NA62 Experiment

$K^+ \rightarrow \pi^+ \nu\nu$

Eduardo Cortina

Center for Particle Physics and Phenomenology
(CP3)
Université catholique de Louvain
Chemin du Cyclotron, 2
B-1348 Louvain-la-Neuve,
Belgium

Outline

1. Kaon Physics in the LHC era
    - Golden modes
    - Theoretical predictions
    - Experimental Status

2. NA62: Measurement of $K^+ \to \pi^+ \nu\nu$
    - Principle of the measurement
    - Experimental setup
    - Status of R_K

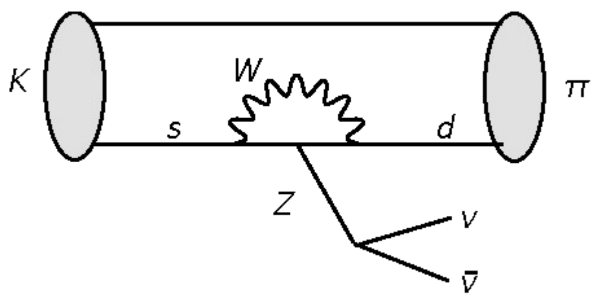
3. Conclusions

Kaon Physics in the LHC era

G. Isidori
Flavour in the era of the LHC

- High Energy experiments:
  - Determine energy scale of new phenomena
  - Direct production
- Low Energy experiments
  - Symmetry properties of new phenomena
  - Indirect effects in precision observables
- Golden Modes in Kaon physics
  - Short distance dynamics constitutes the dominant contribution of the decay amplitude

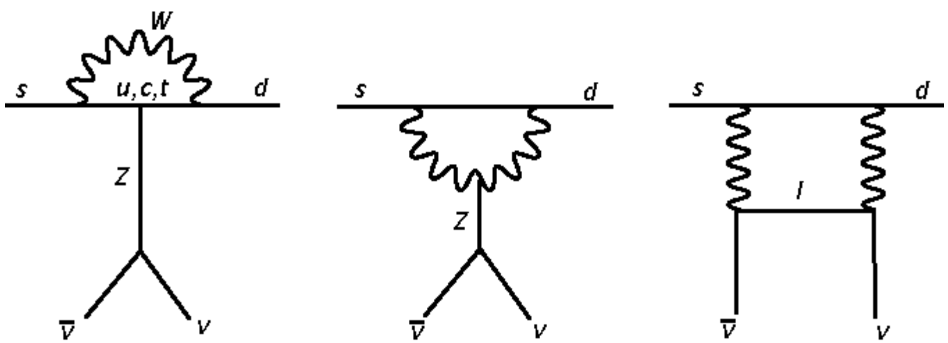
$$K^+ \to \pi^+ \nu\bar{\nu} \qquad K_L \to \pi^0 e^+ e^-$$
$$K_L \to \pi^0 \nu\bar{\nu} \qquad K_L \to \pi^0 \mu^+ \mu^-$$



I. Clean electroweak short distance amplitude
New Physics can show up
II. Long distance contributions due to charm & light quarks
These contributions can obscure New Physics effects

Golden Modes

		Short distance contribution	Standard Model Branching Ratio	
CPC	$K_L \to \pi^0 \nu\bar{\nu}$	>99 %	$(2.76 \pm 0.40) \cdot 10^{-11}$	Phys.Rev. D76 (2007)
CPV	$K^+ \to \pi^+ \nu\bar{\nu}$	88 %	$(8.22 \pm 0.84) \cdot 10^{-11}$	Phys.Rev. D76 (2007)
CPV	$K_L \to \pi^0 e^+ e^-$	38 %	$(3.54^{+0.98}_{-0.85}) \cdot 10^{-11}$	JHEP (2006)
CPV	$K_L \to \pi^0 \mu^+ \mu^-$	28 %	$(1.41^{+0.28}_{-0.26}) \cdot 10^{-11}$	JHEP (2006)

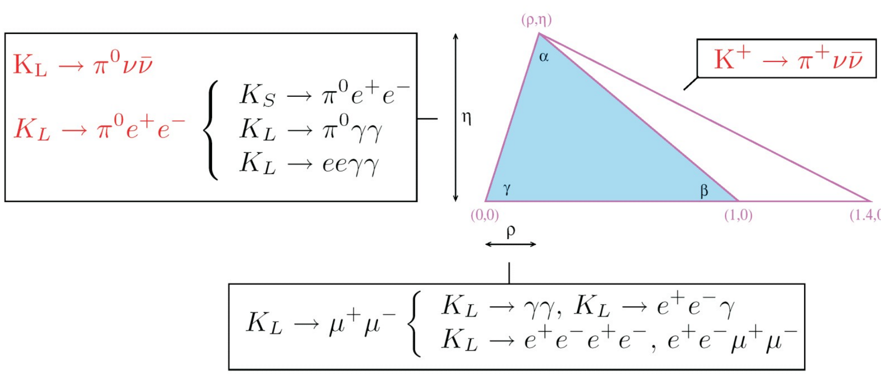


EW short distance amplitude in the SM

... but potentially different BSM

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) \propto \sigma\bar{\eta}^2 + (\rho_c - \bar{\rho})^2$$

$$BR(K^0 \to \pi^0 \nu\bar{\nu}) \propto \bar{\eta}^2$$



PDG08 Review

K → π ν ν Theoretical Status

$$BR(K^+ \to \pi\nu\bar{\nu}(\gamma)) = \kappa_\nu^+(1+\Delta_{EM})|y_\nu|^2 = (8.22 \pm 0.84)\cdot 10^{-11}$$

$$BR(K_L \to \pi^0\nu\bar{\nu}) = \kappa_\nu^L(Imy_\nu)^2 = (2.76 \pm 0.40)\cdot 10^{-11}$$

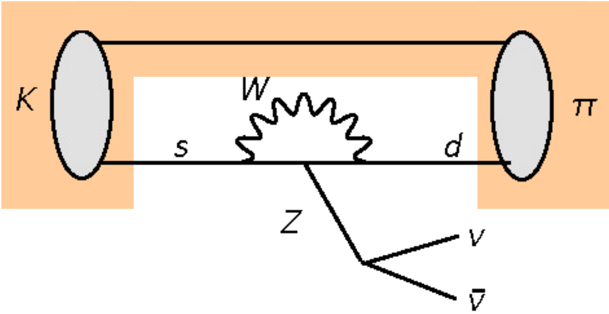
Mescia,Smith PR D76 (2007)

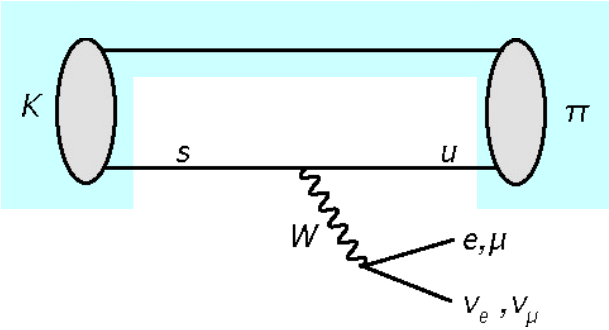
$$SD: y_\nu = \frac{1}{|V_{us}|}\left[(Re\lambda_t + iIm\lambda_t)X_t + (0.2248)^4 Re\lambda_c P_{u,c}\right]$$

$$\lambda_q = V_{qs}^* V_{qd}$$

$$LD: \kappa_\nu^{+,L} = \frac{G_F^2 M_{K^{+,0}}^5 \alpha(M_Z)^2}{256\pi^5 \sin^4\theta_W}\tau_{+,L}|V_{us} \times f_+^{K^{+,0}\pi^{+,0}}(0)|^2 \mathcal{I}_\nu^{+,0}$$

Use K_{l3} to compute κ coeff.





$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto \sigma\bar{\eta}^2 + (\rho_c - \rho)^2$$

$$BR(K^0 \to \pi^0\nu\bar{\nu}) \propto \bar{\eta}^2$$

$$\frac{\sigma(V_{td})}{V_{td}} = \pm 0.41\frac{\sigma(P_c)}{P_c} \sim 1\% \oplus exp$$

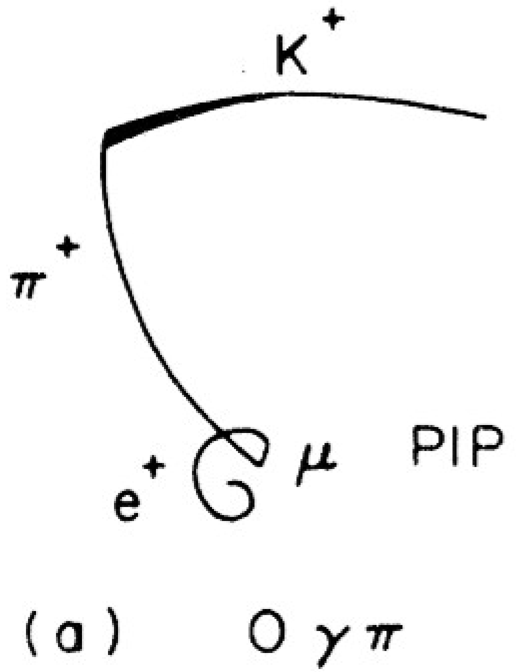
$$\frac{\sigma(\sin 2\beta)}{\sin 2\beta} = \pm 0.34\frac{\sigma(P_c)}{P_c} \sim 0.95\% \oplus exp$$

$$\frac{\sigma(P_c)}{P_c} = 2.8\%$$ NNLO

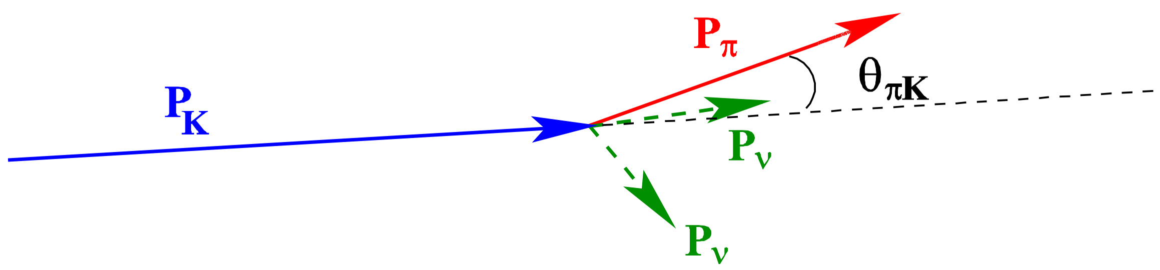
Buras et al. JHEP (2006)

K^+ beam experiments

- K^+ decay at rest
  - Low energy photons
  - Hermeticity
  - Compact experiments
  - ANL and BNL
  - Protons ~ 25 GeV
- K^+ decay in flight
  - Energetic photons
  - Boosted events
  - Long baseline experiments
  - CERN
  - Protons ~400 GeV
  - K+ ~ 75 GeV



Ljung, Cline Phys. Rev (1973)



NA62 proposal (2006)

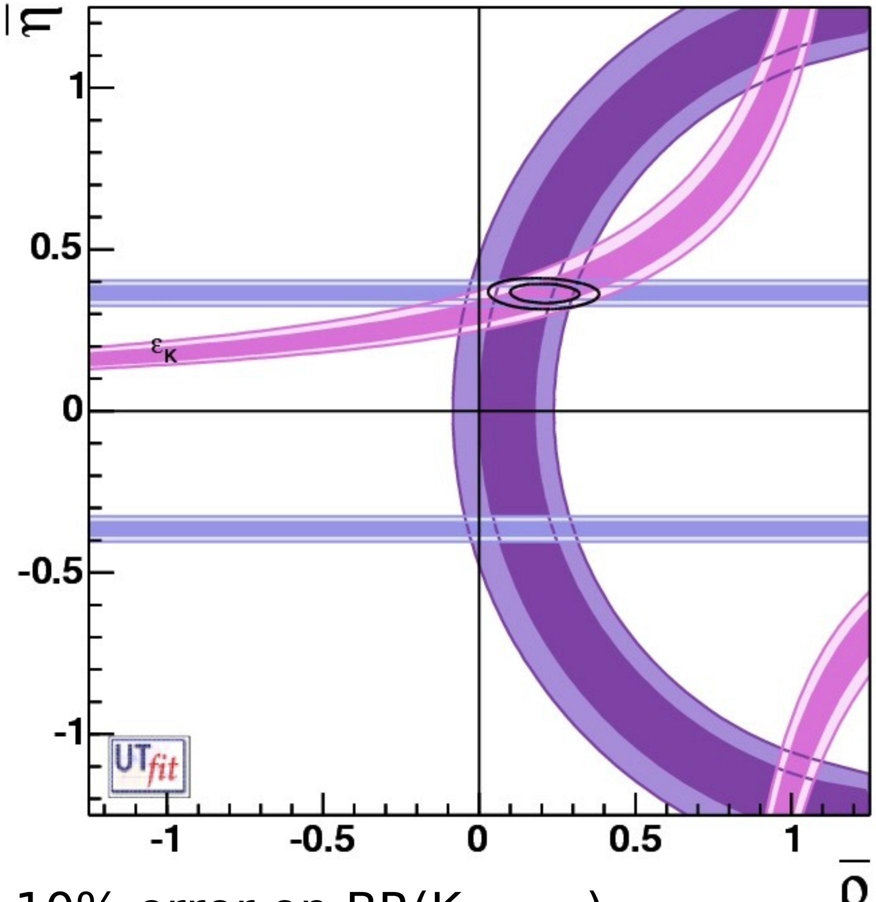
Experimental status $K^+ \to \pi^+ \nu\bar{\nu}$

