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

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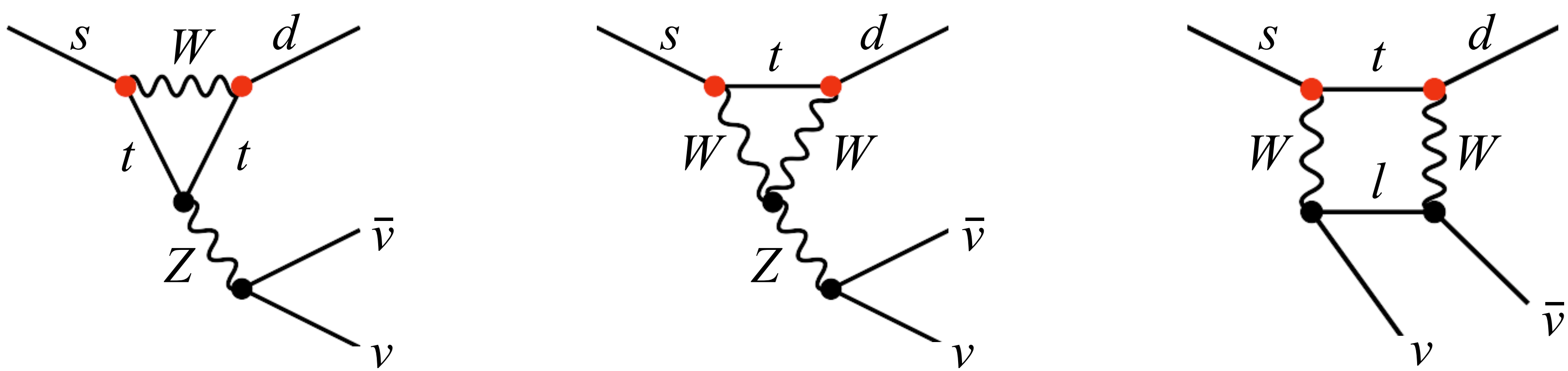
Physics Beyond Colliders Kickoff Workshop
CERN, 7 September 2016

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

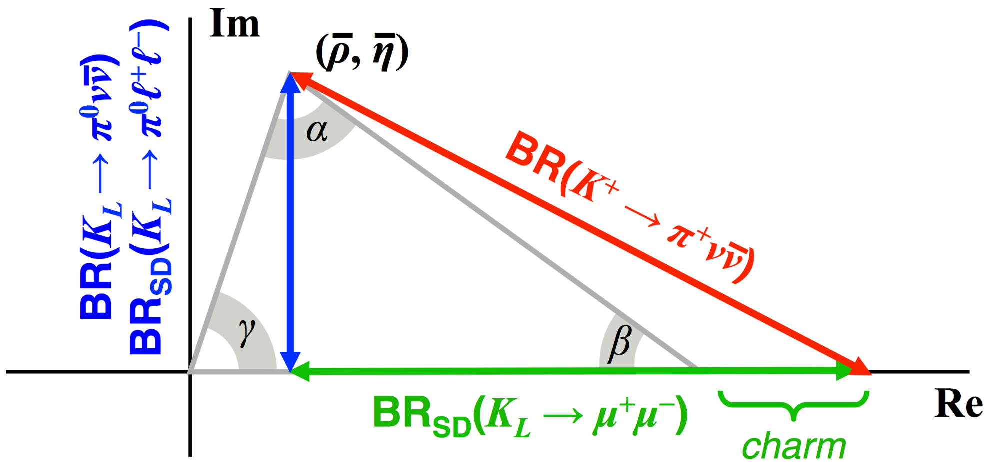
Dominant uncertainties for SM BRs are from CKM matrix elements

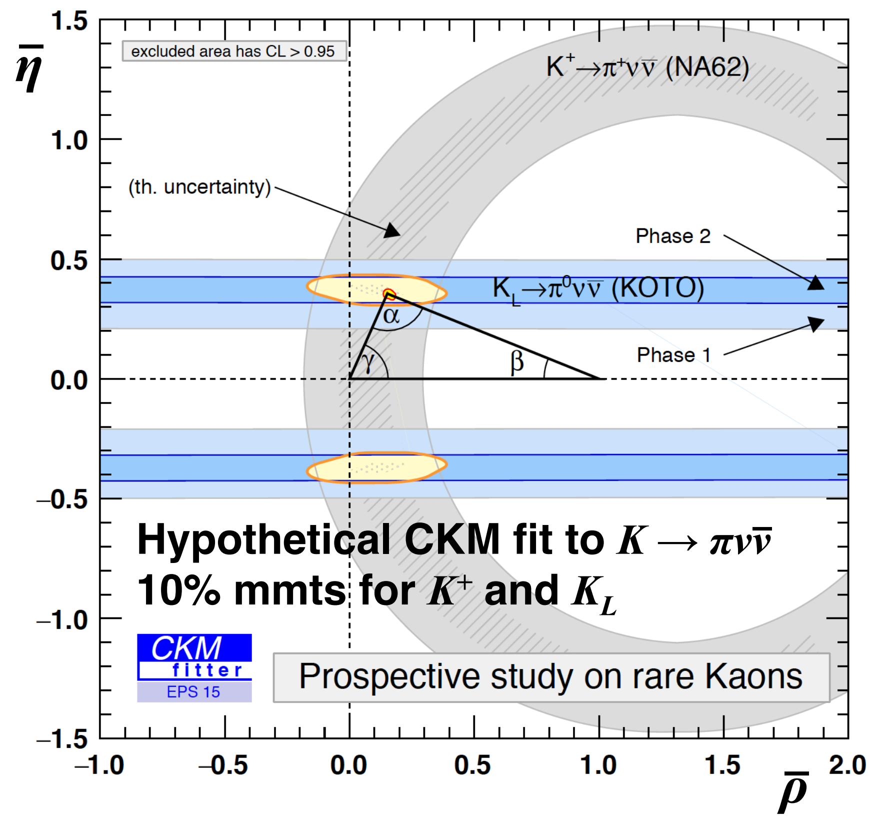
$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

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
- BR measurements for both K^+ and K_L determine the unitarity triangle independently from B inputs
  - Overconstrain CKM matrix → reveal NP?

