Status of the TREK/E36 Experiment at J-PARC

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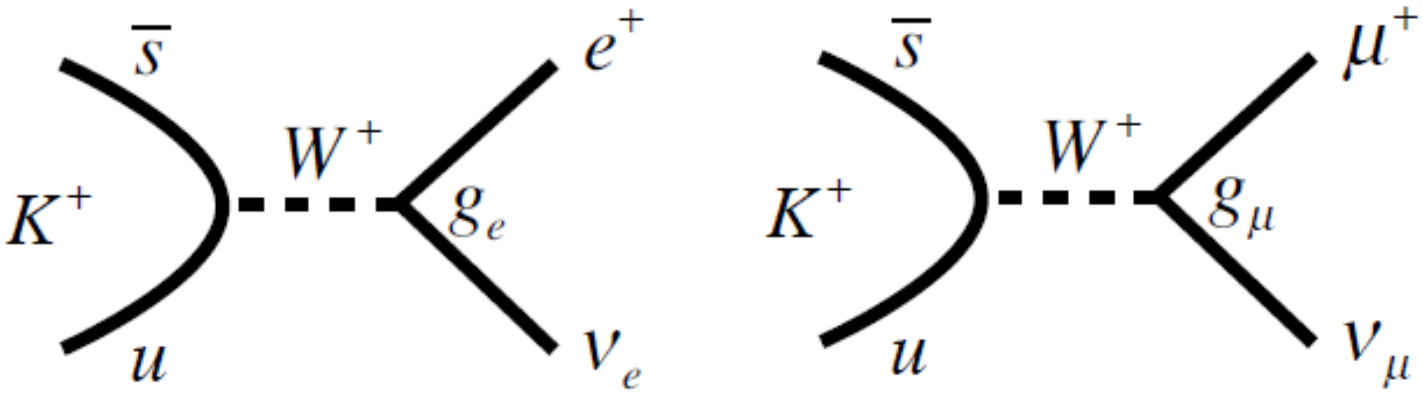
[1]University of Iowa

XIIIth International Conference on Heavy Quark and Leptons

Outline

Lepton Universality

e, μ, and τ: different mass, same gauge couplings (interaction).



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

Ratio: $R_K^{SM} = \frac{\Gamma(K_{e2})}{\Gamma(K_{\mu 2})} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 (1 - \delta R_{QED}) =$

$2.477(1) \times 10^{-5}$ with $g_e = g_\mu$, and $\delta R_{QED} = 0.036$ (PRL 99, 231801)

Recent and Proposed Measurement of R_K

KLOE@DAΦNE

$\Delta R_K/R_K \approx 1.3\%$, K in-flight decay, low intensity kaon beam

NA62@CERN-SPS

$\Delta R_K/R_K \approx 0.4\%$, K in-flight decay, e/μ kinematical separation at high momentum, μ^+ in-flight decay

KLOE: F. Ambrosino et al., Eur. Phys. J. C 64, 627 (2009), $R_K = (2.493 \pm 0.031) \times 10^{-5}$

NA62: C. Lazzeroni et al., Phys. Lett. B 719, 326 (2013), $R_K = (2.488 \pm 0.010) \times 10^{-5}$

LHCb

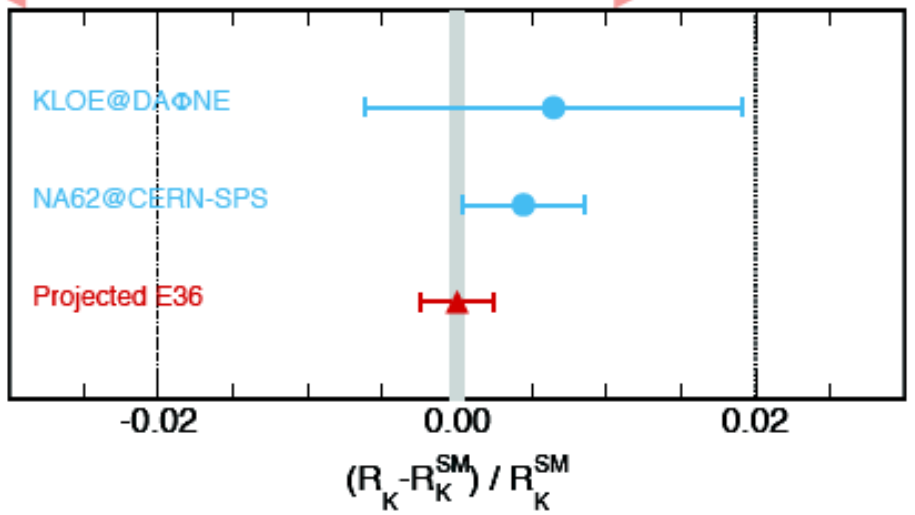
$$\frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.0036$$

Sensitive probe of LFV

A. Masiero, P. Paradisi, and R. Petronzio, Phys. Rev D 74, 011701(R) (2006)

dominant SUSY contribution + interference between SM and SUSY LFC terms (-3.2%)

dominant SUSY contribution (1.3%)

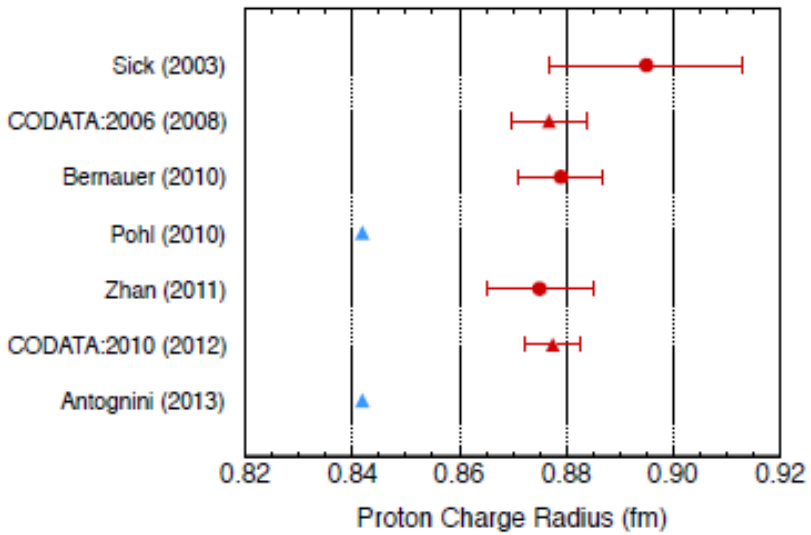


Proposed TREK E36

- proposed uncertainties:
  $\Delta R_K/R_K = \pm 0.20\%$ (stat) $\pm$ 0.15% (syst) = $\pm 0.25\%$
- stopped K beam; complementary to in-flight exp.

Proton Radius Puzzle

The discrepancy between muonic and electronic measurements of the proton radius is a 7σ effect.



▲ Spectroscopy

● Scattering

$r_p = 0.84184(67)$ fm

$r_p = 0.875(10)$ fm

$r_p = 0.8768(69)$ fm

$r_p = 0.84087(39)$ fm

I. Sick, PLB 576, 62 (2003); P.J. Mohr et al., Rev. Mod. Phys. 80, 633 (2008); J.C Bernauer et al., PRL 105, 242001 (2010); R. Pohl et al., Nature 466, 213 (2010); X. Zhan et al., PLB 705, 59 (2011); P.J. Mohr et al., Rev. Mod. Phys. 84, 1527 (2012); A. Antognini et al., Science 339, 417 (2013)

Possible explanations of the proton-radius puzzle

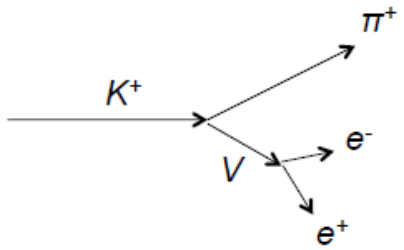
- Beyond Standard Model Physics: **Violation of μ - e universality**
- Novel Hadronic Physics: Strong-interaction effect entering in a loop diagram is important for μp but not for ep.
- Electron scattering & atomic hydrogen data and radius extraction not as accurate as previously reported.

Search for Heavy/Dark Photon

- What is Heavy/Dark Photon: A U(1) extension of the Standard Model in “dark” sector
- Mixing with photon by spontaneously symmetry breaking with a parameter ϵ
- In simplest model, it weakly couples to charge with strength ϵe

Estimate Dark Photon Events

- Light mediator of dark force coupled to SM via kinetic mixing; motivated by astrophysics, $g_\mu - 2$, and R_p
- Measure all charged decay particles and search for peak in the e^+e^- invariant mass spectrum in the range 0-300 MeV

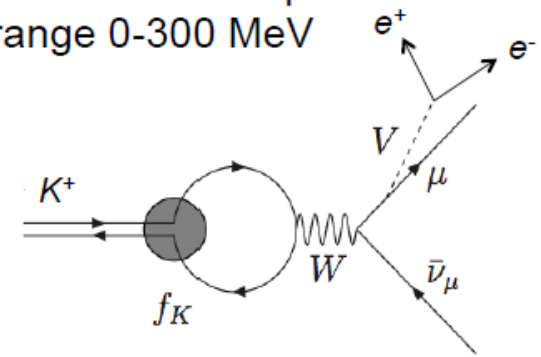


$K^+ \to \pi^+ e^+ e^-$ ($\Delta S = 1$)

$K_{\pi 2}$: $K^+ \to \pi^+ \pi^0$ (~10^{10} events)

Signal: BR($K^+ \to \pi^+ V$) ~10^{-8}
$V \to e^+e^-$ (~100 events)

Background:
BR($K^+ \to \pi^+ e^+ e^-$) ~ 2.9 x 10^{-7}



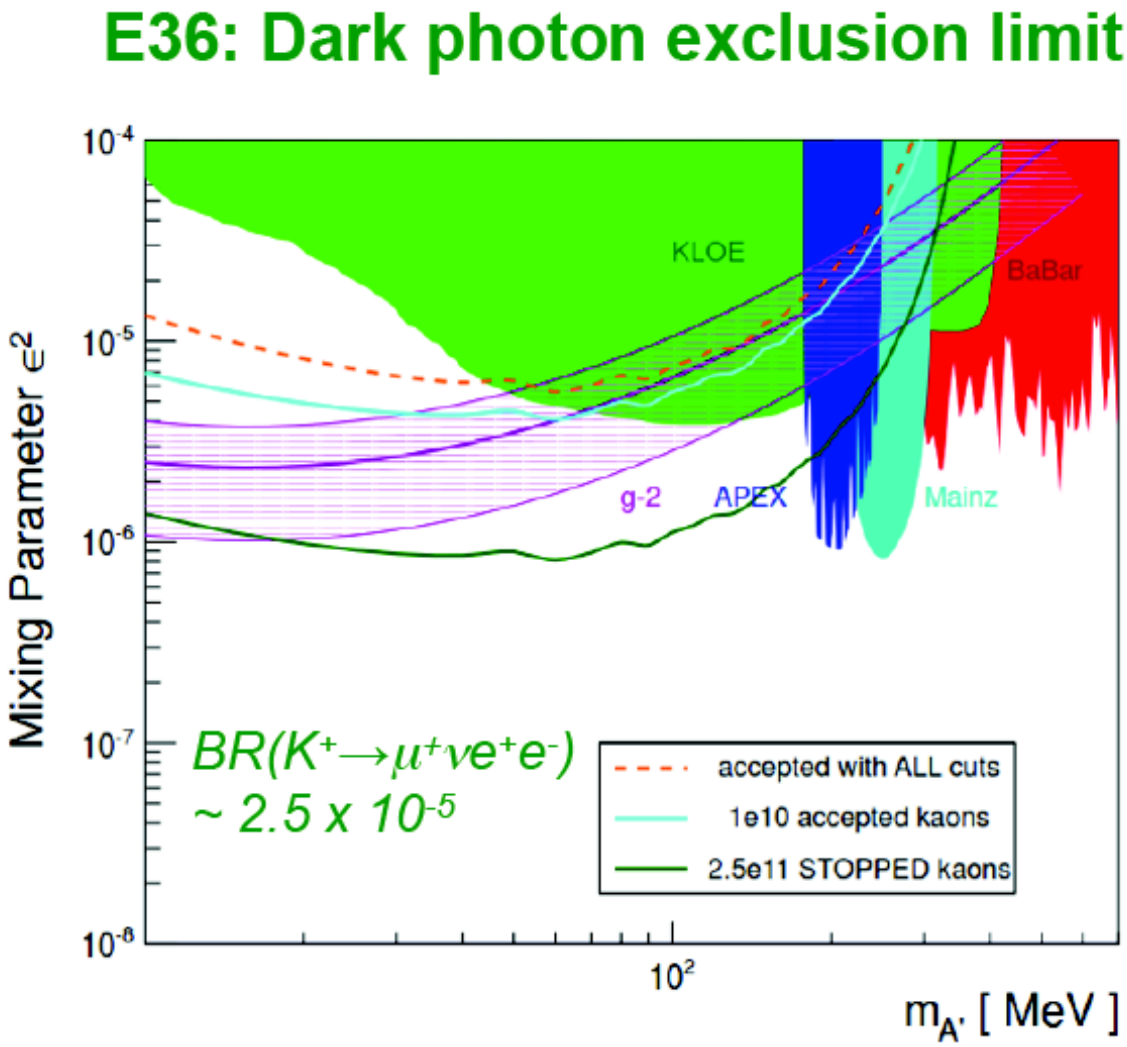
$K_{\mu 2}$: $K^+ \to \mu^+ \nu$ (~10^{10} events)

