TREK @ J-PARC: Beyond the Standard Model with Stopped K^+

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Outline

- TREK Program
  - E06: Search for Time Reversal Symmetry Violation
  - E36: Test of Lepton Universality
  - Search for Heavy Neutrinos
  - Search for Light Bosons

Lower intensity

- TREK Apparatus
- Status

E36 data taking completed!

http://trek.kek.jp

The TREK program

- **E06**
  (Time Reversal Experiment with Kaons, TREK)

  " **Measurement of T-violating transverse muon polarization (P_T) in $K^+ \to \pi^0 \mu^+ \nu$ decays** "

  Proposal to PAC 1 — 100-270 kW

  Stage-1 approved since July 2006

  Spokespeople: Jun Imazato and M.K.

- **E36** (Test of Lepton Universality, Search for Heavy Neutrinos and Light Bosons)

  " **Measurement of $\Gamma(K^+ \to e^+ \nu)$ / $\Gamma(K^+ \to \mu^+ \nu)$ and search for heavy sterile neutrinos using the TREK detector system** "

  Proposal to PACs 10-11,13-18 — 30-50 kW

  Stage-1 approved since August 2012

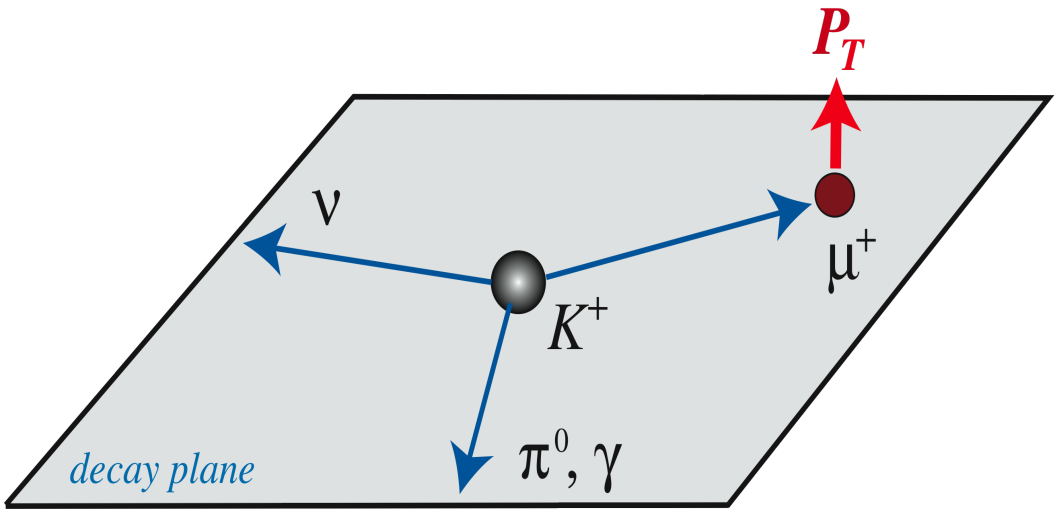
  Stage-2 approved since September 2013

  Spokespeople: M.K. and Suguru Shimizu

Timeline of TREK

- 2006: E06 (T-violation) Proposal (PAC1)
- 2009: J-PARC PS and HF start operating
- 2010: E36 (LFU/HNS) Proposal (PAC10)
- 2011: E36 stage-1 recommended (PAC11)
- 2012: E36 stage-1 approved (PAC15)
- 2013: E36 stage-2 recommended (PAC17)
- 2014: E36 stage-2 approved (PAC18)
- Detector preparation November 2014 – April 2015
- First commissioning run April 8 (24) – May 7, 2015
- Second commissioning run June 3 – 26, 2015
- Implemented improvements in summer 2015
- Production run October 14 – November 24, 2015
- Run extended until December 18, 2015

TREK/E06: Transverse muon polarization



- $K^+ \rightarrow \pi^0 \mu^+ \nu$
- 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 ± 0.0023(*stat*) ± 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

Limits of lepton universality (LU)

- e, μ, and τ: **Different masses, same gauge couplings, valid experimentally**
- μ-e universality has been rather well established
- Recent summary by A. Pich, arXiv:1201.0537v1 [hep-ph] (2012)

	$\Gamma_{\tau\to\nu_\tau e\bar\nu_e}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{\tau\to\nu_\tau\pi}/\Gamma_{\pi\to\mu\bar\nu_\mu}$	$\Gamma_{\tau\to\nu_\tau K}/\Gamma_{K\to\mu\bar\nu_\mu}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to\mu\bar\nu_\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0007 ± 0.0022	0.992 ± 0.004	0.982 ± 0.008	1.032 ± 0.012

	$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\tau\to\nu_\tau e\bar\nu_e}$	$\Gamma_{\pi\to\mu\bar\nu_\mu}/\Gamma_{\pi\to e\bar\nu_e}$	$\Gamma_{K\to\mu\bar\nu_\mu}/\Gamma_{K\to e\bar\nu_e}$	$\Gamma_{K\to\pi\mu\bar\nu_\mu}/\Gamma_{K\to\pi e\bar\nu_e}$
$\lvert g_\mu/g_e\rvert$	1.0018 ± 0.0014	1.0021 ± 0.0016	0.998 ± 0.002	1.001 ± 0.002

	$\Gamma_{W\to\mu\bar\nu_\mu}/\Gamma_{W\to e\bar\nu_e}$		$\Gamma_{\tau\to\nu_\tau\mu\bar\nu_\mu}/\Gamma_{\mu\to\nu_\mu e\bar\nu_e}$	$\Gamma_{W\to\tau\bar\nu_\tau}/\Gamma_{W\to e\bar\nu_e}$
$\lvert g_\mu/g_e\rvert$	0.991 ± 0.009	$\lvert g_\tau/g_e\rvert$	1.0016 ± 0.0021	1.023 ± 0.011

- Recent development of τ spectroscopy

  τ_τ, m_τ, $\tau_\tau/\tau_\mu = (m_\tau/m_\mu)^5(g_\tau/g_\mu)^2$, couplings to *W* and Z^0

- LEP-II [PDG 2010] $R^W_{\tau\ell} = \dfrac{2\,\mathrm{BR}(W\to\tau\bar\nu_\tau)}{\mathrm{BR}(W\to e\bar\nu_e)+\mathrm{BR}(W\to\mu\bar\nu_\mu)} = 1.055(23)$ **2.4 σ dev.**
- BABAR [Phys. Rev. D 82, 072005 (2010)]

  $\mathcal{R}(D^{(*)}) = \mathcal{B}(\bar B\to D^{(*)}\tau^-\bar\nu_\tau)/\mathcal{B}(\bar B\to D^{(*)}\ell^-\bar\nu_\ell)$ **3.5 σ dev.**
- LHCb [Phys. Rev. Lett. 113, 151601 (2014)]

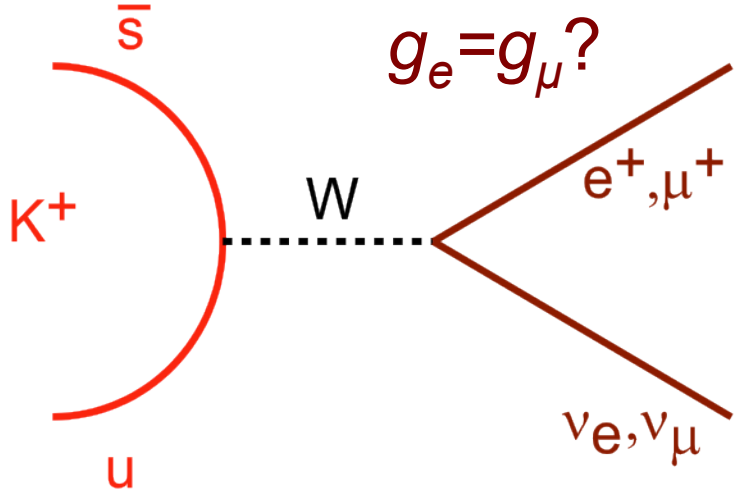
  $\mathrm{BR}(B^+\to K^+\mu^+\mu^-)\,/\,\mathrm{BR}(B^+\to K^+e^+e^-) = 0.745^{+0.090}_{-0.074}\pm 0.0036$ **2.6 σ dev.**
- **Possible link to proton charge radius puzzle** **7 σ dev.**

  r_e (μH) = 0.84087 ± 0.00039 fm, r_e (CODATA2010) = 0.8775 ± 0.0051 fm

Lepton universality in Standard Model K_{l2}

Standard Model:

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



- **In the ratio of $\Gamma(K_{e2})$ to $\Gamma(K_{\mu 2})$, hadronic form factors are cancelled**

- $R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$

helicity suppression

radiative correction (Internal Brems.)

- **Strong helicity suppression of the electronic channel enhances sensitivity to effects beyond the SM**

- **Highly precise SM value**

  R_K^{SM}= (2.477±0.001) x 10^{-5} (with δ_r = -0.036); $\delta R_K/R_K$=0.04%

  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)

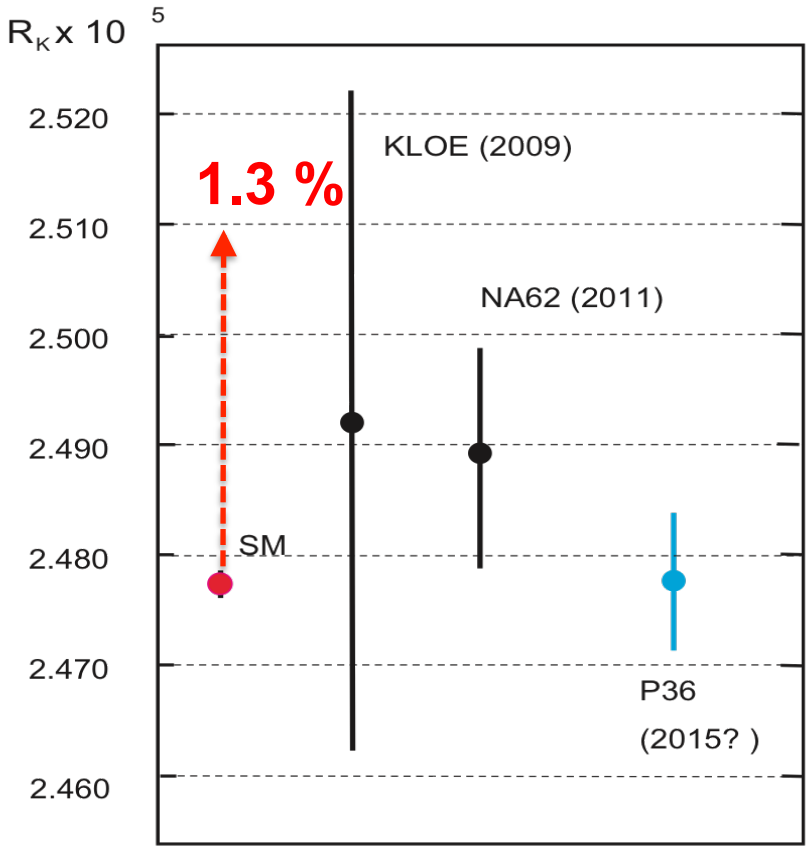
Experimental status of R_K

- **Highly precise SM value**
  $R_K = (2.477 \pm 0.001) \times 10^{-5}$ (with $\delta_r = -0.036$), $\delta R_K/R_K = 0.04\%$
  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)

- **KLOE @ DAΦNE (in-flight decay)**
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
  F. Ambrosino et al., Eur. Phys. J. C64, 627 (2009)

- **NA62 @ CERN-SPS (in-flight decay)**
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
  C. Lazzeroni et al., PLB719, 105 (2013)

- **World average (2012)**
  $R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K = 0.4\%$



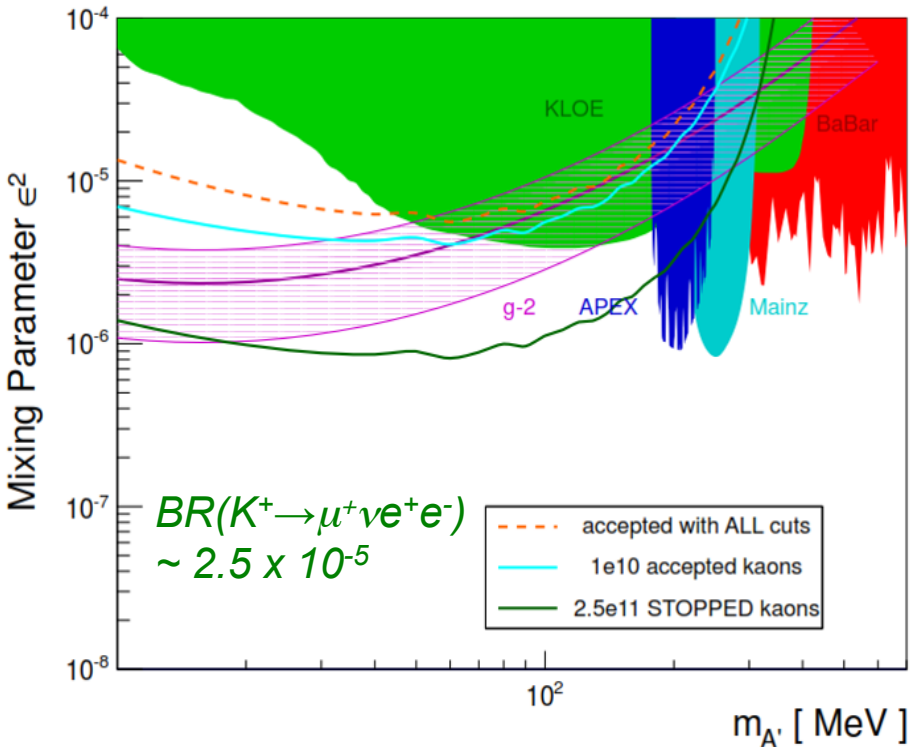
- **Systematics:**
  - In-flight-decay experiments: kinematics overlap
  - E36 stopped K^+: detector acceptance and target
  - E36 complementary to in-flight experiments

