Kaon Physics

Tadashi Nomura

(KEK)

Role of Kaon physics

COMMON context TO
FLAVOR PHYSICS programs in this era

- Indirect search for physics beyond the Standard Model
  - Aiming to find deviations from SM with precise measurements (with high intensity)
  - Possible to reach higher mass scale

- Study of flavor structure beyond SM
  - Part of comprehensive approaches to understand BSM
    - not only through one flavor, but also via others...

Topics in this talk

- Rare decay: $K \rightarrow \pi\nu\nu$
  - J-PARC KOTO ; K_L ; physics run
  - CERN NA62 ; K^+ ; construction & tech. run
  - FNAL ORKA ; K^+ ; scientific approval, R&D

- Lepton universality: $R_K \equiv Br(K^+e3)/Br(K^+\mu3)$
- T-violation via $K^+ \rightarrow \pi^0\mu^+\nu$

will be brief...

I apologize not to cover other important matters...

Decays and experimental reaches

Background source

- $K^+ \to \mu^+ \nu$ 63.6%
- $K^+ \to \pi^+ \pi^0$ 20.7%
- $K^+ \to \pi^+ \pi^+ \pi^-$ 5.6%
- $K^+ \to \pi^0 e^+ \nu$ 5.1%
- $K^+ \to \pi^0 \mu^+ \nu$ 3.4%
- $K^+ \to \pi^+ \pi^0 \pi^0$ 1.8%

- $K^+ \to e^+ \nu$ 1.6×10^{-5}

  precise measurement ~10^5 events (CERN NA62 2007-8)

- $K^+ \to \pi^+ \nu\nu$ 7.8×10^{-11}

  7 events (BNL E787/949)

  $\Rightarrow$ 100 (CERN NA62)

- $K_L \to \pi^\pm e^\mp \nu$ 40.6%
- $K_L \to \pi^\pm \mu^\mp \nu$ 27.0%
- $K_L \to \pi^0 \pi^0 \pi^0$ 19.5%
- $K_L \to \pi^+ \pi^- \pi^0$ 12.5%

CPV
- $K_L \to \pi^+ \pi^-$ 2.0×10^{-3}
- $K_L \to \pi^0 \pi^0$ 0.9×10^{-3}

Background source

- $K_L \to \pi^0 \nu\nu$ 2.4×10^{-11}

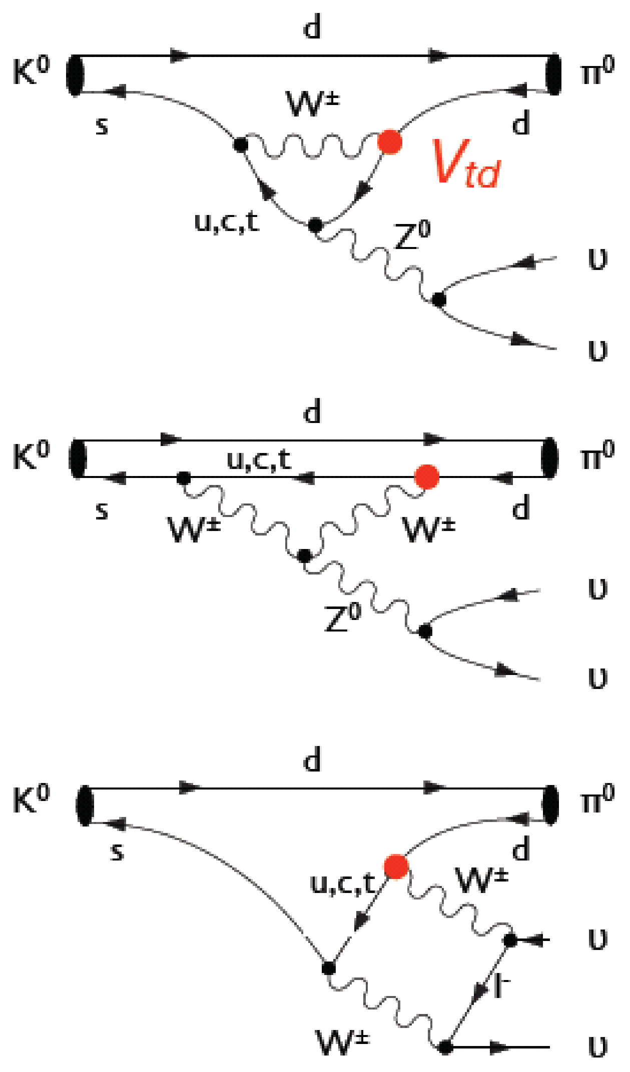
  $<2.6\times10^{-8}$ (KEK E391a)

  $\Rightarrow$ a few events (J-PARC KOTO)

$K \to \pi\nu\nu$ decays

$K \rightarrow \pi\nu\nu$ in the Standard Model

- Process via loop diagrams
  - K_L case:
    - Top quark dominates
      - K^0-anti-K^0 superposition extracts imaginary part of the amplitude
    - **CP violating**
  - K^+ case:
    - Top and charm contribute
      - Absolute value of $s \rightarrow d$ amplitude
- Theoretically clean



$K \to \pi\nu\nu$ in the Standard Model

Hadronic parts (κ_L, κ_+) are obtained from precisely measured $Br(K^+ \to \pi^0 e^+ \nu)$

$$\mathcal{B}r(K_L \to \pi^0 \bar{\nu}\nu) = \kappa_L \left(\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X(x_t) \right)^2$$

$$BR_{SM} = (2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$$

Intrinsic uncertainty

Exp: KEK E391a

$BR < 2.6 \times 10^{-8}$

$$\mathcal{B}r(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) = \kappa_+ (1 + \Delta_{EM}) \times \left| \frac{V_{ts}^* V_{td} X_t(m_t^2) + \lambda^4 \mathrm{Re} V_{cs}^* V_{cd} \left(P_c(m_c^2) + \delta P_{c,u} \right)}{\lambda^5} \right|^2$$

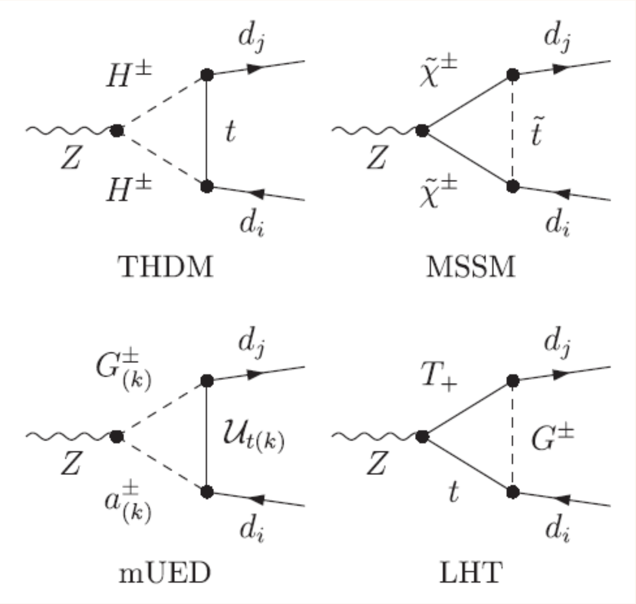
$$BR_{SM} = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$$

Exp: BNL E787/949

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

Possible BSM effects

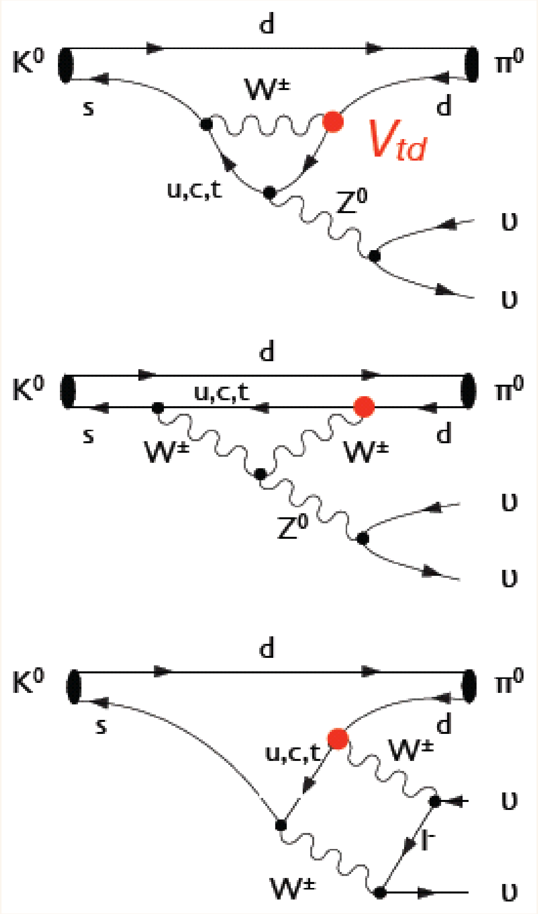
Possible NP diagrams (s→dZ)



