Search for Light Neutral Bosons in The TREK/E36 Experiment at J-PARC LLNL-PRES-XXXXX

Bishoy H. Dongwi For the TREK Collaboration

Lawrence Livermore National Laboratory, Livermore CA 94550

May 26, 2022







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

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

05.26.2022 1 / 23

San

Overview

- 1 Introduction of Stopped K^+ method
- TREK/E36 apparatus 2
- Verification of e36g4MC from 3 tracking

- 4 Generator implementation
- 5 CsI(Tl) analysis
- 6 Upper limit extraction and $\mathcal{B}r(A')$

・ロト ・ 日 ・ ・ 日 ・ ・ 日 ・

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

1 05.26.2022 2/23

DQC

Lepton Universality

- ${\hfill {\hfill 0}}$ LHCb, Belle & BaBar observed lepton non-universality at 3σ level

LHCb (Phys. Rev. Lett. 113)

2-body decay of K⁺



イロト イヨト イヨト イ

Decay width ratio of electronic (K_{e2}) and muonic $(K_{\mu2})$ decay modes

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

- Hadronic uncertainties cancel
- Strong helicity suppression of electronic channel enhances sensitivity to effects beyond SM

• SM prediction is highly precise: $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

San

Anomalies

nature Home News & Comment Research Convers 4. The experiment known as DarkLight, developed by MIT physics professor Pet Fisher and Milner in collaboration with researchers at the Jefferson National News & Comment > News > 2016 > June > A Accelerator Laboratory in Virginia and others, will look for evidence a massive MATURE | NEWS dark photon with a specific energy postulated in one particular theory about Has a Hungarian physics lab found a fifth force of nature? Radioactive decay anomaly could imply a new fundamental force, theorists say PHYS A Popular Mechanics The paper uploaded by the UoC team has created some excitement, as well as public exclamations of doubt-moorts of the possibility of a fifth force of nature have been heard the several teams before, but none have panned out. But still, the idea is intriguing enough that several teams new experiment called David ght that could confirm this gain have announced plans to repeat the experiments conducted by the Hungarian team, and Randal wahed Popular Mechanics through what this new fr all eyes will be on the DarkLight experiments at the Jefferson Laboratory, where a team is understand dark matter, and how DarkLight might prove it excess. **"DARK MATTER MIGHT INTERACT WITH ITSELF VIA** R. Corliss, MIT SOME YET UNKNOWN 'DARK FORCE.'" Ekspeniment DarkLight u Jefferson Laboratoryu, koji traži tamne fotone, moći će za nalviše godinu dana provieriti ovu tvrdnju. NIT fizičar Ivica Friščić je istraživanje nature OIL SPILLS There's mo to come PLAGIARISM It's worse that CHIMPANZEES The batt New value from exotic atom trims radius by four per cent



- Proton radius puzzle, $(g-2)_{\mu}$
- Strong CP problem
- Positron excess and ⁸Be anomaly

イロト イヨト イヨト イヨト 三日

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

05.26.2022 4 / 23

nac

Neutral Boson Search in Stopped K^+ Decays

Carlson Polar-Axial vector K⁺ decays ~ 10¹⁰ Signal 1: $K^+ \rightarrow \pi^+ A'$. $A' \rightarrow e^+e^ K^+ \rightarrow \mu^+ v e^+ e^-$ Required signal Background: BR($K^+ \rightarrow \pi^+ e^+ e^-$) ~ 2.9 x 10⁻⁷ ~ 2.900 ev. M_e = 50 MeV for proton radius δM_{ee}~3 MeV dr(K Signal 2: $K^+ \rightarrow \mu^+ \nu A'$. $A' \rightarrow e^+e^-$ Background: BR($K^+ \rightarrow \mu^+ v e^+ e^-$) ~ 2.5 x 10⁻⁵ ~ 250,000 ev. Add, background from $K^+ \rightarrow \mu^+ \nu \pi^0 \rightarrow \mu^+ \nu e^+ e^- (\nu)$ π^0 decays 1) 3x10⁸ 2) 2x10⁹ π^{0} production: $K^{+} \rightarrow \mu^{+} \nu \pi^{0} (3.3\%)$ $K^{+} \rightarrow \pi^{+} \pi^{0} (21.1\%)$ QED Background Signal 3: $\pi^0 \rightarrow v A' A' \rightarrow e^+e^-$ Background: BR($\pi^0 \rightarrow \gamma e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) x10⁷ ev. M_{e*e}. [MeV/c²] Can light neutral bosons explain both dark • $K^+(u\overline{s})$ matter and particle physics anomalies (muon magnetic moment, ⁸Be decay & proton Mradius)? ν_{μ} Search for light neutral bosons in channels involving a muon (Signal: 2) f_K PRD 89, 0350003 (2014) ・ロト ・ 同ト ・ ヨト Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop 05.26.2022 5/23

