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

Dongwi H. Dongwi (Bishoy)

Pre-Defense Meeting

Hampton University, Hampton VA 23668

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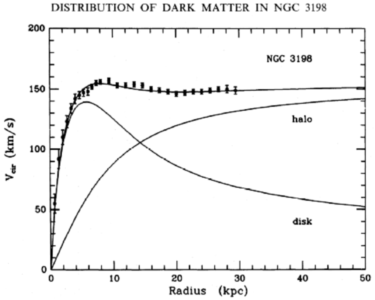
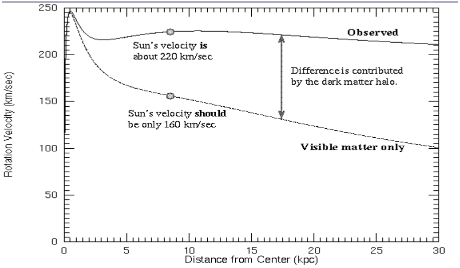
Rotation Curves Of Galaxies

Vera Rubin



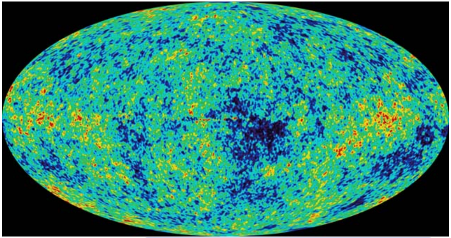


Vera Rubin:

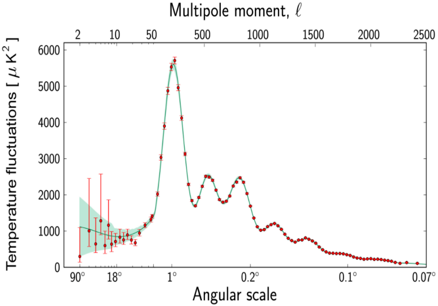
- Zwicky noticed that galaxies in the Coma Cluster were moving too rapidly to be explained by the amount of stella material
- Rubin studied rotation curves of galaxies
- Velocity of objects (stars or gas) orbiting the centers of galaxies, rather than decreasing as a function of the distance from the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

Katherine Freese (Public lecture)

Cosmic Microwave Background (CMB)



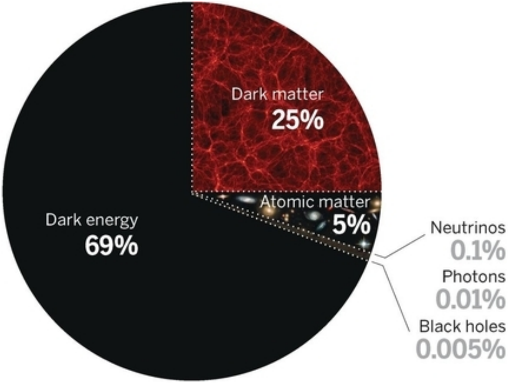
Jeff Filippini (UC Berkeley Cosmology Group)



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

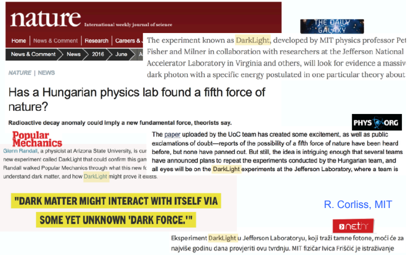
Energy Of The Universe

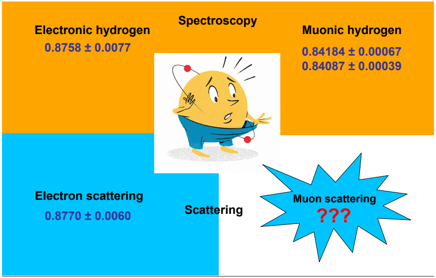


2014 P5 report

"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





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

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

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

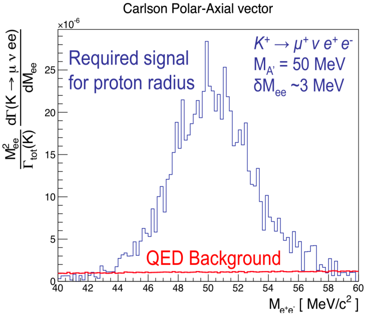
Background: BR($K^+ \rightarrow \mu^+ \nu\ e^+ e^-$) ~ 2.5 x 10^{-5} ~ 250,000 ev.

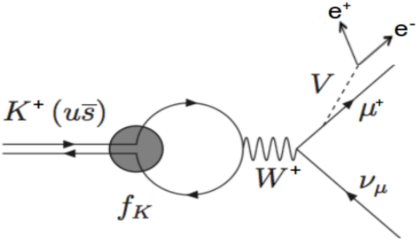
Add. background from $K^+ \rightarrow \mu^+ \nu \pi^0 \rightarrow \mu^+ \nu\ e^+ e^- (\gamma)$

π^0 decays	1) 3x10^8	2) 2x10^9
π^0 production:	$K^+ \rightarrow \mu^+ \nu \pi^0$ (3.3%)	$K^+ \rightarrow \pi^+\pi^0$ (21.1%)

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

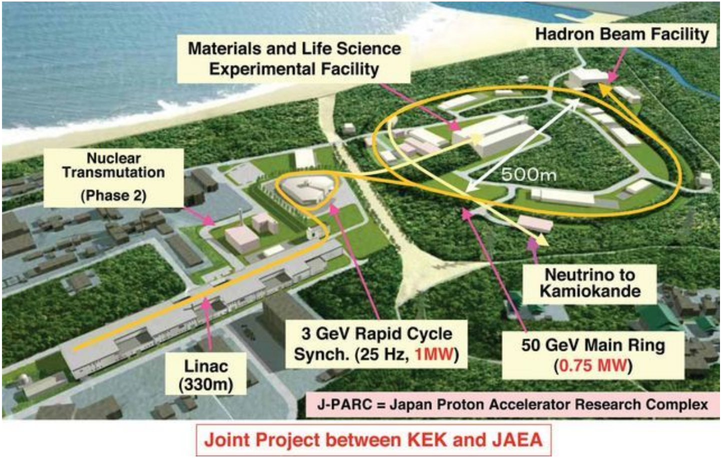
Background: BR($\pi^0 \rightarrow \gamma\ e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) x$10^7$ ev.





