Kaon physics

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Outline

1. A few words on V_{us}
2. Rare kaon decays
   - K_S measurements and LHCb
3. $K \to \pi\nu\nu$
   - Aside: $K \to \pi\nu\nu$ and Re ε'/ε
4. $K \to \pi\nu\nu$: NA62
5. $K \to \pi\nu\nu$: KOTO and KLEVER
6. Outlook and summary

V_{us}, CKM unitarity, gauge universality

At present, first-row condition gives most precise test of CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} \sim |V_{ud}|^2 + |V_{us}|^2 \equiv 1 - \Delta_{\text{CKM}}$$

($|V_{ub}|^2 \approx 2\times10^{-5}$)

From $0^+ \to 0^+$ nuclear β decays: $2|V_{ud}|\delta V_{ud} = 0.0004$

From $K_{\ell 3}$ and $K_{\mu 2}$ decays: $2|V_{us}|\delta V_{us} = 0.0003$

Sensitive to new physics at 10-TeV scale

Model independent effective-theory approach

Cirigliano, González-Alonso, Jenkins '10
González-Alonso, Camalich '16

Effective Lagrangian for $\mu \sim 1$ GeV with general set of dim-6 operators giving rise to (semi)leptonic transitions

$$\mathcal{L}^{\text{eff}}_{d^j \to u^i \ell \bar{\nu}} = \mathcal{L}^{\text{eff,SM}}_{d^j \to u^i \ell \bar{\nu}} + \frac{v^2}{\Lambda^2} \mathcal{L}^{\text{eff,NP}}_{d^j \to u^i \ell \bar{\nu}}$$

Consider the **flavor-blind** limit (or similar: minimal flavor violation, etc.)
New physics appears as a small difference between G_{CKM} and G_μ

$$\Delta_{\text{CKM}} = 2\frac{v^2}{\Lambda^2}\left(-\alpha^{(3)}_{\varphi\ell} + \alpha^{(3)}_{\varphi q} - \alpha^{(3)}_{\ell q} + \alpha^{(3)}_{\ell\ell}\right) = \frac{G_{\text{CKM}}}{G_\mu} - 1$$

For Δ_{CKM} known to ~ 0.5×10^{-3} ➡ **$\Lambda^{\text{eff}}_{\text{NP}} > 10$ TeV (90% CL)**

Determination of V_{us} from $K_{\ell 3}$ data

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{\rm EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\rm EM}\right)$$

with $K \in \{K^+, K^0\}$; $\ell \in \{e, \mu\}$, and:

C_K^2 1/2 for K^+, 1 for K^0

$S_{\rm EW}$ Universal SD EW correction (1.0232)

Inputs from experiment:

$\Gamma(K_{\ell 3(\gamma)})$ Rates with well-determined treatment of radiative decays:

- Branching ratios
- Kaon lifetimes

$I_{K\ell}(\{\lambda\}_{K\ell})$ Integral of form factor over phase space: λs parameterize evolution in t

- K_{e3}: Only λ_+ (or λ_+', λ_+'')
- $K_{\mu 3}$: Need λ_+ and λ_0

Data from BNL865, ISTRA+, KLOE, KTeV, NA48, NA48/2 (2003-2008)

Inputs from theory:

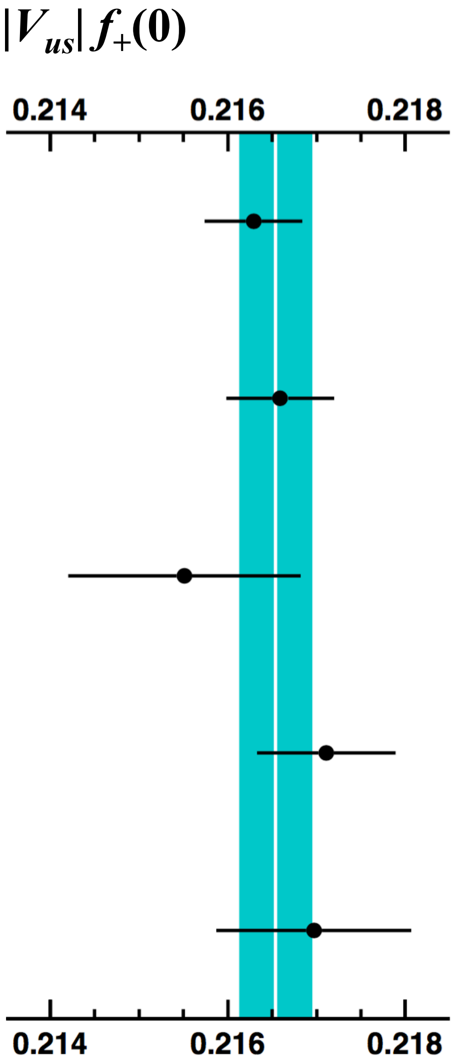
$f_+^{K^0\pi^-}(0)$ Hadronic matrix element (form factor) at zero momentum transfer ($t = 0$)

$\Delta_K^{SU(2)}$ Form-factor correction for $SU(2)$ breaking

$\Delta_{K\ell}^{\rm EM}$ Form-factor correction for long-distance EM effects

Hadronic constants from lattice QCD
See 2017 FLAG review

$|V_{us}|\,f_+(0)$ from world data: Update



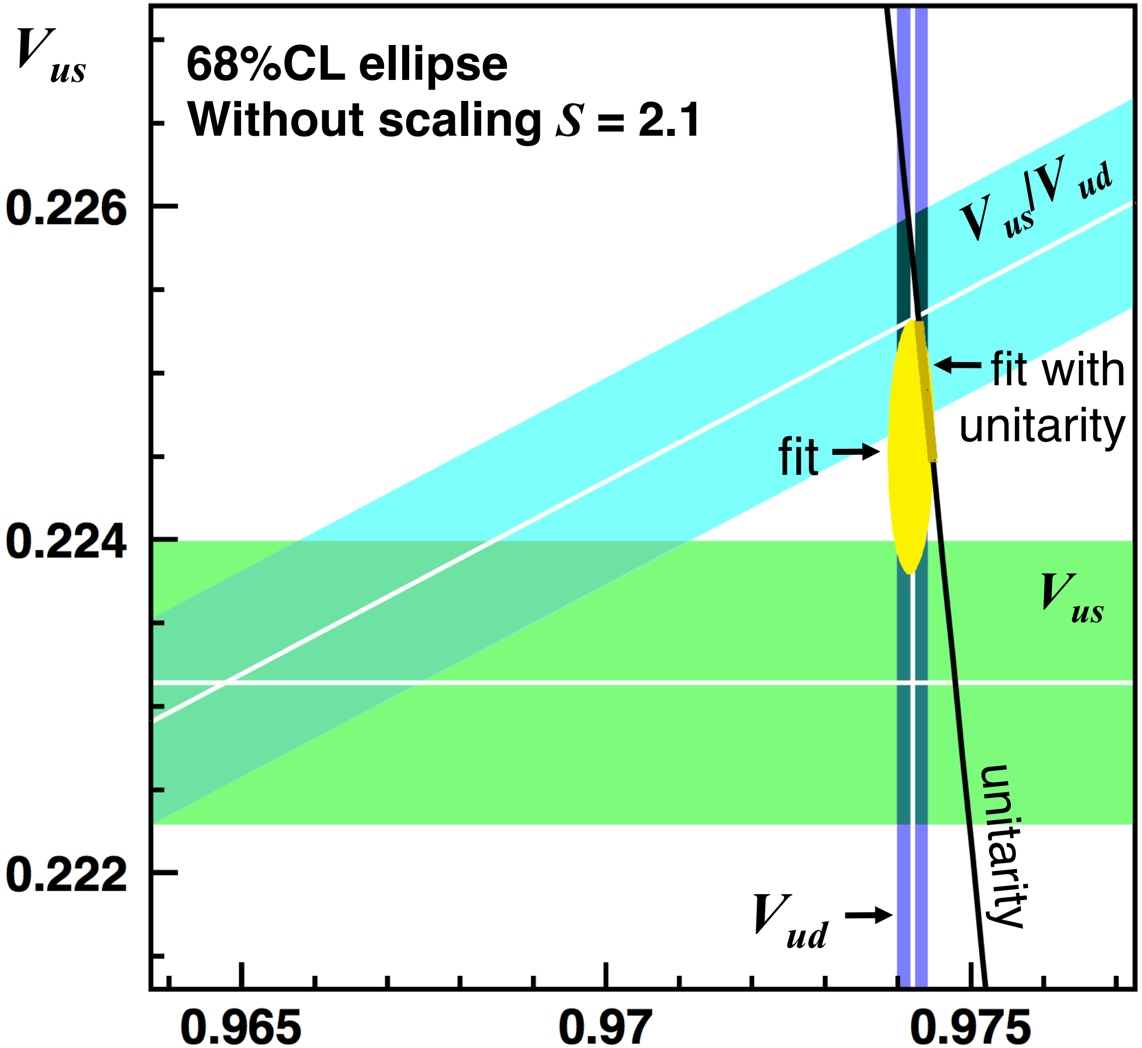
		% err	Approx. contrib. to % err from: BR	τ	Δ	Int
$K_L e3$	**0.2163(6)**	**0.25**	0.09	0.20	0.11	0.05
$K_L \mu 3$	**0.2166(6)**	**0.28**	0.15	0.18	0.11	0.06
$K_S e3$	**0.2155(13)**	**0.61**	0.60	0.02	0.11	0.05
$K^\pm e3$	**0.2171(8)**	**0.36**	0.27	0.06	0.22	0.05
$K^\pm \mu 3$	**0.2170(11)**	**0.51**	0.45	0.06	0.22	0.06

Average: $|V_{us}|\,f_+(0)$ = 0.21654(41) **χ^2/ndf = 1.54/4 (82%)**

V_{us} and CKM unitarity: All data

N_f = 2+1+1: Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$
$f_+(0)$ = 0.9704(32), f_K/f_π = 1.1933(27)

$|V_{ud}|$ = 0.97420(21)
$|V_{us}|$ = 0.2231(9)
$|V_{us}|/|V_{ud}|$ = 0.2308(6)



Fit results, no constraint

V_{ud} = **0.97418(21)**
V_{us} = **0.2246(5)**
χ^2/ndf = 4.2/1 (3.9%)
Δ_{CKM} = **–0.0007(5)**
–1.1σ

With scale factor S = **2.1**

V_{ud} = **0.97418(43)**
V_{us} = **0.2246(10)**

Experimental outlook for V_{us}

- **Uncertainty on V_{us} still (slightly) dominated by hadronic constants**
  Continuing to see impressive progress on the lattice!
- **Good prospects for new round of experimental results to reduce uncertainty on $|V_{us}| f_+(0)$ from current 0.18% to ~0.12% within 5 years**

