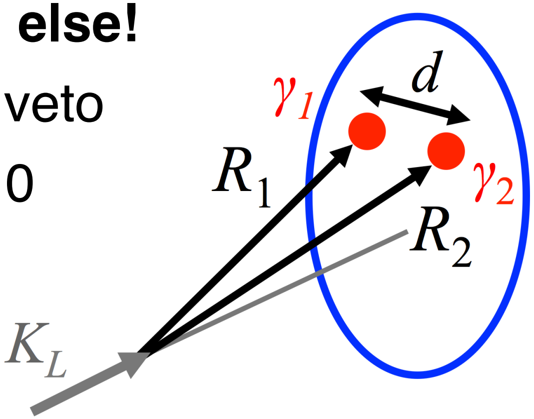
$K_L \to \pi^0 \nu\bar{\nu}$: Experimental issues

KLEVER

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

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

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



K_L momentum generally is not known

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

Generally used to reconstruct vertex position

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

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

Main backgrounds:

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

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

Primary beam: 30 GeV p

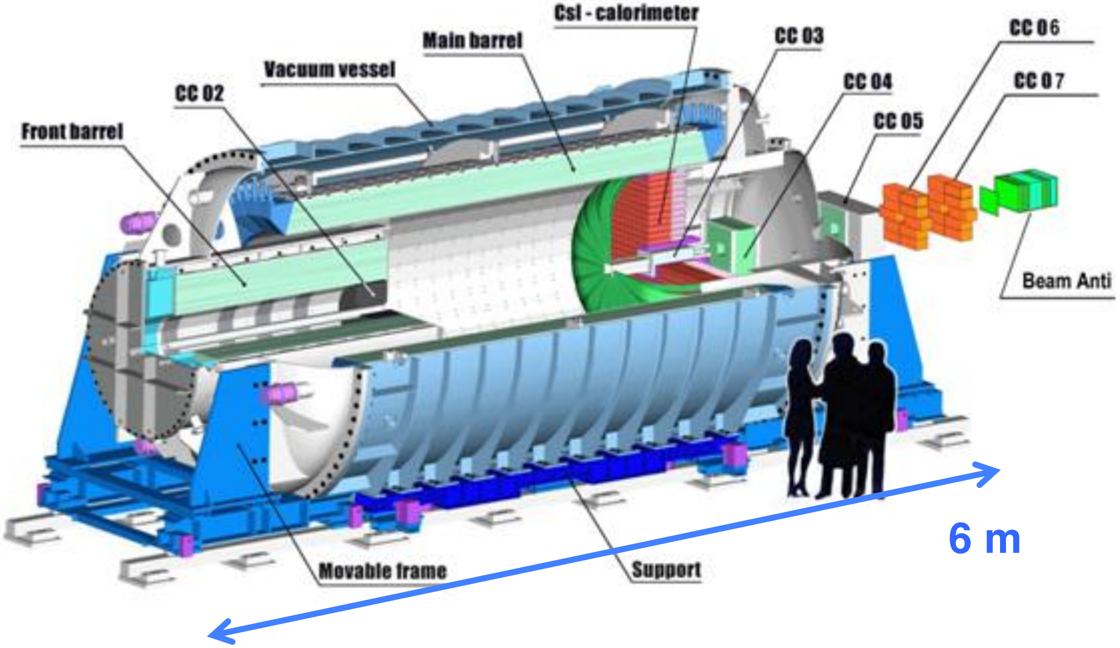
100 kW = 1.2 × 10^{14} p/6 s

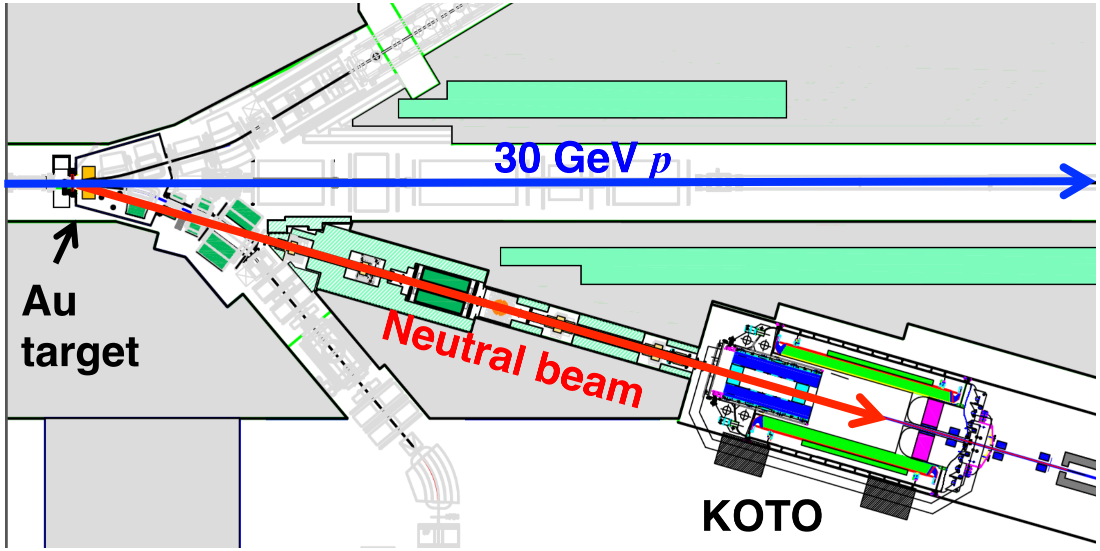
Neutral beam (16°)

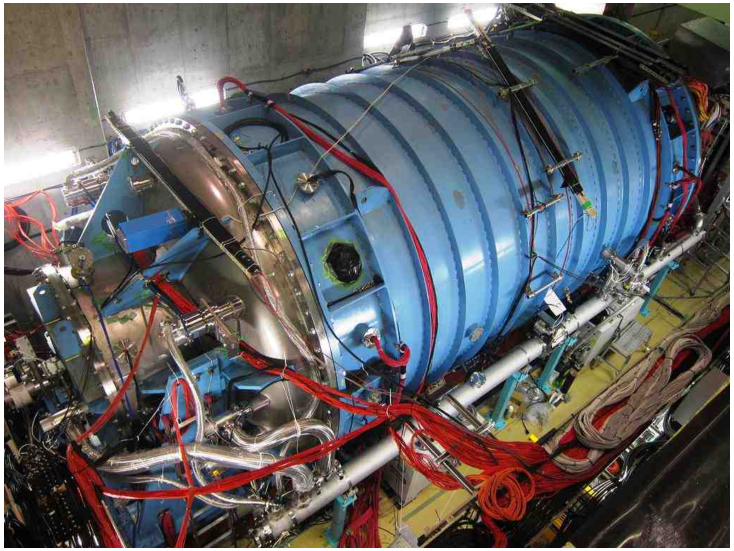
$\langle p(K_L)\rangle$ = 2.1 GeV

50% of K_L have 0.7-2.4 GeV

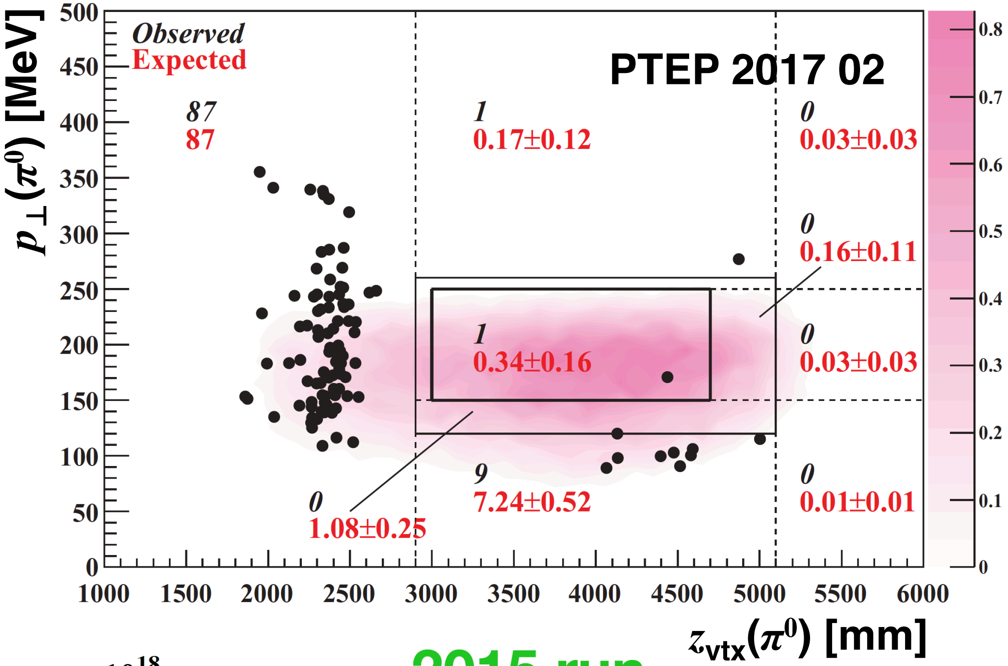
8 µsr "pencil" beam

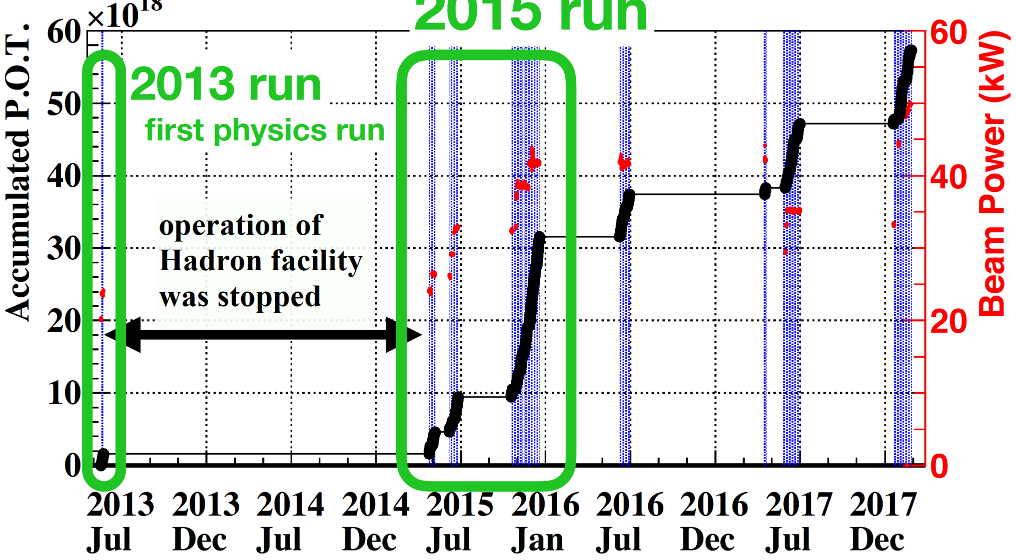






$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC





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

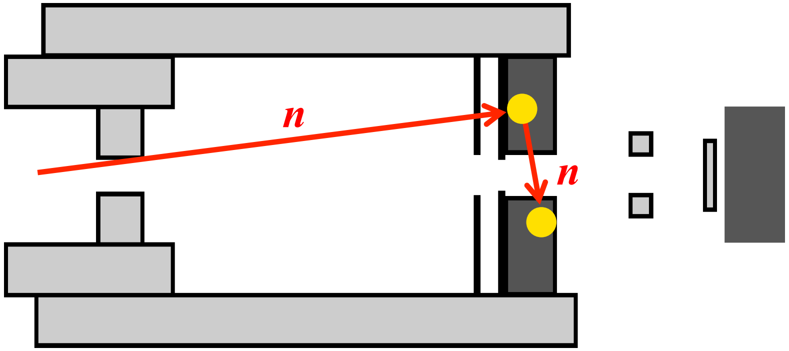
2016-2017

- Beam power increased to **50 kW**
- Additional 3 × 10^{19} pot collected
- With all 2015-2017 data, expected sensitivity below Grossman-Nir limit

Background rejection

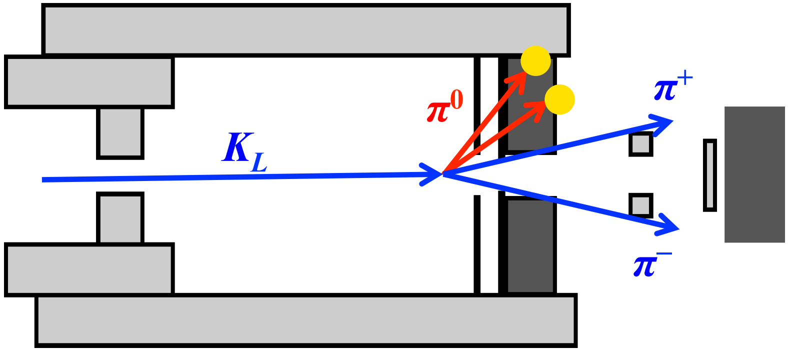
Lessons from 2013 run help to reject backgrounds other than $K_L \to \pi^0\pi^0$

1. Hadron clusters on CsI



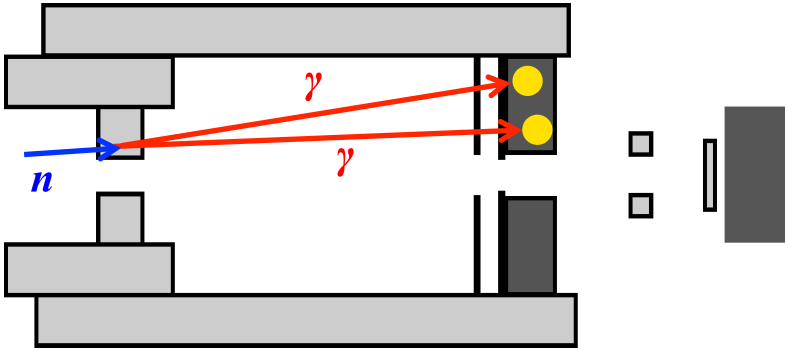
- Control sample with Al plate in beam
- Cluster and pulse shape analysis

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



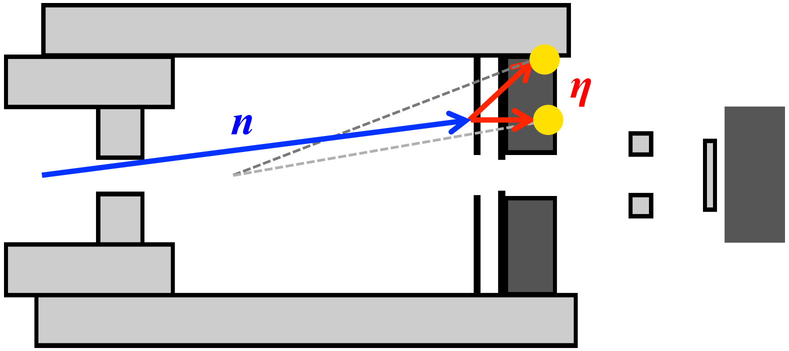
- New charged-particle vetoes lining beam exit

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



- Beam profile monitor for better alignment
- Thinner vacuum window

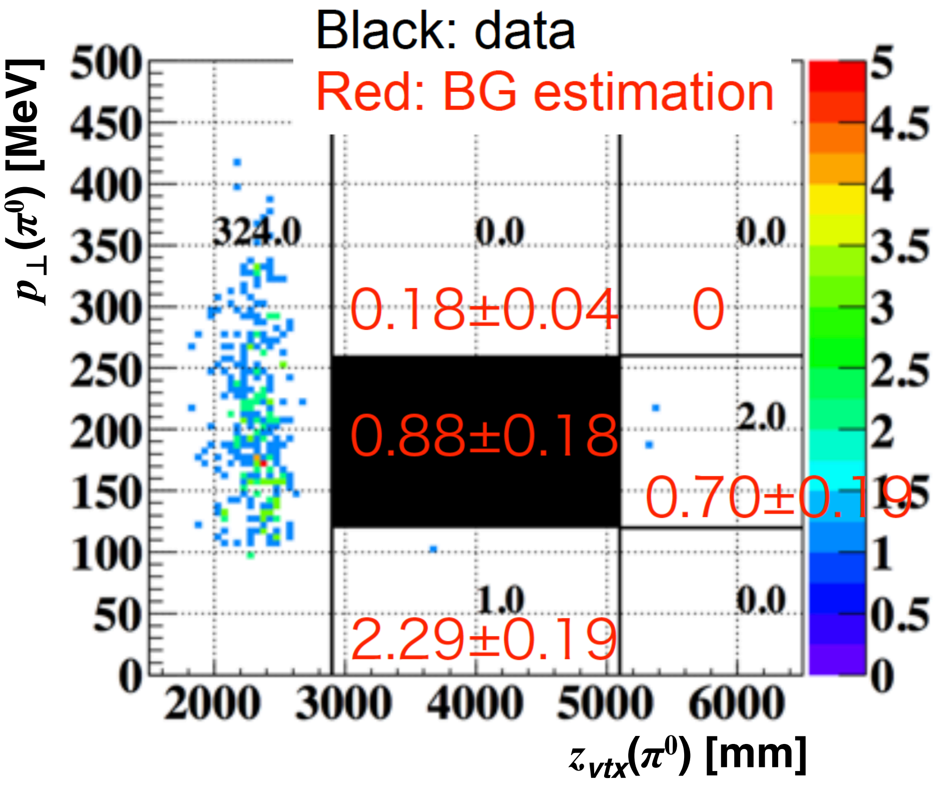
4. $n \to X\eta$ on charged veto (CV)



- Cluster shape (angle of incidence)

Sensitivity from 2015 data

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**



J-PARC PAC, Jan 2018

Black: data

Red: BG estimation

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 × 10^{12}

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

Decay in FV: 3.8%

Overall acceptance: 1.8 × 10^{-4}

Upgrades to improve sensitivity

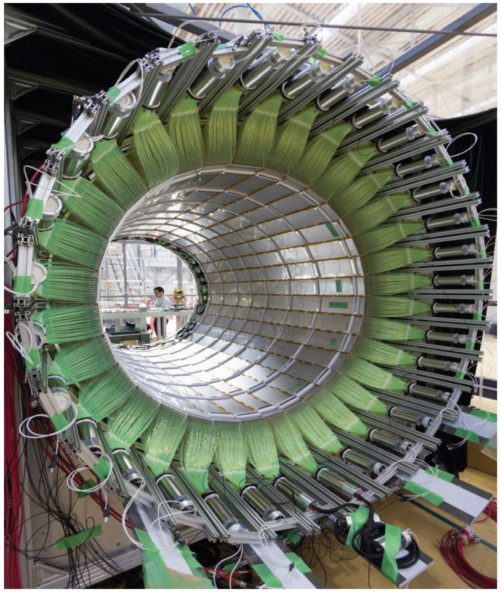
Signal: Need ~40x more flux × acceptance for 1 expected SM $\pi^0\nu\nu$ event

