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

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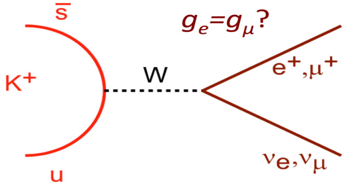
Overview

1. Introduction of Stopped K^+ method
2. TREK/E36 apparatus
3. Verification of e36g4MC from tracking
4. Generator implementation
5. CsI(Tl) analysis
6. Upper limit extraction and $\mathcal{B}r(A')$

Lepton Universality

- LHCb, Belle & BaBar observed lepton non-universality at 3σ level
- E36 will test lepton universality with stopped K^+

LHCb (Phys. Rev. Lett. 113)



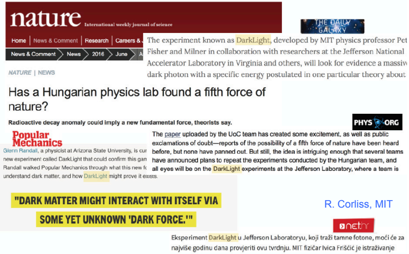
2-body decay of K^+

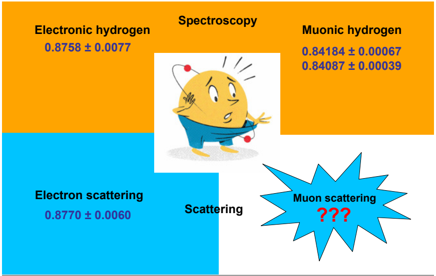
Decay width ratio of electronic (K_{e2}) and muonic $(K_{\mu 2})$ decay modes

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

- Hadronic uncertainties cancel
- Strong helicity suppression of electronic channel enhances sensitivity to effects beyond SM
- SM prediction is highly precise: $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Anomalies





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

Neutral Boson Search in Stopped K^+ Decays

K^+ decays ~ 10^{10}

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

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

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

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

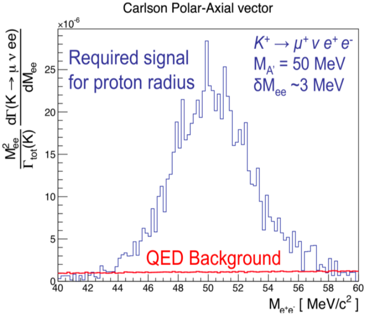
Add. background from $K^+ \to \mu^+ \nu \pi^0 \to \mu^+ \nu\ e^+ e^- (\gamma)$

π^0 decays 1) 3×10^8 2) 2×10^9

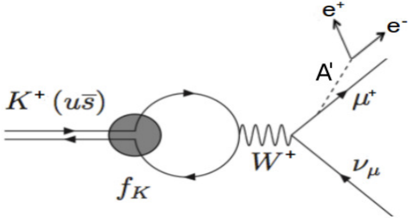
π^0 production: $K^+ \to \mu^+ \nu \pi^0$ (3.3%) $K^+ \to \pi^+\pi^0$ (21.1%)

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

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

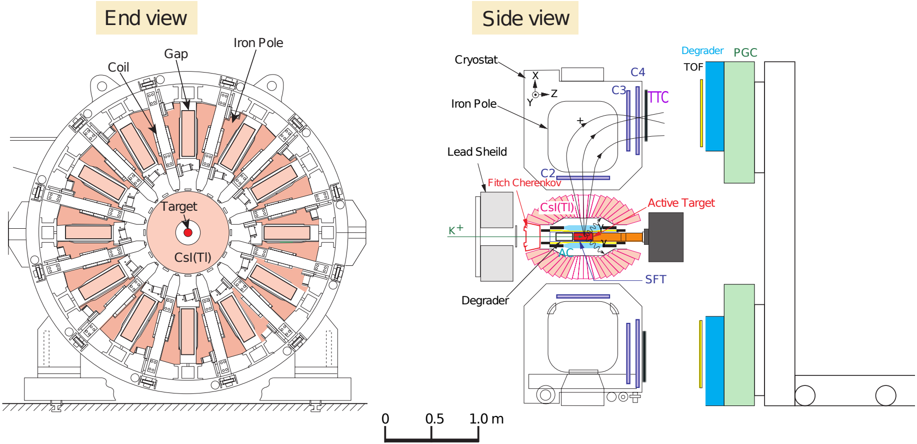


- Can light neutral bosons explain both dark matter and particle physics anomalies (muon magnetic moment, ^{8}Be decay & proton radius)?
- Search for light neutral bosons in channels involving a muon (Signal: 2)