PRD 89, 0350003 (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

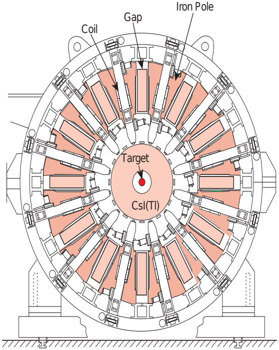
- Completed installation of C3 & C4
- Cabling
- Detector maintenance

September - December 2015

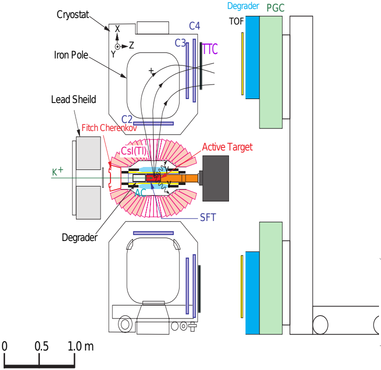
- Physics run
- Data taking

E36 Detector Geometry

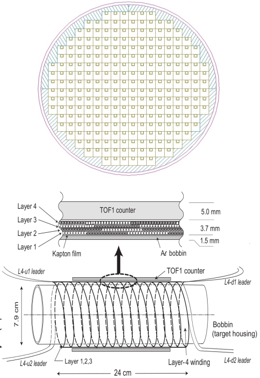
End view



Side view



Target & SFT



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

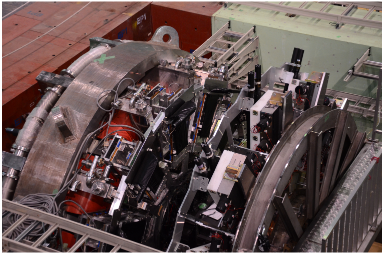
AC

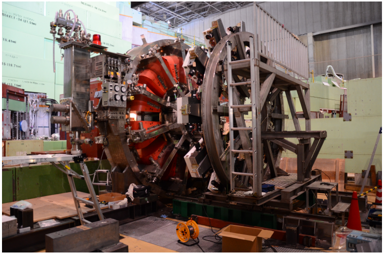
PGC

Gamma ray

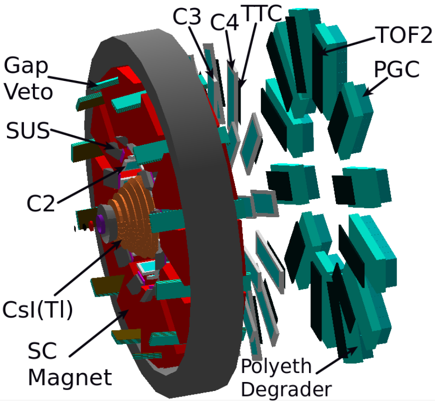
CsI(Tl)

Geant4 Generated Geometry



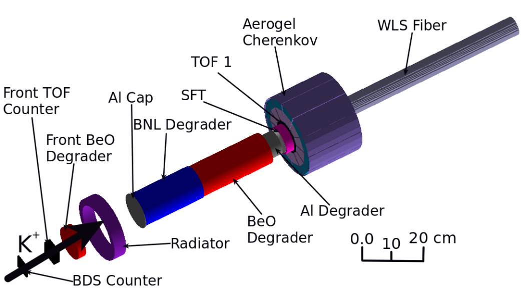


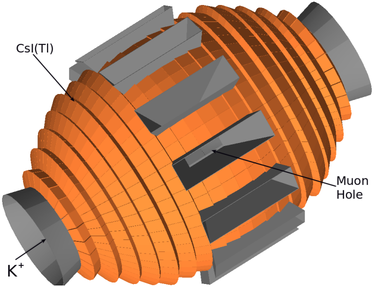
- Detector Assembly



- e36g4MC detector geometry

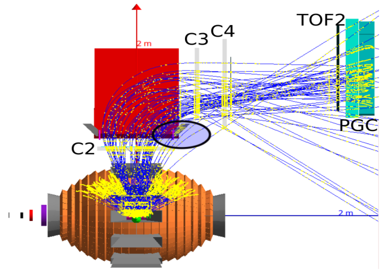
Geant4 Cont.: Central Detector

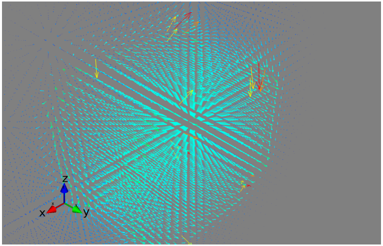




- Central Detector

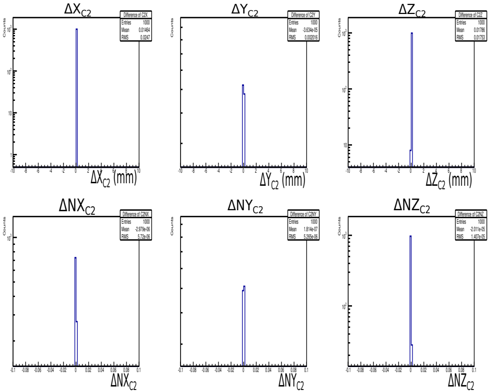
Tracking Package and The e36g4MC Comparison