Year	Lab	Exp	#events	bkg	#K⁺	acc.	BR($K^+ \to \pi^+ \nu\nu$)	Reference
1969	ANL	Bubble Chamber	0	-	206000		< 1.0 x 10^{-4}	PRL 23:326-328,1969
1973	ANL	Bubble Chamber	0	-	367500		< 5.7 x 10^{-5}	PRD 8:1307-1329,1973
1971	BNL	Spark Chamber	0	-			< 1.4 x 10^{-6}	PRD 4:66-80,1971
1973	BNL	Spark Chamber	0	-	1.4 x 10^{9}		<9.4 x 10^{-7} < 5.6 x 10^{-7}	PRD 8:3807-3281,1973
1981	KEK	KEK	0	-	1.49 x 10^{10}		< 1.4 x 10^{-7}	PLB 107:159-1962,1981
1990	BNL	E787/1 (1988)	0+0	-	1.24 x 10^{10}	0.0055	< 3.4 x 10^{-8}	PRL 64:21-24,1990
1993	BNL	E787/1 (1989)	0+0	-	1.12 x 10^{11}	0.0029	< 7.5 x 10^{-9}	PRL 70:2521-2524,1993
1996	BNL	E787/1 (1989-1991)	0+0	0.46	3.49 x 10^{11}	0.0027	< 2.4 x 10^{-9}	PRL 76:1421-1424,1996
1997	BNL	E787/2 (1995)	0+1	0.08±0.03	1.49 x 10^{12}	0.0016	$(4.2^{+9.7}_{-3.5})\times 10^{-10}$	PRL 79:2204-2207,1997
2000	BNL	E787/2 (1995-1997)	0+1	0.08±0.02	3.2 x 10^{12}	0.0021	$(1.5^{+3.4}_{-1.2})\times 10^{-10}$	PRL 84:3768-3770,2000
2002	BNL	E787/2 (1998) E787/2 (1995-1998)	0+1 0+2	$0.066^{+0.044}_{-0.025}$ $0.146^{+0.053}_{-0.039}$	2.7 x 10^{12} 5.9 x 10^{12}	0.0020	$(1.57^{+1.75}_{-0.82})\times 10^{-10}$	PRL 88:04183,2002
2002	BNL	E787/2 (1996)	1+0	0.734±0.177	1.12 x 10^{12}	7.65 x 10^{-4}	< 4.2 x 10^{-9}	PLB 537:211-216,2002
2004	BNL BNL	E787/2 (1997) E787/2 (1996-1997)	0+0 1+0	0.49±0.16 1.22±0.24	0.61 x 10^{12} 1.73 x 10^{12}	9.7 x 10^{-4}	< 2.2 x 10^{-9}	PRD 70:037102,2004
2004/2008	BNL	E949 (2002) E787/E949	0+1 0+3	0.30±0.03 0.44±0.06	1.8 x 10^{12} 7.7 x 10^{12}	0.0022	$(1.47^{+1.30}_{-0.89})\times 10^{-10}$	PRL 93:031801,2004 PRD 77:052003, 2008
2008	BNL BNL	E949 (2002) E787/E949 (1995-2002)	3+0 4+3	$0.93^{+0.36}_{-0.29}$	1.7 x 10^{12} 1.7 x 10^{12} 7.7 x 1012	1.37 x 10^{-3}	$(7.89^{+9.26}_{-5.10})\times 10^{-10}$ $(1.73^{+1.15}_{-1.05})\times 10^{-10}$	PRL 101,191802, 2008

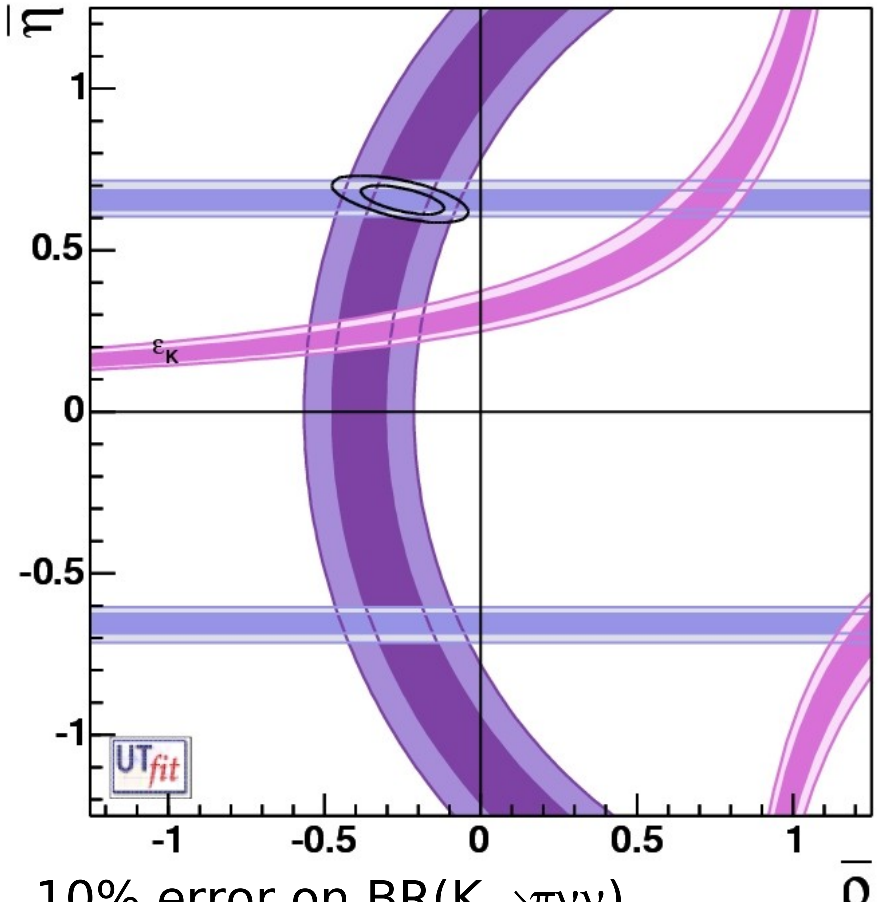
CKM constraints

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$$ E787/E949

$$BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.1 \times 10^{-7} \ \ @90\%CL$$ E391a



10% error on BR(K→πνν)
η,ρ central values

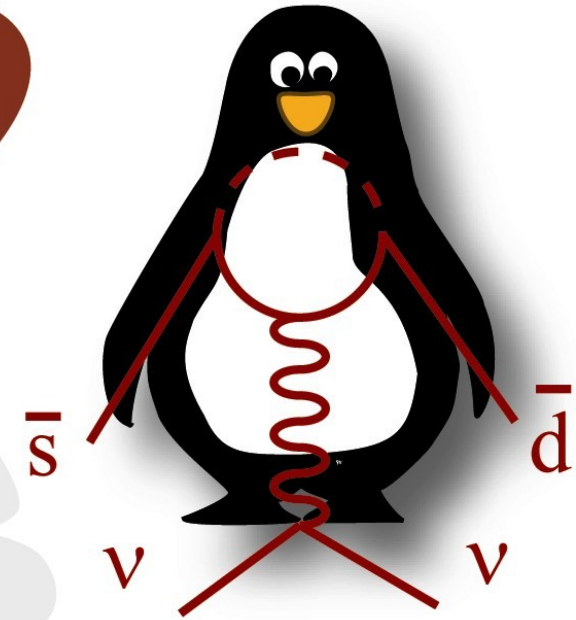


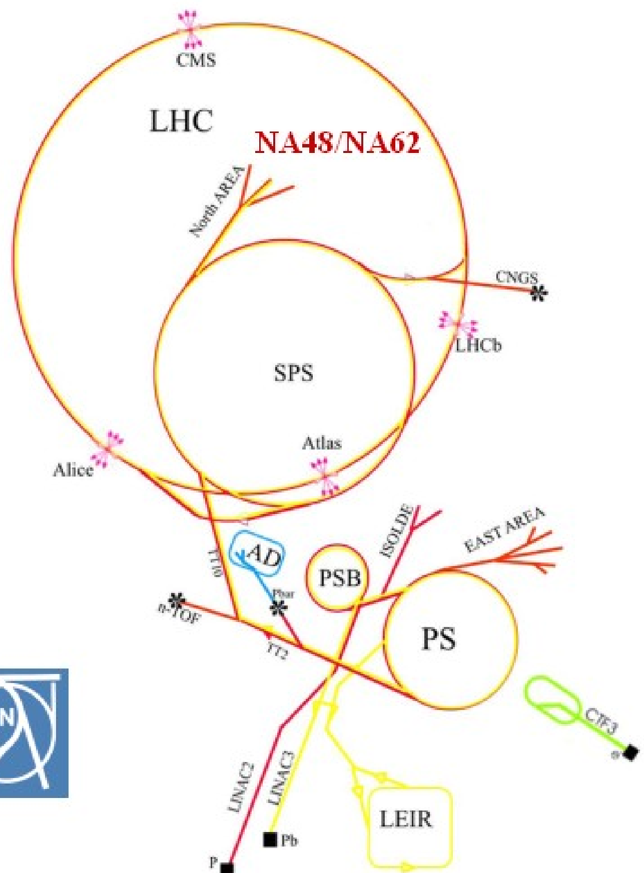
10% error on BR(K→πνν)
η,ρ from exp. values

Rare Kaon decays will not improve the measurement but will provide a powerful consistency check

NA62

P326

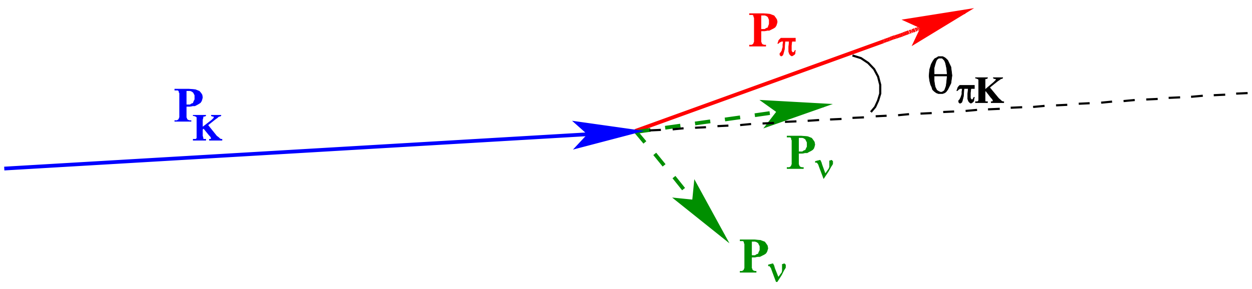




Goal

O(100) $K^+ \to \pi^+ \nu\nu$ events with 10% background

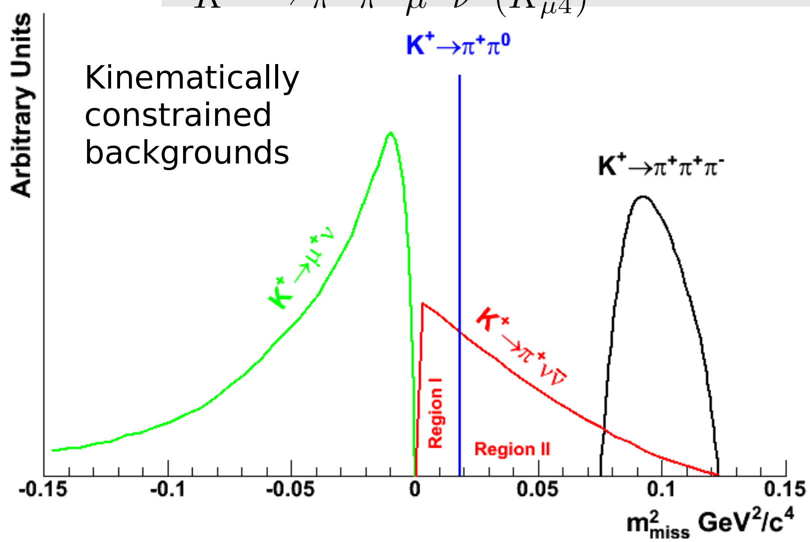
Principle of the measurement



Decay	BR
$K^+ \to \mu^+\nu \ (K_{\mu 2})$	0.634
$K^+ \to \pi^+\pi^0$	0.209
$K^+ \to \pi^+\pi^+\pi^-$	0.056
$K^+ \to \pi^+\pi^0\pi^0$	0.016
$K^+ \to \pi^0 e^+\nu \ (K_{e3})$	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}
$K^+ \to \pi^+\pi^0\gamma$	2.7×10^{-4}
$K^+ \to \pi^+\pi^- e^+\nu \ (K_{e4})$	4.0×10^{-5}
$K^+ \to \pi^+\pi^-\mu^+\nu \ (K_{\mu 4})$	1.4×10^{-5}

1) Kinematical Rejection

$$m^2_{miss} \approx m^2_K \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m^2_\pi \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$$

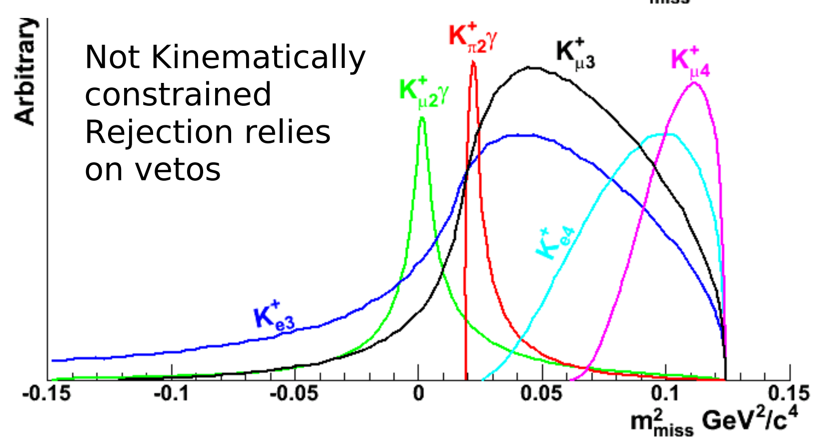


2) Photon vetoes to reject $K^+ \to \pi^+\pi^0$:

