Required technologies:
Kaons @
NA62 + JPARC/Fermilab/KLOE

PPAP Review:
Flavour-changing physics + QCD
Birmingham, 13th July 2009

Cristina Lazzeroni
University of Birmingham

Declaration: I was a member of LHCb and NA48
and now I am a member of NA62

KAONS @ SPS

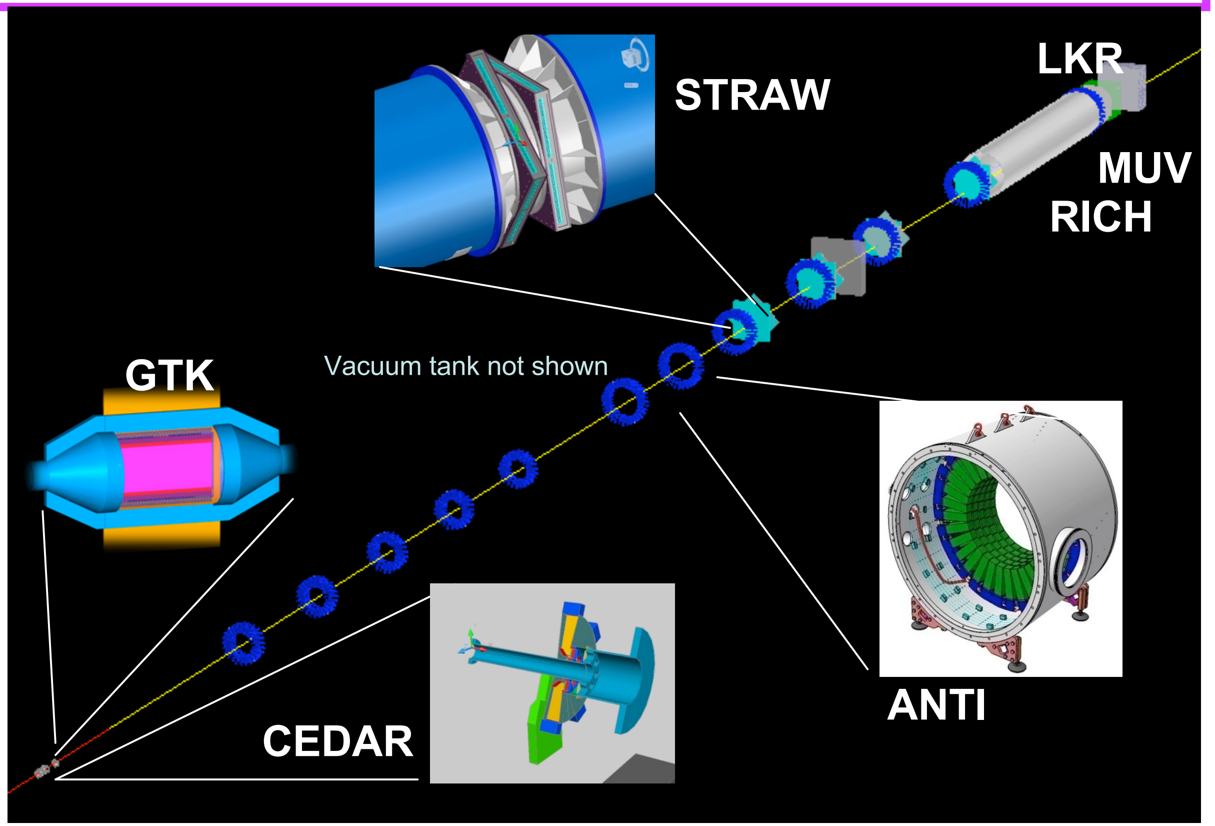
NA62@CERN: Rare Kaon decays

Approved by CERN in 2008
(only fixed-target new project approved in CERN Medium Term Plan)

Collaboration

Bern ITP, Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP, INR, Liverpool, Louvain, Mainz, Merced, Moscow, Naples, Perugia, Pisa, Roma I, Roma II, San Luis Potosi, SLAC, Sofia, Triumf, Turin

UK institutes committed, SoI submitted to PPAN in February 2009, funding now sought

