The TREK-E36 Search for New Physics at J-PARC

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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 in 2015 !

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
- 2016: Analysis in progress

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)]

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

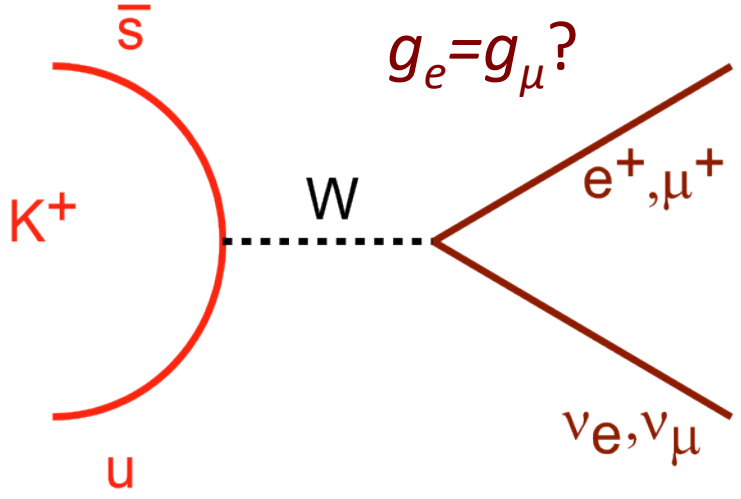
  BR($B^+\to K^+\mu^+\mu^-$) / BR($B^+\to K^+e^+e^-$) = $0.745^{+0.090}_{-0.074}\pm0.0036$ — 2.6 σ dev.
- Possible link to proton charge radius puzzle — 7 σ dev.

  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)

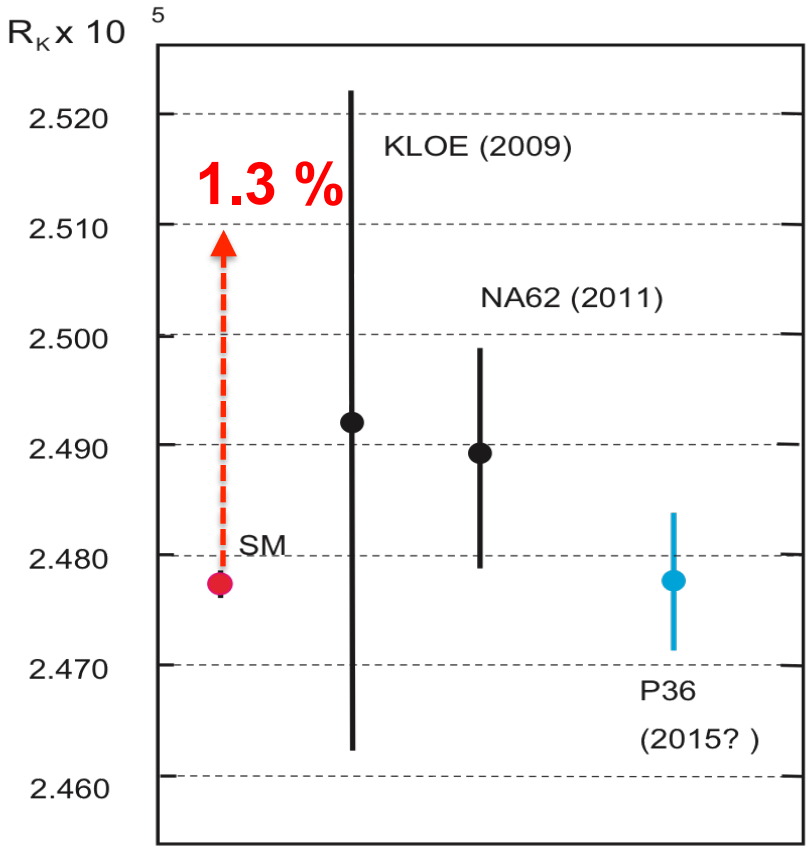
Experimental status of R_K

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



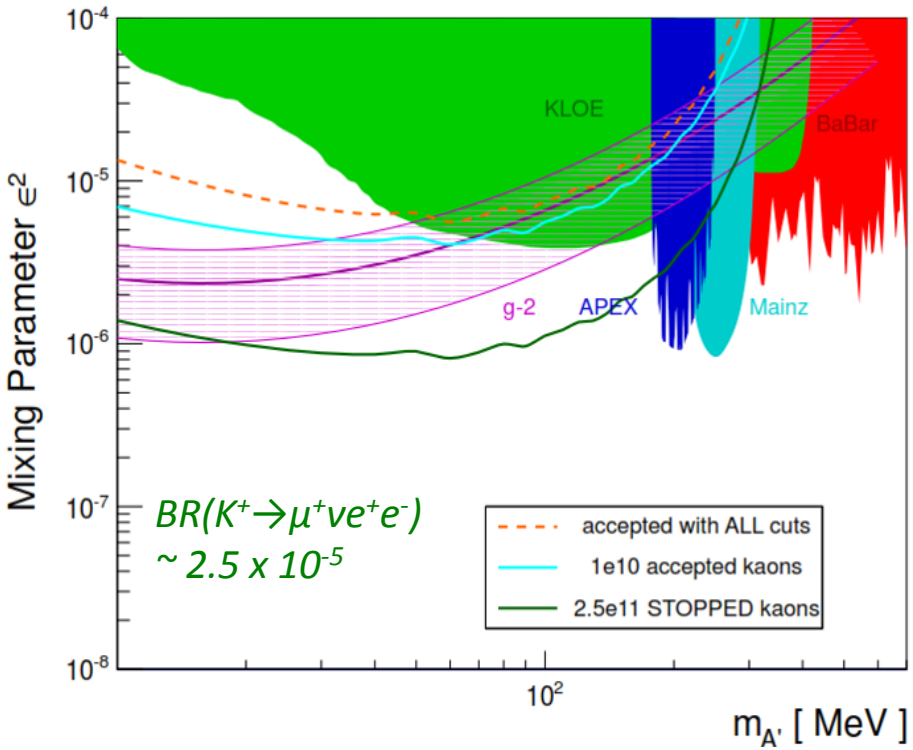
- **Systematics:**
  - In-flight-decay experiments: kinematics overlap
  - E36 stopped K^+: detector acceptance and target
  - E36 complementary to in-flight experiments

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

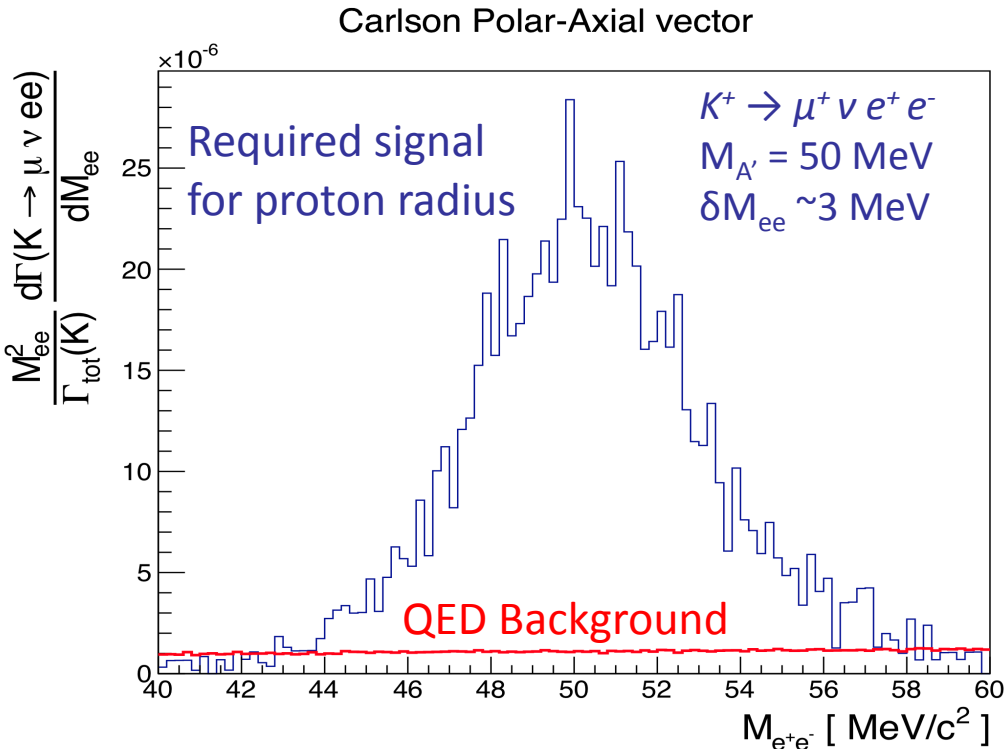
Dark photon / light neutral boson search

- **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 $A' \rightarrow e^+e^-$ 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



Possible kaon decay channels in E36

K^+ decays ~ 10^{10}

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

Background: BR($K^+ \rightarrow \pi^+ e^+ e^-$) ~ 2.9 x 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 x 10^{-5} ~ 250,000 ev.

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

π^0 decays 1) 3x10^8 2) 2x10^9

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

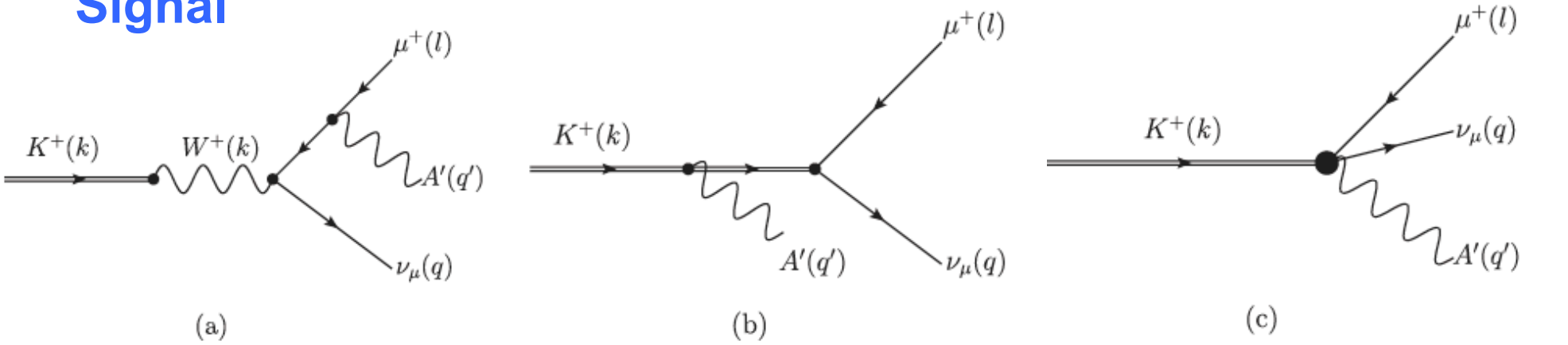
Signal 3: $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$

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

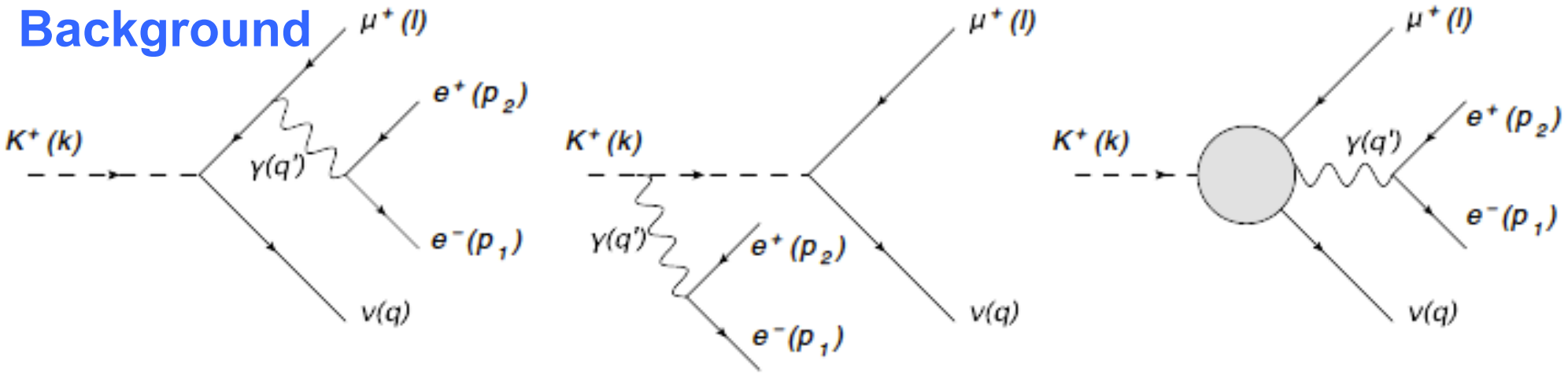
The rare kaon decay $K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$

C. Carlson & B. Rislow; T. Beranek

Signal

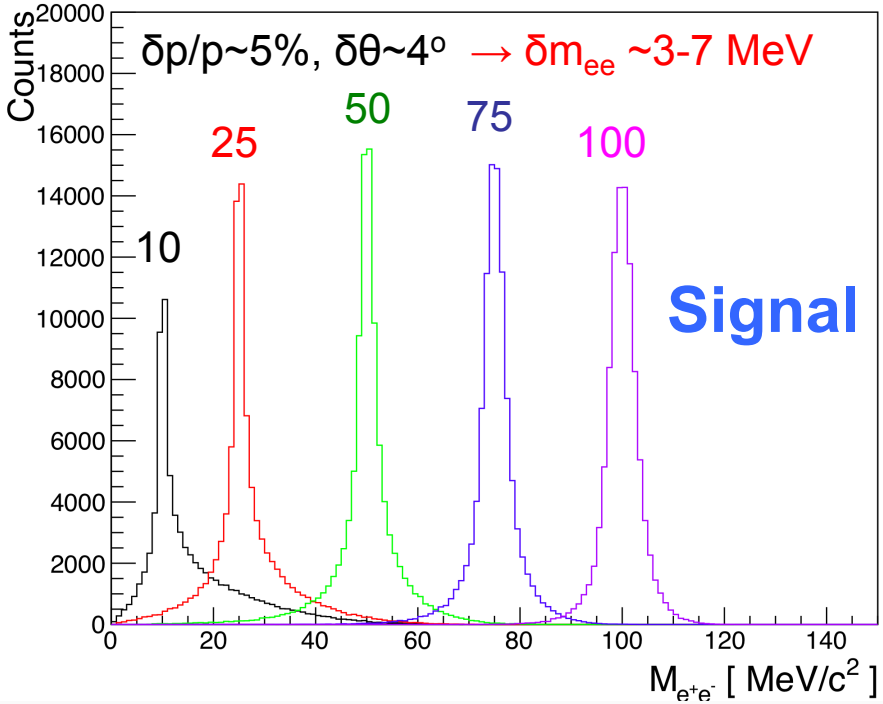


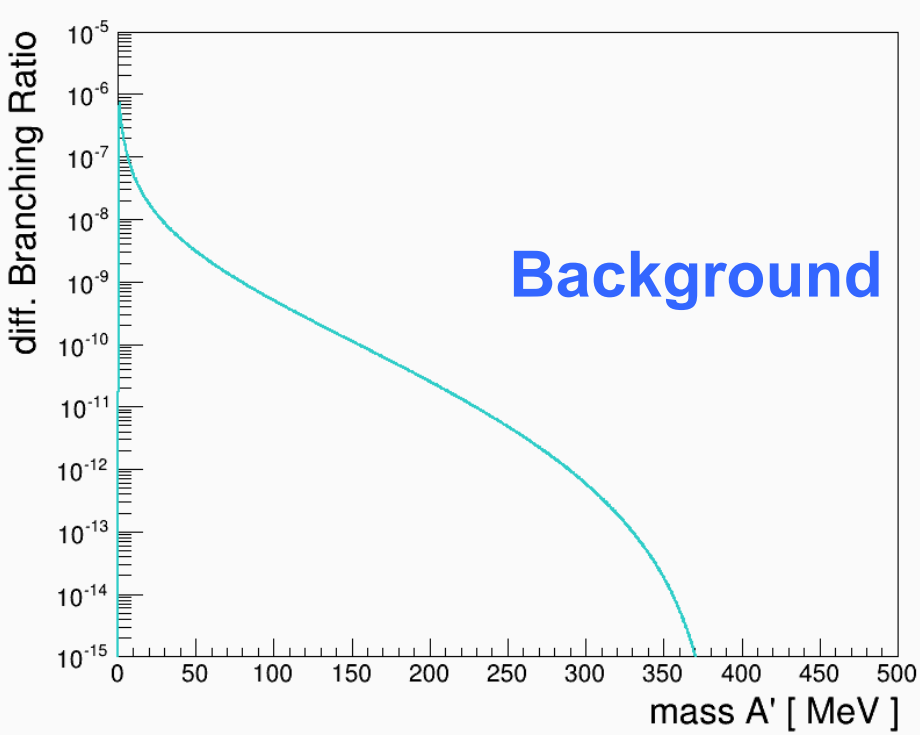
Background



- Background: SM process with time-like (virtual) photon exchange
  - Calculable in QED, BR($K^+ \to \mu^+ \nu\ e^+ e^-$) = 2.49 x 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 $K^+ \rightarrow \mu^+ \nu\, e^+\, e^-$