- 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

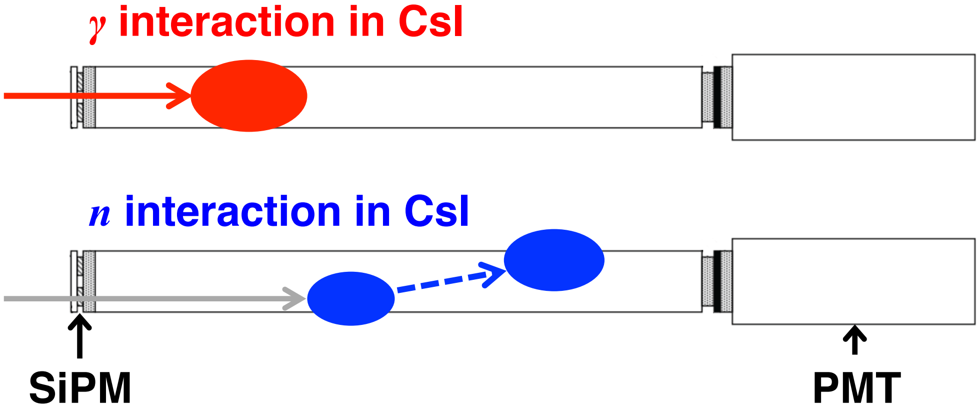


Increase barrel thickness $13.5 + 5\ X_0$

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

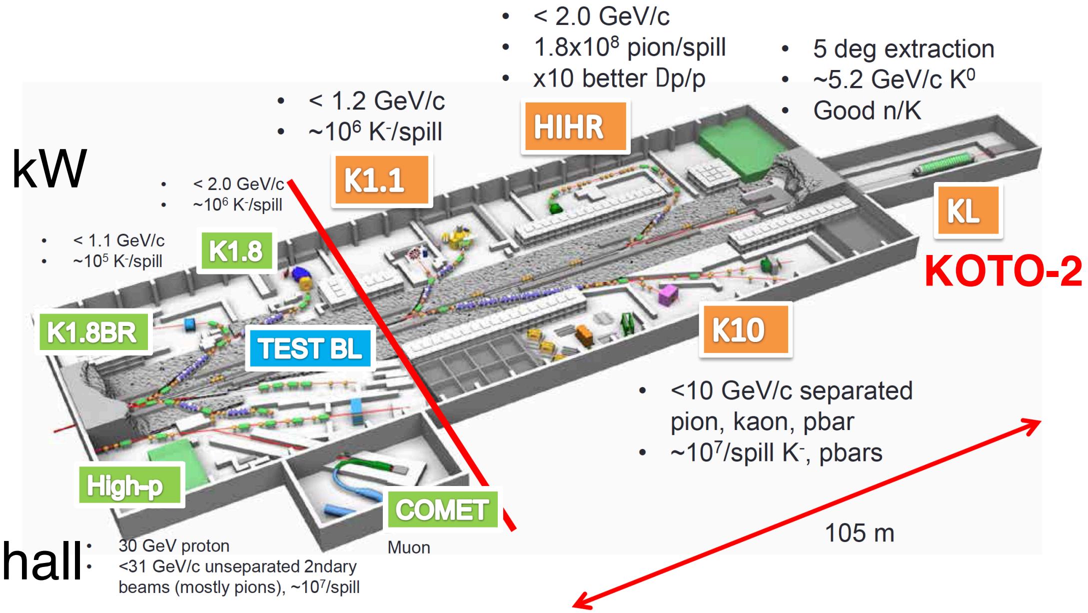
SiPMs to be installed summer 2018

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

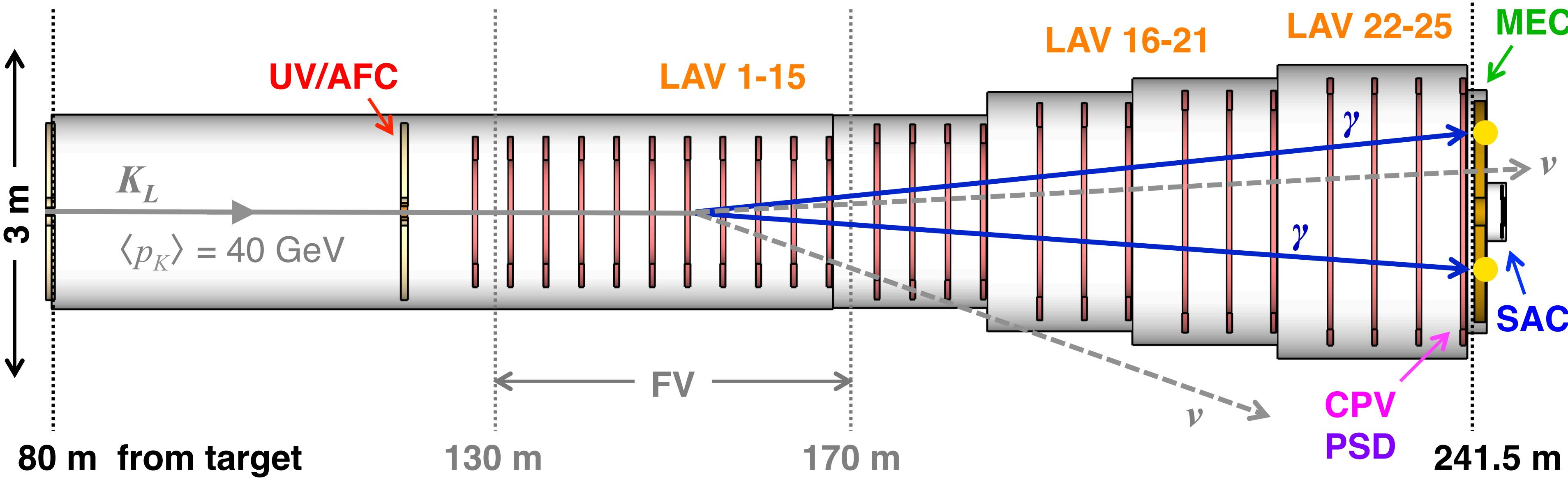


Strong intention to upgrade to O(100) event sensitivity over long term:

- 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 at 100 kW beam power?
- Exploring possibilities for machine & detector upgrades to further increase sensitivity

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

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



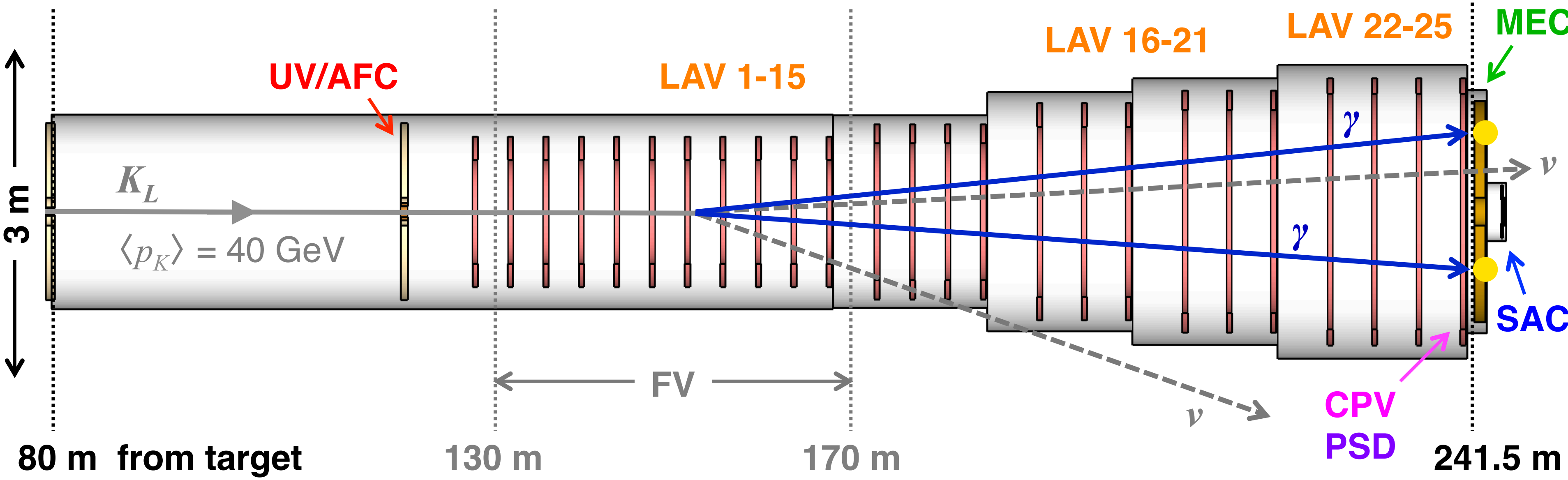
K_LEVER

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

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%

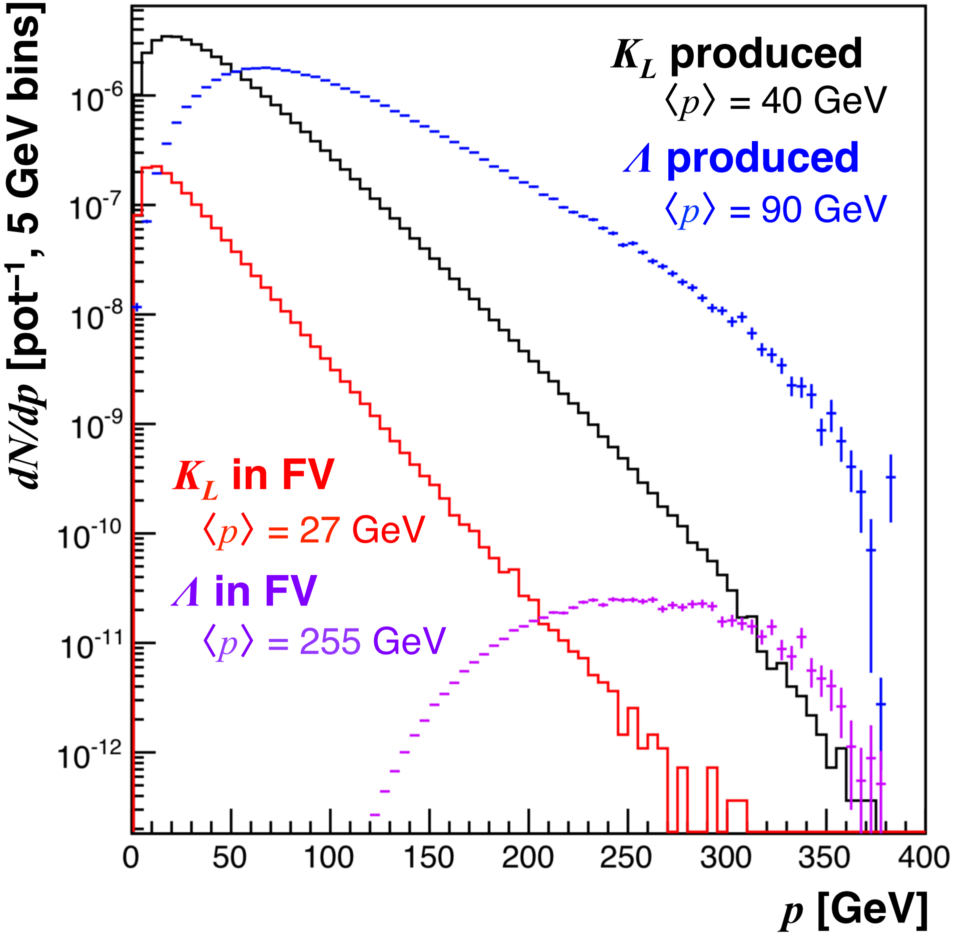
Main detector/veto systems:

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_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**

High-intensity proton beam issues

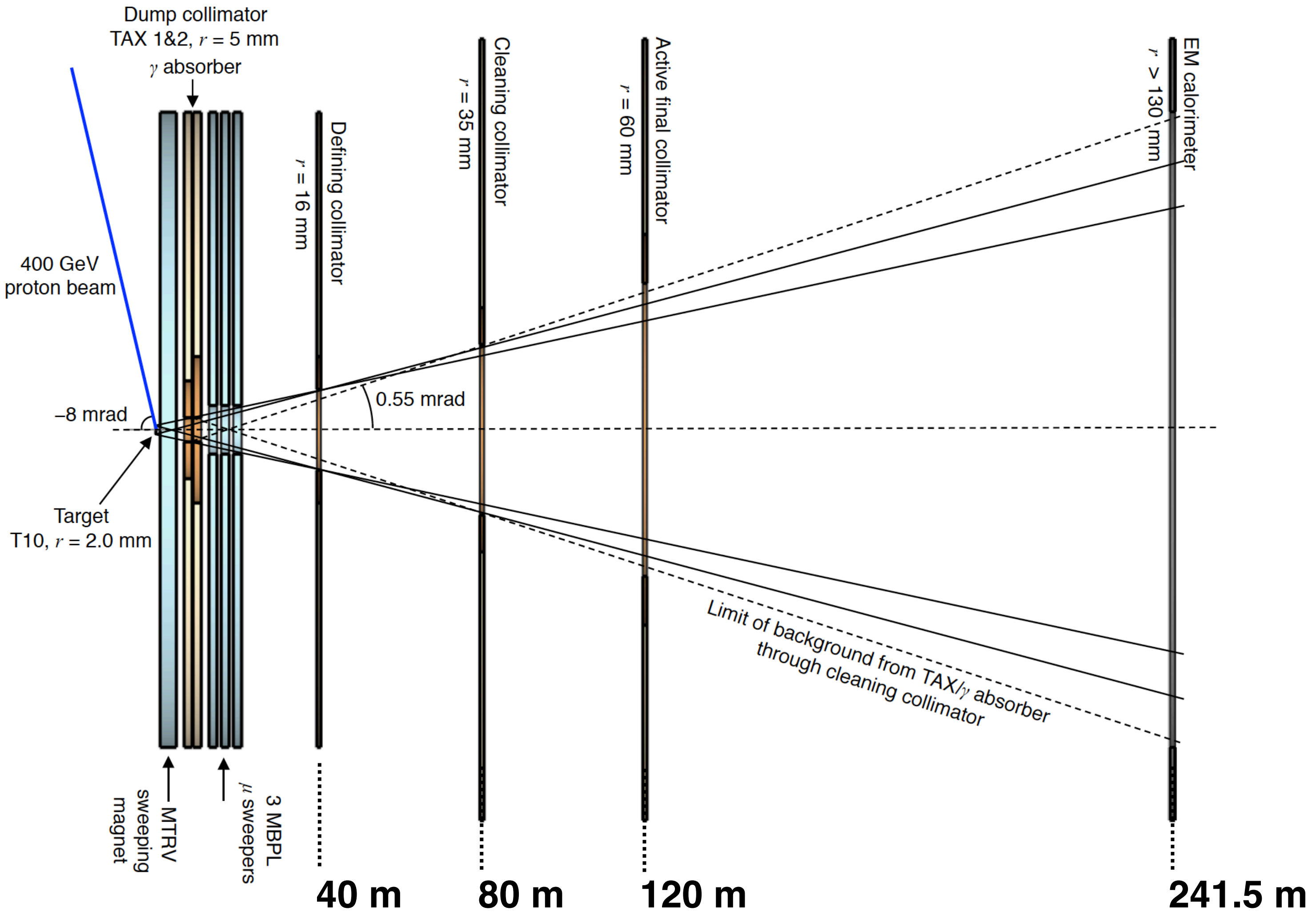
10^{19} pot/yr × 5 years → 2 × 10^{13} ppp/16.8s = 6× increase relative to NA62

Feasibility/cost study a primary goal of our involvement in Physics Beyond Colliders

Preliminary analysis of critical issues by Secondary Beams & Areas group

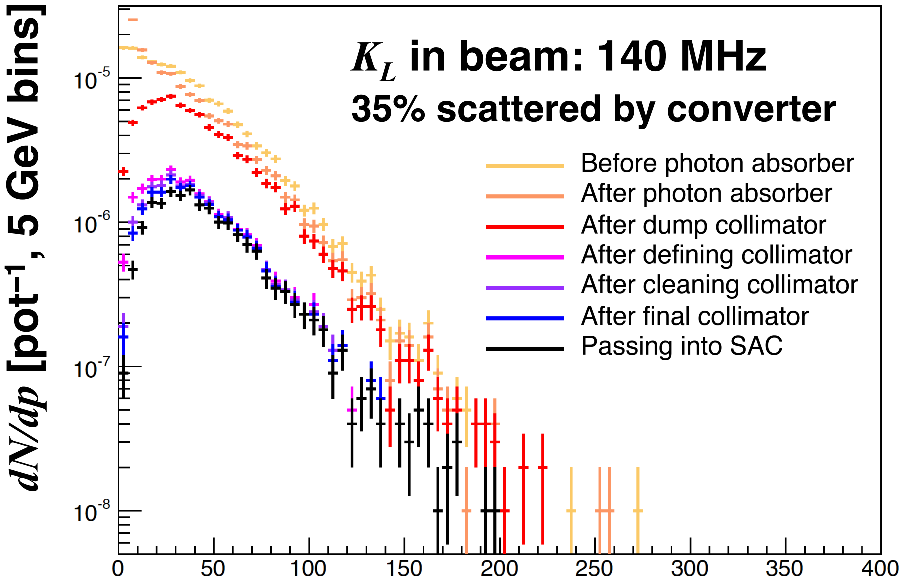
Issue	Approach
Proton availability	SHiP supercycle = 4 × 10^{19} pot/yr with 1 × 10^{13} ppp for users KLEVER requires 1 × 10^{19} pot/yr (25% of SHiP)
Extraction losses	Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) workshop, 9-11 November 2017: https://indico.cern.ch/event/639766/
Beam loss on T4	Vertical by-pass to increase transmission to T10
Equipment protection	Interlock to stop SPS extraction during P0Survey reaction time
Ventilation in ECN3	Preliminary measurements indicate good air containment Comprehensive ventilation system upgrade not needed?
ECN3 beam dump	Significantly improved for NA62 Need to better understand current safety margin
Background fluxes	Starting simulations for prompt background above target 8 mrad vertical targeting angle should help to mitigate