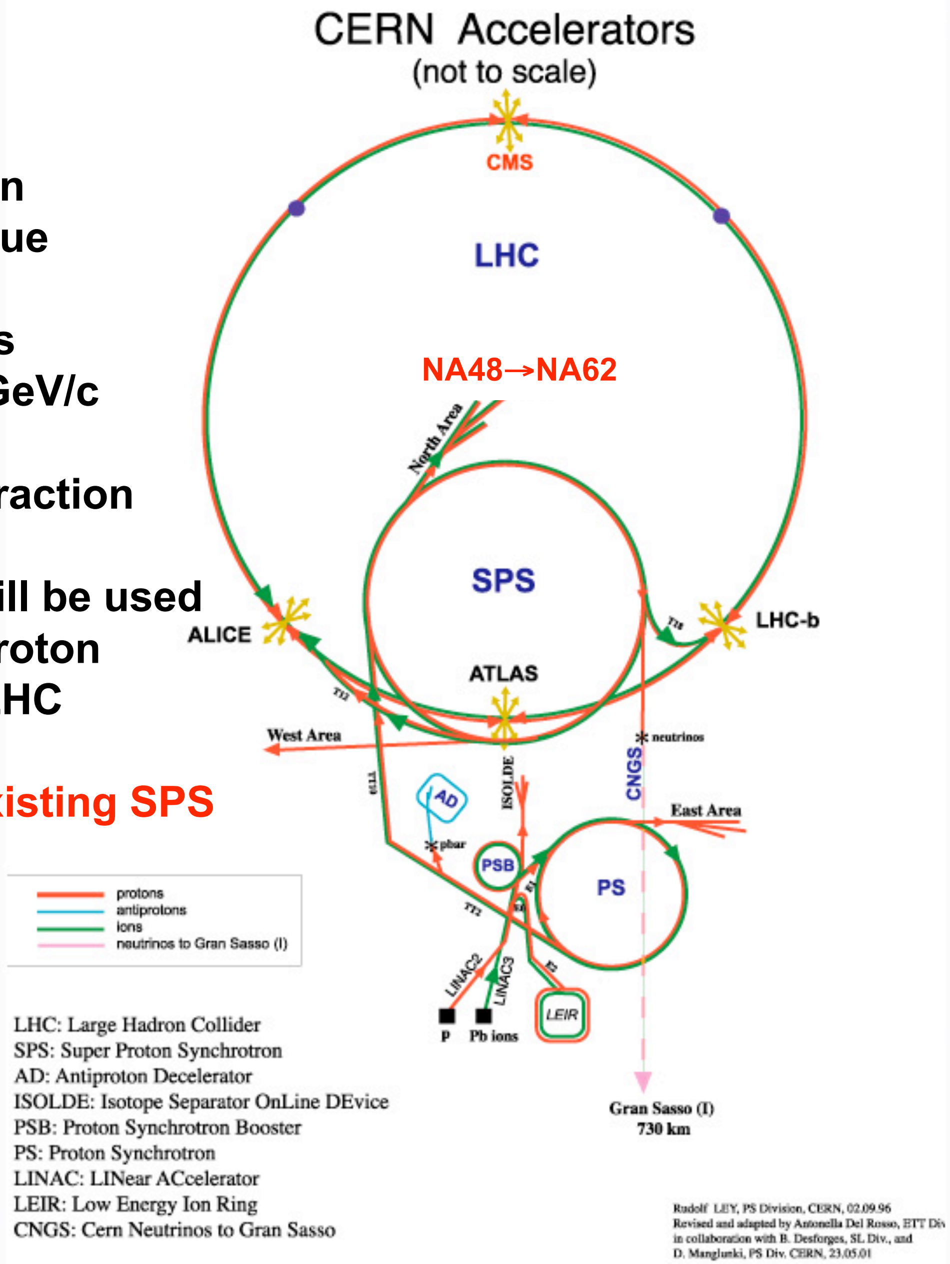


The CERN proton Complex is unique

The SPS delivers Protons of 400 GeV/c Momentum with Fast or slow extraction

Soon the SPS will be used --part time--as proton injector to the LHC

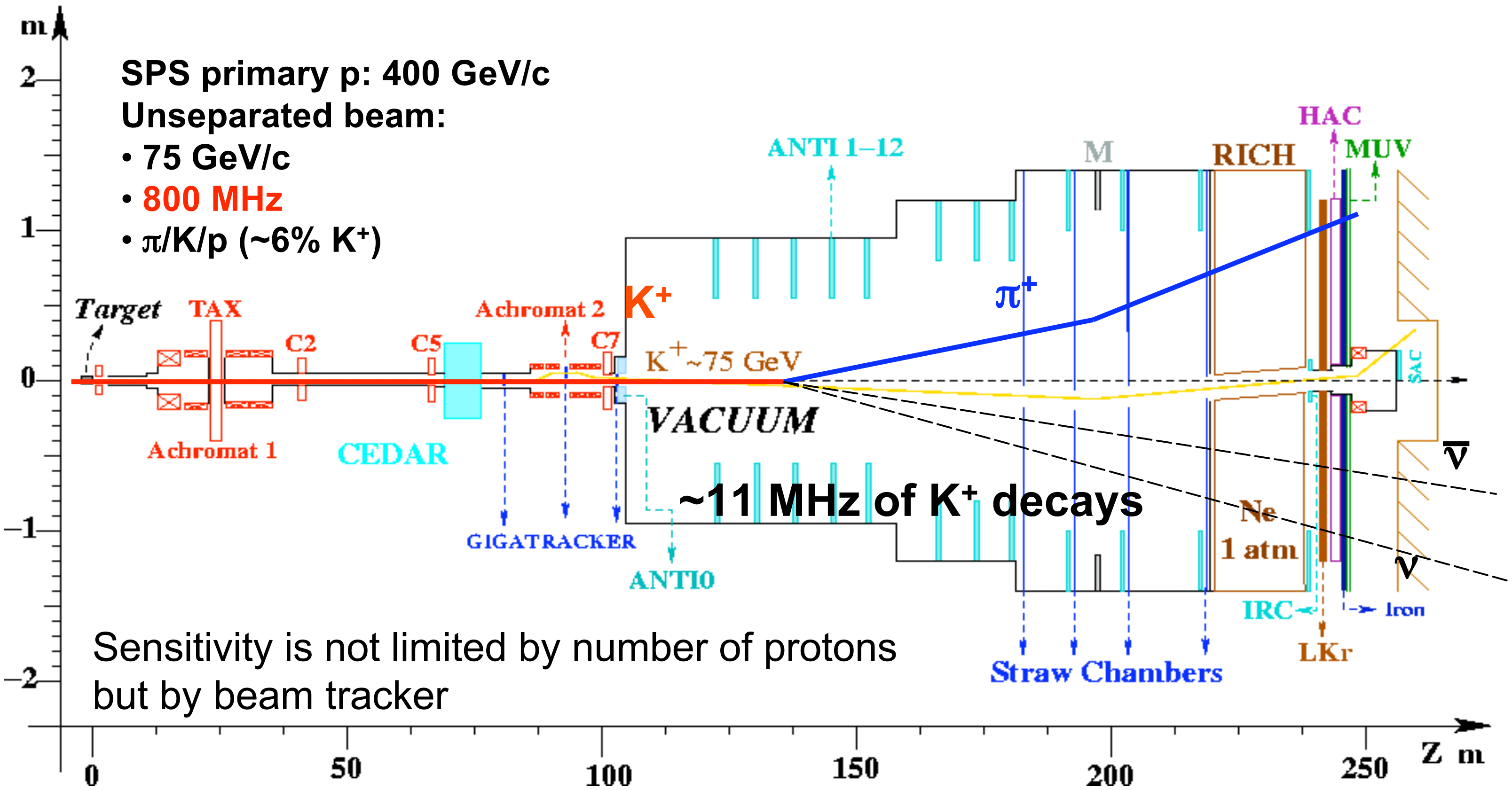
NA62 will use existing SPS



NA62 Detector Layout

Optimised for rare decays - BR($K^+ \to \pi^+ \nu\nu$) ~8 10^{-11} :

to achieve <10% precision needs >150 decays (in 3 years, 100 days/y@60% eff.) with ~10% background - hence ~10^{13} K^+ decays with 10% acceptance and excellent rejection of otherwise overwhelming background



Proposed UK responsibilities: CEDAR, Computing, Trigger

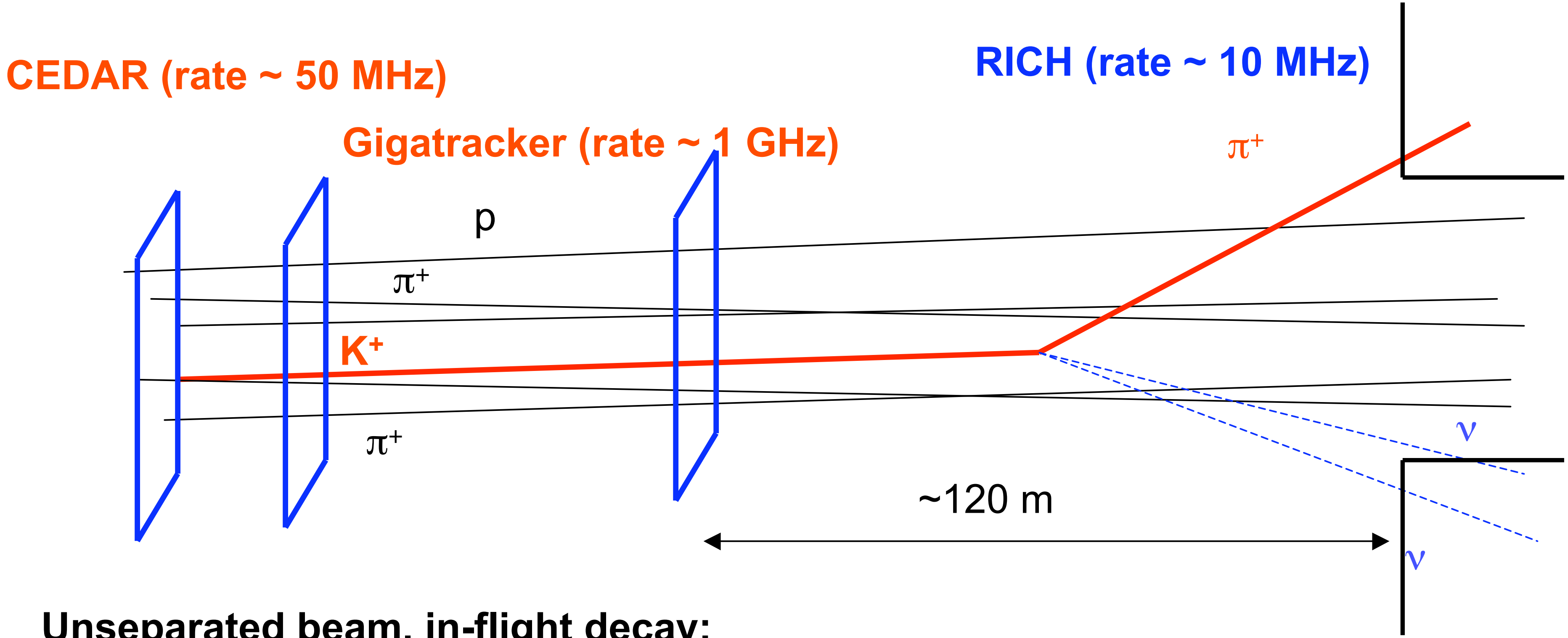
R&Ds

Potential KE/Impact in PET scanners, life-science applicat.

- GTK - track and time each beam particle
  - The R/O prototype chips arrived at CERN
  - R/O : one TDC/pixel or end of column TDC
- STRAW - decay tracks
  - Engineering of a sector prototype
  - Detailed work plan at CERN and Dubna
- ANTI - veto
  - ANTI-A1 to arrive at CERN next week
  - It will be installed in the decay tank and beam tested in the fall
- RICH - Particle identification
  - Successfully beam tested RICH-400 prototype
  - Excellent π/μ separation up to ~35 GeV/c
  - The new electronics was validated

GTK Challenge:
Rate ~ 1 GHz
Time resolution: 200 ps / station
Material Budget: < 0.5 % X_0 / station
Pattern: 300 x 300 μm^2

Challenge: Timing



Unseparated beam, in-flight decay:

How do you associate the parent kaon to the daughter pion in a **~1 GHz beam** ?

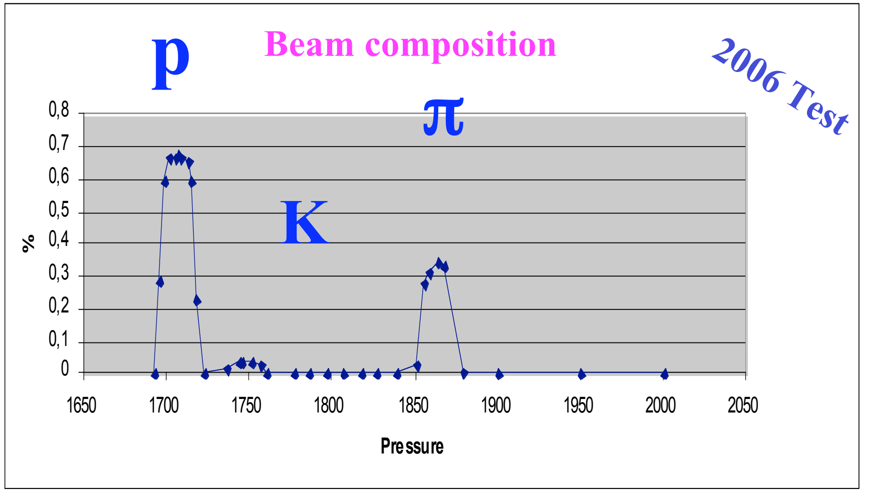
K^+ : Gigatracker, CEDAR with very good time resolution **(~ 100 ps)**
π^+ **: RICH** (Neon, 1 atm) read out by Photomultipliers