J-PARC TREK/E36 Detector Geometry



Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

05.26.2022 6/23

500

《日》 《圖》 《문》 《문》 三臣

e36g4MC Geometry





Detector Assembly •



< = > < = > < = > < = >

• Geant4 E36 detector

Dongwi (LLNL-PRES-XXXXXX)

Light Boson - TRIUMF Workshop

3 05.26.2022 7/23

990

e36g4MC Cont.: Central Detector



• Central Detector

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

E 05.26.2022 8/23

DQC

<ロト <回ト < 三ト < 三ト

Tracking Package and The e36g4MC comparison



CsI Performance: $K_{\pi 2}$ Cluster Analysis



• Preselected $K_{\pi 2}$ events (from two CsI clusters)

• $\cos(\theta_{\pi^+\pi^0}) \leq -.99$: tight opening angle cut

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

05.26.2022 10 / 23

990

Generator channels

Label	Branch	Ratio
0	$K^+ \rightarrow e^+ \nu$	1.582×10^{-5}
1	$K^+ \rightarrow \mu^+ \nu$	6.355×10^{-1}
2	$K^+ \rightarrow e^+ \pi^0 \nu$	5.07×10^{-2}
3	$K^+ \rightarrow \mu^+ \pi^0 \nu$	3.352×10^{-2}
4	$K^+ \rightarrow e^+ \pi^0 \pi^0 \nu$	2.55×10^{-5}
5	$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	4.247×10^{-5}
6	$K^+ \rightarrow \pi^+ \pi^- \mu^+ \nu$	1.4×10^{-5}
7	$K^+ \rightarrow \pi^+ \pi^0$	2.067×10^{-1}
8	$K^+ \rightarrow \pi^+ \pi^0 \pi^0$	1.760×10^{-2}
9	$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	5.583×10^{-2}
10	$K^+ \rightarrow \mu^+ \nu \gamma$	6.2×10^{-3}
11	$K^+ \rightarrow e^+ \nu \gamma$	9.4×10^{-6}
12	$K^+ \rightarrow \mu^+ \pi^0 \nu \gamma$	1.25×10^{-5}
13	$K^+ ightarrow \pi^+ \pi^+ \pi^- \gamma$	1.04×10^{-4}
14	$K^+ ightarrow \mu^+ \nu A^{'}$	$\epsilon^2 \times ratio \ of \ channel \ 16$
15	$K^+ \rightarrow \pi^+ A^{'}$	$\epsilon^2 \times ratio \ of \ channel \ 17$
16	$K^+ \rightarrow \mu^+ e^+ e^- \nu$	2.5×10^{-5}
17	$K^+ \rightarrow \pi^+ e^+ e^-$	3×10^{-7}

K⁺ Channels

π^0 Channels			
	Label	Branch	Ratio
	0	$\pi^0 \rightarrow \gamma \gamma$	9.8823×10^{-1}
	1	$\pi^0 \to e^+ e^- \gamma$	1.174×10^{-2}
	2	$\pi^0 \rightarrow \gamma A'$	$\epsilon^2 \times ratio of channel 2$

ROOT based generator

- Interactive: utilizes Messenger Classes
- Allows for selection of decay modes and branching ratios

A B A B A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

E 05.26.2022 11/23

- E - E

Analysis Strategy for A' Search



Dongwi (LLNL-PRES-XXXXXX)

Light Boson - TRIUMF Workshop

05.26.2022 12/23

Invariant Mass Distribution Invariant Mass



Invariant Mass

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

3 05.26.2022 13/23

San

0.3

Upper Limit Extraction



- N_{K} : Number of K^{+} , $LT(\mu)$: muon lifetime fraction
- $A_{A'}$: acceptance ratio of the A' with a given mass, determined from e36g4MC

- Nuvee: Integrated number of events in a given A' search window
- 2σ limit: ~ 95% CL of no signal observance
- Upper limit obtained from ~ 15% if the data イロト イロト イヨト イヨト

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop 05.26.2022 14/23

Э

5900

Upper Limit Extraction



- ${\ensuremath{\, \bullet }}\ \ \, N_{\,K}\colon {\rm Number \ of \ } K^+, \ LT(\mu)\colon {\rm muon \ lifetime \ fraction}$
- $A_{A'}$: acceptance ratio of the A' with a given mass, determined from e36g4MC
- N_{µvee}: Integrated number of events in a given A' search window

