Rare pion and kaon decays

---Precision measurements of rare decays---

Toshio Numao

TRIUMF

Suppressed decays

$$L = L_{SM} + L_{NewPhysics}$$

Highly suppressed
Well calculated

Helicity suppression for V-A → Pseudoscalar interactions

Branching ratio: $\Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$, $M=\pi$ or K

Clean: Hadronic contributions cancel in the ratio

NA62 and TREK talks

GIM suppression for FCNC → 2nd order weak interactions

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ decays

Clean: Hadronic contributions extracted from $K\text{-}\pi e\nu$

NA62, j-PARC and Proj-X talks

SM branching ratio calculations

$$R^{0}_{e/\mu} = \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)} = \frac{g_e^{\,2}\, m_e^{\,2}\,(m_\pi^{\,2}-m_e^{\,2})^2}{g_\mu^{\,2}\, m_\mu^{\,2}\,(m_\pi^{\,2}-m_\mu^{\,2})^2}$$

$$= 1.284\times10^{-4}$$

$$R^{th}_{e/\mu} = \frac{\Gamma(\pi\to e\nu+\pi\to e\nu\gamma)}{\Gamma(\pi\to\mu\nu+\pi\to\mu\nu\gamma)}$$

$$= 1.2352(1)\times10^{-4}$$

Cirigliano,Rosell 2007

Experimental status:

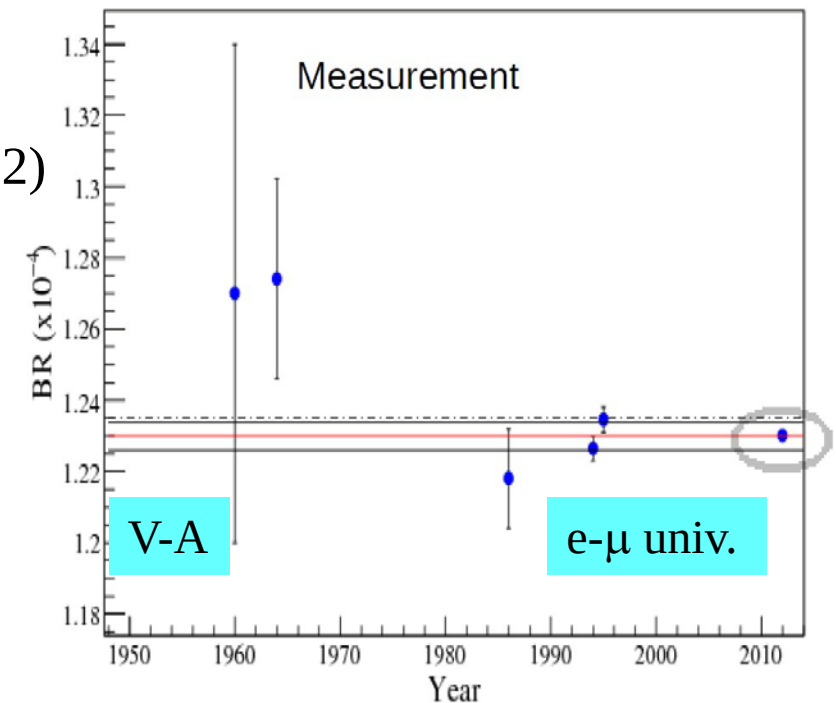
R_{exp}= 1.2265 (34) (44) x 10^{-4} (TRIUMF, 1992)

1.2346 (35) (36) x 10^{-4} (PSI, 1993)

Test of e-μ universality

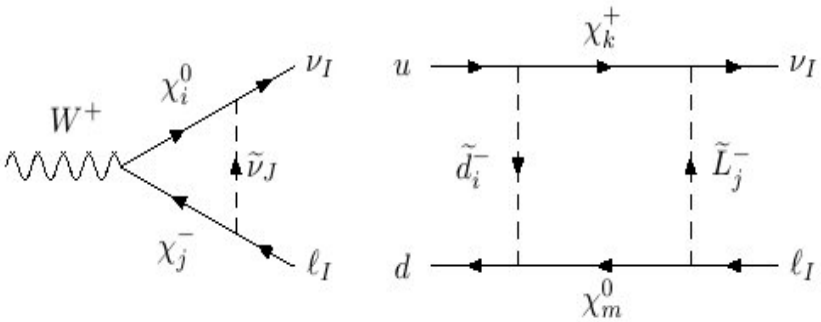
Beyond the SM

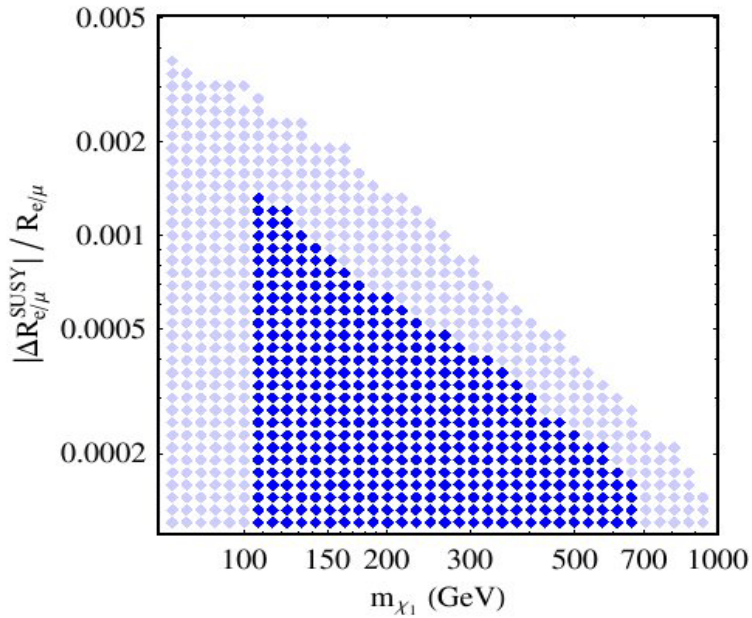
- Mass scale up to 1000 TeV
- Sterile neutrino
- SUSY...



Beyond the Standard Model

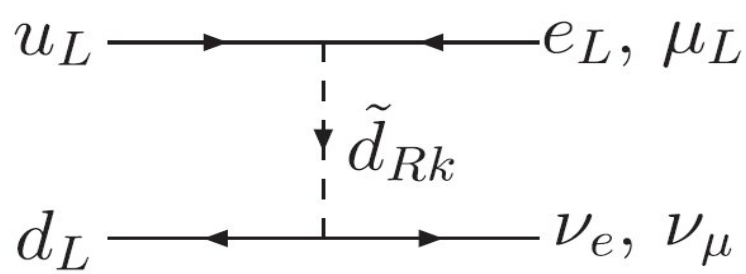
Minimal SUSY SM

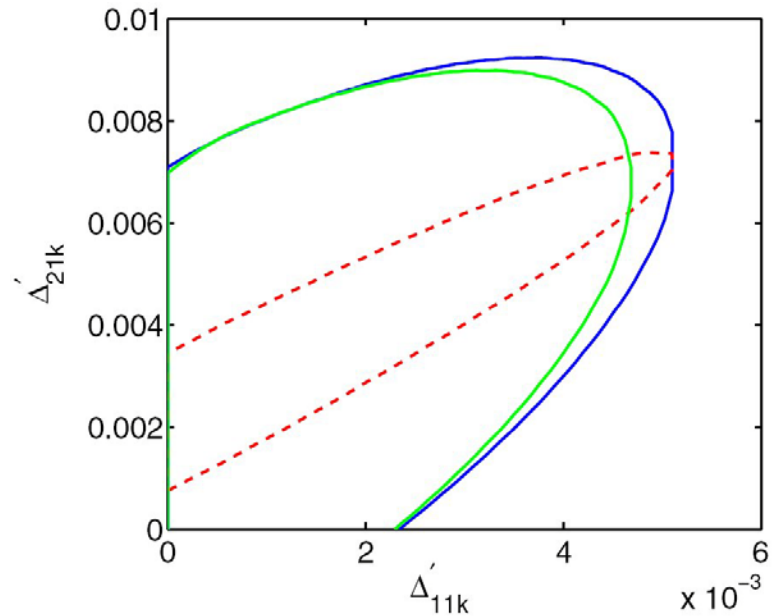




Lowest chargino mass

R-Parity Violating SUSY





Ramsey-Musolf… PRD76 095017 (2007)

Pion decays---Method

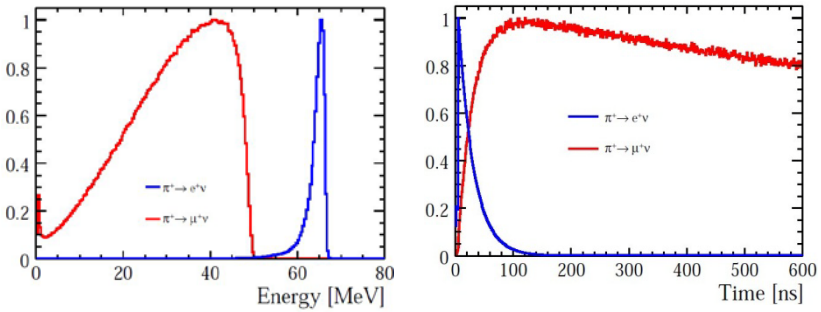
$A(\pi \to e\nu)/A(\pi \to \mu\nu)$ PSI 1993

- Muon range is 1.4 mm plastic.
- Acceptance difference,...

$A(\pi \to e\nu)/A(\pi \to \mu \to e)$ TRIUMF 1992

$\pi^+ \to \mu^+\nu$ 26 ns

$\hookrightarrow e^+\nu\bar{\nu}$ 2 μs



- Small energy-dependent effects for positrons
- Pion life

Unavoidable correction (uncertainty)

- Low energy tail of the $\pi \to e\nu$ peak.

