

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

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The TREK/E36 Experiment at J-PARC: An Overview

1 Introduction

- Additional Mass
- Dark Matter from High Energy Physics
- TREK/E36 Apparatus

2 Simulation Study

- Geant4 Geometry
- Verification of the e36g4MC

3 Analysis

- CsI(Tl) Calibration
- A' Search Strategy
- Generator

4 Upper Limit Extraction

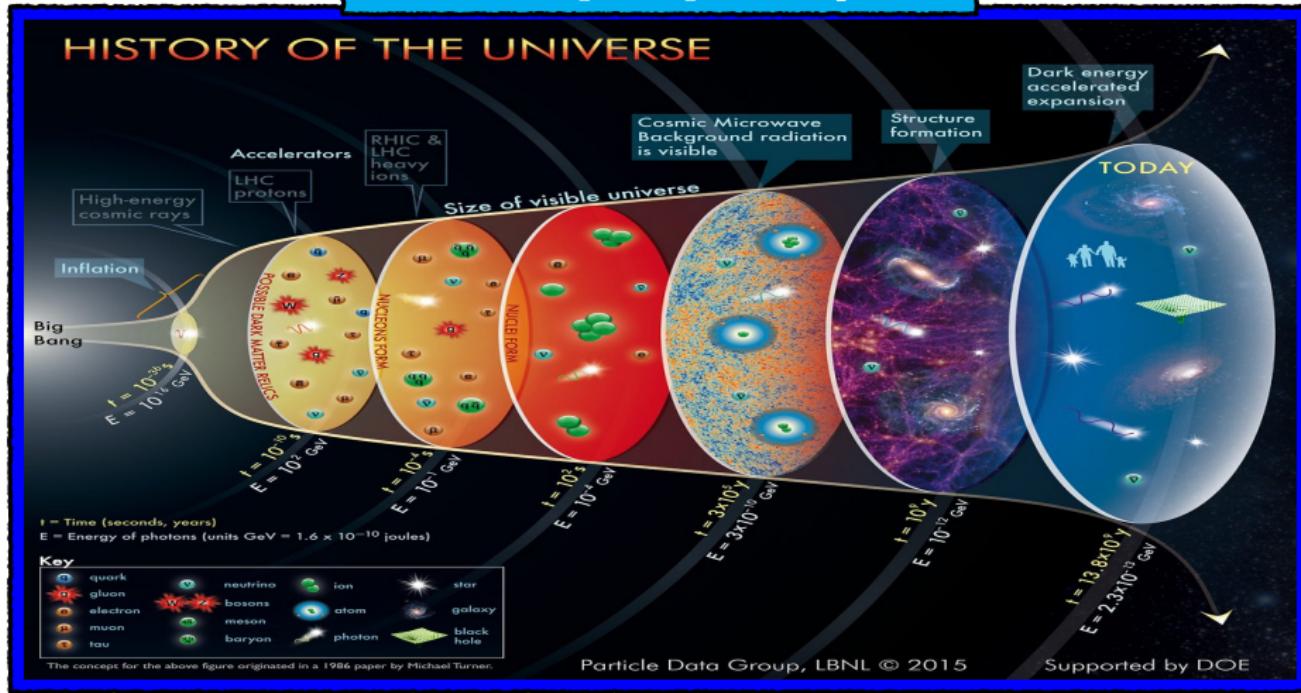
- A' Search

5 Closing

- Summary

Big Bang Nucleosynthesis to Present

From the Big Bang to the present

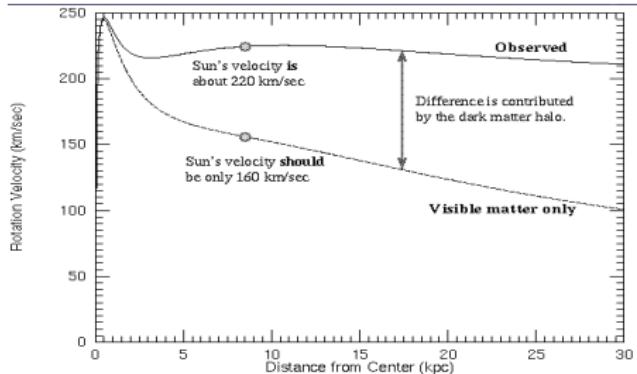
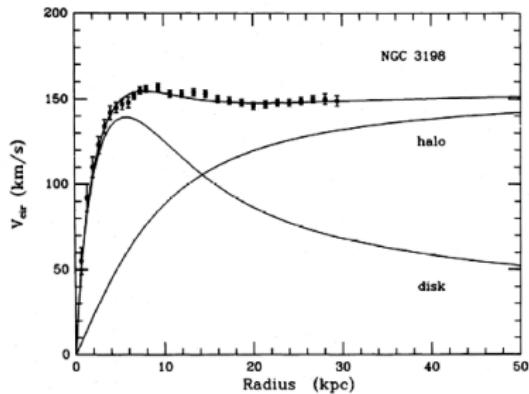


Rotation Curves of Galaxies



Vera Rubin

DISTRIBUTION OF DARK MATTER IN NGC 3198

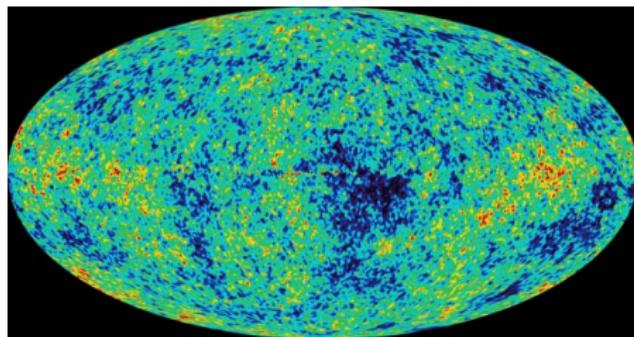


Vera Rubin:

- Zwicky noticed that galaxies in the Coma Cluster were moving too rapidly to be explained by the amount of stellar material
- Rubin studied rotation curves of galaxies
- Velocity of objects (stars or gas) orbiting the centers of galaxies, rather than decreasing as a function of the distance from the galactic centers, remain constant
- Found that they are FLAT!

► Katherine Freese (Public lecture)

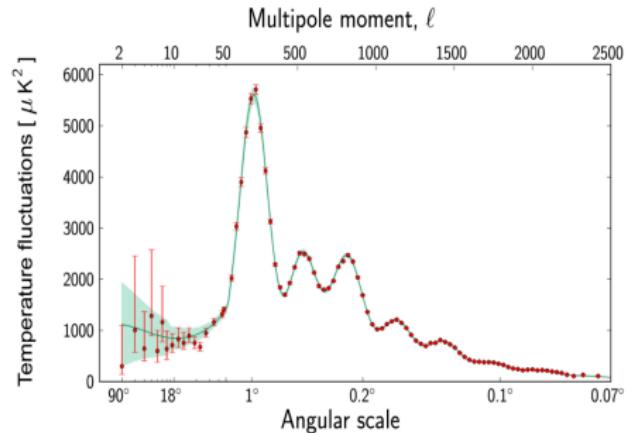
Cosmic Microwave Background (CMB)



Jeff Filippini (► UC Berkeley Cosmology Group)

CMB and power spectrum:

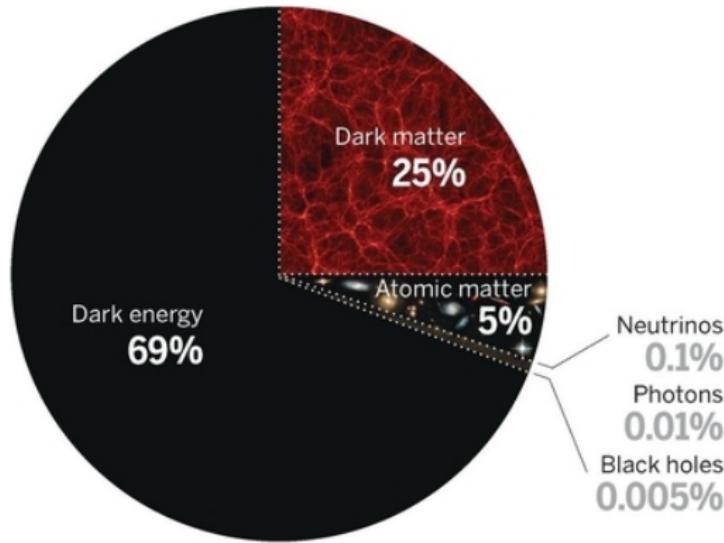
- Left over heat of the Big Bang
- Almost uniform background of radio waves that fill the universe
- Due to redshifting as the universe expands
- Power spectrum of CMB measures the amount of fluctuation in the CMB



temperature spectrum at different angular scales

- The peak at 1° is consistent with a flat geometry of the universe, second peak implies 5% baryonic matter, all other peaks consistent with 26% dark matter

Energy of the Universe



2014 P5 report

"It is imperative to search for dark matter along every feasible avenue," and the breadth of "well-motivated ideas for what dark matter could be, [which] include weakly interacting massive particles (WIMPs), gravitinos, axions, sterile neutrinos, asymmetric dark matter, and hidden sector dark matter"

Anomalies



Has a Hungarian physics lab found a fifth force of nature?

Radioactive decay anomaly could imply a new fundamental force, theorists say.

Popular Mechanics

Given the excitement over the new experiment at Arizona State University, our new experiment called DarkLight that could confirm this gap. Randal Walker Popular Mechanics through what this new is understand dark matter, and how DarkLight might prove it exists.

"DARK MATTER MIGHT INTERACT WITH ITSELF VIA
SOME YET UNKNOWN 'DARK FORCE.'"

THE DAILY GALAXY

The experiment known as DarkLight, developed by MIT physics professor Peter Fisher and Milner in collaboration with researchers at the Jefferson National Accelerator Laboratory in Virginia and others, will look for evidence of a massive dark photon with a specific energy postulated in one particular theory about

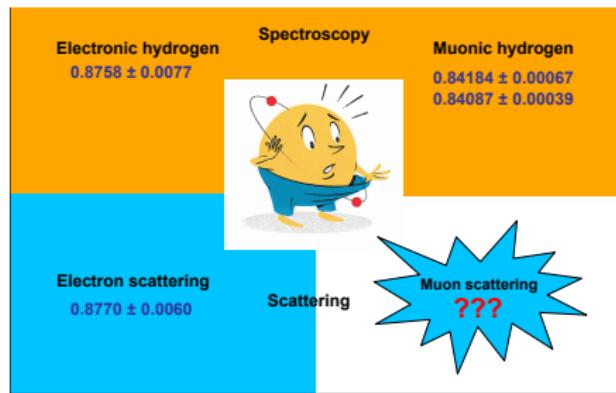
PHYS.ORG

The paper uploaded by the UoC team has created some excitement, as well as public examinations of doubt—reports of the possibility of a fifth force of nature have been heard before, but none have panned out. But still, the idea is intriguing enough that several teams have announced plans to repeat the experiments conducted by the Hungarian team, and all eyes will be on the DarkLight experiments at the Jefferson Laboratory, where a team is

R. Corliss, MIT

PHOTON

Experiment DarkLight u Jefferson Laboratoriju, koji trazi tamne fotone, moći će za raznjeđe godinu dana provjeriti ovo tvrdnju. MIT fizik Ivica Frčić je istraživač



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

Neutral Boson Search in Stopped K^+ Decays

K^+ decays $\sim 10^{10}$

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

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

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

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

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

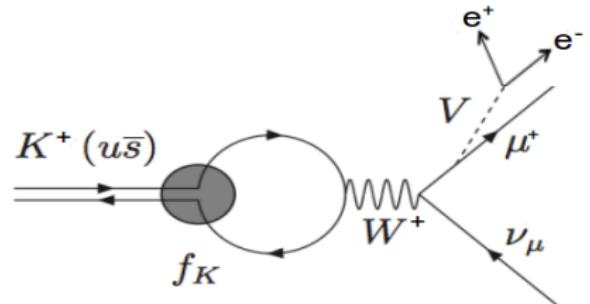
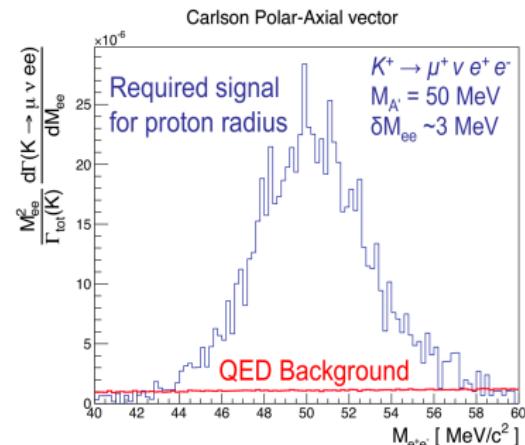
π^0 decays 1) 3×10^8

