Search for New Physics via a Measurement of the Transverse Muon Polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$ Decay

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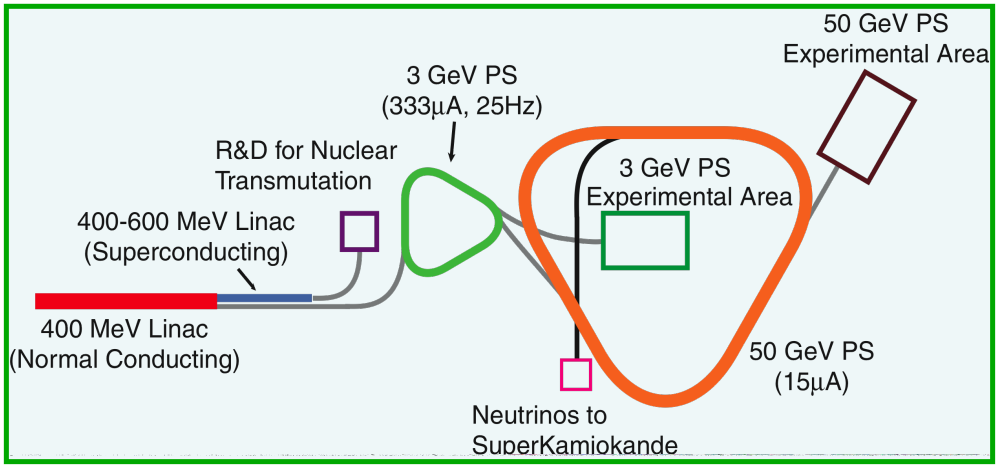
University of British Columbia
on behalf of the TREK--E06 collaboration

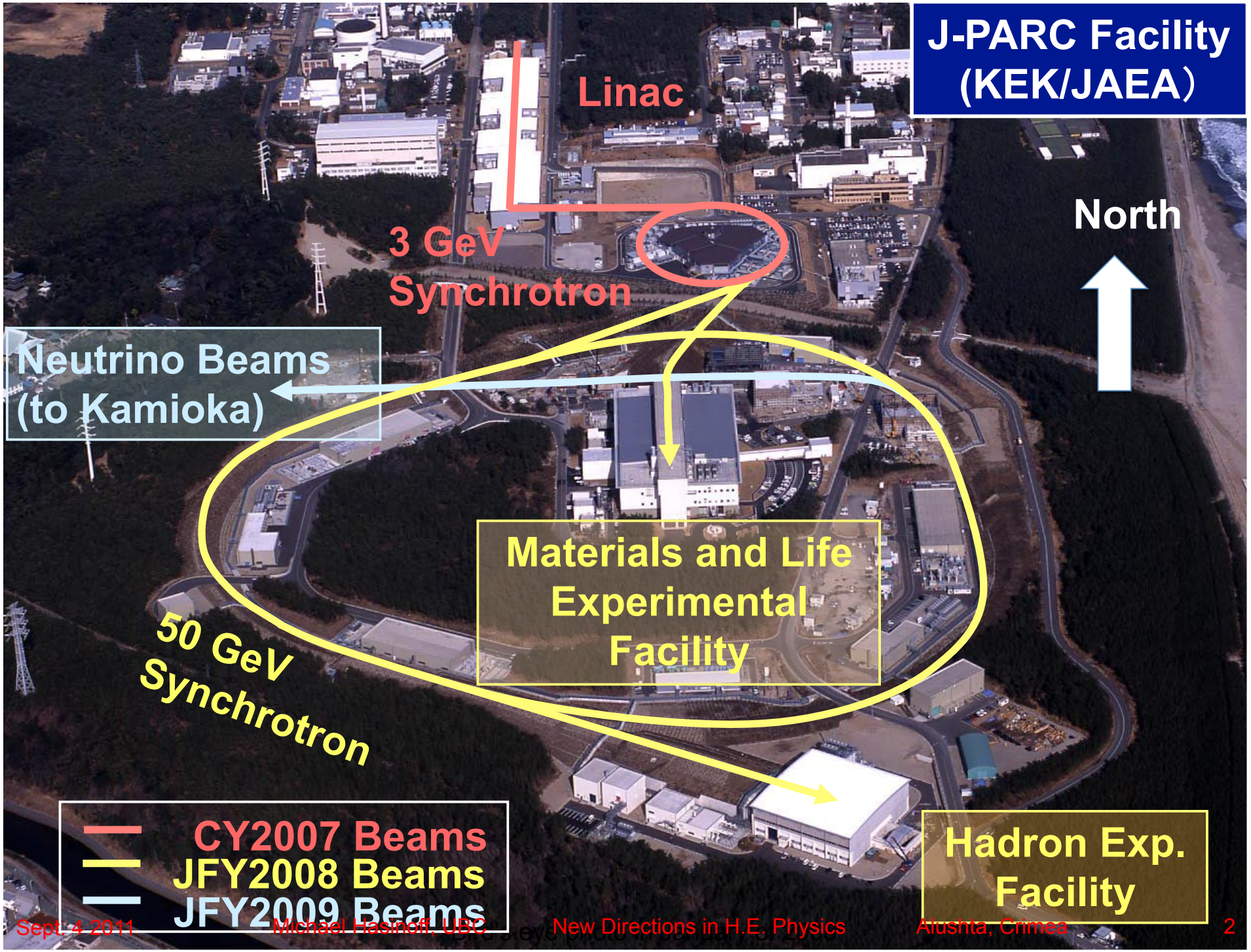
Outline

- **Hadron Facility at J-PARC**
- **TREK Program** TREK = Time Reversal Experiment with Kaons
  - **Search for Time Reversal Symmetry Violation**
  - **Test of Lepton Universality**
  - **Search for Heavy Neutrinos**