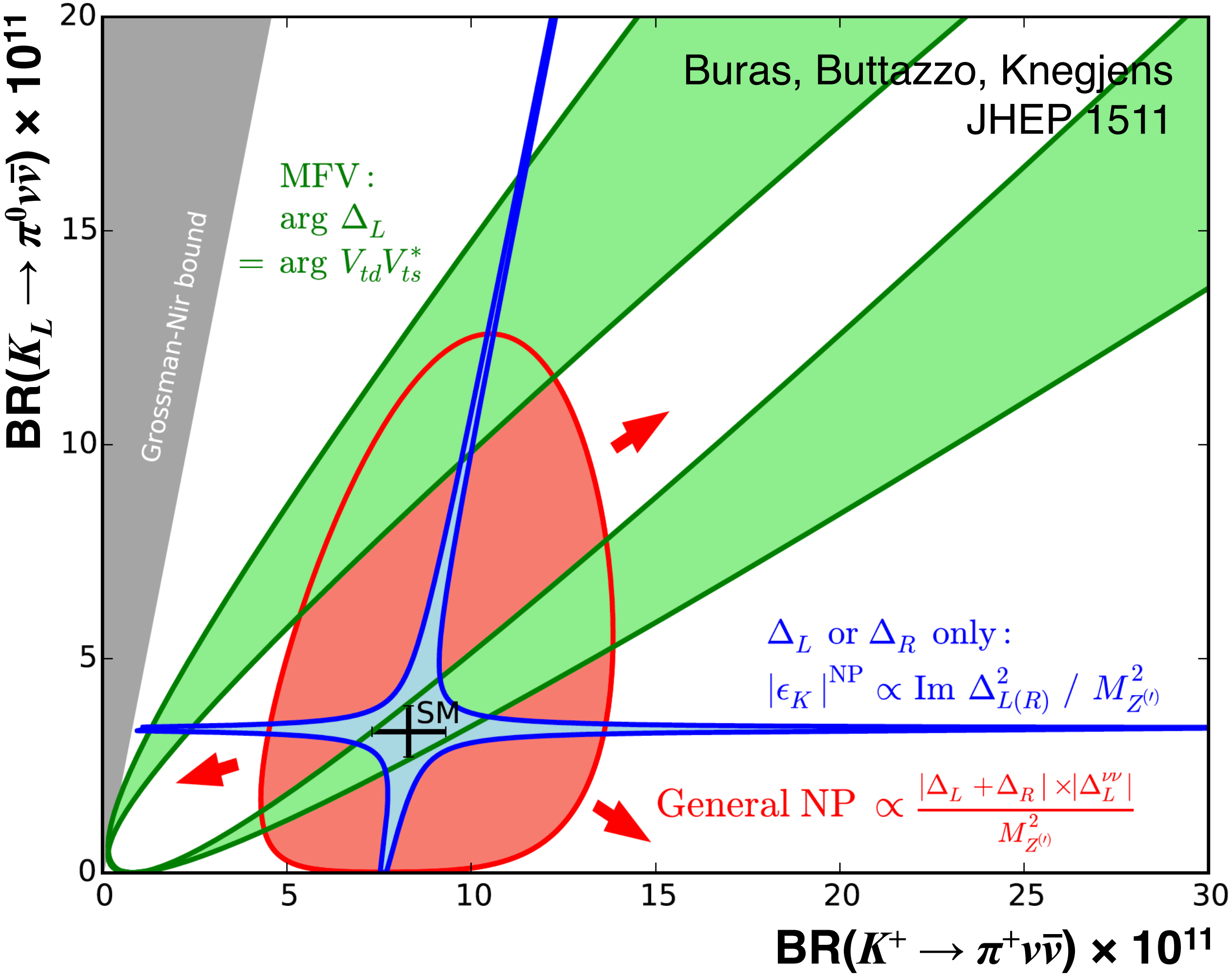




$K \to \pi\nu\bar{\nu}$ and new physics

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

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

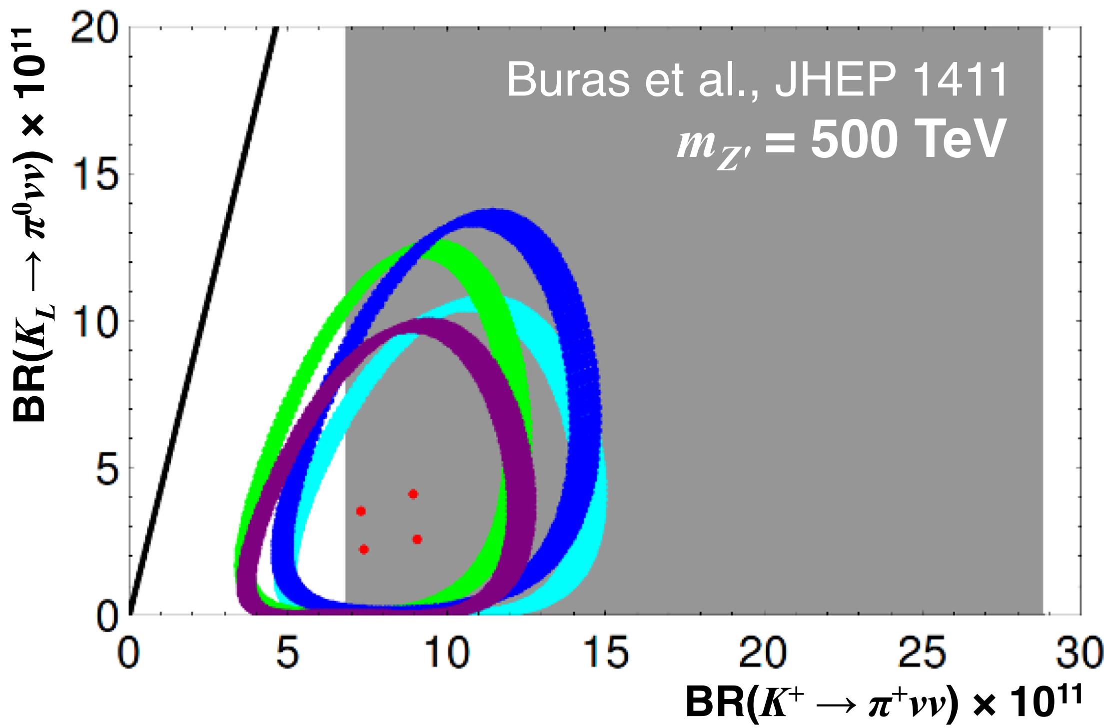
– Null results from direct searches at LHC so far

Indirect probes to explore high mass scales become very interesting!

$K \to \pi\nu\bar{\nu}$ is uniquely sensitive to high mass scales

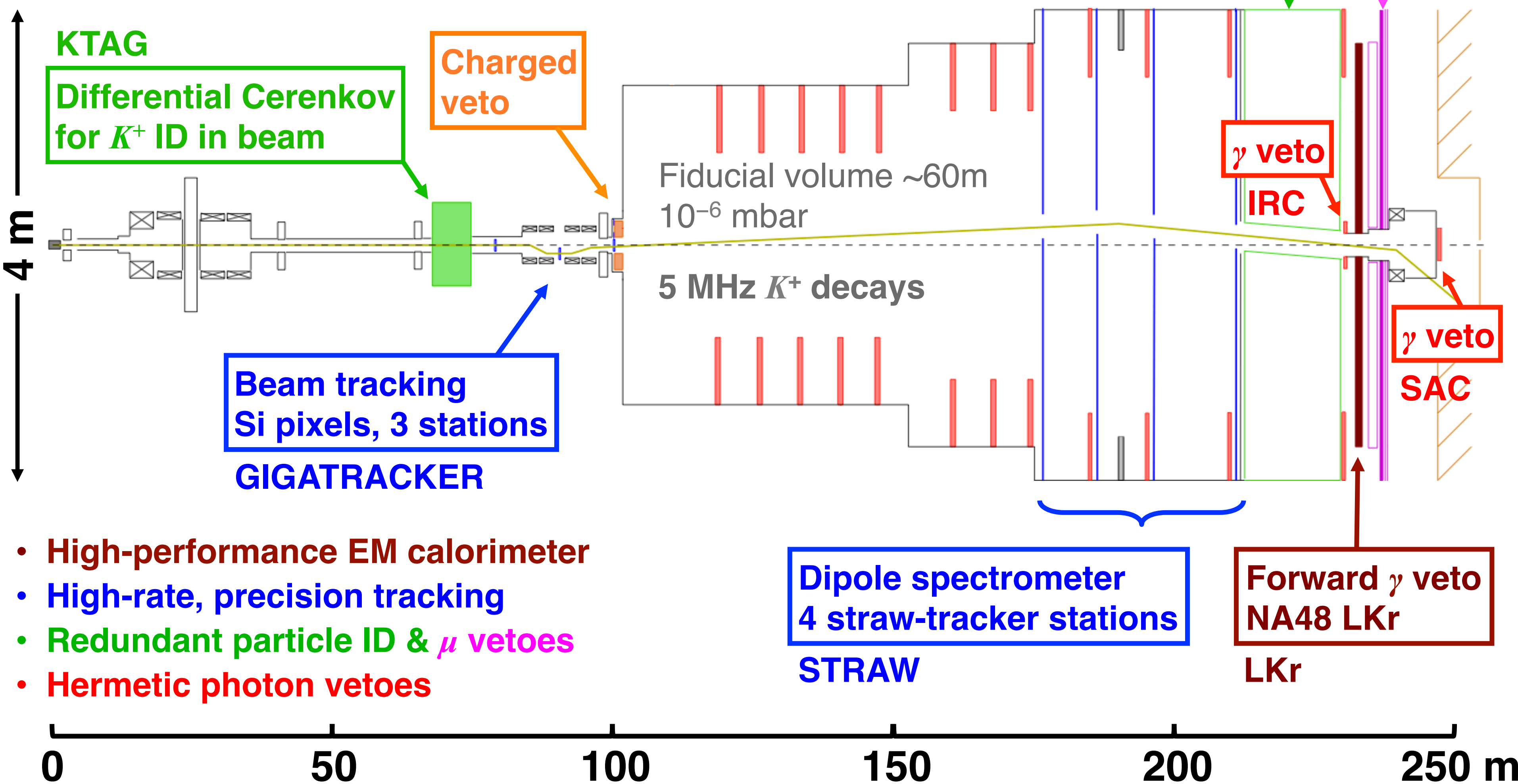
Tree-level flavor changing Z'
LH+RH couplings

- 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



The NA62 experiment at the SPS

- Taking physics data since 2015
- Will measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) to 10% before LS2
  100 signal events, $S/B \sim 5$



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

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

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

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

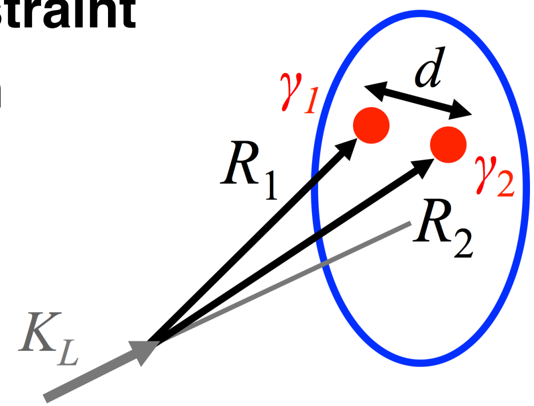
(Exception: $K_L \to \gamma\gamma$, not a big problem since $p_\perp = 0$)

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

Generally used to reconstruct vertex position

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

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

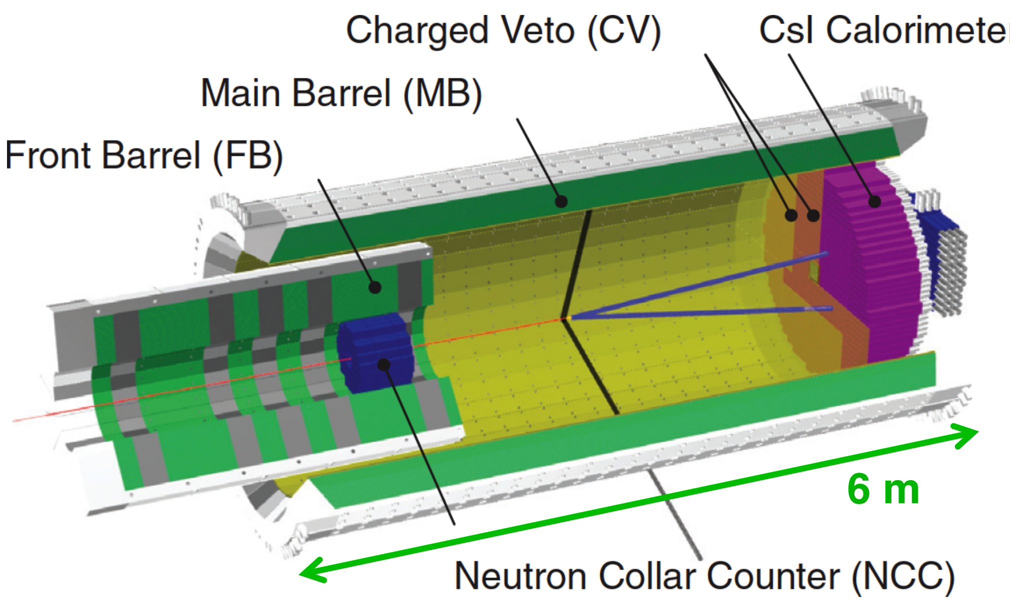


Main backgrounds:

$K_L \to \pi^0\pi^0$ with 2 lost γs
BR = 8.65×10^{-4} → Hermetic veto, including beam exit

n + gas $\to X\pi^0, X\eta$ → High vacuum decay region

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



Primary beam: 30 GeV p
2×10^{14} p/3.3 s = 300 kW (as proposed)

Neutral beam (16°)
$\langle p(K_L) \rangle$ = 2.1 GeV

Proposal sensitivity (3 yr):
SES 8×10^{-12} (3.5 SM evts), S/B = 1.4

Current status:

- Reached **42 kW** of beam power in 2015
- Preliminary result on part of 2015 data expected soon (KAON 2016?)
- SES to 5.9×10^{-9}, expected background = 0.26 events

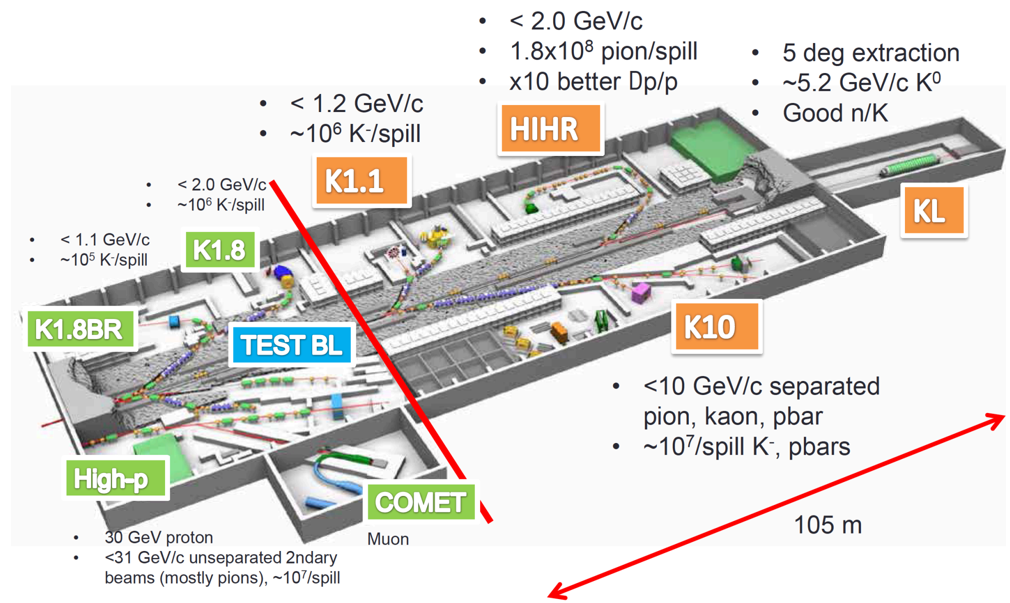
Upgrade path to increase beam power to 100 kW by 2019