- **E36 goal:** $\delta R_K/R_K = \pm 0.2\%$ (stat) $\pm 0.15\%$ (syst) [0.25% total]

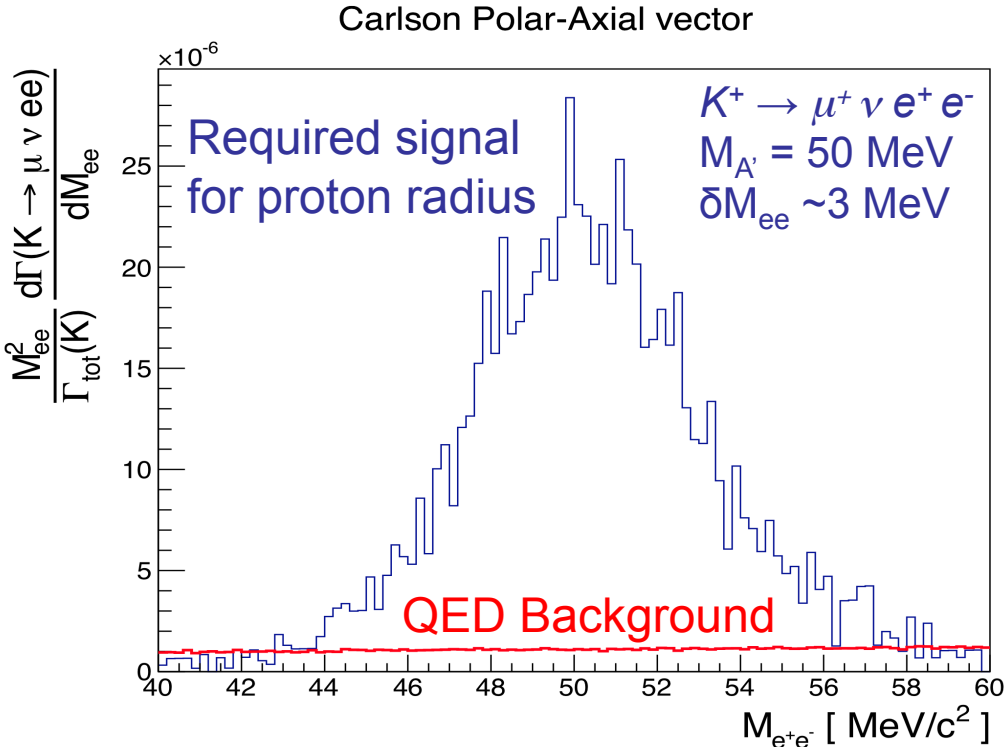
Dark photon / light neutral boson search

- **Dark photons (universal coupling) well motivated by dark matter observations (astronomical, direct, positron excess) and g_μ-2 anomaly**
- **Light neutral bosons (selective coupling) for proton radius puzzle**
- **Search for visible decay mode of $A' \to e^+e^-$ in K^+ decays**
  Kaons: $K^+ \to \mu^+ \nu A'$; $K^+ \to \pi^+ A'$ (also invisible decay);
  Pions: $\pi^0 \to \gamma A'$, using $K^+ \to \pi^+\pi^0$ (21.13%) and $K^+ \to \mu^+ \nu \pi^0$ (3.27%)