NA48/2 ➜ **NA62**	K^+ BRs and form factors Runs through 2018
ISTRA+ ➜ **OKA**	K^+ BRs and form factors Runs through 2018
KLOE ➜ **KLOE-2**	Can measure all observables: BRs, τs, FFs: $K^\pm$, K_L, K_S Runs until 03/2018: 2.4 fb^{-1} KLOE + 5 fb^{-1} KLOE-2 data
LHCb	Proven capability to measure K_S decays to muons Can LHCb measure BR($K_S \to \pi\mu\nu$) to < 1% in Run II?
KEK-246 ➜ **TREK E-36**	Main focus is BR($K_{e2}/K_{\mu2}$) KEK-246 measured BR($K_{\mu3}/K_{e3}$) and K_{e3} FF

Rare kaon decays

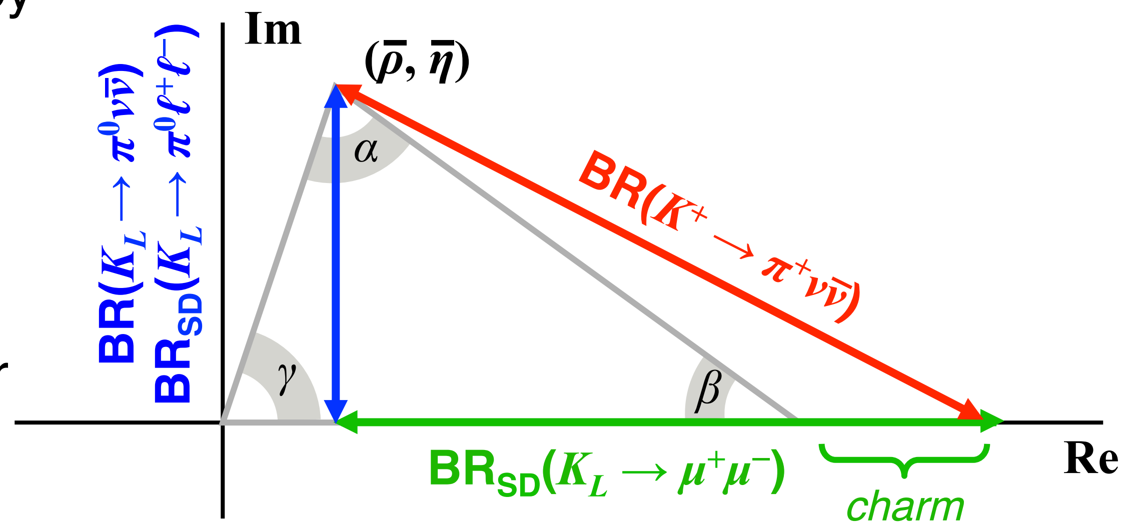
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	35 ± 10	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	14 ± 3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	17 ± 11
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4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

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

FCNC processes dominated by Z-penguin and box diagrams

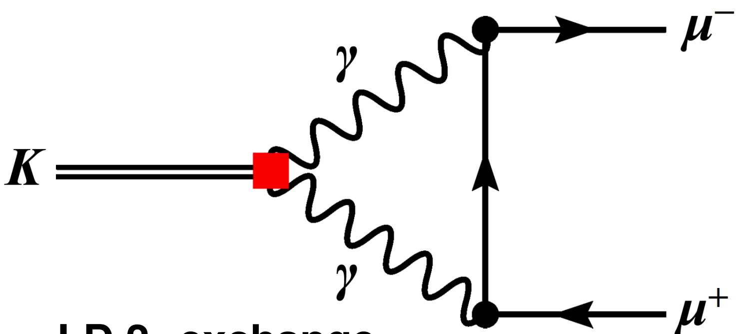
Rates related to V_{CKM} with minimal non-parametric uncertainty

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



Rare K_L and K_S decays

$K_{L,S} \rightarrow \mu\mu$



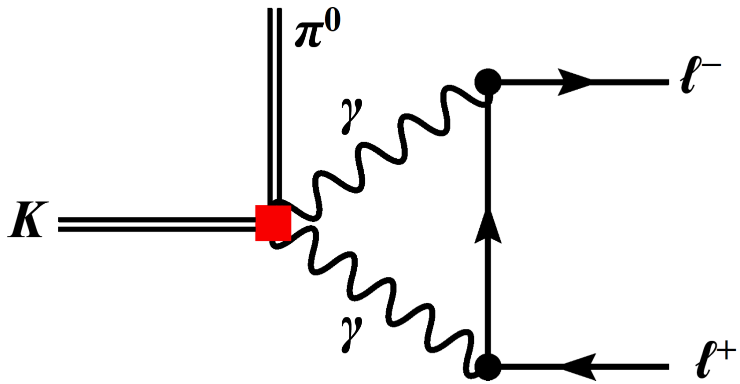
LD 2γ exchange amplitude for $K_L \rightarrow \mu\mu$

LD amplitude from 2γ exchange dominant

$BR_{SM}(K_S \rightarrow \mu^+\mu^-)$ = (5.2 1.5) 10^{-12}

- Significant uncertainty from unknown sign of interference between K_L and K_S amplitudes
- Measurement of K_S BR improves accuracy of theory prediction for K_L BR
- NP contribution to BR($K_S \rightarrow \mu^+\mu^-$) could be as high as 10^{-11}

$K_{L,S} \rightarrow \pi^0\ell\ell$



CPC LD 2γ exchange amplitude for $K_L \rightarrow \pi^0\ell\ell$

Theoretical uncertainties from LD physics

- SD CPV amplitude: γ/Z exchange
- LD CPC amplitude from 2γ exchange
- LD indirect CPV amplitude: $K_L \rightarrow K_S$

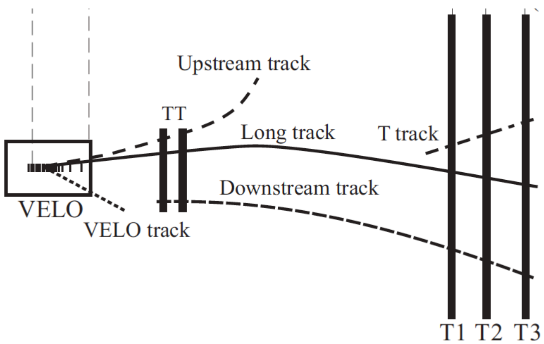
Probes helicity suppression in FCNC decays

Can look for LFU violation, like for $B \rightarrow K\ell\ell$

Rare K_S decays with LHCb

- **10^{13} K_S/fb^{-1} produced in LHCb acceptance**
- Use only “long tracks” to reconstruct K_S

  40% decay in VELO region



- Main limitation:

  HW trigger eff = 2.5%
- Good μ identification and $\mu\mu$ mass resolution

$K_S \to \mu\mu$

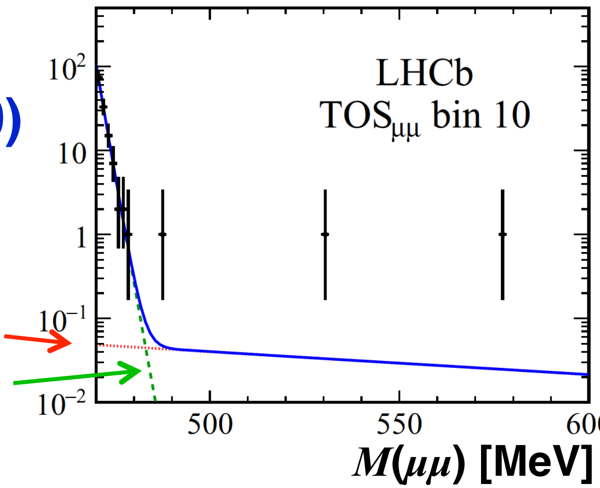
BR < 0.8 × 10^{-9} (CL90)

3 fb^{-1} 2011-12 data

EPJC 77 (2017)

Combinatorial bkg

$\pi^+\pi^-$ mis-ID



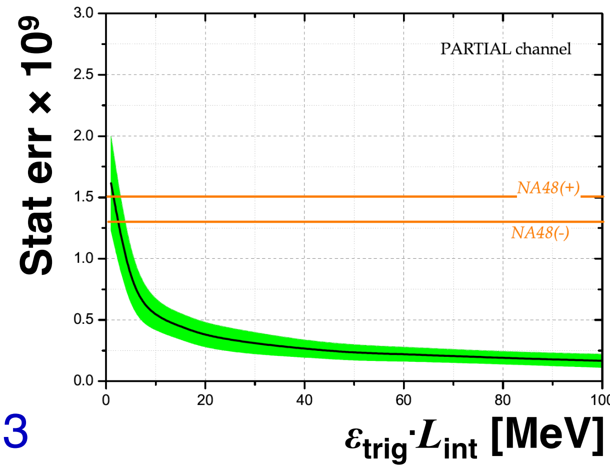
$K_S \to \pi^0\mu\mu$

LHCb Pub 2016-017

Sensitivity study:

- TIS selection
- π^0 not required

Improvement on NA48/1 result is possible in Run 3

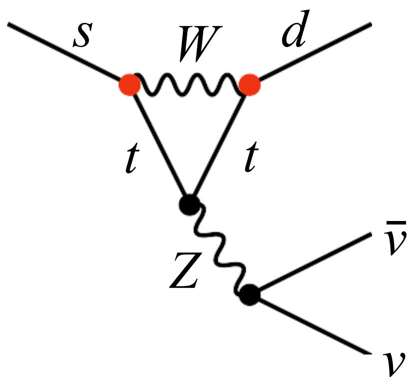


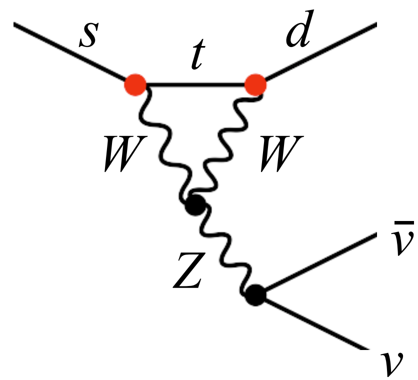
NA48/1 PLB599 (2004)

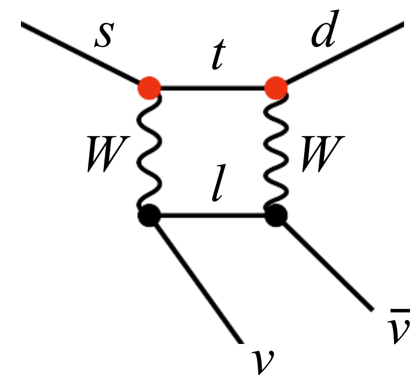
BR($K_S \to \pi^0\mu\mu$) = ($2.9^{+1.5}_{-1.2}$ ± 0.2) × 10^{-9}

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

FCNC processes dominated by Z-penguin and box amplitudes:







Extremely rare decays with rates very precisely predicted in SM:

- Hard GIM mechanism + pattern of CKM suppression ($V_{ts}^* V_{td}$)
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

