

Search for light neutral bosons in the TREK/E36 experiment at J-PARC

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Pre-Defense Meeting

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

1 Introduction

- Additional Mass

2 Dark Matter From High Energy Physics

3 Simulation Study

- Geant4 Geometry

- Verification Of The e36g4MC

4 Analysis

- Overview
- CsI(Tl) Analysis
- Generator
- A' Search

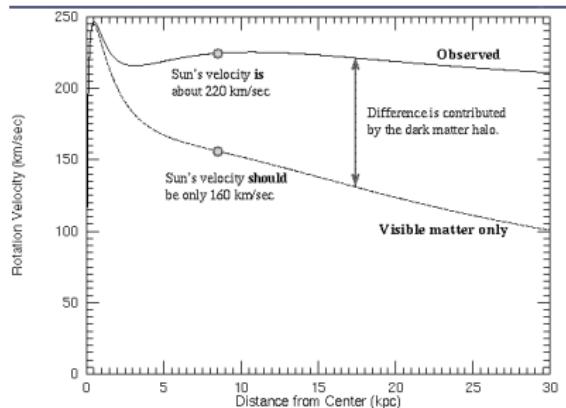
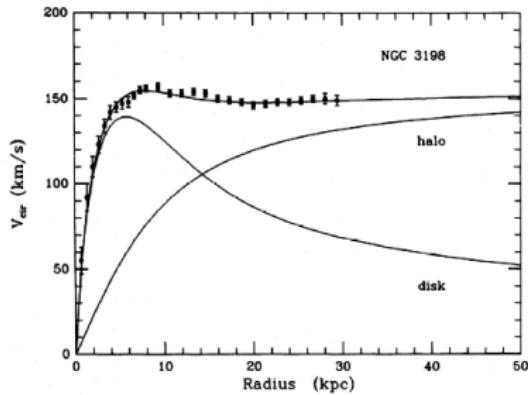
5 Closing

Rotation Curves Of Galaxies



Vera Rubin

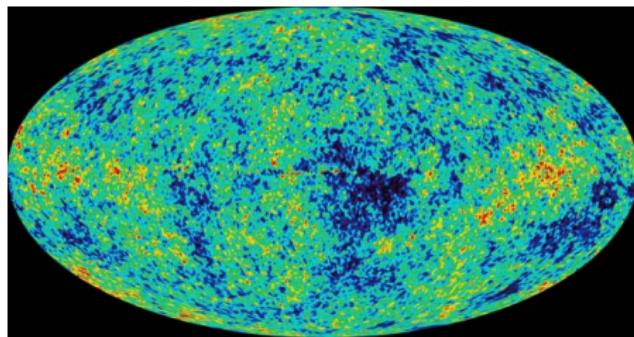
DISTRIBUTION OF DARK MATTER IN NGC 3198



- Studied rotation curves of galaxies
- Found that they are FLAT!

► Katherine Freese (Public lecture)

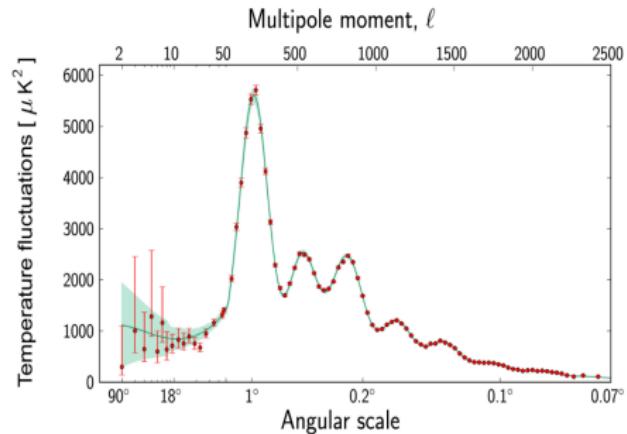
Cosmic Microwave Background (CMB)



Jeff Filippini (► UC Berkeley Cosmology Group)

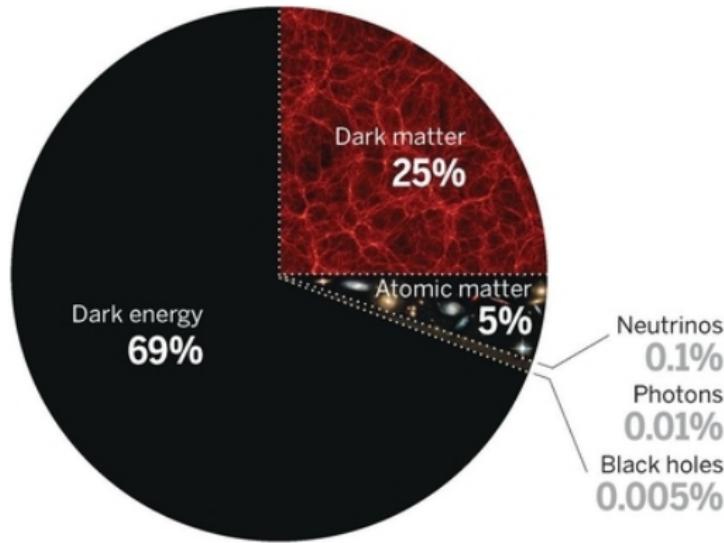
CMB and power spectrum:

- 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
- Oscillations in the hot gas of the early universe, resonant frequencies and amplitudes

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



THE DAILY GALAXY

The experiment known as DarkLight, developed by MIT physics professor Pet 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

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. Renato walked Popular Mechanics through what this new finding means and how DarkLight might prove it exists.

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

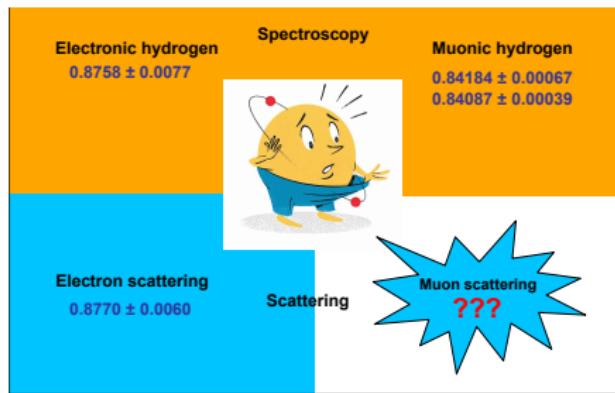
PHYS.ORG

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

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



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

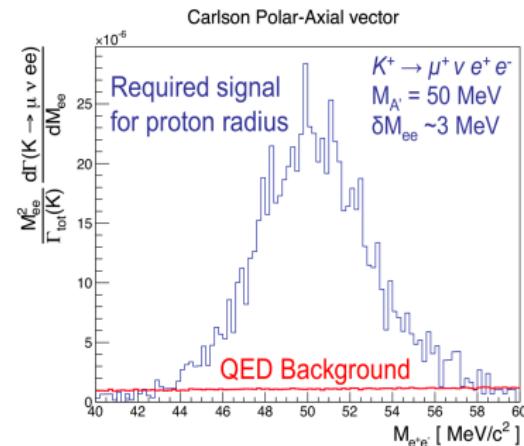
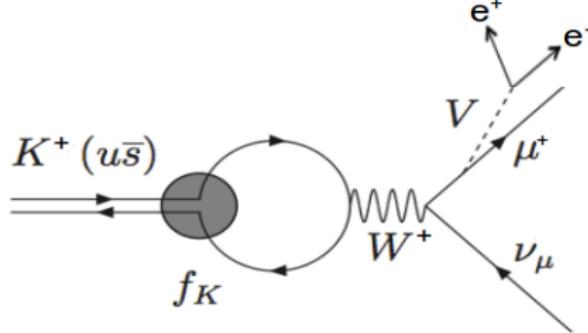
1) 3×10^8

2) 2×10^9

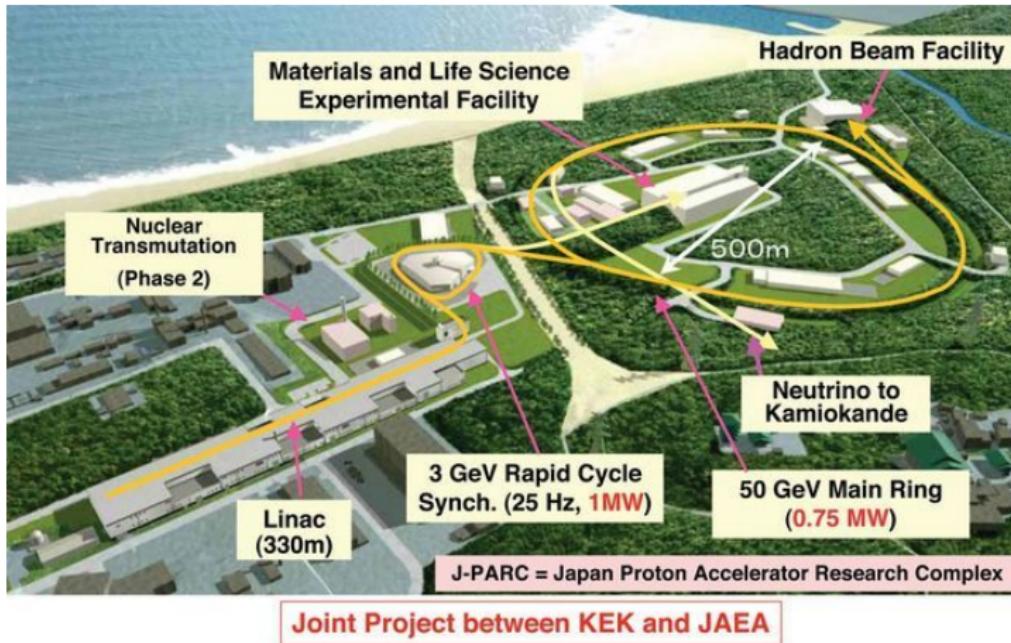
π^0 production: $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.3%) $K^+ \rightarrow \pi^+ \pi^0$ (21.1%)