PIENU at TRIUMF

Data taking: -2012

NaI+CsI: 2 % (FWHM) @70MeV

Radiation length: 20

Solid angle: 25 %

Pion stop: 50 kHz

Goal: <0.1 %

No. of pienu: 5 M (clean)

PEN at PSI

Data taking: -2010

CsI: 6 % (FWHM) @70 MeV

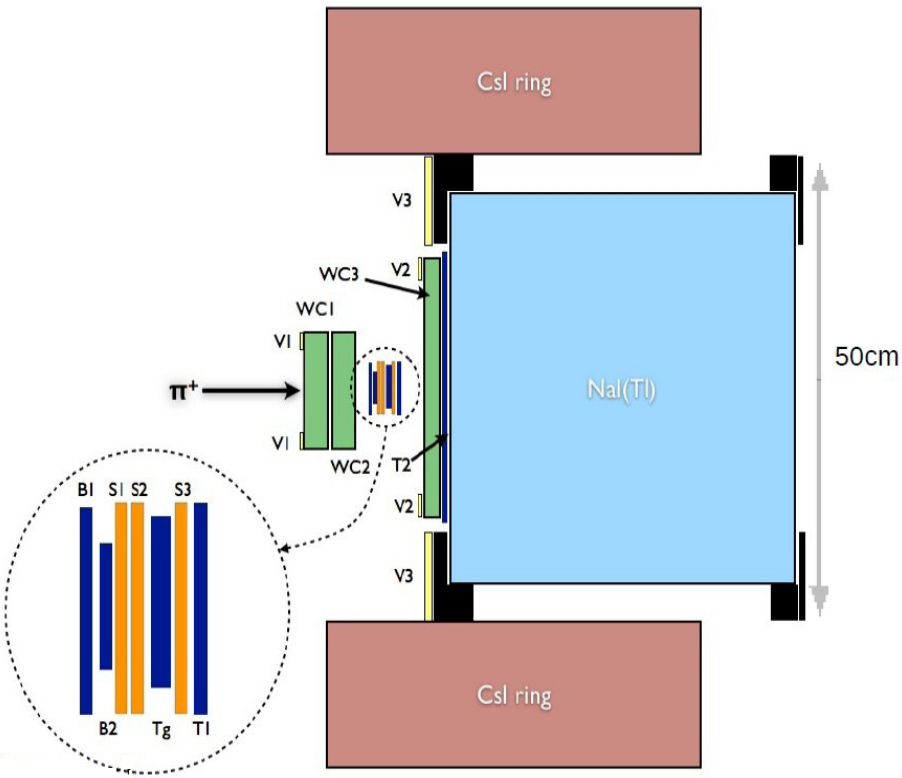
Radiation length: 12

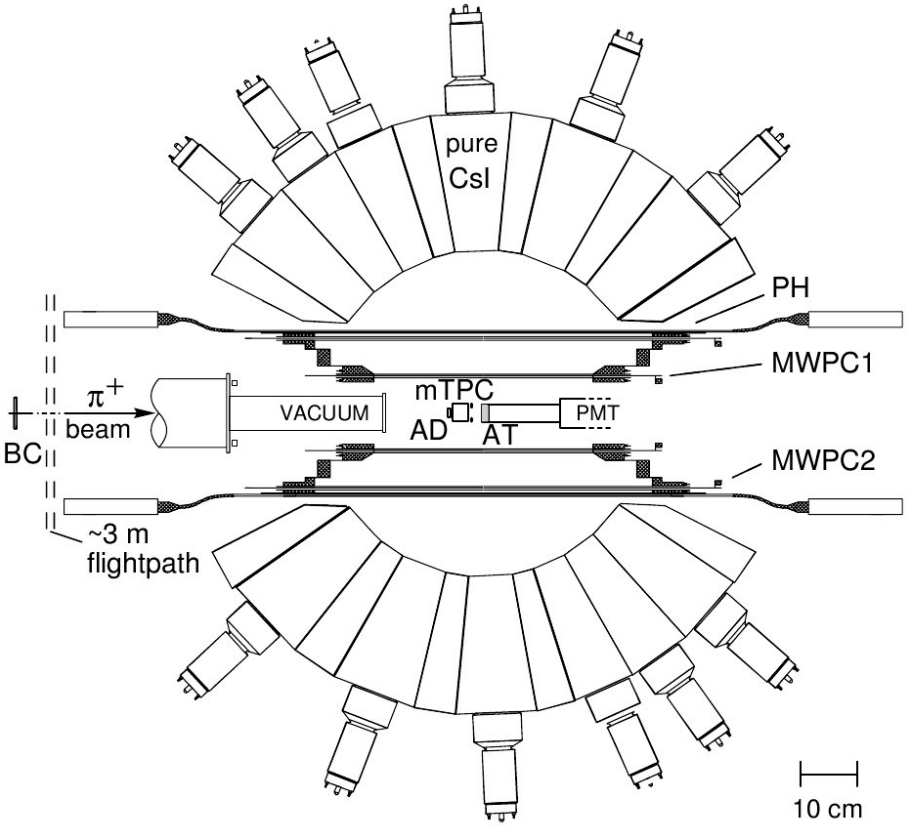
Solid angle: 70 %

Pion Stop: 10-50 kHz

Goal: <0.1 %

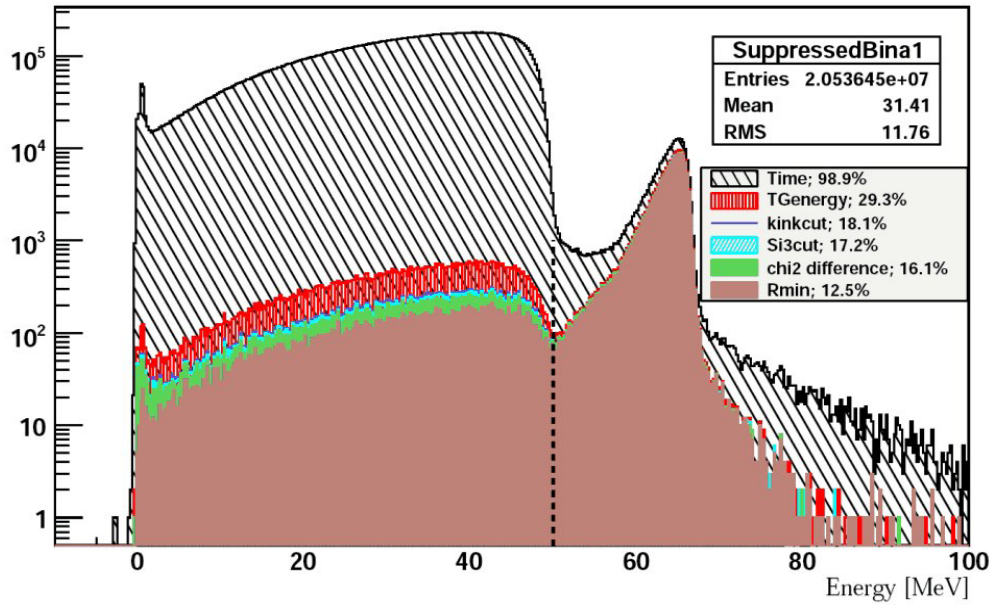
No. of pienu: 22 M

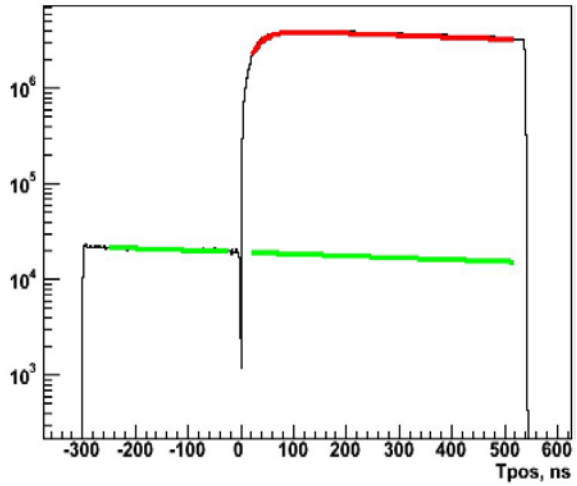


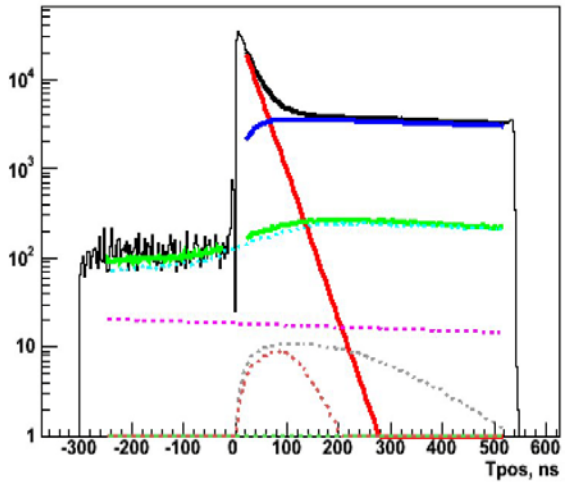


TRIUMF PIENU

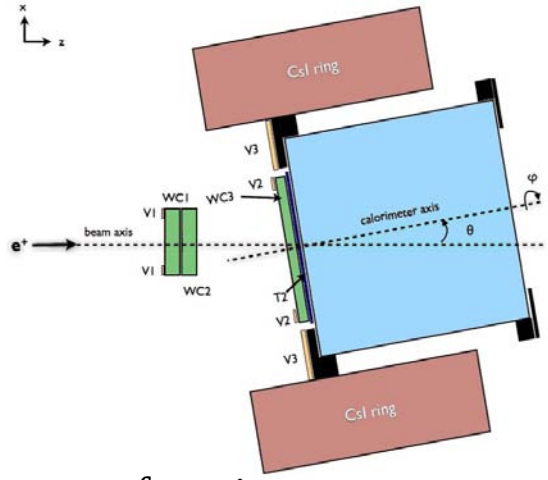
-Time window -300 to 500ns
-Enhance π-eν decay @ trigger
  -Early decays (5-40ns), or
  -High energy (>45MeV)
-Select single π stops.
-Separate time spectra (50 MeV)
-Fit simultaneously
    -π-eν, π–μ–e, (πDIF), old μ
    -radiative π decays
    -π + old μ
    -(μDIF)
-Tail correction
-Other corrections