$K_{\mu 2\gamma}$: $K^+ \to \mu^+ \nu \gamma$ (~10^7 events)

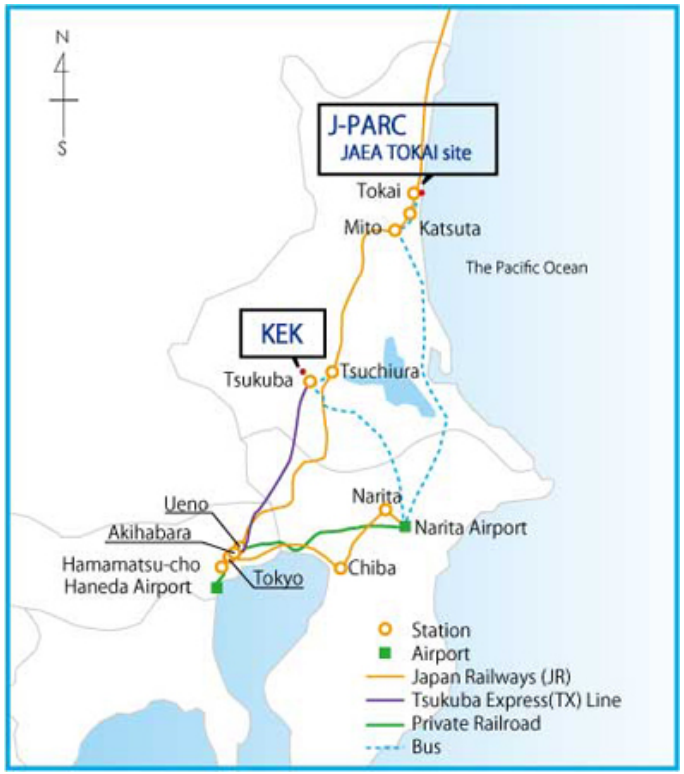
Signal: BR($K^+ \to \mu^+ \nu V$) ~10^{-8}
$V \to e^+e^-$ (~100 events)

Background:
BR($K^+ \to \mu^+ \nu e^+ e^-$) ~ 2.5 x 10^{-5}

Dark Photon Exclusion Limit



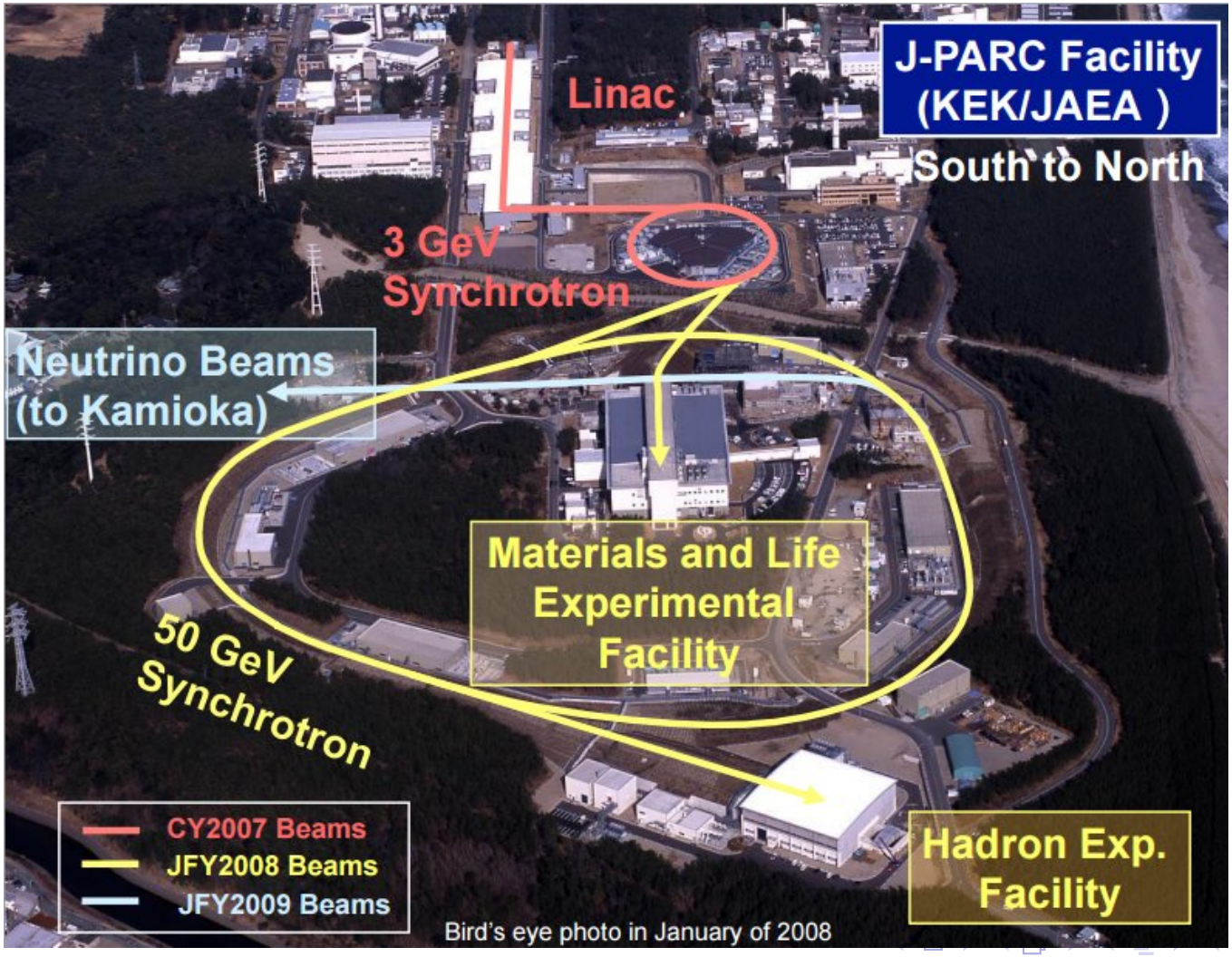
Where is JPARC



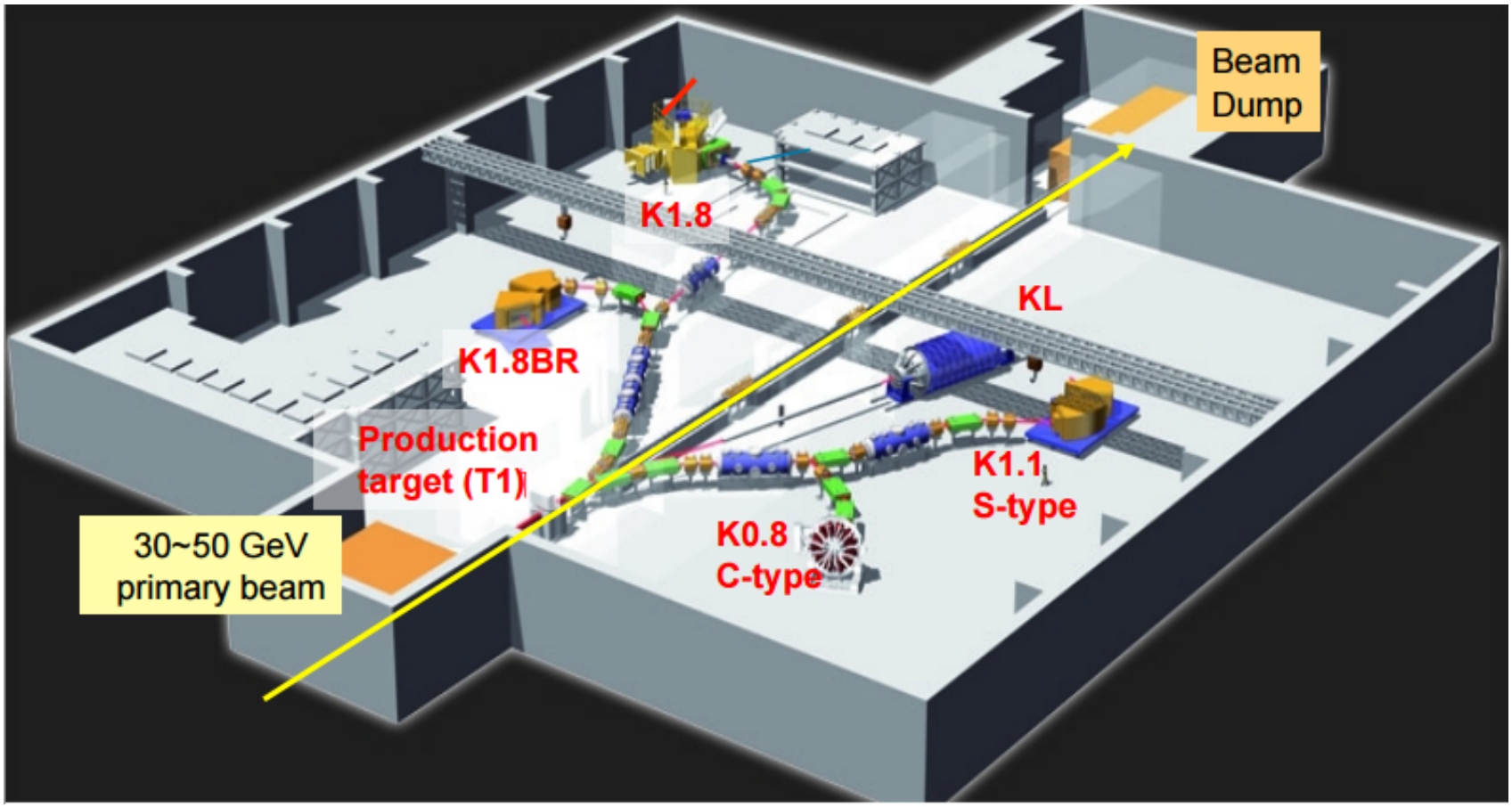
About 80 km north of Narita Airport and 115 km northeast of Tokyo.