The CEDAR (*i.e.* the kaon ID)

- **CEDAR: existing Cherenkov counter at CERN**

- Adapted to NA62 need:
  - H_2 instead of Nitrogen
  - New photo detector and electronics

- Vary gas pressure and diaphragm aperture to select Kaons



Proposed UK responsibility

Kaon rate = 50 MHz and ~100 photons per Kaon on 8 spots of 10x30 mm^2 each

→photon rate = ~ 2 MHz / mm^2
(rate of singles from accidentals, after-pulses, dark noise not included)

New photodetectors SiPM, MCP-PMT --- Potential KE/Impact in PET scanners, life-science applications, new dosimetry

Key points for the new detector:

- Single photon counting application
- Stand very high photon rate / unit area (occupancy in time and space)
- Reduced active area (beam activity)
  (minimum ~150 mm^2 / spot due to optics phase space)
- UV/Blue light sensitivity with the highest efficiency (PDE)
- Excellent timing resolution (100 ps)
- Exposition to the halo of intense hadron beam (radiation damage)

Challenge: photo-detectors

Key Points

- $K^+ \to \pi^+\nu\nu$ very suppressed in SM but theoretically very clear - accessible mass scale up to TeV in certain scenarios -
  acute sensitivity to New Physics (eg. 10-20% deviation in MFV,
  larger effects possible in general MSSM)
  Expected 50 ev/year with 10% background

- Possible extension to $K^0 \to \pi^0\nu\nu$

- LFV tests: improve precision by factor 2 at least in ke2/kmu2; $K^+ \to \pi\mu e$

- With ~50 times the K+ flux of NA48, the physics menu –in addition to the very rare decays- promises to be rich ranging from the precision-tests of lepton universality to the study of the strong interaction at low energy

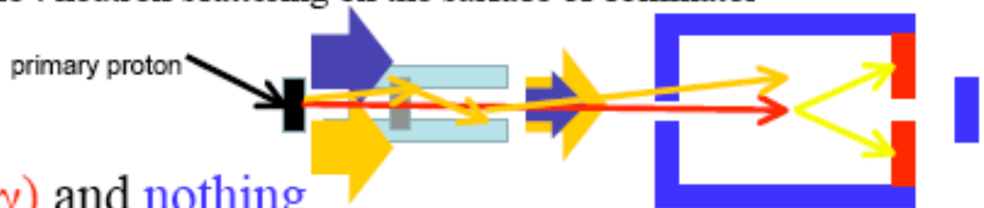
- Excellent resolution, hermetic forward coverage and strong particle ID allow also to study/search for (e.g.):
  - Sgoldstinos (Gorbunov&Rubakov):
    $K^+ \to \pi^+\pi^0 P$, $P \to \gamma\gamma$, $P \to e^+e^-$ or P long-lived
  - νMSM Neutral Leptons (Gorbunov&Shaposhnikov)
  - CPT tests
  - Low-energy QCD
  - form factors in semileptonic decays (related to Vus)

KAONS @ JPARC

JPARC KOTO - designed for $K_L \to \pi^0 \nu\nu$

KOTO Concept of Experiment

- K_L beam (proton → target)
  - neutral beam line
    - » Long beam line → Kill particles with shorter lifetime
    - » Charged particle sweeping magnet.
    - » Pb photon absorber → reduce beam photons
    - » Collimator → shaping KL → Pencil Beam (source of beam halo)
  - Core : K_L, photon, neutron
  - Halo : neutron scattering on the surface of collimator
- Detector



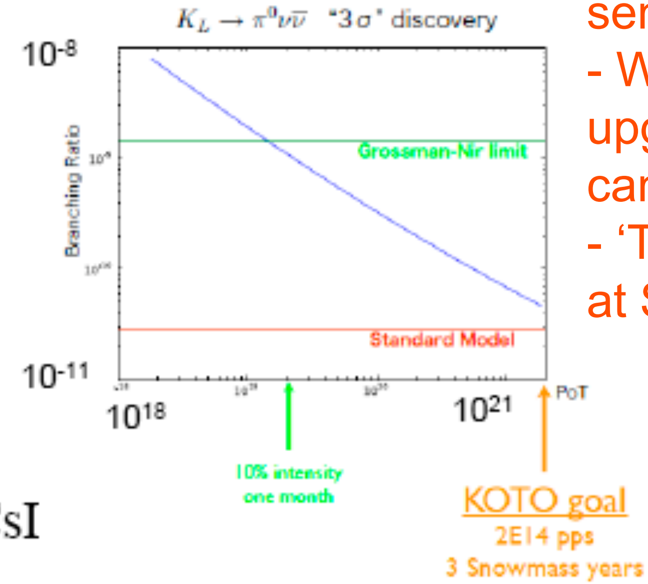
  - $\pi^0 (\to \gamma\gamma)$ and nothing
    - Photon calorimeter and hermetic vetos.
    - Pencil Beam Method. (small beam hole and KL rec.)

5 Kaon09

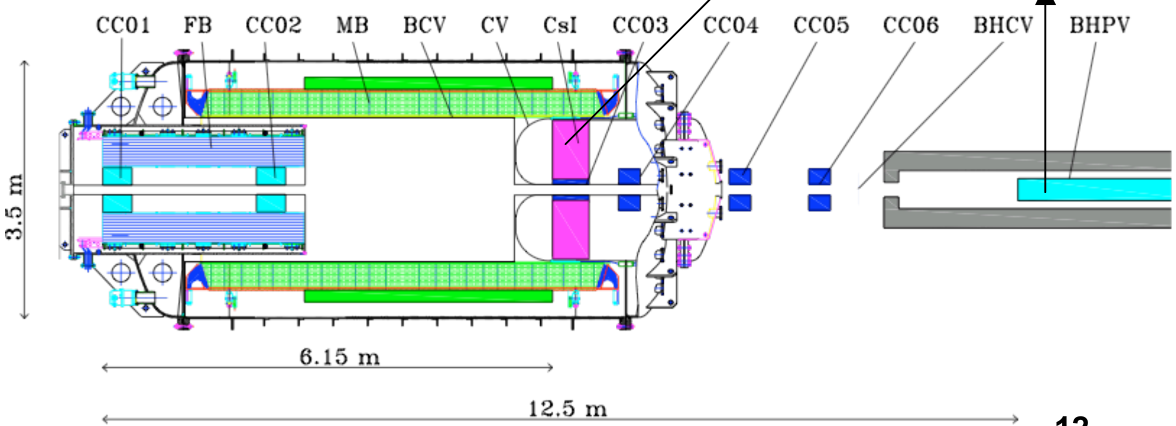
Strategy from E391a with 3 improvements:
- High intensity beam
- New beam line (suppress halo neutrons)
- Detector upgrade (suppress background)

Schedule

- 2009
  - Beamline construction
  - Beam survey
- 2010
  - CsI calorimeter construction
  - Engineering Run with CsI calorimeter
- 2011
  - Physics Run Start.



- Reach SM sensitivity in 3 years
- With major JPARC upgrade >2017?, can reach 100 ev in 3 y
- 'Technique' applicable at SPS



H.Nanjo's talk at KAON09

KAONS @ DAPHNE

NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

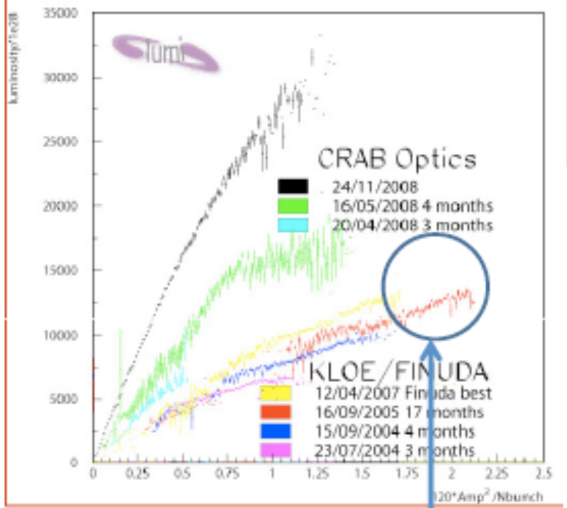
KLOE-2 at upgraded DAΦNE

Branchini's talk at KAON09

Upgrade of DAΦNE in luminosity:

Crabbed waist scheme at DAΦNE (proposal by P. Raimondi)
- increase L by a factor $O(5)$
- requires minor modifications
- relatively low cost

- Successful experimental test at DAΦNE



original collision scheme

KLOE-2 Plan:
- phase 0: KLOE restart taking data end 2009 with a minimal upgrade (L~5 fb^{-1})
- phase 1: full KLOE upgrade (KLOE-2) > 2011 (L>20 fb^{-1})

Physics issues:
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- Dark matter
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, muon anomaly

Detector upgrade issues:
- Inner tracker R&D
- $\gamma\gamma$ tagging system
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, ...)

