Precision Measurements and Fundamental Physics: The Proton Radius Puzzle and Beyond
(PRP2018), Mainz, July 23-27, 2018

TREK/E36 @ J-PARC: Investigating lepton universality with stopped kaon decays

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* **Presently supported by DOE DE-SC0013941, NSF HRD-1649909, PHY-1505934 and PHY-1436680**

Outline

- Lepton non-universality?
- 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 in 2015 !

http://trek.kek.jp

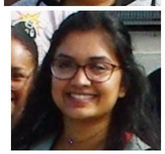
Present working group *

NSF postdoc (Ishara Fernando: MUSE)
shared / funded presently by NSF — Sri Lanka

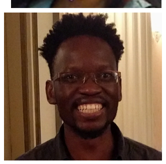
NSF postdoc (Jessica Campbell: MUSE)
to be funded by NSF from September 2018 — Canada

DOE postdoc (Tongtong Cao: TREK/E36)
funded presently by DOE — China

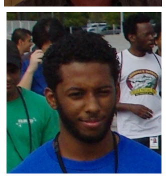
PhD student (Jesmin Nazeer: DarkLight, GEMs)
funded presently by NSF — Sri Lanka

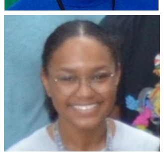


Master's student (Tanvi Patel: MUSE, GEMs)
funded presently by NSF/EAGER — India / USA



PhD student (Bishoy Dongwi: TREK/E36)
funded presently by DOE — Namibia





Undergraduate students
Letrell Harris, HU sophomore: GEMs — USA
Sterlyn McCoy, HU freshman: GEMs — USA
Angel Christopher, HU freshman: GEMs — Nigeria
funded presently by DOE and NSF

Lab Technician (Ameer Blake: GEMs)
funded presently by NSF — USA

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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] $R^W_{\tau\ell} = \dfrac{2\,\mathrm{BR}(W\to\tau\bar\nu_\tau)}{\mathrm{BR}(W\to e\bar\nu_e)+\mathrm{BR}(W\to\mu\bar\nu_\mu)} = 1.055(23)$ 2.4σ dev.
- Belle, Babar, LHCb

  $\mathcal{R}(D^{(*)}) = \mathcal{B}(\bar B\to D^{(*)}\tau^-\bar\nu_\tau)/\mathcal{B}(\bar B\to D^{(*)}\ell^-\bar\nu_\ell)$ 4.1σ dev.

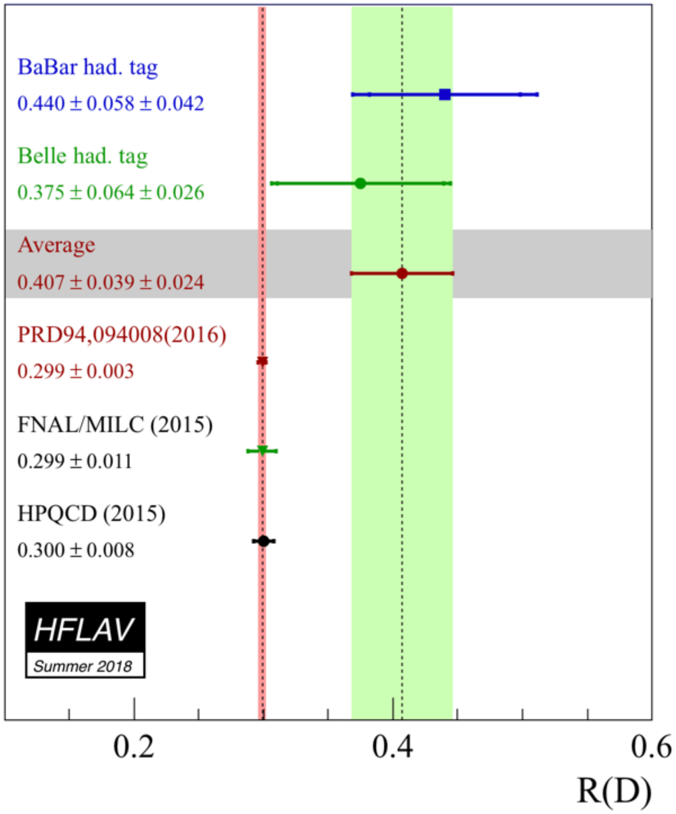
- LHCb [Phys. Rev. Lett. 113, 151601 (2014)] 2.6σ dev.

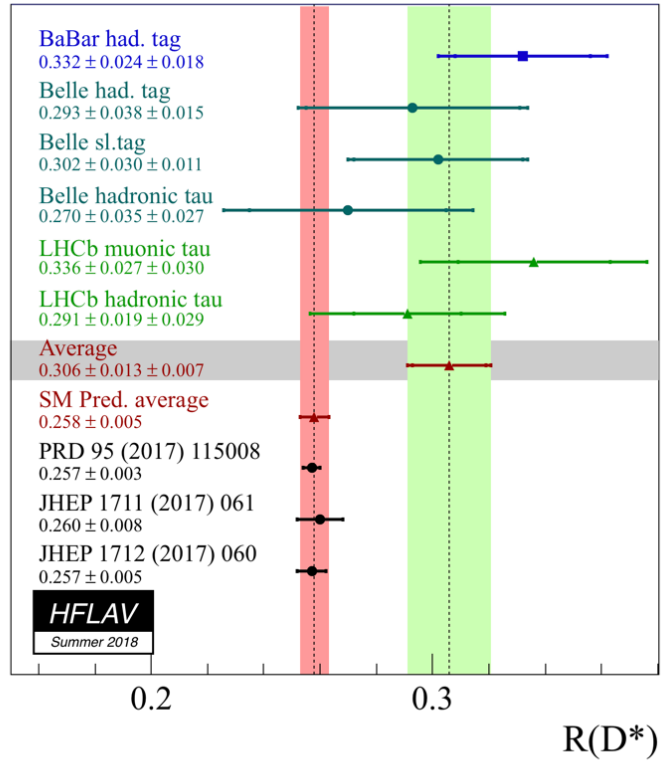
  $\mathrm{BR}(B^+\to K^+\mu^+\mu^-)/\mathrm{BR}(B^+\to K^+e^+e^-) = 0.745^{+0.090}_{-0.074}\pm0.0036$

- Possible link to proton charge radius puzzle 5.6σ dev.

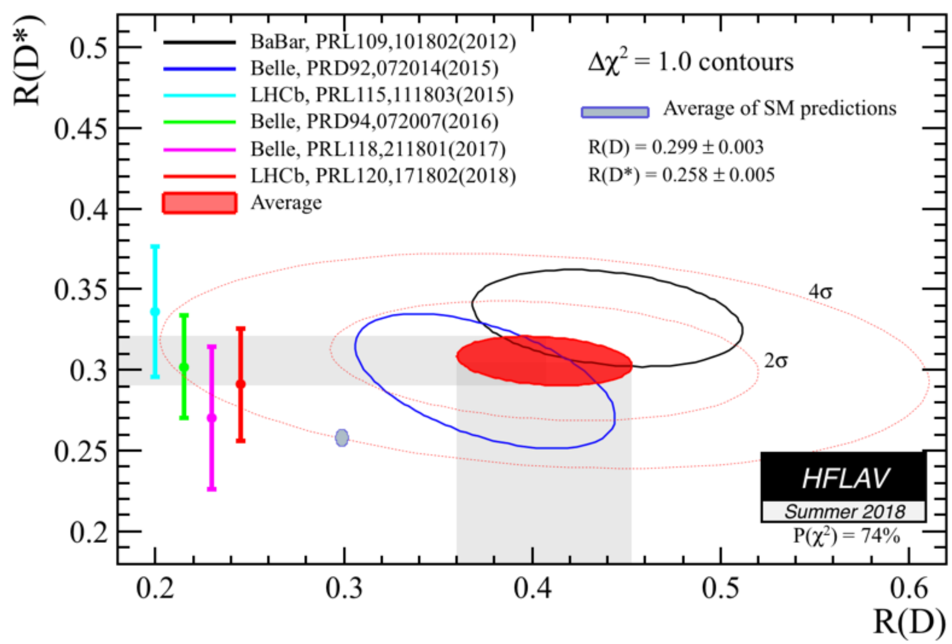
  r_e (μH) = 0.84087 ± 0.00039 fm, r_e (CODATA2010) = 0.8775 ± 0.0051 fm

Lepton non-universality in B-decays (τ-μ)



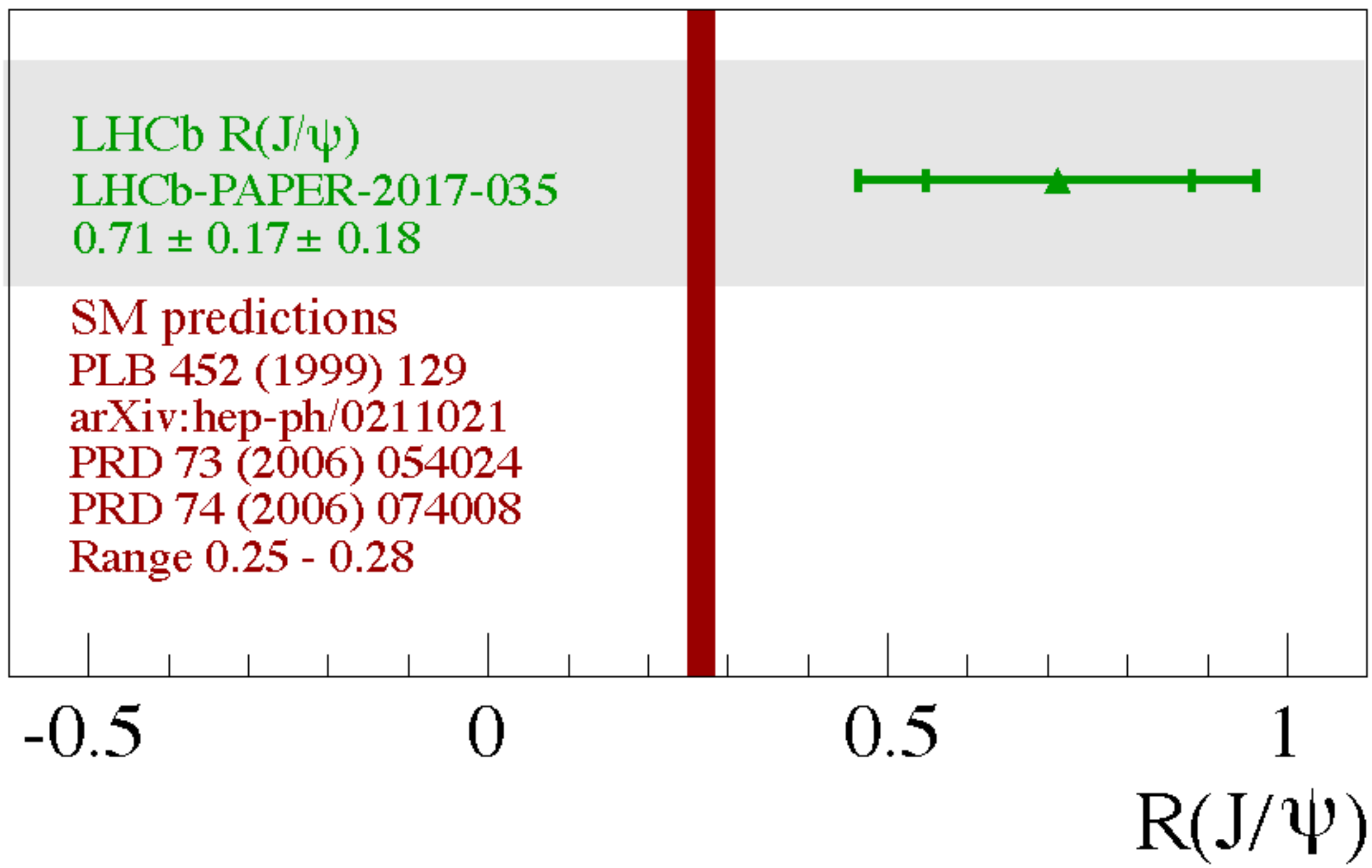


- $R(D^{(*)}) = \Gamma(B \to D^{(*)}\tau^+\nu) / \Gamma(B \to D^{(*)}\mu^+\nu)$
- HFLAV summer 2018 update (slightly reduced significance)
- R(D), R(D*) Individually at 2.3-3.0σ Combined at 3.6-3.8σ



Lepton non-universality in B-decays (τ-μ)

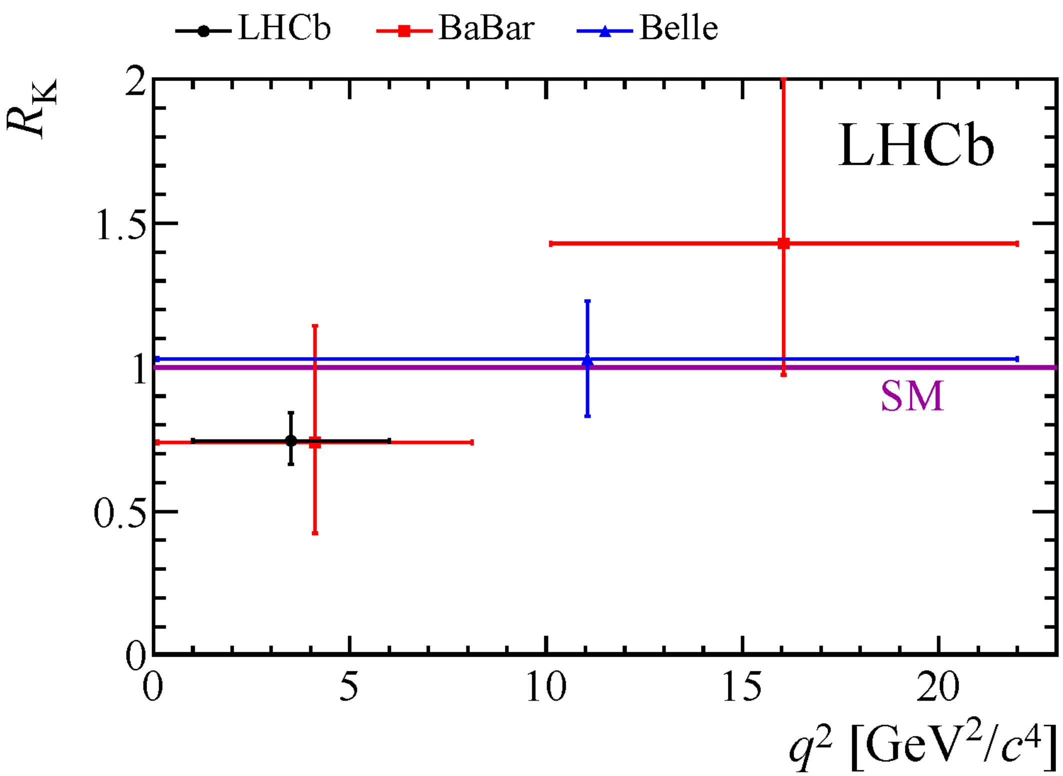
- **Charmed meson J/ψ:**
  $R(J/\psi) = \Gamma(B^+ \rightarrow J/\psi\ \tau^+ \nu) / \Gamma(B^+ \rightarrow J/\psi\ \mu^+ \nu)$
- **Different from SM at ~2σ**
- **Less straightforward than $R(D^{(*)})$**

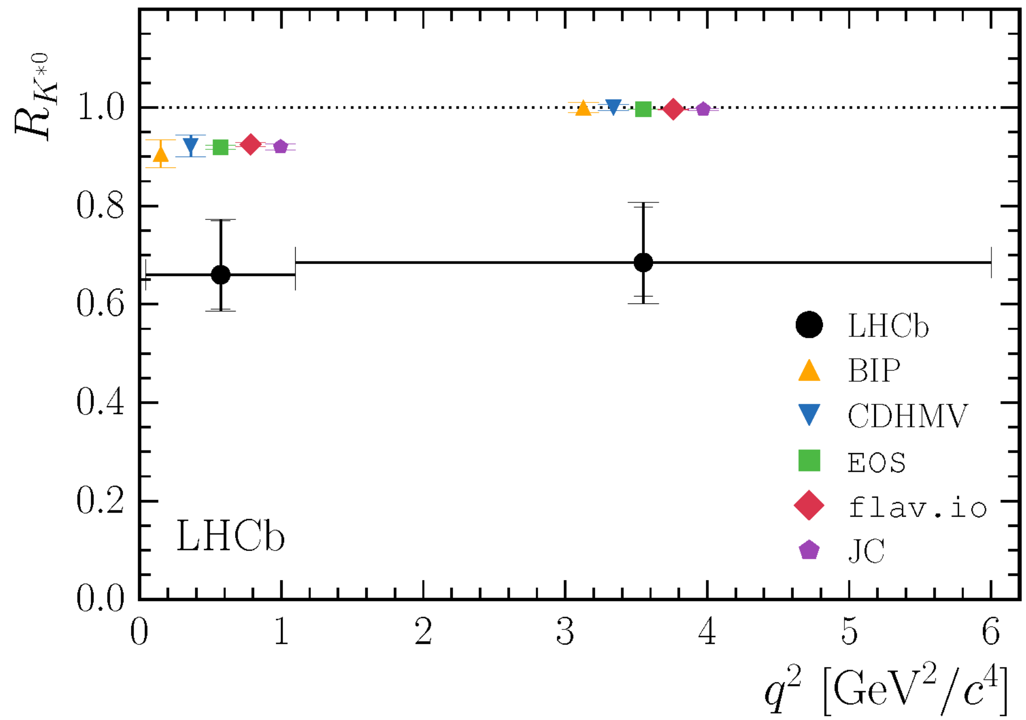


R. Aaji *et al.*, arXiv:1711.05623, PRL 120, 121801 (2018)

Lepton non-universality in B-decays (μ-e)

- LHCb: $R(K^{(*)}) = \Gamma(B \to K^{(*)} \mu^+\mu^-) / \Gamma(B \to K^{(*)} e^+e^-)$
- $R(K^{(*)})$ different from SM at the 2.5σ level; R(K) update awaited





R. Aaji et *al.*,
arXiv:1406.6482
PRL 113, 151601 (2014)

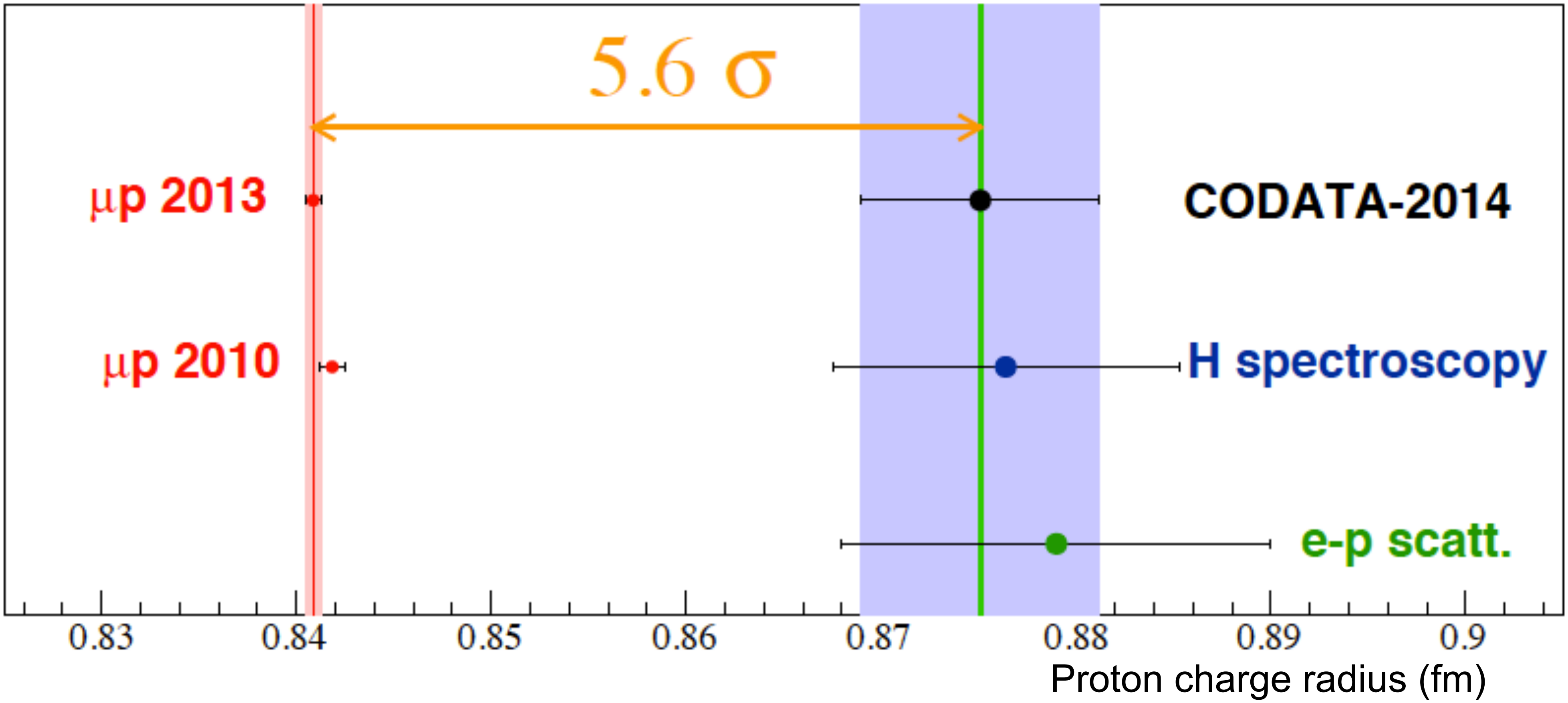
R. Aaji et *al.*,
arXiv:1705.05802
JHEP 08 (2017) 055