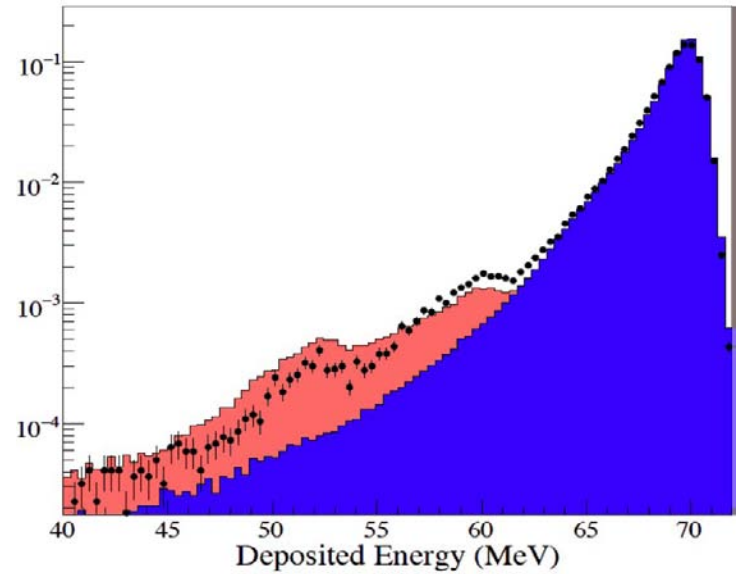




Correction for low energy π-eν (tail)

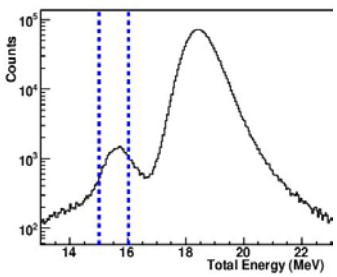


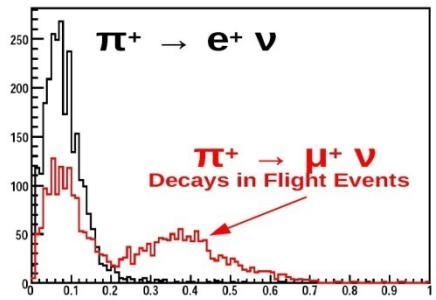
Response function measurements



70 MeV e^+ at 0°.

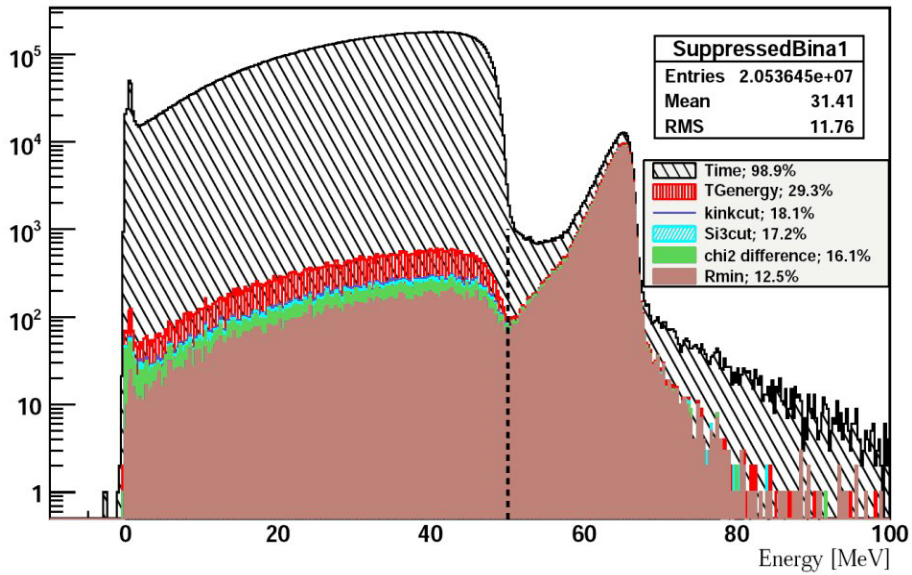
Response function measurement.
Lower bound.





-Suppress π-μ-e background.
-Subtract π,μDIF background.
-Correct for selection bias.

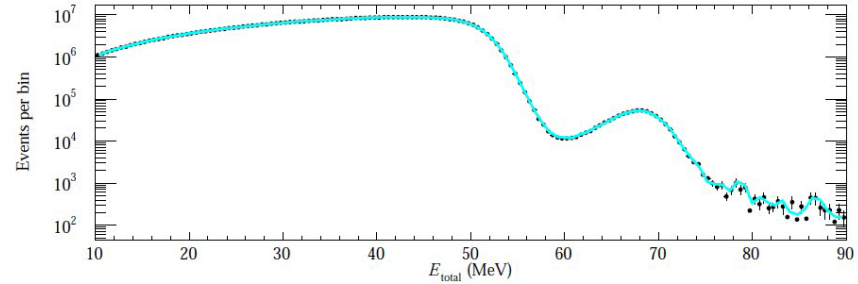
Fraction = 2 ±0.1 % (improvement expected)

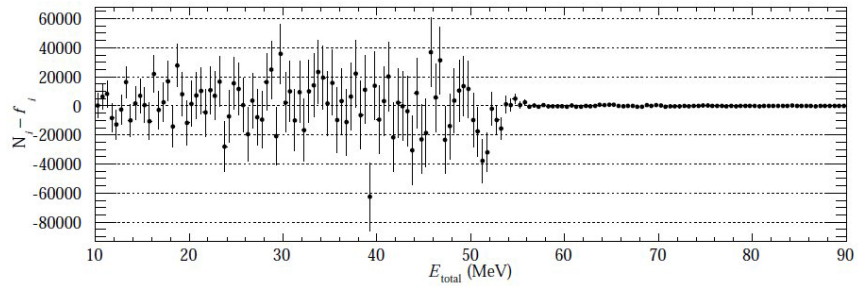


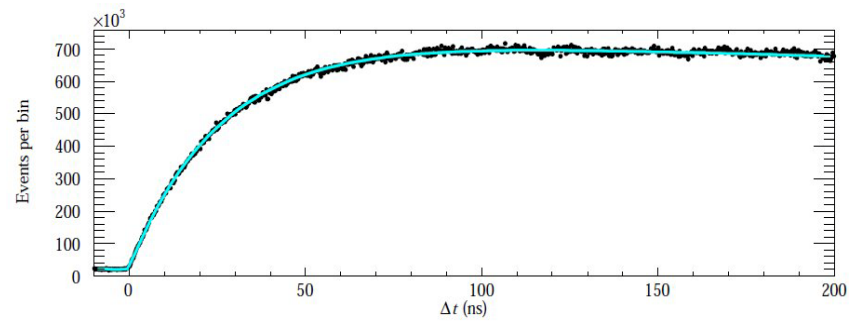
BG suppressed spectra

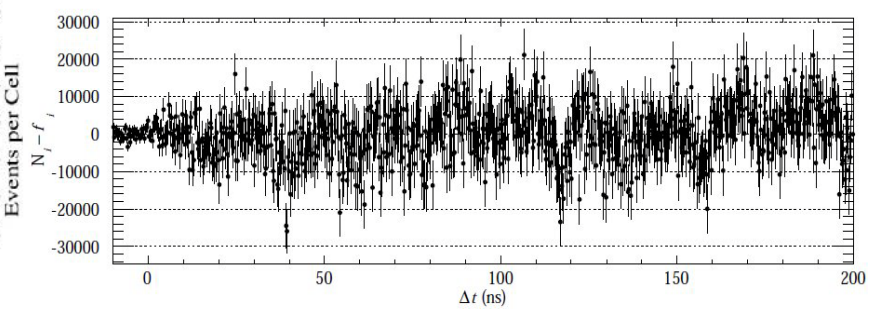
PEN @PSI

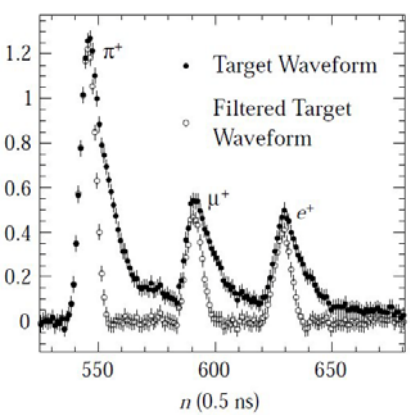
-Time window -25 to 250ns
-Enhance π-eν events @trigger
  -Above 50 MeV
  -No μ pulse
-Single π stops
-Maximum Likelihood Meth.
-5 main components; π-eν, π–μ–e, πDIF, old μ, proton (prompt)…
-Inputs; Energy, time…
-Tail included in the estimates