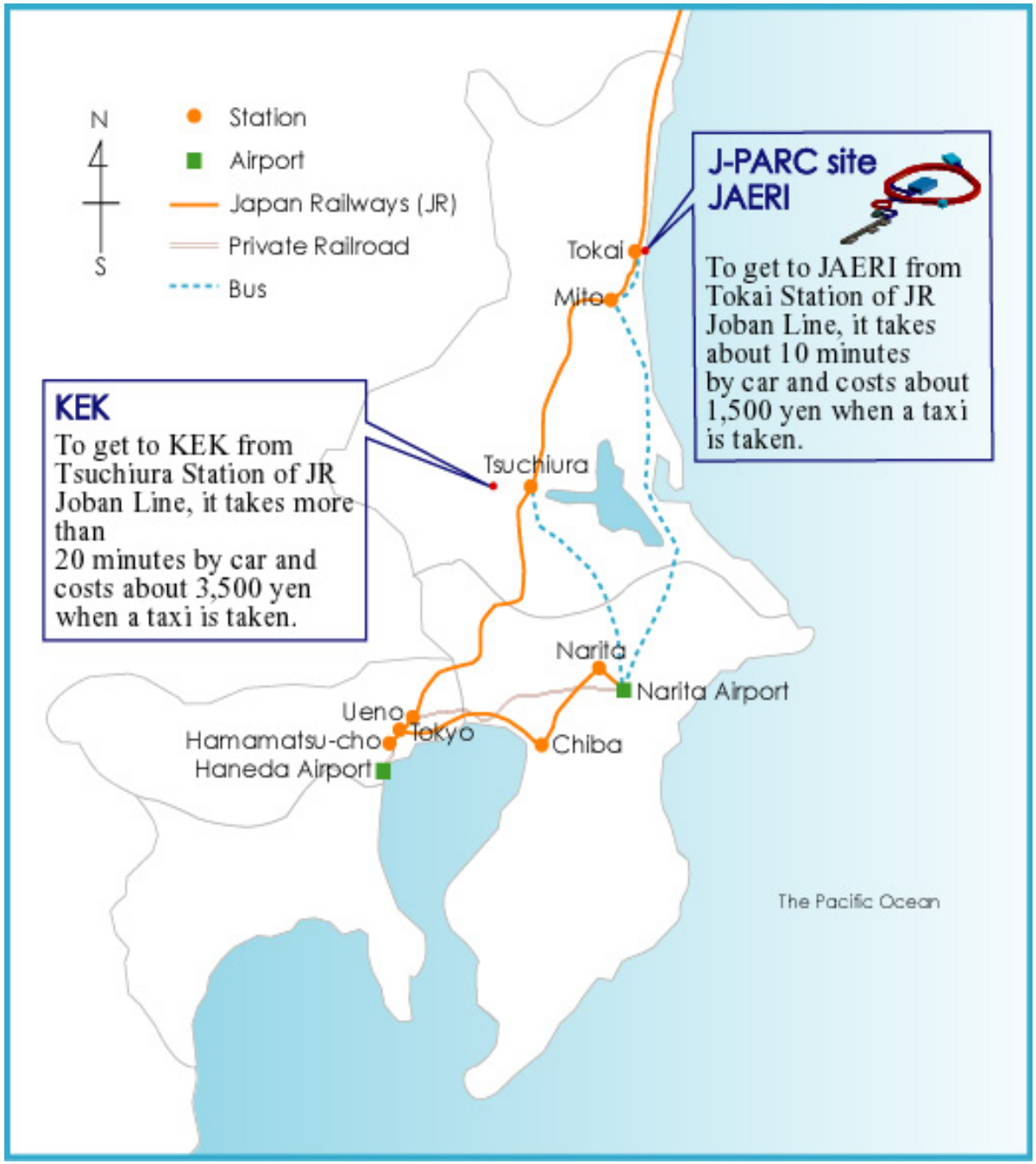
E36: Dark photon exclusion limit

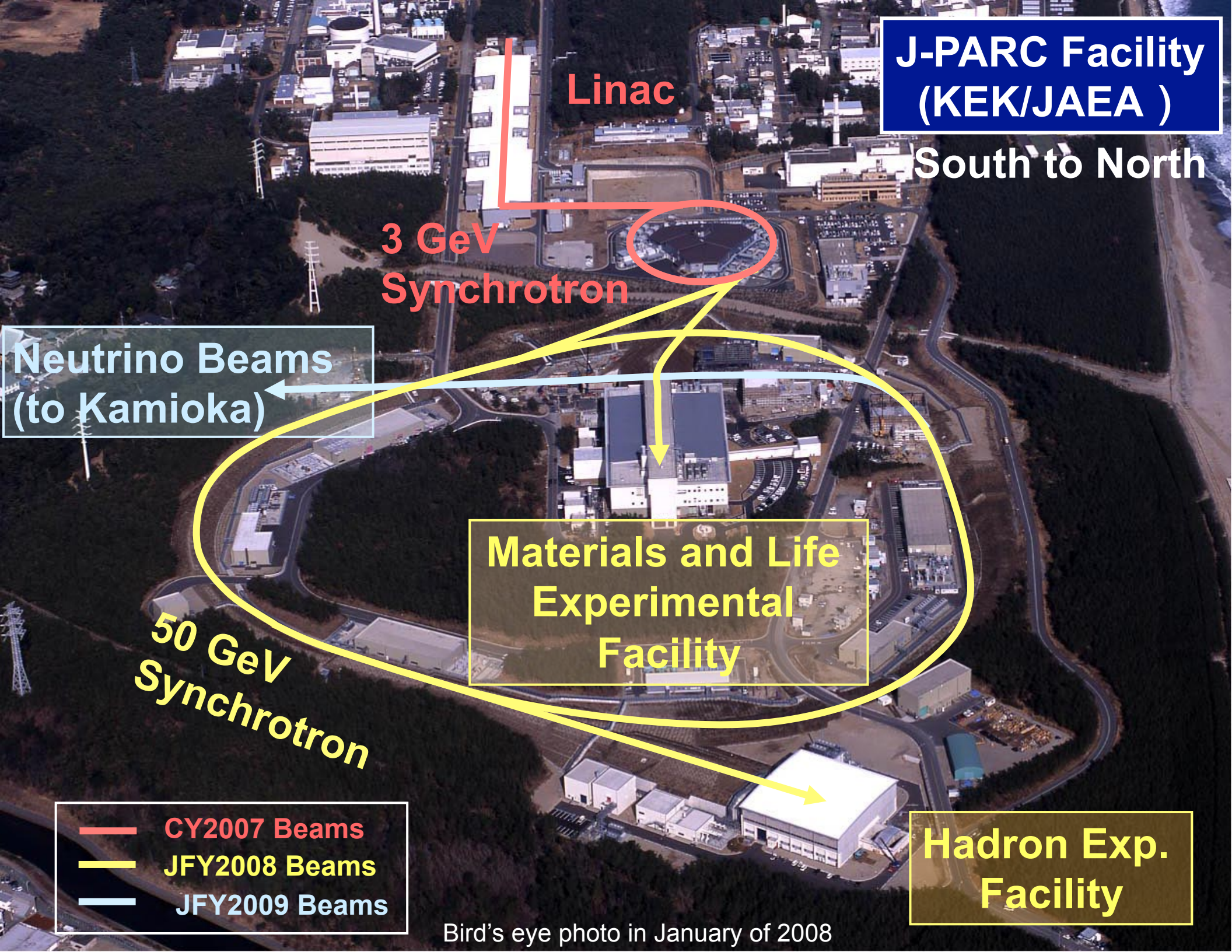


E36: Light boson expected signal

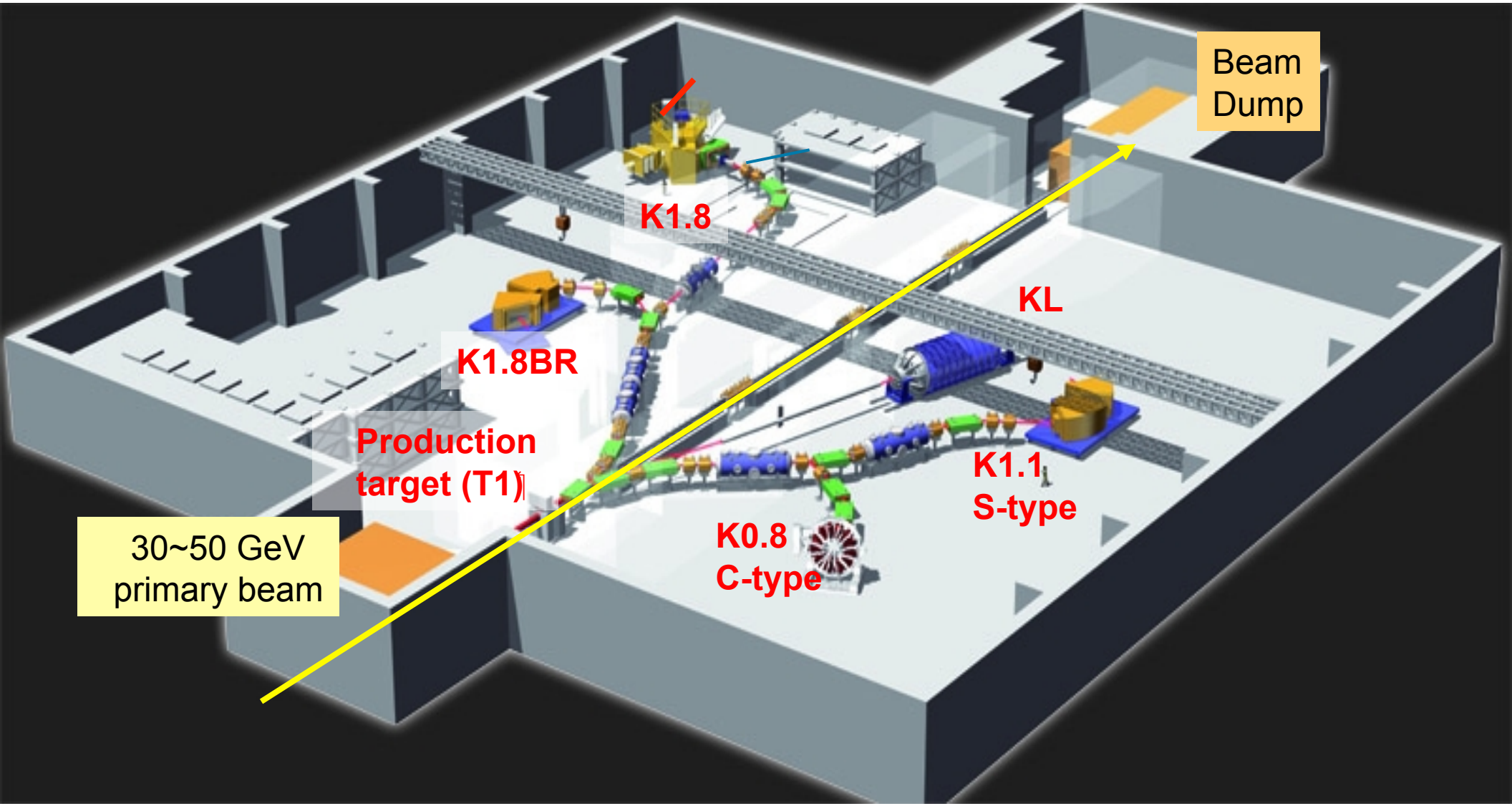


Location of J-PARC




J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

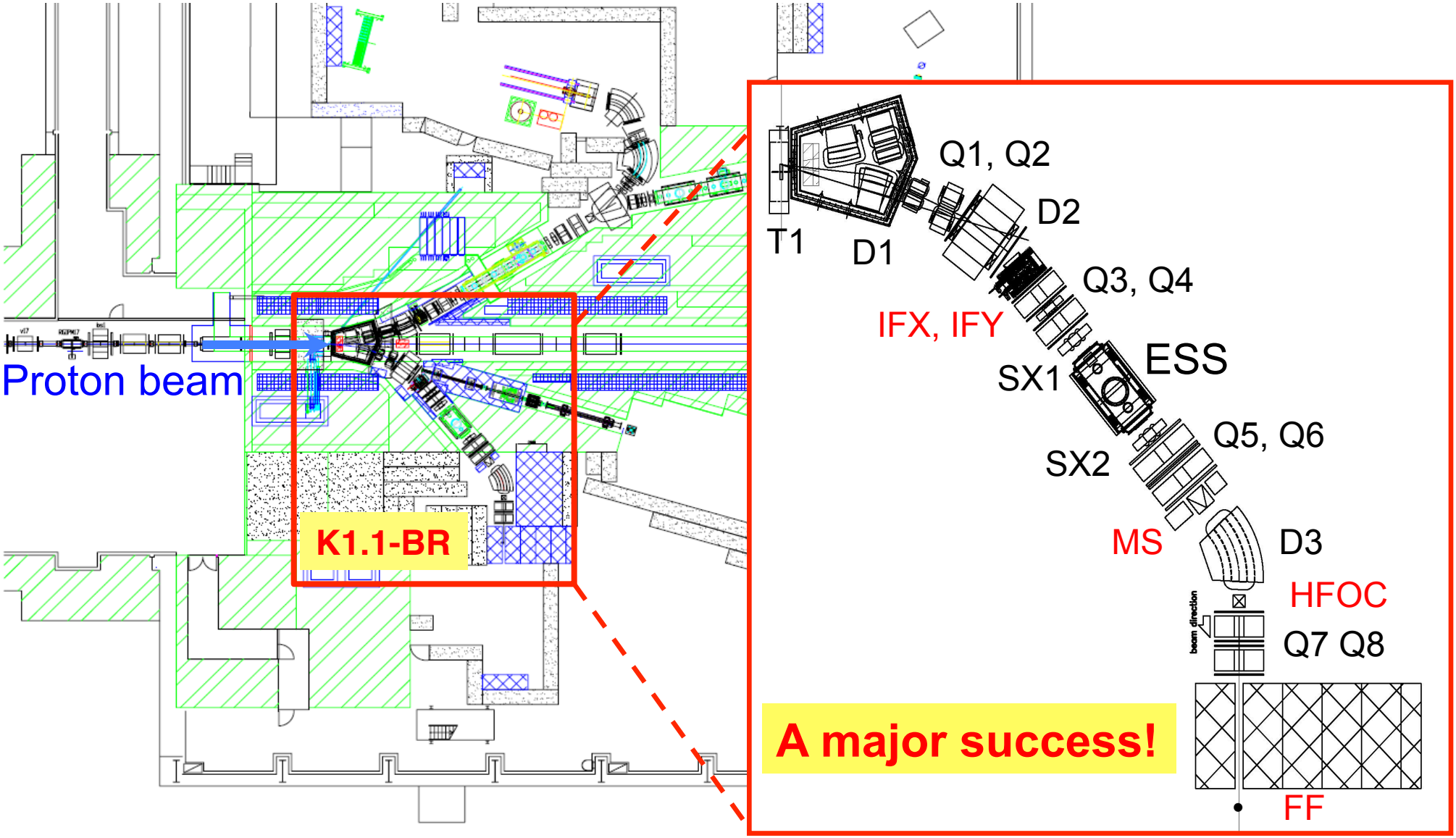
J-PARC Hadron Experimental Hall



K1.1BR beamline

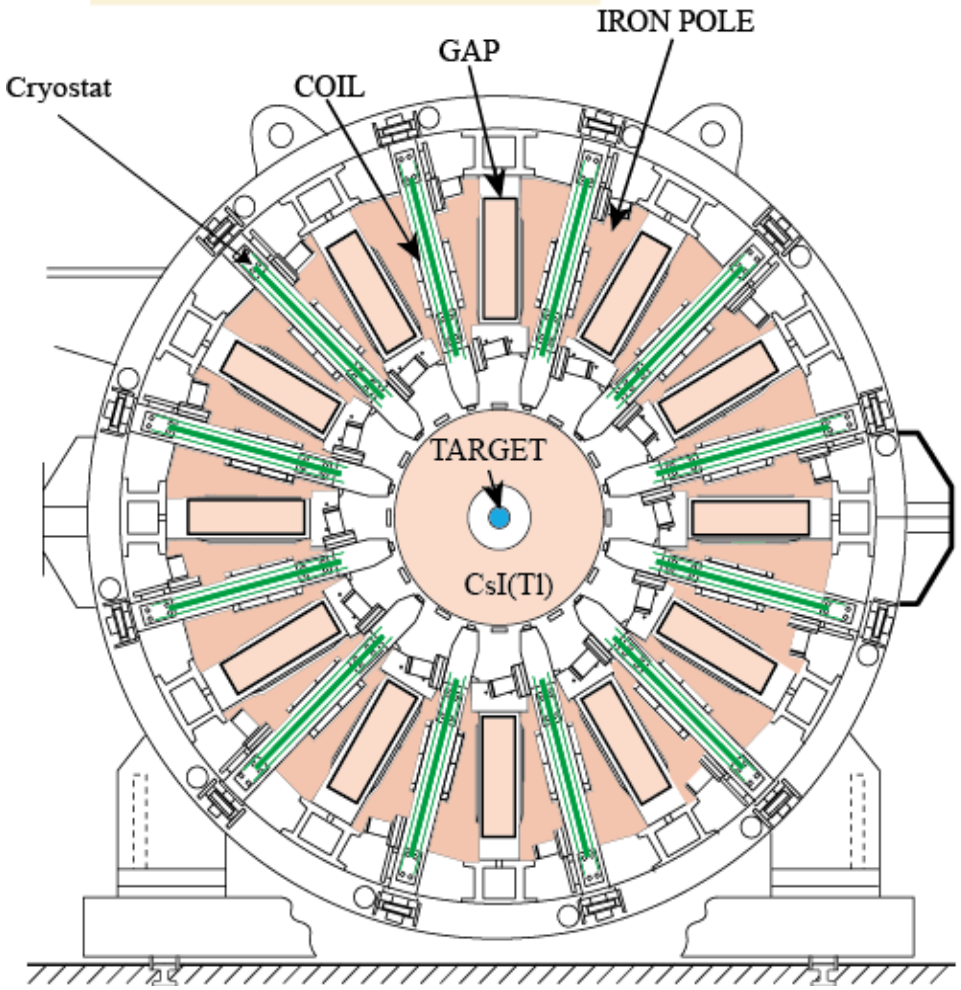
- K1.1BR constructed in 2009/10, commissioned by TREK Coll. in Oct. 2010
- Re-aligned after 11/3/11 earthquake, re-commissioned in June 2012
- J-PARC Hadron Hall operations restarted in April 2015

  π/K ratio of ~1.3 observed, kaon flux within expectation (1.4x10^6/spill @ 32kW)

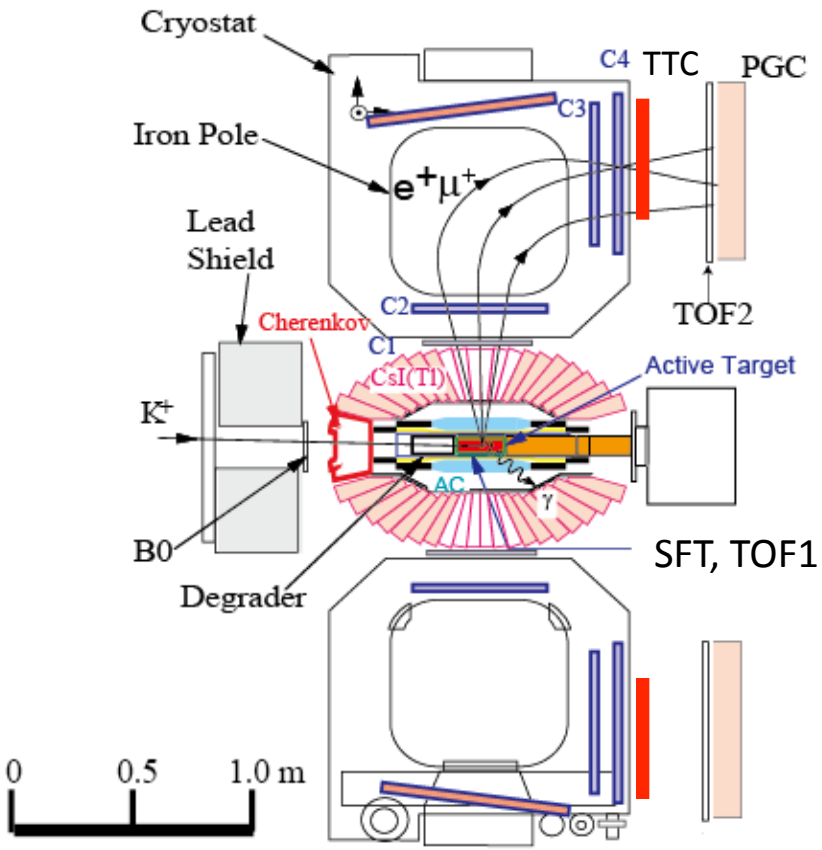


The TREK apparatus for E36

End View



Side View



Modest upgrade of KEK-PS E246

Stopped K method

- K1.1BR beamline
- Fitch Cherenkov
- K^+ stopping target

Tracking

- MWPC (C2, C3, C4)
- Spiral Fiber Tracker(SFT)

PID

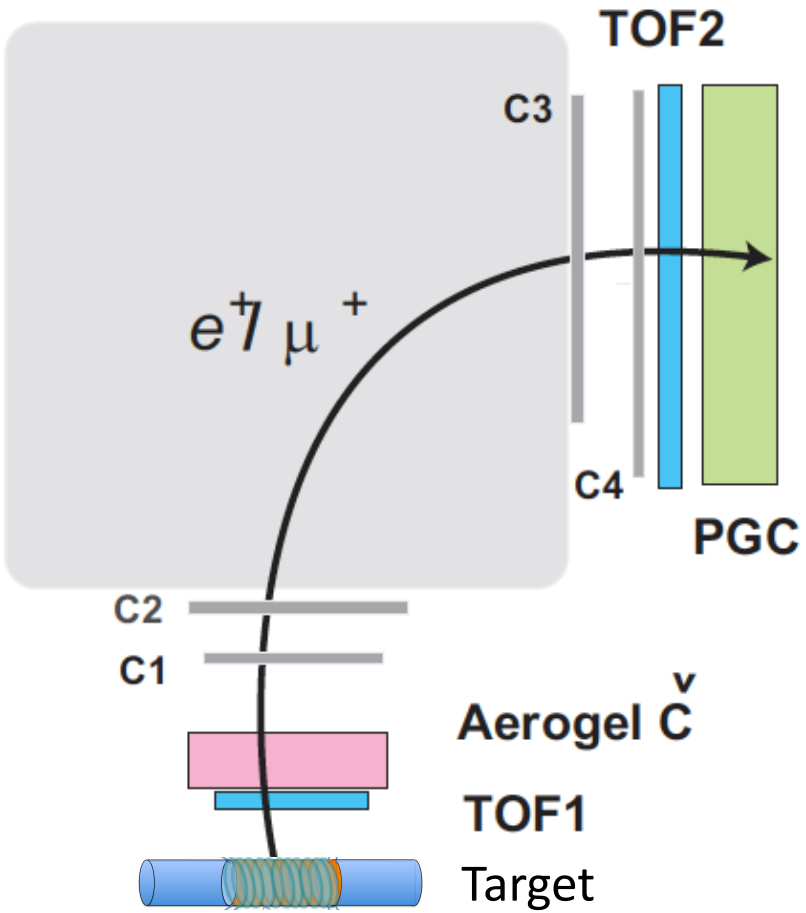
- TOF1,2; TTC
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