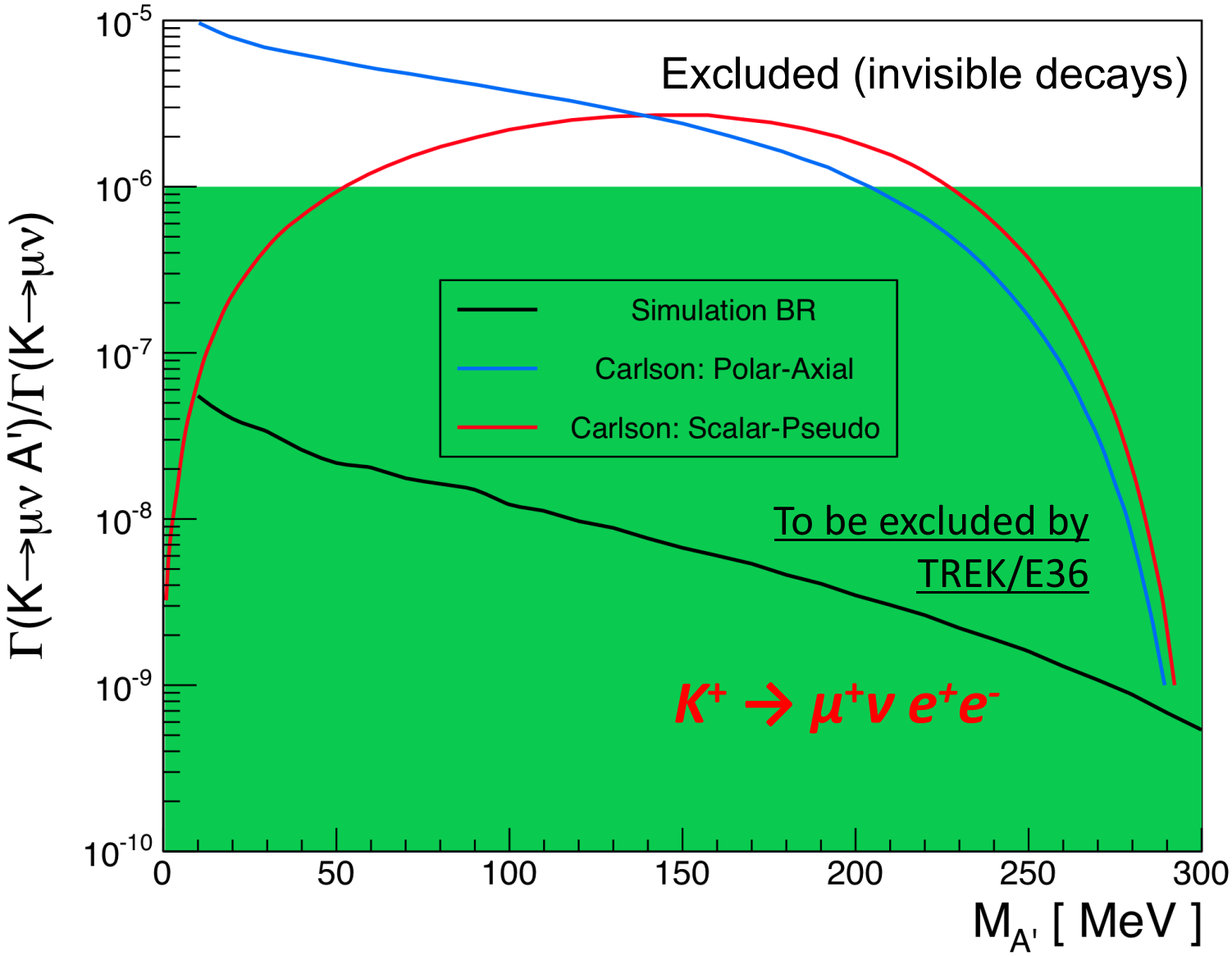
Investigated for E36:

- 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

→ Exclusion limits for ε^2 versus m_{ee}

P. Monaghan, B. Dongwi (Hampton)

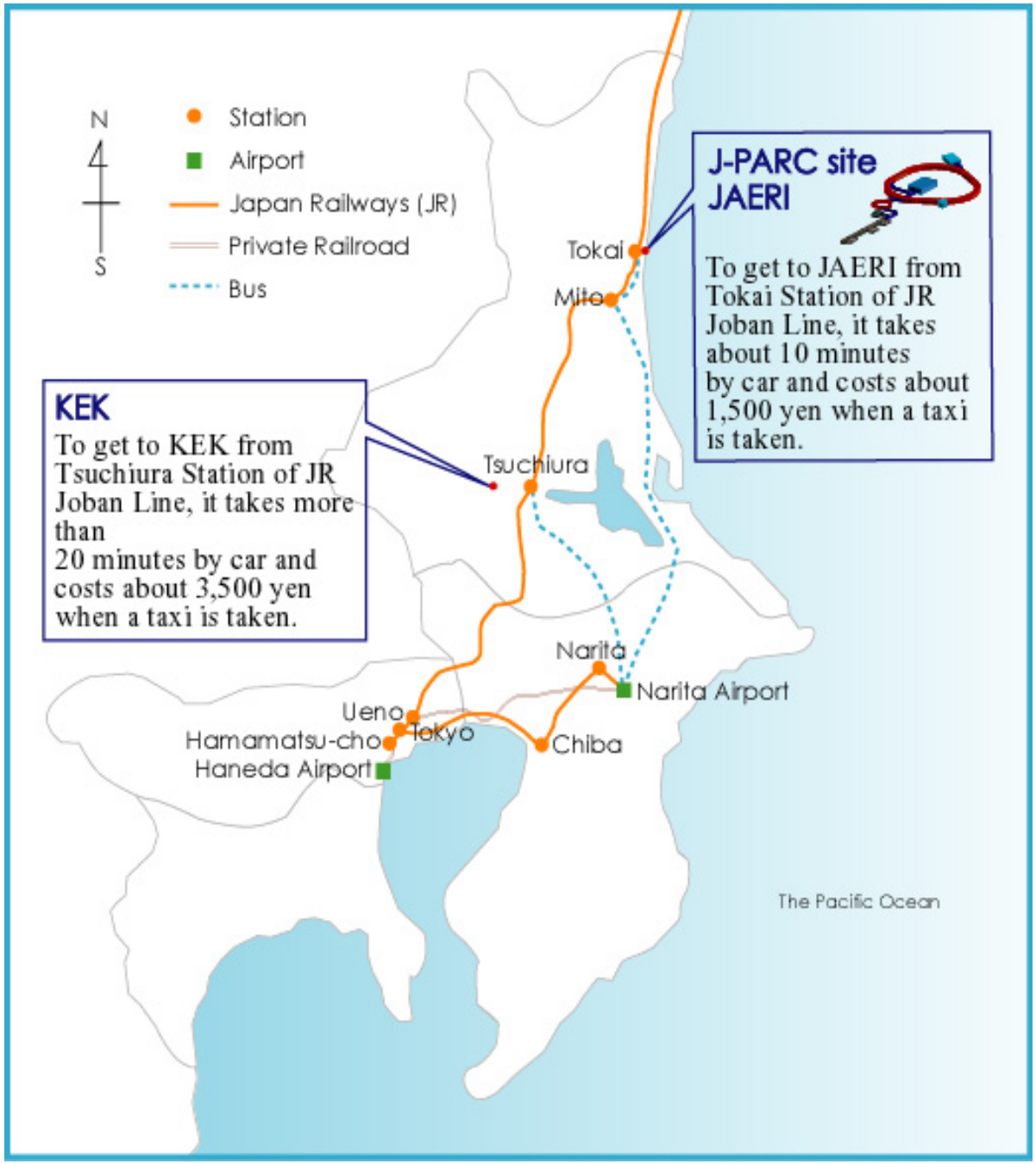
Proton radius and New Physics

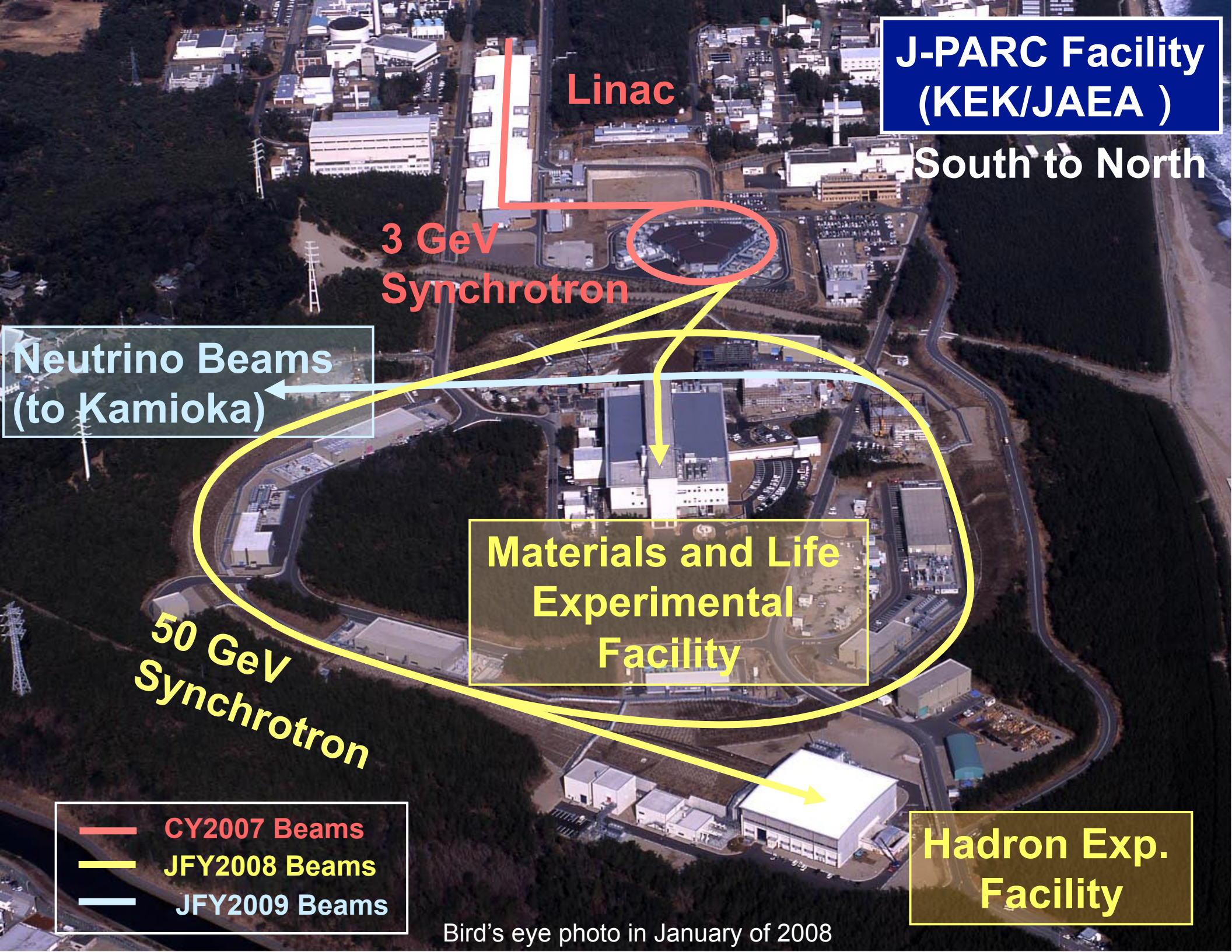


Expected signal BR's: C. Carlson and B. Rislow, PRD86, 035013 (2012)
Exclusion limit with TREK/E36: simulation by Peter Monaghan (HU)

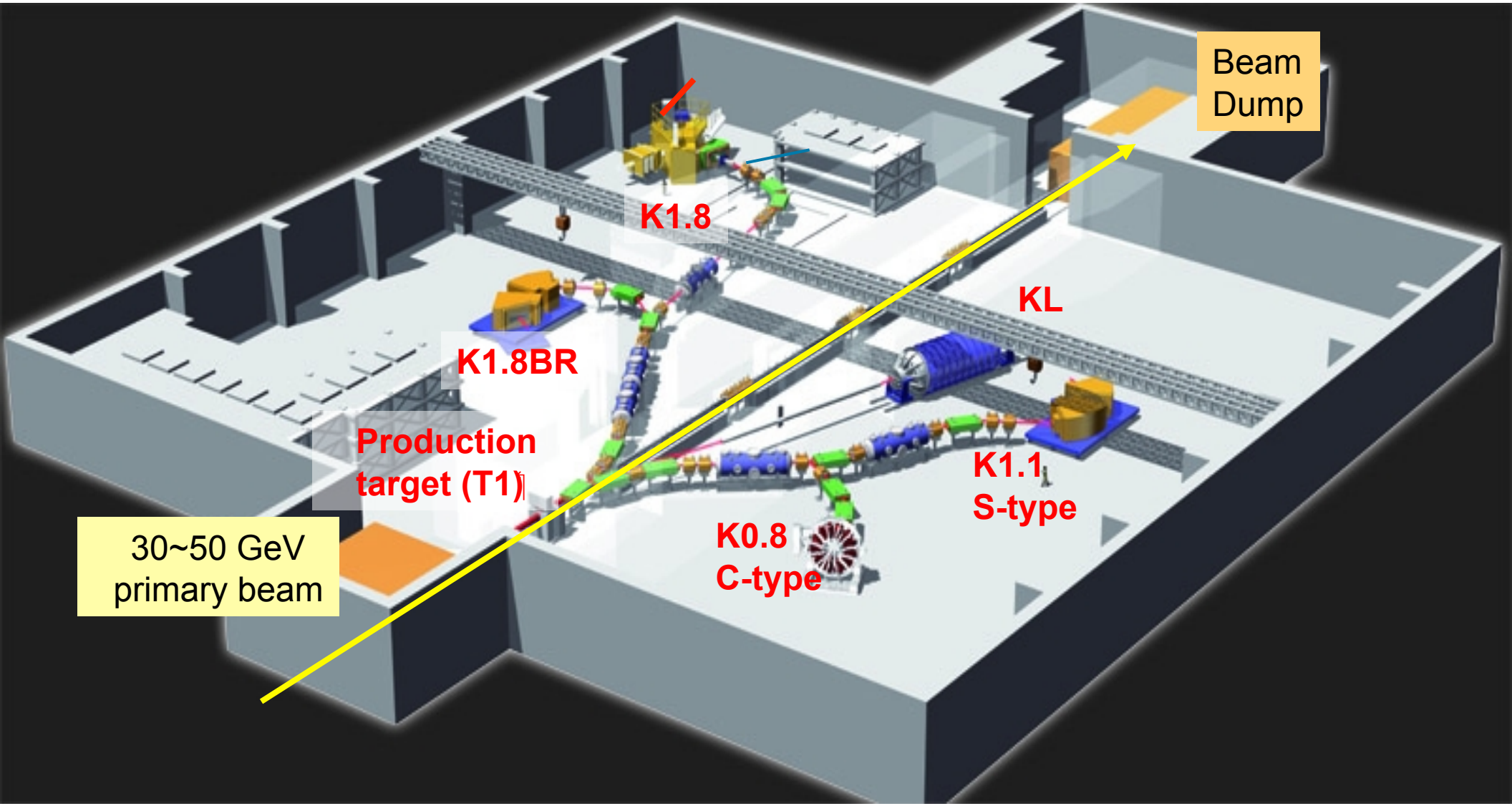
Existing limit: **C. Pang, R. Hildebrand, G. Cable, and R. Stiening, PRD8, 1989 (1973)**

