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

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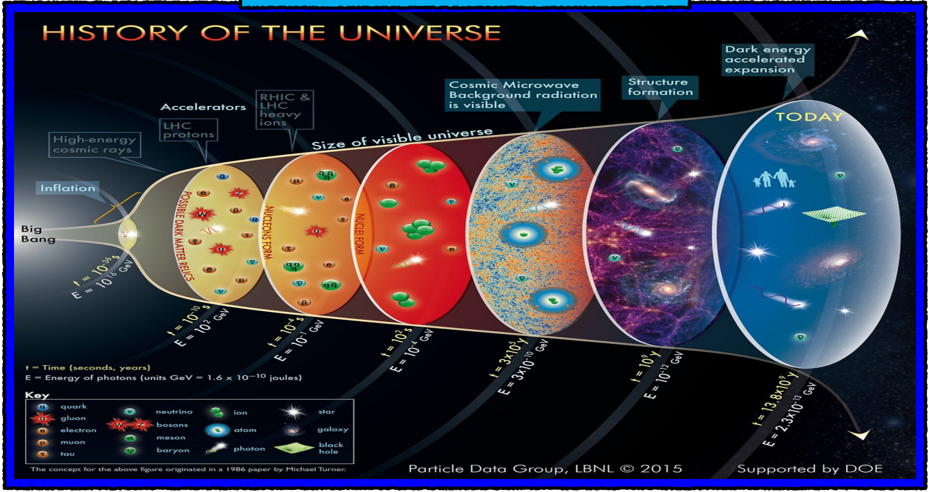
The TREK/E36 Experiment at J-PARC: An Overview

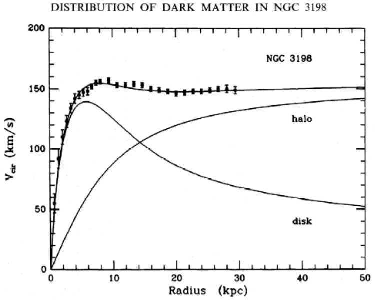
Big Bang Nucleosynthesis to Present

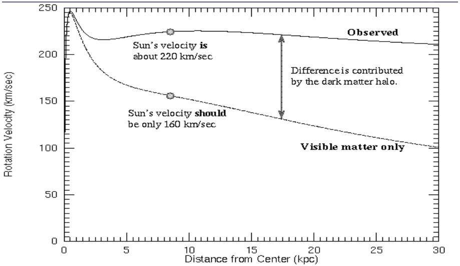
From the Big Bang to the present



Rotation Curves of Galaxies

Vera Rubin



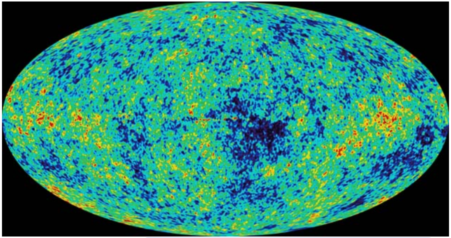


Vera Rubin:

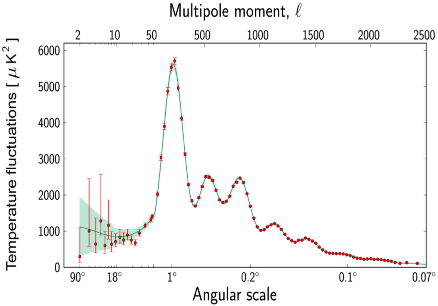
- Zwicky noticed that galaxies in the Coma Cluster were moving too rapidly to be explained by the amount of stella material
- Rubin studied rotation curves of galaxies
- Velocity of objects (stars or gas) orbiting the centers of galaxies, rather than decreasing as a function of the distance from the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

Katherine Freese (Public lecture)

Cosmic Microwave Background (CMB)



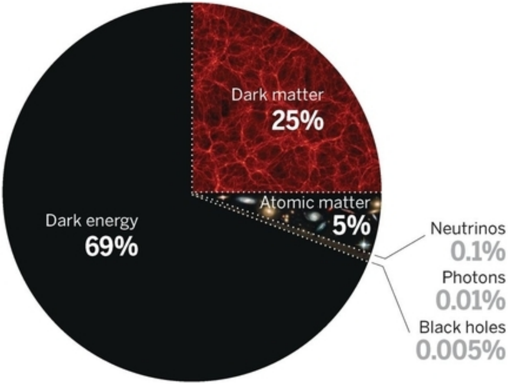
Jeff Filippini (UC Berkeley Cosmology Group)



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
- 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

