Search for Lepton Universality Violation in Kaon Decays

- J-PARC E36 experiment -

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for E36 collaboration
IPNS, KEK and J-PARC

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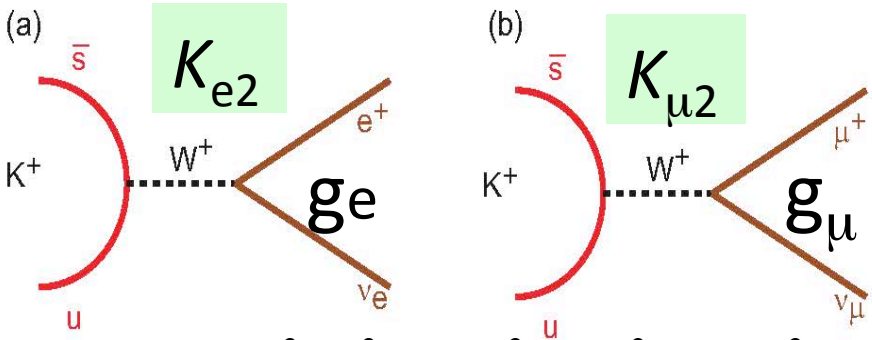
Outline

- Introduction
- J-PARC E36 experiment
  - Stopped K^+ experiment
  - Detector
  - Systematic errors
  - Expected sensitivity
  - Byproduct physics
- Summary

Lepton universality and K_{l2} decays

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- Three generations of leptons in SM
  - Different masses of e, μ, and τ, but the same gauge couplings of g_e, g_μ, and g_τ.
  - It should be tested with high precision experiments.
- Kaon decays:



$$\Gamma(K_{l2}) = g_l^2\,(G^2/8\pi)\,f_K^2 m_K m_l^2\,\{1 - m_l^2/m_K^2\}^2$$

- $g_e = g_\mu$?
- Vertex correction due to New Physics ?

R_K measurement

- Ratio of K_{l2} decay widths:

$$R_K = \Gamma(K^+ \to e^+\nu\ (\gamma)\ ) / \Gamma(K^+ \to \mu^+\nu\ (\gamma)\ )$$

  - small (~ 10^{-5}) due to helicity suppression, but
  - free from hadronic form factors

- Standard Model prediction:

δ_r : radiative decay contribution of $K^+ \to l^+ \nu \gamma$

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu_e\,[\gamma]\,)}{\Gamma(K^+ \to \mu^+\nu_\mu\,[\gamma]\,)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta_r)$$

$= 2.477\ (1) \times 10^{-5}$ with $\delta_r = -0.036$

Cirigliana and Rosell, Phys. Rev. Lett. 99, 231801 (2007)

- New Physics contribution:

$$\Delta R_K = R_K - R_K^{SM}$$

New physics effects

- SUSY with lepton flavor violation
  Masiero, Paradisi and Petronzo, Phy. Rev. D74 (2006) 011791
  Masiero, Paradisi and Petronzo, JHEP 11 (2008) 042
  - charged Higgs exchange with
    a LF changing sleptpn loop
  - K_{e2} can be enhanced
  - ΔR_K can be as large as $\mathcal{O}(1\%)$
  Girrbach and Nierste, arXiv.1202.4906

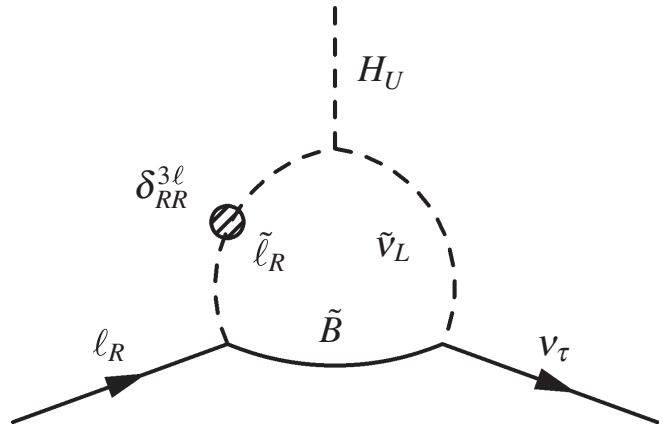


FIG. 1. Contribution to the effective $\bar{\nu}_\tau \ell_R H^+$ coupling.

- general discussions of SUSY effects
  Fonseca, Romao, and Teieira, Eur.Phys.J. C(2012) 72:2228
  - strong constraints from $B_s \to \mu^+\mu^-$ and $B_u \to \tau\nu$

- fourth generation of quarks and leptons
  Lacker and Menzel, JHEP07 (2010) 006
  - constraint to neutrino mixing matrix $|U_{e4}|$

- sterile neutrino
  Abada, Das, Teixeira, Vicente, and Weiland, arXiv:1211.3052v2
  - tree-level enhancement by modified $Wl\nu$ couplings with sterile neutrinos
  - a large effect of $\mathcal{O}(1)$ is also possible

Experimental status

- KLOE @ DAFNE (2009)

  in-flight decay

  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
- NA62 @ CERN (2011)

  in-flight decay

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

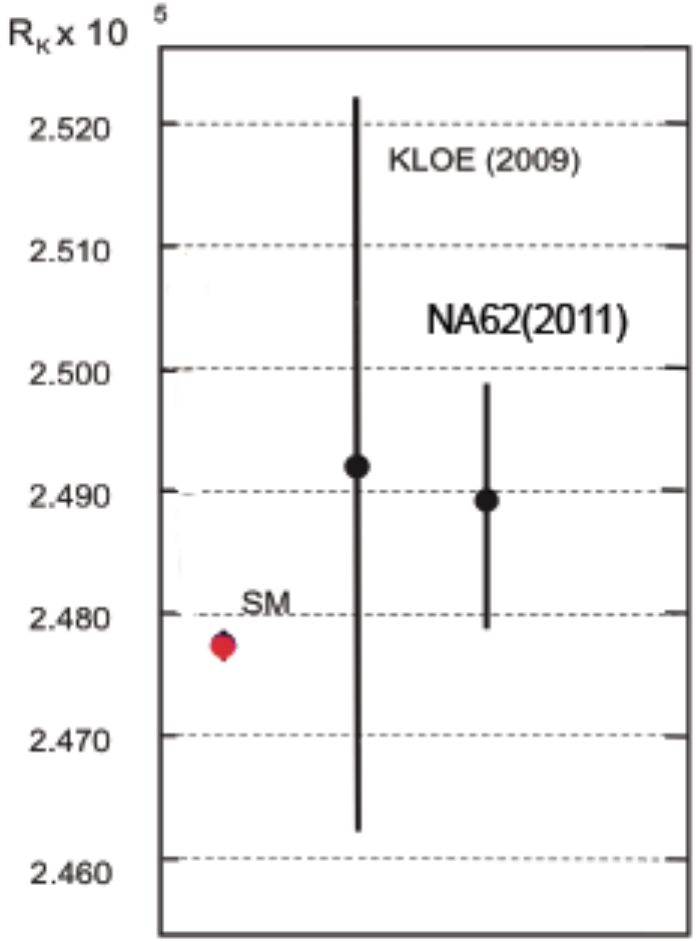
- World average (2011)