Location of J-PARC



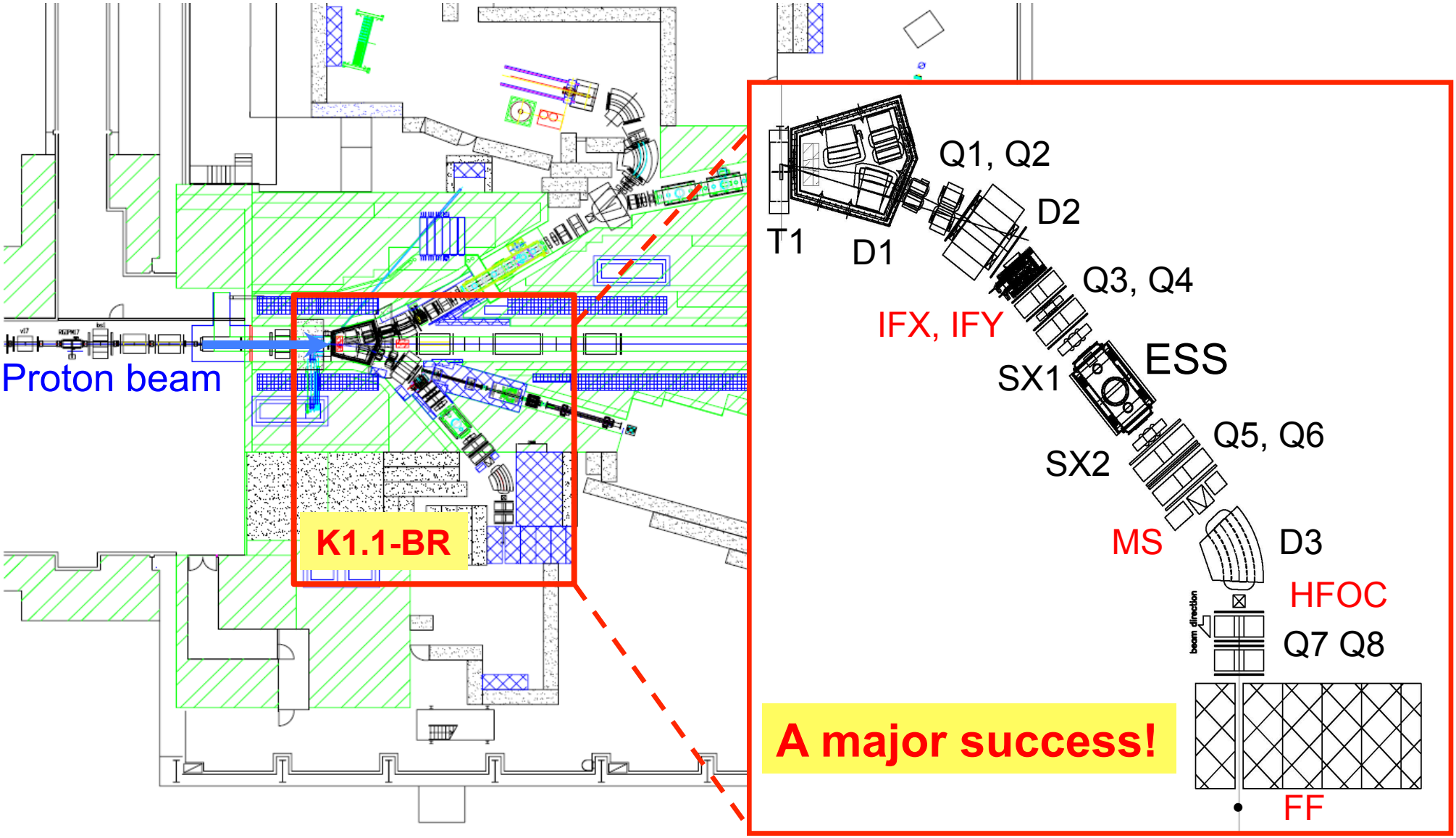

J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

J-PARC Hadron Experimental Hall



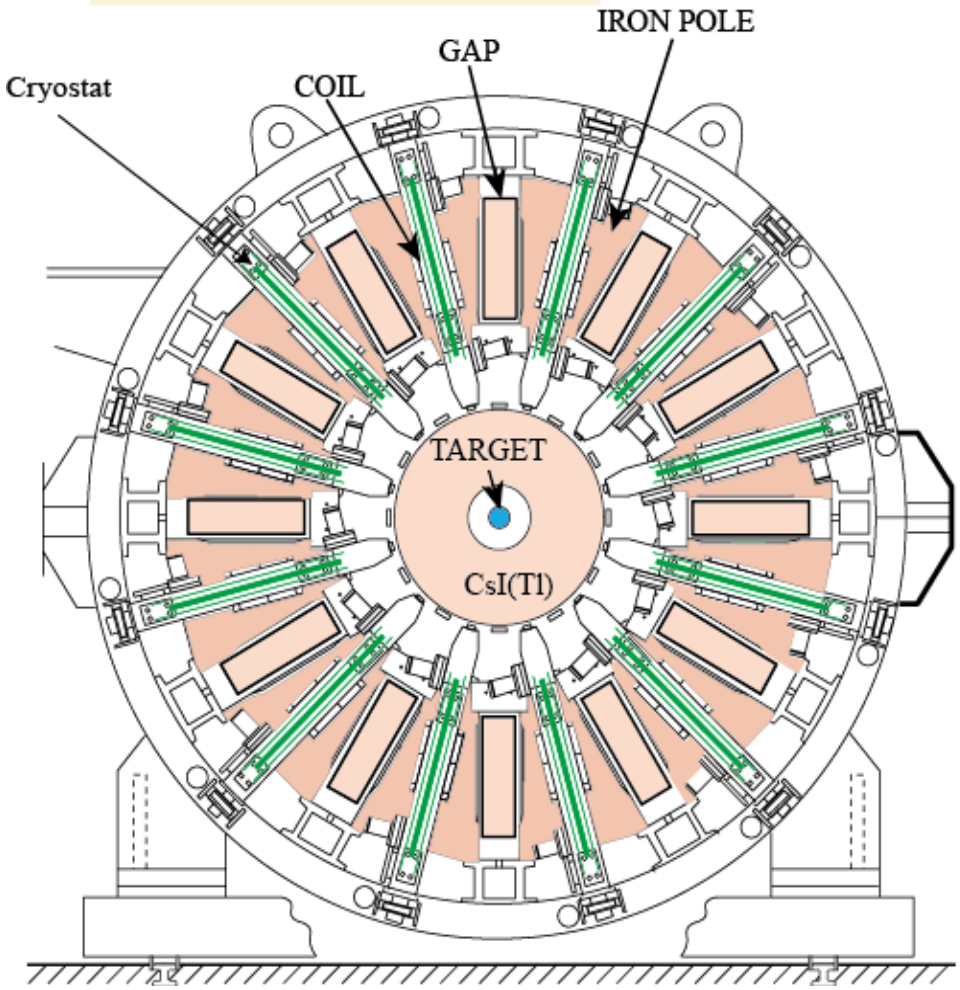
K1.1BR beamline

- **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 @ 40kW)

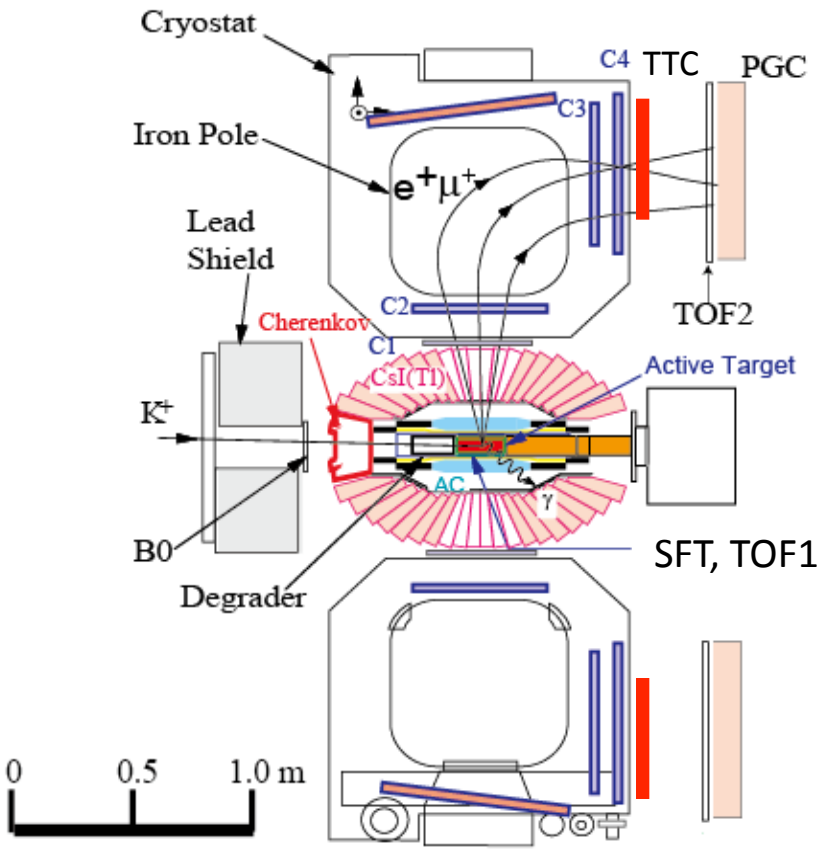


The TREK apparatus for E36

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)

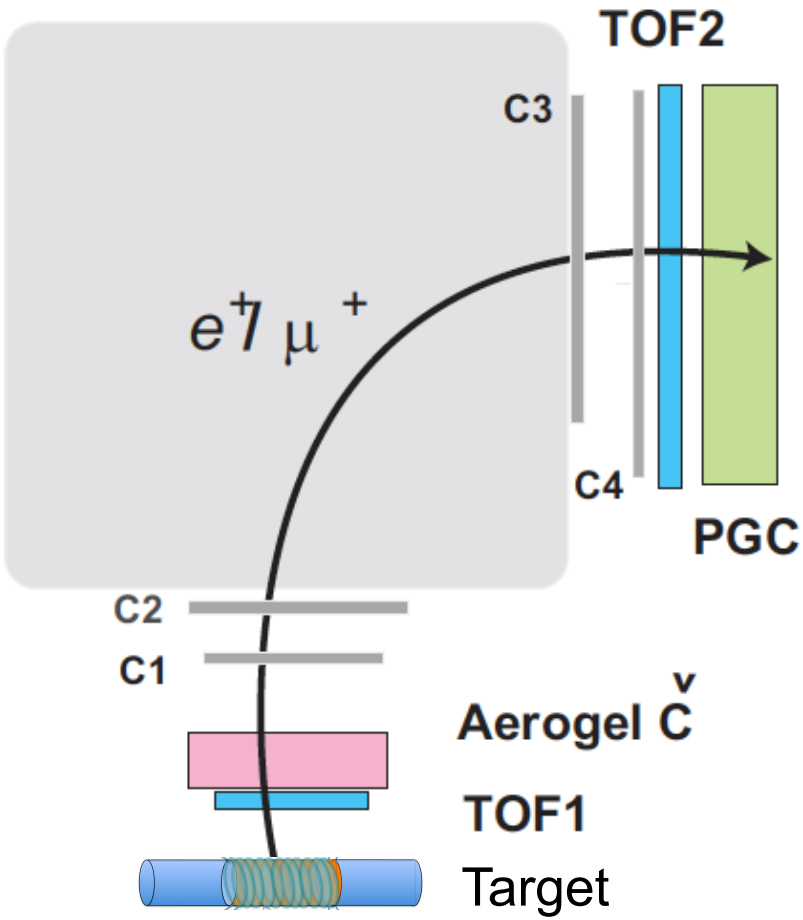
PID
- TOF1,2; TTC
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

Gamma ray
- CsI(Tl)

μ^+/e^+ identification

PID with:

- TOF
- Aerogel Č
- Lead glass

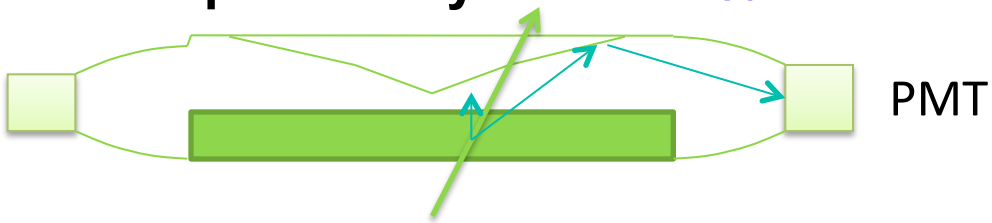


TOF

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%



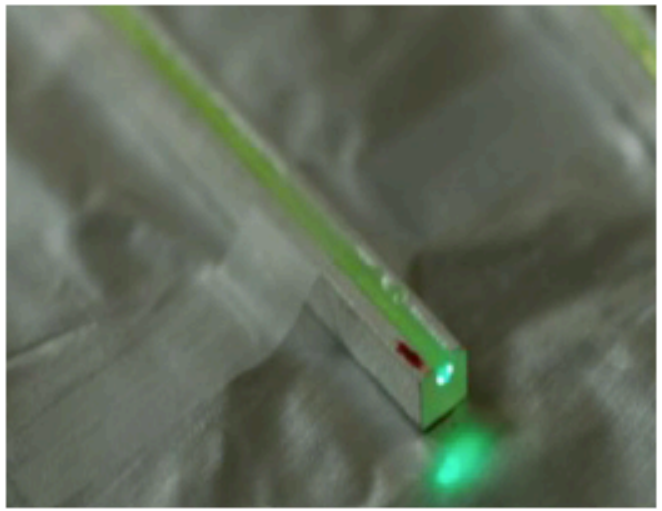
Lead glass (PGC)

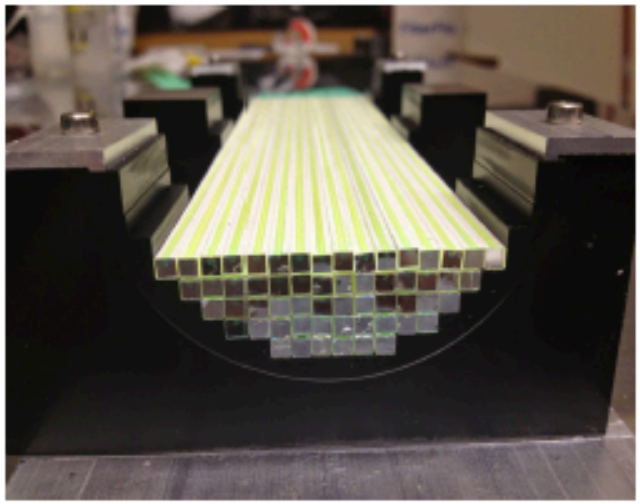
Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

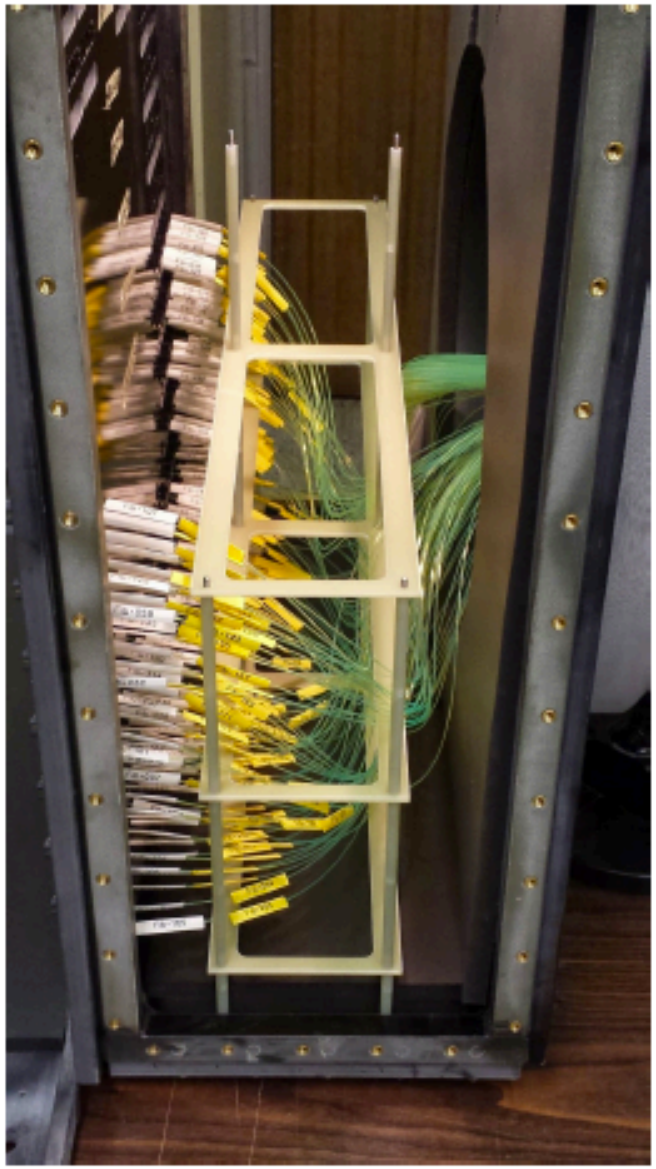
$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