- K_L yield 2.4× expected value → **may reach SM sensitivity**

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

KOTO Step 2 upgrade:

- Increase beam power to >100 kW
  (Originally 450 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 100 event sensitivity

- **No official Step 2 proposal yet** (plan outlined in 2006 KOTO proposal)
- Scaling from original estimates: **~10 SM evts/yr per 100 kW of beam power**
- New possibilities:
  - Increase slow-extracted beam power via improvements to septum
  - Use COMET pulsed-proton beam (1700 ns) to obtain TOF constraints à la KOPIO
- Indicative timescale: **data taking starting 2025?**

KLEVER: $K_L \to \pi^0 \nu\bar{\nu}$ at the SPS

Can a competitive measurement of BR($K_L \to \pi^0 \nu\bar{\nu}$) be made at the SPS?

NA62-16-03

Status report on design studies for an experiment to measure BR($K_L \to \pi^0 \nu\bar{\nu}$) at the CERN SPS

A. Bradley, M.B. Brunetti, F. Bucci, A. Cassese, N. Doble, D. Di Filippo, E. Gamberini, L. Gatignon, A. Gianoli, E. Imbergamo, M. Lenti, S. Martellotti, A. Mazzolari, M. Moulson[1], I. Neri, F. Petrucci, P. Rubin, R. Volpe

April 27, 2016

Interesting features:

- 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
- Possible to re-use LKr calorimeter, NA62 experimental infrastructure?

Required intensity for $K_L \rightarrow \pi^0 \nu\bar{\nu}$

Assumptions:

- BR($K_L \rightarrow \pi^0 \nu\bar{\nu}$) = 3.4×10^{-11}
- Acceptance for decays in FV ~ 10%

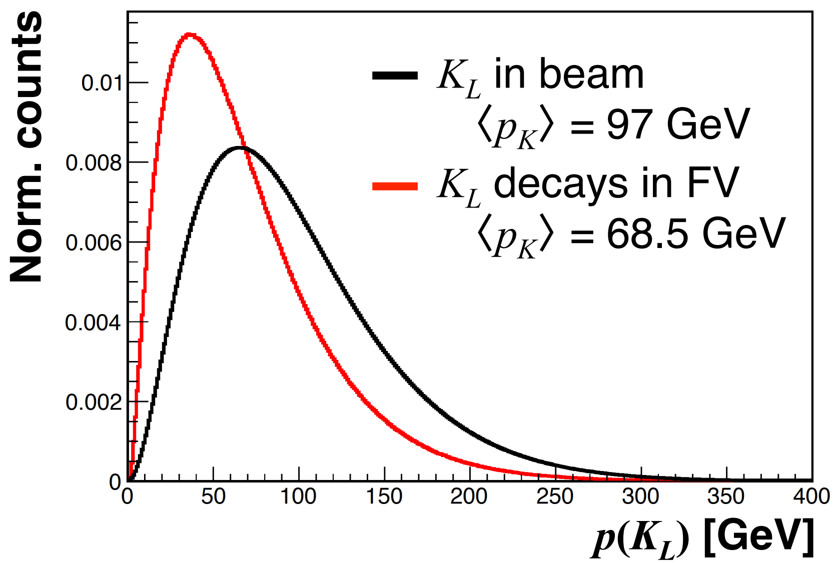
→ **3×10^{13} K_L decay in FV for 100 signal evts**

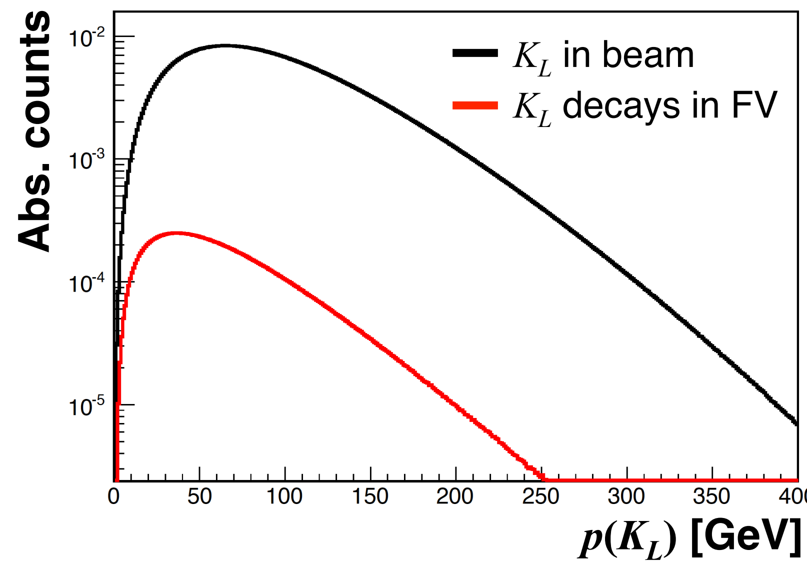
Beam parameters:

- **400 GeV p on 400 mm Be target**
- Production at **2.4 mrad** to optimize (K_L in FV)/n

→ **2.8×10^{-5} K_L in beam/pot**

Fiducial volume acceptance **~ 2%**





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

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

Neutral beamline layout

Beam acceptance

- $\Delta\theta \rightarrow 0.3$ mrad : $\Delta\Omega \rightarrow 0.283$ µsr
  - Just fits inside LKr central vacuum tube (r = 80 mm)

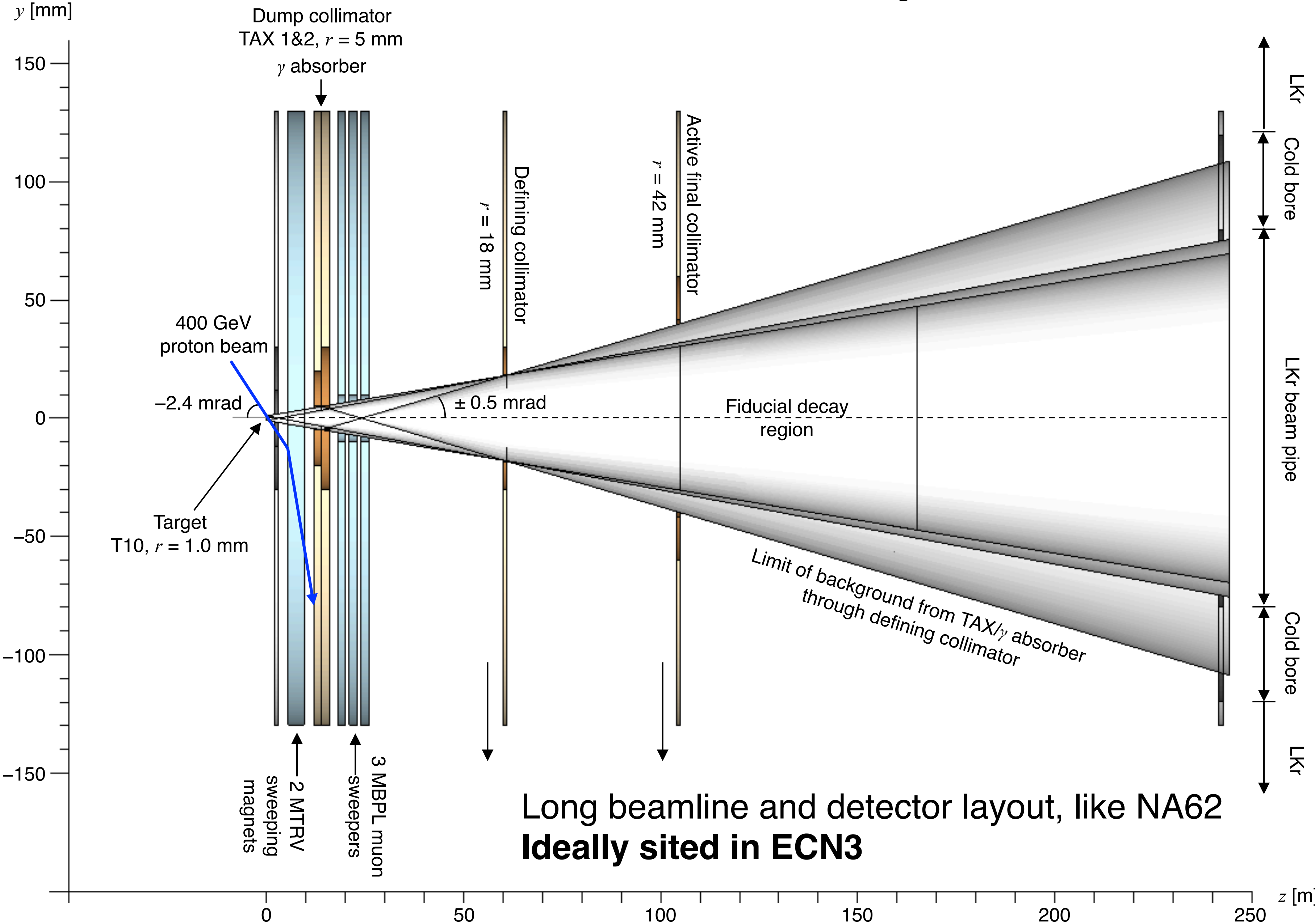
Collimators:

1. **Dump collimator:** TAX1/2 (r = 5 mm) moved forward to z = 15 m
   - 2 vertical sweeping magnets upstream of TAX
   - 3 horizontal muon sweeping magnets downstream of TAX
2. **Defining collimator:** r = 42 mm at z = 60 m
   - Keep background from TAX/converter within LKr bore (r < 120 mm)
3. **Final collimator:** z = 105 m to remove upstream decay products
   - Regenerated K_S reduced to 10^{-4} between defining and final collimators
   - Regenerated K_S reduced to 10^{-4} over 45 m to final collimator

Photon converter between TAX1/2

- Explore use of crystal converter to optimize K_L transmission
  - Pair production enhanced by coherent effects in crystals