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8751 ± 0.0061 fm **(CODATA2014)**

muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)

A. Antognini et al., Science 339, 417 (2013)

Possible resolutions to the puzzle

- **The μp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement
- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5 sigma
- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors
- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
  Hadronic effects different for μp and ep:
  e.g. proton polarizability (*effect* $\propto m_l^4$)
- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics e.g. from kaon decays (TREK@J-PARC)

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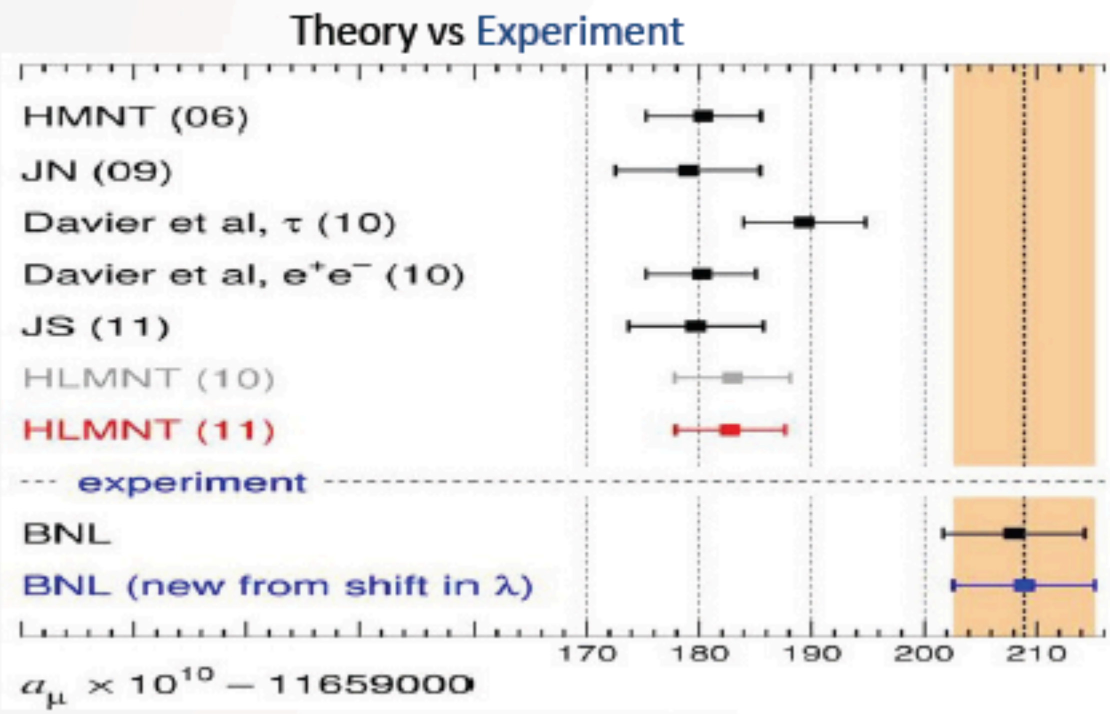
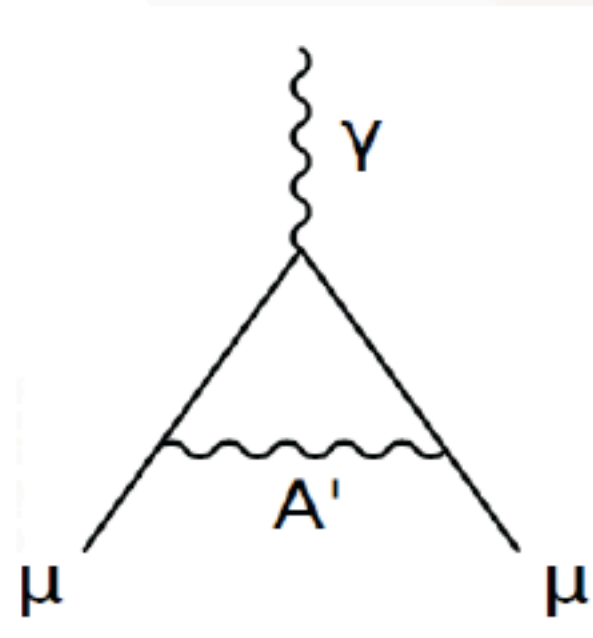
TREK/E36 will test

- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics e.g. from kaon decays (TREK@J-PARC)

Muon anomalous magnetic moment

Muon g-2 experiment disagrees with theory at the 3 sigma level.
A heavy photon with $m \sim$ 10-100 MeV and $\varepsilon \sim 10^{-2} - 10^{-3}$ could solve the problem!



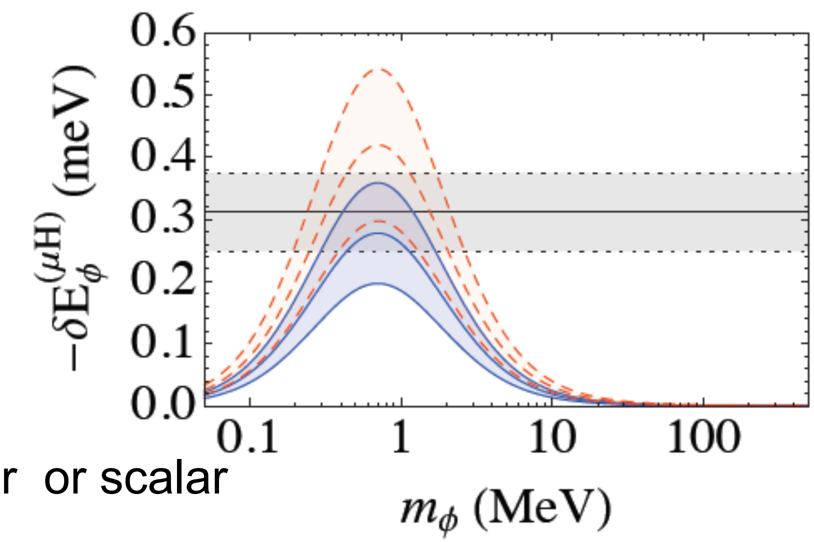


Anomaly 'usually' explained by SUSY with large tanβ
-> no evidence
Anomaly can be explained with dark photon or light boson

A light boson and the proton radius puzzle

Jaeckel, Roy (arXiv:1008.3536)

- Hidden U(1) photon can decrease charge radius for muonic hydrogen, however even more so for regular hydrogen



Tucker-Smith, Yavin (arXiv:1011.4922)

can solve proton radius puzzle

- MeV particle coupling to p and μ (not e) consistent with g_μ-2

Batell, McKeen, Pospelov (arXiv:1103.0721):

can solve proton radius puzzle

- New e/μ differentiating force consistent with g_μ-2, vector or scalar
- Resulting in large PV μp scattering

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- New e/μ differentiating force, fine-tuned scalar/pseudoscalar or vector/axial gauge bosons

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- Generic new particle along with global fit of fundamental constants

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

- Light bosons constrained by $K \to \mu\nu$ decay

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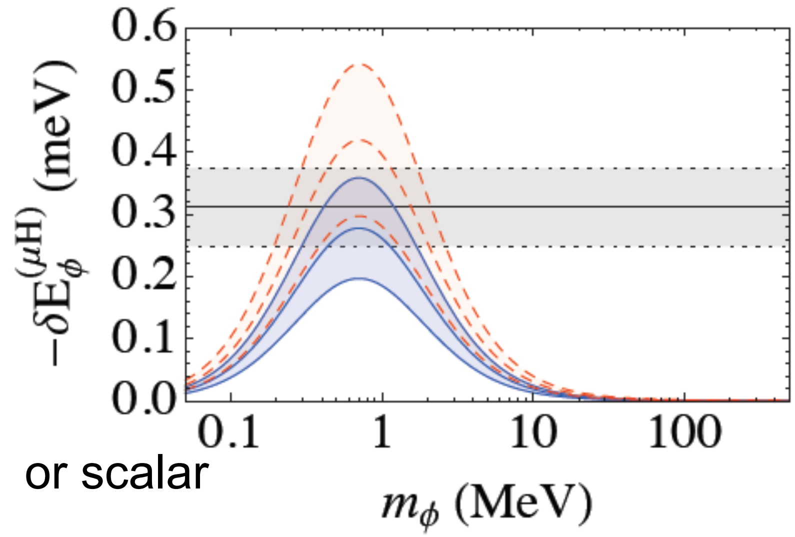

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TREK/E36 will test

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The TREK program

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

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

Proposal to PAC 1 (2006) 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 $\Gamma(K^+ \rightarrow e^+\nu)$ / $\Gamma(K^+ \rightarrow \mu^+\nu)$ and search for heavy sterile neutrinos using the TREK detector system** ”

Proposal to PACs 10 (2010), 11,13-18 30-50 kW

Stage-1 approved since August 2012

Stage-2 approved since September 2013

Spokespeople: M.K. and Suguru Shimizu

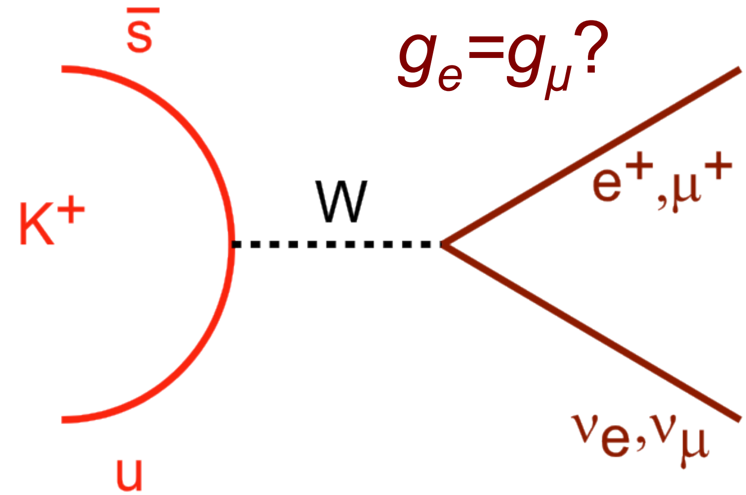
Timeline of TREK

- 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
- 2016-18: Analysis in progress

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 $\Gamma(K_{\mu2})$, hadronic form factors are cancelled**

- $$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{helicity suppression}} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \underbrace{(1+\delta_r)}_{\text{radiative correction (Internal Brems.)}}$$

- **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)

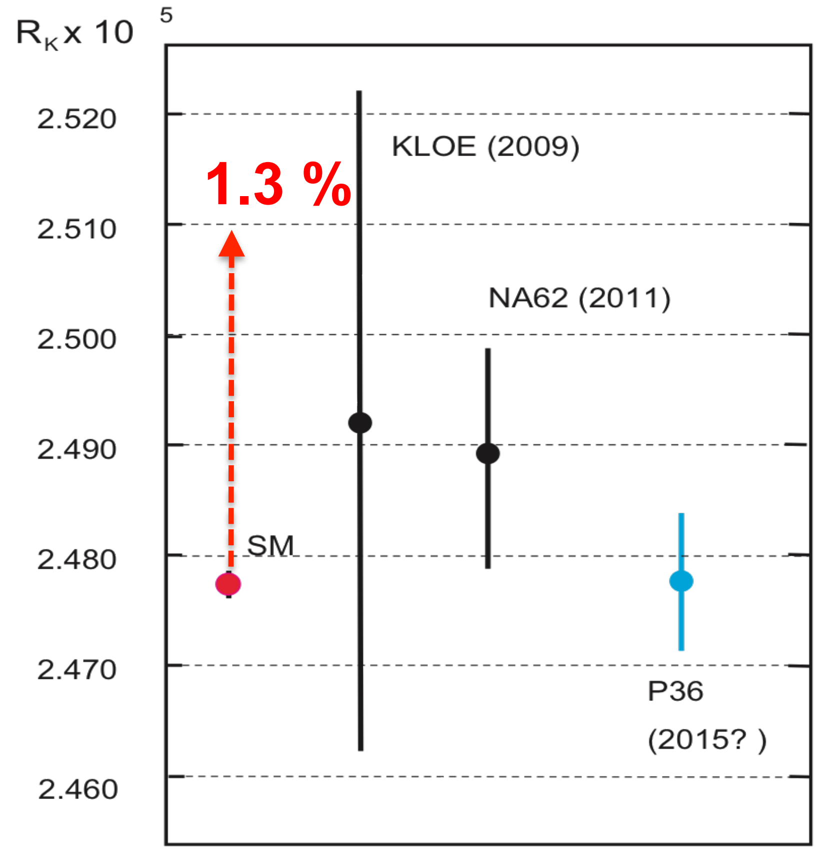
Experimental status of R_K

- **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)

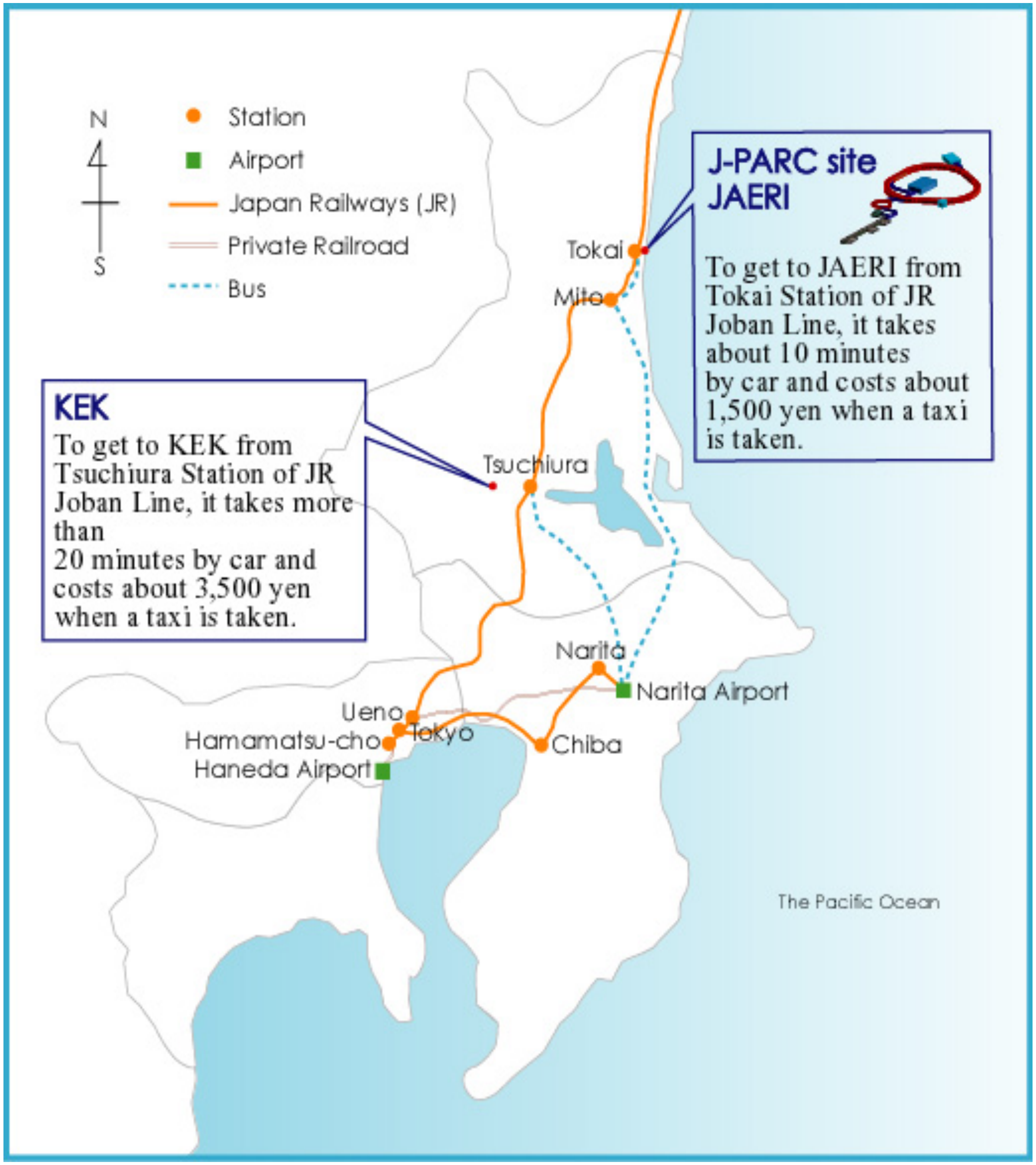
- **World average (2012)**
  $R_K = (2.488 \pm 0.009)\times 10^{-5}$, $\delta R_K/R_K$=0.4%

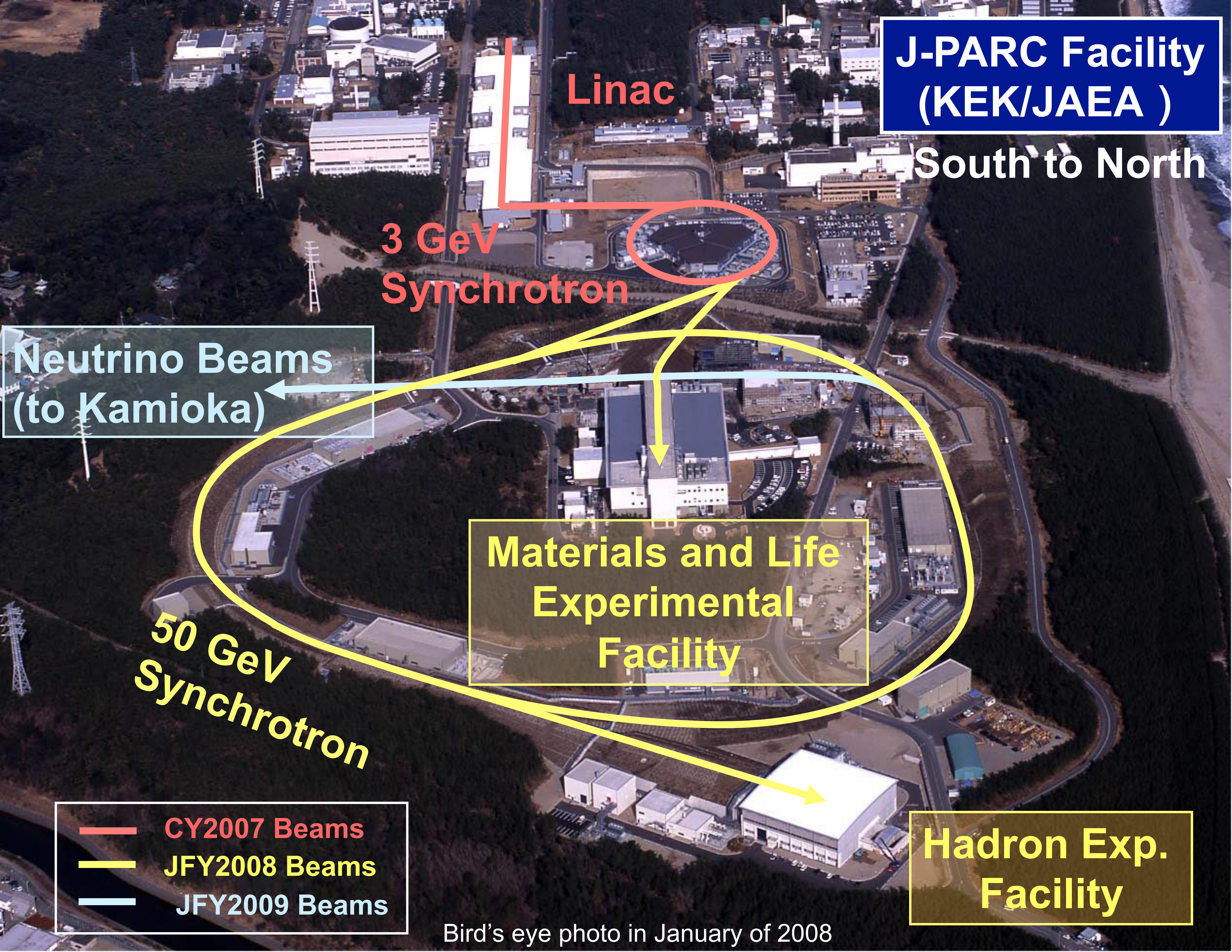


- **Systematics:**
  - In-flight-decay experiments: kinematics overlap
  - E36 stopped K^+: detector acceptance and target
  - E36 complementary to in-flight experiments

