NA62 and precision kaon experiments

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Outline:

1) $K\to\pi\nu\bar{\nu}$ decays: theory and experiment.
2) Approved $K\to\pi\nu\bar{\nu}$ projects: NA62@CERN and E14@J-PARC.
3) NA62: the wider physics programme and UK involvement.
4) Summary.

UNIVERSITY OF BIRMINGHAM

PPAP community meeting • University of Birmingham
11 July 2011

CERN

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

Theoretically clean, sensitive to new physics, almost unexplored

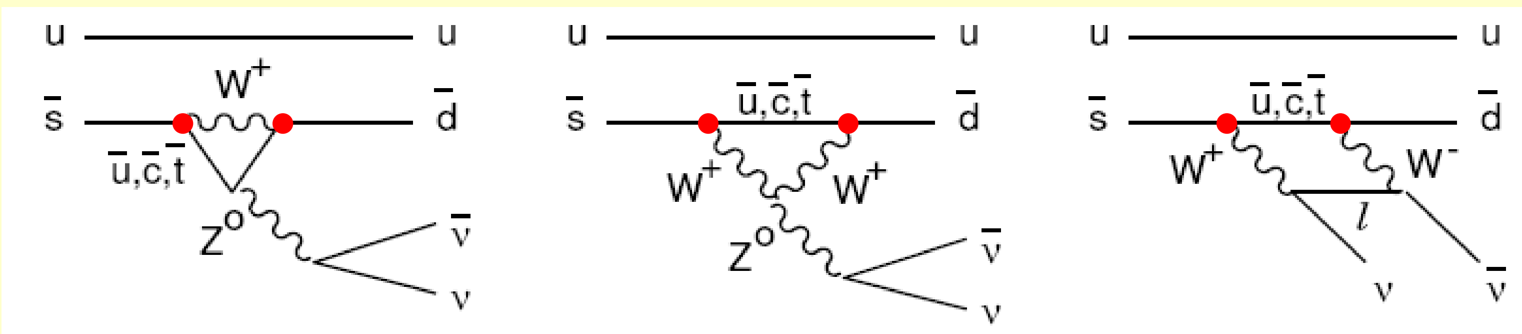
Ultra-rare decays with
the highest CKM suppression:
$|V_{ts}^{*} V_{td}| \sim \lambda^5$

SM branching ratios

(Brod et al., PRD83 (2011) 034030)

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu \bar{\nu}(\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \to \pi^0 \nu \bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

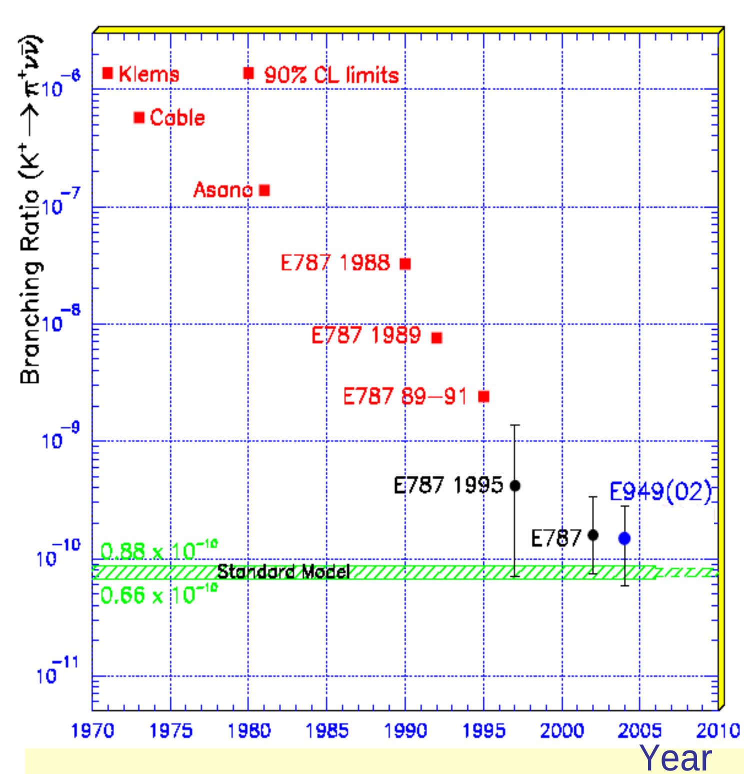
CKM parametric   Intrinsic



- Hadronic matrix element can be related to measured quantities ($K \to \pi e \nu$ form factors).
- Exceptional SM precision not matched by any other loop-induced meson decay.
- Measurement of $|V_{td}|$ complementary to those from B–$\bar{B}$ mixing and $B^0 \to \rho \gamma$.
- $\delta BR/BR = 10\%$ would lead to $\delta|V_{td}|/|V_{td}| = 7\%$.

$K^+ \to \pi^+ \nu\bar{\nu}$: BNL E787/E949

($K_L \to \pi^0 \nu\bar{\nu}$ never observed)



Technique: K^+ decay at rest.

Data taking: E787(1995–98), E949(2002).

Incoming K^+ (710 MeV/c) stopped in target (1.6MHz).

PID: range (entire $\pi^+ \to \mu^+ \to e^+$ decay chain).

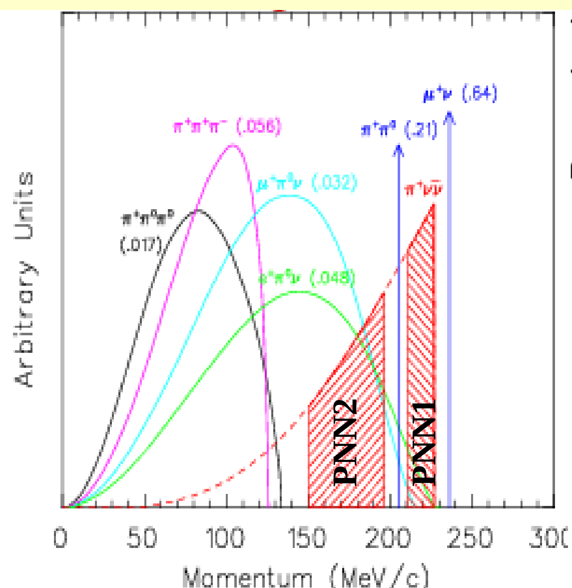
Hermetic photon veto system.