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

  $\delta R_K / R_K = 0.0037$

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

  – Uncertainty : $\delta R_K / R_K \sim 0.0004$



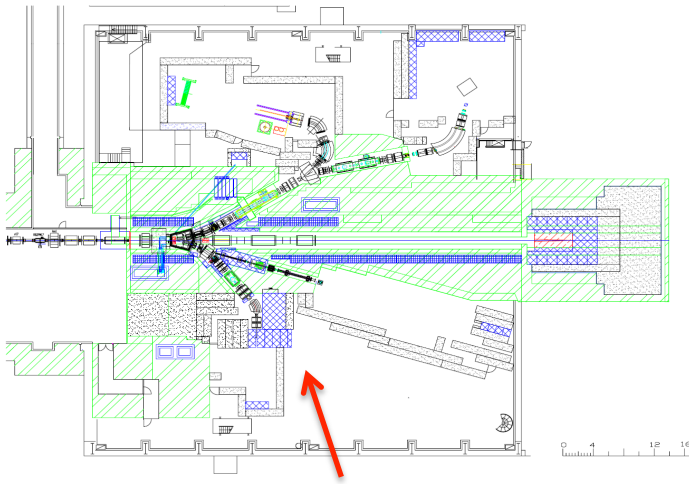
J-PARC E36 experiment

- Use of high-intensity K^+ beam of K1.1BR at J-PARC
- Stopped beam experiment
  - different systematics from KLOE and NA62
- TREK detector with SC Toroid
  - future application to E06 ($K_{\mu 3}$ T violation)
- Sensitivity:

$$\delta R_K / R_K = 0.0020\ (\text{stat}) \pm 0.0015\ (\text{syst}) = 0.0025$$

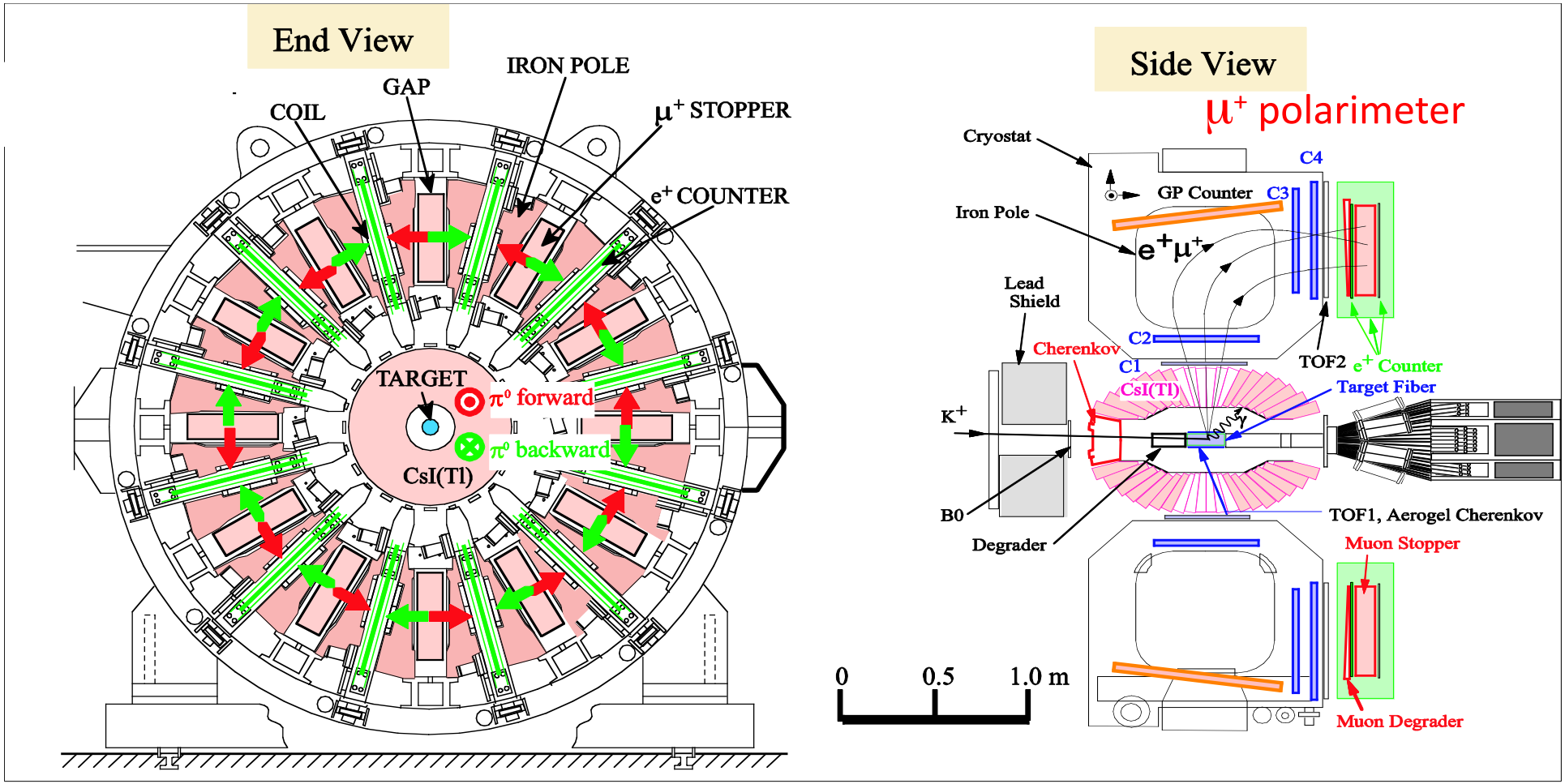
- Now in preparation
  - scheduled to run in 2014-2015