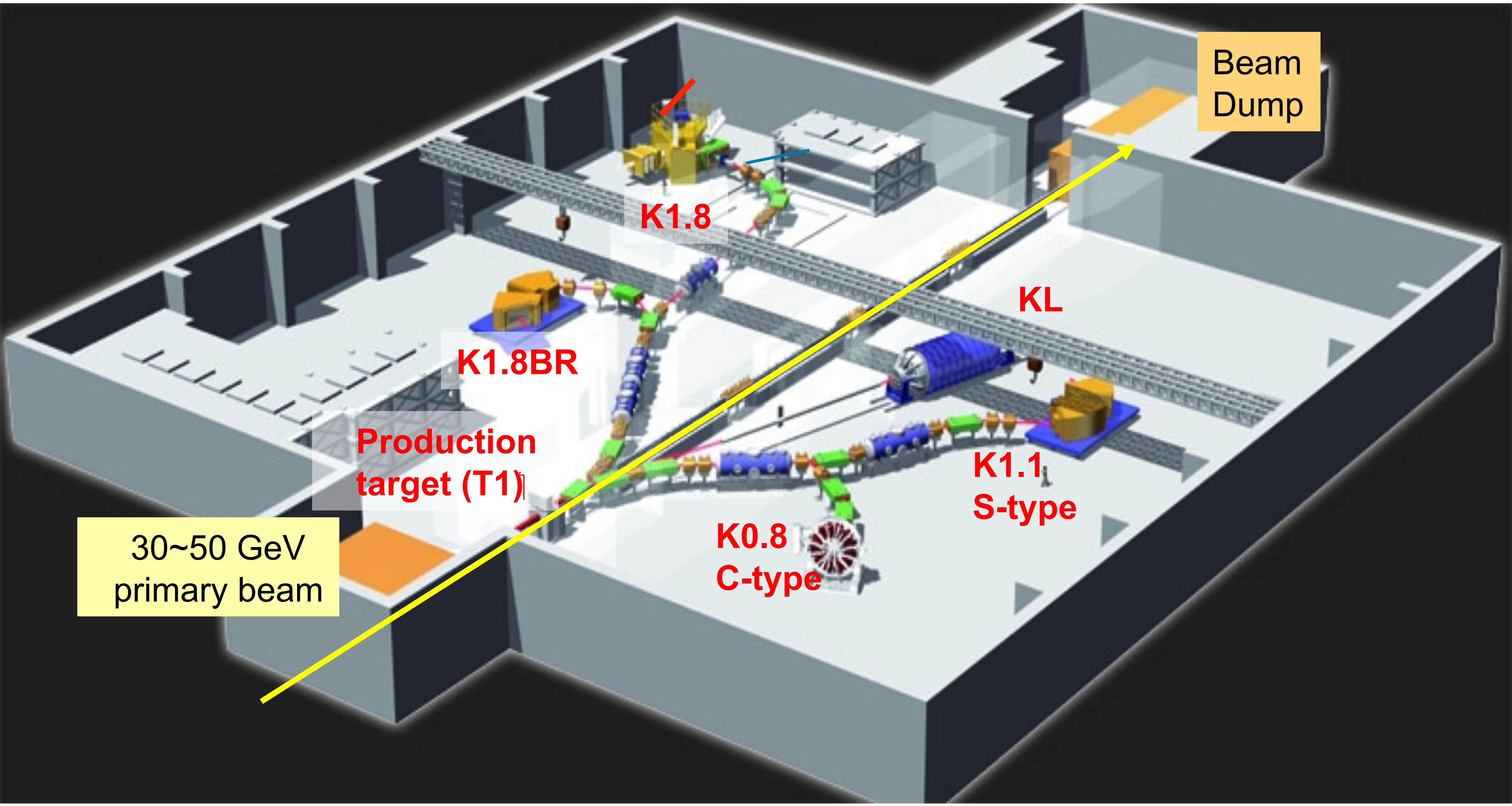
- **E36 goal:** $\delta R_K/R_K = \pm 0.2\%$ (stat) $\pm 0.15\%$ (syst) [0.25% total]

Location of J-PARC



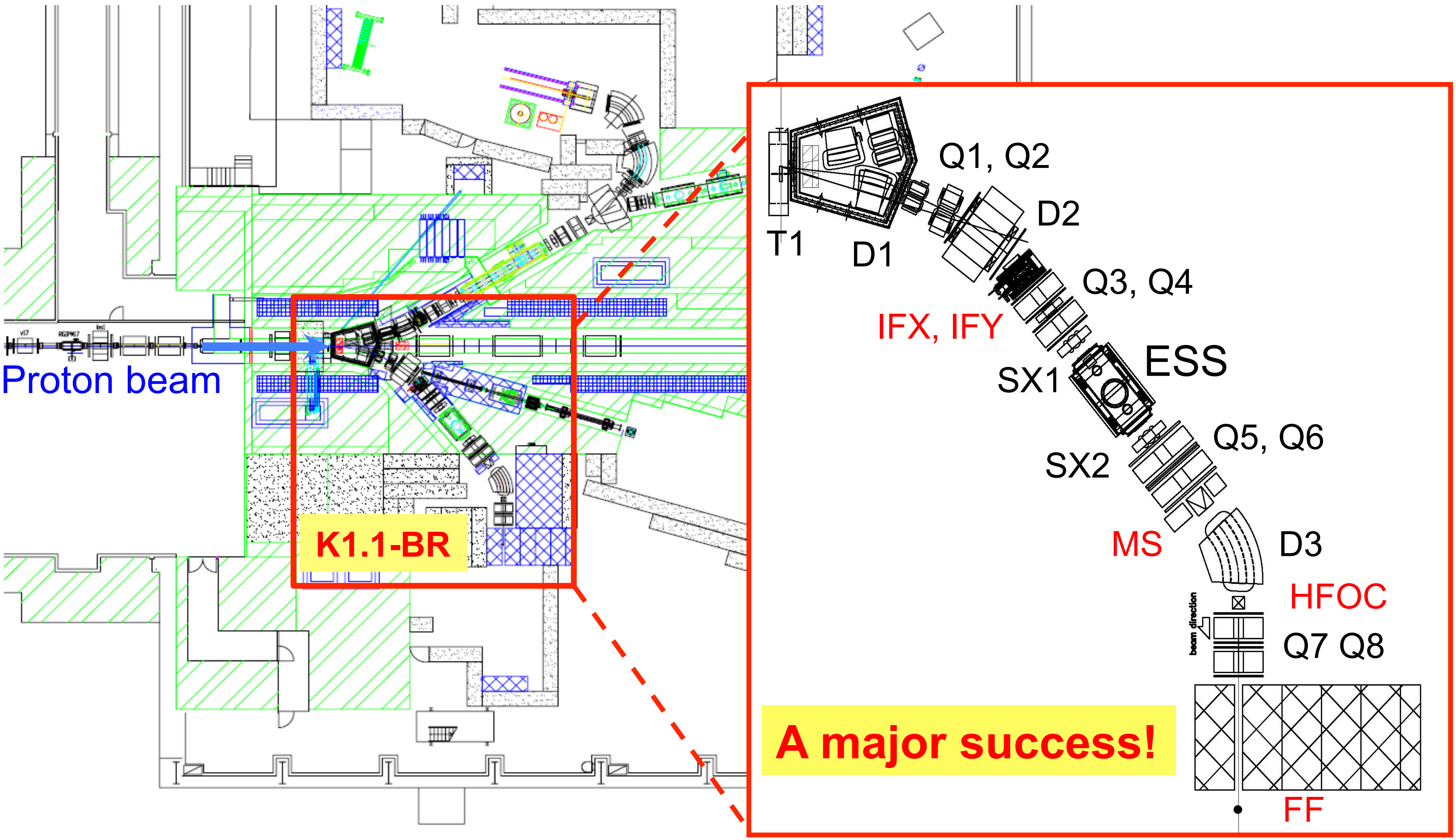

J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

J-PARC Hadron Experimental Hall

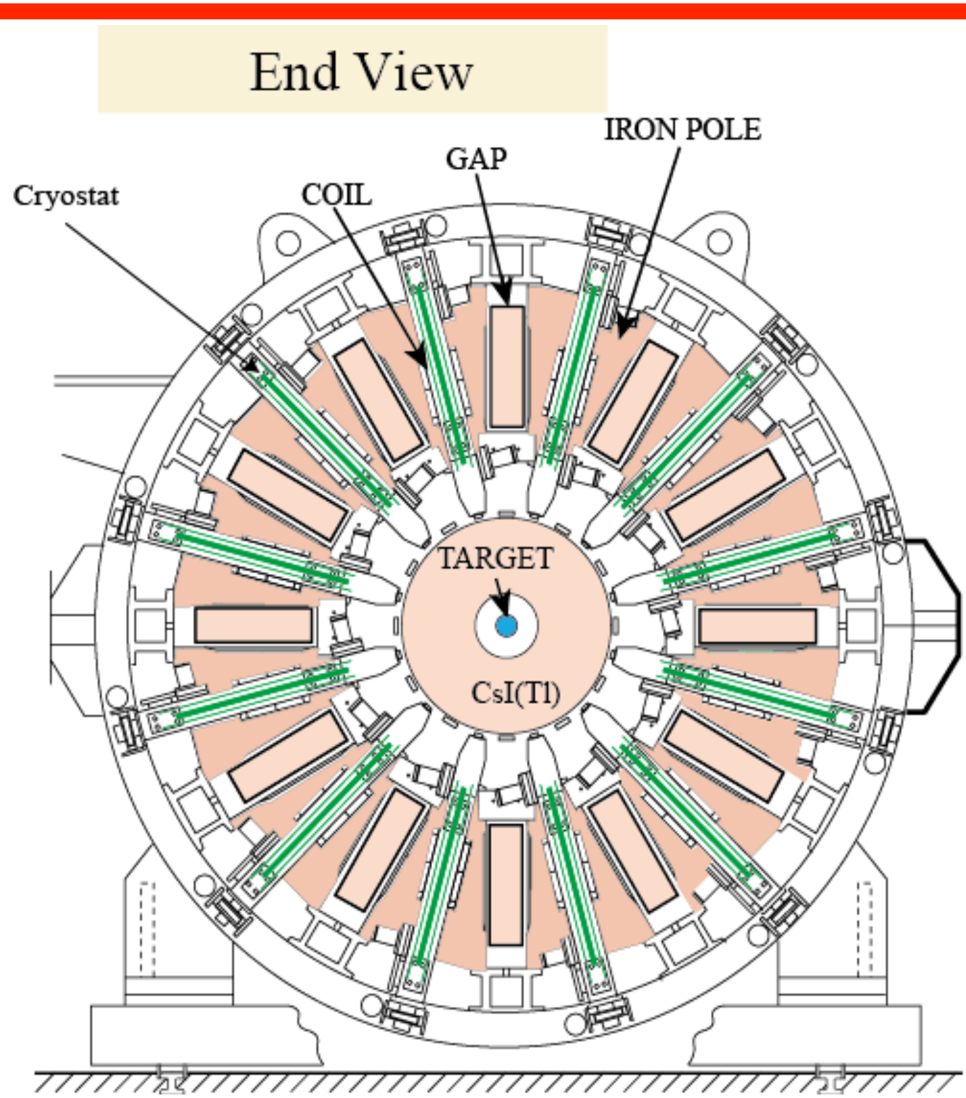


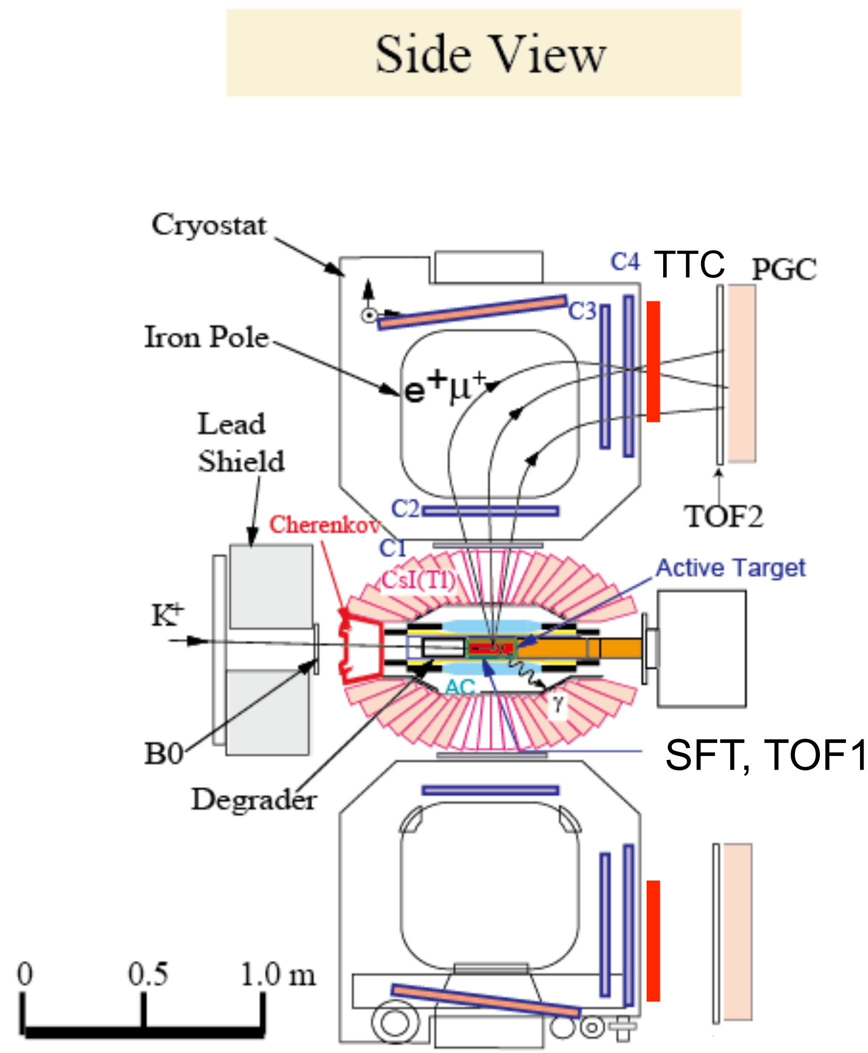
K1.1BR beamline

- 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 (1.4×10^6/spill @ 40kW)



The TREK apparatus for E36





Modest upgrade of KEK-PS E246

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

Tracking (π,μ,e)
- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)

PID
- TOF1,2; TTC
- Aerogel Che. (AC)
- Pb glass (PGC)

Gamma
- CsI(Tl)
- Gap veto

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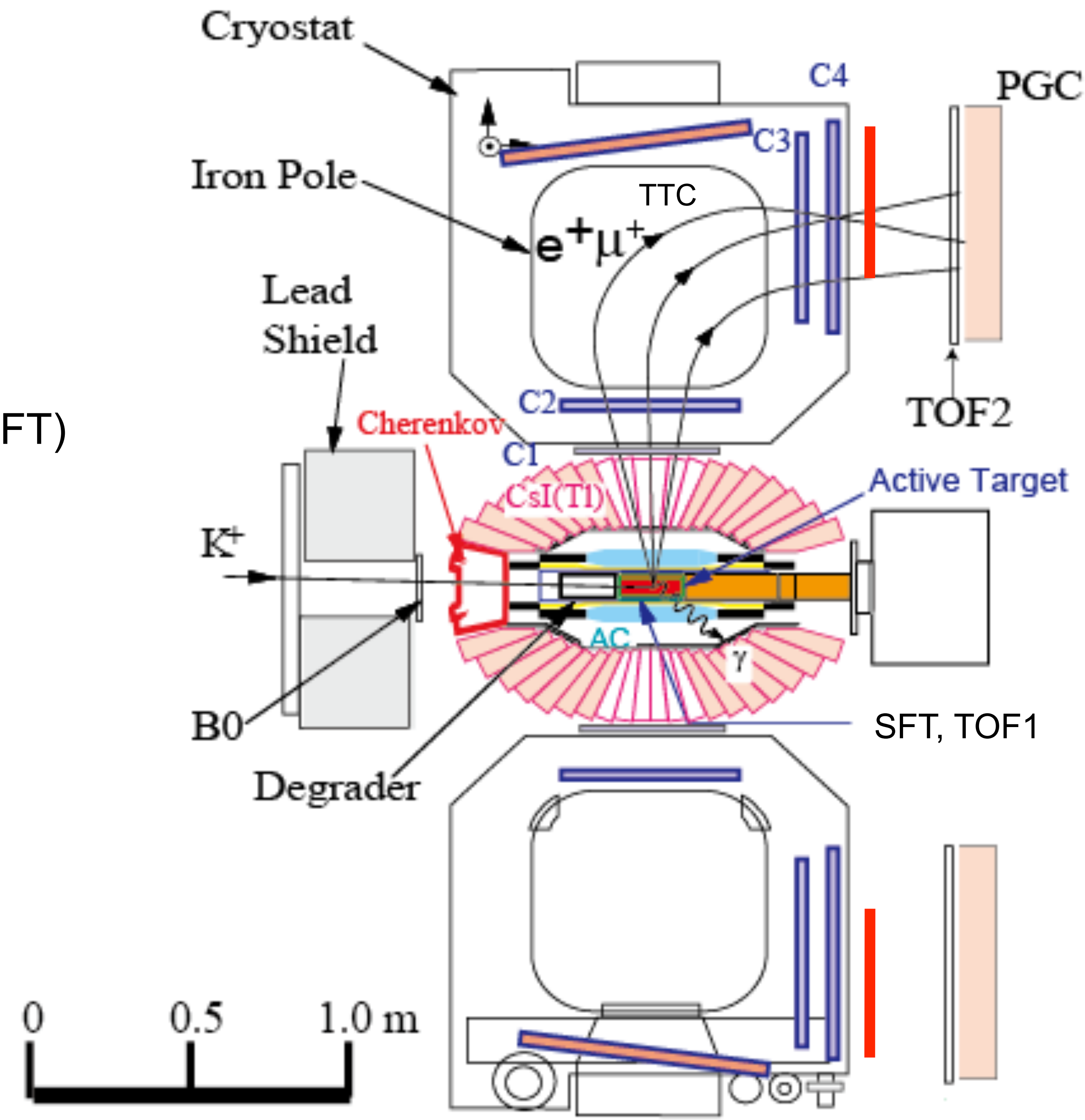
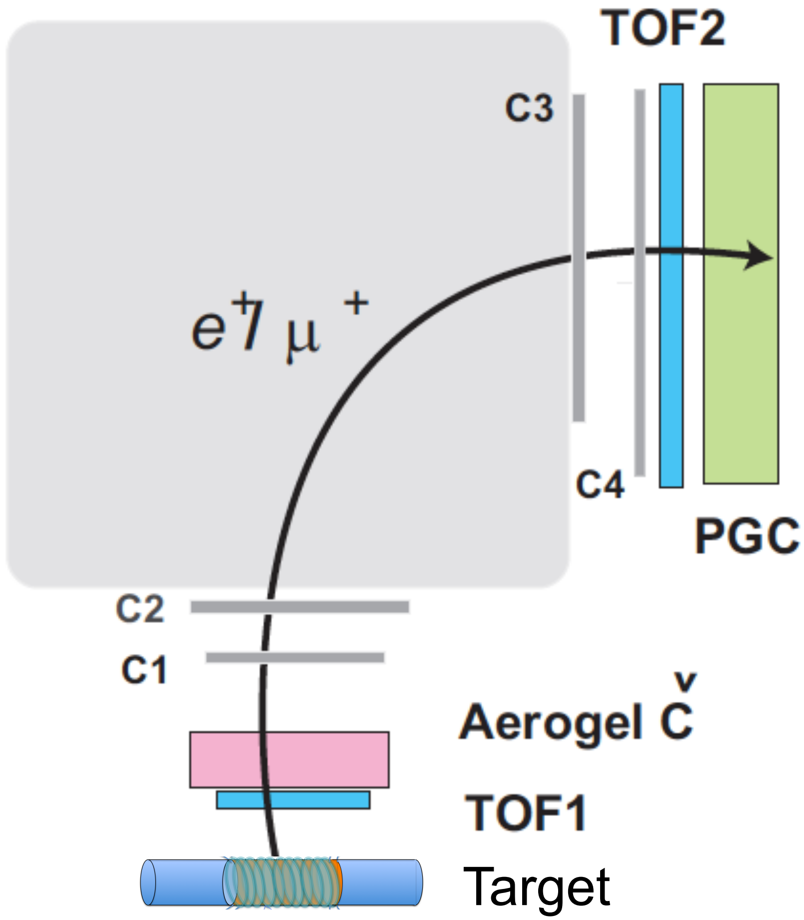


μ⁺/e⁺ identification

PID with:

- TOF
- Aerogel Č
- Lead glass

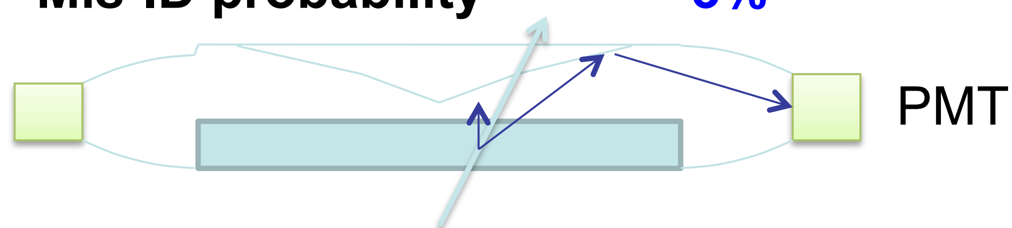


TOF

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%



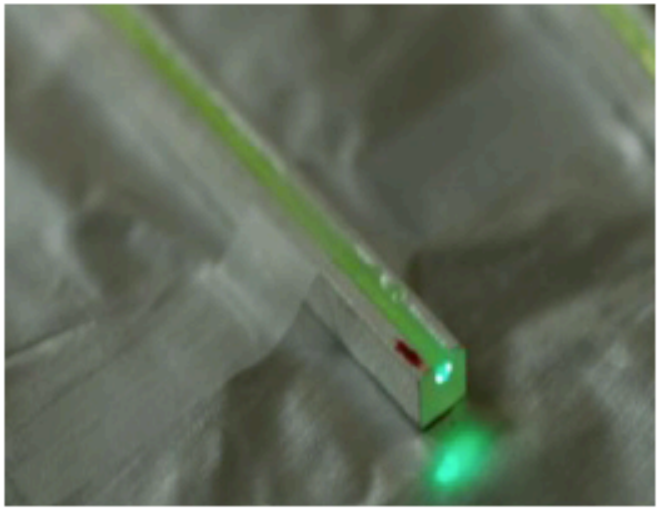
Lead glass (PGC)

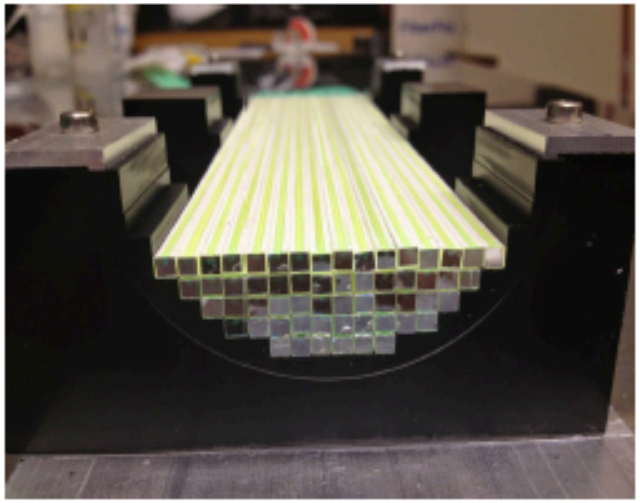
Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

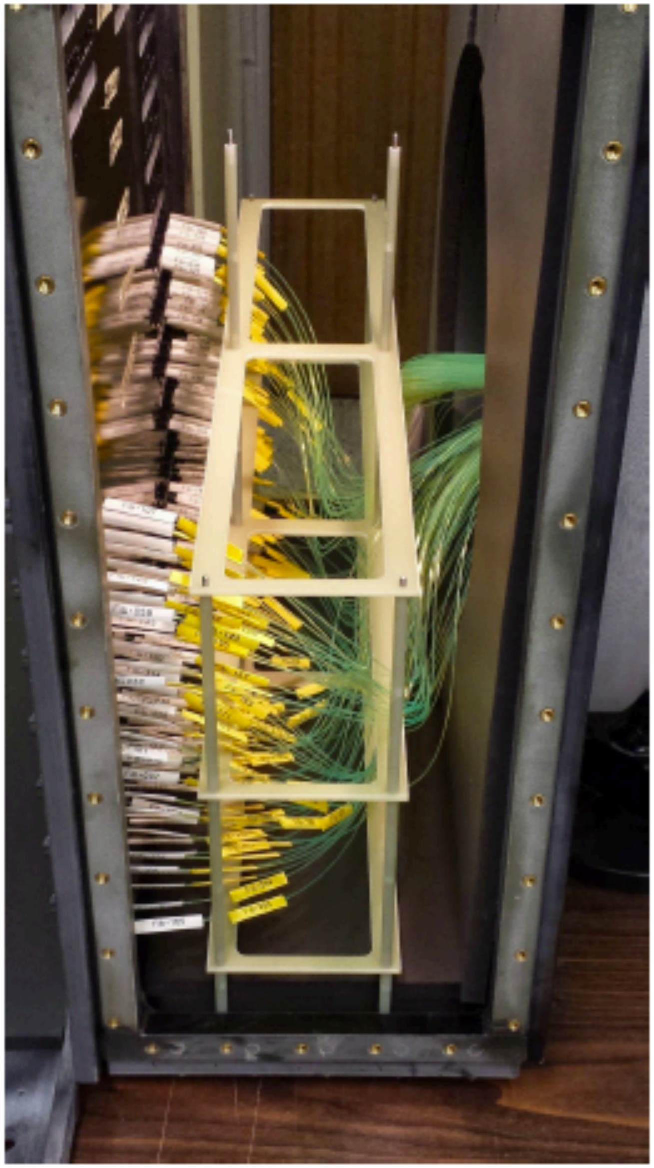
$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

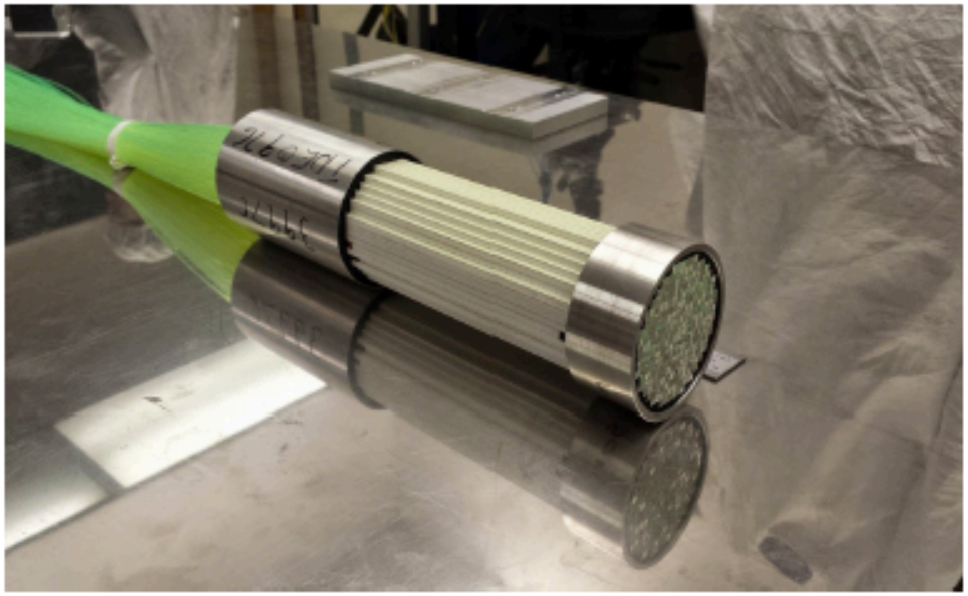
Scintillating-fiber kaon stopping target

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



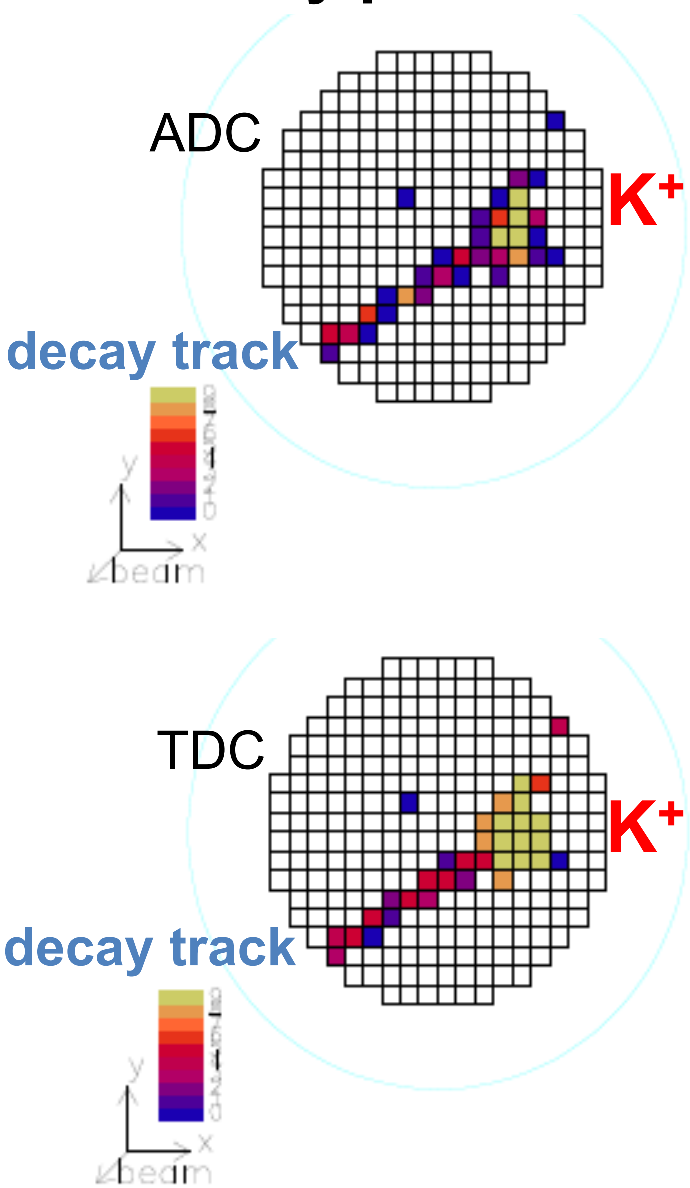




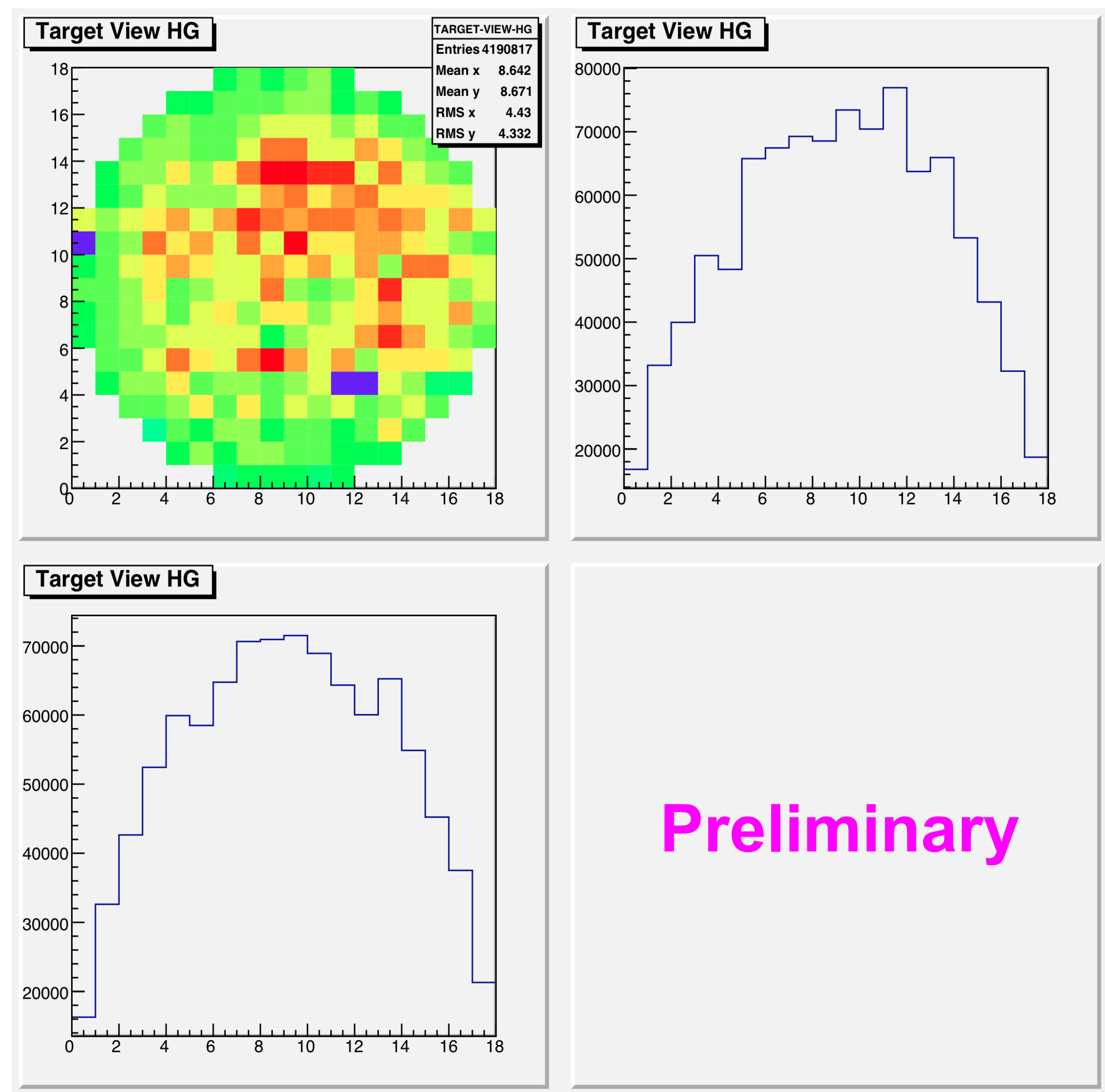


Target performance

Kaon stop and track of decay particle

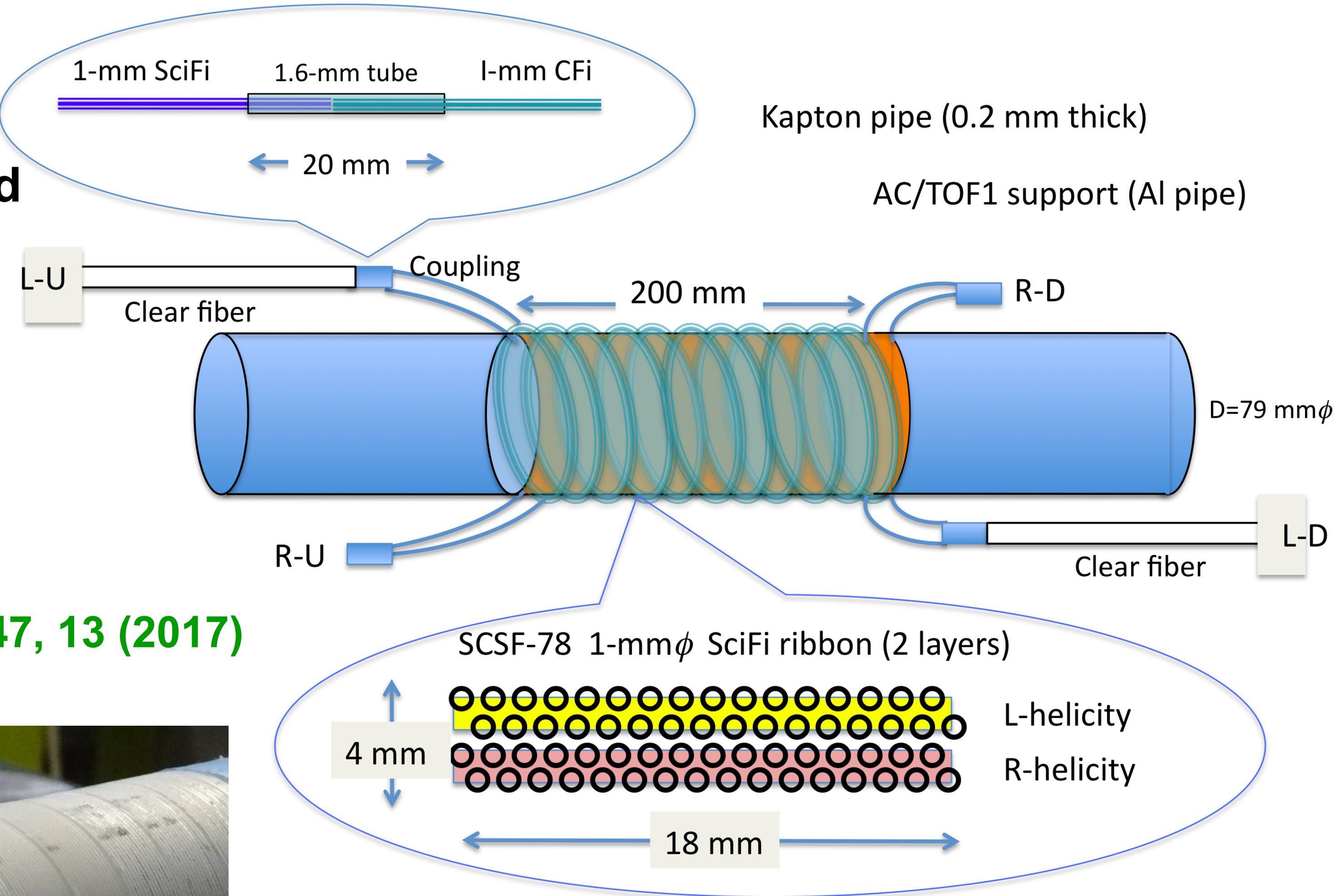


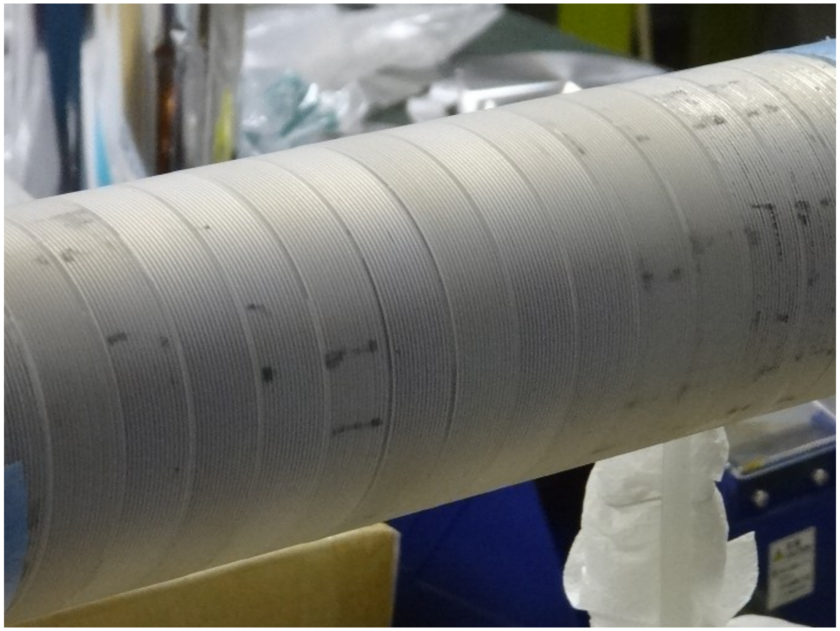
Kaon beam profile

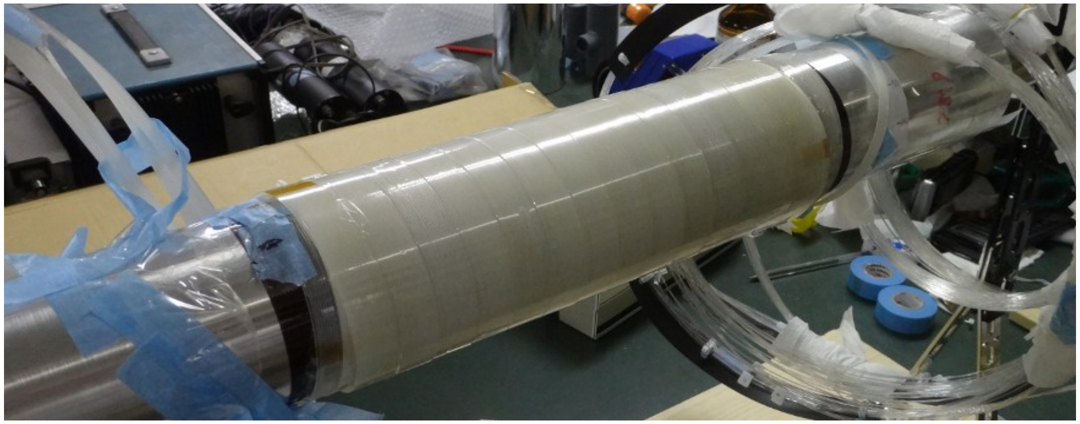


Spiraling fiber tracker (SFT)