2) 2×10^9

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

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

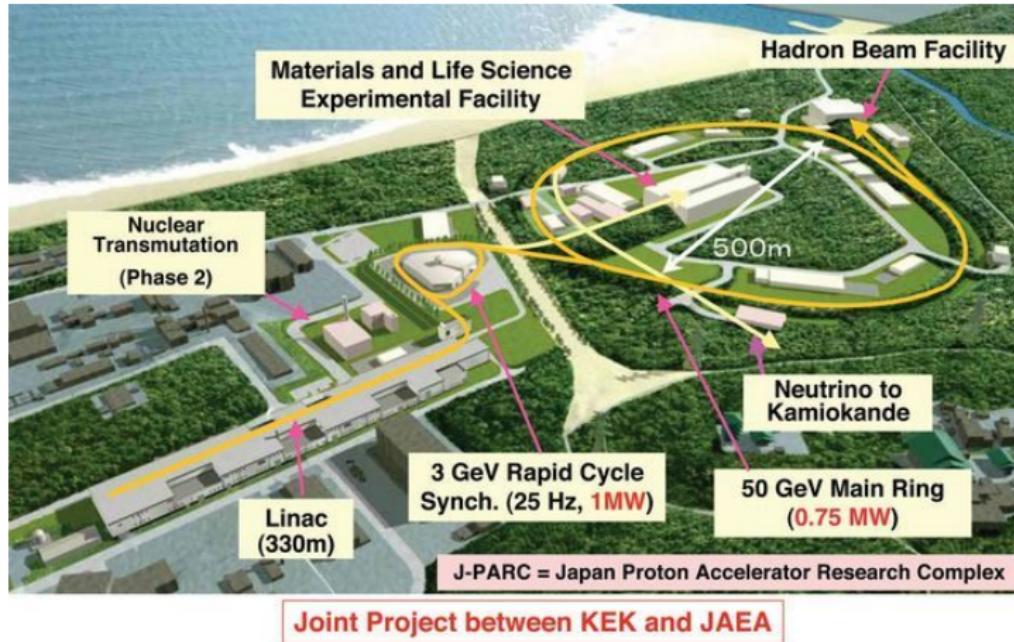
Background: $\text{BR}(\pi^0 \rightarrow \gamma e^+ e^-) \sim 1.2\% \sim 0.3 (2.3) \times 10^7 \text{ ev.}$



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

PRD 89, 035003 (2014)

Bird's Eye View of J-PARC



Timeline of TREK/E36

TREK: Time Reversal Experiment with Kaons



December 2014

- Installed detector components

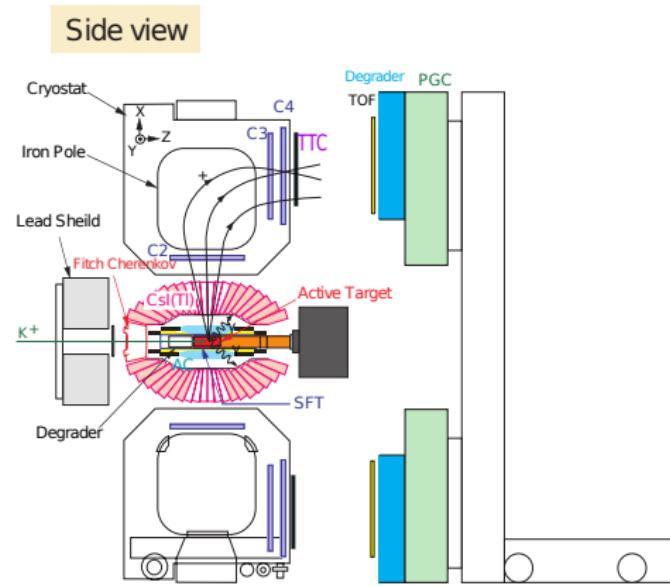
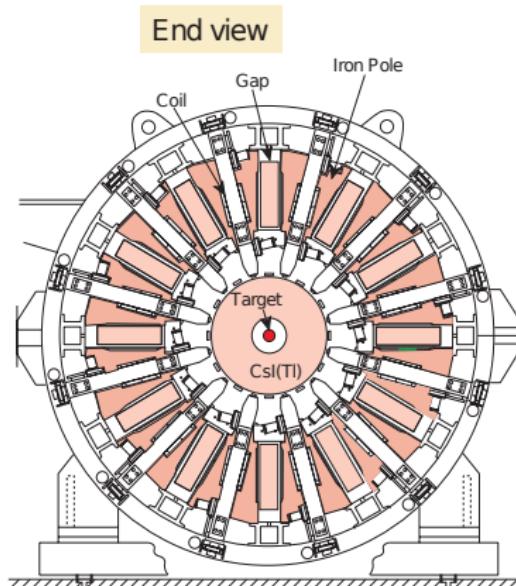
February - June 2015

- Completed installation of C3 & C4
- Cabling
- Detector maintenance

September - December 2015

- Physics run
- Data taking

E36 Detector Geometry



Stopped K⁺ method
K1.1BR beamline
K⁺ stopping target

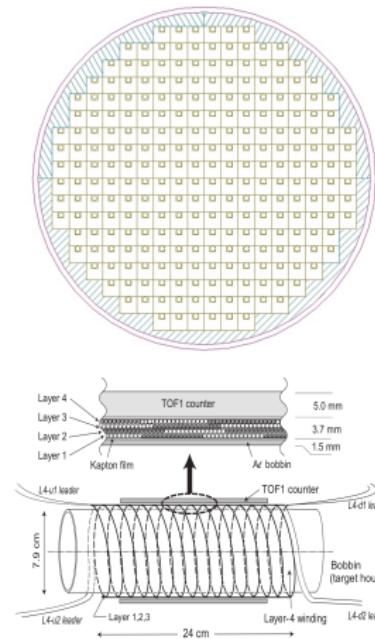
Momentum measurement
MWPC (C2, C3, C4)
Spiral fiber tracker (SFT)
Thin trigger counter (TTC)

Particle ID
TOF
AC
PGC

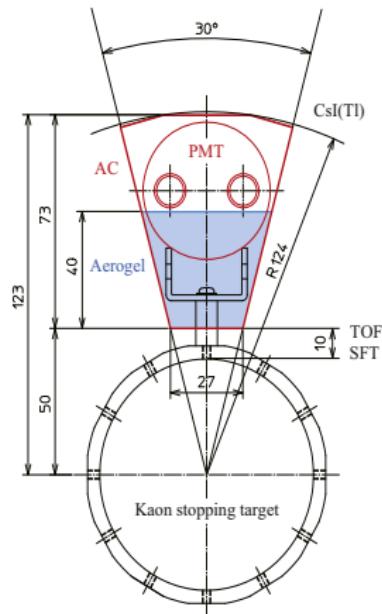
Gamma ray
CsI(Tl)

E36 Central Detector Geometry

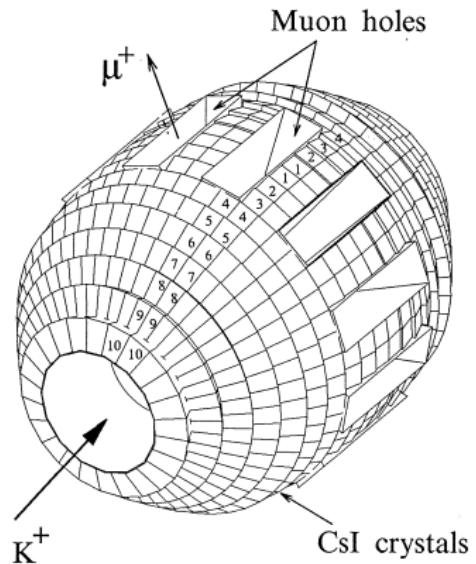
Target & SFT



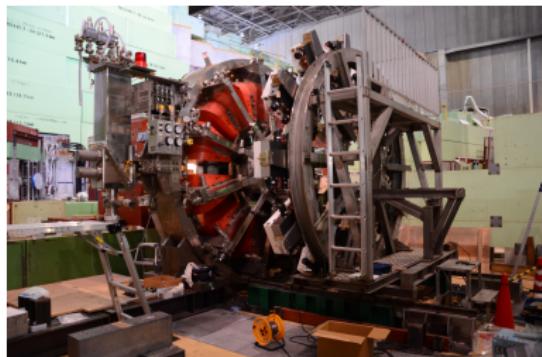
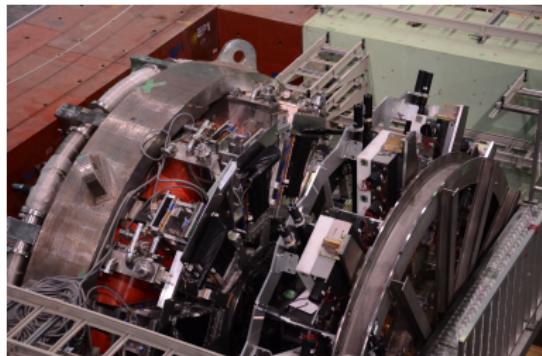
Aerogel Čerenkov