Gamma ray

- CsI(Tl)

μ^+/e^+ identification

PID with:
- TOF
- Aerogel Č
- Lead glass

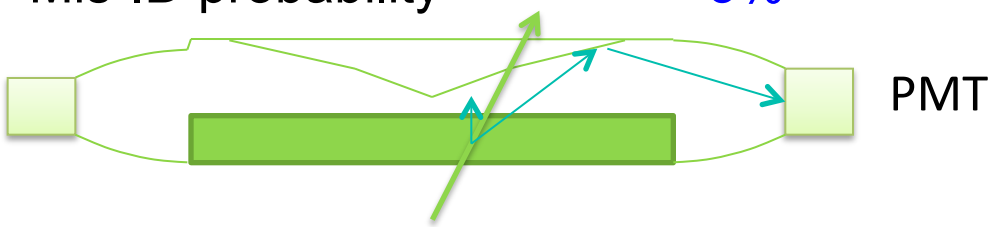


TOF

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%



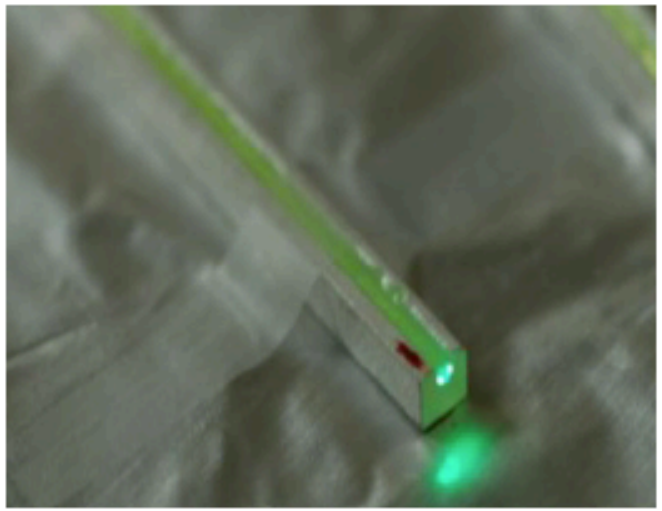
Lead glass (PGC)

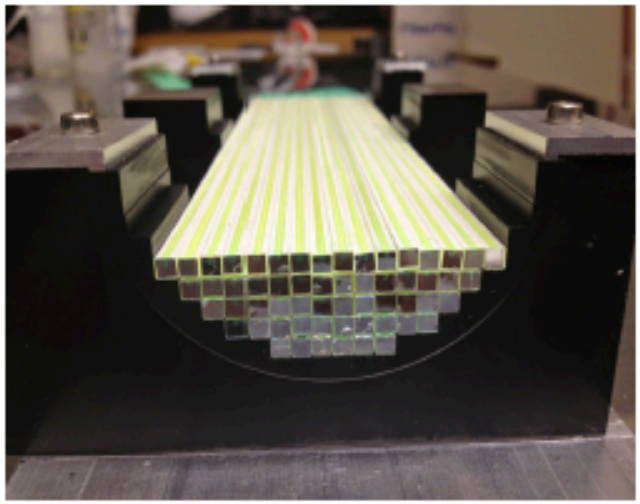
Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

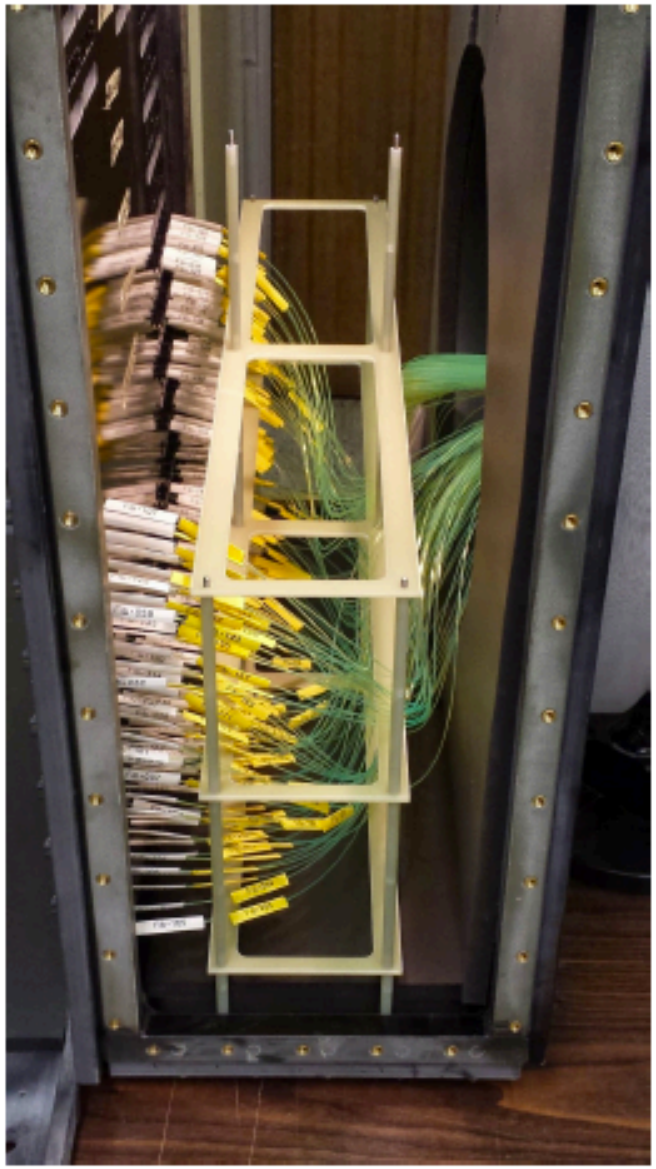
$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

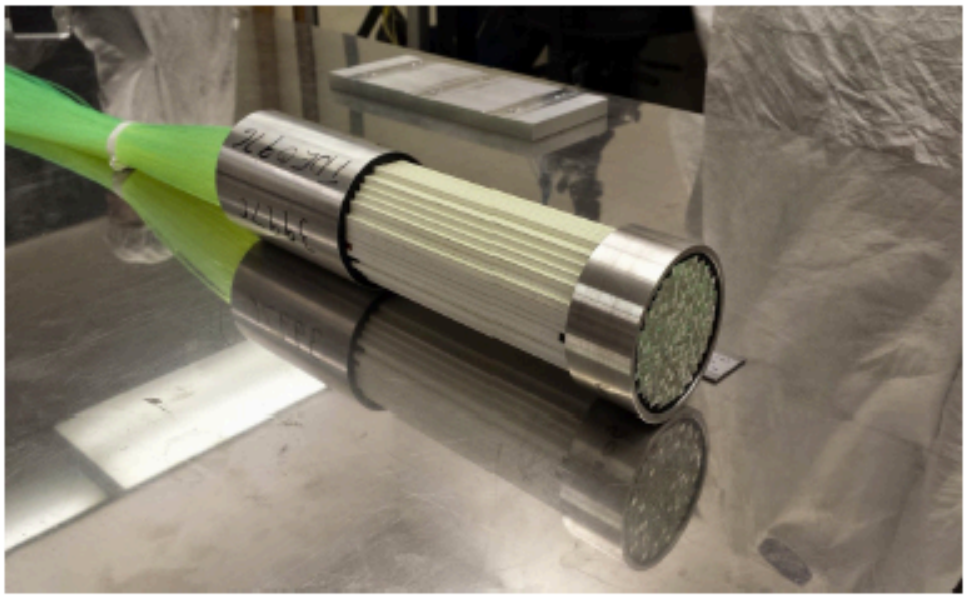
Scintillating-fiber kaon stopping target

- Built at TRIUMF (delivered to J-PARC in September 2014)
- 256 scintillating fibers (3x3 mm^2), WLS fiber in groove
- MPPC readout