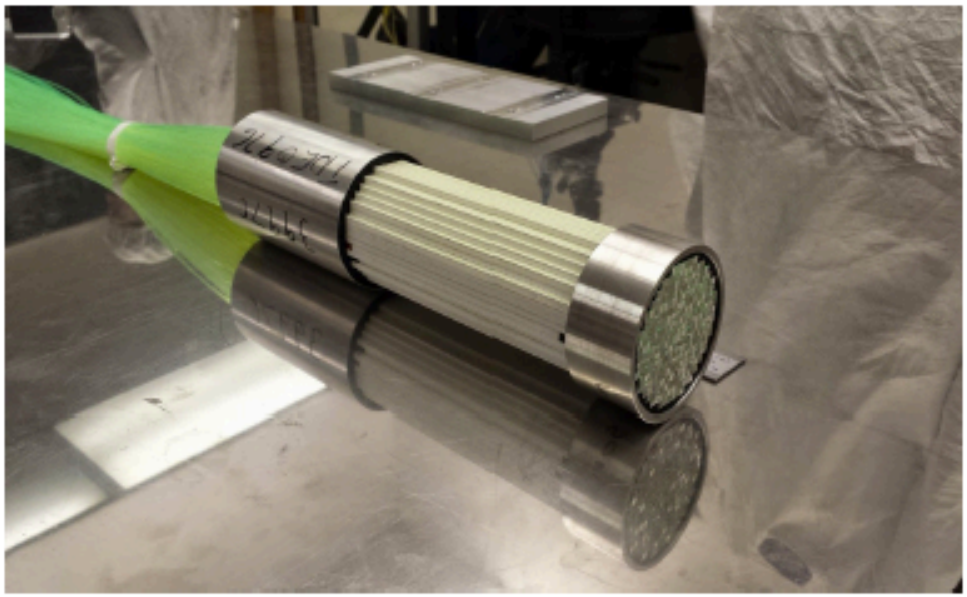
Scintillating-fiber kaon stopping target

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



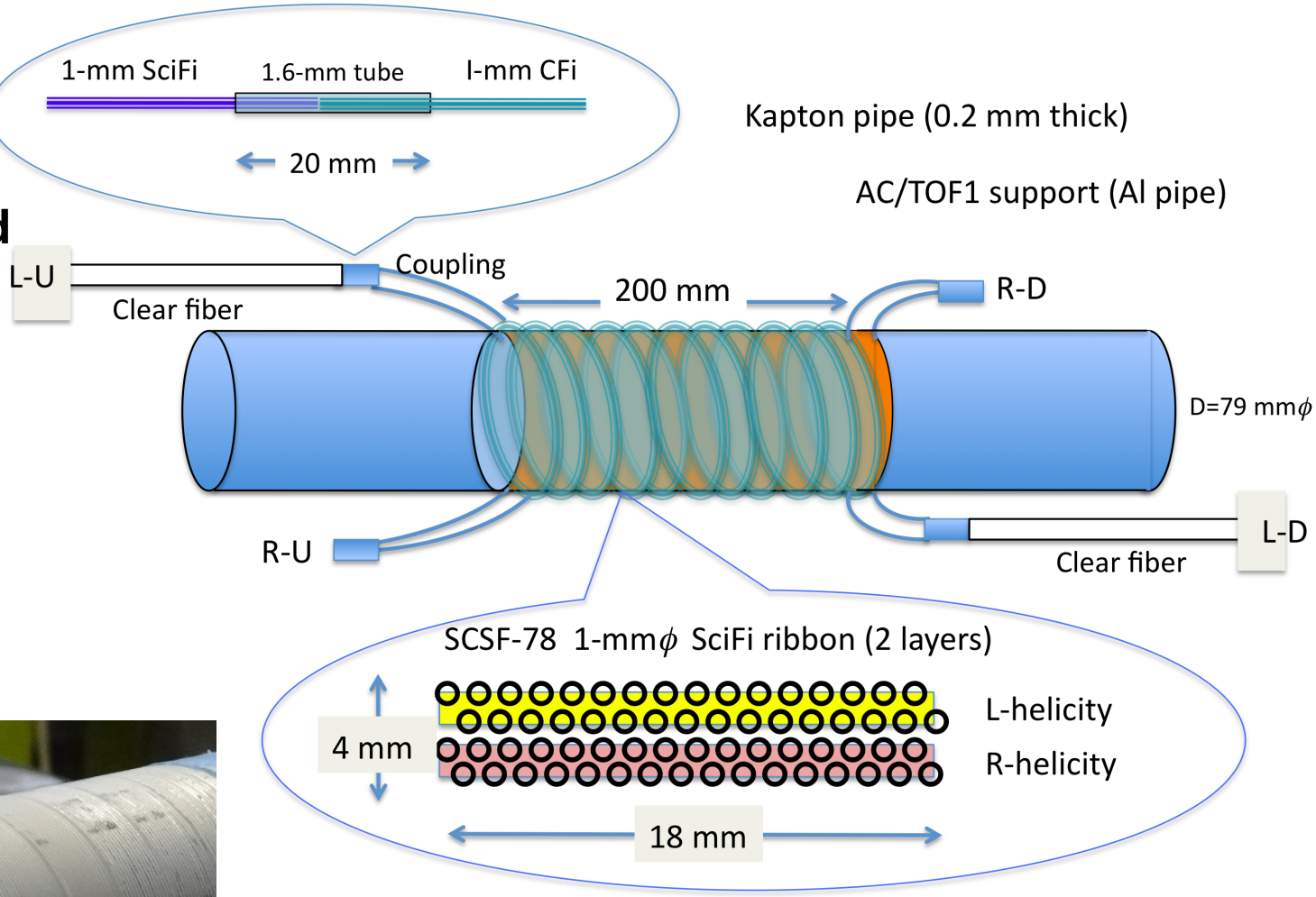


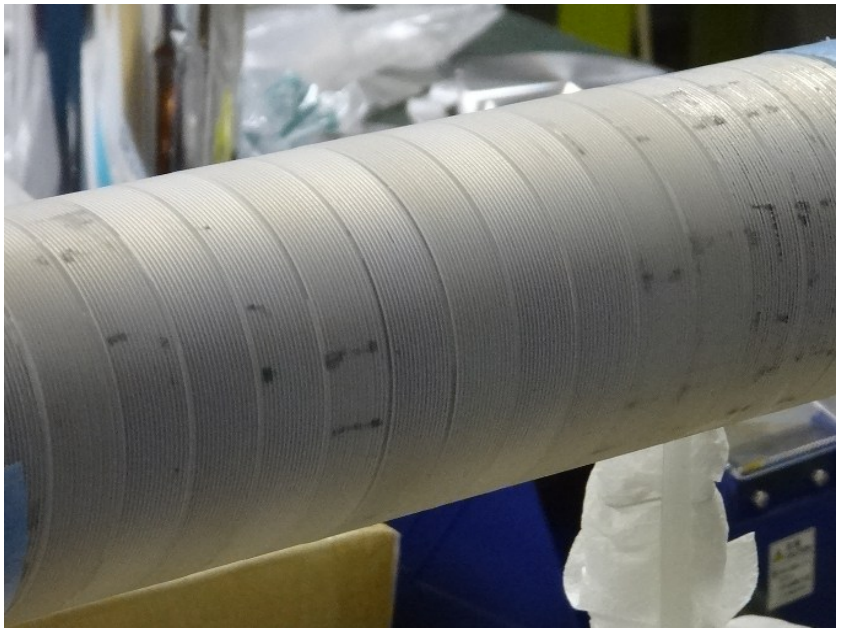


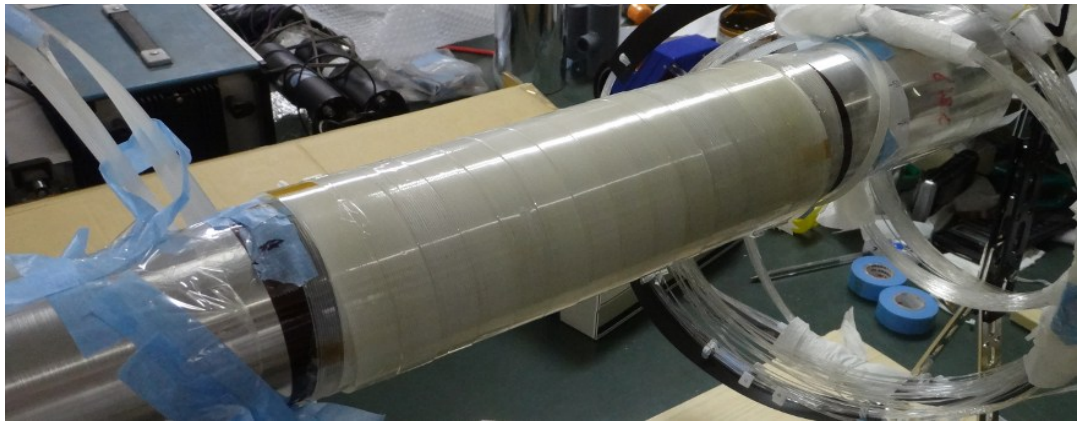


Spiraling fiber tracker (SFT)