$P(K^+) = 75$ GeV/c

Requiring $P(\pi^+) < 35$ GeV/c $\to P(\pi^0) > 40$ GeV/c

It cannot be missed in the calorimeters



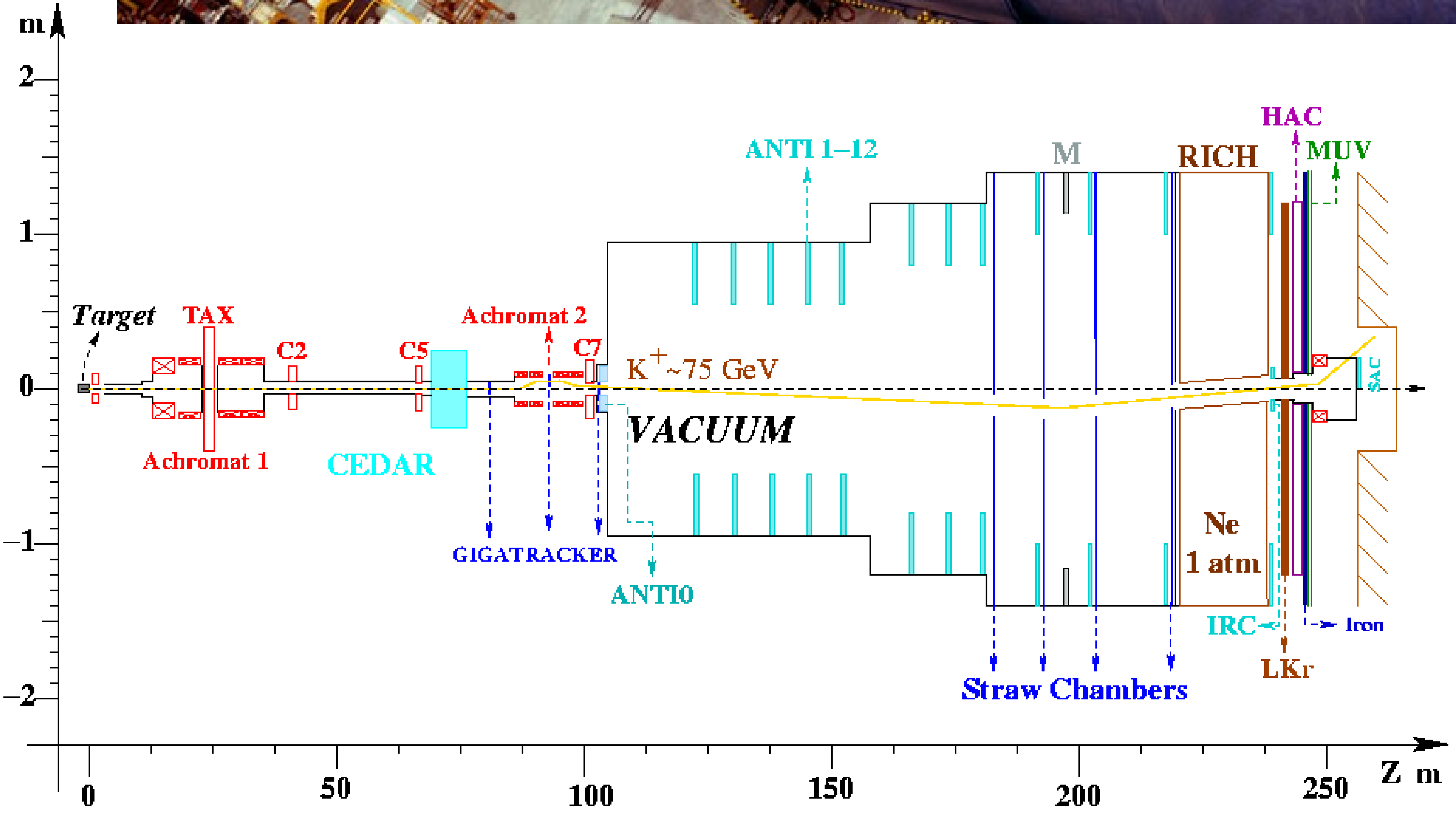
3) PID (RICH) for $K^+ \to \mu^+\nu$ rejection

Region I: $0 < m^2_{miss} < 0.01 GeV^2/c^4$
Region II: $0.026 < m^2_{miss} < 0.068 GeV^2/c^4$

NA62 - Beam

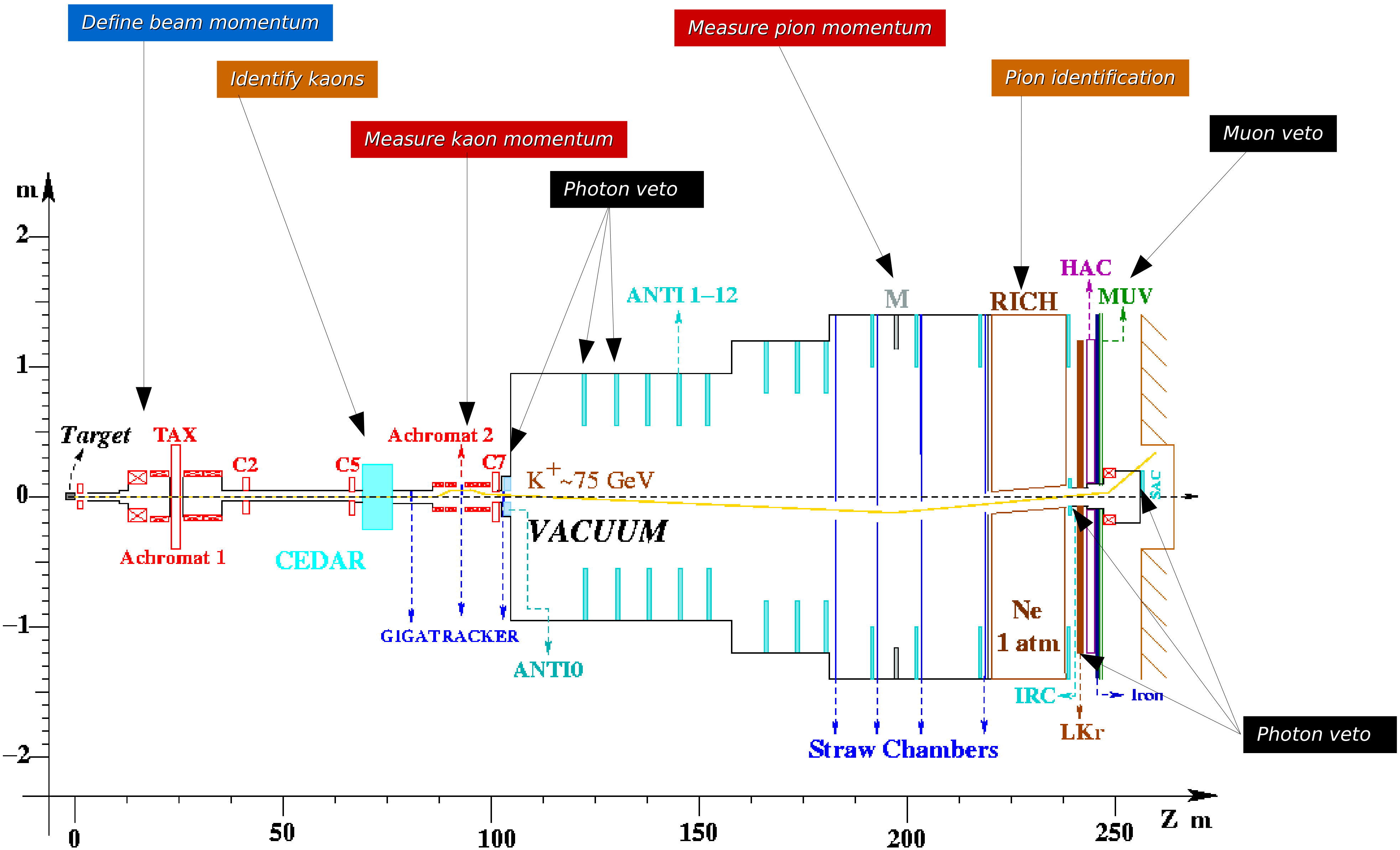
Beam	NA48/2	NA62
SPS protons per pulse	1×10^{12}	3.3×10^{12}
Duty cycle (s /s)	4.8/16	4.8/16
Beam Acceptance H,V (mr)	±0.36	±2.6, ±1.3
Solid Angle (μsterad)	≈0.40	≈12
Central K+ Momentum (GeV/c)	60	75
$\Delta p_K / p_K$	4.0%	1.0%
Beam size (±2 RMS)(cm)	r=1.5 cm	25.9,11.9
Decay fid. Length (m)	50	60
τ_{K+}	0.11	0.11
Beam flux/pulse ($\times 10^7$): protons	0.86	55
K^+	0.31	14.5
π^+	3.32	168.5
e^+,μ^+	0.95	0.1,2
Total beam flux/pulse ($\times 10^7$)	5.5	250
Rate (3s eff. spill length) (MHz)	18	800
Rate in GTK (MHz/cm^2)	2.5	60
Running time/year (days)	120	100
Overall Efficiency	0.5	0.6
Effective number of pulses	3×10^5	3×10^5
K^+ decays per year	1×10^{11}	4.8×10^{12}
$K^+ \to \pi^+ \nu\nu$ Events/year (Bkg)		55 (7-9)

NA62



m
2
1
0
−1
−2
Target
TAX
C2
C5
Achromat 2
C7
K+~75 GeV
Achromat 1
CEDAR
GIGATRACKER
ANTI0
ANTI 1–12
VACUUM
M
RICH
HAC
MUV
SAC
Ne
1 atm
IRC
LKr
Iron
Straw Chambers
0
50
100
150
200
250
Z m

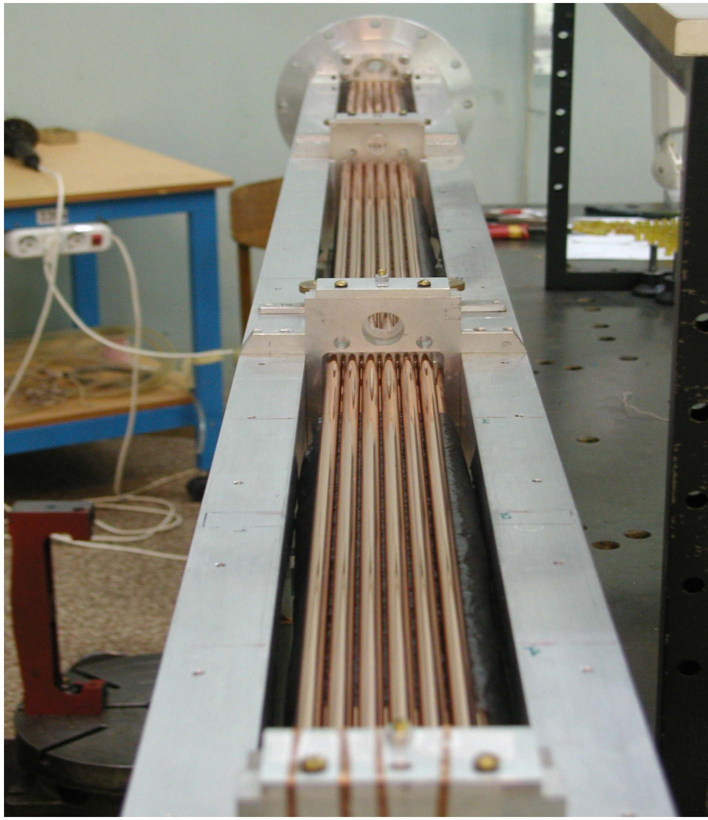
NA62

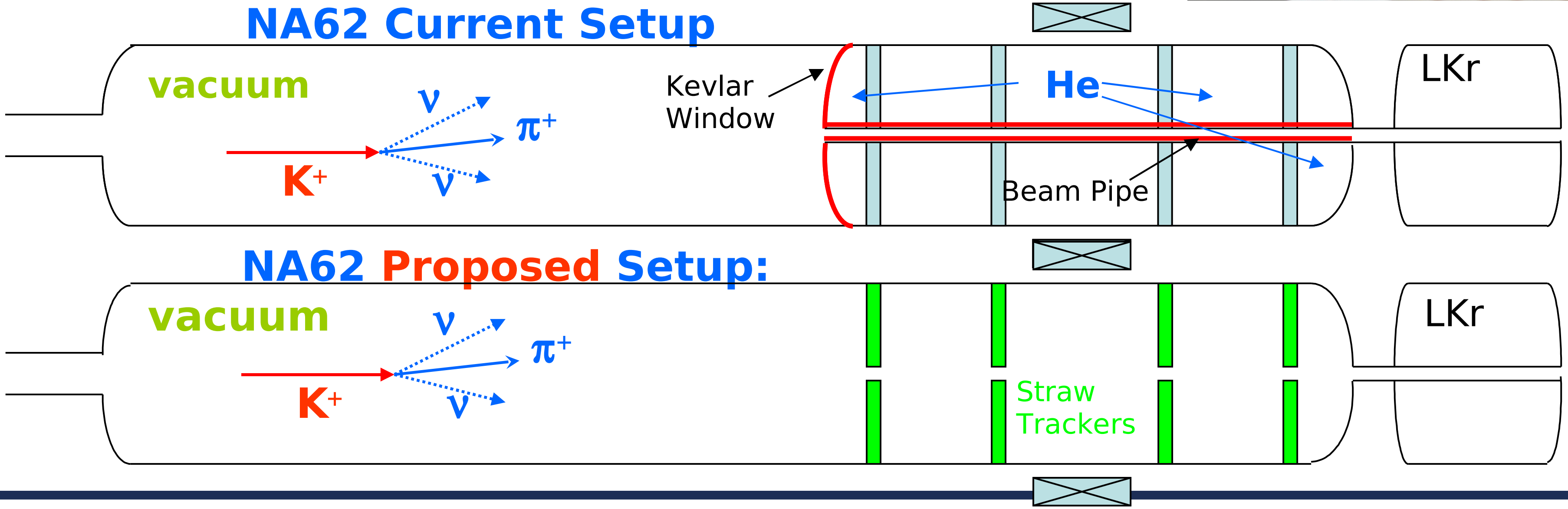


Define beam momentum
Identify kaons
Measure kaon momentum
Photon veto
Measure pion momentum
Pion identification
Muon veto
Photon veto
Target
TAX
Achromat 1
C2
C5
CEDAR
Achromat 2
C7
GIGATRACKER
ANTI0
K+~75 GeV
VACUUM
ANTI 1–12
M
Straw Chambers
RICH
Ne
1 atm
HAC
MUV
SAC
IRC
LKr
Iron
m
2
1
0
−1
−2
0
50
100
150
200
250
Z m