Hadron Expemeimental Hall



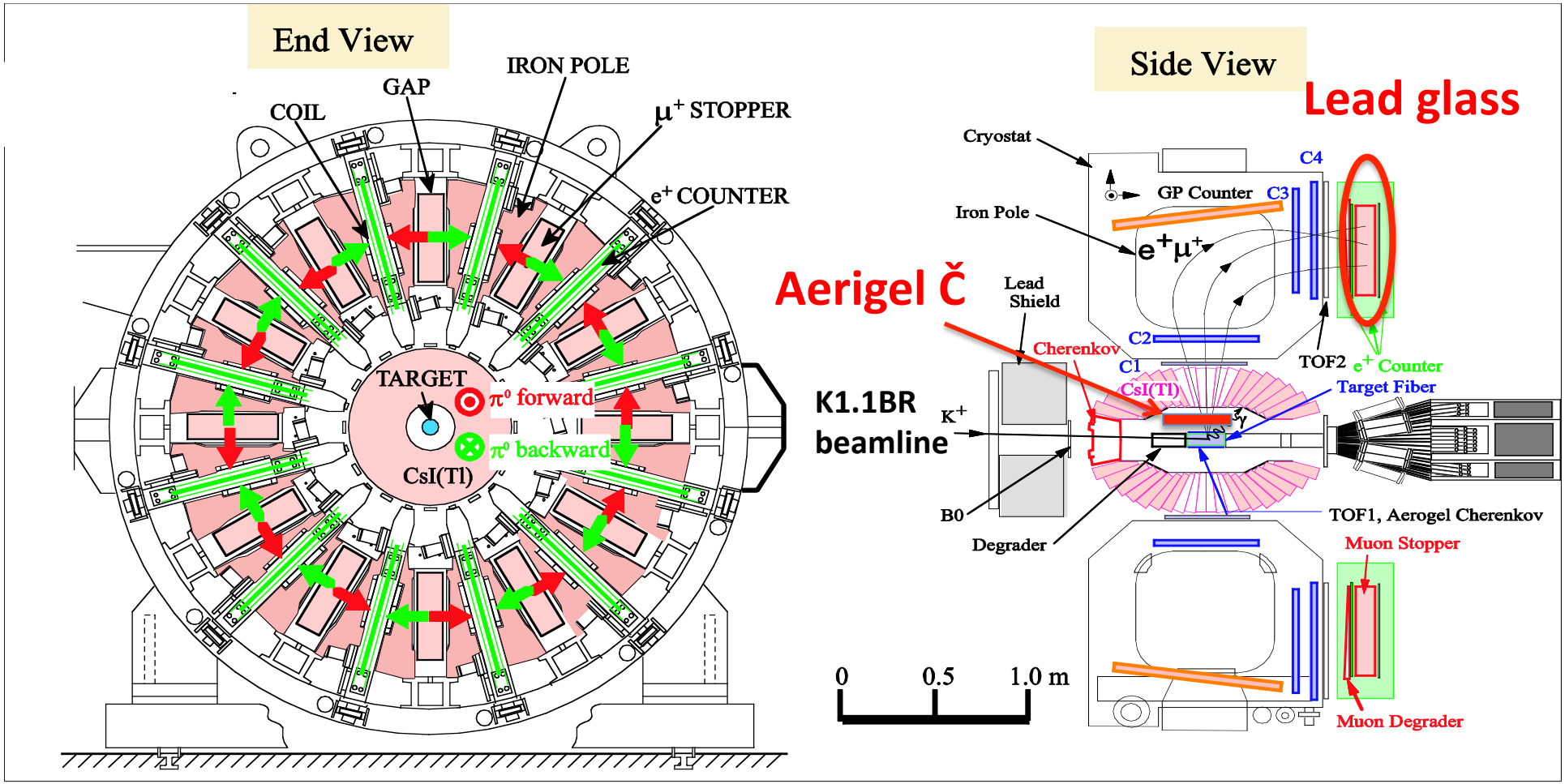
K1.1BR beamline

TREK detector



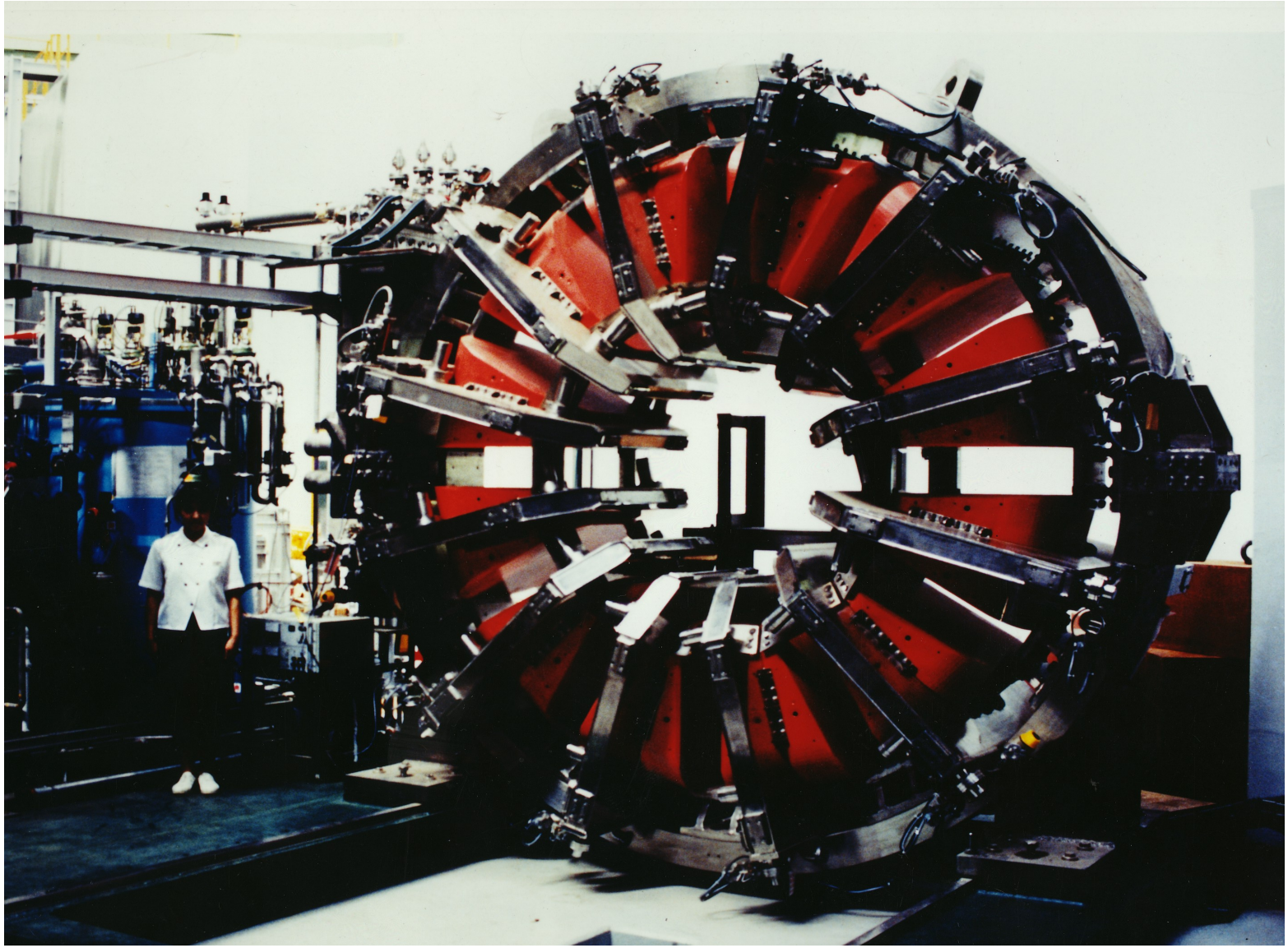
- Spectrometer system with 12-gap toroidal magnet
- Originally designed for E06 ($K_{\mu 3}$ T violation) by upgrading KEK-E246