J-PARC March11 Earthquake Damage

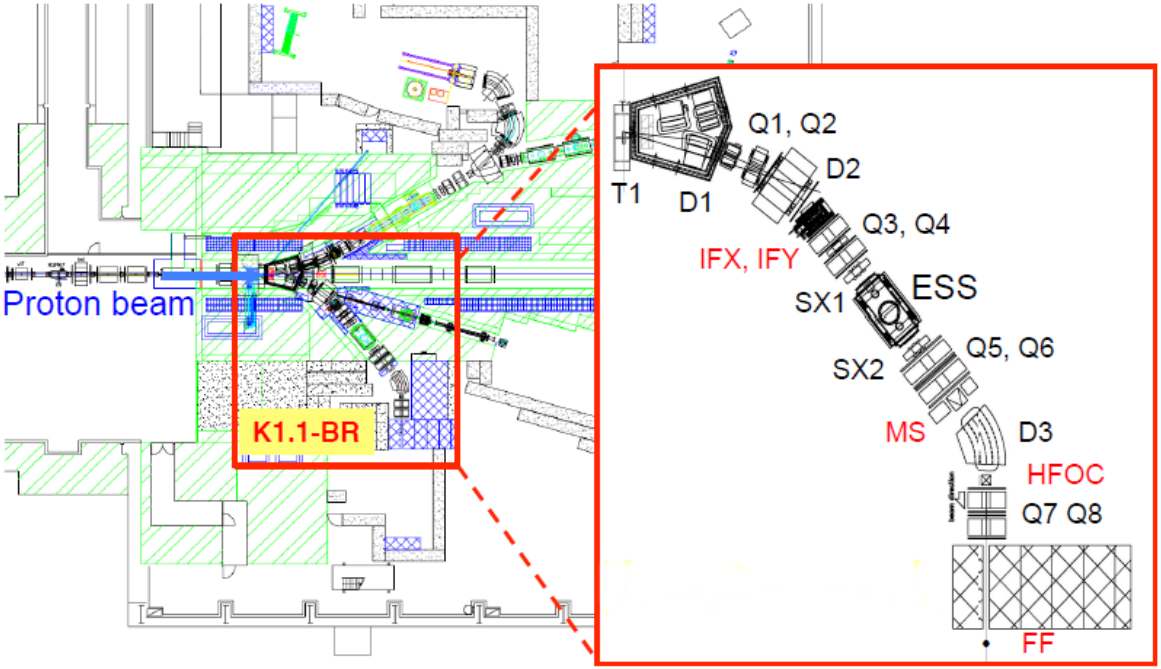
JPARC Facilities



JPARC Hadron Hall

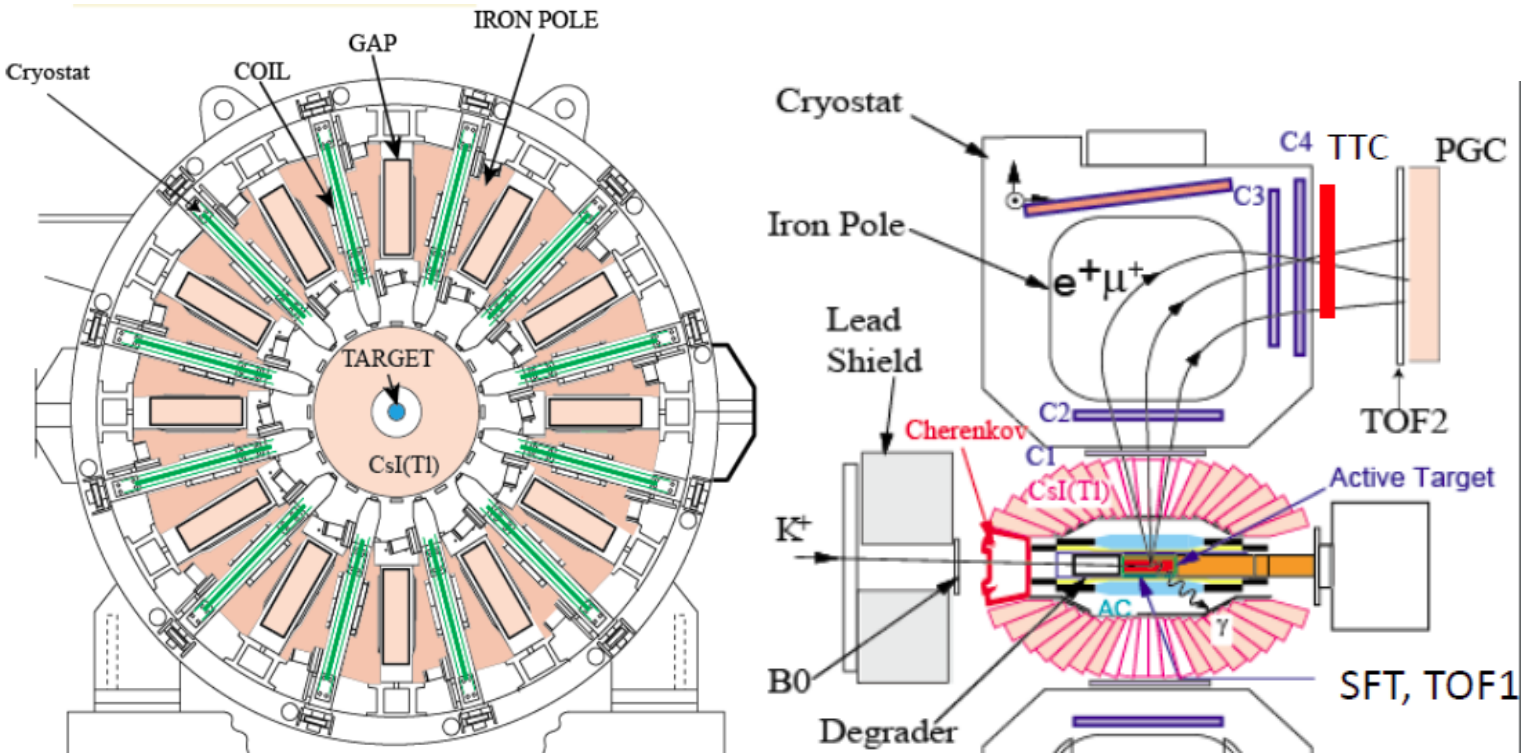


Secondary Beam Line



- K1.1BR constructed in 2009/10, commissioned by TREK Coll. in Oct. 2010
- Re-aligned after 11/3/11 earthquake, re-commissioned in June 2012
- π/K ratio of 1.0 observed with 1.4x10^6 K^+/spill @ 40kW

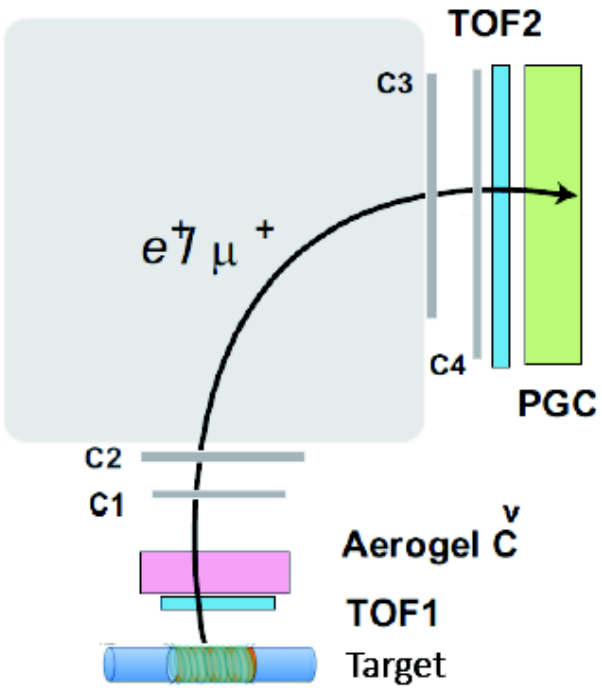
Overview of Detector



Fitch Cherenkov; Active target; MWPC (C2, C3, C4); Spiral Fiber Tracker (SFT); TOF1,2;Aerogel Cherenkov (AC); Pb-glass counter (PGC); CsI(Tl)

Particle Identification

PID with:
- TOF
- Aerogel Č
- Lead glass

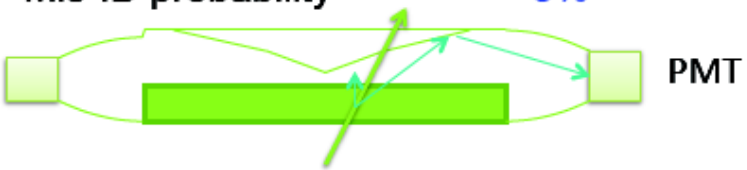


TOF

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

Aerogel Č counter

Radiator thickness	4.0 cm
Refraction index	1.08
e^+ efficiency	>98%
Mis-ID probability	3%

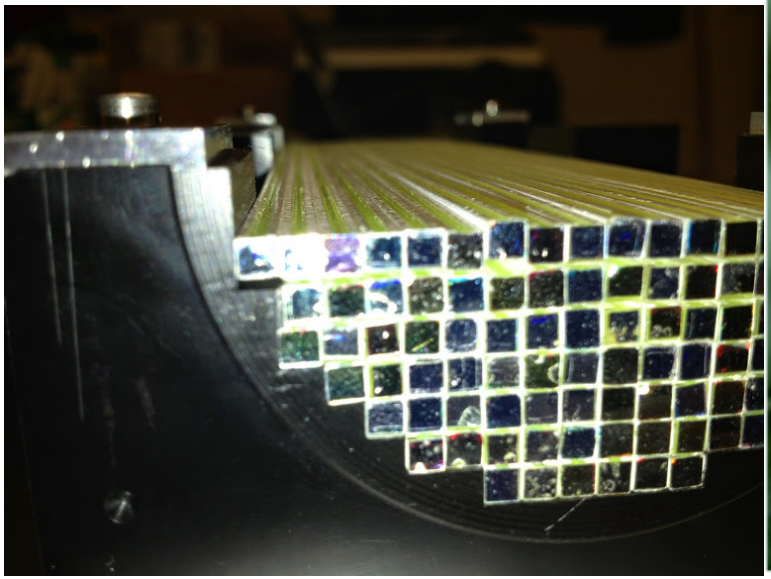


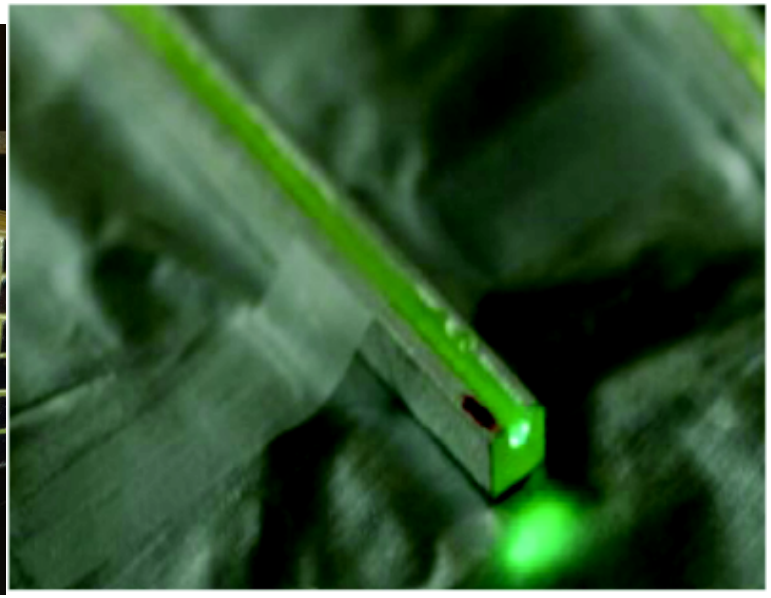
Lead glass (PGC)

