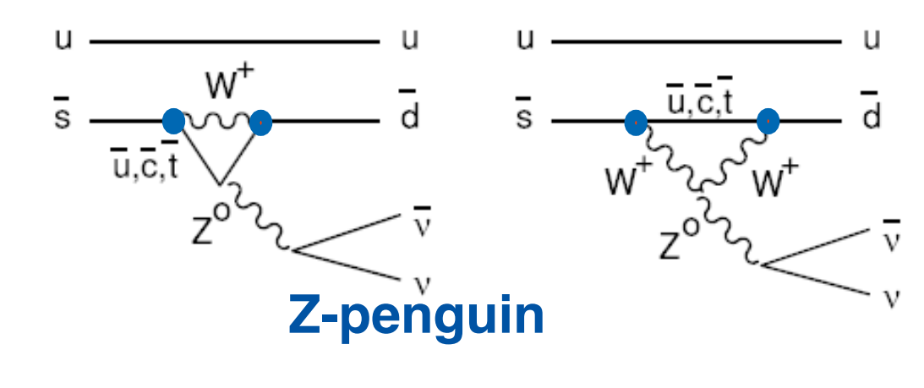
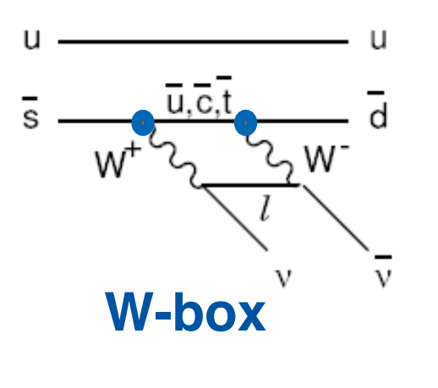
An experiment to measure BR($K_L \to \pi^0 \nu\nu$) at the CERN SPS

BR($K \to \pi\nu\nu$) in the Standard Model

Extremely suppressed **flavor-changing neutral current quark transition s→dνν** forbidden at tree level, dominated by short-distance dynamics (GIM mechanism) and characterized by theoretical cleanness in the SM prediction of the BR.



Z-penguin



W-box

Highly suppressed

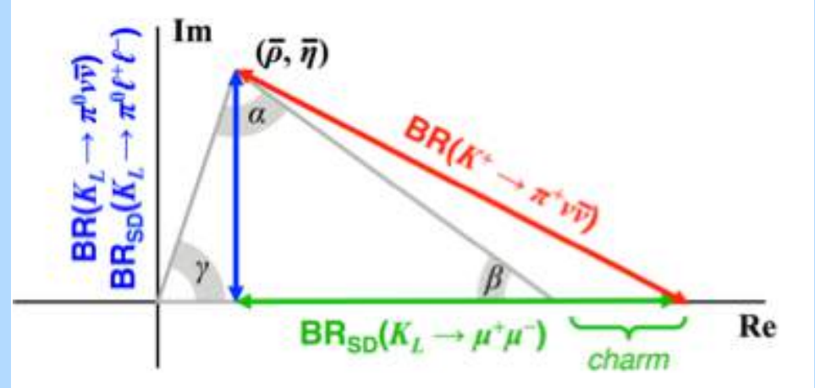
Very well predicted

Excellent laboratory complementary to LHC

Dominant uncertainties for SM BRs are from CKM matrix elements

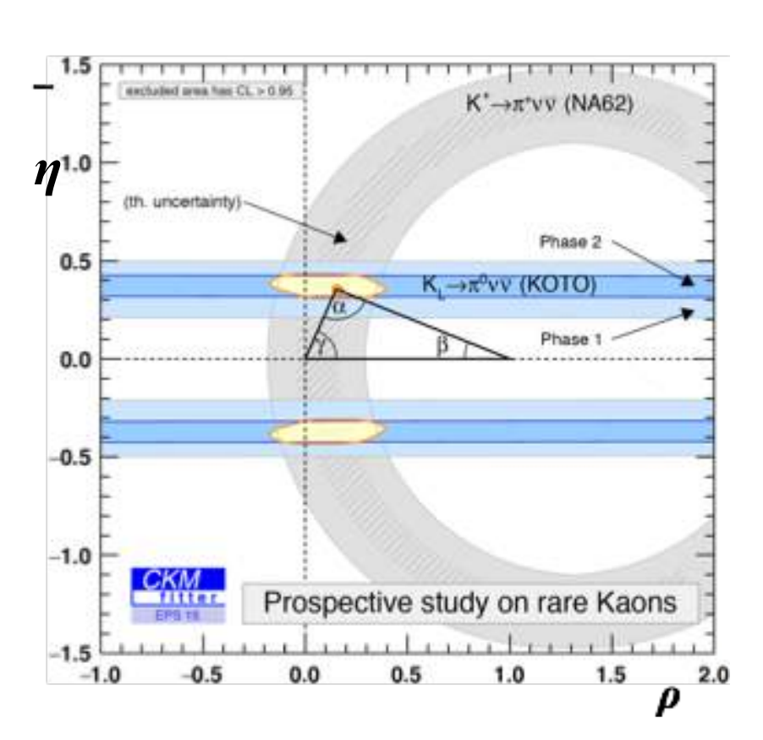
$$BR(K^+ \to \pi^+ \nu\bar\nu) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2°}\right]^{0.74}$$

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



Measurement of BRs of charged ($K^+ \to \pi^+ \nu\nu$) and neutral ($K_L \to \pi^0 \nu\nu$) modes can determine the **unitarity triangle** independently from B inputs.