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

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



Bird's Eye View Of J-PARC



Timeline Of TREK/E36

TREK: Time Reversal Experiment with Kaons



December 2014

- Installed detector components

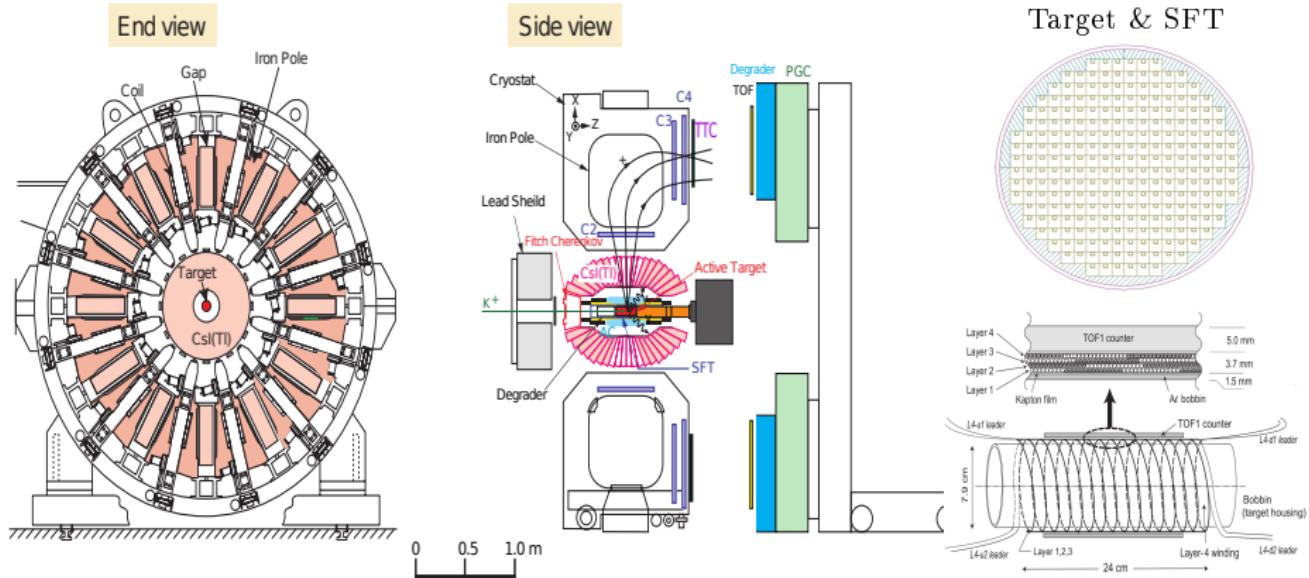
February - June 2015

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

September - December 2015

- Physics run
- Data taking

E36 Detector Geometry



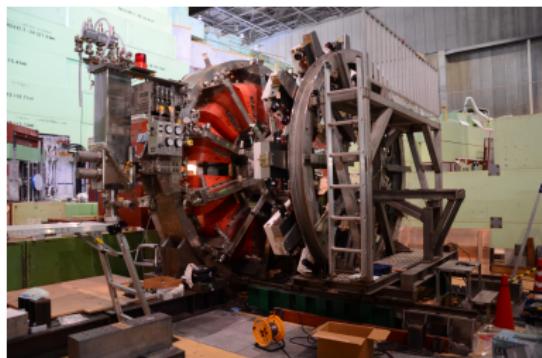
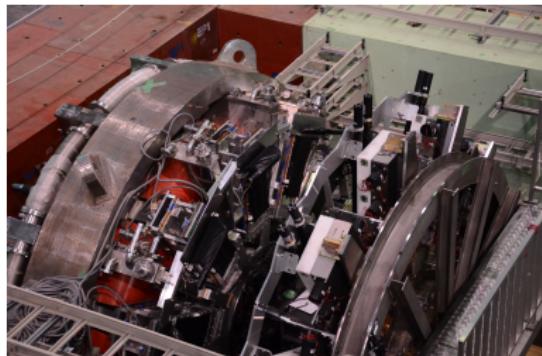
Stopped K⁺ method
K1.1BR beamline
K⁺ stopping target

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

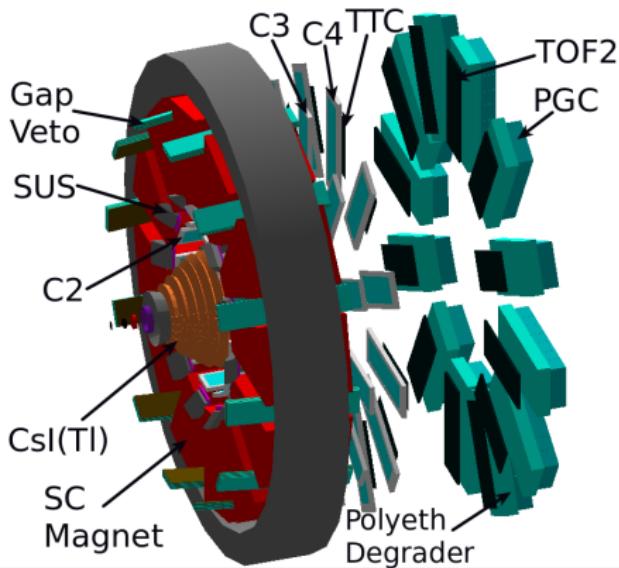
Particle ID
TOF
AC
PGC

Gamma ray
CsI(Tl)

Geant4 Generated Geometry

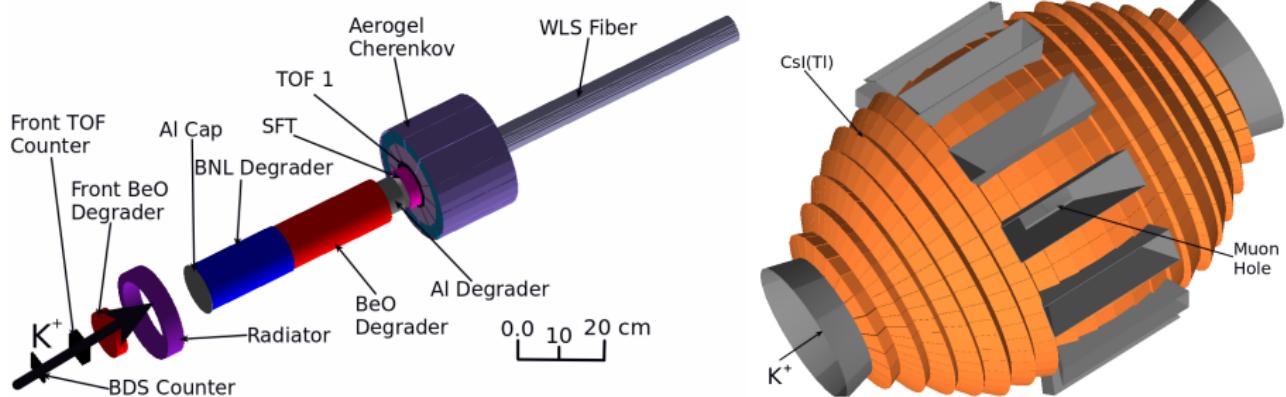


- Detector Assembly



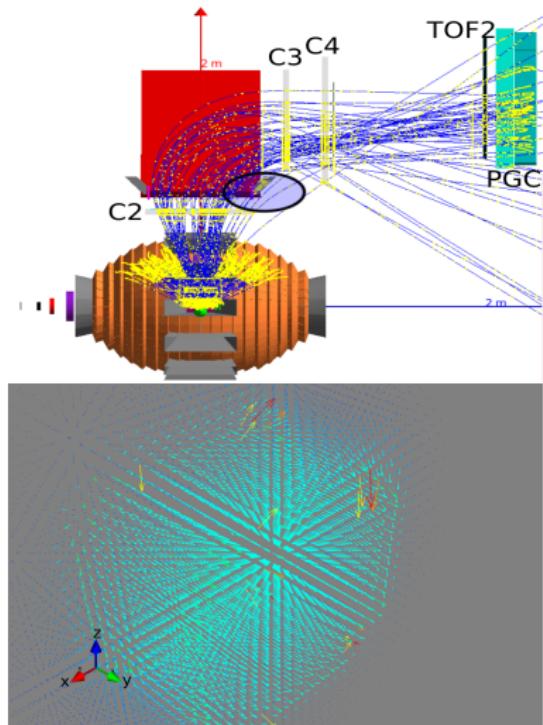
- e36g4MC detector geometry

Geant4 Cont.: Central Detector

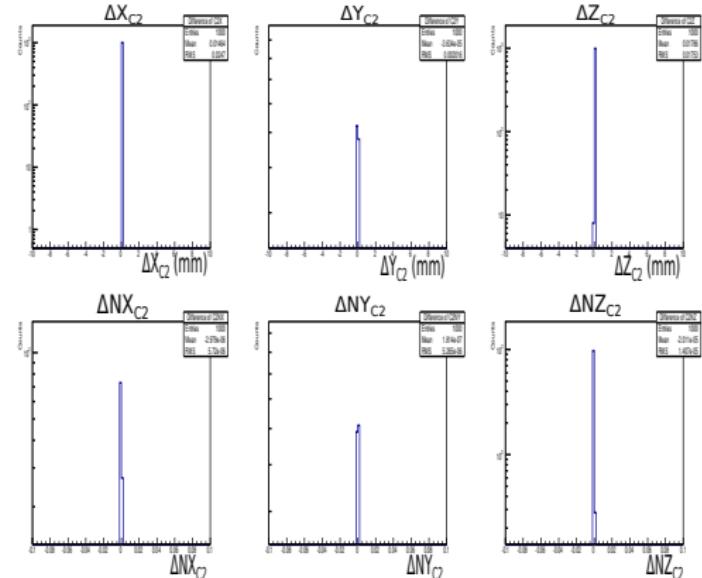


- Central Detector

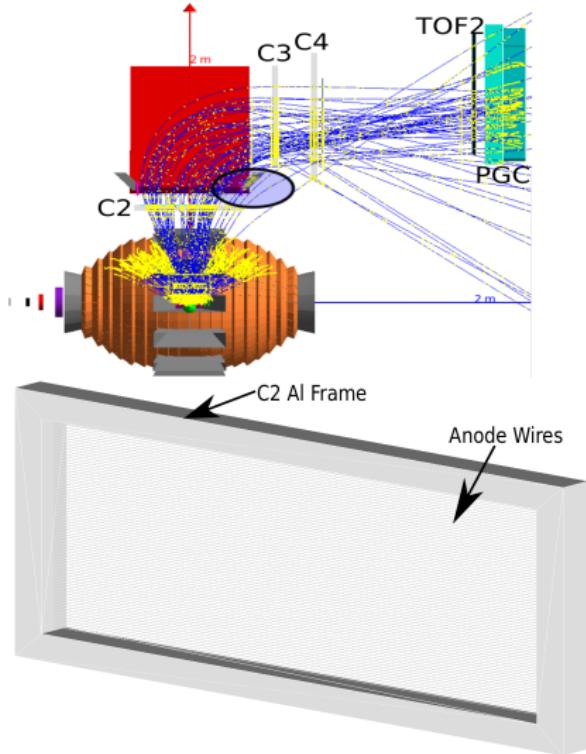
Tracking Package and The e36g4MC Comparison