Material	SF6W
Refraction index	1.5
e^+ efficiency	98%
Mis-ID probability	4%

$$P_{mis}(\text{total}) = P_{mis}(\text{TOF}) \times P_{mis}(\text{AČ}) \times P_{mis}(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

Active Stopping Target

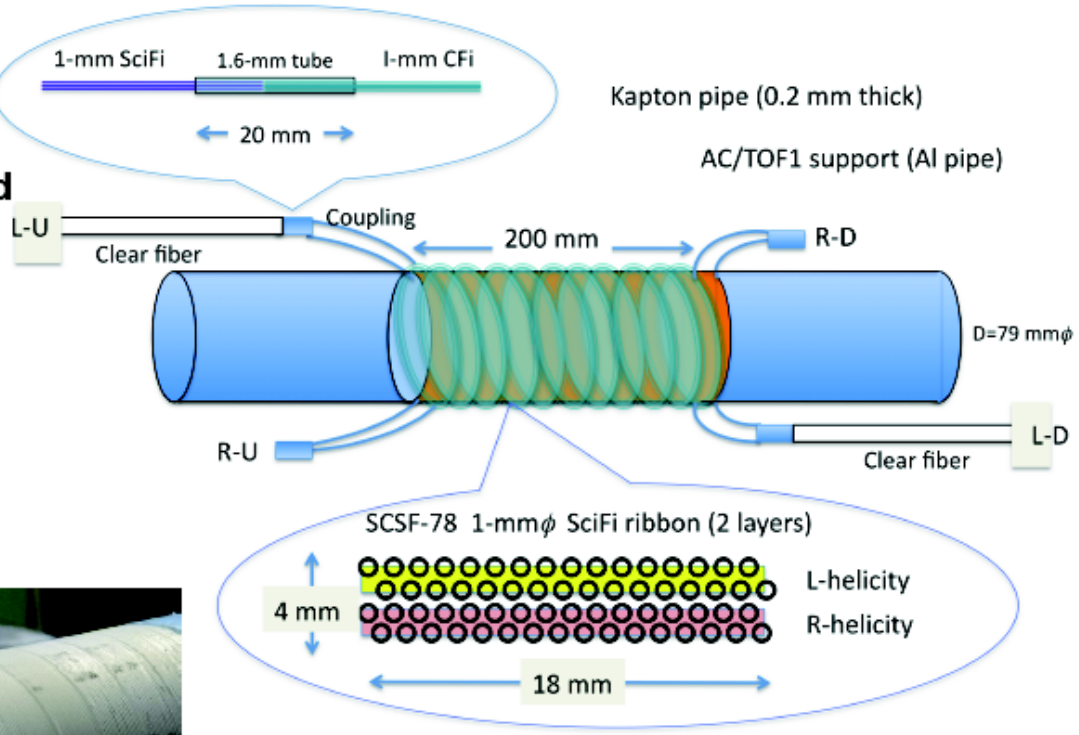


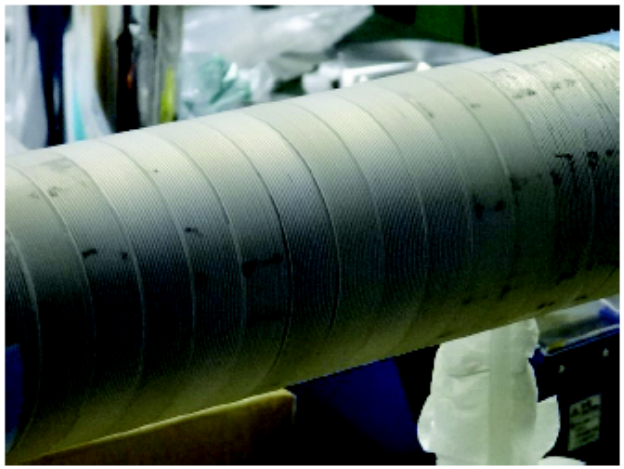


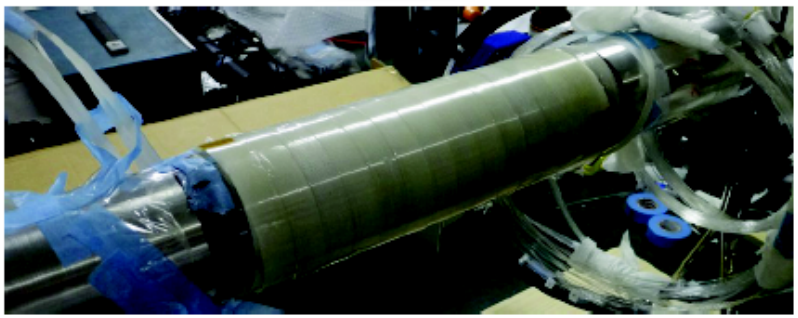
- Built at TRIUMF (Canada)
- 256 scintillating fibers (3x3 mm^2), WLS fiber in groove
- Multi-Pixel Photon Counter (MPPC) readout

Spiraling Fiber Tracker (SFT)

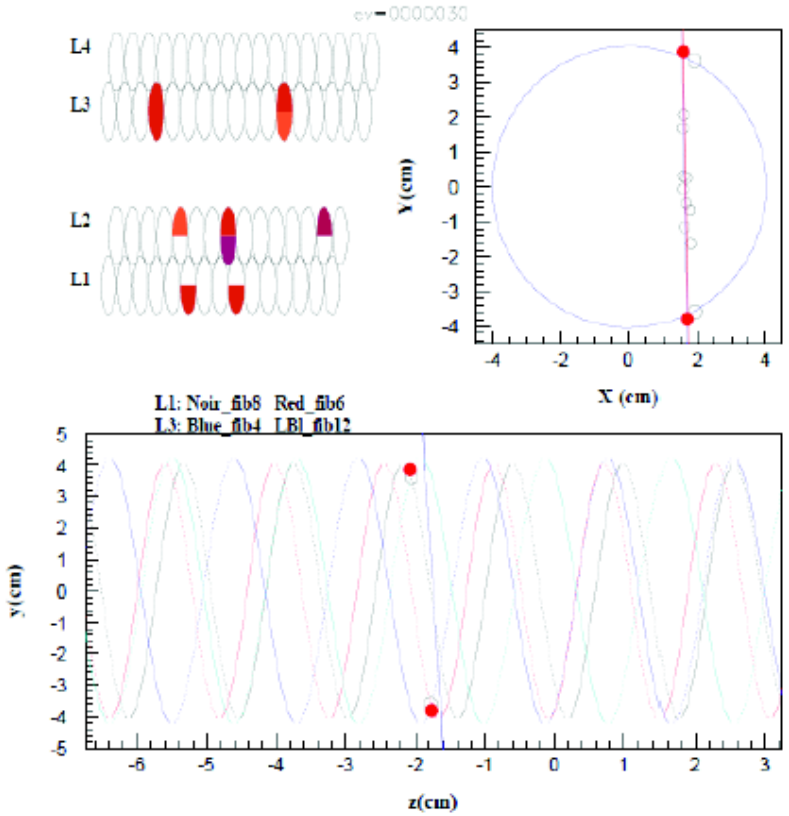
- **Double-layer fibers in 2 helicities wrapped around target bundle for near target vertex**
- **Using spare MPPC channels from fiber target**



