Searches for New Physics with the TREK Detector

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Outline

J-PARC experiment E06, Jun Imazato and Michael Kohl, spokespeople.

E06 is stage 1 approved.

J-PARC experiment E36, Michael Kohl and Suguru Shimizu, spokespeople.

E36 is stage 1 and 2 approved.

http://trek.kek.jp

Aerial view of J-PARC

	The TREK Program - Study of rate Kaon decays		Exp. (K Intensity)
1	Search for T violation in kaon decays	$\pi^0\mu^+\nu_\mu$	E06 (100-270 kW)
2	Search for lepton universality violation in a measurement of the ratio of the K_{e2} and $K_{\mu 2}$ decay widths	$e^+\nu(\gamma)$ $\mu^+\nu(\gamma)$	E36 (30-50 kW)
3	Search for a heavy sterile neutrino	e^+N μ^+N	
4	Search for a light neutral gauge boson	$\pi^+e^+e^-$ $\mu^+\nu e^+e^-$	

The TREK E06/E36 detector will be the upgraded detector of KEK E246

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

KEK E246 experiment:
Observables: μ^+ momentum, π^0 momentum, and μ^+ polarization

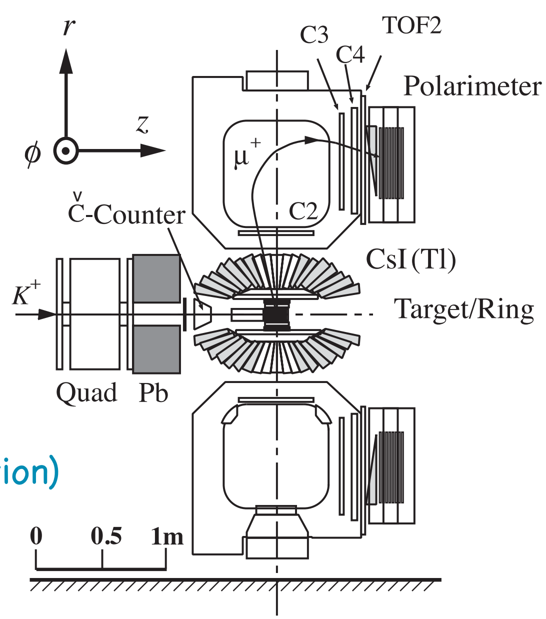
Muon polarimeter
(transverse μ^+ polarization)

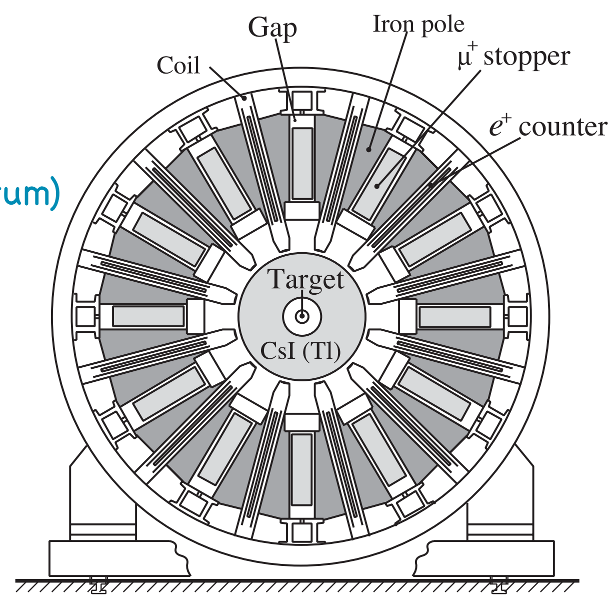
12-Sector Toroidal spectrometer
(charged particle momentum)

CsI(Tl) calorimeter
(π^0 detection, photon momentum)

Active target
(reaction vertex information)

Beam Cherenkov
(K/π separation)

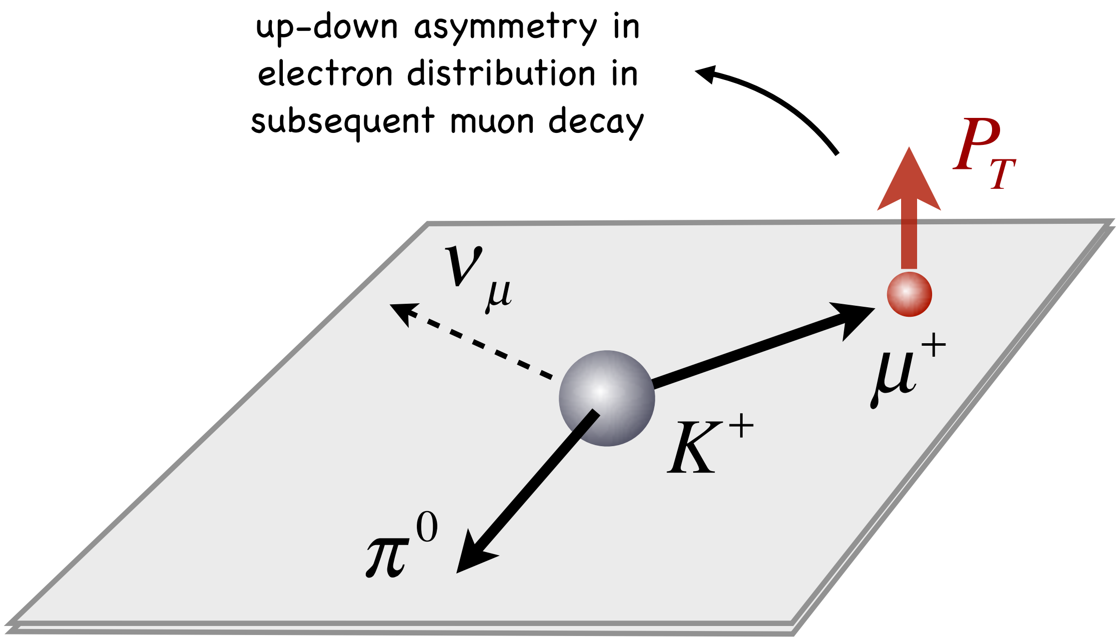




TREK detector: Upgrade of E246 detector for the study of various Kaon decay channels at **J-PARC**.

Figure of E246 setup from M. Abe et al., Phys. Rev. D **73**, 072005 (2006)

T-odd polarization asymmetry in $K^+_{\mu 3}$ decay



K+ decay in its rest frame

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

study of direct CP violation, possibly due to non-standard mechanisms, with the help of T-odd correlation variables

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

Most stringent upper bound set by KEK-E246 collaboration:

$|P_T| < 5 \times 10^{-3}$ at 90% C.L.

M. Abe et al., Phys. Rev. Lett. **83**, 4253 (1999); M. Abe et al., Phys. Rev. Lett. **93**, 131601 (2004); M. Abe et al., Phys. Rev. D **73**, 072005 (2006)

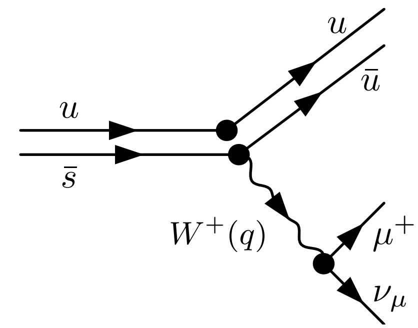
P_T is sensitive to new physics

Projected J-PARC E06:
$|P_T| < 2 \times 10^{-4}$ at 90% C.L.