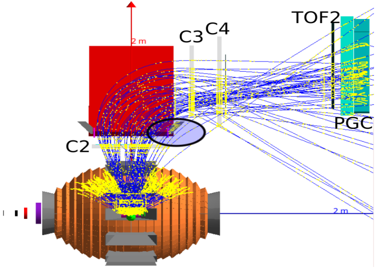
TOSCA generated field (P. Monaghan)

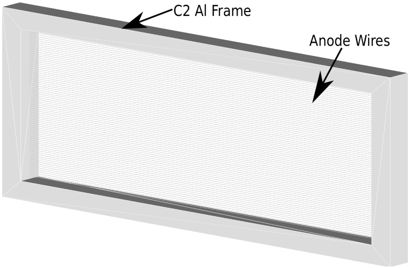
- Consistency check: propagation and magnetic field evaluation
- Simulated data: tracks propagated and reconstructed with Kalman Filter (KF)
- Established that KF tracking/propagation fully consistent with G4

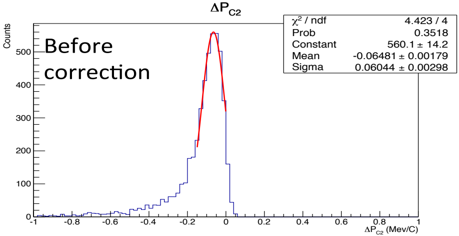


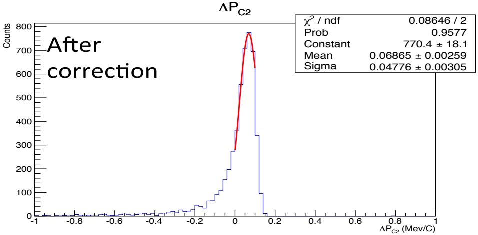
Tracking Package and The e36g4MC Comparison

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

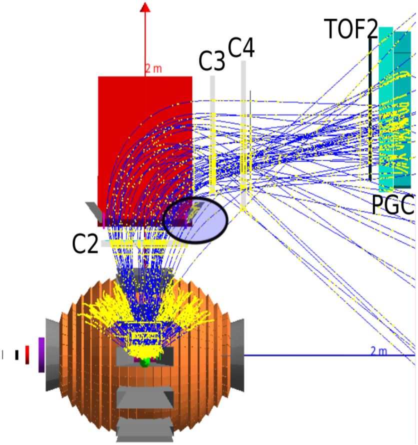






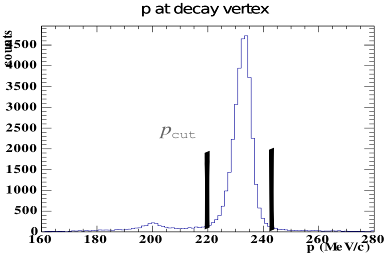


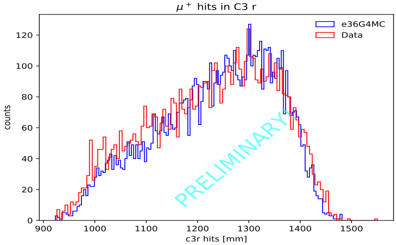
Tracking Package and The e36g4MC Comparison

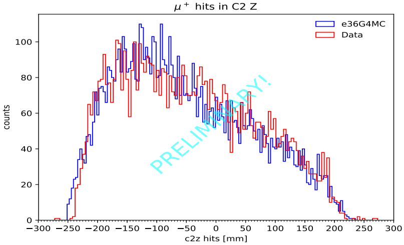


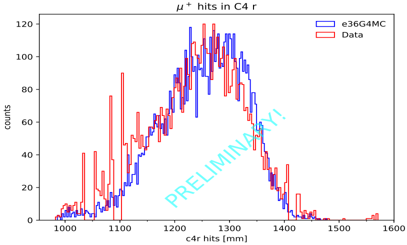
- Energy loss/material budget comparison
- Momentum distribution of $K_{\mu2}$ and $K_{\pi2}$ at C4
- No detector resolution in the simulation

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



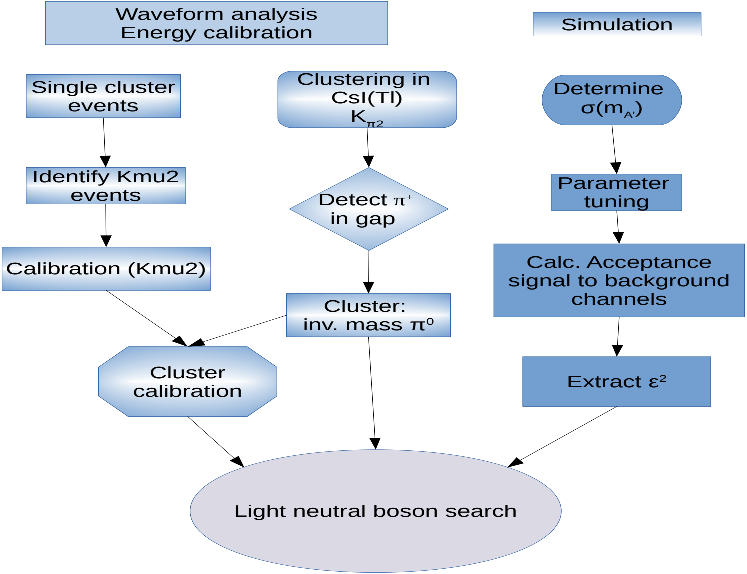




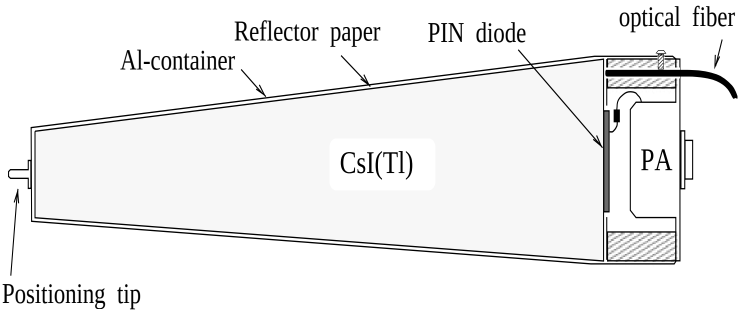


- Trigger on Target $\otimes$ TOF1 $\otimes$ TTC $\otimes$ TOF2
- $z = 2.5$cm and $x = y = 0.0$cm $\sigma_z = 8.75$cm, $\sigma_{x,y} = 0.15$cm
- Updates in progress