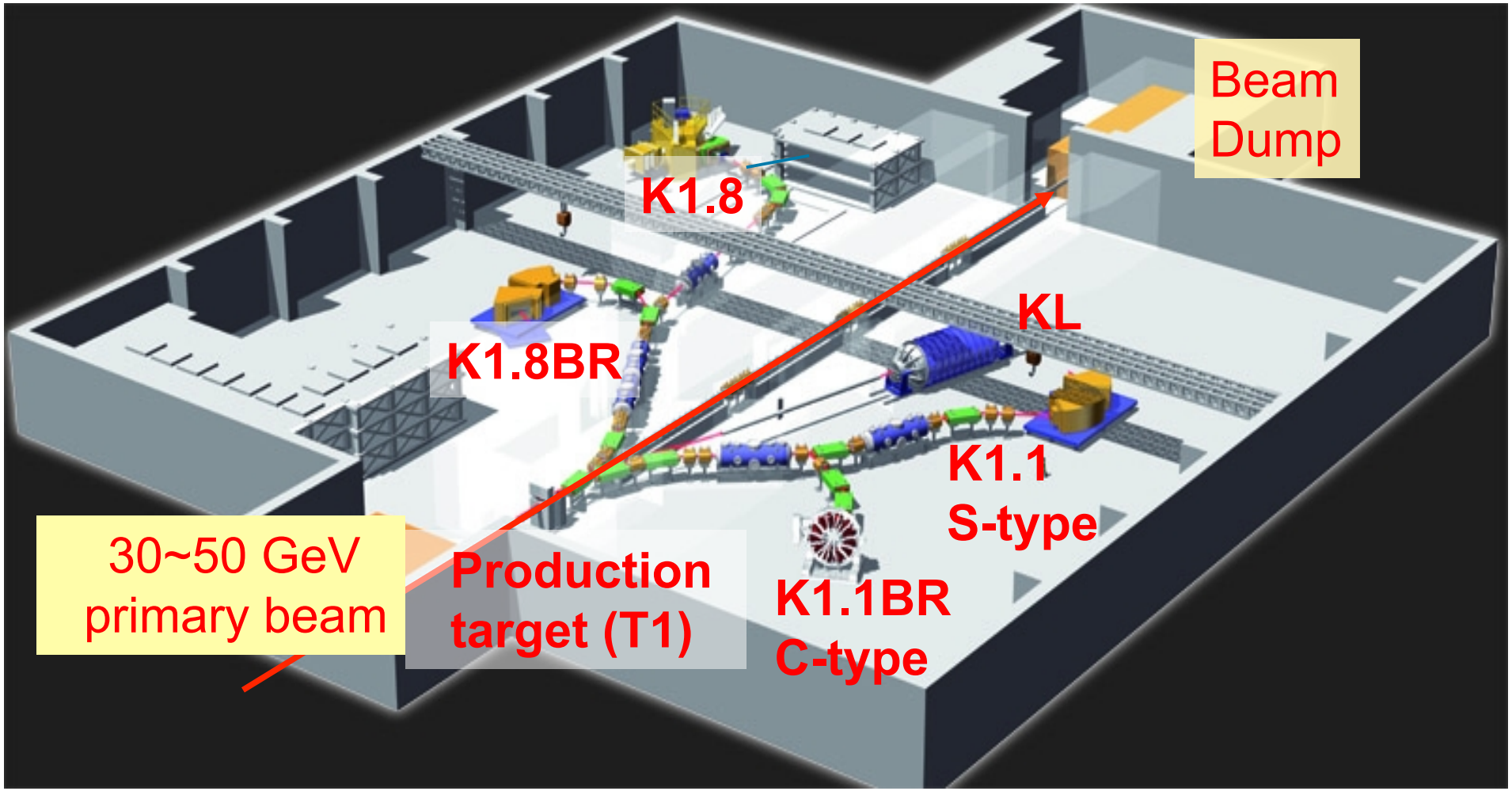
  } Lower intensity

- **TREK Apparatus -- R & D**
- **Status & Schedule**



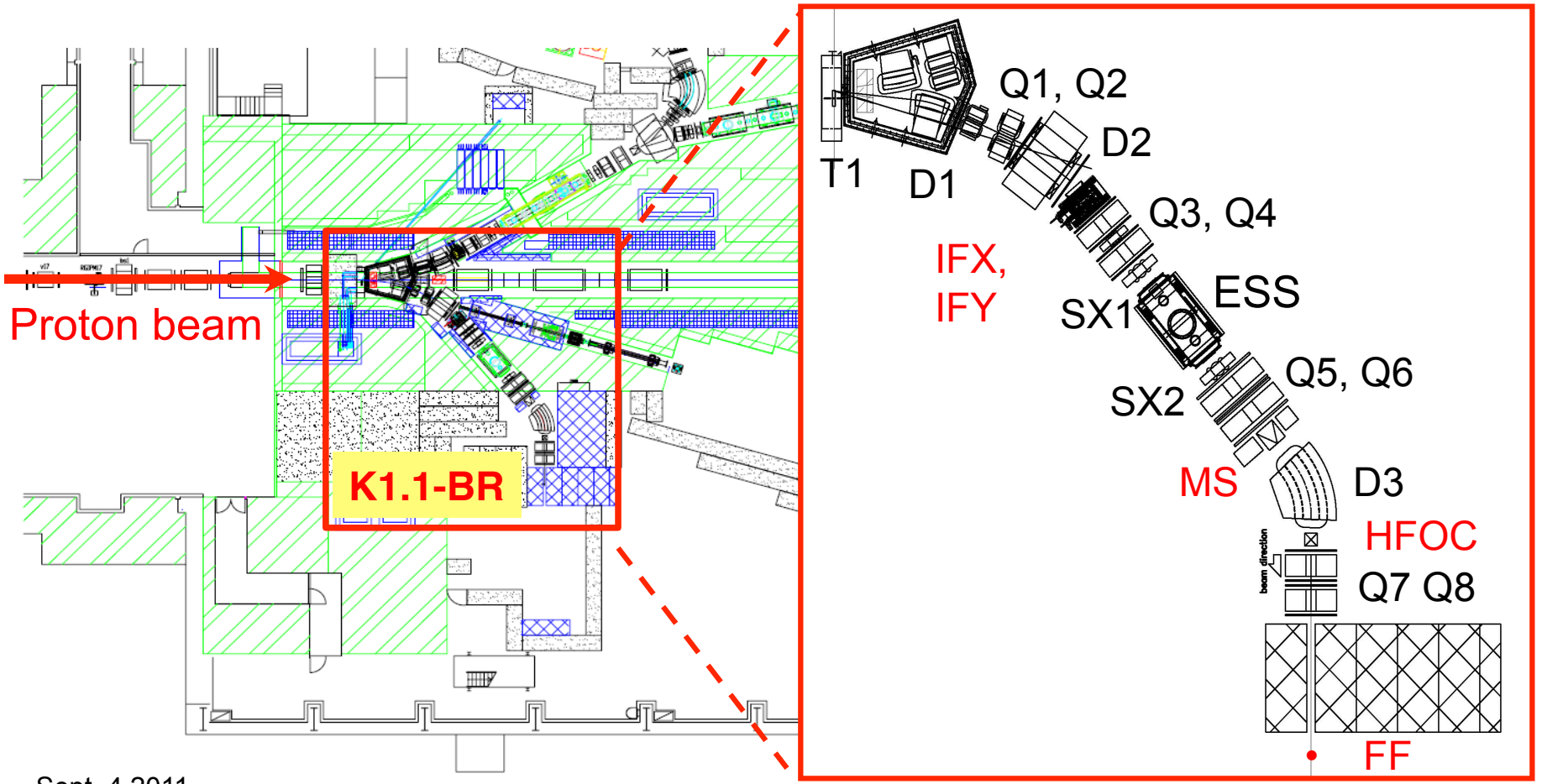

J-PARC Facility
(KEK/JAEA)
Linac
3 GeV
Synchrotron
North
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams

J-PARC Hadron Hall



K1.1BR = K0.8 Beam Line Installation

- K1.1BR completed in summer 2010 using the supplementary budget of FY09
- Commissioned in Oct. 2010 by the TREK collaboration
  - ESS Length of 2.0m to be increased to 2.5m
  - Length Q8-FF of 3.3m to be reduced to 1.5m (remove iron shielding wall)



Stopped K^+ Experiments K1.1BR

- E06 (TREK)

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

  Stage-1 270 kW

- P36 (LFU)

  "Measurement of $R_K = \Gamma(K^+ \to e^+ \nu) / \Gamma(K^+ \to \mu^+ \nu)$ and search for heavy sterile neutrinos"

  Stage-1 (PAC11-Jan'11) 30 kW

TREK Collaboration

CANADA
University of British Columbia
University of Manitoba
Universite de Montreal
University of Saskatchewan
TRIUMF

USA
Massachusetts Inst. of Technology (MIT)
University of South Carolina
Iowa State University
Hampton University
Jefferson Laboratory

RUSSIA
Russian Academy of Sciences (RAS)
Institute for Nuclear Research (INR)--Moscow

JAPAN
Osaka University
National Defense Academy
Tohoku University
High Energy Accelerator Research Org. (KEK)
Kyoto University
Tokyo Institute of Technology (TiTech)

VIETNAM
University of Natural Sciences

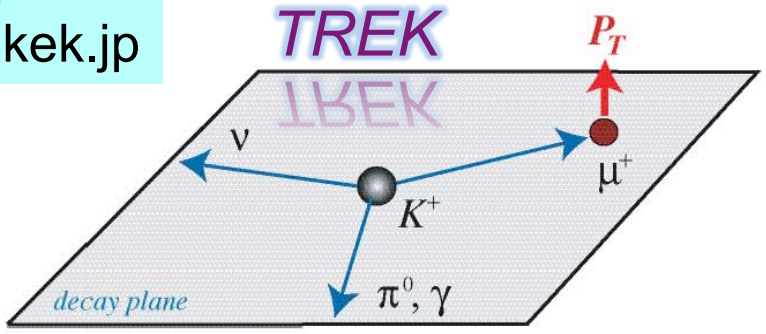
New collaborators are welcome!

Transverse μ^+ polarization in $K_{\mu 3}$ Decay

$K^+ \to \pi^0 \mu^+ \nu$ decay

http://trek.kek.jp

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|\,(p_{\pi^0,\gamma} \times p_{\mu^+})\,|}$$



- P_T is T-odd, and spurious effects from final state interaction are small: $P_T(\mathrm{FSI}) < 10^{-5}$

  Non-zero P_T is a signature of T violation.

- Standard Model (SM) contribution to P_T : $P_T(\mathrm{SM}) < 10^{-7}$

  Hence P_T in the range 10^{-3} – 10^{-5} is a sensitive probe of CP violation beyond the SM.

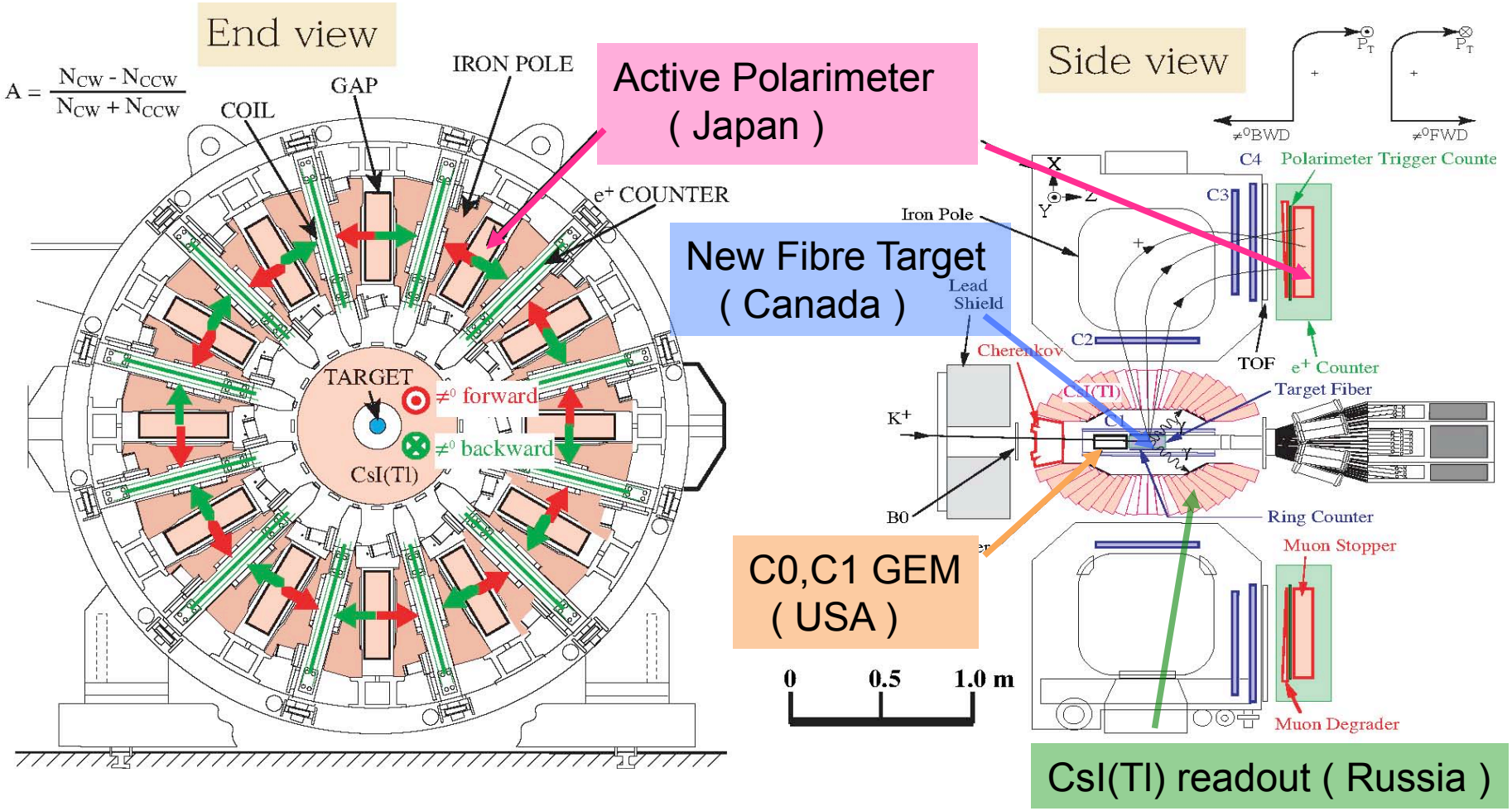
- There are theoretical models of new physics which allow a sizable P_T value without conflicting with other experimental constraints.