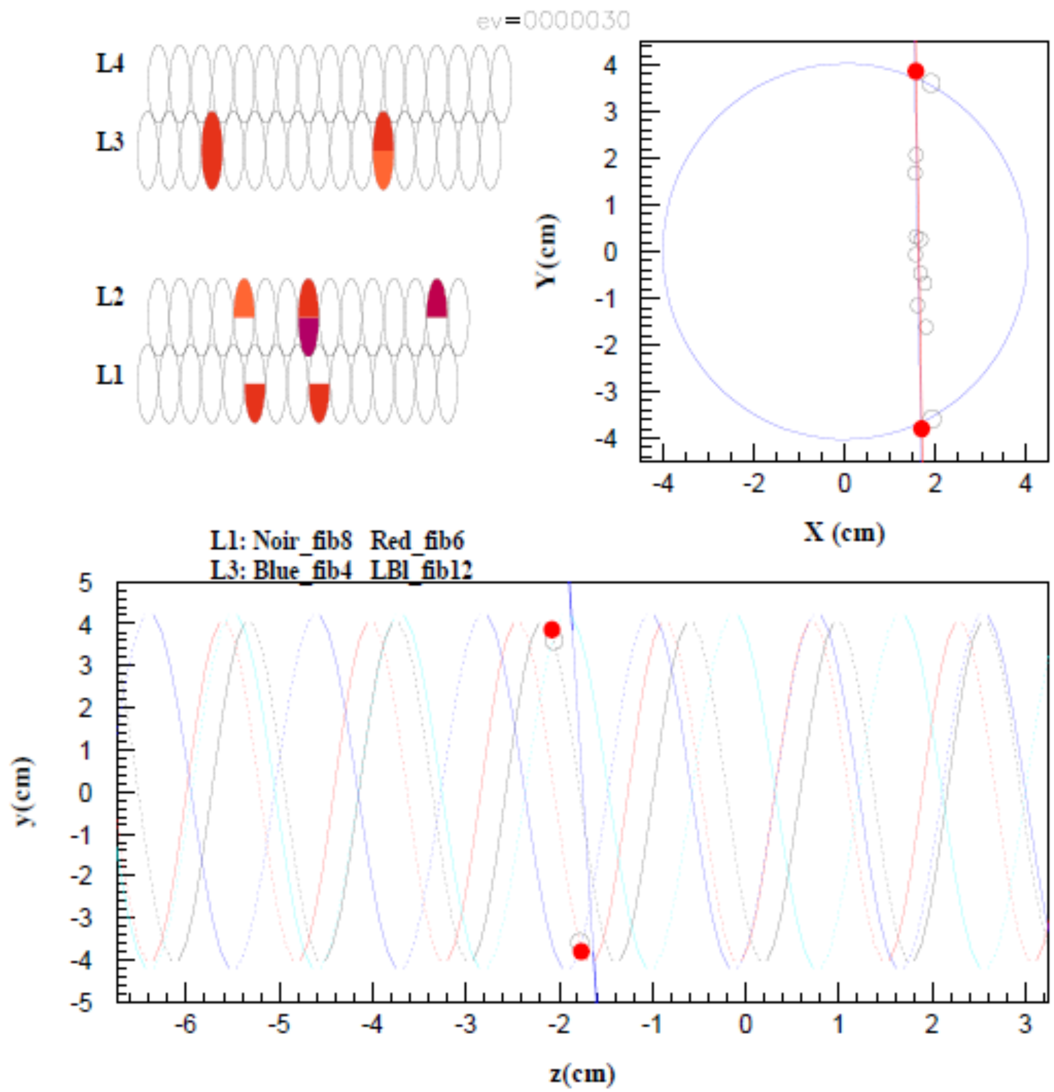
- **Double-layer fibers in 2 helicities wrapped around target bundle for near target vertex**
- **Using spare MPPC channels from fiber target**
- **V. Mineev *et al.*, NIM A847, 13 (2017)**

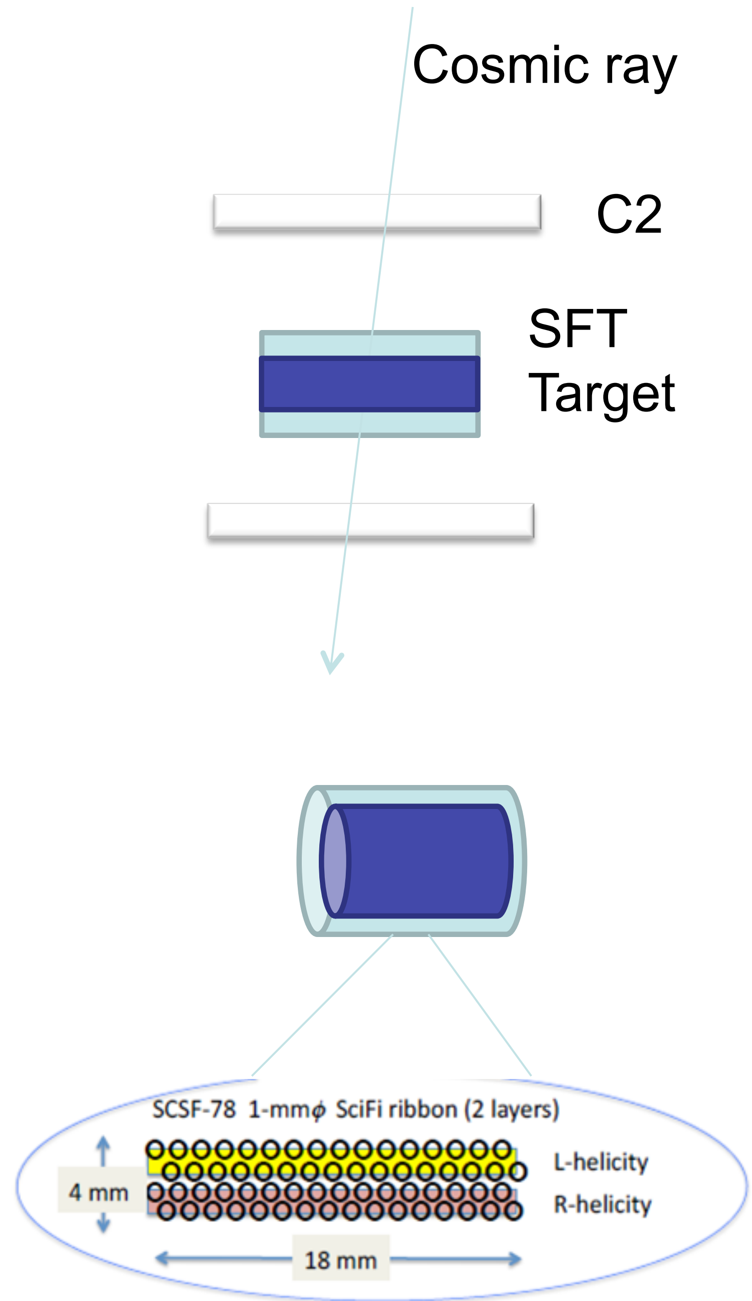






Track identification by central detector

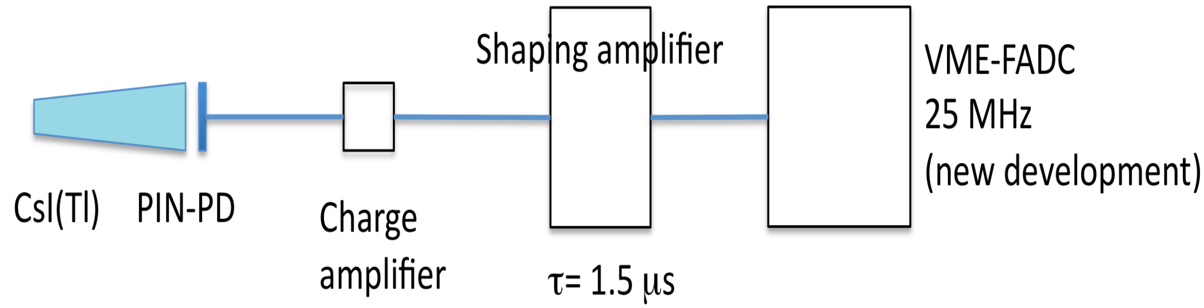




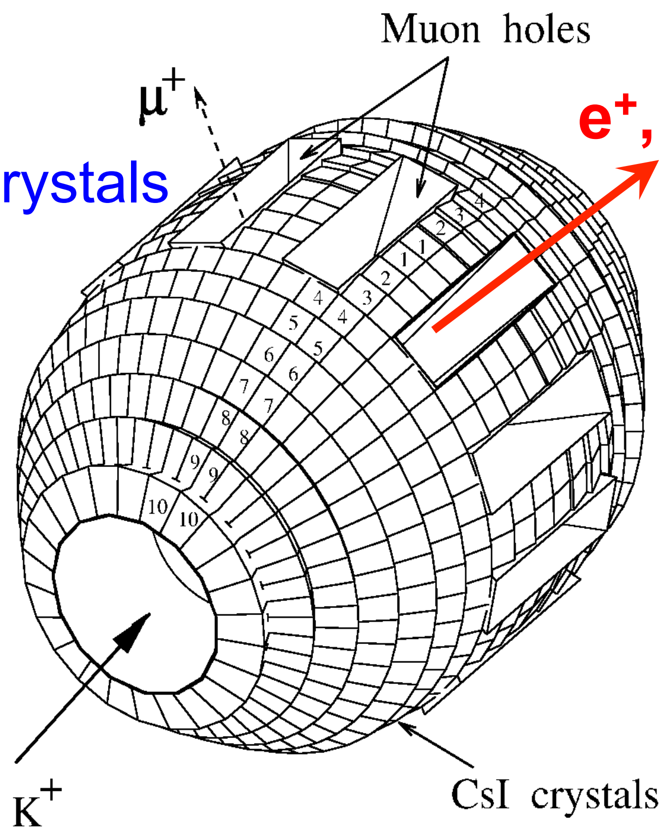
SFT+Target consistency established with cosmic rays

CsI(Tl) calorimeter

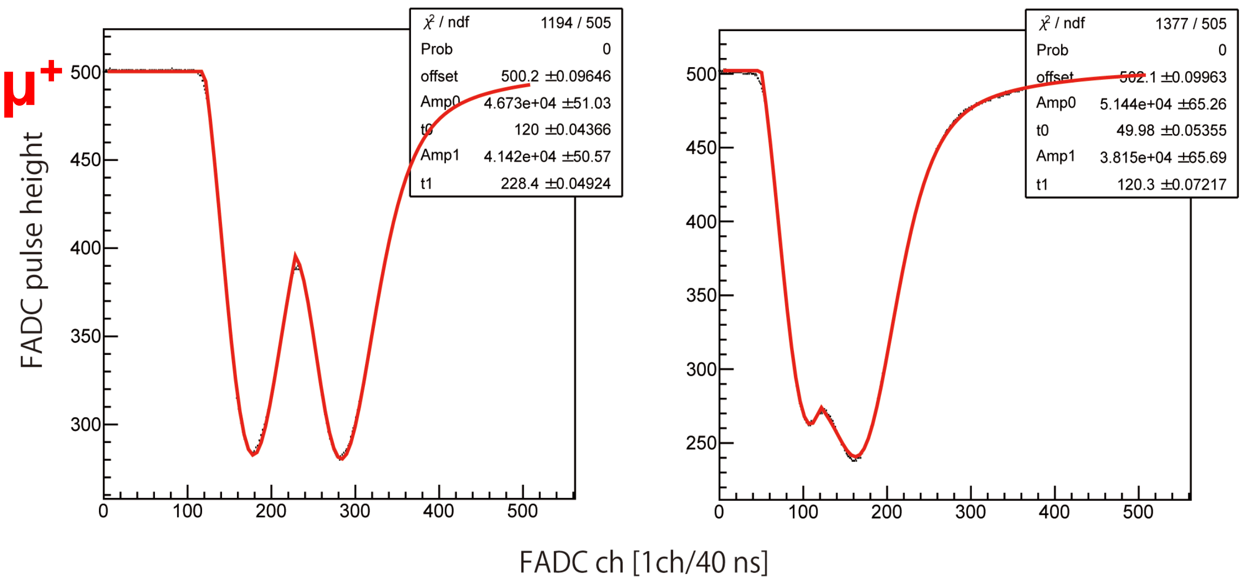
Crystal length	**250 mm**
Number of crystals	**768**
Segmentation	**7.5°**
Coverage	**~75%**
Readout	**PIN diodes**
Maximum rate	**~200 kHz**



768 crystals



Typical pileup events

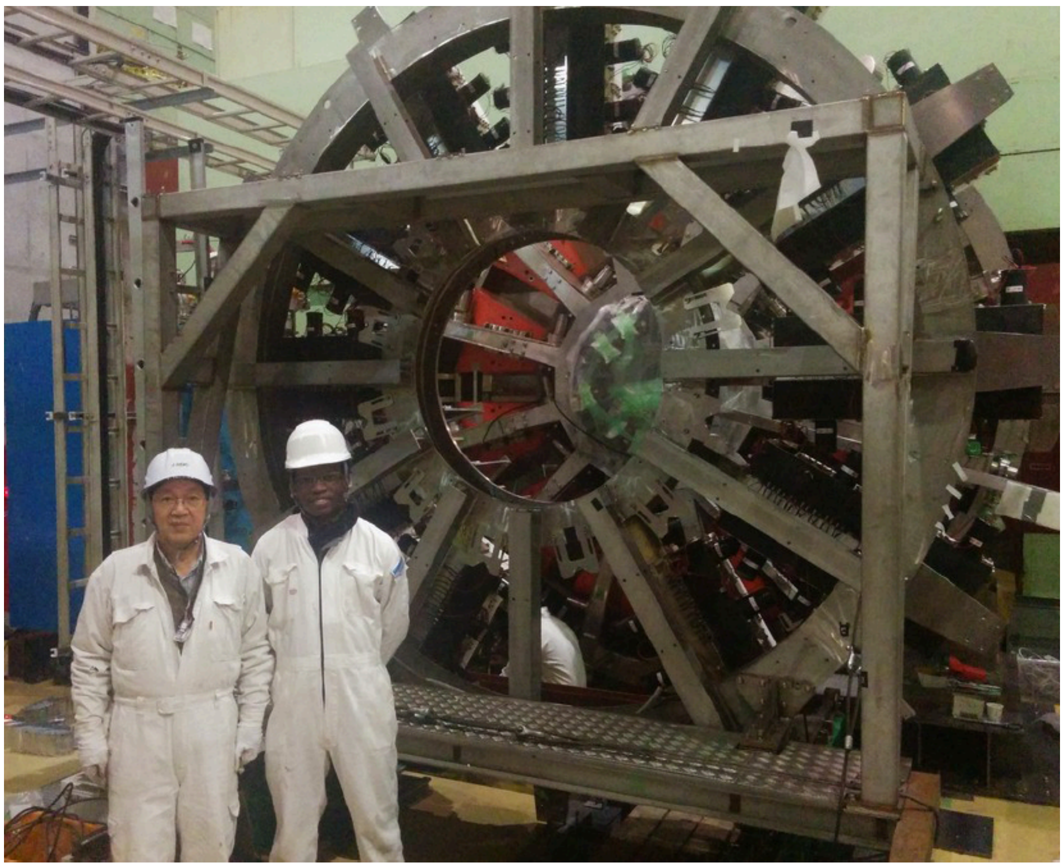


- *possible to separate with FADC*
- *has been implemented successfully*
- ***H. Ito et al., NIM A901, 1 (2018)***

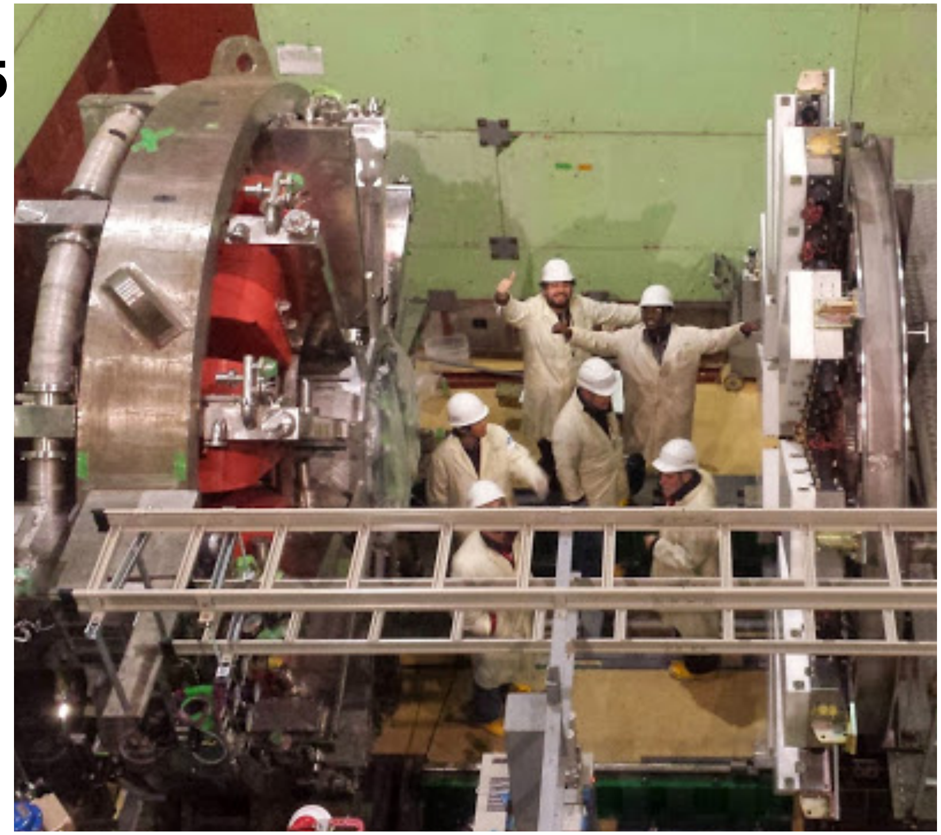
Detection of photons from ***$K^+ \rightarrow \mu^+(e^+)\ \nu\ \gamma$ from IB+SD***
Detection of ***e^+, e^- from A' decay***

TREK/E36 installation and commissioning

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



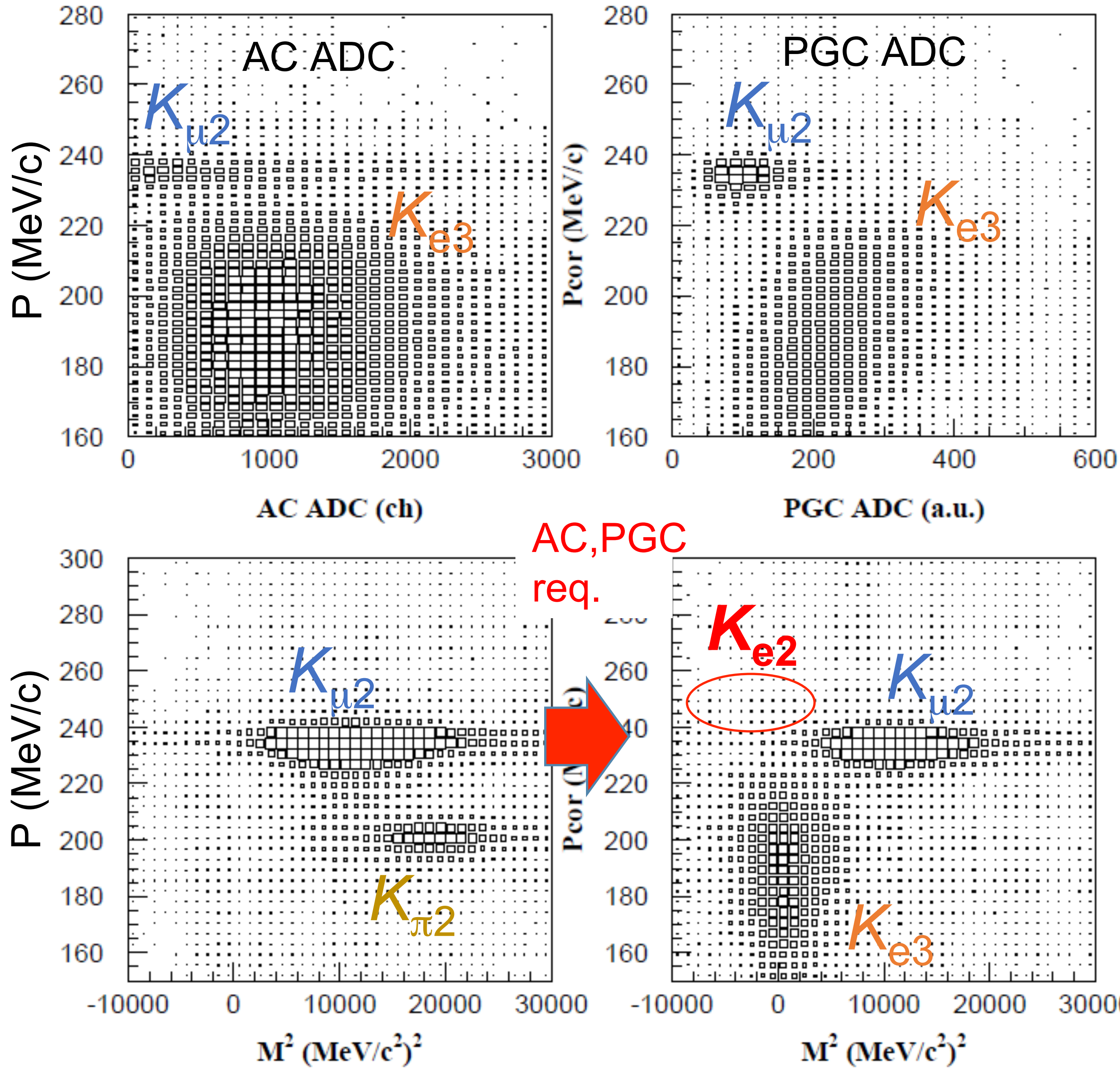
Bishoy Dongwi (Hampton U.)