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



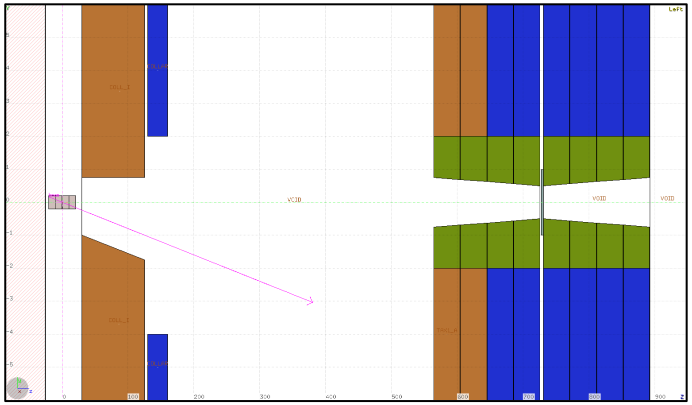
K_L in beam: 140 MHz

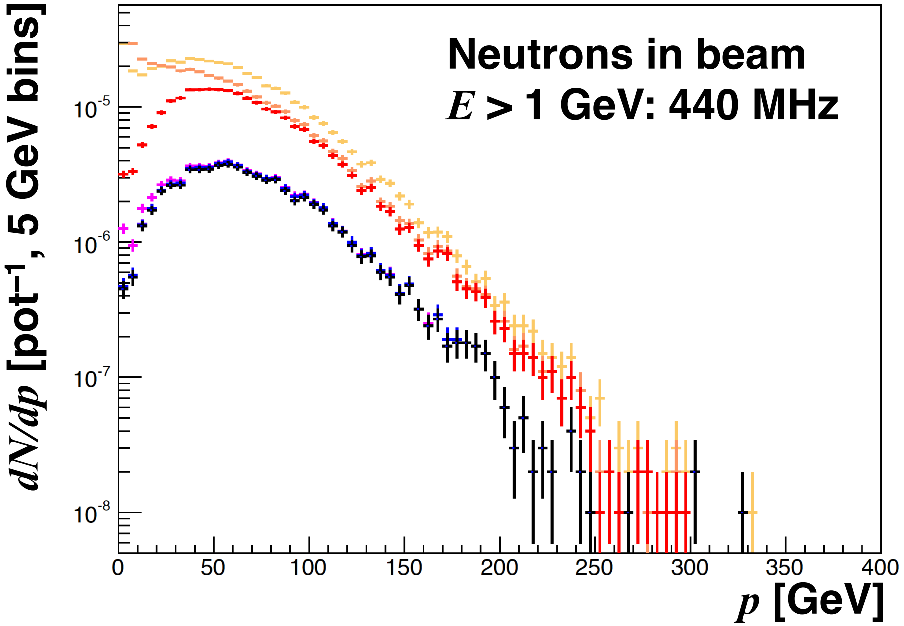
35% scattered by converter

FLUKA simulation of beamline

32-mm tungsten coverter ($9X_0$)

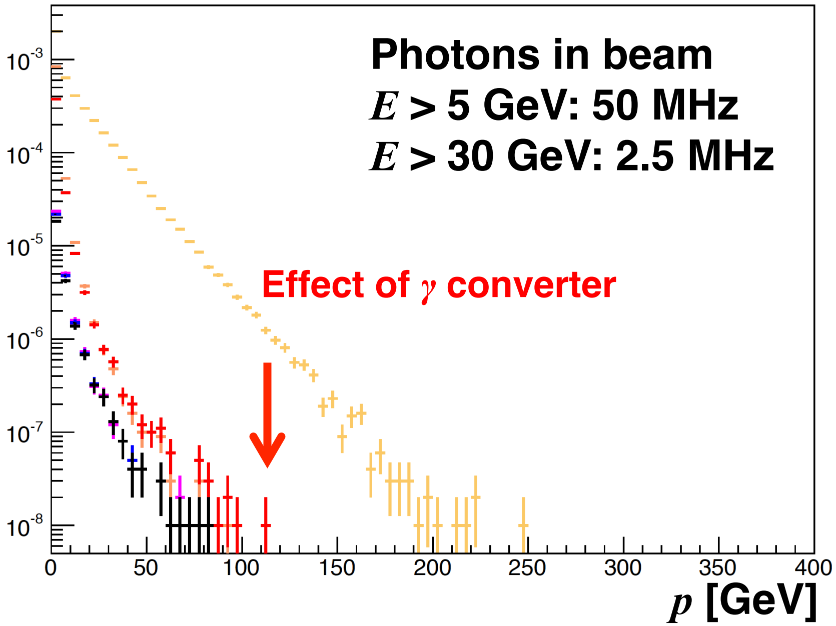
Detail of target and dump collimator:





Neutrons in beam

$E > 1$ GeV: 440 MHz



Photons in beam

$E > 5$ GeV: 50 MHz

$E > 30$ GeV: 2.5 MHz

Effect of γ converter

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

Shashlyk calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

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

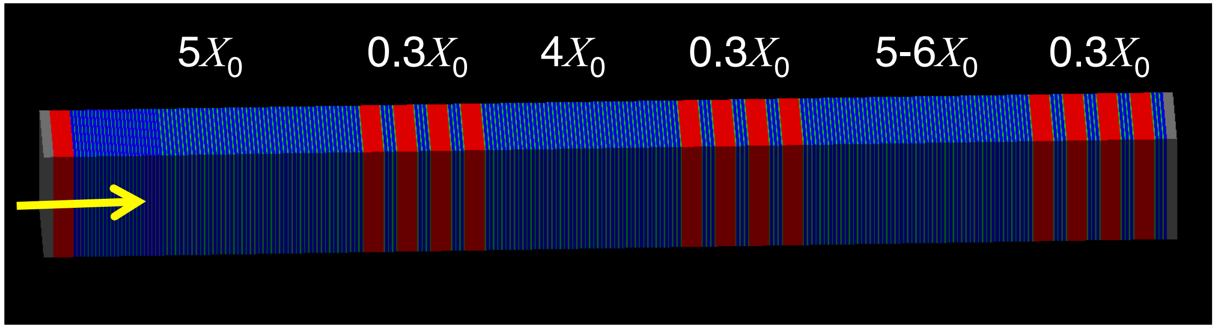
0.275 mm Pb + 1.5 mm scintillator

PANDA/KOPIO prototypes:

- $\sigma_E/\sqrt{E}$ **~ 3%** $/\sqrt{E}$ (GeV)
- σ_t **~ 72 ps** $/\sqrt{E}$ (GeV)
- σ_x **~ 13 mm** $/\sqrt{E}$ (GeV)

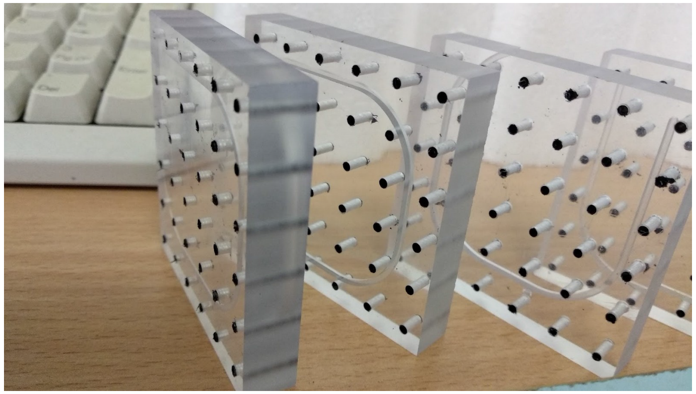
New for KLEVER: Longitudinal shower information from spy tiles

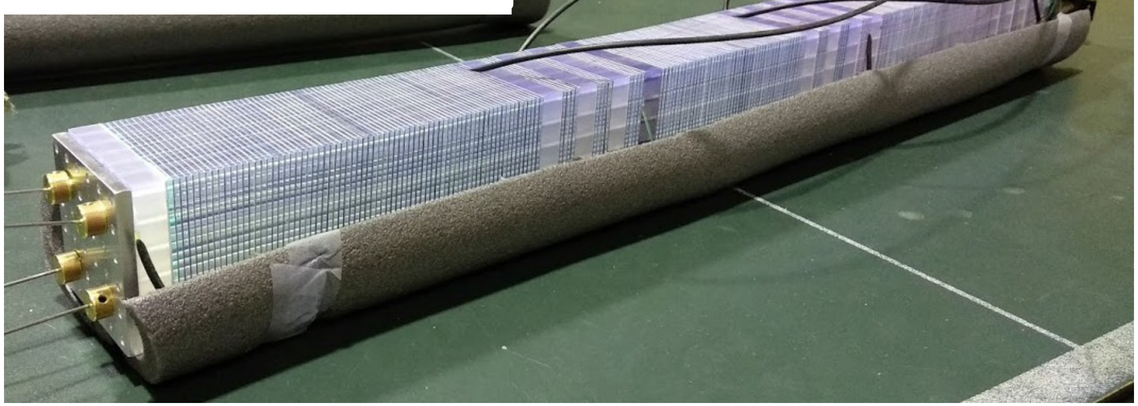
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



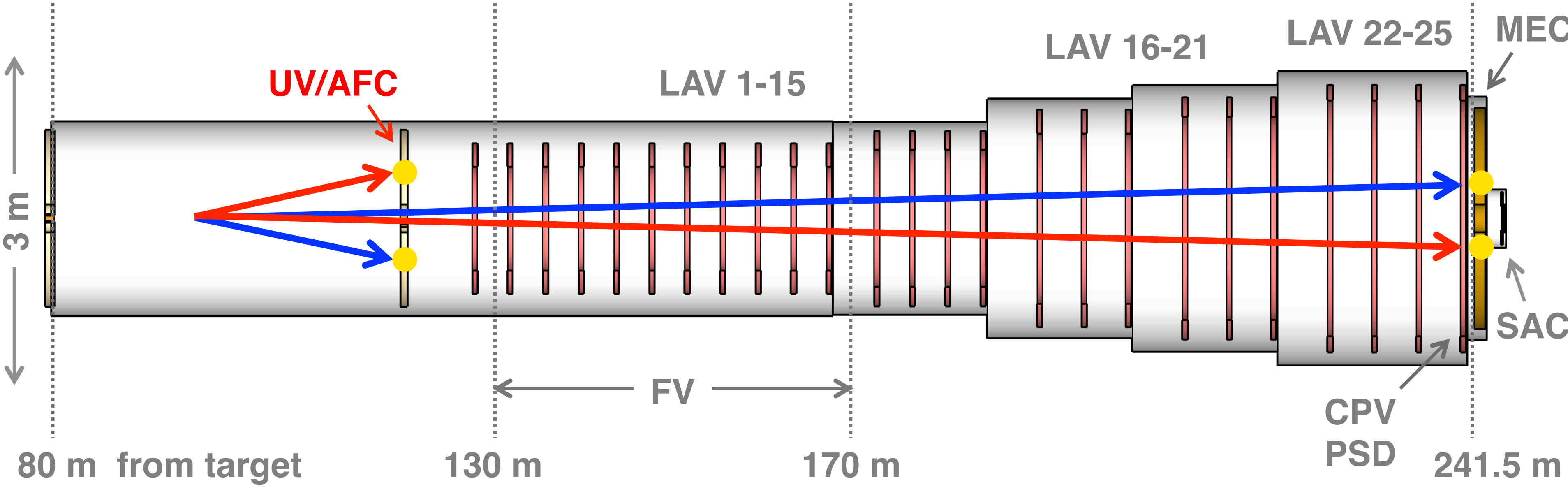
1st prototype assembled and tested at Protvino

OKA beamline, April 2018



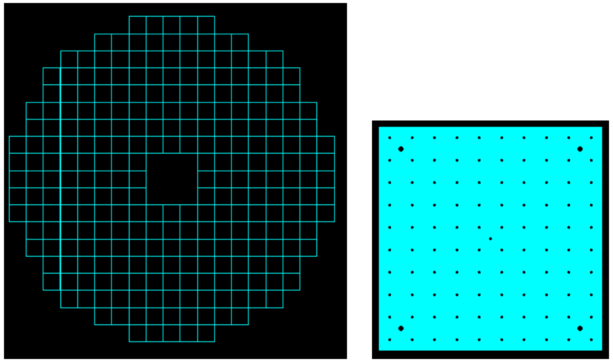


Vetoes for upstream $K_L \to \pi^0\pi^0$

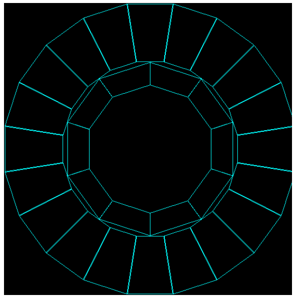


Upstream veto (UV):

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



Active final collimator:

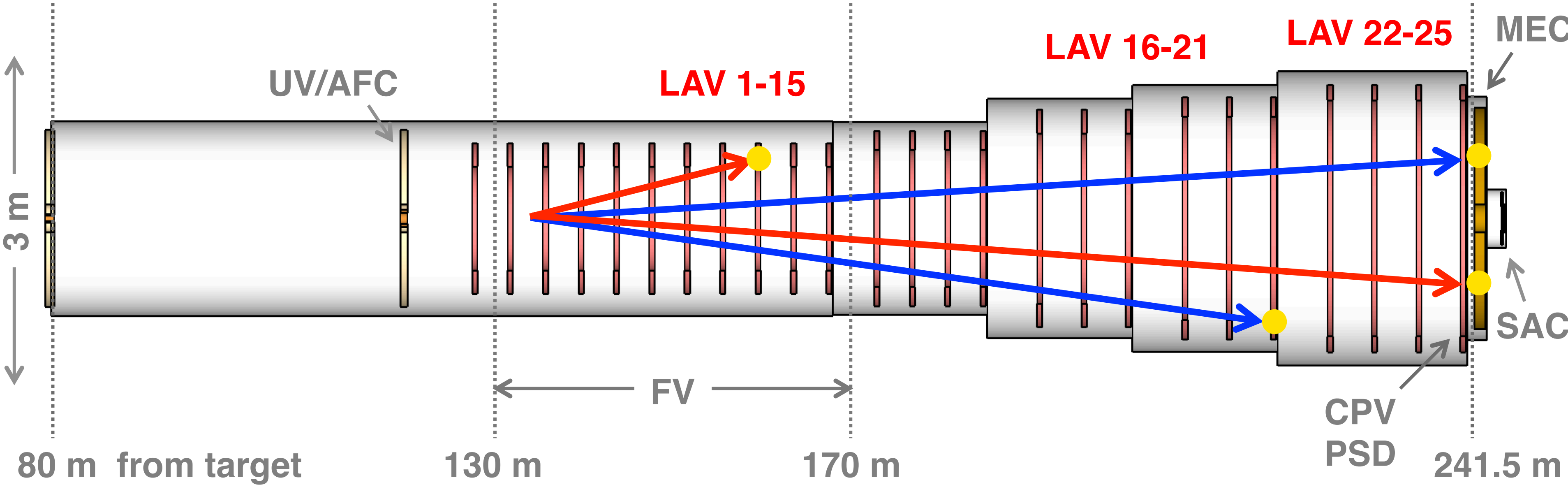


- 4.2 < r < 10 cm
- LYSO collar counter
- 80 cm long
- Internal collimating surfaces

- Intercepts halo particles from scattering on upstream collimators or γ absorber

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

Large-angle photon vetoes



25 new large-angle photon veto stations (LAV)

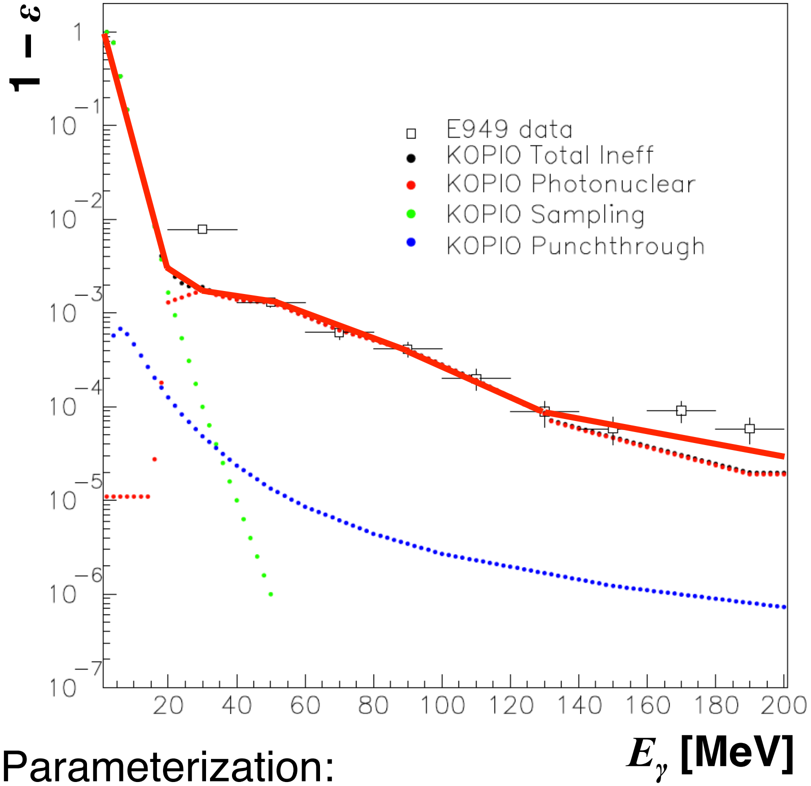
- 5 sizes, sensitive radius 0.85 to 1.5 m, at intervals of 4 to 5 m
- Hermetic coverage out to 100 mrad
  Need good detection efficiency at low energy ($1 - \varepsilon \sim 0.5\%$ at 20 MeV)
- Baseline technology: Lead/scintillator tile with WLS readout
  Based on design of CKM VVS
  Assumed efficiency based on E949 and CKM VVS experience