E36 detector



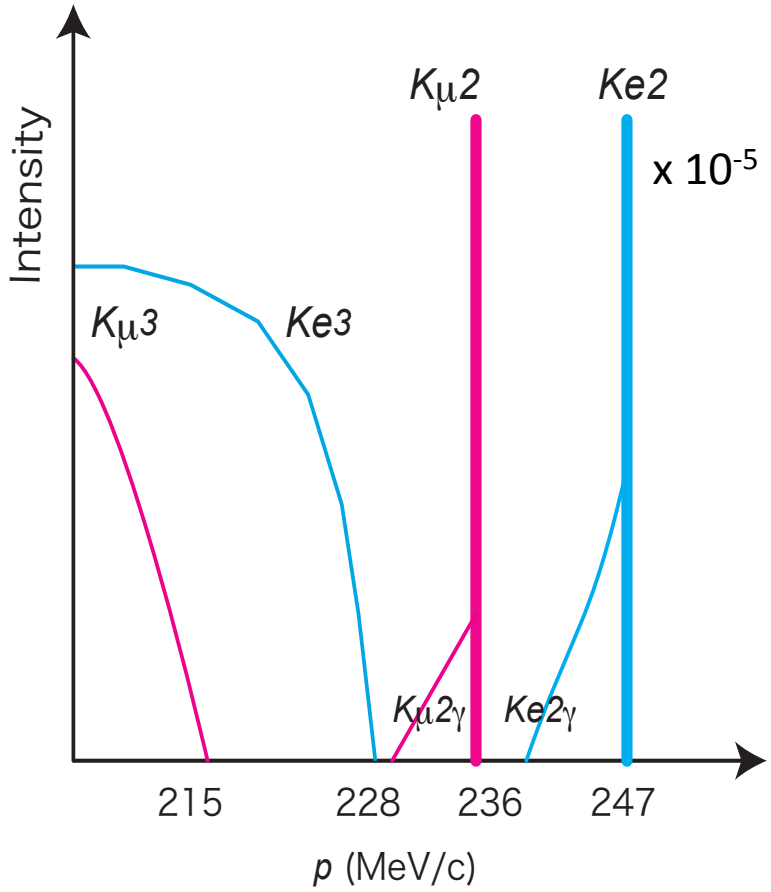
- In place of muon polarimeter a lead glass counter is installed
- e^+/μ^+ identification with TOF, aerogel Č and lead glass

SC Toroidal Spectrometer



Measurement and analysis

schematic momentum spectrum



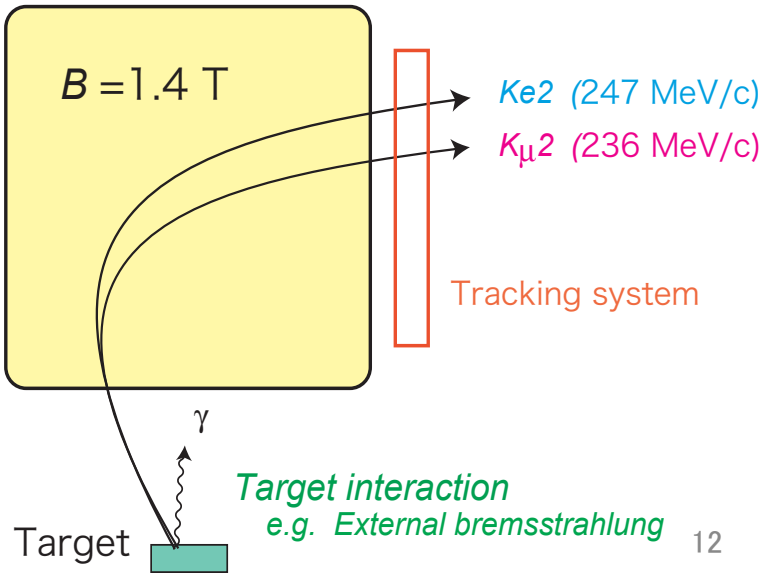
- Charged particle momentum spectrum
  - including $K_{e2\gamma}$ and $K_{\mu2\gamma}$
  - above 228 MeV
- Rejection of "Structure dependent radiative decay (SD)"
  - rejected as a background
  - with the help of CsI(Tl) calorimeter
- Determination of R_K

$$R_K = \underbrace{\frac{N\,(K_{e2}+K_{e2\gamma}^{IB})}{N\,(K_{\mu2}+K_{\mu2\gamma}^{IB})}}_{\text{event rate ratio}} \; \underbrace{\frac{\Omega\,(K_{\mu2}+K_{\mu2\gamma}^{IB})}{\Omega\,(K_{e2}+K_{e2\gamma}^{IB})}}_{\text{acceptance ratio} = Q}$$

- Comparison of R_K with R_K^{SM}
  - also including $K_{e2\gamma}$ and $K_{\mu2\gamma}$

Systematic feature

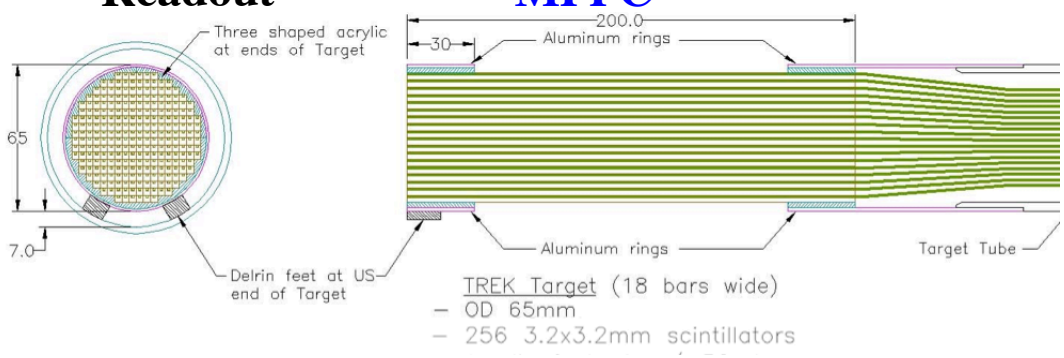
- Separate momentum spectra of $K_{e2(\gamma)}$ and $K_{\mu 2(\gamma)}$
  - No physics BG other than SD radiative decays
  - *c.f.* Overlap of M^2_{miss} of $K_{e2(\gamma)}$ and $K_{\mu 2(\gamma)}$ in in-flight-decay
- Significant systematics from possible detector acceptance difference between $K_{e2(\gamma)}$ and $K_{\mu 2(\gamma)}$
  1) slightly different spectrometer acceptance
  2) different interaction of e^+ and μ^+ in the target
- Acceptance difference should be carefully corrected



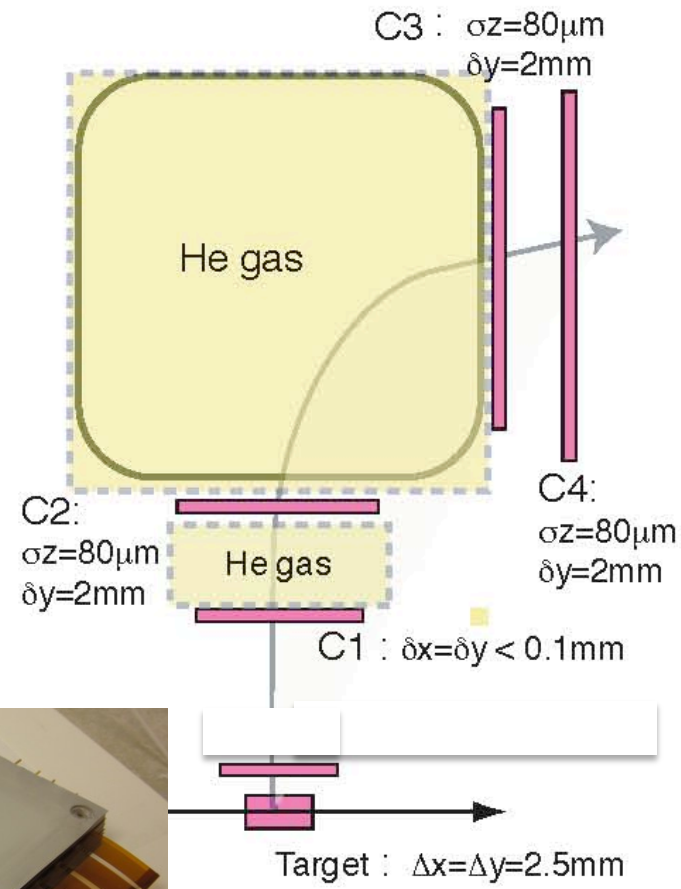
Detector components (1)

