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The spokesperson is Cristina Lazzeroni

First search for $K^+ \to \pi^+ \nu\bar{\nu}$ using the decay-in-flight technique

The NA62 Collaboration

using 2% data sample of all data taking 2016~2018

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This paper is dedicated to the memory of our colleagues S. Balev and F. Hahn.

ABSTRACT

The NA62 experiment at the CERN SPS reports the first search for $K^+ \to \pi^+ \nu\bar{\nu}$ using the decay-in-flight technique, based on a sample of 1.21×10^{11} K^+ decays collected in 2016. The single event sensitivity is 3.15×10^{-10}, corresponding to 0.267 Standard Model events. One signal candidate is observed while the expected background is 0.152 events. This leads to an upper limit of 14×10^{-10} on the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio at 95% CL.

Goals [edit]

See also: Baryon asymmetry of the universe and CP violation

The experiment is designed to conduct precision tests of the Standard Model by studying rare decays of charged kaons. The principal goal, for which the design has been optimized, is the measurement of the rate of the ultra-rare decay $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ with a precision of 10%, by detecting about 100 decay candidates with low background. This will lead to the determination of the CKM matrix element $|V_{td}|$ with a precision better than 10%.[2] This element relates very accurately to the likelihood that top quarks decay to down quarks. The Particle Data Group's *2008 Review of Particle Physics* lists $|V_{td}| = 0.008\,74\,^{+0.000\,26}_{-0.000\,37}$.[3] A broad program of studies of kaon physics is run in parallel including studies of other rare decays, searches for forbidden decays, and for new exotic particles not predicted by the standard model (for example Dark Photons).

https://en.wikipedia.org/wiki/NA62_experiment

About K+

main decay modes

STRANGE MESONS
$(S = \pm 1,\ C = B = 0)$

$K^+ = u\overline{s}$, $K^0 = d\overline{s}$, $\overline{K}^0 = \overline{d}s$, $K^- = \overline{u}s$, similarly for K^*'s

$K^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [n] (S = 2.8)
Mean life $\tau = (1.2380 \pm 0.0020) \times 10^{-8}$ s (S = 1.8)
$c\tau = 3.711$ m

***CPT* violation parameters (Δ = rate difference/sum)**

$\Delta(K^\pm \to \mu^\pm \nu_\mu) = (-0.27 \pm 0.21)\%$
$\Delta(K^\pm \to \pi^\pm \pi^0) = (0.4 \pm 0.6)\%$ [o]

***CP* violation parameters (Δ = rate difference/sum)**

$\Delta(K^\pm \to \pi^\pm e^+ e^-) = (-2.2 \pm 1.6) \times 10^{-2}$
$\Delta(K^\pm \to \pi^\pm \mu^+ \mu^-) = 0.010 \pm 0.023$

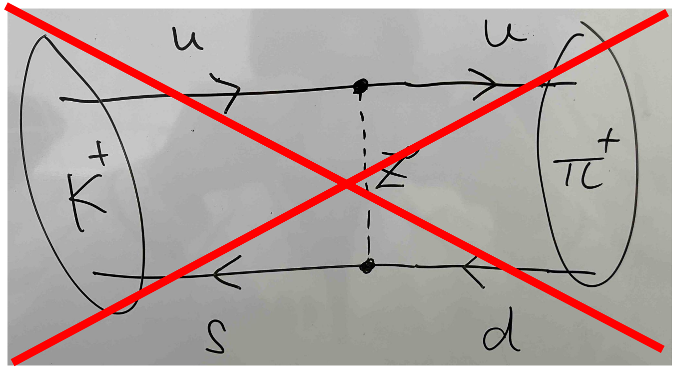
K^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Leptonic and semileptonic modes			
$e^+ \nu_e$	$(1.582 \pm 0.007) \times 10^{-5}$		247
$\mu^+ \nu_\mu$	(63.56 ± 0.11) %	S=1.2	236
$\pi^0 e^+ \nu_e$	(5.07 ± 0.04) %	S=2.1	228
Called K^+_{e3}.			
$\pi^0 \mu^+ \nu_\mu$	(3.352 ± 0.033) %	S=1.9	215
Called $K^+_{\mu 3}$.			
$\pi^0 \pi^0 e^+ \nu_e$	$(2.55 \pm 0.04) \times 10^{-5}$	S=1.1	206
$\pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$		203
$\pi^+ \pi^- \mu^+ \nu_\mu$	$(1.4 \pm 0.9) \times 10^{-5}$		151
$\pi^0 \pi^0 \pi^0 e^+ \nu_e$	$< 3.5 \times 10^{-6}$	CL=90%	135
Hadronic modes			
$\pi^+ \pi^0$	(20.67 ± 0.08) %	S=1.2	205
$\pi^+ \pi^0 \pi^0$	(1.760 ± 0.023) %	S=1.1	133
$\pi^+ \pi^+ \pi^-$	(5.583 ± 0.024) %		125

Lepton family number (*LF*), Lepton number (*L*), $\Delta S = \Delta Q$ (*SQ*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes

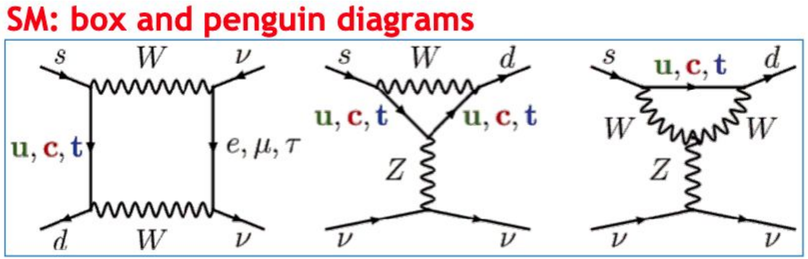
Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+ \pi^+ e^- \overline{\nu}_e$	*SQ*	$< 1.3 \times 10^{-8}$	CL=90%	203
$\pi^+ \pi^+ \mu^- \overline{\nu}_\mu$	*SQ*	$< 3.0 \times 10^{-6}$	CL=95%	151
$\pi^+ e^+ e^-$	*S1*	$(3.00 \pm 0.09) \times 10^{-7}$		227
$\pi^+ \mu^+ \mu^-$	*S1*	$(9.4 \pm 0.6) \times 10^{-8}$	S=2.6	172
$\pi^+ \nu \overline{\nu}$	*S1*	$(1.14 {}^{+0.40}_{-0.33}) \times 10^{-10}$		227
$\pi^+ \pi^0 \nu \overline{\nu}$	*S1*	$< 4.3 \times 10^{-5}$	CL=90%	205
$\mu^- \nu e^+ e^+$	*LF*	$< 2.1 \times 10^{-8}$	CL=90%	236

decay mode
focusing this exp.