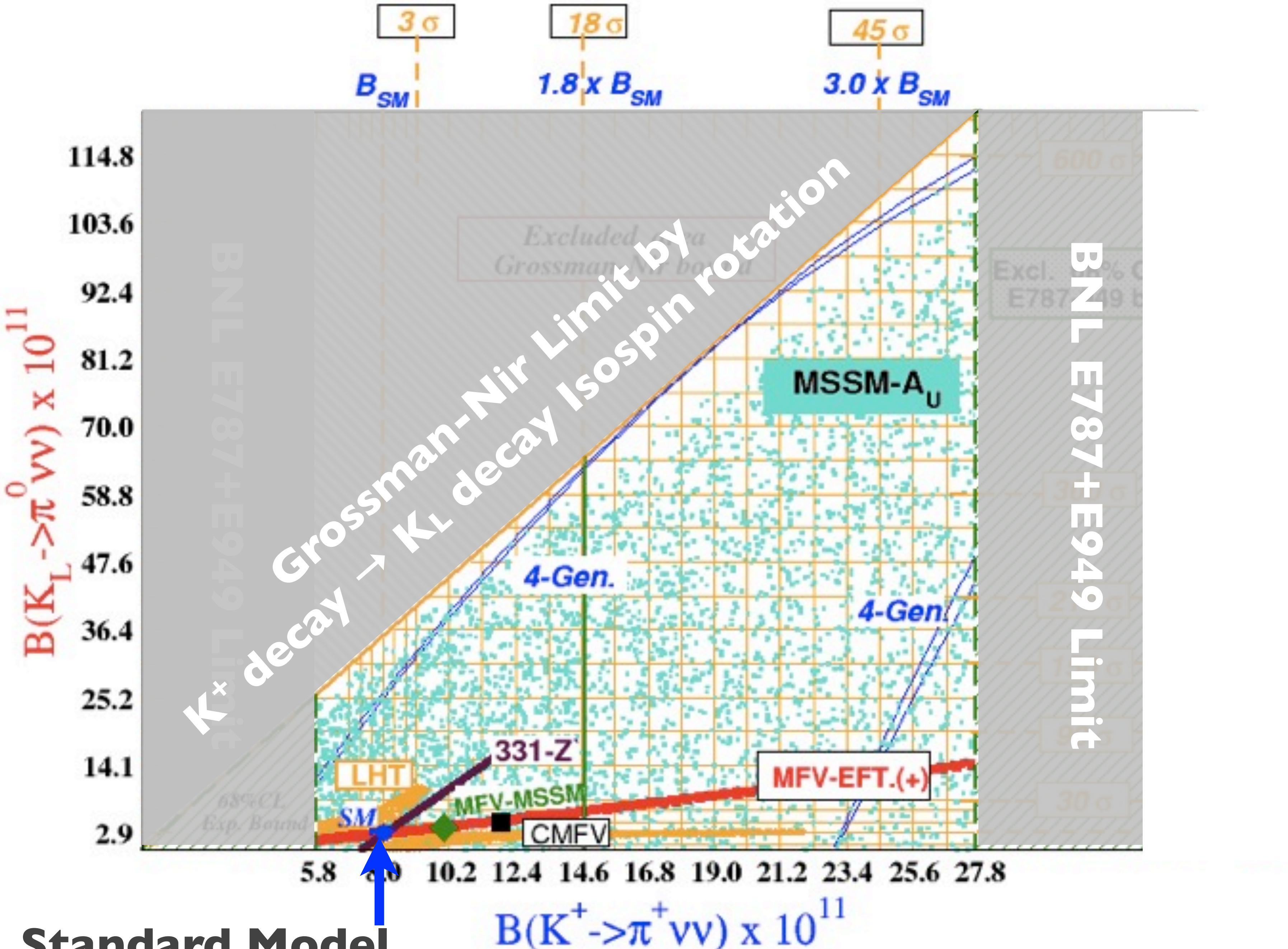
from PRD76.074027

+

SM diagrams



THDM: two-HIggs-doublet model
MSSM: minimal-supersymmetric SM
mUED: minimal universal extra dimension
LHT : littlest Higgs model with T parity



http://www.lnf.infn.it/wg/vus/content/Krare.html

$K \rightarrow \pi\nu\nu$ Experiments

How to identify $K \to \pi\nu\nu$ signal

	Initial state	Decay	Final state	Kinematics
$K_L \to \pi^0\nu\nu$	K_L (not detected)	in flight	2γ (from π^0) and nothing else	Missing momentum taken by 2ν
$K^+ \to \pi^+\nu\nu$	K^+	stopped	π^+ and nothing else	
		in flight		

$K_L \rightarrow \pi^0 \nu\nu$ measurement: J-PARC KOTO

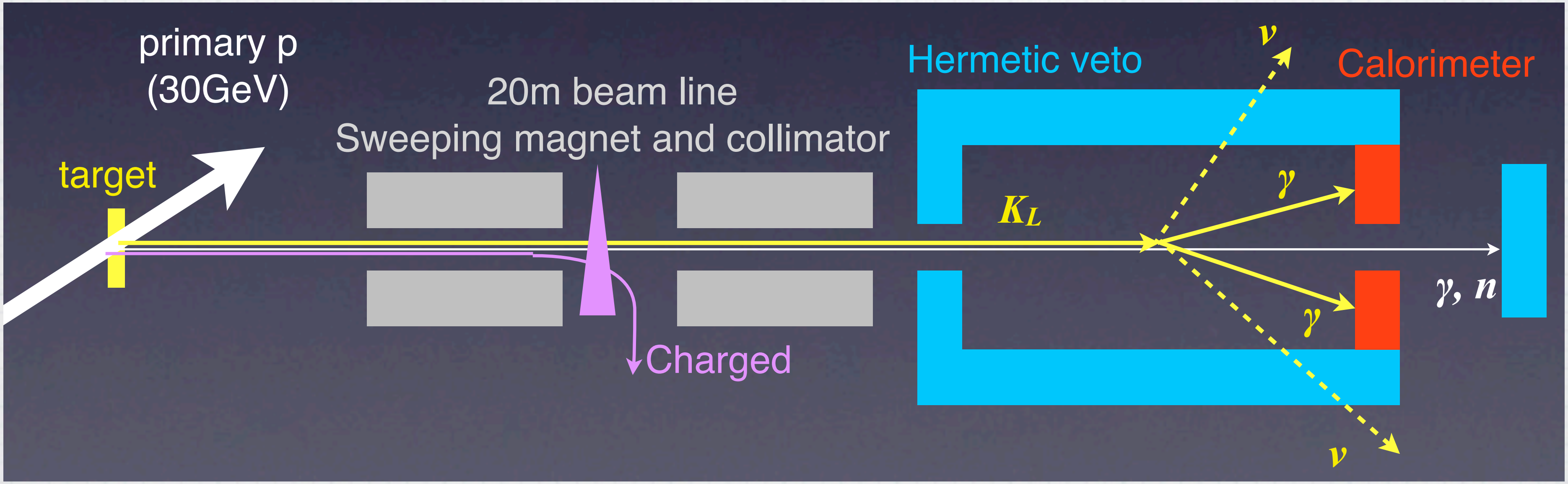
- Goal: ~3 SM events / 3 years
  with S/N ratio ~ 2

(*** assuming design beam power ~270kW)

Genealogy: KEK E391a (record holder)→KOTO
FNAL KTeV EM calorimeter ↗

Principle of experiment

- Signature of $K_L \rightarrow \pi^0 \nu\nu$ = 2γ+nothing
  - Calorimeter + Hermetic veto detectors



Principle of experiment

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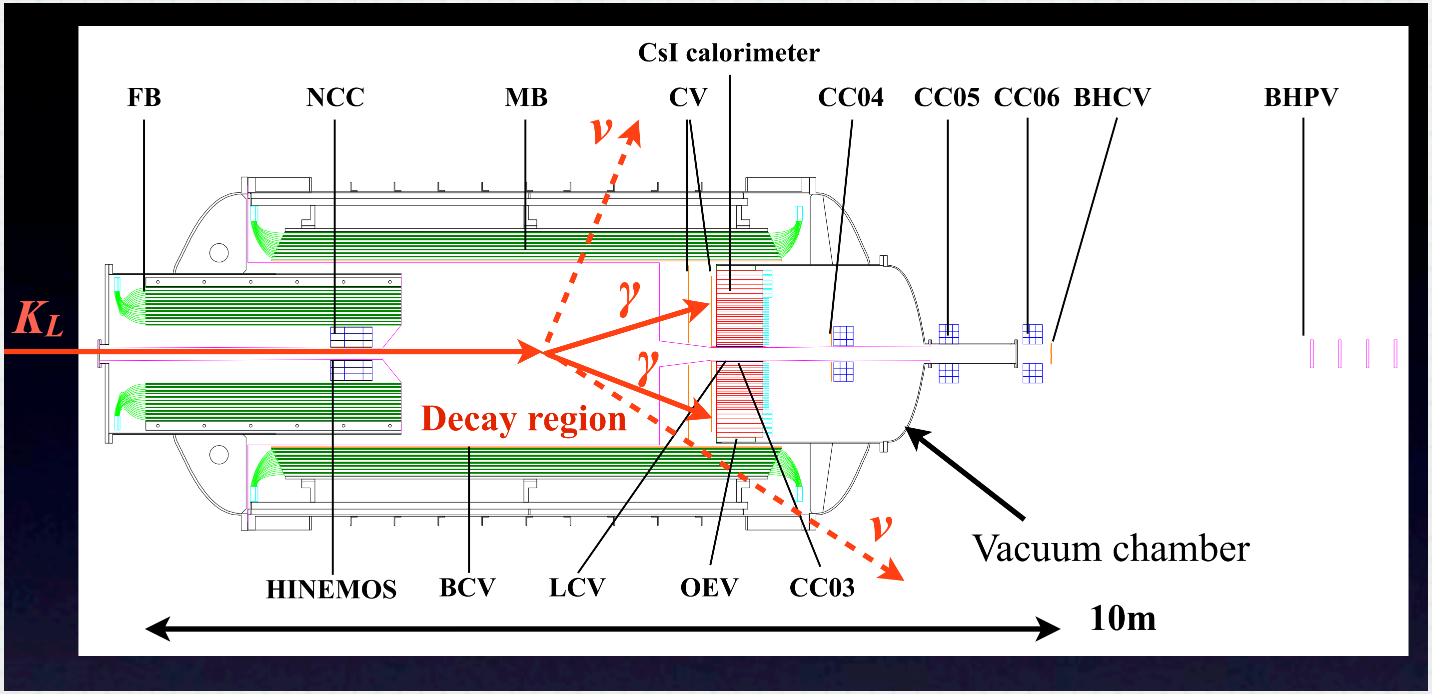
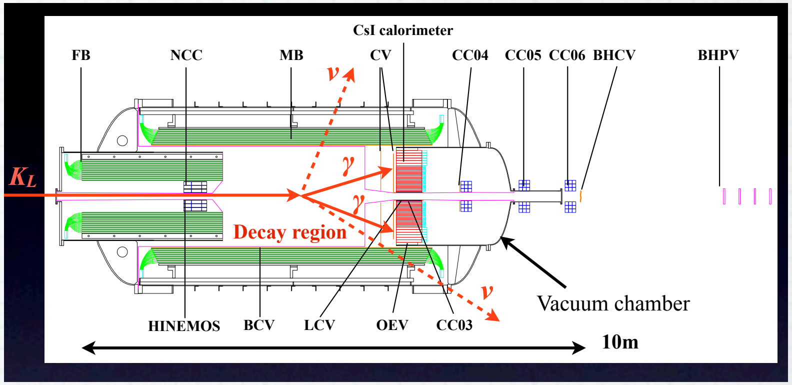
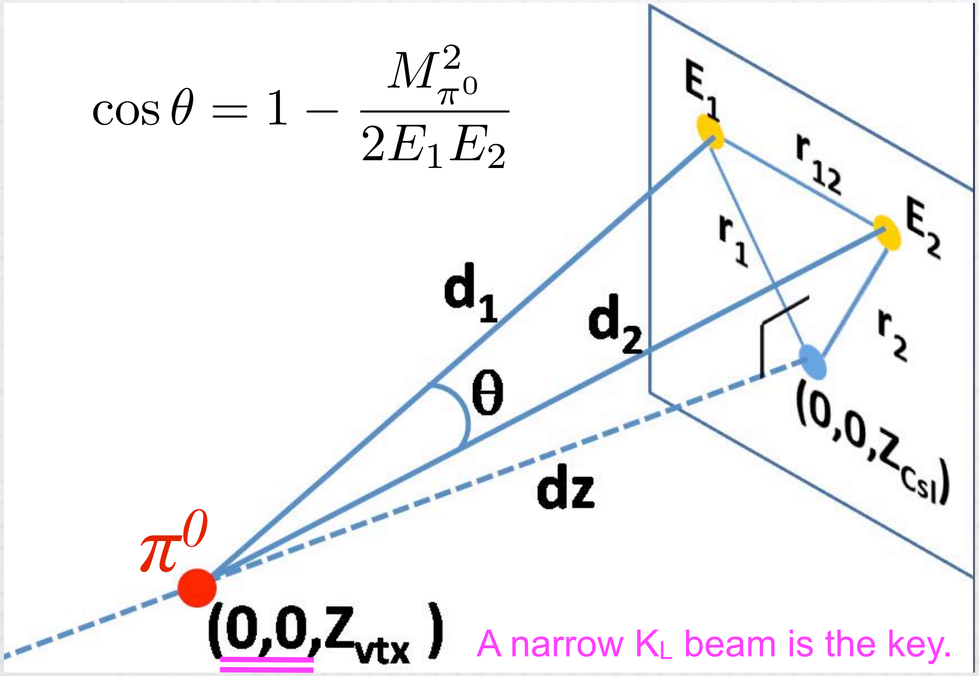