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

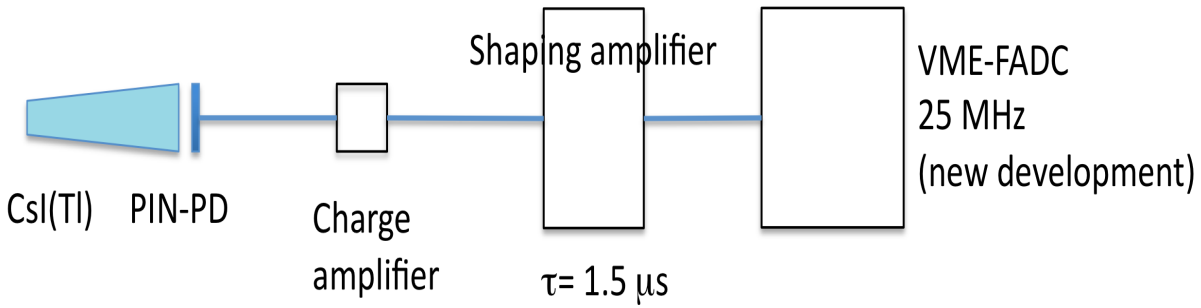


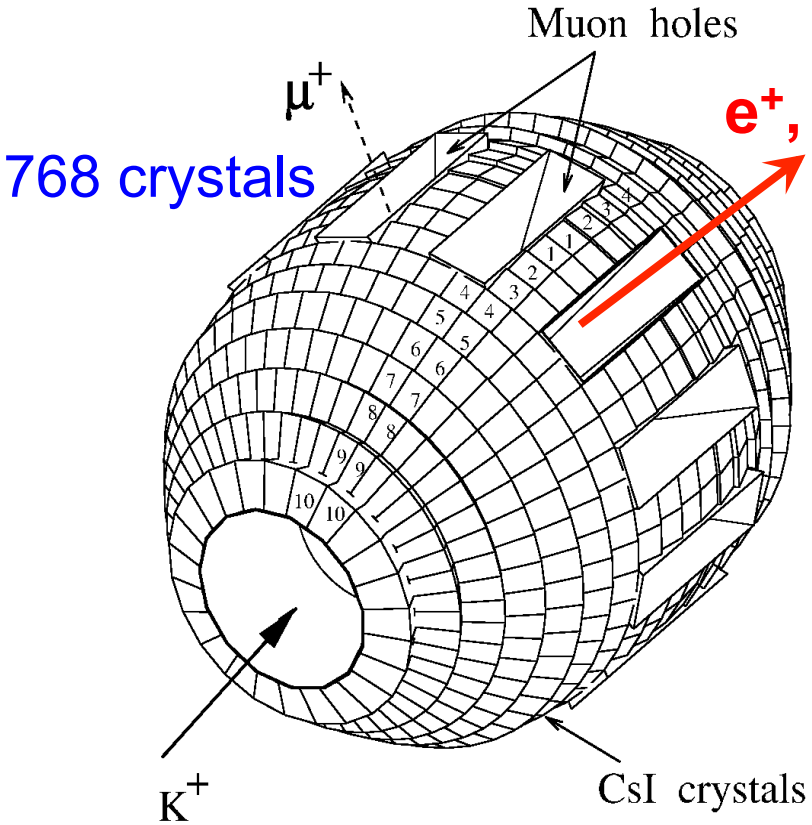




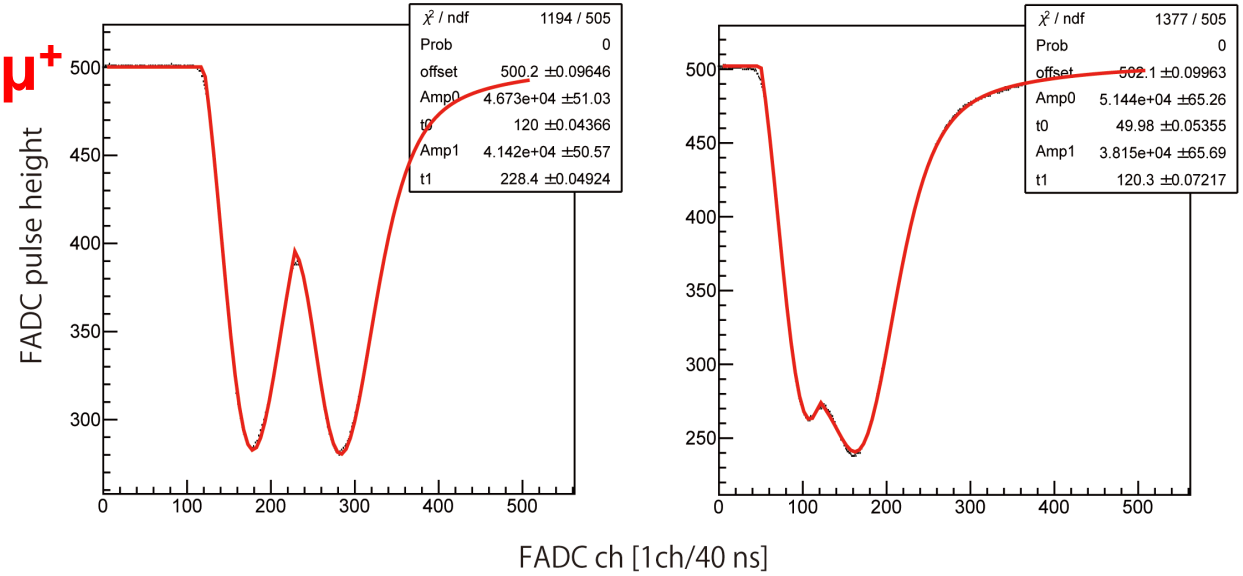
CsI(Tl) calorimeter

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





Typical pileup events

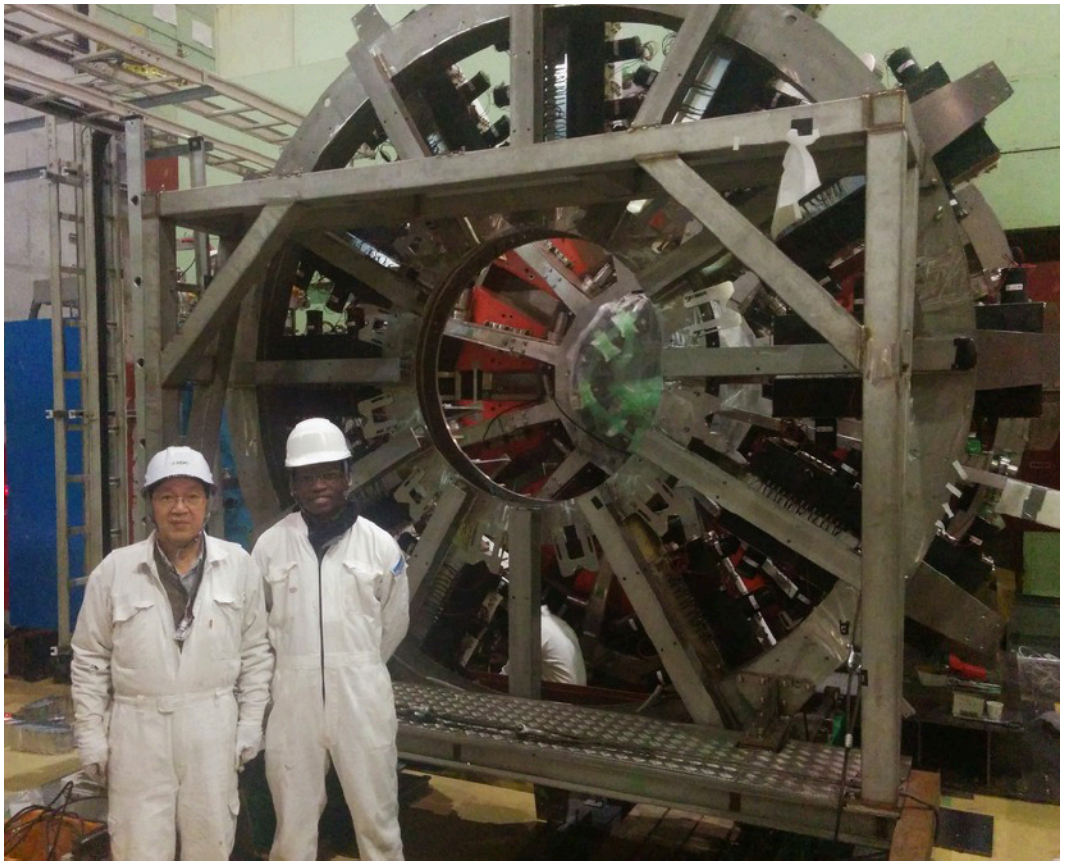


- *possible to separate with FADC*
- *has been implemented successfully*

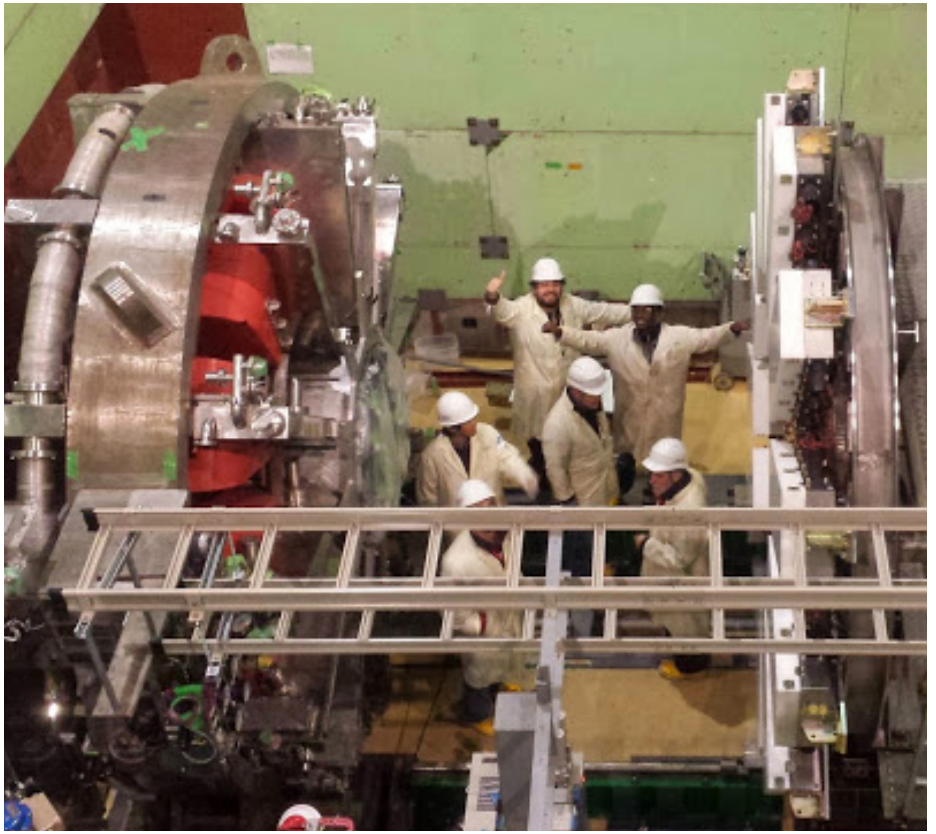
Detection of photons from *$K^+ \rightarrow \mu^+(e^+)\, \nu\, \gamma$ from IB+SD*
Detection of *e^+, e^- from A' decay*

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



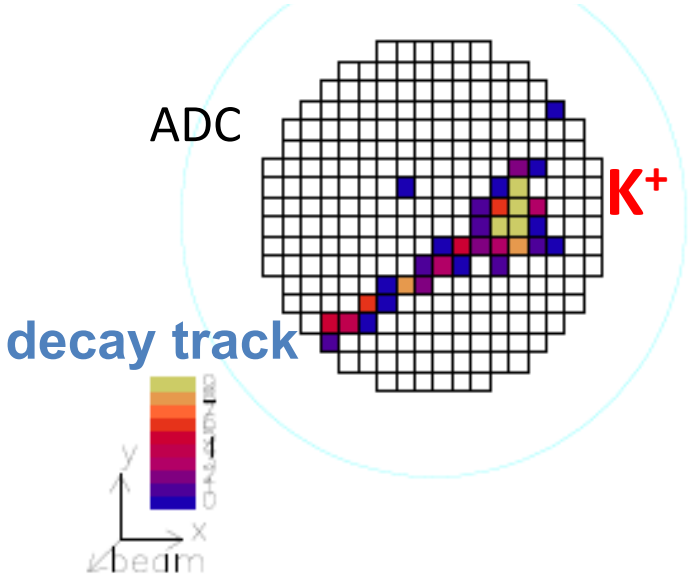
Bishoy Dongwi (Hampton U.)

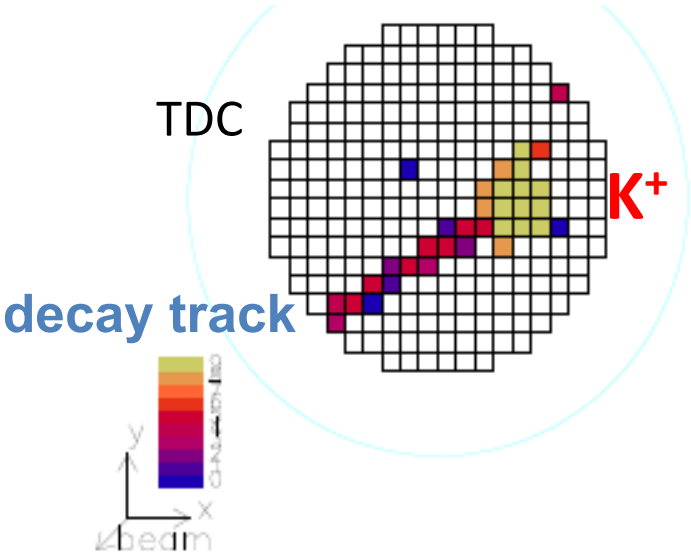


- Commissioning of TGT+TOF1+SFT with cosmic rays
- Check-out of all detectors with beam
- Commissioning of toroidal magnet including cryogenics