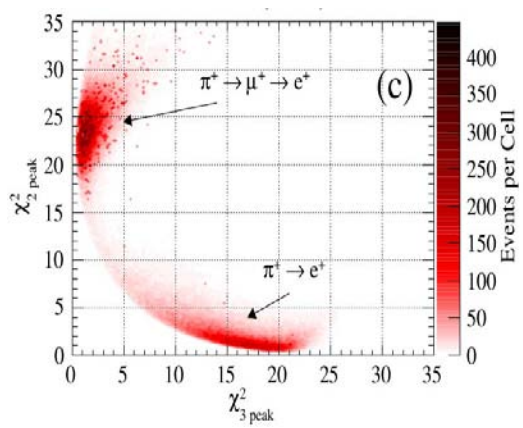




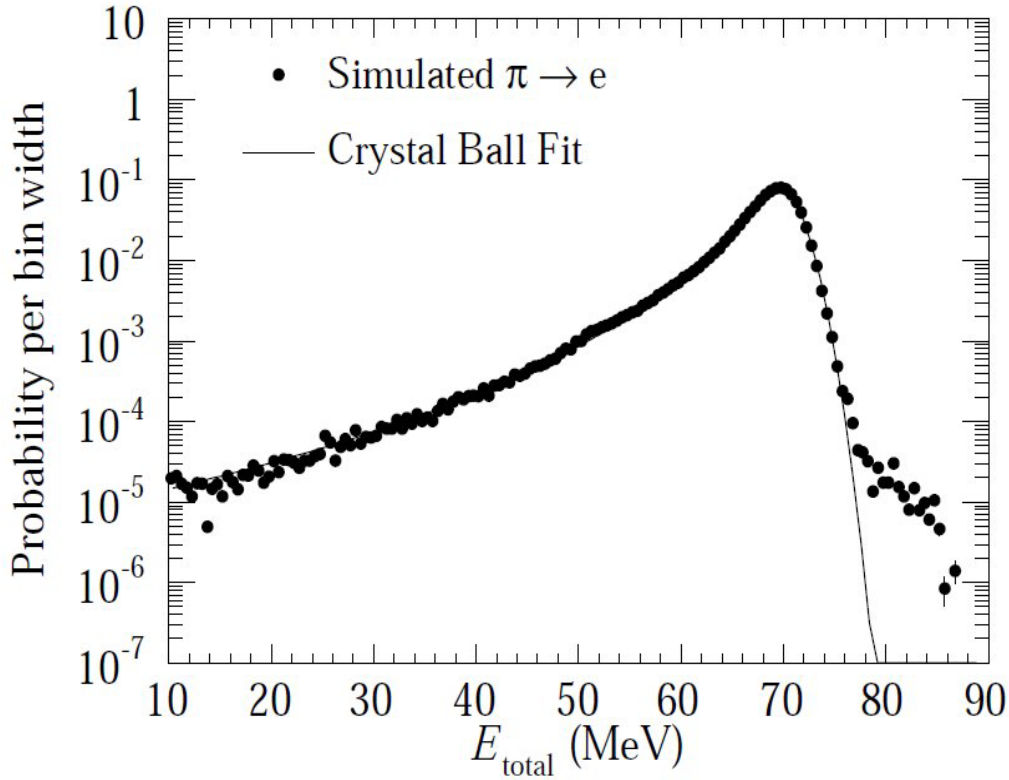


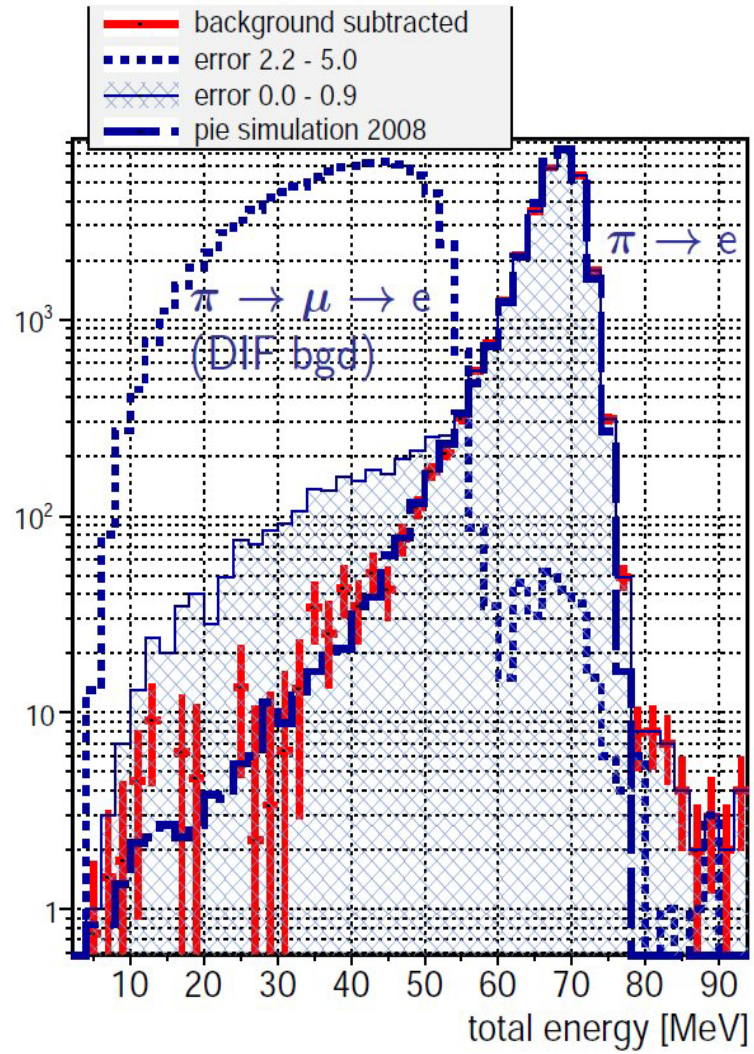






Correction for low energy pienu (tail)





-Fit to MC generated spectrum

-Iteration

Summary of uncertainties

		From proposal	
Source	Old Triumf	PIENU	PEN
Statictical	0.0028	0.0005	0.0002
Low-energy tail	0.0025	0.0003	?
Accept diff.	0.0011	0.0003	0.0002
Pion life	0.0009	0.0002	?
Other	0.0011	0.0003	0.0002
Total	0.0047	0.0006	0.0005

K-eν/K-μν

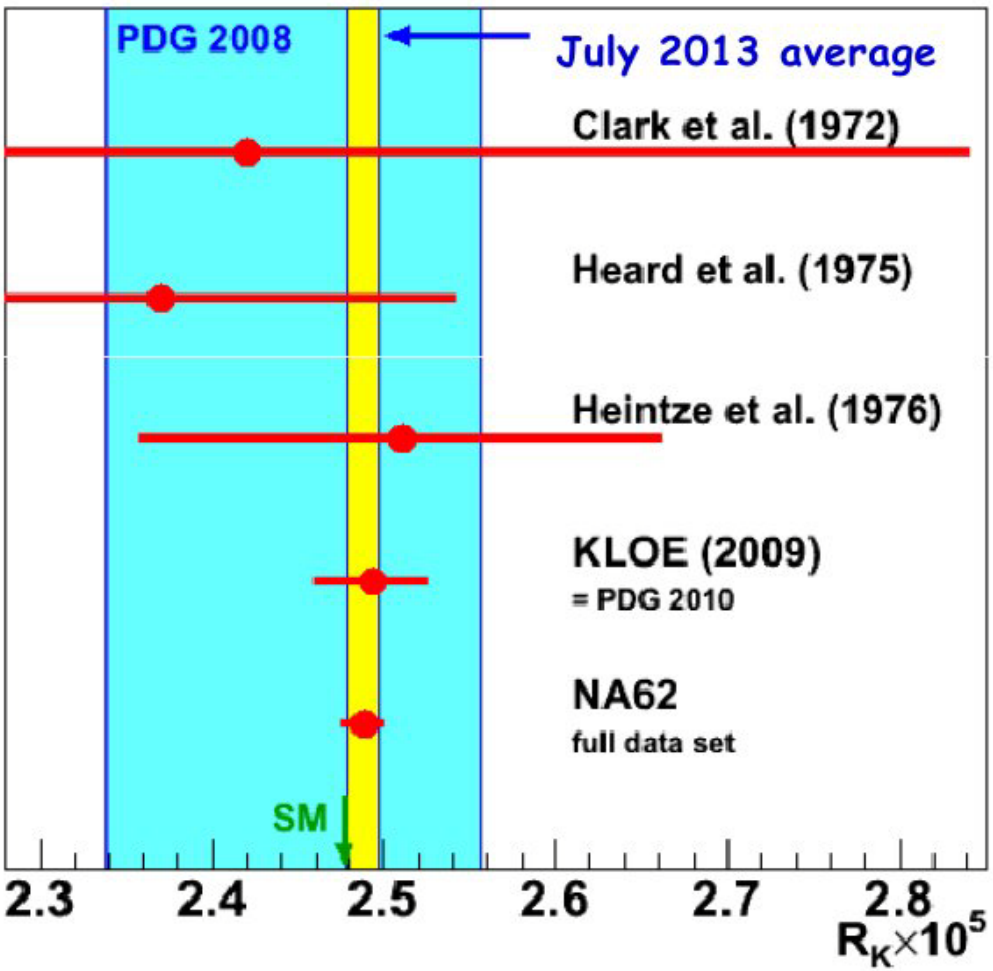
$$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$$

$$= \frac{g_e^2\, m_e^2\, (m_K^2 - m_e^2)^2}{g_\mu^2\, m_\mu^2\, (m_K^2 - m_\mu^2)^2}$$