The TREK experiment aims for a sensitivity of 10^{-4}

TREK Experimental Apparatus

$K^+ \to \pi^0 \mu^+ \nu$

Use an upgraded E246 detector



P_T is measured as the azimuthal asymmetry A_{e^+} of the μ^+ decay positrons

Stopped beam method $K^+ \to \pi^0 \mu^+ \nu$

Double ratio experiment

$A_T = (A^{fwd} - A^{bwd}) / 2$

$$A^{fwd(bwd)} = \frac{N_{cw} - N_{ccw}}{N_{cw} + N_{ccw}}$$

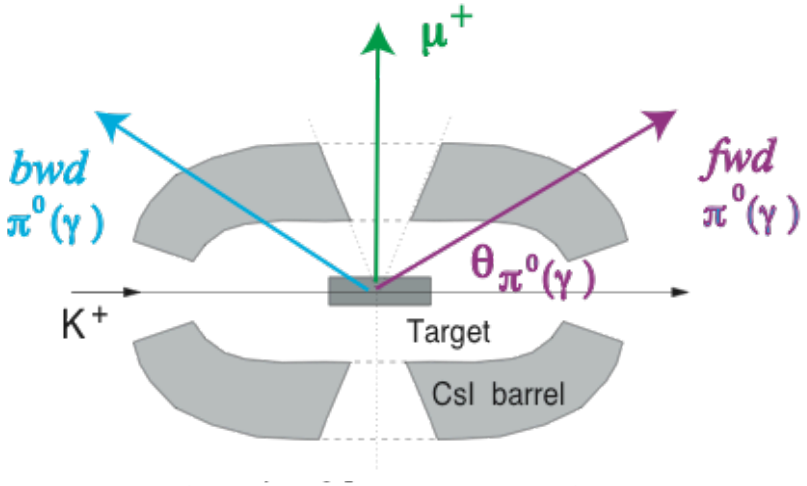
$P_T = A_T / \{\alpha \langle \cos\theta_T \rangle\}$

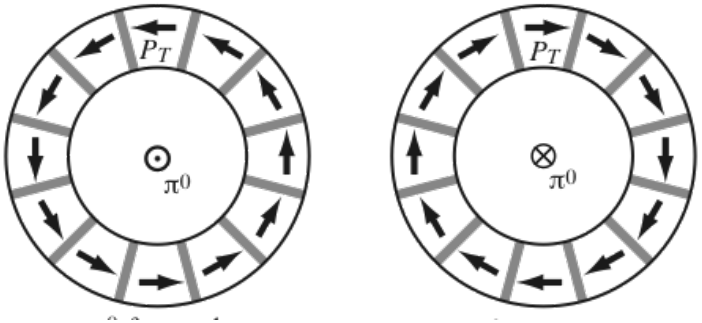
α : analyzing power

$\langle \cos\theta_T \rangle$: attenuation factor

$\mathrm{Im}\xi = P_T / KF$: physics parameter

KF : kinematic factor





***bwd* - π^0 (γ)** ***fwd* - π^0 (γ)**

Current limit from KEK--E246

$P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$

$|P_T| < 0.005$: 90% *C.L.*

$\mathrm{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$

$|\mathrm{Im}\xi| < 0.016$: 90% *C.L.*

Statistical error dominates

Expected sensitivity -- TREK

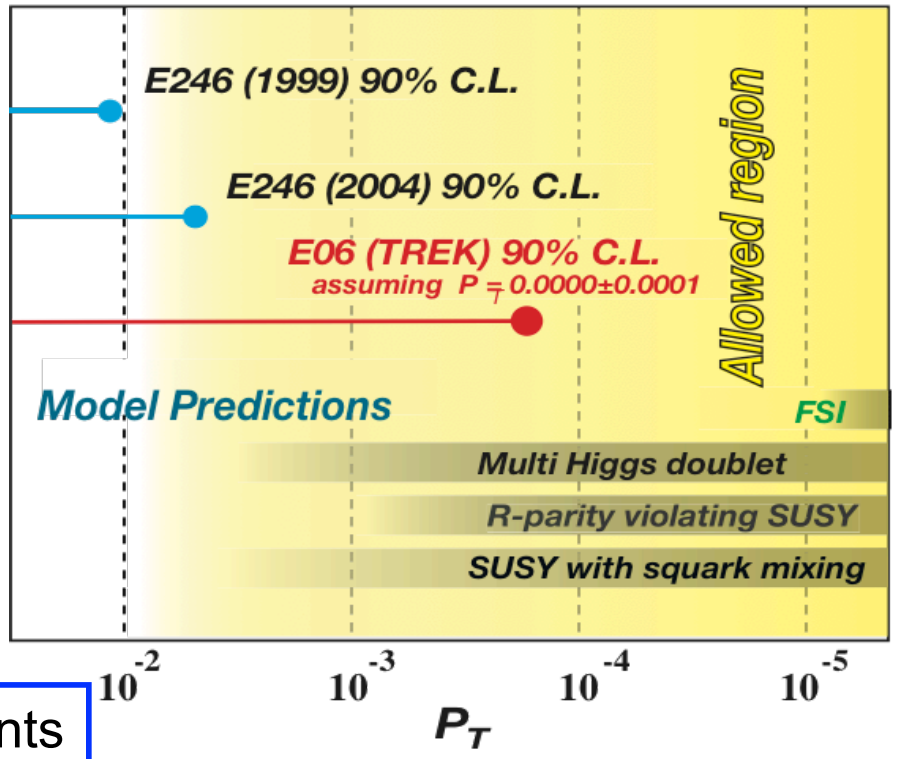
We are aiming for a sensitivity of $\delta P_T \sim 10^{-4}$

- $\delta P_T^{stat} \sim 0.05\ \delta P_T^{stat}$ (E246) $\sim 10^{-4}$: 1.4 x 10^7 sec runtime

1) Beam intensity x 30
2) Detector acceptance x 10
3) Larger analyzing power

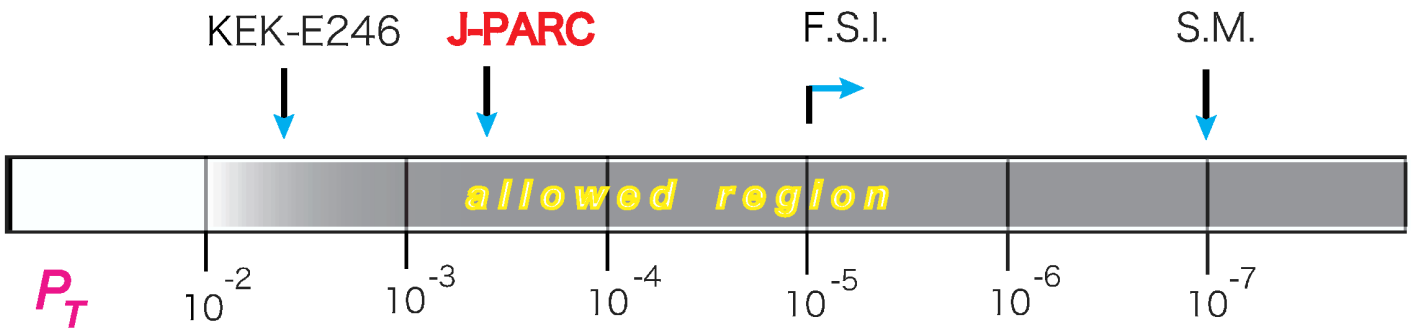
- $\delta P_T^{syst} \sim 0.1\ \delta P_T^{syst}$ (E246)