Principle of experiment

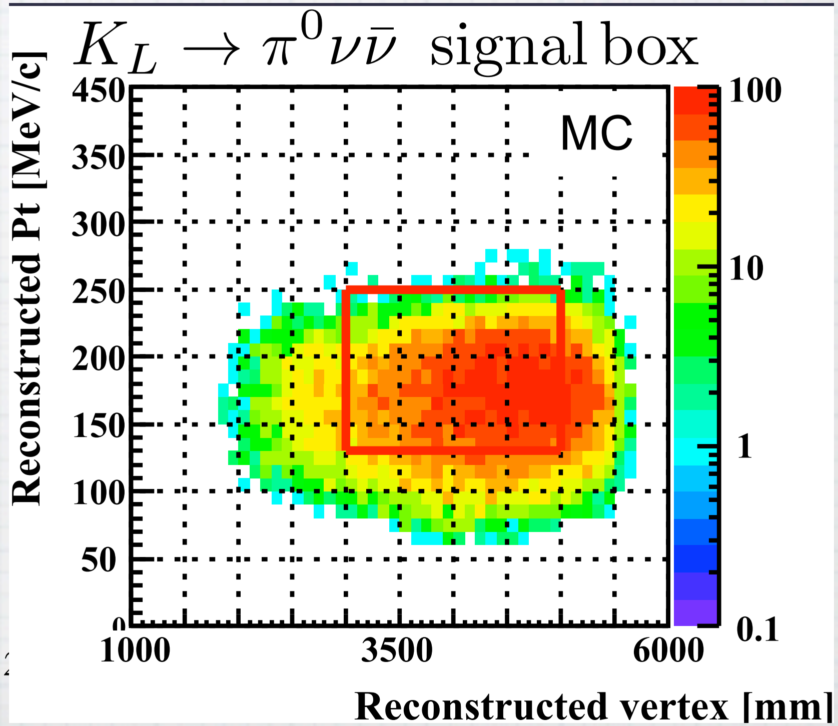


- Signal reconstruction
  - Assuming 2γ come from π^0,
    - Calculate Z vertex
    - Calculate π^0 transverse momentum

$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$



A narrow K_L beam is the key.

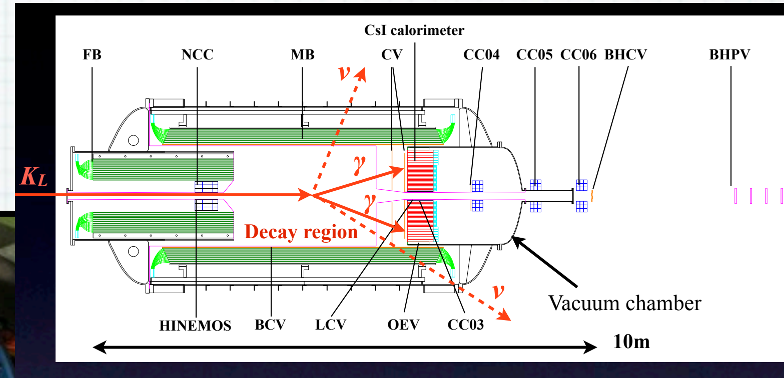


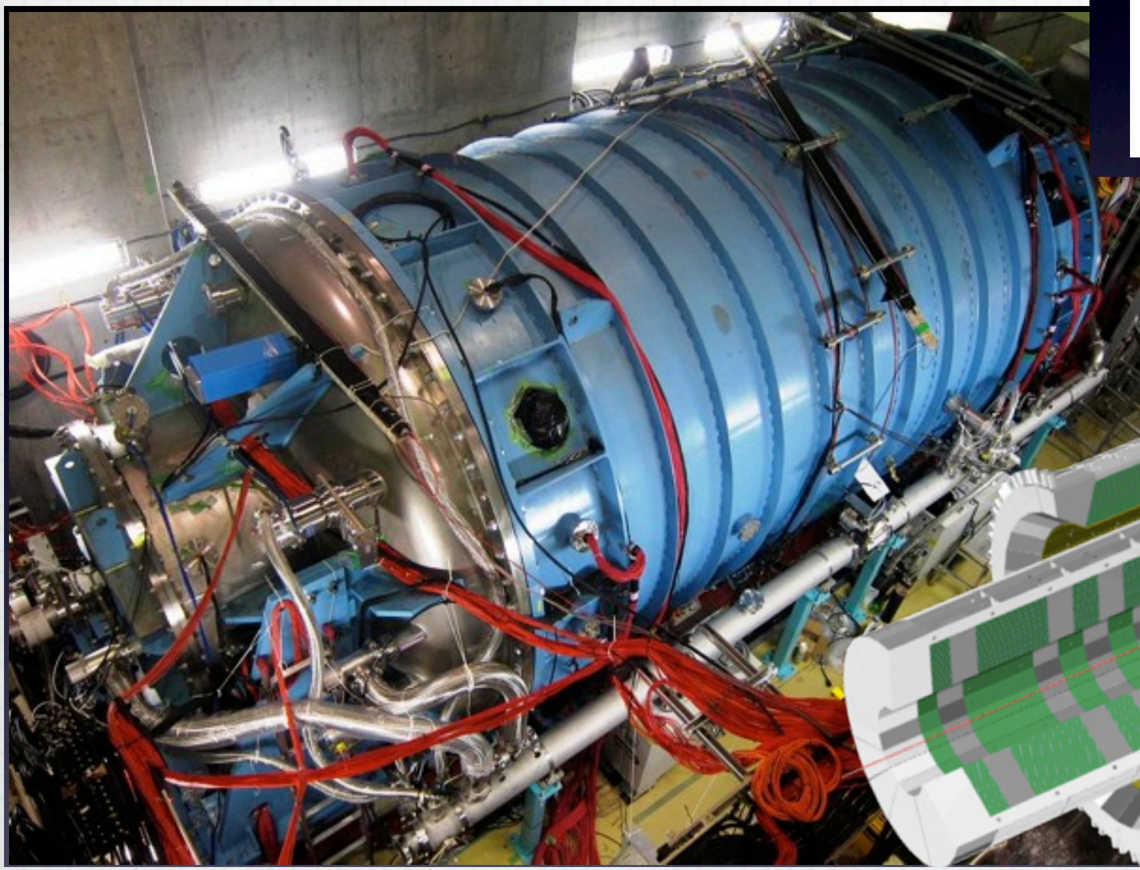
Key upgrades from KEK E391a

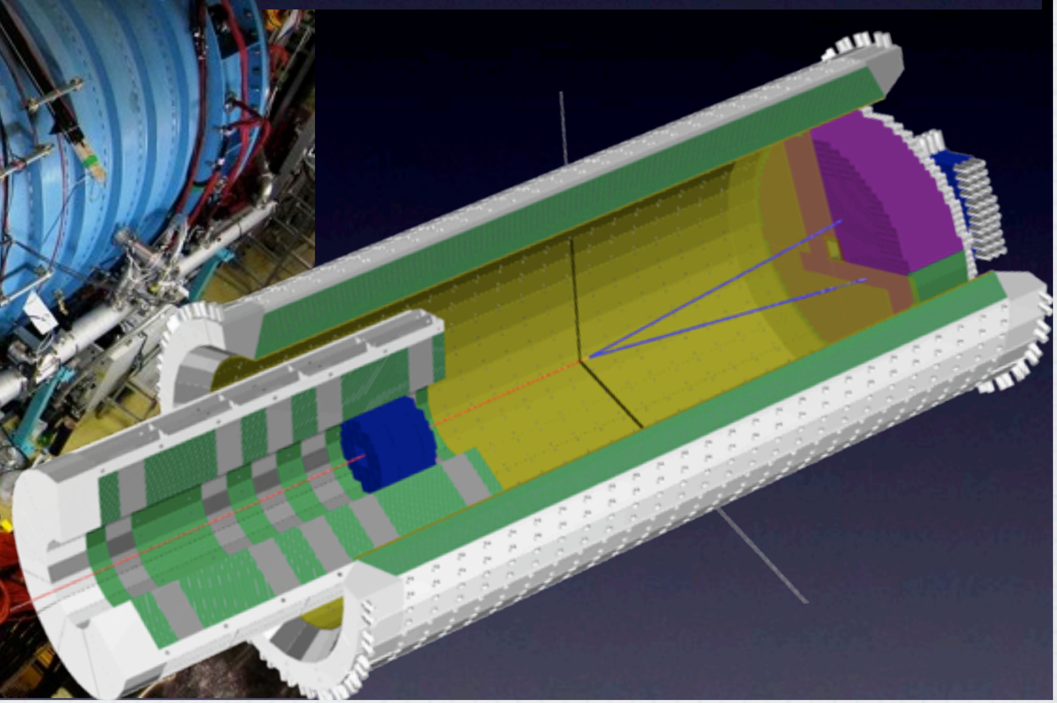
- CsI crystals for calorimeter came from FNAL-KTeV
  - Longer (30➛50cm), finer granularity (7x7➛2.5x2.5cm^2)
    ⇒ Better energy and position resolutions
- Improvement of detectors close to the beam
  - "Collar" counters with CsI crystal
  - Charged-particle veto detector with thinner scintillator
    ⇒ Suppress backgrounds from "halo neutron" interactions
- Record waveforms of all detectors
  - 125MHz 14bit ADC (500MHz, 12bit for detectors in the beam)
    ⇒ Accommodate with double pulses in high rate

Detector in the vacuum tank

~10^{-5} Pa for decay region
~0.1 Pa for detector region





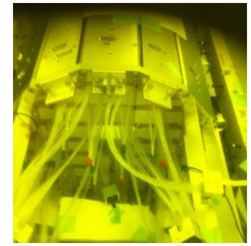


Timeline of KOTO

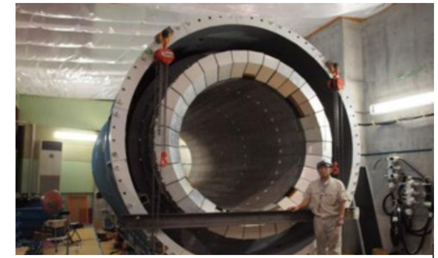
2009 · 2010 · 2011 · 2012 · 2013 · 2014

Beamline construction finished (2009 Aug)