NA62 Detectors - Tracking

- Tracking detectors
  - Gigatracker
    - 3 planes of (300 um x 300 um) pixels
    - ~200 ps time resolution
    - 800 MHz tracking
    - Measure incoming beam momentum
  - Straw tubes
    - 4 planes of straw tubes
    - Replacement of existing spectrometer
      - Removal of Kevlar window
      - Beam pipe inside decay tunnel



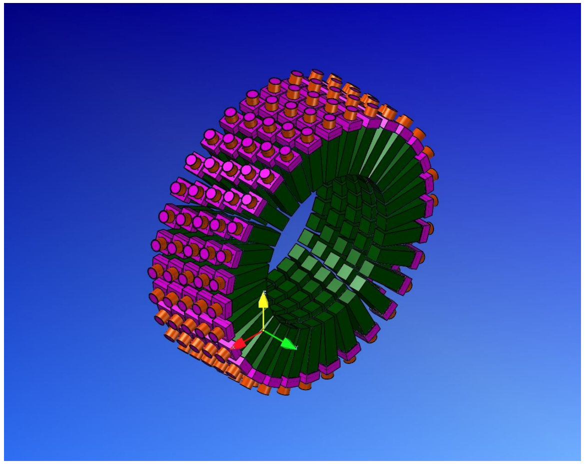


NA62 Detectors – Particle Id

- CEDAR – Differential Cerenkov
  - Incoming K+ identification
    - 50 MHz
  - Same CEDAR built for SPS in 70's
    - Substitution of radiator: H instead of He
    - New readout system: SiPM
- RICH
  - π id (p>15 GeV/c),e,μ separation
  - 2000 phototubes (~1cm diameter). Main limitation for cerenkov angle measurement
  - 17 m radiator (Ne)
  - Beam pipe to let pass non decaying beam
  - Segmented mirror
  - Prototype with 400 PM to be tested in 2009

NA62 Detectors" Photon Vetos

- Rejection of $K^+ \to \pi^+\pi^0$ @ 10^{-12}
  - 10^4 factor achieved by kinematical cuts (K^+,π^+)
  - $\eta < 10^{-4}$ for LAV
  - $\eta < 10^{-5}$ for LKR
  - $\eta < 10^{-6}$ for SAC/IRC

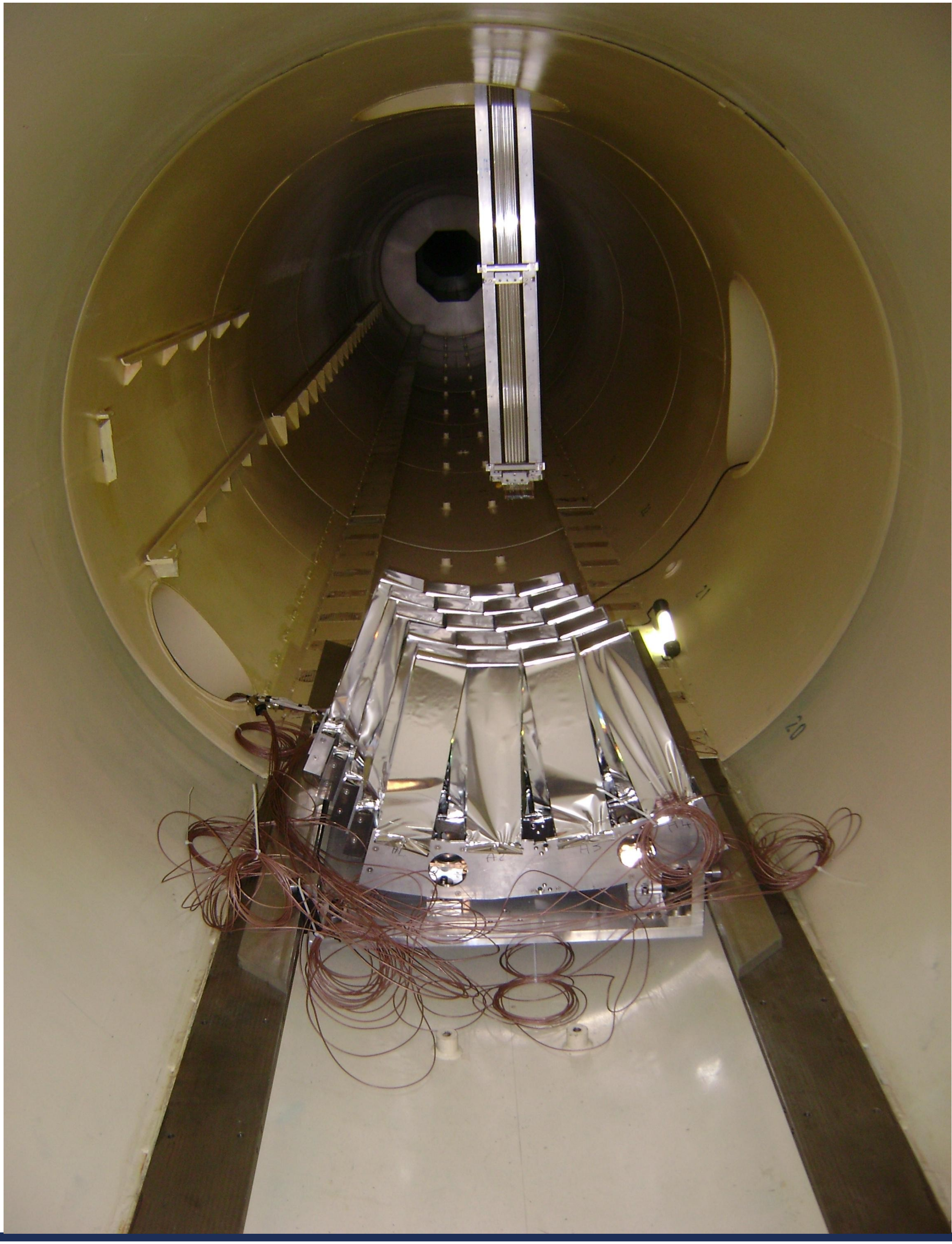


	Angular coverage	Energy range	Inefficiency
Large Angle Vetos	8.5 mr – 50 mr	>10 MeV	1.2×10^{-4} (200 MeV) 1.1×10^{-5} (500 MeV)
Liquid Krypton	1 mr -8.5 mr	>1 GeV	<10-3 [2.5,5.5] GeV $<10^{-4}$ [2.5,5.5] GeV $<1.1 \times 10^{-5}$ [7.5,10.0] GeV $<8.0 \times 10^{-6}$ >10 GeV
Intermediate Ring Calorimeter Small Angle Calorimeter	<1 mr	>6 GeV	$<6.4 \times 10^{-5}$ Limited by stat.

Good photon vetos open possibility to convert NA62 in a $K^0 \to \pi^0\nu\nu$ experiment

NA62 schedule

- 2005: P-326
  - Proposal to SPSC CERN-SPSC-2005-013
- 2007/8: NA62
  - Measurement of $R_K = K_{e2}/K_{\mu2}$.
  - Test beams (LAV,STRAW)
    - Postponed to 2009 due to LHC incident/accident



NA62 schedule

- 2005: P-326
  - Proposal to SPSC

Experiment approved by SPSC in Dec 5, 2008

  - Postponed to 2009 due to LHC incident/accident
- 2009:
  - Prototypes test beams
    - LAV,RICH,STRAWS
    - GTK
- 2010-11:
  - Construction
- End 2011:
  - START DATA TAKING

Status R_K

SM theoretical predictions

$$R_\pi = (1.2352 \pm 0.0001) \times 10^{-4}$$

$$R_K = (2.472 \pm 0.001) \times 10^{-5}$$

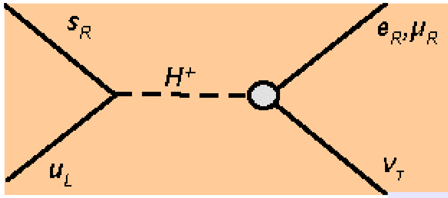
$$\delta R_K = -0.0378 \pm 0.0004$$

$$\Delta R_K / R_K = 0.04\%$$

M. Finkemeier PLB 387 (1996)

$$R_M = \frac{\Gamma(M \to e\nu(\gamma))}{\Gamma(M \to \mu\nu(\gamma))} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{1-\left(\frac{m_e}{m_M}\right)^2}{1-\left(\frac{m_\mu}{m_M}\right)^2}\right)^2 \times (1+\delta R_M)$$

$$R_K^{LFV} = \frac{\Sigma_i K \to e\nu_i}{\Sigma_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to e\nu_e)}$$

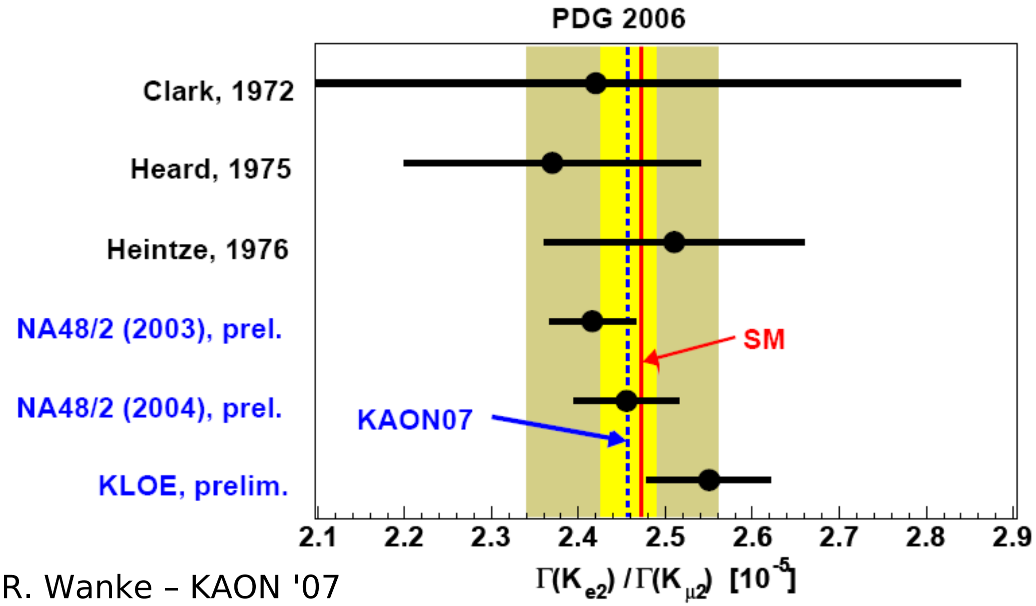


Masiero,Paradisi,Petronzio
PRD 74 (2006)

Experimental situation (PDG)