- Commissioning of TGT+TOF1+SFT with cosmic rays
- Check-out of all detectors with beam
- Commissioning of toroidal magnet including cryogenics

Particle identification by AC, PGC, and TOF

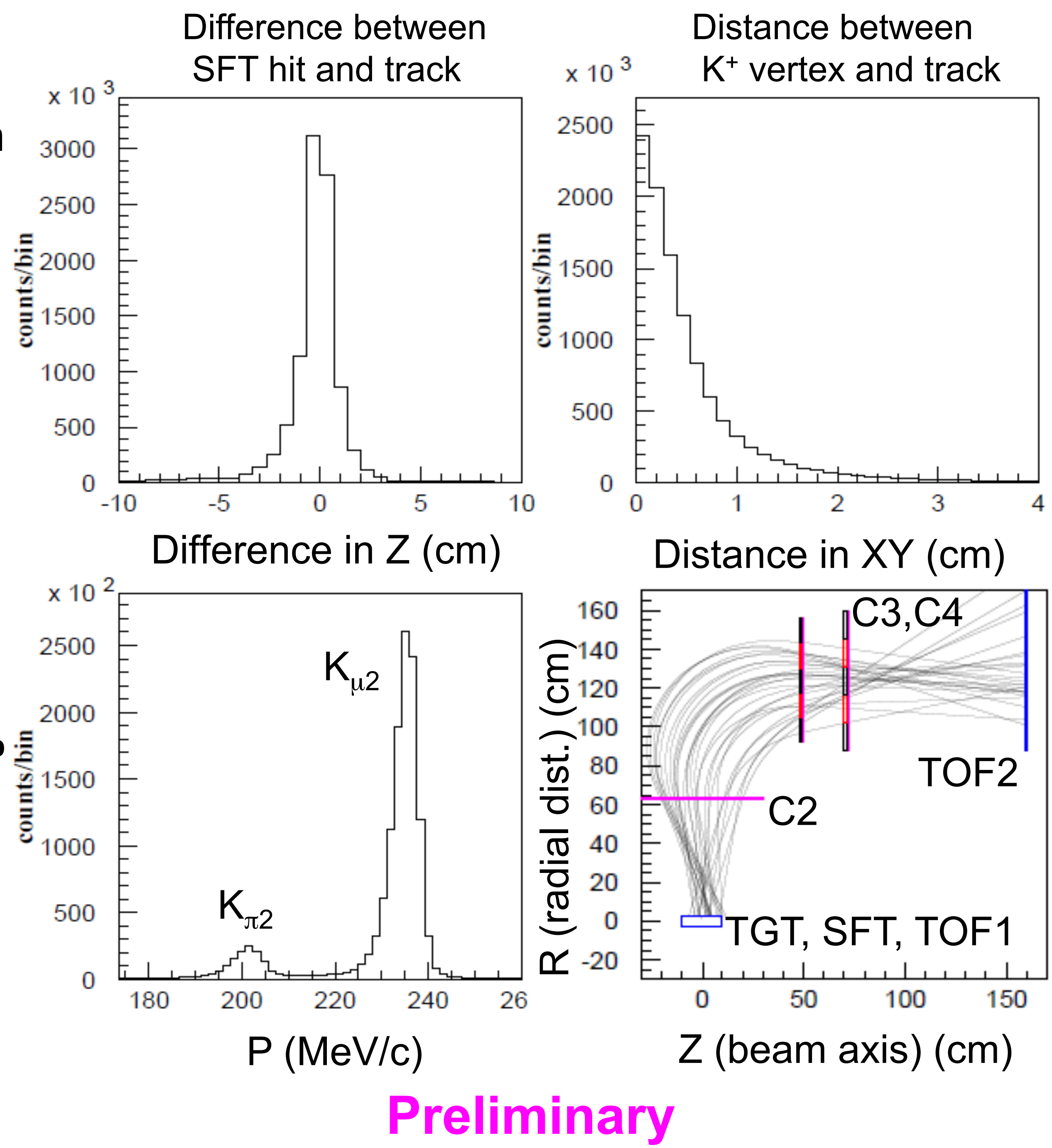
- **Positrons are selected by AC, PGC and TOF**
- **PID performance by combining the three detectors is now being optimized**
- **Suppression of muon mis-identification below O(10^{-8}) level achievable with refined analysis**
- **Refined analysis of PID performance in progress**



Preliminary

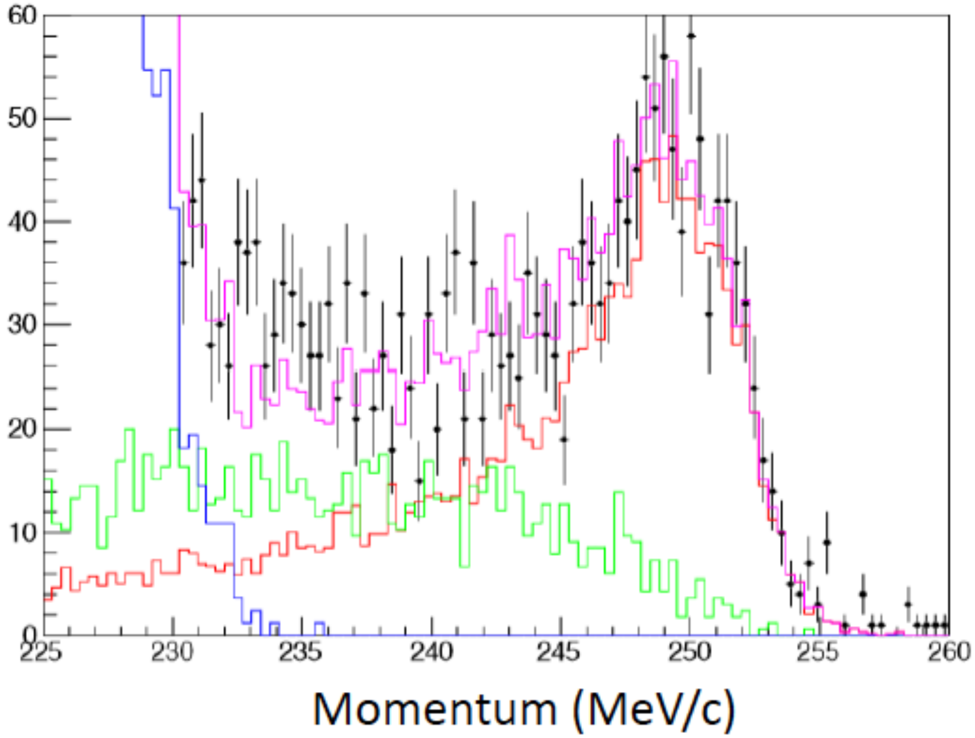
Momentum determination

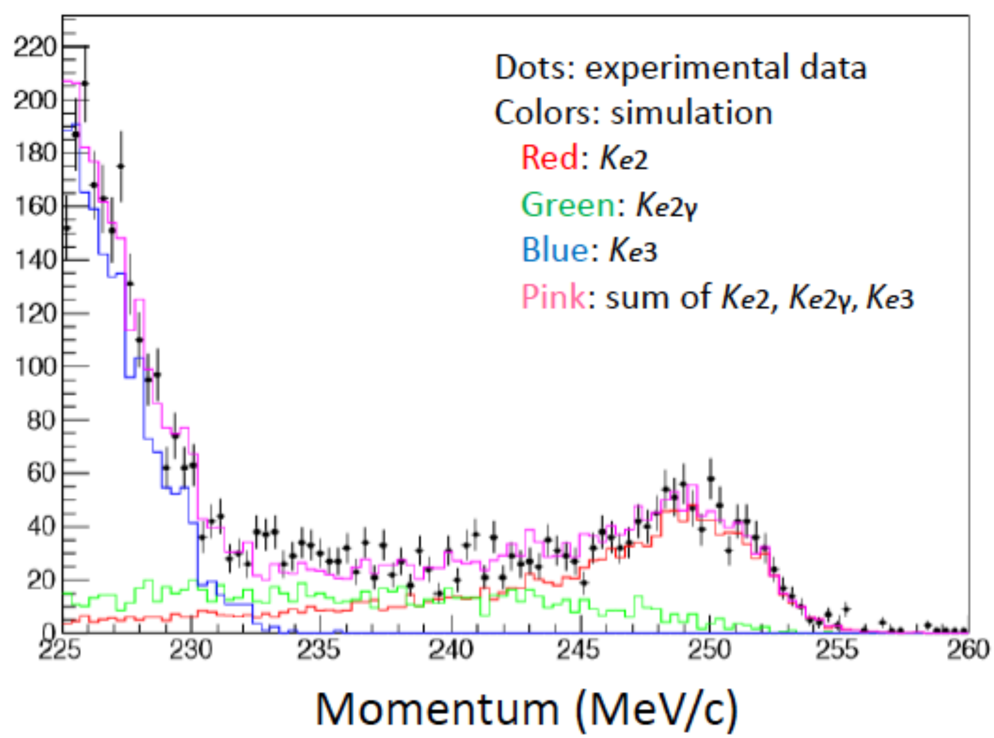
- **Charged particle momentum from 4-point tracking (C2, C3, C4, and TGT)**
- **Events selected requiring track consistency with SFT**
- **Monochromatic peaks from $K_{\mu 2}$ and $K_{\pi 2}$ observed**
- **Momentum resolution ~1.4% to be improved to 1% with optimized energy loss correction**



Momentum determination

- **Positron momentum spectrum (900 runs)**
- **PID applied with AC, PGC, TOF**
- **Decomposition of *Ke2, Ke2γ, Ke3 yields***





Preliminary

Simulation and analysis

Team: Hampton (T. Cao, B. Dongwi, M.K.)

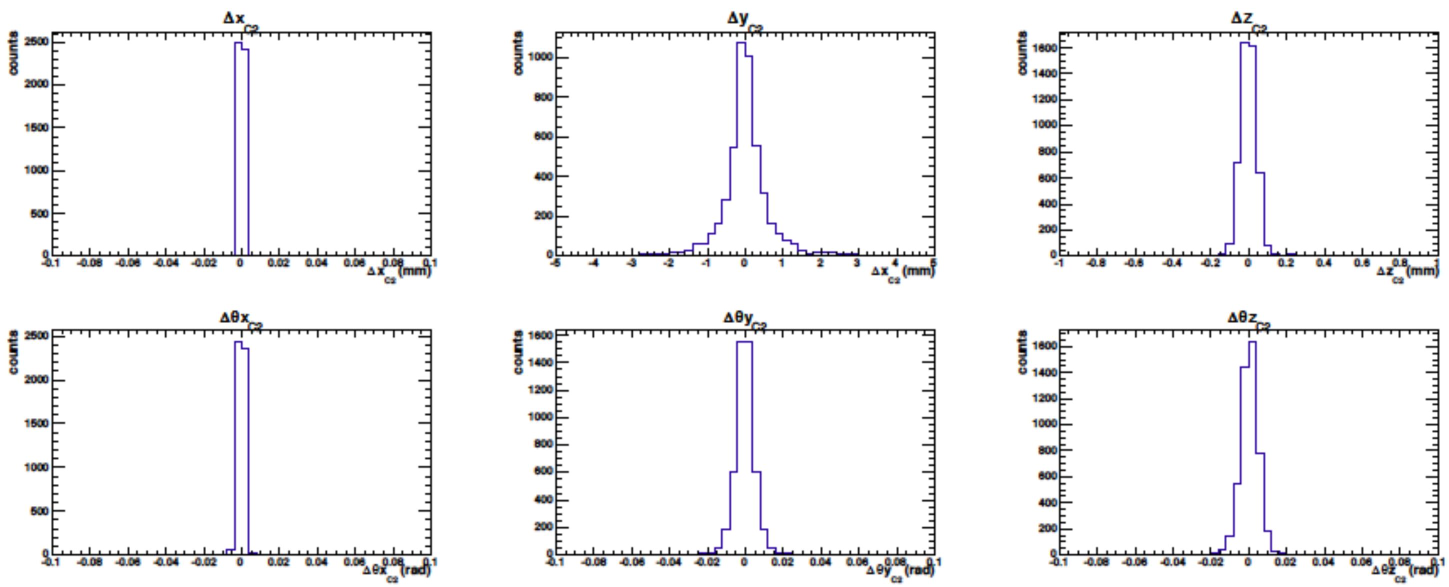
Accomplishments

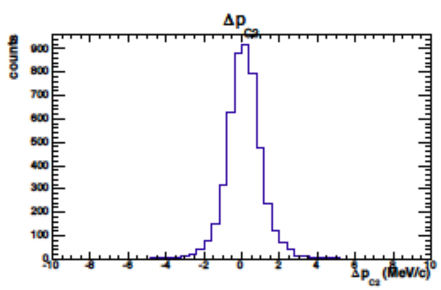
- Geant4: Completed geometry, now including target, SFT, CsI
- Established, tested Kalman Filter for tracking, fully consistent with G4
- Kaon decay generator developed and implemented into Geant4

Plans

- Acceptance ratio for K_{l2}
- Simulation of DP signal and bkg processes for realistic reach
- DP analysis: CsI clustering

Diff. between tracking results and true values for the state vector at C2



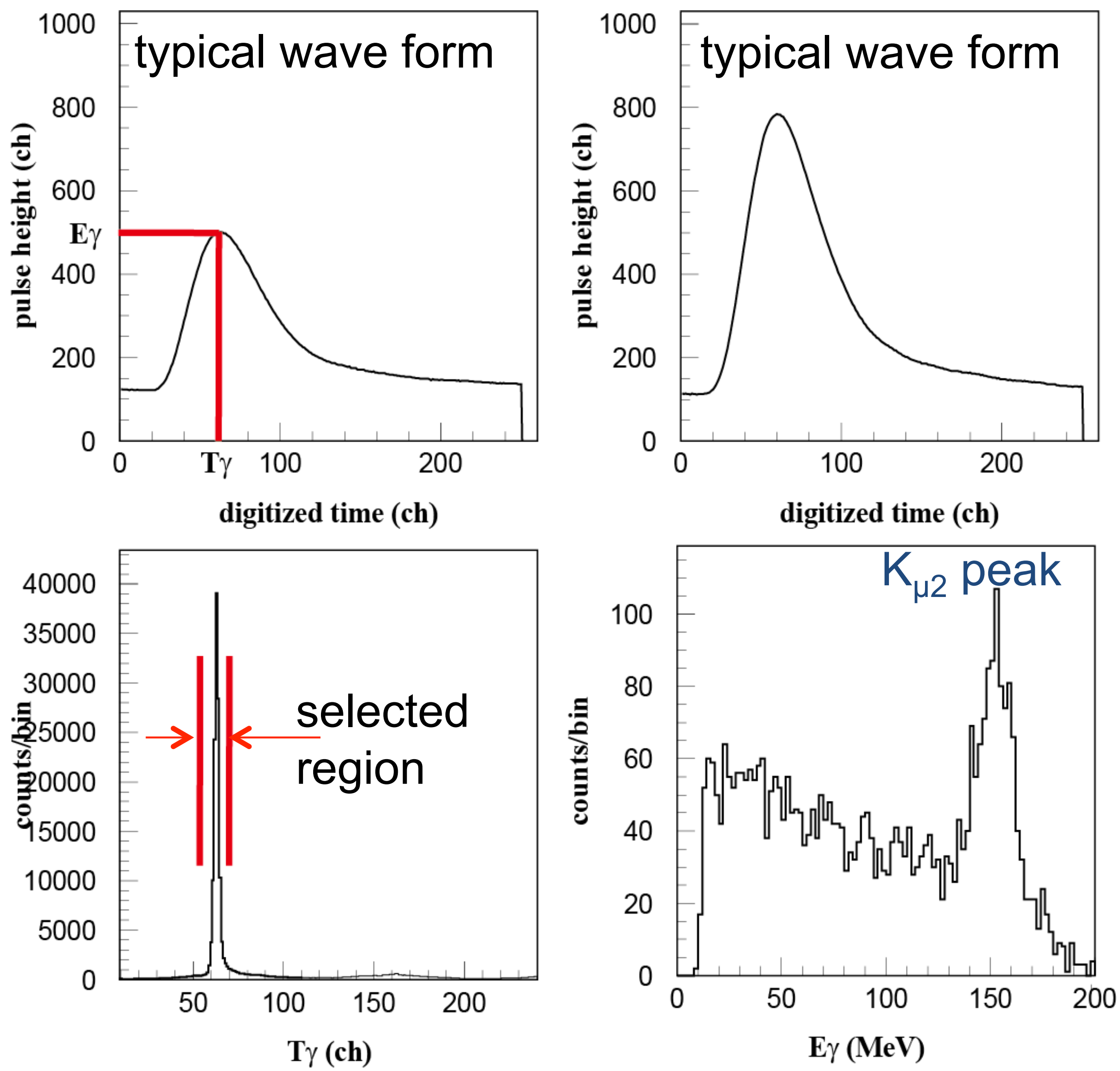


- Simulated data: propagated and reconstructed tracks
- Tracking efficiency ~100%
- No bias, narrow resolutions

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**

Preliminary

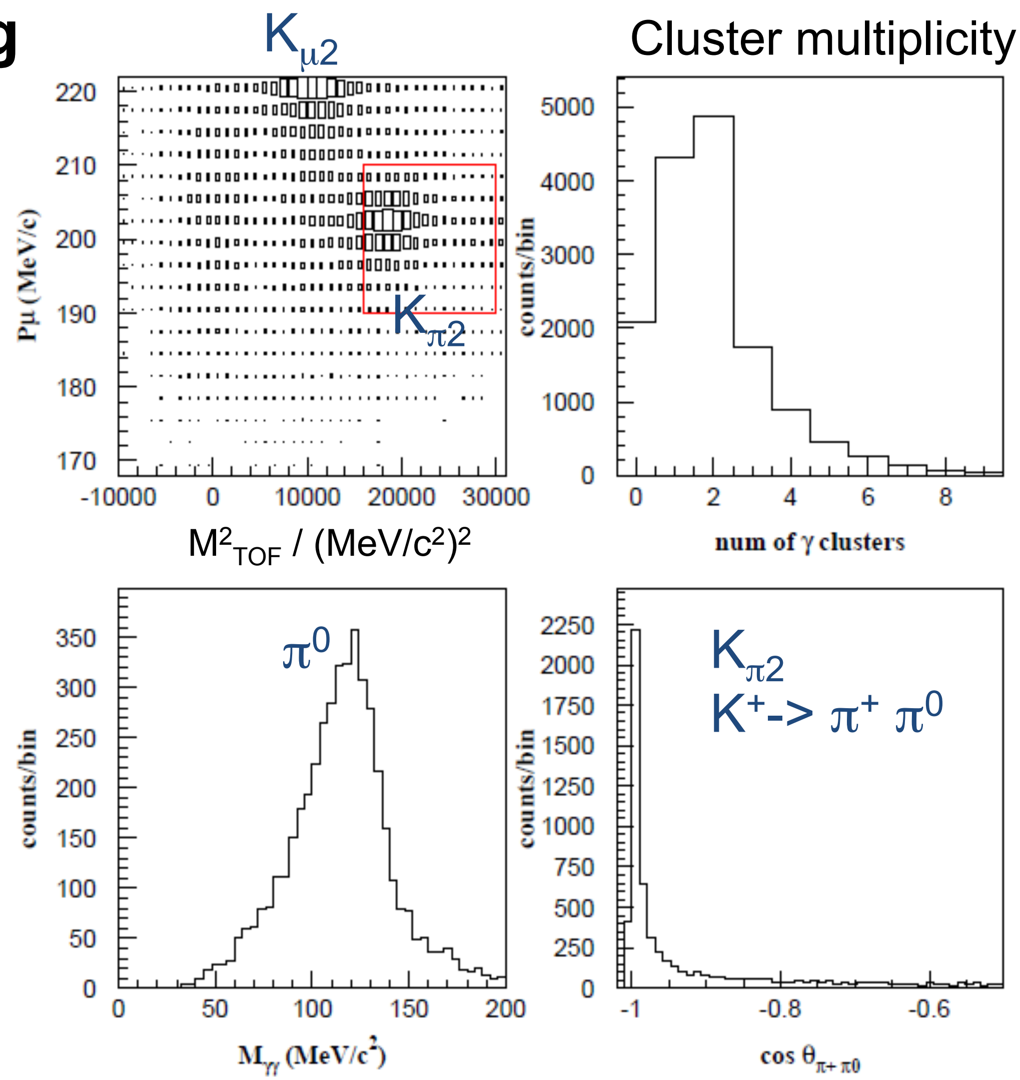


Calibration data from early June

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 observed to select $K_{\pi 2}$
- Confirmed that the total E36 system works correctly and is consistent with E246

Preliminary



Possible A' decay channels in TREK/E36

K^+ decays ~ 10^{10}

Signal 1: $K^+ \rightarrow \pi^+ A'$, $A' \rightarrow e^+e^-$

Background: BR($K^+ \rightarrow \pi^+ e^+ e^-$) ~ 2.9×10^{-7} ~ 2,900 ev.