$$\times\ (1 + \delta R_K)$$

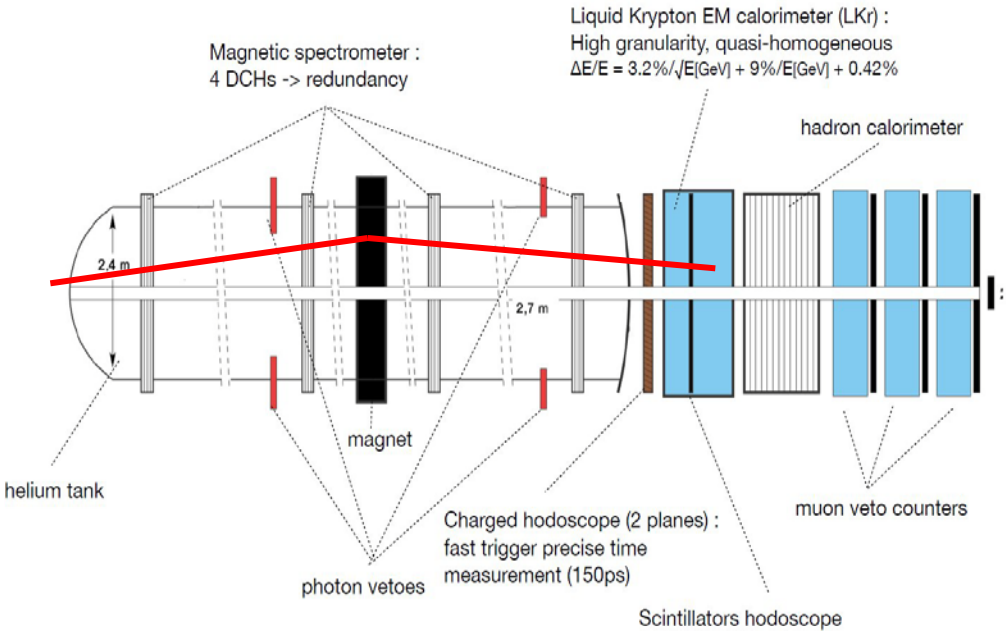
$$= (2.477 \pm 0.001) \times 10^{-5}$$

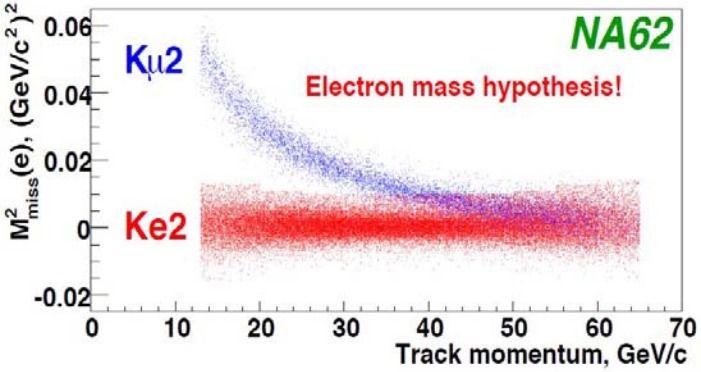
Cirigliano,Rosell 2007

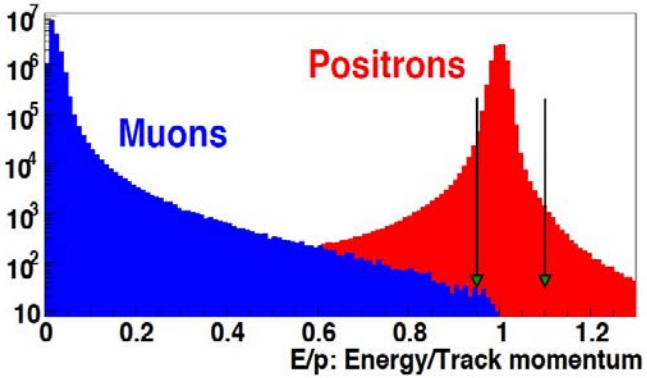


Average = $(2.488 \pm 0.009) \times 10^{-5}$

NA48-3/NA62@CERN







DIF experiment

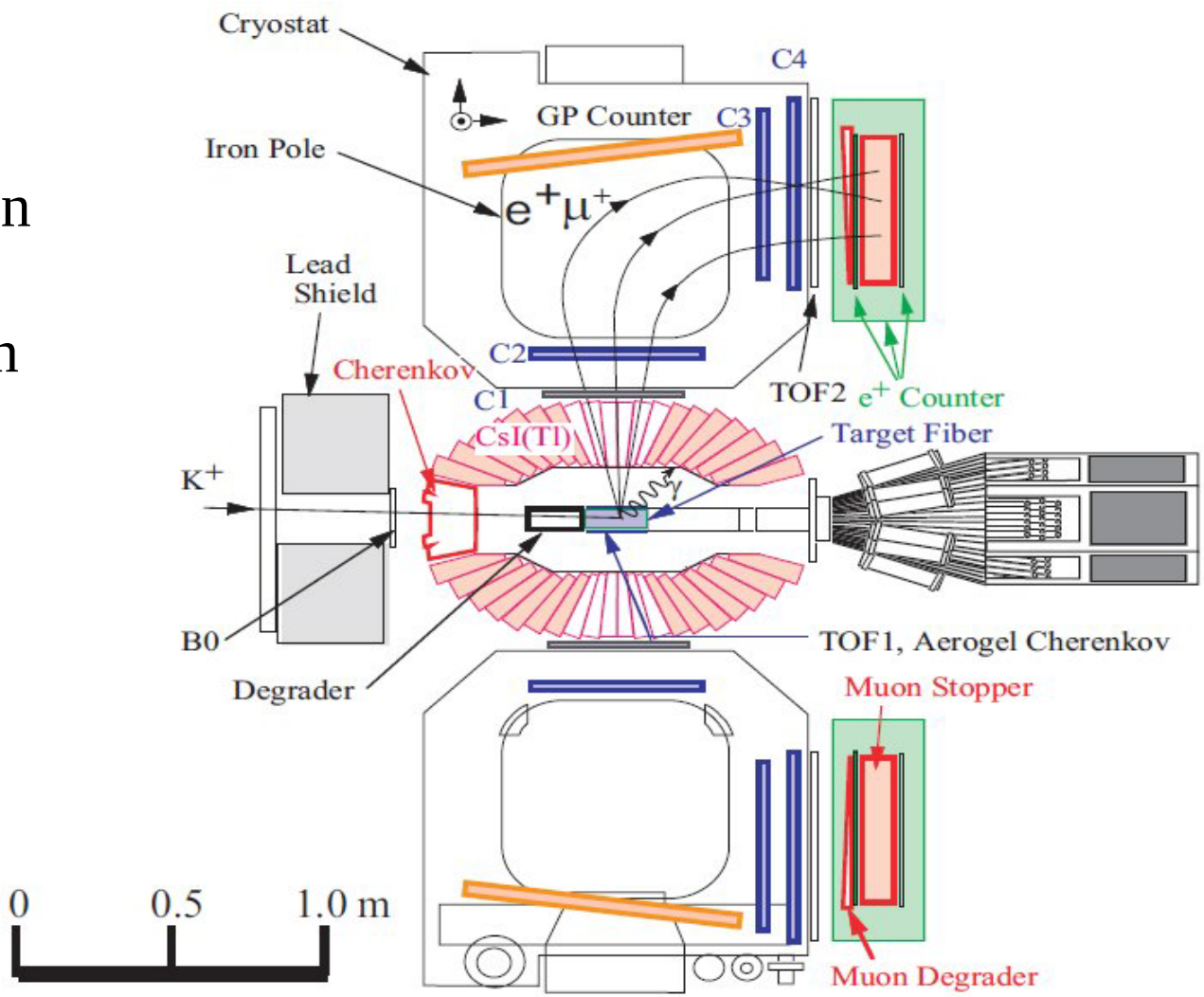
$$M^2_{miss} = (P_K - P_{lep})^2$$

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$

RICH for less BG in future?

TREK @J-PARC

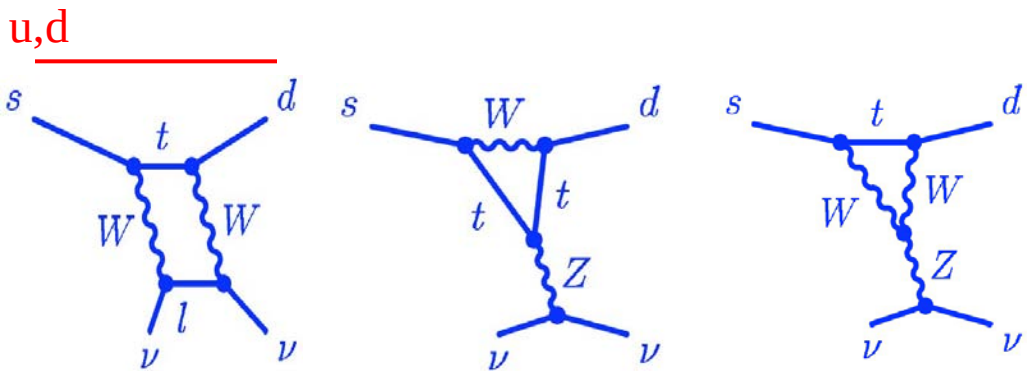
-Designed for T-violation
-Decay at rest
-Aims at 0.2 % precision

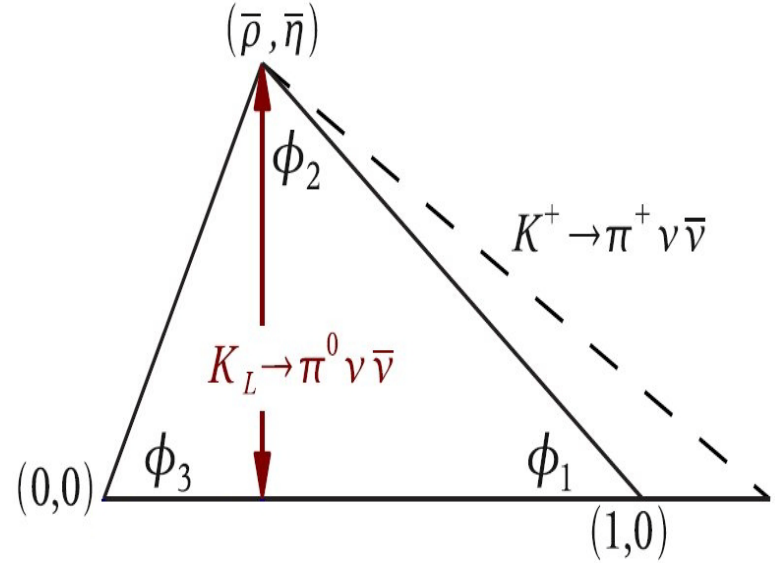


Summary of μ-e universality

Modes	g_e/g_μ	Goals
π-eν /π-$\mu\nu$	0.9979 $\pm$0.0016	→ 0.0004>
K-eν / K-$\mu\nu$	1.0022 $\pm$0.0018	→ 0.0010
τ-e$\nu\bar{\nu}$ / τ-$\mu\nu\bar{\nu}$	0.9980 $\pm$0.0015	
W-eν/W-$\mu\nu$	0.999 $\pm$0.011	
Average	0.9991 $\pm$ 0.0009	