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

* Tree-level determinations of CKM matrix elements

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

Dominant uncertainties for SM BRs are from CKM matrix elements

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

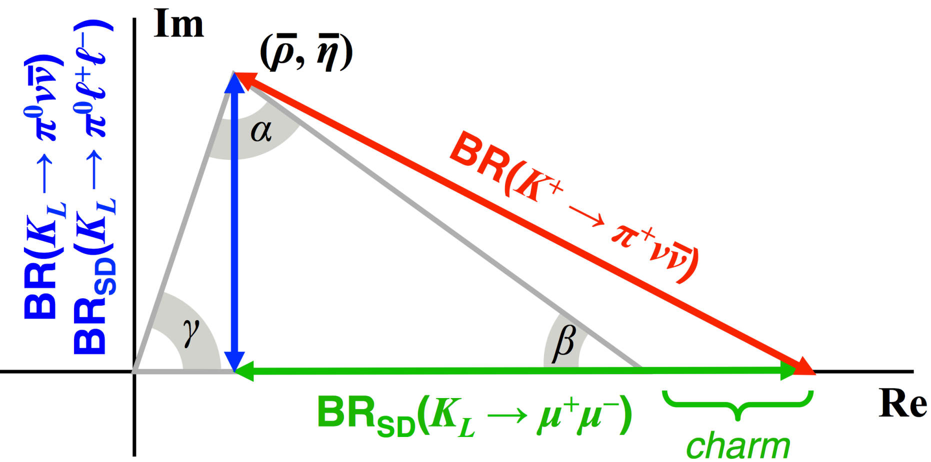
Buras et al., JHEP 1511

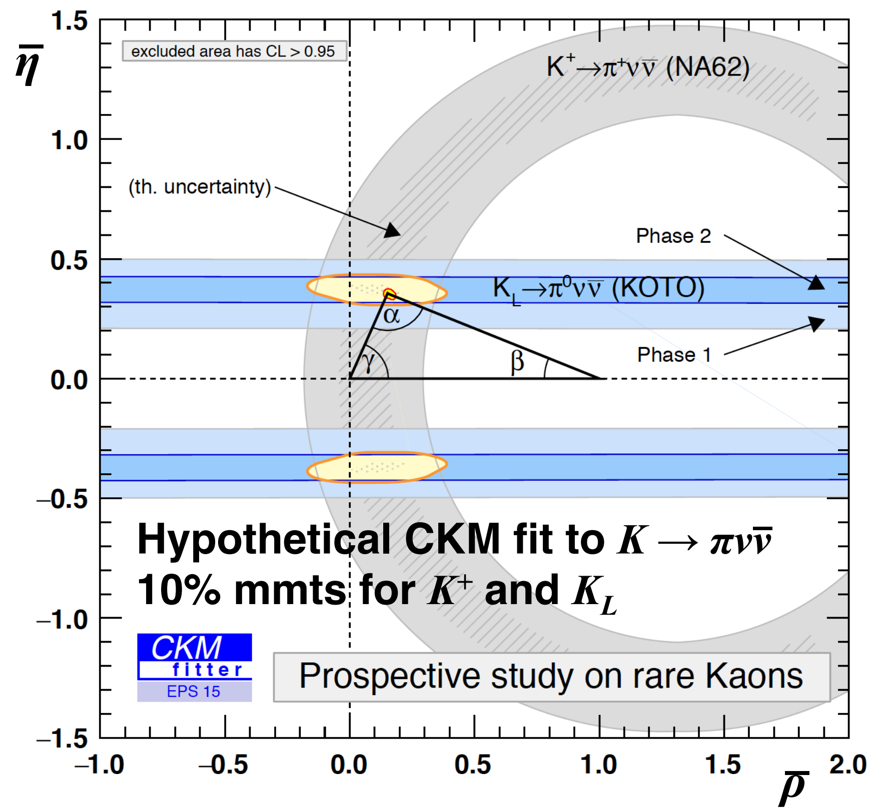
$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

Intrinsic theory uncertainties ~ few percent

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

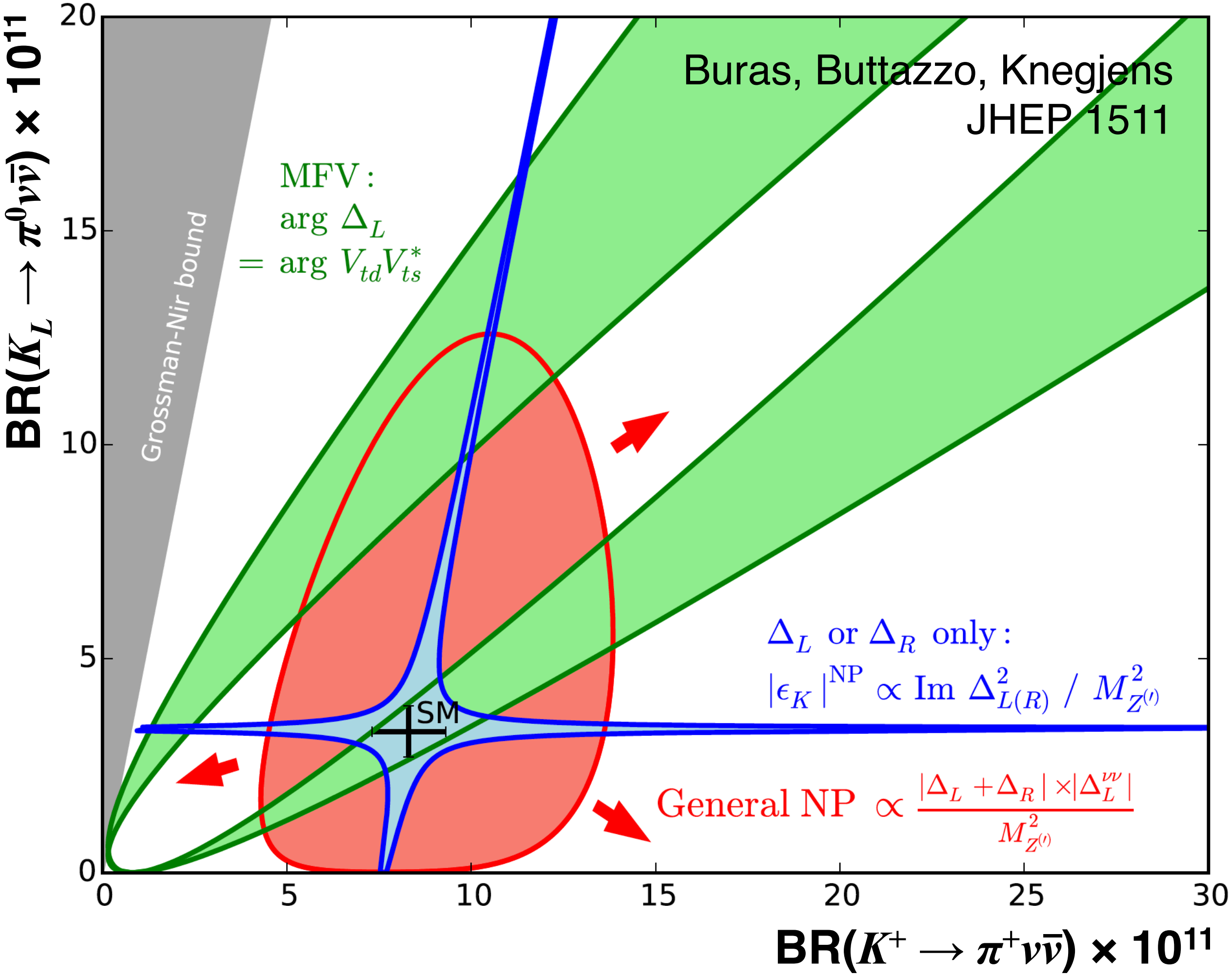
- Overconstrain CKM matrix → reveal NP?





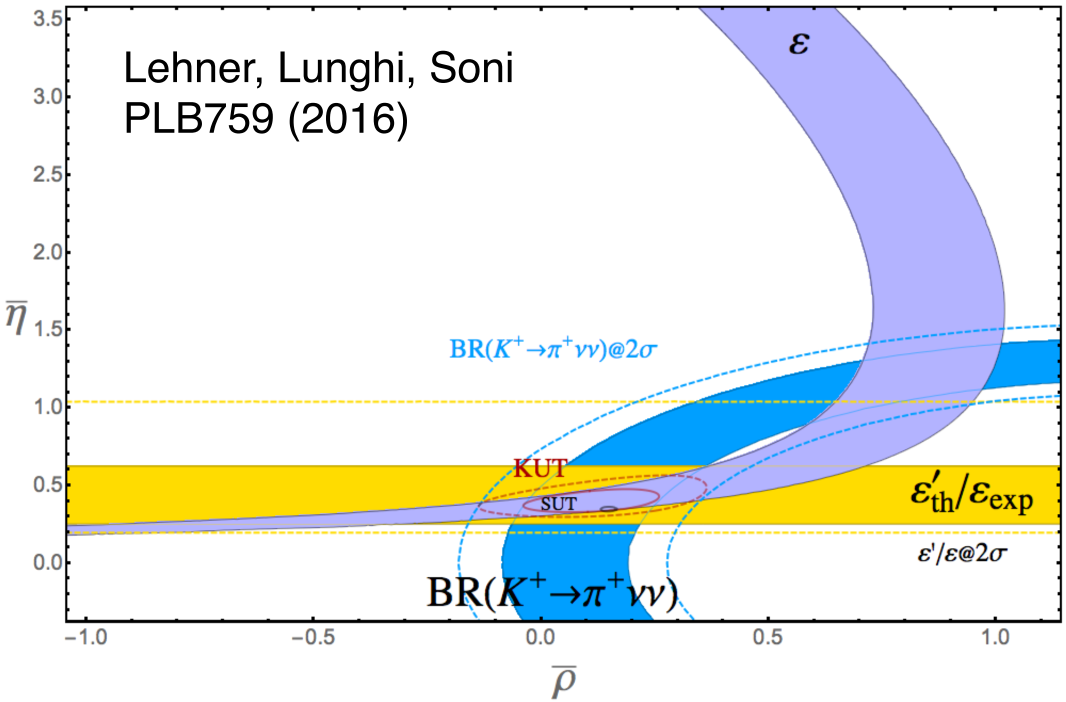
$K \to \pi\nu\bar{\nu}$ and new physics

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

Re ε'/ε vs BR($K_L \to \pi^0 \nu\nu$)



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) = 18%
  $\to \delta$(Re ε'/ε) = 1.6 × 10^{-4}
- BR($K^+ \to \pi^+ \nu\nu$) = SM value with 10% error