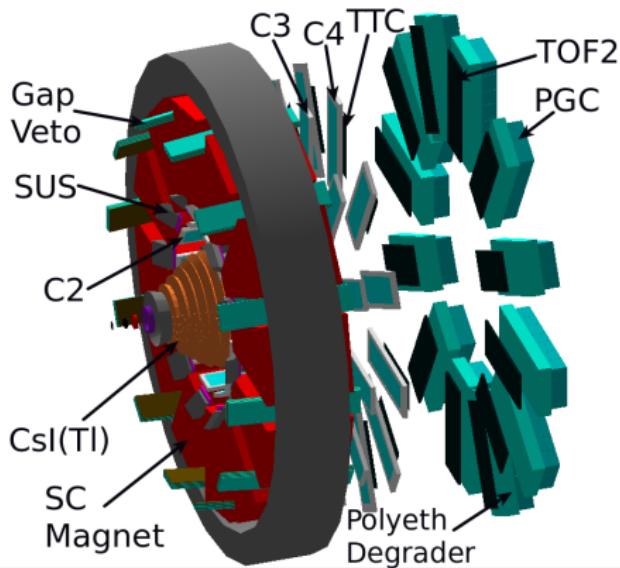
Muon holes



Geant4 Generated Geometry

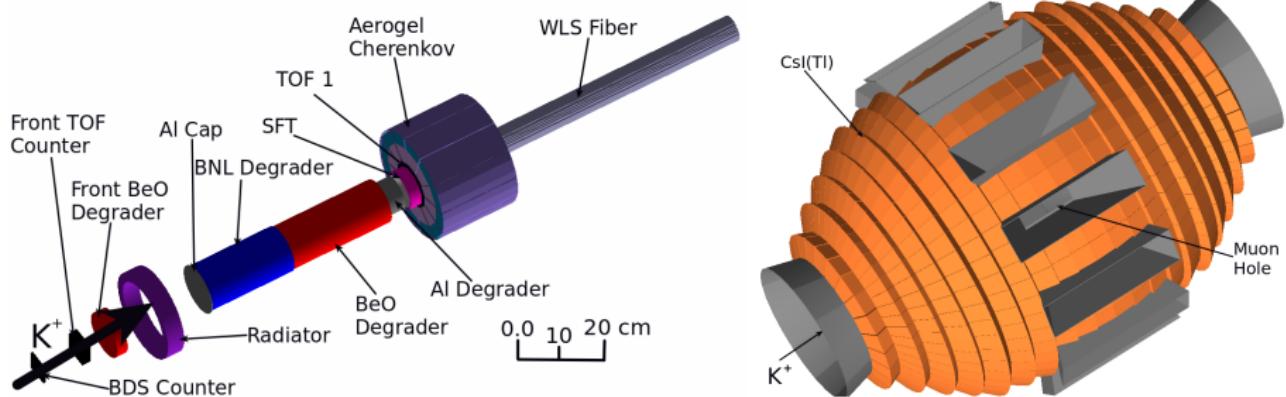


- Detector Assembly



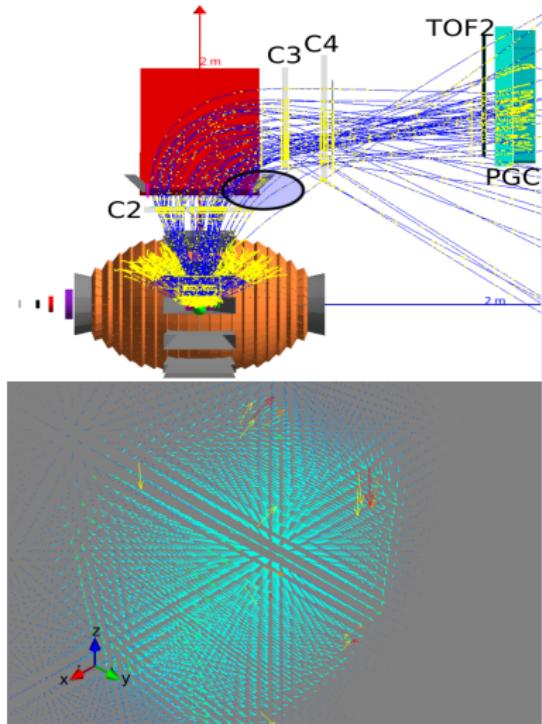
- e36g4MC detector geometry

Geant4 Cont.: Central Detector

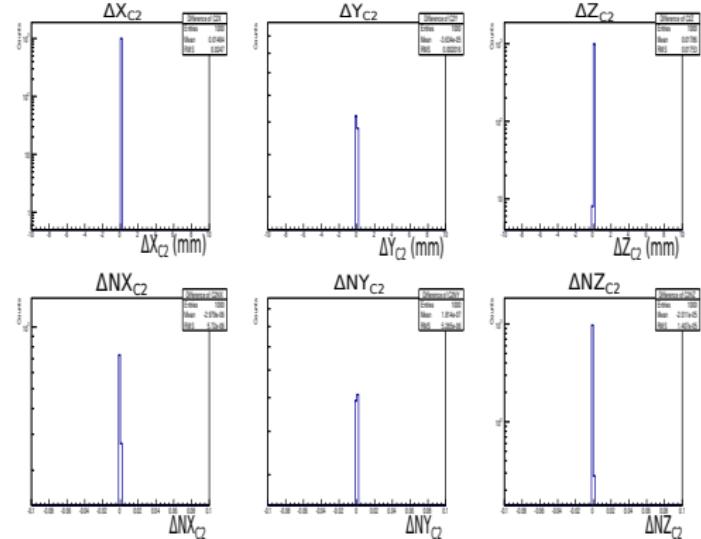


- Central Detector

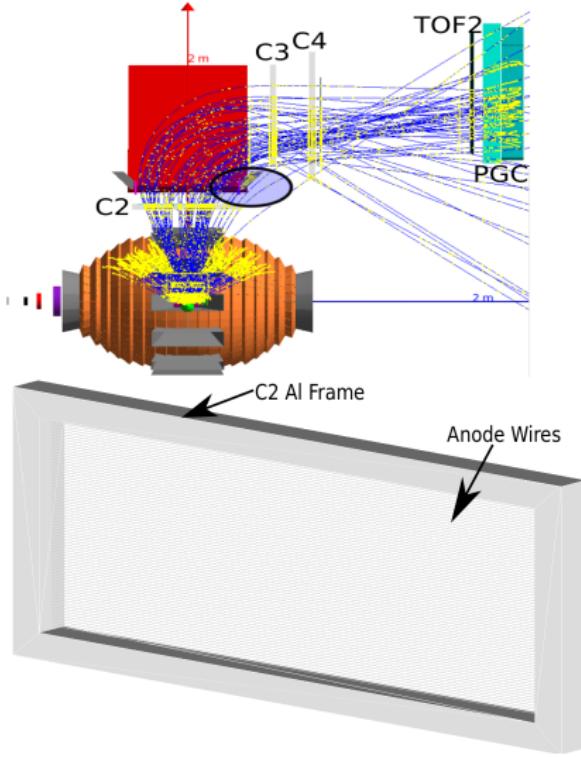
Tracking Package and the e36g4MC Comparison



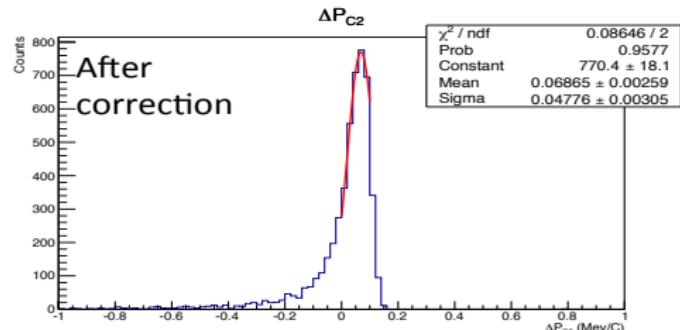
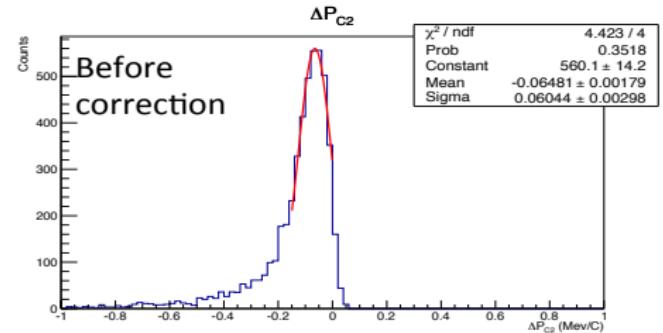
- Consistency check: propagation and magnetic field evaluation
- Simulated data: tracks propagated and reconstructed with Kalman Filter (KF)
- Compared differences at C2 coordinates ΔX_{C2} , ΔY_{C2} , ΔZ_{C2}
- Compared differences at C2 direction cosines $\Delta N X_{C2}$, $\Delta N Y_{C2}$, $\Delta N Z_{C2}$
- KF tracking/propagation fully consistent with G4



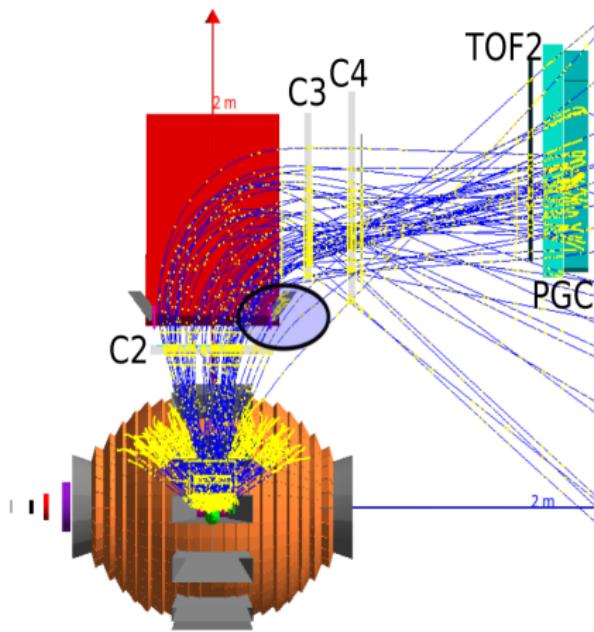
Tracking Package and the e36g4MC Comparison



- Energy loss check & e36g4MC material budget
- Δp_{C2} : momentum difference at C2 between reconstructed MC from tracking package and MC
- Anode plane → anode wires

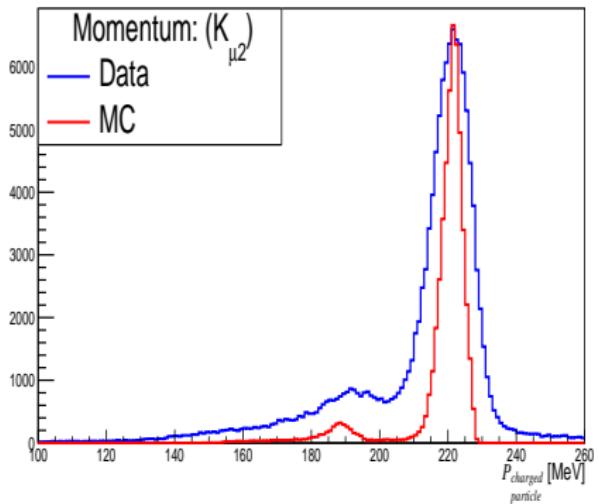


Tracking Package and the e36g4MC Comparison

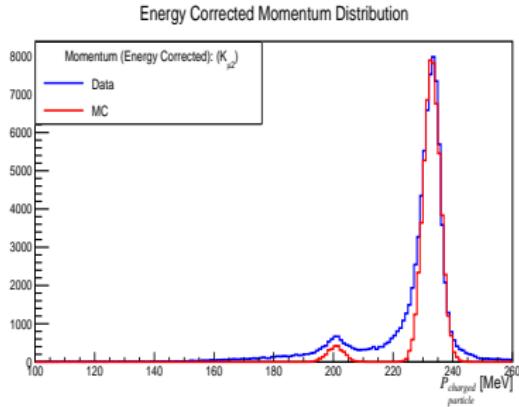
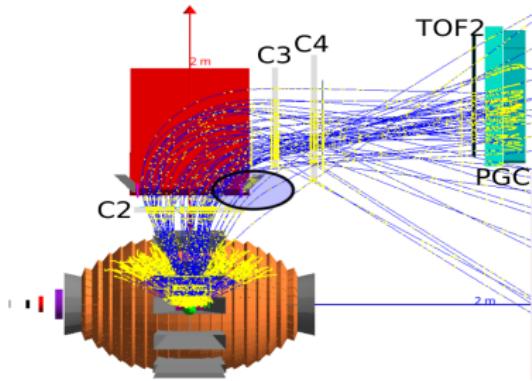


- Energy loss check & e36g4MC material budget
- Charged particle momentum at C4
- Applied offset (-2.5 MeV) to MC due to incorrect field map
- No detector resolution in the simulation

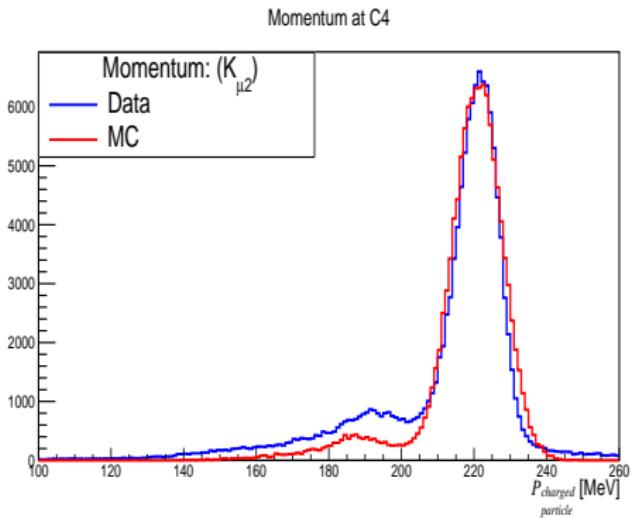
Momentum at C4



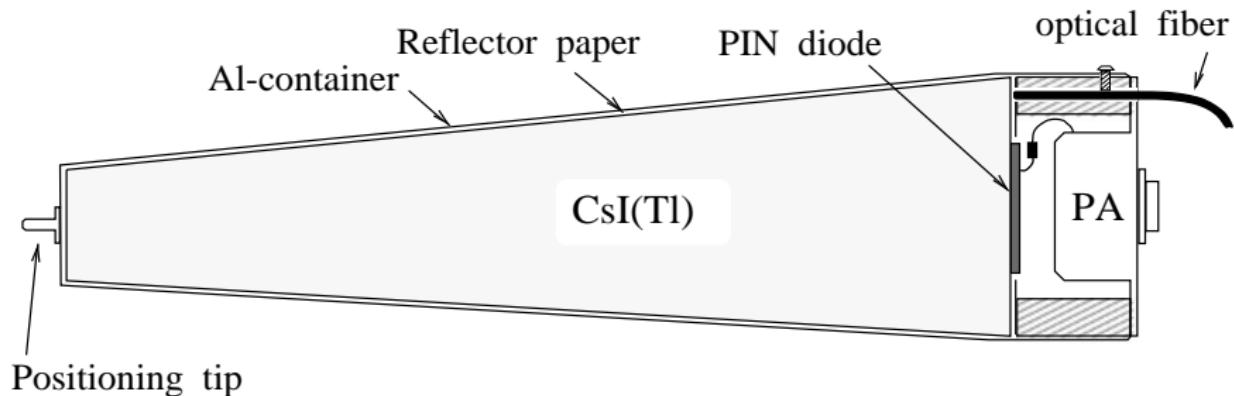
Tracking Package and the e36g4MC Comparison



- Energy loss check & e36g4MC material budget
- Charged particle momentum at C4
- Applied offset (-2.5 MeV) to MC due to incorrect field map
- Energy corrected momentum distribution
- Applied smearing of 2.86 MeV (energy corrected) and 6.01 MeV (C4)
- Smearing value was obtained by fitting a Gaussian to data



CsI(Tl) Analysis



CsI Crystal: length (25 cm), $\theta = \varphi = 7.5^\circ$

- PIN photodiodes: readout the scintillation light of the CsI(Tl) crystals
- PIN diodes and pre-amplifier was assembled in an Al container
- Output signal from pre-amplifier was fed into shaping amplifier with 1 μ s shaping time
- VF48 flash ADCs used to record shaping amplifier outputs