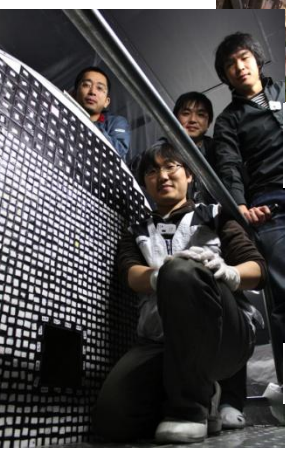
Earthquake (2011.3.11)



NCC installation (2012 Nov)



Main Barrel installation (2012 Dec)



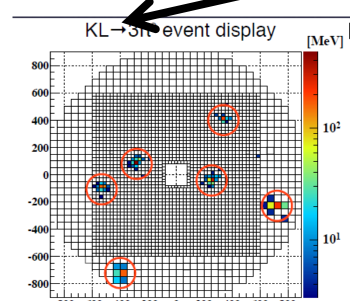
CsI calorimeter stacking finished (2011 Feb)

Charged Veto installation (2012 June)

Closing vacuum chamber (2012 Dec)

FB installation (2012 Nov)

Sub detectors (CC04 etc.) Installation (2012 Dec)



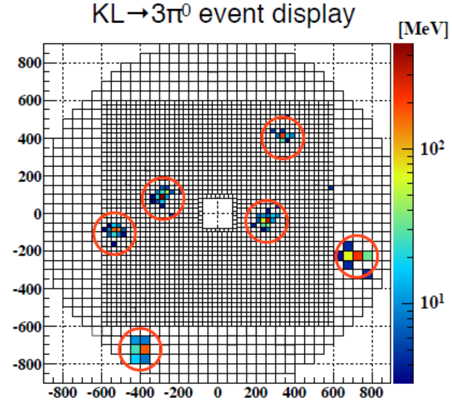
2013 Jan engineering run

1st physics run 2013 May

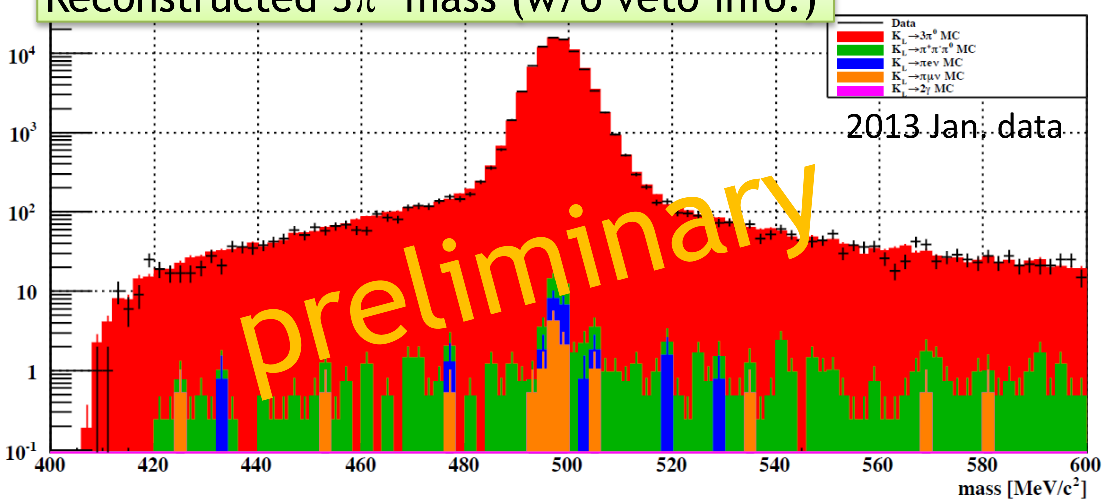
Results from 2013 January engineering run

- $K_L \to 3\pi^0$ reconstruction
  - Good statistics 20%
  - studying CsI performance, reconstruction method and MC.

KL→3π0 event display

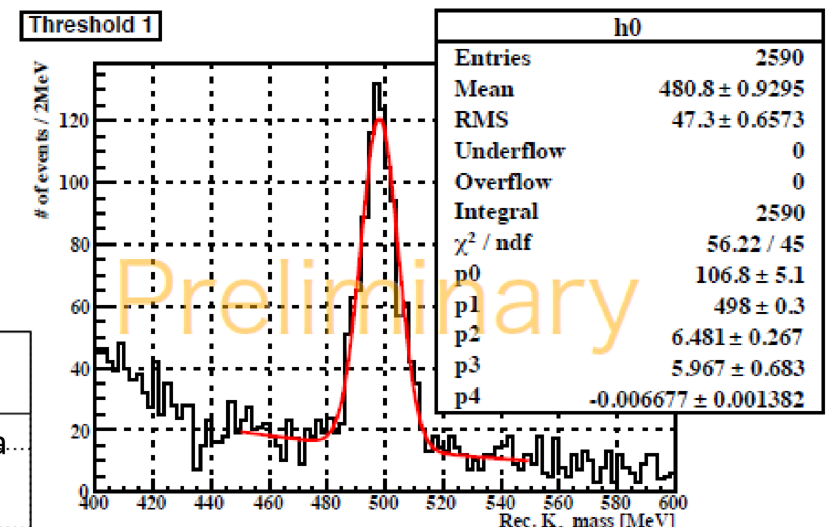


Reconstructed $3\pi^0$ mass (w/o veto info.)



- $K_L \to 2\pi^0$ reconstruction
  - Main background
  - Good tool for studying veto performance

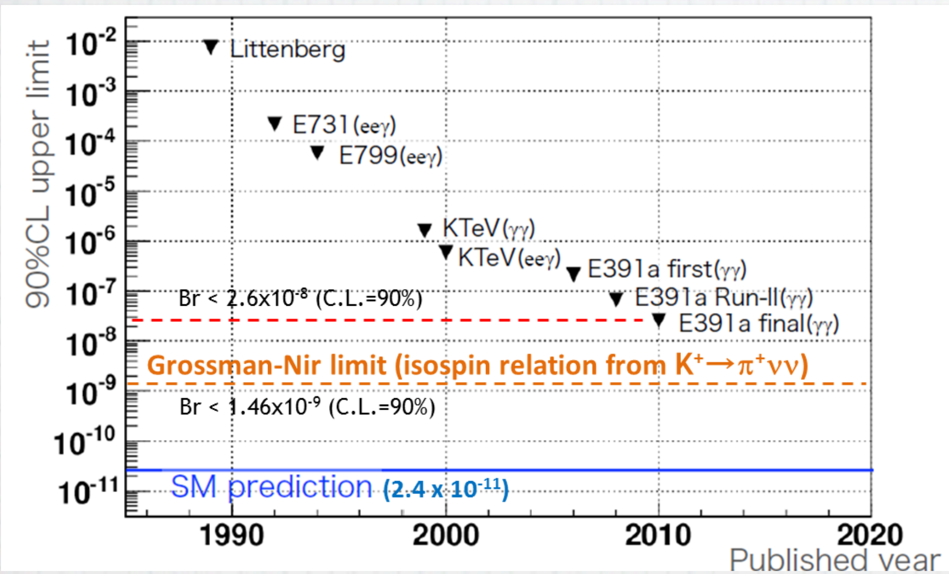
Rec. $2\pi^0$ mass distribution

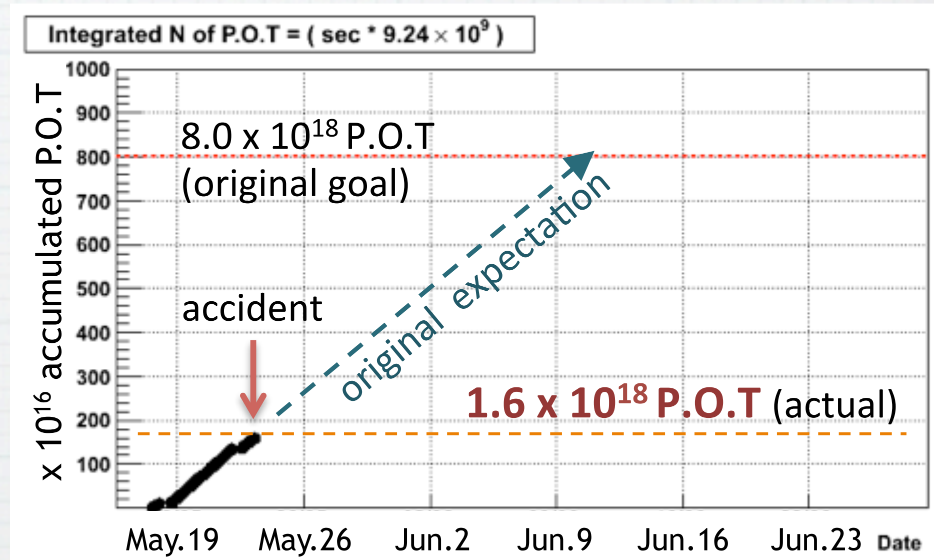


1^{st} physics run (May-June 2013)

Slow extraction beam power was 24kW.
(~1/10 of design value)

- **Original goal** was
  to reach the Grossman-Nir limit (~10^{-9}) by running for a month.
- **BUT...,** a radiation accident on May 23^{rd} at J-PARC hadron hall terminated the run. (~1/5 of expected statistics)





- We expect even this amount will improve the KEK-E391a limit.

Now, analysis ongoing

Prospect

- Dec 2012 - : Engineering runs with full detector
- May 2013 : Physics run started! ... until the accident

J-PARC is now discussing plans for safety measures.
Restart plan will be discussed later.