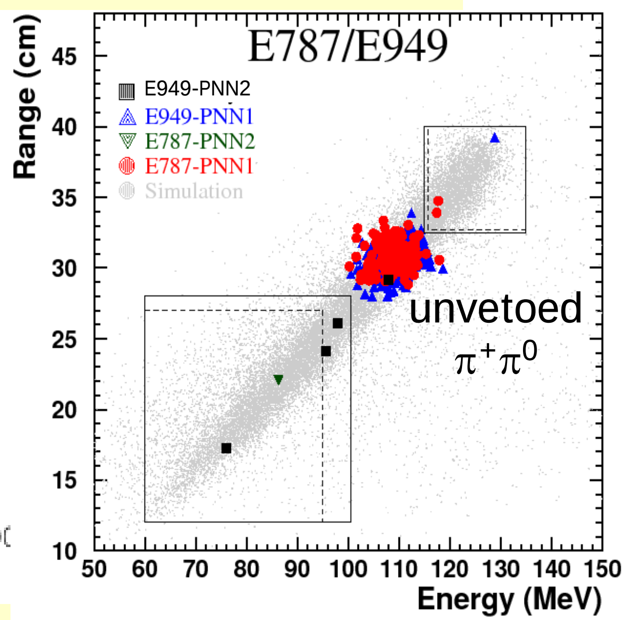
Observed candidates: 7

Expected background: 2.6

Final result: $BR = (1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$

PRL 101 (2008) 191802, PRD 79 (2009) 092004



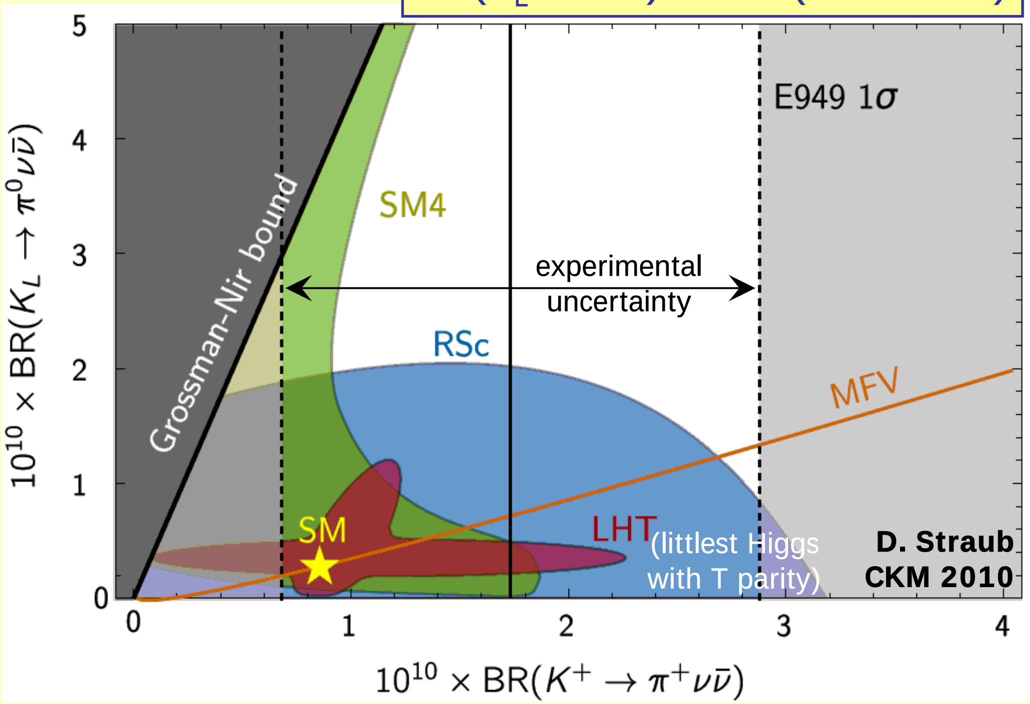


Drawbacks of the method:

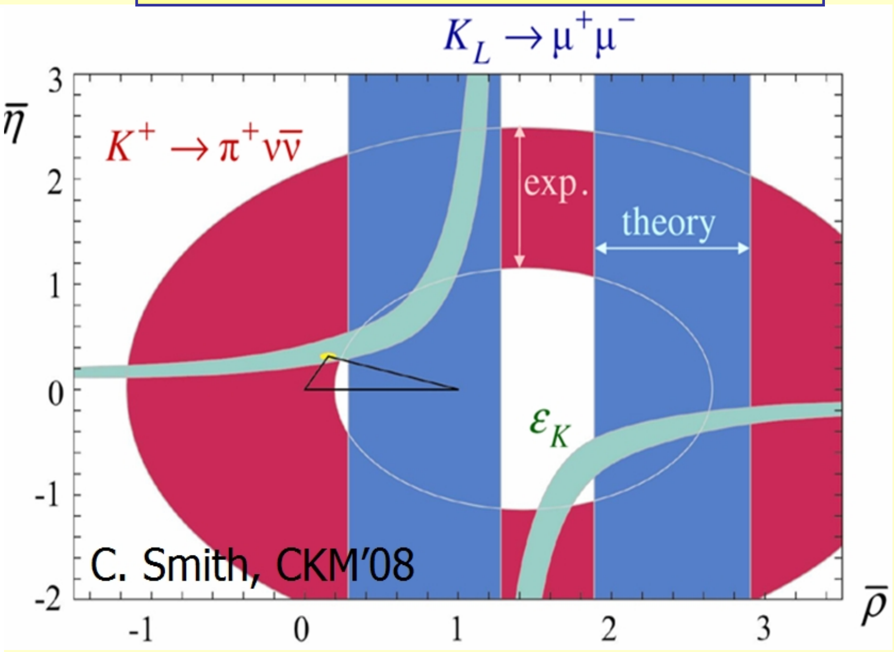
- Low acceptance (~1%);
- significant background (~30%) due to π scattering in the target.

CERN NA62 vs BNL E949

BR($K_L \to \pi\nu\bar{\nu}$) vs BR($K^+ \to \pi^+\nu\bar{\nu}$)



CKM unitarity triangle with kaons



NA62@CERN aims to collect O(100) $K^+ \to \pi^+\nu\bar{\nu}$ decays with ~10% background in 2 years of data taking using novel decay-in-flight technique.

Decay signature: high momentum K^+ (75GeV/c) → low momentum π^+ (15-35 GeV/c).