Fiber target

Active length (z)	**200 mm**
Active diameter (d)	**67 mm**
Fiber size	**3 x 3 mm**
Number of fibers	**256**
Readout	**MPPC**



Tracking system

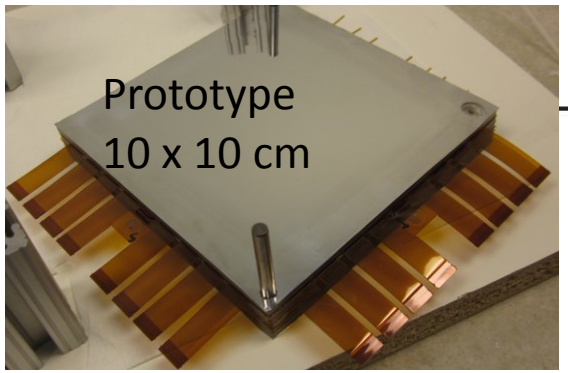


C2, C3, C4: MWPCs

C1 GEM

12 C1 triple-GEMs to cover muon holes of CsI(Tl)

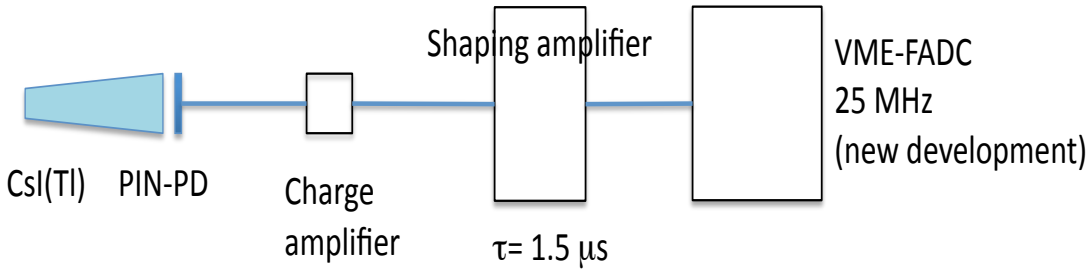
Active length (z)	**300 mm**
Active width (y)	**100 mm**
Spatial resolution	**<100 μm**
Readout strips: pitch	**400 μm**

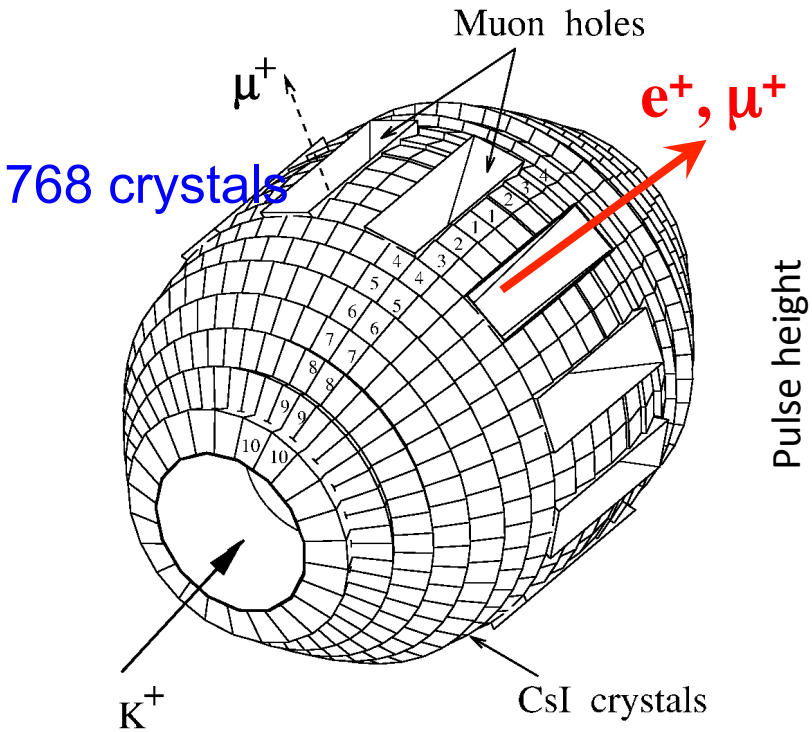


Detector components (2)

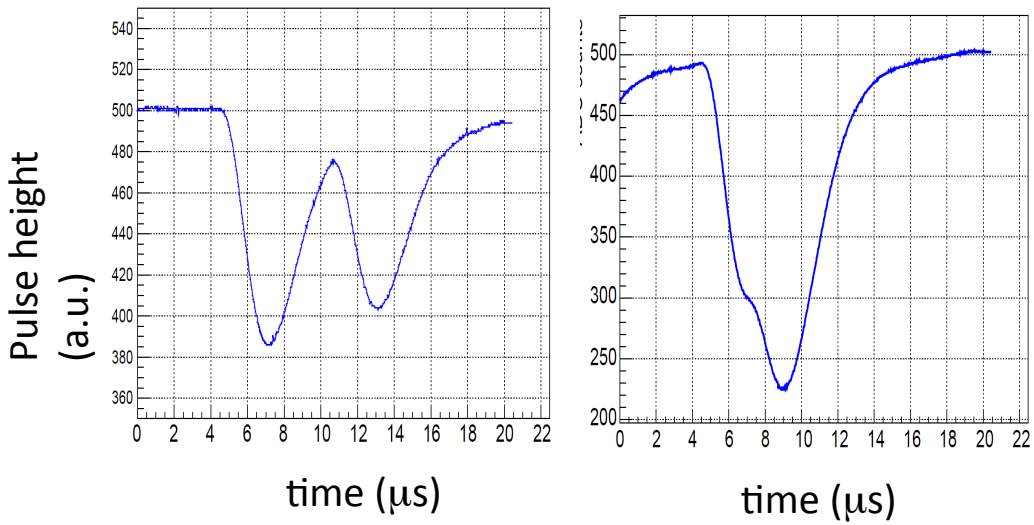
CsI(T*l*) calorimeter

Crystal length	**250 mm**
Number of crystals	**768**
Segmentation	**7.5°**
Coverage	**~75%**
Readout	**PIN**
Maximum rate	**~200 kHz**