- $@~2\sigma$ limit: $\sim 95\%$ CL of no signal observance
- \blacksquare Upper limit obtained from $\sim 15\%$ if the data
- Theoretical predictions: polar and axial vector or Scalar and Pseudoscalar couplings

A B A B A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

05.26.2022 14 / 23

San

∃ ∃ ≥

Summary

Summary and Future Work

- Universe is littered with anomalies that must be explained (exciting times!)
- TREK/E36 experiment has been successfully conducted, completed data-taking, decommissioned and analysis is currently underway
- e36g4MC has been developed from ground-up
- ${\small \bullet }~ K^+$ decay generator has been implemented into the e36g4MC
- ${\small \bullet}~{\rm Energy}$ calibration for CsI(Tl) using $K_{\mu 2}$ and checked with $K_{\pi 2}$
- Generated various masses for A'
- ${\rm \bullet}~$ Upper limits for ${\cal B}r(K^+\to\mu^+\nu A')$ have been extracted for various $\mathfrak{m}_{A'}$
- Improvements from PID analysis for reducible background reduction currently underway

◆□▶ ◆□▶ ◆三▶ ◆三▶ → □ ◆ ��や

05.26.2022

15/23

• Work on M^2_{miss} UL extraction

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

Collaborators

Spokespeople: M. Kohl, S. Shimizu

CANADA

University of British Columbia Department of Physics and Astronomy TRIUME

USA

University of South Carolina Department of Physics and Engineering Iowa State University College of Liberal Arts & Sciences Hampton University Department of Physics

JAPAN

Osaka University Department of Physics Chiba University **Department of Physics** High Energy Accel. Research Organization (KEK) Institute for Particle and Nuclear Studies

RUSSIA

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

Dongwi (LLNL-PRES-XXXXXX)

Light Boson - TRIUMF Workshop

05.26.2022 16/23

-

DQC

イロト イポト イヨト

Backup

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

 $05.26.2022 17\,/\,23$

・ロト ・ 直 ・ ミヨト ・ ヨー ・ つへぐ

Number of Stopped K^+ (N_K)



$$\begin{split} N_{K} &= \frac{N_{\mu 2}}{\mathcal{B}r(\mu 2) PS(\mu) A_{\mu} LT(\mu)} \\ &= 4.08836 \cdot 10^{9} \end{split}$$

- ${\small { o } } \ N_K :$ number of stopped kaons
- $N_{\mu 2}$: number of muons
- $A_{\mu 2}$: number of muon accepted events
- $\bullet \ PS = 49: \ {\rm muon \ prescale \ factor}$
- $LT(\mu) = 1.0$: muon lifetime fraction
- $\bullet~ \mathcal{B}r(\mu 2): K_{\mu 2}$ branching ratio
- Select 1 σ cut around mean P_{μ} , from $K_{\mu 2}$ decays



Dongwi (LLNL-PRES-XXXXXX)

Light Boson - TRIUMF Workshop

05.26.2022 18 / 23



- \bullet PID stringent cut: AC cut <650 ADC and $.875 \leq \beta \leq .925$
- Work on M^2_{miss} UL extraction

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

Additional Discussion Slide: M_{ee}



< = > < = > < = > < = > 05.26.2022 990

20/23

Э

Dongwi (LLNL-PRES-XXXXXX) Light Boson - TRIUMF Workshop

End Point Momentum Cuts

Charged Particle Momentum

Endpoint Momenta



Full Width at Quarter Max.

- For variable endpoint momentum cuts, the FWQM was taken
- $\bullet~$ If FWQM $> 230~{\rm MeV}/c$ then the endpoint cut is 230 ${\rm MeV}/c$
- Used 5th order polynomial function on range of [210.0, 230.]

A^\prime Acceptance and m_{A^\prime} Distribution



A' Invariant Mass Spectrum



- $\hfill A'$ masses generated on interval 20-110 MeV
- ${\mbox{ \ \ one }} \ \ m_{A^{\,\prime}}$ reconstructed from e^+e^- clusters in the CsI
- Mean $\mathfrak{m}_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(\mathfrak{m}_{A'})$ was obtained from fit

Dongwi (LLNL-PRES-XXXXX) Light Boson - TRIUMF Workshop

4 ロ ト 4 回 ト 4 国 ト 4 国 ト 国 今 Q @
p
05.26.2022
22 / 23

μ/e miss-identification



Dongwi (LLNL-PRES-XXXXXX)

Light Boson - TRIUMF Workshop

05.26.2022 23 / 23

San