Rare decay $K^+ \to \pi^+ \nu \bar{\nu}$



- Flavour Changing Neutral Current (FCNC)
  - very small BR in exp., not match to theory
  - Feynman diagram tree level is suppressed somehow.
- GIM mechanism
  - consider charm quark (second generation)
  - consider the diagram including loops
- CKM matrix
  - third generation is needed to explain CP violation
  - weak eigenstate mixed with mass eigenstate
  - like amplitudes of changing flavour
- Penguin diagram
  - sensitive to Beyond Standard Model (BSM)



Rare decay $K^+ \to \pi^+ \nu \bar{\nu}$

- ➢ sensitive to Lepton Flavour non-universality
- ➢ can constrain Leptoquark models
- ➢ can limit the parameter of supersymmetric models
- ➢ CP-violation ←→ BR(K+ → pi+ nu nubar) / BR(K_L →pi0 nu nubar)

- ➢ Result by past exp. “E787 and E949 at BNL”, using a decay-at-rest technique
  - ○ BR(K+ → pi+ nu nubar) = ($17.3^{+11.5}_{-10.5}$) × 10^-11
- ➢ SM predicts
  - ○ BR(K+ → pi+ nu nubar) = ($8.4^{+1.0}_{-1.0}$) × 10^-11

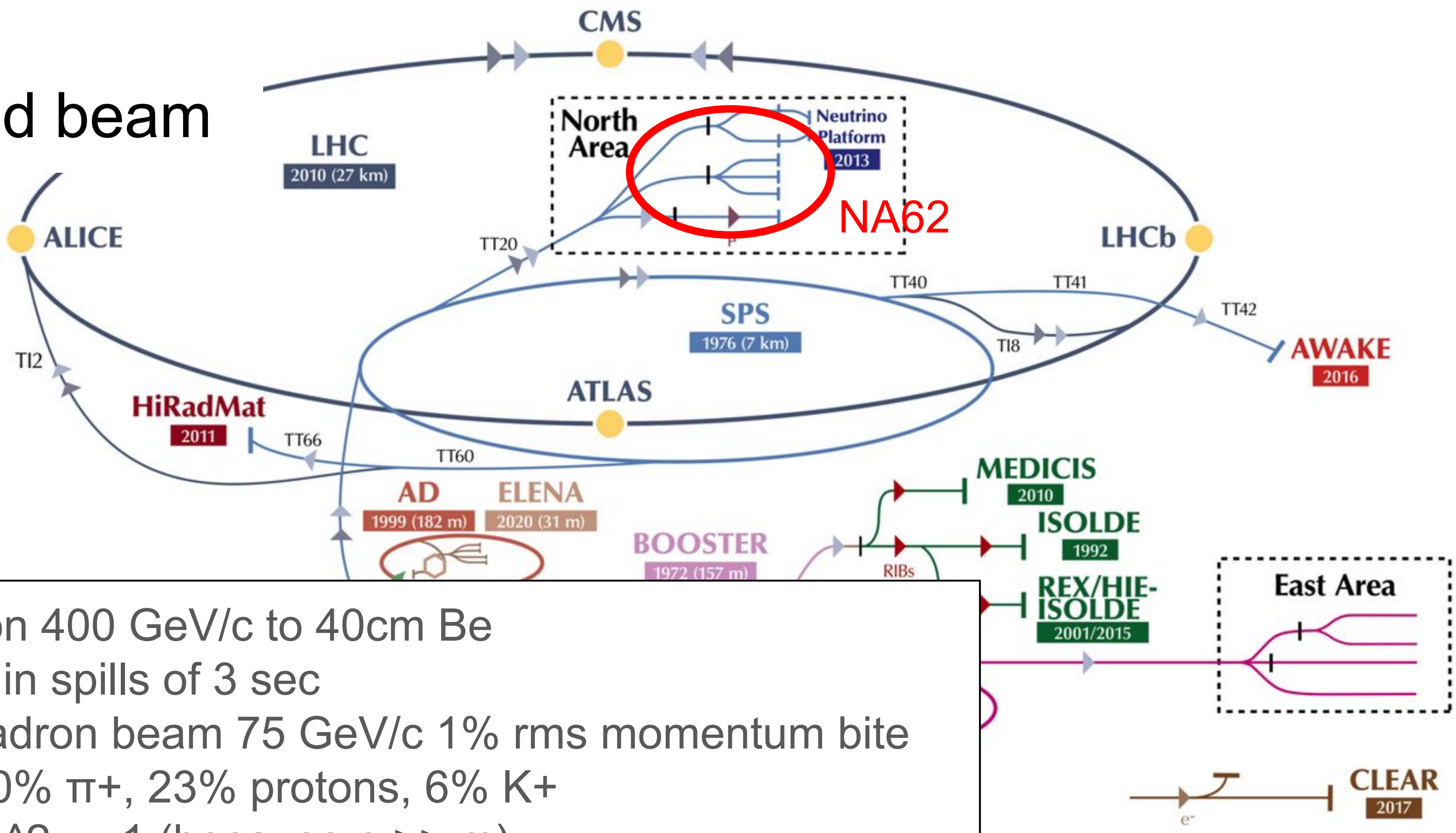
→ Need to measure BR(K+ → pi+ nu nubar) more precisely

decay-in-flight technique

Compared to decay-at-rest technique,

- ➢ not need to stop K+ → get high efficiency
- ➢ allow us detect the decay particles in small angular region
- ➢ can see more various decay modes thanks to its high energy