R&D of accelerator technology

V_{us} error : 0.3% (now) $\Rightarrow$ 0.17% ; 1 - $|V_{us}|^2$ - $|V_{ud}|^2$ error : 6 10^{-4} (now) $\Rightarrow$ 3-4 10^{-4}

Lepton universality tests with Ke3/Kmu3, $K\to\mu\nu/\pi\to\mu\nu$

Absolute branching ratios

Limited by theory

Wide physics programme but not tuned for rare decays:
20 fb^{-1} = 2 10^{10} Kaon decays
In general, not large improvement with respect to KLOE

KAONS @ Fermilab

Intensity Frontier at Fermilab: Now and in the Future

Now:

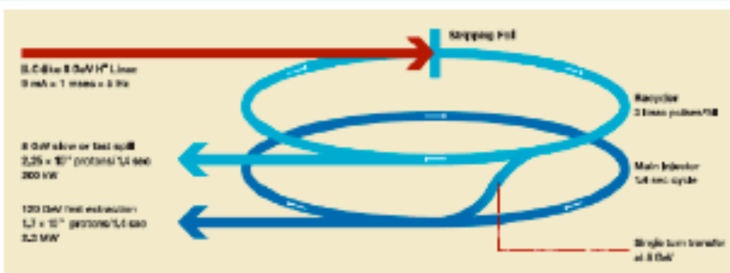
Main Injector Neutrino Program (MINOS,Miniboone,Minerva,NOVA)

8 GeV Booster: Proposals Mu2E (10^{-16}), g-2 (4x), ...

Tevatron Stretcher: $K \to \pi\nu\bar{\nu}$? + ...

Future:

Project X



Douglas Bryman's talk at KAON09

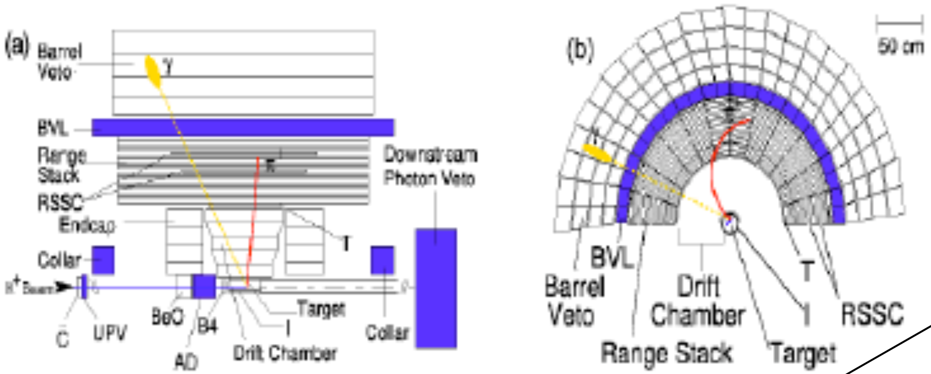
Problem: uncertainty in timescale

New opportunity: $K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab/Tevatron Strecher:

Stopped K technique:

Principal Improvement: Lower P_k ~450 MeV/c

Upgrade of E949



still per mille acceptance

- **4-5 x higher stop efficiency at low momentum**
- **Improved Acceptance (x5)**
- **Reduced randoms and accidental spoiling of events (photon veto) due to low momentum.**

Improvement wrt E949

Douglas Bryman's talk at KAON09

Intrinsically poor PID

Conclusions

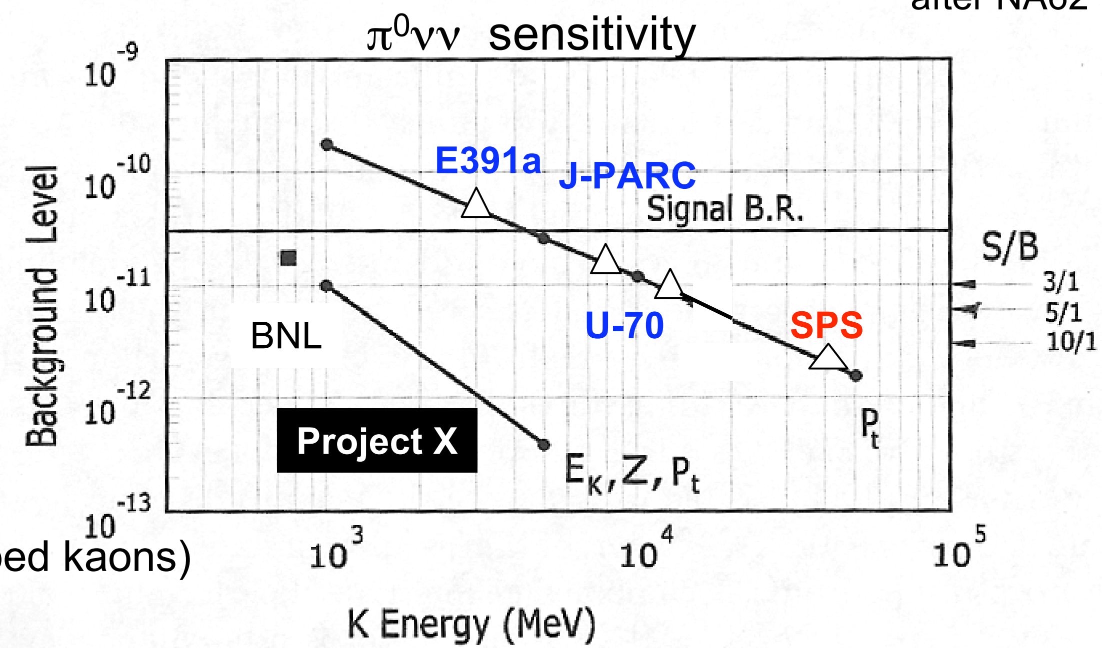
Comparison of facilities/experiments

recommended for approval approved

Facility/Exper.	Data taking	Physics reach	Main aims	Improvement
SPS/NA62	2012-2015	wide, 5×10^{12} k decays	50 $\pi^+\nu\nu$/y, LFV, QCD new-physics searches	large
JPARC/KOTO	2011-2014 $>$ 2017?	focused, $\pi^0\nu\nu$ focused, $\pi^0\nu\nu$	SM sensitivity, few events 100 ev, S/B = 1.5	large large
DAPHNE/KLOE DAPHNE/KLOE2	$>$ 2009 $>$ 2011?	wide, 10^{10} K decays wide, 4×10^{10} K decays	V_{us}, LFV, BR V_{us}, LFV, BR	small medium
Fermilab Stret. Project X	$>$ 2014? $>$ 2018?	focussed,$\pi^+\nu\nu$? ,$\pi^+\nu\nu/\pi^0\nu\nu$	200 ev/y 200/300 ev/y	medium large

after NA62

Notes:
1) JPARC $\pi^0\nu\nu$ technique accessible also to SPS
2) KLOE2 not much improvement wrt KLOE but DAPHNE R&D into accelerator technology
3) Fermilab/JPARC/DAPHNE upgrades timescale uncertain
4) NA62 year = 100 days@60% eff. ,
Others 1 year = 10^7 sec
5) NA62 (decays in flight)/Fermilab (stopped kaons) different systematics



UK involvement in NA62

4 Institutes : Birmingham, Bristol, Glasgow, Liverpool with ~7 FTE/year
committed and established involvement after invitation to join;
UK funding now sought

Responsibilities : CEDAR (Cherenkov for kaons), Computing, Trigger
Good use of UK technological expertise: RICH, photo-detectors, electronics

Leadership: already leading Lepton Flavour Universality tests - Analysis coordinator in UK !

historically UK had leadership in NA48 Ks rare decays,CPLEAR, BABAR - great potential for leading role in other rare decay analyses
already significant contribution to computing - 100% of the MC production required for RK measurement and simulations of beam line radiation conditions done in UK - heavy involvement in TD and Physics Book, both in preparation

KE/Impact with SiPM, MCP-PMT GTK in PET scanner, life-science, new dosimetry

Cost : 1.2 M ('new money'), all elements included to have real impact on experiment
Well defined, reasonably short timescale (data taking and exploitation now- 2015)

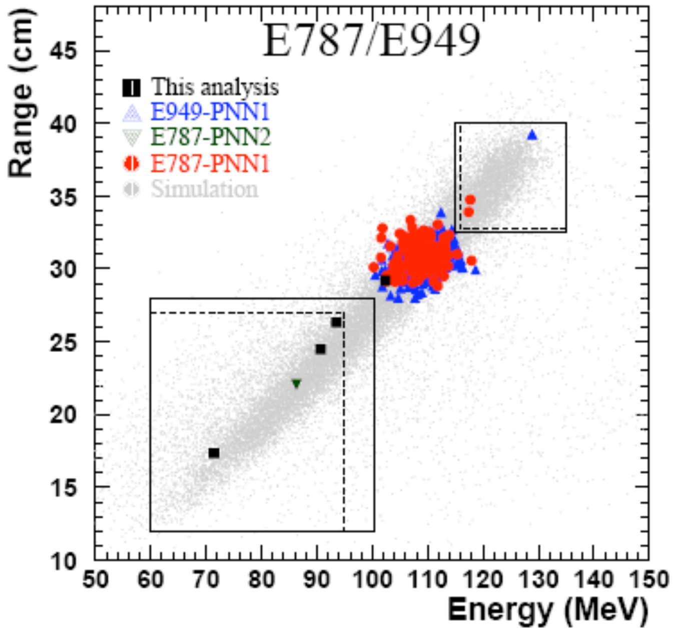
Good sensitivity for NP, large flux and wide range of rare decays: Excellent physics return per unit time per unit cost

Spares

New measurement of the $K^+ \rightarrow \pi^+ \nu\nu$ branching ratio (BNL E949)

Three events for the decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ have been observed in the pion momentum region below the $K^+ \rightarrow \pi^+\pi^0$ peak, $140 < P_\pi < 199$ MeV/c, with an estimated background of $0.93 \pm 0.17(\text{stat.})^{+0.32}_{-0.24}(\text{syst.})$ events. Combining this observation with previously reported results yields a branching ratio of $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ consistent with the standard model prediction.