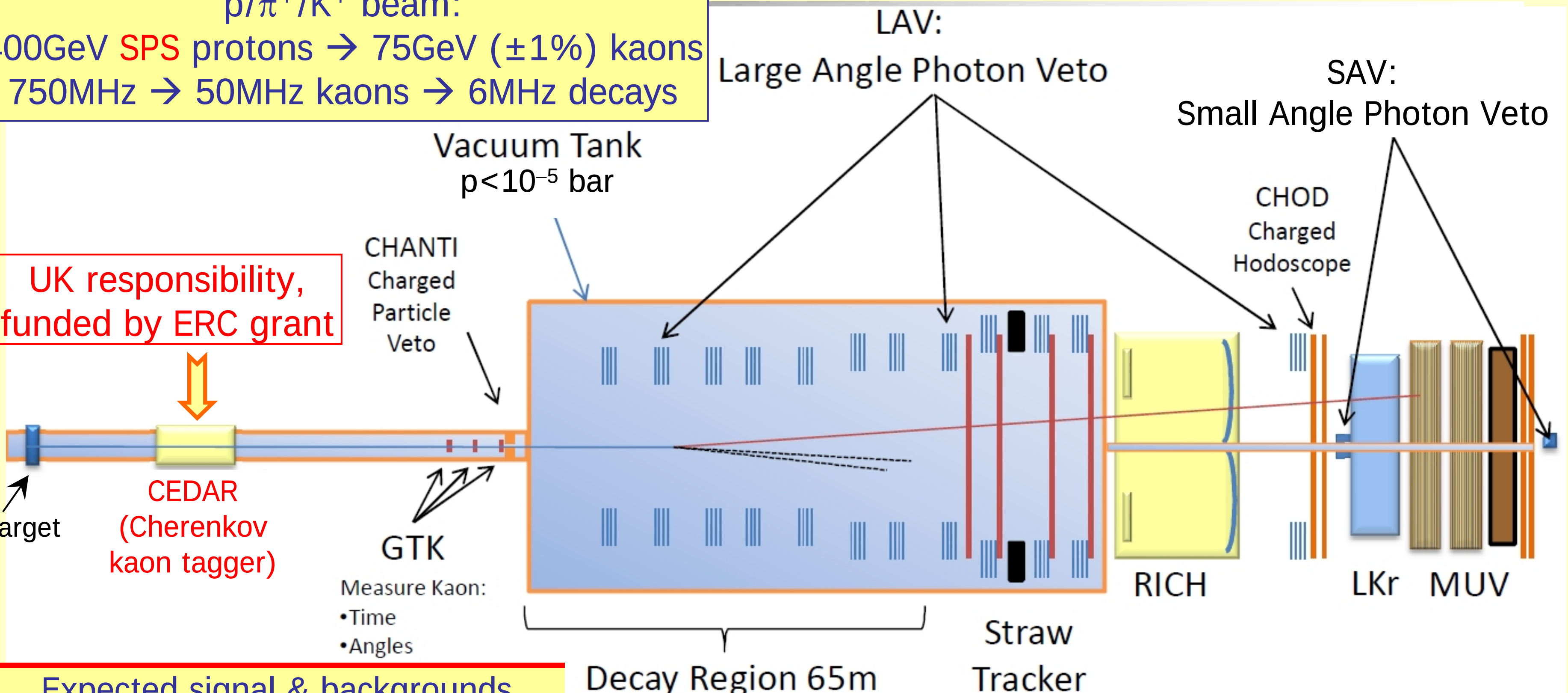
Advantages: high K^+ production rate (~p_K^2); high acceptance (~10%); efficient photon veto (>40 GeV missing energy) + good π^+/μ^+ separation by RICH.

However: unseparated beam (kaon fraction: 6%).

NA62: sensitivity

p/π⁺/K⁺ beam:
400GeV SPS protons → 75GeV (±1%) kaons
750MHz → 50MHz kaons → 6MHz decays

UK responsibility, funded by ERC grant



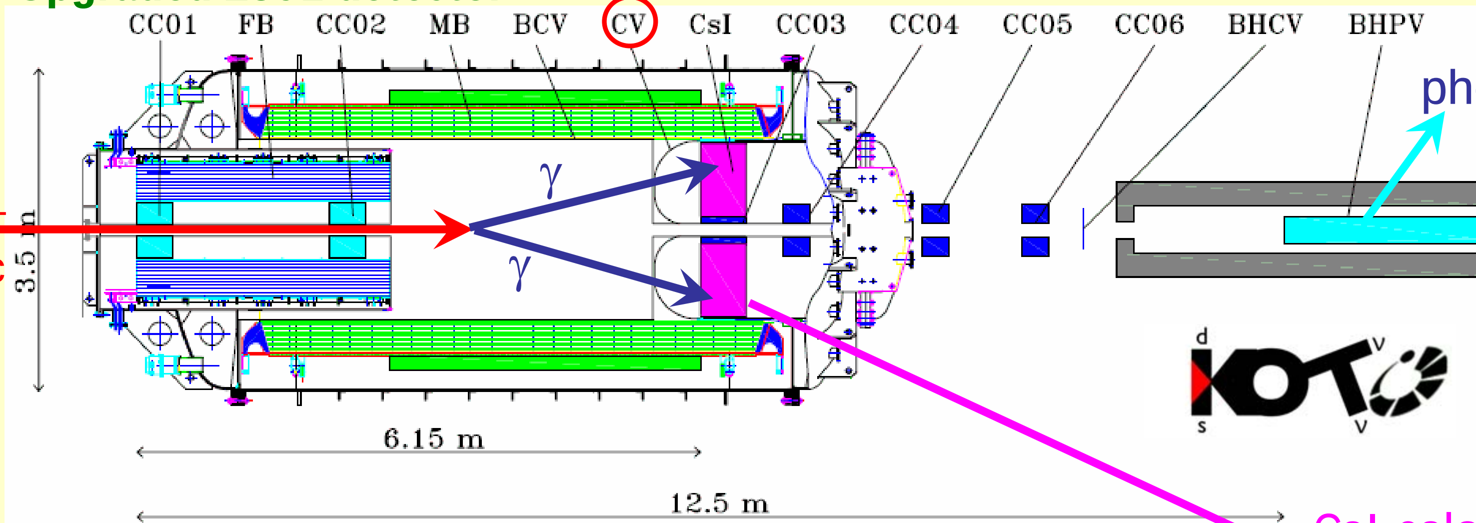
Expected signal & backgrounds	
Signal	45 evt/year
$K^+ \to \pi^+\pi^0$	4.3%
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to$ 3 charged tracks	<4.5%
$K^+ \to \pi^+\pi^0\gamma$	~2%
$K^+ \to \mu^+\nu\gamma$	~0.7%
Total background	<13.5%

- 5×10^{12} K⁺ decays/year → record SES of $\sim10^{-12}$;
- Hermetic veto & redundant kinematics measurements;
- R&D finished in 2010, detector construction in progress;
- Test runs in 2011, 2012;
- Physics runs after the LHC shutdown.