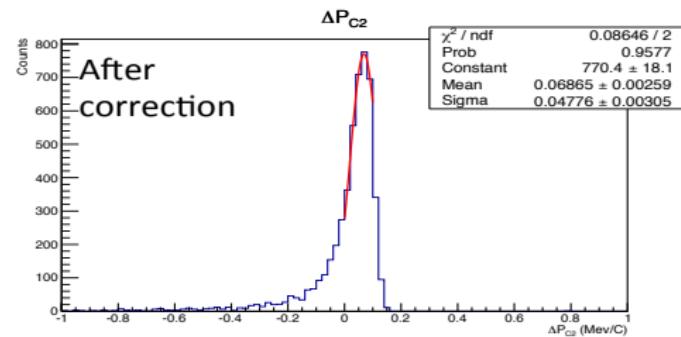
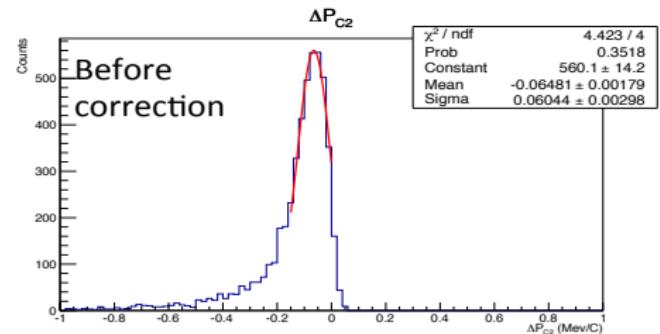
- Consistency check: propagation and magnetic field evaluation
- Simulated data: tracks propagated and reconstructed with Kalman Filter (KF)
- Established that KF tracking/propagation fully consistent with G4



Tracking Package and The e36g4MC Comparison

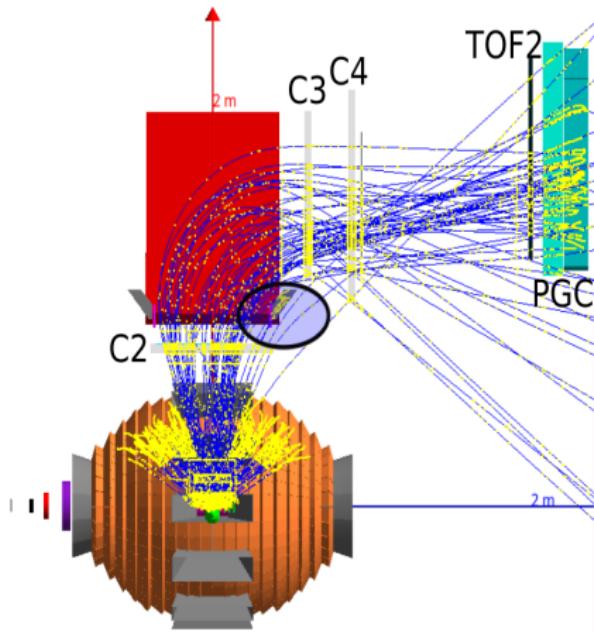


- Energy loss/material budget comparison
- Anode plane → anode wires

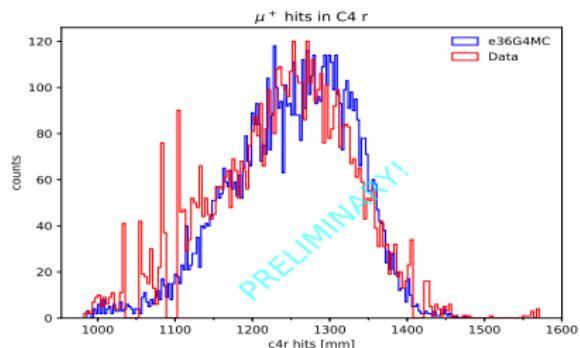
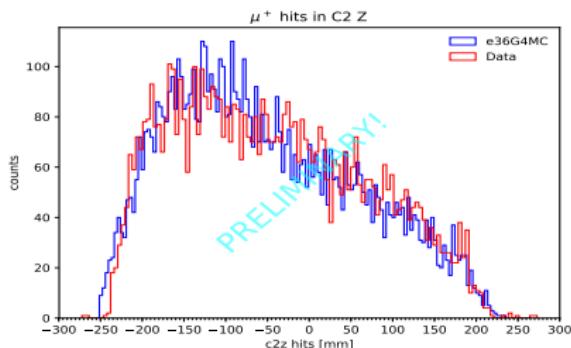
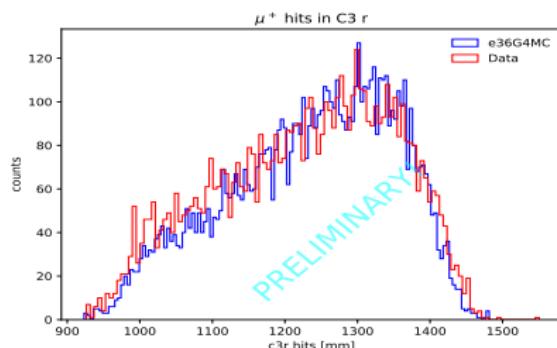
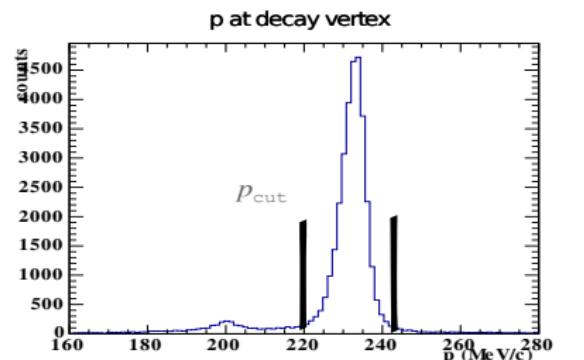


Tracking Package and The e36g4MC Comparison

- Energy loss/material budget comparison
- Momentum distribution of $K_{\mu 2}$ and $K_{\pi 2}$ at C4
- No detector resolution in the simulation