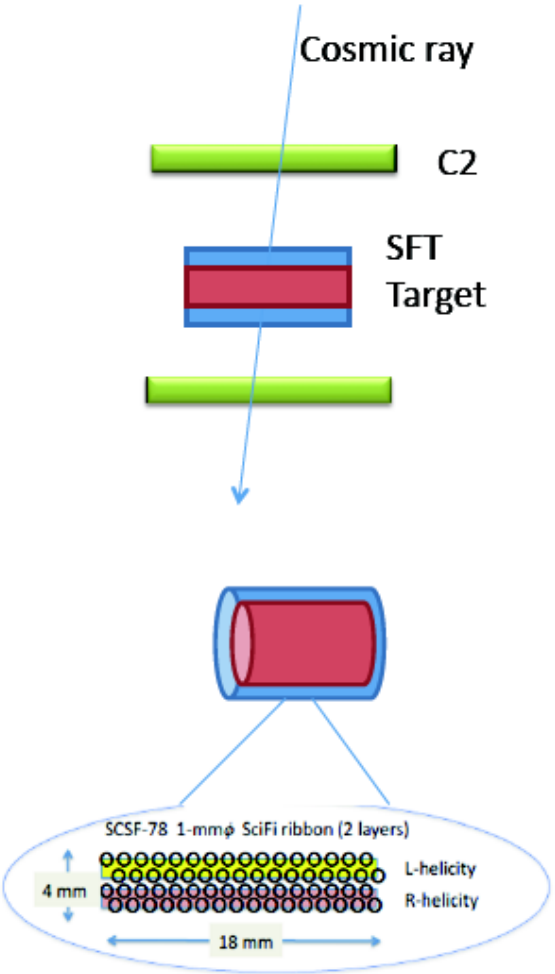




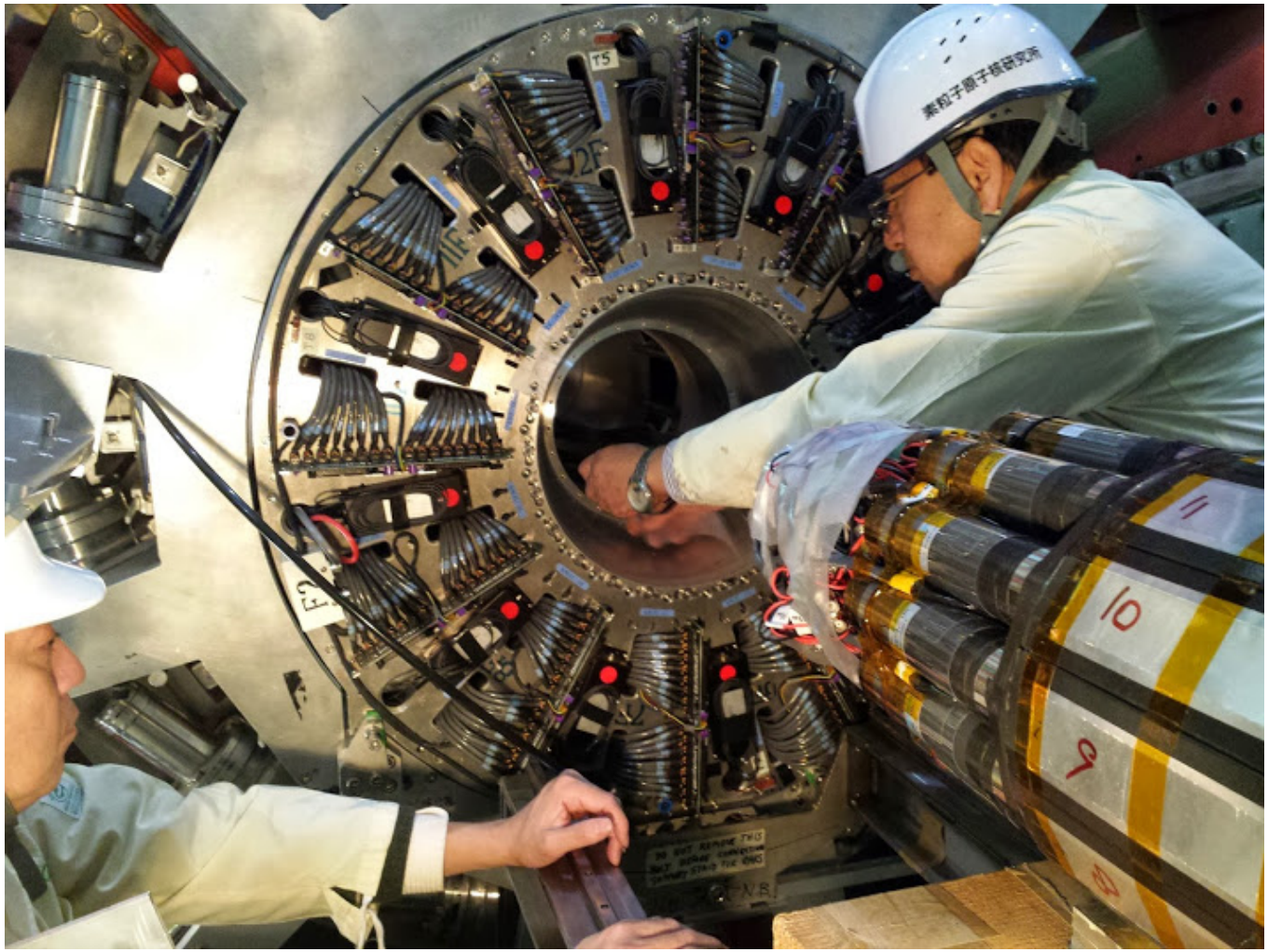
Central Detector



SFT+Target consistency established with C-ray

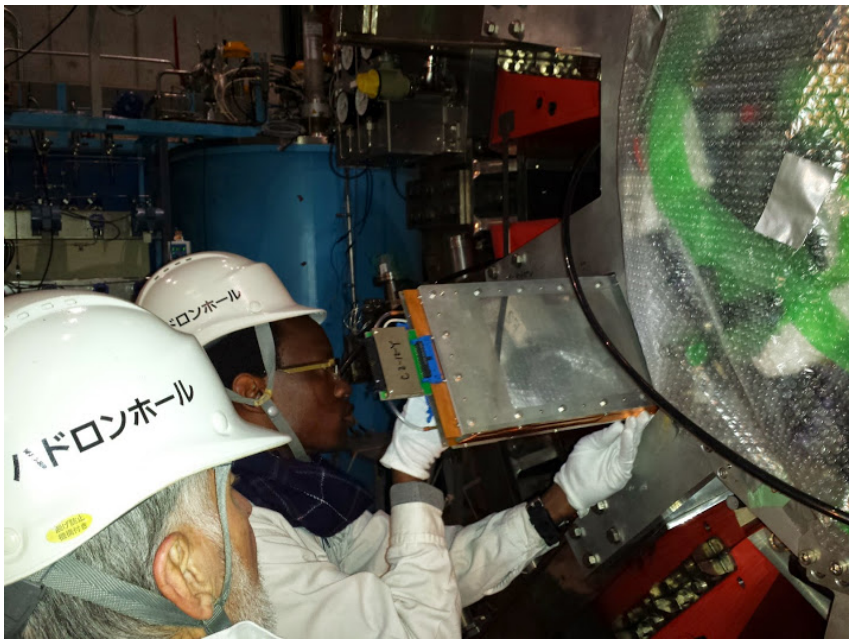


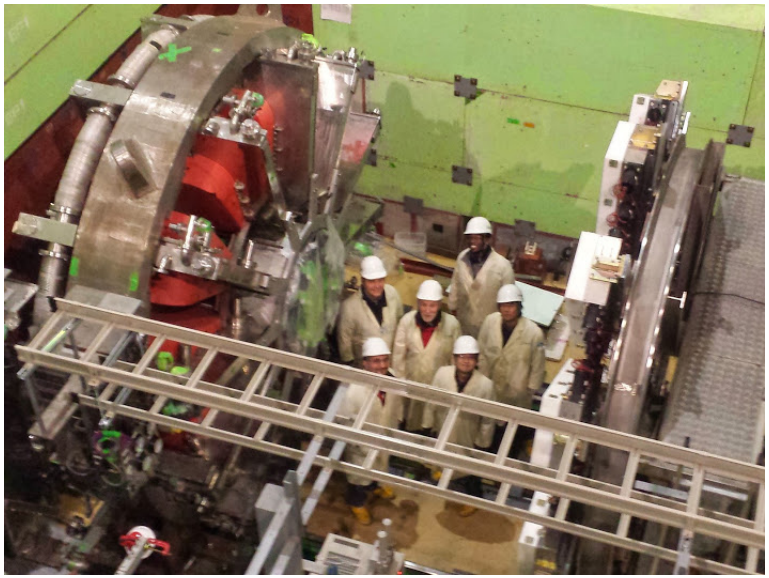
Target Installation



Timeline and Milestones

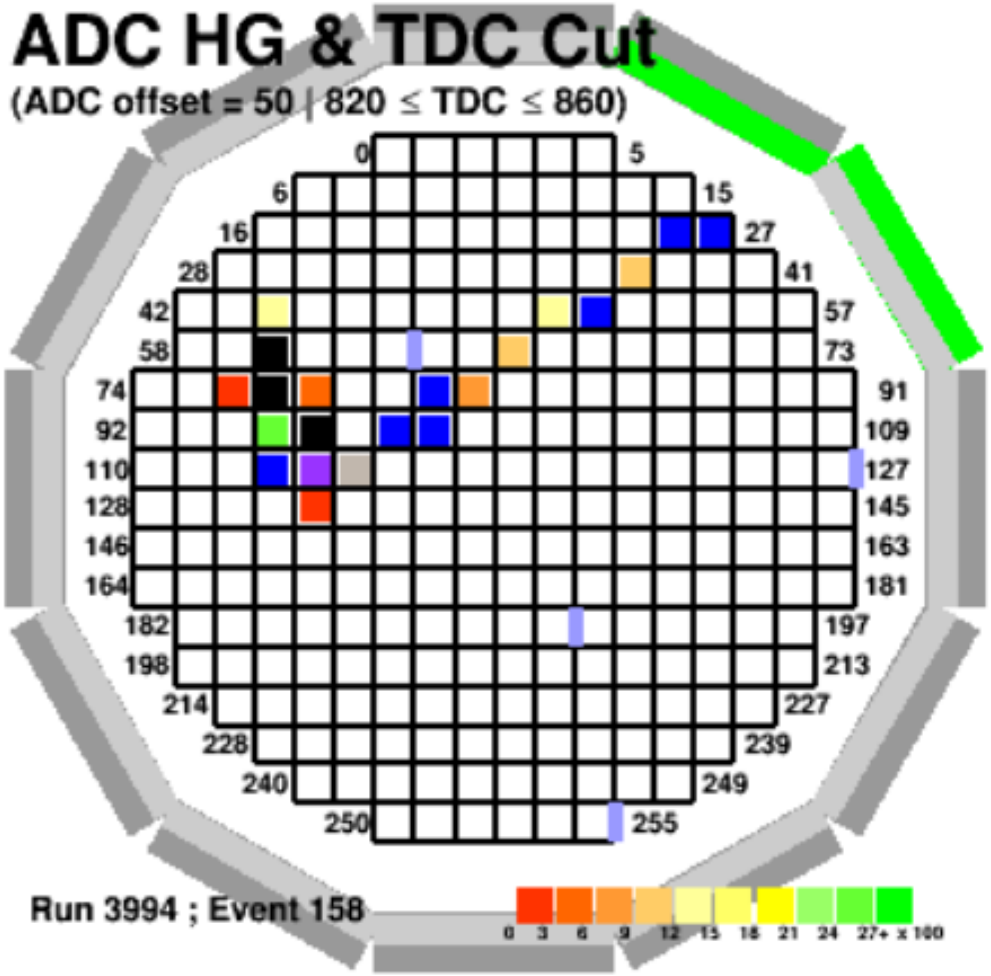
- Area available in November 2014
- Installation completed in Apr. 2015
- Commissioning/production run in June 2015





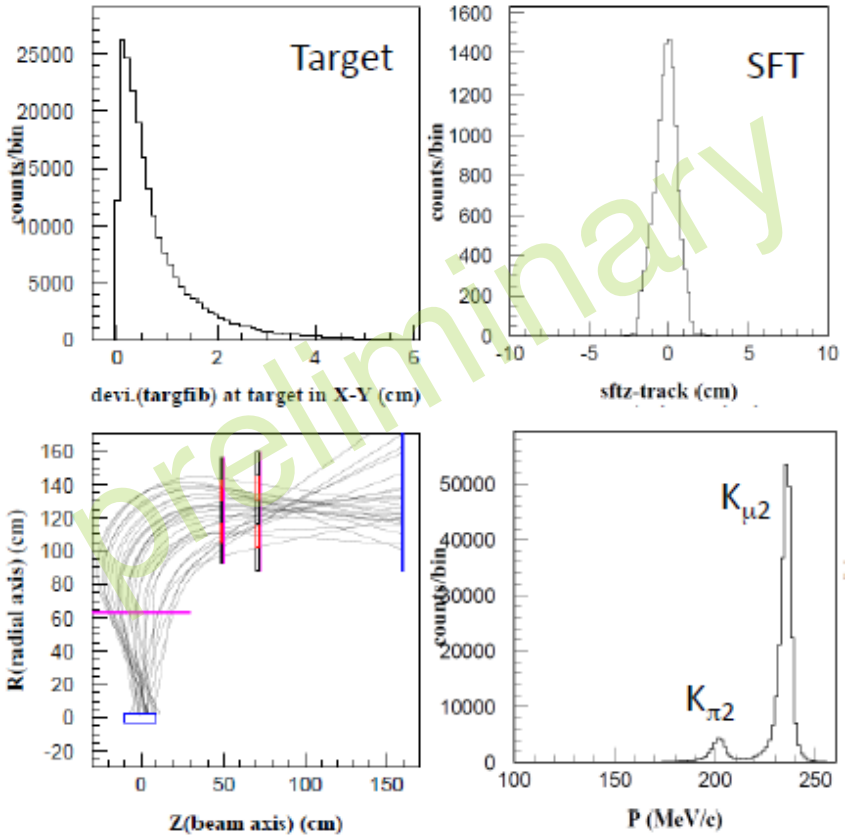
- Commissioning data check and detector conditioning during summer 2015
- TTC added to improve trigger during summer 2015
- Production runs from Oct. to Dec. 2015

Event Display



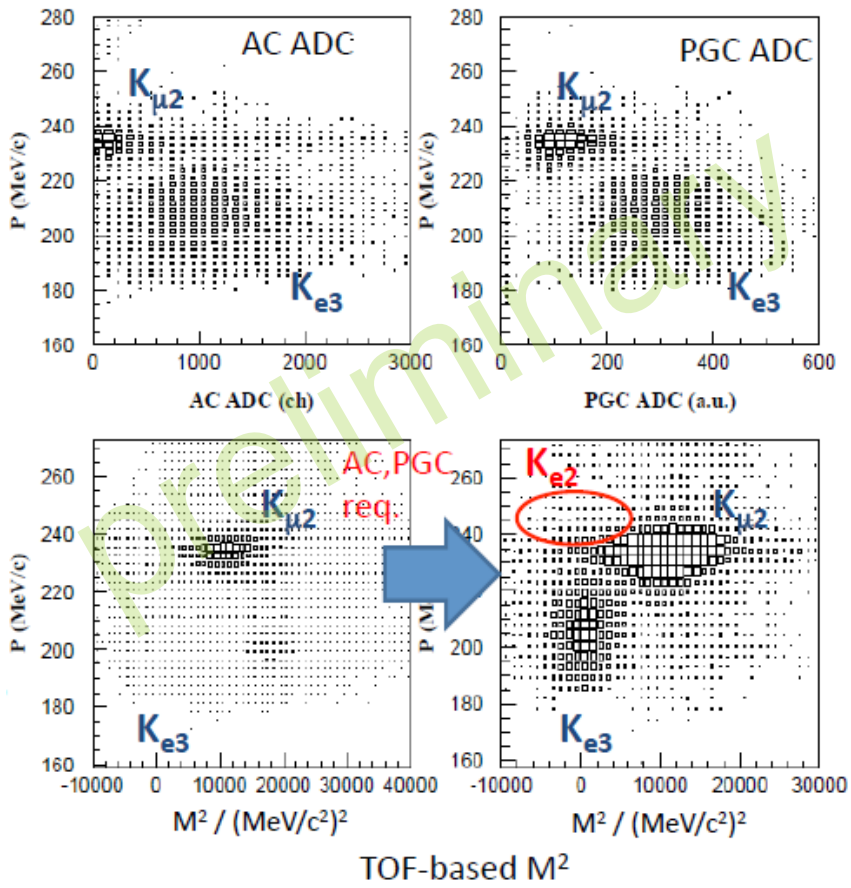
Track Reconstruction

- Charged particle momentum determined by 3-point tracking (c2, c3, c4)
- Event selection requires track consistency with target and SFT
- Monochromatic peaks from $K_{\mu 2}$ and $K_{\pi 2}$