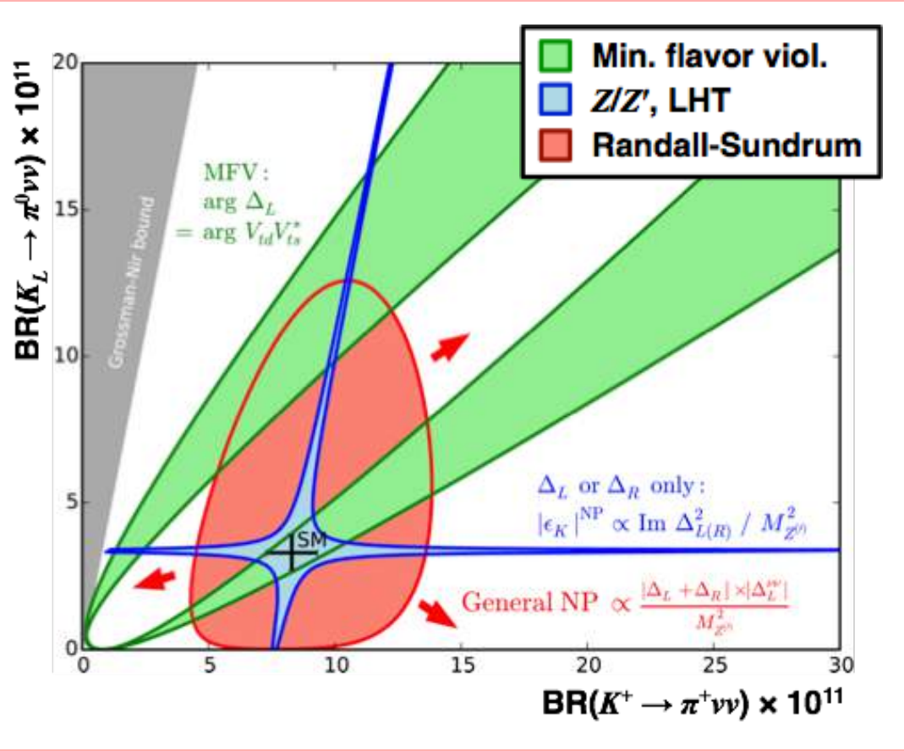
Hypothetical CKM **fit to $K \to \pi\nu\nu$ 10%** mmts for K^+ and K_L



Stringent test of the SM and possible **evidence for New Physics**

Beyond the SM

New constraints to CKM matrix are sensitive to New Physics (NP)



New physics affects BRs differently for K^+ and K_L channels. Measurements of both could discriminate among NP scenarios

State of the art

Current theoretical prediction:

$$BR(K_L \to \pi^0 \nu\bar\nu) = (3.4 \pm 0.6) \times 10^{-11}$$
$$BR(K^+ \to \pi^+ \nu\bar\nu) = (8.4 \pm 1.0) \times 10^{-11}$$

Intrinsic theoretical uncertainties (1-3%) slightly larger for the charged channel because of the corrections from lighter-quark contributions

Main contribution to the errors comes from the uncertainties on the SM input parameters

Experimental status:

$BR(K_L \to \pi^0 \nu\bar\nu)_{exp}$ never been measured

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

Only measurement was obtained by E787 and E949 experiments at BNL with stopped kaon decays (7 events in final sample)

Gap between theoretical precision and experimental result status motivates a strong experimental effort.

Significant new constraints can be obtained.

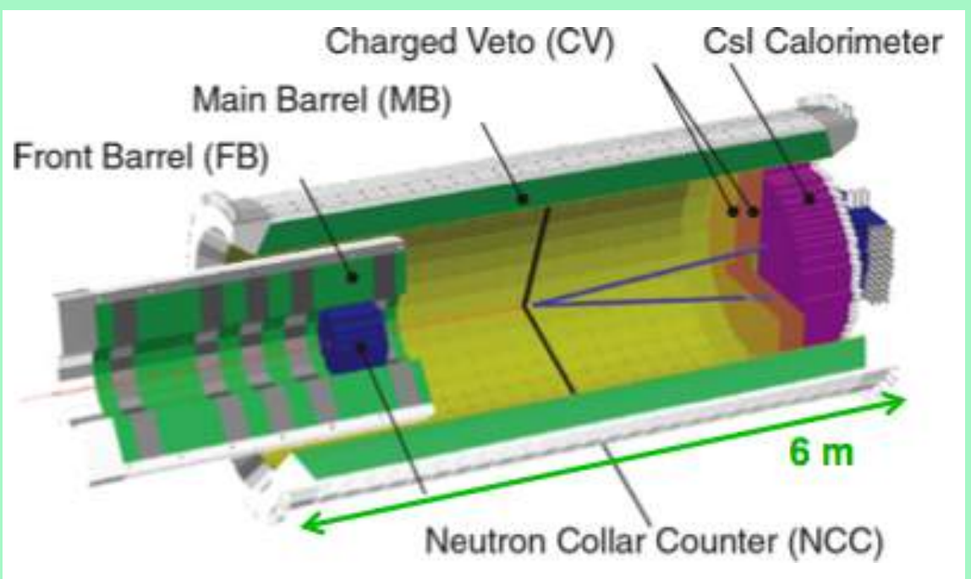
KOTO at J-PARC

Only experiment to pursue the measurement of BR($K_L \to \pi^0 \nu\nu$).