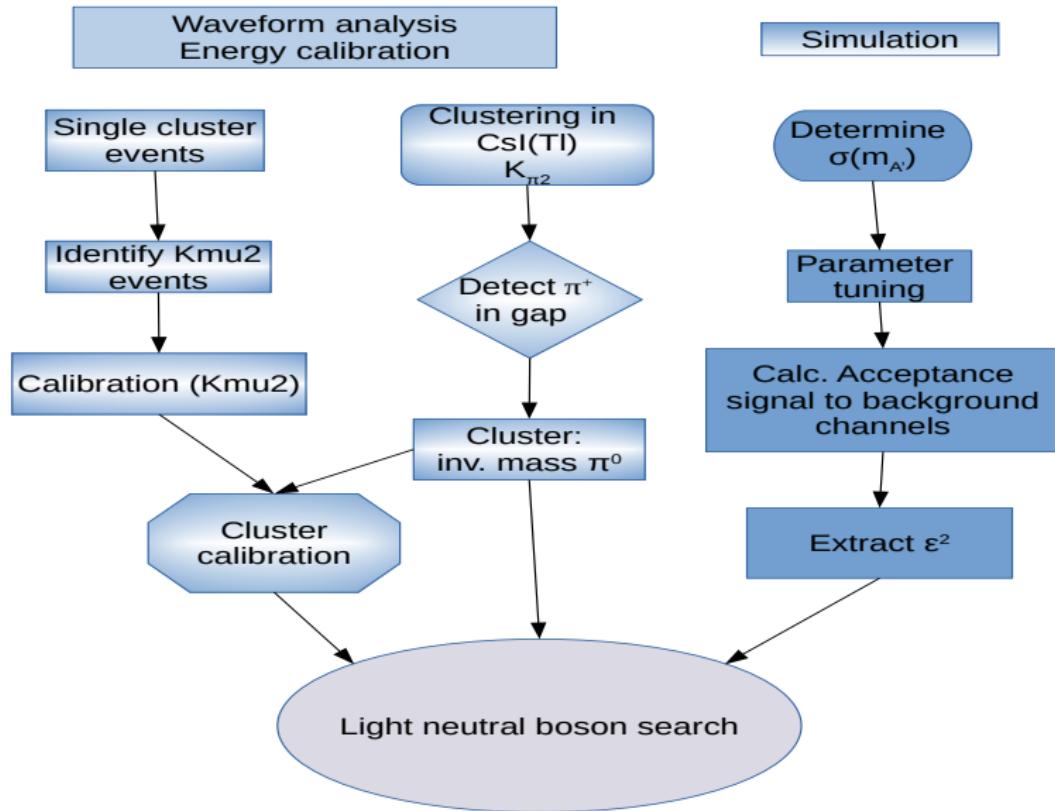


$$K^+ \rightarrow \mu^+ \nu_\mu \quad (P_{\mu^+} = 236 \text{ MeV/c})$$

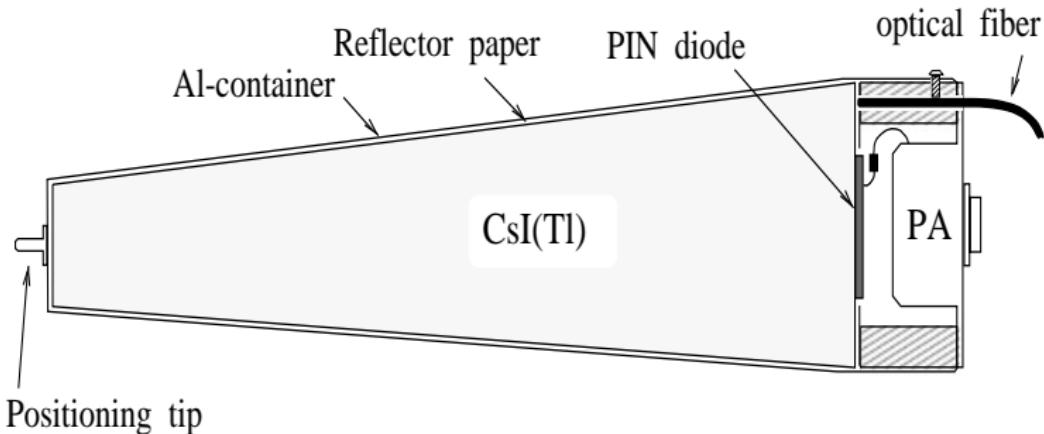


- Trigger on Target \otimes TOF1 \otimes TTC \otimes TOF2
- $z = 2.5\text{cm}$ and $x = y = 0.0\text{cm}$ $\sigma_z = 8.75\text{cm}$, $\sigma_{x,y} = 0.15\text{cm}$
- Updates in progress

Analysis Scheme



CsI(Tl) Analysis



- 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)

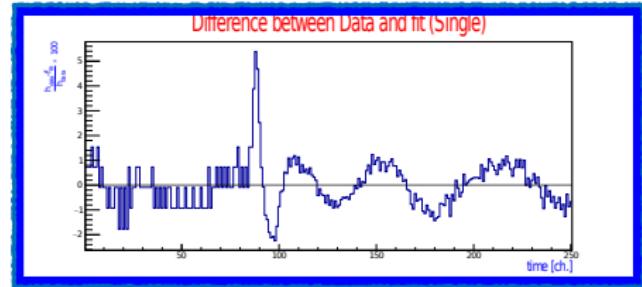
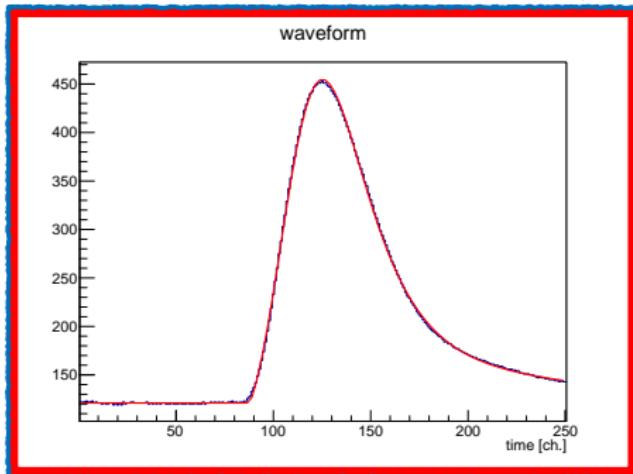
CsI(Tl) Waveform Analysis

- μ rising factor

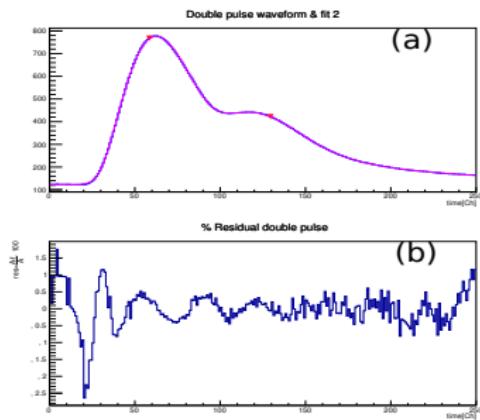
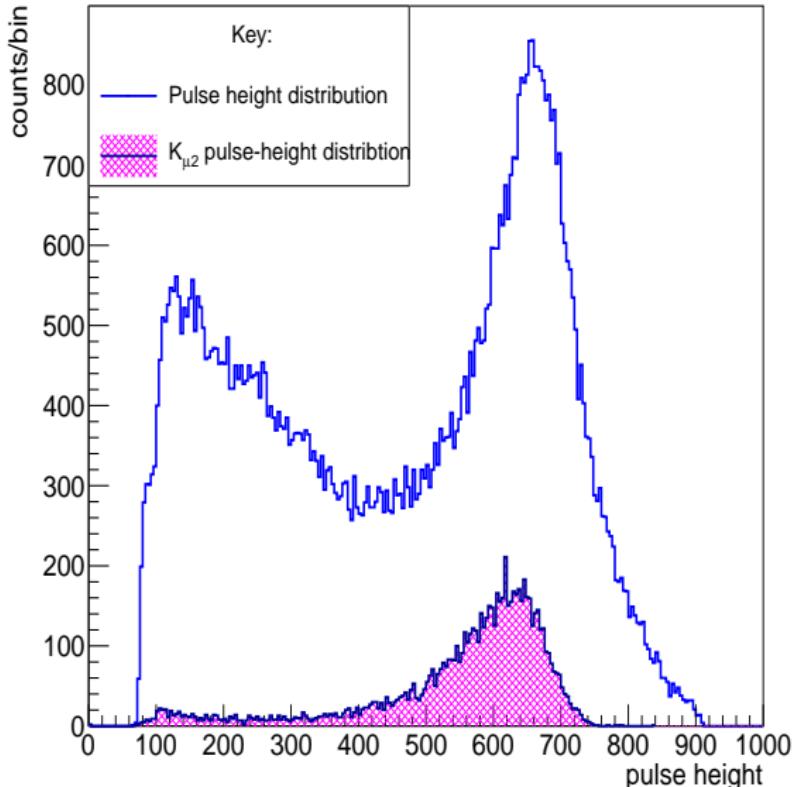
$$F(t) = \frac{A}{1 - e^{-(t-\tau_0)/\lambda}} \cdot \text{Freq} \left[\frac{t-\tau_0-d}{\mu} \right] \cdot \left(\frac{t-\tau_0}{\tau_1} e^{\left[1 - \frac{t-\tau_0}{\tau_1}\right]} + e^{\frac{t-\tau_0}{\tau_2}} e^{\left[1 - \frac{t-\tau_0}{\tau_2}\right]} \right)$$