2



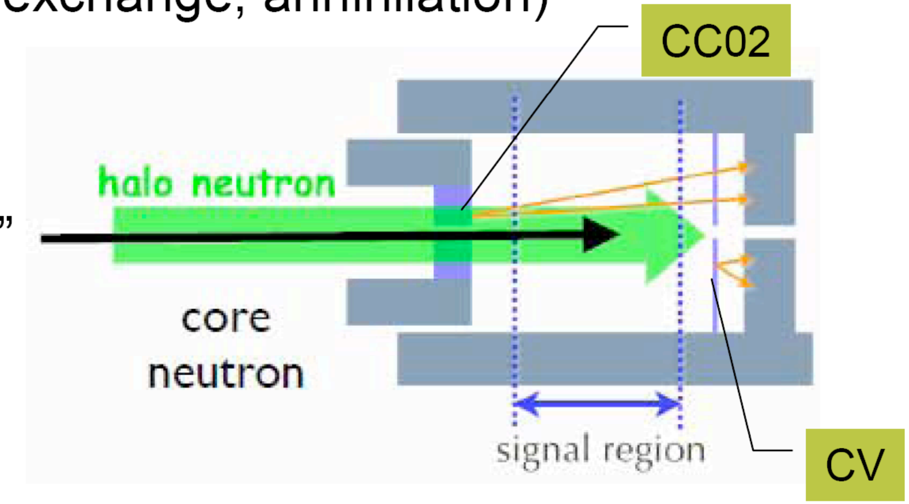
Process	Background events
$K_{\pi 2}$ TG	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$
Muon	0.011 ± 0.011
Beam	0.001 ± 0.001
Total	$0.927 \pm 0.168^{+0.320}_{-0.237}$

TABLE I: Summary of the estimated number of events in the signal region from each background component. Each component is described in the text.

$$BR(K^+ \rightarrow \pi^+ \nu\nu) = 1.73\ ^{+1.15}_{-1.05} \times 10^{-10}$$

E391a: technique

- Kaon Decay
  - $K_L \rightarrow \pi^0\pi^0$ (2γ missed; due to inefficiency or fusion)
  - $K_L \rightarrow \pi^+\pi^-\pi^0$ (2 charged pion missed)
  - $K_L \rightarrow \pi^- e^+ \nu$ (charge exchange, annihilation)
- Halo neutron
  - Interact with "CC02","CV"
  - Produce π^0, η

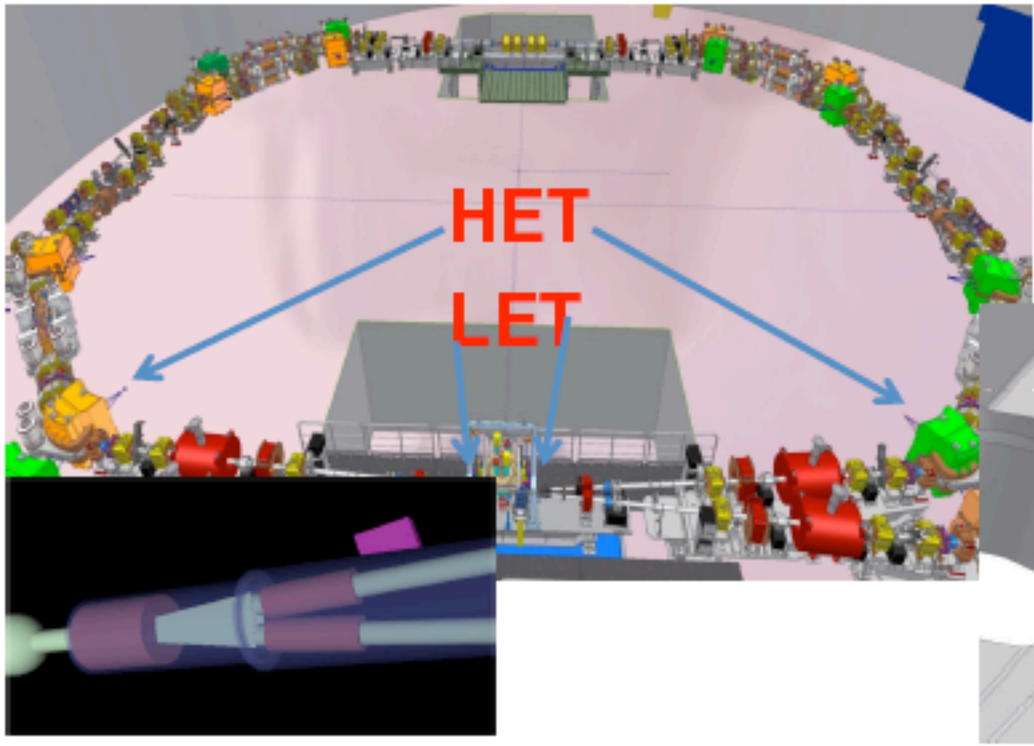


RUN II (2005)

- Pencil beam, p_K peaked around 2 GeV/c
- Total K^0_L decays: 5.1×10^9
- Acceptance: 0.67 %
- Background in signal box: 0.41±0.11 events
- S.E.S. = $(2.9\pm0.3) \times 10^{-8}$

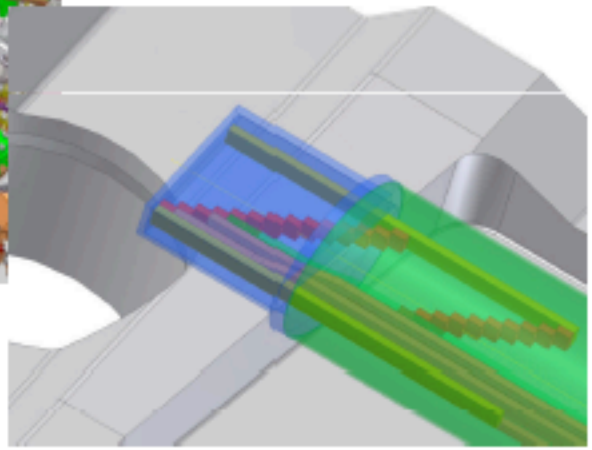
$BR(K^0 \rightarrow \pi^0 \nu\bar{\nu}) < 6.7 \times 10^{-8}$ (90%CL)
arXiv:0712.4164v1 (27 Dec 2007)

KLOE $\gamma\gamma$ taggers



The HET detector consists in a position detector with a pitch of few millimeter (¾$_E$ ~ 0.6 MeV/mm). The characteristics of this detector are the following:

- Good time resolution to disentangle each bunch (~2.7 ns bunch spacing);
- Capability to acquire data at a frequency of 368 MHz in order to permit event