Typical pileup events

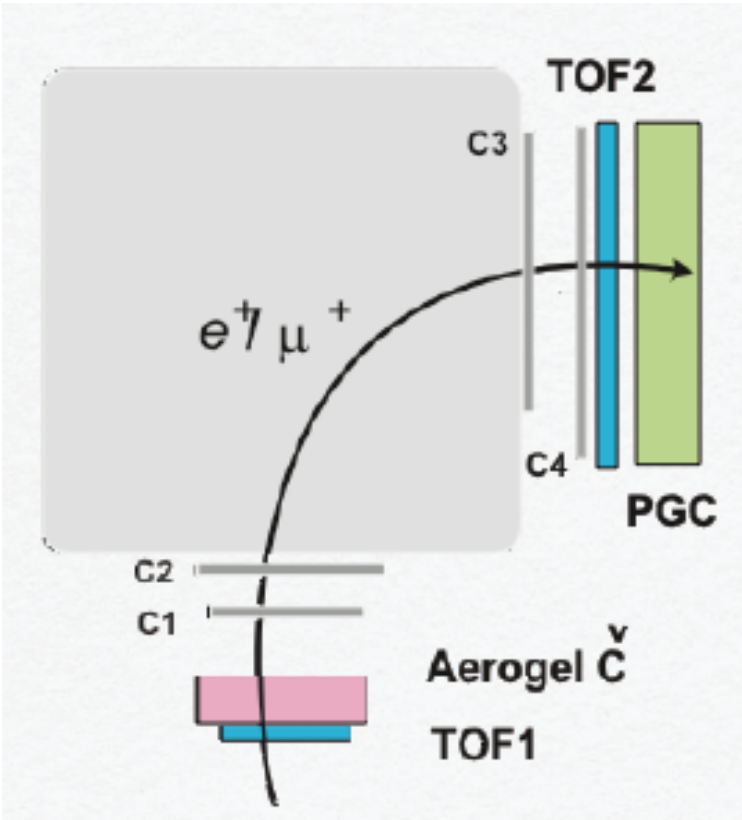


➢ *possible to separate with FADC*

e^+/μ^+ identification

PID with:

- TOF
- Aerogel Č
- Lead glass

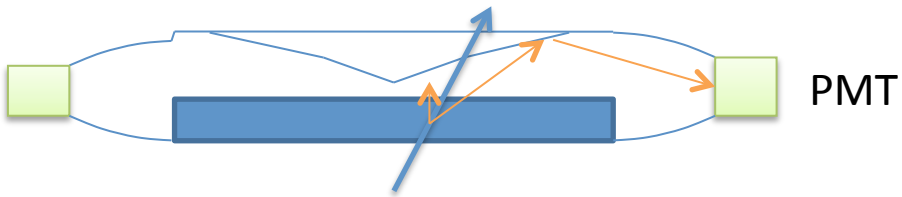


TOF

Flight length	**250 cm**
Time resolution	**<100 ps**
Mis-ID probability	**7×10^{-4}**

Aerogel Č counter

Radiator thickness	**4.0 cm**
Refraction index	**1.05**
Mis-ID probability	**3 %**



Lead glass

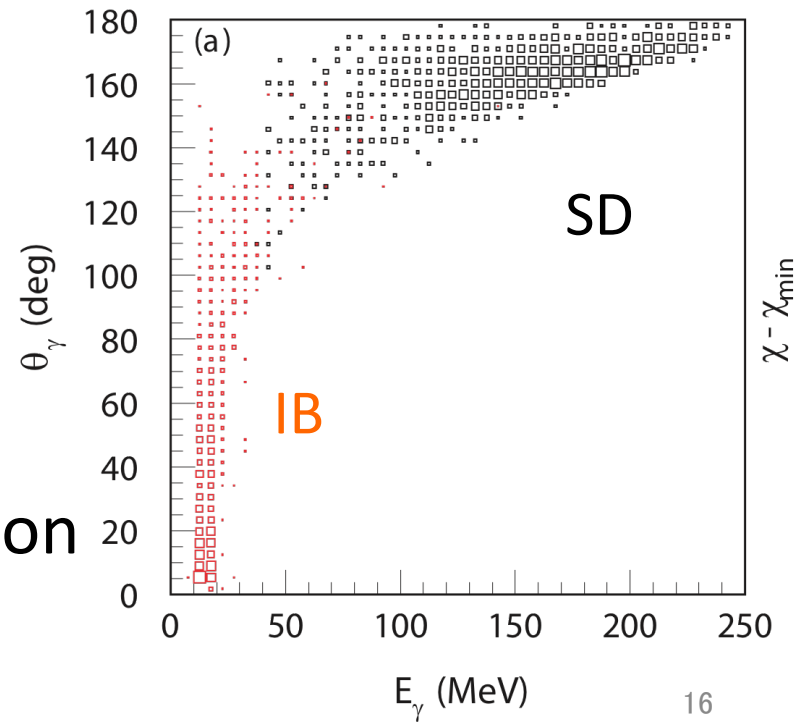
Material	**SF6W**
Refraction index	**1.05**
e^+ efficiency	**98 %**
Mis-ID probability	**4%**

$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7}$$

Subtraction of SD $K_{l2\gamma}$

- $K_{l2\gamma}$ = Internal bremsstrahlung (IB) : *calculable*
  + Structure dependent rad. (SD) : *ambiguous*
- SD is rejected as a background
- How to subtract SD:
  - measurement of E_γ and θ_γ
  - separation of SD from ID in the $E_\gamma - \theta_\gamma$ plot
  - determination of SD form factors
  - correction for no-γ SD events
- The error due to this subtraction process is estimated

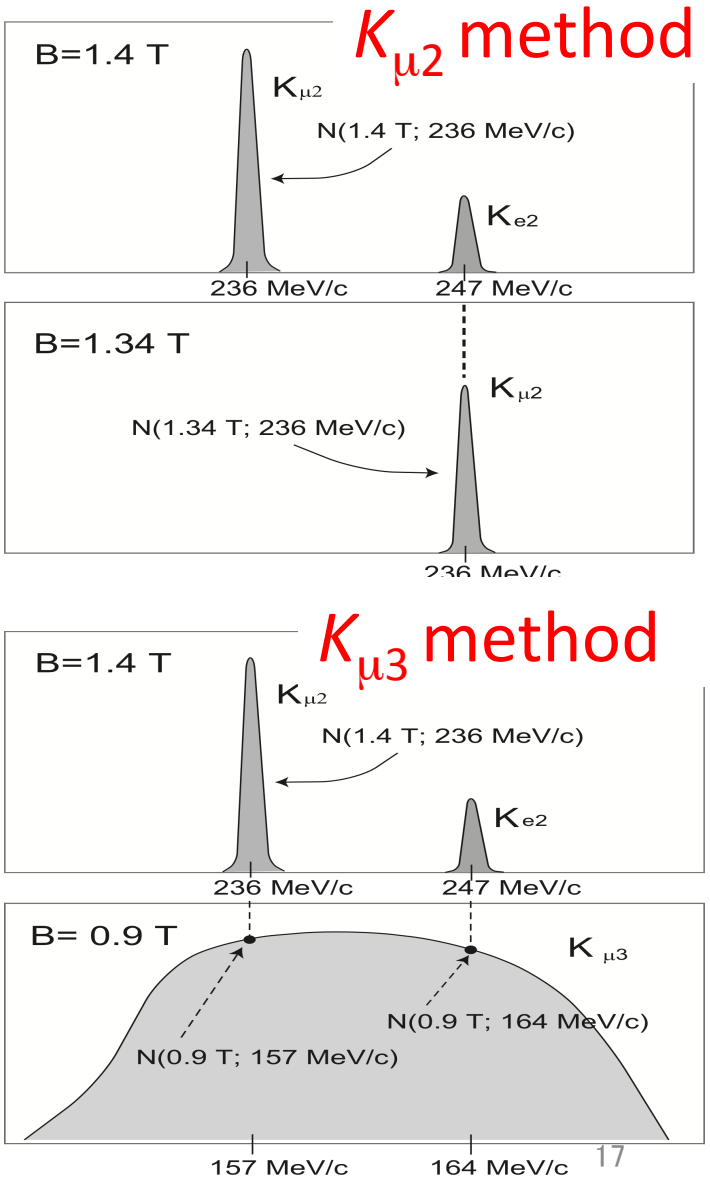
$E_\gamma - \theta_\gamma$ distribution in CsI(Tl)