facility and beam



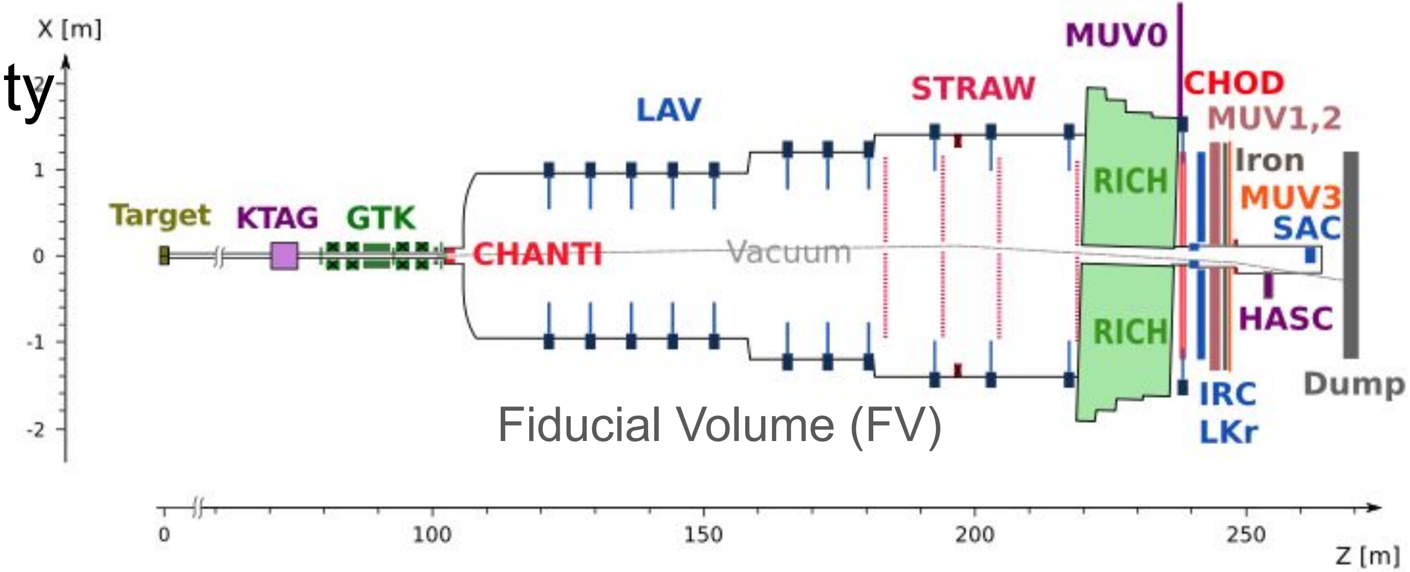
primary : proton 400 GeV/c to 40cm Be
SPS in spills of 3 sec

secondary : hadron beam 75 GeV/c 1% rms momentum bite
70% π^+, 23% protons, 6% K^+

$\beta_K = p/\sqrt{p^2 + m_K^2} \to 1$ (because p >> m)

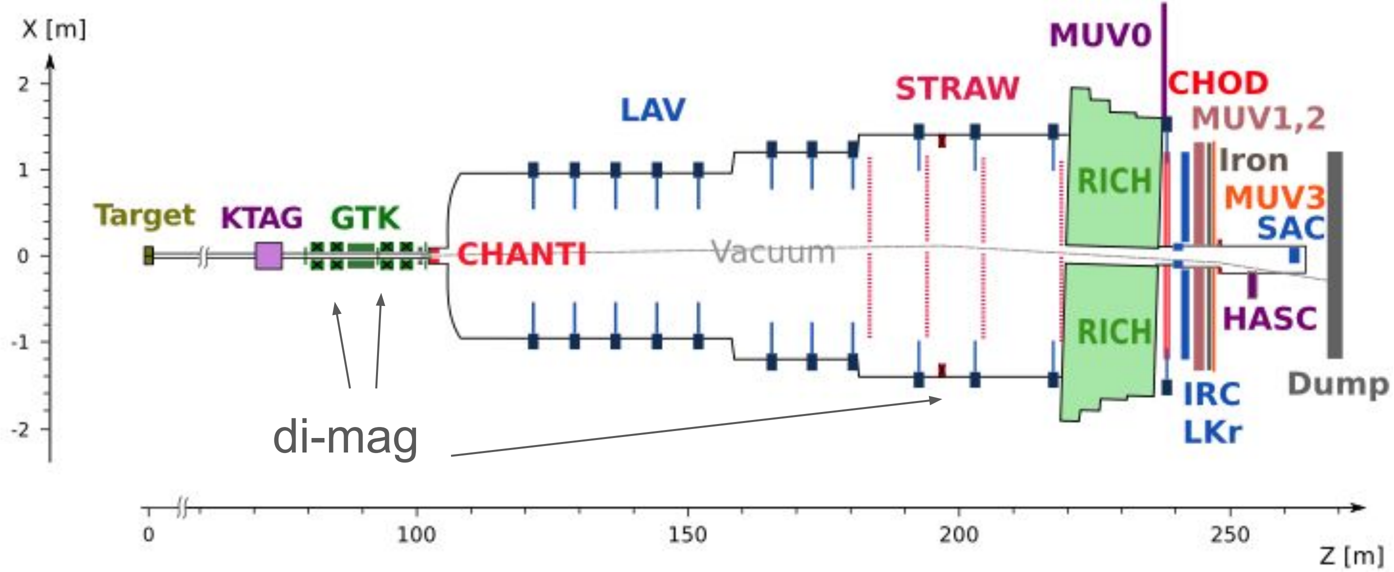
https://cds.cern.ch/record/2813716?ln=en

Beam propaty



- ➢ at FV entrance,
  - ○ 52*24 (x*y) mm beam shape
  - ○ have a divergence of 0.11 mrad
  - ○ beam rate 300 MHz
- ➢ in the first 80 m of FV, 13% K+ decay

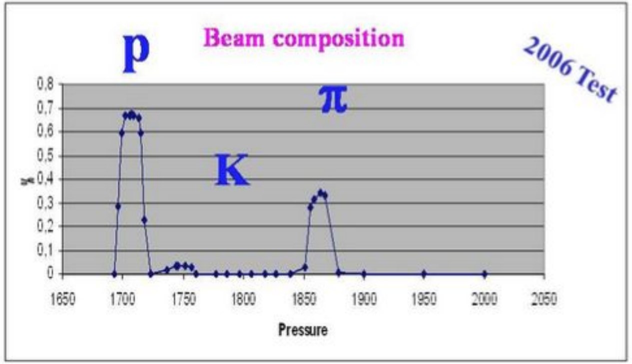
Beam Line Detectors Outline



KTAG : K+ id
GTK : coordinates and momentum of beam
CHANTI : collimeter
LAV : photon and muon veto
STRAW : coordinates and momentum of decay charged particle
RICH : pi+ id with respect to muon
MUV : muon veto
LKr, IRC, SAC : photon veto