Neutral beamline layout



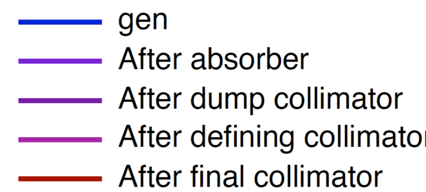
Long beamline and detector layout, like NA62

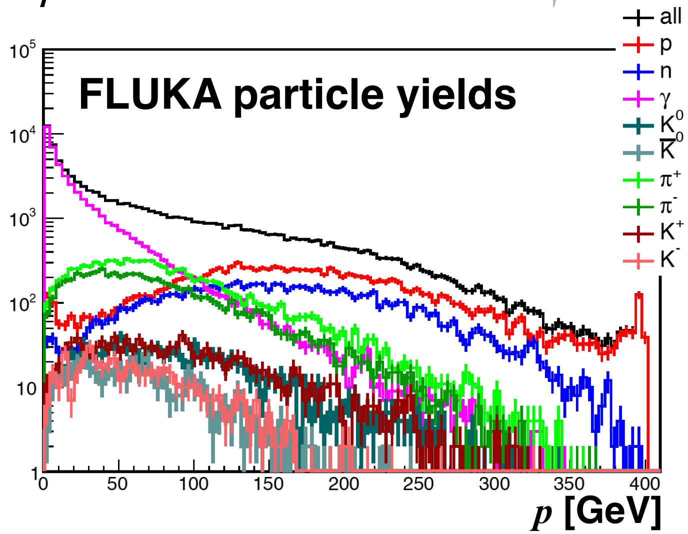
Ideally sited in ECN3

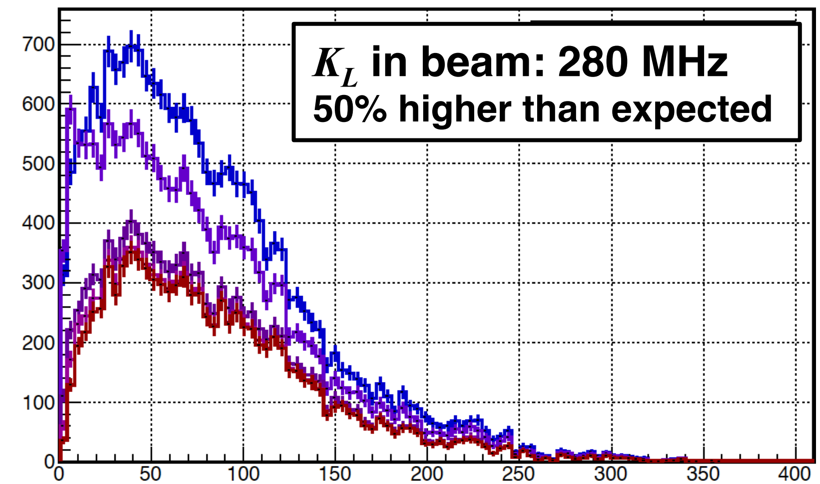
Beam simulation and flux estimates

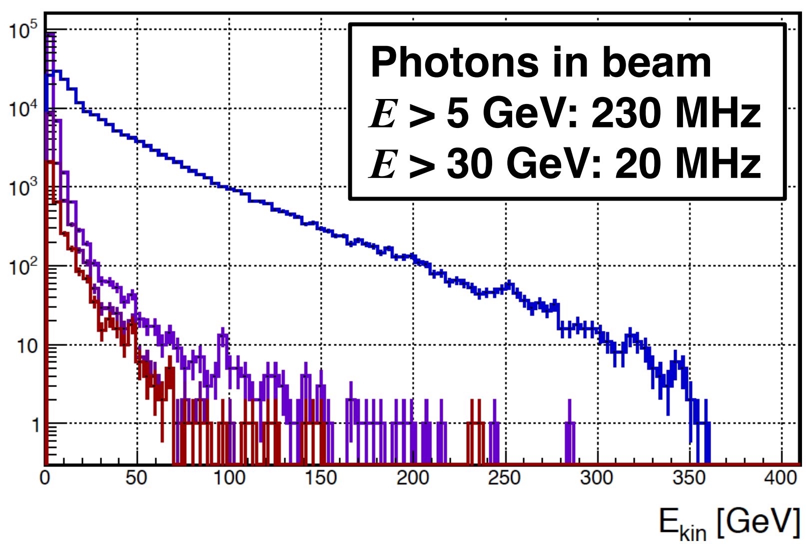
FLUKA target simulation
400 GeV p + Be, 2.4 mrad
Obtain p vs. θ distributions

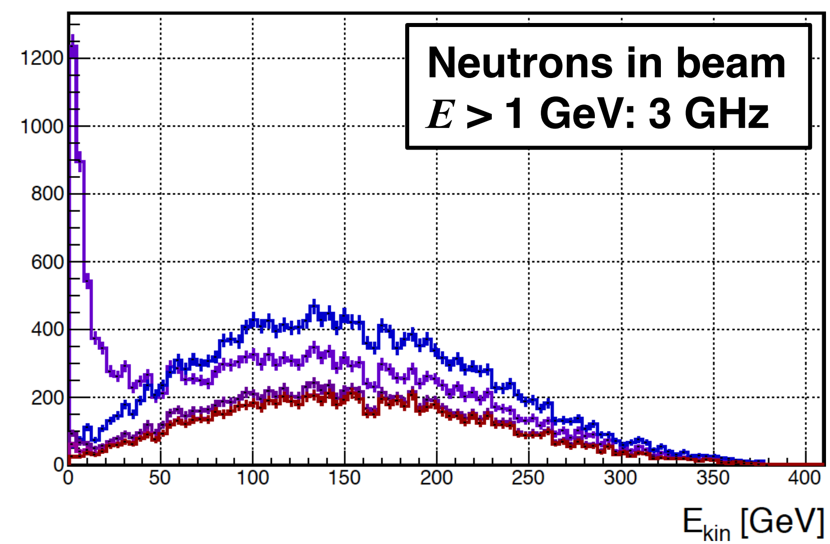
Geant4 beamline simulation
30-mm Ir photon converter
3-collimator layout



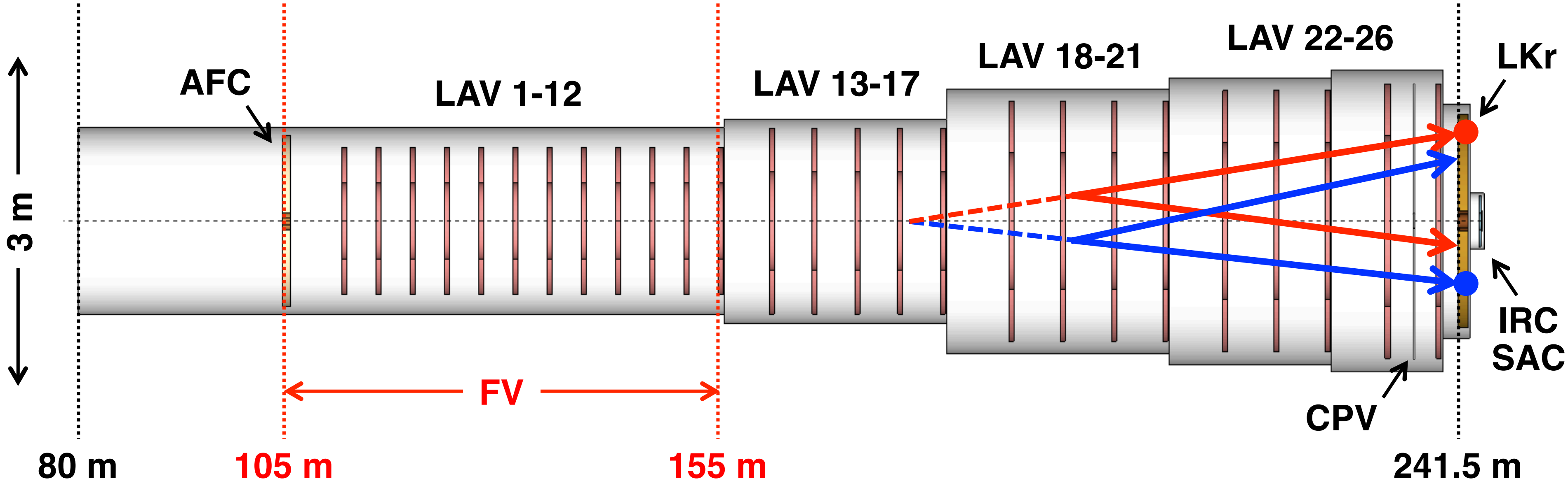








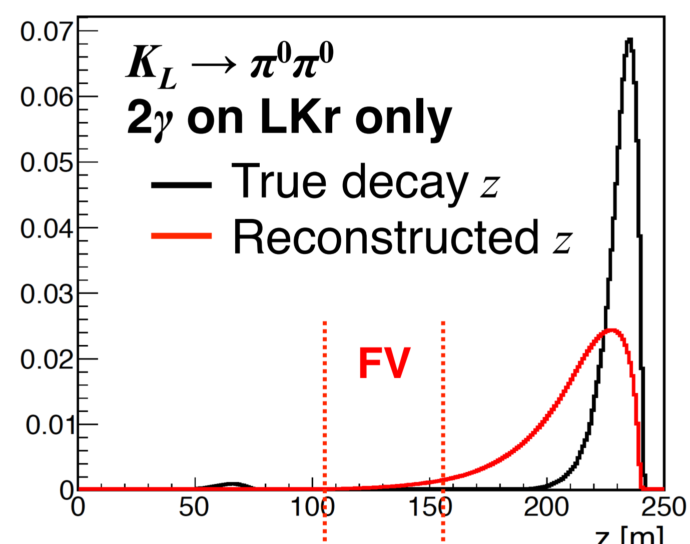
Detector layout for $K_L \to \pi^0 \nu\bar{\nu}$