$K_L \to \pi^0 \nu\bar{\nu}$: E14(KOTO)@J-PARC

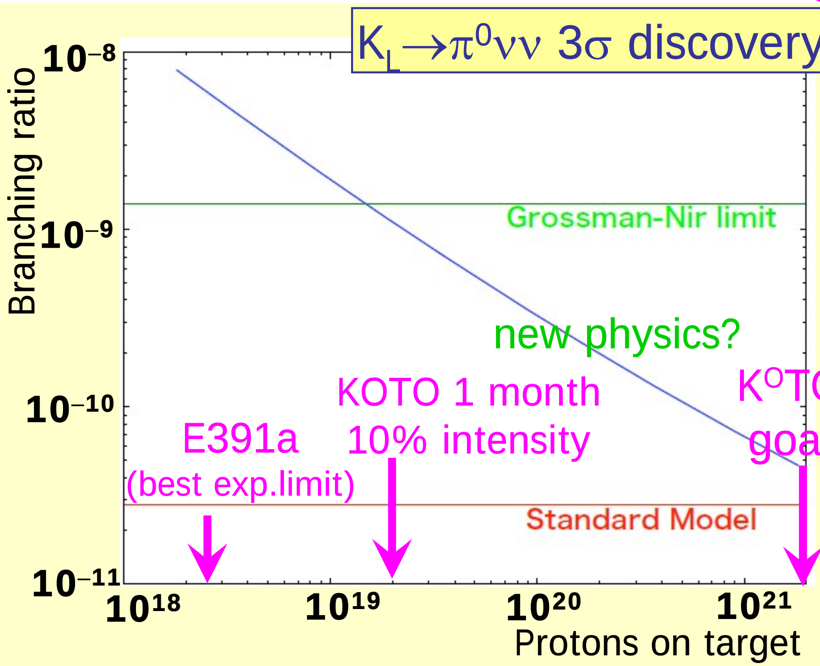
physics runs: 2012–

Upgraded E391 detector

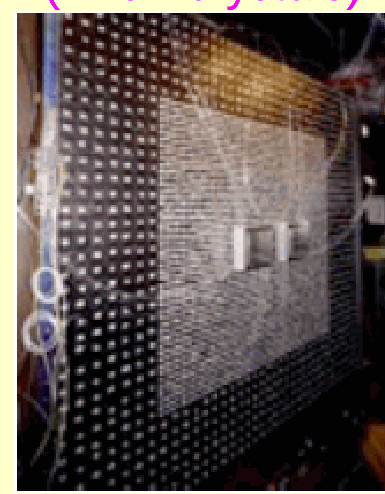


Signal & background (3 years) PoS(KAON09)047	
Signal	2.7
$K_L \to \pi^0\pi^0$	1.7
Halo neutron: CC02	0.01
Halo neutron: CV-π^0	0.08
Halo neutron: CV-η	0.3
Total background	2.1

NA62 might join in ~2017



CsI calorimeter (KTeV crystals)



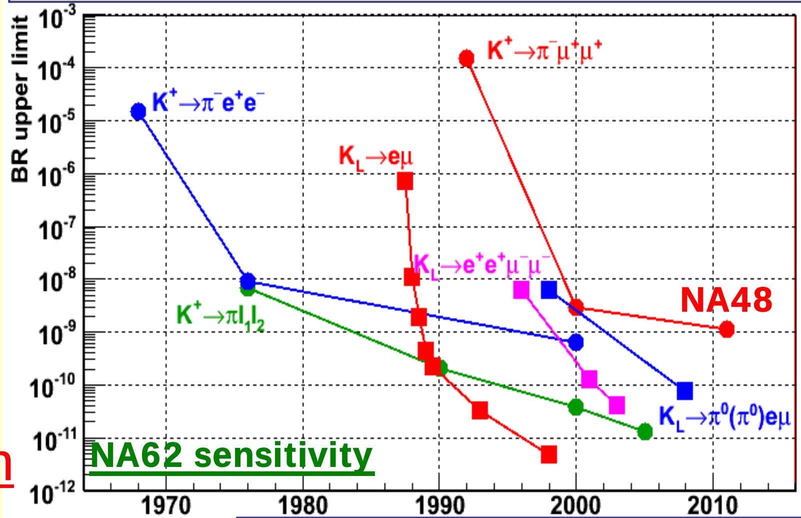
The wider NA62 programme

- <u>Lepton Flavour Universality test</u>
  [UK contribution]
  $R_K = BR(K^+ \to e^+\nu)/BR(K^+ \to \mu^+\nu)$.
  Decay-in-flight technique established at CERN.
  Expected NA62 precision: $\delta R_K/R_K < 0.2\%$.
  Competition: TREK@J-PARC (stopped K^+).

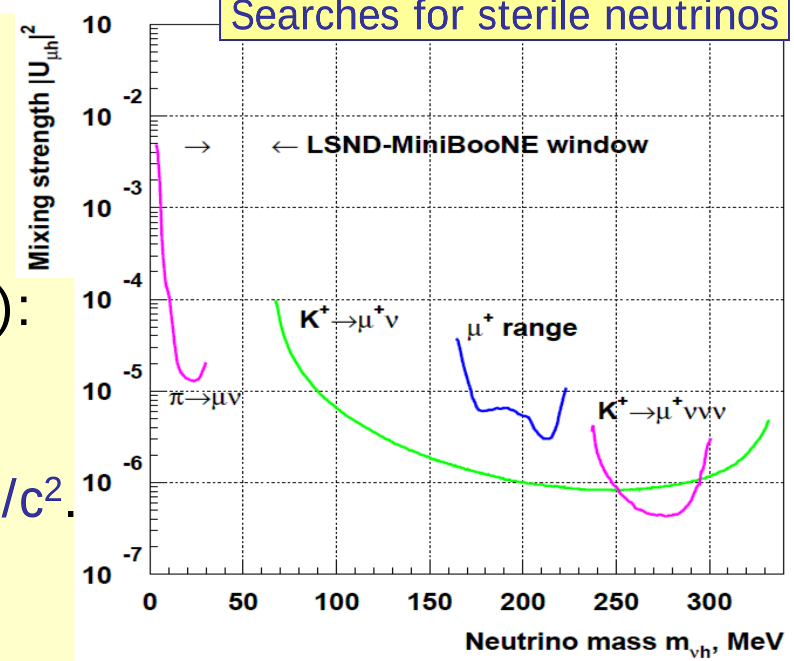
- <u>Searches for lepton flavour/number violation</u>
  $K^+ \to \pi^+\mu^+e^-$, $K^+ \to \pi^+\mu^-e^+$, $K^+ \to \pi^-\mu^+e^+$,
  $K^+ \to \pi^-\mu^+\mu^+$, $K^+ \to \pi^-e^+e^+$.
  Current upper limits: $\sim 10^{-10} \ldots 10^{-11}$.
  Expected NA62 limits: $\sim 10^{-12}$.

- <u>Searches for heavy sterile neutrinos</u> ($m_\nu < m_K$):
  $K^+ \to \mu^+\nu_H$; missing mass or $\nu_H \to \nu\gamma$ decay.
  Possible interpretation of LSND/MiniBooNE results: existence of neutrino with $m \sim 60 MeV/c^2$.
  S.N.Gninenko, PRD83 (2011) 015015

Searches for LFV/LNF: BR upper limit vs year



Searches for sterile neutrinos



Lepton Flavour Physics

(the UK contribution to NA62)

Lepton Flavour Universality (LFU): not a fundamental law (violated in ν sector).
New physics models (2HDM, SUSY, SM4): significant LFU violation.

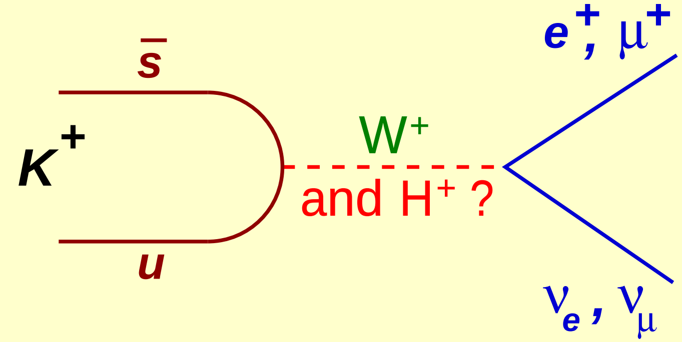
Observable sensitive to LFU violation:

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

Helicity suppression: $f \sim 10^{-5}$

Radiative correction (well known, few %)

- SM prediction: excellent sub-permille accuracy: not obstructed by hadronic uncertainties.
- Measurements of R_K (and R_π) have long been considered as tests of LFU.
- NP contributions accessible experimentally due to the suppression of the SM value.