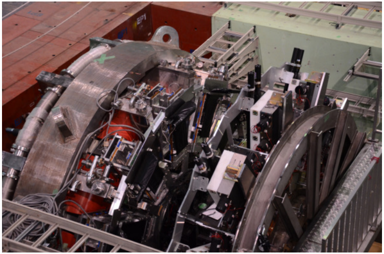
PRD 89, 0350003 (2014)

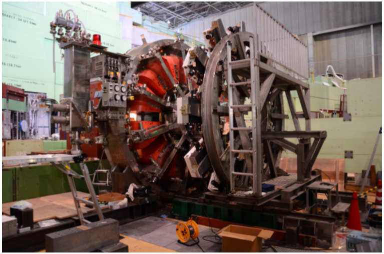
J-PARC TREK/E36 Detector Geometry



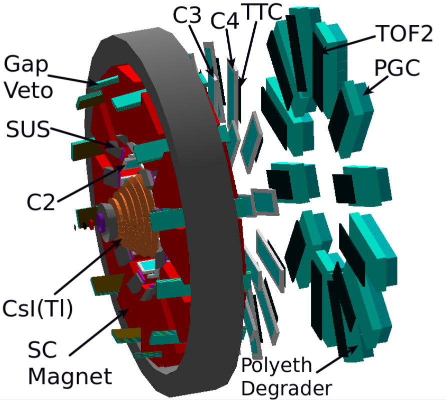
Stopped K^+ method	Momentum measurement	Particle ID	Gamma ray
K1.1BR beamline	MWPC (C2, C3, C4)	TOF	CsI(TI)
K^+ stopping target	Spiral fiber tracker (SFT)	AC	
	Thin trigger counter (TTC)	PGC	

e36g4MC Geometry



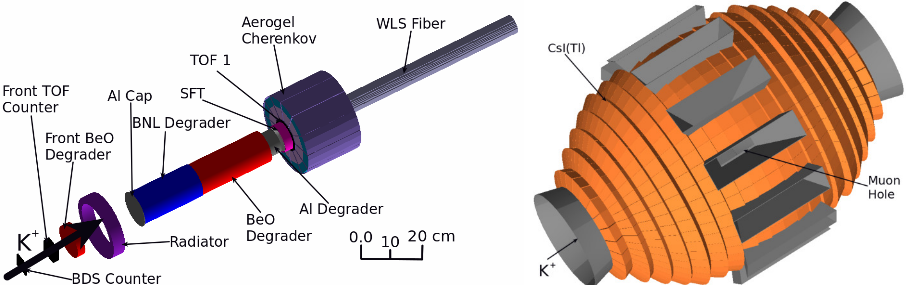


- Detector Assembly



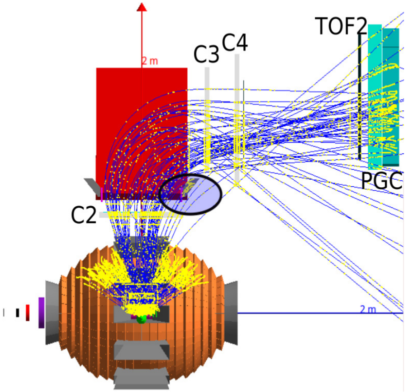
- Geant4 E36 detector

e36g4MC Cont.: Central Detector

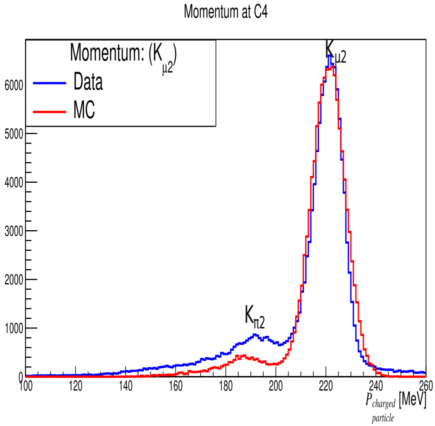


- Central Detector

Tracking Package and The e36g4MC comparison



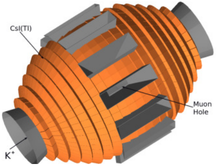
- Momentum distribution of $K_{\mu 2}$ and $K_{\pi 2}$ at C4
- E_{loss} and material budget well described
- Magnetic field integral is well described
- MC smeared with detector resolution

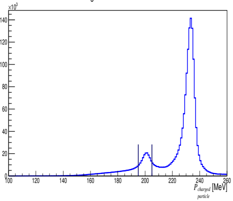


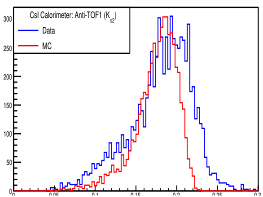
Terminology:

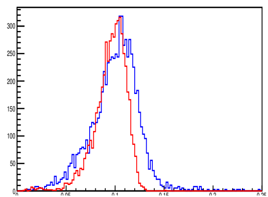
- $K_{\mu 2}$: $K^+ \to \mu^+ \nu$
- $K_{\pi 2}$: $K^+ \to \pi^+ \pi^0$

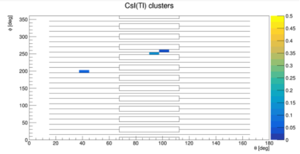
CsI Performance: $K_{\pi 2}$ Cluster Analysis

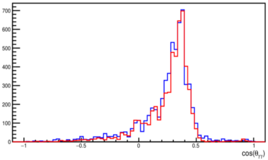












- Preselected $K_{\pi 2}$ events (from two CsI clusters)
- $\cos(\theta_{\pi^+\pi^0}) \leq -.99$: tight opening angle cut

Generator channels

K^+ Channels

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

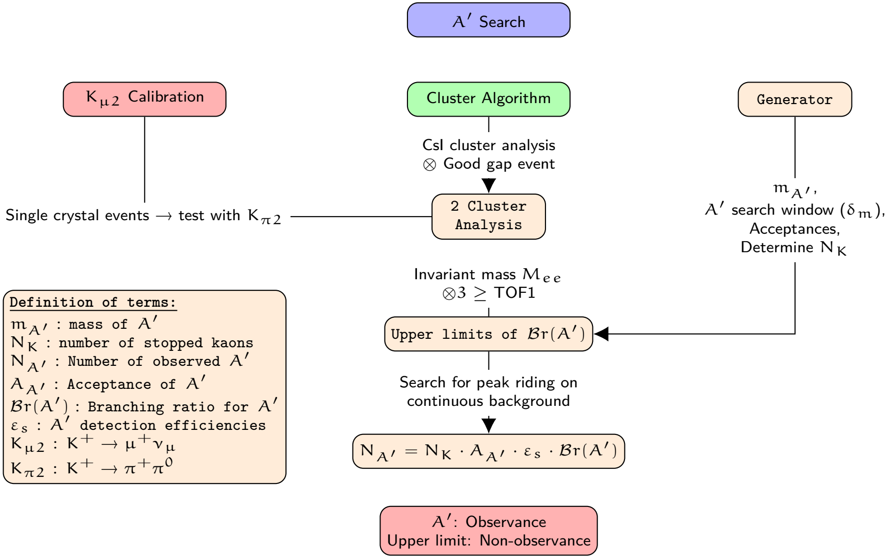
π^0 Channels

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

ROOT based generator

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

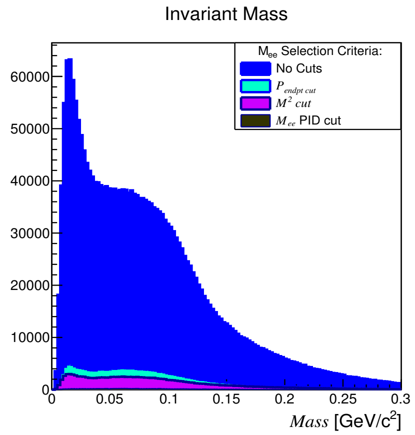
Analysis Strategy for A' Search

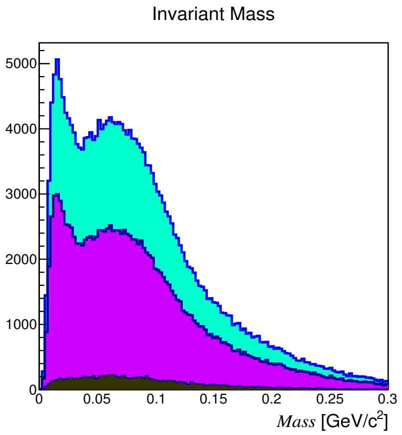


Definition of terms:

$m_{A'}$: mass of A'
N_K : number of stopped kaons
$N_{A'}$: Number of observed A'
$A_{A'}$: Acceptance of A'
$\mathcal{B}r(A')$: Branching ratio for A'
ε_s : A' detection efficiencies
$K_{\mu 2}$: $K^+ \rightarrow \mu^+ \nu_\mu$
$K_{\pi 2}$: $K^+ \rightarrow \pi^+ \pi^0$