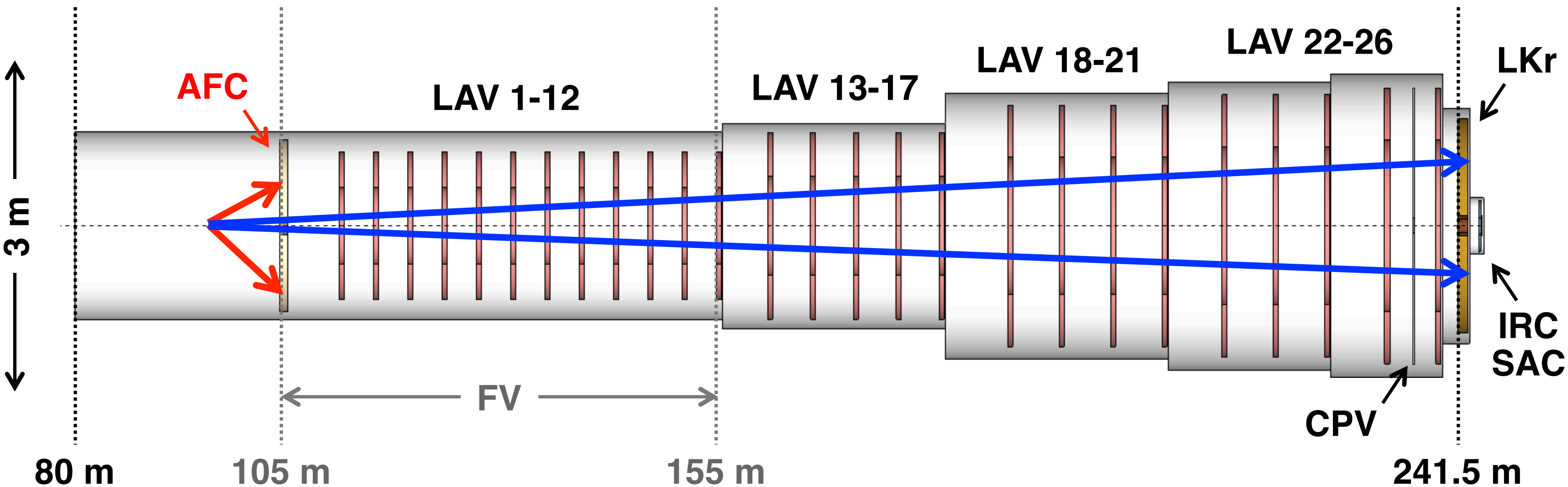
Vacuum tank layout and FV similar to NA62

90-m distance from FV to LKr significantly helps background rejection

- 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 downstream of FV



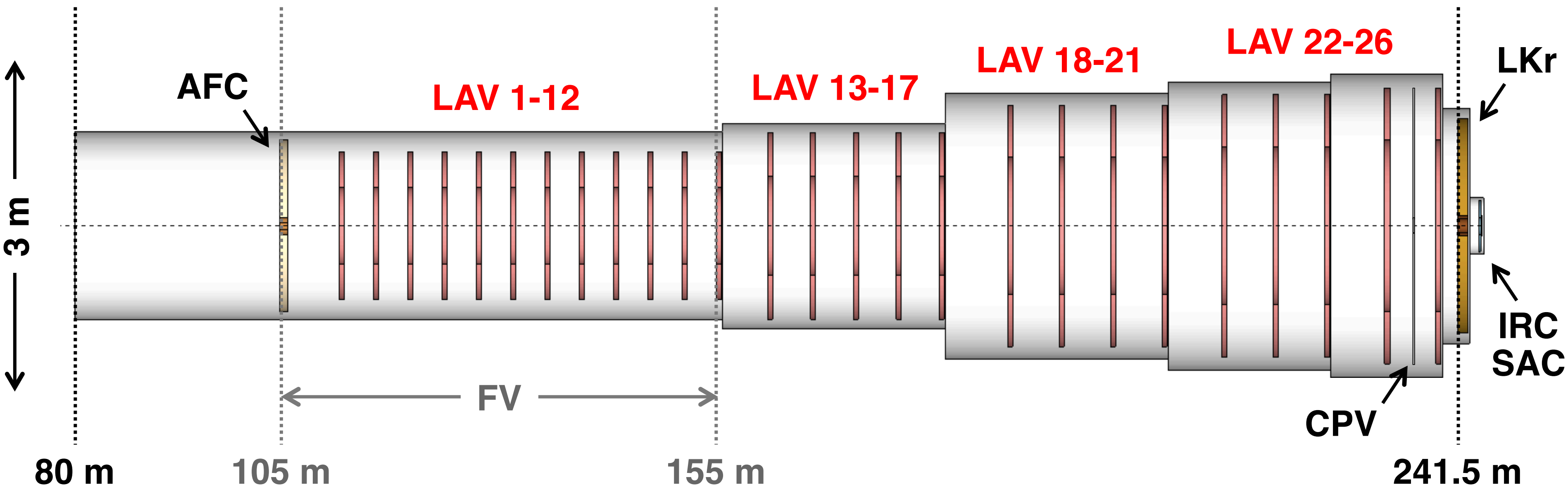
Detector layout for $K_L \to \pi^0 \nu\bar{\nu}$



Active final collimator (AFC) to veto upstream decays

- **25 m of vacuum upstream of final collimator**
  No obstruction for γs from decays with 80 m < z < 105 m
- **Outer ring:** Shashlyk calorimeter, Pb/scint in 1:5 ratio
  10 cm < r < 1 m, 1/3 of total rate
- **Inner ring:** LYSO collar counter, 80 cm deep, shaped crystals
  4.2 cm < r < 10 cm, 2/3 of total rate

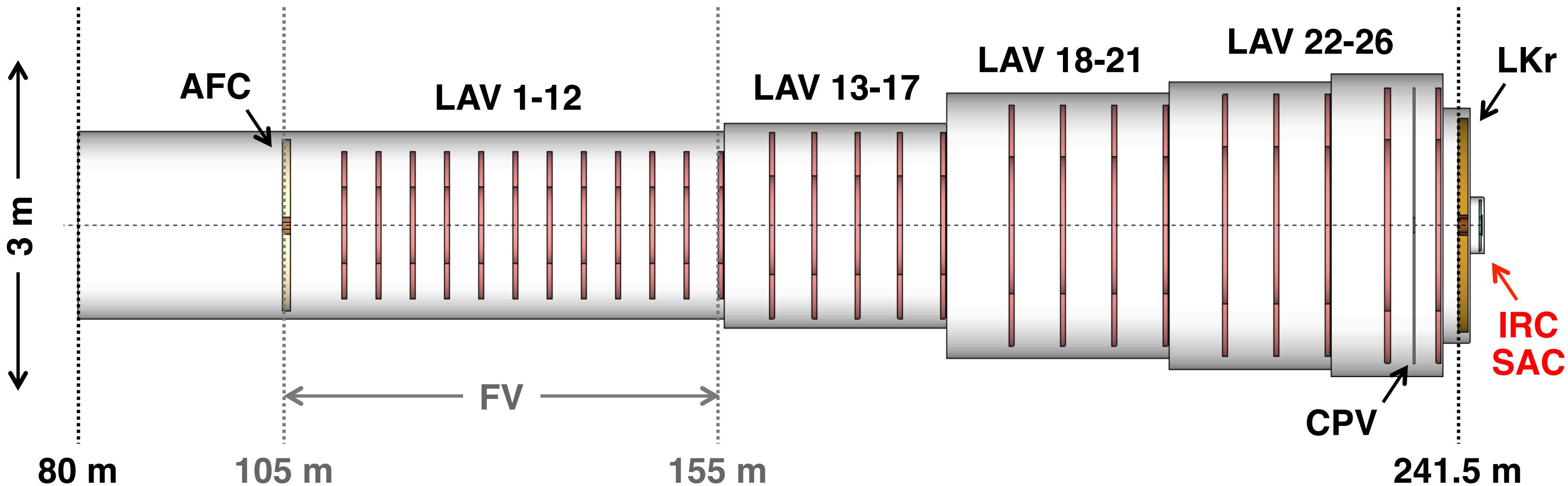
Detector layout for $K_L \to \pi^0 \nu \bar{\nu}$



26 new large-angle photon veto stations (LAV)

- 5 sizes, sensitive radius 0.9 to 1.6 m, at intervals of 4 to 6 m
- Hermetic coverage out to 100 mrad for E_γ down to ~100 MeV
- Baseline technology: Lead/scintillator tile with WLS readout
  Based on design of CKM VVS
  Assumed efficiency based on E949 and CKM VVS experience

Detector layout for $K_L \to \pi^0 \nu\bar{\nu}$



Small-angle photon veto systems (IRC, SAC)

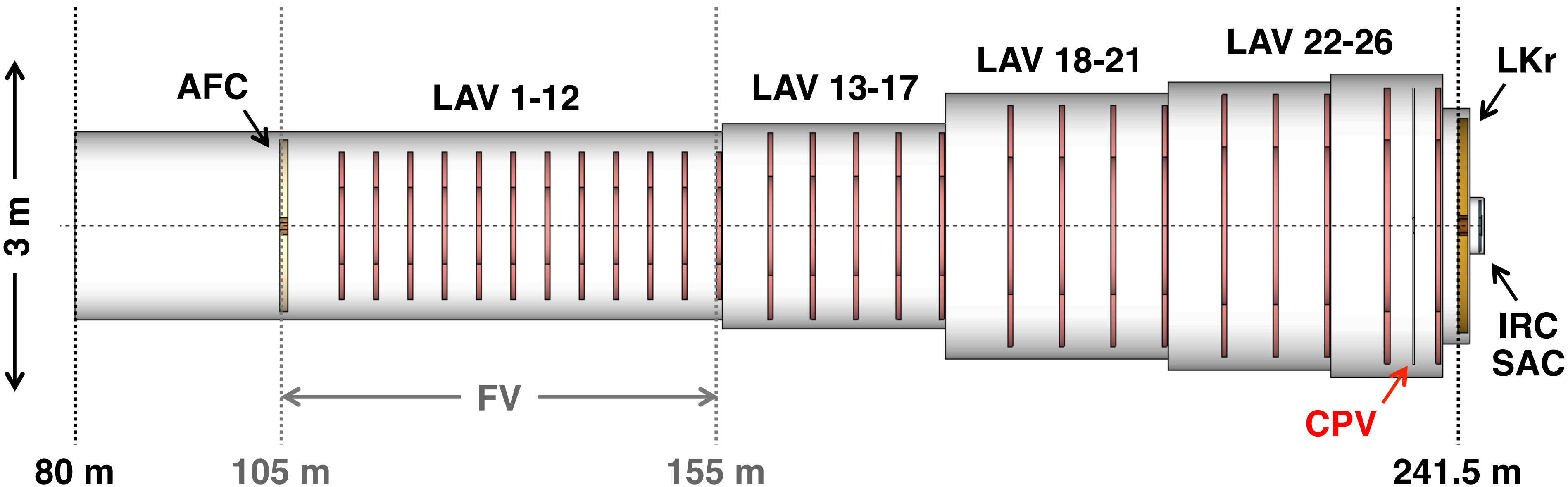
- Reject high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 3 GHz of beam neutrons