$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

PL99 (2007) 231801

R_K: new physics

2HDM (including SUSY) – H± mediated

$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right]$$

PRD 74 (2006) 011701
JHEP 0811 (2008) 042

uniquely sensitive to slepton mixing

→ O(1%) effect in large tanβ regime;
→ ~$\tan^6\beta$, *cf.* $B_s \to \mu^+\mu^-$;
→ possibly first evidence for charged Higgs boson [J.Ellis, 2009].

SM with 4-th generation:

$R_K^{4SM} = R_K^{SM} (1-|U_{e4}|^2)/(1-|U_{\mu 4}|^2)$

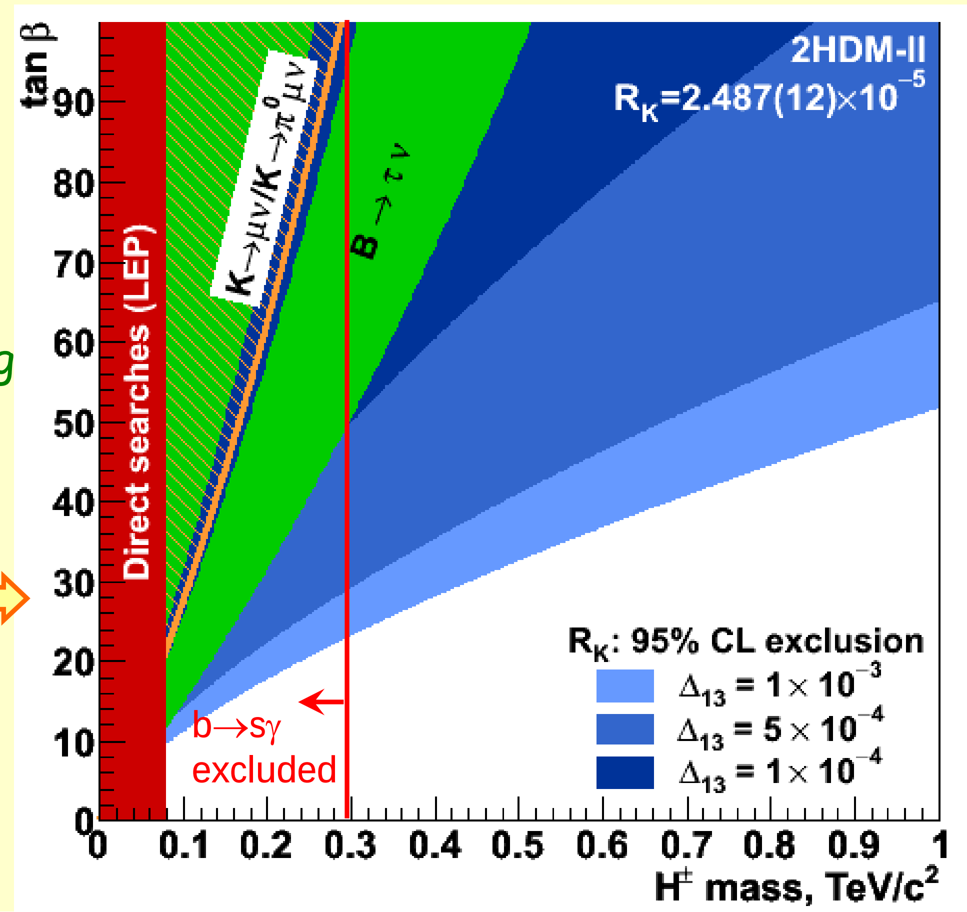
→ sub-percent precision on R_K provides non-trivial constraints on neutrino mixing
JHEP 1007 (2010) 006

NA62 (phase I, 2007-08):

- 0.5% precision with 60K candidates;
- limits on H± mass and slepton mixing.

NA62 goal:

- <0.2% precision with low background sample of ~1M K_{e2} events.



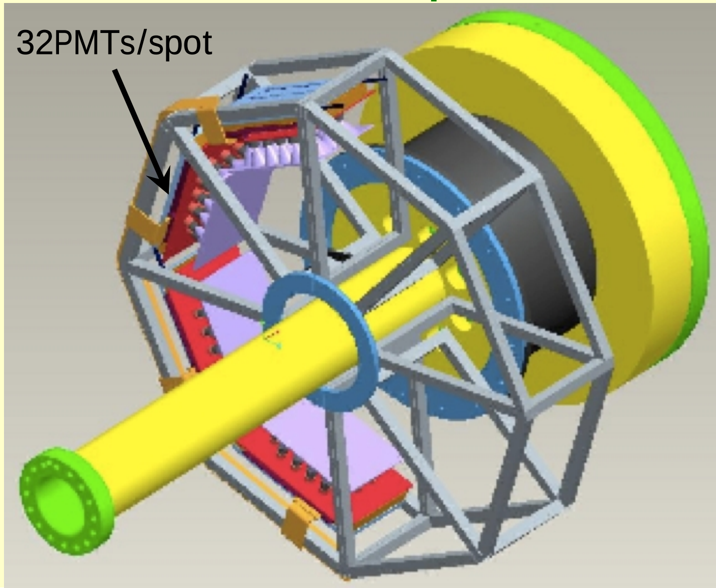
NA62: UK involvement

NA62UK collaboration:
Birmingham, Bristol, Glasgow, Liverpool.
ERC Advanced Grant funding: ~£2M.


(CERN report 82-13)

(1) Delivery of CEDAR beam Cherenkov tagger
- developed in 1980s for ~1MHz signal rates;
- to be upgraded to NA62 kaon rate (~50MHz): replacement of existing PMTs and readout;
- unseparated beam (K^+ fraction: 6%)
  → crucial detector for background suppression

Nose mechanical design (Liverpool).
256 PMTs, ~3MHz/PMT photon rate.



(2) Broadening the physics programme:
- Lepton Universality: $BR(K^+ \to e^+ \nu)/BR(K^+ \to \mu^+ \nu)$.

(3) Key UK responsibilities:
→ CEDAR project leader;
→ co-convener of lepton flavour and exotics WG;
→ chair of the conference committee;
→ 3 (out of 10) members of editorial board.