- 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

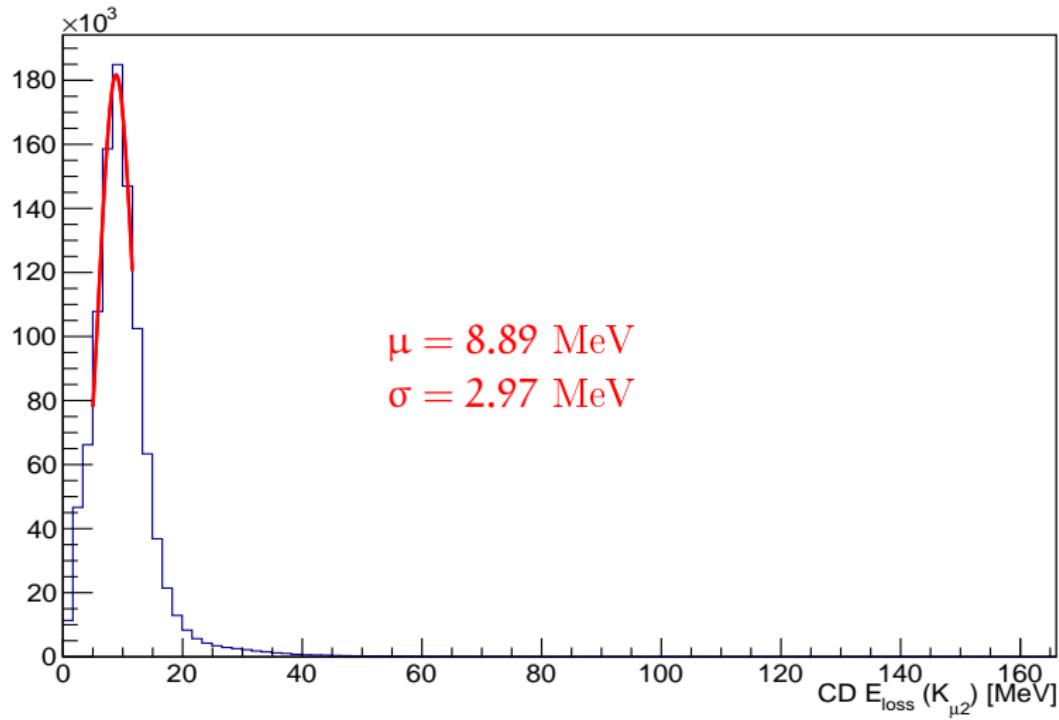


$K_{\mu 2}$ selection criteria

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

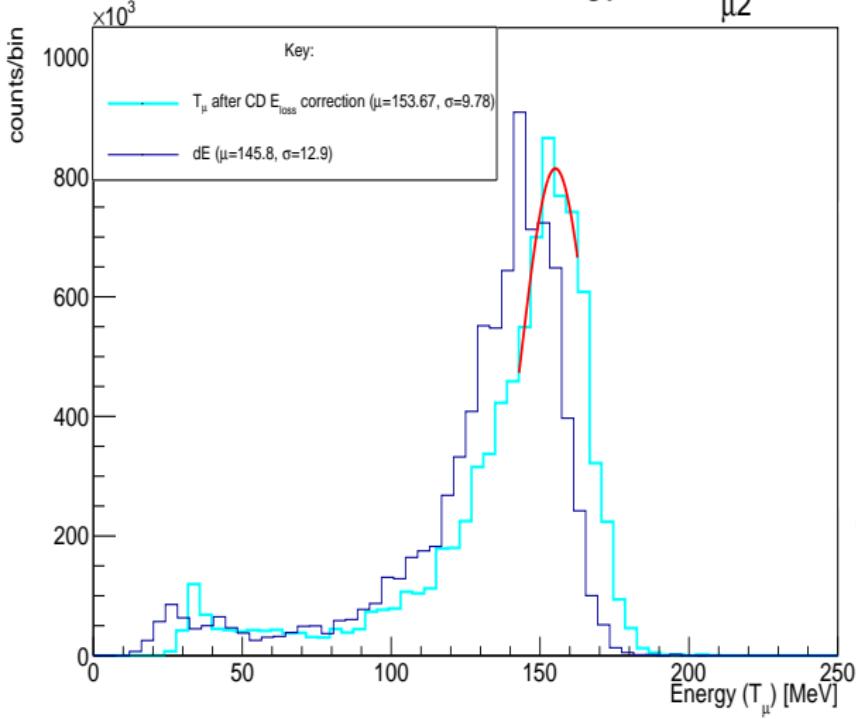
Pulse Fitting In Action: Energy Calibration From $K_{\mu 2}$

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



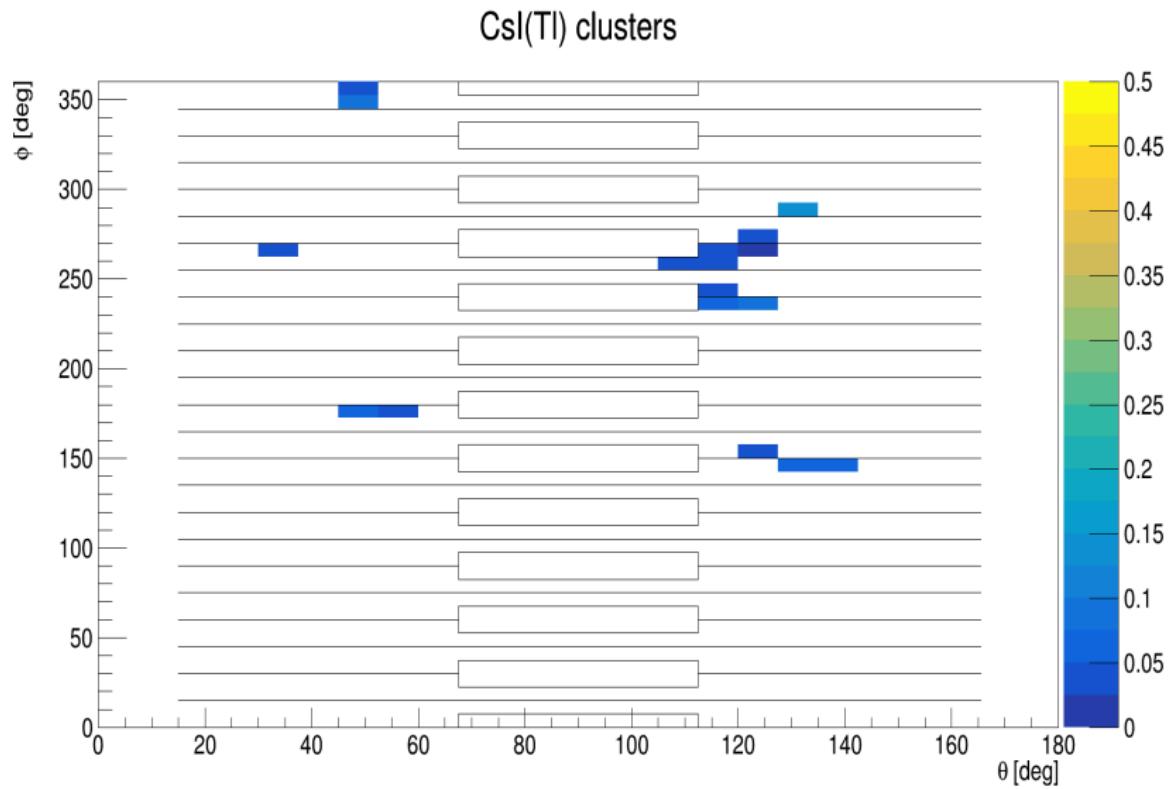
Pulse Fitting In Action: Energy Calibration From $K_{\mu 2}$

CsI: reconstructed energy for $K_{\mu 2}$

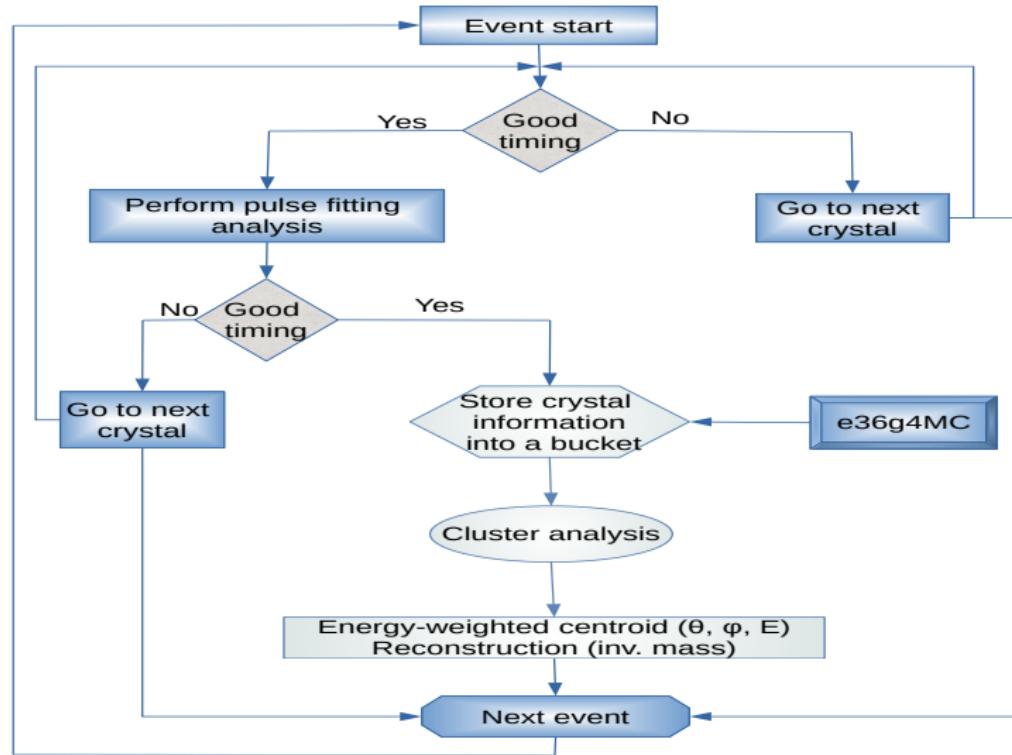


- $C_i = \frac{dE_{CsI}}{(A - P)_i}$, $i = 1, \dots, 768$
- A is the waveform amplitude and P is the baseline
- $T_\mu = dE_{CsI} + CDE_{loss}$
- Correction for energy loss from CD system

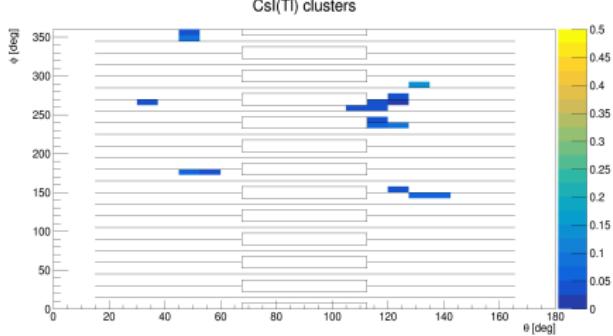
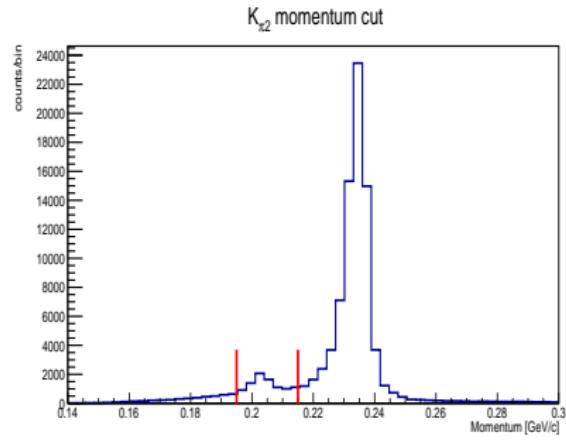
Cooker Framework Event Viewer



CsI cluster analysis



CsI Cluster Analysis Cont...