Detector acceptance calibration

$$Q = \frac{N_{MC}^{accpt}(K_{e2} : B = 1.4\mathrm{T})}{N_{K_{e2}}^{decay}} \Big/ \frac{N_{MC}^{accpt}(K_{\mu 2} : B = 1.4\mathrm{T})}{N_{K_{\mu 2}}^{decay}}$$

- MC simulation
  - precise geometry input
- Use of $K_{\mu 2}$ peak
  - reduced magnetic field (1.34 T)
  - beam normalization needed
- Use of $K_{\mu 3}$ spectrum
  - reduced magnetic field (0.9T)
  - precise $K_{\mu 3}$ spectral shape needed
- Validity of these methods were checked using data and their systematic errors are estimated.



Systematic errors (1)

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

$$= \underbrace{N(\tilde{K}_{e2})/N(\tilde{K}_{\mu 2})}_{\text{Ratio of event rate}} \cdot \underbrace{\Omega(\tilde{K}_{\mu 2})/\Omega(\tilde{K}_{e2})}_{\text{Ratio of detector acceptance}}$$

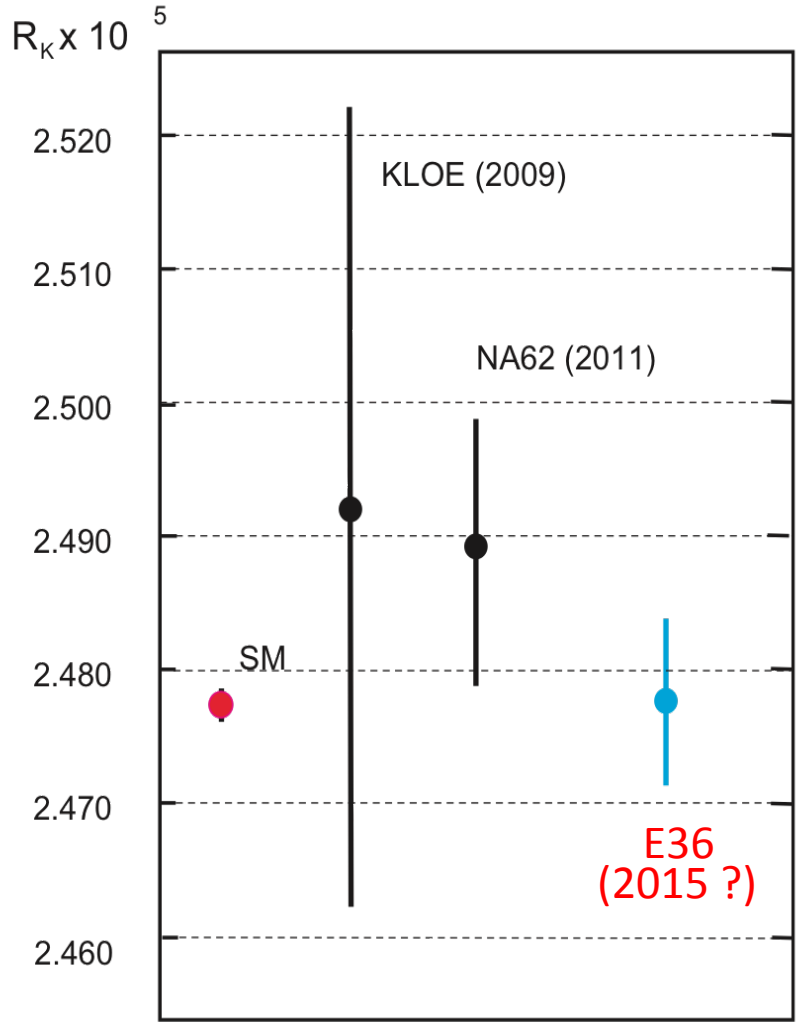
Category	Source
$N(K_{e2})/N(K_{\mu 2})$	1) Detector origin 2) Background origin 3) Analysis origin
$\Omega(K_{e2})/\Omega(K_{\mu 2})$ =Q	1) MC simulation

Error source	$\Delta R_K/R_K$
(1) **Detector performance**	
Chamber efficiency	0.0004
PID performance	0.00035
CsI(Tl) performance	0.0007
Trigger and DAQ	small
(2) **Background**	
Muon decay in flight	0.00015
Photon conversion	0.0002
CsI(Tl) beam hit	0.00018
AC beam hit	0.0001
K^+ conversion	0.00003
(3) **Analysis**	
Code and cut parameters	small
SD subtraction	0.00036
(4) **MC simulation**	
Acceptance ratio	0.00078
Magnetic field	small
Input parameters	small
Kaon stopping distribution	0.00015
Target interactions	0.0004
Material thickness	0.0002
IB theory	small
Total	0.0015

$\delta R_K/R_K(\text{syst}) = 0.0015$

Expected sensitivity

- Proton beam
  - 30 GeV , 30 kW
- K^+ beam
  - 800 MeV/c , 200 kHz
- Run time
  - 50 days
- Accumulated K_{e2}
  - 250,000
- Statistical error
  - $\delta R_K/R_K$(stat) = 0.0020
- Total error
  - $\delta R_K/R_K$(total) = 0.0025