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 µs shaping time
- VF48 flash ADCs used to record shaping amplifier outputs

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

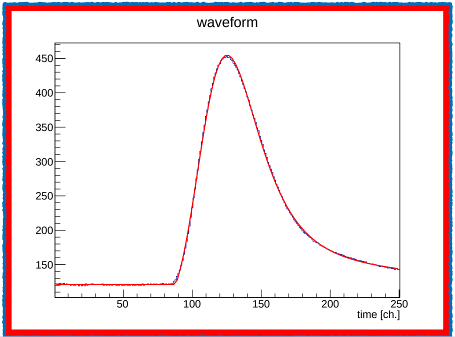
CsI(Tl) Waveform Analysis

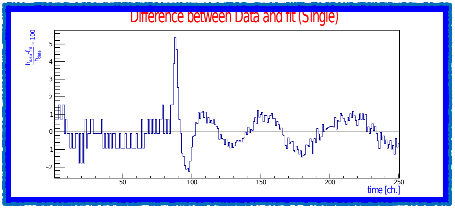
- μ rising factor

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

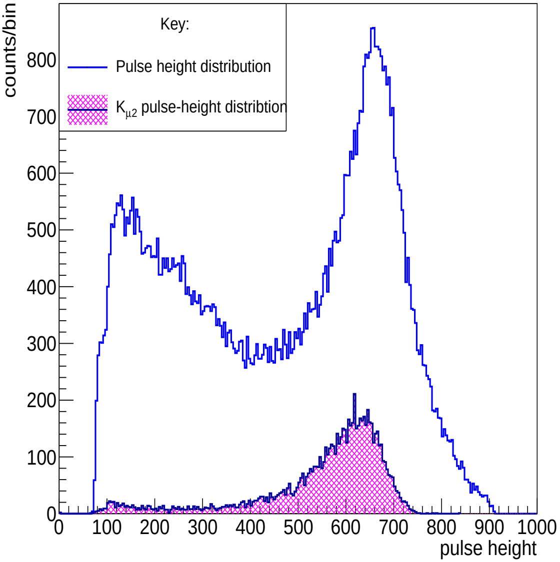
- λ is slow shape constant
- τ_0 is rise time
- τ_1 decay constant
- τ_2 local decay constant

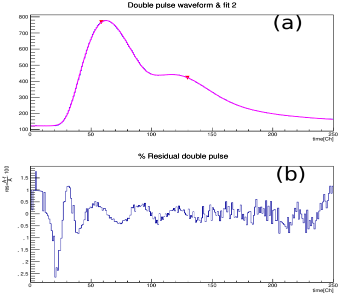
H. Ito (Nucl. Instrum. Meth., A901 2018)





Pulse Fitting In Action: Pulse Height Distribution



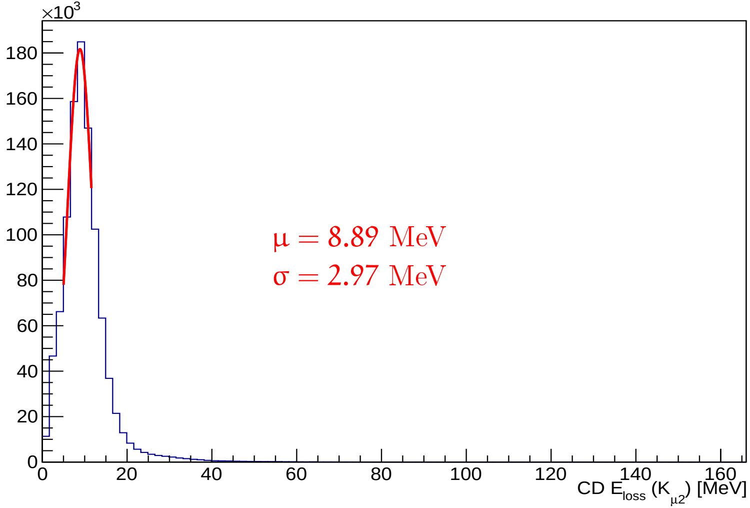


$K_{\mu 2}$ selection criteria

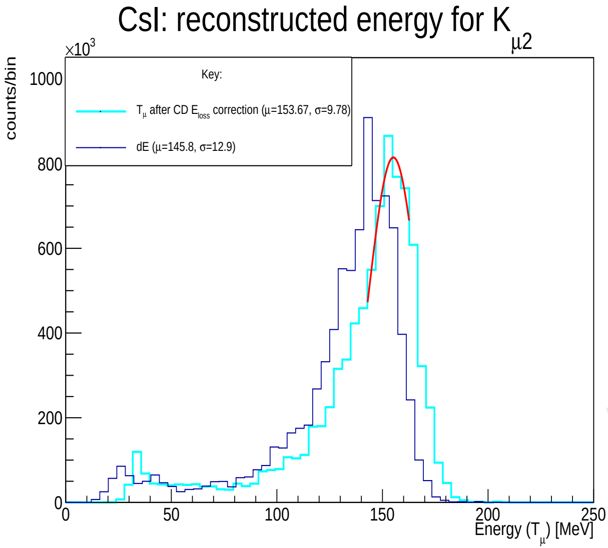
- Require single crystal per event
- First pulse time coincides with the K^{+} decay
- Require a second peak