PDG average: NA48 + KTeV

Re ε'/ε = (16.6 ± 2.3) × 10^{-4}

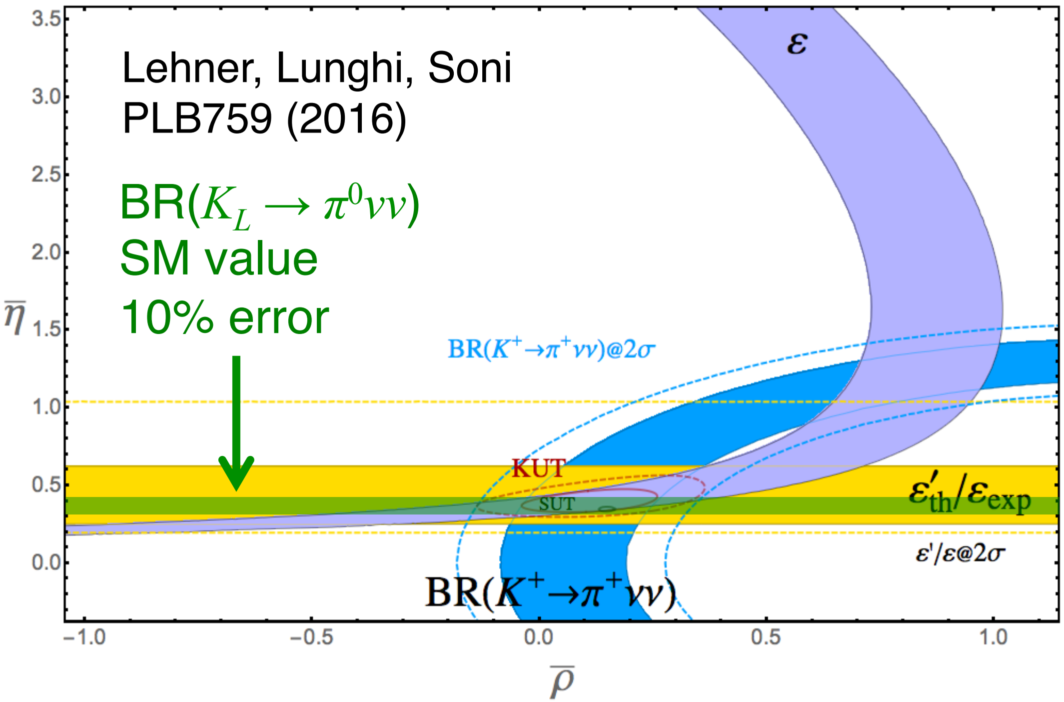
Calculations for Re ε'/ε × 10^4:

Lattice: RBC/UKQCD '15	**1.38 ± 5.15 ± 4.59**
ChPT: Gisbert & Pich '17	**15 ± 7**

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

- Dominant uncertainty is lattice spacing (single spacing for A_0)
- Claim: Uncertainty ~10% of experimental value can be reached in ~5 years!
- Results with 2nd lattice spacing should be available sooner

Re ε'/ε vs BR($K_L \to \pi^0 \nu\nu$)



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Does this impact the attractiveness as an observable of BR($K_L \to \pi^0\nu\nu$)?

- Re ε'/ε is dominated by **systematics**

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

- Can R ever be measured to ~0.06% for δ(Re ε'/ε) ~ 1 × 10^{-4}?
- **A 10% mmt of BR($K_L \to \pi^0\nu\nu$) offers better constraint on UT**

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

What about constraints from Re ε'/ε, ε_K, Δm_K, $K_L \to \mu\mu$?

Particular interest in NP scenarios to explain difference between experimental and lattice QCD values for Re ε'/ε

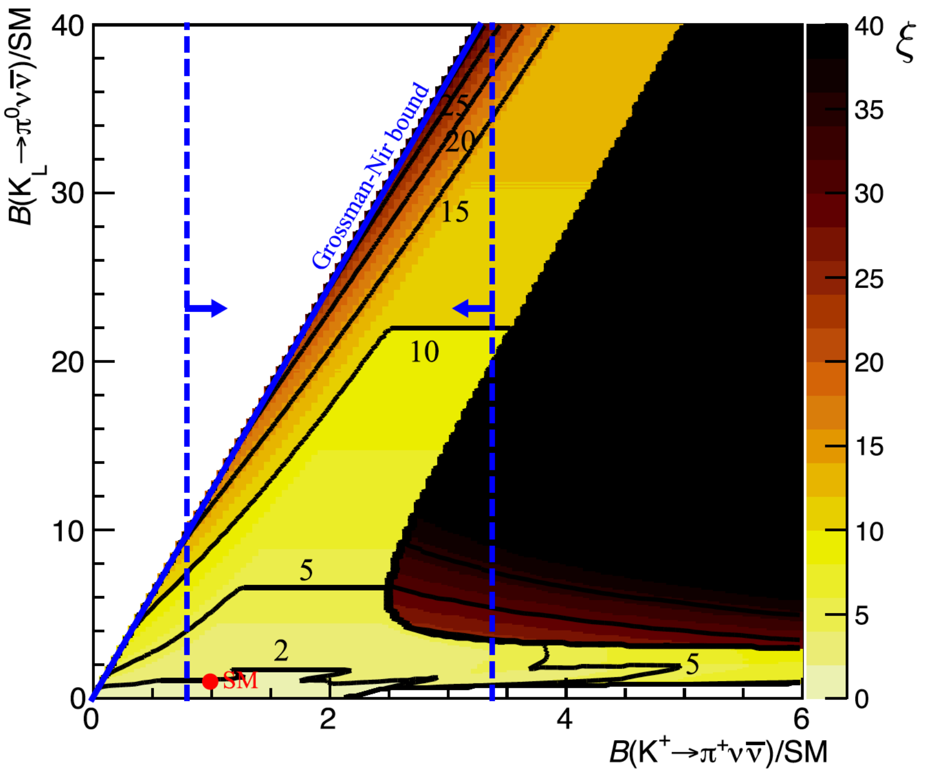
Example: Endo et al. PLB771 (2017)

General Z scenario with modified couplings, Λ = 1 TeV

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

  BR($K \to \pi\nu\nu$) ~ 0.5 SM BR

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



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

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

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

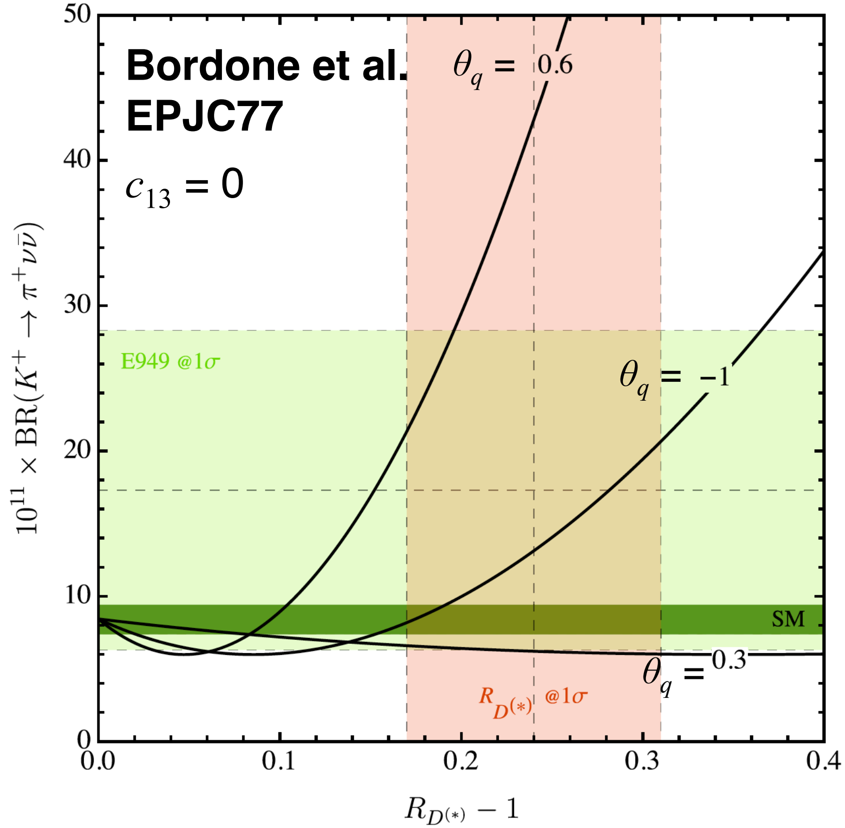
$R_{D(*)}$: $\tau/(\mu, e)$ LFU in $B \to D^{(*)}\ell\nu$