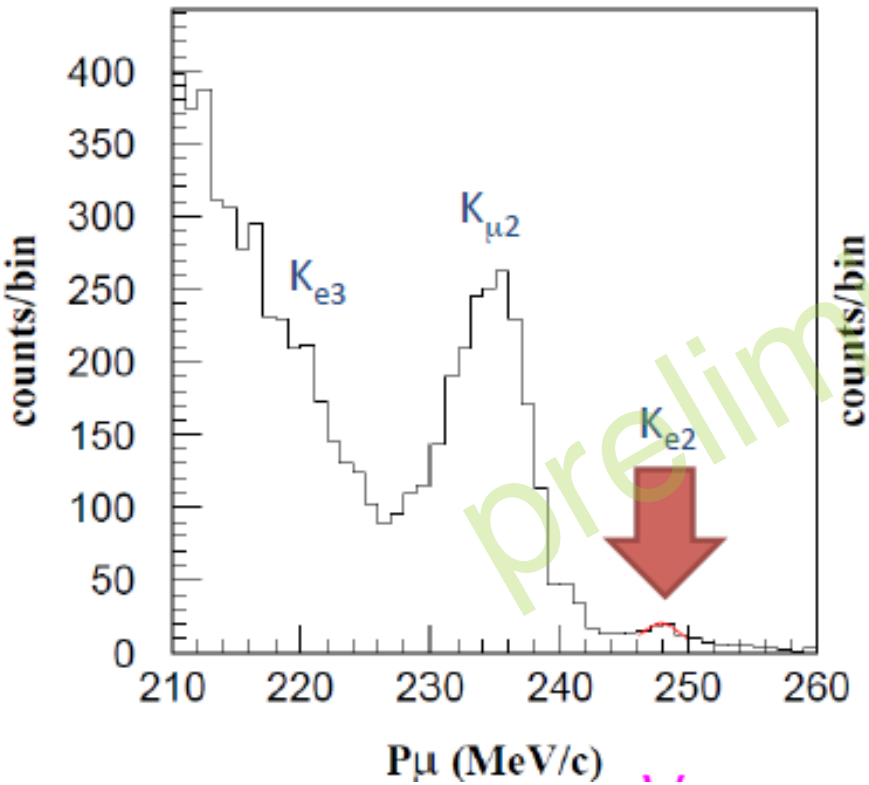
PID by AC, PGC, and TOF

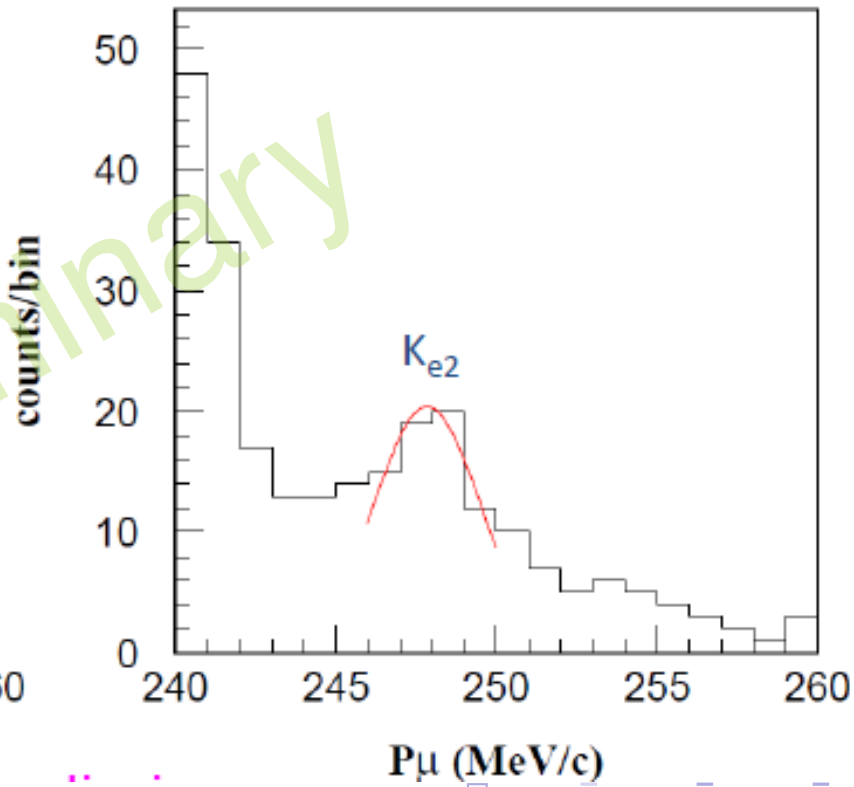
- AC and PGC performing as expected
- TOF resolution performing as expected after fixing under-performed TOF1 (after June)
- Suppression of muon mis-identification below 10^{-8} achievable with refined analysis
- Quantitative analysis in progress



K_{e2} events

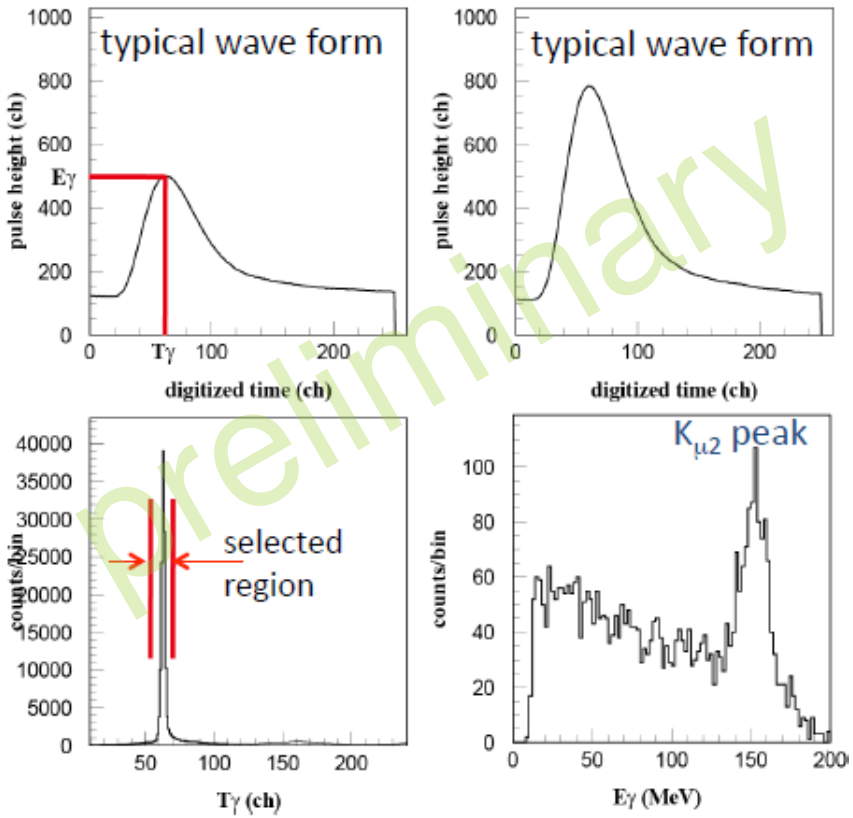
- Observed K_{e2} peak in momentum spectrum
- Statistics from 100 runs in June data
- Estimate >40K K_{e2} events in fall 2015 based on $K_{\mu 2}$ events





CsI(Tl) Calorimeter Analysis

- Energy and timing obtained by pulse data from FADC (VF48)
- $K_{\mu 2}$ events with single crystal hit used for energy calibration



Summary

- The first high precision experiment of Ke2/Kmu2 ratio using stopped kaons
- Successful completion of runs in 2015
- Search for Dark Photon and other U(1) Bosons
- Calibration and analysis by two parallel groups
- Pursue TREK/E06 (T-violation) in the future at extended Hadron Hall

TREK/E36 Collaboration

- University of British Columbia, Canada
- TRIUMF, Canada
- University of South Carolina, US
- University of Iowa, US
- Hampton University, US
- Osaka University, Japan
- Chiba University, Japan
- Rikkyo University, Japan
- KEK, Japan
- Institute for Nuclear Research, Russia

Backup

STOP

Lepton Universality Violation in K_{l2}

- SUSY with LFV for K_{e2}
  - Charged Higgs H^+ mediated LFV SUSY
  - Large enhancement from m_τ^2/m_e^2
  - A sizable effect of $\Delta R_K/R_K$~1.3% possible

J. Girrbach and U. Nierste, arXiv:1202.4906;
A. Masiero, P. Paradisi, and R. Petronzio, Phys. Rev. D 74, 011701 (2006); JHEP11, 042 (2008)

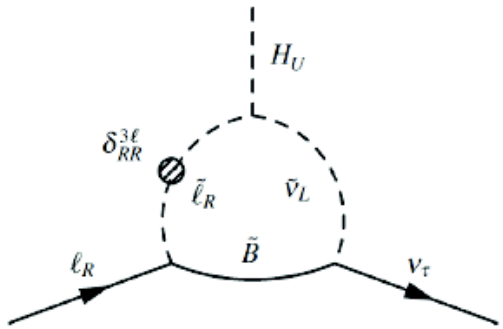


FIG. 1. Contribution to the effective $\tilde{\nu}_\tau \ell_R H^+$ coupling.

- General discussions on SUSY effects

R.M. Fonseca, J.C. Romão, A.M. Teixeira, Eur. Phys. J. C 72, 2228 (2012)

  - strong constraints from $B_s \to \mu^+\mu^-$ and $B_u \to \tau\nu$
  - $|\Delta R_K/R_K| \sim O(10^{-3})$

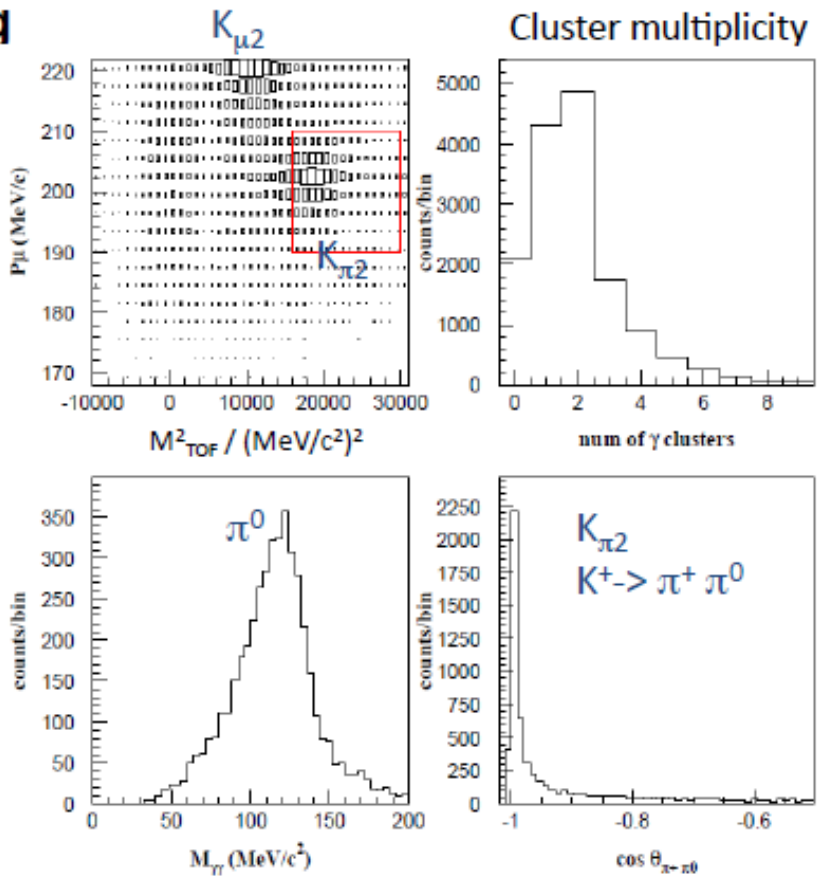
- Neutrino mixing

R_K constrains neutrino mixing parameters within SM extensions involving

  - 4th generation of quarks and leptons H. Lacker, A. Menzel, JHEP07, 006 (2010)
  - sterile neutrinos A. Abada et al., JHEP02, 048 (2013) [arXiv: 1211.3052]