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

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

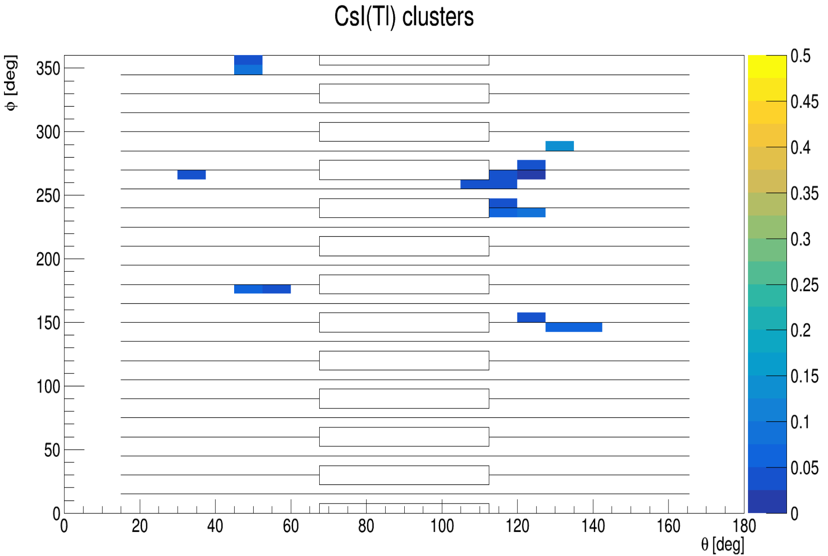


Pulse Fitting In Action: Energy Calibration From $K_{\mu 2}$

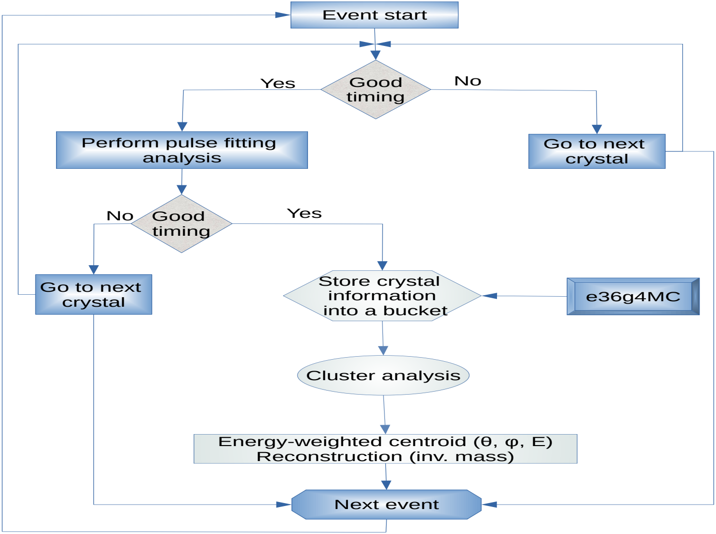


- $C_i = \frac{dE_{CsI}}{(A-P)_i}$, $i = 1, ..., 768$
- A is the waveform amplitude and P is the baseline
- $T_\mu = dE_{CsI} + CDE_{loss}$
- Correction for energy loss from CD system

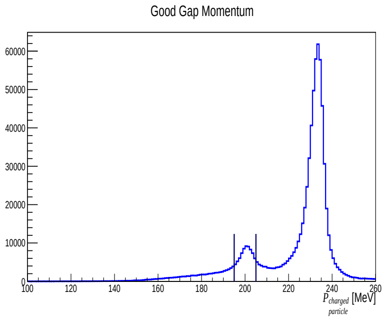
Cooker Framework Event Viewer

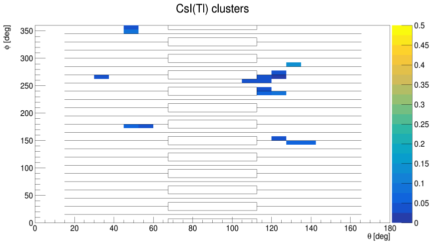


CsI cluster analysis



CsI Cluster Analysis Cont...



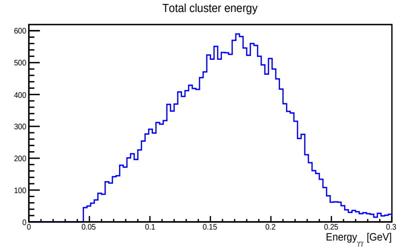


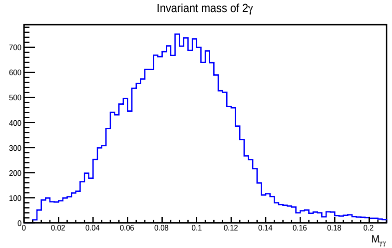
Cluster criterion: $K^+ \to \pi^+\pi^0$

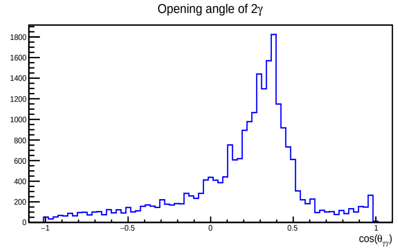
- High hardware trigger due to high rate
- Several clustering patterns need to be considered
- $N_{crys} \geq 2$ and $N_{crys} = 1$ (single crystal clusters)
- Currently single crystal clusters are considered as well
- Analysis is performed for $\pi^0 \to \gamma\gamma$, while allowing for a maximum of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