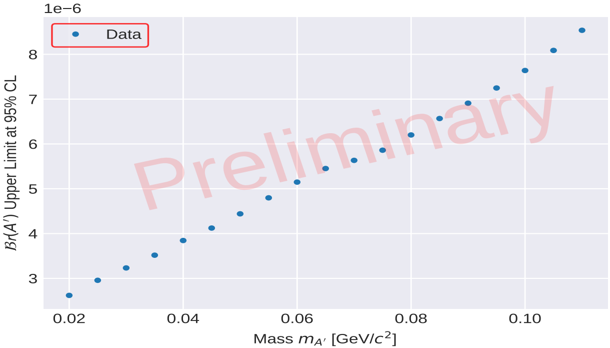
Invariant Mass Distribution





- Applied PID selection from the target system and tracking
- Applied end point momentum cut
- M^2 cut applied (magenta)
- M_{ee} distribution used for analysis has both $P_{endpoint}$ and M^2_{cut} (magenta)

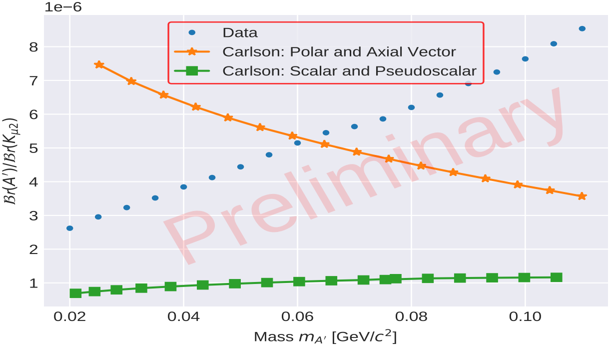
Upper Limit Extraction



$$\mathcal{B}r(A') < \frac{2\sqrt{N_{\mu\nu ee}}}{N_K A_{A'} LT(\mu)}$$

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

Upper Limit Extraction



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

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

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
- K^+ decay generator has been implemented into the e36g4MC
- Energy calibration for CsI(Tl) using $K_{\mu 2}$ and checked with $K_{\pi 2}$
- Generated various masses for A'
- Upper limits for $\mathcal{B}r(K^+ \to \mu^+ \nu A')$ have been extracted for various $m_{A'}$
- Improvements from PID analysis for reducible background reduction currently underway
- Work on M^2_{miss} UL extraction

Collaborators

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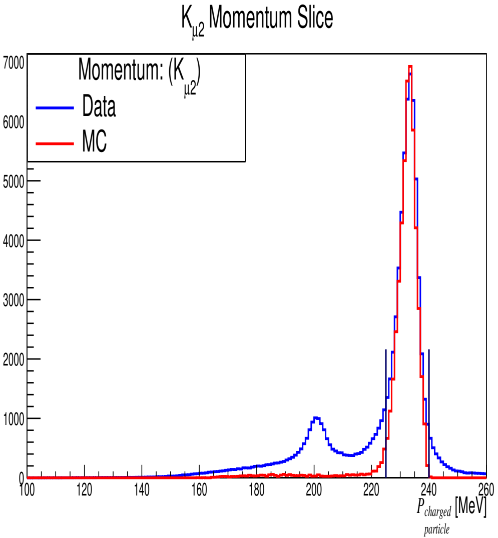
Backup

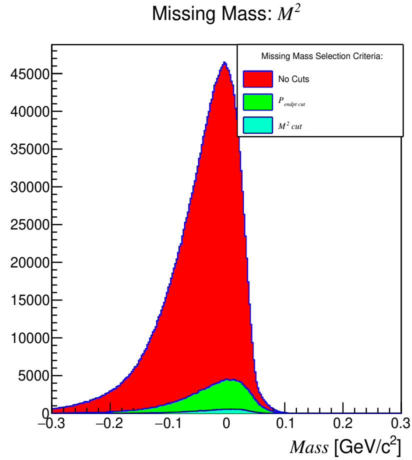
Number of Stopped K^+ (N_K)

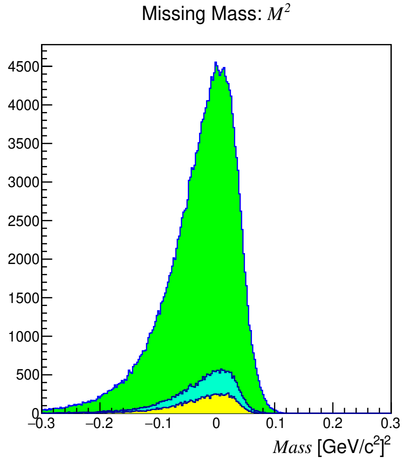
$$N_K = \frac{N_{\mu 2}}{\mathcal{B}r(\mu 2) PS(\mu) A_\mu LT(\mu)} = 4.08836 \cdot 10^9$$