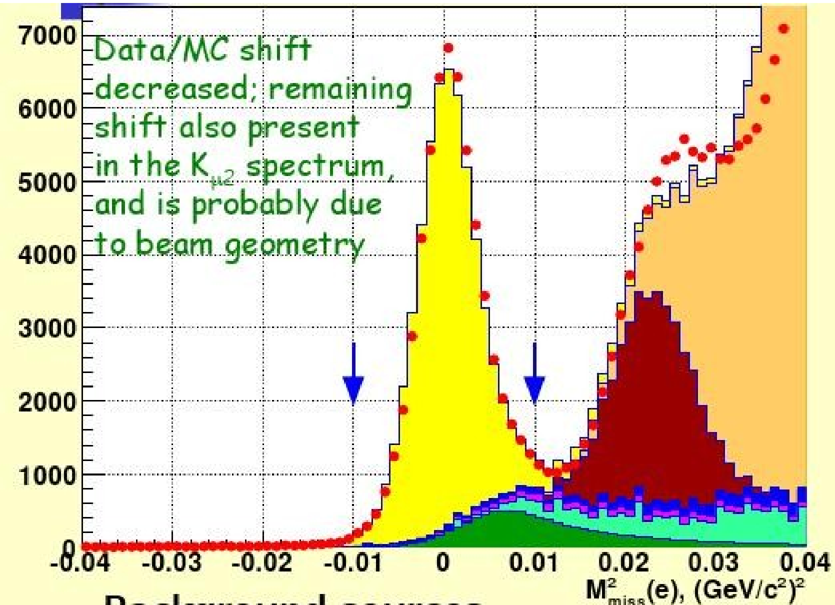
$$R_K = (2.45 \pm 0.11) \times 10^{-5}$$

$$\Delta R_K / R_K = 4.5\%$$



R. Wanke – KAON '07

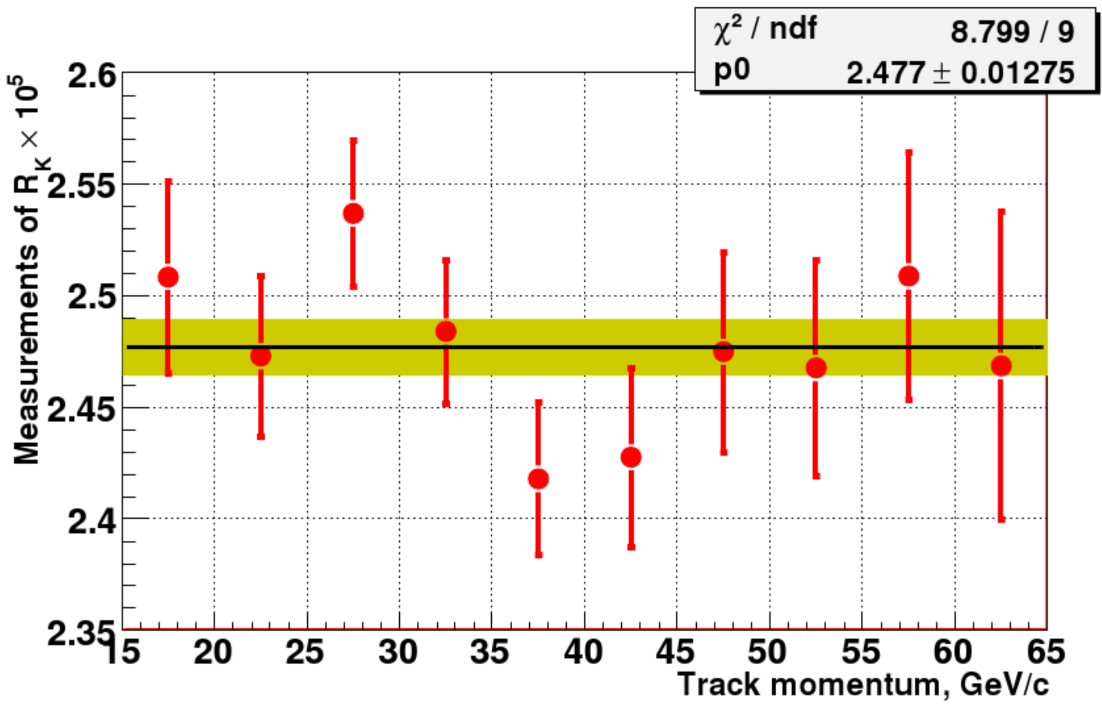
- KLOE + NA48/2 + PDG
  - RK = $(2.457 \pm 0.032) \times 10^{-5}$
  - $\Delta R_K/R_K$=1.3% (stat.)
- NA62 (2007/8)
  - ~160000 K_{e2} candidates
    - 2003 and 2004 ~4000 ev.
  - $\Delta R_K/R_K$=0.3% (stat.)
  - $\Delta R_K/R_K$=0.5% (incl. Syst.)



<u>Background sources</u>

$K_{\mu 2}$	(7.87±0.20)%
$K_{\mu 2}$ ($\mu \to e$ decay)	(1.53±0.25)%
$K_{e2\gamma}$ (SD+)	(1.25±0.31)%
Beam halo	(1.23±0.07)%
$K_{2\pi}$	0.08%
K_{e3}	0.03%

- NA62 (2007/8)
  - ~160000 K_{e2} candidates
    - 2003 and 2004 ~4000 ev.
  - $\Delta R_K/R_K$=0.3% (stat.)
  - $\Delta R_K/R_K$=0.5% (incl. Syst.)
  - Results will be published "soon"



Conclusions

- There is again an interest in flavor physics in Kaon system
  - Improvement in theoretical calculations.
  - Evolution of detection techniques will give access to rare decays ~10^{-12}
- New Physics should show up in loops
  - Golden modes: Rare Kaon Decays
    - $K \to \pi\nu\nu$ and $K_L \to \pi^0 l^+ l^-$
- Experimental program at different labs
  - NA62 @ SPS: $K^+ \to \pi^+ \nu\nu$
    - Based on NA48 experience. Measurement of R_K
    - Data taking foreseen for end 2011!!!
    - Experimental program is not reduced to one channel
- NA62 opens a new series of Rare K Decays experiments
  - 2012-2015: NA62 100 $K^+ \to \pi^+ \nu\nu$
  - >2015: NA62/2 1000 $K^+ \to \pi^+ \nu\nu$
    NAxx $K^0 \to \pi^0 \nu\nu$ experiment

Backup

$K \to \pi \nu \nu$ Theoretical Status

$$BR(K^+ \to \pi\nu\bar{\nu}(\gamma)) = \kappa_\nu^+ (1+\Delta_{EM})|y_\nu|^2 = (8.22 \pm 0.84)\cdot 10^{-11}$$

$$BR(K_L \to \pi^0\nu\bar{\nu}) = \kappa_\nu^L (Imy_\nu)^2 = (2.76 \pm 0.40)\cdot 10^{-11}$$

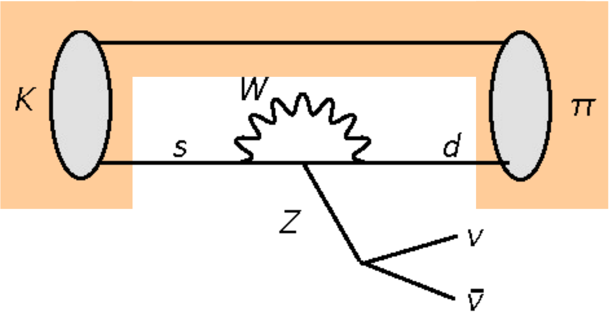
Mescia,Smith PR D76 (2007)

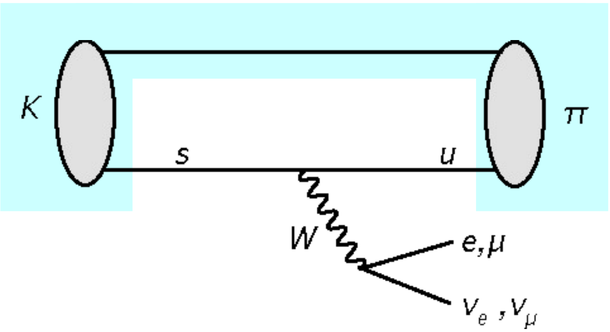
$$SD: y_\nu = \frac{1}{|V_{us}|}\left[(Re\lambda_t + iIm\lambda_t)X_t + (0.2248)^4 Re\lambda_c P_{u,c}\right]$$

$$\lambda_q = V_{qs}^* V_{qd}$$

$$LD: \kappa_\nu^{+,L} = \frac{G_F^2 M_{K^{+,0}}^5 \alpha(M_Z)^2}{256\pi^5 \sin^4\theta_W}\tau_{+,L}|V_{us} \times f_+^{K^{+,0}\pi^{+,0}}(0)|^2 \mathcal{I}_\nu^{+,0}$$

Use K_{l3} to compute κ coeff.





$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto \sigma\bar{\eta}^2 + (\rho_c - \rho)^2$$

$$BR(K^0 \to \pi^0\nu\bar{\nu}) \propto \bar{\eta}^2$$

$$\frac{\sigma(V_{td})}{V_{td}} = \pm 0.41 \frac{\sigma(P_c)}{P_c} \sim 1\% \oplus exp$$

$$\frac{\sigma(\sin 2\beta)}{\sin 2\beta} = \pm 0.34 \frac{\sigma(P_c)}{P_c} \sim 0.95\% \oplus exp$$

Buras et al. JHEP (2006)

$$\frac{\sigma(P_c)}{P_c} = 2.8\%$$ NNLO

CKM matrix

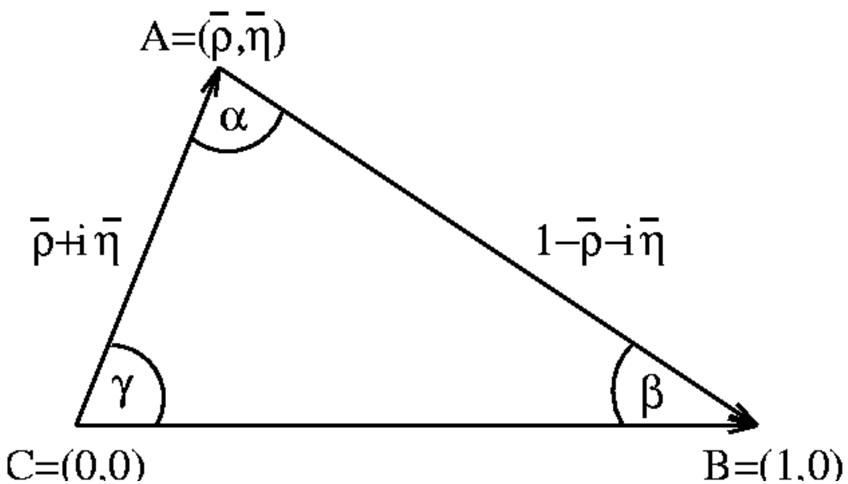
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho+i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$V^\dagger V = V V^\dagger = 1$$

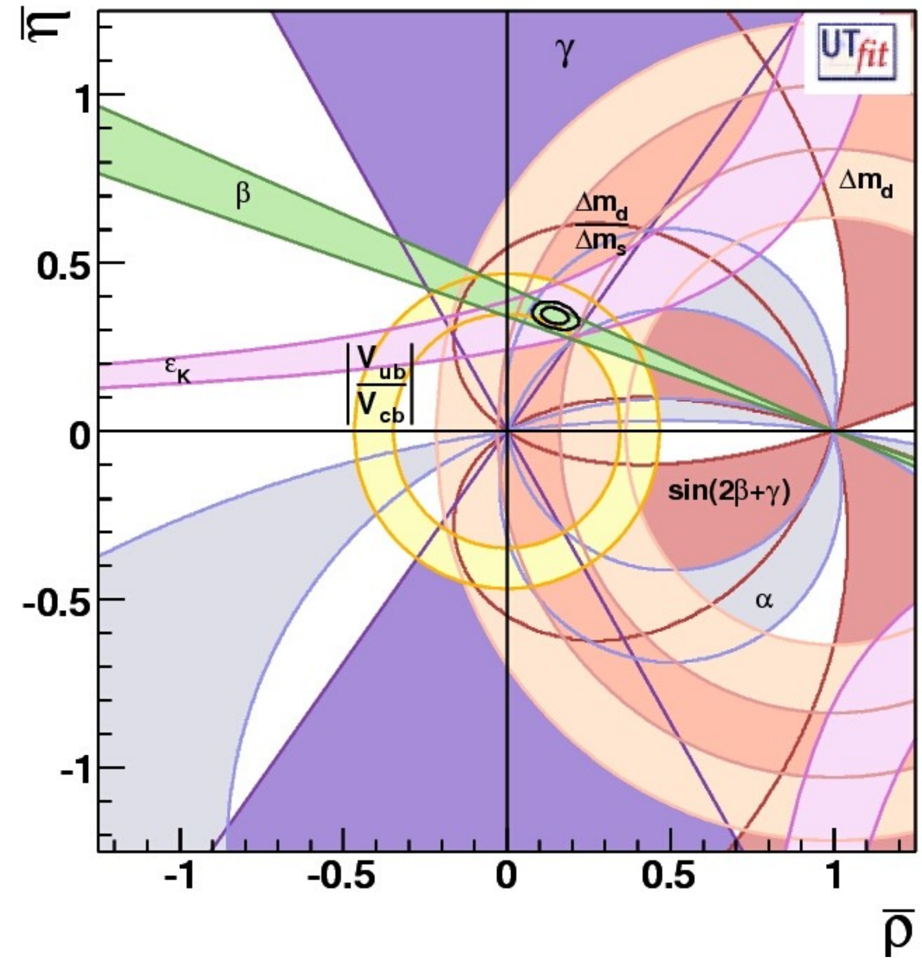
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$\bar\rho = \rho\left(1-\frac{\lambda^2}{2}\right) \qquad \bar\eta = \eta\left(1-\frac{\lambda^2}{2}\right)$$

$$V_{ud}V_{ub}^* = A\lambda^3(\bar\rho + i\bar\eta)$$
$$V_{td}V_{tb}^* = A\lambda^3(1-\bar\rho - i\bar\eta)$$
$$V_{cd}V_{cb}^* = -A\lambda^3$$