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

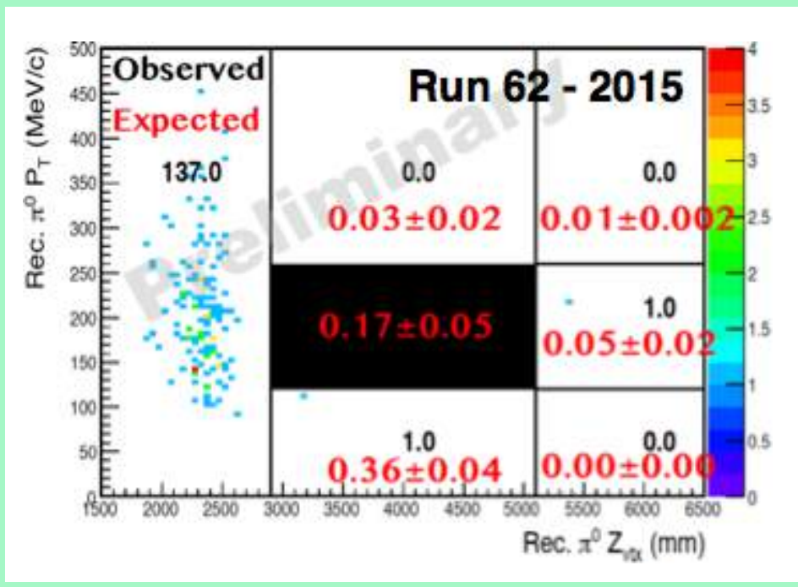
Primary beam:
30 GeV protons

Secondary neutral beam:
P_K = 2.1 GeV/c
average



Current status:
Reached 42 kW of slow-extracted beam power in 2015
Preliminary results: 10% of 2015 data

- SES = 5.9 × 10^{-9}
- Expected background = 0.17 events
- Background estimate under study, signal box not yet unblinded



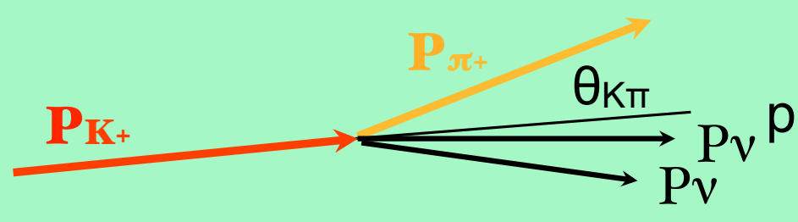
Beam power will increase to 100 kW by 2018
Continuing upgrades to reduce background:

- New barrel veto (2016)
- Both-end readout for CsI crystals (2018)

Expected to reach SM sensitivity by ~ 2021

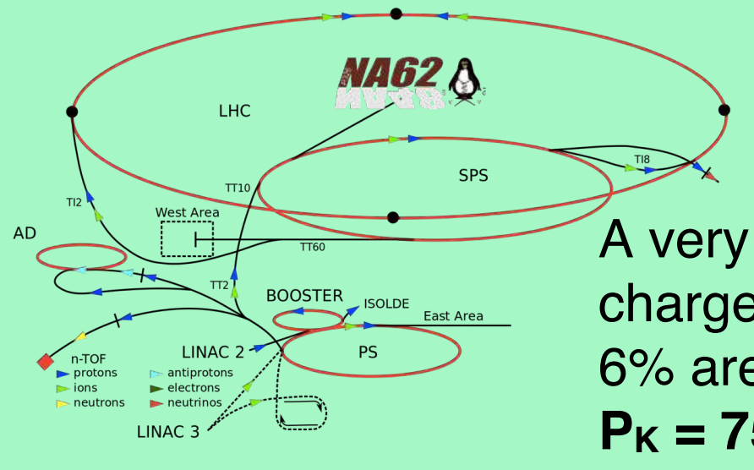
NA62 Experiment at the CERN SpS

GOAL: measure BR($K^+ \to \pi^+ \nu\nu$) with 10% accuracy **O(100) SM events** + control of systematics at % level