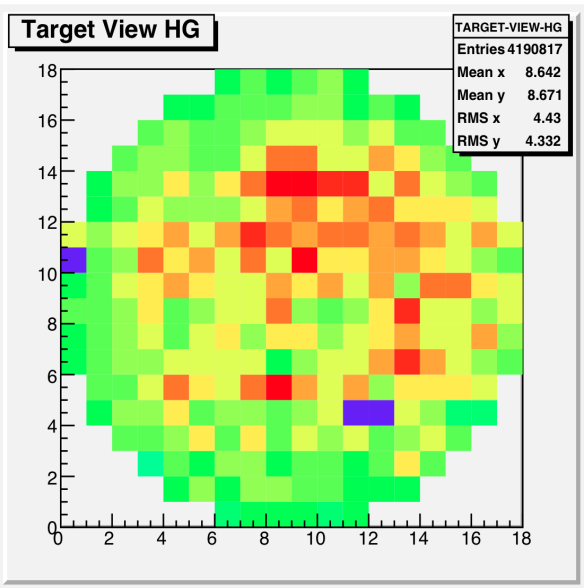
Target performance

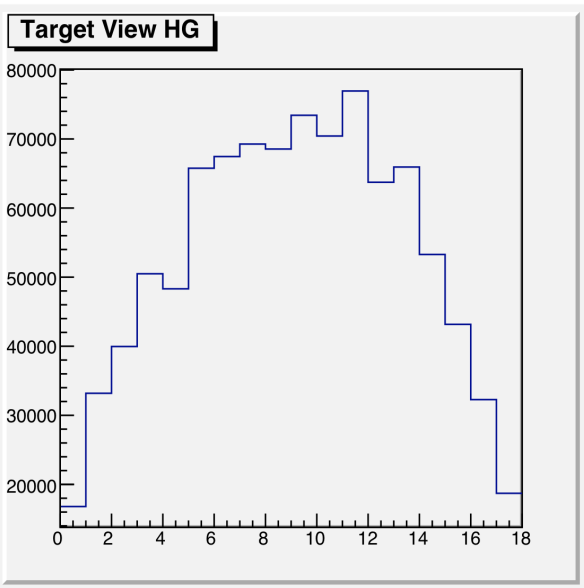
Kaon stop and track of decay particle

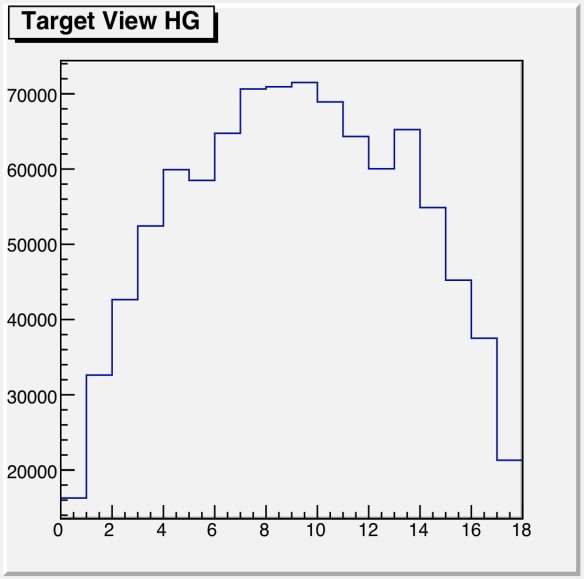




Kaon beam profile



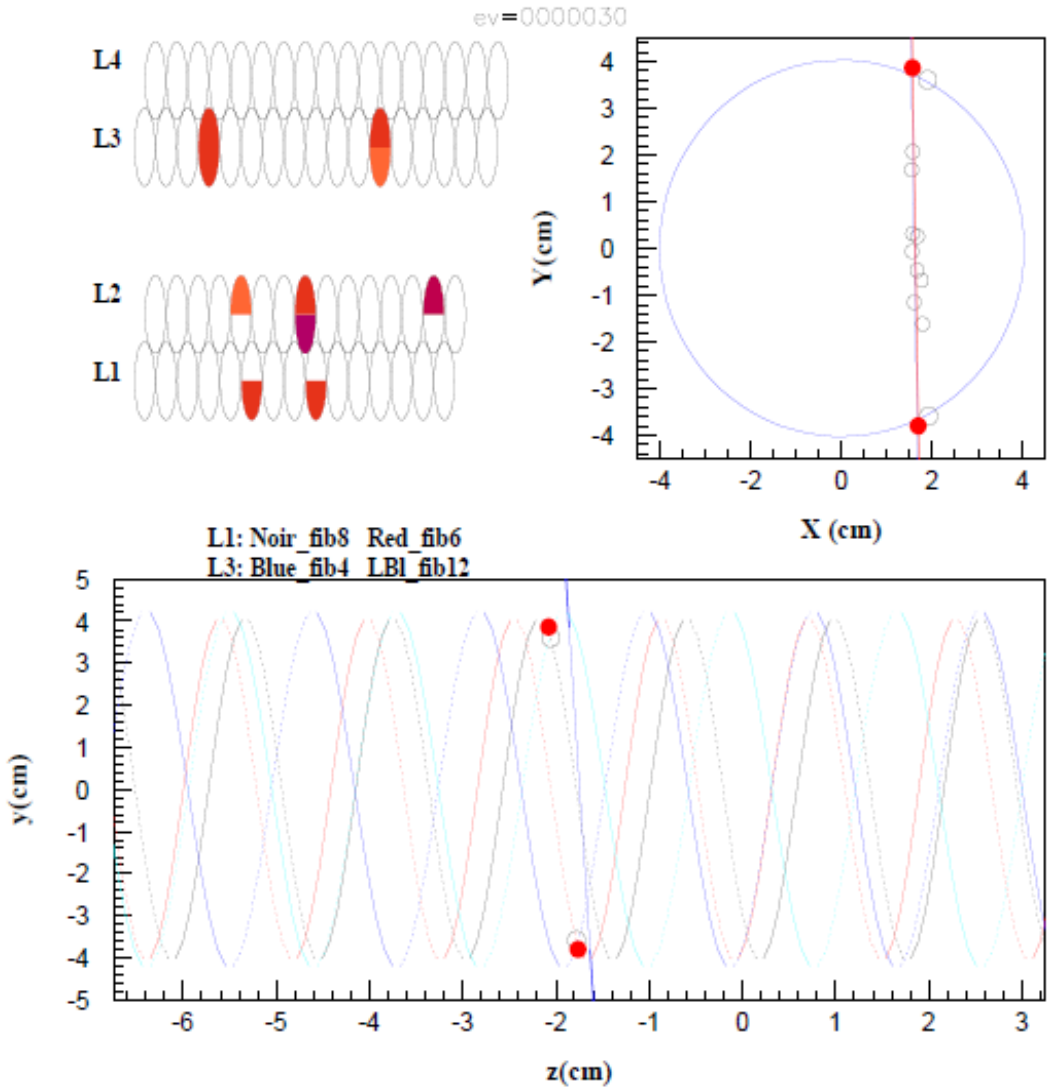


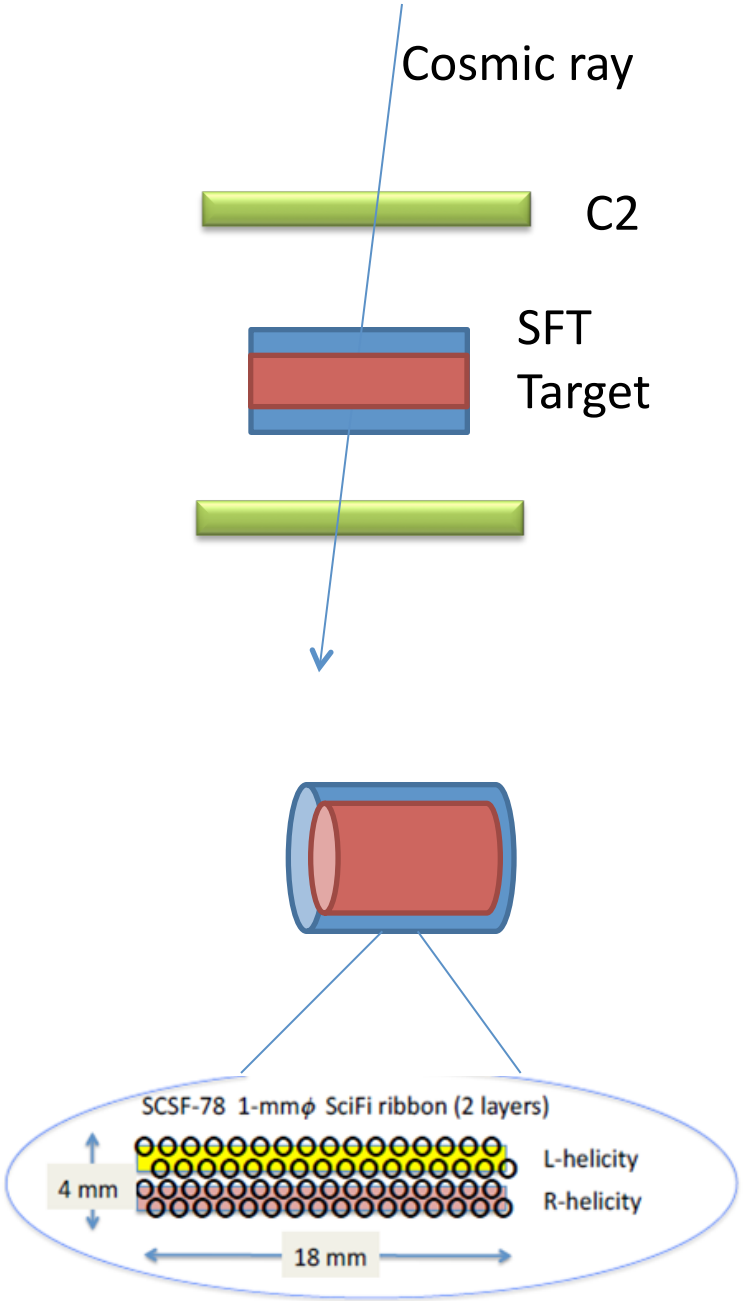


June 2015 data

Preliminary

Track identification by central detector

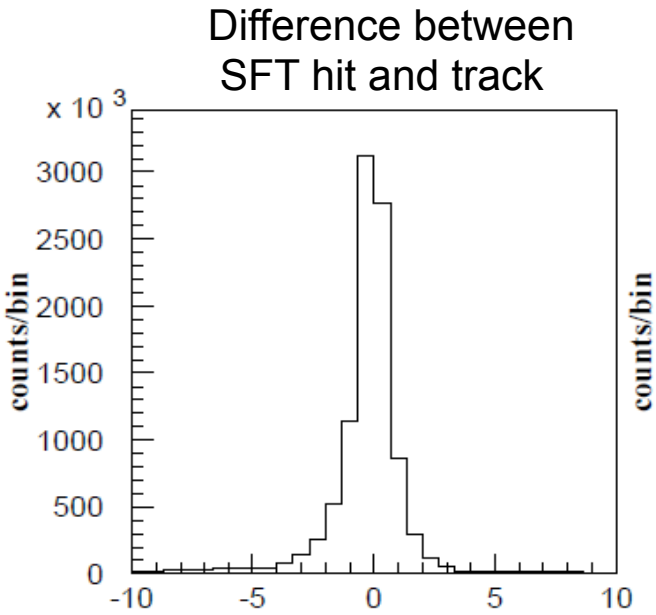


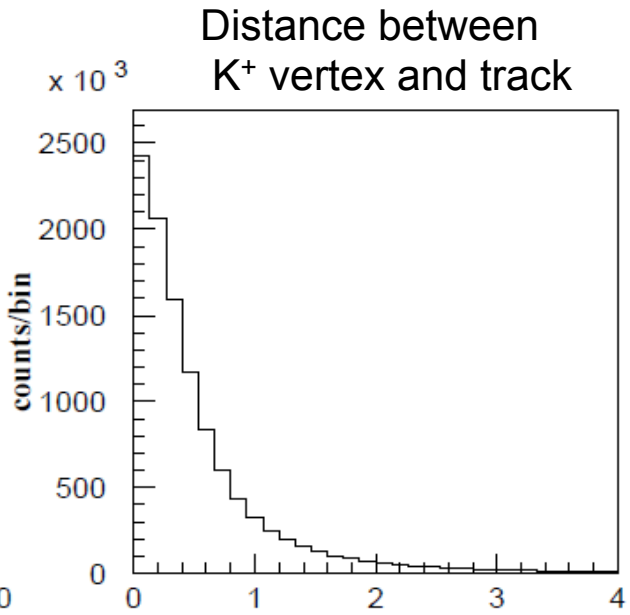


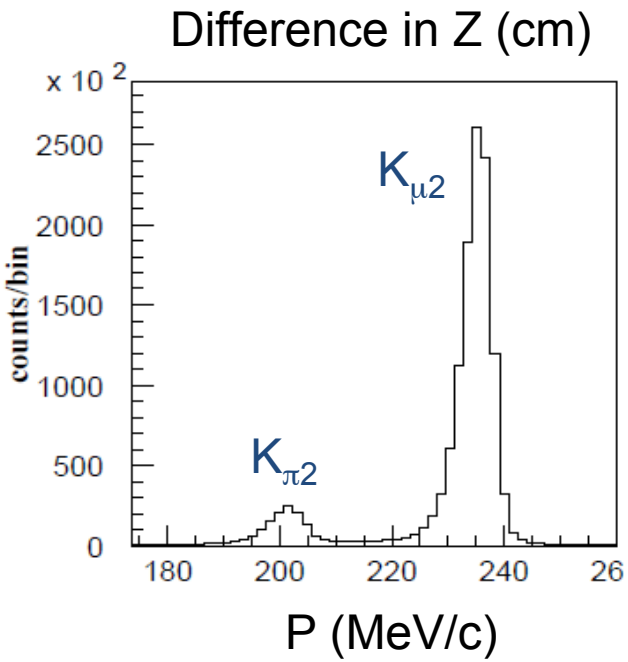
SFT+Target consistency established with cosmic rays