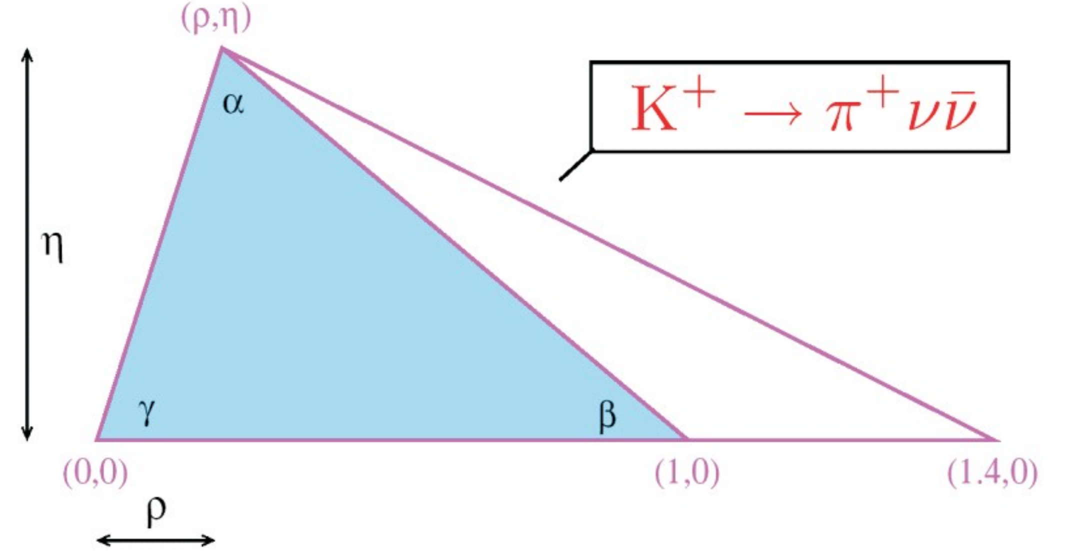


$\bar\rho = 0.147 \pm 0.029$ $\bar\eta = 0.342 \pm 0.016$



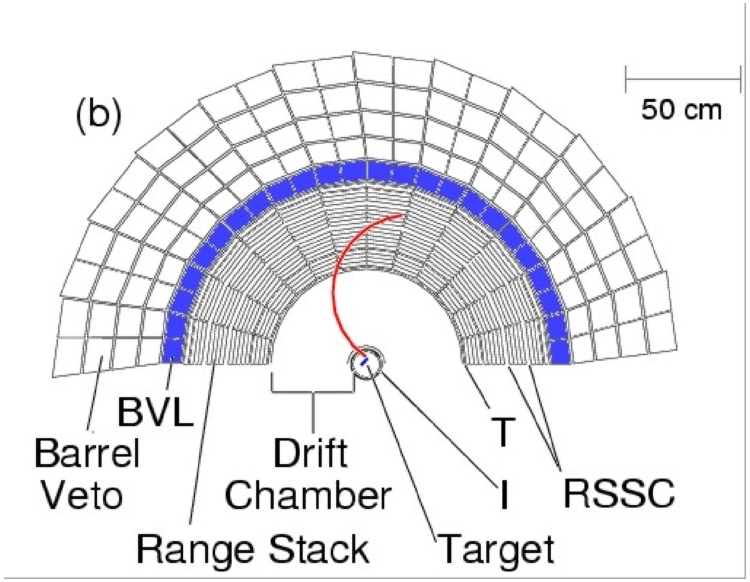
$K_L \rightarrow \pi^0 \nu \bar{\nu}$

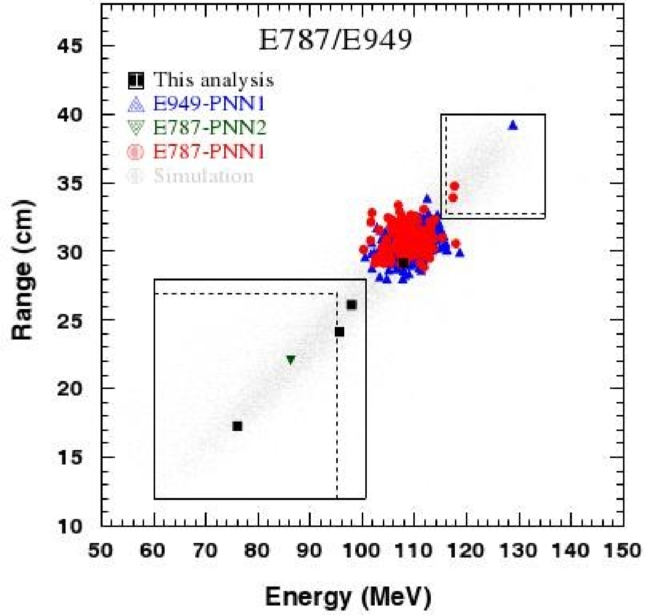
$K_L \rightarrow \pi^0 e^+ e^-$
$$\begin{cases} K_S \rightarrow \pi^0 e^+ e^- \\ K_L \rightarrow \pi^0 \gamma\gamma \\ K_L \rightarrow ee\gamma\gamma \end{cases}$$

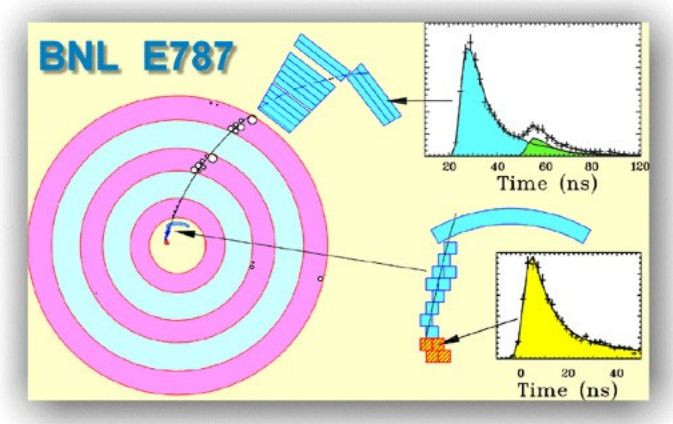


$$K_L \rightarrow \mu^+ \mu^- \begin{cases} K_L \rightarrow \gamma\gamma,\ K_L \rightarrow e^+ e^- \gamma \\ K_L \rightarrow e^+ e^- e^+ e^-,\ e^+ e^- \mu^+ \mu^- \end{cases}$$

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







Region 2 — 2 events in E787, 1 events in E949

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$

Phys. Rev. D77 052003(2008)

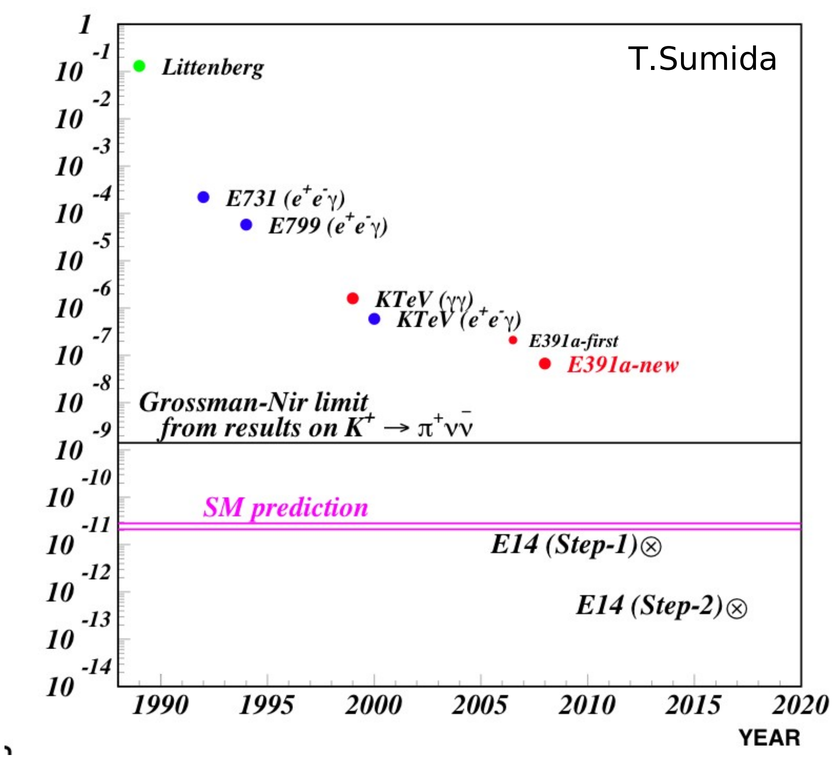
Region 1 — 1 events in E787, 3 events in E949

Region 2 — 2 events in E787, 1 events in E949

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

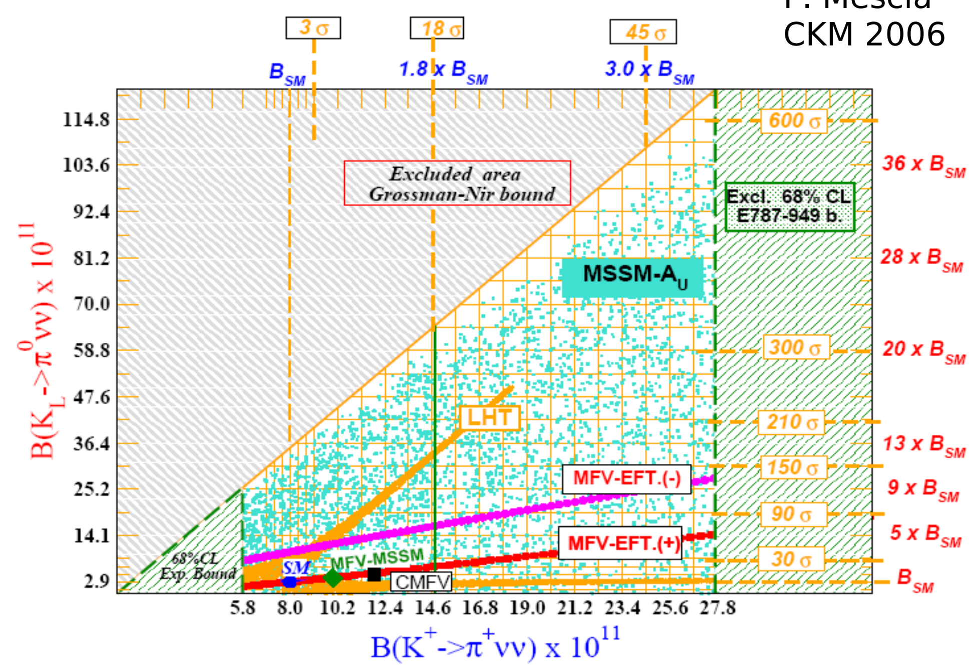
Phys. Rev. Let. 101 191802 (2008)

- No events found so far
- Dedicated experiment for this channel (KOPIO) was not approved by BNL.
  - Expected to have 40-60 events (SM)



Grossman,Nir (1997)

$$BR(K_L \to \pi^0 \nu \bar{\nu}) < 4.4 \times BR(K^+ \to \pi^+ \nu \bar{\nu})$$

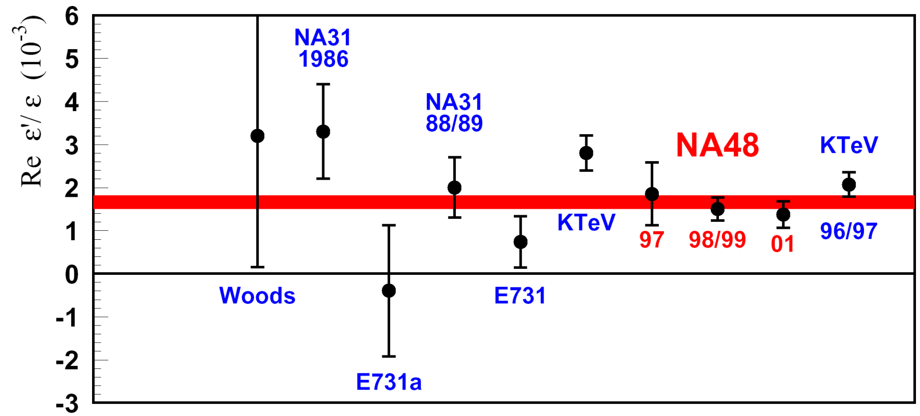


From NA48 to NA62

NA48	**ε'/ε**	1997	
	ε'/ε	1998	
	ε'/ε	1999	
no spectrometer K_L	NA48/1 K_S	2000	
lower inst. intensity	**ε'/ε**	2001	
NA48/1	K_S	2002	$K_s^0 \to \pi^0 e^+ e^-$ PLB 576 (2003) 43; $K_s^0 \to \pi^0 \mu^+ \mu^-$ PLB 599 (2004) 197
NA48/2:	$K^{\pm}$	2003	ππ scattering PLB 633 (2006) 173; Search for Direct CP-Violation in charged kaon decays EPJ C52 (2007) 875
	$K^{\pm}$	2004	
NA62: μ - e universality	K^+	2007	$R_K = \frac{\Gamma(K^+ \to e^+\nu(\gamma))}{\Gamma(K^+ \to \mu^+\nu(\gamma))}$
μ - e universality	K^+	2008	
Rare Kaon decays	$K^{\pm,0}$	……	$K^+ \to \pi^+ \nu\bar{\nu}$; $K^0 \to \pi^0 \nu\bar{\nu}$

1997–2001:

$$\frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} = 1 - 6Re(\epsilon'/\epsilon)$$