	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

Detector layout for $K_L \rightarrow \pi^0 \nu \bar{\nu}$



Charged particle rejection

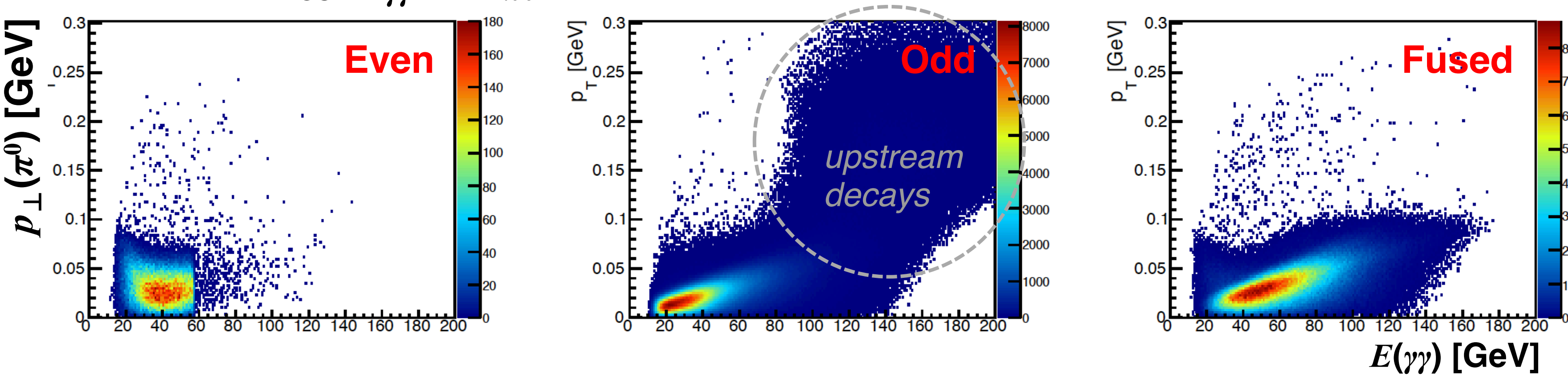
- **Charged particle vetoes (CPV):** Scintillating tiles, 5 m upstream of LKr
- **Re-use NA62 hadronic calorimeters** (MUV1/2, not shown)
  Ratio of hadronic/total energy effective to identify π showers
- **LKr shower profile:** Use cluster RMS to identify and reject π

$K_L \to \pi^0\pi^0$ rejection

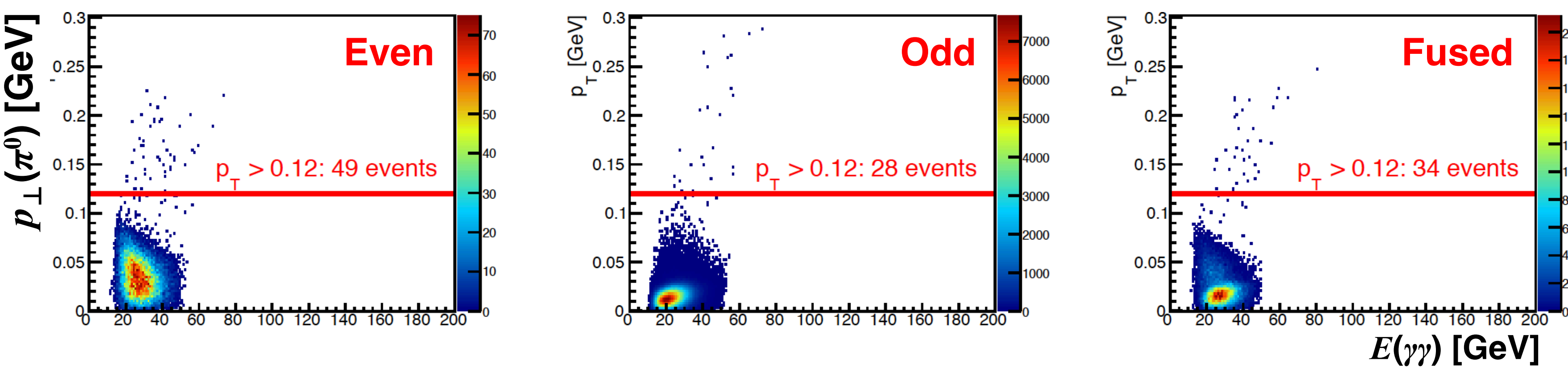
$K_L \to \pi^0\pi^0$ simulated with fast MC (5 yr equivalent statistics)

- Accept only events with 2 γs in LKr and no hits in AFC, LAV, IRC/SAC
- Distinguish between even/odd pairs and events with fused clusters

1. Require $z_{\mathrm{rec}}(m_{\gamma\gamma} = m_{\pi 0})$ in fiducial volume (105 m < z < 155 m)



2. Require r_{min} > 35 cm on LKr and $p_\perp(\pi^0)$ > 0.12 GeV



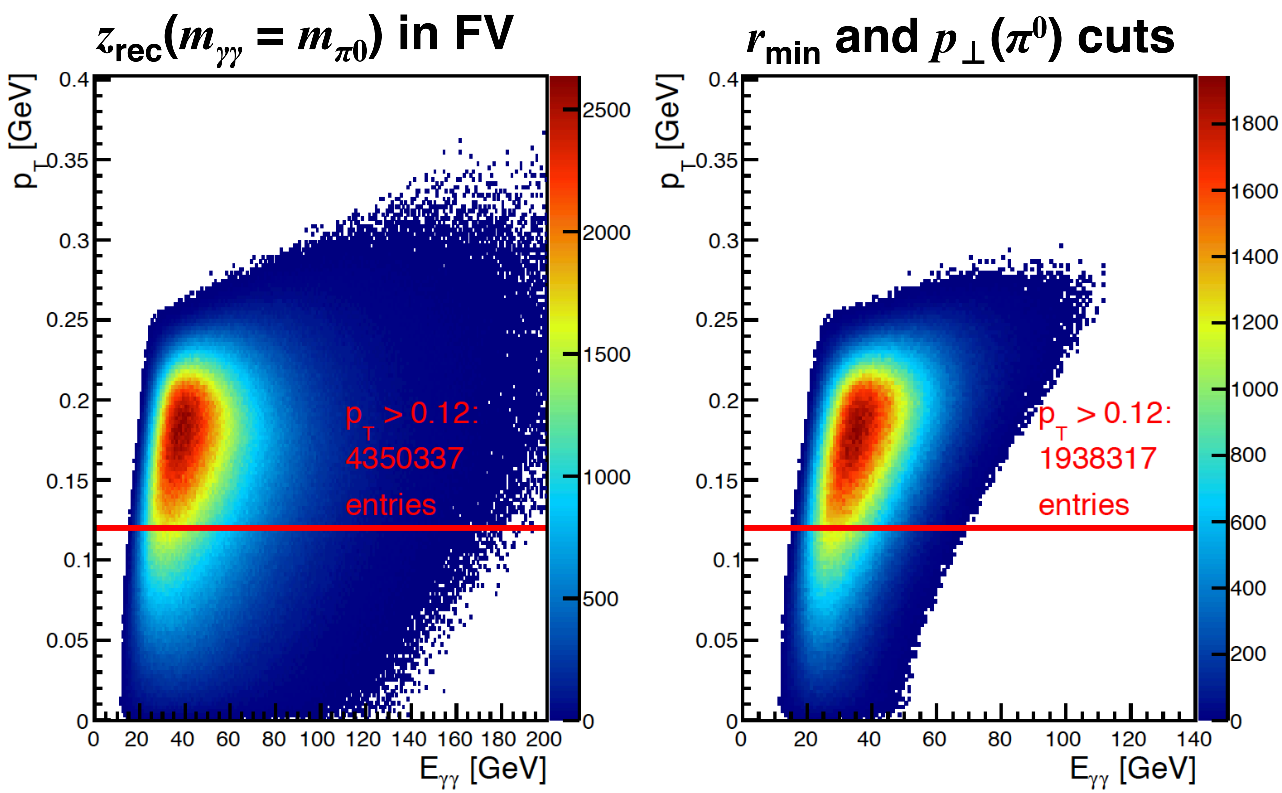
22 $\pi^0\pi^0$ evts/year About 50% with 1γ with 100 < θ < 400 mrad, E < 50 MeV

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

Cut stage	Cut eff.	Cuml. eff.
$K_L \to \pi^0 \nu\bar{\nu}$ evts with 2γ on LKr	2.0%	2.0%
$z_{\rm rec}(m_{\gamma\gamma} = m_{\pi 0})$ in FV	31%	0.62%
$r_{\rm min} > 35$ cm on LKr	42%	0.26%
$p_\perp(\pi^0) > 0.12$ GeV	78%	0.20%

Alternatively:
- 2.2% K_L decay in FV
- 27% $\pi^0\nu\bar{\nu}$ with 2γ on LKr

π^0 in $\pi^0\nu\bar{\nu}$ has large $E_{\rm kin}$
$V - A$ matrix element



With:
- 10^{19} pot/year
- 2.8×10^{-5} K_L/pot
- BR = 3.4×10^{-11}
- $\varepsilon_{\rm total} = 0.20\%$

19.4 $\pi^0\nu\bar{\nu}$ evts/year

excluding transmission losses from γ converter

$K_L \to \pi^0 \nu\bar{\nu}$ sensitivity summary

Channel	Simulated statistics	Events found	Expected in 5 yrs*
$K_L \to \pi^0 \nu\bar{\nu}$	100k yr	1.94M	**97**
$K_L \to \pi^0\pi^0$	5 yr	111	**111**
$K_L \to \pi^0\pi^0\pi^0$ All bkg evts from cluster fusion Upstream decays not yet included	1 yr	3	**15**
$K_L \to \gamma\gamma$ $p_\perp$ cut very effective	3 yr	0	**0**
$K_L \to$ **charged**	**thought to be reducible**		

*Must subtract 35% for K_L losses in dump γ converter

~ 60 SM $K_L \to \pi^0 \nu\bar{\nu}$ in 5 years with S/B ~ 1

Background study incomplete!

π^0 from interactions of halo neutrons on residual gas, detector materials

Radiative K_L decays, K_S/hyperon decays

Items requiring particular attention

Feasibility of obtaining required intensity

- Extent & costs of upgrades to beam transport from extraction point to T10 and to TCC8 cavern infrastructure
- Requires collaboration with ATS

Viability of concept for small-angle calorimeter

- Realistic simulation of pair-creation enhancement in crystal absorber

Background rates from neutron halo and beam-gas interactions

Validation of LKr efficiency and two-cluster separation using NA62 data

- Investigation of readout improvements to optimize LKr time resolution?

Add detail to simulation of beamline and detector

- Use this simulation to perform general survey of backgrounds
  - Radiative decays, K_S/hyperon decays

Possibility of adding charged-particle tracking to layout

- Final-state reconstruction for efficiency estimation & systematic control
- Possible expansion of physics program ($K_L \to \pi^0 \ell^+ \ell^-$, LFV, etc.)