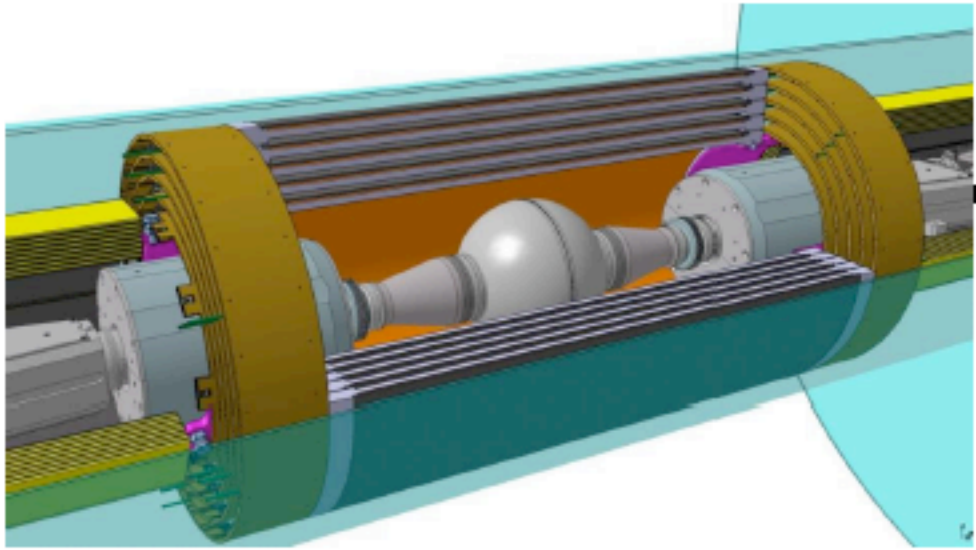


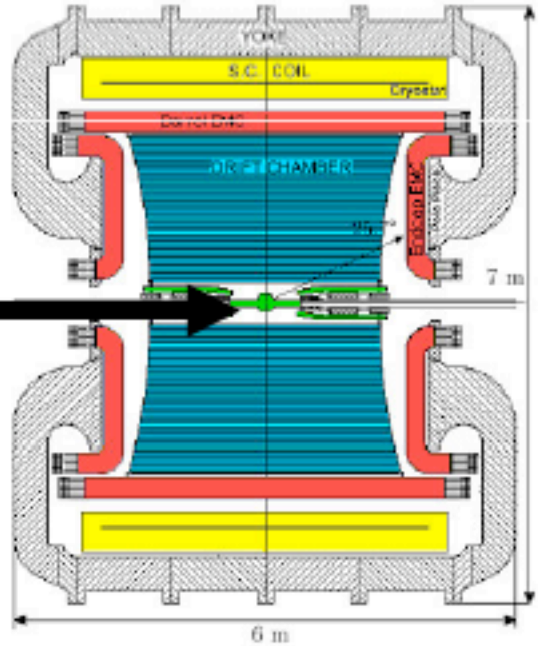
The LET detector consists of a calorimeter capable of detecting electrons and positrons within a wide energy range peaked around 200 MeV. The environmental conditions require radiation-tolerant devices, insensitive to magnetic fields. The physical requirements are the following:

- Good energy resolution to improve the reconstruction of the $\gamma\gamma$ invariant mass from the decay products;
- Good time resolution to associate detected events with the proper bunch crossing;
- Small size.

Inner tracker at KLOE

- 5 independent tracking layers for a fine vertex reconstruction of K_S and η
- 200 μm $\sigma_{r\varphi}$ and 500 μm σ_Z spatial resolutions with XV readout
- 700 mm active length
- from 150 to 250 mm radii
- 1.8% X_0 total radiation length in the active reg
- Realized with **Cylindrical-GEM** detectors

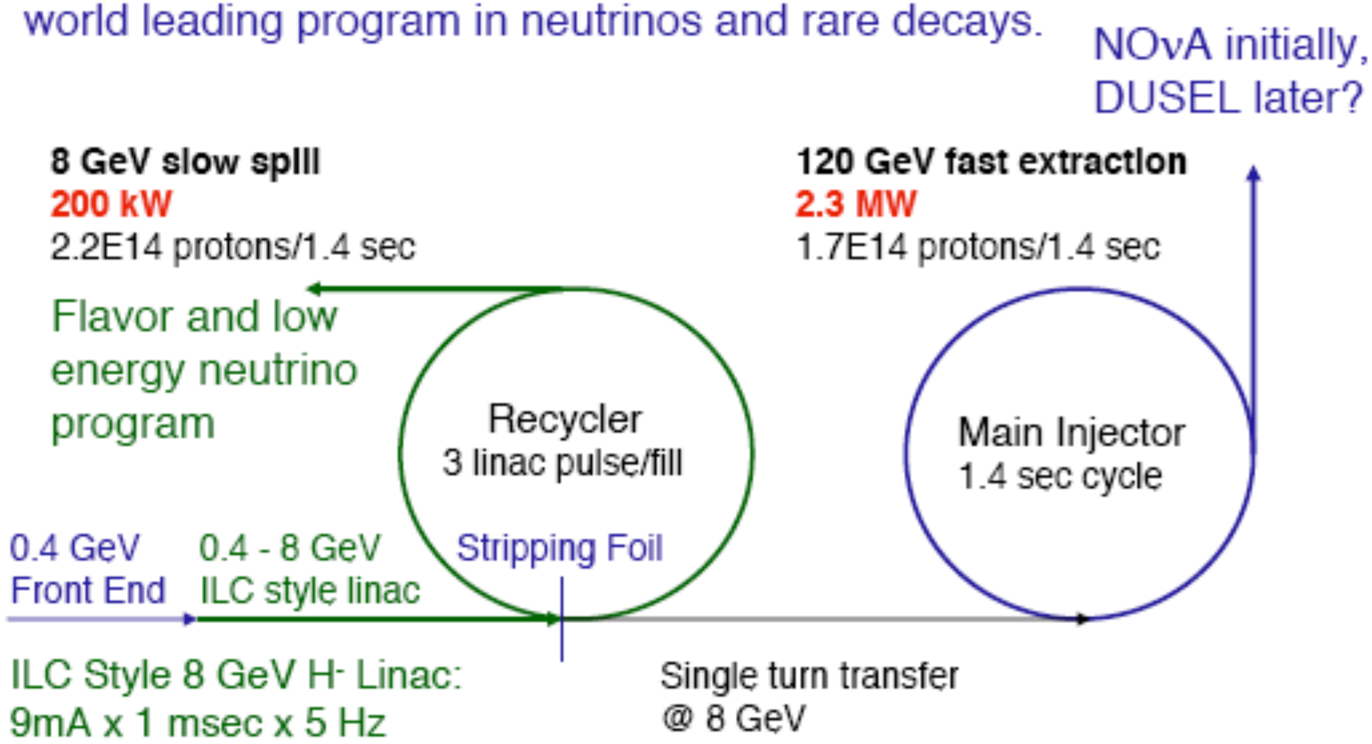




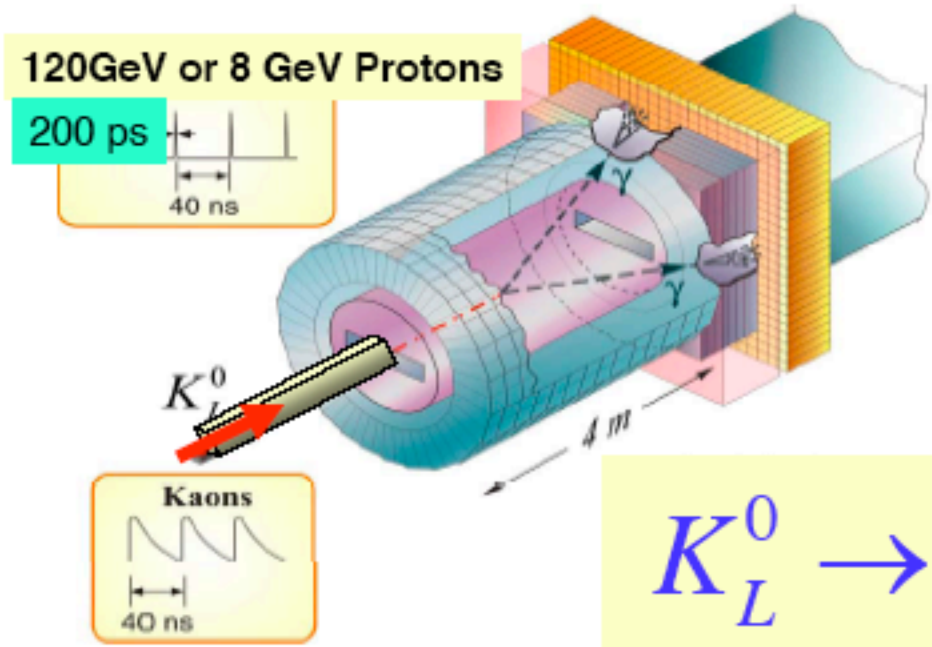
Steve Holmes
APT seminar 2008

Project X Facility Overview

Project X is a high intensity proton facility aimed at supporting a world leading program in neutrinos and rare decays.



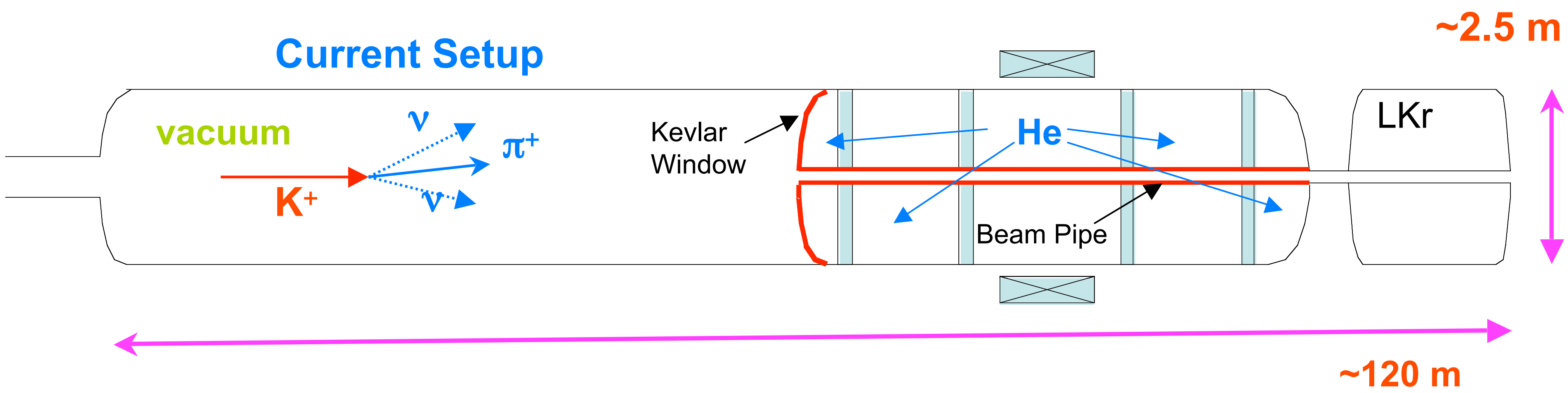
$K_L^0 \to \pi^0 \nu \bar{\nu}$ Experiment Concept