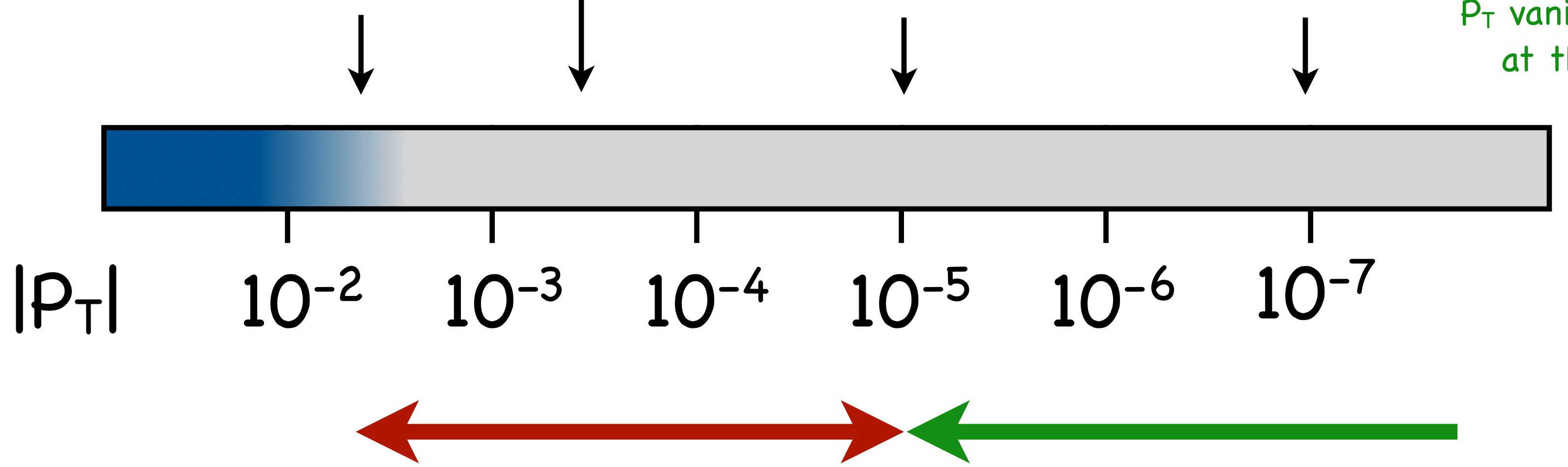
KEK-E246:
$|P_T| < 5 \times 10^{-3}$ at 90% C.L.

S.M.
incl. FSI

S.M.



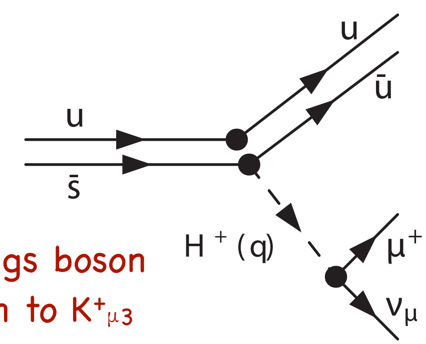
P_T vanishes in the SM
at the tree-level



potential for physics beyond the standard model

- Multi-Higgs,
- SUSY with squarks mixing,
- SUSY with R-parity breaking,
- Leptoquark model

SM background



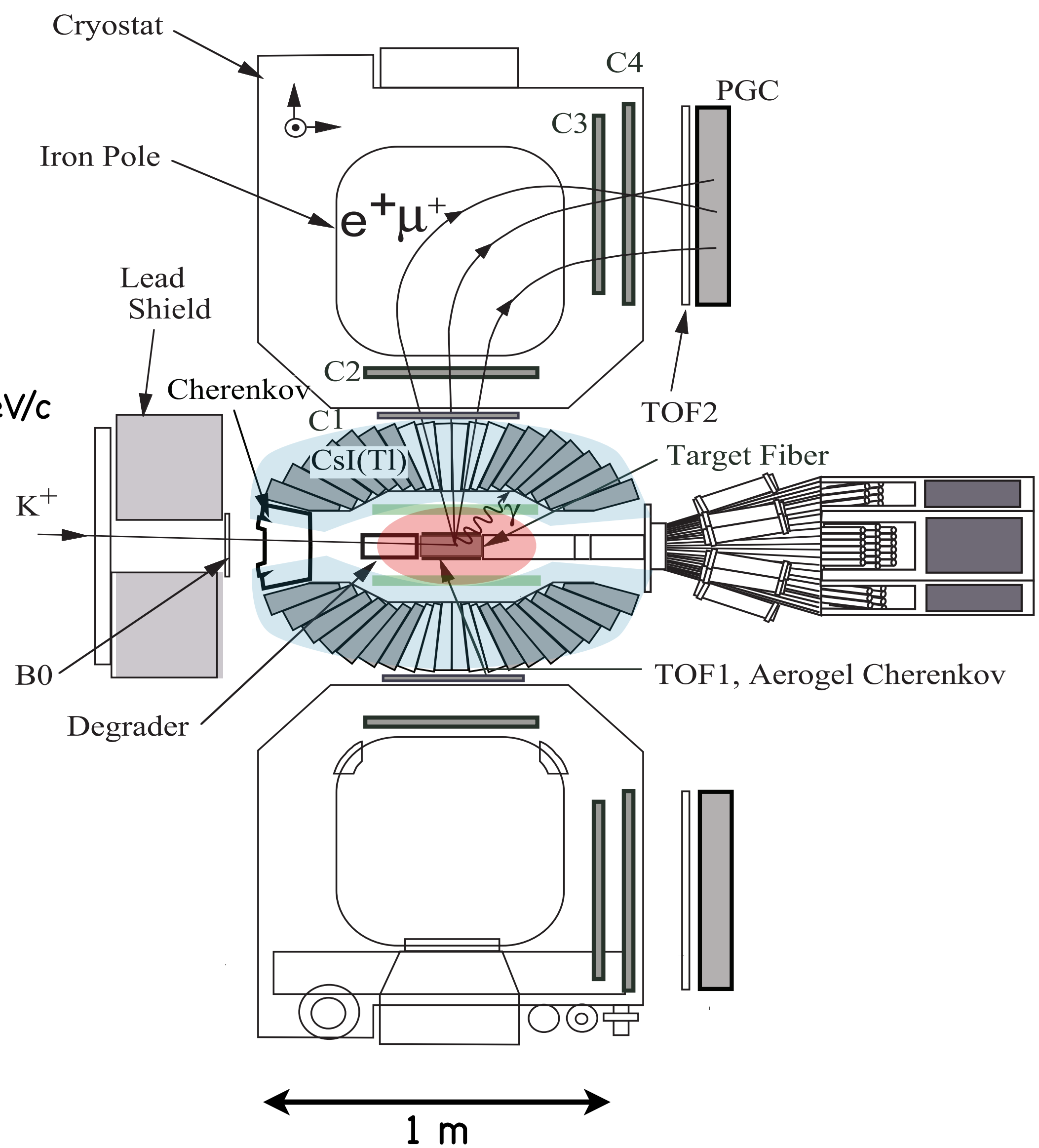
Charged Higgs boson
contribution to $K^{+}_{\mu 3}$

G. López Castro, L. López-Lozano and A. Rosado, Phys. Rev. D **80**, 096004 (2009)

TREK sub-detector upgrade for E36

J-PARC
K1.1BR

800 MeV/c



Fiber target

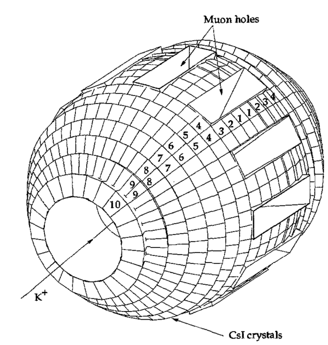
Finer segmentation of target scintillating fibers. Readout: MPPC (SiPMT) via wavelength shifting fibers.