- 2014 or early 2015? : Cross the G-N limit

Will upgrade the barrel veto detector

- KOTO goal (~SM sensitivity) in 3-4 years run
  - depending on the accelerator schedule and SX power

$K^+ \rightarrow \pi^+ \nu\nu$ measurement: CERN NA62

·Decay in flight technique

·Aims to detect ~100 events
(45 events/year with <10 backgrounds)

Genealogy: CERN NA31→NA48→NA62

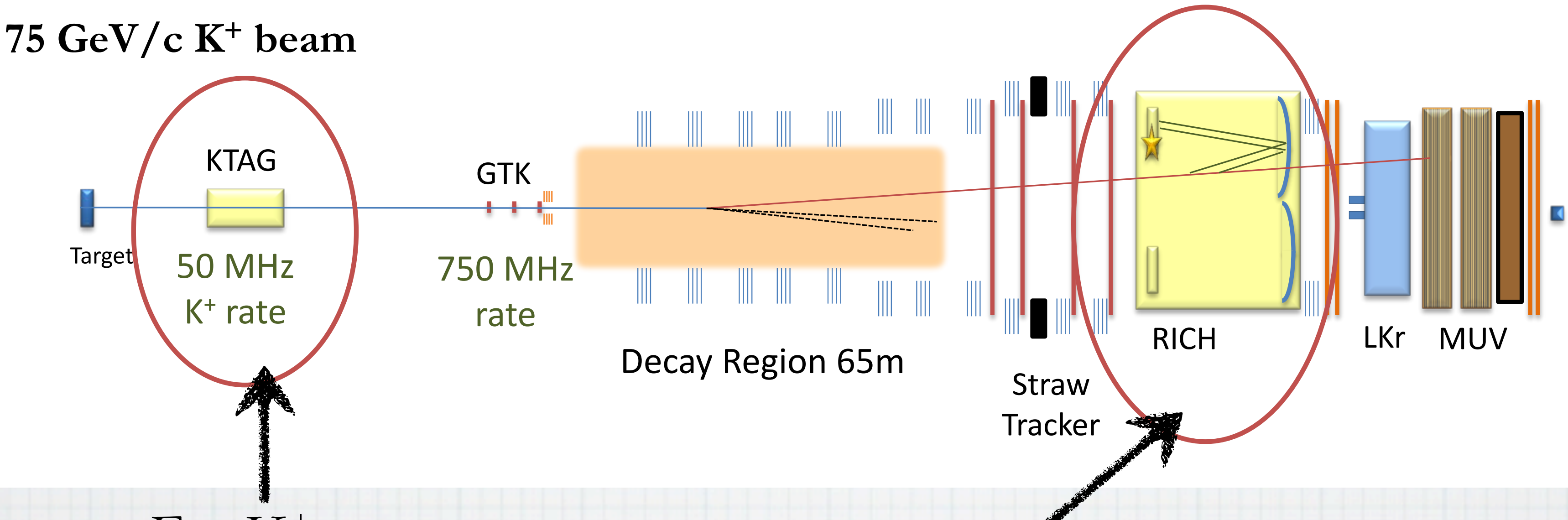
Neutral K (ε'/ε, rare decays)→K^+ rare decays

K^+ **in**, π^+ **out**, nothing else, missing P

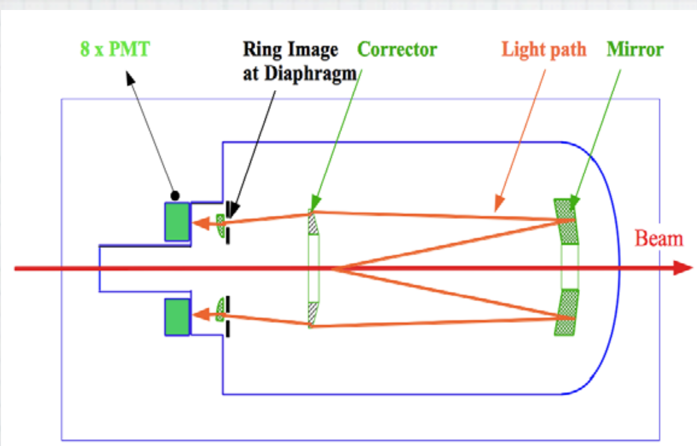
NA62 detector

Particle ID

F. Hahn, Kaon 2013

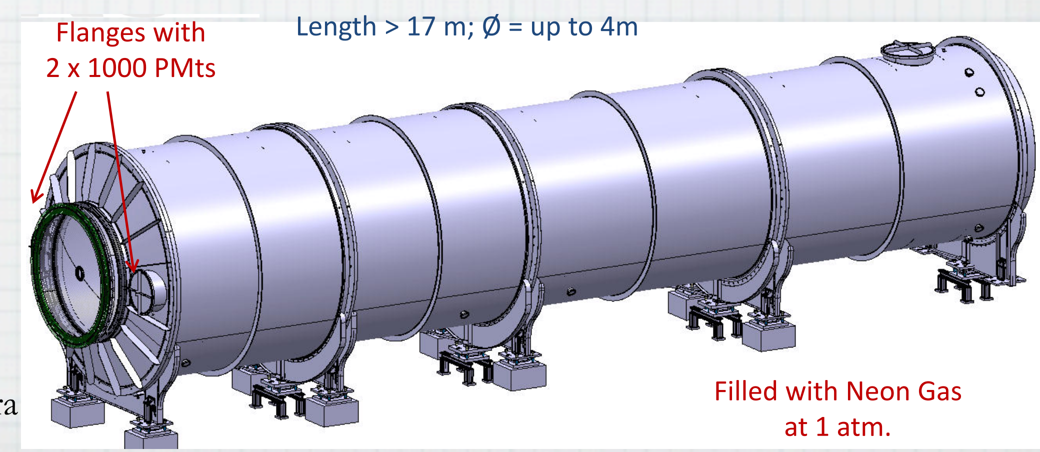


- For K^+



Nomura

- For π^+

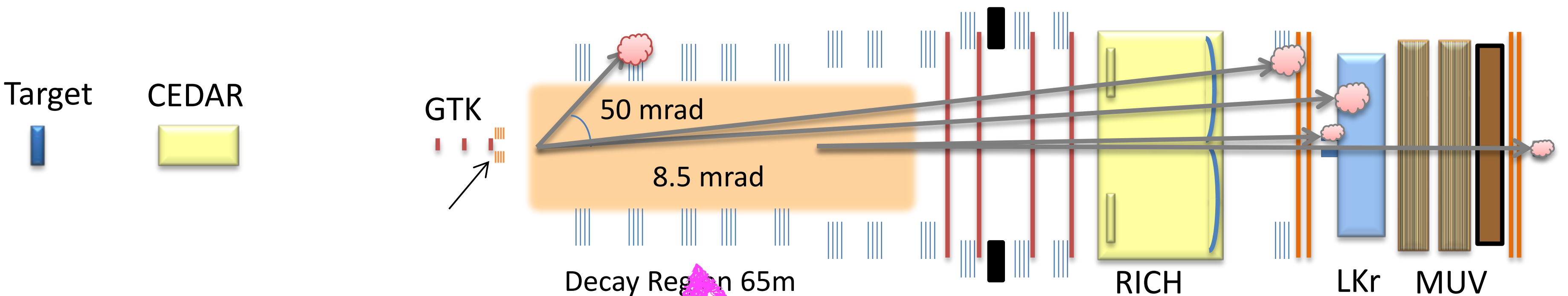


K⁺ in, π⁺ out, **nothing else**, missing P

NA62 detector

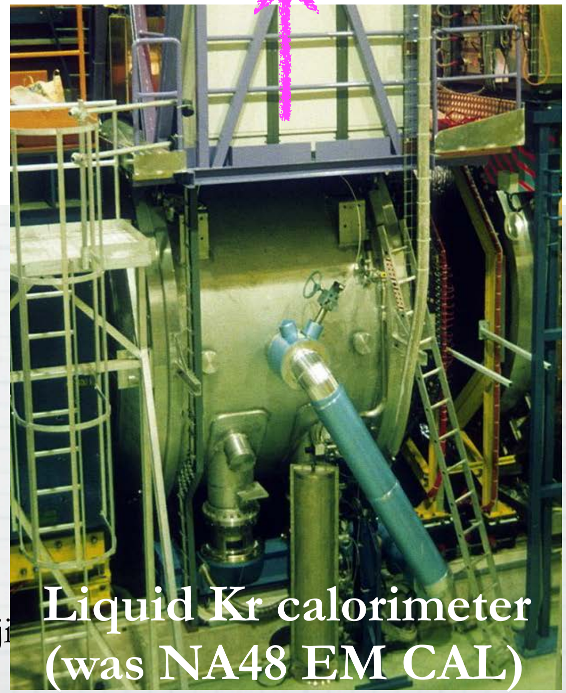
Hermetic vetoes

F. Hahn, Kaon 2013



- Photo vetoes
  - Large-angle veto covers 8.5 - 50 mrad
  - Liq. Kr calorimeter covers 1 - 8.5 mrad
  - Small-angle veto covers < 1 mrad

Large-angle veto (LG from OPAL)

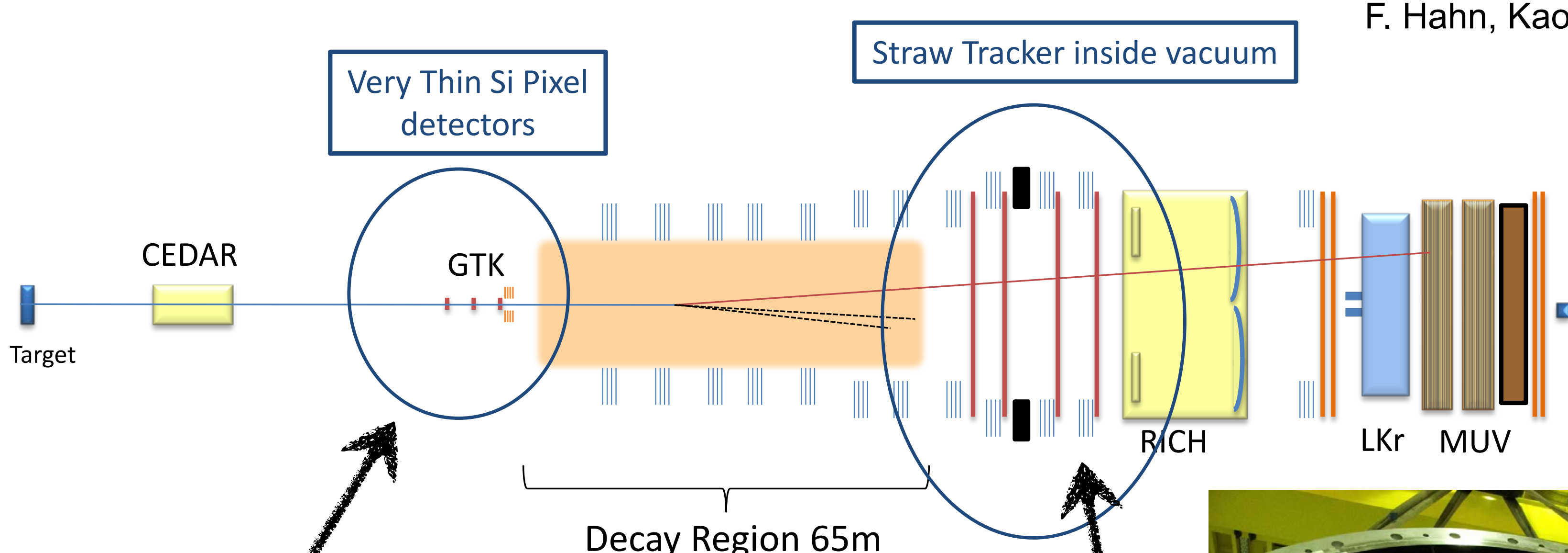

Liquid Kr calorimeter (was NA48 EM CAL)