  $\sim 10^{-4}$



1) Precise calibration of misalignments
2) Correction of systematic effects
3) Precise ***fwd-bwd*** cancellation

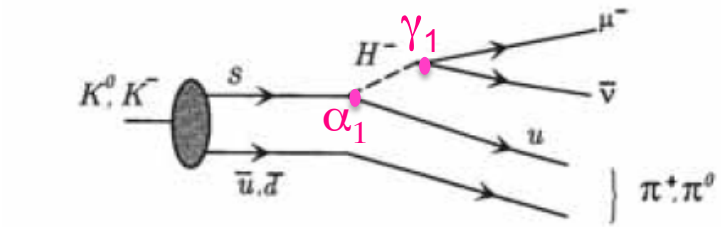
New Physics: Model predictions for P_T

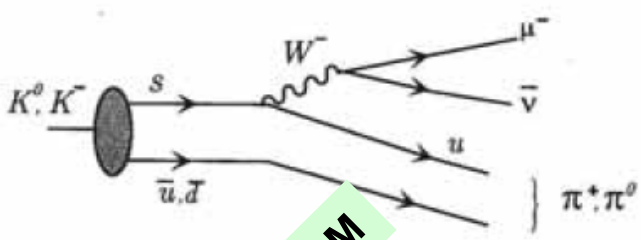


Model	$K^+ \to \pi^0\mu^+\nu$	$K^+ \to \mu^+\nu\gamma$
■ Standard Model	$< 10^{-7}$	$< 10^{-7}$
■ Final State Interactions	$< 10^{-5}$	$< 10^{-3}$
■ Multi-Higgs	$\leq 10^{-3}$	$\leq 10^{-3}$
	$P_T(K^+ \to \pi^0\mu^+\nu) \approx +3\, P_T(K^+ \to \mu^+\nu\gamma)$	
■ SUSY with squark mixing	$\leq 10^{-3}$	$\leq 10^{-3}$
	$P_T(K^+ \to \pi^0\mu^+\nu) \approx -3\, P_T(K^+ \to \mu^+\nu\gamma)$	
■ 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	$< 7 \times 10^{-3}$

Three Higgs doublet model

$$L = (2\sqrt{2}G_F)^{\frac{1}{2}} \sum_{i=1}^{2} \{\alpha_i \bar{u}_L V M_D d_R H_i^+ + \beta_i \bar{u}_R M_U V d_L H_i^+ + \gamma_i \bar{\nu}_L M_E e_R H_i^+\} + \text{h.c.},$$





$$\text{Im}\xi = \frac{m_K^2}{m_H^2}\text{Im}(\gamma_1 \alpha_1^*)$$

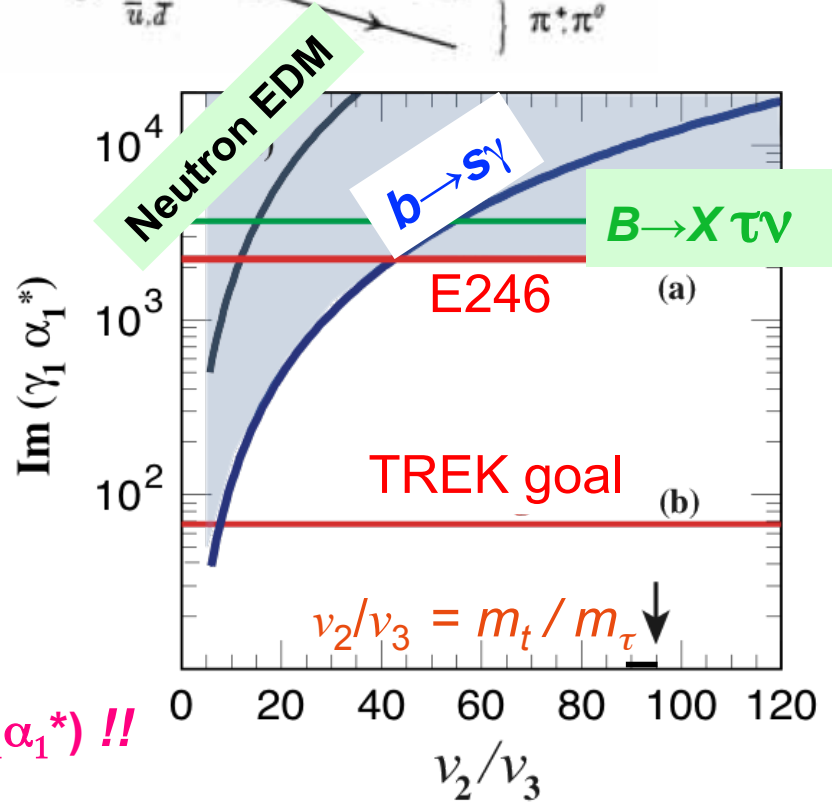
- c.f. d_n , $b \to s\gamma$ $\propto$ Im($\alpha_1\beta_1^*$), ($\alpha_1\beta_1^*$)

  Im($\alpha_1\beta_1^*$) = $-v_2^2/v_3^2$ Im($\gamma_1\alpha_1^*$)

  Higgs field v.e.v.

- $B \to X\tau\nu$ and $B \to \tau\nu$ at Super-Belle corresponds to $P_T < 3 \times 10^{-4}$

  c.f. TREK goal : $P_T \leq 1 \times 10^{-4}$



P_T is most stringent constraint for* Im($\gamma_1\alpha_1^*$) *!!

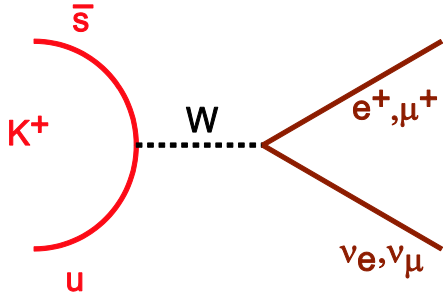
Lepton universality in $K_{\ell 2}$ and $\pi_{\ell 2}$ decays

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

- **Highly precise SM values**

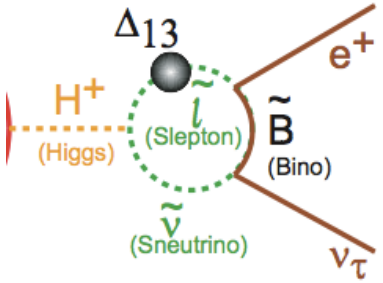
$R_K^{SM} = (\ 2.477 \pm 0.001) \times 10^{-5}$

$R_\pi^{SM} = (12.352 \pm 0.004) \times 10^{-5}$



- **High sensitivity to LFV beyond SM**

e.g. MSSM with charged-Higgs SUSY-LFV



$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H^+}^4} \cdot \frac{m_\tau^2}{m_e^2}\Delta_{13}^2 \tan^6\beta\right) \Rightarrow R_K^{LFV} \sim R_K^{SM}(1 \pm 0.013)$$

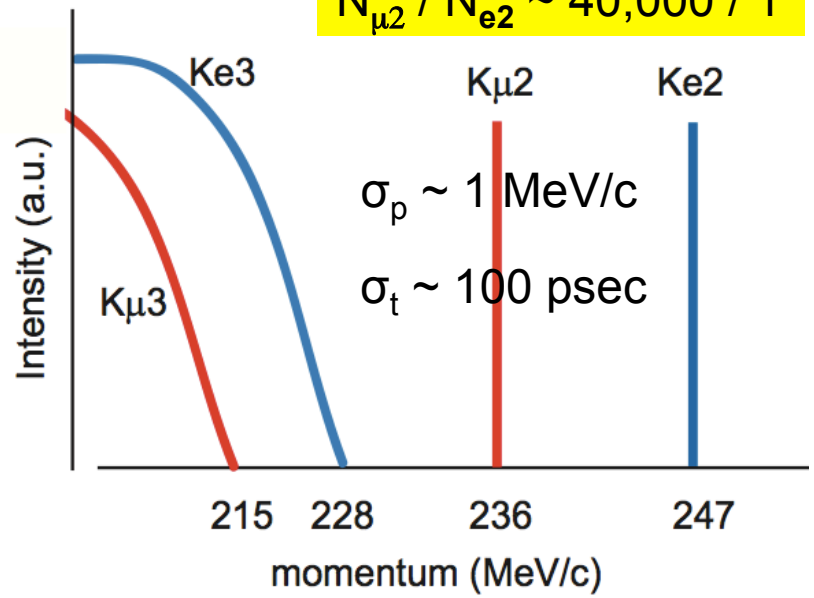
- **Current experimental precision (NA62, KLOE)**

$R_K = (2.488 \pm 0.012) \times 10^{-5}$, 1.1σ dev., $\Delta R_K/R_K = 0.5\%$ ⇒ 0.4%