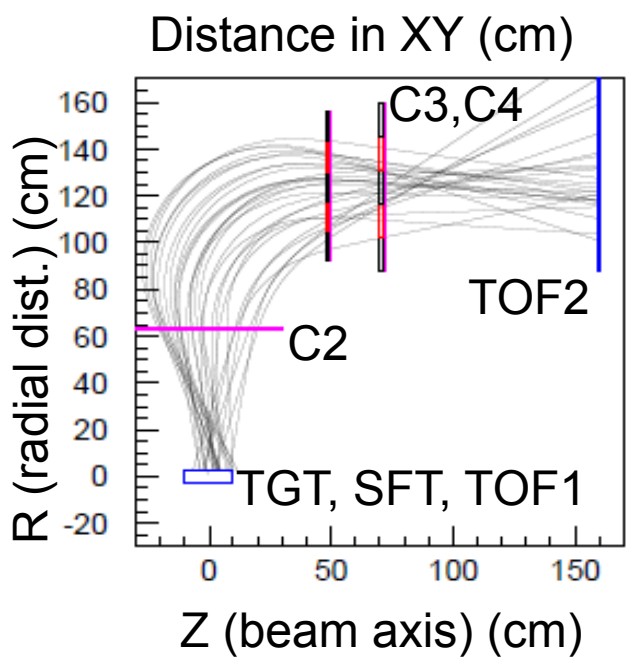
Momentum determination

- **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**





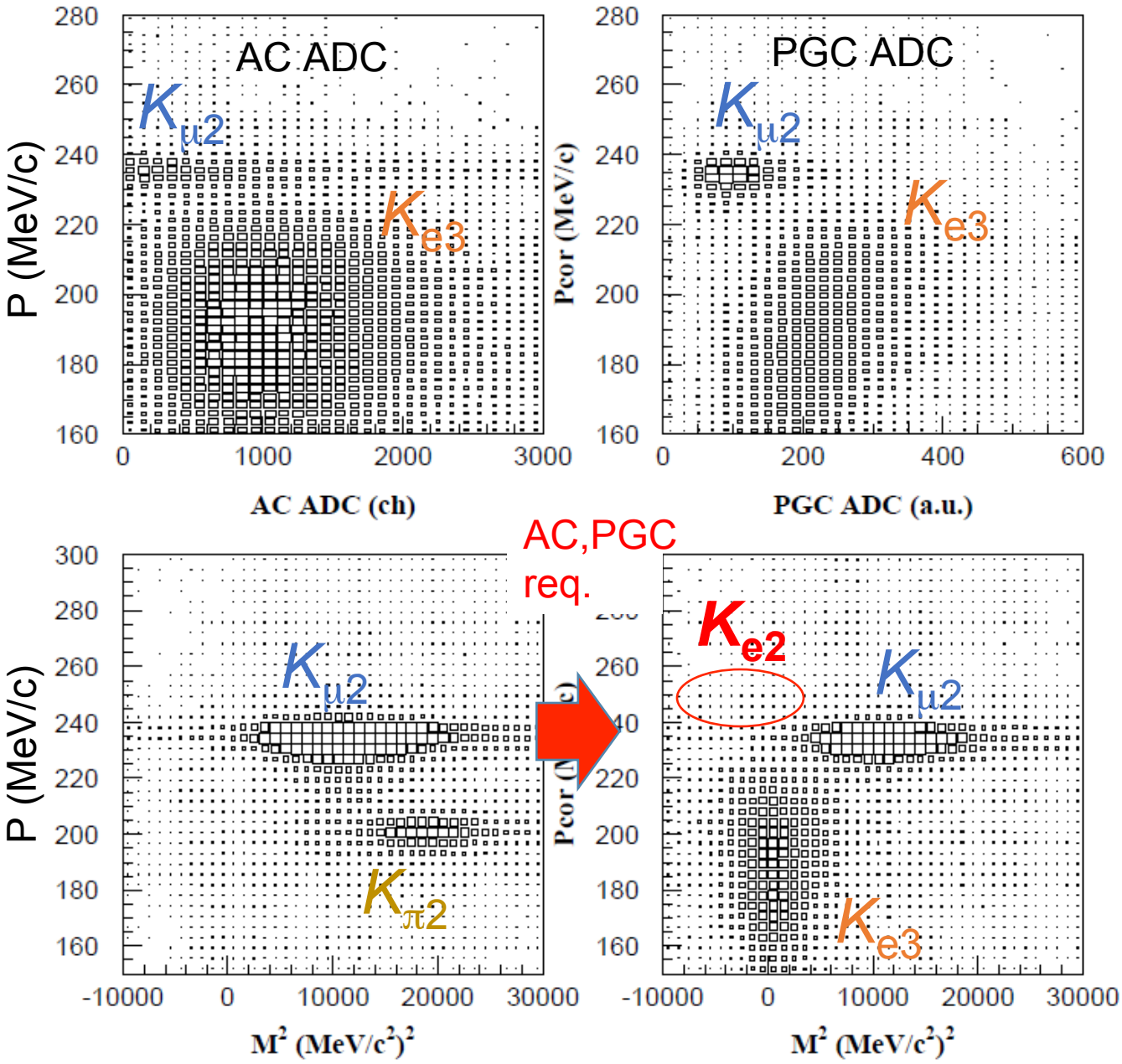




Very preliminary

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

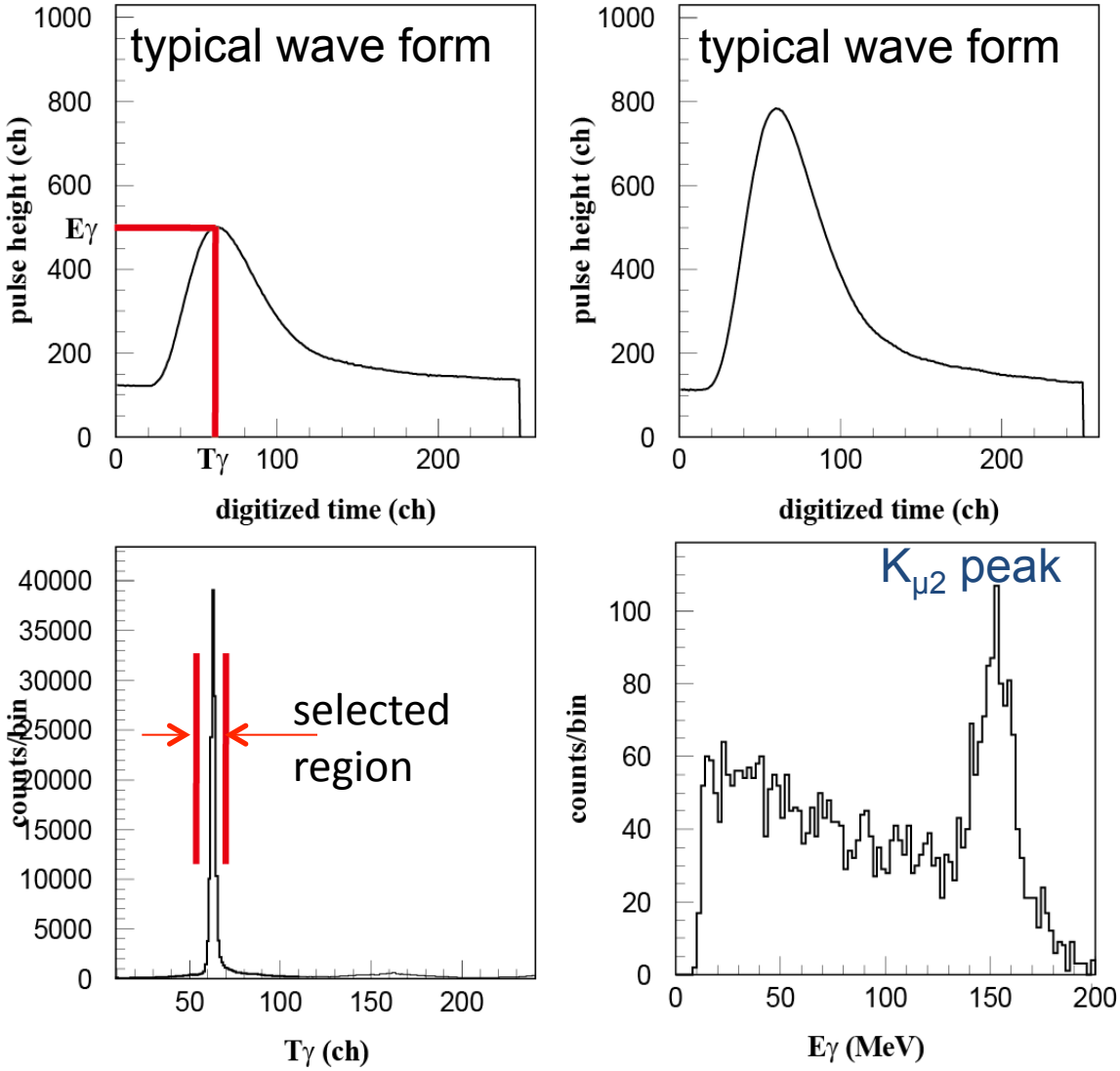


Very preliminary

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

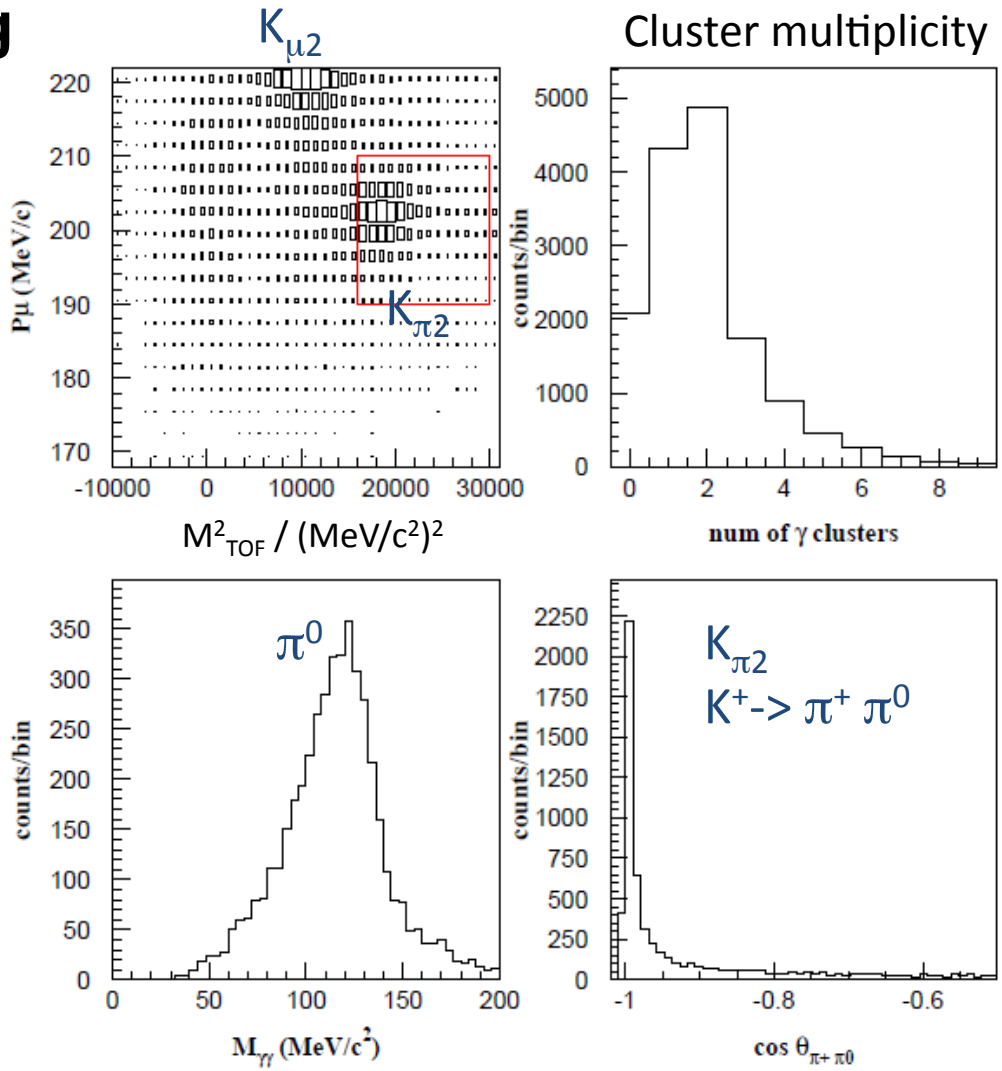


Calibration data from early June

Combining spectrometer + calorimeter

Very preliminary

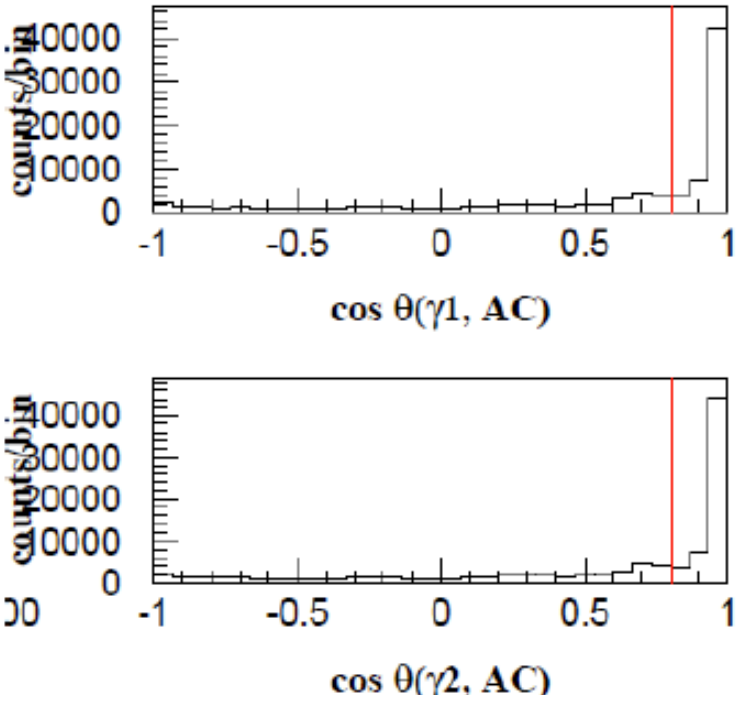
- **$K_{\pi 2}$ events selected by analyzing momentum and TOF (M^2)**
- **π^0 invariant mass reconstructed by selecting two-cluster events**
- **Large π^+ / π^0 opening angle obtained**
- **Confirmed that the total E36 system works correctly and is consistent with E246**



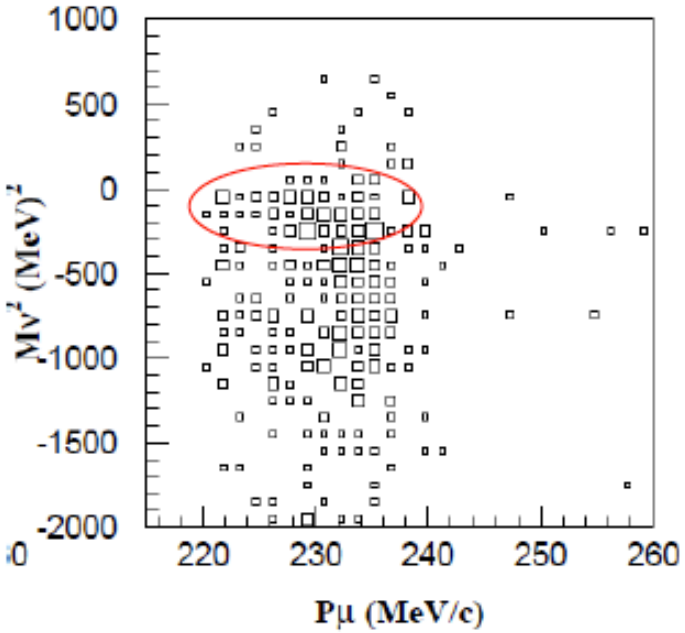
Search for light boson events

- 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: $\pi^0 \rightarrow \gamma A'$, using $K^+ \rightarrow \pi^+\pi^0$ (21.13%) and $K^+ \rightarrow \mu^+ \nu \pi^0$ (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 backgrounds are $K^+ \rightarrow \pi^+ \pi^o$ 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



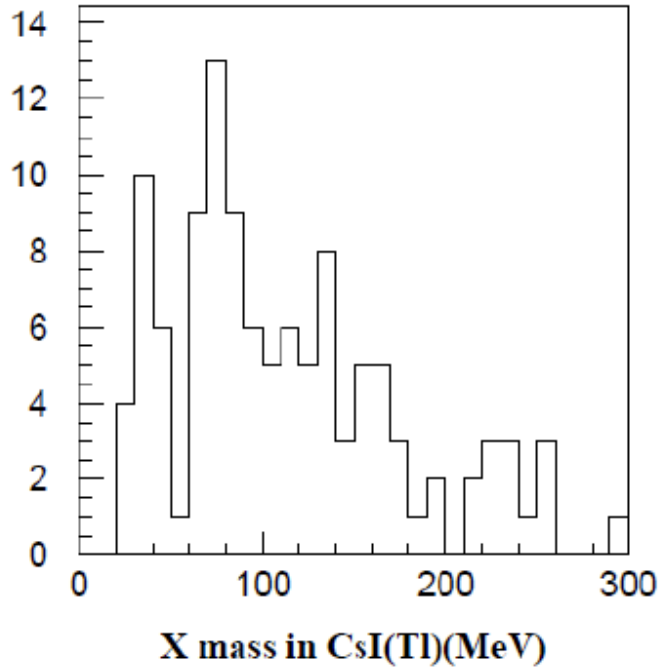
Correlate CsI e^+e^- hits with AC sector



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

Select μ^+ momentum > 205 MeV/c ($K_{\pi 2}$)

Evaluate $A' \rightarrow e^+ e^-$ invariant mass



TREK (E36/E06) collaboration

~30 collaborators

Spokespeople:
M.K., S. Shimizu

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Rikkyo University
Department of Physics

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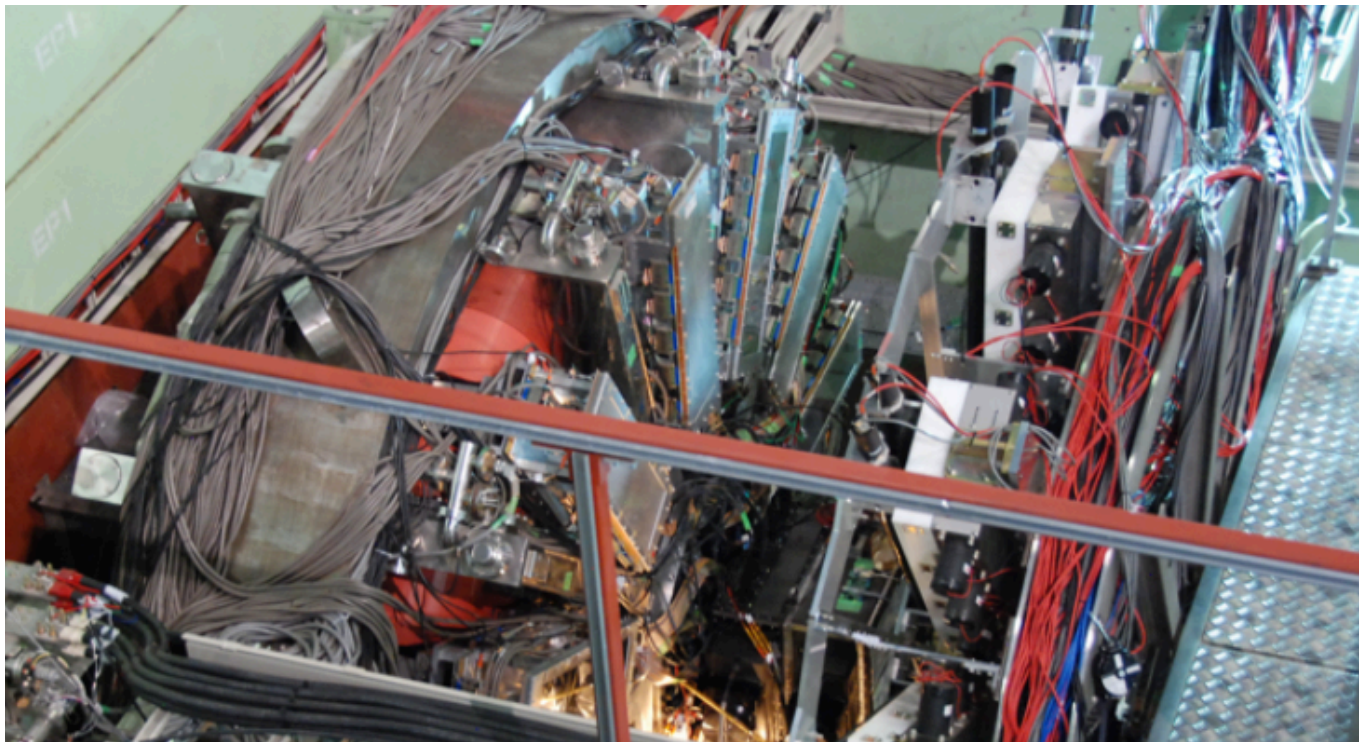
RUSSIA

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

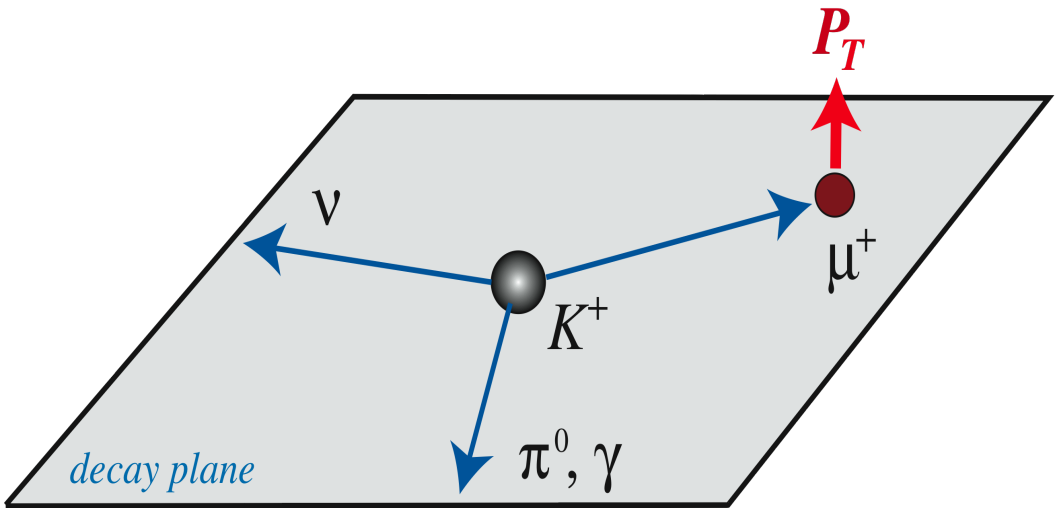
Summary

- **Substantial progress of TREK/E36 @ J-PARC**
- **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 Facility**



Backup

TREK/E06: Transverse muon polarization



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

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

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

$P_T \neq 0 \Rightarrow$ T violation

(CPT theorem) $\Rightarrow$ CP violation

Sakurai 1957

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

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

TREK/E06 T-violation to be pursued at J-PARC phase 2 – extended Hadron Hall

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)

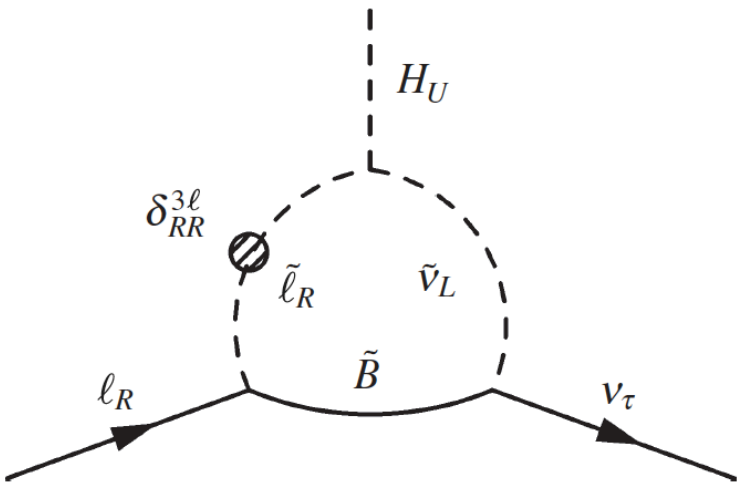


FIG. 1. Contribution to the effective $\bar{\nu}_\tau \ell_R H^+$ coupling.

- **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 $B_u \to \tau\nu$
  - $|\Delta R_K/R_K| \sim O(10^{-3})$

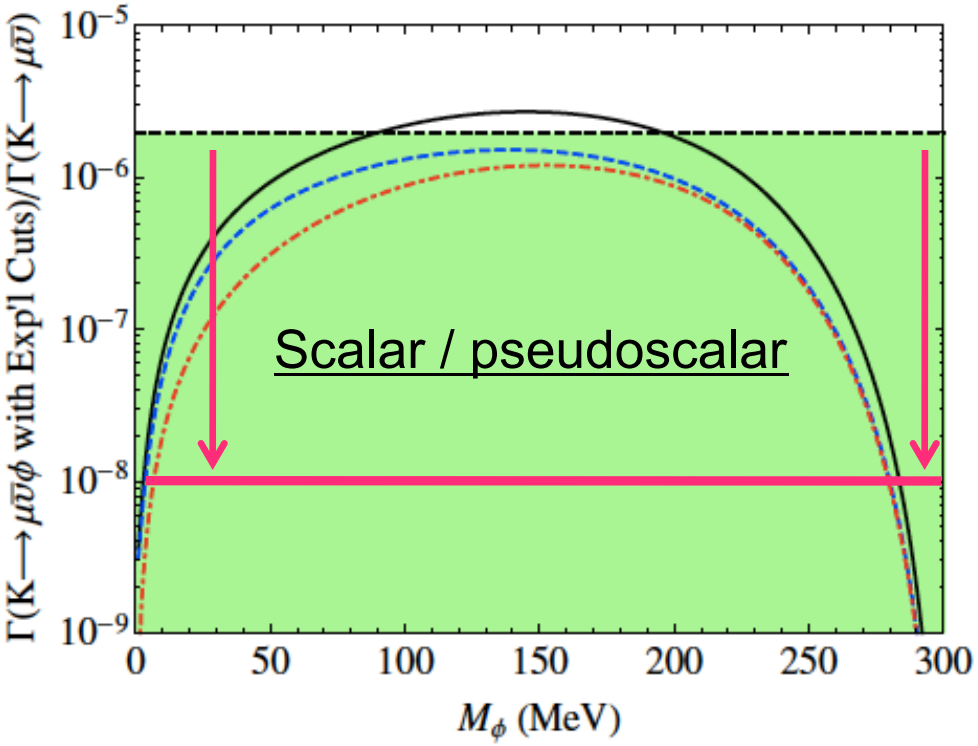
- **Neutrino mixing**

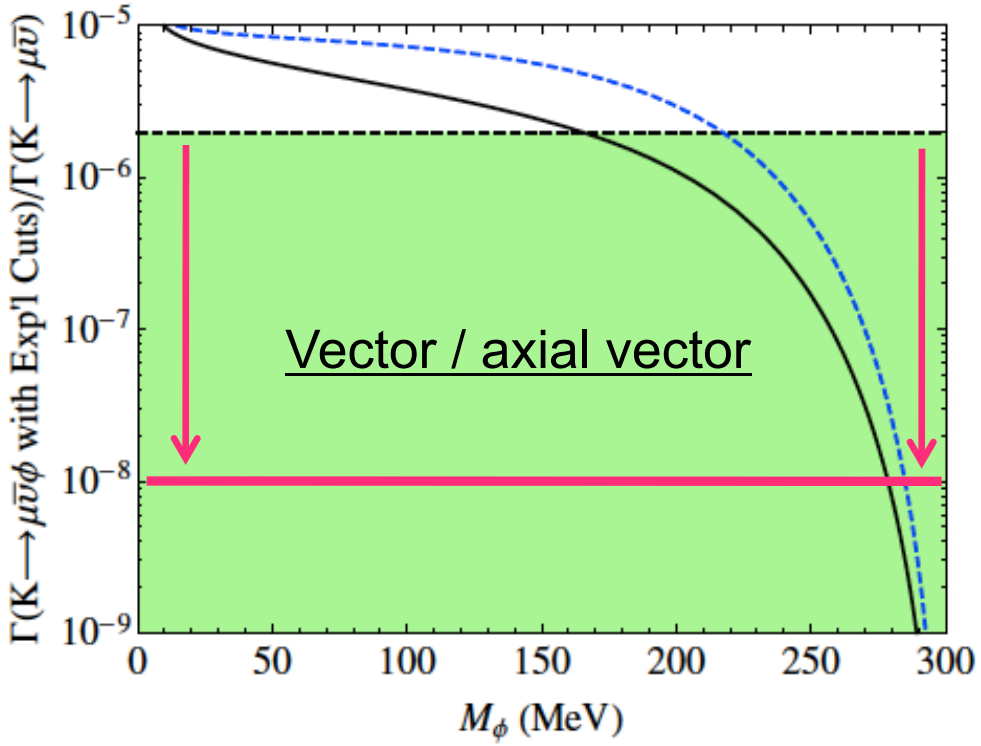
R_K constrains neutrino mixing parameters within SM extensions involving