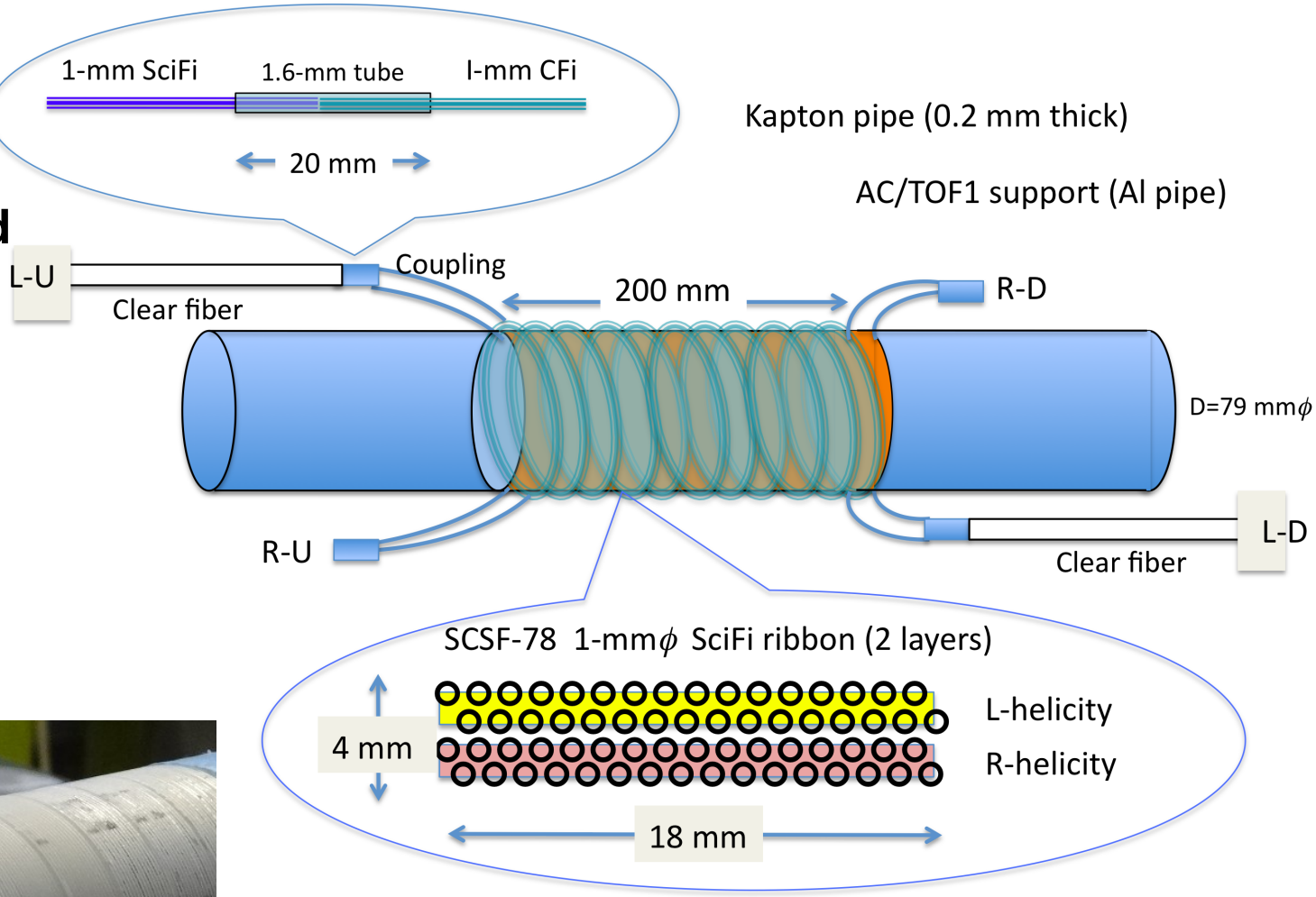


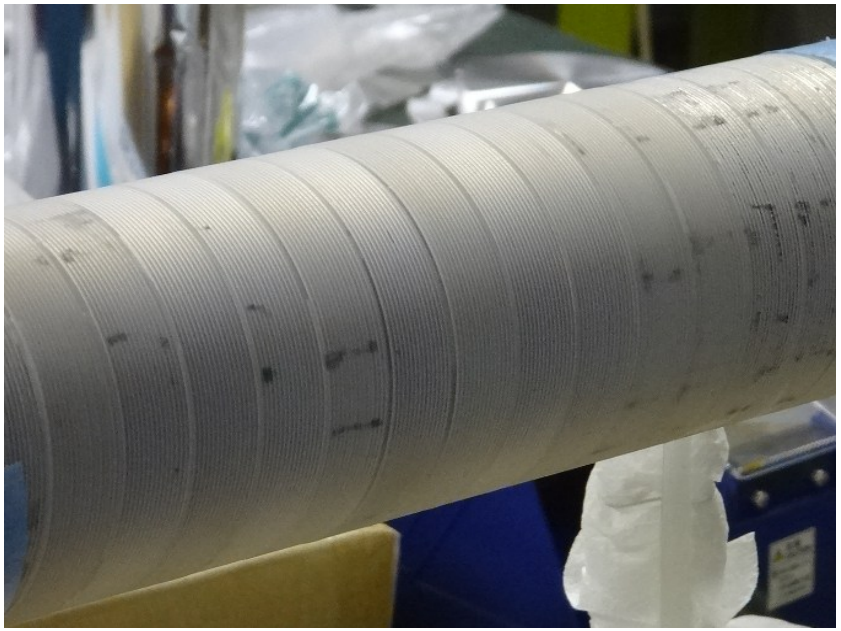


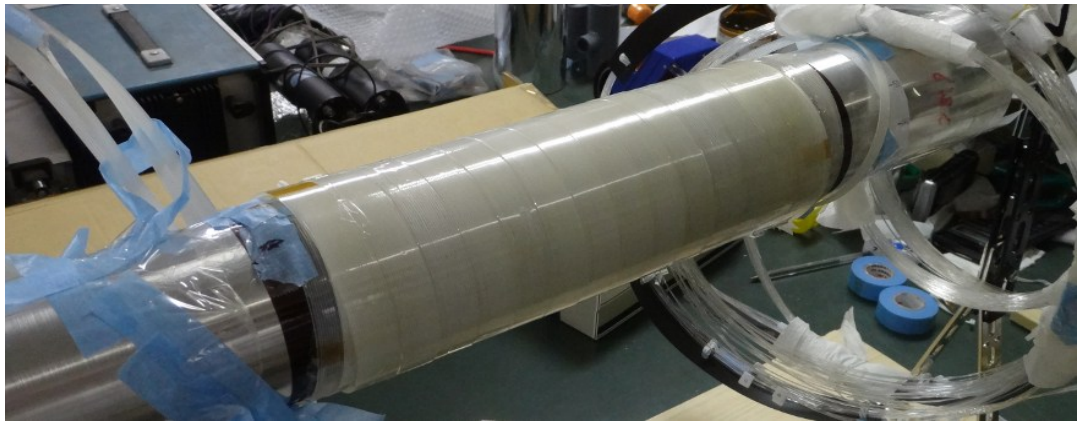


Spiraling fiber tracker (SFT)

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

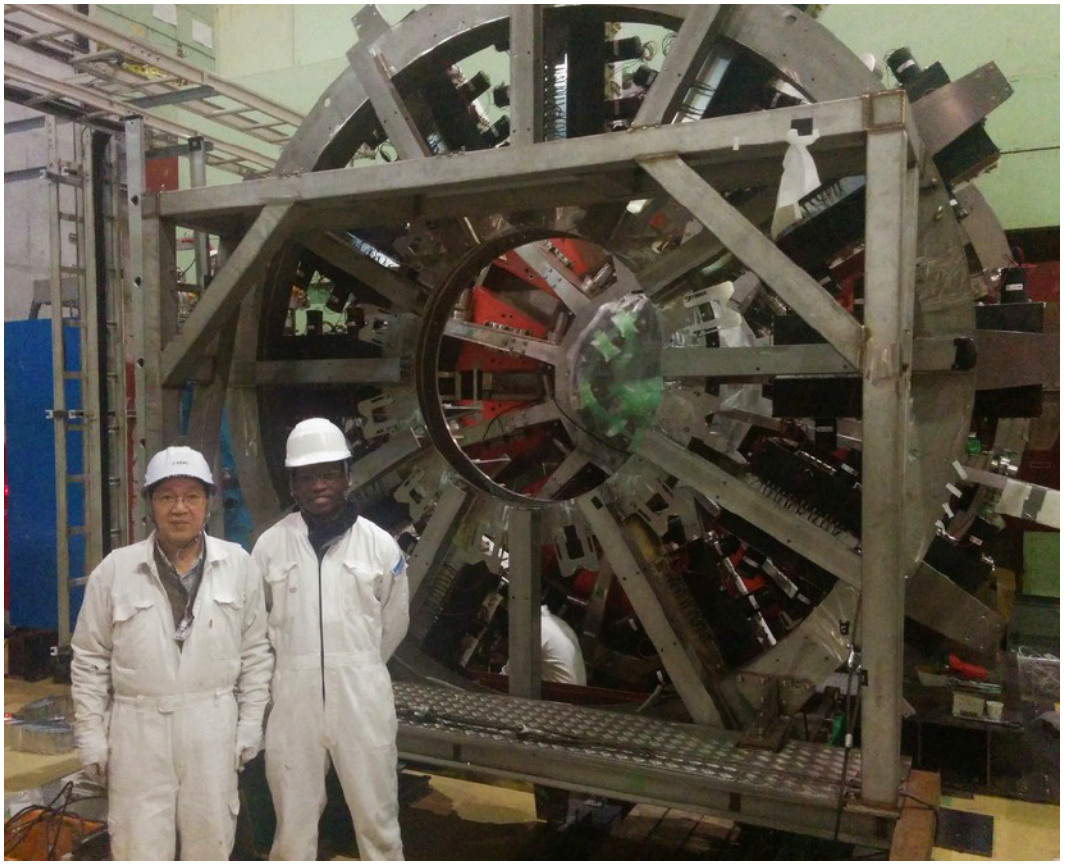




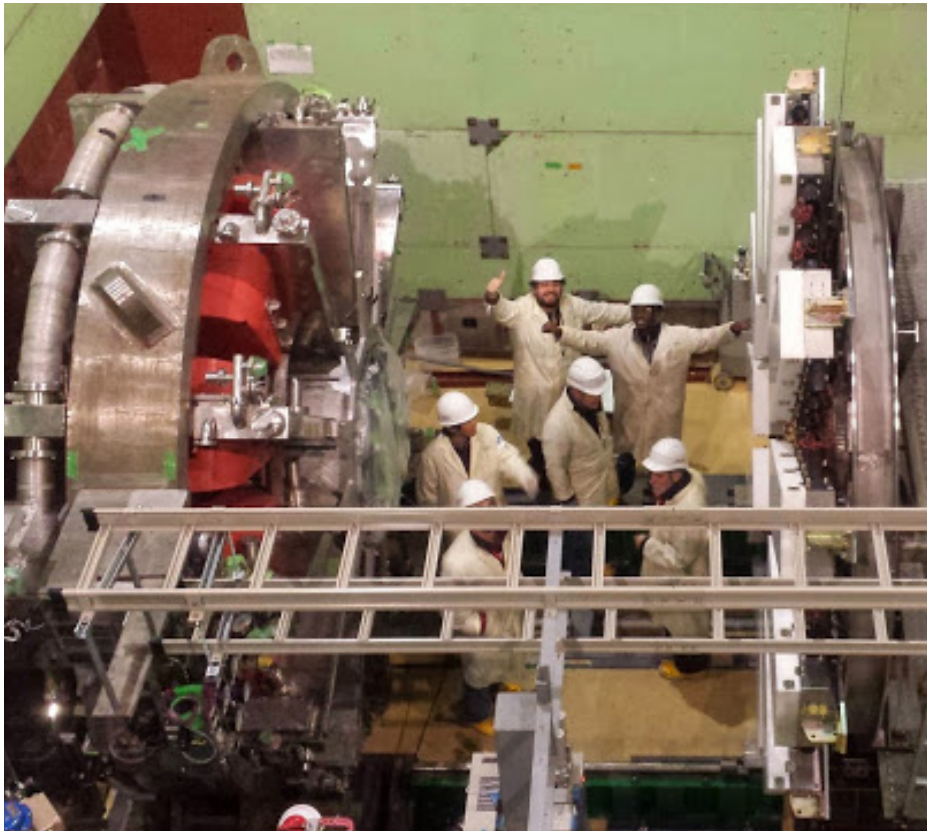


TREK/E36 installation and commissioning

- Completed detector installation Apr. 2015
- Electronics and DAQ set up and tested (area available only mid-January)
- Conditioning of MWPCs



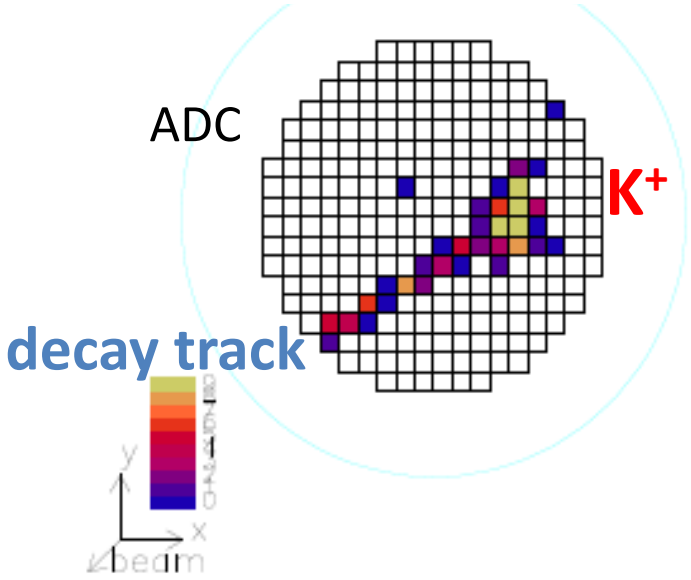
Bishoy Dongwi (Hampton U.)

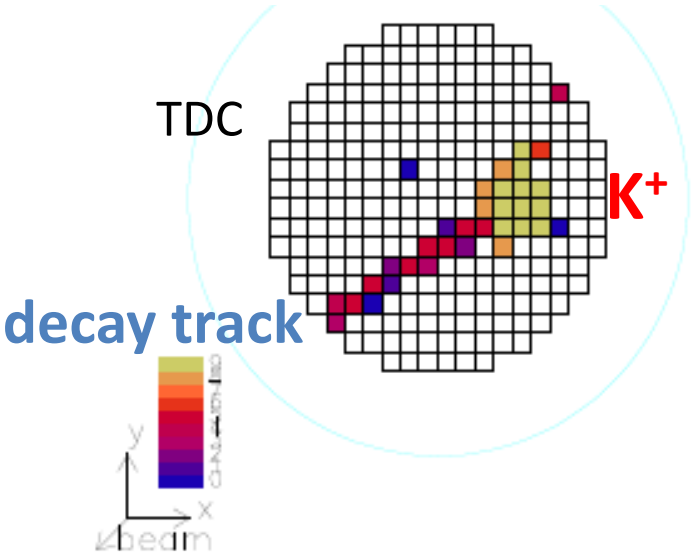


- Commissioning of TGT+TOF1+SFT with cosmic rays
- Check-out of all detectors with beam
- Commissioning of toroidal magnet (cryogenics) only after April 24