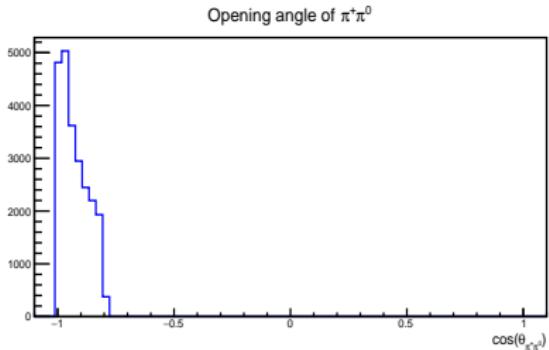
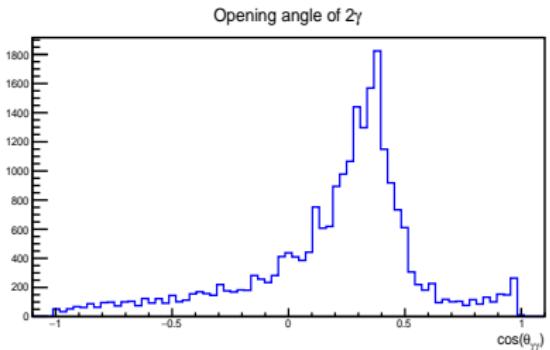
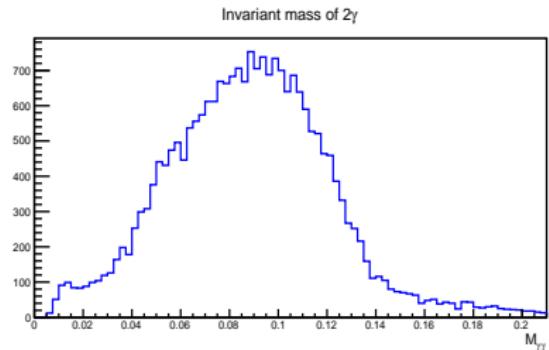
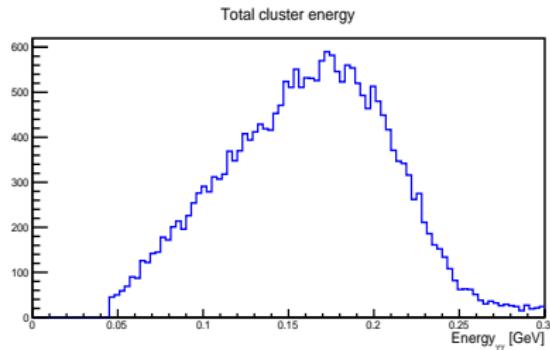


Cluster criterion: $K^+ \rightarrow \pi^+ \pi^0$

- High hardware trigger due to high rate
- Several clustering patterns need to be considered
- $N_{\text{crys}} \geq 2$ and $N_{\text{crys}} = 1$ (single crystal clusters)
- Currently single crystal clusters are considered as well
- Analysis is performed for $\pi^0 \rightarrow \gamma\gamma$, while allowing for a maximum of 3 cluster
- In case of 3 clusters, sum over combinations in search for which clusters have

$$.90 \leq M_{\text{inv}}(\pi^0) \leq .140 \text{ GeV}/c^2$$

CsI $K\pi_2$ Cluster Analysis



- $E_{\text{total}}(2\gamma)$: total energy of 2γ clusters

- $\cos(\theta_{\gamma\gamma})$: opening angle of 2γ clusters

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}

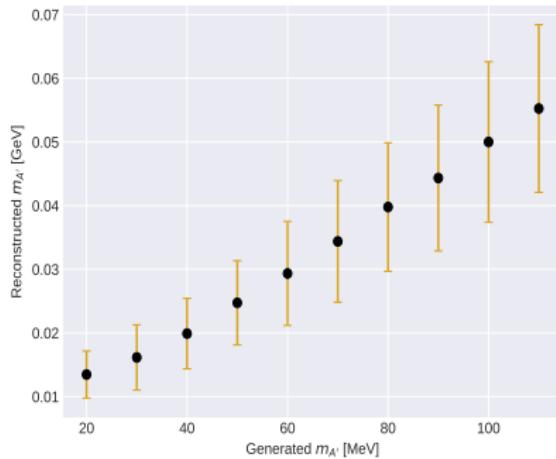
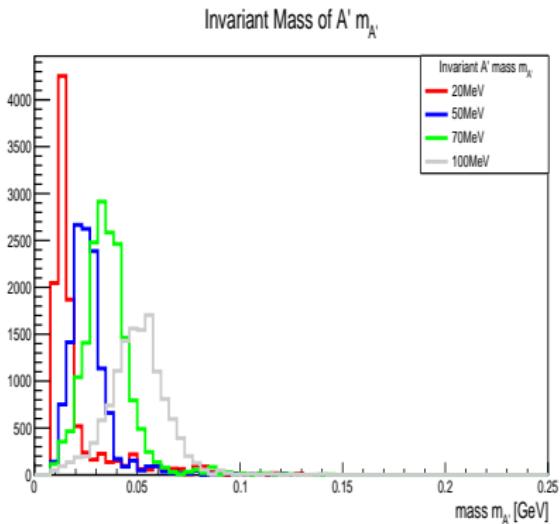
π^0 Channels

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

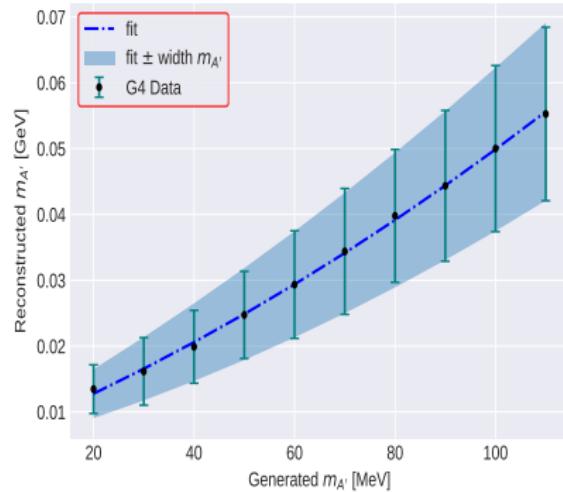
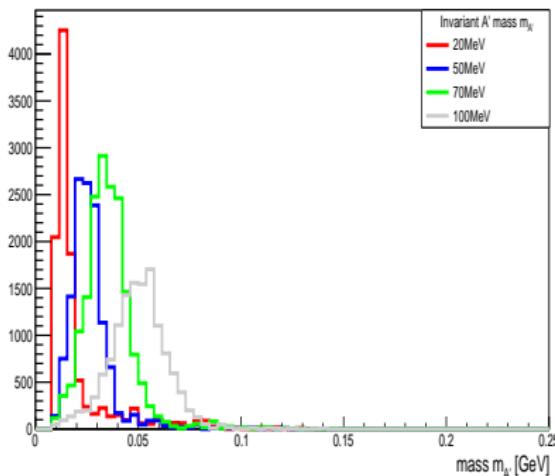
A' Mass $m_{A'}$ Distribution



- 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' Mass $m_{A'}$ Distribution

Invariant Mass of A' $m_{A'}$ 

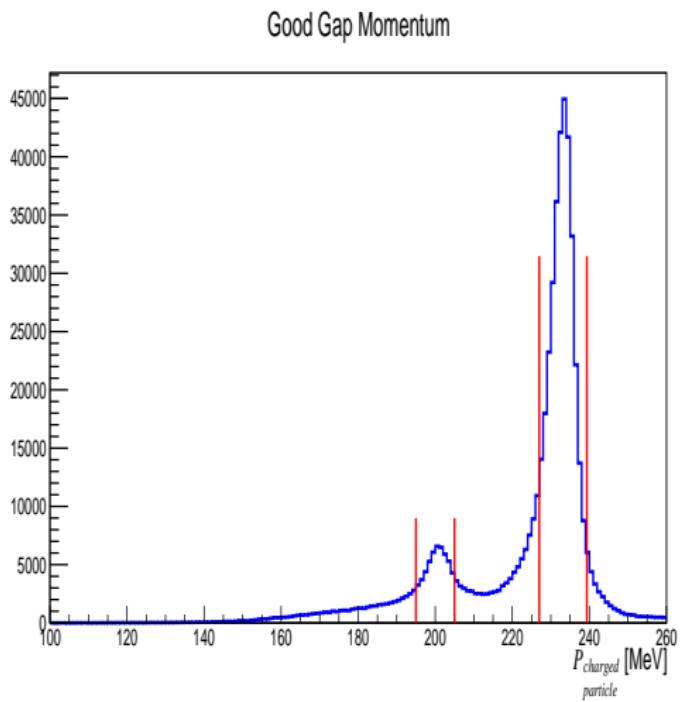
- A' masses generated on interval $20 - 110$ MeV
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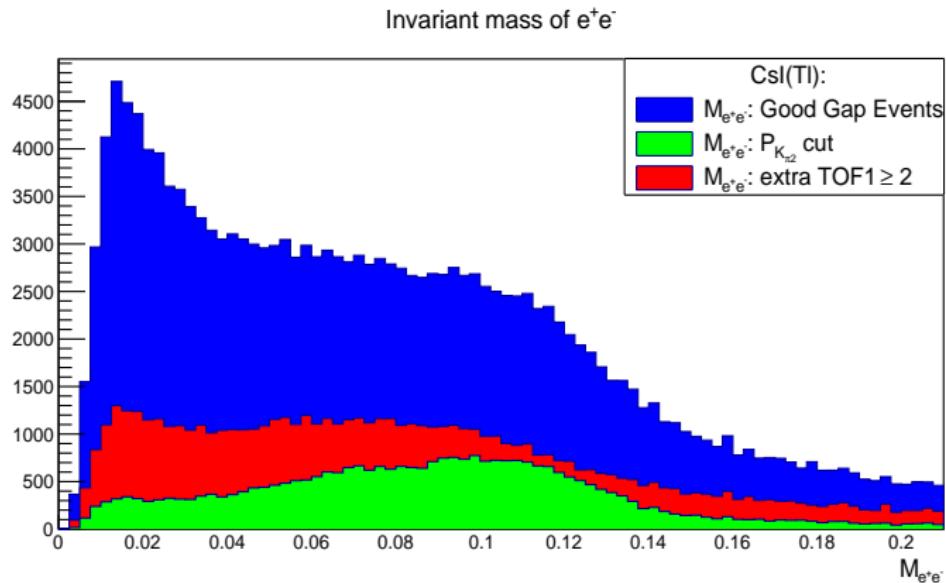
Number Of Stopped K^+