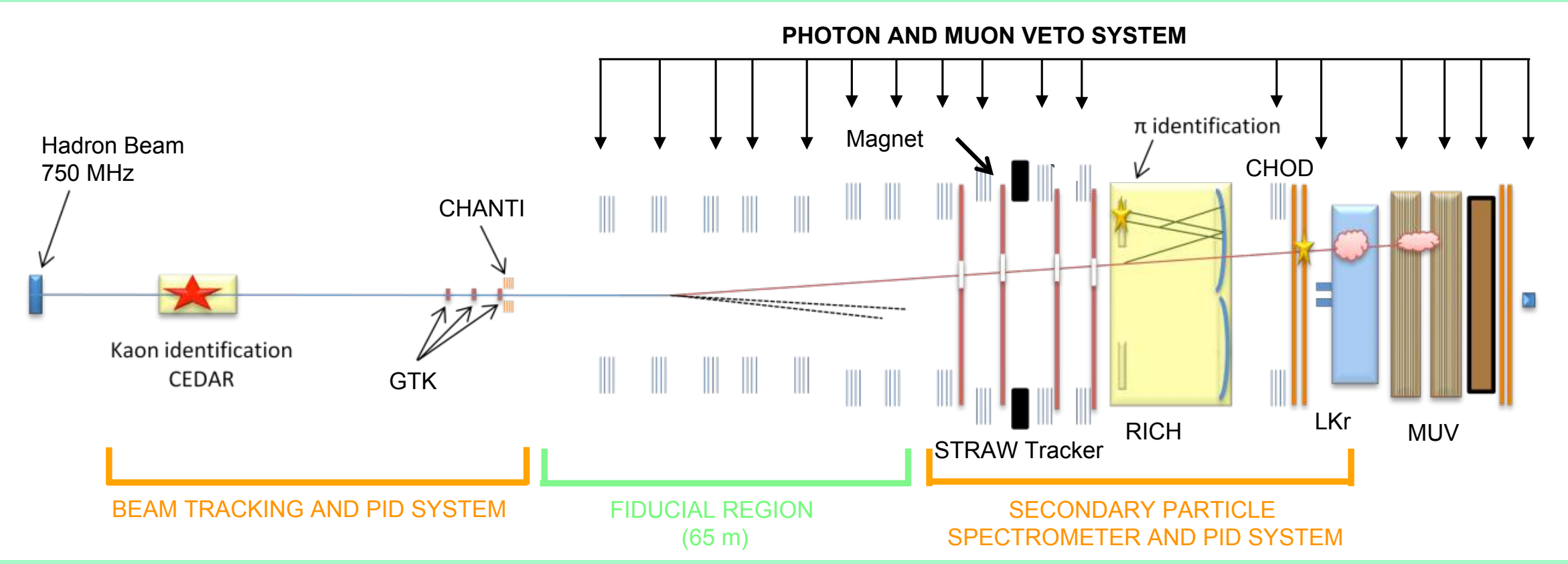
Basic ingredients: precise timing and track reconstruction, redundant particle ID & hermetic photon vetoes

Housed in the **CERN North Area** where a beam line provides 1.1 × 10^{12} protons/eff. second incident on a beryllium target with **P = 400 GeV/c**



A very intense secondary charged beam of which 6% are K+ is produced, **P_K = 75 GeV/c** is selected.

4.5 MHz of kaon decays in 60-m fiducial region



Data taking foreseen till LHC LS2 (end 2018).

KLEVER Project

In contrast to KOTO, the KLEVER project would use a high-energy beam (~**97 GeV**): photon vetoing significantly easier but size of the detector and volume to be covered with photon vetoes considerably increases

Experimental infrastructure & NA48 LKr calorimeter already in place

Advantages of siting in NA62 site:

- Long beam cavern and experimental hall needed
- 100-m neutral beamline to reduce background from Λ and regenerated K_S
- 140-m experiment length to contain FV and provide effective background rejection

Assuming BR($K_L \to \pi^0 \nu\nu$) = 3.4 × 10^{-11} and acceptance for decays occurring in FV ~ 10%

3 × 10^{13} K_L decay in fiducial volume (FV) needed for 100 signal events

Primary Beam:
400 GeV/c p on 400 mm Be target
with production at 2.4 mrad to optimize (K_L in FV)/n

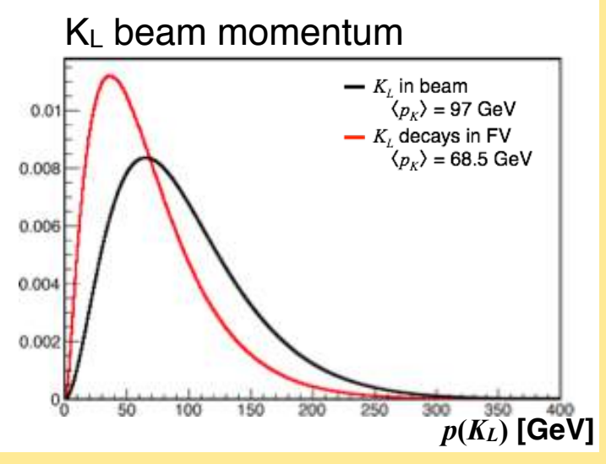
Required total proton flux:

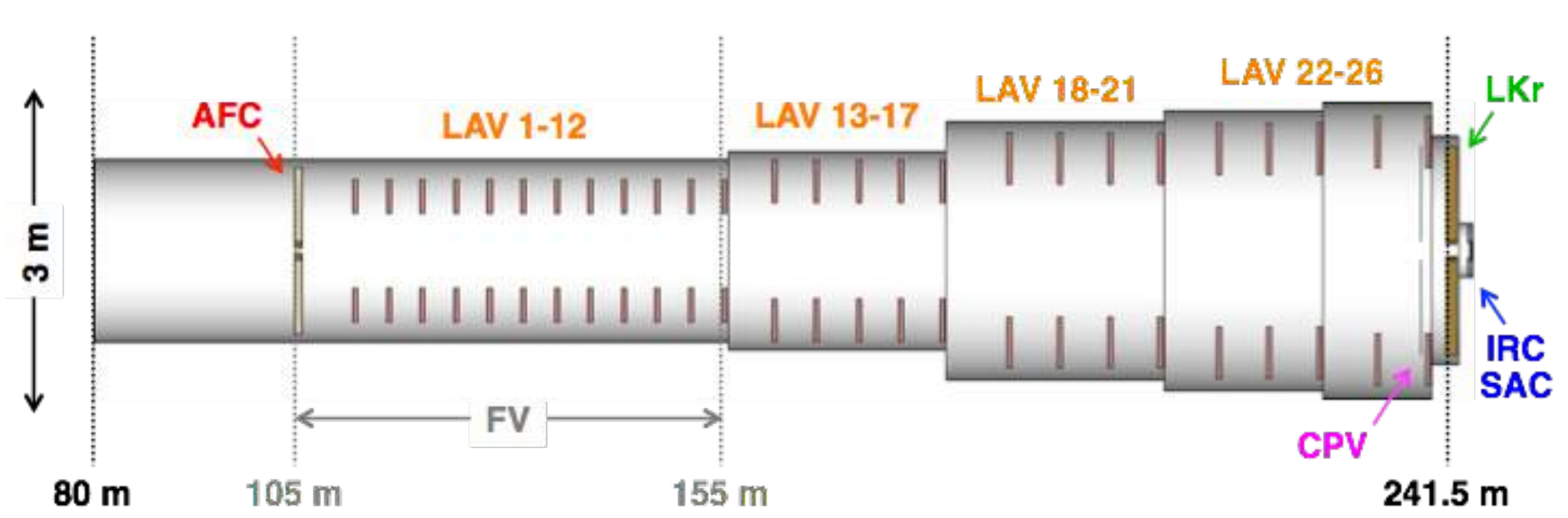
- 5 × 10^{19} pot
- 10^{19} pot/year (= 100 eff. days)
- E.g.: 2 × 10^{13} ppp/16.8 s
- uniform spill structure

upgrades to target area and transfer lines

Secondary neutral Beam:

- **2.8 × 10^{-5} K_L in beam/pot**
- Probability for decay inside FV **~ 2%**





Apparatus

Main detector/veto systems:

AFC: Active Final Collimator/Upstream Veto

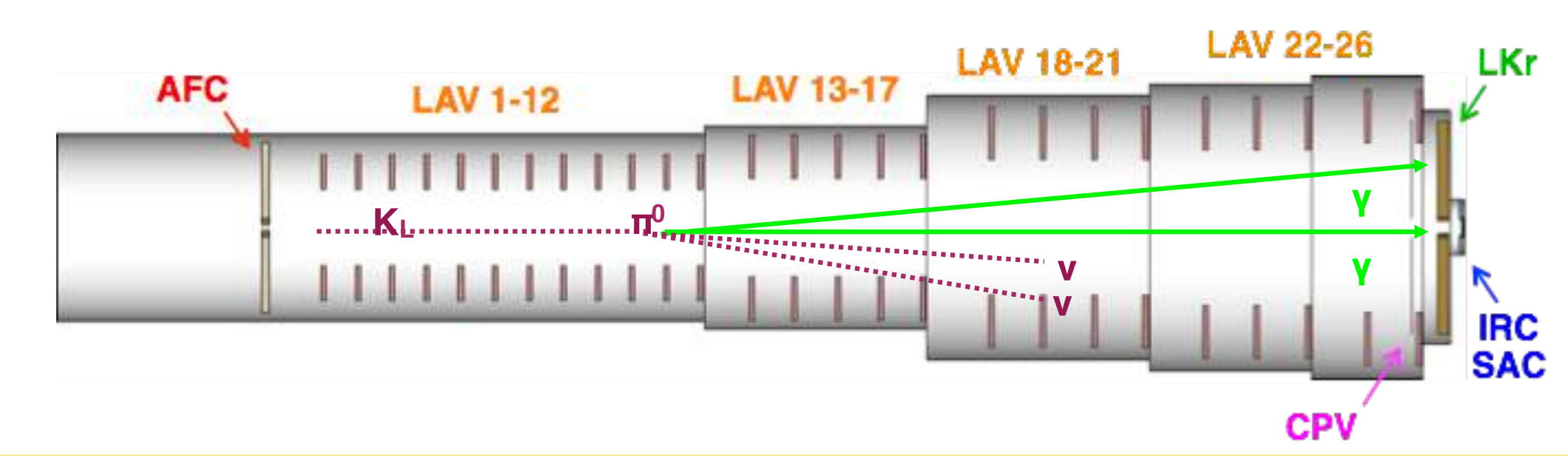
- 25 m of vacuum upstream of final collimator.
- No obstruction for γs from decays with 80 m < z < 105 m.
- Outer ring: Shashlyk calorimeter, Pb/scint in 1:5 ratio. 10 cm < r < 1 m, 1/3 of total rate.
- Inner ring: LYSO collar counter, 80 cm deep, shaped crystals 4.2 cm < r < 10 cm, 2/3 of total rate.