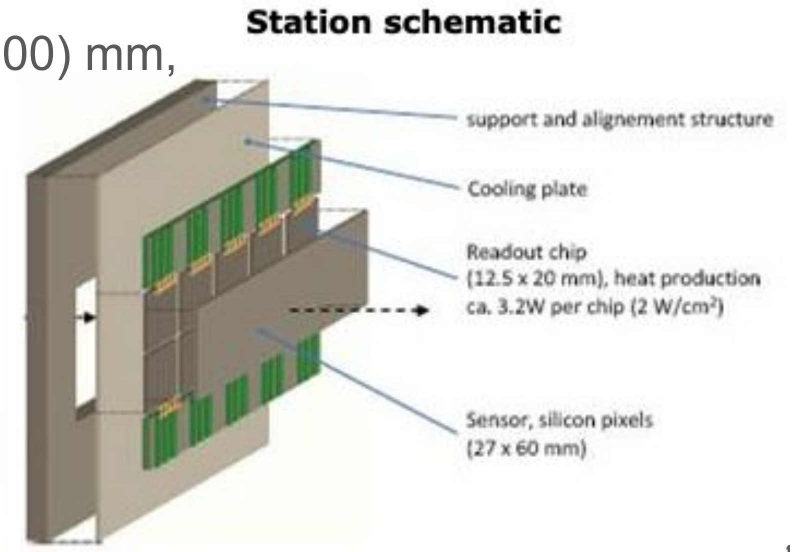
KTAG… differential Cherenkov counter

- ➢ filled with N_2 at 1.75 bar
- ➢ 70 ps time resolution



GTK… silicon pixel tracker

- ➢ three station in vacuum of Si pixel (300*300) mm, 200 mm thick
- ➢ 18,000 pixel/station
- ➢ 100 ps/station time resolution
- ➢ 16 urad angle resolution
- ➢ 0.15 GeV/c (0.2%) momentum resolution

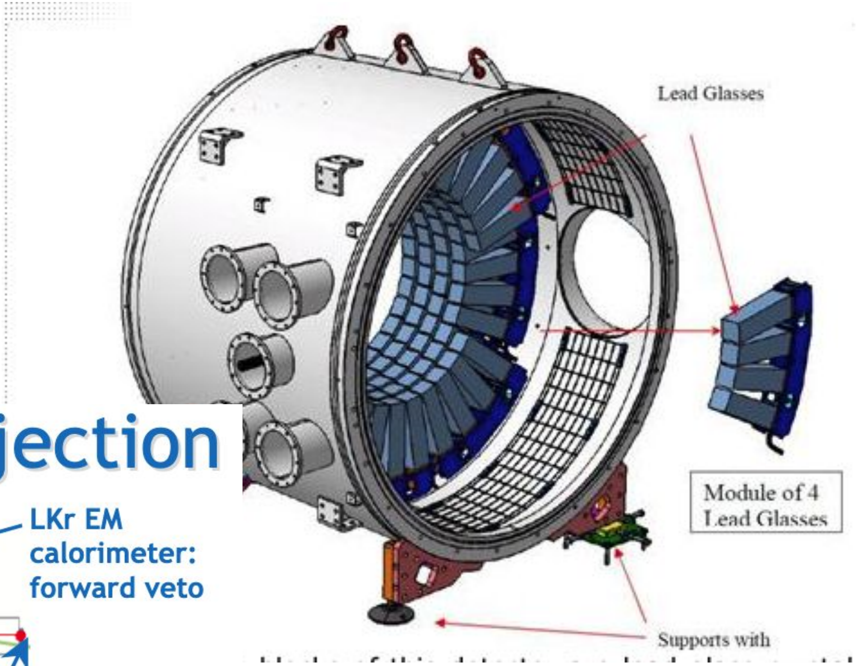


CHANTI… guard detector

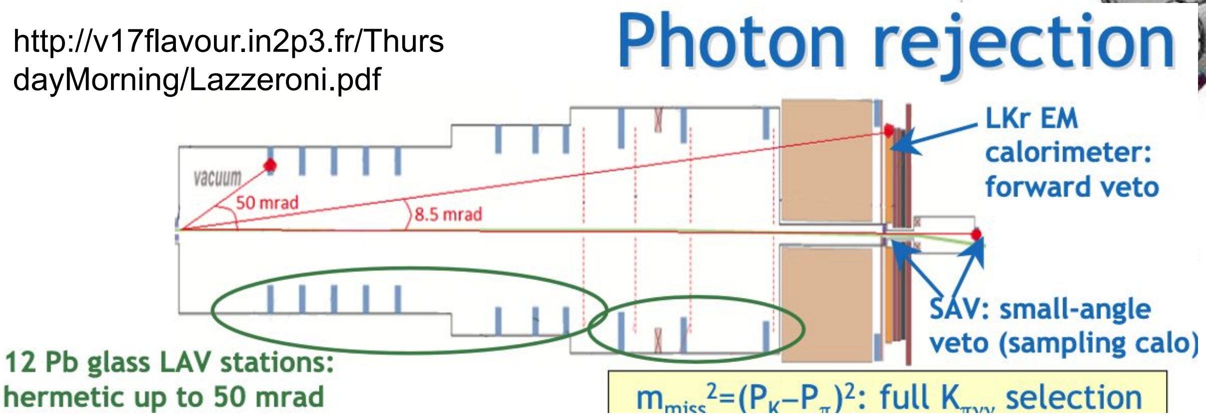
- hole size 90*50 mm(x*y)
- outer square side length 300 mm
- can veto ~95% of all inelastic interactions of K in GTK-3 regardless of the final state
- can veto ~99% in signal-like events

LAV… The Large Angle Veto (photon veto)

- ➢ to suppress the dominant background originating K+ → pi+ + pi0
- ➢ inefficiency for the rejection of the pi0 is smaller than 10^-8