J. A. Macdonald (Nucl. Instrum. Meth., A506 2003)

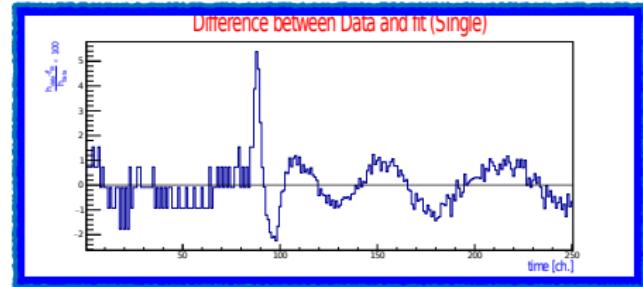
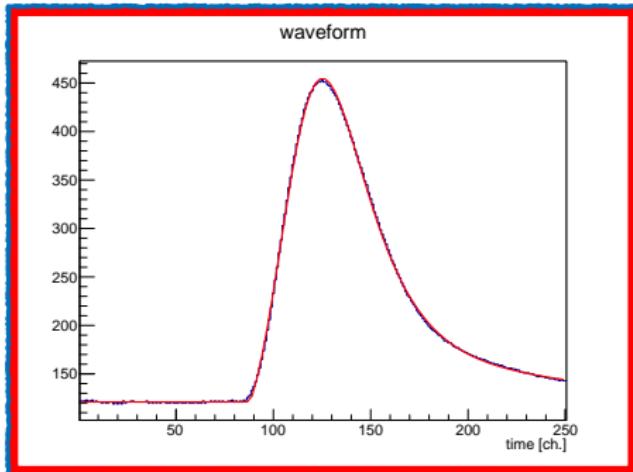
CsI(Tl) Waveform Analysis

- μ rising factor

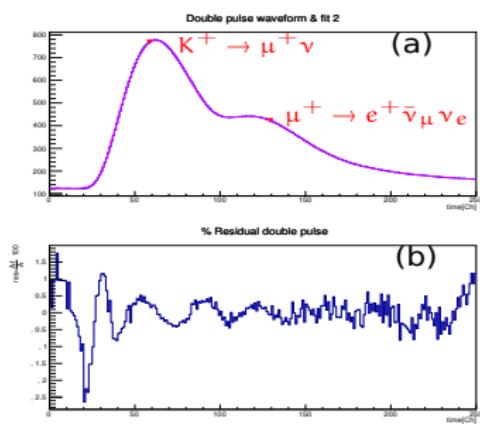
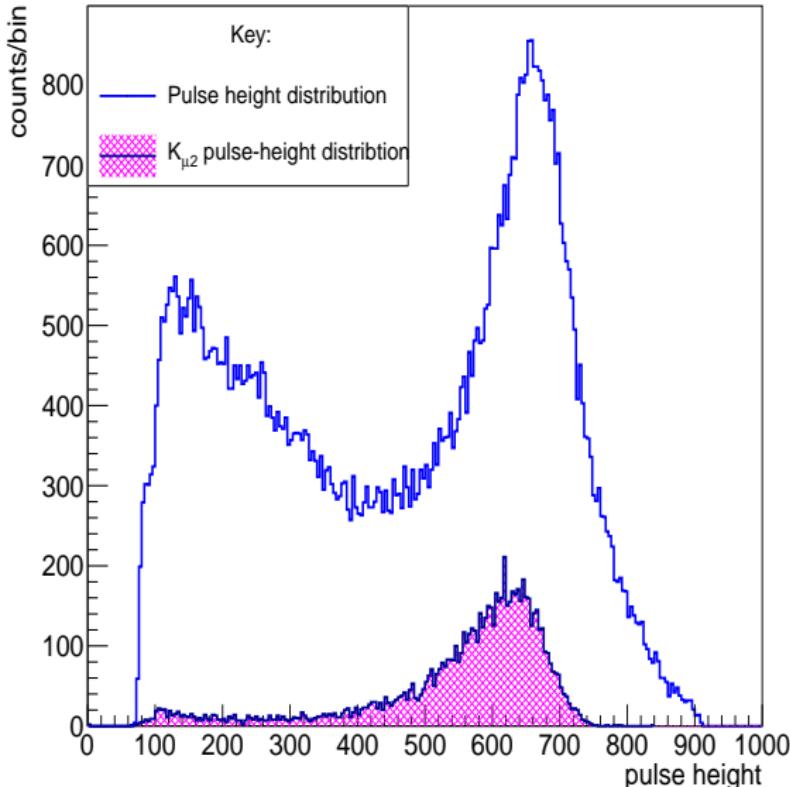
$$F(t) = \frac{A}{1 - e^{-(t-\tau_0)/\lambda}} \cdot \text{Freq} \left[\frac{t-\tau_0-d}{\mu} \right] \cdot \left(\frac{t-\tau_0}{\tau_1} e^{\left[1 - \frac{t-\tau_0}{\tau_1}\right]} + e^{\frac{t-\tau_0}{\tau_2}} e^{\left[1 - \frac{t-\tau_0}{\tau_2}\right]} \right)$$

- λ is slow shape constant
- τ_0 is rise time
- τ_1 decay constant
- τ_2 local decay constant

H. Ito (Nucl. Instrum. Meth., A901 2018)



Pulse Fitting in Action: Pulse Height Distribution

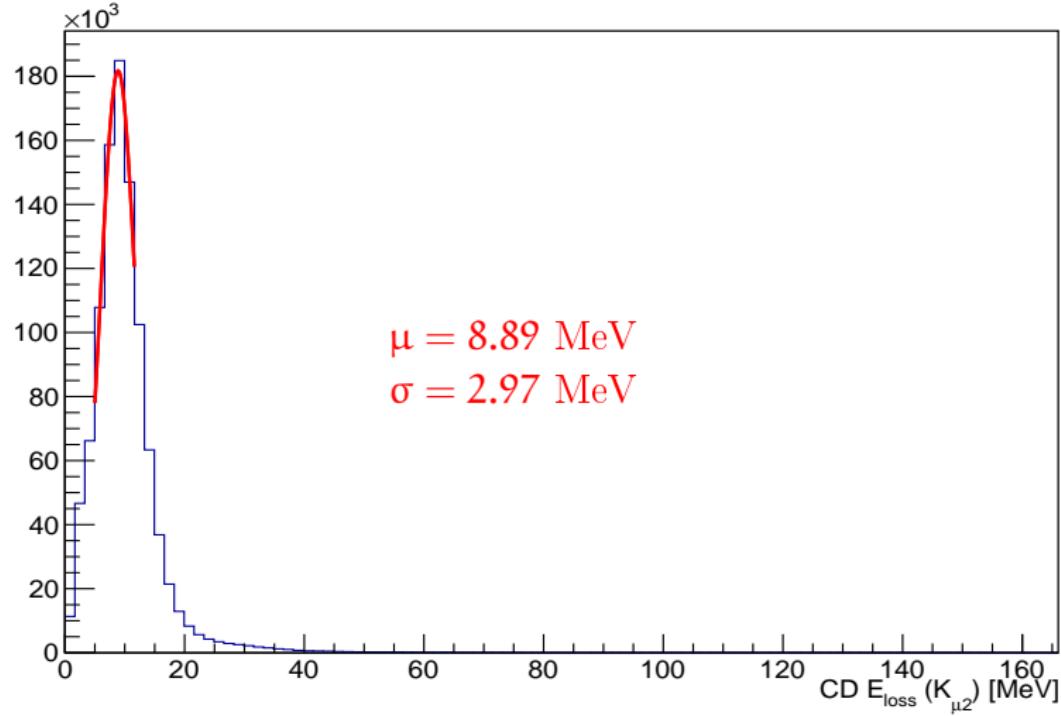


$K_{\mu 2}$ selection criteria

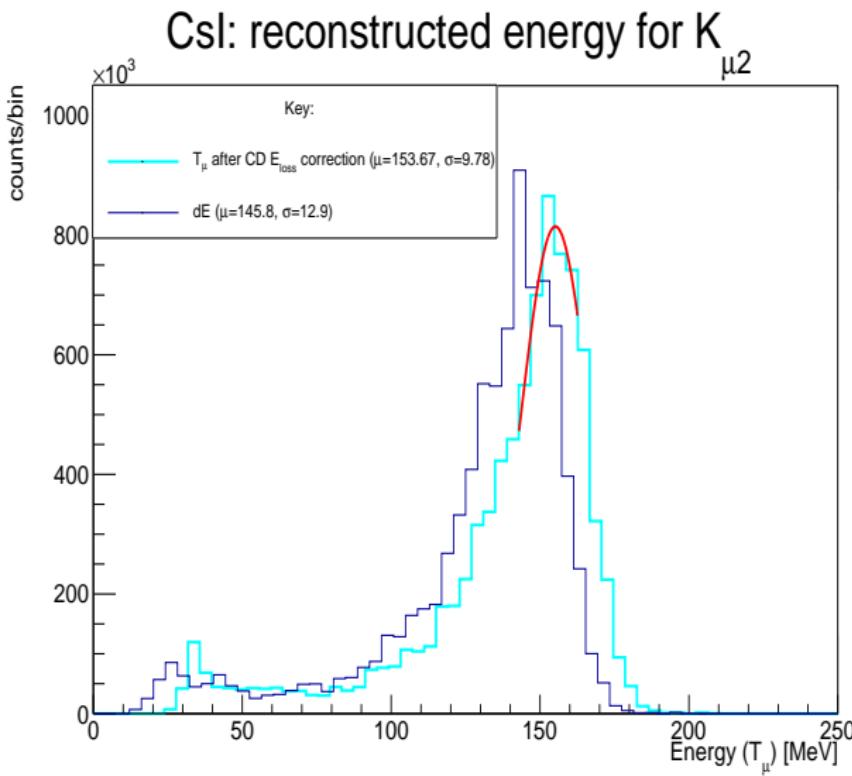
- Require single crystal per event
- First pulse time coincides with the K^+ decay
- Require a second peak