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

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

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

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



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

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

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

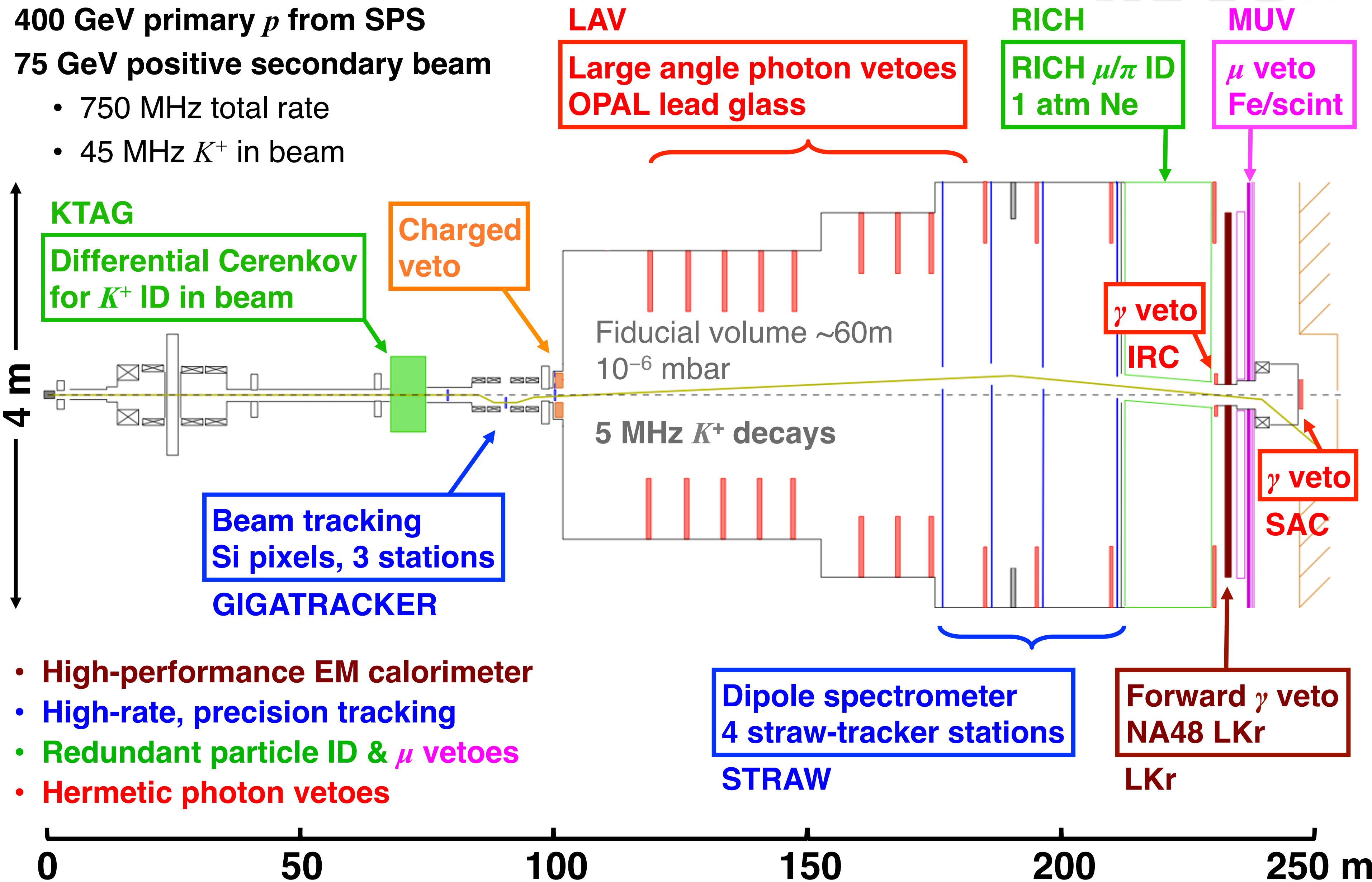
The NA62 experiment at the CERN SPS

The NA62 experiment at the SPS

400 GeV primary p from SPS

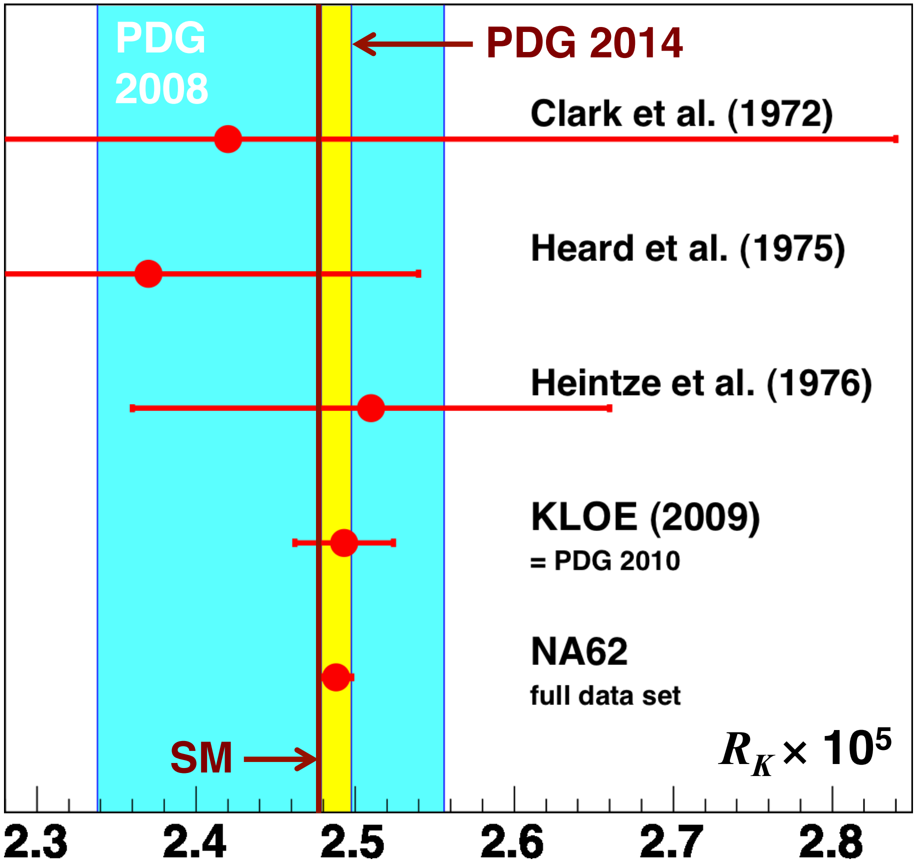
75 GeV positive secondary beam

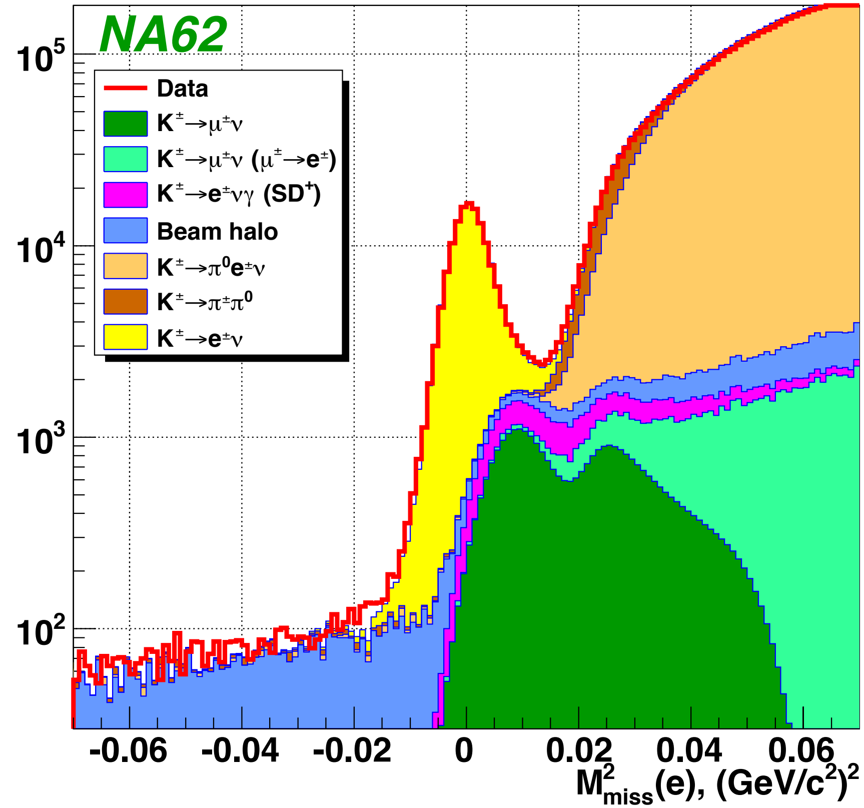
- 750 MHz total rate
- 45 MHz K^+ in beam



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

NA62-R_K result for $\Gamma(K_{e2})/\Gamma(K_{\mu2})$





2007 data taking, pre $\pi\nu\nu$-phase

PLB 719 (2013)

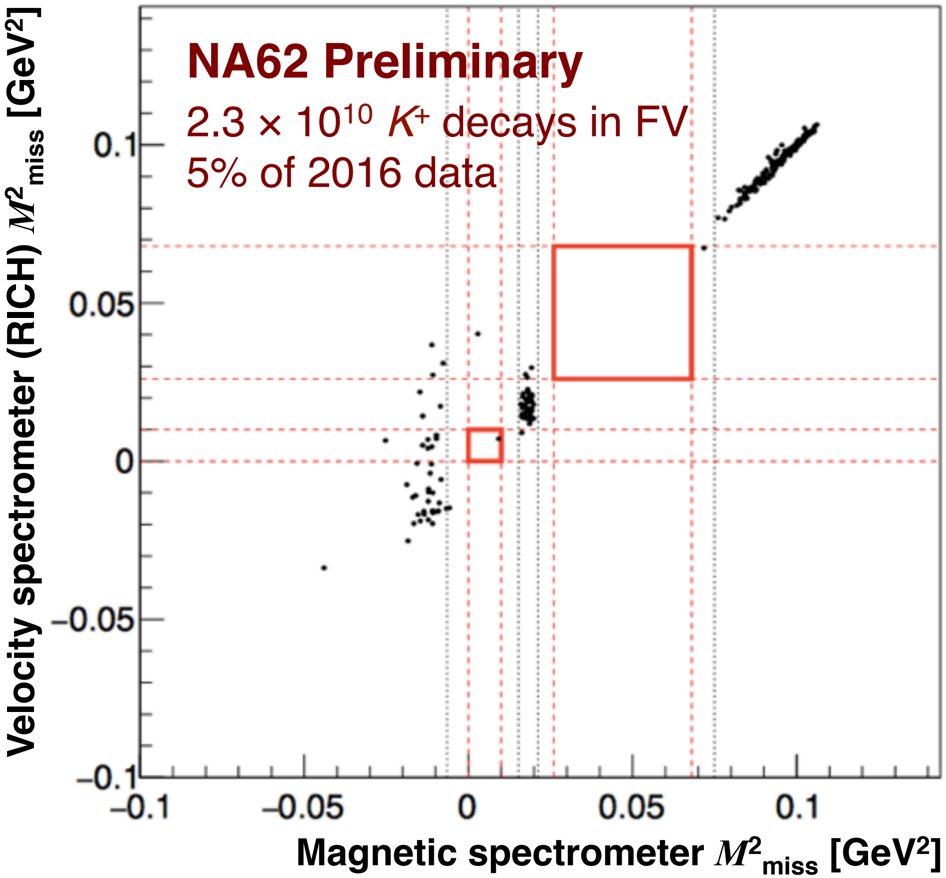
$$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5}$$
$$= 2.488(10) \times 10^{-5}$$

0.4% overall precision

Better background rejection expected with NA62 detectors for $K \to \pi\nu\nu$:

- RICH to suppress $K_{\mu2}$ with catastrophic bremsstrahlung
- Photon vetoes to suppress $K_{e2\gamma}$(SD+)
- Straw chambers in vacuum to reduce MS and improve $M^2_{\rm miss}$ resolution

Status and outlook for $K^+ \to \pi^+ \nu\nu$



Preliminary results: 2016 data
First physics run with full detector

Expected backgrounds

$\pi^+\pi^0$	0.035
$\mu\nu$	0.024
$\pi^+\pi^+\pi^-$	0.003

Ongoing evaluation of contributions from upstream decays, radiative decays and beam interactions

With all 2016 data, SM sensitivity (BR ~ 10^{-10}) reached

Results from full 2016 data set will be presented in spring 2018

30 weeks of data taking per year for 2017-2018

- Processing of 2017 data in progress

Assuming running is as smooth as in 2017, by the end of 2018 NA62 will reach a sensitivity of 20-30 SM $K^+ \to \pi^+\nu\nu$ events

Fixed target runs at the SPS

2021 (Run 3):

- NA62 will continue data taking for $K^+ \to \pi^+ \nu\nu$
  O(100) SM events – measure BR to 10%
- Searches for hidden particles in beam-dump mode
  Dark photons, ALPs, heavy neutrinos, scalars…

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

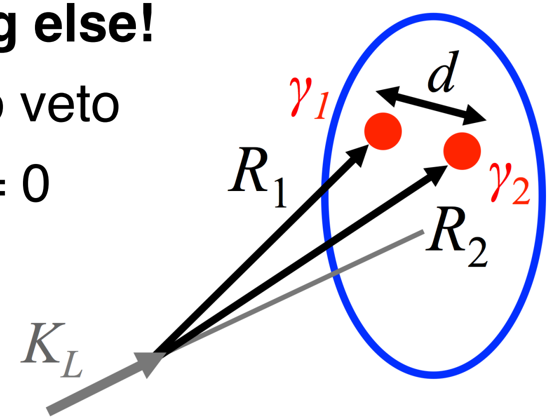
F. Bordry, presentation to HEPAP, Dec 2015