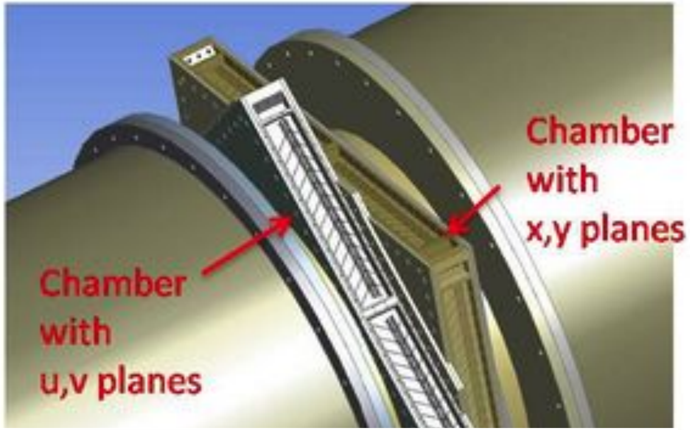


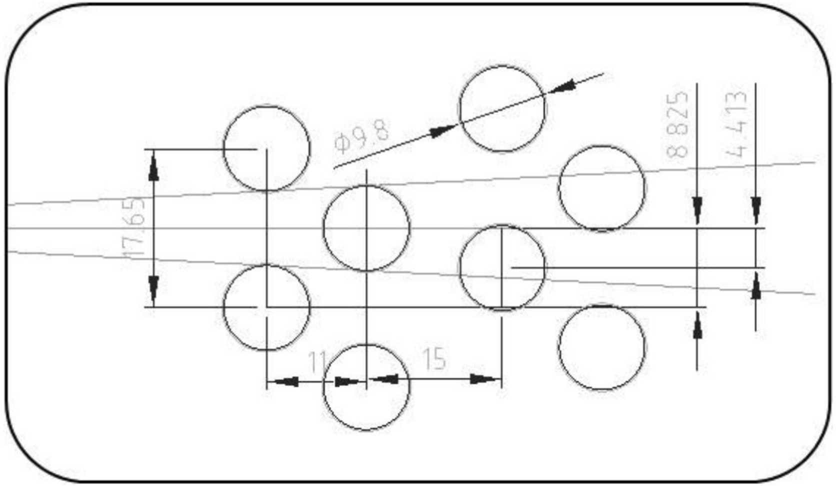
http://v17flavour.in2p3.fr/ThursdayMorning/Lazzeroni.pdf



STRAW… Plane Chamber tracker

- ➢ CO_2 (90%) CF_4 (5%) Isobutene (5%)
- ➢ 448 straws in each plane
- ➢ 4 station
- ➢ 2.1 m long with diameter 9.8 mm
- ➢ Precise tracking < 120 um
- ➢ 0.3% : momentum resolution
- ➢ Particle rate in the straw < 0.5 MHz

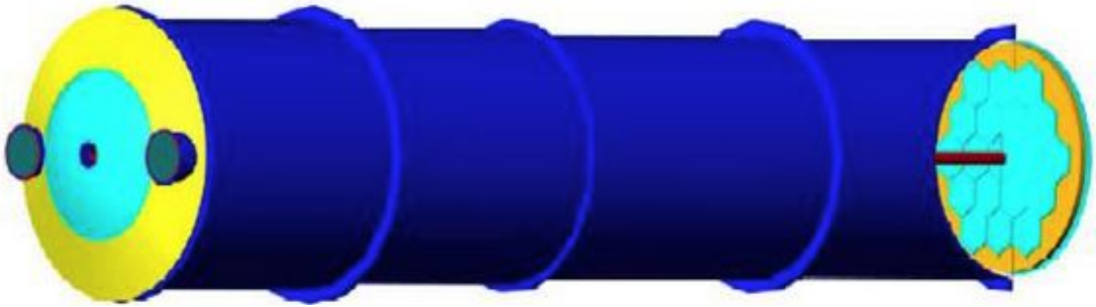




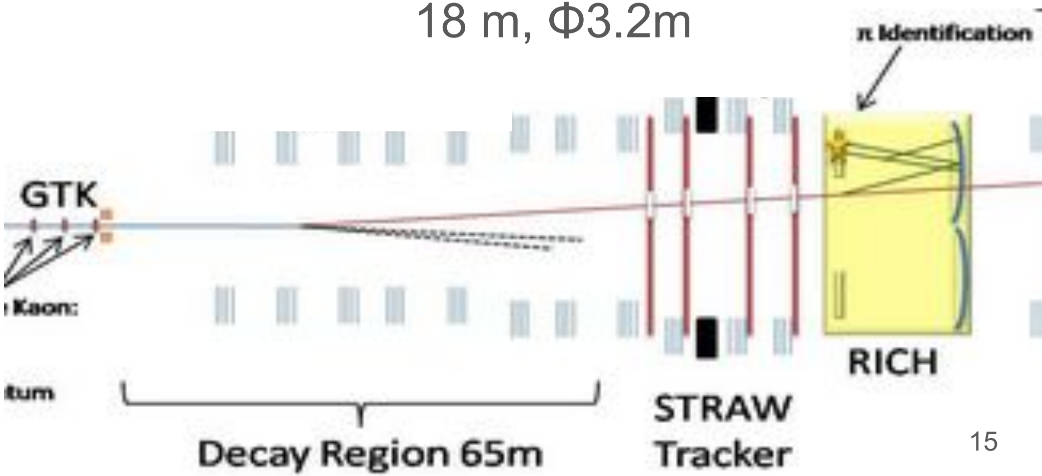
Section of straw layout in one view

RICH…Ring-Imaging Cherenkov counter (mirror type)

- filled with Neon at 1 atom
- 2*1000 photo detectors
- time resolution < 100 ps
- to suppress a background
  from K+ → μ+ + nu
  due to distinguish pi+ from μ+
  (15~35 GeV/c)