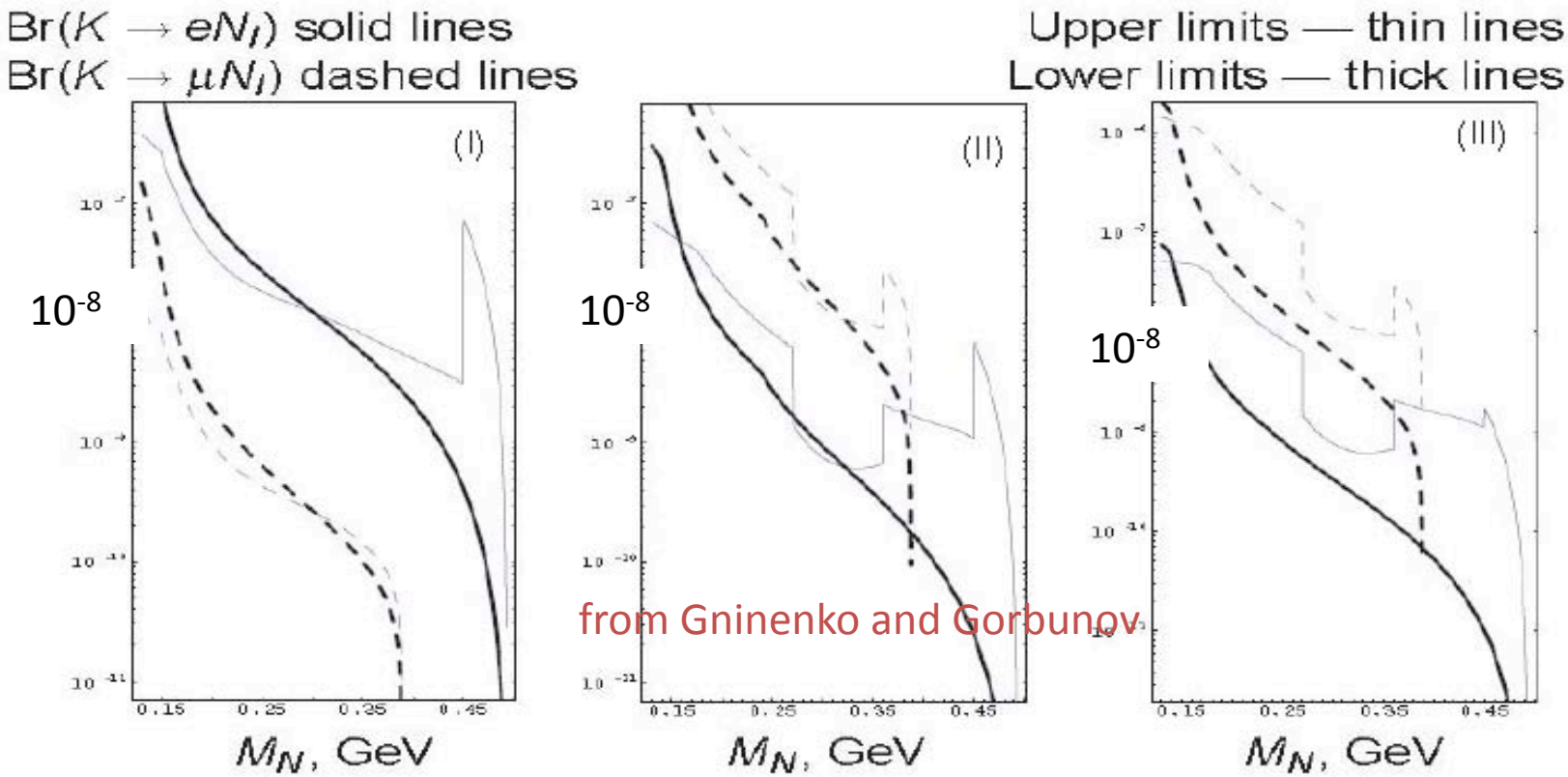


Byproduct (1)

- Search for heavy sterile ν (N) in $K^+ \rightarrow \mu^+ N$

Neutrino minimal standard model (νMSM)

- L.Canetti, M.Drewes, and M.Shaposhinikov, PRL 100, 061801 (2013)
- Gninenko and Gorbunov, hep-ph/0907.4666



from Gninenko and Gorbunov

- Sensitivity in E36 : BR($K^+ \rightarrow \mu N$) ~ 10^{-8}

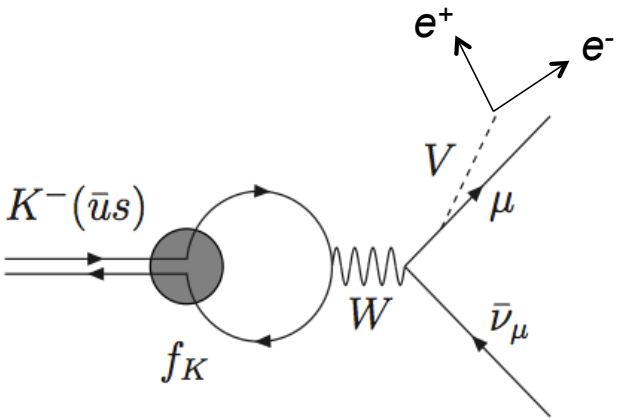
Byproduct (2)

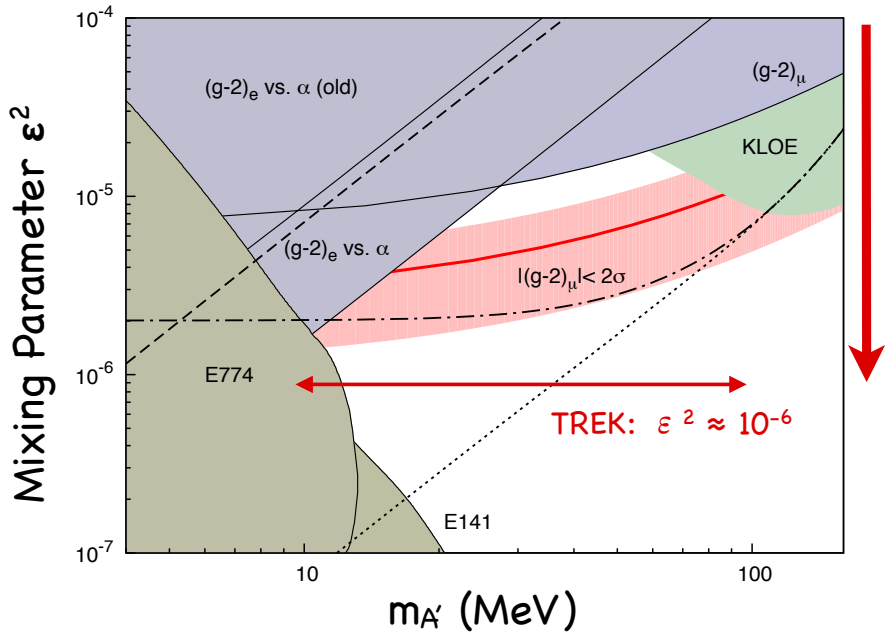
- Search for dark photon in $K^+ \to \mu^+ \nu\, e^+ e^-$

photon-like massive gauge boson V : $K^+ \to \mu^+ \nu V$, $V \to e^+ e^-$

Barger, Chiang, Keung, and Marfatia (arXiv:1109.6652)

Beranek and Vanderhaeghen, Phys. Rev. D87, 015124 (2013)





- $BR(K^+ \to \mu^+ \nu V) \approx \varepsilon^2 BR(K^+ \to \mu^+ \nu \gamma) = 0.55\ \varepsilon^2$
- Sensitivity of $\varepsilon^2 \approx 10^{-6}$ is feasible

Summary

- Lepton universality violation is a sensitive probe of new physics.
- J-PARC experiment E36, employing the K^+ stopped decay method, aims for $\delta R_K/R_K$=0.25%.
- E36 is schedule to run in 2014-2015. Now the detector is being prepared.
- As byproducts:
  - Heavy neutrino search, and dark photon search
- Final goal with the TREK detector :
  - E06 : Search for T violation in $K_{\mu 3}$ with transverse muon polarization