Signal 2: $K^+ \rightarrow \mu^+ \nu A'$, $A' \rightarrow e^+e^-$

Background: BR($K^+ \rightarrow \mu^+ \nu\ e^+ e^-$) ~ 2.5×10^{-5} ~ 250,000 ev.

Add. background from $K^+ \rightarrow \mu^+ \nu \pi^0 \rightarrow \mu^+ \nu\ e^+ e^- (\gamma)$

π^0 decays 1) 3×10^8 2) 2×10^9

π^0 production: $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.3%) $K^+ \rightarrow \pi^+ \pi^0$ (21.1%)

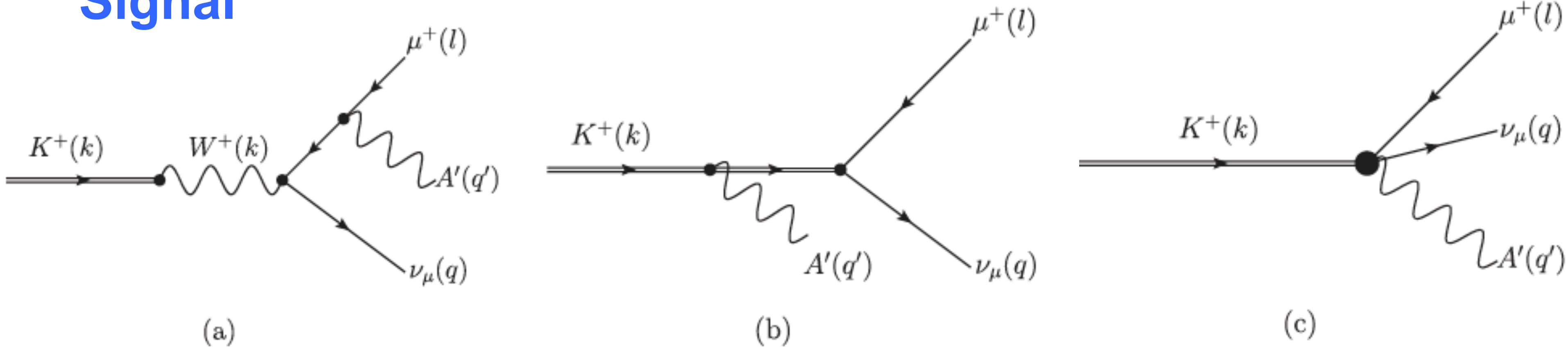
Signal 3: $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$

Background: BR($\pi^0 \rightarrow \gamma\ e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) x$10^7$ ev.

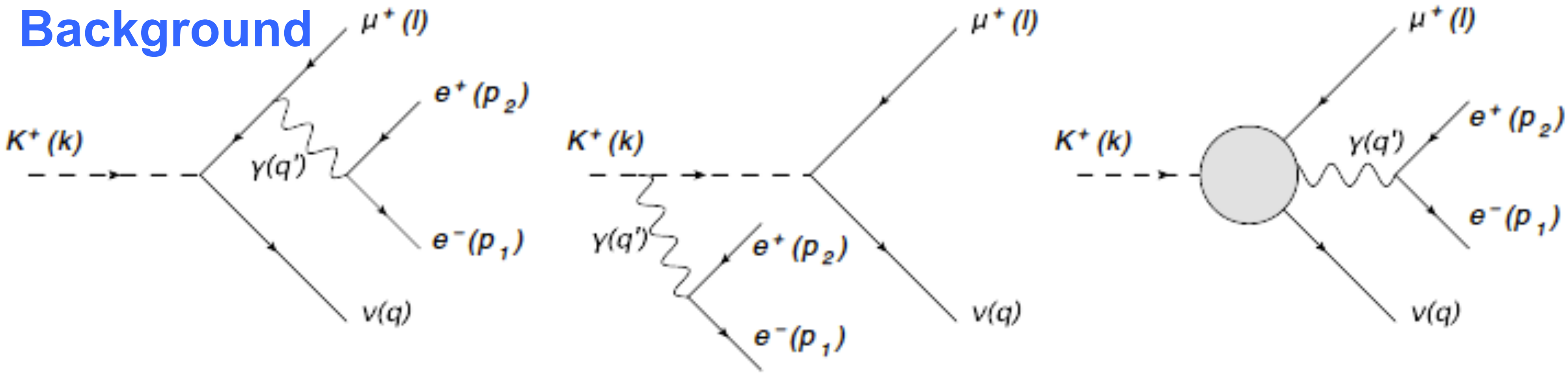
The rare kaon decay $K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$

C. Carlson & B. Rislow; T. Beranek

Signal

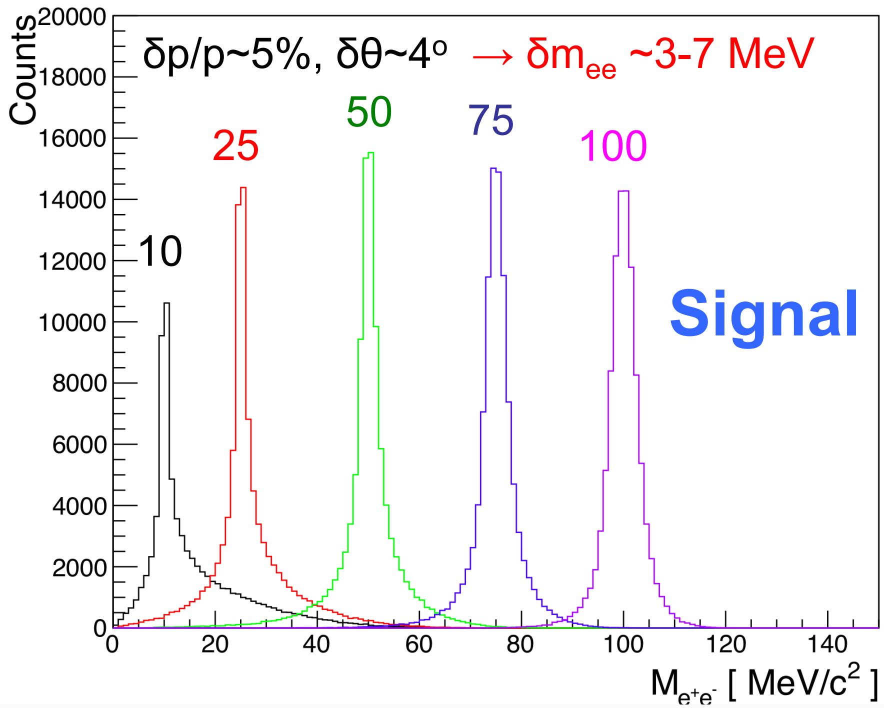


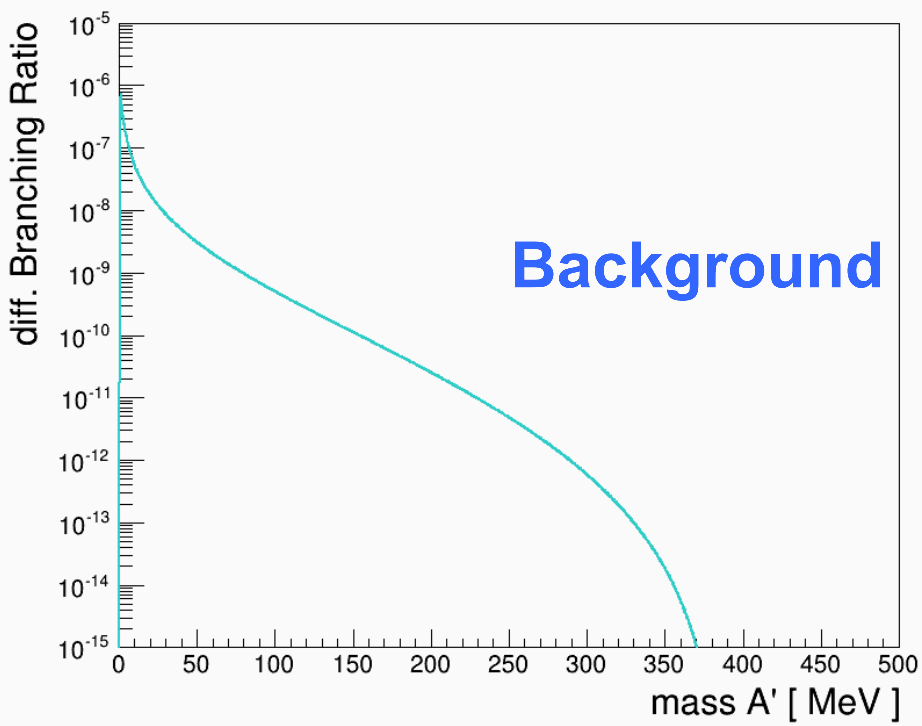
Background



- Background: SM process with time-like (virtual) photon exchange
  - Calculable in QED, BR($K^+ \to \mu^+ \nu\ \ e^+ e^-$) = 2.49×10^{-5}
    J. Bijnens et al., Nucl. Phys. B396, 81 (1993), hep-ph/9209261
  - Measured for $m_{ee} > 145$ MeV/c^2
    A. Poblaguev et al., Phys. Rev. Lett. 89, 061803 (2002), hep-ex/0204006

Search for a new particle in $K^+ \rightarrow \mu^+ \nu e^+ e^-$





Investigated for E36:

- Detect μ^+ in toroid, e^+e^- in CsI(Tl)
- Simulate achievable resolution for invariant mass m_{ee}
- Simulate QED background (radiative decay $K^+ \rightarrow \mu^+ \nu \; e^+ e^-$)
- Sensitivity from QED background fluctuation

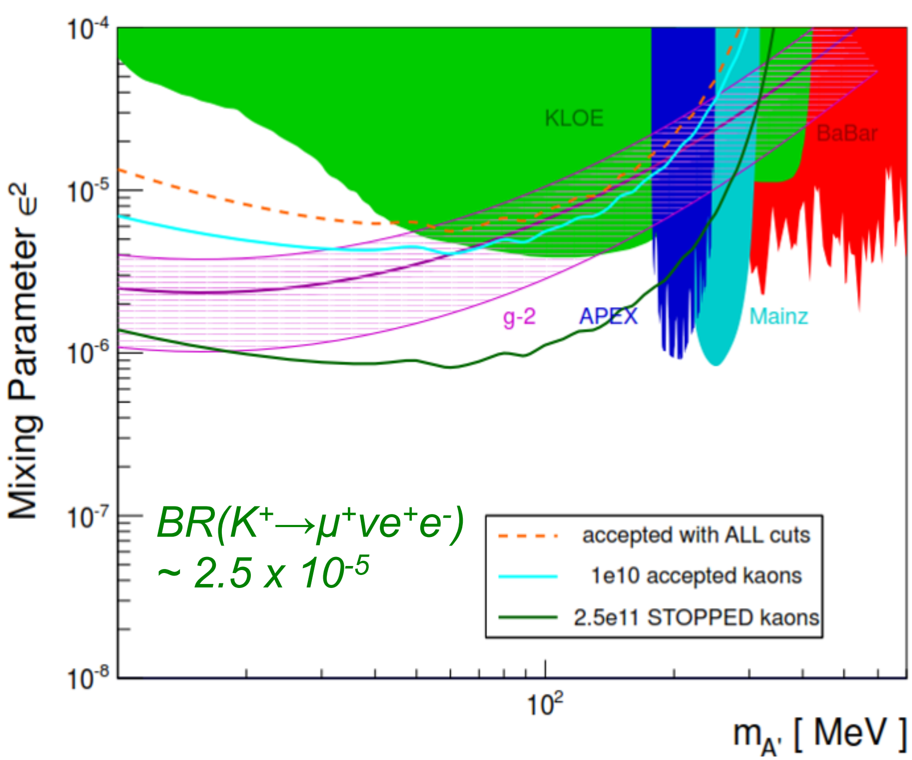
$\rightarrow$ Exclusion limits for ε^2 versus m_{ee}

P. Monaghan, T. Cao, B. Dongwi (Hampton)

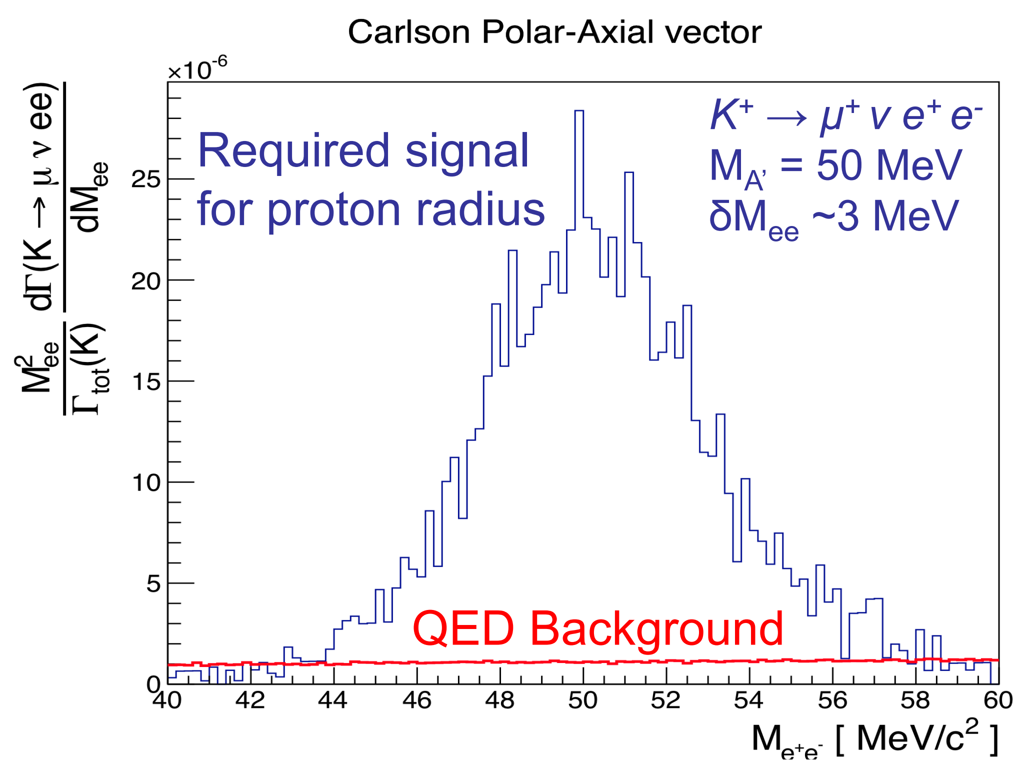
Dark photon / light neutral boson search

- **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 $A' \rightarrow e^+e^-$ in K$^+$ decays**
  Kaons: $K^+ \rightarrow \mu^+ \nu A'$; $K^+ \rightarrow \pi^+ A'$ (also invisible decay);
  Pions: $\pi^0 \rightarrow \gamma A'$, using $K^+ \rightarrow \pi^+\pi^0$ (21.13%) and $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%)

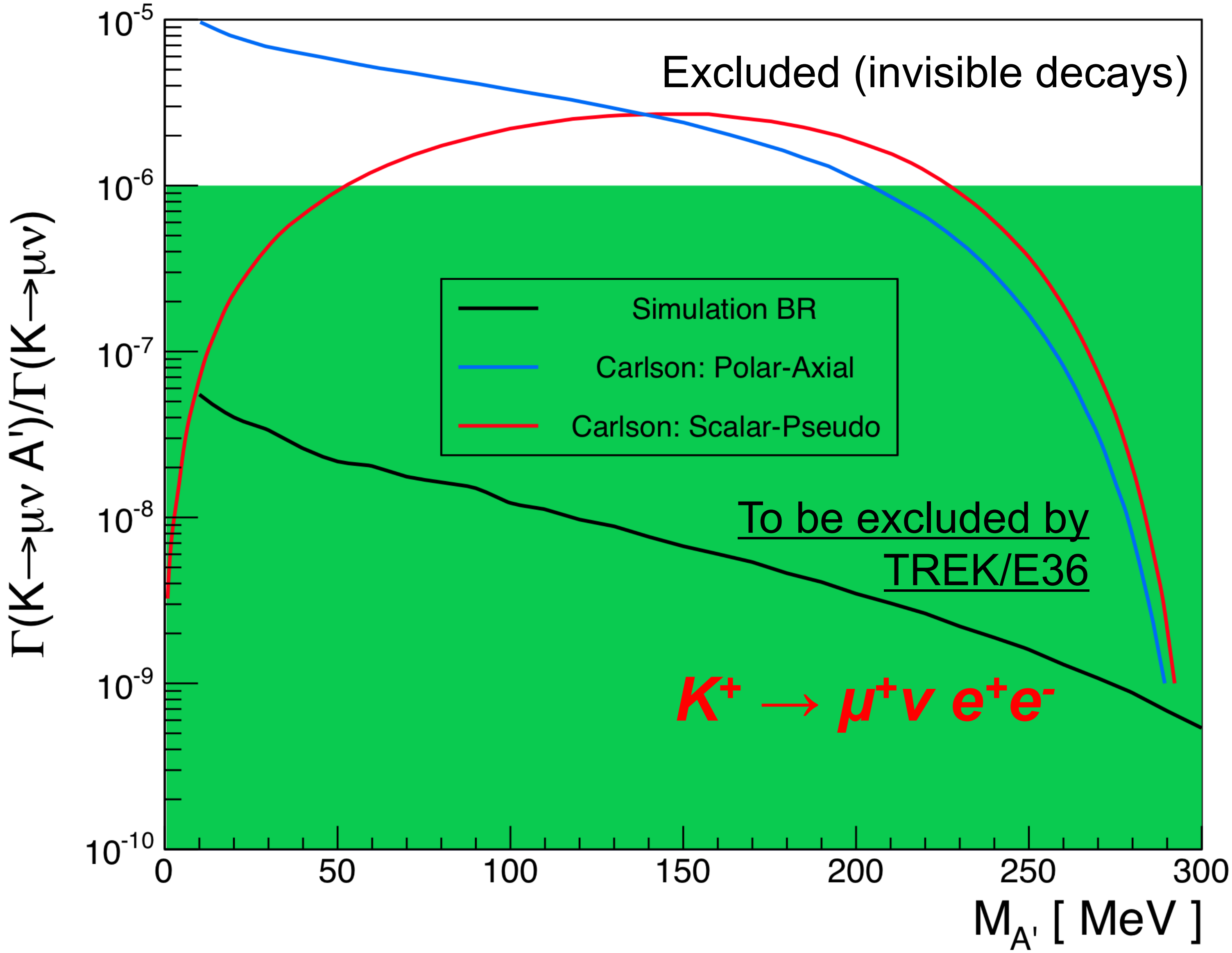
E36: Dark photon exclusion limit



E36: Light boson expected signal



Proton radius and New Physics



Expected signal BR's: C. Carlson and B. Rislow, PRD86, 035013 (2012)

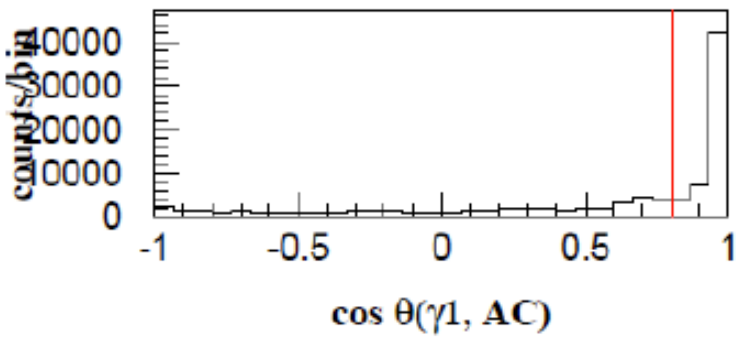
Exclusion limit TREK/E36: simulation by P. Monaghan, T. Cao, B. Dongwi (HU)

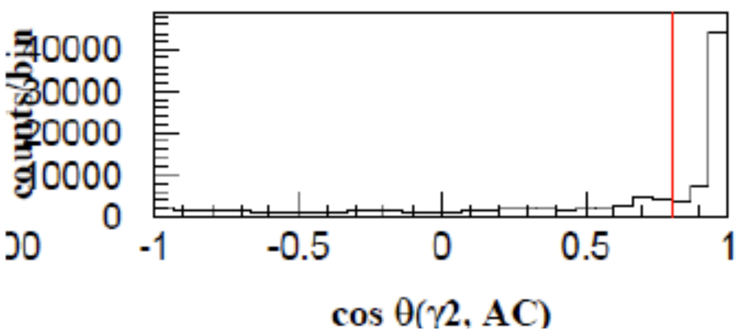
Existing limit: **C. Pang, R. Hildebrand, G. Cable, and R. Stiening, PRD8, 1989 (1973)**

Search for light boson events

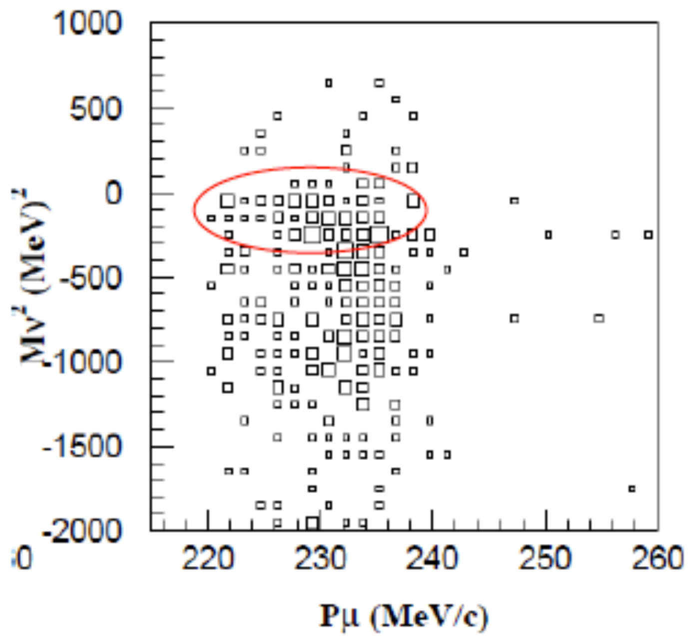
- Search for visible decay mode of $A' \rightarrow e^+e^-$ in K^+ decays
  Kaons: $K^+ \rightarrow \mu^+ \nu A'$; $K^+ \rightarrow \pi^+ A'$ (also invisible decay);
  Pions: $\pi^0 \rightarrow \gamma A'$, from $K^+ \rightarrow \pi^+\pi^0$ (21.13%), $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%)
- DP trigger: 3+ TOF1 bars
- $K^+ \rightarrow \mu^+ e^+ e^- \nu$ decays recorded in E36 data with DP trigger
- Reconstruct $K^+ \rightarrow \mu^+ e^+ e^- \nu$ decays with μ^+ track in toroid and e^+e^- pair in the CsI(Tl) calorimeter
- e^+ and e^- are identified by the aerogel Cherenkov counters surrounding the K^+ stopping target
- Main background: $K^+ \rightarrow \pi^+ \pi^o$ and $K^+ \rightarrow \mu^+ \pi^o \nu$, with $\pi^o \rightarrow e^+ e^- \gamma$
- [Can also use $\pi^o \rightarrow e^+ e^- \gamma$ as another signal channel!]