- Number of tracked muons $N_{\mu 2}$ obtained from good target events (events with target vertices)
- Select 1σ cut around mean P_μ , from $K_{\mu 2}$ decays
- Acceptance of μ^+ , A_μ was calculated from e36g4MC

$$N_K = \frac{N_{\mu 2}}{\text{Br}(\mu 2) \text{PS}(\mu) A_\mu \text{LT}(\mu)}$$



Invariant mass spectrum



- 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

Summary

Summary and Future Work

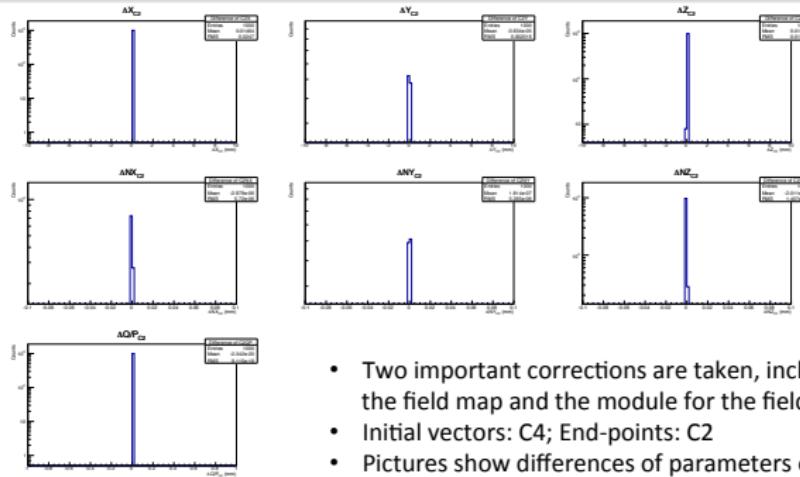
- Universe is littered with anomalies that must be explained
(exciting times!)
- TREK/E36 experiment has been successfully conducted, completed data-taking, decommissioned and analysis is currently underway
- e36g4MC has been developed from ground-up
- K^+ decay generator has been implemented into the e36g4MC
- Energy calibration for CsI(Tl) using both $K_{\mu 2}$ and $K_{\pi 2}$
- CsI cluster finder developed within Cooker analysis framework
- Event viewer implemented
- We have generated various masses for A' and analysis is currently underway
- Signal search for light bosons currently underway

Backup

Tracking: propagation with G4 and reconstruction with Kalman Filter

Use geantinos as the primary particle

Propagate through magnetic field and compare the results



Geantinos propagate in the field without any physics.

- Two important corrections are taken, including the setup of the field map and the module for the field evaluation.
- Initial vectors: C4; End-points: C2
- Pictures show differences of parameters of state vectors at C2 extracted from two packages
 - ✓ Magnetic field map is consistent with each other
 - ✓ Evaluation of magnetic field is consistent with each other

Runge-Kutta methods are consistent

CsI Waveform

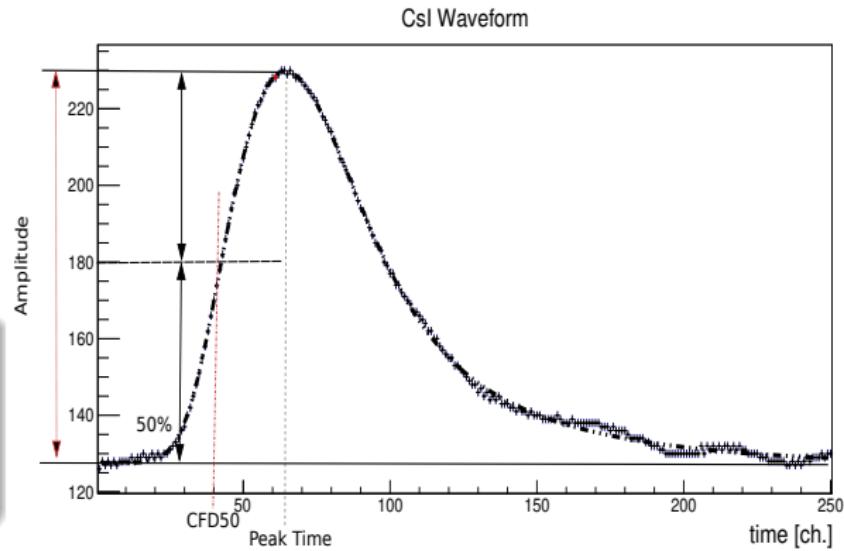
$$F(t) = \frac{A}{1 - e^{-(t-\tau_0)/\lambda}} \cdot \text{Freq} \left[\frac{t-\tau_0-d}{\mu} \right] \cdot \left(\frac{t-\tau_0}{\tau_1} e^{\left[1 - \frac{t-\tau_0}{\tau_1}\right]} + e^{\frac{t-\tau_0}{\tau_2}} e^{\left[1 - \frac{t-\tau_0}{\tau_2}\right]} \right)$$

- μ rising factor
- 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)

CsI (Timing) Variables

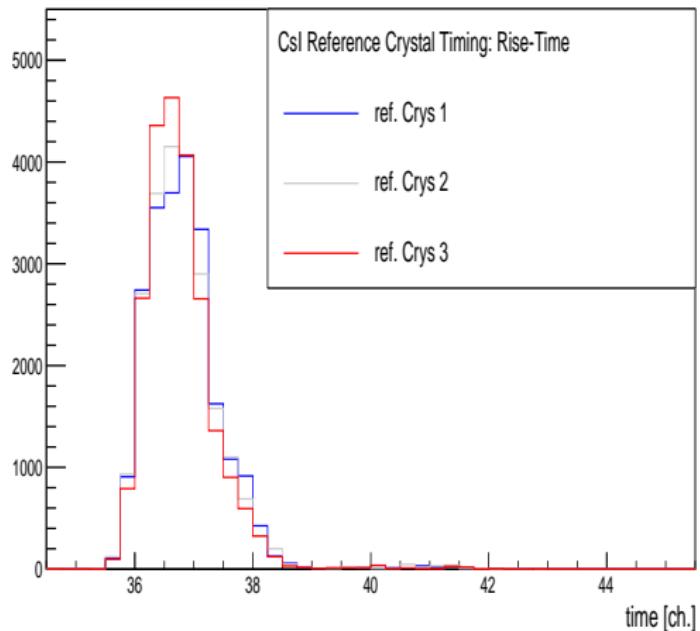
- τ_0 is rise time (from fit function)
- Constant discrimination fraction (CDF) at 50%
- Peak time



CsI Timing Study

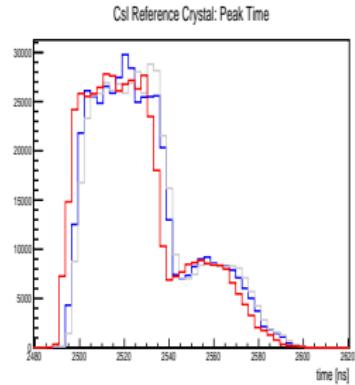
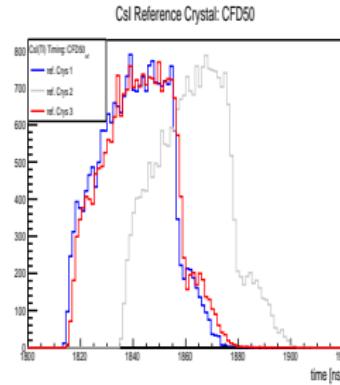
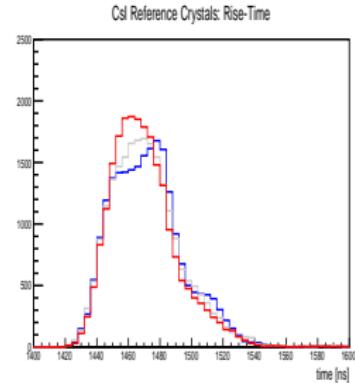
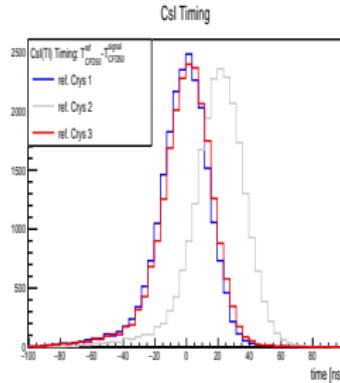
- The CsI has 3 self-timed VF48 channels
- Use these channels to establish the timing of the signal crystals
- The main parameters of interest for timing are τ_0 & CDF50
- τ_0 is consistent for reference crystals

CsI Reference Crystals: Rise-Time



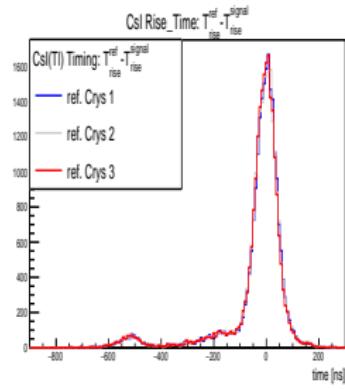
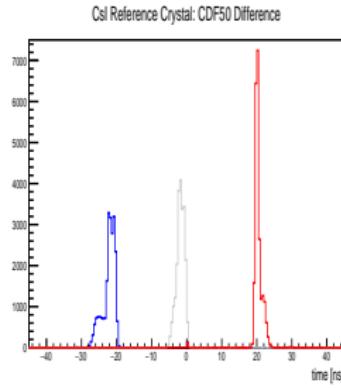
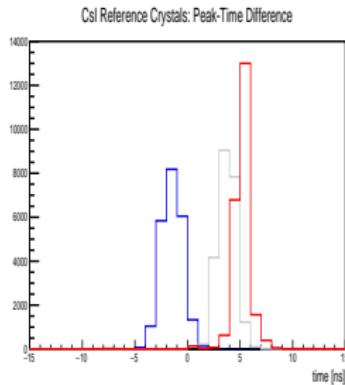
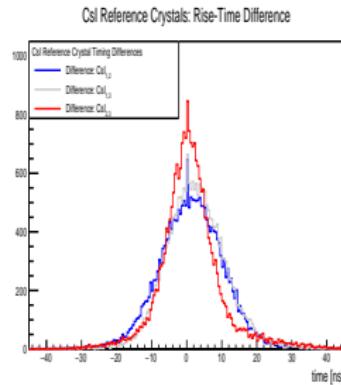
CsI Timing Study