Summary

- The $K \to \pi\nu\nu$ decays are extremely suppressed and precisely predicted within the SM.
  → *unique sensitivity to new physics;*
  → *a way of pushing the energy frontier above 14 TeV pp interactions.*

- NA62 is the first experiment to measure $BR(K \to \pi\nu\nu)$ to ~10% precision.
  → *A timely measurement complementary to the LHC programme.*

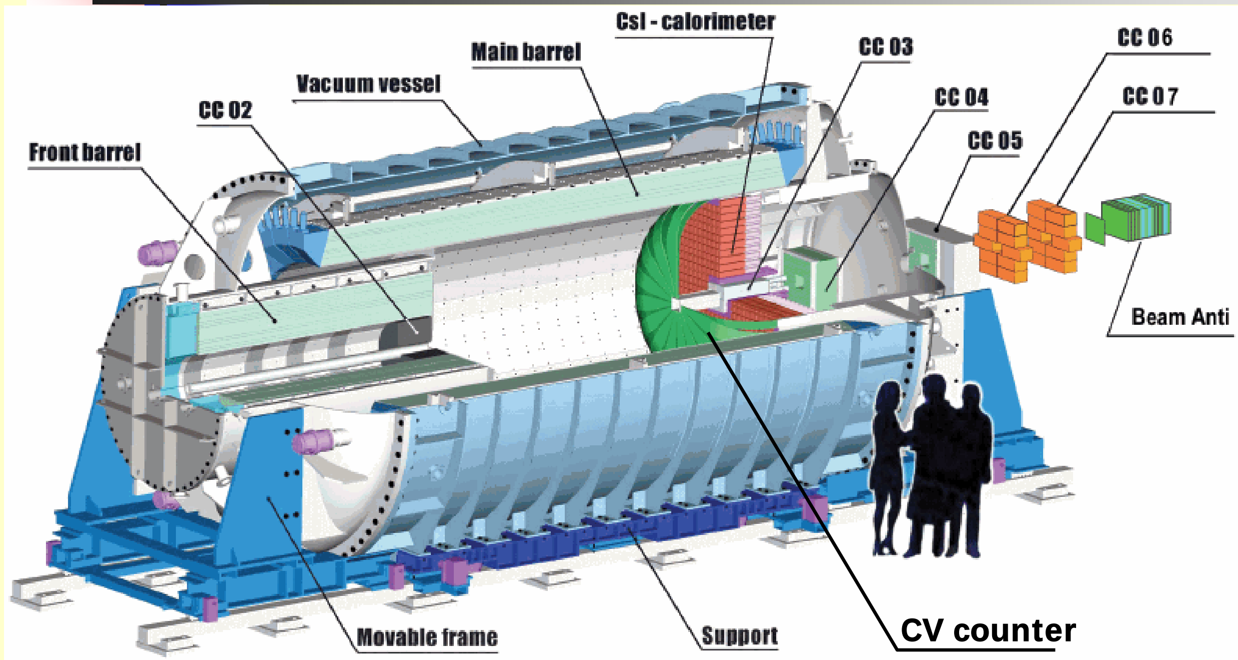
- NA62 programme spans well beyond the flagship decay mode.
  → *Lepton flavour and number violation, sterile neutrinos, …*

- NA62UK: funding secured (ERC Advanced grant, Royal Society University fellowship). Significant hardware contribution + solid physics leadership.
  → *Occasion for STFC to broaden physics programme at a modest investment.*

- In the longer term, NA62 aims at a precision $K_L \to \pi^0\nu\nu$ measurement.

Spares

KEK E391a: $K_L \to \pi^0 \nu\nu$



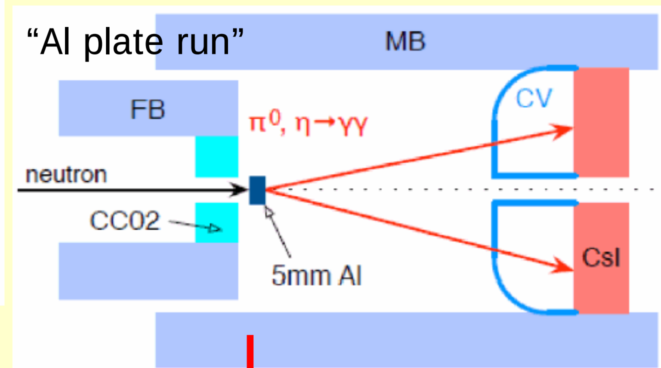
Good physics runs (Runs2,3): Feb-Dec 2005

Pencil K_L beam, 2.5×10^{18} PoT.

Calorimeter:

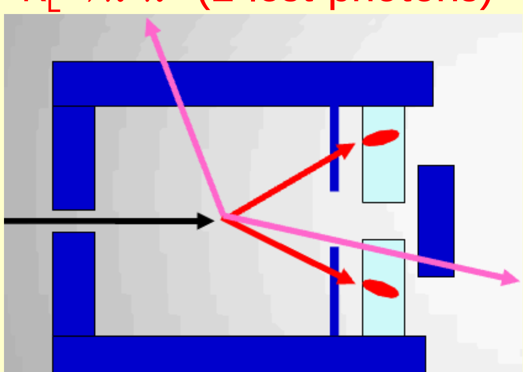
496 $(7\times7\times30)\mathrm{cm}^3$ CsI crystals

Veto: Pb+scintillator+WLS fibers

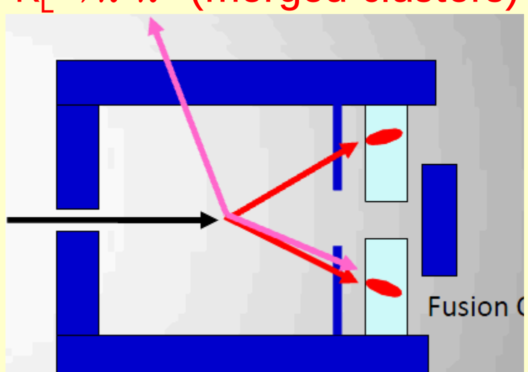


Principal backgrounds:

$K_L\to\pi^0\pi^0$ (2 lost photons)

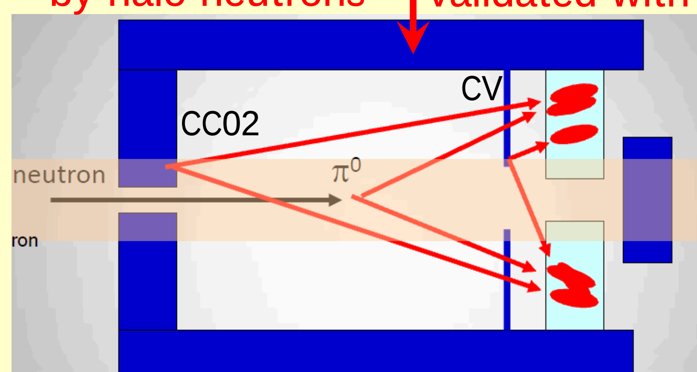


$K_L\to\pi^0\pi^0$ (merged clusters)