Large-angle photon vetoes

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

Baseline technology: CKM VVS
Scintillating tile with WLS readout

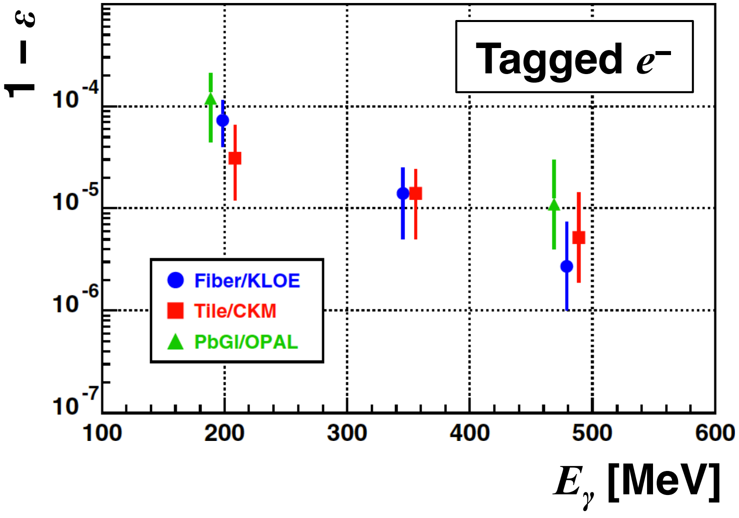
Good efficiency assumptions based on E949 and CKM VVS experience



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

E949 barrel veto efficiencies
Same construction as CKM

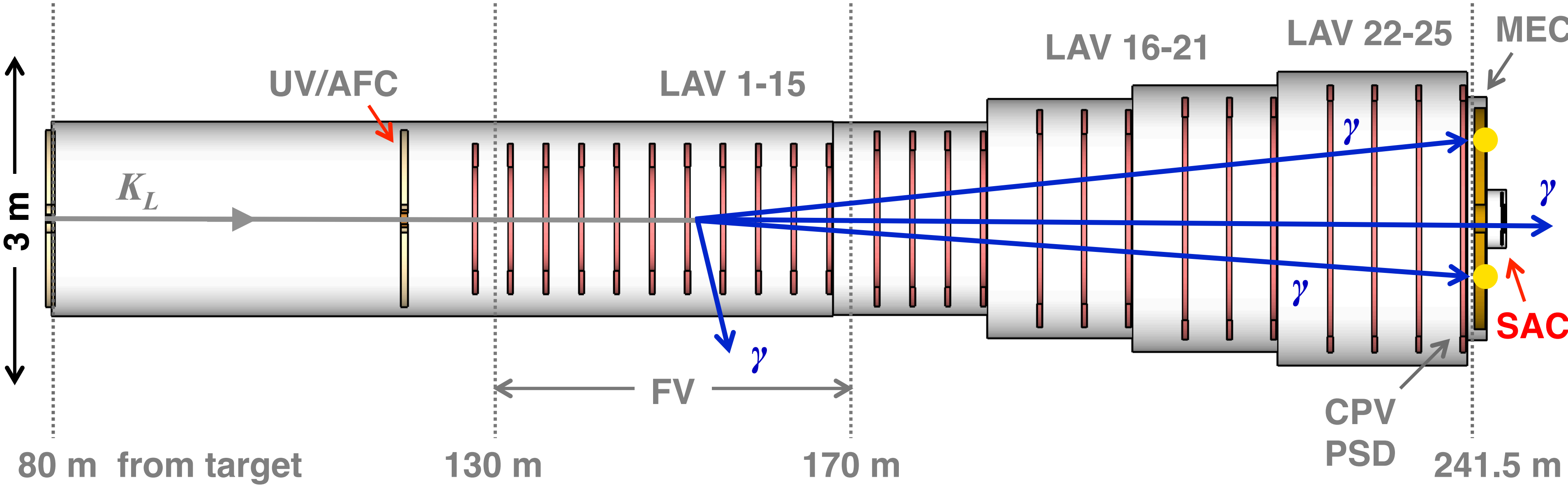
Tests for NA62 at Frascati BTF



Tests at JLAB for CKM:

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

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

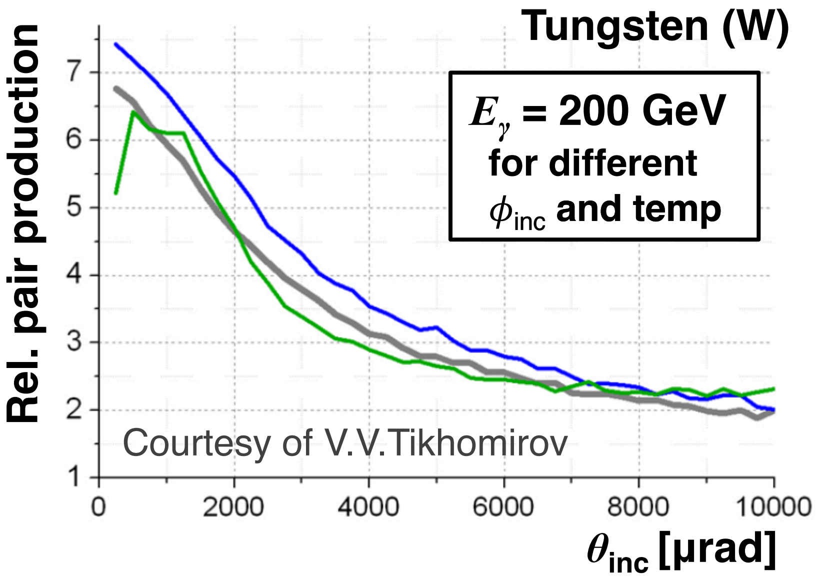
Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

Baseline solution:

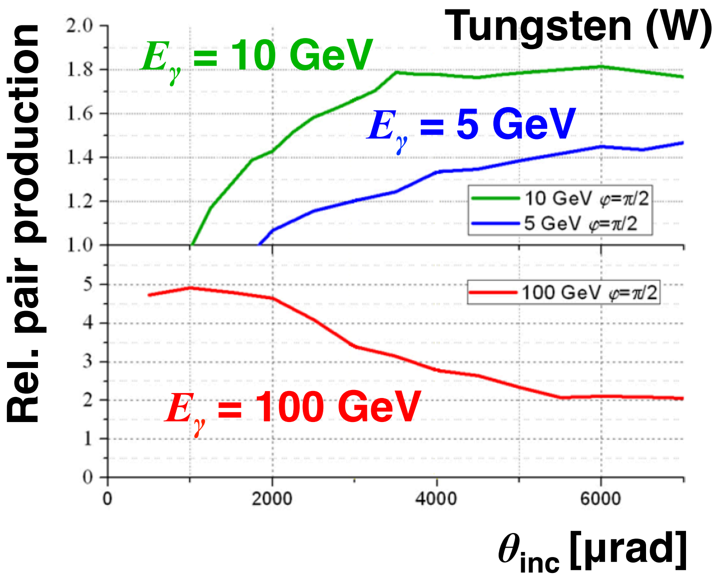
- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber

Efficient γ conversion with crystals

Coherent effects in crystals enhance pair-conversion probability



Courtesy of V.V.Tikhomirov



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

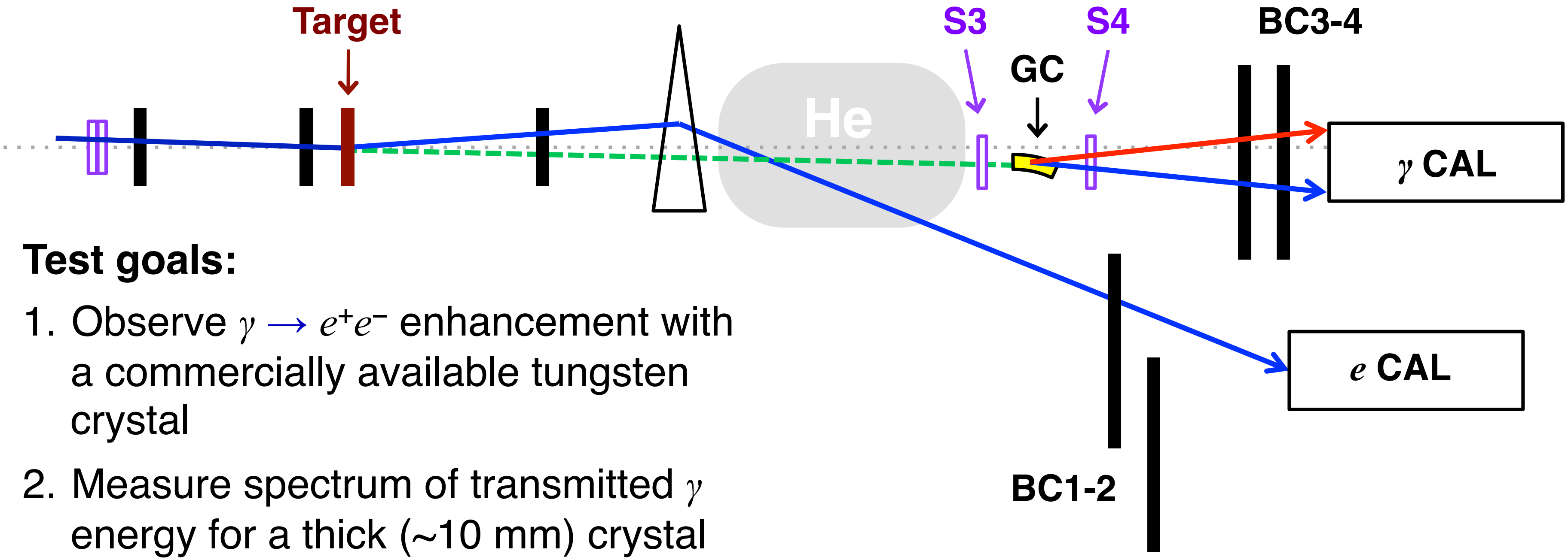
2. **Absorber material for small-angle calorimeter (SAC)**

   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

Tagged photon test beam setup:

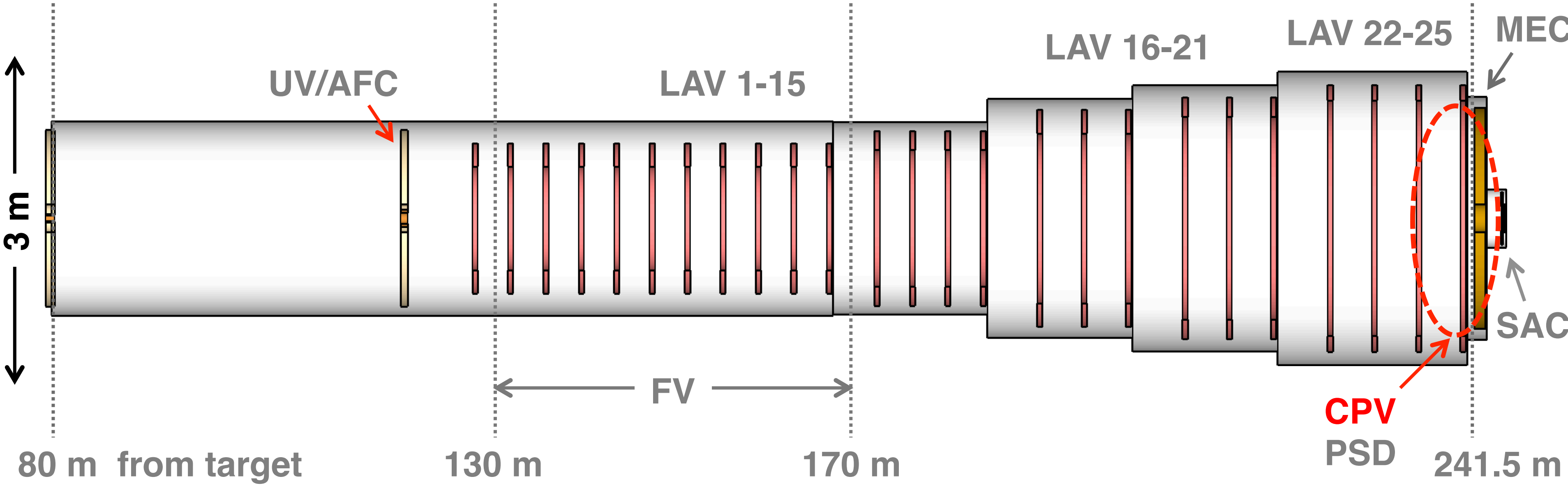


Test goals:

1. Observe $\gamma \to e^+e^-$ enhancement with a commercially available tungsten crystal
2. Measure spectrum of transmitted γ energy for a thick (~10 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**

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

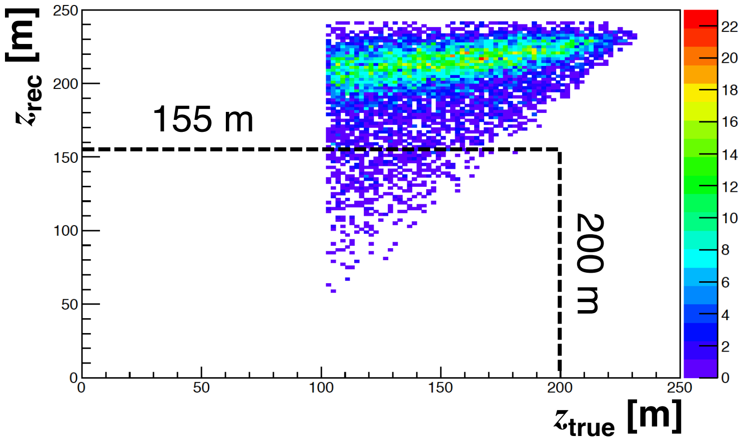
- Shower profile in MEC
- Re-use NA62 hadronic calorimeters MUV1/2 (not shown), downstream of MEC

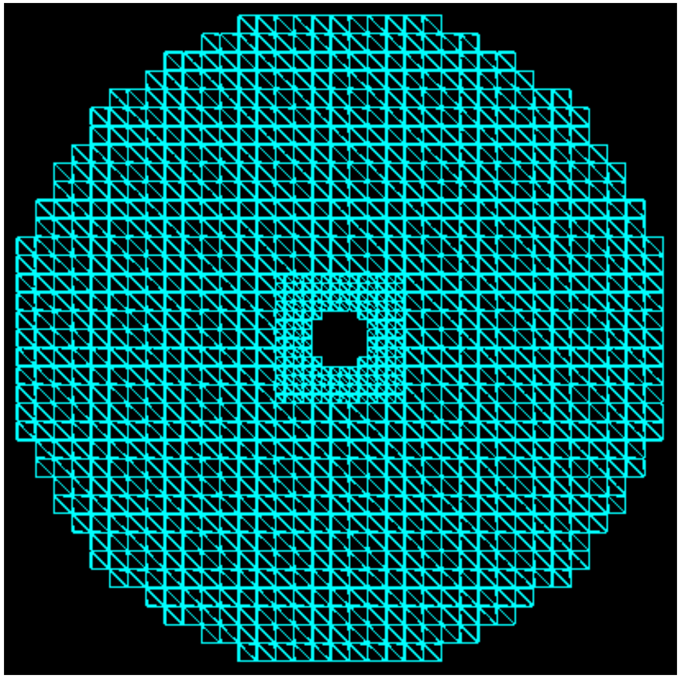
Charged particle veto

KLEVER

$K_L \to \pi e \nu$ can emulate signal when both π and e deposit energy in MEC

- Fake π^0 vertexes from πe all reconstructed downstream of true decay
  - π^+ deposits only a fraction of its energy
- K_{e3} decays with "π^0" reconstructed in FV have $z_\text{rec} < 200$ m
  - All within the acceptance of the CPV





Baseline CPV design

Square scintillator tiles, 5-mm thick, supported on carbon fiber membrane

- 2 planes → 3% X_0

Tile geometry: 4x4 cm^2 or 8x8 cm^2

- Smaller tiles near beam line
- Cracks staggered between planes
- 4 chamfered corners (45°) for direct SiPM coupling

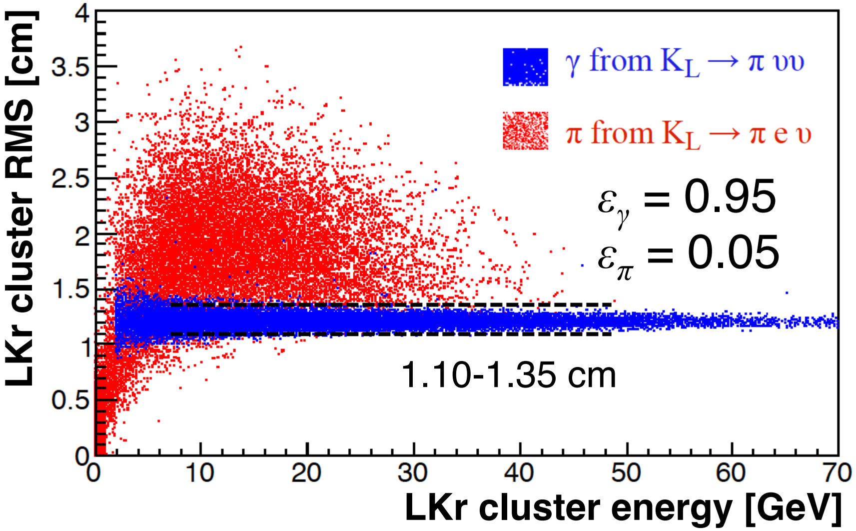
Charged particle rejection

$K_L \to \pi e \nu$ can emulate signal when both π and e deposit energy in LKr

Use cluster RMS in LKr to identify and reject π interactions

- Geant4 confirmed by preliminary analysis of $\pi\pi^0$ events in NA62 data:
  $\varepsilon_\gamma = 0.95$
  $\varepsilon_\pi = 0.05$

If LKr replaced by shashlyk, longitudinal shower profile information also available