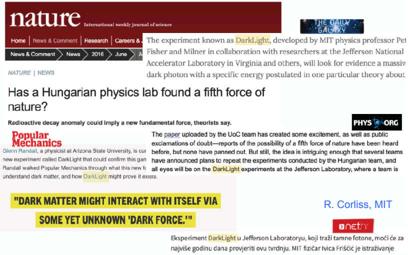
Energy of the Universe

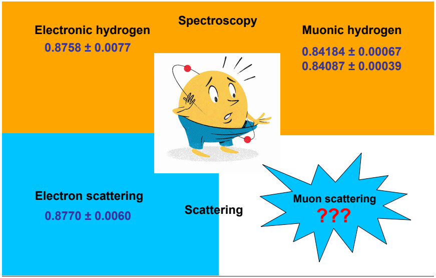


2014 P5 report

“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





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

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

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

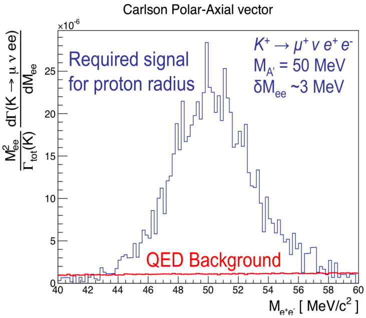
Add. background from $K^+ \to \mu^+ \nu \pi^0 \to \mu^+ \nu\ e^+ e^- (\gamma)$

π^0 decays 1) 3×10^8 2) 2×10^9

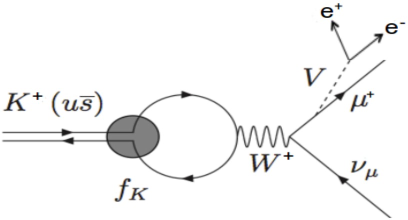
π^0 production: $K^+ \to \mu^+ \nu \pi^0$ (3.3%) $K^+ \to \pi^+\pi^0$ (21.1%)

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

Background: $BR(\pi^0 \to \gamma\ e^+ e^-) \sim 1.2\%$ ~ 0.3 (2.3) $\times10^7$ ev.

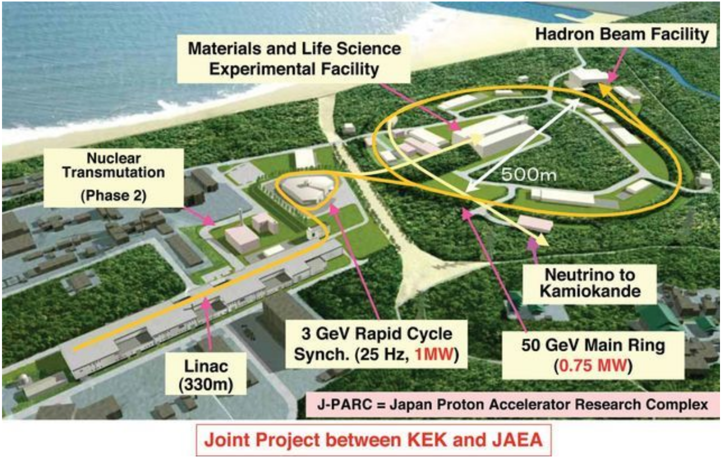


- Can light neutral bosons explain both dark matter and particle physics anomalies (muon magnetic moment, ^{8}Be decay & proton radius)?
- Search for light neutral bosons in channels involving a muon (Signal: 2)



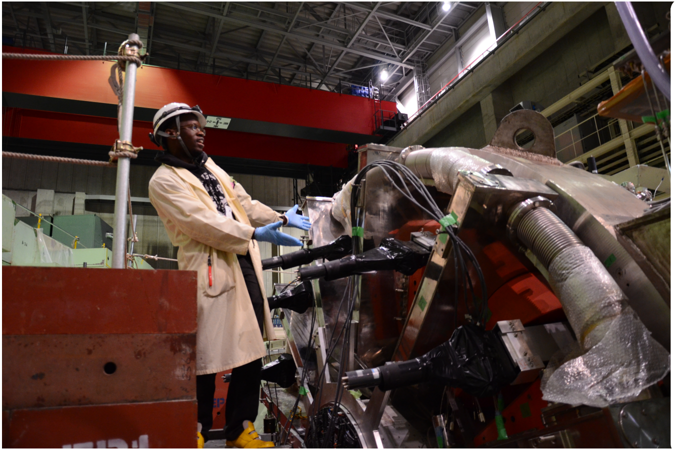
PRD 89, 0350003 (2014)

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

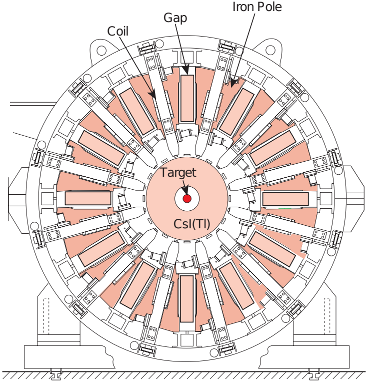
- Completed installation of C3 & C4
- Cabling
- Detector maintenance