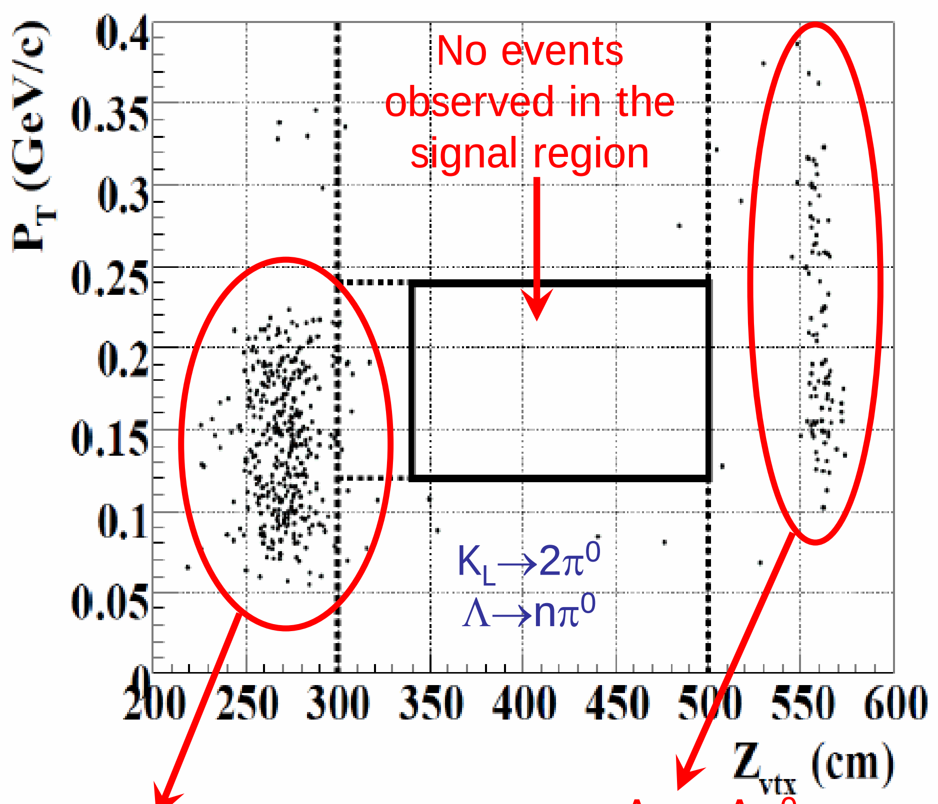
π^0/η production by halo neutrons

FLUKA simulation validated with data



KEK E391a: final result

Signature: a high-p_T π^0 + nothing
Blind analysis technique employed.



$nA \to nA\pi^0$ at CC02

$nA \to nA\pi^0$, $nA \to nA\eta$ at CV

Background source		Estimated number of BG
halo neutron BG	CC02-π^0	0.66 ± 0.39
	CV-π^0	< 0.36
	CV-η	0.19 ± 0.13
K_L^0 decay BG	$K_L^0 \to \pi^0\pi^0$	$(2.4 \pm 1.8) \times 10^{-2}$
	$K_L^0 \to \gamma\gamma$	negligible
	charged modes	negligible ($\mathcal{O}(10^{-4})$)
other BG	backward π^0	< 0.05
	residual gas	negligible ($\mathcal{O}(10^{-4})$)
total		0.87 ± 0.41

Background is dominated by beam interactions

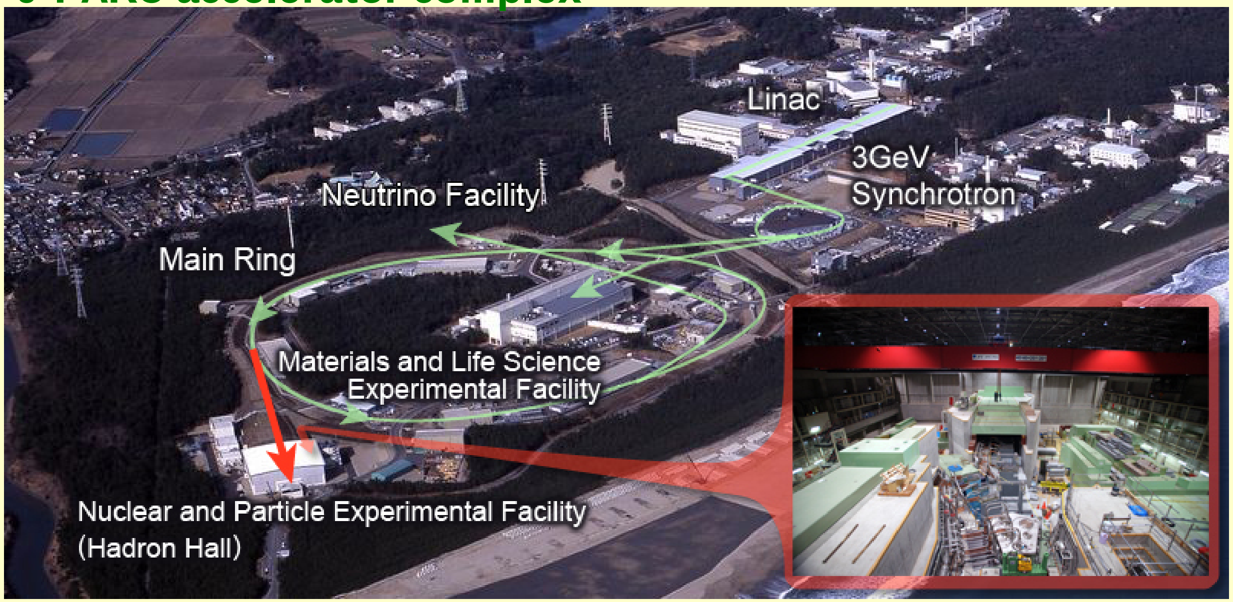
Number of K_L decays:
$N=(8.70\pm0.17_{stat}\pm0.59_{syst})\times10^9$
Signal acceptance: ~1%
SES: $(1.11\pm0.02_{stat}\pm0.10_{syst})\times10^{-8}$

Final result:
$BR(K_L\to\pi^0\nu\nu)<2.6\times10^{-8}$ @90% CL
PRD81 (2010) 072004

Order of magnitude above the GN limit; seen as preparation for JPARC E14

Next step: JPARC E14 (K^OTO)