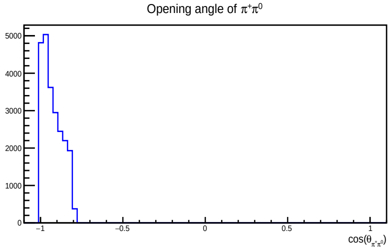
$$.90 \leq M_{inv}(\pi^0) \leq .140 \text{ GeV}/c^2$$

CsI $K_{\pi 2}$ Cluster Analysis









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

Generator Channels

K^+ Channels

Label	Branch	Ratio
0	$K^+ \to e^+\nu$	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}

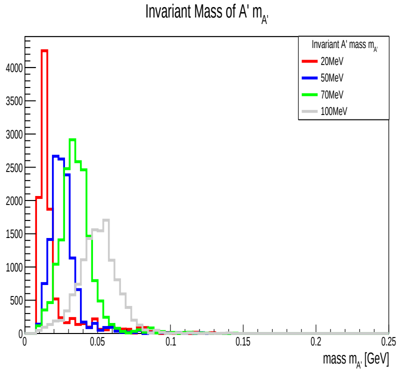
π^0 Channels

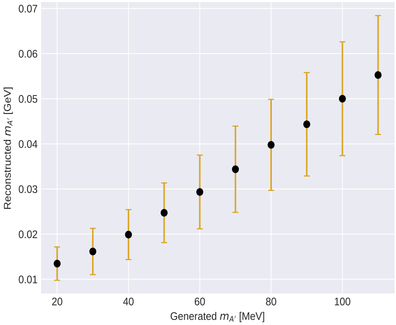
Label	Branch	Ratio
0	$\pi^0 \to \gamma\gamma$	9.8823×10^{-1}
1	$\pi^0 \to e^+e^-\gamma$	1.174×10^{-2}
2	$\pi^0 \to \gamma A^{'}$	$\epsilon^2 \times ratio\ of\ channel$ 2

ROOT based generator

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

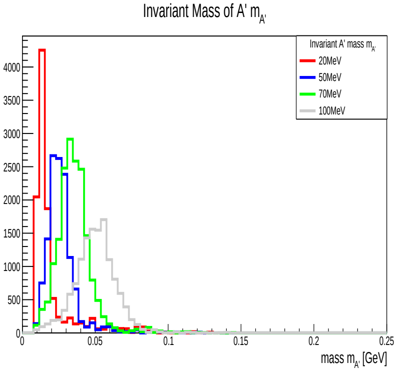
A' Mass $m_{A'}$ Distribution

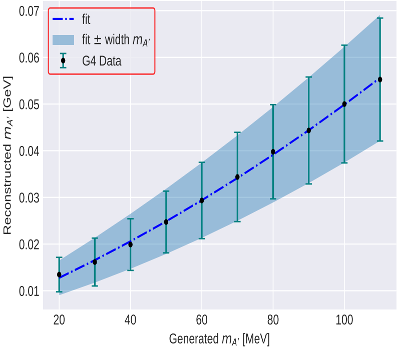




- A' masses generated on interval $20 - 110$ MeV
- $m_{A'}$ reconstructed from e^+e^- clusters in the CsI
- Mean $m_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(m_{A'})$ was obtained from fit

A' Mass $m_{A'}$ Distribution





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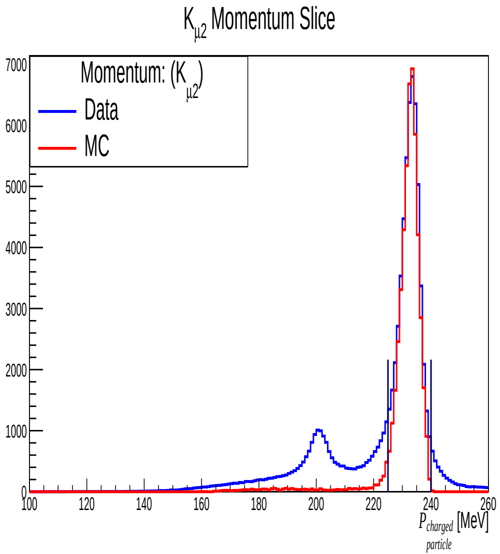
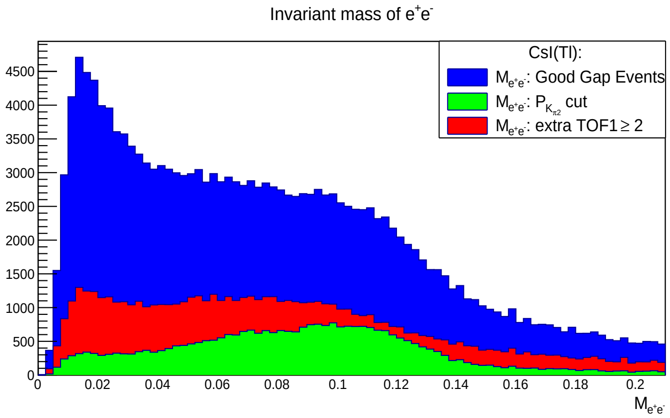
Number Of Stopped K^+

- Charged particle momentum as evaluated at K^+ stopped vertex within the target volume
- Number of tracked muons $N_{\mu 2}$ obtained from good target events (events with target vertices)
- Acceptance of μ^+, A_μ was calculated from e36g4MC
- Muon momentum selection was based on energy corrected tracks at C4 because target tracks are produced with monochromatic momentum
- Select 1 σ cut around mean P_μ, from $K_{\mu 2}$ decays