Summary and outlook

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

New physics found at LHC

Explore flavor structure of "new" SM

Obtain **precision information** from measurements of $K \to \pi\nu\bar{\nu}$

No new physics from LHC

Explore extremely high mass scales with indirect probes

$\boldsymbol{K \to \pi\nu\bar{\nu}}$ **uniquely sensitive**

2. **NA62 and KOTO Step 1 results will arrive within next few years**

NA62/KOTO obtain unexpected results

Precise measurement of BR($K_L \to \pi^0\nu\bar{\nu}$) **extremely interesting**

NA62/KOTO obtain SM results

BR($K_L \to \pi^0\nu\bar{\nu}$) ~ (0.5 – 2) SM not excluded: precise measurement **may still reveal NP**

3. **An experiment to measure BR($\boldsymbol{K_L \to \pi^0\nu\bar{\nu}}$) with ~ 60 SM event sensitivity and $\boldsymbol{S/B}$ ~ 1 can be performed at the CERN SPS with 5 × $\boldsymbol{10^{19}}$ pot**

Additional information

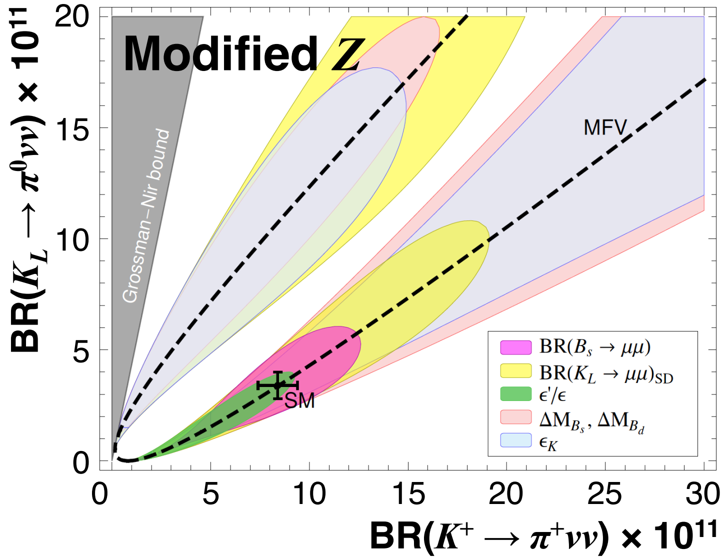
$K \to \pi\nu\bar{\nu}$ and other flavor observables

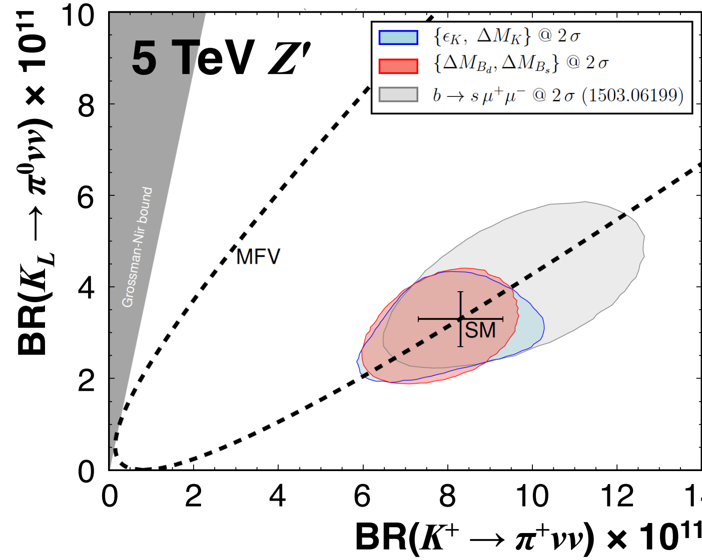
Simplified Z, Z' model used as paradigm

Buras, Buttazzo, Knegjens, JHEP 1511

CMFV hypothesis:

Constraints from B and K observables

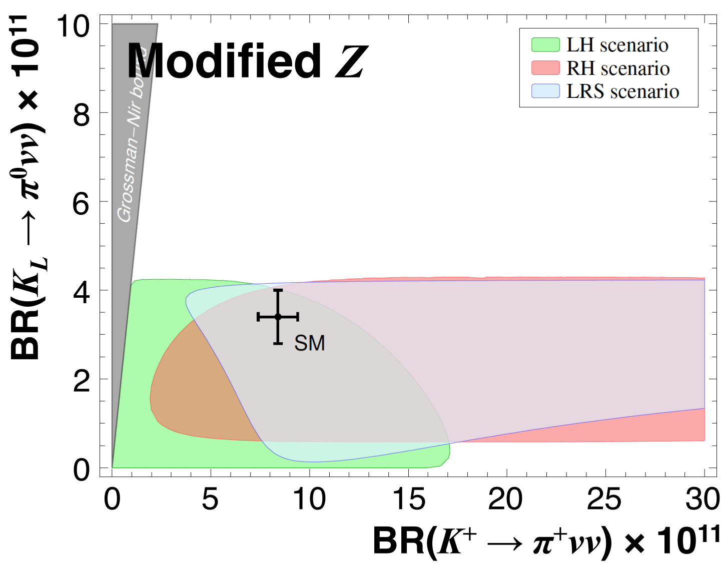


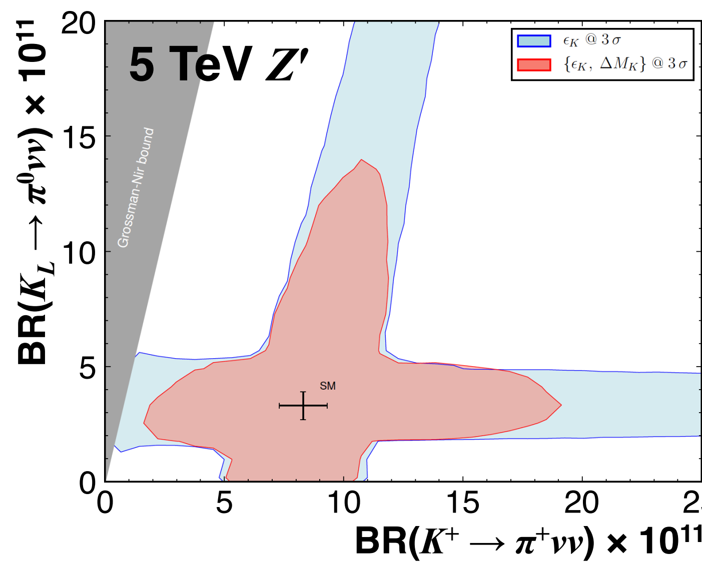


LH and RH couplings allowed:

Constraints from K observables:

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





Feasibility of intensity upgrade

2 × 10^{13} p/16.8 s = 6× increase in intensity relative to NA62

Tight neutral beam collimation

Longer K_L lifetime ($\tau_L/\tau_+ \sim 5$)

Max. intensity from SPS to North Area (TT20): 4 × 10^{13} ppp

Must be divided among users: T2 + T4 + T6

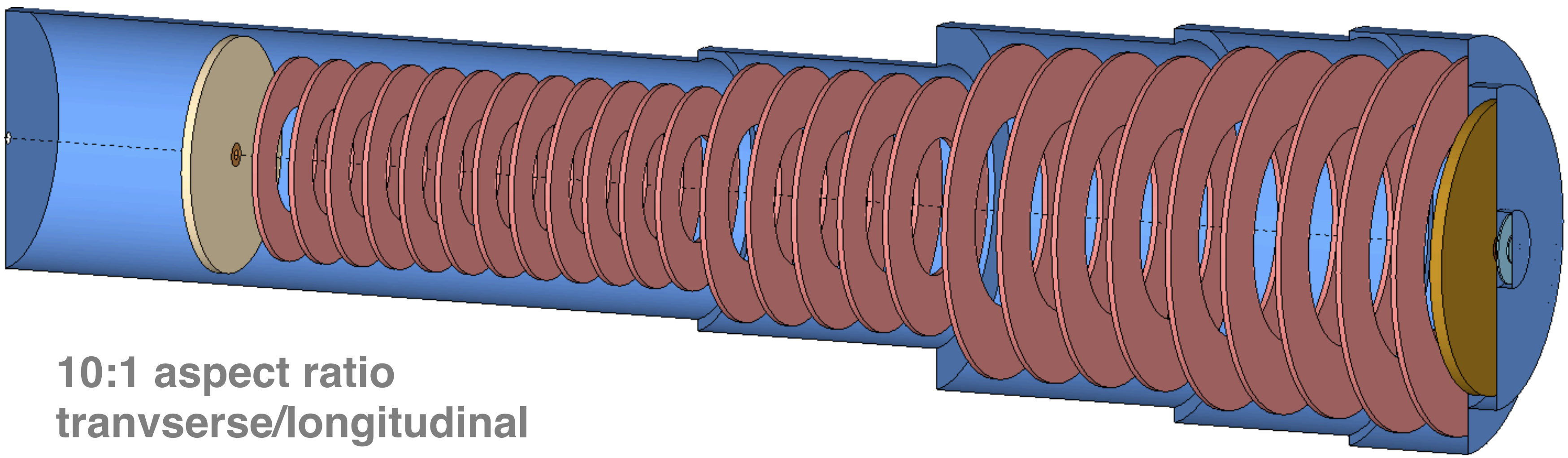
2 × 10^{13} ppp not currently available on North Area targets

Target area and transfer lines would require upgrades

- Minimization of consequences of beam loss
- Additional shielding against continuous small losses
- Study issues of equipment survival, e.g., TAX motors
- Ventilation, zone segmentation, etc.

Detailed solutions & meaningful cost estimates would require serious study by the CERN ATS, as was done for SHiP

Detector layout for $K_L \rightarrow \pi^0 \nu \bar{\nu}$



10:1 aspect ratio
tranvserse/longitudinal

Roughly same vacuum tank layout and fiducial volume as NA62

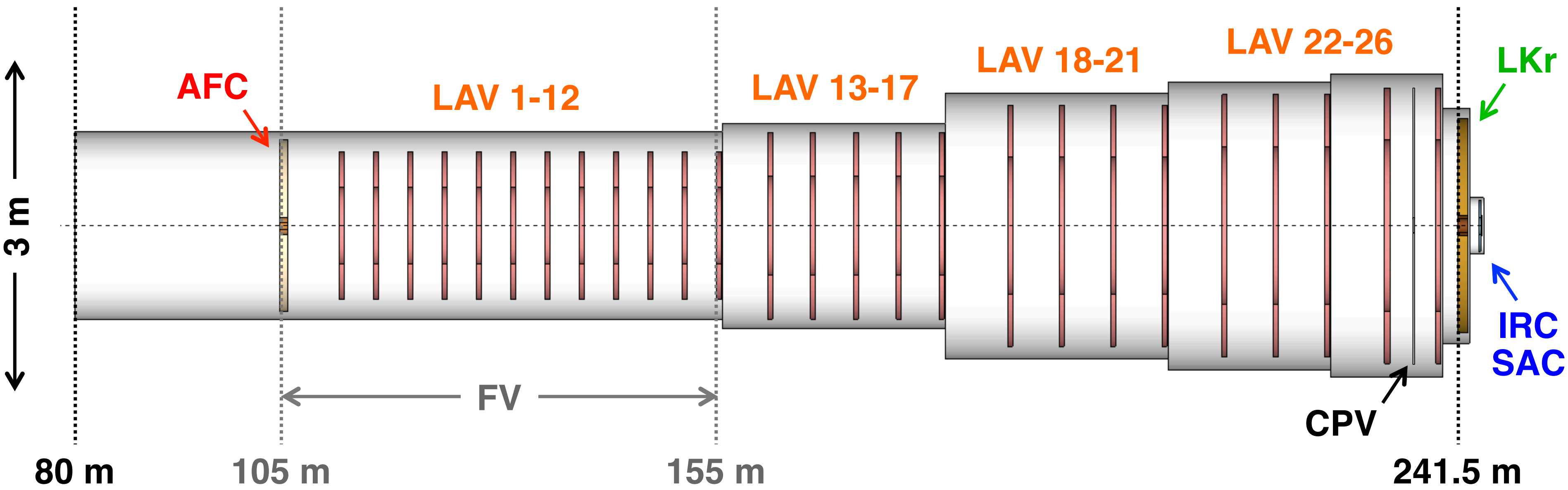
- Upstream edge of vacuum tank 20 m in front of AFC
- FV starts ~105 m downstream of target – decay away Λ, K_S
- About 2.2% of K_L in beam decay in FV

Possible to re-use NA48 LKr calorimeter (?)