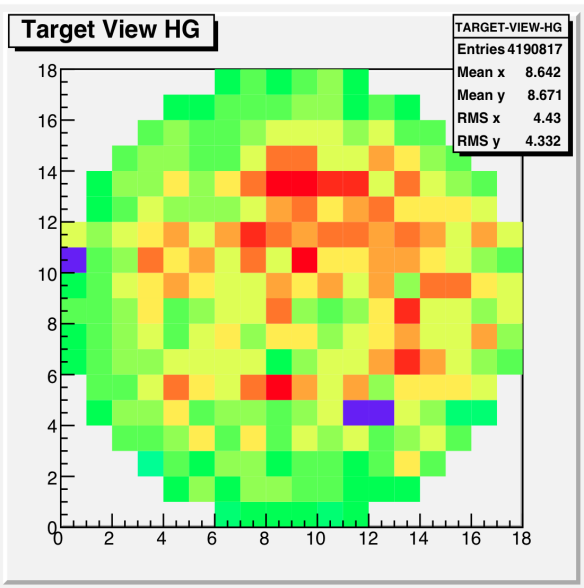
Target performance

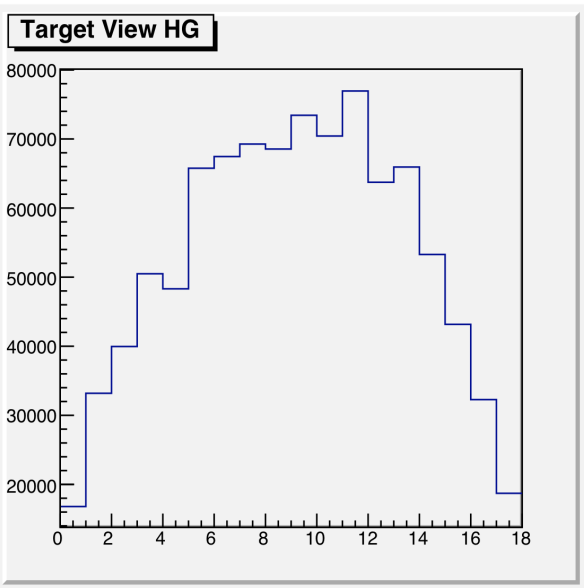
Kaon stop and track of decay particle

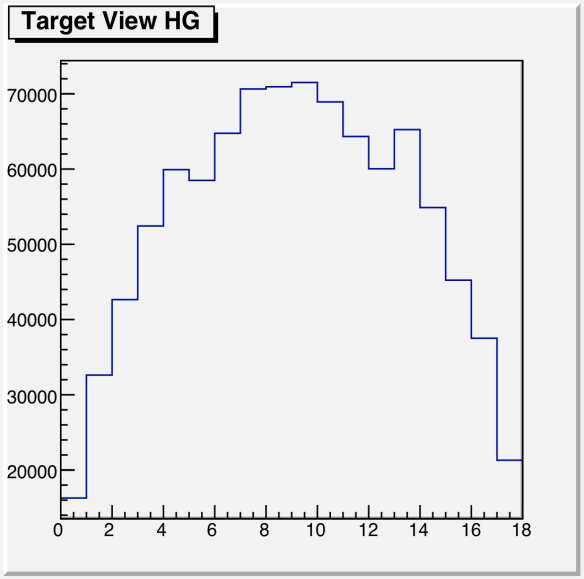




Kaon beam profile



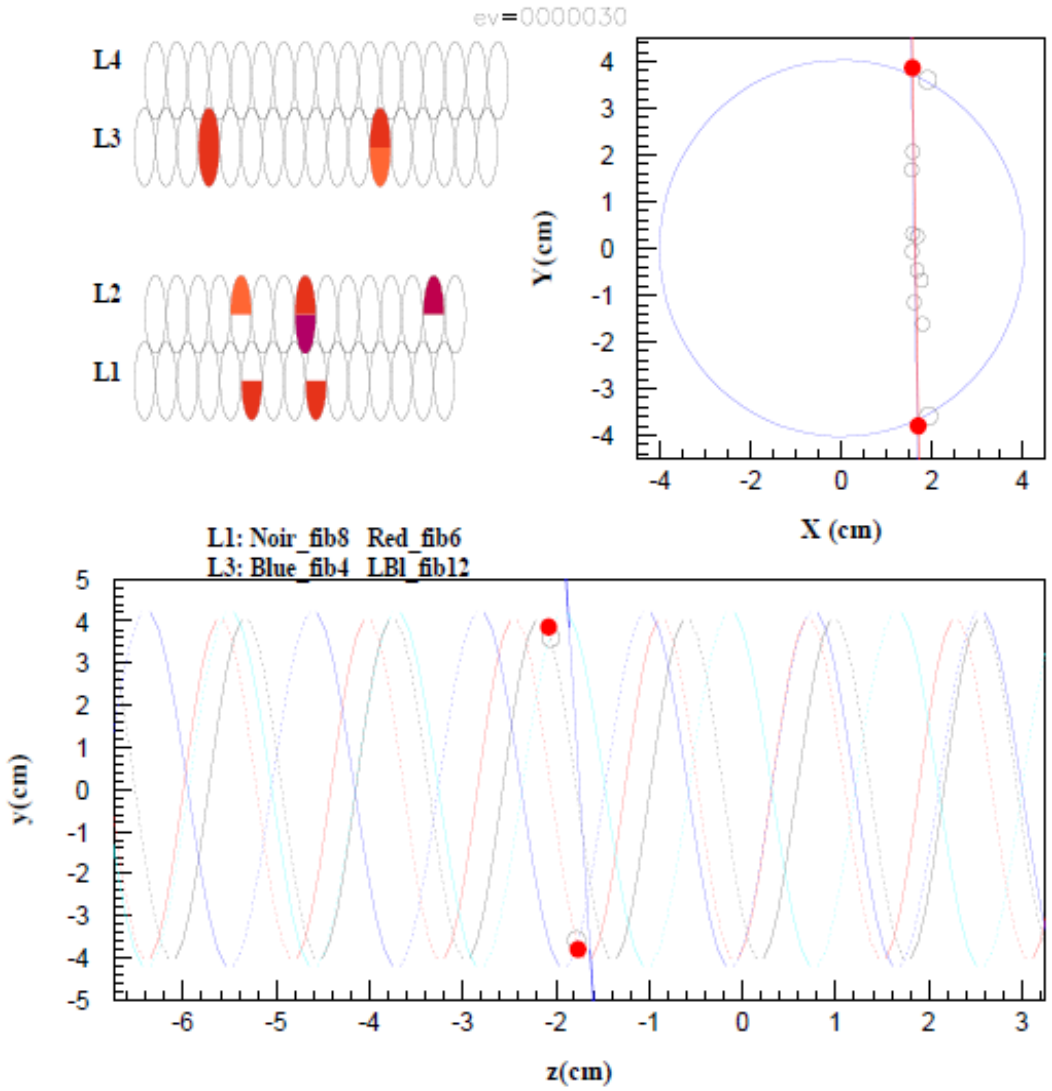


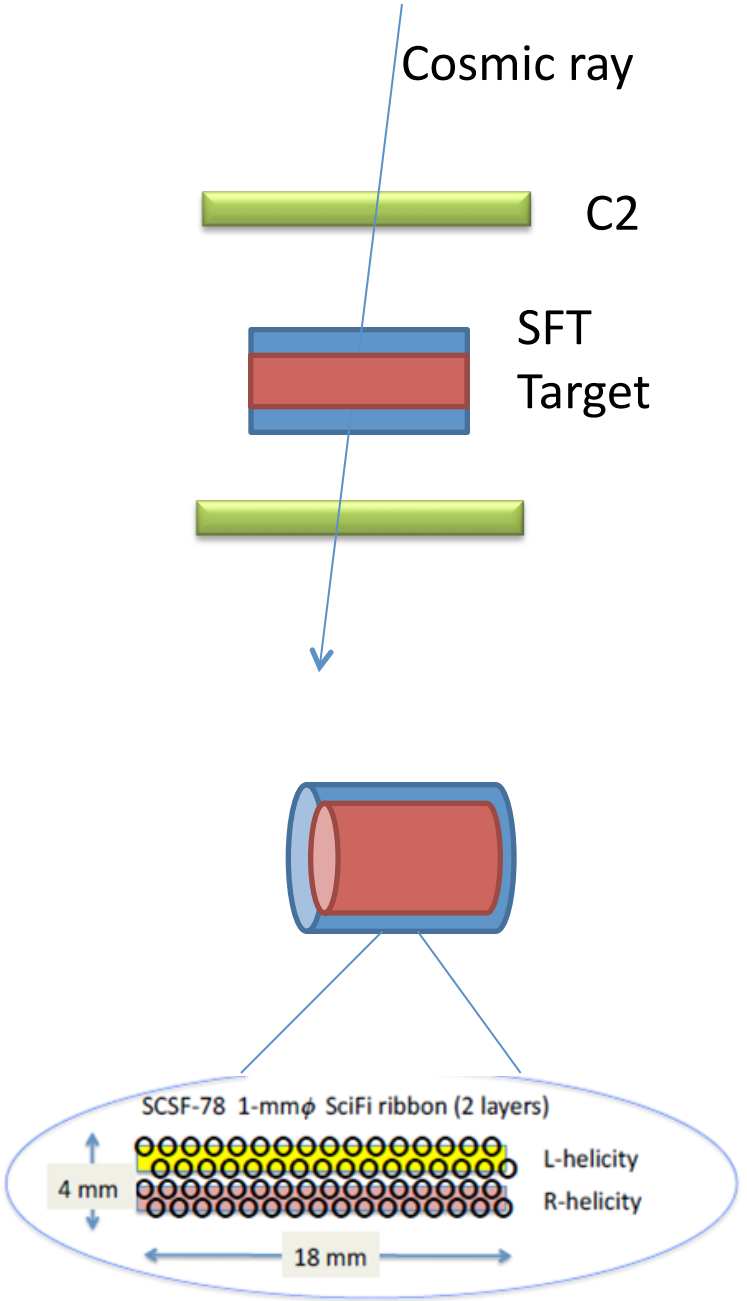


June 2015 data

Preliminary

Track identification by central detector



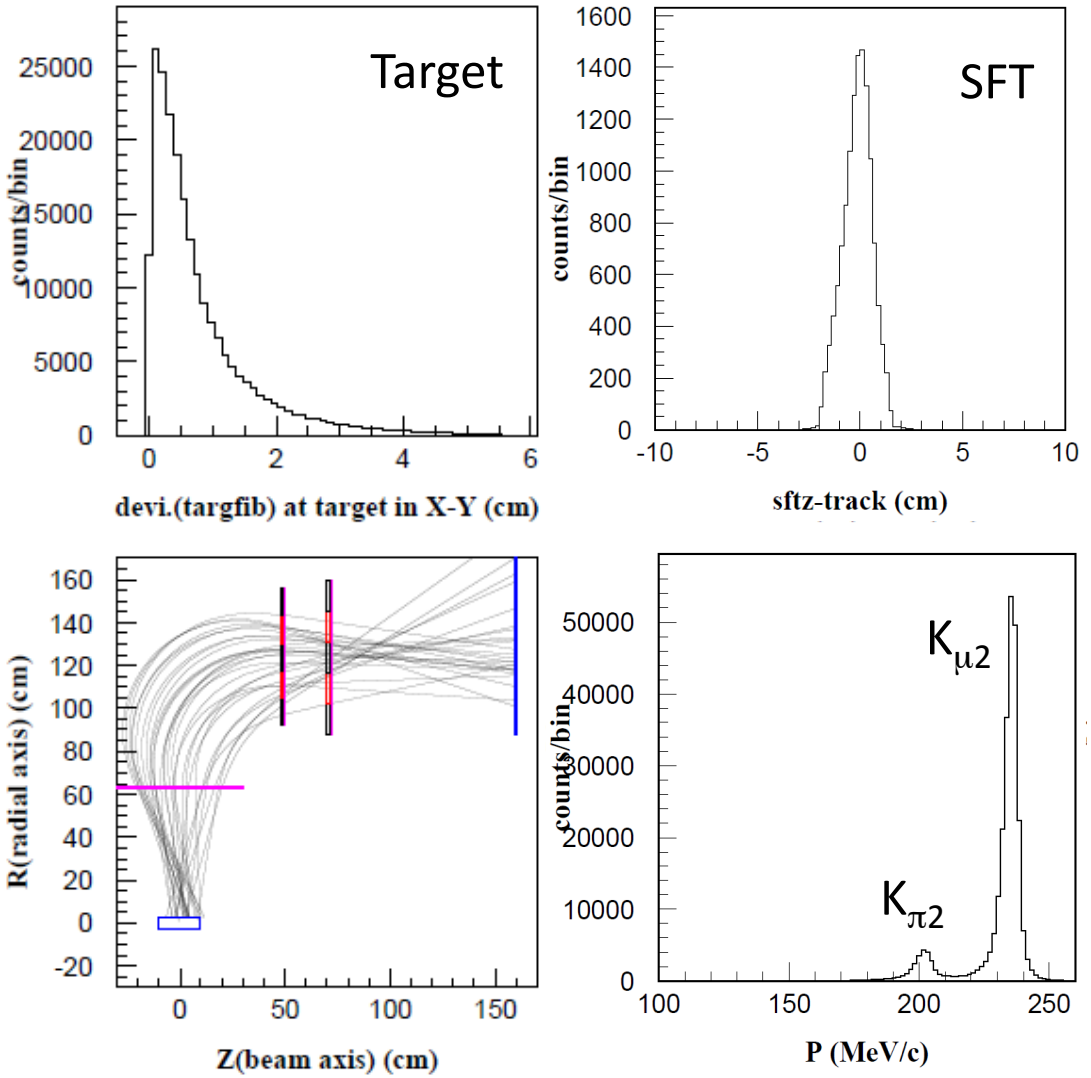


SFT+Target consistency established with C-ray

Momentum determination

- **Charged particle momentum determined by 3-point tracking (C2, C3, C4)**
- **Events selected requiring track consistency with target and SFT**
- **Monochromatic peaks from $K_{\mu 2}$ and $K_{\pi 2}$**