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

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

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

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



K_L momentum generally is not known

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

Generally used to reconstruct vertex position

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

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

Main backgrounds:

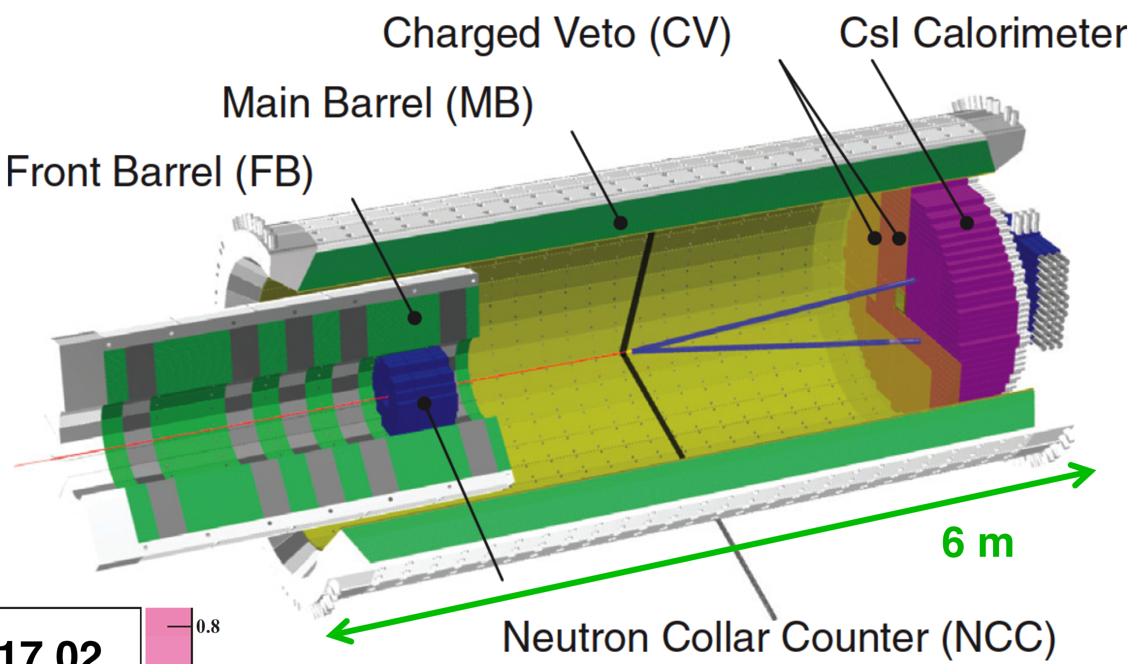
Mode	BR	Methods to suppress/reject
$K_L \to \pi^0\pi^0$	8.64×10^{-4}	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi^0\pi^0\pi^0$	19.52%	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi e\nu(\gamma)$	40.55%	Charged particle vetoes, π ID, γ vetoes
$\Lambda \to \pi^0 n$		Beamline length, $p_\perp$
n + gas $\to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

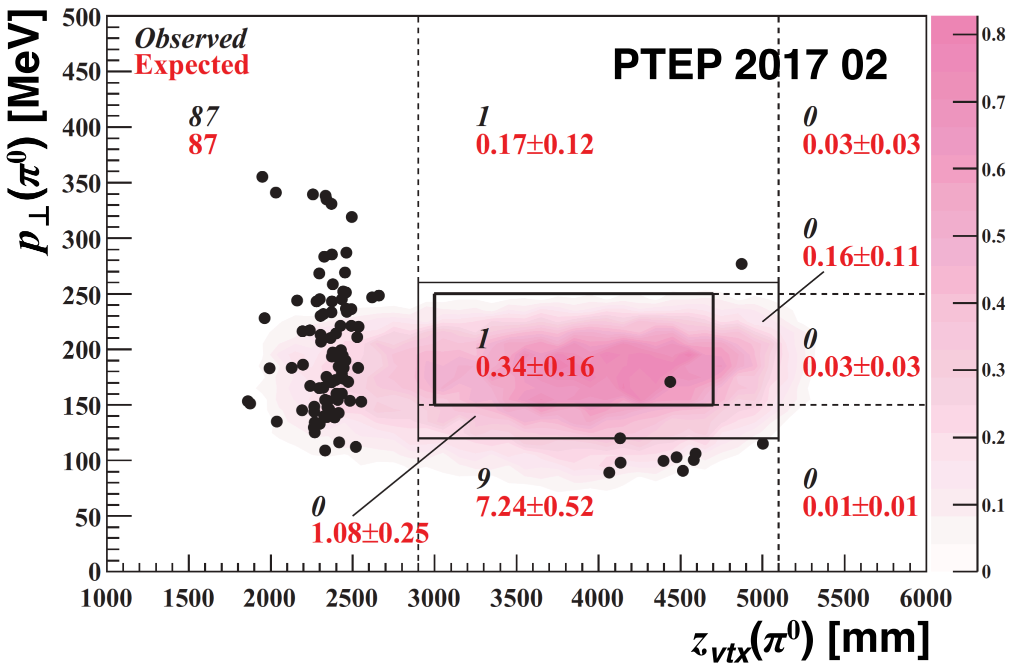
$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC

KOTO

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





Based on KEK-391a:
- Current experimental value
- **BR($K_L \to \pi^0 \nu\nu$) ≤ 2.6 × 10^{-8} (90%CL)**

100-hour KOTO pilot run in 2013:
- **BR($K_L \to \pi^0 \nu\nu$) ≤ 5.1 × 10^{-8} (90%CL)**

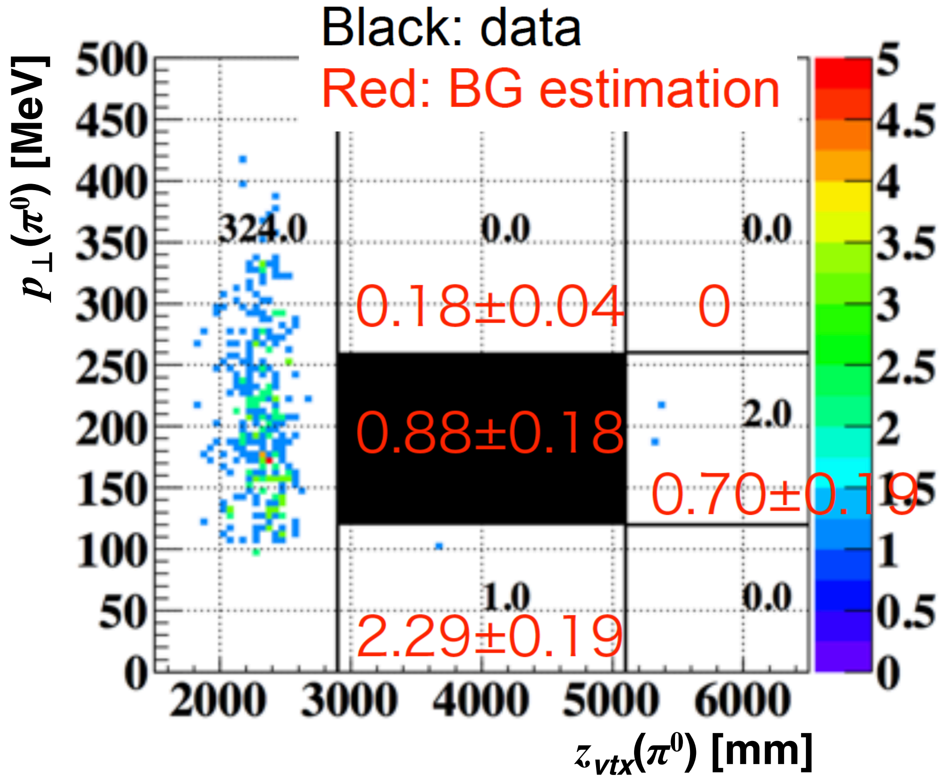
Taking data since 2015

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

Current status:

- Reached **44 kW** of slow-extracted beam power in 2017
- Preliminary results, all 2015 data:
  SES = 1.2 × 10^{-9}
  Expected bkg = 0.9 ± 0.2 events
  Signal box not yet unblinded
  Bkg estimate still under study
- With all 2015-2017 data, expected sensitivity below Grossman-Nir limit
- In 2018 beam power will increase to **50 kW**

J-PARC PAC, Jan 2018

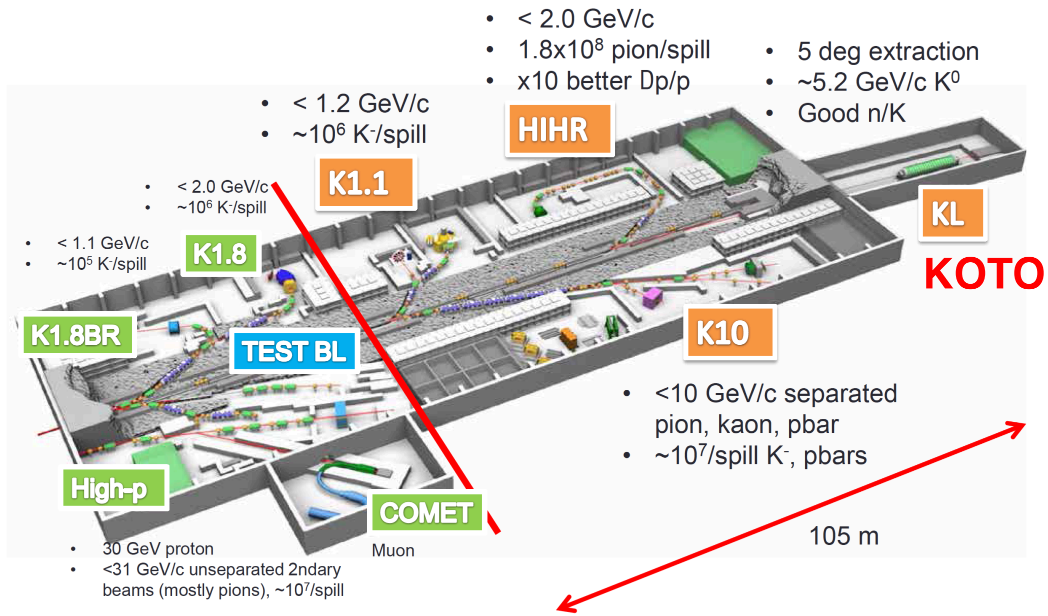


- Continuing program of upgrades to reduce background:
  New barrel veto (2016), both-end readout for CsI crystals (2018)
- **Expect to reach SM sensitivity by 2021**