LAV1-26: Large Angle Veto (26 station)

- 5 sizes, sensitive radius 0.9 to 1.6 m, at intervals of 4 to 6 m.
- Hermetic coverage out to 100 mrad for Eγ 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.

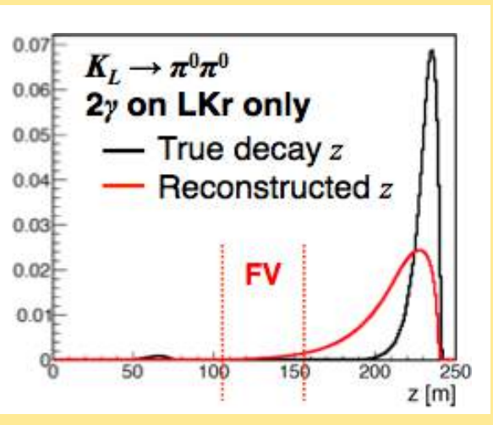
LKr
NA48 Liquid Krypton calorimeter.

Signal Selection: 2 γ in the LKr and no signal in the other detectors



90-m distance from FV to LKr 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



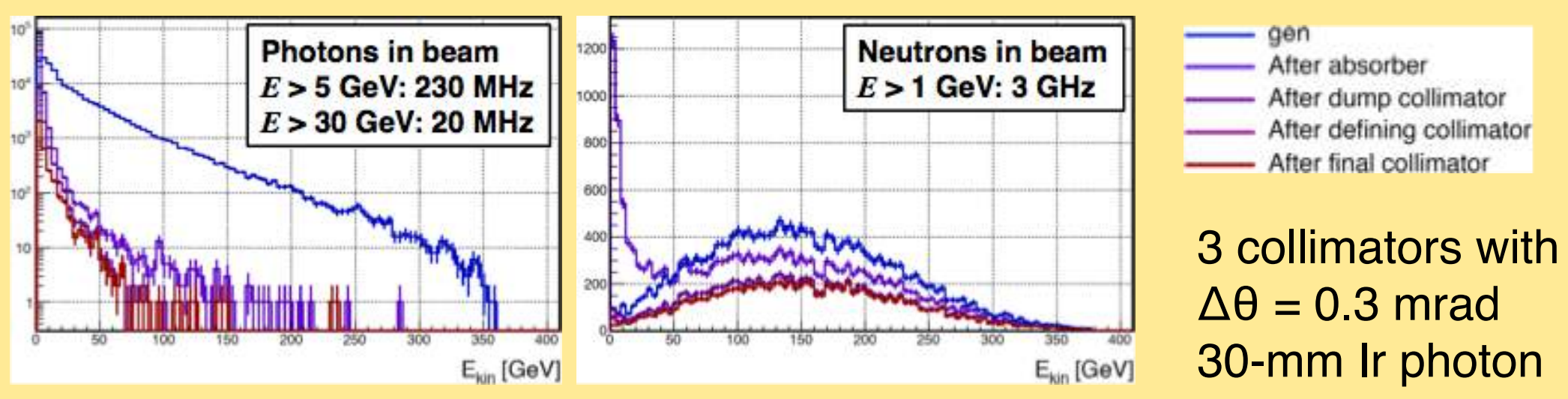
CPV: Charged Particle Veto

- Scintillating tiles, just 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.

IRC/SAC: Small Angle Veto
(SAC in neutral beam).

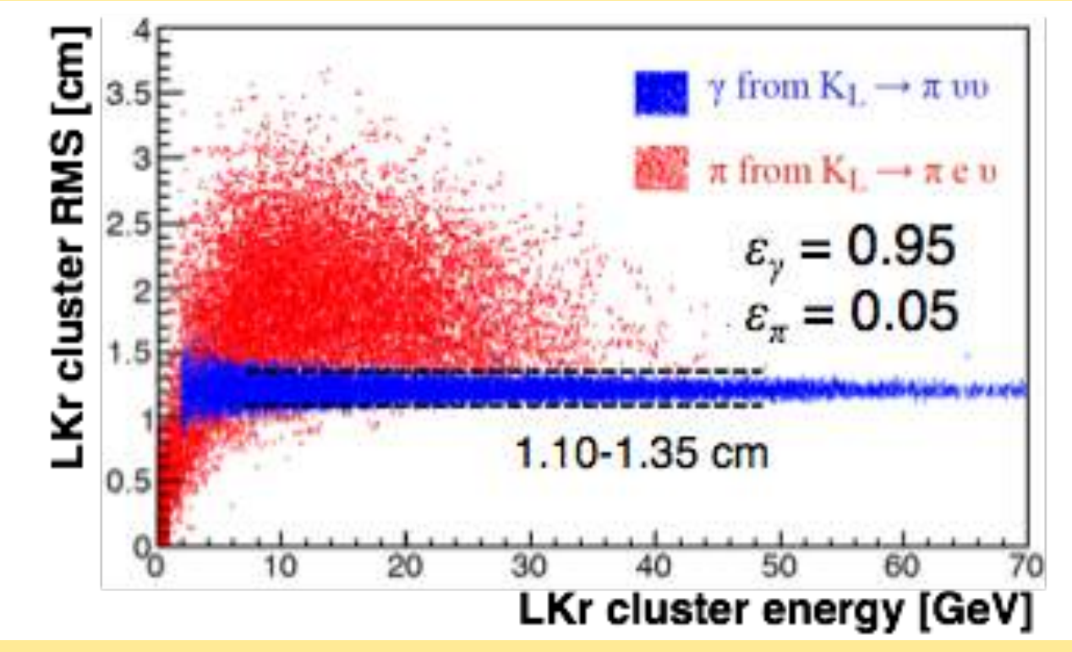
- Reject high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole. Must be insensitive as possible to 3 GHz of beam neutrons.
- Baseline solution: Tungsten/silicon-pad sampling calorimeter with crystal metal absorber.