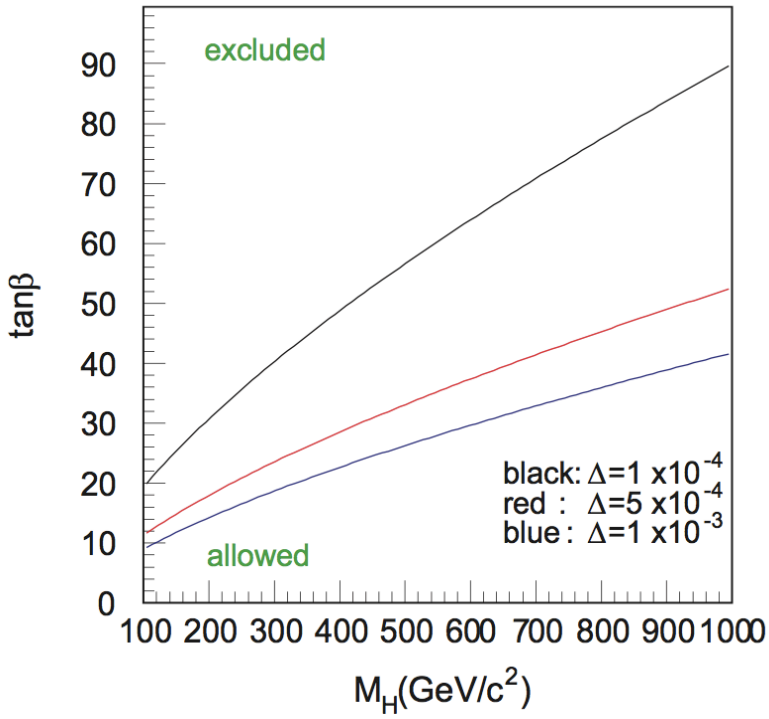
Improve precision to ~ 0.2%, presentation to PAC11

Lepton Flavour Universality

$N_{\mu 2} / N_{e2} \sim 40{,}000 / 1$



MSSM with charged-Higgs SUSY--LFV



New Pseudoscalar Interaction --

$\Delta R_K/R_K = 0.2\%$

$\Lambda_{eP} \sim 750$ TeV

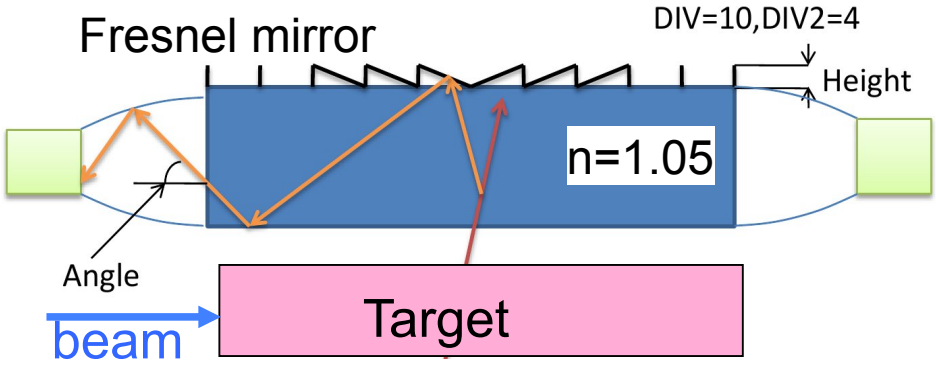
$$R_K^P \sim R_K^{SM}\left[1 \pm \frac{\sqrt{2}\pi}{G}\frac{1}{\Lambda_{eP}^2}\frac{m_K^2}{m_e(m_d+m_u)}\right]$$

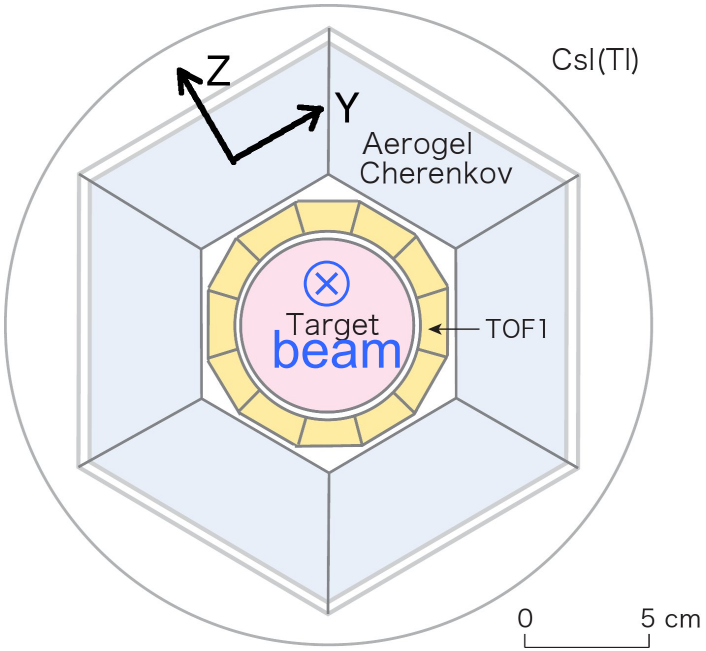
$$\frac{R_K^P}{R_K^{SM}} \sim 1 + \left(\frac{1\text{TeV}}{\Lambda_{eP}}\right)^2 \times 10^3,$$

e/μ Identification -- LFU

- Momentum measurement of e^+, μ^+
- TOF measurement between TOF_1 and TOF_2
- e^+ trigger by aerogel Cherenkov detector

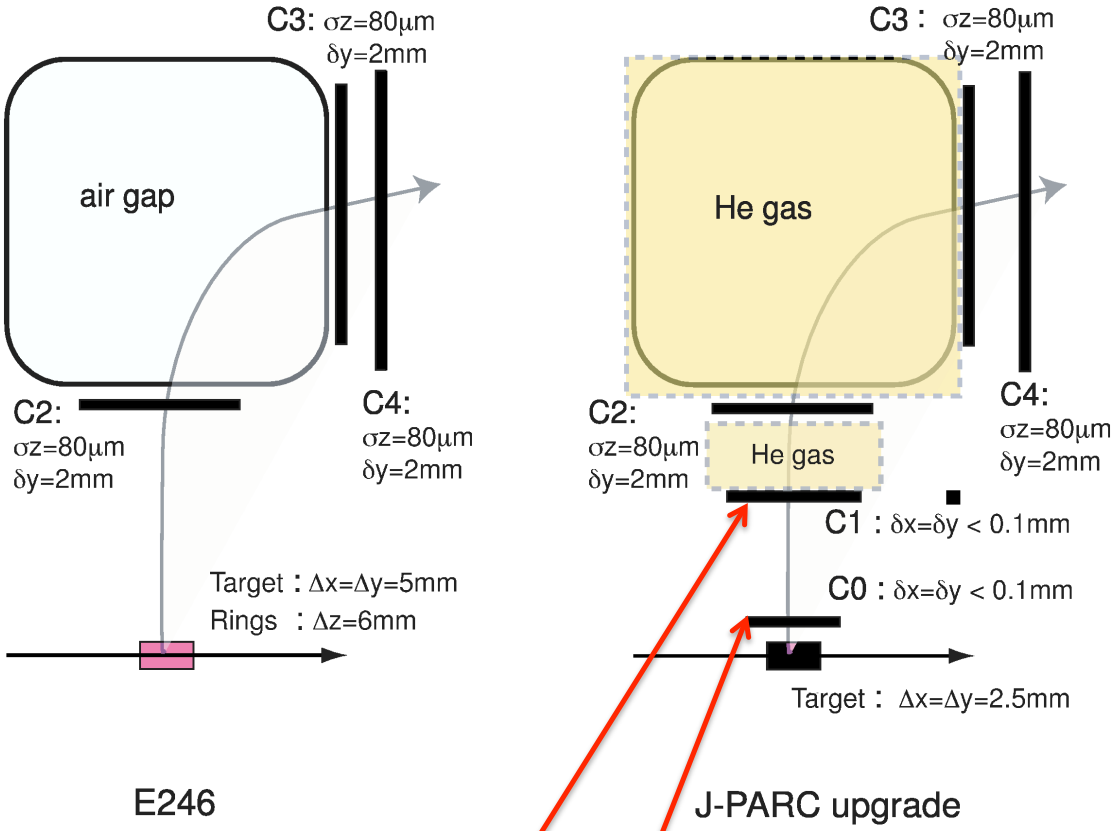
$\beta(e^+ \text{ from } K_{e2})$ ~1
$\beta(\mu^+ \text{ from } K_{\mu 2})$ ~ 0.92 = 1 / 1.087
Estimated efficiency = 99.2 ± 0.2%



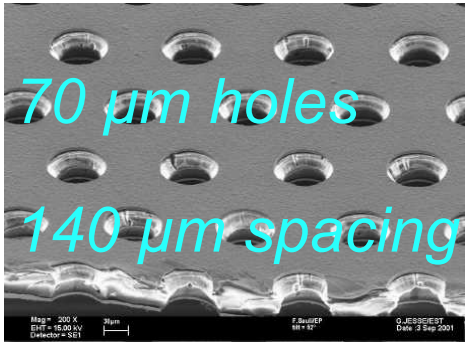


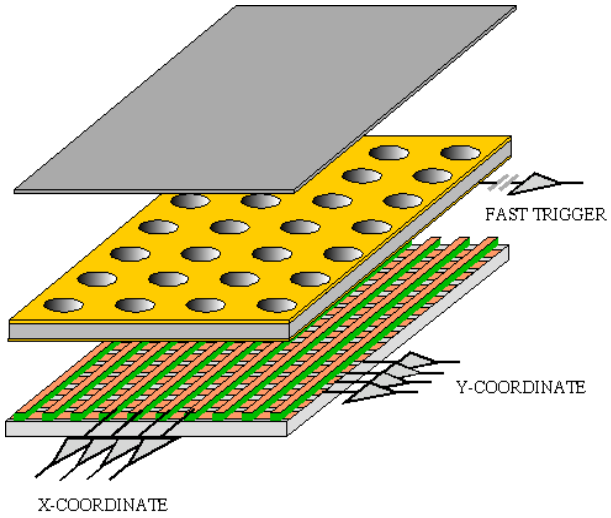
PID performance and detector efficiency will be measured & controlled using K_{e3} and $K_{\mu 3}$ data.