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



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

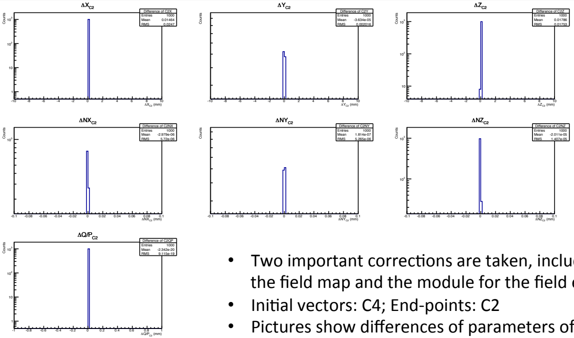
Summary and Future Work

- 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

$\boxed{\text{Runge-Kutta methods are consistent}}$

T. Cao

CsI Waveform

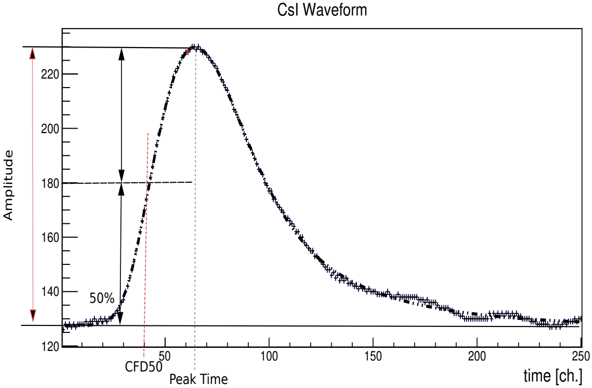
$$F(t) = \frac{A}{1 - e^{-(t-\tau_0)/\lambda}} \cdot \mathrm{Freq}\left[\frac{t-\tau_0-d}{\mu}\right] \cdot \left(\frac{t-\tau_0}{\tau_1} e^{\left[1-\frac{t-\tau_0}{\tau_1}\right]} + \epsilon \frac{t-\tau_0}{\tau_2} e^{\left[1-\frac{t-\tau_0}{\tau_2}\right]}\right)$$

- 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)

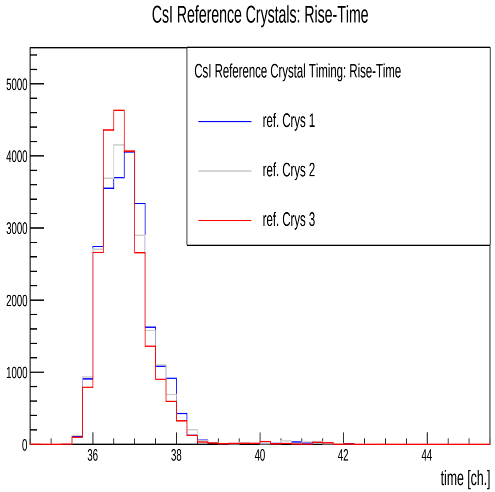
CsI (Timing) Variables

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



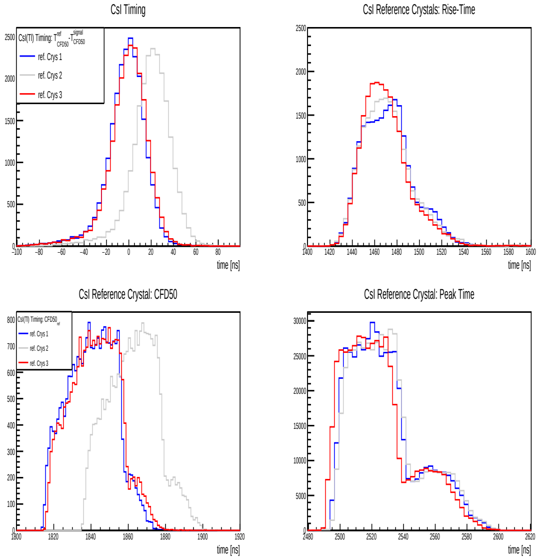
CsI Timing Study

- 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 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 amonst reference crystals (including the jitter)
- The CDF50 for crystals 1 & 3 is consistent, but crystal 2 is shifted



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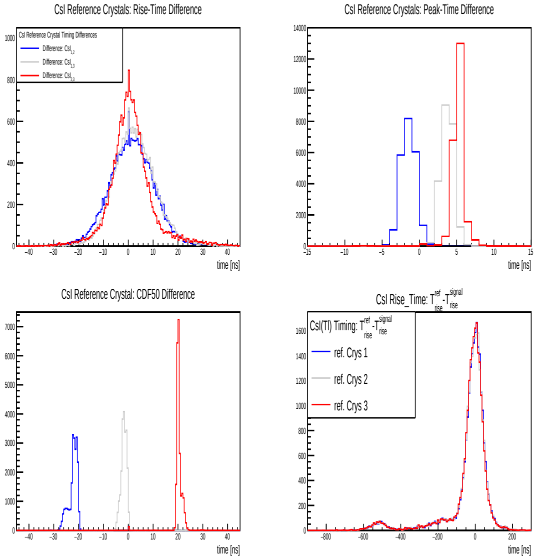