Pulse Fitting in Action: Energy Calibration from $K_{\mu 2}$

Energy loss from Central Detector (CD E_{loss}) using e36g4MC

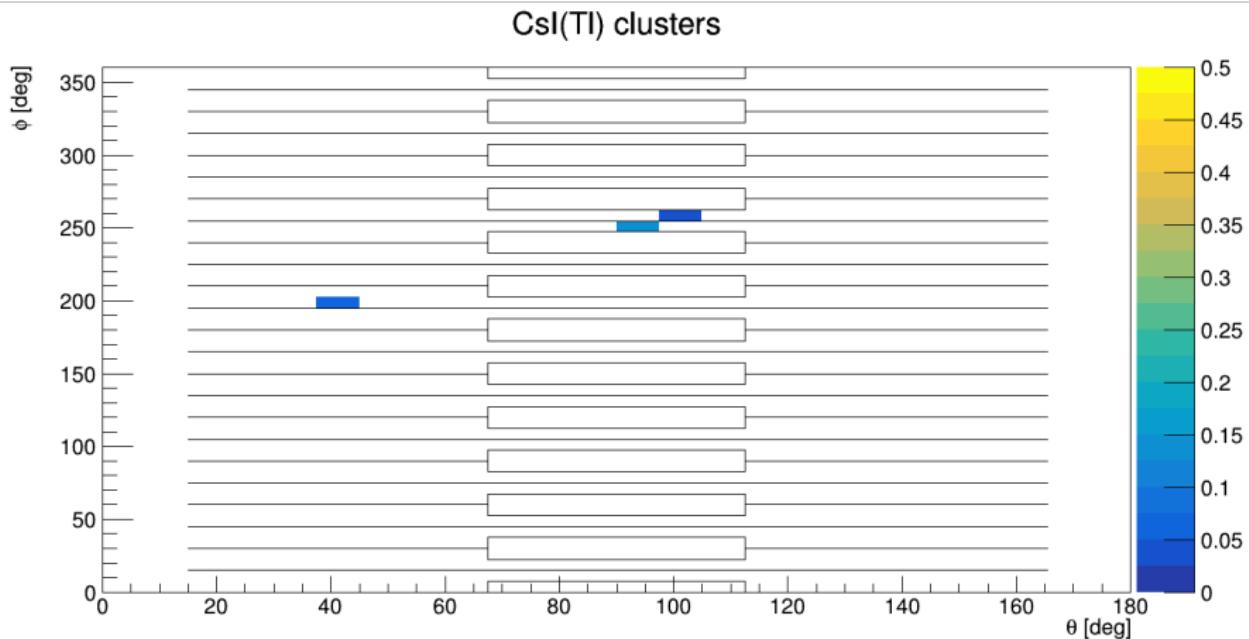


Pulse Fitting in Action: Energy Calibration from $K_{\mu 2}$



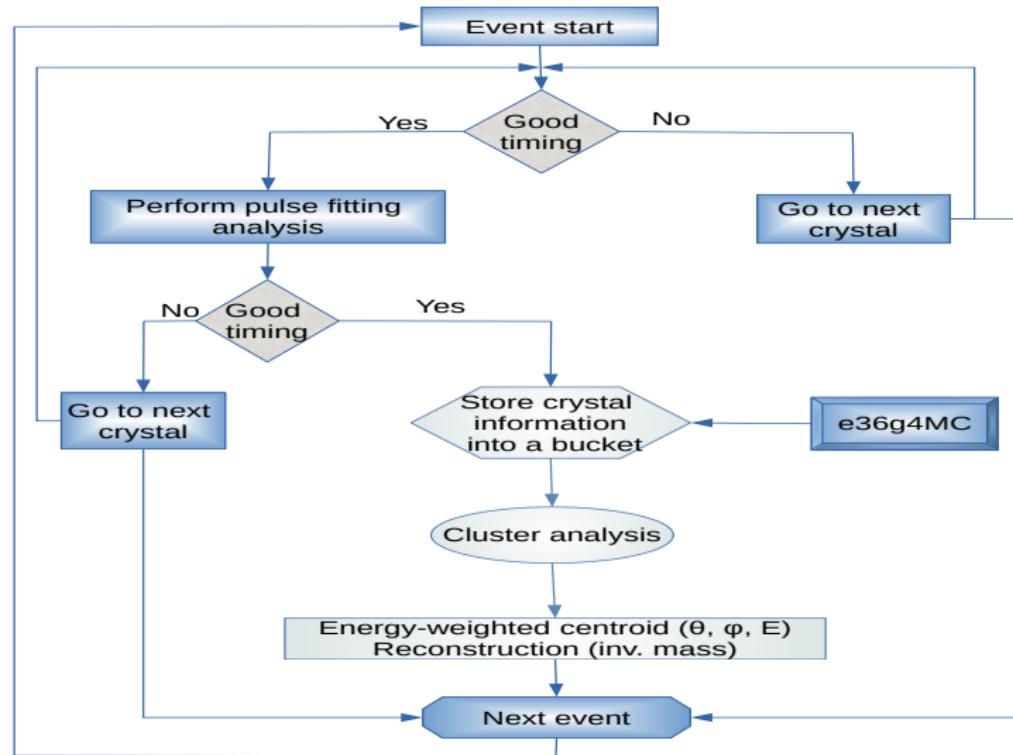
- Calibration coefficients C_i to convert pulse heights into energy
- $C_i = \frac{dE_{CsI}}{(A-P)_i}, i = 1, \dots, 768$
- dE_{CsI} : deposited energy
- A : waveform amplitude
- P : baseline
- $T_\mu = dE_{CsI} + CDE_{loss}$
- Correction for energy loss from CD system

Cluster Analysis: Event Viewer

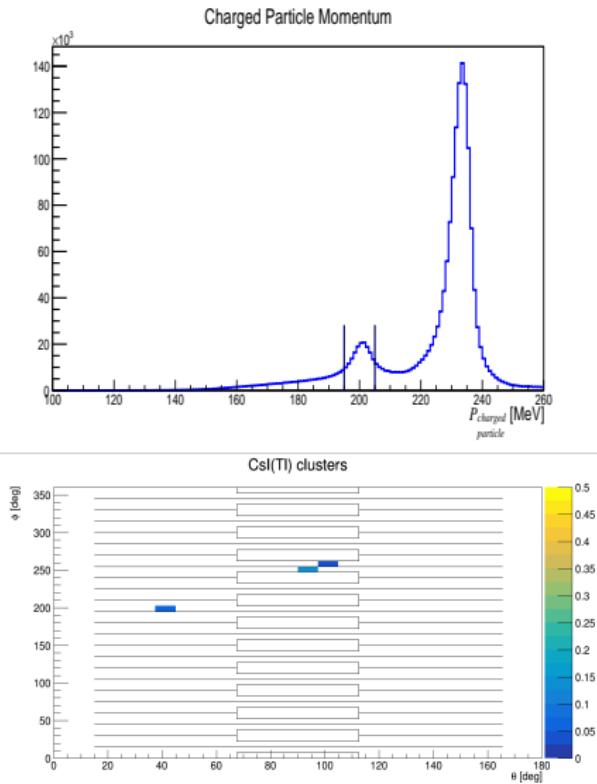


- Single event
- Reconstructed m_{π^0} from $M_{\gamma\gamma} = 123.7 \text{ MeV}/c^2$
- PDG: $m_{\pi^0} = 134.9766 \text{ MeV}/c^2$

CsI Cluster Analysis



CsI Cluster Analysis Cont...

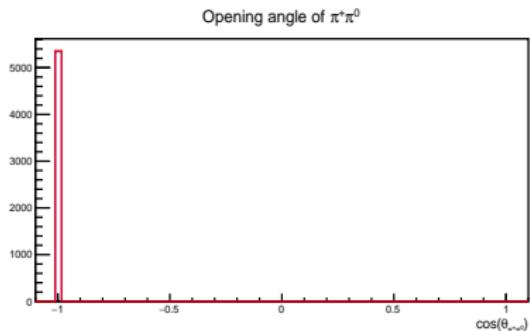
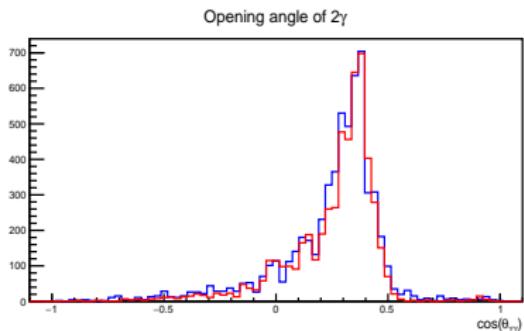
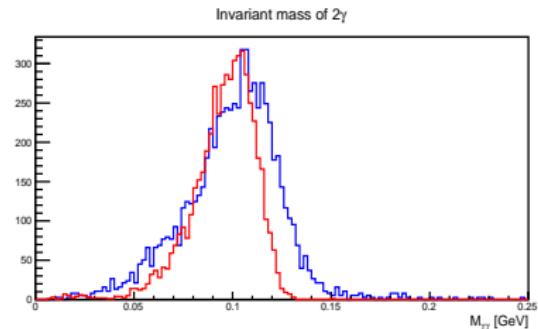
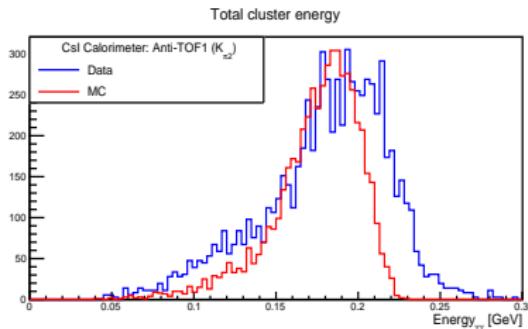


Cluster criterion: $K^+ \rightarrow \pi^+ \pi^0$

- High hardware trigger due to high rate
- Several clustering patterns need to be considered
- Currently single crystal clusters are considered as well
- Analysis is performed for prompt $\pi^0 \rightarrow \gamma\gamma$, while only considering two cluster events
- Suppress backgrounds by requiring only single TOF1 counter has fired
- Apply tight angle cut:

$$\cos(\theta_{\pi^+ \pi^0}) \leq -0.99$$

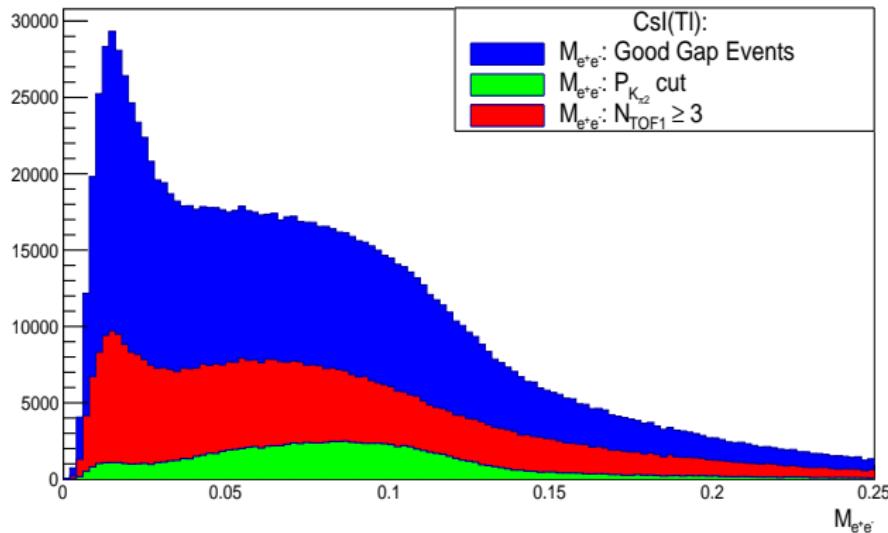
CsI $K_{\pi 2}$ Cluster Analysis



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

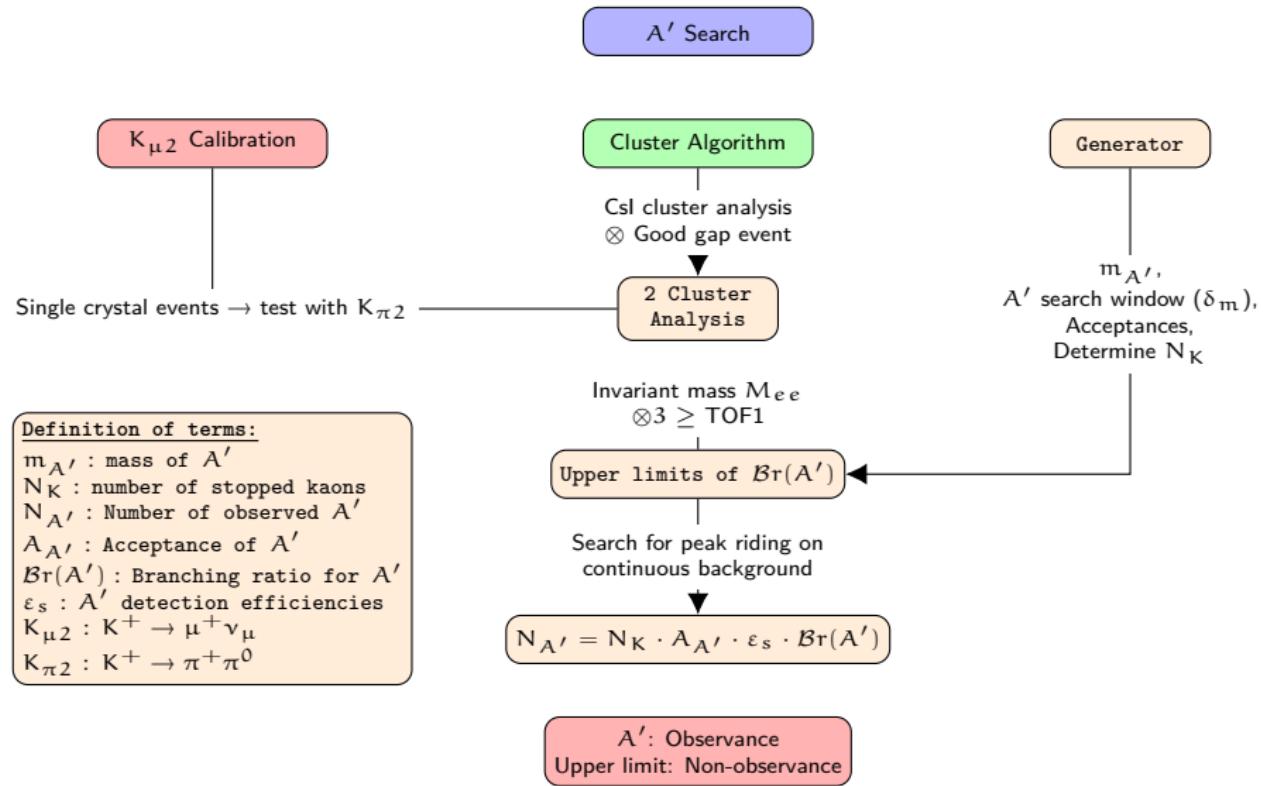
- $\cos(\theta_{\pi^+\pi^0}) \leq -0.99$: tight opening angle cut

Invariant Mass Spectrum

Invariant mass of e^+e^- 

- Invariant mass spectrum under the 3 cut conditions
- The blue histogram contains all events
- Green histogram has pronounced bump around the π^0 mass
- Interested in the red histogram for the A' search