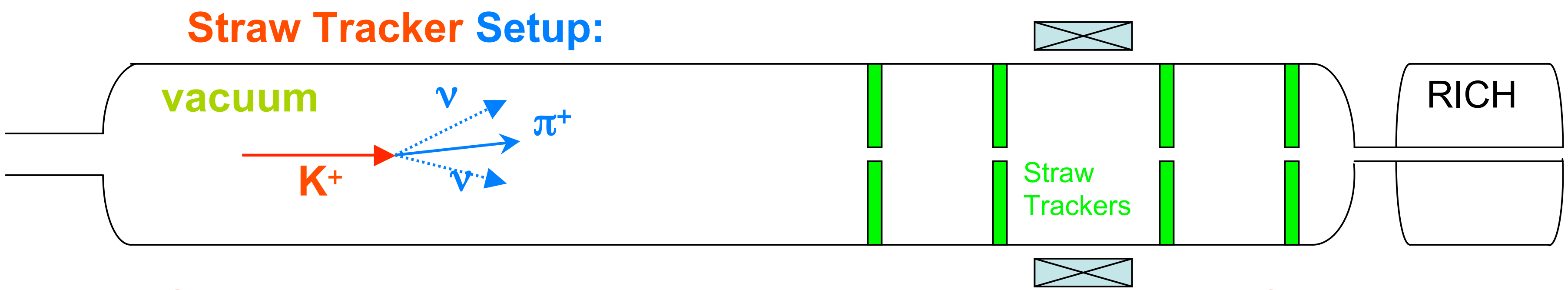
$$K_L^0 \to \pi^0 \nu \bar{\nu}$$

- Use TOF to work in the K_L^0 c.m. system
- Identify main 2-body background $K_L^0 \to \pi^0 \pi^0$
- Reconstruct $\pi^0 \to \gamma\gamma$ decays with pointing calorimeter
- 4π solid angle photon and charged particle vetos

NA62 Straw Tracker

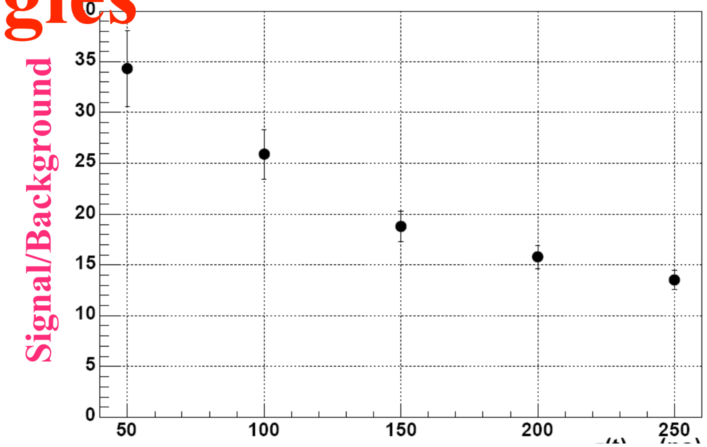


Straw Trackers operated in vacuum would enable us to:
- **Remove the multiple scattering due to the Kevlar Window**
- **Remove the acceptance limitations due to the beam-pipe**
- **Remove the helium between the chambers**



- **The Straw Tracker is essential to study ultra-rare-decays in flight**

Crucial detectors and technologies

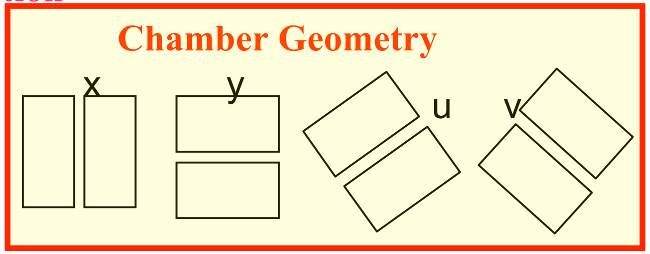


The Gigatracker (*i.e.* the beam spectrometer)

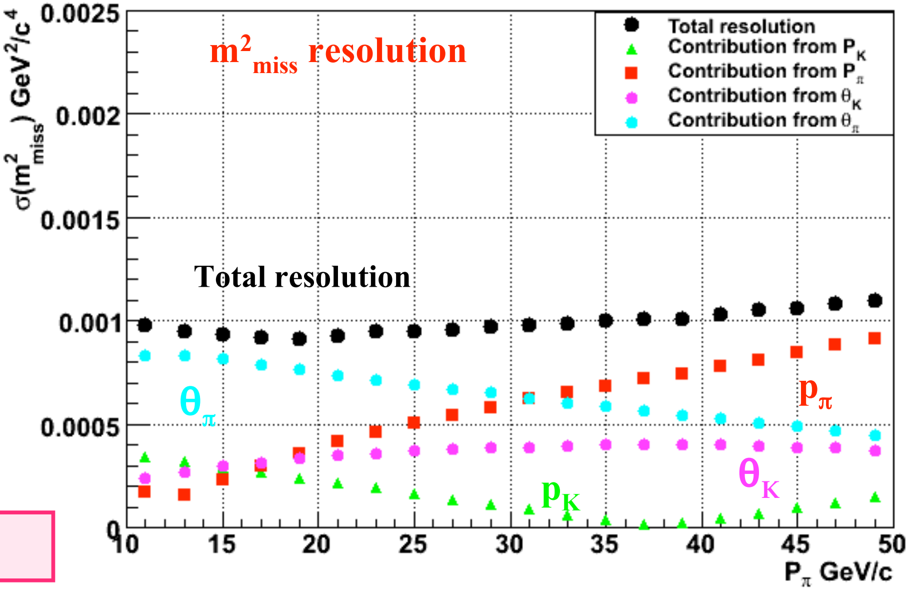
- 3 Si pixel stations across the 2nd achromat: (60×27 mm^2)
  - Rate 760 MHz (charged particles) → ~ 80 MHz / cm^2
  - 300×300 μm^2 pixels → ($\sigma(P_K)/P_K \sim 0.2\%$, $\sigma(dX,Y/dZ) \sim 12$ μrad)
  - 200 Si μm sensor + 100 Si μm chip → Low X/X_0
  - 54000 channels

Excellent time resolution needed for K^+/π^+ association → $\sigma(t)\sim200$ ps / station

The Magnetic Spectrometer (*i.e.* the downstream tracker)



- 4 chambers with 4 double layers of straw tubes each (∅ 9.6 mm)
- 1 magnet (P_{kick} = 260 MeV/c), 8000 wires in total
  - Rate: ~ 45 KHz per tube (max 0.8 MHz beam halo)
  - Low X/X_0 → 0.1% X_0 per view in vacuum
  - Good hit space resolution → 130 μm per view
  - Veto for charged particles → 5cm radius beam hole displaced in the bending plane according to beam path



$\sigma(P_k)/P_k = 0.3\% \oplus 0.007\%P$, $\sigma(dX,Y/dZ) = 45 \div 15$ μrad

m^2_{miss} resolution $\sim1.1\times10^{-3}$ GeV^2/c^4

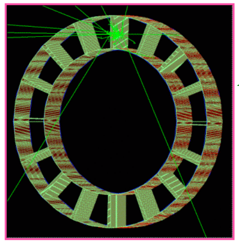
✓ Full length Prototype tested in actual vacuum tank

Photon vetoes

- **Large angle (10-50 mrad): 12+1 ANTIS**
  - Rings calorimeters (in vacuum)
  - Rate: ~4.5 MHz (μ) + ~0.5 MHz (γ) (OR 12)
  - 10^{-3} inefficiency for $0.05 < E_\gamma < 1$ GeV
  - 10^{-4} inefficiency for $E_\gamma > 1$ GeV
  - 2500 channels