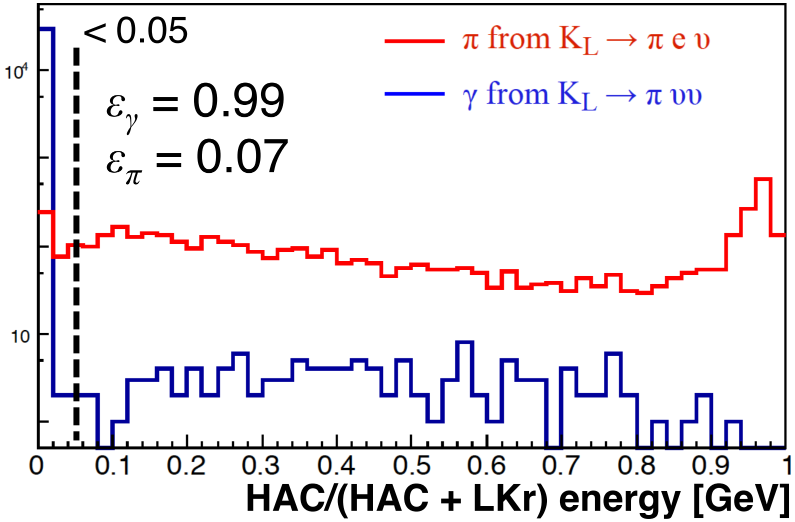


Ratio of hadronic/total energy effective to identify π showers

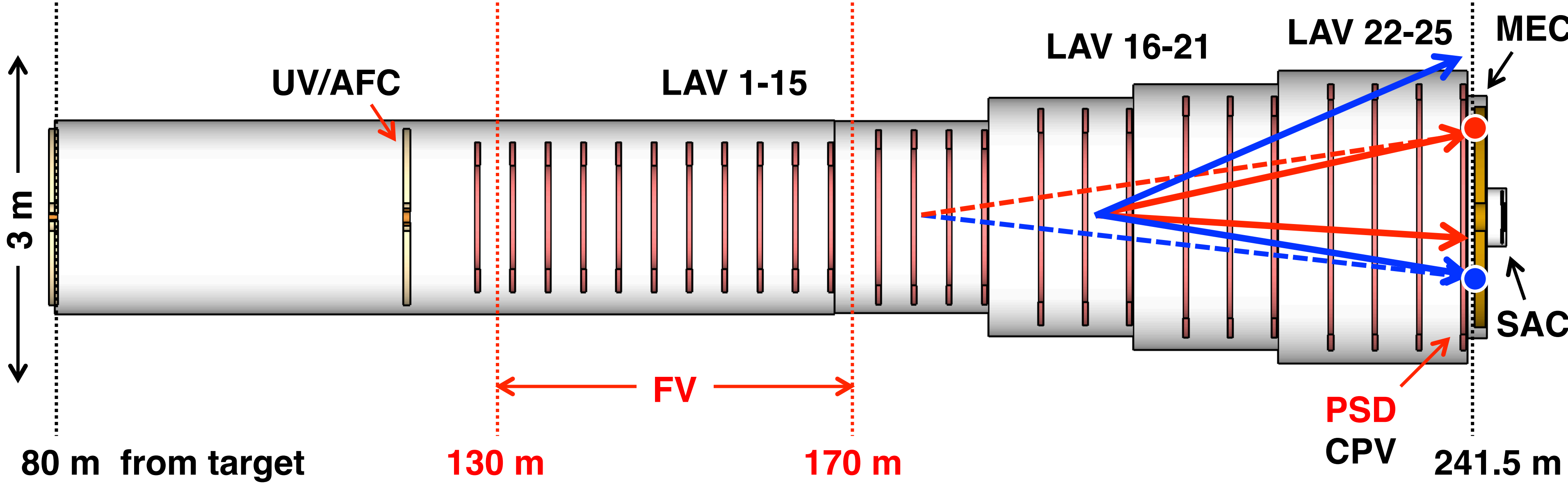
- Preliminary results based on Geant4:
  $\varepsilon_\gamma = 0.99$
  $\varepsilon_\pi = 0.07$

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

- Parameterization of response for inclusion in fast simulation



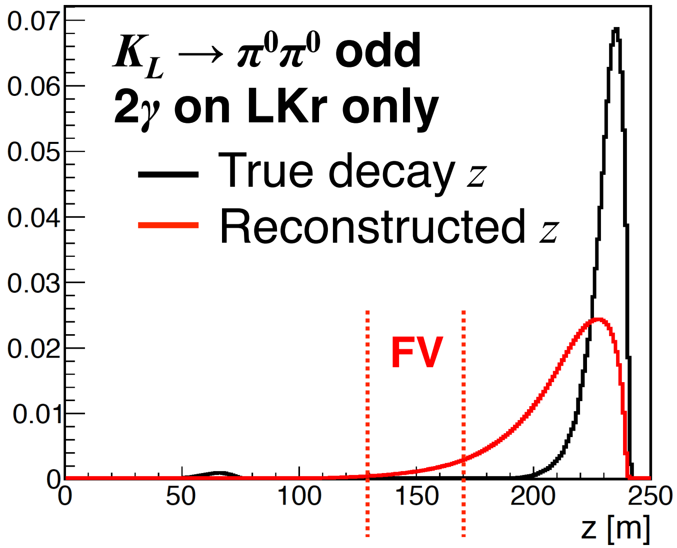
Mispaired $K_L \to \pi^0\pi^0$ events



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

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

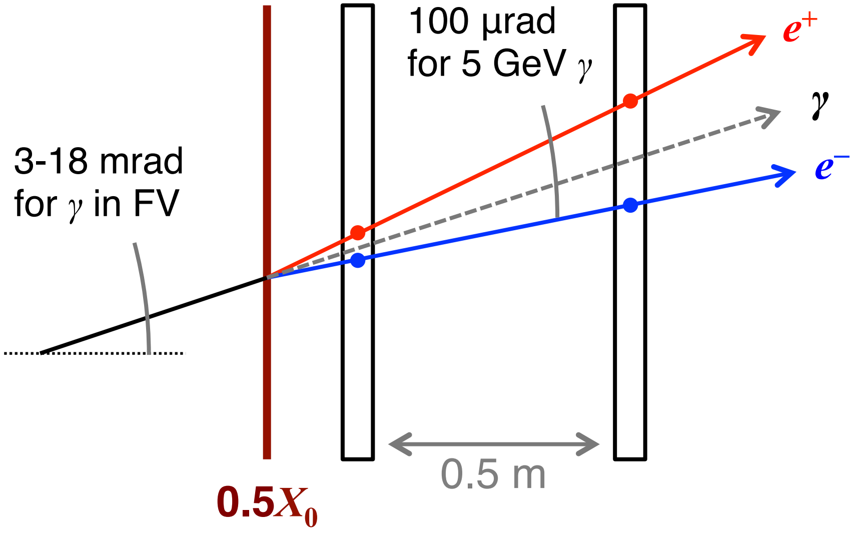
Preshower detector (PSD) is particularly effective against downstream decays



Concept for preshower detector

Advantages

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



Issues

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

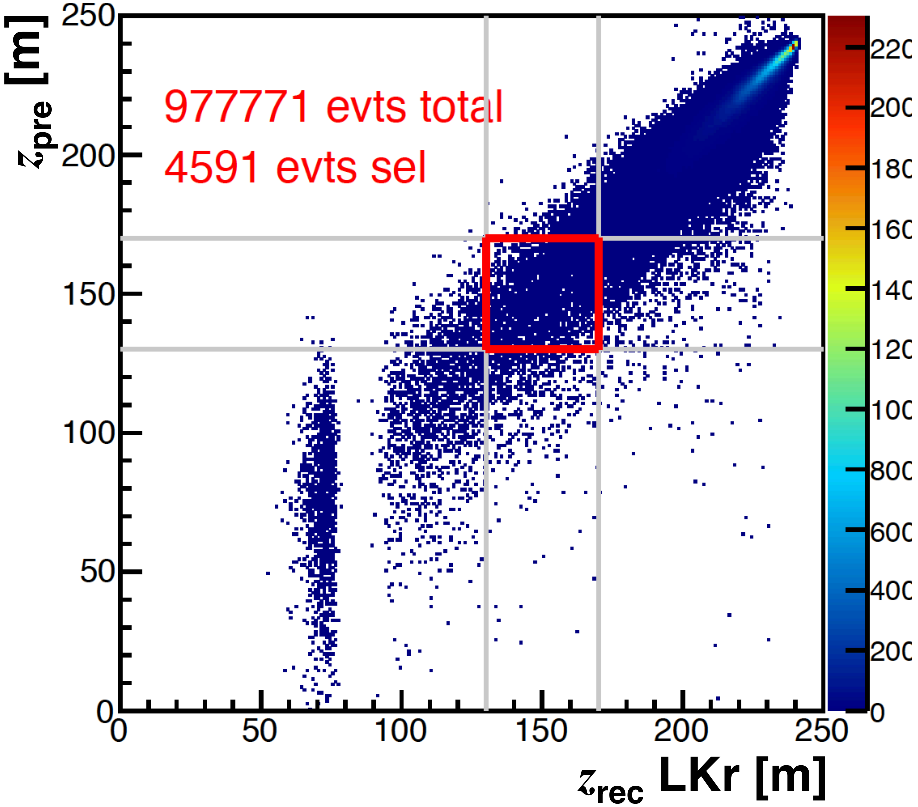
Preshower background rejection

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

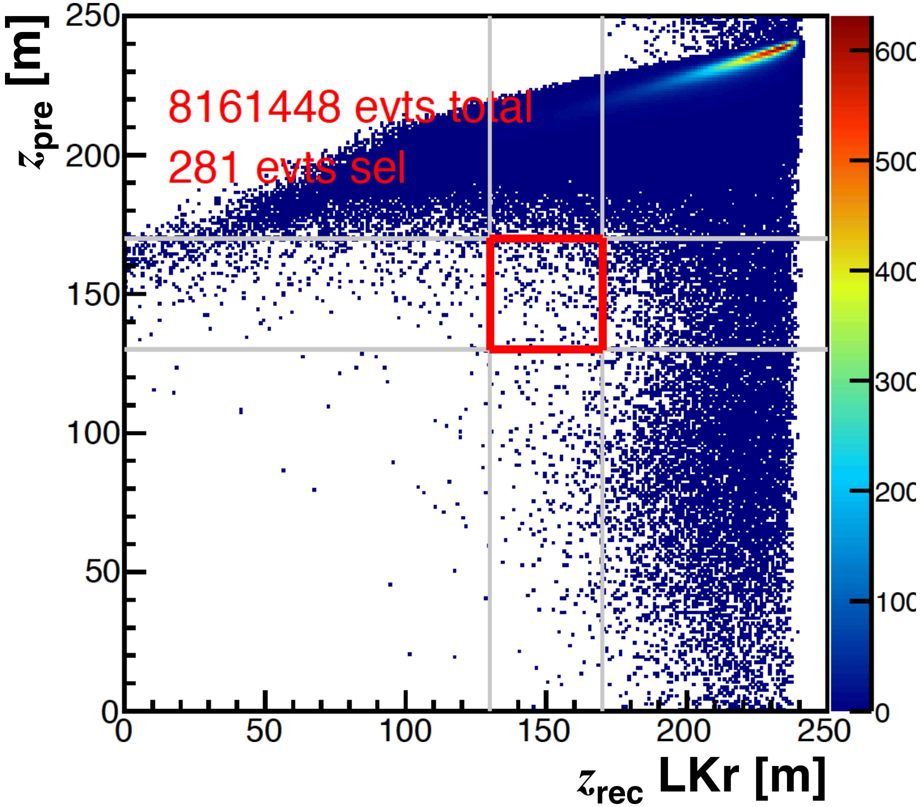
z_{rec} reconstructed by imposing $M(\gamma\gamma) = m_{\pi 0}$

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

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

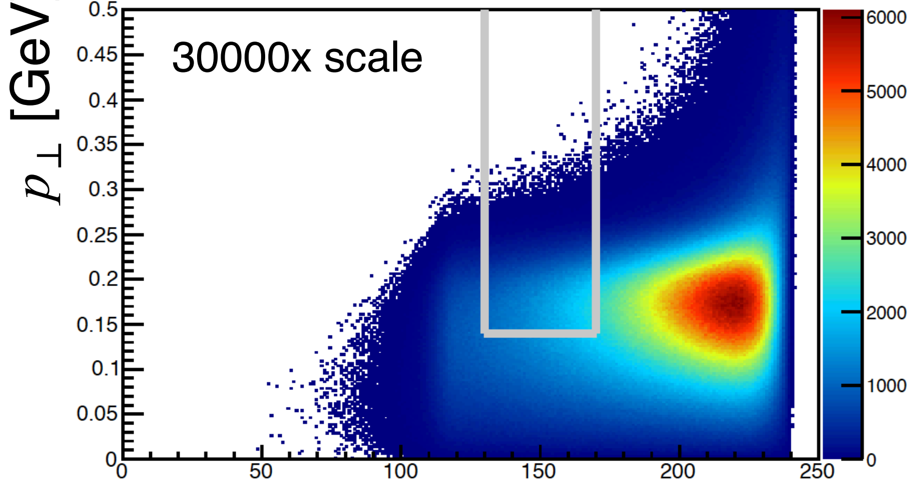

977771 evts total
4591 evts sel

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

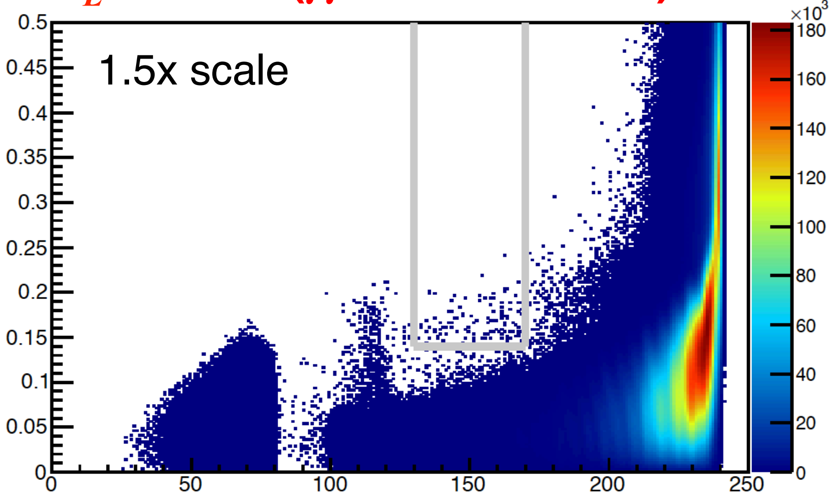

8161448 evts total
281 evts sel

Basic signal selection

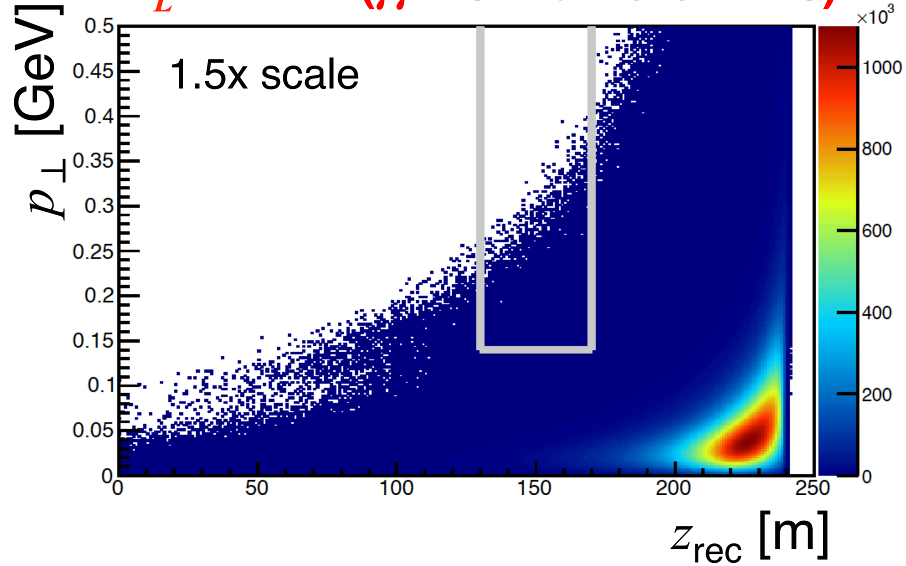
No hits in UV, AFC, LAV, SAC + fiducial volume (FV) and $p_\perp$ cuts



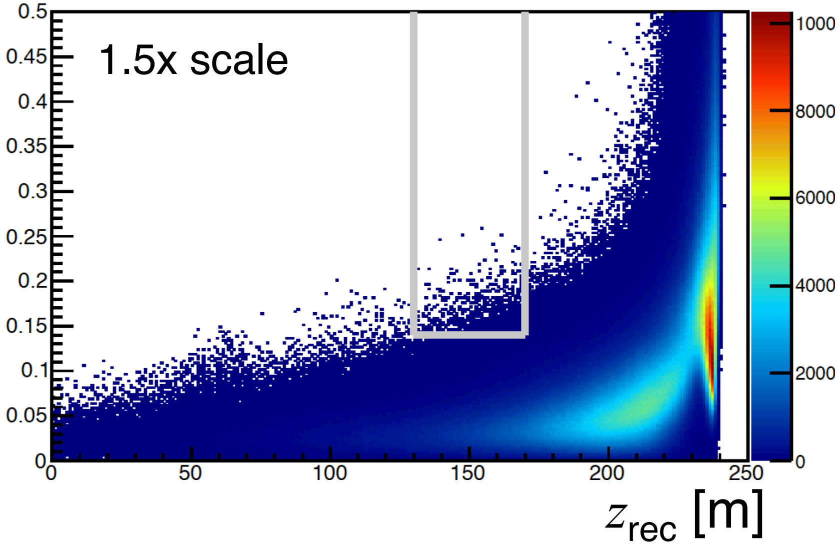
$K_L \to \pi^0 \nu\nu$



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



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

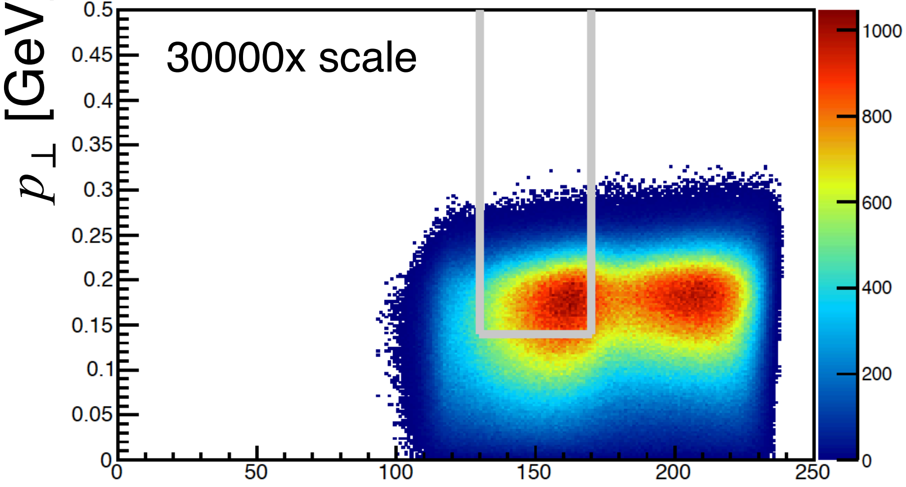


$K_L \to \pi^0\pi^0$ (overlapped clusters)