Spiraling Fiber Tracker (SFT)

Double-layer fibers in 2 helicities wrapped around target bundle for near target vertex reconstruction.

FADC readout of CsI(Tl)

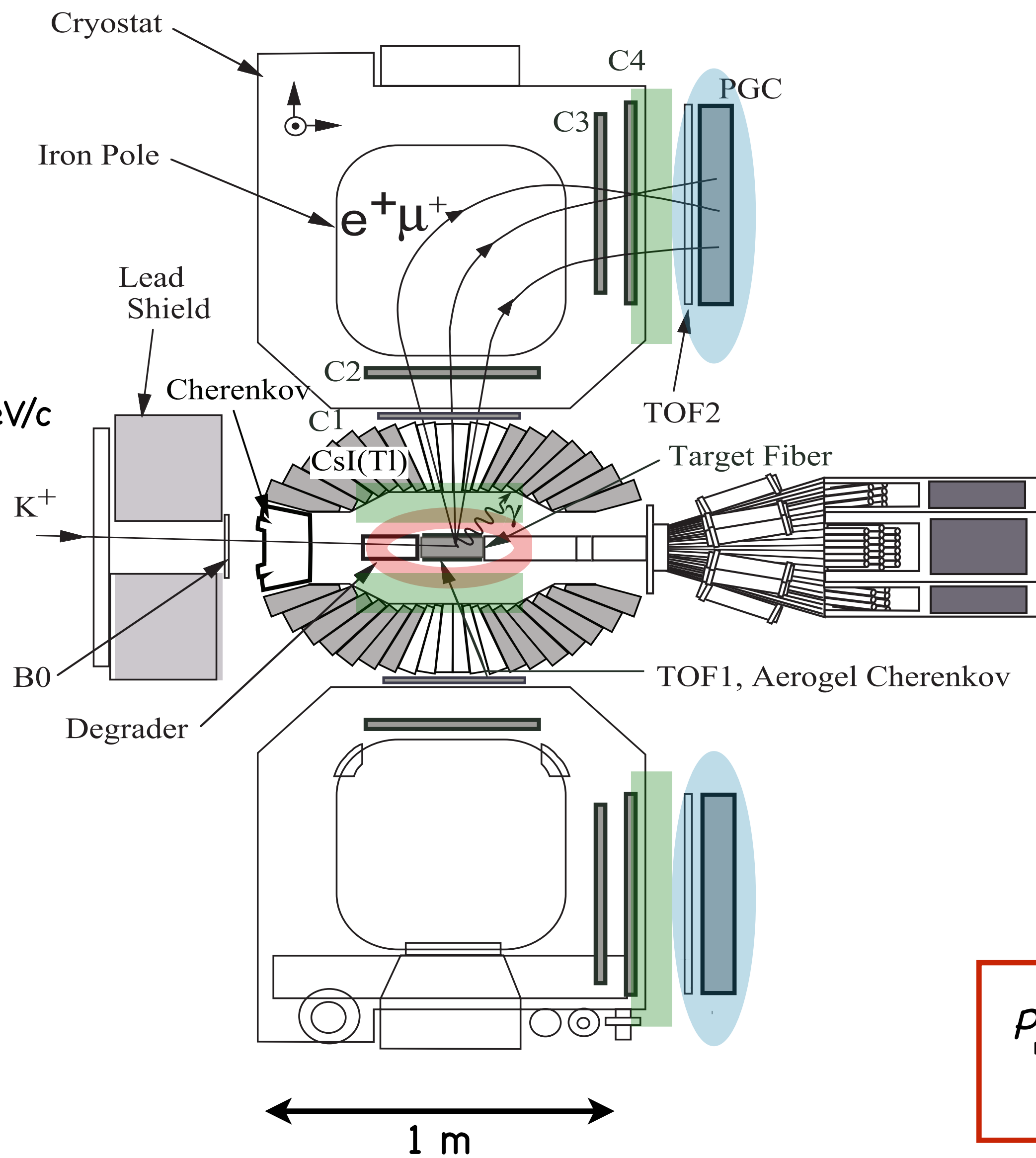
Improved pileup analysis



Improved e/μ particle separation with upgraded TREK detector

J-PARC
K1.1BR

800 MeV/c



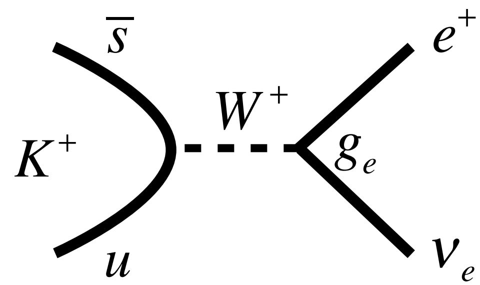
P_{mis} = probability of μ^+ mis-identification as e^+

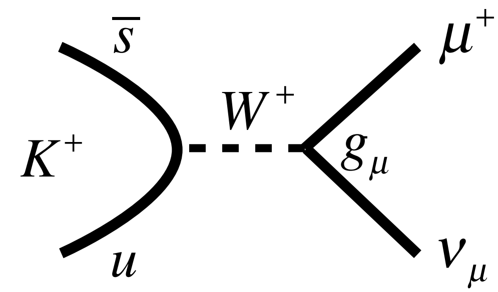
- Time of flight (TOF1, TOF2)
  σ_t < 100 ps,
  P_{mis}(TOF) = 7 x 10^{-4}
- e^+ trigger by Aerogel Cherenkov detector (AC)
  $\varepsilon(e^+)$ > 98%,
  P_{mis}(AC) = 0.03
- Lead glass Cherenkov detector (PGC)
  $\varepsilon(e^+)$ > 98%,
  P_{mis}(PGC) = 0.04

$$P_{mis}(\text{Total}) = P_{mis}(\text{TOF}) \times P_{mis}(\text{AC}) \times P_{mis}(\text{PGC})$$
$$= 8 \times 10^{-7} < 10^{-6}$$

The $K_{\ell 2}$ decay in the Standard Model

$$K^+ \to e^+ \nu(\gamma)$$
$$K^+ \to \mu^+ \nu(\gamma)$$





Decay-width

$$\Gamma(K_{\ell 2}) = g_\ell^2 (G^2/8\pi) f_K^2 m_K m_\ell^2 \left\{1-(m_\ell^2/m_K^2)\right\}^2$$

Decay-width ratio

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

hadronic form factor f_K cancels

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+ \nu_e[\gamma])}{\Gamma(K^+ \to \mu^+ \nu_\mu[\gamma])} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta R_{QED}) = 2.477(1)\times 10^{-5}$$

$g_e / g_\mu = 1$ in the standard model

helicity suppression

radiative correction (incl. internal brems., IB)

R_K as probe of new physics effects

R_K sensitive to lepton flavor violating effects

Large contributions to R_K, $\Delta R/R \approx O(1\%)$, from SUSY lepton-flavor violating contributions