TREK/E06 Tracking Upgrade



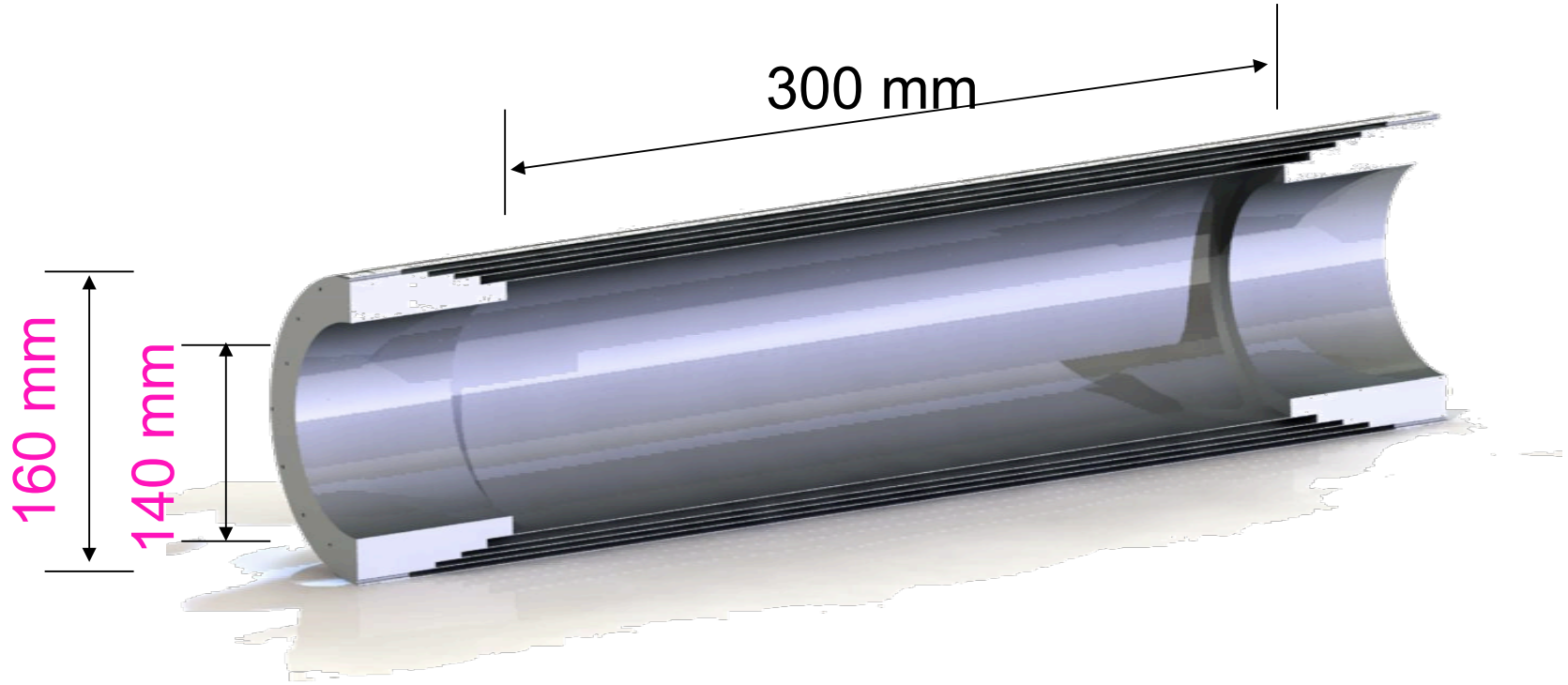
GEM technology – in collaboration with Jefferson Lab, Hampton U. and MIT





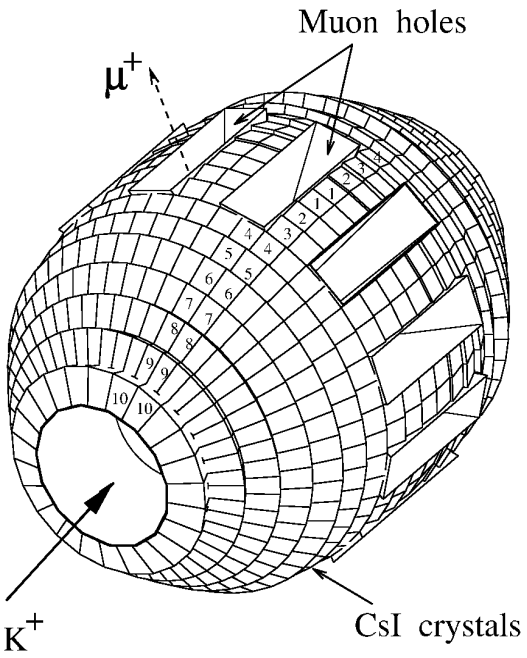
- **Planar GEMs (C1) between CsI and C2**
- **Cylindrical GEM (C0) as replacement for old C1**

C0 Cylindrical GEM for TREK



- Vertex tracking near target, $\delta < 0.1$ mm
- Very high rate capability > 1 kHz/mm^2
- Radiation-hardness >> 10^7 particles/mm^2

R&D(1) APD Readout for CsI(Tl)

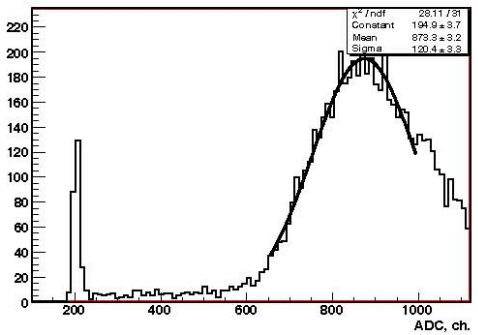


ISC, Kharkov, Ukraine

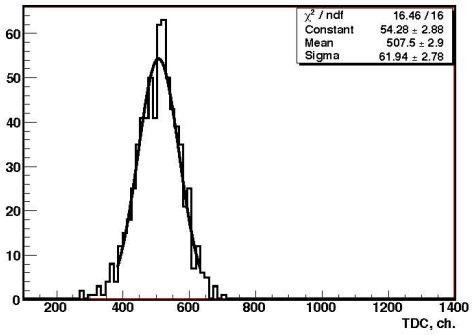
Yuri Kudenko, INR, Moscow

- Improve the timing characteristics of CsI(Tl) by replacing PIN diode with APD
- Pulse shaping and pile-up analysis

One-module energy



One-module timing



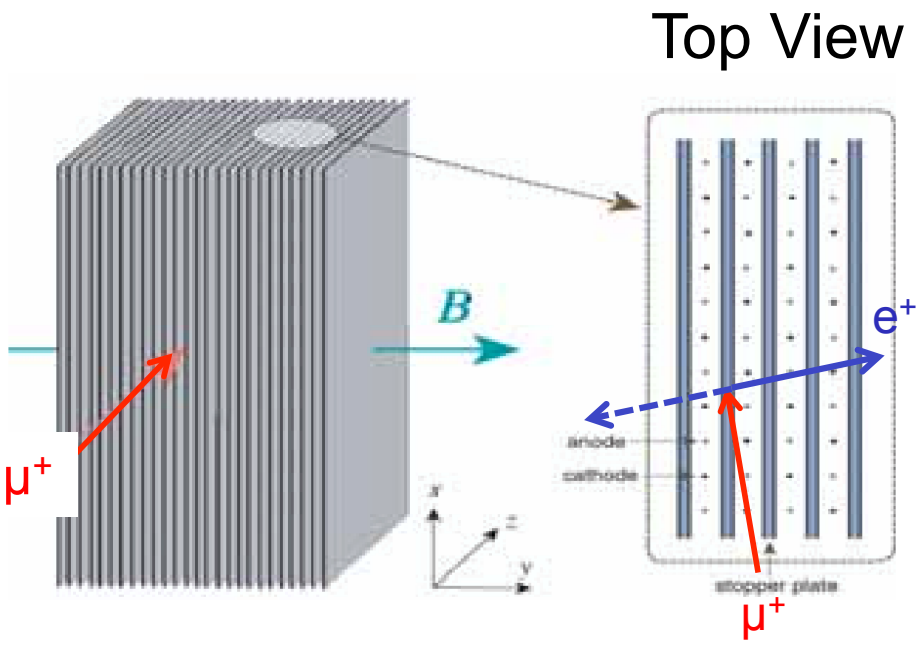
Parameter	E06 APD readout	E246 PIN readout
Electron yield	47,000/MeV	11,000/MeV
Noise level	not yet measured	70 keV
Energy resolution	~12% for C.R.	12% for C.R.
Time rsolution	3 ns for C.R.	12 ns for C.R. (9 ns for all)
Pulse width	$\sim$ 1.5 μs	15 μs
Rate performance	$\sim$ 500 kHz	34 kHz