Search for light boson events

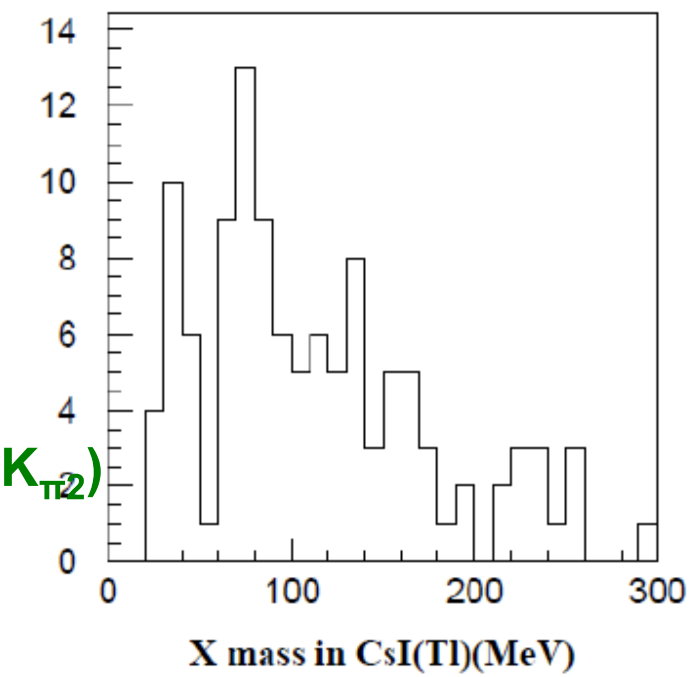




Correlate CsI e^+e^- hits with AC sector



Evaluate $K^+ \rightarrow \mu^+ e^+ e^- \nu$ missing mass



Select μ^+ momentum > 205 MeV/c ($K_{\pi2}$)
Evaluate $A' \rightarrow e^+ e^-$ invariant mass

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New Physics Search with the TREK/E36 experiment at J-PARC

Dr. Tongtong Cao, Bishoy Dongwi, Letrell Harris, Dr. Michael Kohl, Aruna Liyanaarachchi, Dr. Anusha Liyanage, Jesmin Nazeer
for the TREK Collaboration
Department of Physics, Hampton University, Hampton, VA, 23668, USA

J-PARC

Overview

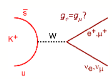
"In the world of *weak interactions* do *electrons* and *muons* behave the same?" That is the question.

The Standard Model (SM) represents our best description of the subatomic world and has been very successful at explaining how elementary particles interact under the influence of the four fundamental forces. However the following questions still linger:

- what is *dark matter?*
- what happened to all the antimatter after the big bang?
- why do neutrinos have mass?

Introduction

Lepton universality: In the SM e, μ and τ : Have different masses **but** identical coupling constants.



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

Decay width ratio

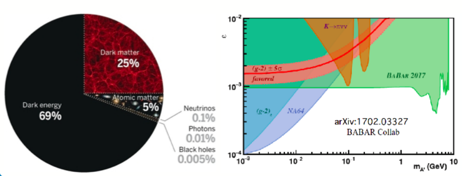
$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r) \longrightarrow \textit{radiative corr.}$$

- Hadronic *form factors* cancel
- Strong *helicity* suppression of electronic channel enhances sensitivity to effects beyond SM
- SM: $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$ (very precise!)
  NA62: $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$ (in-flight K^+ decay)

E36 proposal : 0.25% (0.20% *stat.*+0.15% *sys.*), *stopped* K^+

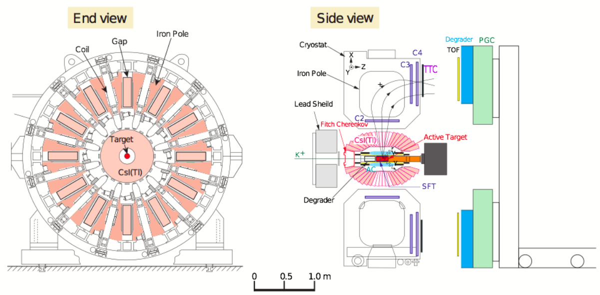
The mystery of Dark Matter

- Well motivated by dark matter observations (astronomical; direct: positron excess) and $g_\mu - 2$ anomaly
- Light neutral boson (selective coupling): proton radius puzzle
- Search for the A' with *Kaons*: $K^+ \to \mu^+ \nu A'$; $K^+ \to \pi^+ A'$ (also invisible decay)
- Also search for A' with *pions*: $\pi^0 \to \gamma A'$ (π^0 from $K_{\pi 2}$ and $K_{\mu 3}$)



TREK/E36 experiment at J-PARC

The E36 experiment was conducted at the Japan Proton Accelerator Research Complex (J-PARC) using the TREK detector system. E36 was successfully completed in the fall of 2015.



December 2014

- Installed detector components

February - June 2015

- Completed installation of C3 & C4
- Cabling and detector maintenance

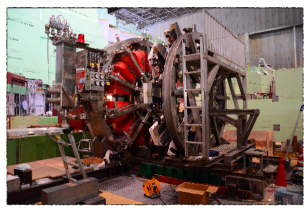
September - December 2015

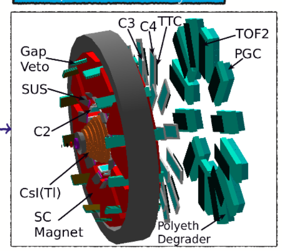
- Physics run and data taking

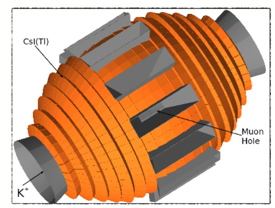
Stopped K^+	Tracking	Particle ID	Gamma ray
K1.1BR beamline	MWPC (C2, C3, C4)	Time of fl. (TOF)	CsI(TI)
K^+ stopping target	Spiral fib. tracker (SFT)	Aerogel Cheren.	
	Thin trig. counter (TTC)	Pb glass Counter	

Living in a simulation

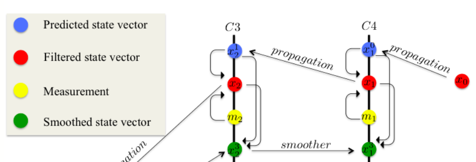
TREK/E36 detector system





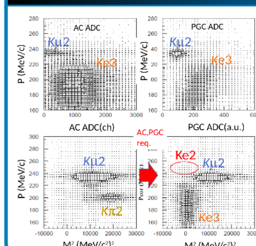


Kalman Filter



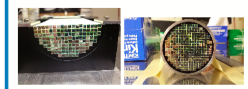
- The prediction makes an estimate of the future state of the system by the Runge-Kutta method.
- The filter estimates the system state in the present.
- The smoother allows to estimate the state of the system in the past.

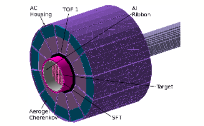
Particle Identification

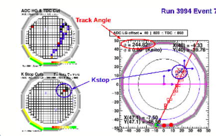


- e^+ are selected by aerogel cherenkov (AC), lead-glass counter (PGC) and TOF detectors
- PID will be performed by combing all three detectors

Target Tracking



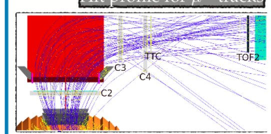


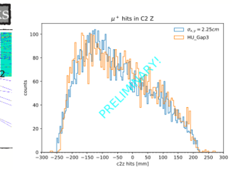


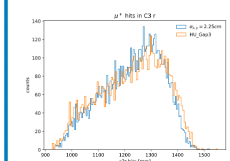
- Determination of K^+ stopping position lepton track length
- Measurement of lepton emission azimuthal angle to help determine SFT-Z
- Development of *target analysis algorithm* is nearly completed

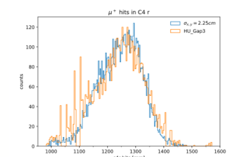
Geant4 Verification

Hit profile for μ^+ tracks



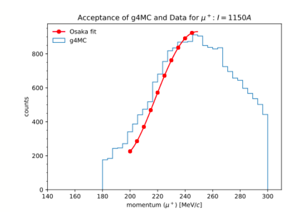






- Trigger on Target ⊗ TOF1 ⊗ TTC ⊗ TOF2
- Compare hit distribution between dispersive coordinates of the MWPCs

Acceptance Study



- Comparison of acceptance calibration between *Monte Carlo* and experimental data

Acknowledgements

Japan Osaka University, Chiba University, Rikkyo University, KEK
Russia Russian Academy of Sciences (RAS)
Canada University of Saskatchewan, University of British Columbia, TRIUMF
USA University of South Carolina, University of Iowa, Hampton University

*This work has been supported by DOE awards DE-SC0003884 and DE-SC0013941

Bishoy Dongwi - EINN2017 Poster Prize

New Physics Search with the TREK/E36 experiment at J-PARC

Dr. Tongtong Cao, Bishoy Dongwi, Letrell Harris, Dr. Michael Kohl, Aruna Liyanaarachchi, Dr. Anusha Liyanage, Jesmin Nazeer
for the TREK Collaboration
Department of Physics, Hampton University, Hampton, VA, 23668, USA

tor Research Complex (J-PARC) using the TREK detector system.

December 2014

- Installed detector components

February - June 2015

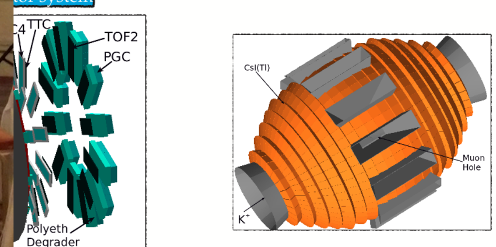
- Completed installation of C3 & C4
- Cabling and detector maintenance

September - December 2015

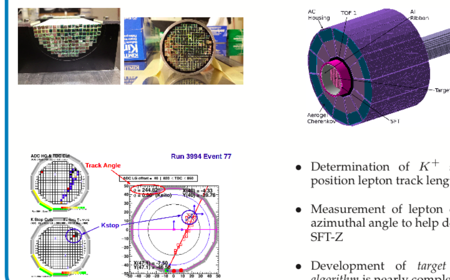
- Physics run and data taking

Gamma ray
CsI(TI)

tor system

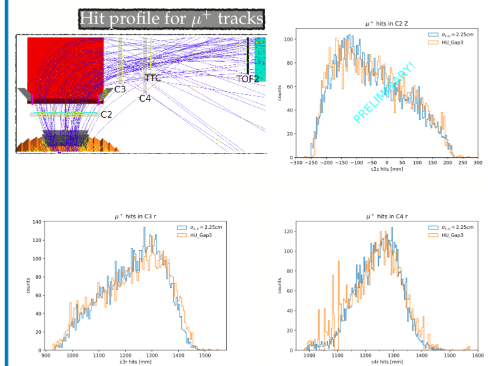


Target Tracking



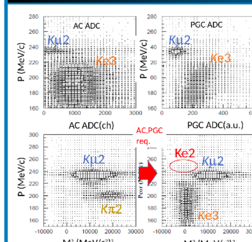
- Determination of K^+ stopping position lepton track length
- Measurement of lepton emission azimuthal angle to help determine SFT-Z
- Development of *target analysis algorithm* is nearly completed

Geant4 Verification



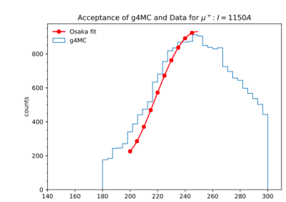
- Trigger on Target ⊗ TOF1 ⊗ TTC ⊗ TOF2
- Compare hit distribution between dispersive coordinates of the MWPCs

Particle Identification



- e^+ are selected by aerogel cherenkov (AC), lead-glass counter (PGC) and TOF detectors
- PID will be performed by combing all three detectors

Acceptance Study



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Bishoy Dongwi - EINN2017 Poster Prize

TREK (E36/E06) collaboration

~30 collaborators

Spokespeople:
M.K., S. Shimizu

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Rikkyo University
Department of Physics

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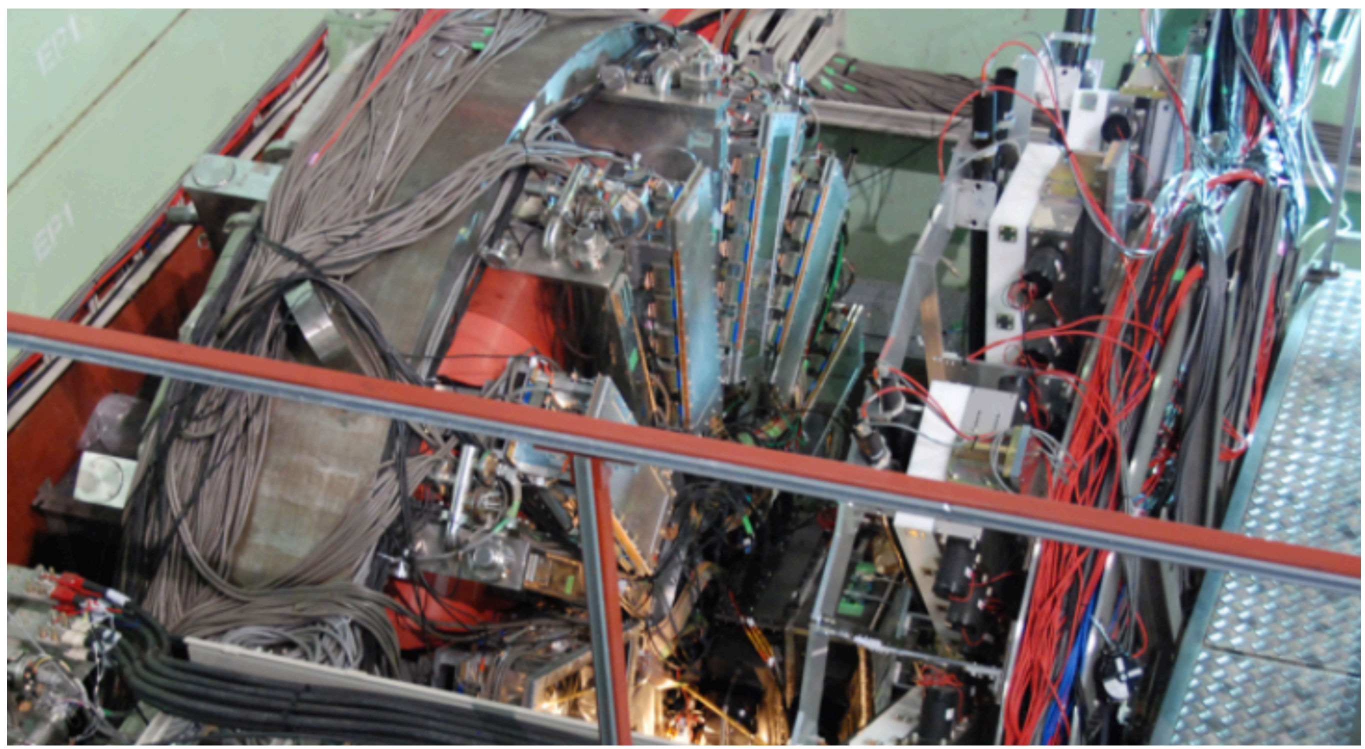
Institute of Particle and Nuclear Studies

RUSSIA

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

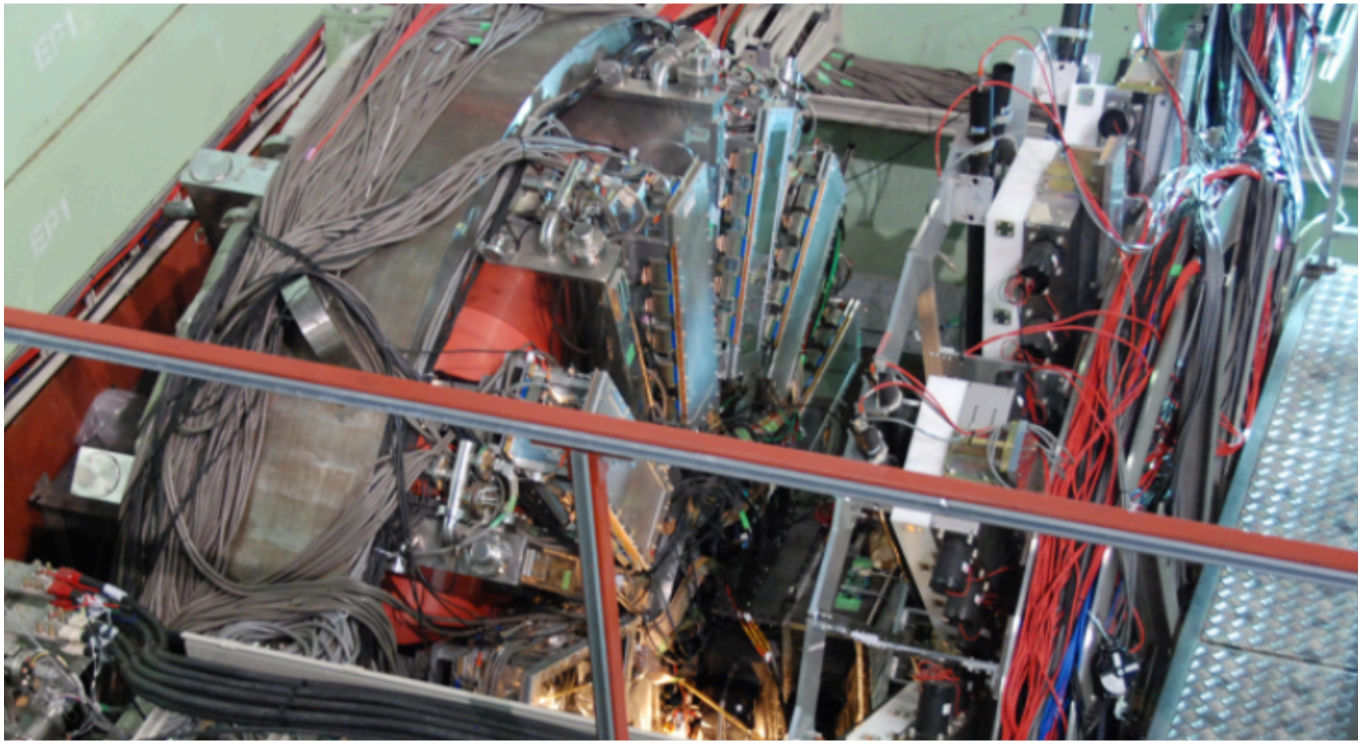
Summary

- 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)
- TREK/E36 @ J-PARC analysis underway
- TREK/E06 (T-violation) planned at J-PARC Extended Hadron Facility



Summary

- Lepton universality is challenged (BaBar, Belle, LHCb)
- Non-universally coupled light bosons to explain a_μ and R_p puzzles
  - ➔ Rare kaon decays with TREK/E36 @ J-PARC
  - ➔ Data taken in 2015, under analysis
- Proton radius puzzle / lepton universality: MUSE @ PSI
  - ➔ Size of TPE could be different for $\mu^{\pm}p$, $e^{\pm}p$
  - ➔ μp and ep interaction could be fundamentally different
  - ➔ Running in 2018-2020 (stay tuned for the next talk!)



Backup