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

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

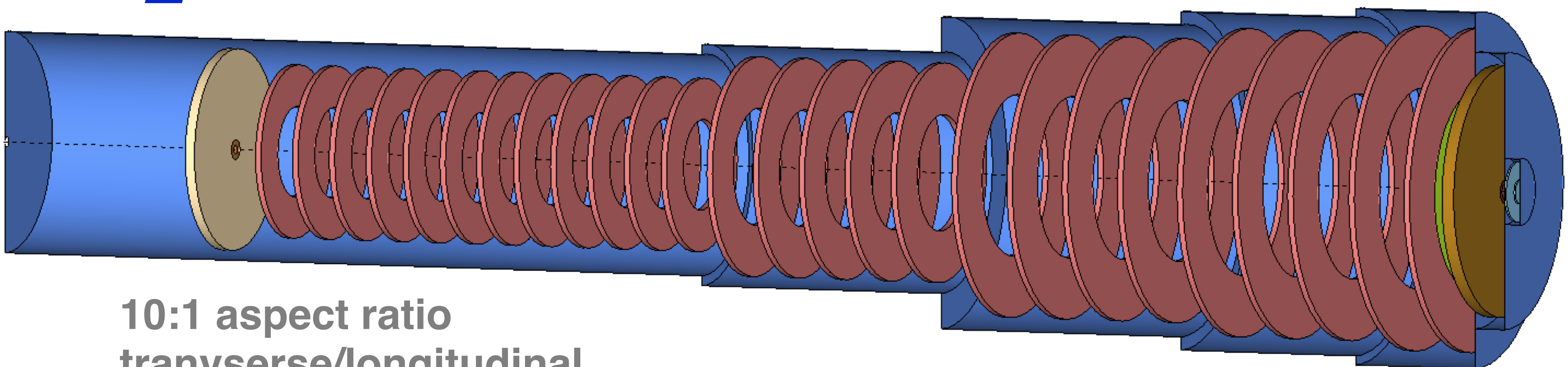


Strong intention to upgrade to O(100) event sensitivity over long term:

- No official Step 2 proposal yet (plan outlined in 2006 KOTO proposal)
- Scaling from 2006 estimates: **~10 SM evts/yr per 100 kW beam power**
- Exploring possibilities for machine & detector upgrades to further increase sensitivity
- Indicative timescale: data taking starting 2025?

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

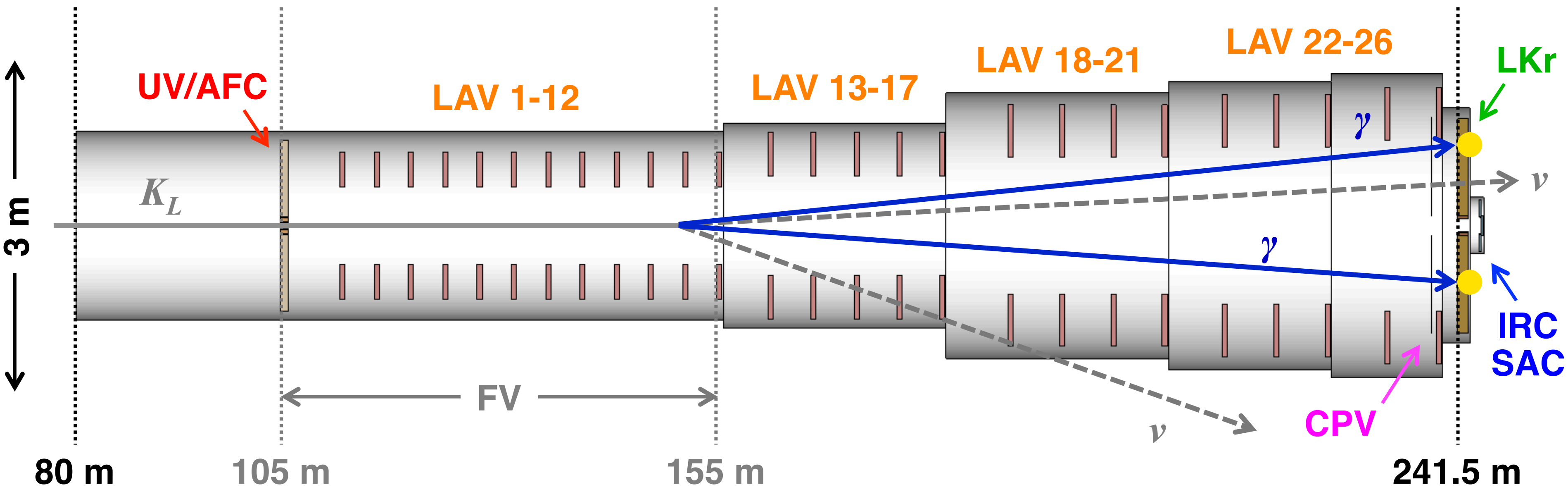
K_LEVER — K_L Experiment for VEry Rare events



10:1 aspect ratio
tranvserse/longitudinal

- High-energy experiment: Complementary approach 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
- Possible to re-use LKr calorimeter, NA62 experimental infrastructure?
- **Target sensitivity: 60 $K_L \to \pi^0 \nu\nu$ events at SM BR, with $S/B = 1$**

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



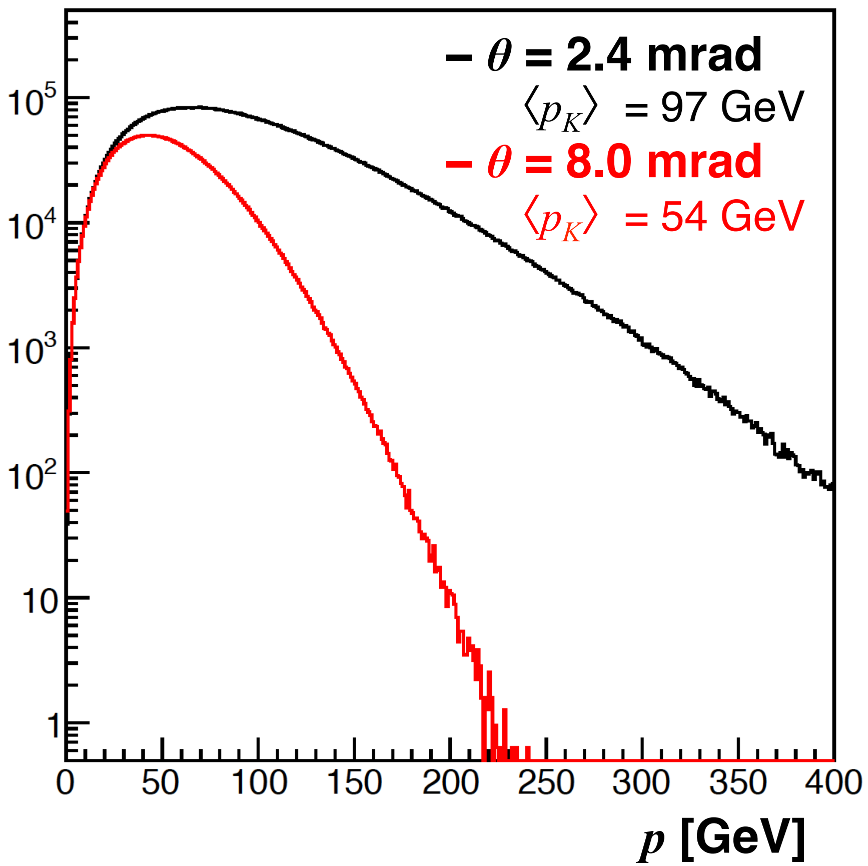
Main detector/veto systems:

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

Beam and intensity requirements

KLEVER

All K_L in beam



Beam parameters:

- **400 GeV p on 400 mm Be target**
- **Production at $\theta = 8.0$ mrad:**
  - As much K_L production as possible
  - Low ratio of (K_L in FV)/n
  - Reduce Λ production and soften momentum spectrum
- Solid angle $\Delta\theta = 0.4$ mrad
  - Large $\Delta\theta$ = high KL flux
  - Tight beam collimation improves background rejection

1.6 x 10-5 KL in beam/pot

Required total proton flux = 5 × 10^{19} pot

10^{19} pot/year (= 100 eff. days)
E.g.: 2 × 10^{13} ppp/16.8 s

Probability for decay inside FV **~ 2%**
Acceptance for decays occurring in FV ~ 10%

50-60 detected $K_L \to \pi^0 \nu\nu$ evts/yr

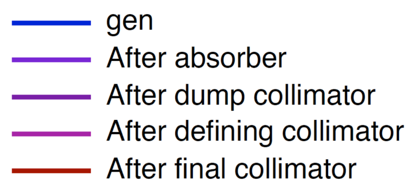
Neutral beam simulation

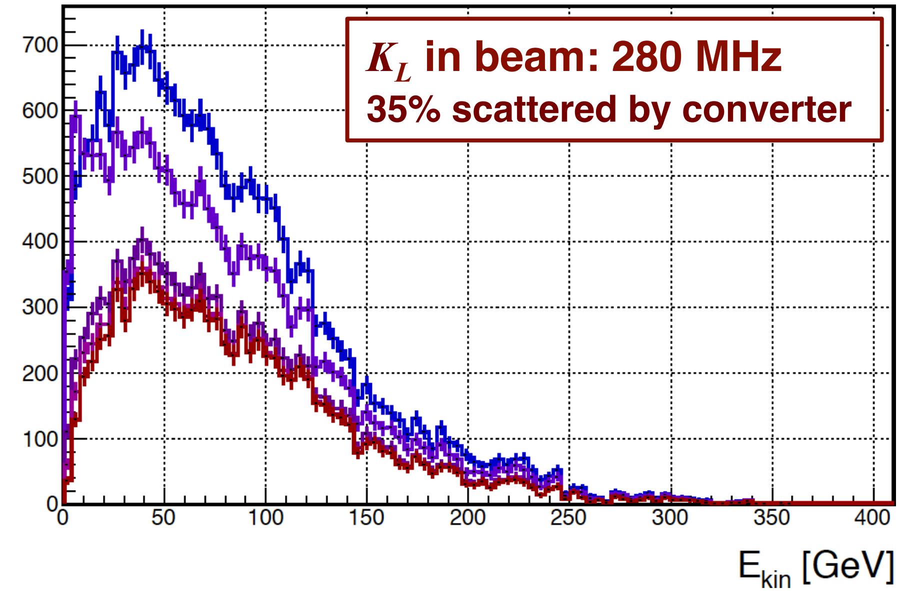
KLEVER

FLUKA simulation of 400 GeV p on 400-mm Be target

Geant4 simulation of beamline

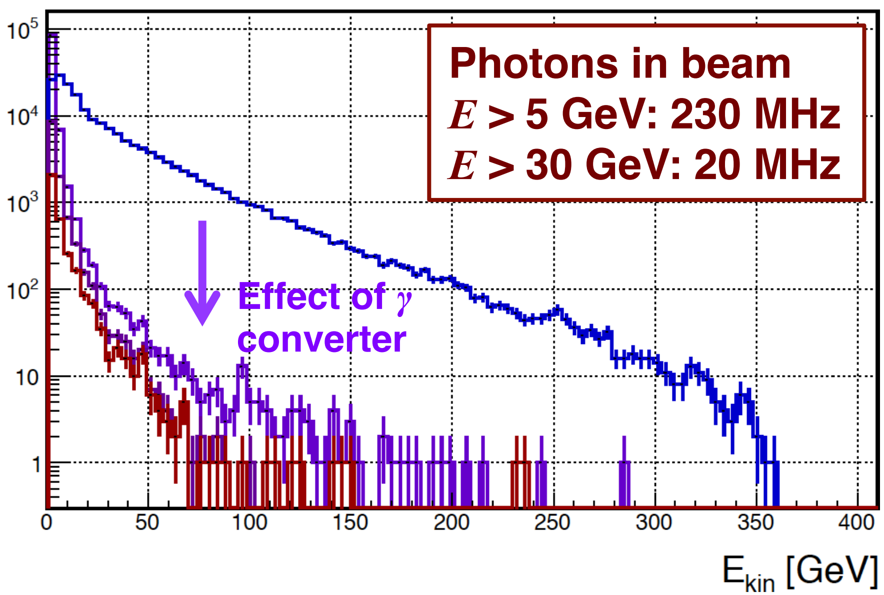
- 3 collimators, $\Delta\theta = 0.3$ mrad
- 30-mm Ir photon converter in dump collimator