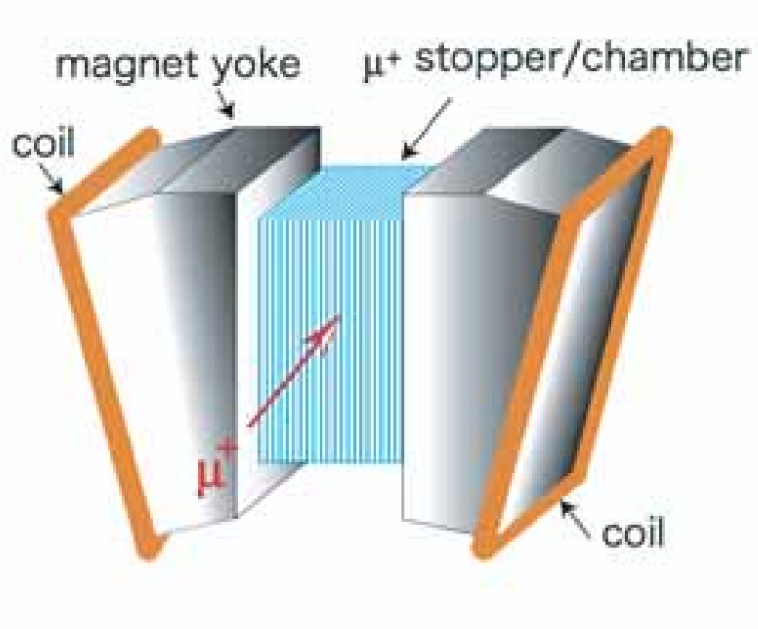
new requirement

too slow

- Both 1 and 9 module tests have been performed using an e+ beam at Tohoku Univ. to check the energy resolution and high-rate performance of APD readout

R&D(2) Active Muon Polarimeter





- **Full angular acceptance for positrons – 10x higher than in E-246**
- **Determination of decay vertex – background-free measurement**
- **Measurement of e^+ angle and approx. energy – higher analyzing power**
- **Improved field alignment – suppressed systematic error**

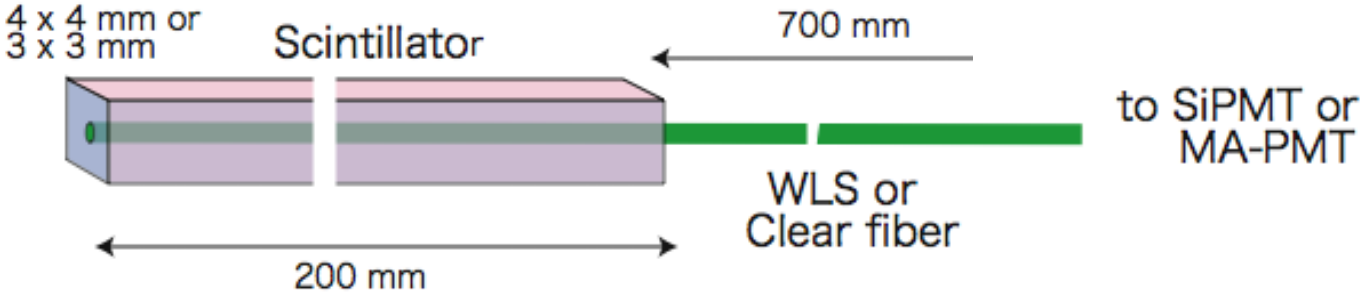
- **Full-size prototype was tested at TRIUMF in Nov. 2009**

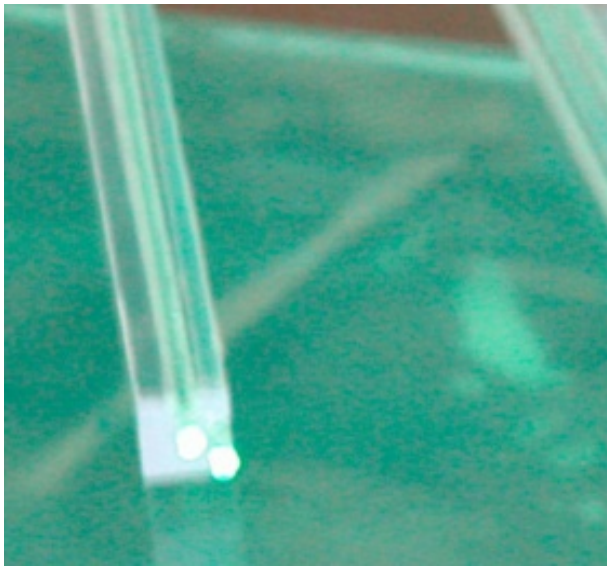
R&D(3) Active scintillating fibre target