K$^+$ in, π^+ out, nothing else, **missing P**

NA62 detector

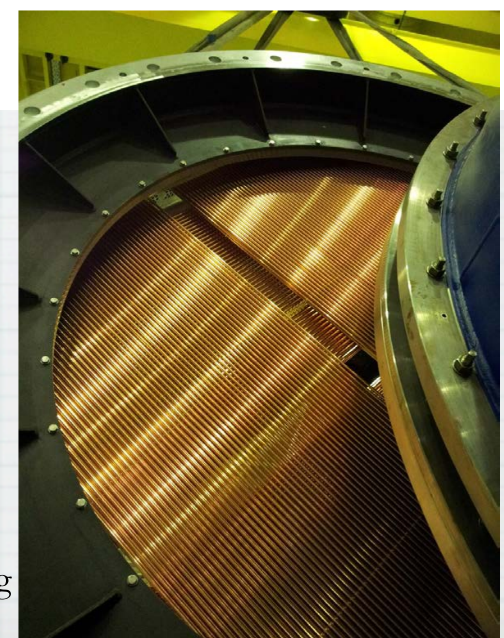
Low mass trackers

F. Hahn, Kaon 2013



- <u>For K$^+$</u>
- 300μm pixels, <500μm thick
- $\Delta\theta$~0.016 mrad
- Δt ~ 200ps

- <u>For π^+</u>
- 7168 Straw tubes
- Δx~140μm

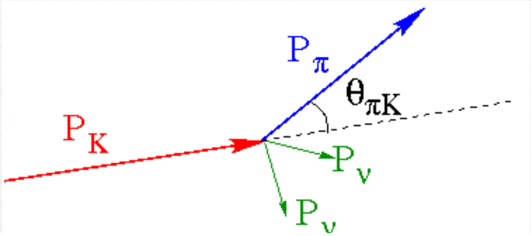


K+ in, π+ out, nothing else, **missing P**

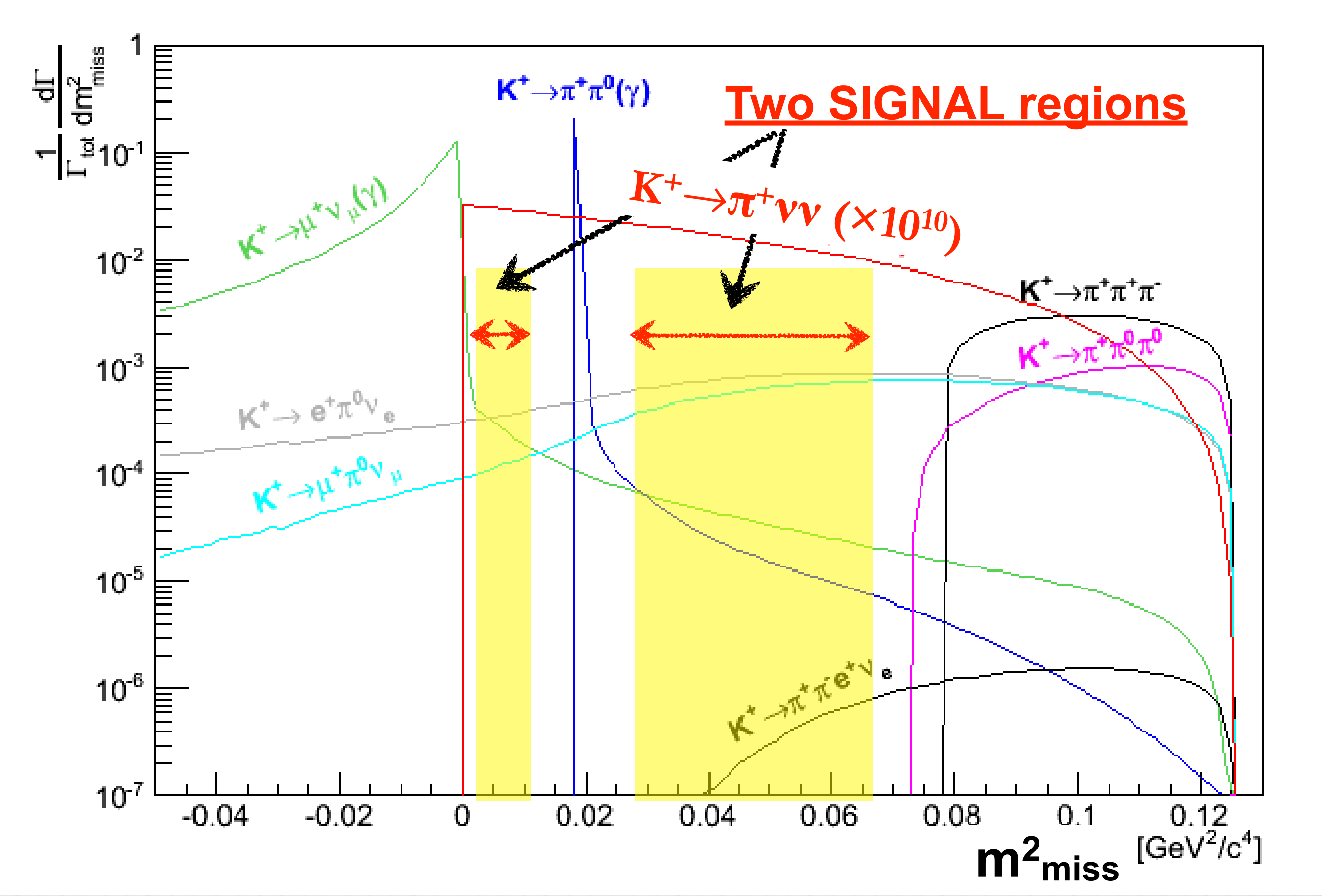
CERN NA62

Signal and Background kinematics

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



Avoid $m^2_{miss} = 0$ or m_π^2 to reject BG

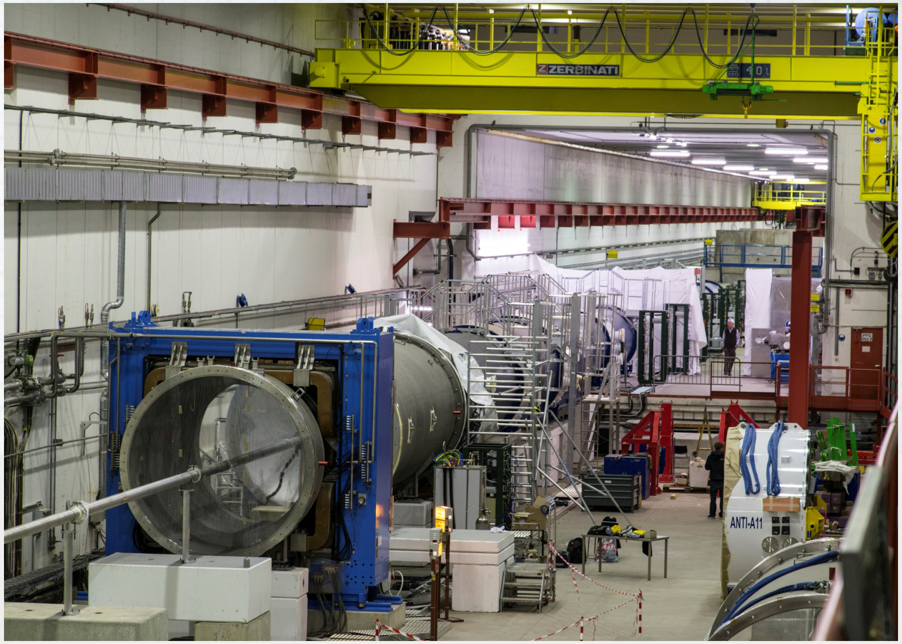


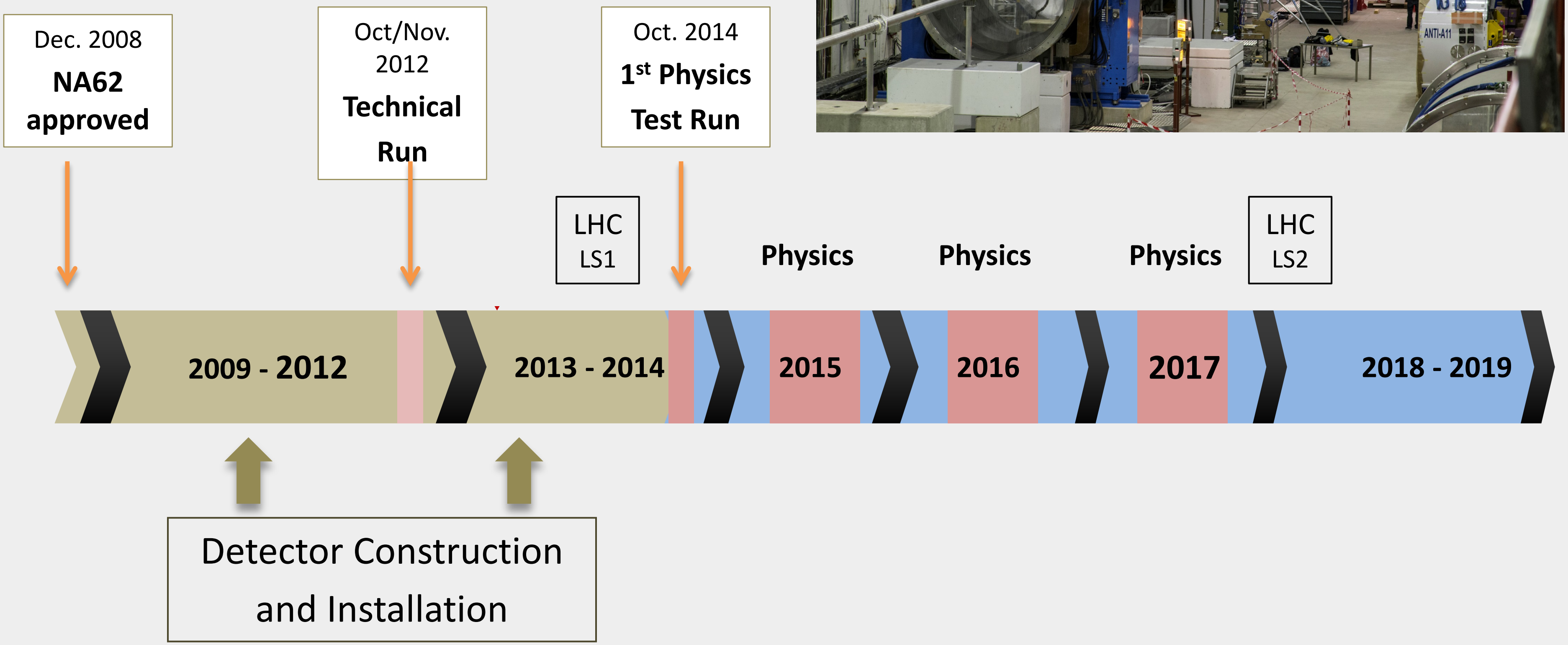
G. Ruggiero, Kaon 2013

CERN NA62

Schedule

Tech run 2012 demonstrated time resolution and efficiency of (a part of) sub-detectors.