NA62 detectors

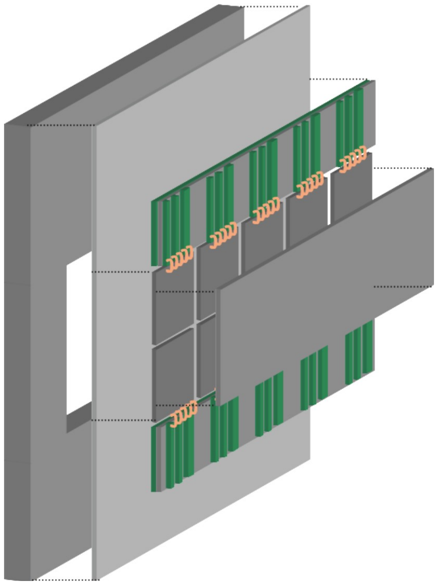
Detector	Function	Status	
CEDAR	•Event by event K^+ identification (50 MHz)	•CEDAR Exists •To be modified for H_2 •Needs New Front end •Needs New Read – out	Birmingham
GTK	•Gigatracker for beam tracking •Three Stations of Si pixels 300x300 μm •~200 ps per station time resolution •0.5 % radiation length per station •800 MHz beam	•Sensor qualified after irradiation •0.13 μm CMOS front end blocks under test •Next step: 8 x 8 pixel array (bump bonded to R/O chip)	CERN Ferrara Torino Louvain
LAV	•12 Ring Calorimeters for photon detection •Chosen solution: OPAL lead glass	•Performed prototype beam tests •Design of Mechanics under way	Frascati Pisa Roma 1 Naples
STRAW	•4 Large (6 m^2) straw tracker stations to track ~10 MHz particles from kaon decays	•Full length prototype beam tested inside actual vacuum tank	CERN Dubna Mainz

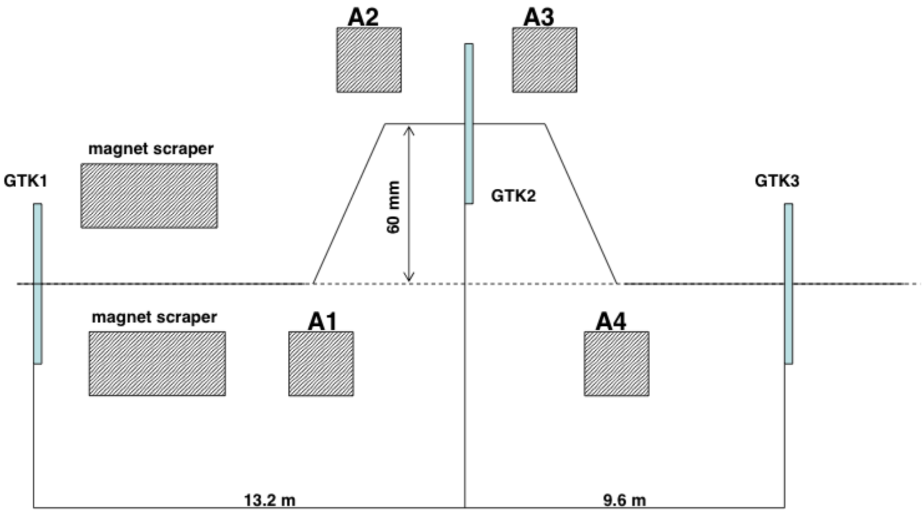
NA62 detectors

Detector	Function	Status	Current Collaboration
RICH	•Pion muon separation 17 m STP Ne radiator: $(n-1)\times10^6=63$ •Spherical mirrors (r.c. 34 m) ~2000 Hamamatsu R7400 06 (18 mm ø) •Fast timing of the outgoing charged track	•Full length prototype (96 PMT) tested Oct-Nov '07 •Timing demonstrated •400 PMT prototype to be tested in 2008	CERN Florence Merced Perugia San Luis Potosi George Mason Stanford
LKR	NA48 Liquid Krypton Calorimeter for forward photon. 20 tons of liquid krypton. Available!	•Validated as veto •New cryogenics installed in 2007 •Electronics to be updated/replaced	CERN Pisa Roma II
MUD	•Muon Detector based on the NA48 Hadron Calorimeter + iron and a fast veto plane for triggering	•Sample tested this year	Protvino Moscow (INR)
IRC/SAC	•Intermediate Ring and Small Angle Calorimeter to detect photons at small angle	•Shashlik prototype (SAC) tested in 2006	Sofia JINR

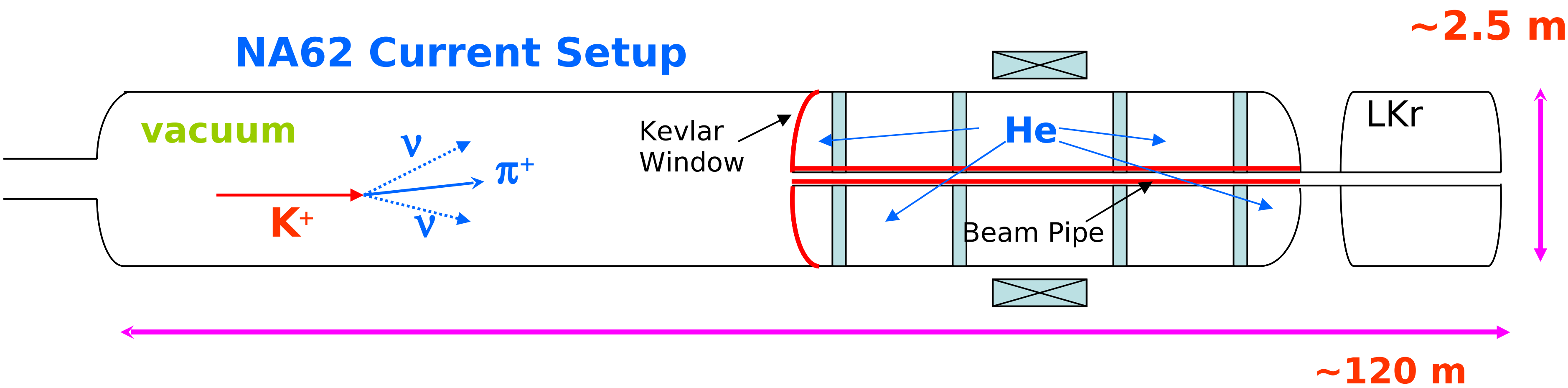
Gigatracker

Number of stations	3
Dimensions	60 mm x 27 mm
Number of pixels per station	18000
Number of chips per station	2 rows x 5 columns
Number of pixels per chip	1800
Size of pixels	300 µm x 300 µm
Thicknes of sensor	200 µm
Thicknes of readout chip	100 µm
Time resolution of GTK (rms)	150 ps
Time resolution of one station (rms)	200 ps
Particle rate per station	800 MHz
Average particle intensity per station	0.5 MHz/mm^2
Design particle rate per chip	130 MHz
Latency	>1 µs up to 1 ms
Tirgger window	≥ 10 ns
Dead time due to read out	1% (2% in beam center)
Time stamp resolution	< 200 ps
Fluence in 1 year	≈ 2 x 10^{14} (1 MeV n cm^{-2})
Total dose in 1 year	≈ 10^5 Gy
Material budget	0.5% X_0 per station
Power dissipation per station	≤ $2W/cm^2$, 32 W
Operating temperature vacuum	< 0 °C



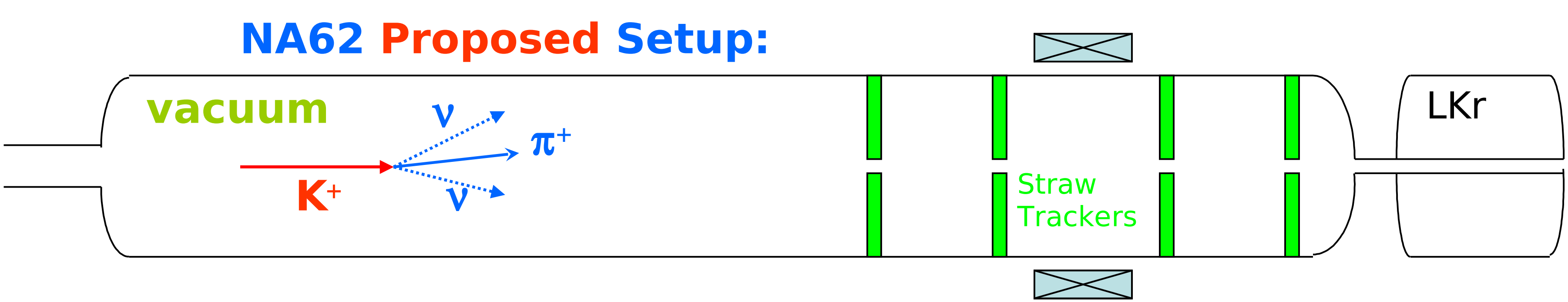


Straw Tracker



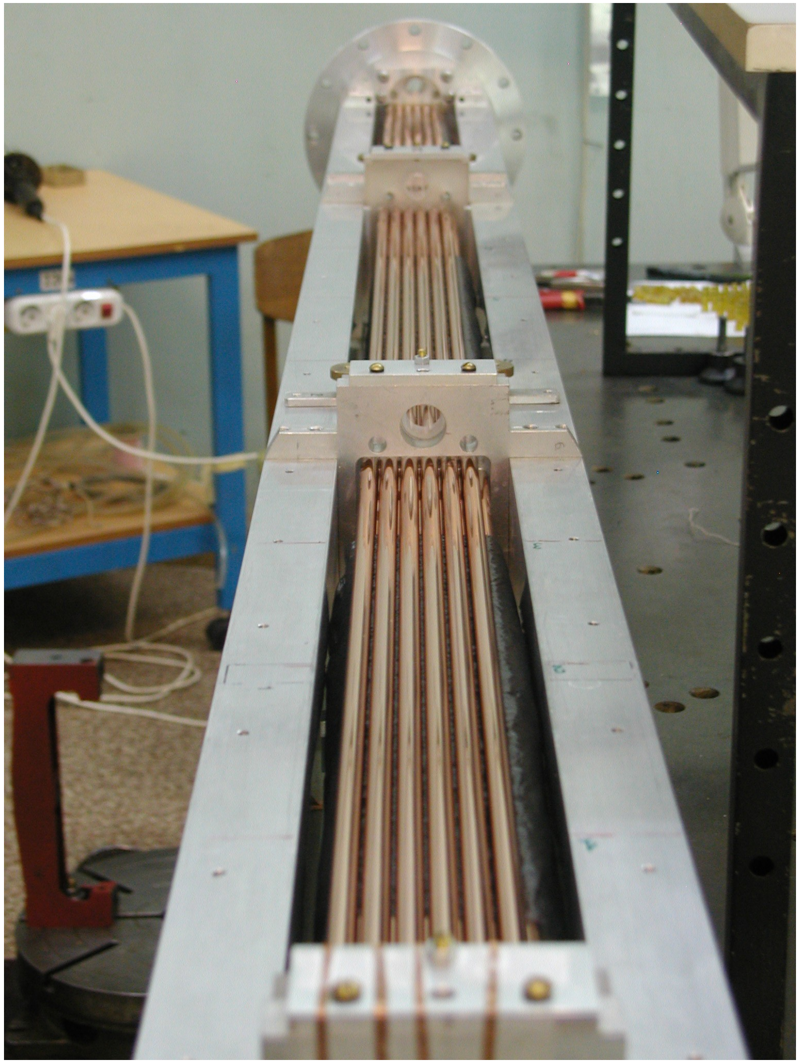
Straw Trackers operated in vacuum would enable us to:

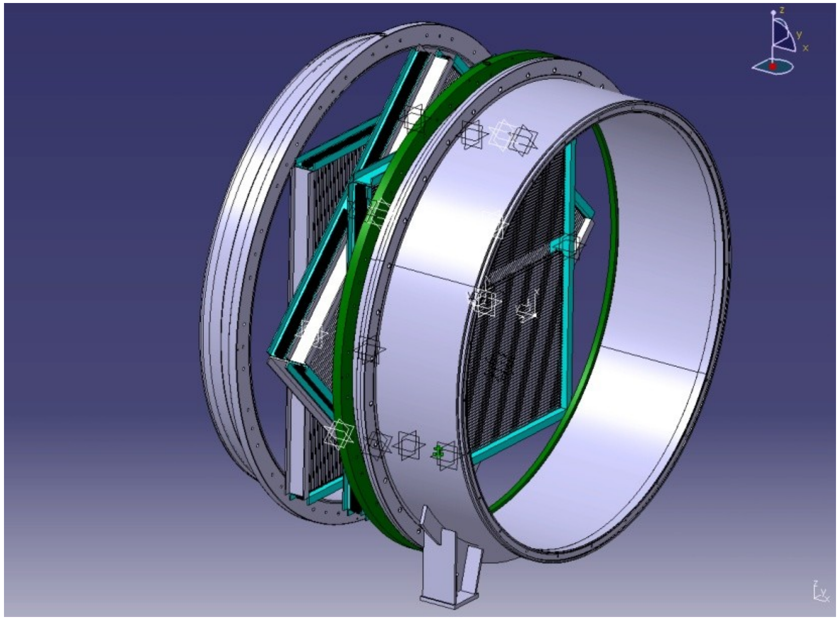
- **Remove the multiple scattering due to the Kevlar Window**
- **Remove the acceptance limitations due to the beam-pipe**
- **Remove the helium between the chambers**