K→πνν̄ decays

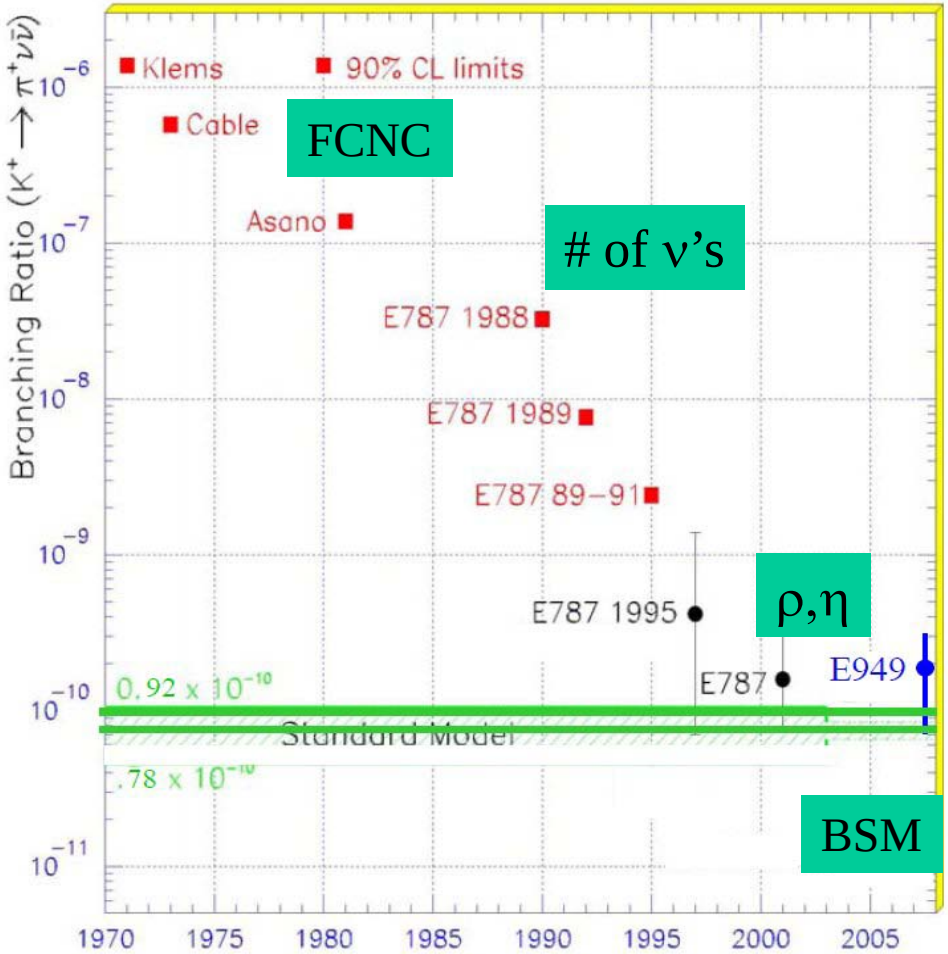


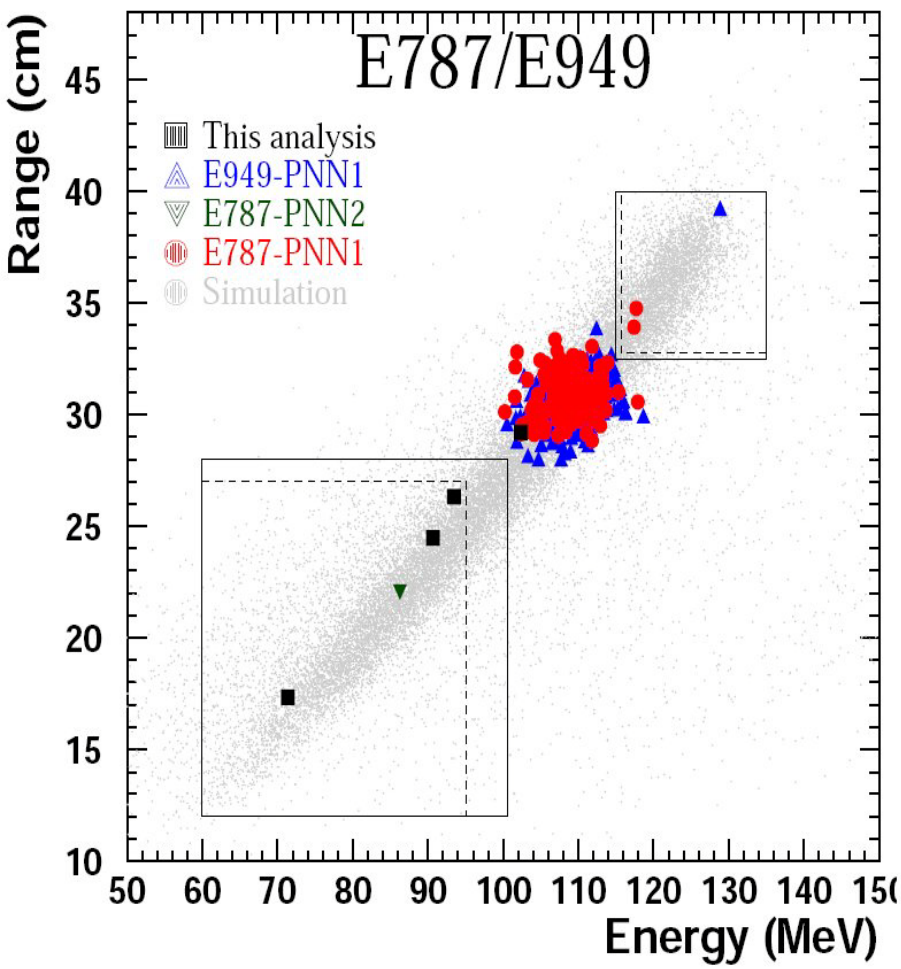


-K-πeν decay provides hadronic form factors.
-Calculated including the full 2-loop EW corrections.
-Uncertainties come from that of the CKM matrix.
-Uncertainty in the charm contribution in K^+ decay is 5 %.
-K_L decay is CP violating with very small uncertainty (1 %).

$Br(K^+)=(7.81\pm0.75\pm0.29)\times10^{-11}$
$Br(K_L)=(2.43\pm0.39\pm0.06)\times10^{-11}$ J.Brod et.al., 2011

K^+ decays

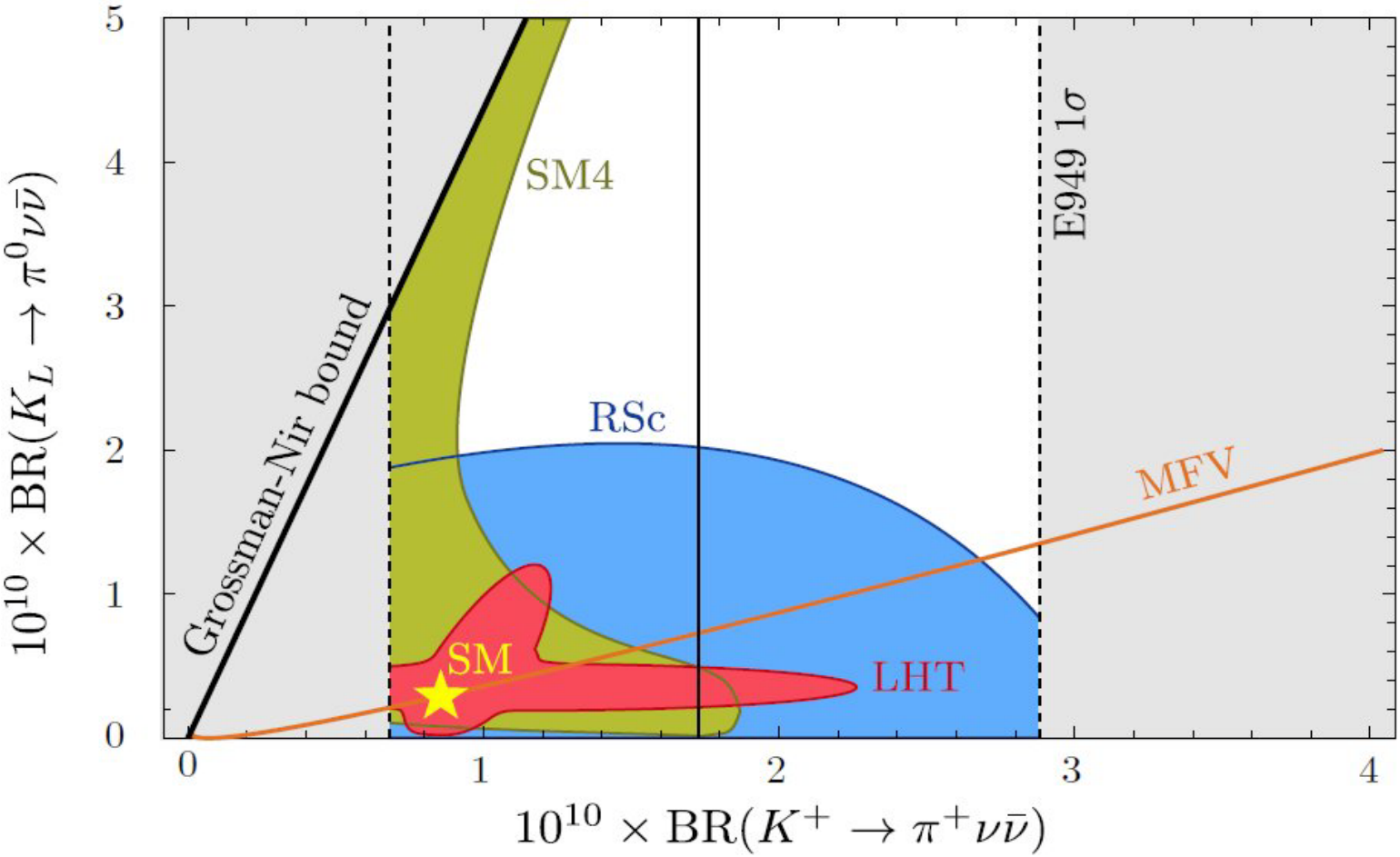




Present = $(1.73 +1.15-1.05)\times 10^{-10}$

BNL E949

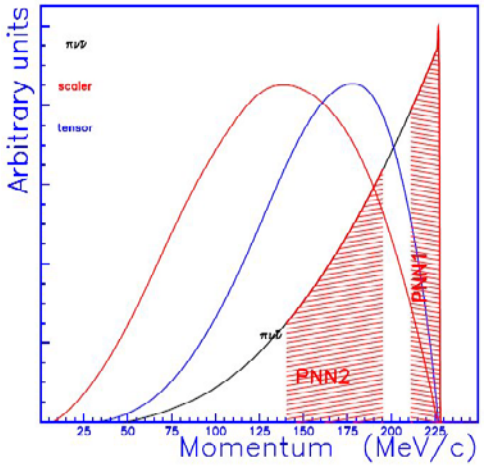
K-πνν̄ beyond the Standard Model



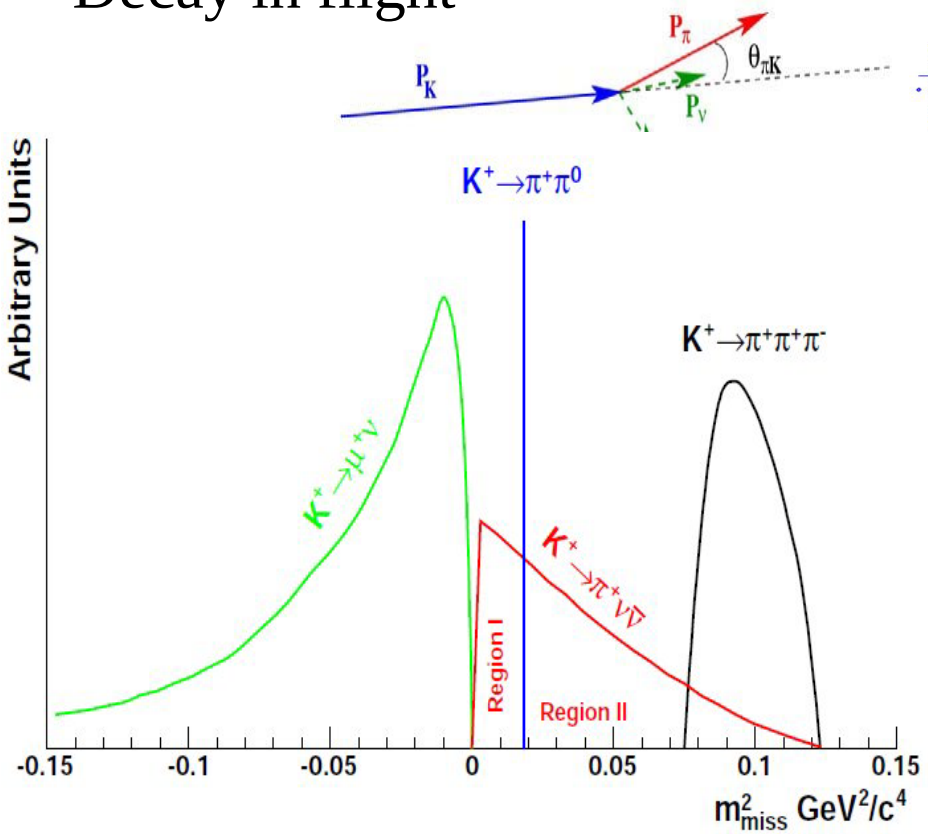
Straub, arXiv:1012.3893[hep-ph]