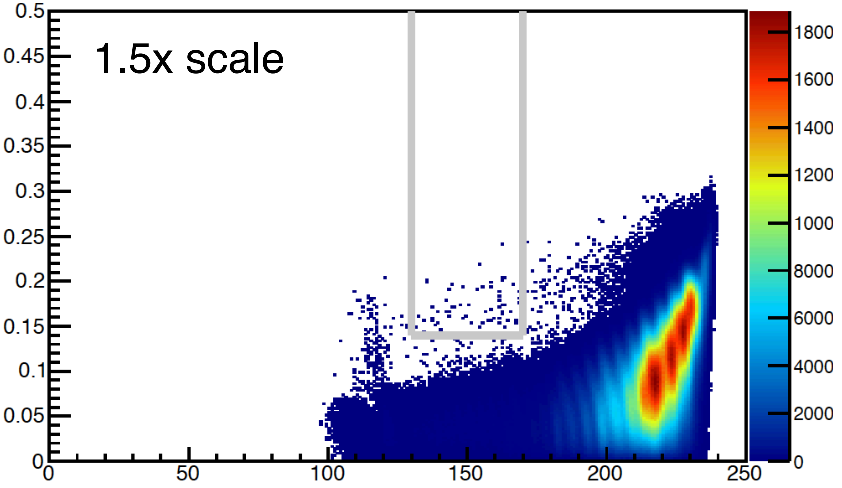
Additional background rejection

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

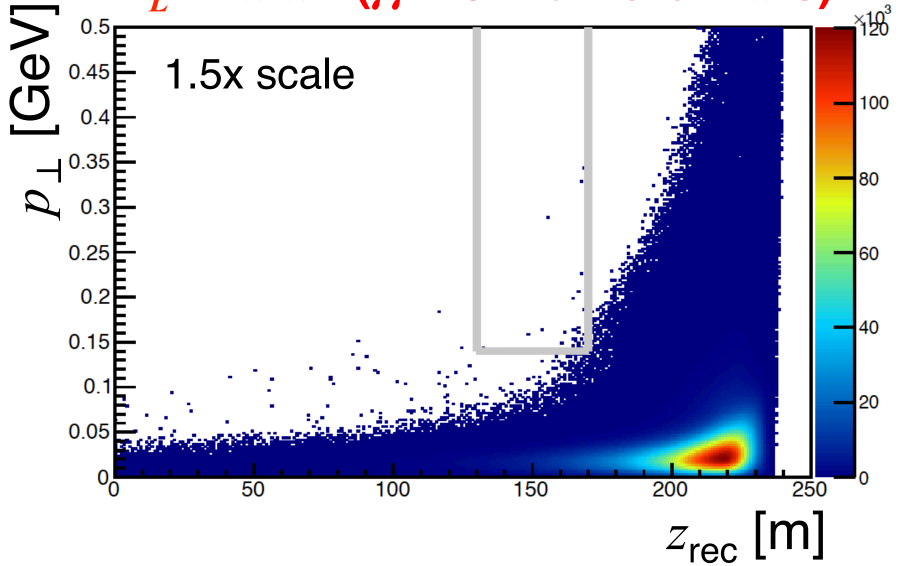
$K_L \to \pi^0 \nu\nu$



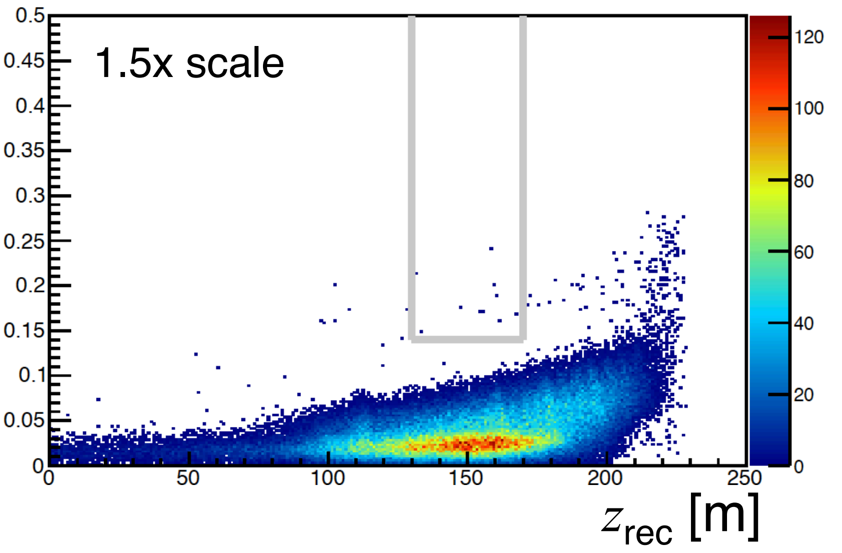
$K_L \to \pi^0\pi^0$ ($\gamma\gamma$ from same π^0)



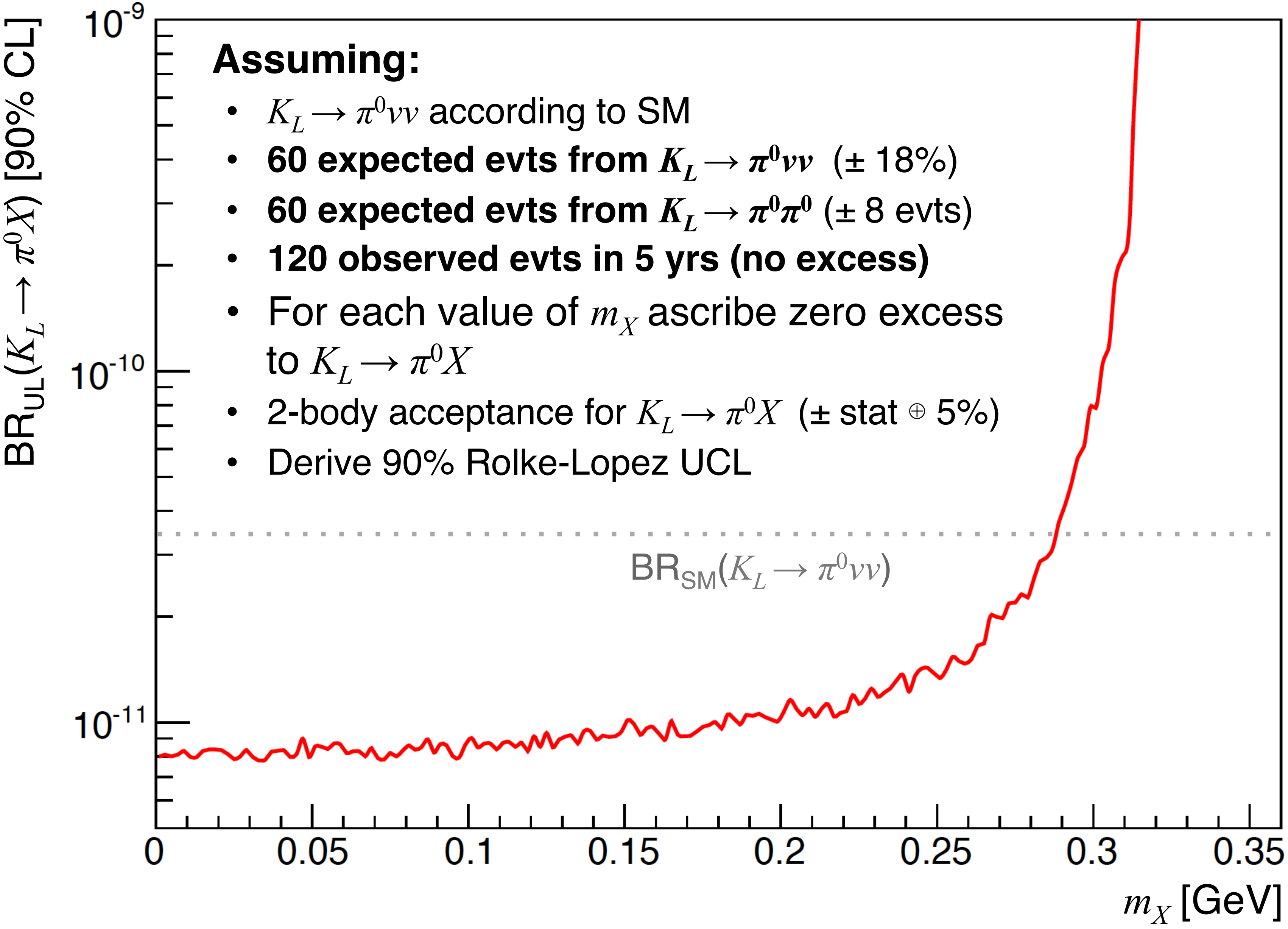
$K_L \to \pi^0\pi^0$ ($\gamma\gamma$ from different π^0s)



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



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



Assuming:

- $K_L \to \pi^0 \nu\nu$ according to SM
- **60 expected evts from $K_L \to \pi^0 \nu\nu$** (± 18%)
- **60 expected evts from $K_L \to \pi^0 \pi^0$** (± 8 evts)
- **120 observed evts in 5 yrs (no excess)**
- For each value of m_X ascribe zero excess to $K_L \to \pi^0 X$
- 2-body acceptance for $K_L \to \pi^0 X$ (± stat ⊕ 5%)
- Derive 90% Rolke-Lopez UCL

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

KLEVER

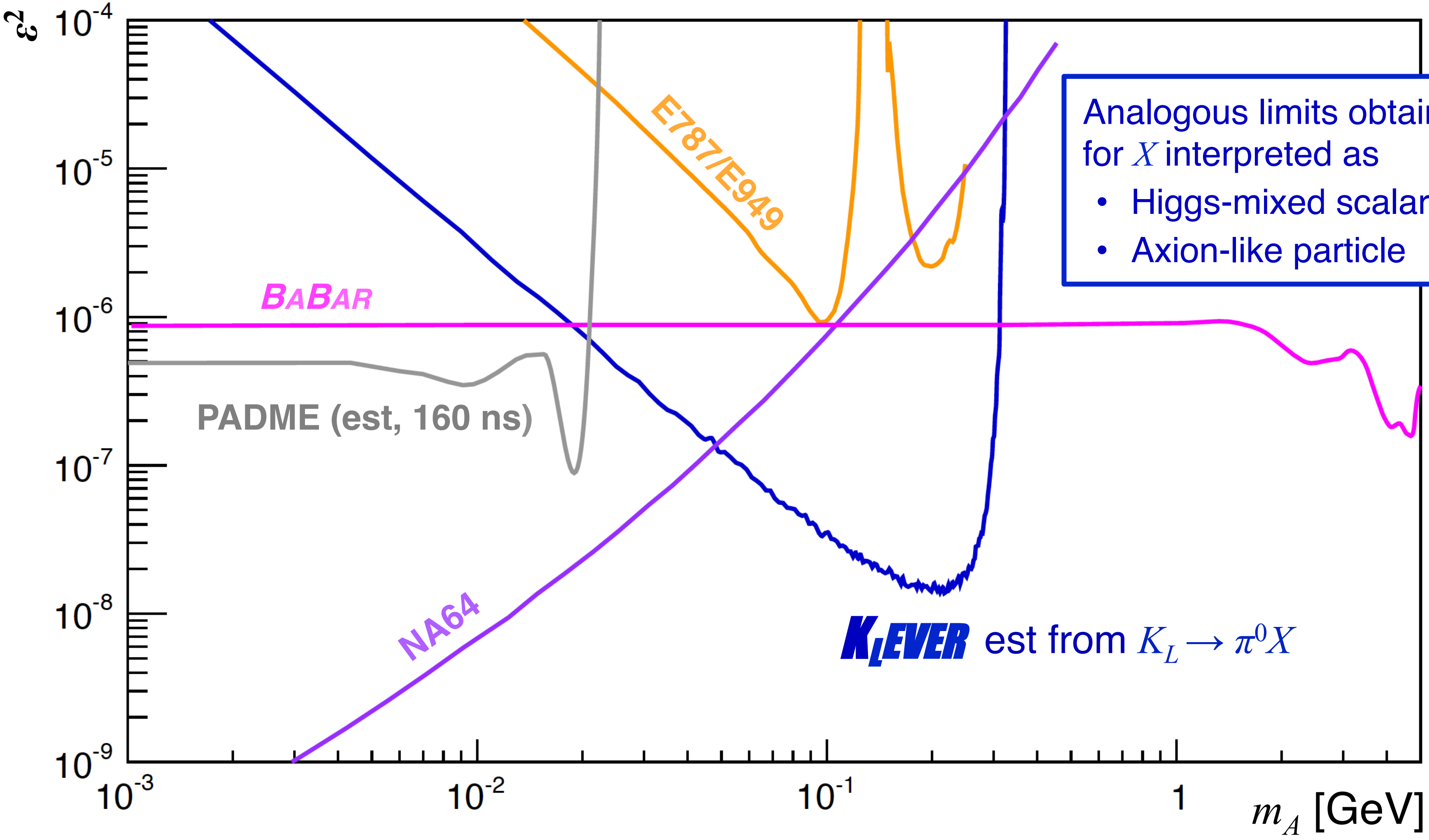
For $K_L \to \pi^0 X$ interpret X as dark photon A' with no decays to SM particles

Obtain limits in ε^2 vs. m_A plane

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

As per Davoudiasl, Lee, Marciano 2014

Weaker limits obtain if A' also mixed with Z



Analogous limits obtained for X interpreted as

- Higgs-mixed scalar
- Axion-like particle

Status and timeline

Project timeline – target dates:

2017-2018	**Project consolidation and proposal** • Participation in Physics Beyond Colliders • PRIN and MAECI proposals in Italy • Beam test of crystal pair enhancement • Design consolidation • Input to European Strategy for Particle Physics • Expression of Interest to CERN SPSC
2019-2021	**Detector R&D**
2021-2025	**Detector construction** • Possible K12 beam test if compatible with NA62
2024-2026	**Installation during LS3**
2026-	**Data taking beginning Run 4**

Most groups participating in NA62 have expressed interest in KLEVER

We are actively seeking new collaborators!

Summary and outlook

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

$K \rightarrow \pi \nu\nu$ 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($K^+ \rightarrow \pi^+ \nu\nu$) in the short term, ultimately reaching ~100 event sensitivity

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

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

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

KLEVER is actively seeking new collaborators

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

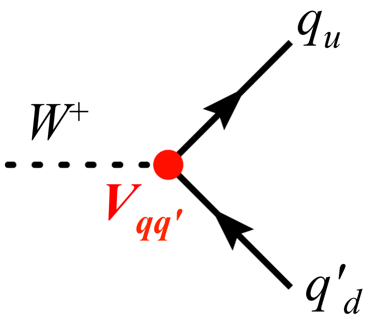
Additional information

Matthew Moulson

For the KLEVER project

The CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



V is unitary: $\mathbf{V}^\dagger\mathbf{V} = \mathbf{1}$

$$\sum_i V_{ij} V_{ik}^* = \sum_i V_{ji} V_{ki}^* = \delta_{jk}$$

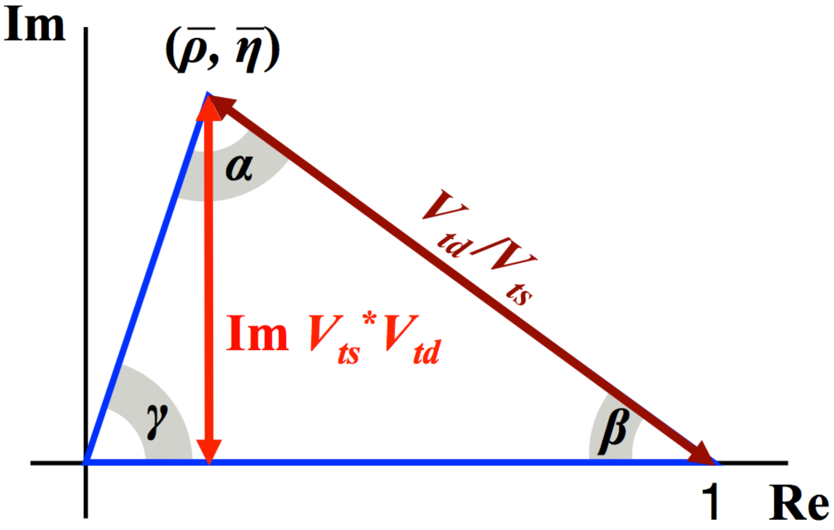
B unitarity triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