Analysis Strategy for A' Search



Generator Channels

K⁺ 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	$K^+ \rightarrow \pi^+ \pi^+ \pi^- \gamma$	1.04×10^{-4}
14	$K^+ \rightarrow \mu^+ \nu A'$	$\epsilon^2 \times \text{ratio of channel 16}$
15	$K^+ \rightarrow \pi^+ A'$	$\epsilon^2 \times \text{ratio of channel 17}$
16	$K^+ \rightarrow \mu^+ e^+ e^- \nu$	2.5×10^{-5}
17	$K^+ \rightarrow \pi^+ e^+ e^-$	3×10^{-7}

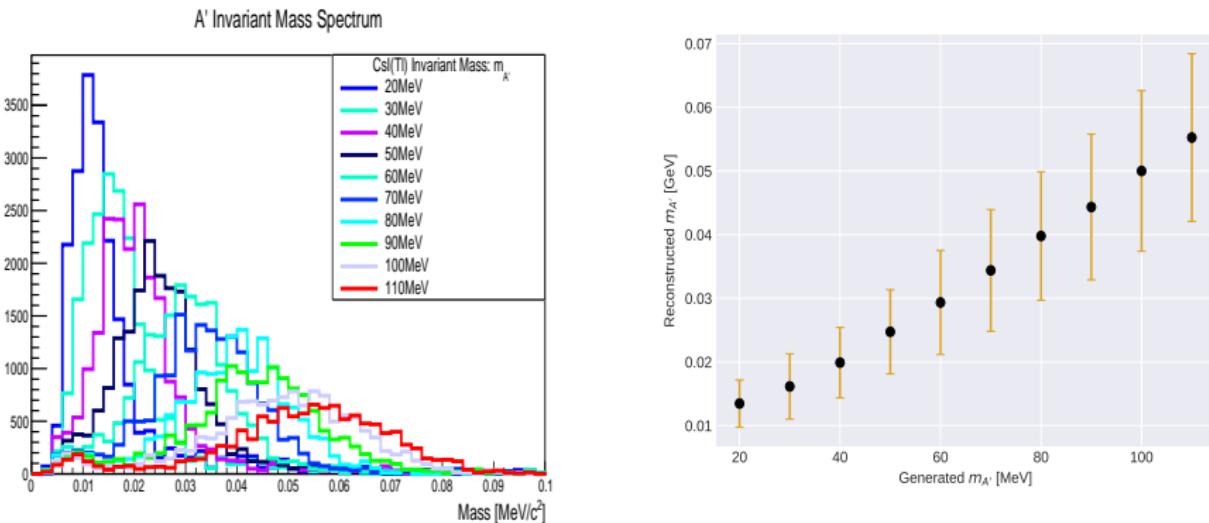
π^0 Channels

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

ROOT based generator

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

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

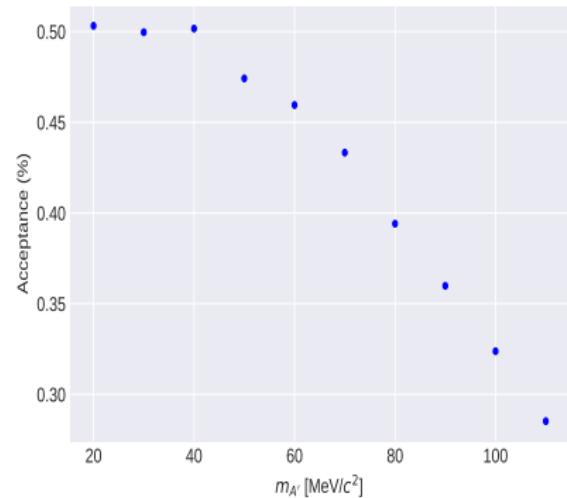
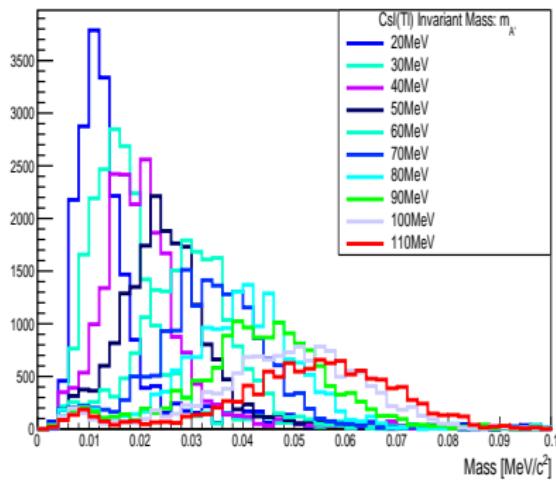


- A' masses generated on interval 20 – 110 MeV
- $m_{A'}$ reconstructed from e^+e^- clusters in the CsI

- Mean $m_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(m_{A'})$ was obtained from fit

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

A' Invariant Mass Spectrum

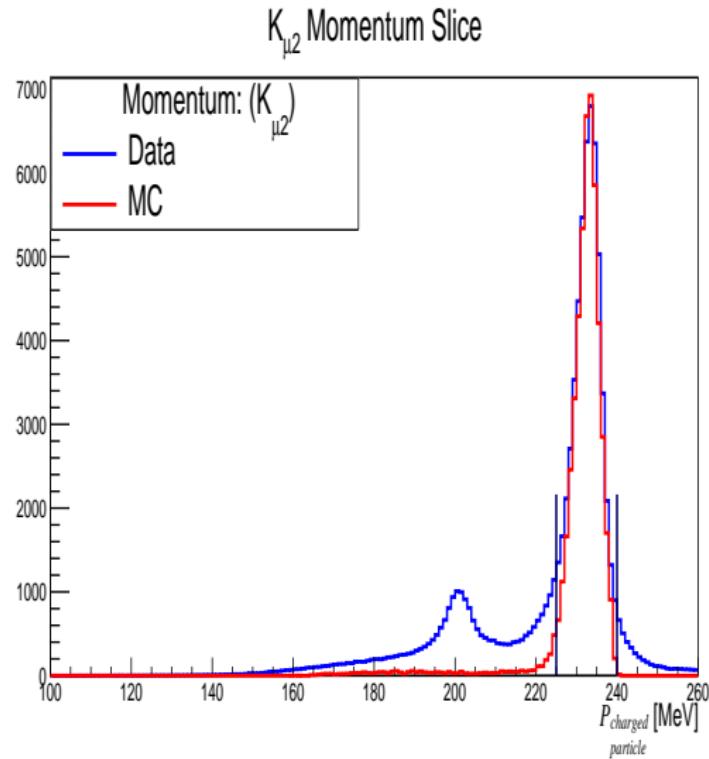


- A' masses generated on interval 20 – 110 MeV
- $m_{A'}$ reconstructed from e^+e^- clusters in the CsI
- Mean $m_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(m_{A'})$ was obtained from fit

Number of Stopped K^+ (N_K)

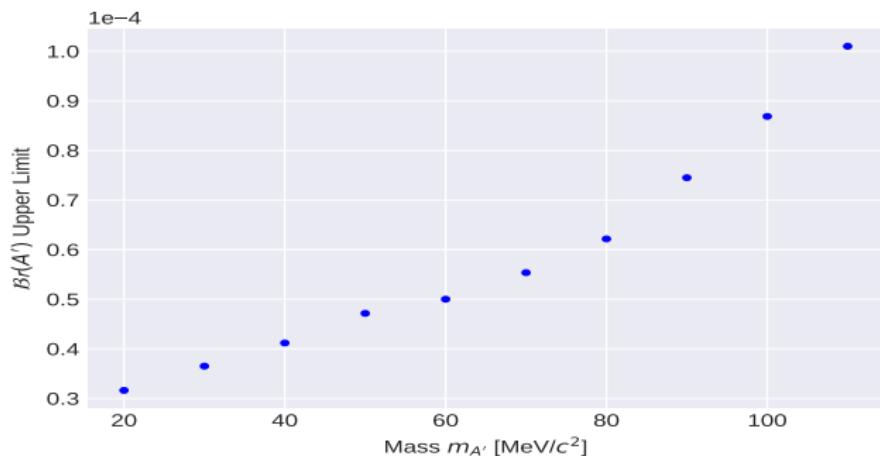
$$N_K = \frac{N_{\mu 2}}{\mathcal{B}r(\mu 2) PS(\mu) A_\mu LT(\mu)} \\ = 2.81 \cdot 10^9$$

- 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 1σ cut around mean P_μ , from $K_{\mu 2}$ decays



Expected $N_K = 3.48 \cdot 10^{10}$

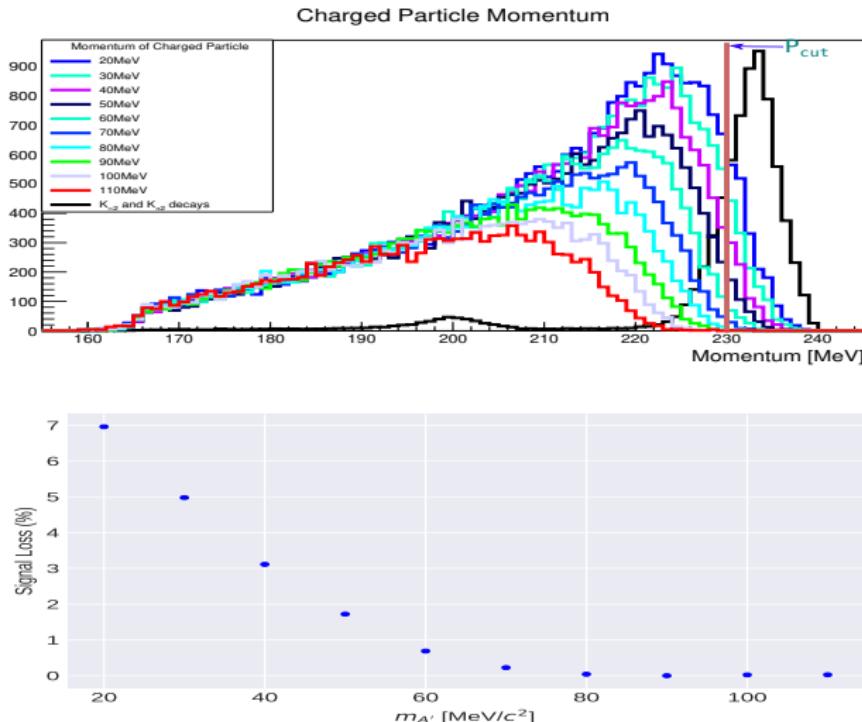
Upper Limit Extraction



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

- No peak in M_{ee} spectrum \rightarrow twice background fluctuation in search window
- 2σ limit: $\sim 95\%$ CL of no signal observance
- $A_{A'}$: 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

$K_{\mu 2}$ Contamination Reduction

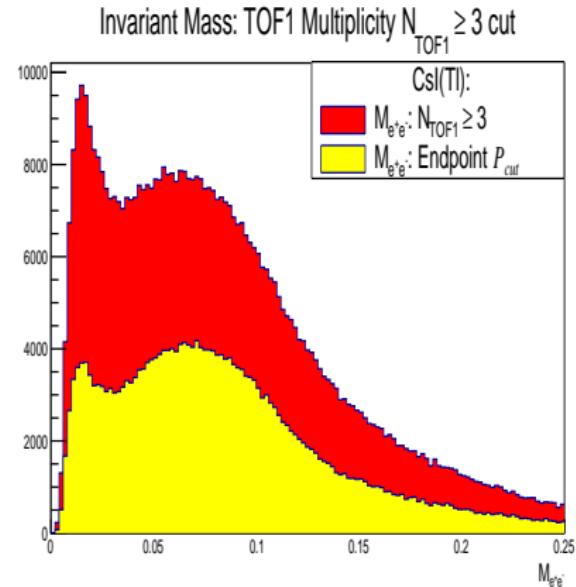
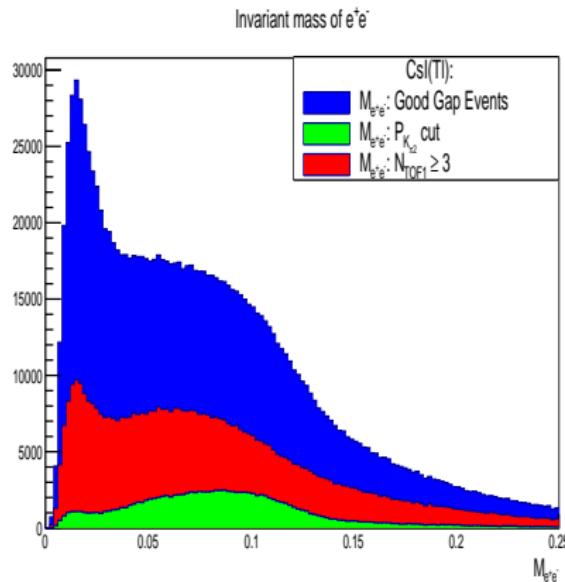