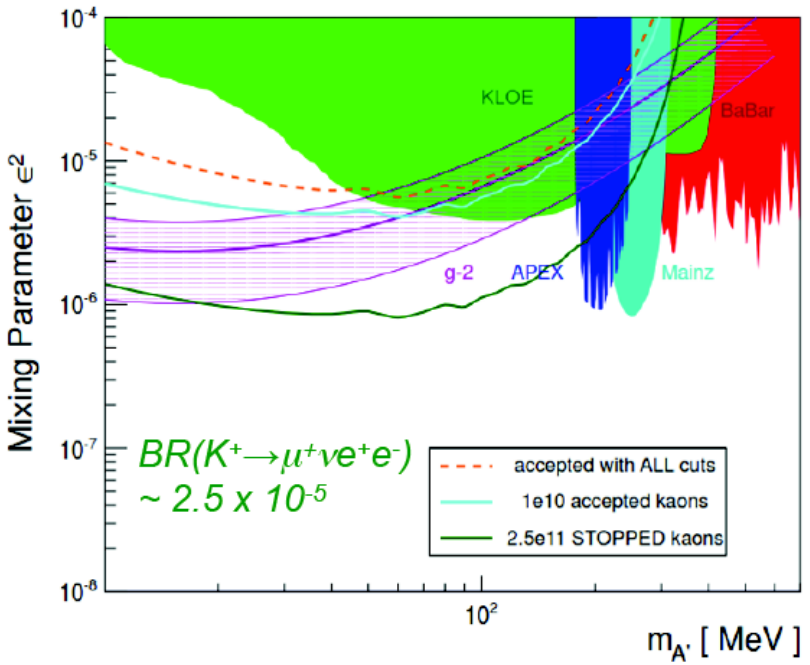
Pion from CsI

- $K_{\pi 2}$ events selected by analyzing momentum and TOF (M^2)
- π^0 invariant mass reconstructed by selecting two-cluster events
- Large π^+ / π^0 opening angle obtained
- Confirmed that the total E36 system works correctly and is consistent with E246

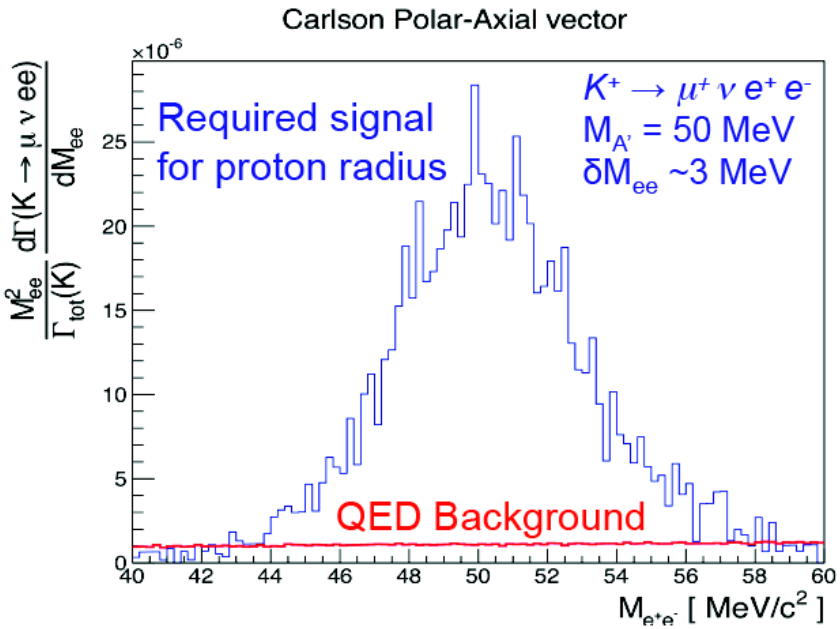


Dark Photon in E36

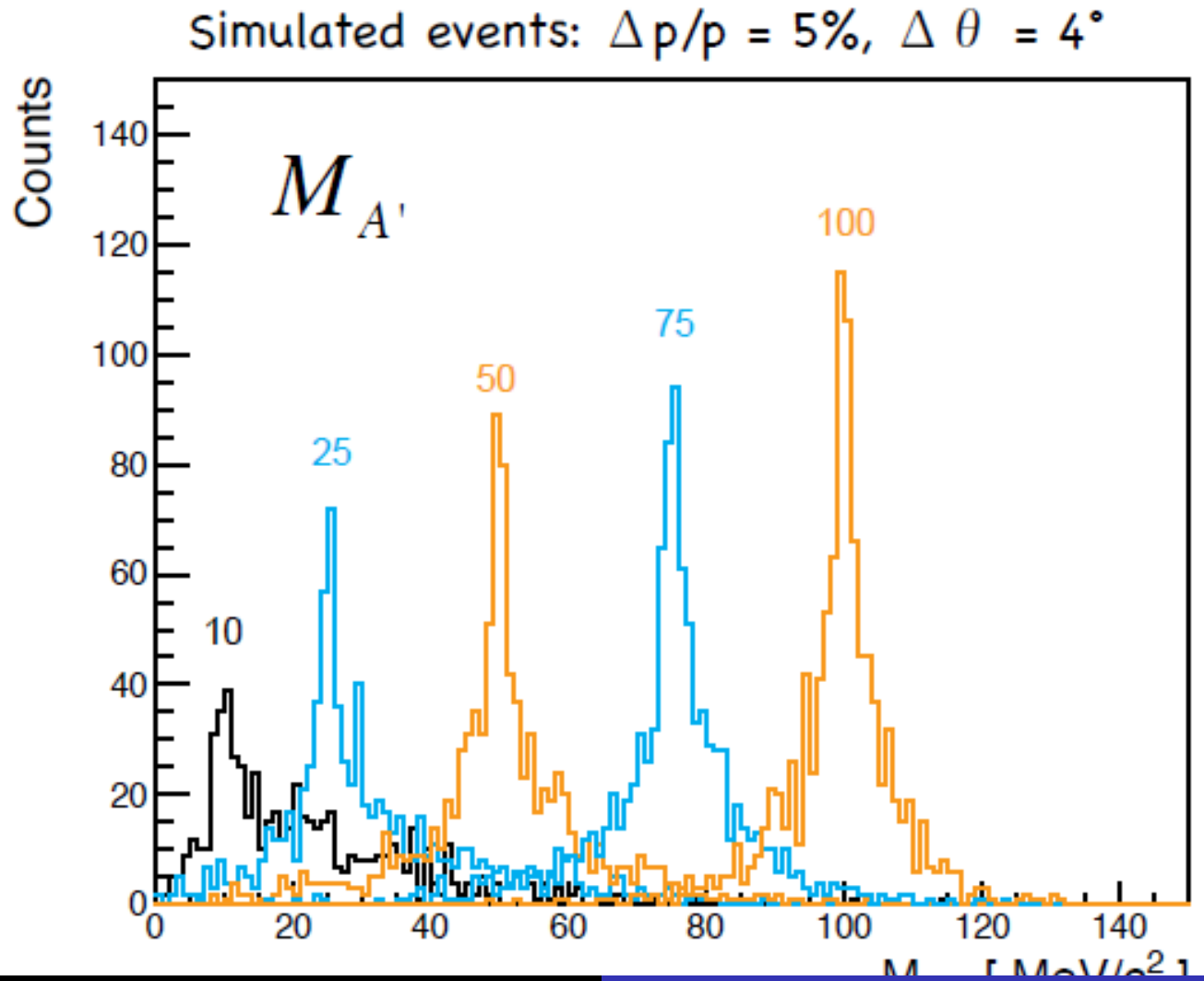
E36: Dark photon exclusion limit



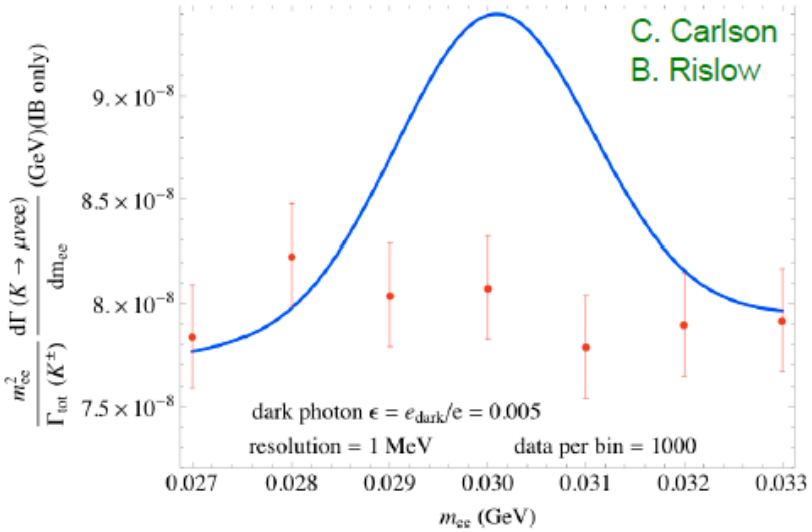
E36: Light boson expected signal



Dark Photon Simulation



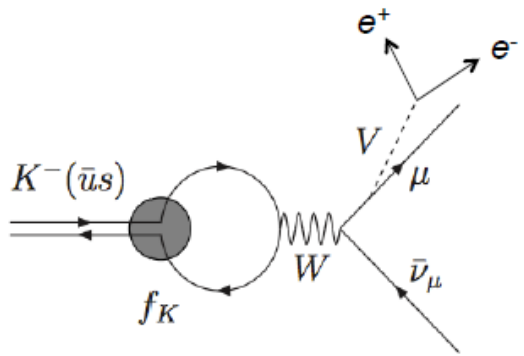
Dark Photon Simulation



QED background: $K^+ \to \mu^+ \nu\, e^+ e^-$
- $\Gamma(K^+ \to \mu^+ \nu\, ee) \sim 2.5 \times 10^{-5}$
- *Expect 10^{10} stopped K^+ in E36*
- *250k QED evts or ~1000 / MeV*

Signal: $K^+ \to \mu^+ \nu A'$
$A' \to e^+ e^-$ (30 MeV)