$K^+ \rightarrow \pi^+ \nu\nu$ measurement: FNAL ORKA

·Stopped K^+ technique, using FNAL Main Injector

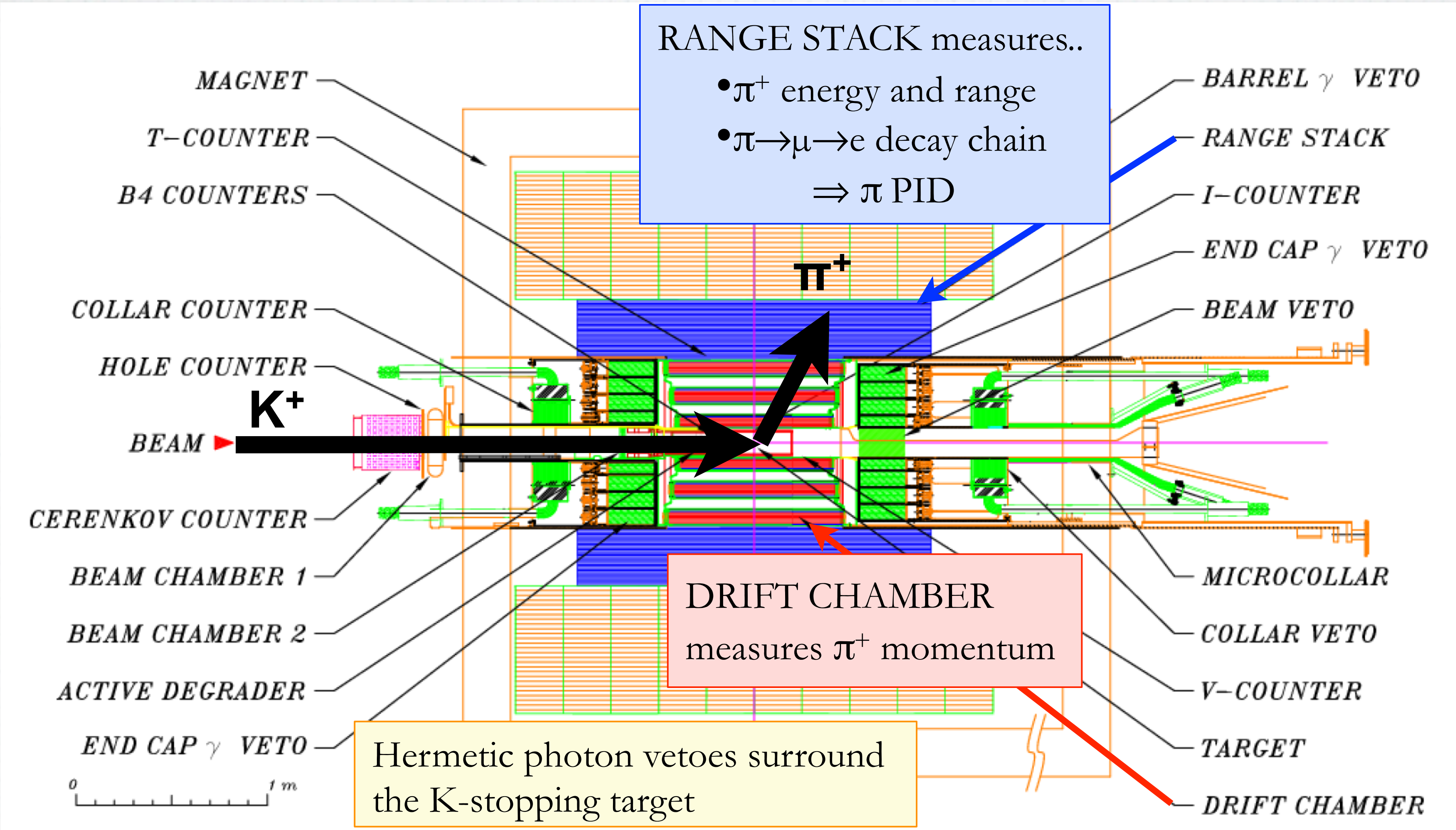
·Aims to collect ~1000 events

Genealogy: BNL E787→E949 (record holder)→FNAL ORKA

FNAL ORKA

Detector - cutaway view

ORKA detector plans to sit inside CDF magnet (recycle infrastructure)



RANGE STACK measures..

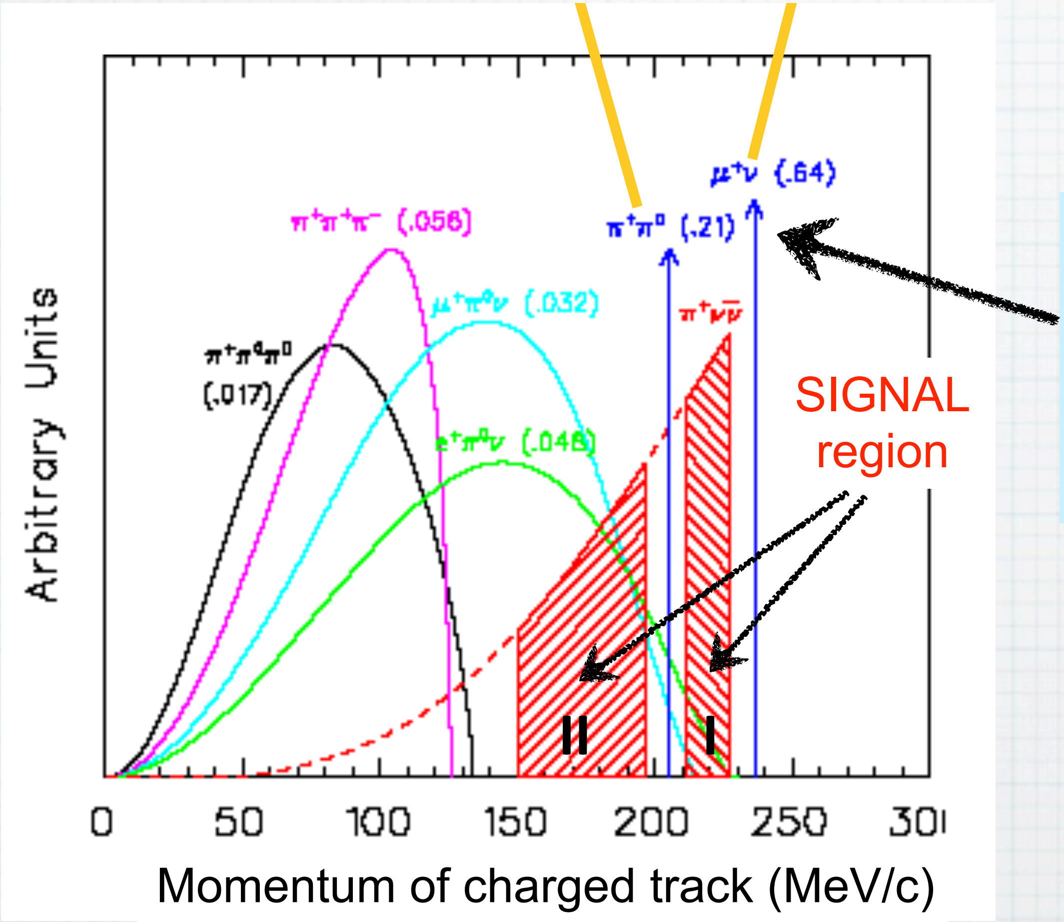
- π^+ energy and range
- $\pi \rightarrow \mu \rightarrow e$ decay chain

$\Rightarrow \pi$ PID

DRIFT CHAMBER measures π^+ momentum

Hermetic photon vetoes surround the K-stopping target

Signal and Background kinematics



Avoid peaks of
$K^+ \to \pi^+\pi^0$ (Br=21%)
and
$K^+ \to \mu^+\nu$ (Br=64%)

Established technique used in BNL E787/949

Sensitivity, status, ...

- 210 SM events/year with FNAL Main Injector
  - Improvements from BNL E949
    - K beam: ×10 (improvement of secondary beam line)
    - Acceptance: ×11 (PID, DAQ, ...)
- 5% measurement in 5 years
    - statistic + systematic (uncertainty of backgrounds)
- Detector R&D ongoing
- If FNAL Project X is realized, it speeds up ORKA

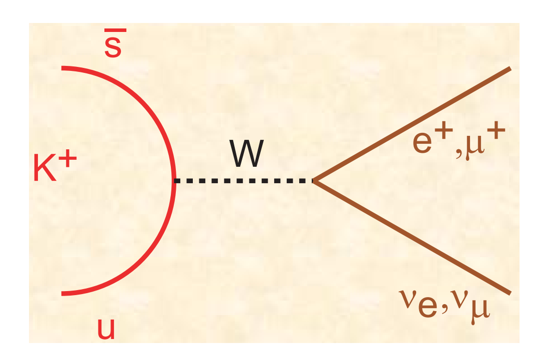
Other topics

Lepton universality in $K^+ \rightarrow e^+\nu / K^+ \rightarrow \mu^+\nu$

- SM well calculate R_K

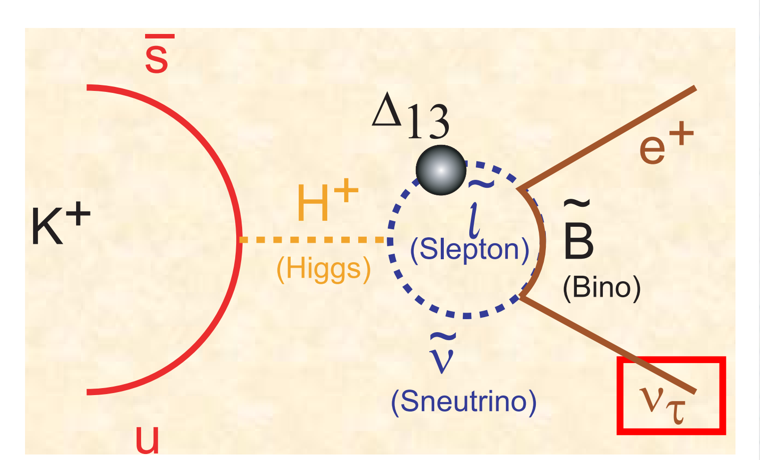
$$R_K^{SM} \equiv \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)(1+\delta_{rad.corr.})$$