- Signal Loss $S_L = \frac{S_{cut}}{S_{tot}}$

- S_{cut} is integrated signal that survives cut

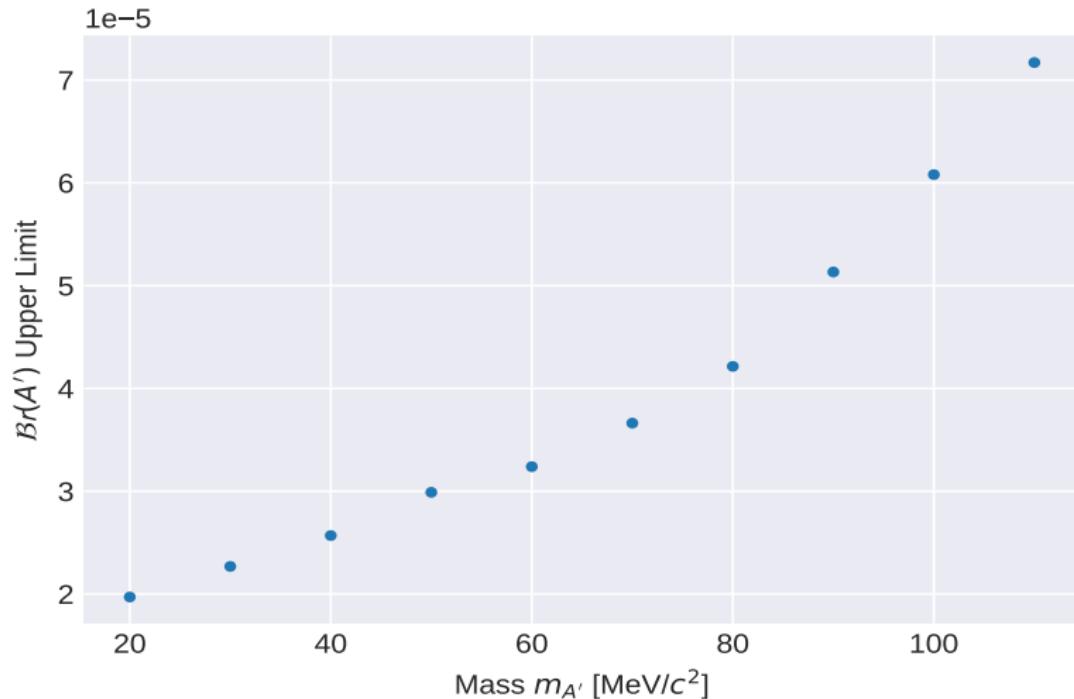
- S_{tot} is total integrated signal

Invariant Mass Spectrum M_{ee} after $K_{\mu 2}$ Cut



- From 105 runs ($\sim 8.08\%$ of total Fall data)
- Improvements to tracking, M_{TOF}^2 , and PID is underway \rightarrow background reduction
- Analysis of more data files is currently underway

Background Suppressed Upper Limits



105 runs: ~ 8.08% data

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 $K_{\pi 2}$
- CsI cluster finder developed within Cooker analysis framework
- We have generated various masses for A'
- Upper limits for $\mathcal{Br}(K^+ \rightarrow \mu^+ \nu A')$ have been extracted for various $m_{A'}$
- Improvements from PID analysis for reducible background reduction
- Digitizing e36g4MC CsI can improve comparison with data
- Improve CsI calibration with $K_{\pi 2}$, global gain correction

Collaborators

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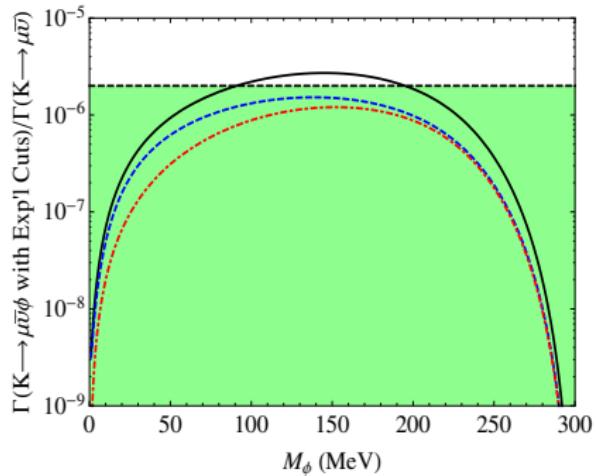
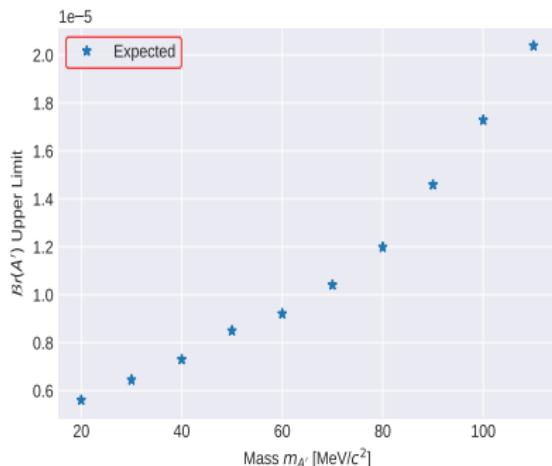
Osaka University
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Institute for Particle and Nuclear Studies

RUSSIA

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

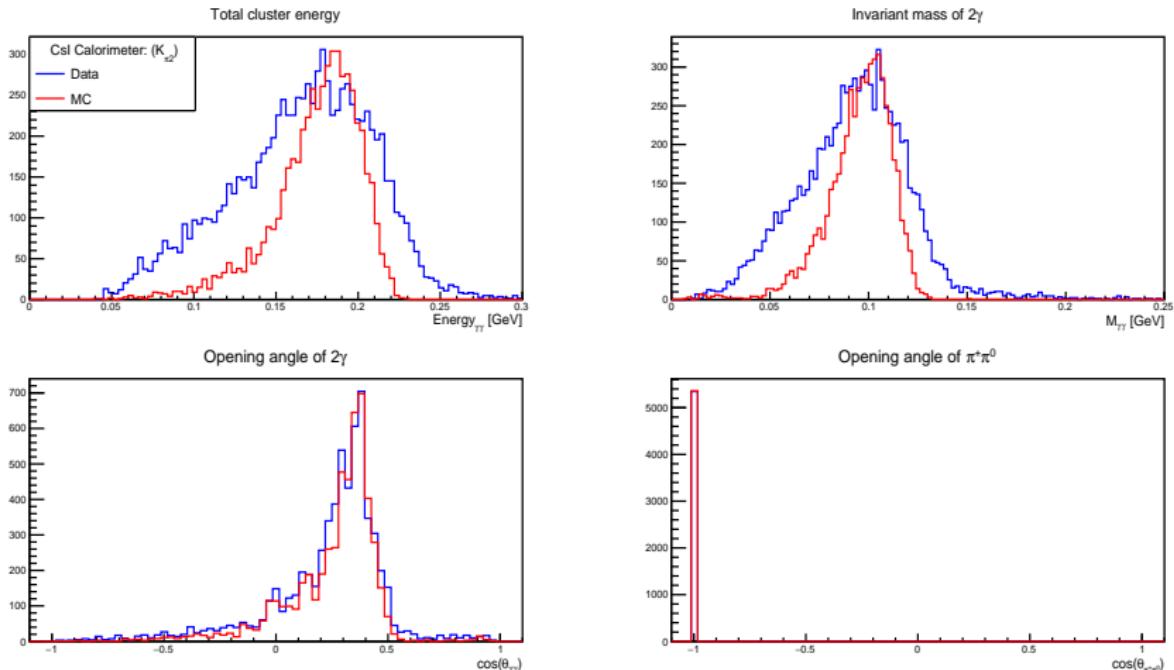
Backup

Expected Upper Limits



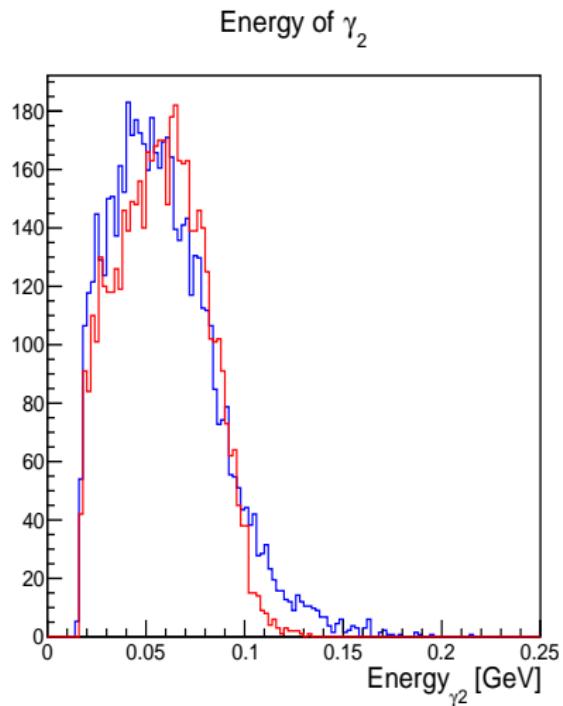
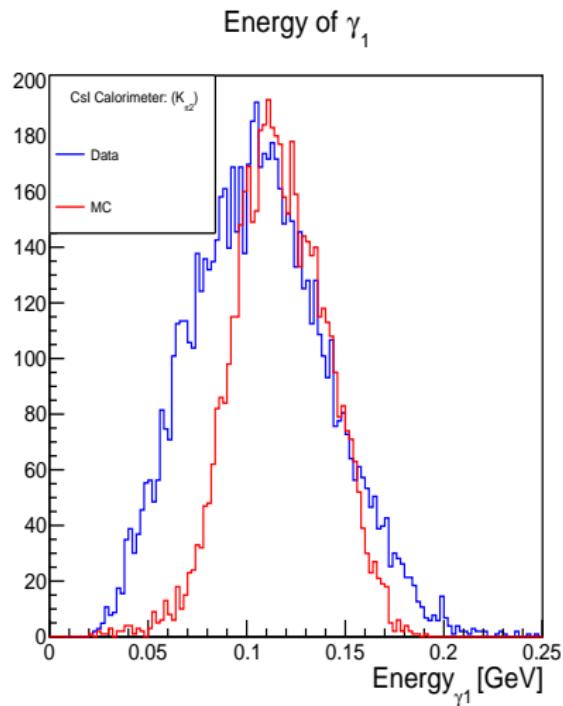
- Solid curve full result satisfying proton radius and $(g-2)_\mu$
- Shaded region is allowed: $< \mathcal{O}(-6)$

CsI 2 Cluster Events



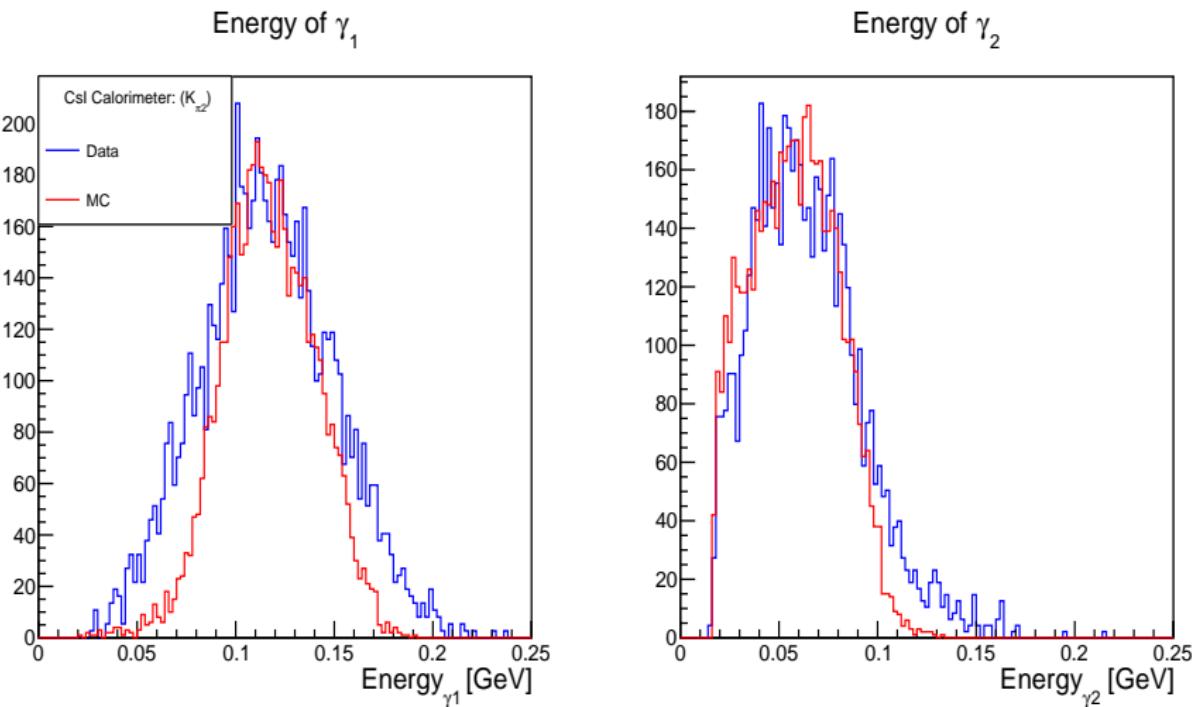
- Two cluster events under K _{π^2} momentum cut
- e36g4MC: Generator channel 7 was used