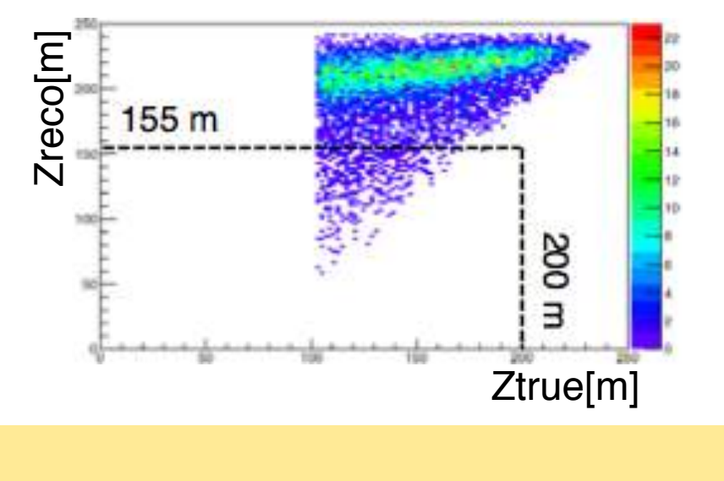
Beam rates from FLUKA simulation



3 collimators with Δθ = 0.3 mrad
30-mm Ir photon absorber in beamline

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!





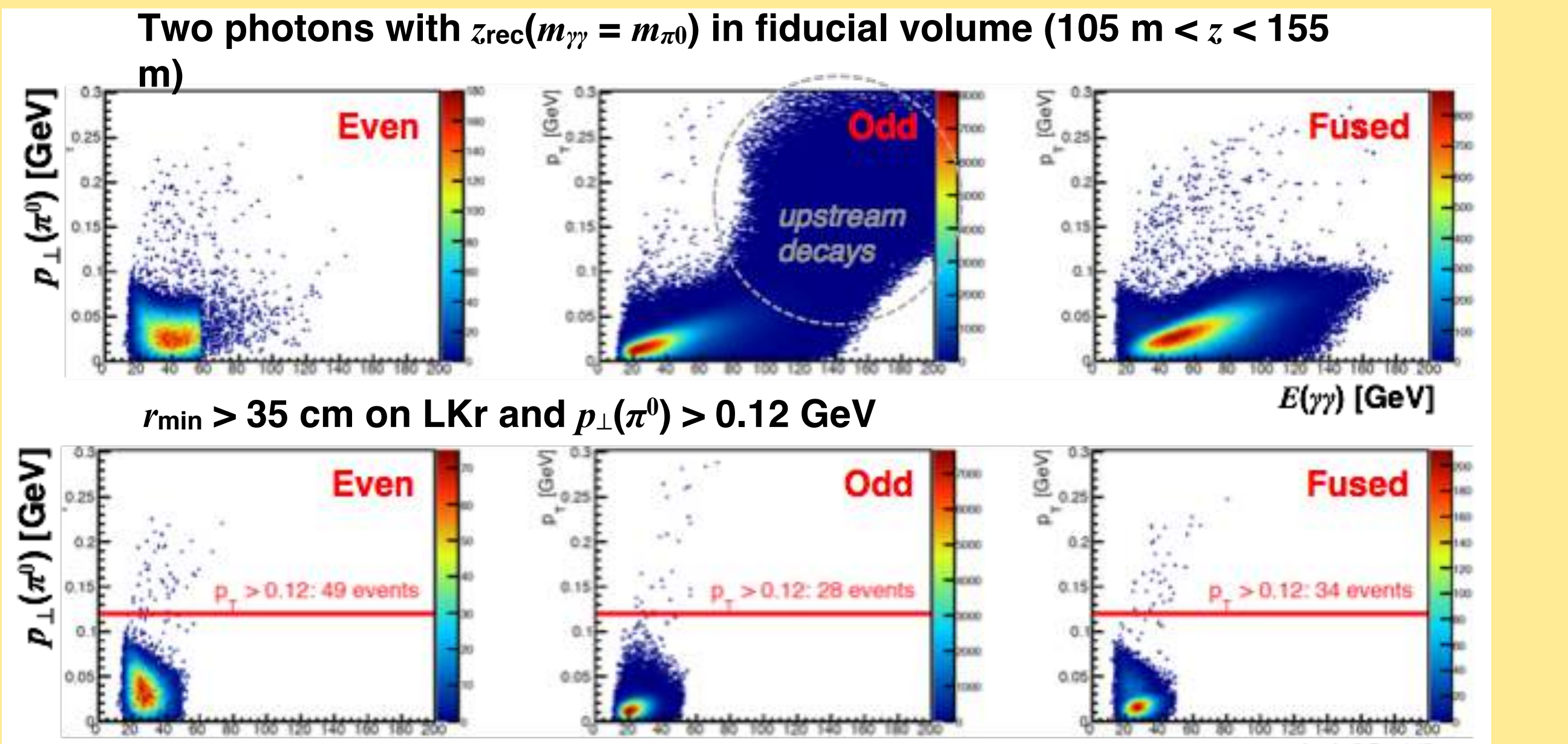
All πe from K_{e3} reconstructed as π^0 have z_{true} < 200 m