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

Strong constraints to SUSY contributions to R_K from B-meson decays, $\Delta R/R \approx O(0.1\%)$

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

R_K sensitive to neutrino mixing parameters within SM extensions involving a fourth generation of quarks and leptons

R_K constrains fourth generation of quarks and leptons

$$\frac{1-|U_{e4}|^2}{1-|U_{\mu 4}|^2}$$

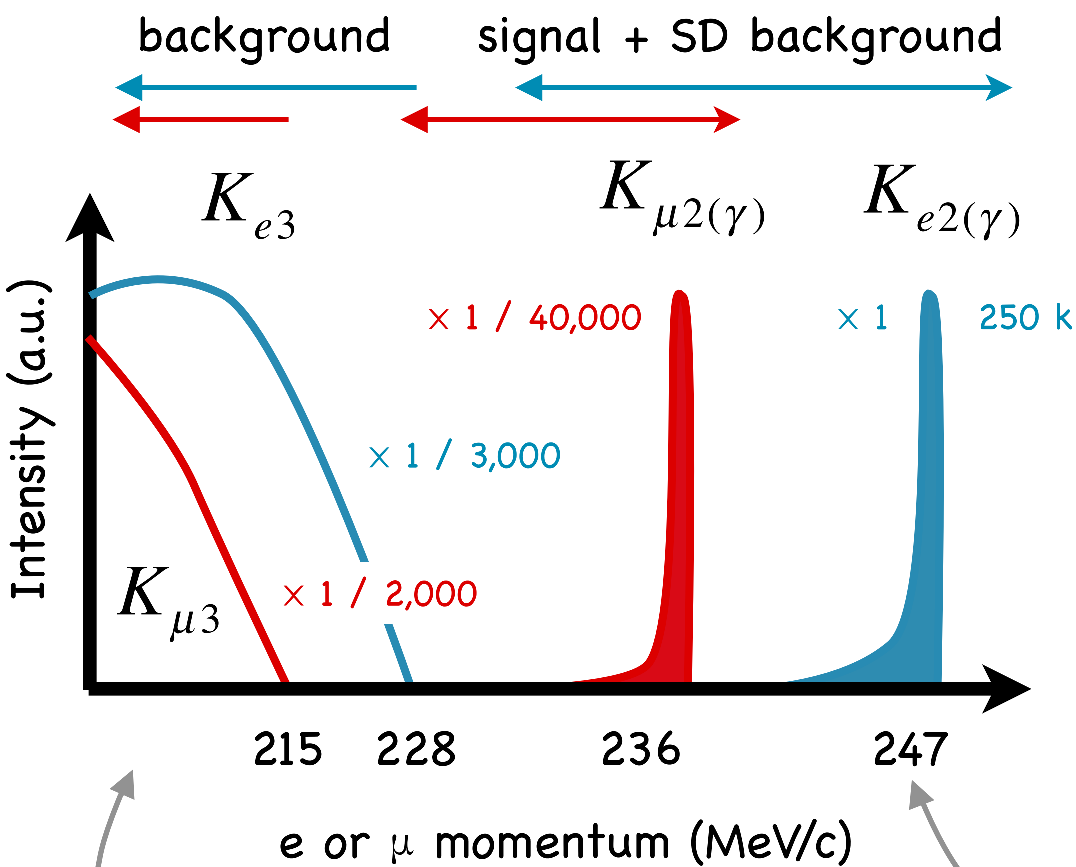
H. Lacker and A. Menzel, JHEP07, 006 (2010)

R_K sensitive to neutrino mixing parameters within SM extensions involving sterile neutrinos

R_K depends on masses, hierarchy, and mixings of new neutrino states

A. Abada, D. Das, A.M. Teixeira, A. Vicente, and C. Weiland, arXiv: 1211.3052v2 (2012)

Determining R_K from $K_{e2(\gamma)}$, $K_{\mu 2(\gamma)}$ yields



$$R_K = \frac{N(\tilde{K}_{e2})}{N(\tilde{K}_{\mu 2})} \frac{\Omega(\tilde{K}_{\mu 2})}{\Omega(\tilde{K}_{e2})}$$

$$\tilde{K}_{e2} = K_{e2} + K^{IB}_{e2\gamma}$$

$$\tilde{K}_{\mu 2} = K_{\mu 2} + K^{IB}_{\mu 2\gamma}$$

e^+/μ^+ Particle separation crucial

(momentum, TOF, AC, PGC)

μ^+ mis-identification probability as e^+ to be < 10^{-6}

Rejection of K_{e3} and $K_{\mu 3}$

(particle momentum)

Inclusion of **radiative decay** $K^{IB}_{l2\gamma}$,

subtraction of $K^{SD}_{l2\gamma}$

(0γ or 1γ, CsI(Tl))

Recent and projected measurements of R_K

Standard Model

$\Delta R_K/R_K \approx$ **0.04%**

KLOE@DAΦNE

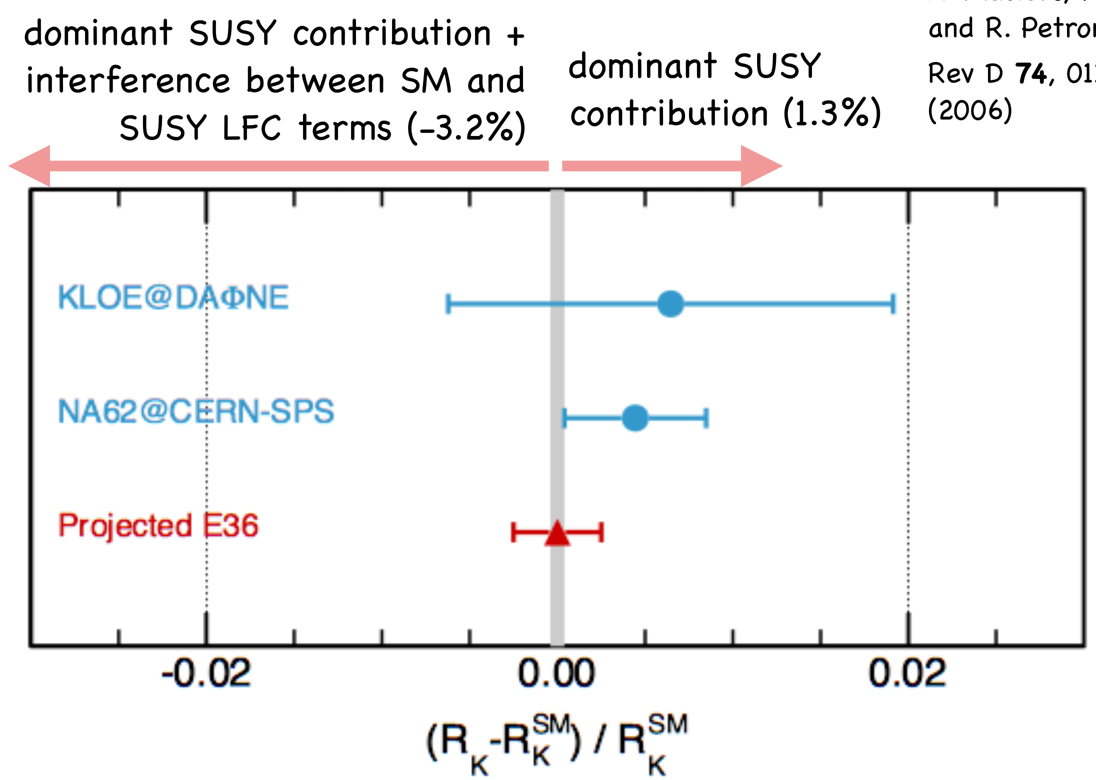
$\Delta R_K/R_K \approx$ **1.3%**, K in-flight decay, low intensity kaon beam.
$R_K = (2.493 \pm 0.031) \times 10^{-5}$
F. Ambrosino et al., Eur. Phys. J. C **64**, 627 (2009).