K^+-$\pi^+\nu\bar{\nu}$ experiments

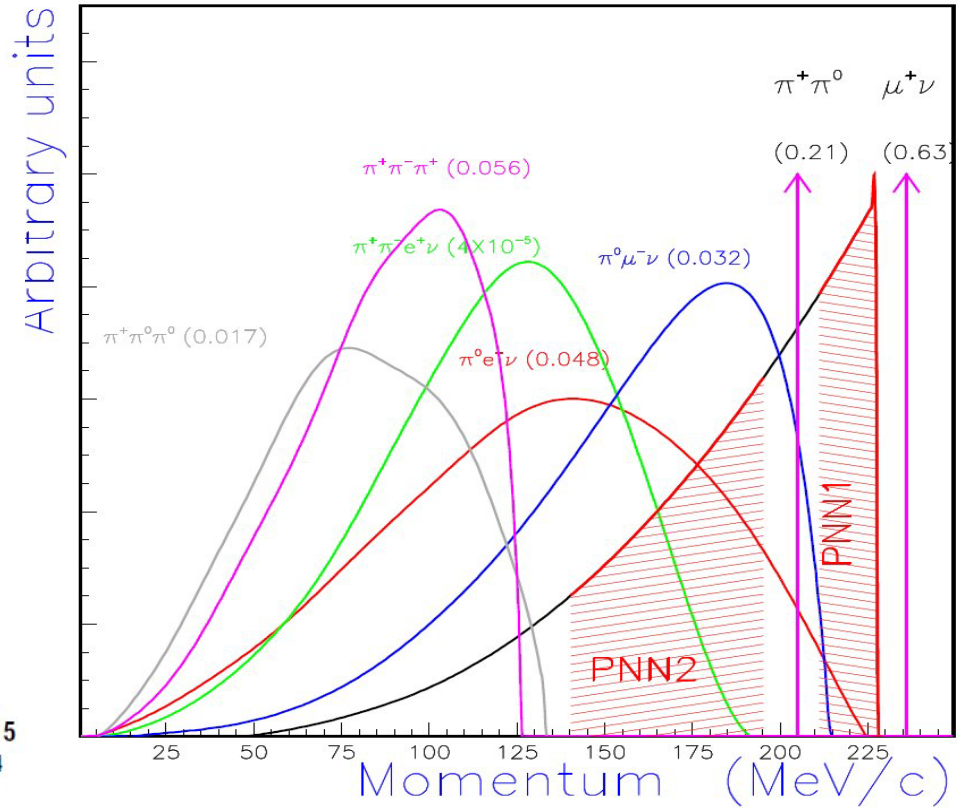
Signature: a single π^+



NA62
-Decay in flight

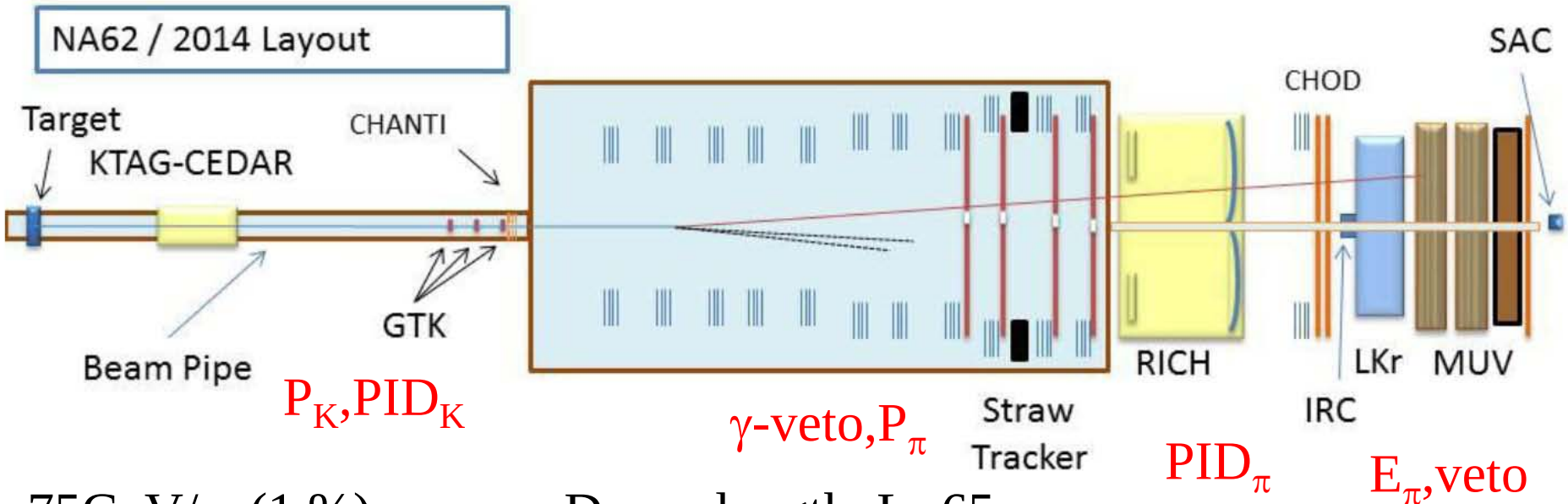


ORKA
-Decay at rest



Kinematics, particle ID, Photon veto

NA62@CERN



P_K,PID_K γ-veto,P_π PID_π E_π,veto

75GeV/c, (1 %)
(50MHz K's)

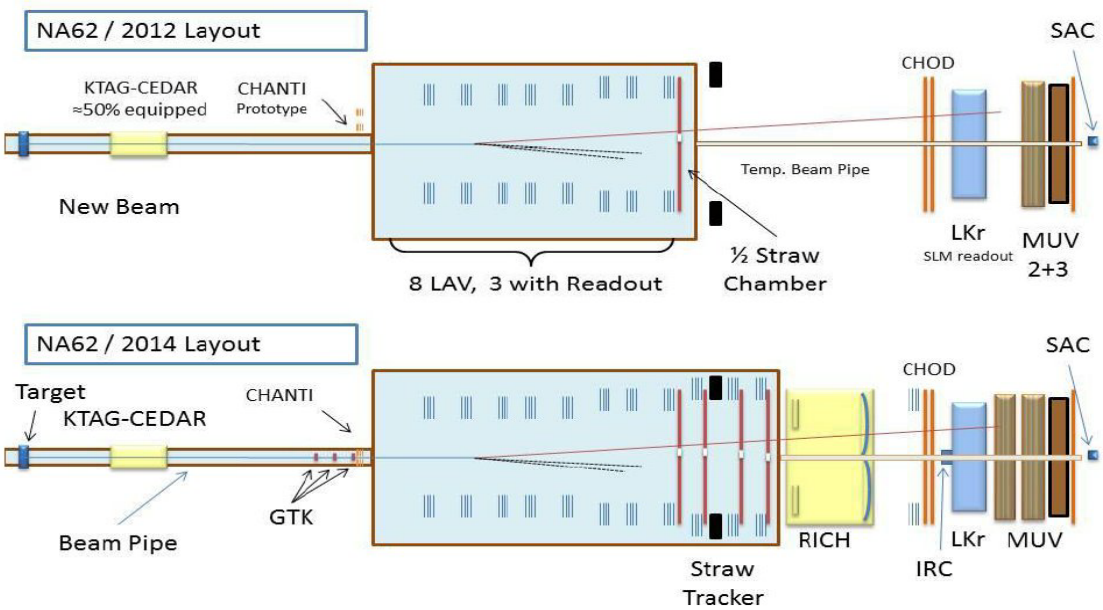
Decay length L=65 m
(6 MHz decays)

Kin. Rejection: 2×10^{-4} ($K_{\pi2}$), 7×10^{-5} ($K_{\mu2}$)
PID: 10^{-7} (μ/π)
PV: 10^{-8} for $\pi^0\rightarrow\gamma\gamma$