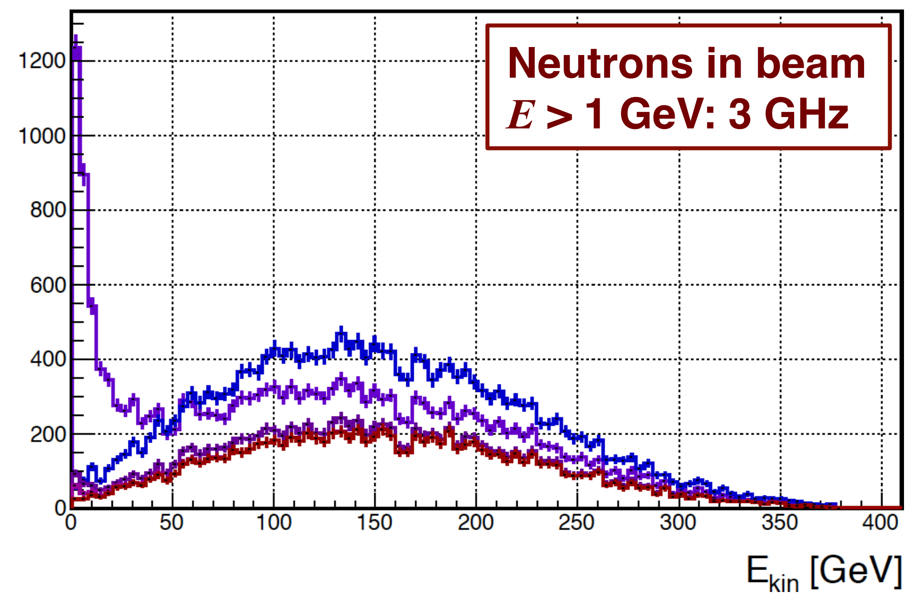




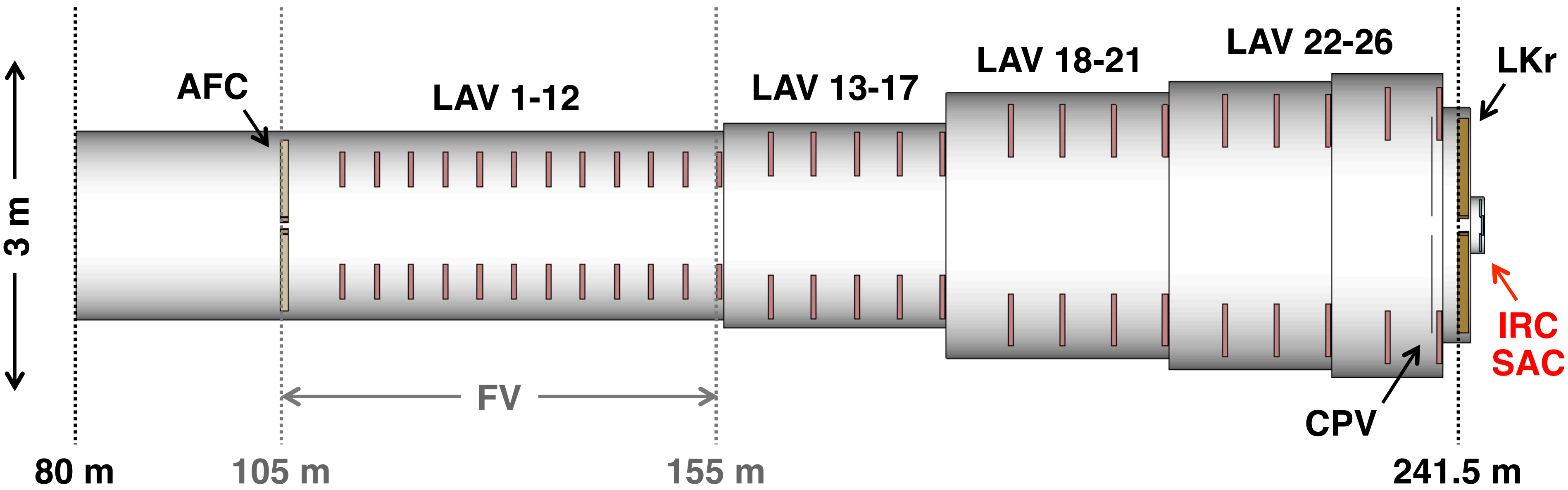
2.4 mrad

Simulation for 8 mrad in progress





Small-angle photon vetoes



Small-angle photon veto systems (IRC, SAC)

- Reject high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 3 GHz of beam neutrons

Beam comp.	Rate (MHz)	Req. $1-\varepsilon$
γ, $E > 5$ GeV	**230**	**10^{-2}**
γ, $E > 30$ GeV	**20**	**10^{-4}**
n	**3000**	**–**

Baseline solution:

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

Efficient γ conversion with crystals

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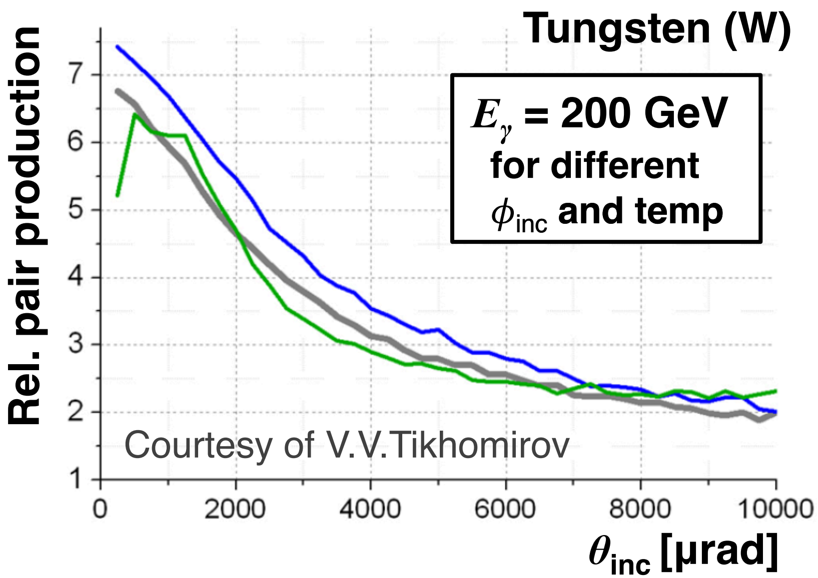
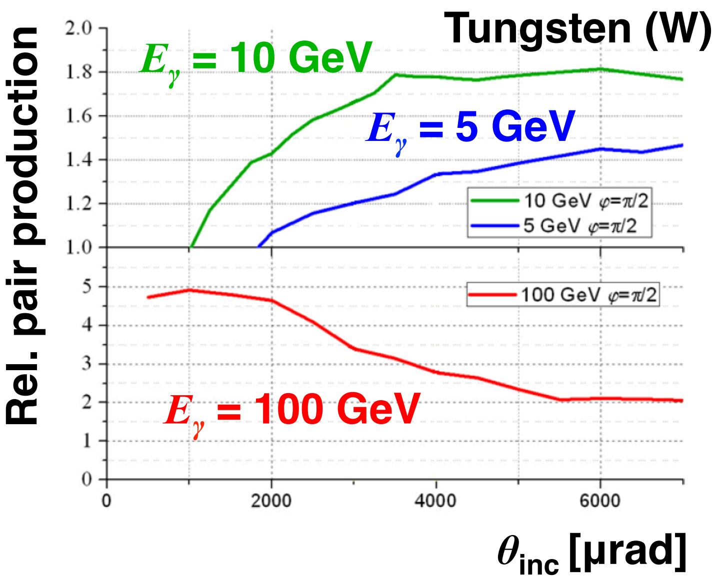
Coherent effects in crystals enhance pair-conversion probability





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

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

Status and timeline

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Project timeline – target dates:

2017-2018	**Project consolidation and proposal** • Beam test of crystal pair enhancement • Consolidate design
2019-2021	**Detector R&D**
2021-2025	**Detector construction** • Possible K12 beam test if compatible with NA62
2024-2026	**Installation during LS3**
2026-	**Data taking beginning Run 4**

- **KLEVER is actively seeking new collaborators!**
- Expression of Interest to the SPSC is under preparation in context of Physics Beyond Colliders initiative

Summary and outlook

Good progress from lattice and prospects for new experimental results to improve 1st -row unitarity test from V_{us}

LHCb has demonstrated unprecedented sensitivity for rare K_S decays

$K \to \pi\nu\nu$ is a uniquely sensitive indirect probe for high mass scales

- Need precision measurements of both K^+ and K_L decays

NA62 will improve on current knowledge of BR($K^+ \to \pi^+\nu\nu$) in short term, ultimately reaching ~100 event sensitivity

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

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

- Many issues still to be addressed!
- Expected sensitivity: ~ 60 SM events with $S/B \sim 1$
- Comparable in precision to KOTO Step 2, with complementary technique (high vs. low energy) and different systematics

Additional information

GDR-InF Workshop: The Future of the Intensity Frontier
CERN, 2 February 2018

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High-intensity neutral beam issues

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

Feasibility/cost study a primary goal of our involvement in Conventional Beam WG

Preliminary analysis of critical issues by Secondary Beams & Areas group

Issue	Approach
Extraction losses	Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) Slow extraction workshop, 9-11 November: https://indico.cern.ch/event/639766/
Beam loss on T4	Vertical by-pass to increase transmission to T10
Equipment protection	Possibly use SIS interlock to stop extraction during P0Survey reaction time
Ventilation in ECN3	Need to understand better current safety margin May need comprehensive ventilation system upgrade
ECN3 beam dump	Significantly improved for NA62 Need to understand better current safety margin
Background fluxes	Detailed simulations getting started