NA62@CERN-SPS

$\Delta R_K/R_K \approx$ **0.4%**, K in-flight decay, e/μ kinematical separation at high momentum, μ^+ in-flight decay.
$R_K = (2.488 \pm 0.010) \times 10^{-5}$
C. Lazzeroni et al., Phys. Lett. B **719**, 326 (2013).
Future NA62: $\Delta R_K/R_K$ = 0.1 - 0.2%.

Sensitive probe of LFV

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



Projected TREK E36

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

Search for heavy sterile neutrino, $M_N < M_K$

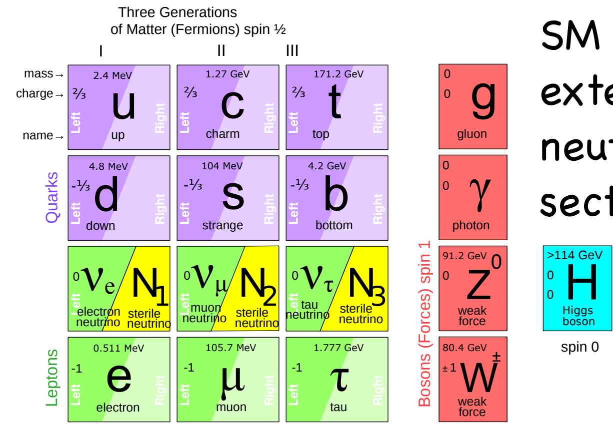
Add to the SM

> three right-handed sterile neutrinos with masses roughly of the order of masses of known quarks and leptons.

to handle in an economic and unified way the problems of

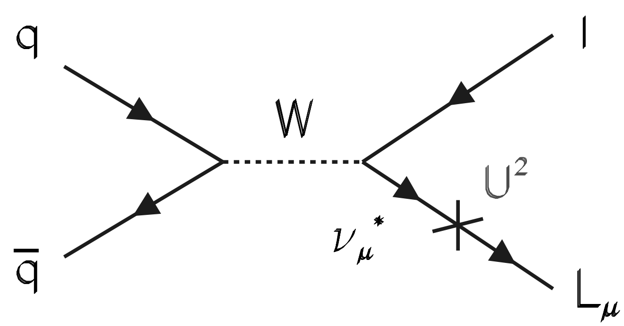
- dark matter (N_1),
- neutrino masses (N_2 and N_3),
- baryon asymmetry of the universe (N_2 and N_3)

$M(N_1) \approx 1$ keV
$M(N_2) \approx M(N_3) \approx 100$ MeV



SM minimal extension in neutrino sector

$$K^+ \to \mu^+ N$$

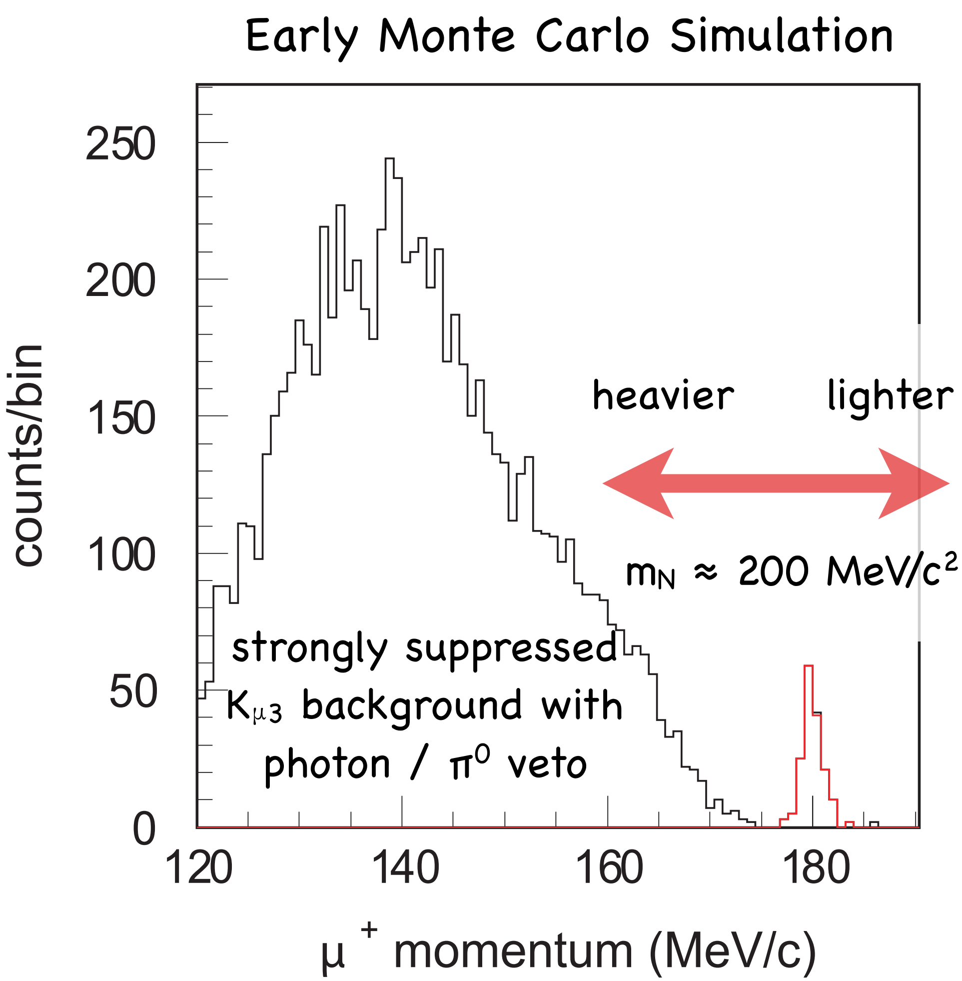


Neutral heavy lepton production

Fig. from Vaitaitis et al., Phys. Rev. Lett. **83**, 4943 (1999).

S.N. Gninenko, D.S. Gorbunov, M.E. Shaposhnikov,
Advances in High Energy Physics **2012**, ID 718259 (2012)