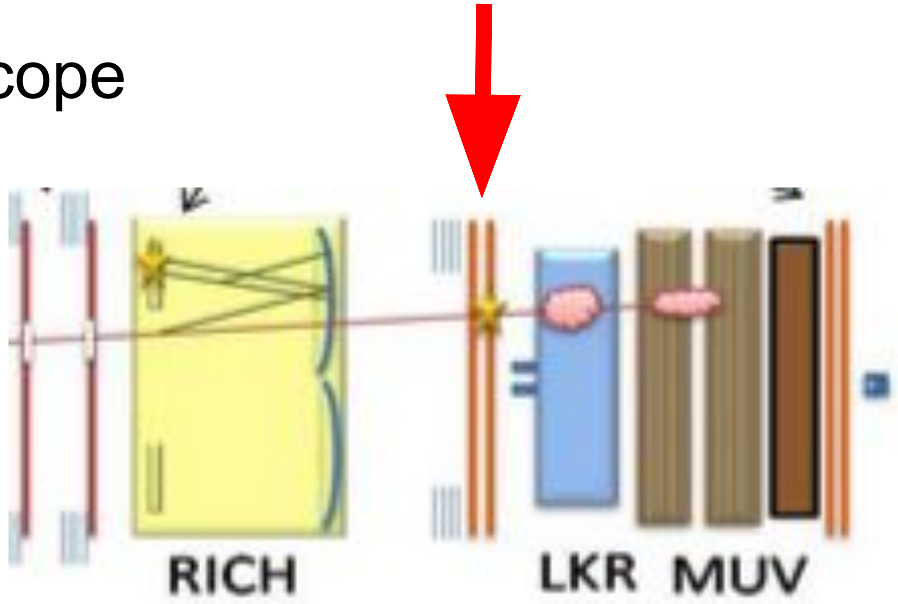


18 m, Φ3.2m



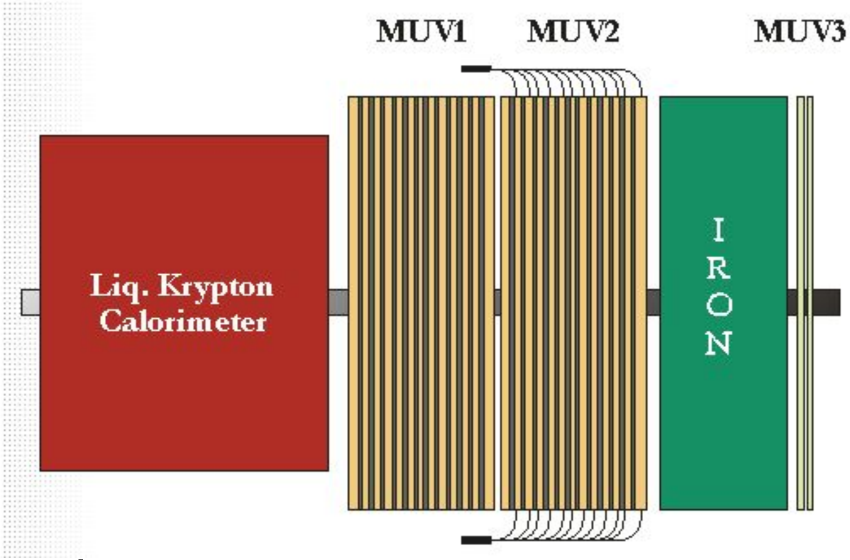
CHOD… two scintillator hodoscope

- ➢ used for triggering and timing
- ➢ 200 ps resolution for charged particles



LKr… E.M calorimeter for photon veto

- ➢ 10 m^3 liquid Kr, 1.25 m deep
- ➢ 27 radiation length
- ➢ very good intrinsic energy resolution
  - ○ 1.4% at an E dep of 25 GeV
- ➢ veto photon from K+ decay
  - ○ inefficiency ~ 10^-5



MUV… muon veto system

- ➢ iron-scintillator sandwich
- ➢ 25 iron(25 mm), 12 vertical & 12 horizontal scintillator layers, 260*260 cm^2
- ➢ scinti width 4 cm or 6 cm, thickness 10 mm
- ➢ Two layers (x,y) scinti

Data taking

“PNN trigger”

- L0 trigger (Low level trigger)
  - RICH && CHOD 1 hit (within 10 ns from RICH) && LKr Edep < 20 GeV && $\overline{\text{LAV}}$ && $\overline{\text{MUV3}}$
  - O(10 MHz) → O(1 MHz)
- L1 trigger (Software level trigger)
  - K+ by KTAG && LAV 0~2 hits (within 10 ns from RICH) && STRAW track (< 50 GeV/c)
- in the end, data acquisition by O(kHz)
- data sample : 1 month in 2016, ~520 SPS spill

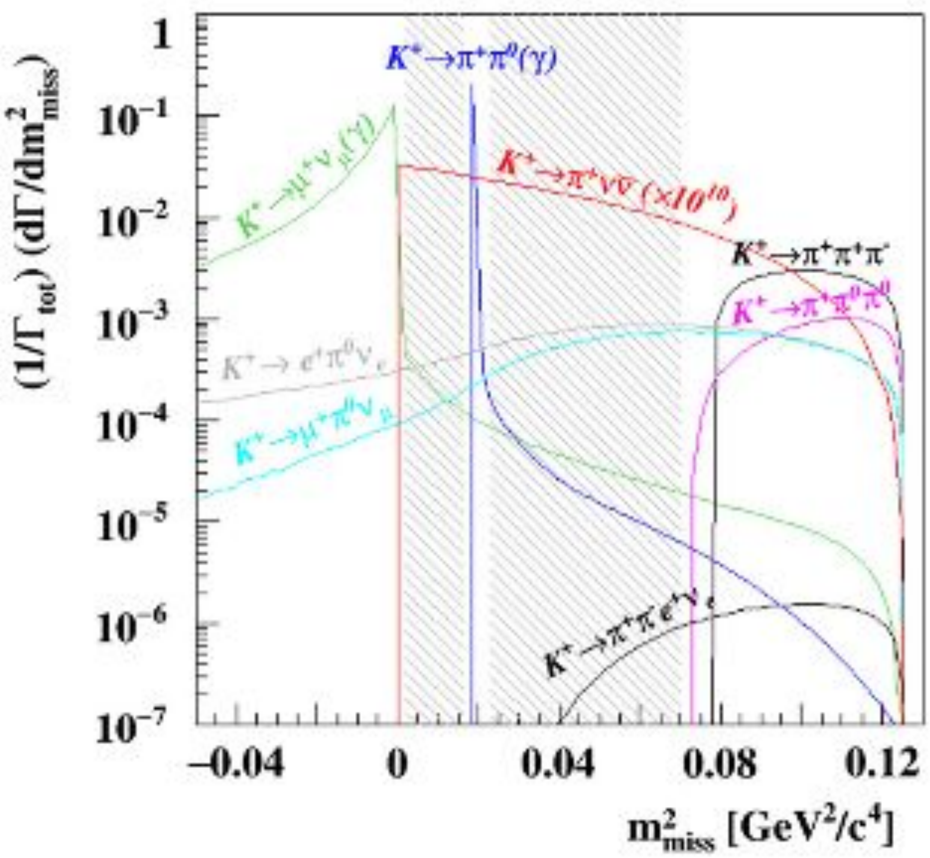
Also took the data by only L0 trigger, prescale factor 400,
to measure efficiencies and estimate background, “control events”