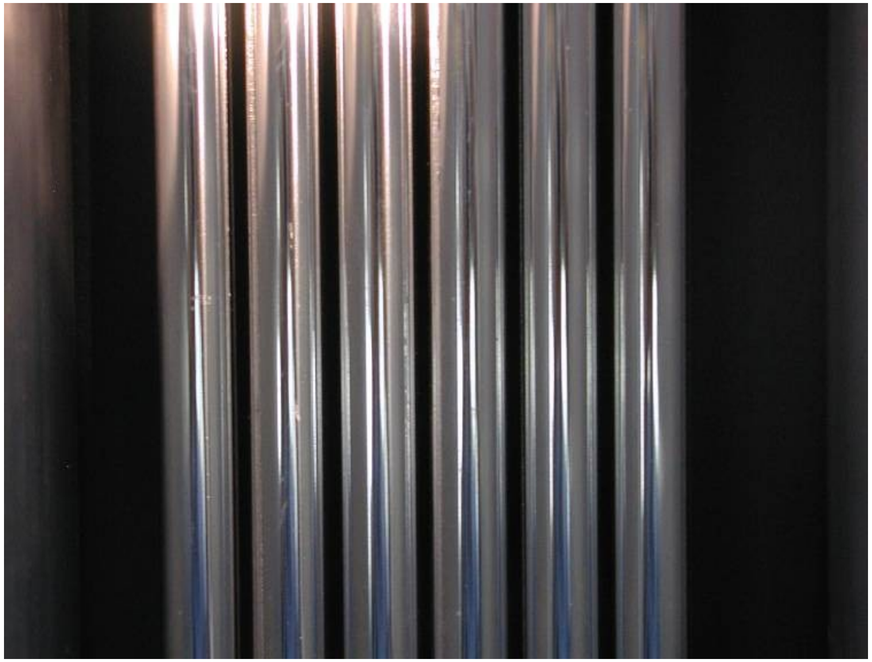


- **The Straw Tracker is essential to study ultra-rare-decays!**

Straw Tracker

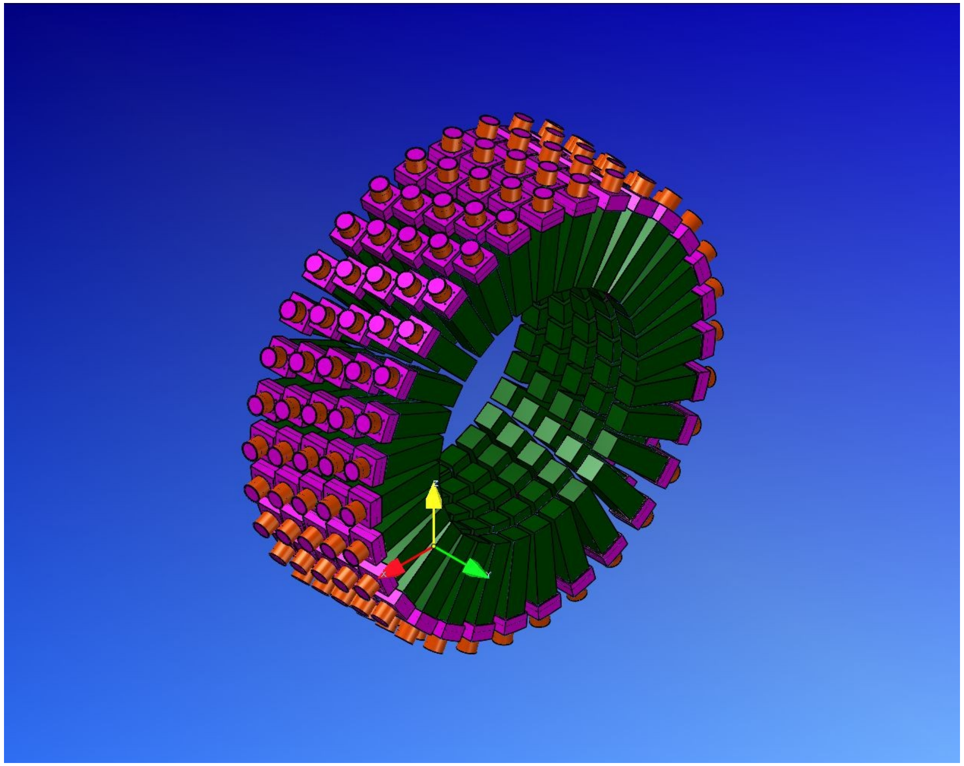






Photon Vetos

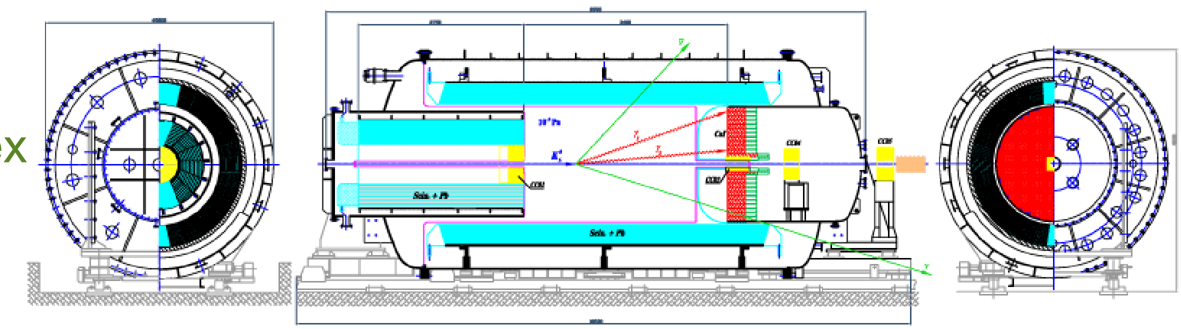
- Rejection of $K^+ \to \pi^+\pi^0$ @ 10^{-12}
  - 10^4 factor achieved by kinematical cuts (K^+,π^+)
  - $\eta < 10^{-4}$ for LAV
  - $\eta < 10^{-5}$ for LKR
  - $\eta < 10^{-6}$ for SAC/IRC
- Good photon vetos open posibility to convert NA62 in a $K^0 \to \pi^0 \nu\nu$ experiment

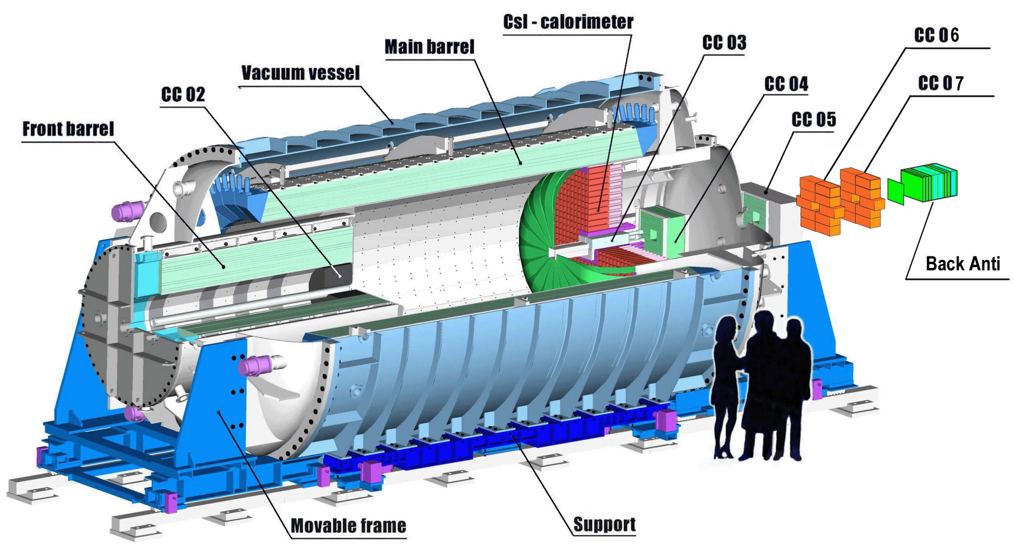


	Angular coverage	Energy range	Inefficiency
Large Angle Vetos	8.5 mr – 50 mr	>10 MeV	1.2×10^{-4} (200 MeV) 1.1×10^{-5} (500 MeV)
Liquid Krypton	1 mr -8.5 mr	>1 GeV	<10-3 [2.5,5.5] GeV $<10^{-4}$ [2.5,5.5] GeV $<1.1 \times 10^{-5}$ [7.5,10.0] GeV $<8.0 \times 10^{-6}$ >10 GeV
Intermediate Ring Calorimeter Small Angle Calorimeter	<1 mr	>6 GeV	$<6.4 \times 10^{-5}$ Limited by stat.

E391a @ KEK $K^0 \to \pi^0 \nu \bar{\nu}$

- E391a: First experiment dedicated to $K^0 \to \pi^0 \nu\nu$ (KEK)
  - Taking data since 2004
- Pencil beam (12 μsterad)
  - 12 GeV protons $\to$ 2 GeV K^0
- Detector with complete veto system
  - 4π coverage with thick calorimeter
  - Require 2 photons
    - Measure energy and direction
    - Reconstruct π^0 mass and vertex
  - High miss P_T selection
- Step by step approach
  - KEK-PS E391a
  - JPARC E14
- No events found



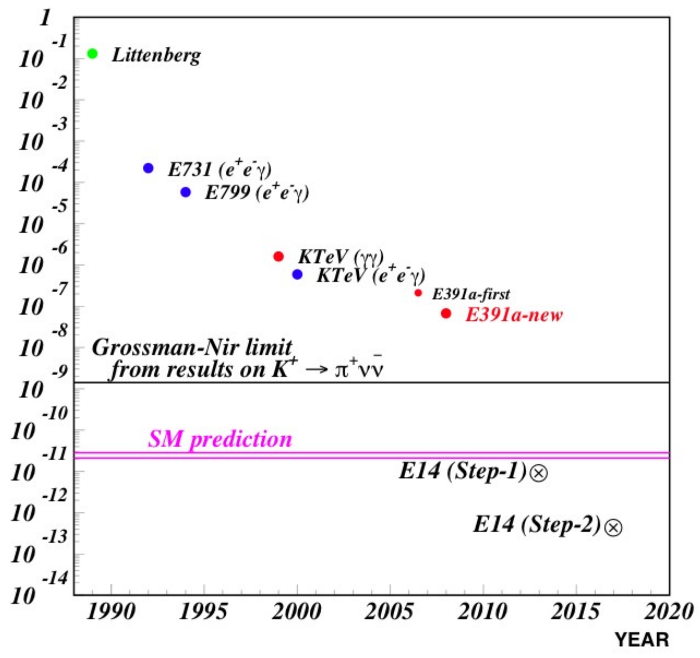


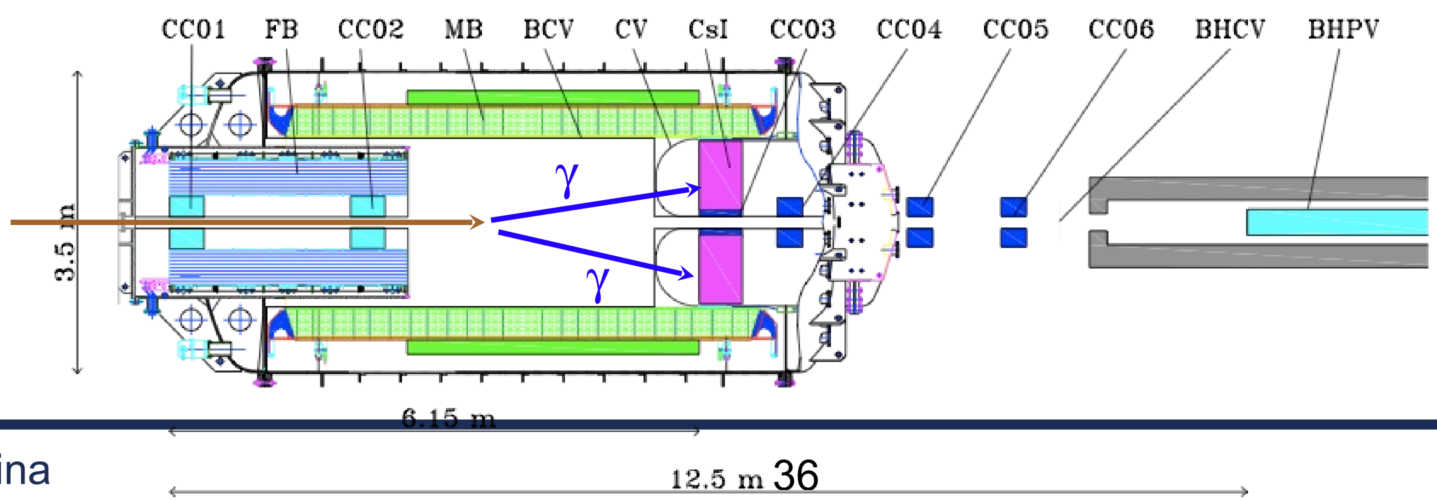
$$BR(K^0 \to \pi^0 \nu \bar{\nu}) < 6.7 \times 10^{-8}$$

arxiv:0712.4164 (2007)

Kaon projects in Japan

- KEK- E391a moves to JPARC → E14
  - $K_L \to \pi^0 \nu\nu$
    - Detection of 2 photons from π^0
    - High efficiency hermetic calorimeters
    - Well collimated K_L beam
  - Upgraded E391a
    - CsI from KTeV
- Step 1(2013)
  - First Observation(~3.5evts)
- Step 2 (2017)
  - ~100 events





Kaon Projects at FNAL: Project-X

- USA has killed Rare Kaon Decays during last ten years
  - KOPIO at BNL
  - CKM at FNAL
- Project X: intense 8 GeV proton source
  - Time scale ~2015
- Kaon program
  - $K_+ \rightarrow \pi^+ \nu\nu$
    - Same principle as E949 (K^+ decay at rest)
    - High intensity beam 10^{15} p/spill (x30 wrt BNL)
    - 1000 events
  - $K_L \rightarrow \pi^0 \nu\nu$
    - Resurection of KOPIO project
    - Almost same design as BNL project.
    - 300-900 evts/year

ππ scattering

- “Cusp” effect in $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$
  - Unexpected discovery
- Destructive interference between virtual $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ followed by $\pi^{+}\pi^{-}\rightarrow\pi^{0}\pi^{0}$d and the $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ amplitude. N. Cabibbo, PRL 93 (2004)
- Simplest non-trivial hadron scattering
  - Theoretically attractive (no spin)
- Provides understanding of strong interactions in the non perturvative regime
  - Ideal laboratory to test low energy QCD
- No experimental choice: lack of pion targets