Search for sterile neutrinos in the Kaon weak decay with TREK



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

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

TREK E36

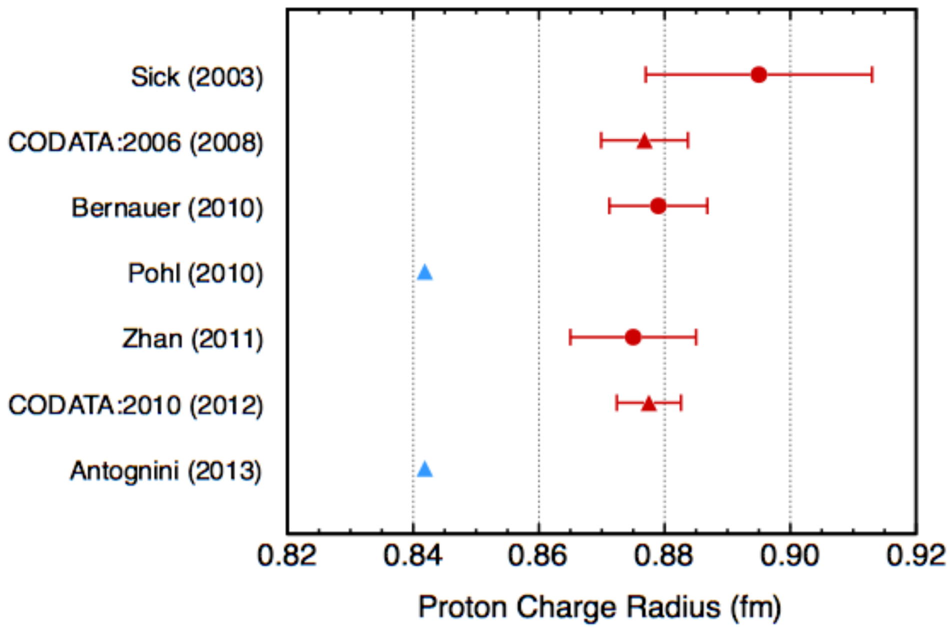
- Present E36 run plan with limited muon statistics (suppressed in trigger); trigger and acceptance optimized for K_{e2} decays.
- Background from radiative channels ($K\mu3$, $Ke3$, $K\mu2\gamma$, $Ke2\gamma$, ...) requires hermetic photon veto.

Dedicated running with changed setup needed for adequate sterile-neutrino search.

Signal: Peak in μ^+ or e^+ momentum distribution from two-body decay of K^+.

The proton radius puzzle: Muonic and electronic measurements give different proton radii

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



▲ Spectroscopy

● Scattering

r_p = 0.84184(67) fm

r_p = 0.875(10) fm

r_p = 0.8768(69) fm

r_p = 0.84087(39) fm

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

Possible explanations of the proton-radius puzzle

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

Search for dark light

Explore U(1) extension of the Standard Model with photon-like massive gauge boson A′.

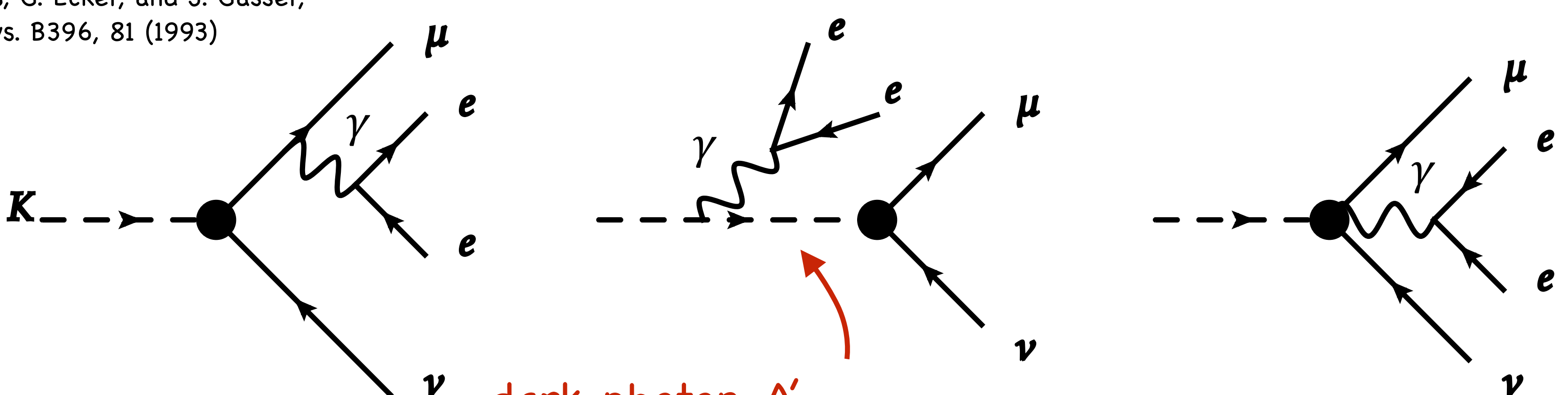
Motivation: Explain anomalies in astrophysics and particle physics, proton radius puzzle, …

Constrain dark photon parameter space with rare kaon-decay data.

$$K^+ \to \mu^+ \nu A'$$
$$A' \to e^+ e^-$$

QED background $\Gamma(K^+ \to \mu^+ \nu e^+ e^-) \approx 2.5 \times 10^{-5}$

full phase-space value of:
J. Bijnens, G. Ecker, and J. Gasser,
Nucl. Phys. B396, 81 (1993)

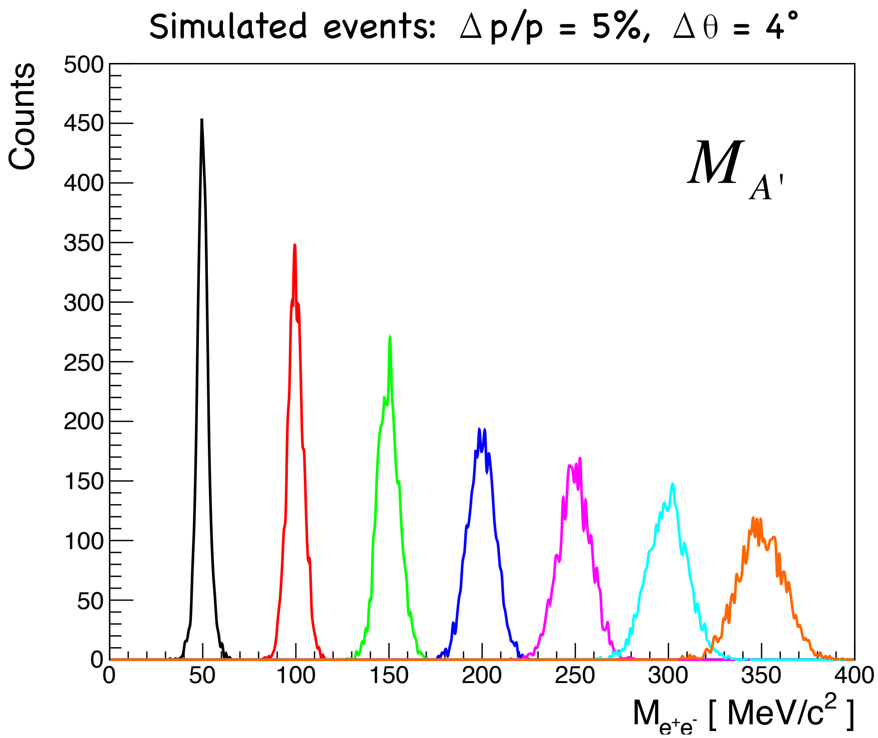


dark photon, A′
replaces photon, γ (weak coupling)