Energy of $\gamma 1$ and $\gamma 2$



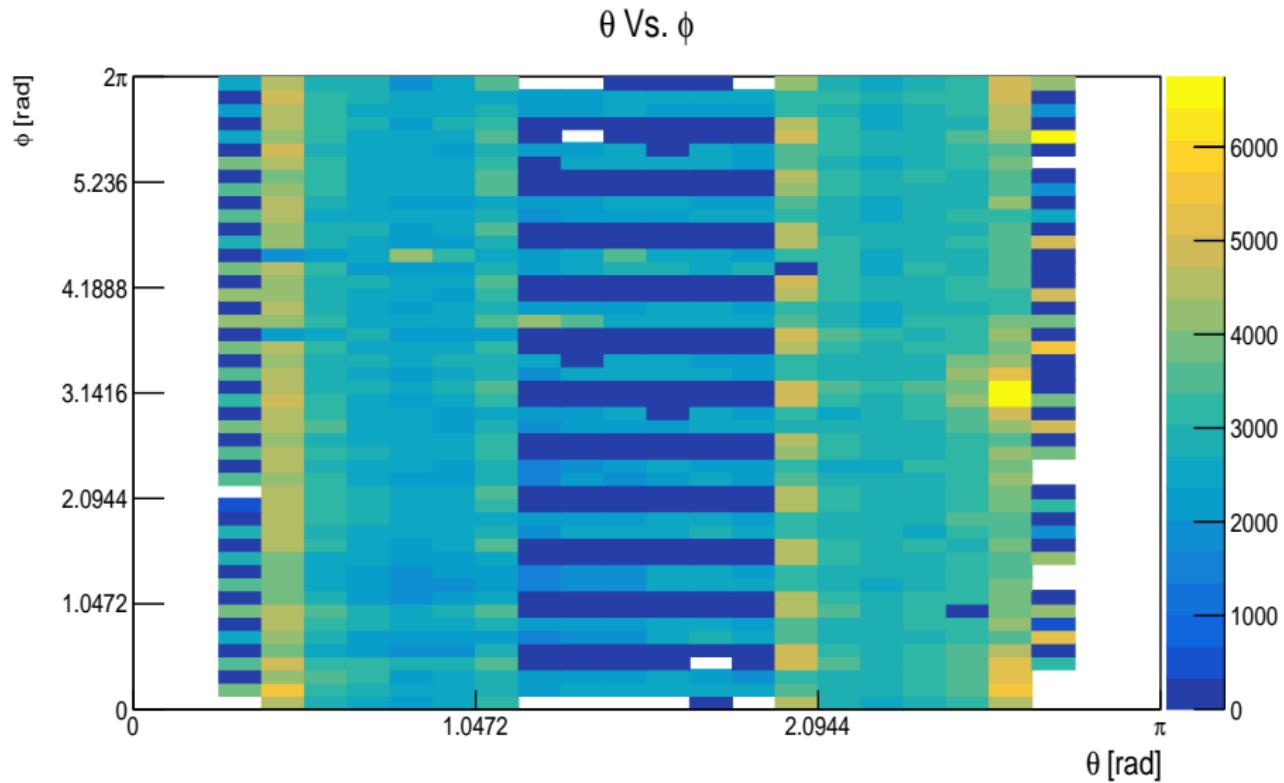
- $\cos(\theta_{\pi^+ \pi^0}) \leq -0.995$

Energy of γ_1 and γ_2 TOF1 cut

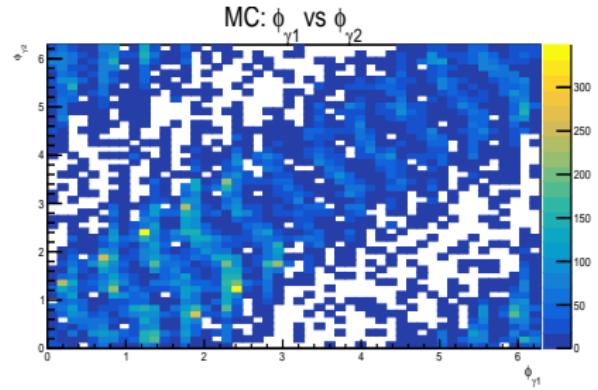
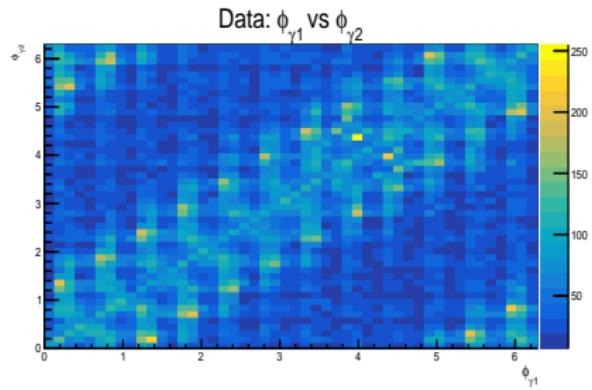
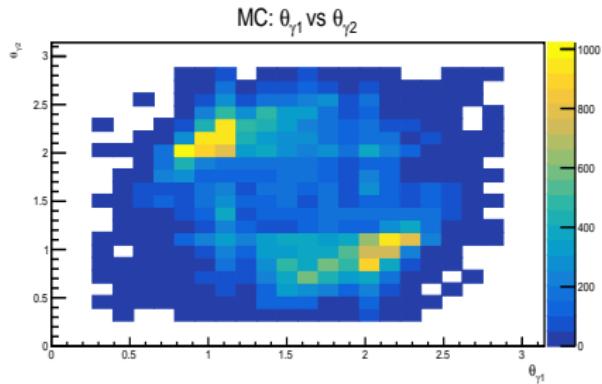
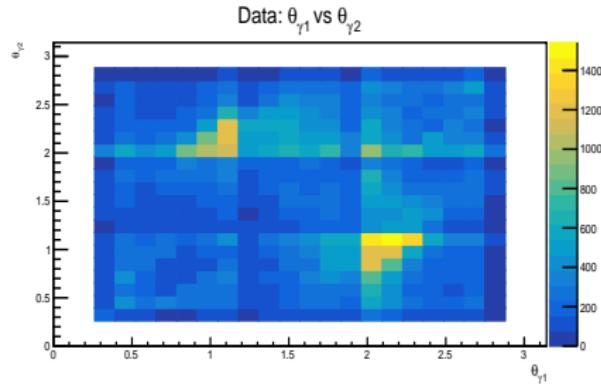


- $\cos(\theta_{\pi^+ \pi^0}) \leq -0.995$
- only one TOF1 counter has fired

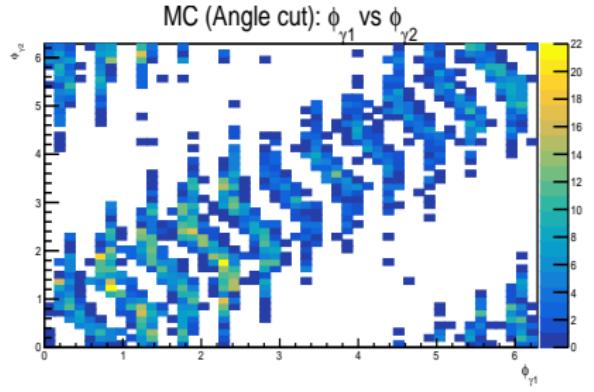
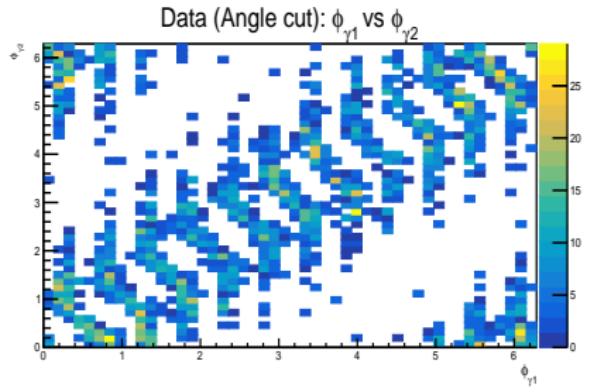
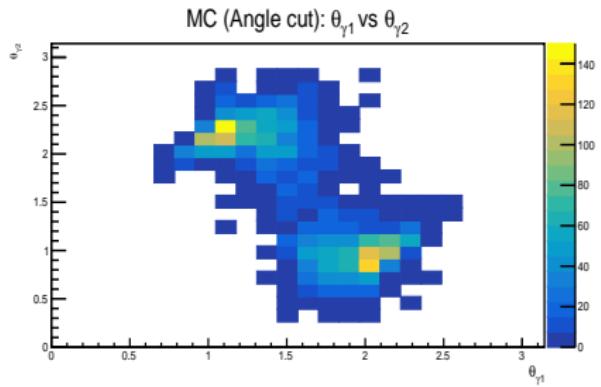
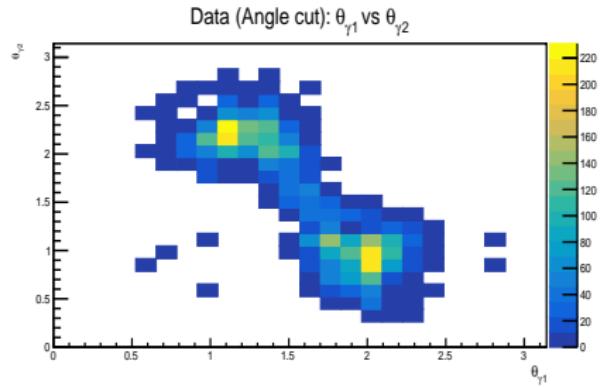
Theta Vs Phi



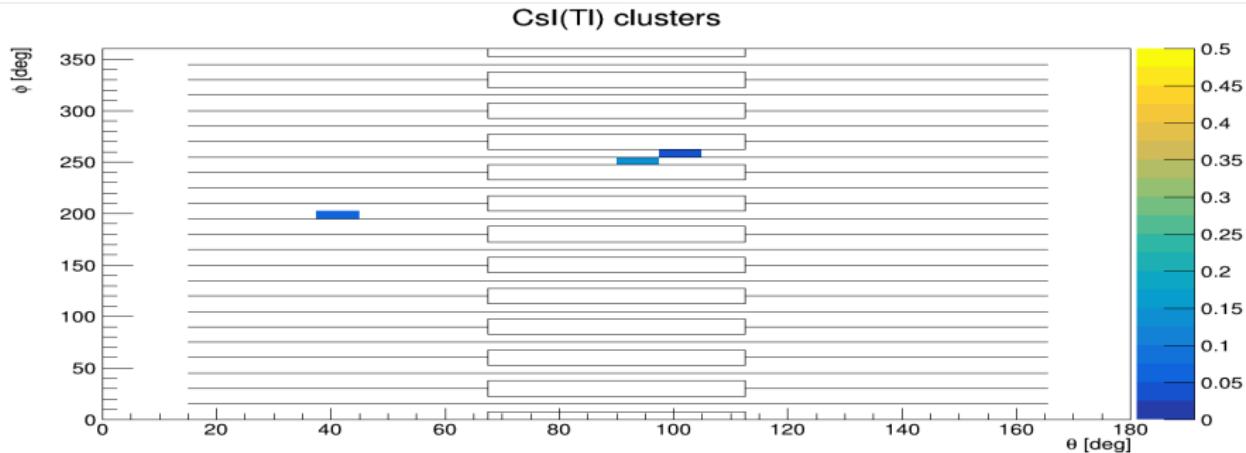
Angular Correlations: $\theta_{\gamma 1}$ vs. $\theta_{\gamma 2}$



Angular Correlations: $\theta_{\gamma 1}$ vs. $\theta_{\gamma 2}$ ($\cos(\theta_{\pi^+\pi^0})$ cut)



Cluster Analysis



```
Terminal
File Edit View Search Terminal Help
piPecking total Cluster Energy: 0.228424
Angular1 checking (centriod) (1.6597, 4.40859)
Angular2 checking (centriod) (0.719948, 3.46884)
Checking pi0 InvMass: 0.123707
Checking cos(theta): 0.32072
Checking vertex opening -0.900161
cluster multiplicity: 2

Number of clusters is : 1
Number of single clusters is: 1
*****
```