  - 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]

Proton radius and New Physics

C. Carlson and B. Rislow, Phys. Rev. D 86, 035013 (2012); [arXiv1206.3587v2]





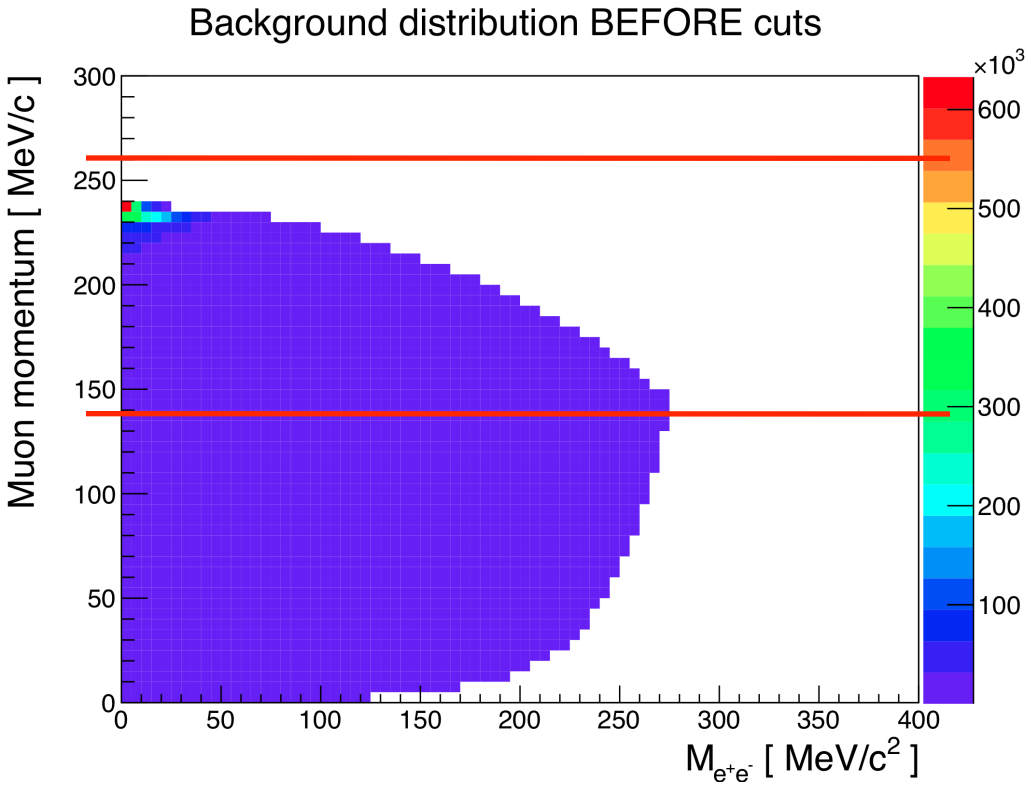
New Physics involving light U(1) bosons can explain proton radius puzzle
Fine tuning, preferred coupling to muon (not electron) – lepton non-universality
Emission of A' as radiative correction to K → μν decay

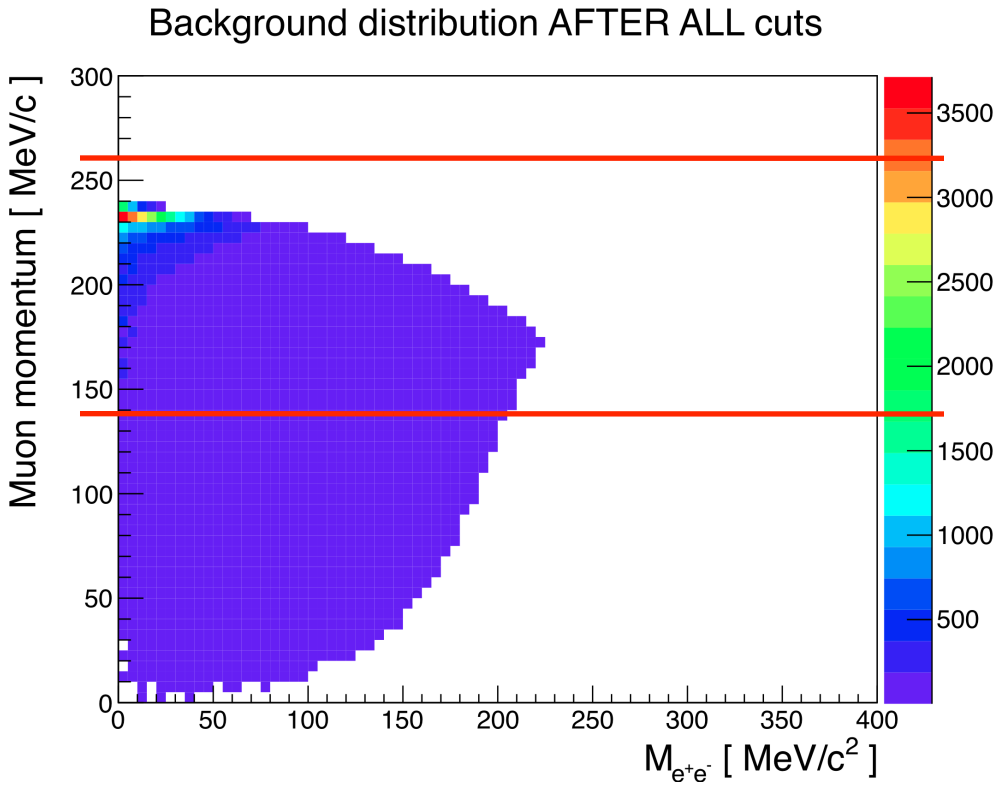
Experimental limit from stopped kaons at Bevatron in 1970's (INVISIBLE only):
C. Pang, R. Hildebrand, G. Cable, and R. Stiening, Phys. Rev. D8, 1989 (1973)

E36 can probe entire allowed range: BR($K^+ \to \mu^+ \nu A'$) ~10^{-8}

Light boson phase space

$$K^+ \rightarrow \mu^+ \nu \; e^+ e^-$$

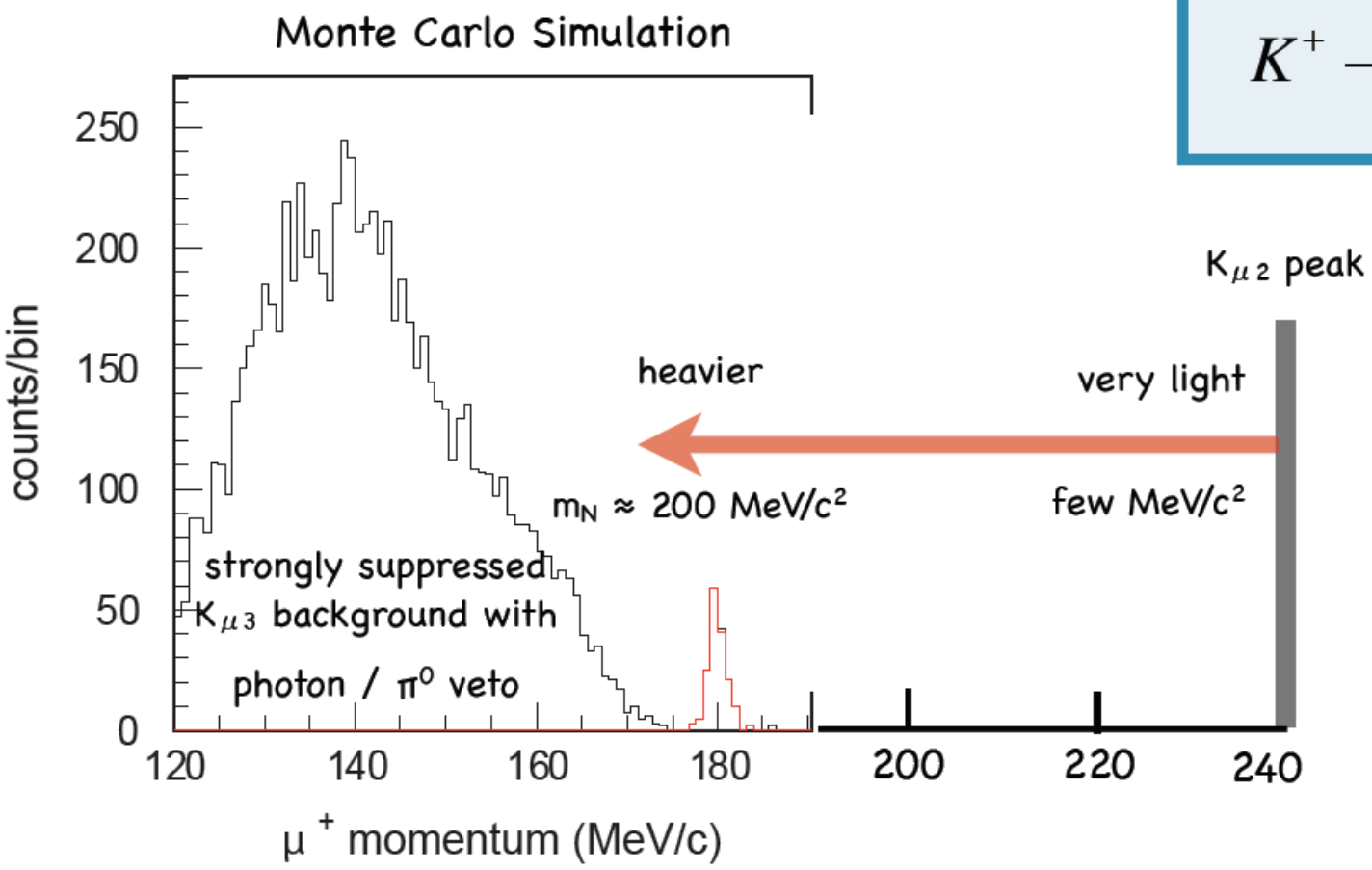




Muon in gap
e+/e- pair in CsI(Tl); e+ || e- in AC
CsI threshold

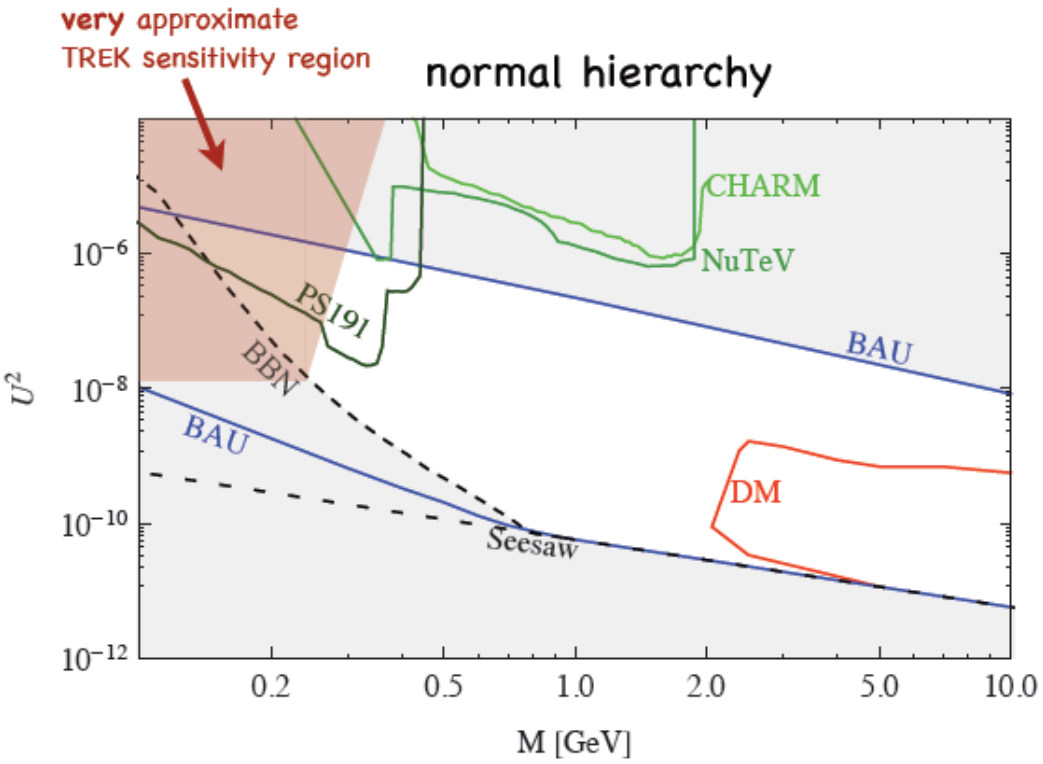
Heavy neutrino search in $K^+ \to \mu^+ N$, $e^+ N$

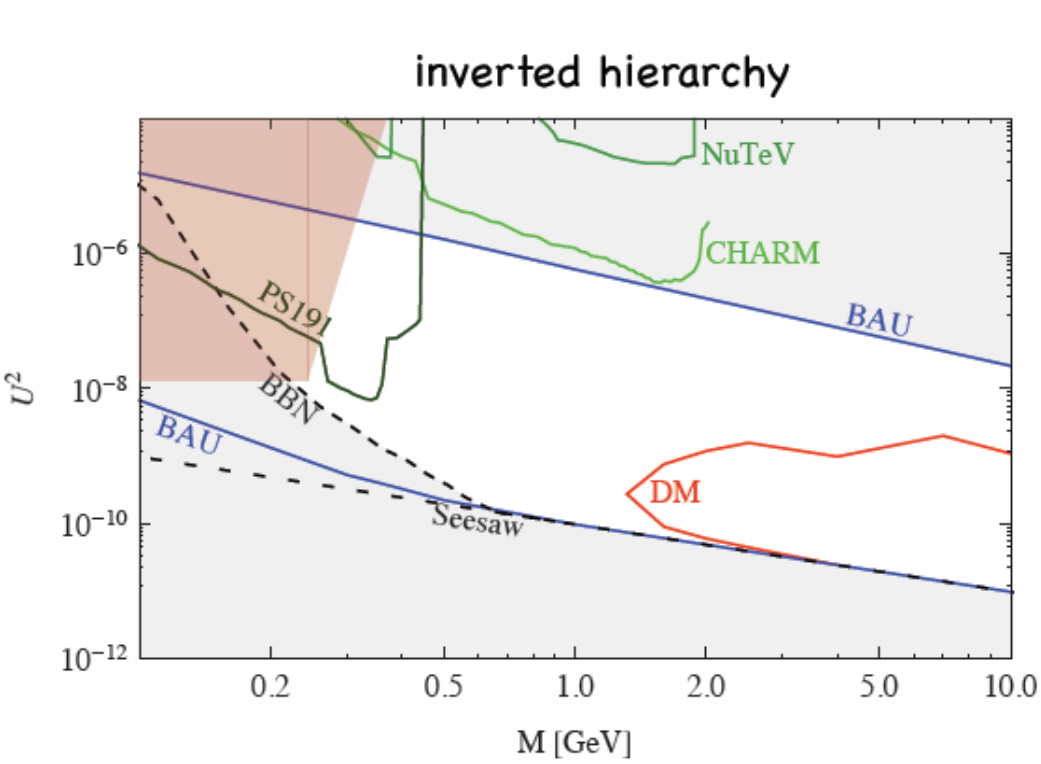
$$K^+ \to \mu^+ N_{2,3}$$



- **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

Hadron Hall Extension