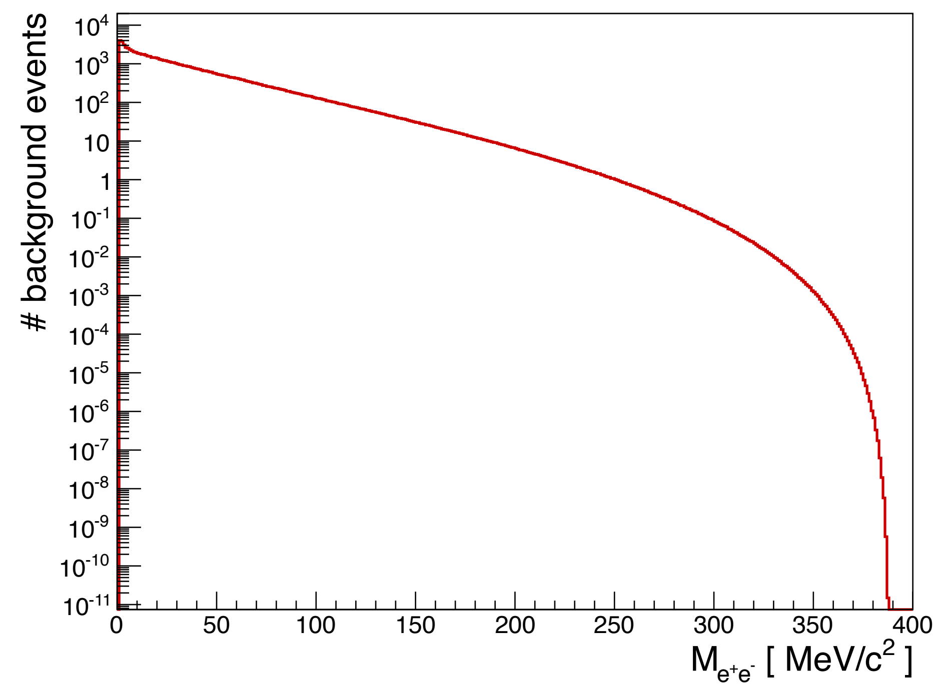
Simulation for E36 gauge boson search

Anticipated 10^{10} kaon decays.
Full reconstruction of the $\mu^+ \nu e^+ e^-$ final state.

$$K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$$



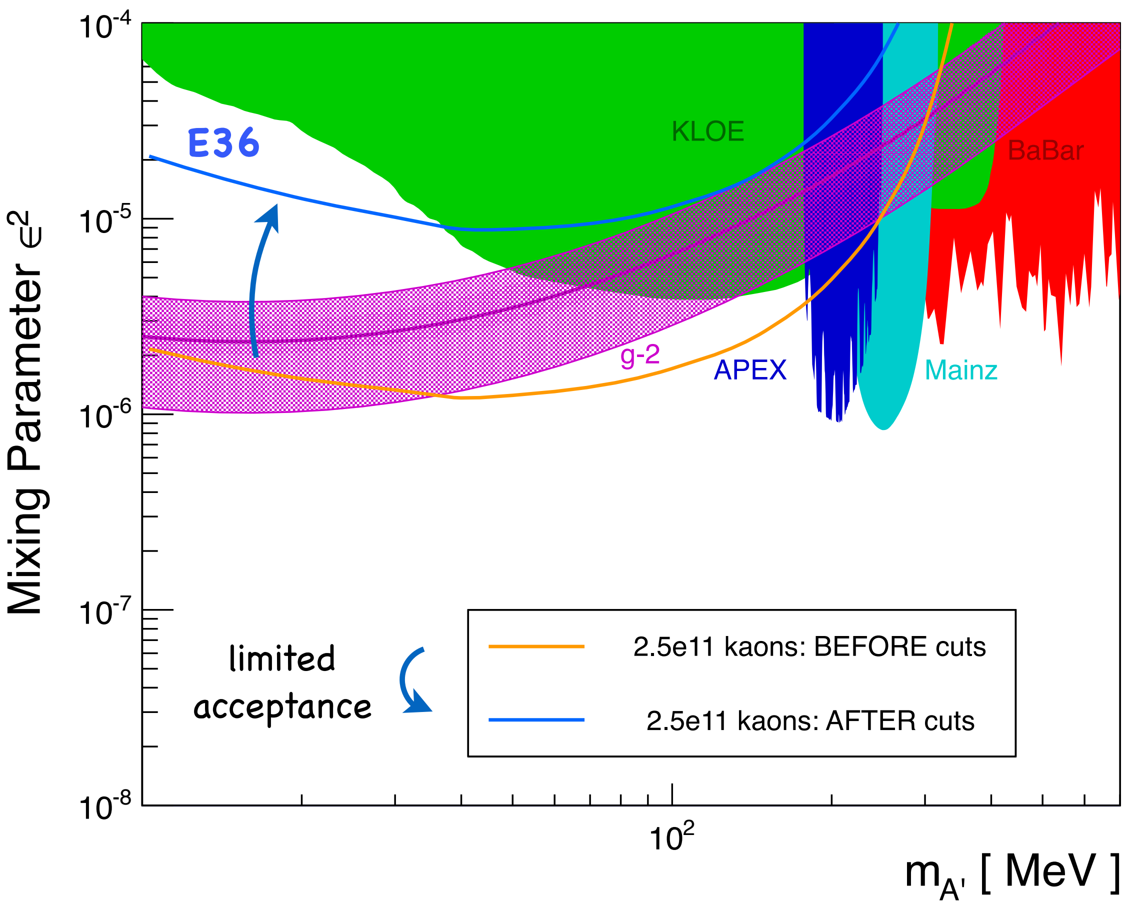
Signal: Peak in $M(e^+e^-)$ spectrum measured in the CsI(Tl) calorimeter.



Smooth, predictable **background** from QED processes.

Simulation: P. Monaghan, HU/CNU (2014)

A' parameter space exclusion limits (universal coupling)



recent progress by
JLab, MAMI, KLOE, BaBar

Estimate from P. Monaghan HU/CNU

$$K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$$
$$K^+ \to \pi^+ A' \to \pi^+ e^+ e^-$$

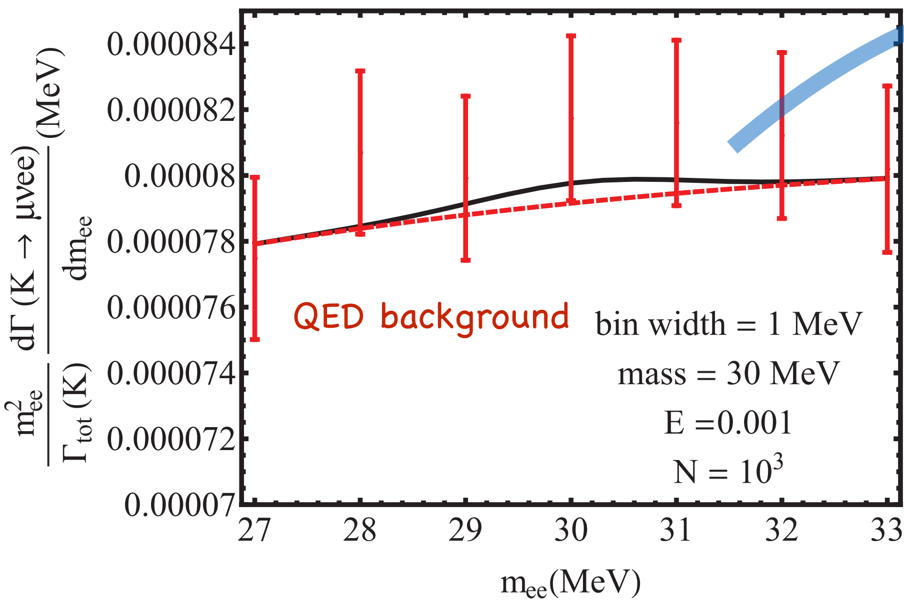
Full reconstruction of the $\mu^+\nu e^+e^-$ and $\pi^+e^+e^-$ final states.

Under the assumption of **universal coupling** E36 result will be mostly **complementary** to previous data.