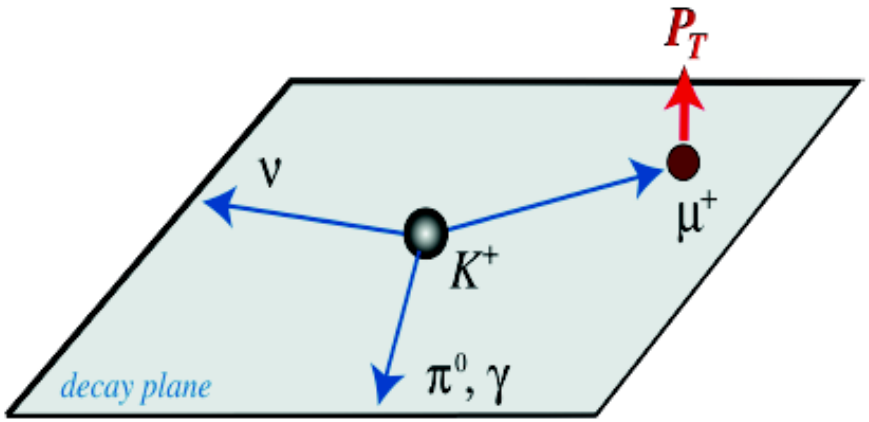
Assumed:
- *Eff. coupling $\varepsilon^2 \sim 2.5 \times 10^{-5}$*
- *m_{ee} resolution 1 MeV*



Now investigating for E36:
- Achievable resolution for m_{ee}
- Exclusion limits for ε^2 versus m_{ee} (likely in the $\varepsilon^2 \sim 10^{-6}$ region)

P. Monaghan, B. Dongwi

E06



- $K^+ \rightarrow \pi^0 \mu^+ \nu$
- Decay at rest
- T-odd correlation

$$P_L = \frac{\vec{\sigma}_\mu \cdot \vec{p}_\mu}{|\vec{p}_\mu|},$$

$$P_N = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu))}{|\vec{p}_\mu \times (\vec{p}_\pi \times \vec{p}_\mu)|},$$

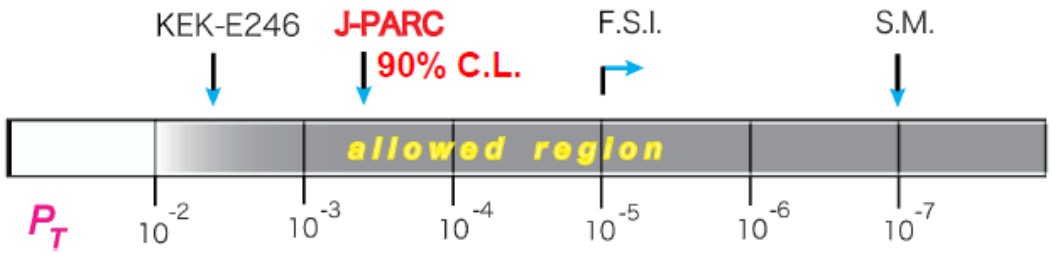
$$P_T = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|}.$$

$P_T \neq 0$ ⇒ T violation
(CPT theorem) ⇒ CP violation
Sakurai 1957

KEK-E246:
$P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(sys)$
$(|P_T| < 0.0050 : 90\%\ C.L.)$

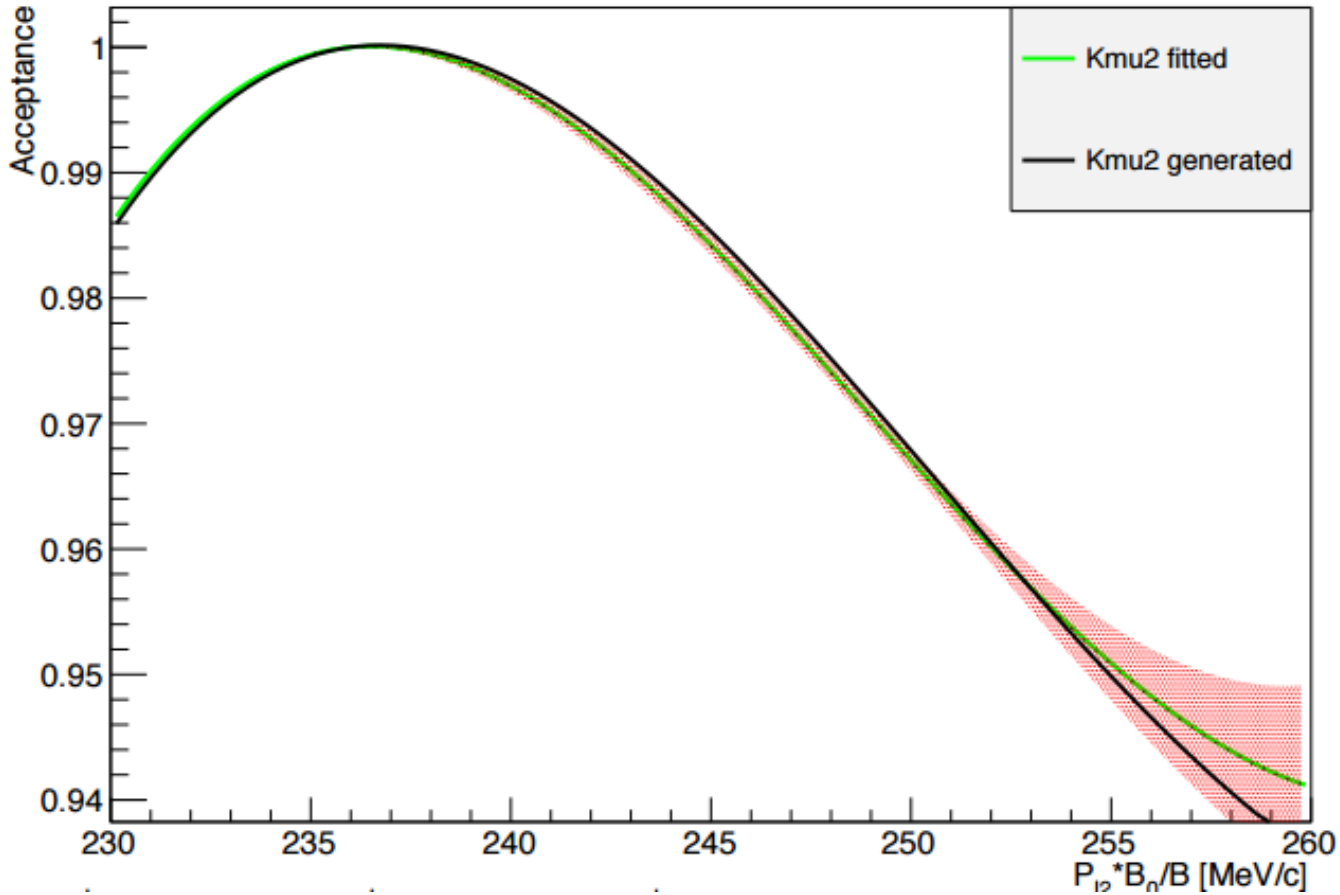
M. Abe et al., PRL83 (1999) 4253
M. Abe et al., PRL93 (2004) 131601
M. Abe et al., PRD72 (2006) 072005

E06 Model

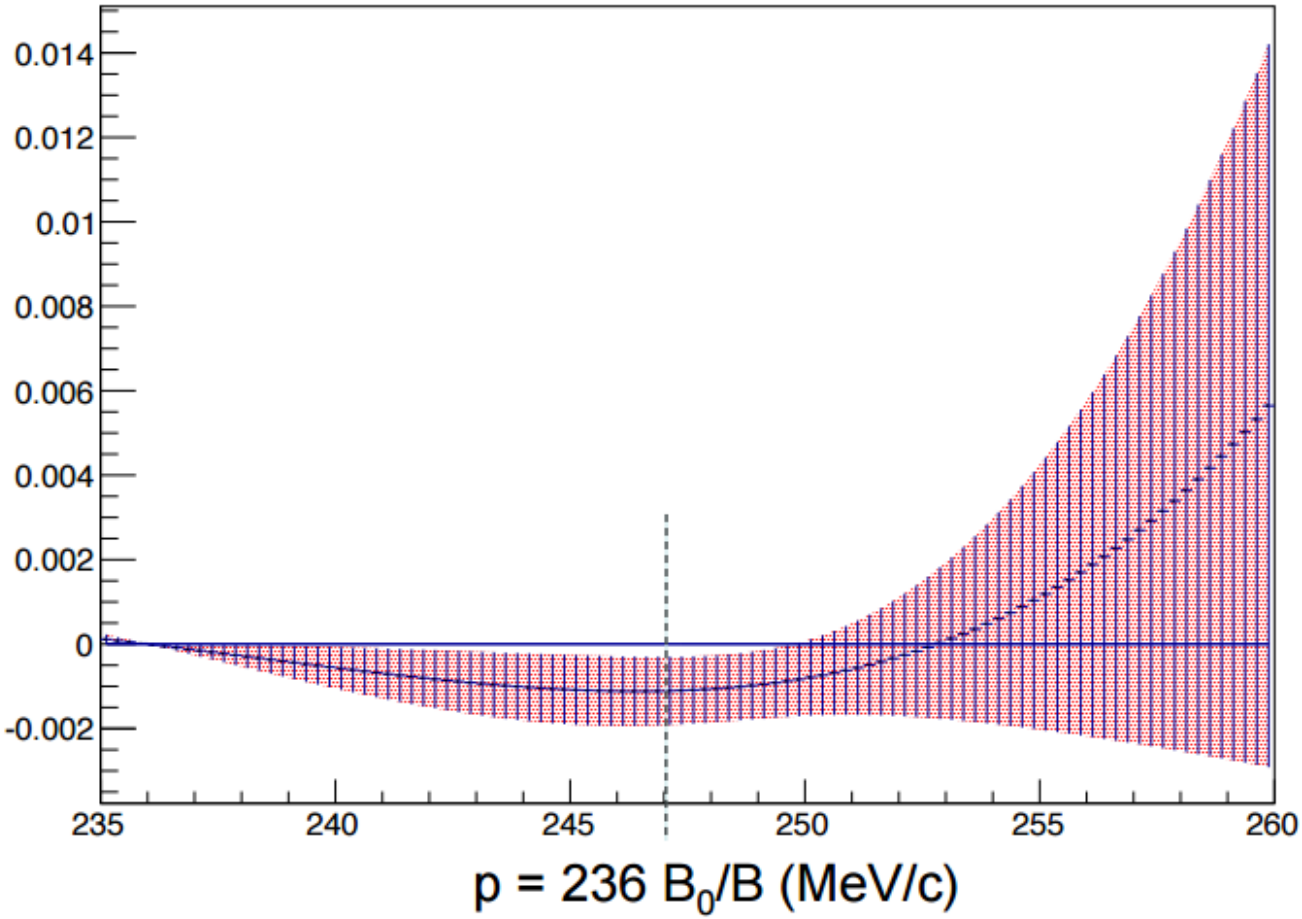


Model	$K^+ \to \pi^0\mu^+\nu$	$K^+ \to \mu^+\nu\gamma$
■ Standard Model	$<10^{-7}$	$<10^{-7}$
■ Final State Interactions	$<10^{-5}$	$<10^{-3}$
■ Multi-Higgs	$\leq 10^{-3}$ $P_T(K^+ \to \pi^0\mu^+\nu)$	$\leq 10^{-3}$ $\approx 3\ P_T(K^+ \to \mu^+\nu\gamma)$
■ SUSY with squarks mixing	$\leq 10^{-3}$ $P_T(K^+ \to \pi^0\mu^+\nu)$	$\leq 10^{-3}$ $\approx -3\ P_T(K^+ \to \mu^+\nu\gamma)$
■ SUSY with *R*-parity breaking	$\leq 4 \times 10^{-4}$	$\leq 3 \times 10^{-4}$
■ Leptoquark model	$\leq 10^{-2}$	$\leq 5 \times 10^{-3}$
■ Left-Right symmetric model	0	$< 7 \times 10^{-3}$

Acceptance


Acceptance
1
0.99
0.98
0.97
0.96
0.95
0.94
230
235
240
245
250
255
260
P_{l2}*B_0/B [MeV/c]
Kmu2 fitted
Kmu2 generated

Acceptance Uncertainty



Distribution