26 new large-angle photon veto stations (LAV), coverage to 100 mrad

New small-angle photon veto detectors (IRC/SAC)

Detector layout for $K_L \rightarrow \pi^0 \nu \bar{\nu}$



Assumed 1 – ε for indicative values of E_γ

AFC		LAV		LKr		SAC	
Required performance		From E949, CKM VVS		Standard NA62 values		Required performance	
< 50 MeV	1	< 20 MeV	1	< 1 GeV	1	> 5 GeV	10^{-2}
> 1 GeV	10^{-4} (in)	200 MeV	0.5%	1 GeV	0.1%	> 30 GeV	10^{-4}
> 1 GeV	10^{-5} (out)	> 0.5 GeV	5×10^{-6}	> 10 GeV	8×10^{-6}		

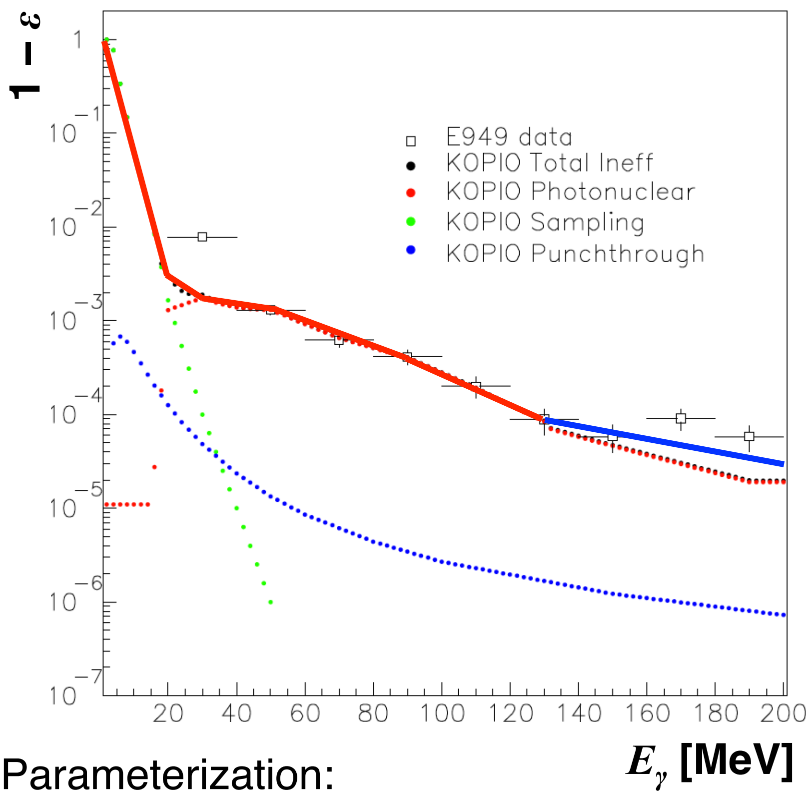
Large-angle vetoes

26 new LAV detectors providing hermetic coverage out to 100 mrad

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

Baseline technology: CKM VVS
Scintillating tile with WLS readout

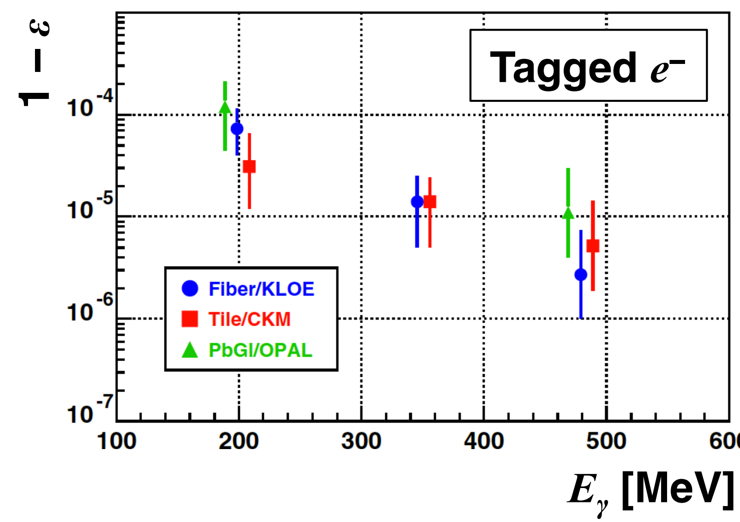
Good efficiency assumptions based on E949 and CKM VVS experience



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

Suitability of LKr calorimeter

LKr

Energy (GeV)	$1-\varepsilon$
< 1	1
$1 \to 5.5$	$10^{-3} \to 10^{-4}$
$5.5 \to 7.5$	$10^{-4} \to 5 \times 10^{-5}$
$7.5 \to 10$	$5 \times 10^{-5} \to 10^{-5}$
$10 \to 15$	8×10^{-6}
> 15	4×10^{-6}

Efficiency

- Same efficiency estimates as in NA62
- Slightly better efficiency for $E_\gamma > 15$ GeV
- Need to be proven with NA62 data

Two-cluster separation

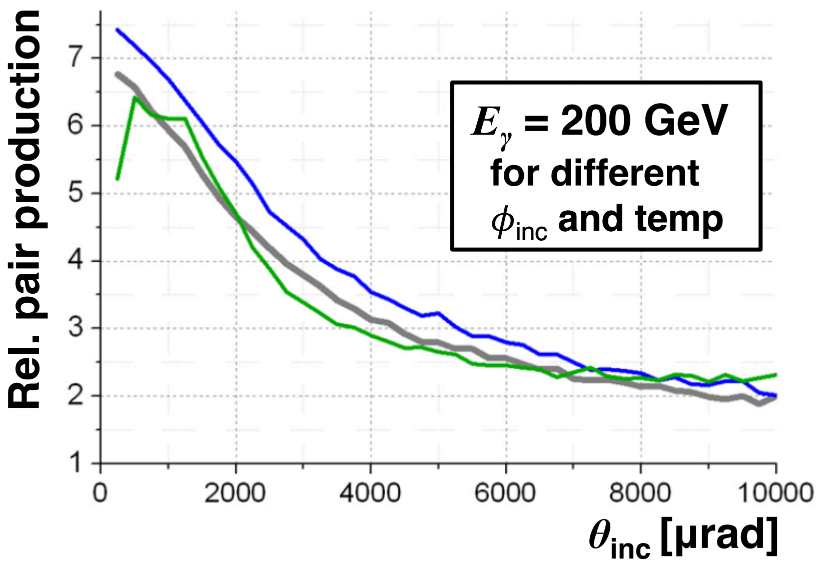
- Clusters resolved if $d > 6$ cm in simulation
- Simplistic approach to take into account cluster-profile analysis

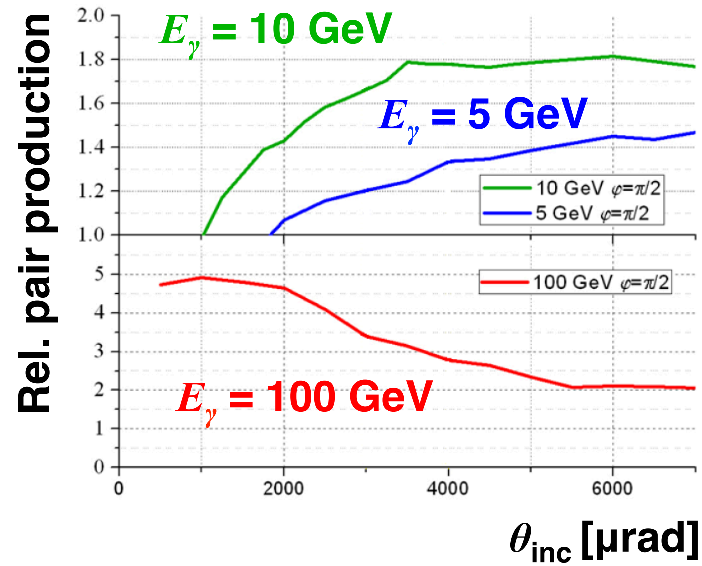
Time resolution

- Signal candidates all have $E_{\gamma\gamma} > 20$ GeV
  $\sigma_t = 2.5$ ns/$\sqrt{E}$ (GeV) → 500 ps or better
- Needs improvement – SAC may have O(100 MHz) accidental rate
- Possible to improve using new readout system?

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 in-beam calorimeter (SAC)**
   – Must be insensitive as possible to 3 GHz of beam neutrons while efficiently vetoing γs from K_L decays

Work in progress in context of UA9 to introduce detailed simulation of coherent effects in crystals into Geant4

Small-angle vetoes

Proof-of-concept simulation for baseline solution:

- W-Si pad calorimeter, 14 layers × 1 mm crystal absorber, θ_{inc} = 2 mrad
  - Depth = 14X_0 for E_γ = 30 GeV, but only 4X_0 for E_γ = 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_γ = 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 UA9 collaborators to introduce into Geant4 detailed simulation of coherent effects in crystals
- Optimize segmentation to obtain additional γ/n separation
  - Use backstop layer with different longitudinal segmentation to identify n

Charged particle rejection

K_{e3} most dangerous mode: e easy to mistake for γ in LKr

Acceptance $\pi^0 \nu\nu / K_{e3}$ = 30 → Need 10^{-9} suppression!

Item	Rej. factor
Charged particle veto planes: 5 mm scintillator tiles	0.005/track 2 planes
Cluster RMS Or other LKr shower profile cuts	0.05
HAC/LKr energy ratio Re-use MUV1/2 from NA62	0.07

All πe from K_{e3} reconstructed as π^0 have z_{true} < 200 m