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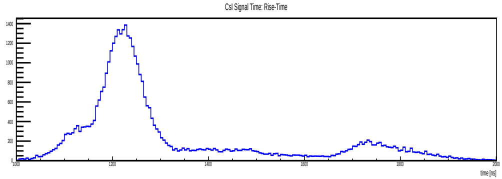
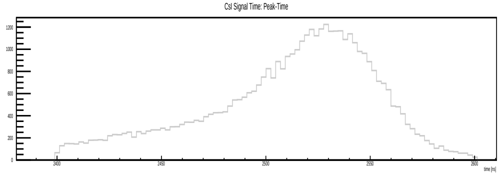
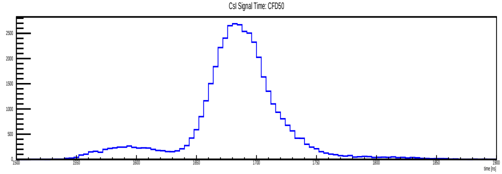
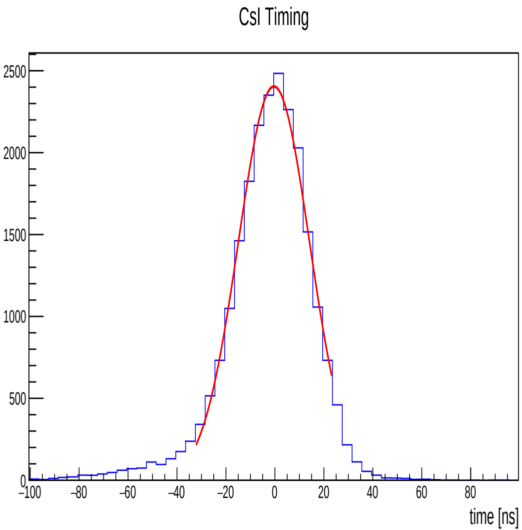






CsI Timing Study

- 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 resolution: $\sigma = 14.1318$



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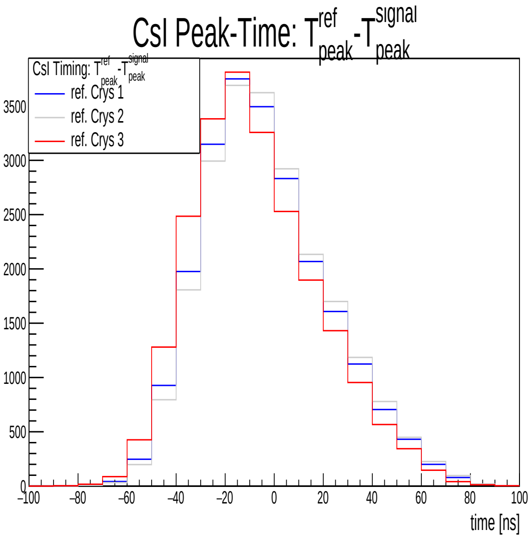
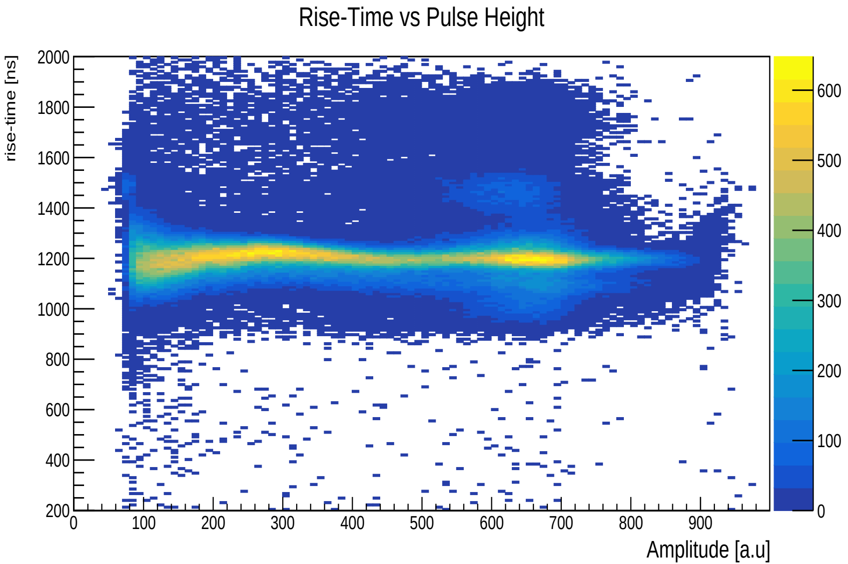
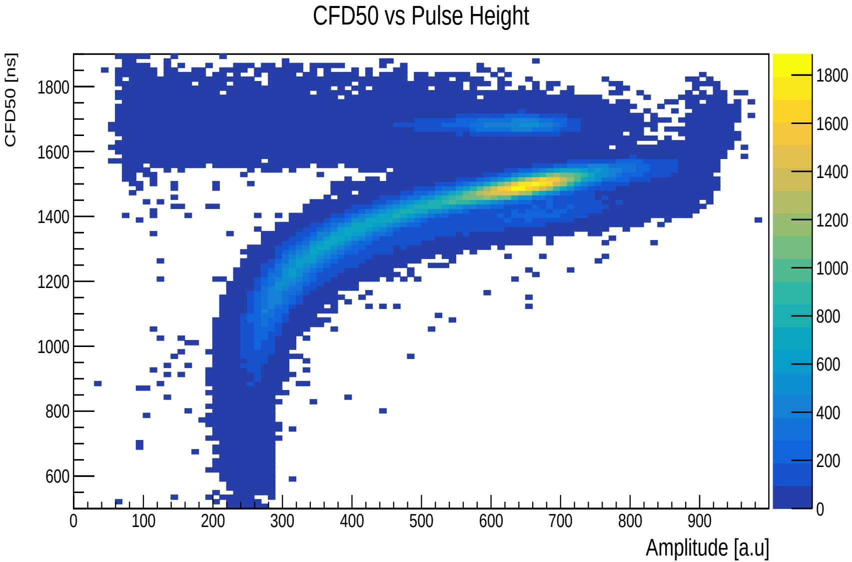


2D Plots


Rise-Time vs Pulse Height
rise-time [ns]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
100
200
300
400
500
600
700
800
900
Amplitude [a.u]
600
500
400
300
200
100
0

2D Plots


CFD50 vs Pulse Height
CFD50 [ns]
1800
1600
1400
1200
1000
800
600
0
100
200
300
400
500
600
700
800
900
Amplitude [a.u]
1800
1600
1400
1200
1000
800
600
400
200
0