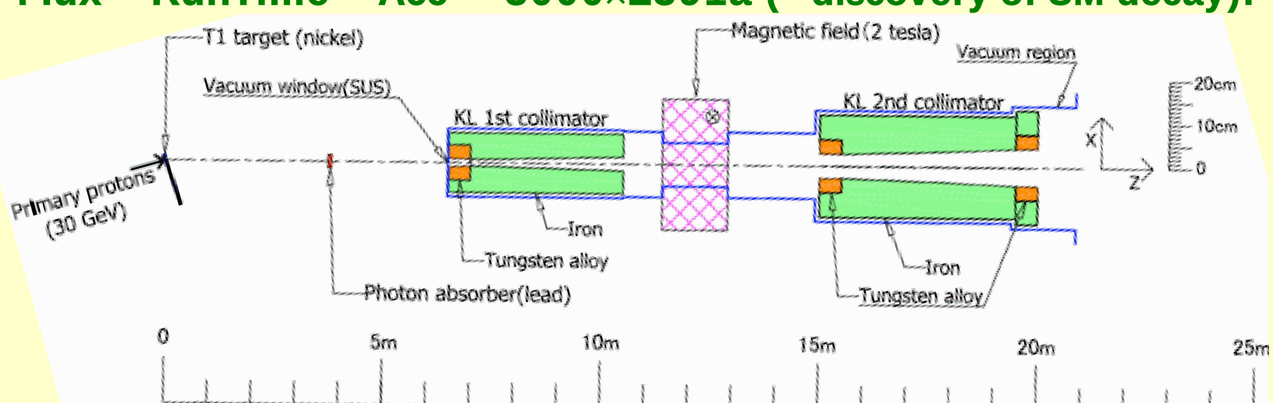
J-PARC accelerator complex

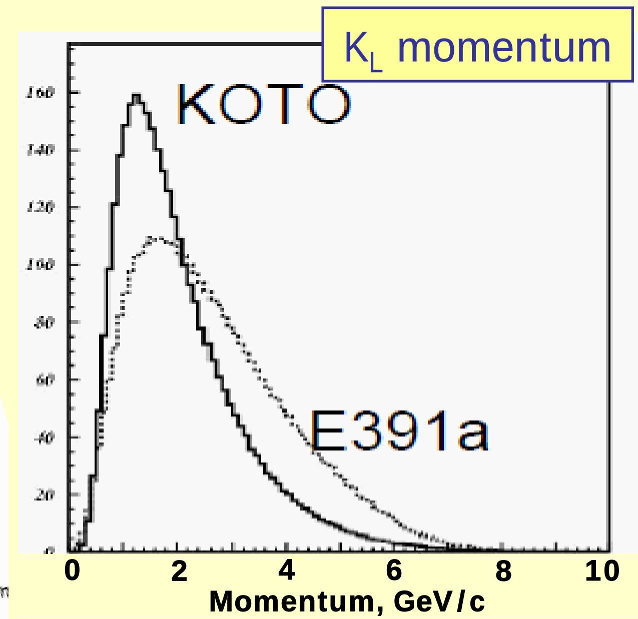


- Proton energy: 30 GeV
- Intensity: 2×10^{14} PoT/spill
- Spill duration: 0.7s/3.3s
- Solid angle: 9μStr
- K_L/spill: 7.8×10^6
- Decay probability: 4%

Physics runs planned: 2012-2014
(12 months in total)

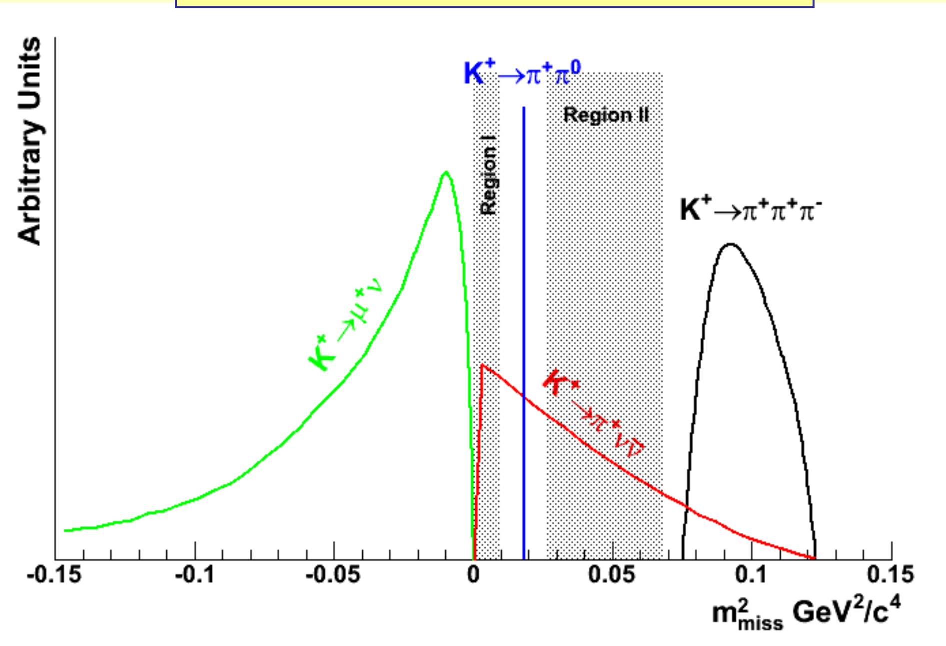
K_L beam: suppression of halo neutrons to ~$10^{-3}/K_L$.
Flux * RunTime * Acc = 3000×E391a (=discovery of SM decay).





NA62: signal region

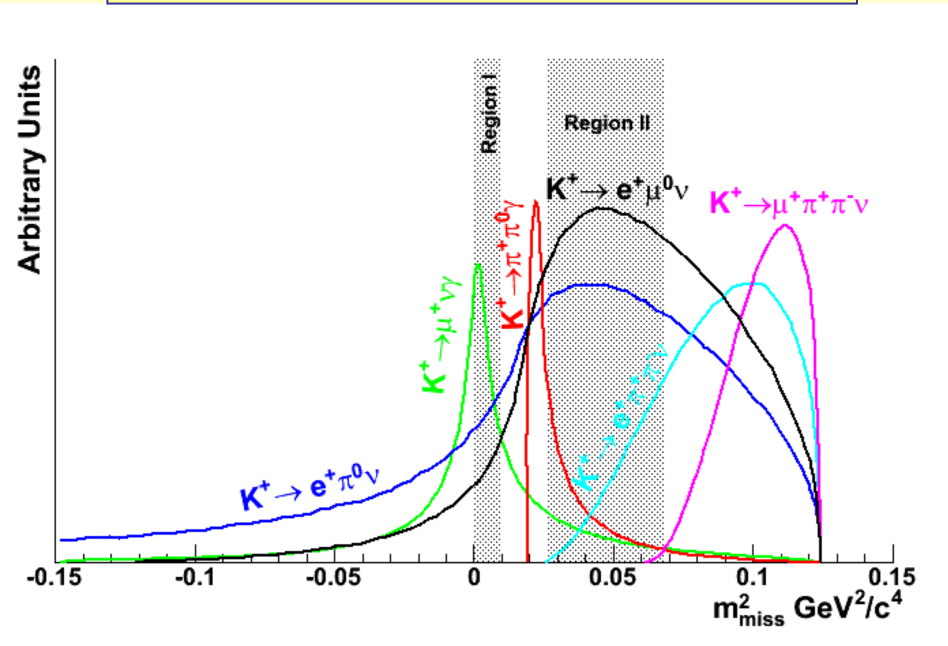
Kinematically constrained



92% of total background

- **Definition of the signal region**
- **$K^+ \to \pi^+\pi^0$ forces us to split it into two parts (Region I and Region II)**

NOT kinematically constrained



8% of total background

- **Span across the signal region**
- **Rejection relies on vetoes/PID**

Kinematic rejection power: 10^4 ($K^+ \to \pi^+\pi^0$), 10^5 ($K^+ \to \mu^+\nu$)

Background contributes via non-Gaussian MS tails; K/π mismatch.