Reconstruction and calibration

miner and complicated, so let me skip

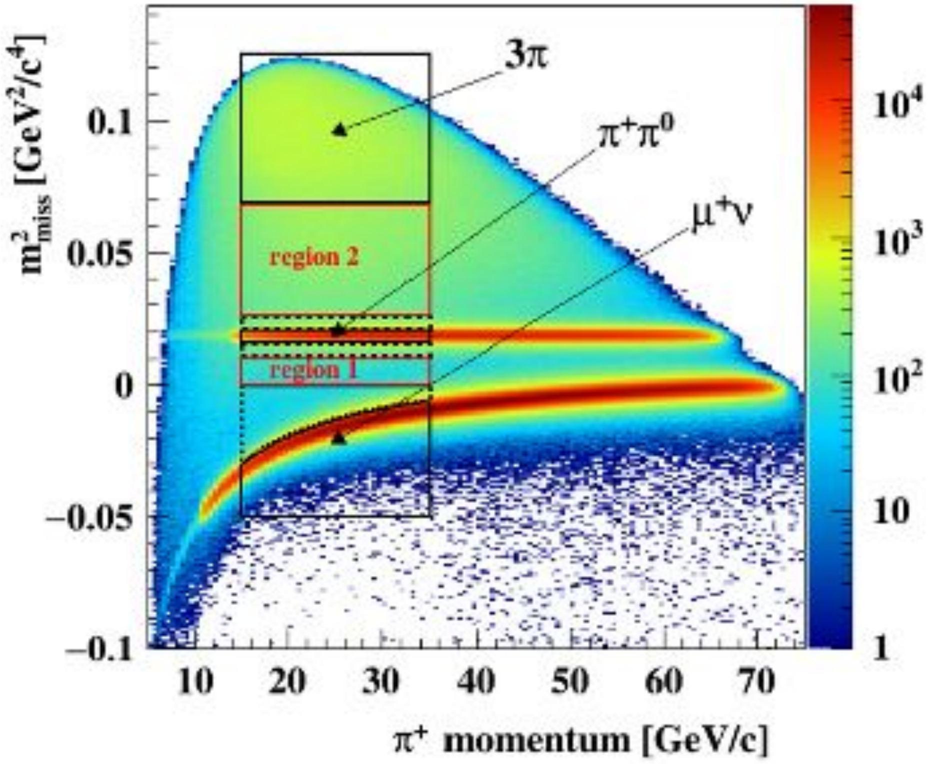
Event selection 1

- ➢ MC simulation based on Geant4
    - ○ signal and backgrounds
- ➢ The dashed areas are the signal search region.
- ➢ Section criteria based on m2 miss alone are not sufficient to reduce the background.



Event selection 2

- ➢ reconstructed m2 miss
  as a function of π+ momentum
  for control events
  - ○ signal and backgrounds
- ➢ pi+ momentum region is restricted due to RICH effective range
- ➢ region1,2 : signal search areas



Event selection 3

- K+, pi+ vertex condition
- signal timing cut
- photon cut
- …

Single Event Sensitivity (SES)

- SES = 1 / (N_K * $\varepsilon_{\pi\nu\nu}$)
  - N_K : the number of K+ decay in FV
  - $\varepsilon_{\pi\nu\nu}$: the signal efficiency
  - smaller SES, higher sensitivity
  - some parameters are based on MC simulation

$$\epsilon_{\pi\nu\nu} = A_{\pi\nu\nu} \cdot \epsilon_{trig} \cdot \epsilon_{RV}$$

ε_{trig} : PNN trigger efficiency

ε_{RV} : Random Veto efficiency

1. フィデューシャルボリューム内の崩壊数（N_K）の計算：

- N_K は次の式で計算されます：
  $N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR_{\pi\pi}}$
  ここで、
  - $N_{\pi\pi}$ はK+ → π+π0崩壊の検出数です。
  - D はデータ収集期間中のスケールファクターです。
  - $A_{\pi\pi}$ はK+ → π+π0崩壊の受容（アクセプタンス）です。
  - $BR_{\pi\pi}$ はK+ → π+π0崩壊の分岐比です。

例：NA62実験の場合

NA62実験において、SESは次のように計算されます：

$$\text{SES} = \frac{1}{(1.21\times10^{11})\cdot(4.0\%\cdot0.93\cdot0.97\cdot0.76)}$$

具体的な数値は以下のように置き換えられます：

- $N_K = 1.21 \times 10^{11}$
- $A_{\pi\backslash n\nu\backslash n\nu} = 4.0\%$
- $\epsilon_{trig} = 0.93 \cdot 0.97$
- $\epsilon_{RV} = 0.76$

- SES = (3.15 ± 0.01stat ± 0.24syst) × 10^−10,
- Nexp(πνν)(SM) = 0.267 ± 0.001stat ± 0.020syst ± 0.032ext.