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

Accept only events with 2 γs in LKr and no hits in other detectors.
Distinguish between even/odd pairs and events with fused clusters (5 yr equivalent statistics)

Two photons with $z_{rec}(m_{\gamma\gamma} = m_{\pi 0})$ in fiducial volume (105 m < z < 155 m)

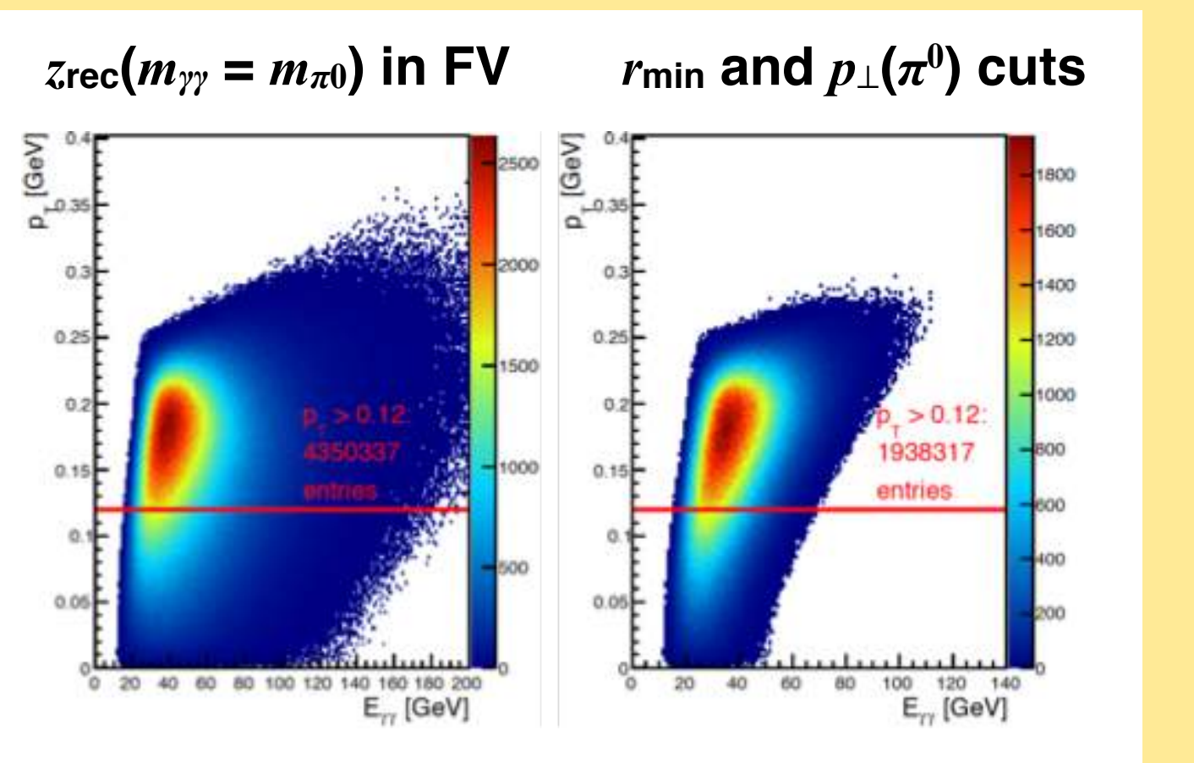
r_{min} > 35 cm on LKr and $p_\perp(\pi^0)$ > 0.12 GeV



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

Signal Acceptance

$z_{rec}(m_{\gamma\gamma} = m_{\pi 0})$ in FV **r_{min} and $p_\perp(\pi^0)$ cuts**



10^{19} pot/year
2.8 × 10^{-5} K_L/pot
BR = 3.4 × 10^{-11}
ε_{total} = 0.20%

19.4 $\pi^0\nu\nu$ evts/year

Channel	Expected in 5 yrs*
$K_L \to \pi^0\nu\nu$	97
$K_L \to \pi^0\pi^0$	111
$K_L \to \pi^0\pi^0\pi^0$ All bkg evts from cluster fusion Upstream decays not yet included	15
$K_L \to \gamma\gamma$ $p_\perp$ cut very effective	0
$K_L \to$ charged	thought to be reducible

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

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