$R_K=(2.477\pm0.001)\times10^{-5}$



- New physics may contribute
  - ex., model with 2 Higgs doublets

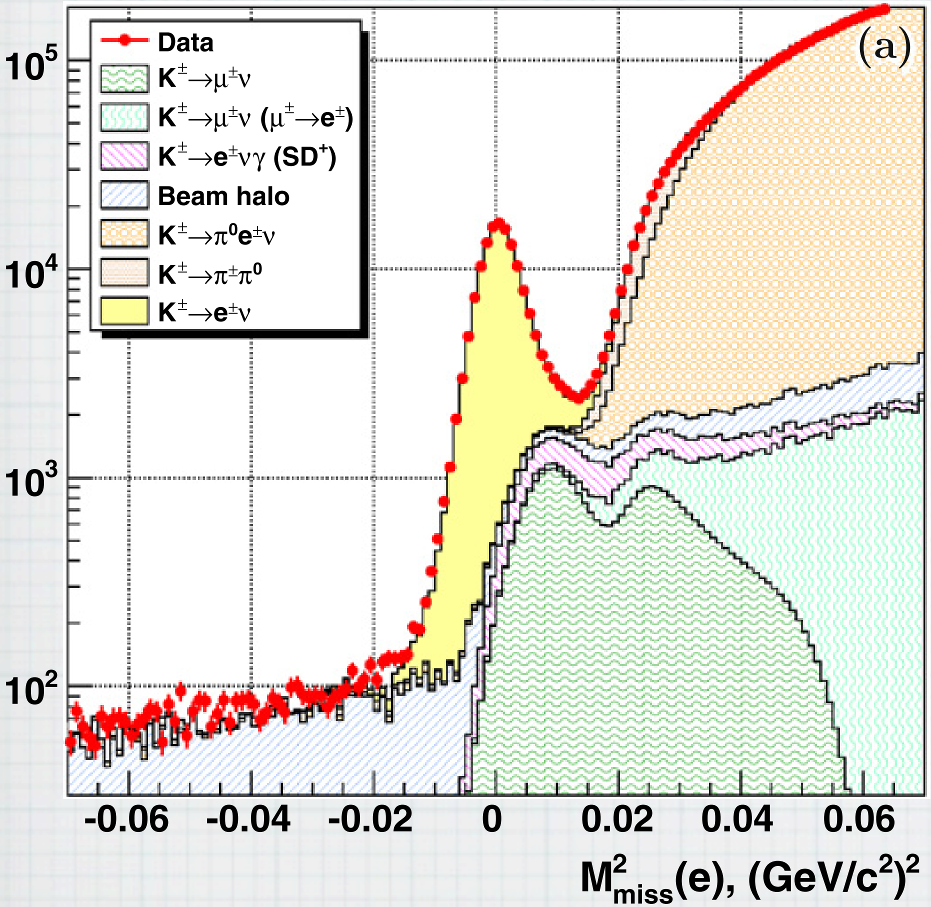
$$R_K^{NP} = R_K^{SM}\left[1+\frac{m_K^4}{m_{H^\pm}^4}\cdot\frac{m_\tau^2}{m_e^2}\cdot\Delta_{13}\cdot\tan^6\beta\right]$$



lepton family number violated

Lepton Universality in $K^+ \to e^+\nu / K^+ \to \mu^+\nu$

CERN NA62 result

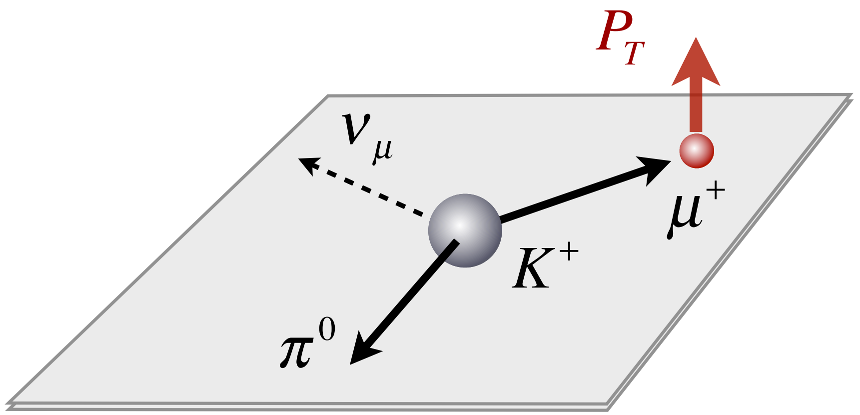


NA62, Phys. Lett. B716 (2013) 326

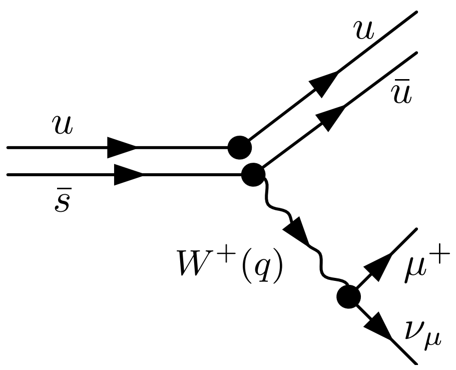
- **CERN NA62** result based on data taken in 2007-8
  - Collected 1.5×10^5 $K^+ \to e^+\nu$
  - $R_K=(2.488\pm0.010)\times10^{-5}$ ⇐0.4% measurement
  - Consistent with SM
- J-PARC TREK/E36 plans to do $\Delta R_K/R_K \sim 0.25\%$ measurement
  - Scientific approval, R&D

T-odd polarization asymmetry in $K^+\mu3$

$$P_T = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{\left|\vec{p}_\pi \times \vec{p}_\mu\right|}$$



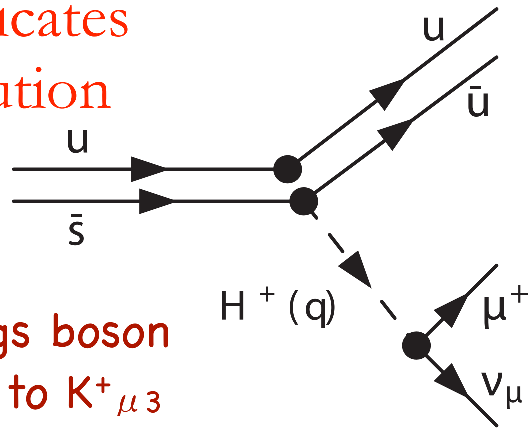
K+ decay in its rest frame



P_T vanishes in the SM at the tree-level

SM:
$P_T \sim 10^{-7}$
with FSI:
$P_T \sim 10^{-5}$ →

$P_T \sim 10^{-4}$ indicates NP contribution



Charged Higgs boson contribution to $K^+_{\mu 3}$

- Current limit: $P_T < 5\times10^{-3}$ (90%CL) by KEK E246

⇒ **J-PARC TREK aims to reach $\delta P_T \sim 2\times10^{-4}$**

J-PARC TREK(E06)/E36

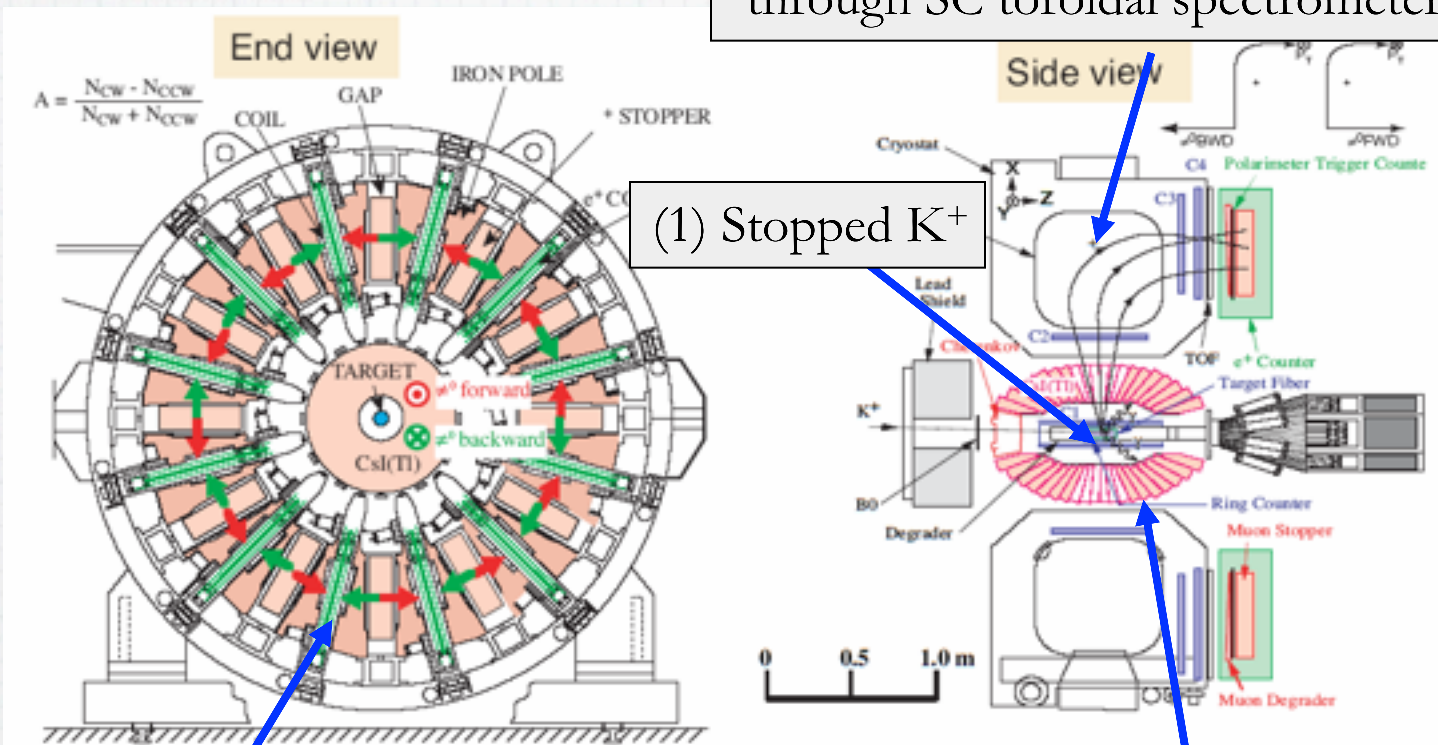
Detector and status

- Upgrade of KEK E246
  ⇒ **TREK aims to reach $\delta P_T \sim 2\times10^{-4}$**

Step1: E36
R_K measurement

Step2: TREK
T-violation study
(when
beam power
gets higher)

Status: R&D



(3) μ^+ to polarimeter through SC toroidal spectrometer

(1) Stopped K^+

(4) Measure CW/CCW asymmetry of e^+ in azimuthally symmetrical detector

(2) Tag π^0 and define direction (FWD/BWD)

Summary

- Kaon physics is one of the important approaches to BSM in the context of flavor physics.
- Active experimental efforts are ongoing.
  - J-PARC KOTO ($K_L \to \pi^0 \nu\nu$) performed 1st physics run.
  - CERN NA62 ($K^+ \to \pi^+ \nu\nu$) is in preparation.
  - Experiments aiming further sensitivity (ORKA, ...) are under consideration.

KAON efforts proceed step by step
to take a role to explore
physics beyond SM.