One element

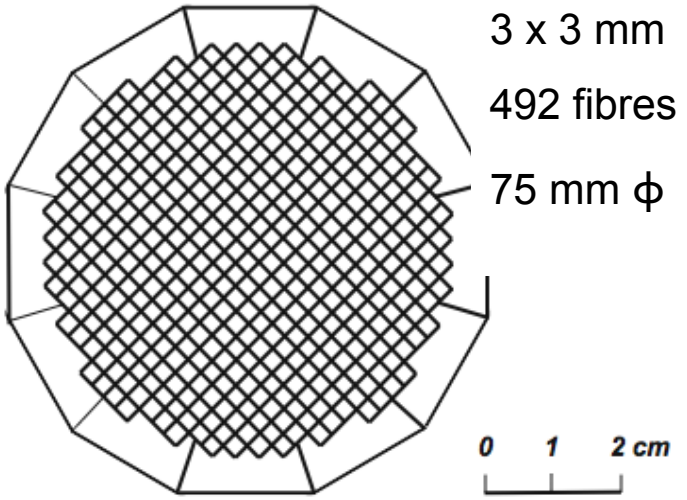
Baseline design

c.f. E246 Ring counters
PSI FAST target





Cross section



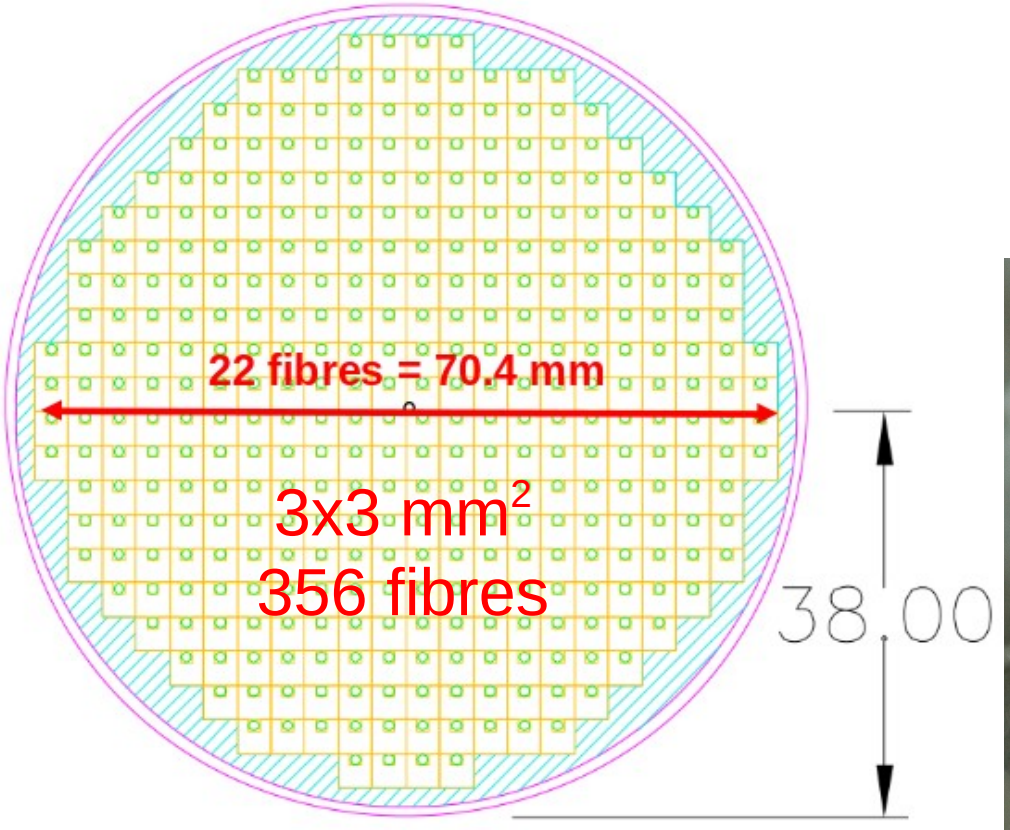
3 x 3 mm

492 fibres

75 mm ϕ

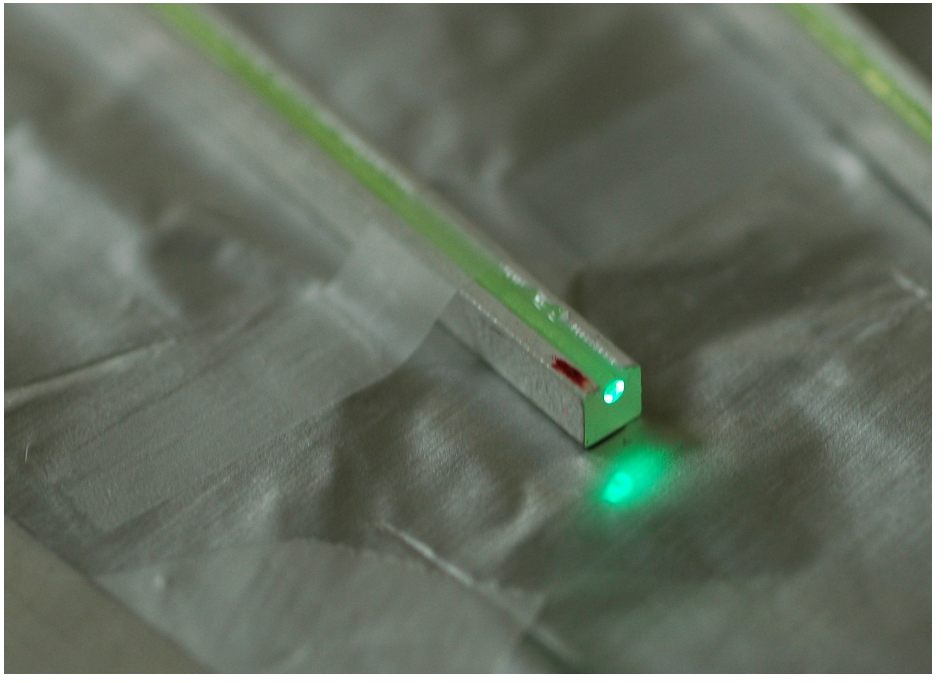
- Light guide:
  Kuraray Y11 WLS fibre
- Readout:
  SiPMT (Hamamatsu MPPC)
- Beam test using 130 MeV/*c* π's
  at TRIUMF – radiation damage

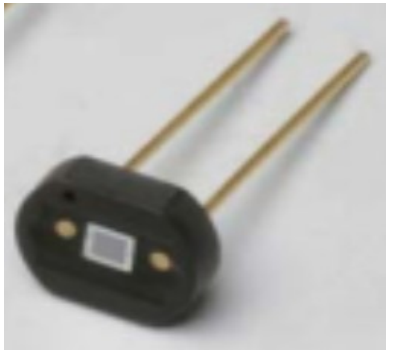
R&D(3) – Active Scintillating Fiber Target



Light Guide:

Kuraray Y11 WLS Fibre





Readout:

SiPMT (Hamamatsu MMPC)

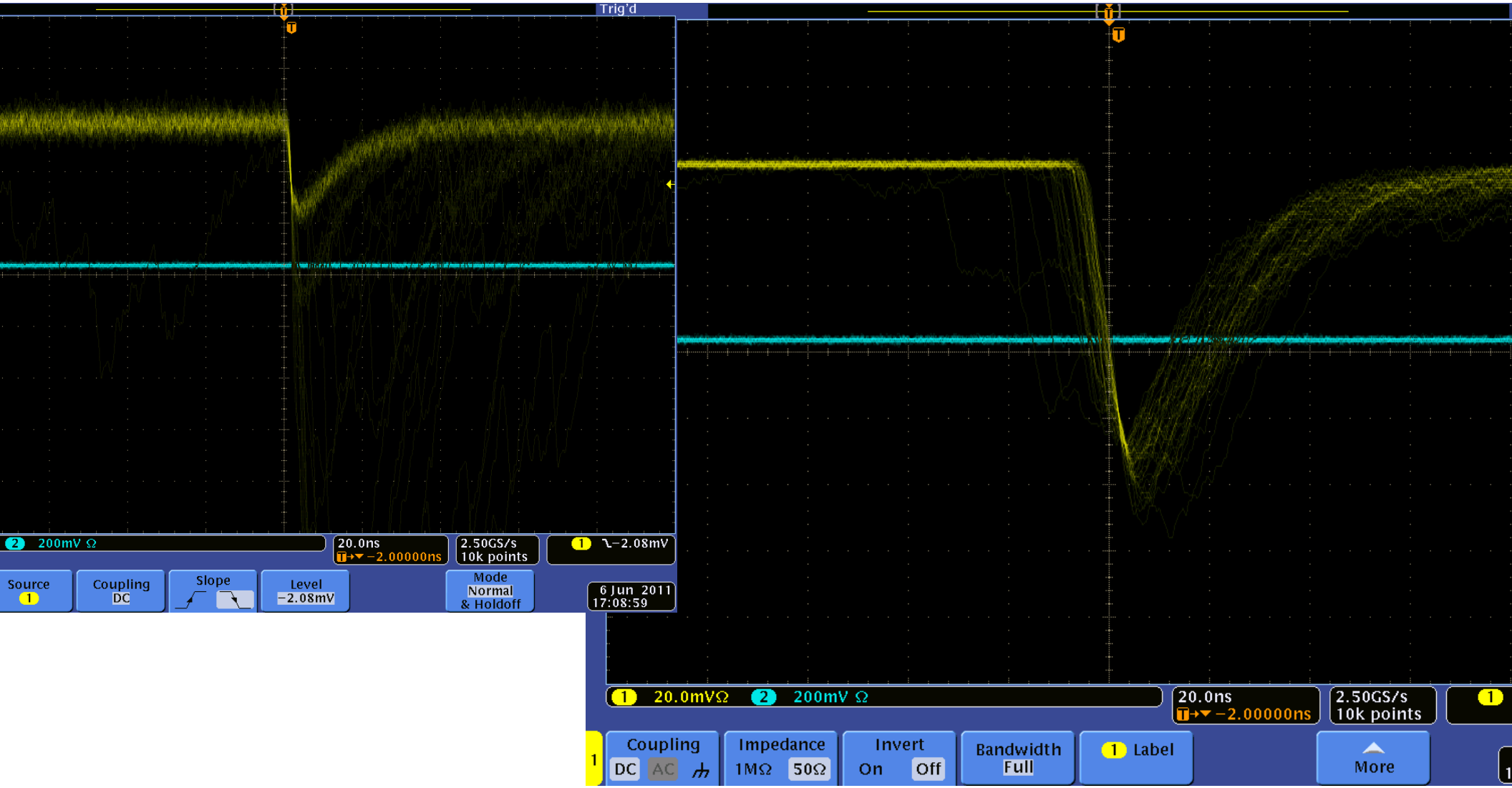
1x1 mm^2 / 400 px

Gain 7.5×10^5

R&D(4) MPPC Pulses

1 pe ~ 4 mV

Sr source ≤ 80 mV



UpgradeTimeline

- **Target:**
  - Finer segmentation of TGT scintillating fibres
    Readout: MPPC (SiPMT) Hamamatsu
- **Particle ID:**
  - Aerogel Cherenkov surrounding target, TOF
- **Charged particle tracking:**
  - Add new element C1 between CsI(Tl) and C2
  - Add cylindrical GEM (C0) (remove aerogel)
- **π^0 (1&2 photon) detection:**
  - New, faster readout of CsI(Tl): APD, MAPD
  - Wave form analysis using FADCs
- **Muon polarimeter :**
  - Active polarimeter with increased acceptance
  - New muon holding field magnet with a parallel field

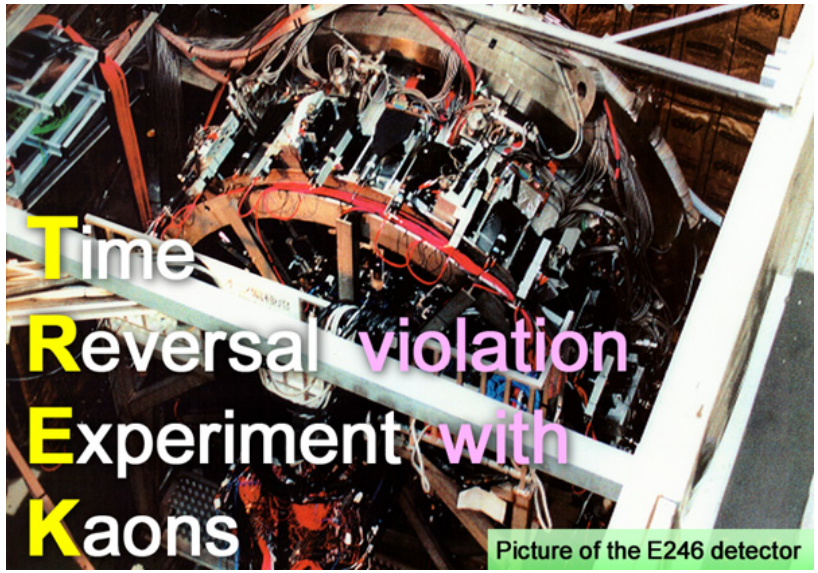
LFU
30 kW
~2013

TREK
270 kW
>100 kW
~2014

Summary

- **TREK at J-PARC is gaining momentum**
- **"K1.1BR" secondary beamline has been commissioned**
- **Measurement of the T-violating transverse muon polarization in $K_{\mu 3}$ decay (~2014)**
  - **Large potential for the discovery of New Physics**
  - **Upgrade of existing experimental setup of KEK E-246**
- **Measure $K_{e2}/K_{\mu 2}$ ratio to test lepton universality (~2013)**
- **Search for heavy neutrinos**
  - **Use E-246 apparatus with partial upgrades**

New collaborators are welcome!



Picture of the E246 detector

J-PARC Mar 11 Earthquake Damage

Thank You

J-PARC Recovery Schedule (@2011.5.20)