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



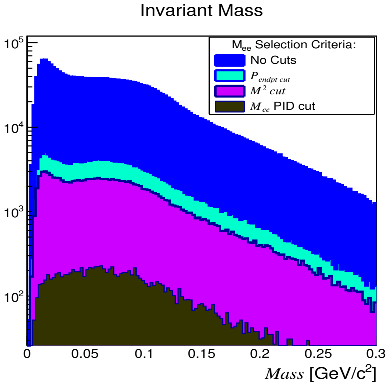
Miss Mass^2 M^2_{miss}

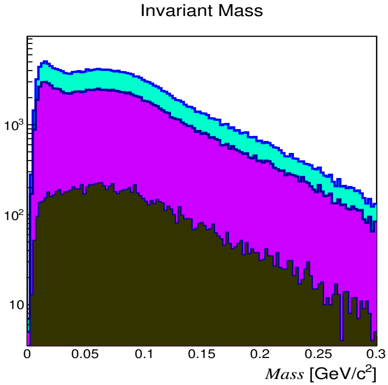




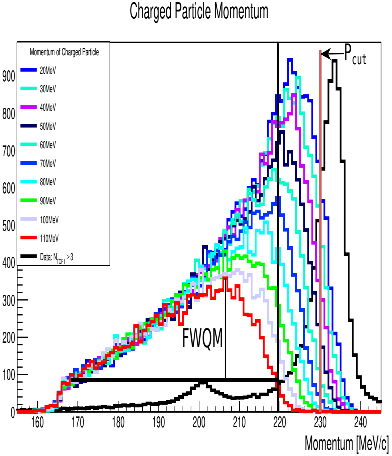
- PID stringent cut: AC cut < 650 ADC and $.875 \leq \beta \leq .925$
- Work on M^2_{miss} UL extraction

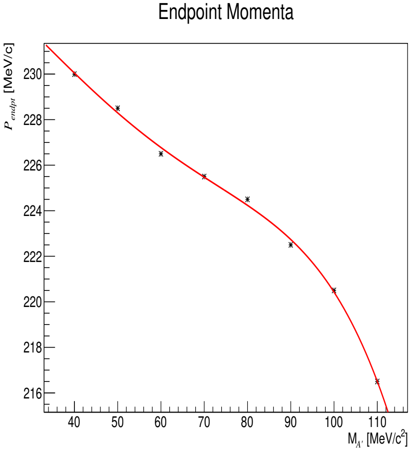
Additional Discussion Slide: M_{ee}





End Point Momentum Cuts

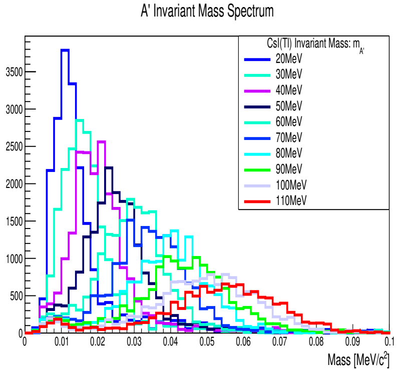


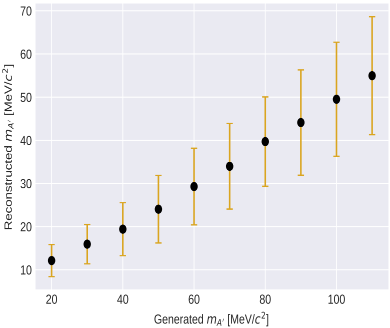


Full Width at Quarter Max.

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

A' Acceptance and $m_{A'}$ Distribution



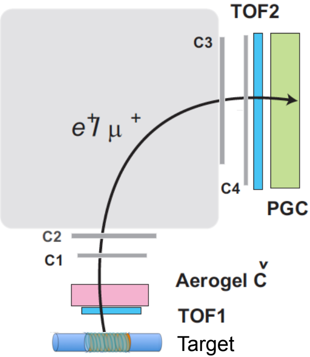


- A' masses generated on interval $20 - 110$ MeV
- $m_{A'}$ reconstructed from e^+e^- clusters in the CsI
- Mean $m_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(m_{A'})$ was obtained from fit

μ/e miss-identification

PID with:

- TOF
- Aerogel Č
- Lead glass

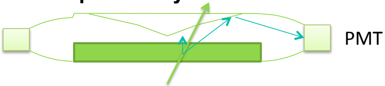


TOF

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%

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

M. Kohl (ICHEP 2016)