- The CsI has 3 self-timed VF48 channels
- Use these channels to establish the timing of the signal crystals
- The main parameters of interest for timing are τ_0 & CDF50
- Time spectra for reference crystals
- τ_0 is consistent for reference crystals
- The rise-time is consistent amongst reference crystals (including the jitter)
- The CDF50 for crystals 1 & 3 is consistent, but crystal 2 is shifted



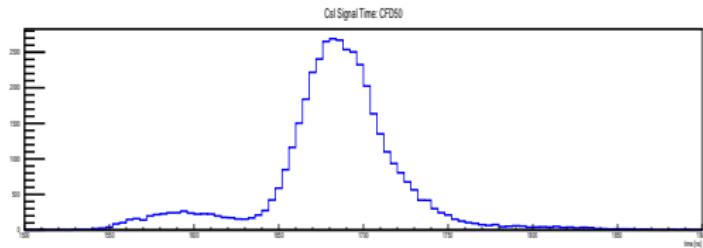
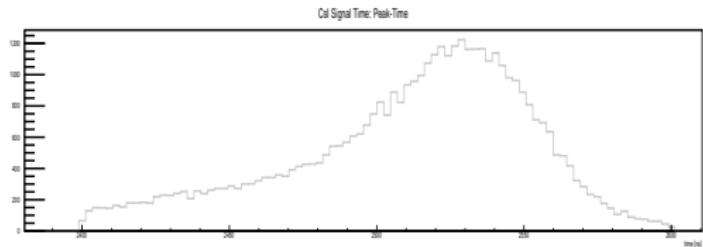
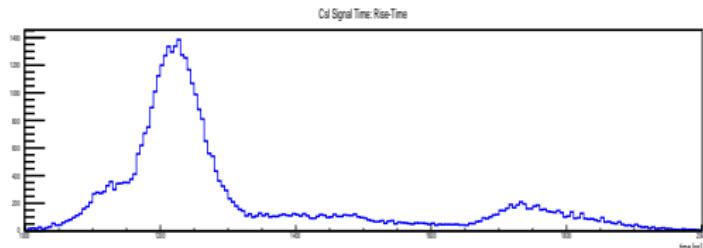
CsI Timing Study

- The CsI has 3 self-timed VF48 channels
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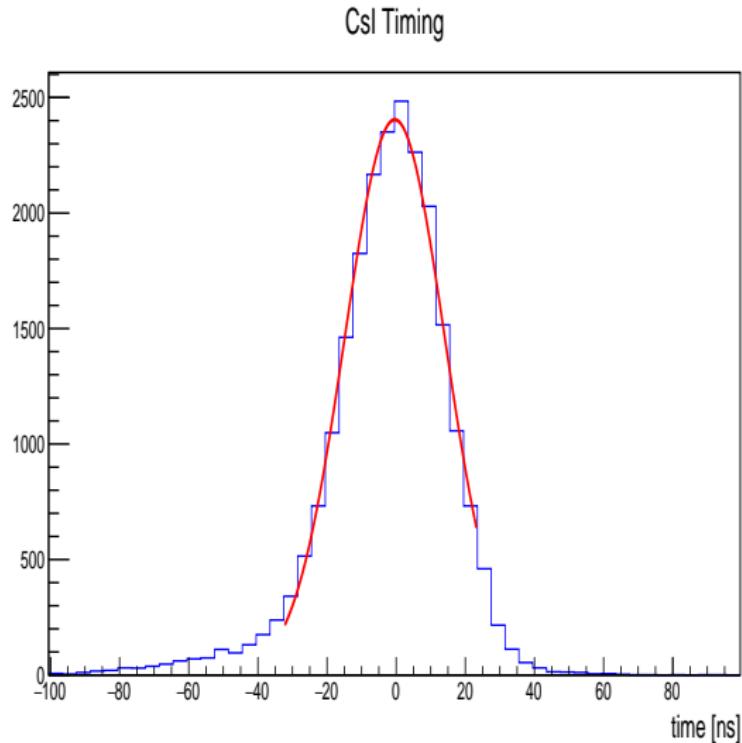
CsI Timing Study

- The CsI has 3 self-timed VF48 channels
- Use these channels to establish the timing of the signal crystals
- The main parameters of interest for timing are τ_0 & CDF50



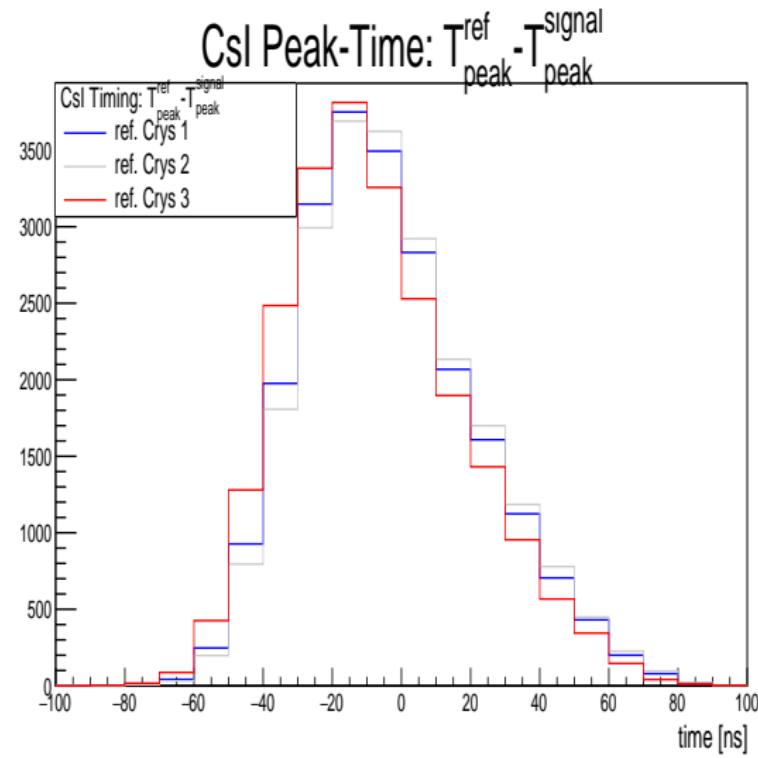
CsI Timing Study

- The CsI has 3 self-timed VF48 channels
- Use these channels to establish the timing of the signal crystals
- The main parameters of interest for timing are τ_0 & CDF50
- **CsI-timing resolution:**
 $\sigma = 14.1318$



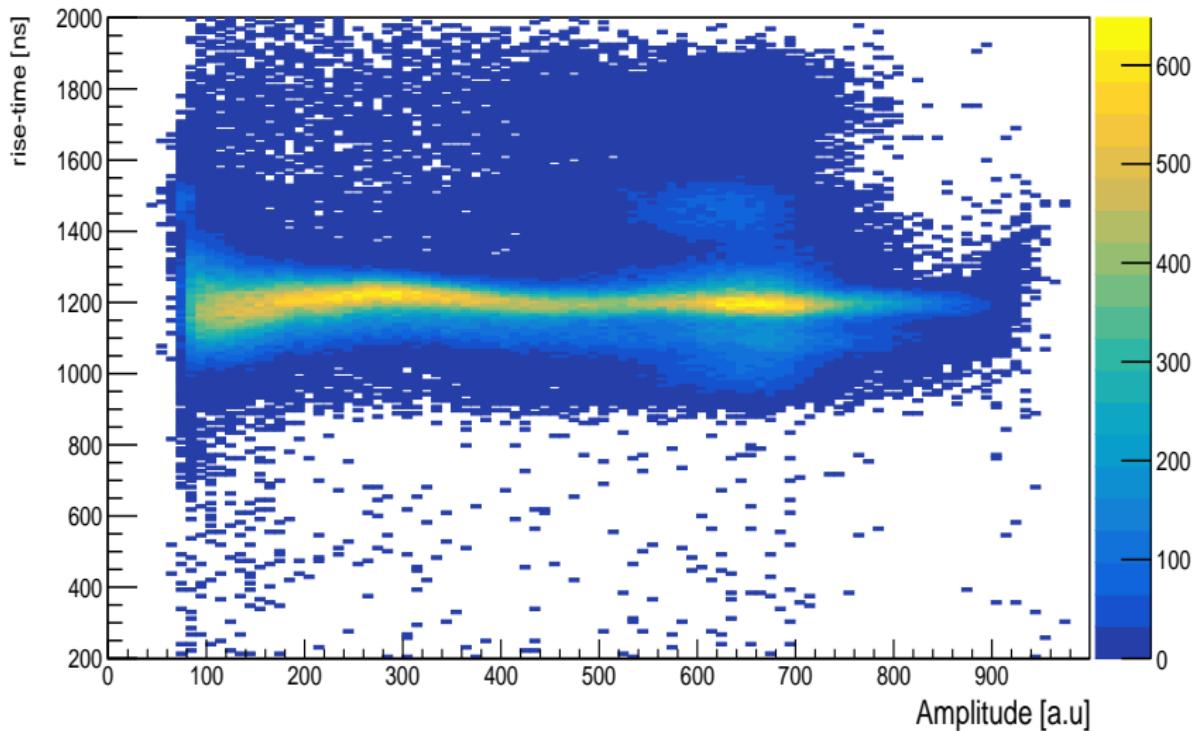
CsI Timing Study

- The CsI has 3 self-timed VF48 channels
- Use these channels to establish the timing of the signal crystals
- The main parameters of interest for timing are τ_0 & CDF50



2D Plots

Rise-Time vs Pulse Height



2D Plots

CFD50 vs Pulse Height