Track consistency

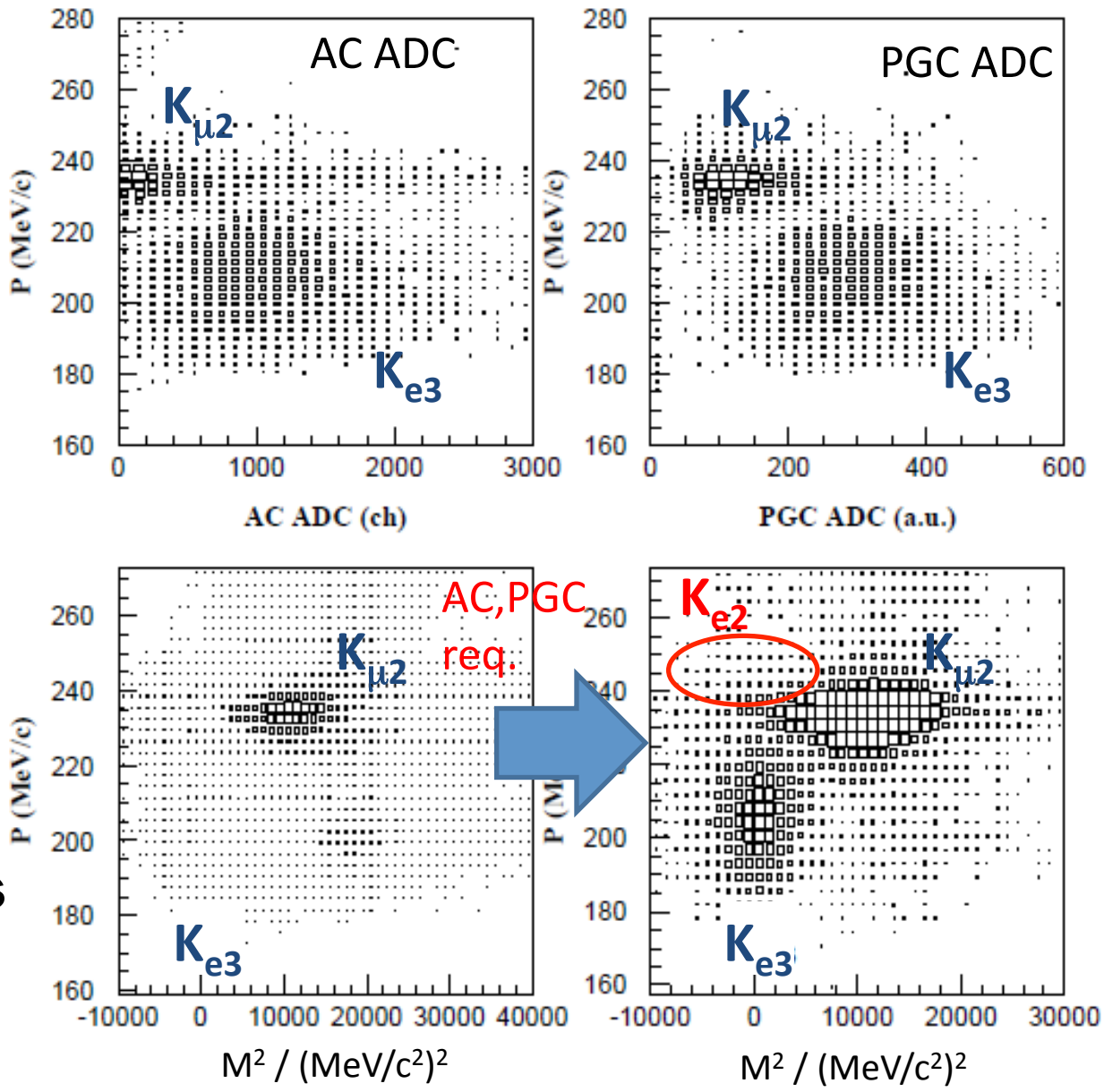


Very preliminary

Particle identification by AC, PGC, and TOF

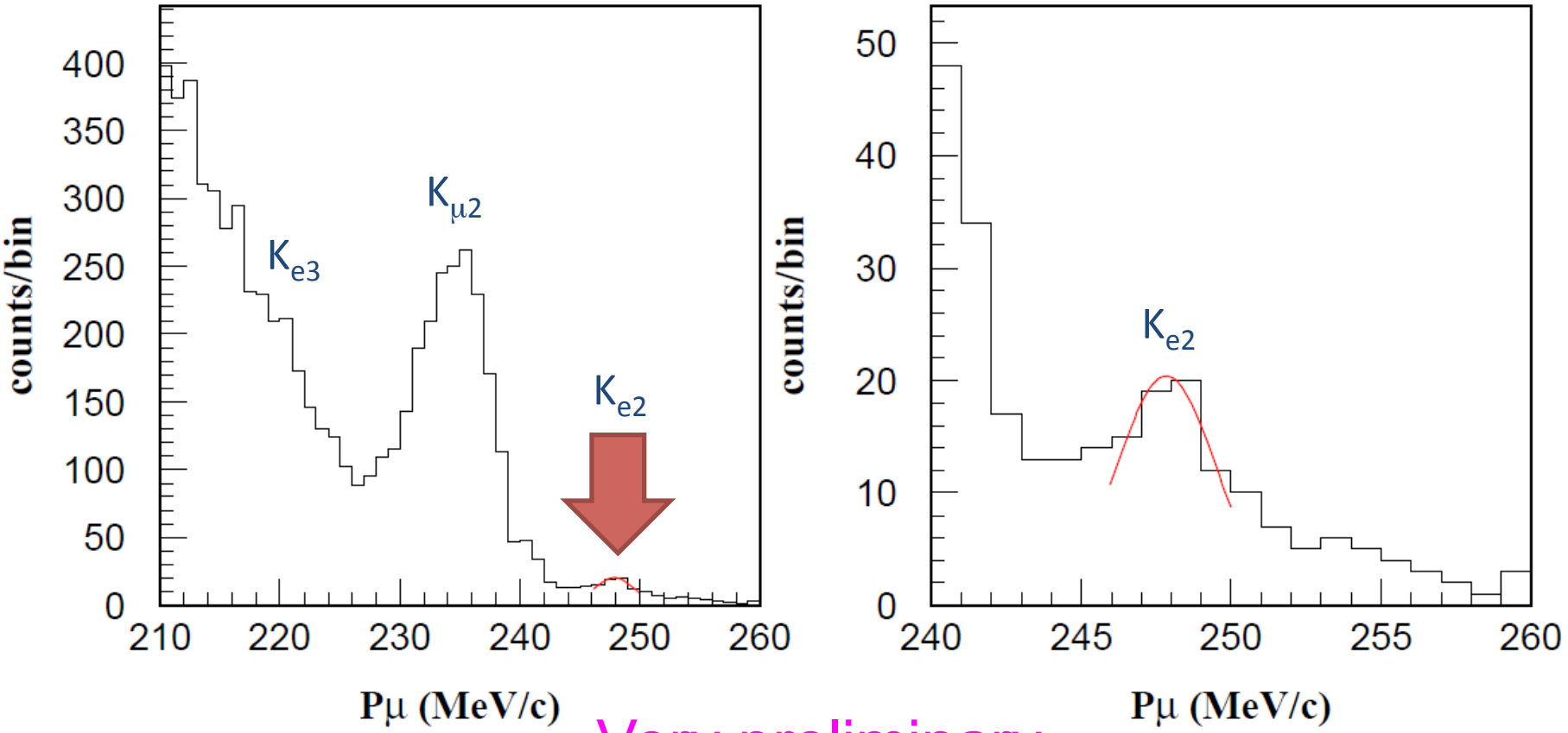
- AC and PGC performing as expected
- TOF resolution below expectation due to TOF1 performance (June data)
- Suppression of muon mis-identification below O(10^{-8}) level achievable with refined analysis
- Refined analysis of PID performance in progress

Very preliminary



K_{e2} events

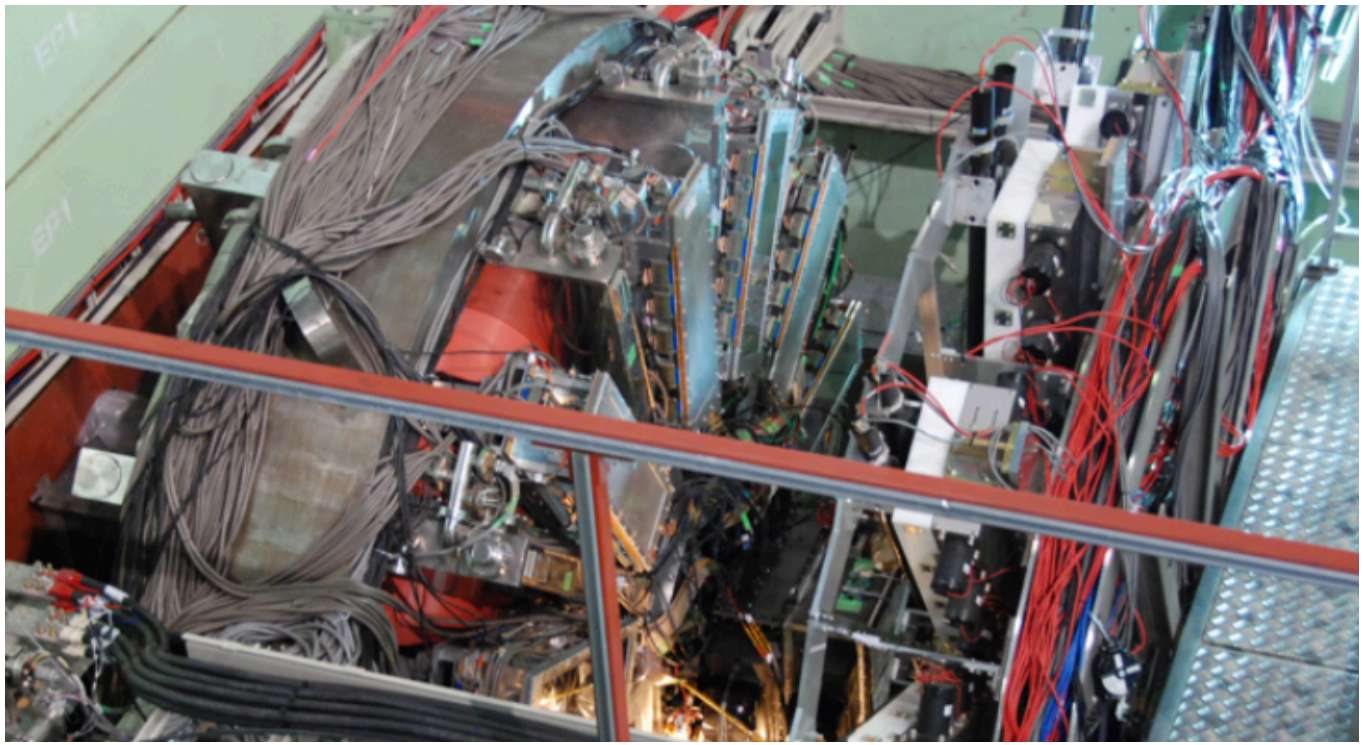
- Observed K_{e2} peak in the momentum spectrum after PID cuts
- Statistics from 100 runs in June 2015
- Improved trigger purity and dead time by additional trigger counter (TTC) and by requiring >1 target fiber hit in the trigger
- Collected ~40k K_{e2} events in fall 2015 (estimate based on $K_{\mu 2}$)



Very preliminary

Summary

- **Substantial progress of TREK/E36 @ J-PARC toward realization**
- **E36: Measure $K_{e2}/K_{\mu 2}$ ratio – test of lepton universality to 0.25% (beam power 30-40 kW)**
- **Searches for dark photon/light boson and heavy sterile neutrino**
- **Experiment has been fully commissioned in spring 2015**
- **Production running has been completed (Oct. 14 – Dec. 18, 2015)**
- **Pursue TREK/E06 (T-violation) in the future at extended Hadron F.**



TREK (E36/E06) collaboration

~30 collaborators

Spokespeople:
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Backup

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)

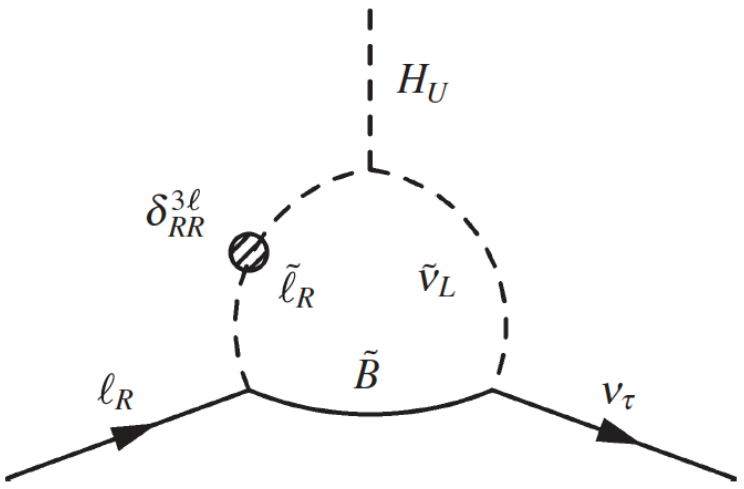


FIG. 1. Contribution to the effective $\bar{\nu}_\tau \ell_R H^+$ coupling.