K unitarity triangle

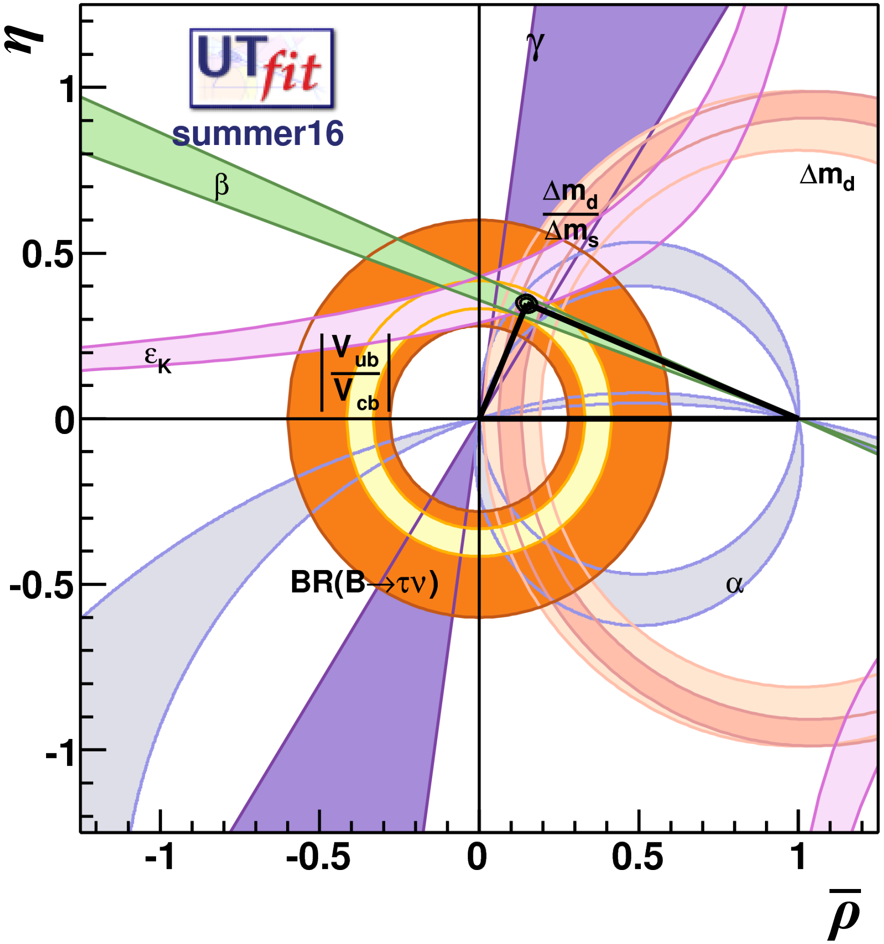
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

Observable	Measurement
$K^+ \to \pi^+ \nu\bar{\nu}$	$\lvert V_{ts}^* V_{td} \rvert$
$K_L \to \pi^0 \nu\bar{\nu}$	$\mathrm{Im}\, V_{ts}^* V_{td} \propto \eta$
$B_d \to J/\psi K_S$	$\sin 2\beta$
$\frac{\Delta m_{B_d}}{\Delta m_{B_s}} = \frac{B_d - \bar{B}_d}{B_s - \bar{B}_s}$	$\lvert V_{td}/V_{ts} \rvert$

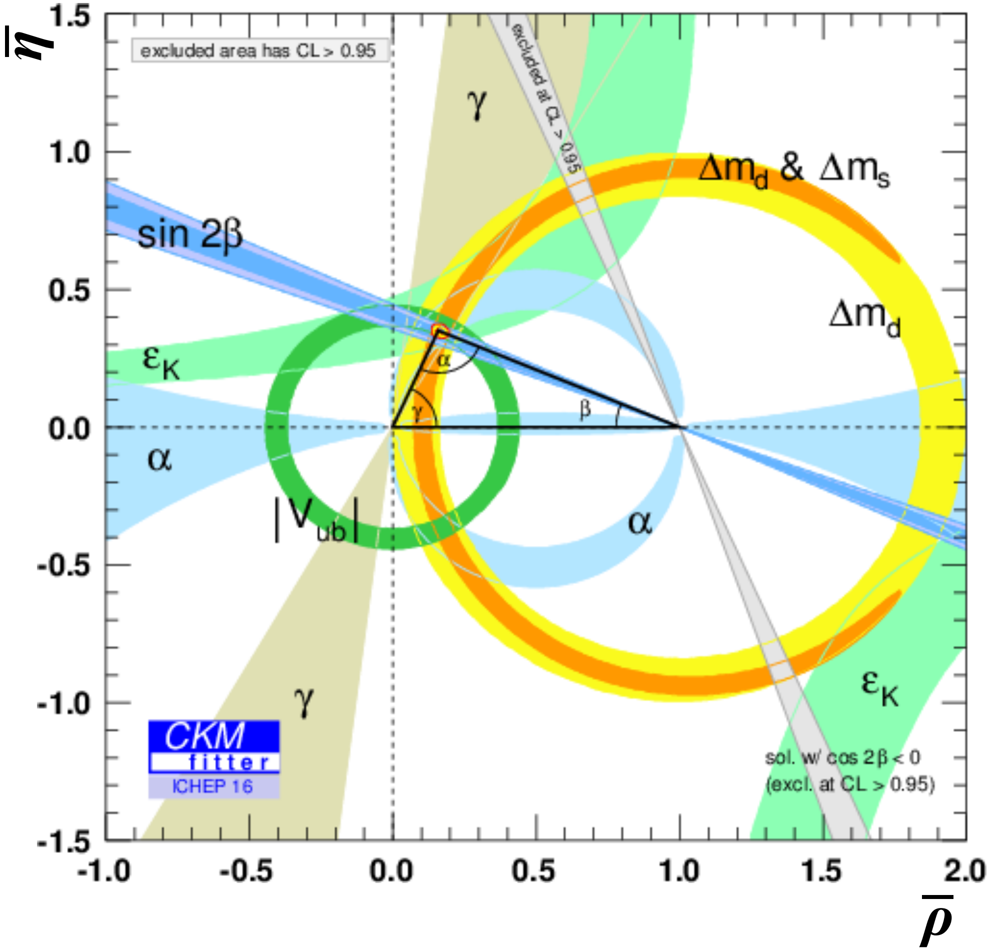


Unitarity triangles: state of the art

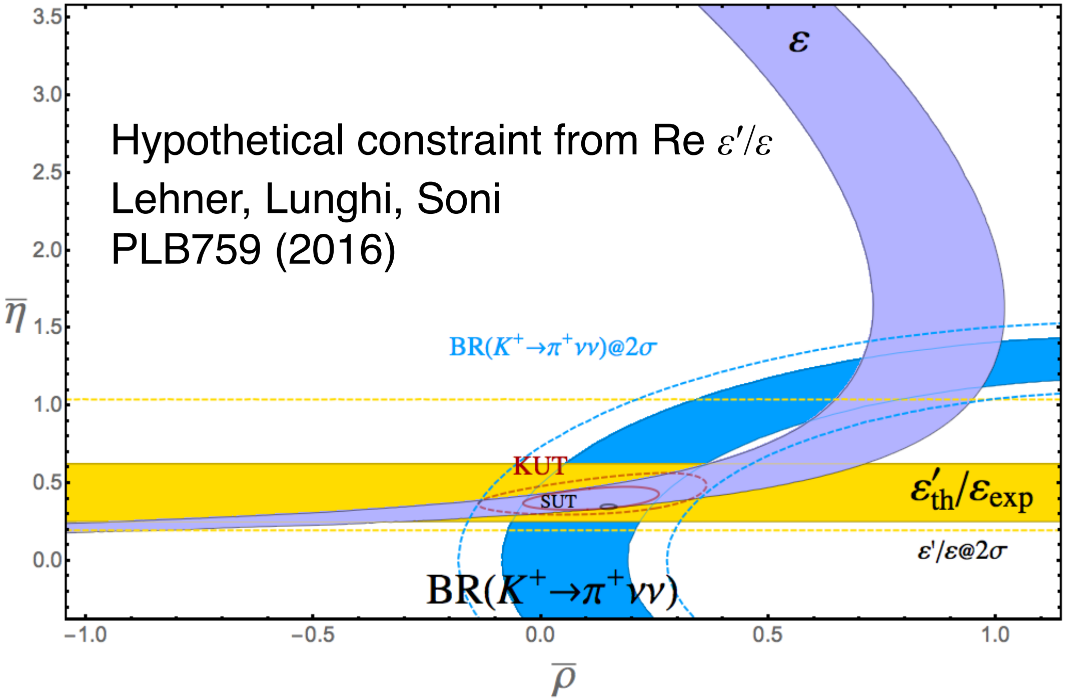
www.utfit.org - ICHEP ’16



ckmfitter.in2p3.fr – ICHEP ’16



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



Hypothetical constraint from Re ε'/ε
Lehner, Lunghi, Soni
PLB759 (2016)

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 $\varepsilon'_{\text{th}}/\varepsilon$) = 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

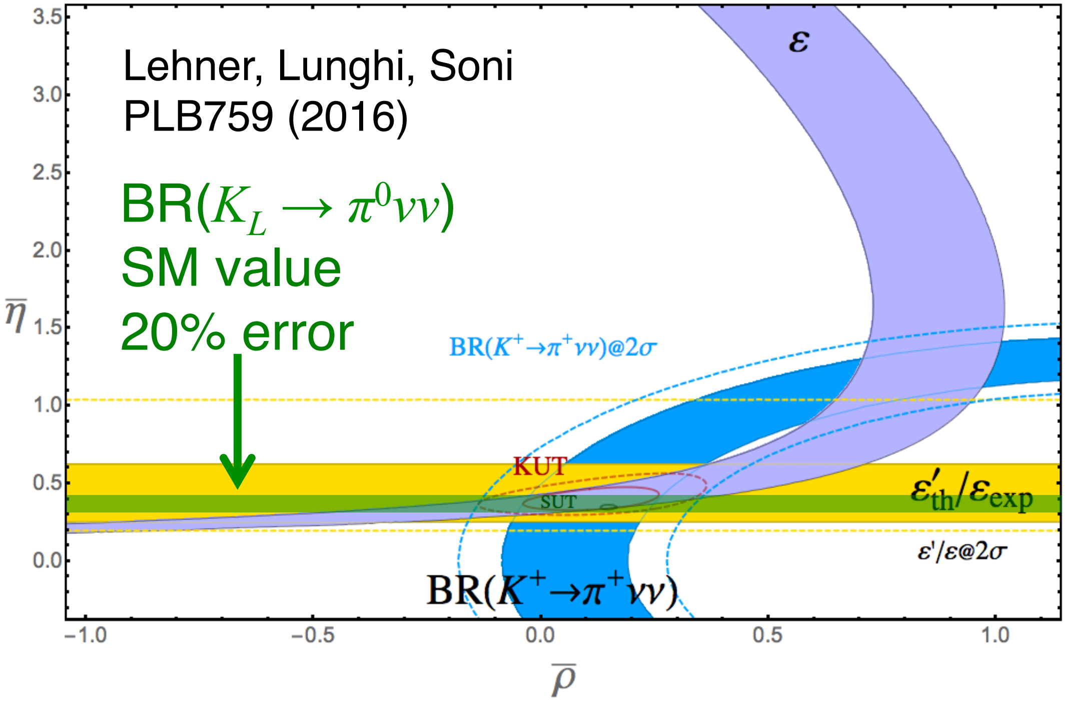
Measurements: Re ε'/ε × 10^4

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:

- Claim: Uncertainty ~10% of experimental value can be reached by ~2020
- In progress: Increased statistics, larger volumes, additional lattice spacings

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



Lehner, Lunghi, Soni
PLB759 (2016)

BR($K_L \rightarrow \pi^0 \nu\nu$)
SM value
20% error

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

Scenario assumes:

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

How does progress on Re ε'/ε impact experimental interest in BR($K_L \rightarrow \pi^0 \nu\nu$)?

- Measurement of Re ε'/ε is dominated by systematics

$$R = \frac{\mathrm{BR}(K_L \rightarrow \pi^0\pi^0)}{\mathrm{BR}(K_S \rightarrow \pi^0\pi^0)} \cdot \frac{\mathrm{BR}(K_S \rightarrow \pi^+\pi^-)}{\mathrm{BR}(K_L \rightarrow \pi^+\pi^-)} \approx 1 - 6\,\mathrm{Re}\,\varepsilon'/\varepsilon$$

- NA48 and KTeV measured R to 0.1%: Very difficult to improve!
  Small gains from statistics and from resolution of S =1.6 in PDG fit
- **δBR($K_L \rightarrow \pi^0 \nu\nu$) ~ 20% gives tighter UT constraint than δ(Re ε'/ε) ~ 1 × 10^{-4}**

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

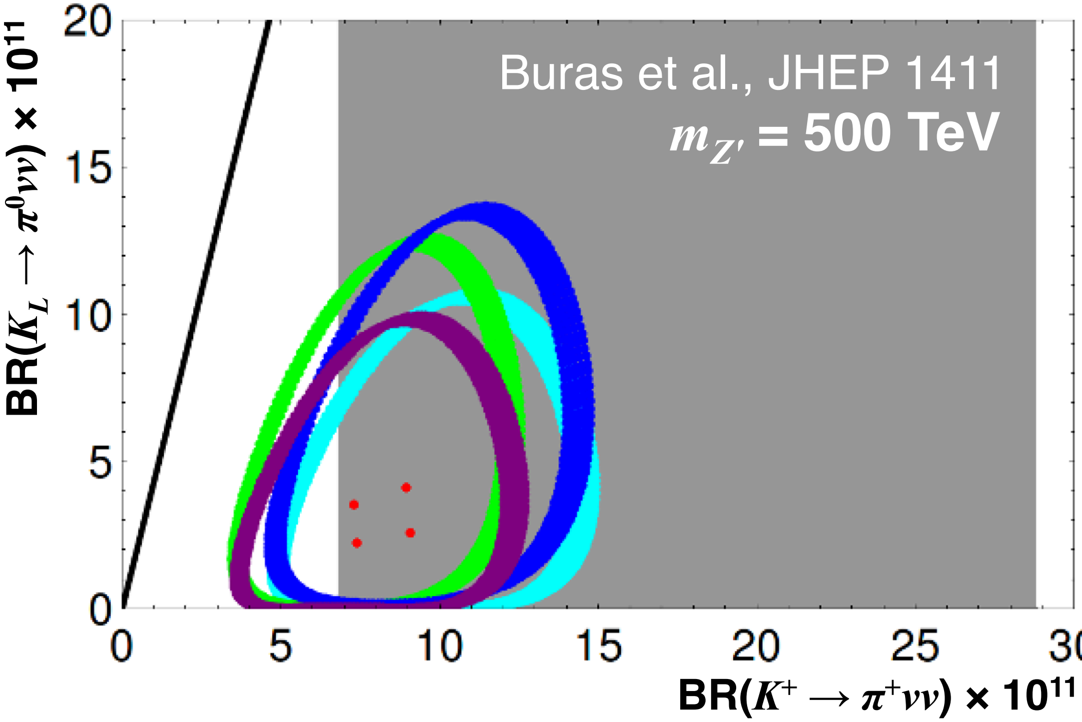
- Null results from direct searches at LHC so far

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



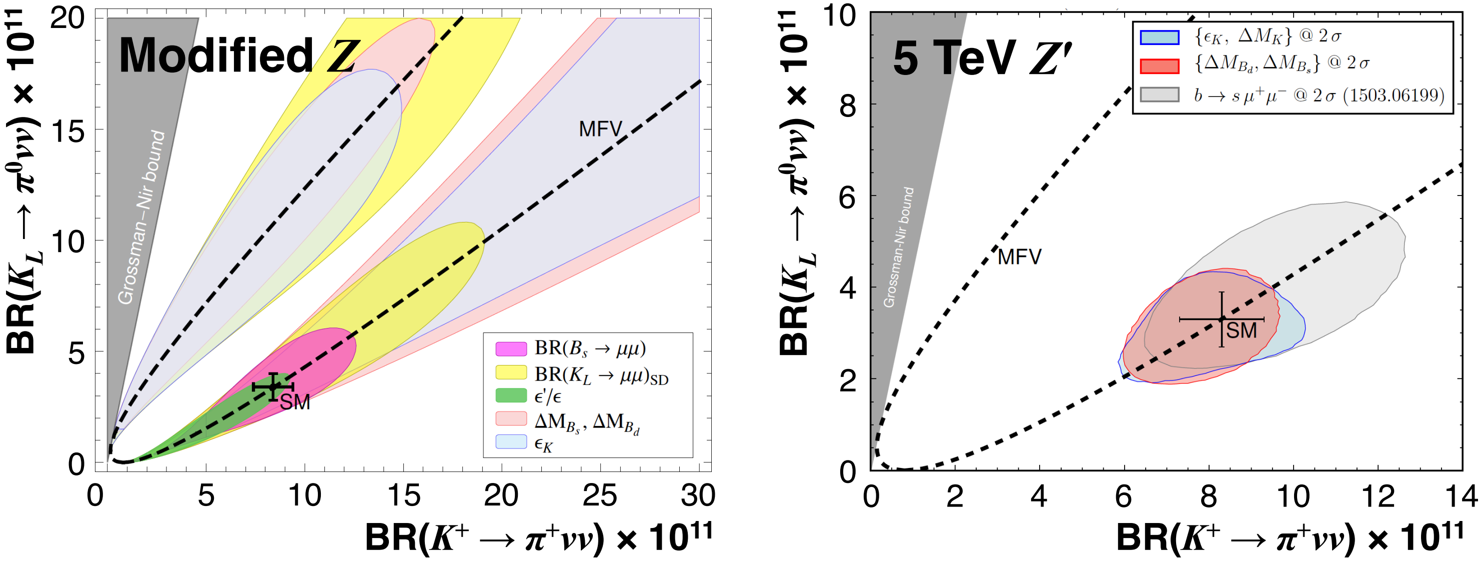
$K \to \pi\nu\bar{\nu}$ and other flavor observables

Simplified Z, Z' model used as paradigm

Buras, Buttazzo, Knegjens, JHEP 1511

CMFV hypothesis:

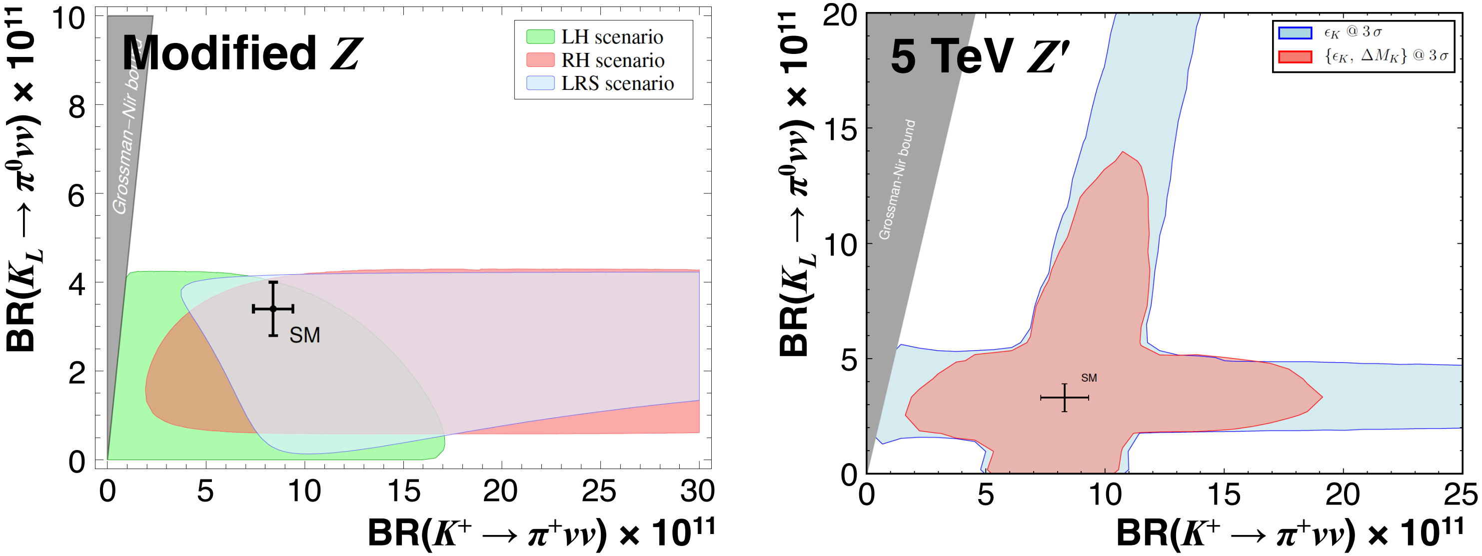
Constraints from B and K observables



LH and RH couplings allowed:

Constraints from K observables:

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

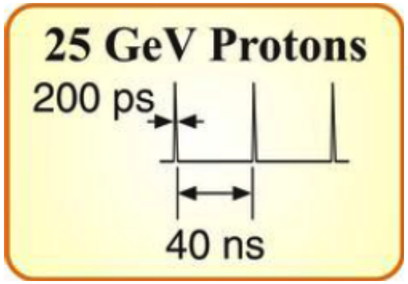


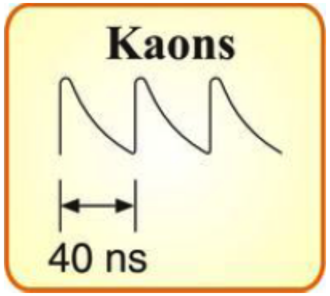
Extra constraints for $K_L \to \pi^0 \nu\bar{\nu}$

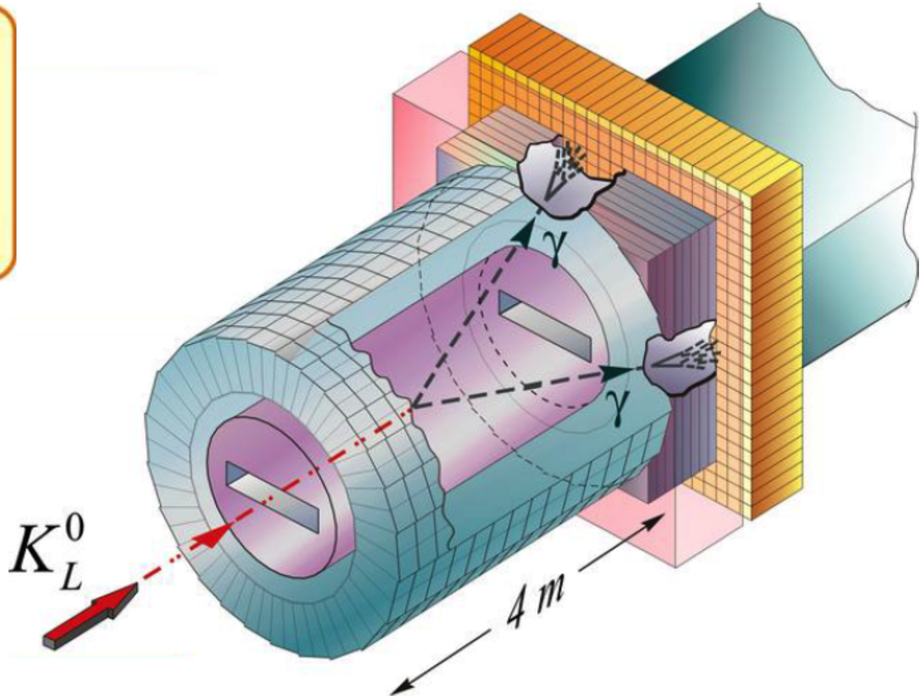
KOPIO
Brookhaven AGS
Cancelled 2005

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

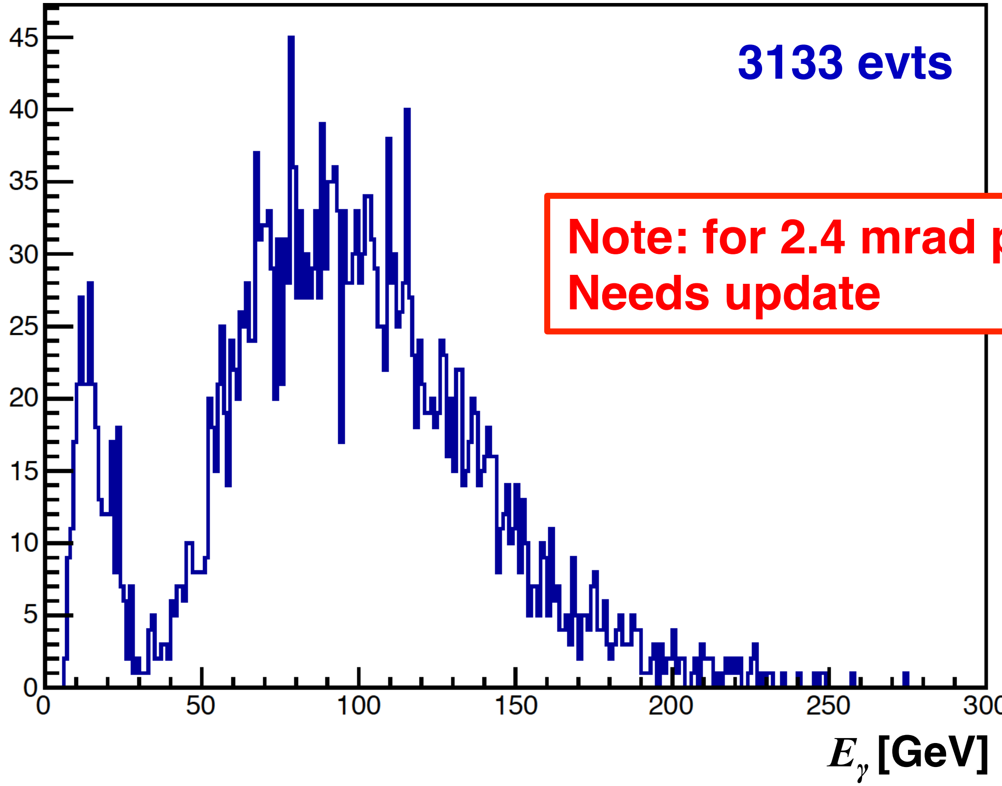
Advantages:
- $p(K_L)$ from time of flight
- Vertex position from preradiator
- Redundant constraints

Disadvantages:
- Difficult to veto low-energy γs
- Much lower K_L flux at high angle

Small-angle calorimeter

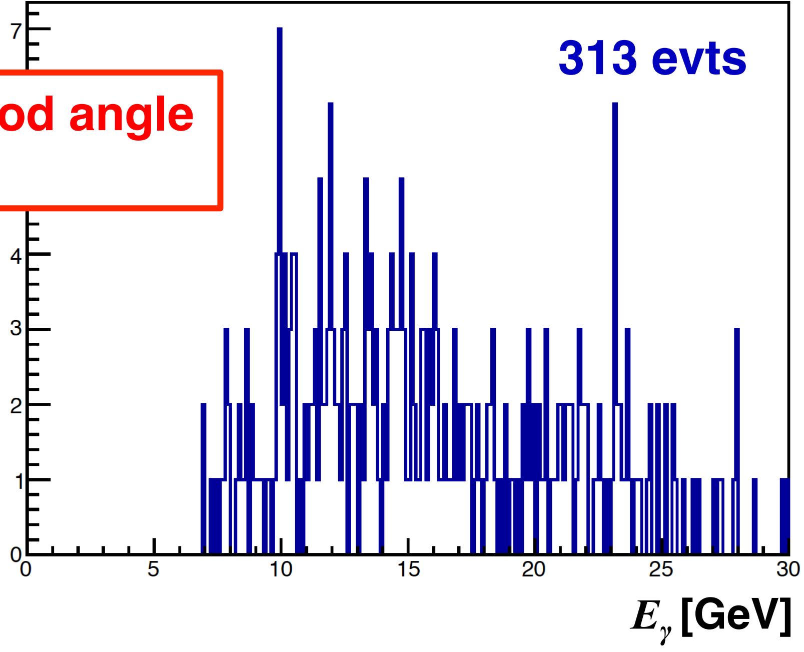
Energy of photons from $K_L \rightarrow \pi^0\pi^0$ on SAC after all cuts (5 years):

- 2γ on LKr
- No γs on LAV or IRC
- Cuts on z_{FV}, r_{min}(LKr), $p_\perp$



Note: for 2.4 mrad prod angle
Needs update

Detail for E_γ < 30 GeV



90% of γs from K_L on SAC have $30 < E_\gamma < 250$ GeV

- Need inefficiency $< 10^{-4}$ for $E_\gamma > 30$ GeV
- Can tolerate 1% inefficiency for $E_\gamma < 30$ GeV
- Can be blind for $E_\gamma < 5$ GeV

Small-angle calorimeter

Proof-of-concept simulation for baseline solution:

- W-Si pad calorimeter, 14 layers × 1 mm crystal absorber, $\theta_{\text{inc}} = 2$ mrad
  - Depth = $14X_0$ for $E_\gamma = 30$ GeV, but only $4X_0$ for $E_\gamma = 5$ GeV
- Naïve simulation of pair-conversion enhancement with Geant4:
  - Increase overall density as function of E_γ, instead of X_0

Photons

E_γ (GeV)	ρ/ρ_0	$1-\varepsilon$
350 GeV	3.5	**5×10^{-5}**
30 GeV	3.5	**1×10^{-4}**
10 GeV	1.5	**4.5%**
5 GeV	1.0	**20%**

Neutrons

50-300 GeV **$1 - \varepsilon = 20\%$**

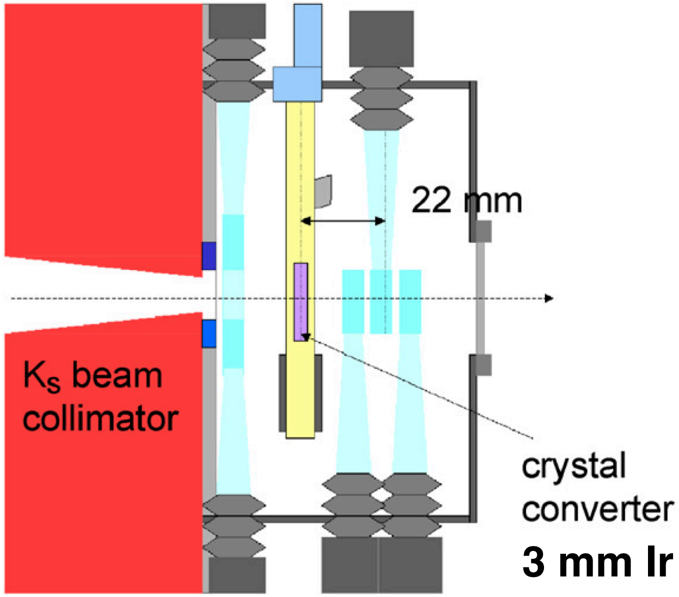
- E_{vis} thr. = 16 MeV chosen for $E_\gamma = 30$ GeV
- Inefficiency at small E_γ from punch through
- Need better treatment of coherent effects
- Need additional handles for γ/n separation

Work in progress:

- Better simulation with X_0 for photons a function of E_γ and θ_γ
  - Benefit from effort by AXIAL collaborators to introduce into Geant4 detailed simulation of coherent effects in crystals
- Optimize transverse and longitudinal segmentation to increase γ/n separation

Crystal converter for the NA48 AKS

AKS used to define start of FV for $K_S \rightarrow \pi^0\pi^0$ decays in NA48



22 mm

K_S beam collimator

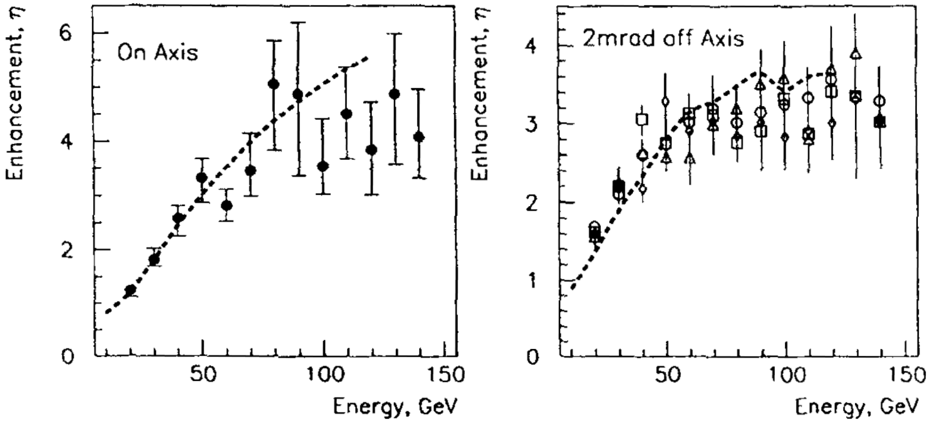
crystal converter

3 mm Ir

Pair-production enhancement from coherent interaction with crystal lattice was studied for AKS development

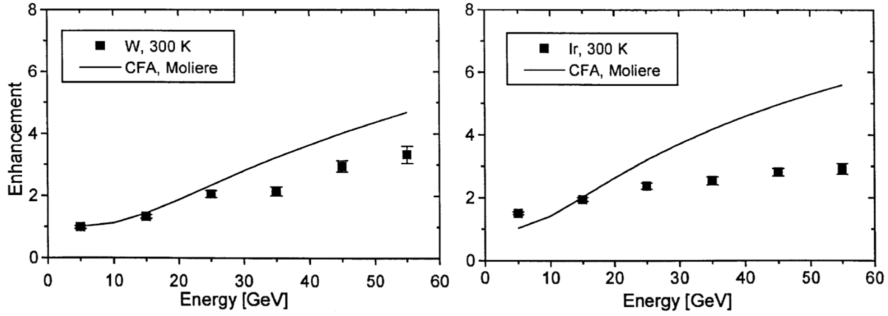
Pair prod. enhancement vs E_γ and θ_γ

Moore et al., NIMB 119, 149 (1996)



On–axis pair prod. enhancement for W and Ir

Kirsebom et al., NIMB 135, 248 (1998)



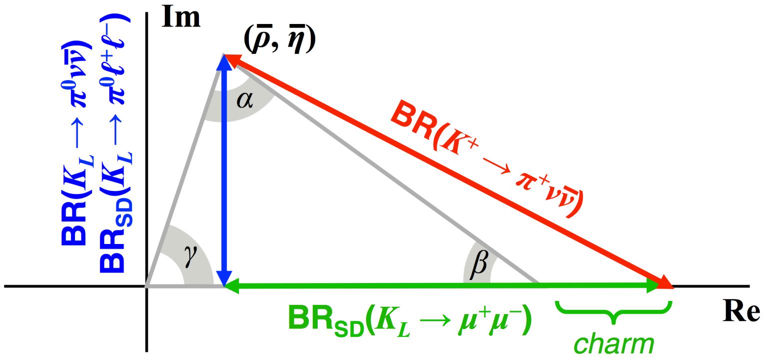
NA48 had use of high-quality crystals from MPI Stuttgart (mosaicity ~ 0.02 deg)
These crystals appear no longer to be commercially available!

$K_L \rightarrow \pi^0 \ell^+ \ell^-$

KLEVER

$K_L \rightarrow \pi^0\ell^+\ell^-$ vs $K \rightarrow \pi\nu\nu$:

- Somewhat larger theoretical uncertainties from long-distance physics
    - SD CPV amplitude: γ/Z exchange
    - LD CPC amplitude from 2γ exchange
    - LD indirect CPV amplitude: $K_L \rightarrow K_S$
- $K_L \rightarrow \pi^0\ell^+\ell^-$ can be used to explore helicity suppression in FCNC decays



$K_L \rightarrow \pi^0\ell^+\ell^-$ CPV amplitude constrains UT in same way as BR($K_L \rightarrow \pi^0\nu\nu$)

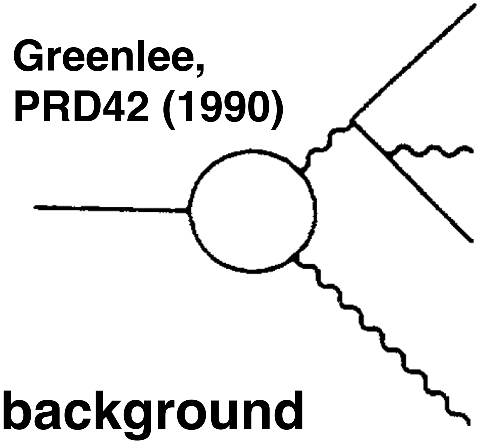
Main background: $K_L \rightarrow \ell^+\ell^-\gamma\gamma$

- Like $K_L \rightarrow \ell^+\ell^-\gamma$ with hard bremsstrahlung

BR($K_L \rightarrow e^+e^-\gamma\gamma$) = (6.0 ± 0.3) × 10^{-7} $E_\gamma^* > 5$ MeV

BR($K_L \rightarrow \mu^+\mu^-\gamma\gamma$) = $10^{+8}_{-6} \times 10^{-9}$ $m_{\gamma\gamma} > 1$ MeV

Greenlee, PRD42 (1990)



$K_L \rightarrow \pi^0e^+e^-$ channel is plagued by $K_L \rightarrow e^+e^-\gamma\gamma$ background

– Small acceptance because of tight cuts on Dalitz plot

$K_L \rightarrow \pi^0\mu^+\mu^-$ channel may be more tractable