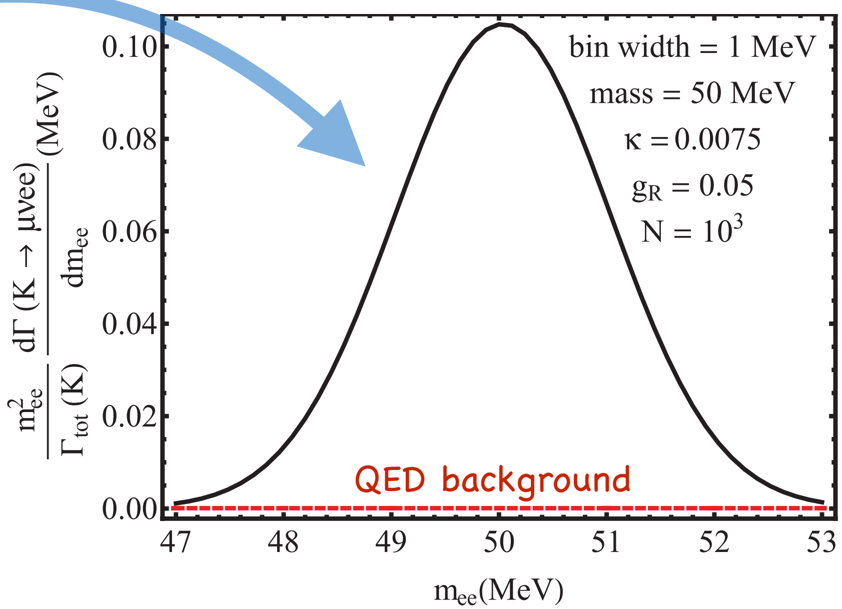
Constraints to new physics models for the proton charge radius puzzle from the decay $K^+ \to \mu^+ \nu e^- e^+$

An explanation of the proton-radius puzzle involving new particles must include larger couplings to muons than electrons (the interactions must **violate lepton universality**).

Dark photon contribution
(Kinetic mixing only)



Batell et al. **modified dark photon contribution**
(additional direct coupling to right-handed muons)



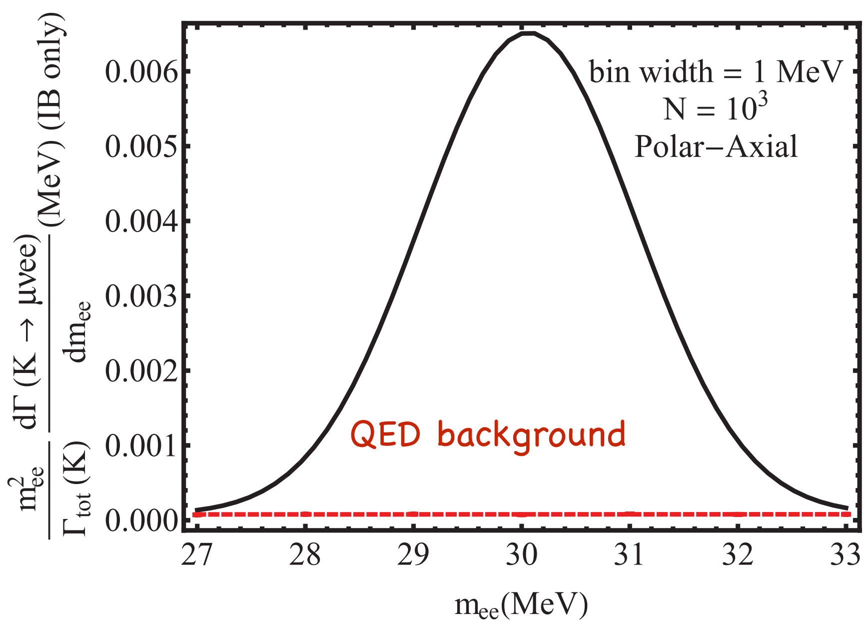
C.E. Carlson and B.C. Rislow, Phys. Rev. D **89**, 035003 (2014)
B. Batell, D. McKeen, and M. Pospelov, Phys. Rev. Lett. **107**, 011803 (2011)

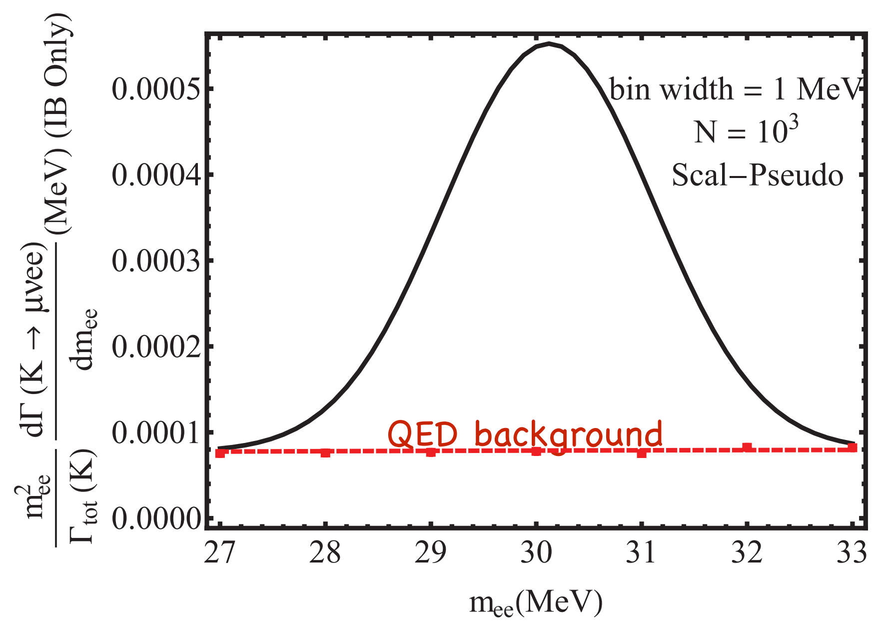
Constraints to new physics models for the proton charge radius puzzle from the decay $K^+ \to \mu^+ \nu e^- e^+$

Carlson & Rislow **modified dark photon contribution**

(New particles with **polar-axial vector** or **scalar-pseudoscalar couplings**

to muons and protons.





TREK E36 can rule out any new physics explanation of the proton radius puzzle involving light bosons with preferred couplings to muons.

C.E. Carlson and B.C. Rislow, Phys. Rev. D **89**, 035003 (2014)

E246 apparatus is being upgraded by the TREK collaboration to search for new physics in the decay of stopped kaons at J-PARC.

E06	Search for T violation in kaon decays	$K^+ \to \pi^0 \mu^+ \nu_\mu$	transverse muon polarization
E36 (partial upgrade)	Search for lepton universality violation in a measurement of the ratio of the K widths	$K^+ \to e^+ \nu(\gamma)$ $K^+ \to \mu^+ \nu(\gamma)$	R_K decay-width ratio
	Search for a heavy sterile neutrino	$K^+ \to e^+ N$ $K^+ \to \mu^+ N$	peaks in lepton momentum distributions
	Search for lepton flavor violating contributions in dark light	$K^+ \to \mu^+ \nu A' \to \mu^+ \nu e^+ e^-$ $K^+ \to \pi^+ A' \to \pi^+ e^+ e^-$	peaks in $M(e^+e^-)$ or π^+ momentum distributions

E36: detector construction & installation until December 2014, engineering run January and February 2015, physics run March-June 2015

E06: when higher beam power is available at J-PARC