- General discussions on SUSY effects

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

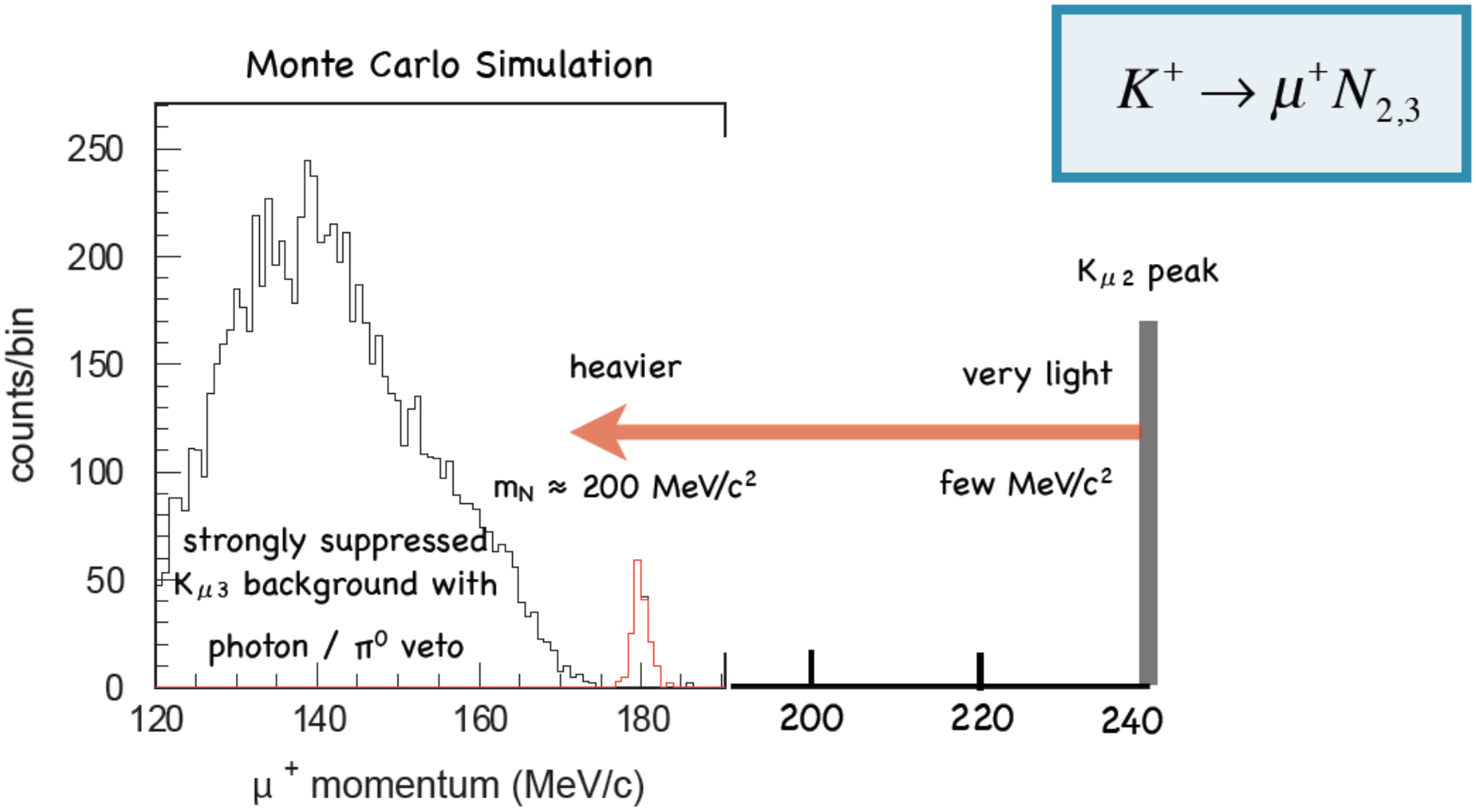
  - strong constraints from $B_s \to \mu^+\mu^-$ and $B_u \to \tau\nu$
  - $|\Delta R_K/R_K| \sim O(10^{-3})$

- 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]

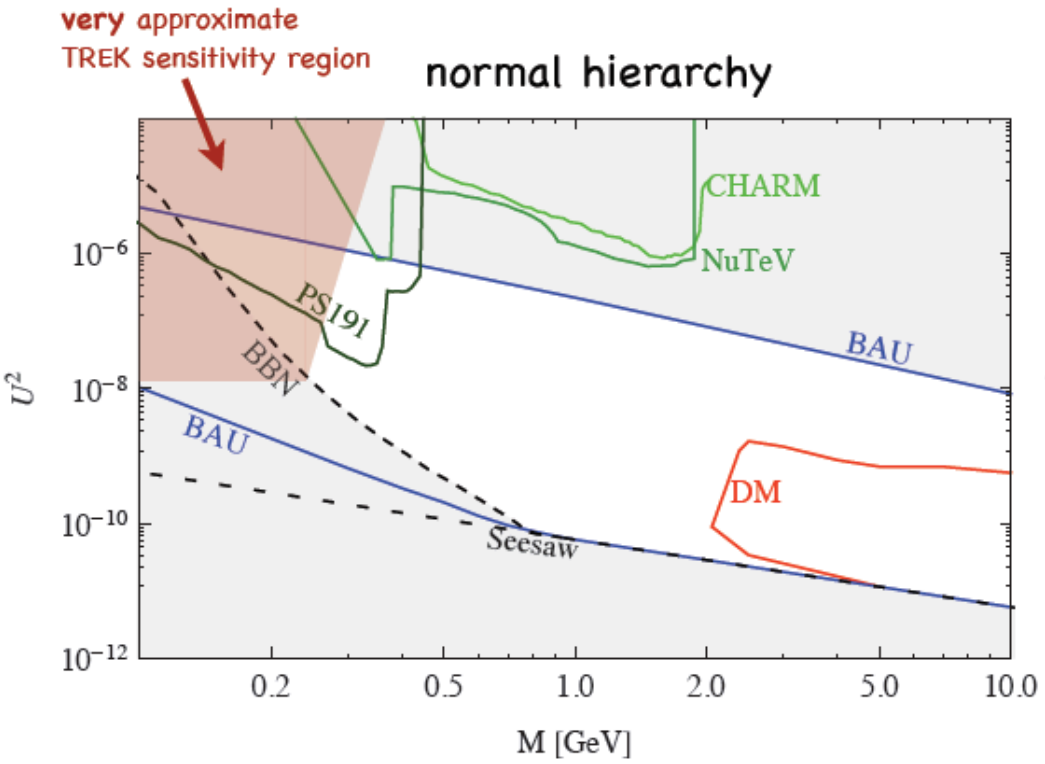
Heavy neutrino search in $K^+ \to \mu^+ N$, $e^+ N$

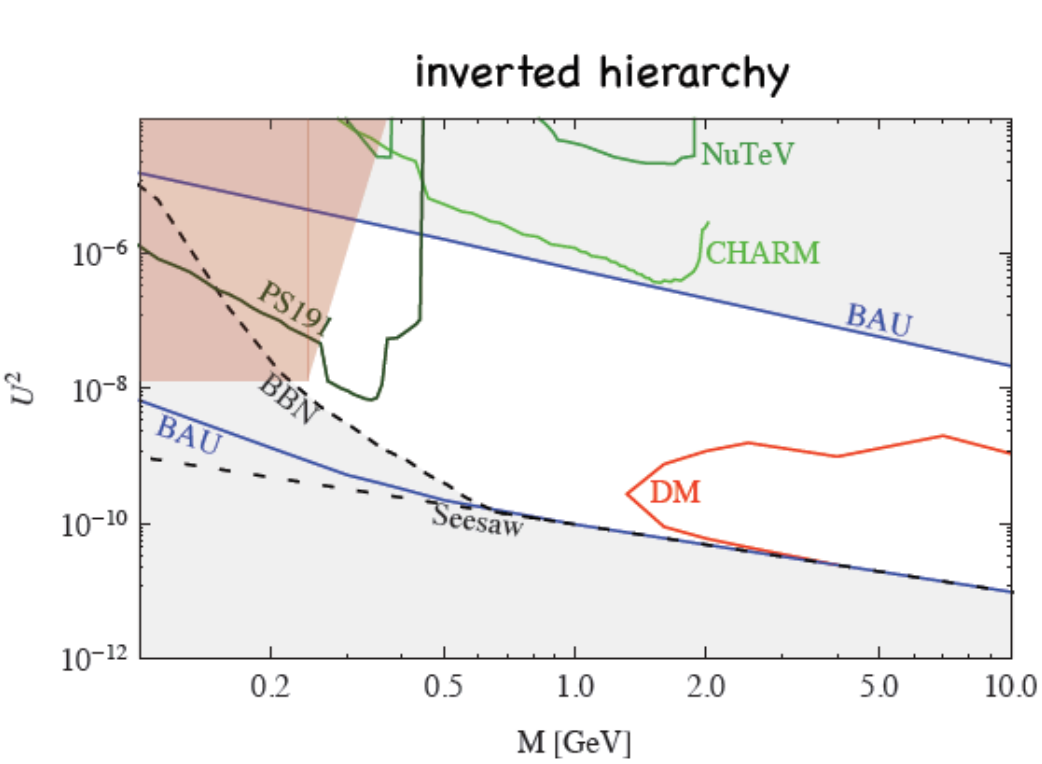


- ν Minimal Standard Model (νMSM)
  - -- Explanation of DM and BAU
  - -- Possibility of $M_N \leqq M_K$
- Search for monochromatic peaks in $K^+ \to \mu^+ N$, $K^+ \to e^+ N$

  D. Gorbunov and M. Shaposhnikov, JHEP0710, 015 (2007)

Heavy neutrino search in $K^+ \to \mu^+ N$, $e^+ N$





BAU Baryon asymmetry of the Universe
DM Dark matter
BBN Big bang nucleosynthesis
Sterile neutrino searches

L. Canetti, M. Drewes, M. Shaposhnikov,
Phys. Rev. Lett. **110**, 061801 (2013)

Projected TREK / E36

$BR(K^+ \to \mu^+ N, e^+ N) \lesssim 2 \times 10^{-8}$

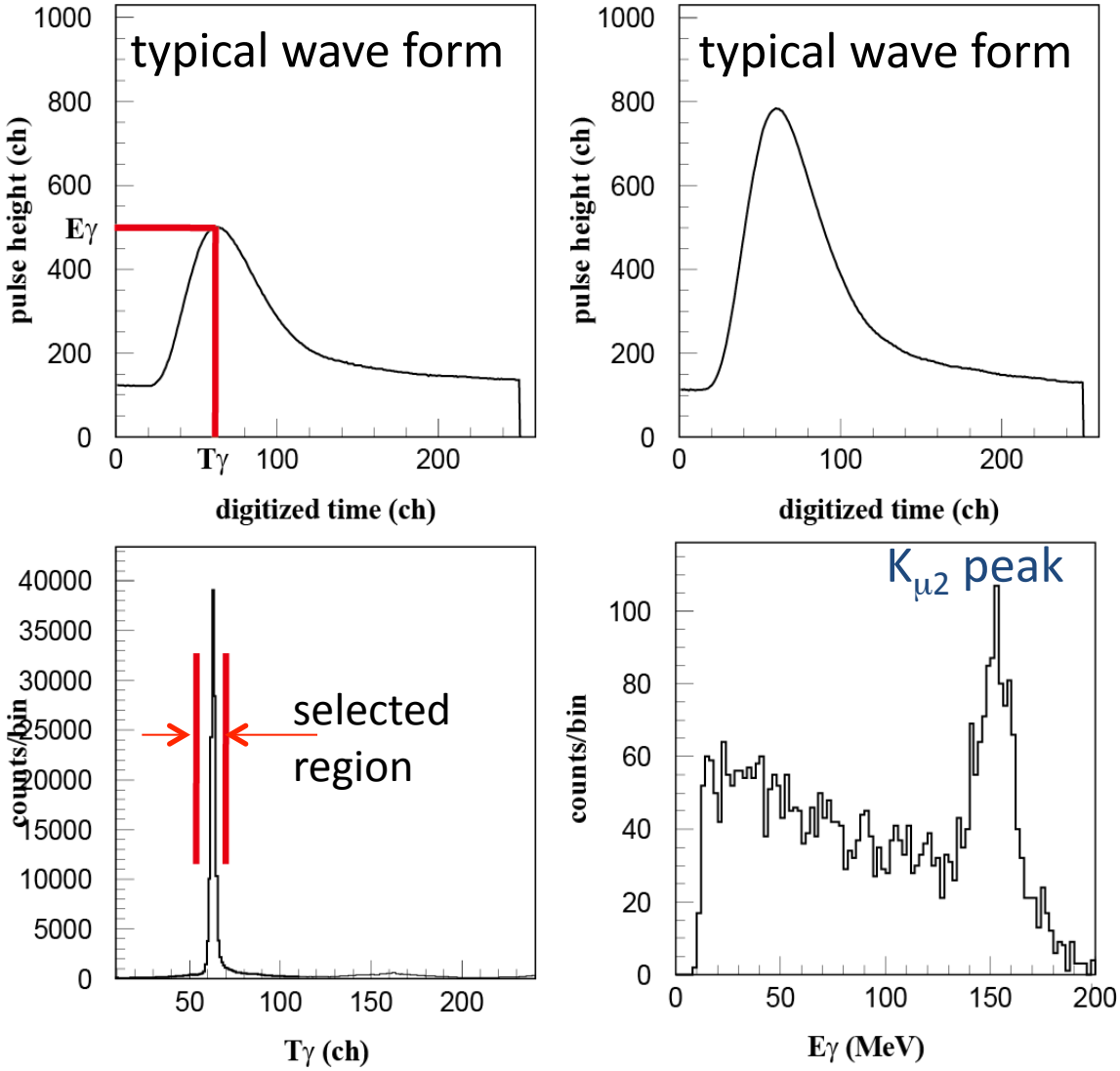
$U^2 \lesssim 3 \times 10^{-8}$ for $M_N < 200$ MeV

sensitivity for $M_N > 200$ MeV needs more study

CsI(Tl) calorimeter analysis

- **Energy and timing obtained by pulse shape data from FADC (VF48)**
- **Events from the K^+ decays were selected**
- **$K_{\mu 2}$ events with single crystal hit used for the energy calibration**
- **Deposited muon energy used for energy calibration of each crystal**

Very preliminary



Calibration data from early June

Combining spectrometer + calorimeter

- $K_{\pi 2}$ 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