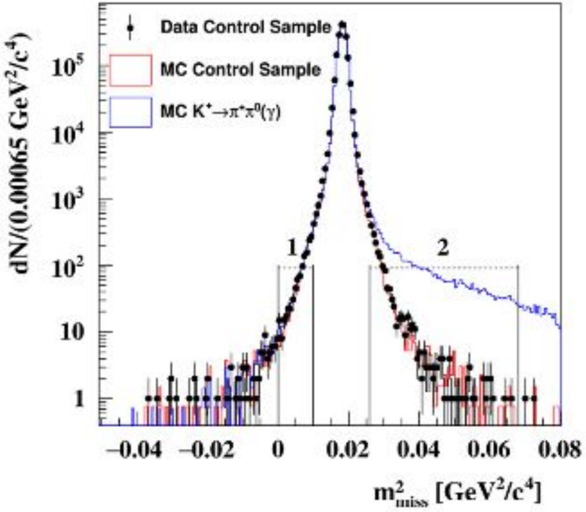
(1/SES) × BR(SM) = 8.4×10^−11

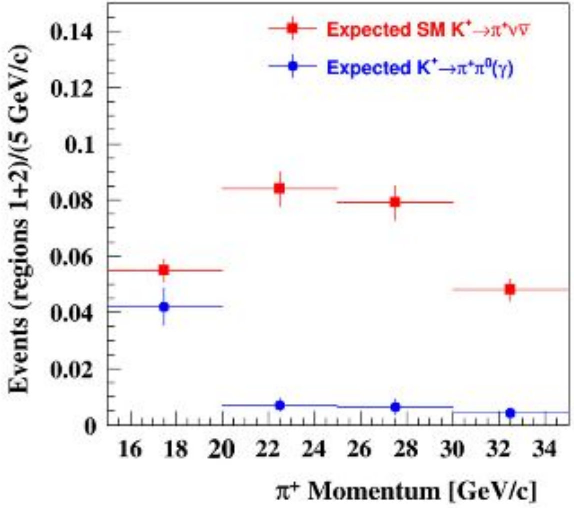
Background

- ➢ K+ → pi+ + pi0
- ➢ K+ → u+ + v
- ➢ K+ → pi+ + pi+ + pi-
- ➢ K+ → pi+ + pi- + e + v
- ➢ even after event selection, it is possible to remain background like above 4

Table 1
Summary of the background estimates summed over the two signal regions.

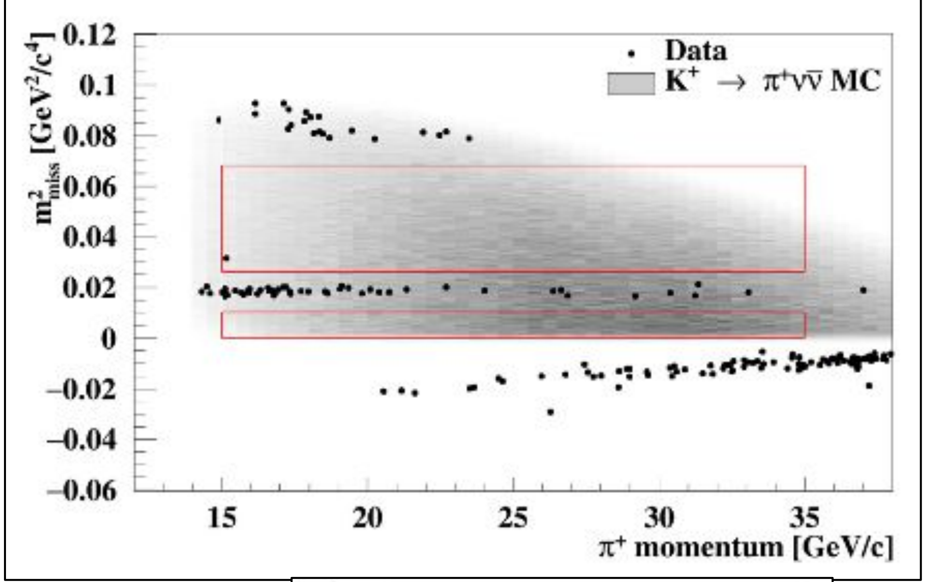
Process	Expected events
$K^+ \to \pi^+\pi^0(\gamma)$	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$	$0.020 \pm 0.003_{stat} \pm 0.006_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.013^{+0.017}_{-0.012}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^0\mu^+\nu,\ K^+ \to \pi^0e^+\nu$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	< 0.002
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{stat}$
Total background	$0.152^{+0.092}_{-0.033}\vert_{stat} \pm 0.013_{syst}$





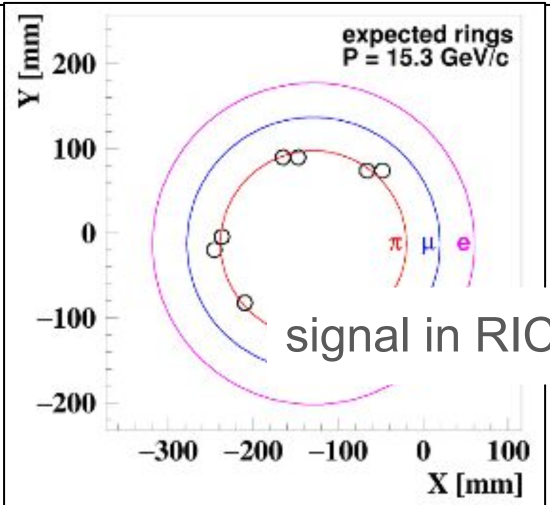
Results and conclusion

- 1 event in region2
- The p-value of the muon hypothesis based on calorimetric identification is 0.2%.
- Signals in the other detectors exist within 1 sigma of K+, pi+.
- The p-values of signal and background hypothesis are 15% too.
- BRexp(K+ → π+νν̄) < 10 × 10−10
- BR(K+ → π+νν̄) < 14 × 10−10（95%CL）



could not claim any strong statement,
but could show the validity of decay-in-flight technique in terms of background rejection

They are in progress using the full data sample.



signal in RICH

おまけ

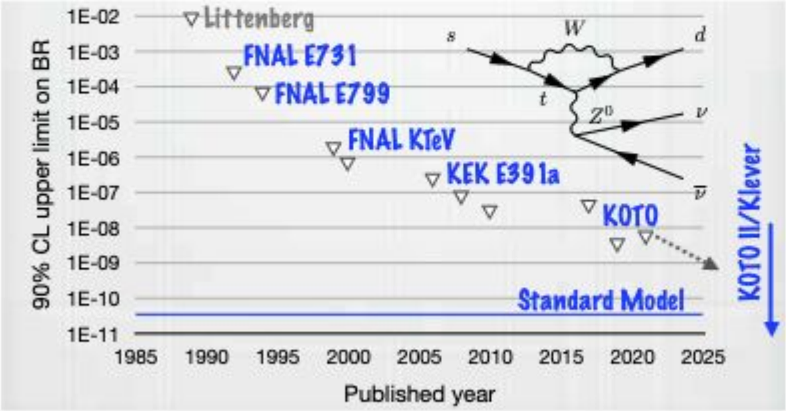


図 1: $K_L \to \pi^0 \nu\bar{\nu}$ の崩壊分岐比の上限値の推移

https://www.jahep.org/hepnews/2023/42-3-2-yamanaka.pdf