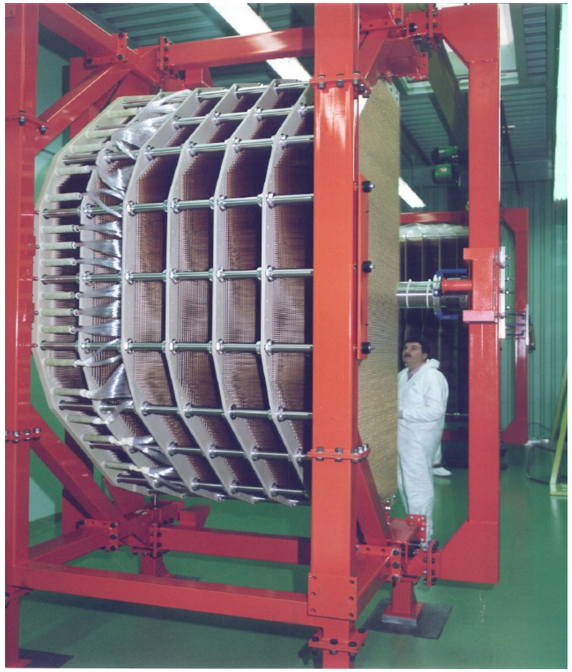
Options tested:
Lead-scintillator tiles (CKM)
Lead-scintillator fibers (KLOE-like)
OPAL Lead-Glass (barrel)

All satisfying requirements,
OPAL Lead Glass is the most cost-effective solution


ANTI ring

- **Medium angle (1-10 mrad): NA48 LKr Calorimeter**
  - Rate: ~8.7 MHz (μ) + ~4 MHz (γ) + ~4 MHz (π) → **New Readout**
  - 10^{-4} inefficiency for $1 < E_\gamma < 5$ GeV
  - 10^{-5} inefficiency for $E_\gamma > 1$ GeV → **Few 10^{-7} inefficiency for $E_\gamma > 10$ GeV tested on NA48/2 data ($K^+ \rightarrow \pi^+ \pi^0$)**
  - 13000 cells, no zero suppression

The NA48 LKr calorimeter



- **Small angle (< 1 mrad): Shashlik technology**
  - Rate: ~0.5 MHz (μ)
  - 10^{-5} inefficiency for high energy (>10GeV) photons

Muon veto MUD

- **Sampling calorimeter + Magnet for beam deflection**
  - Rate: ~7 MHz (μ) + ~3 MHz (π)
  - 10^{-5} inefficiency for μ detection

• Sensitivity to the MIP
• em/hadronic cluster separation
• 5Tm B field in a 30×20cm² beam hole: deviate the beam out from the SAC

NA62 : principle of experiment

O(100) events $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in 2 years

~ 10% background

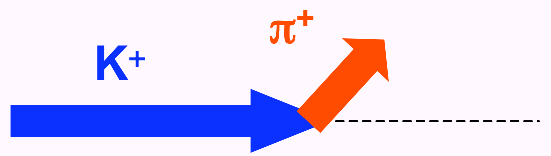
$BR(SM) = 8 \times 10^{-11}$

~ 10^{13} K^+ decays

Acceptance= 10%

- K decays in flight
- Intense beam of protons from SPS
- High energy K (P_K = 75 GeV/c)
- Cherenkov K ID: CEDAR

Kinematic rejection



$$m^2_{miss} = (P_K - P_\pi)^2$$

Signature:

•Incoming **high** momentum K^+

•Outgoing **low** momentum π^+

- Kaon: beam tracking
- Pion: spectrometer
- Excellent timing for K-π association

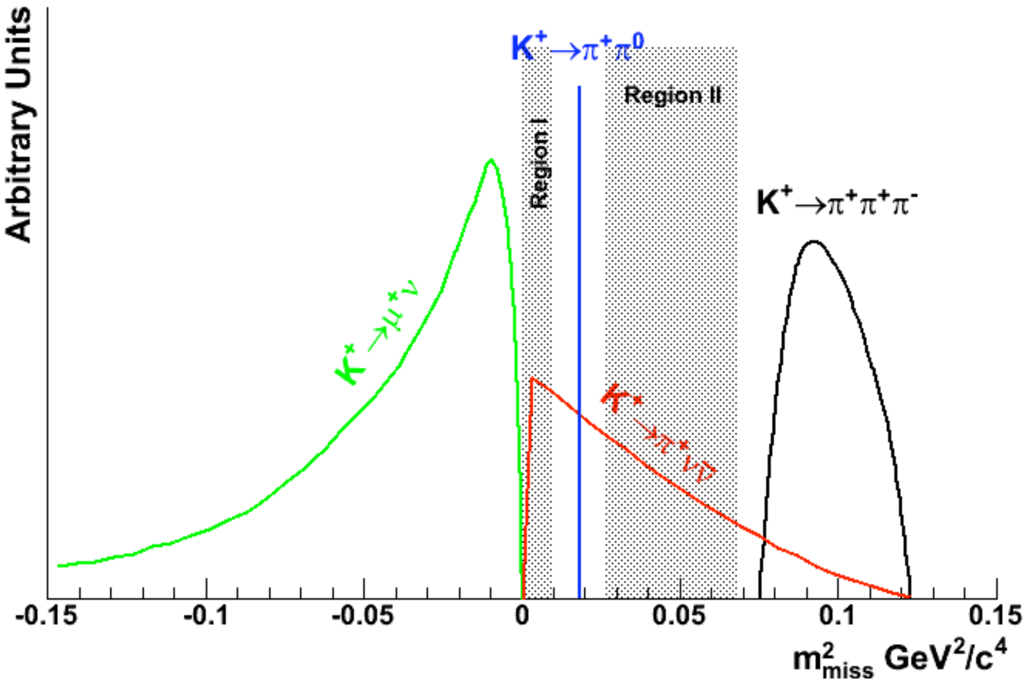
Veto and PID

- γ / μ : calorimeter
- Charge Veto : spectrometer
- π / μ separation : RICH

Background with kinematic threshold

Decay	BR
$K^+ \to \mu^+ \nu$ ($K_{\mu 2}$)	0.634
$K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$)	0.209
$K^+ \to \pi^+ \pi^+ \pi^-$ $K^+ \to \pi^+ \pi^0 \pi^0$	0.073

92% K^+ decays



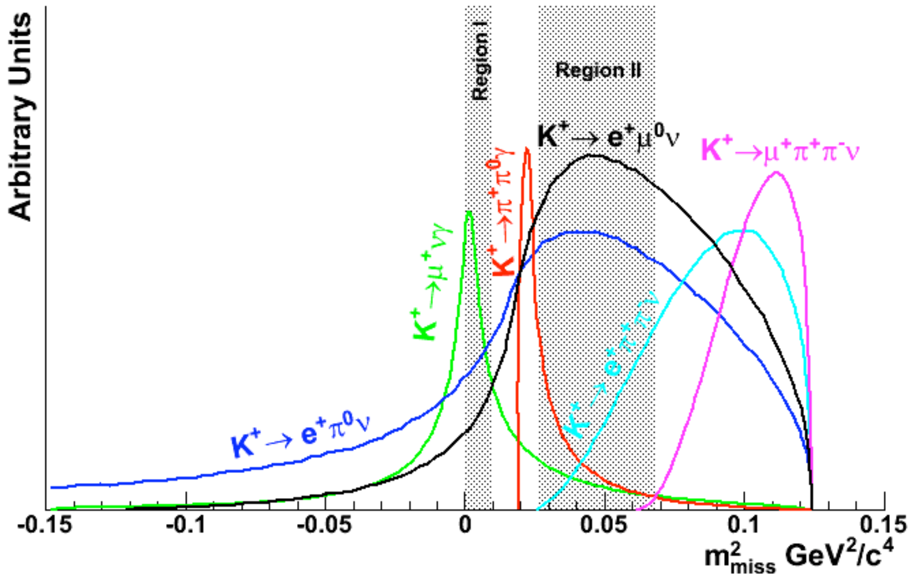
- **Definition of signal region**
- **$K^+ \to \pi^+ \pi^0$: division between Region I and Region II**

Region I: $0 < m^2_{miss} < 0.01$ GeV^2/c^4

Region II: $0.026 < m^2_{miss} < 0.068$ GeV^2/c^4

Background with no kinematic threshold

Decay	BR
$K^+ \to \pi^0 e^+ \nu$ (K_{e3})	0.049
$K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu 3}$)	0.033
$K^+ \to \mu^+ \nu \gamma$ ($K_{\mu 2\gamma}$)	6.2×10^{-3}
$K^+ \to \pi^+ \pi^0 \gamma$	1.5×10^{-3} (2.75×10^{-4} PDG)
$K^+ \to \pi^+ \pi^- e^+ \nu$ (K_{e4})	4.1×10^{-5}
$K^+ \to \pi^+ \pi^- \mu^+ \nu$ ($K_{\mu 4}$)	1.4×10^{-5}



8% K^+ decays

- Across signal region
- Rejection using Veto and Particle ID

- **Background from detector:** accidental interactions due to material on the beam line

Decay Mode	Events
Signal: $K^+ \to \pi^+ \nu\nu$ *[flux = 4.8×10^{12} decay/year]*	55 *evt/year*
$K^+ \to \pi^+ \pi^0$ [$\eta_{\pi0} = 2\times10^{-8}$ (3.5×10^{-8})]	4.3% (7.5%)
$K^+ \to \mu^+ \nu$	2.2%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%
$K^+ \to \mu^+ \nu \gamma$	~0.7%
$K^+ \to e^+(\mu^+)\ \pi^0 \nu$, others	negligible
Expected background	≤13.5% (≤17%)

Definition of "year" and running efficiencies based on NA48 experience: ~100 days/year; 60% overall efficiency