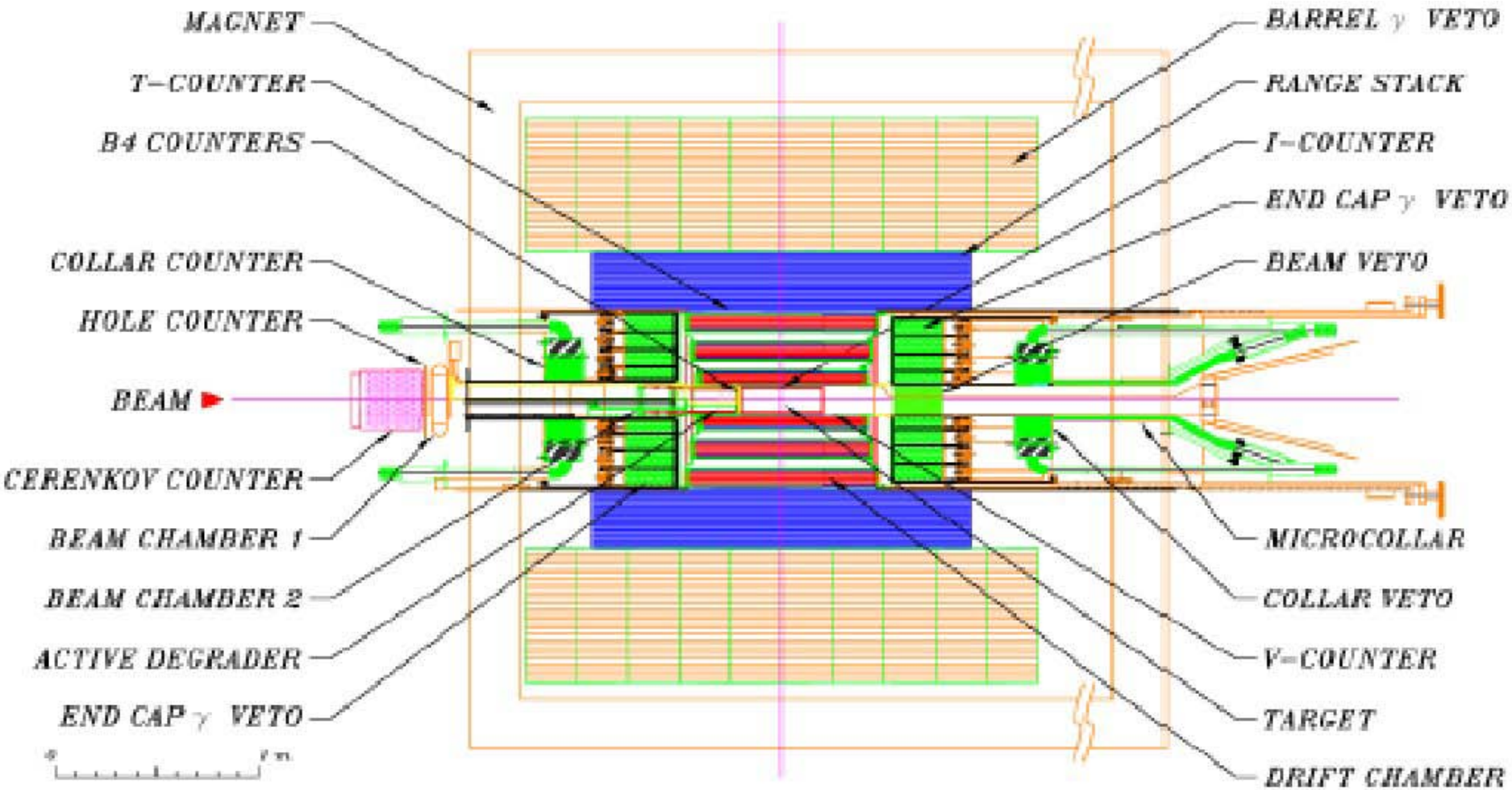
NA62

-Decay in flight
-100 events
-Data taking, 2014-

Decay	evt/year
$K^+ \to \pi^+ \nu\nu$ [SM] (flux 4.5×10^{12})	45
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \mu^+ \nu$	1
$K^+ \to \pi^+ \pi^+ \pi^-$	< 1
$K^+ \to \pi^+ \pi^- e^+ \nu$ + other 3 tracks decays	< 1
$K^+ \to \pi^+ \pi^0 \gamma$(IB)	1.5
$K^+ \to \mu^+ \nu \gamma$(IB)	0.5
$K^+ \to \pi^0 e^+ (\mu^+) \nu$, others	negligible
Total background	< 10



ORKA@FNAL



Improved Kin.

PID: P/E/R, π-μ-e chain

Veto: Hermetic detector

ORKA

-Decay at rest
-Based on E949 experience
-Improved res. and granul.
-500 events
-2018?

Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product (R_{acc})	$11.28^{+3.25}_{-2.22}$

Improvement factors over E949 acceptance

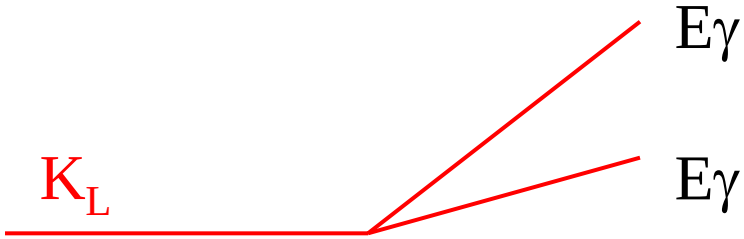
Background	Standard	Extended
$K_{\pi 2}$	0.019 ± 0.004	0.216 ± 0.023
$K_{\mu 2}$ range tail	0.010 ± 0.001	0.044 ± 0.005
Muon band	0.005 ± 0.002	0.024 ± 0.010
Single beam	0.004 ± 0.002	0.006 ± 0.002
Double beam	0.003 ± 0.002	0.003 ± 0.002
CEX	0.004 ± 0.001	0.005 ± 0.001
Total	0.05 ± 0.01	0.30 ± 0.03

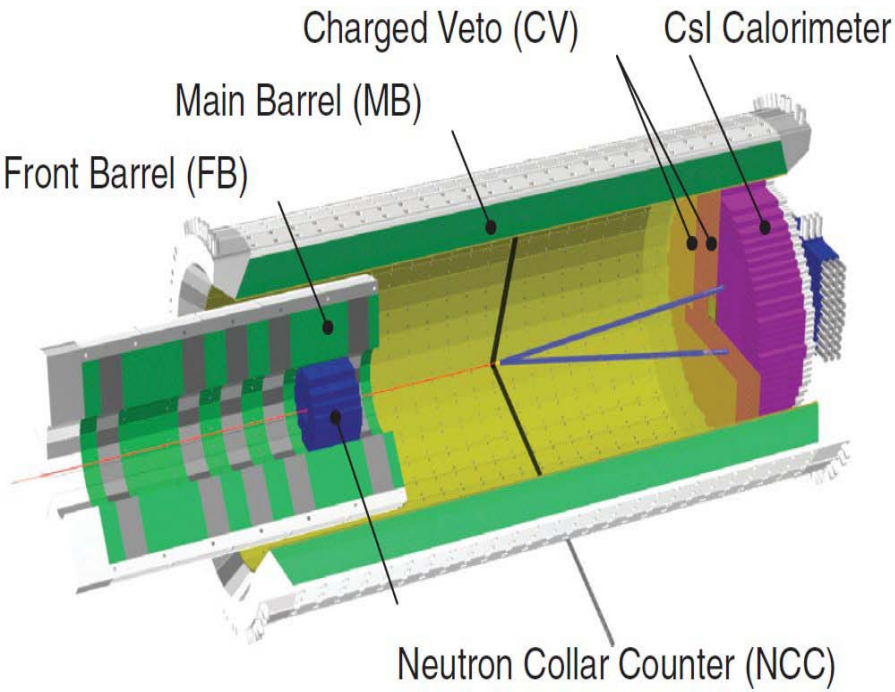
Expected backgrounds

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

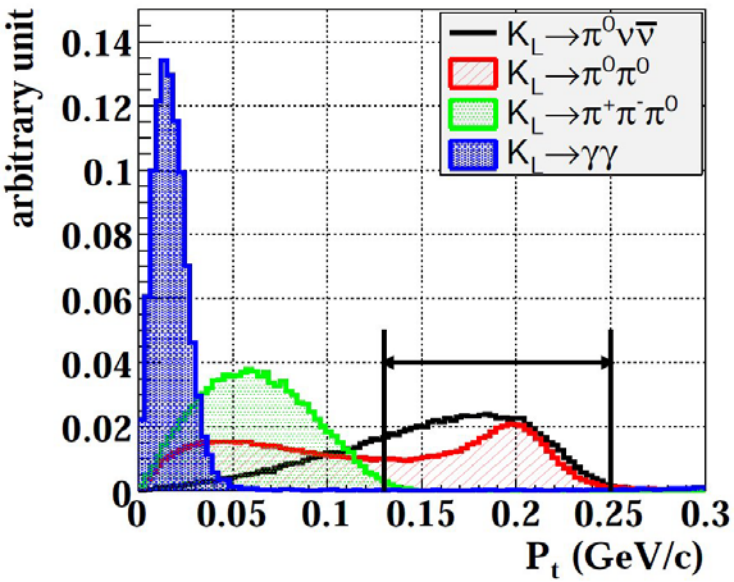
Present limit=2.6×10^{-8} @90 % c.l.

PRD 81 072004(2009)





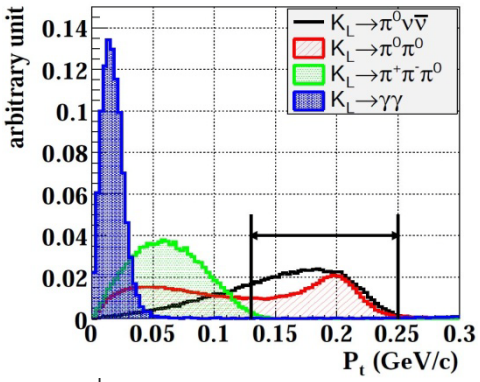
-E391a→KOTO@JPARC
-Pencil beam
-Assumes π^0 mass for 2 γ's
→vertex, P_T
-Large P_T
-No other activity
-Use KTEV CsI's (better res.)



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

From original proposal

Background source	#Background events
Other K_L decays	
$K_L \to \pi^0\pi^0$	3.65
$K_L \to \pi^+\pi^-\pi^0$	0.93
$K_L \to \pi^- e^+ \nu$	0.01
$K_L \to \gamma\gamma$	negligible
$K_L \to \pi^0\pi^0\pi^0$	negligible
Neutron Interaction	
With Residual gas	0.07
At the CC02	0.26
At the C.V.	negligible
Accidental Coincidence	0.20



Expect 3.5 SM events with s/n=1.4.
Searches NP for 3 orders of magnitude.

Next generation experiment?
- -KOTO Stage-2; 100 SM events.
- -Project-X?

Conclusion

There are many world-wide efforts for precision measurements of rare pion and kaon decays, which are significantly suppressed in the standard model and therefore sensitive to new physics.

M-eν/M-$\mu\nu$ branching ratio measurements are extremely sensitive to a presence of PS interactions. The ratio also provides the best test of e-μ universality. A factor of 3-5 improvement is expected in a few years, but there will be a room for improvement by another factor of 5.

There are several challenging K-$\pi\nu\bar{\nu}$ experiments, either running or planned to run soon. Results are expected in the next few years.