September - December 2015

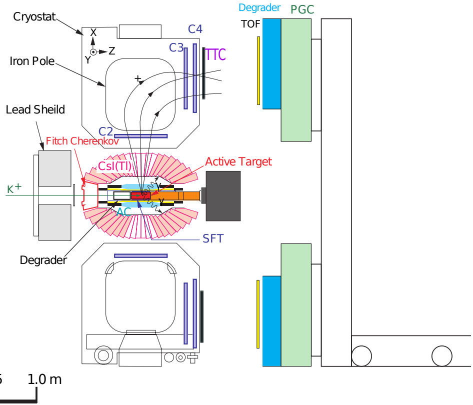
- Physics run
- Data taking

E36 Detector Geometry

End view



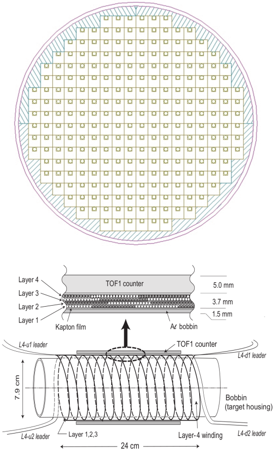
Side view



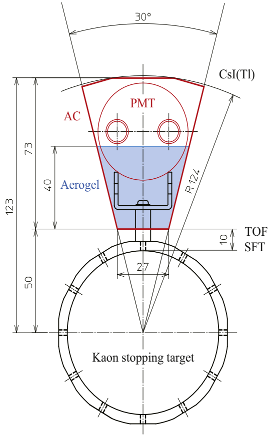
Stopped K^+ method	Momentum measurement	Particle ID	Gamma ray
K1.1BR beamline	MWPC (C2, C3, C4)	TOF	CsI(TI)
K^+ stopping target	Spiral fiber tracker (SFT)	AC	
	Thin trigger counter (TTC)	PGC	

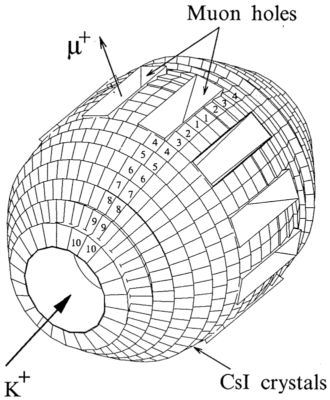
E36 Central Detector Geometry

Target & SFT

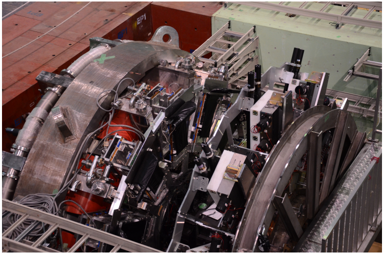


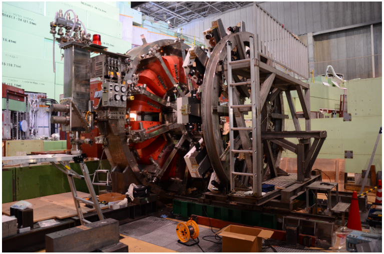
Aerogel Čerenkov



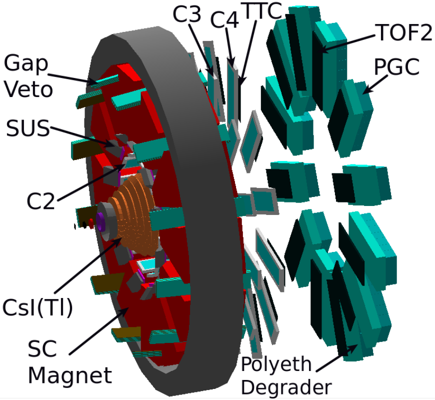


Geant4 Generated Geometry



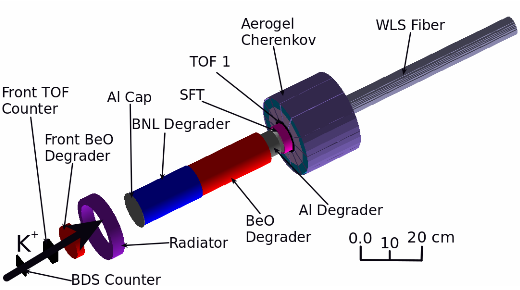


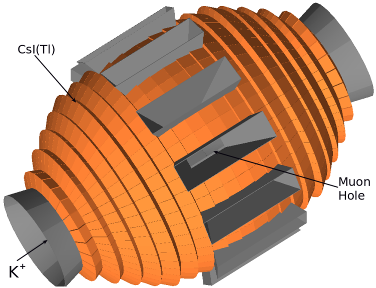
- Detector Assembly



- e36g4MC detector geometry

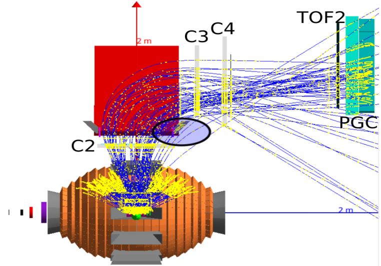
Geant4 Cont.: Central Detector

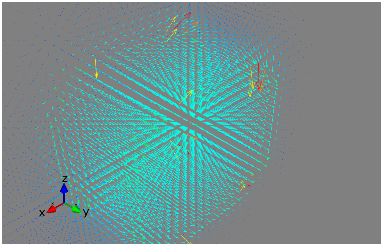




- Central Detector

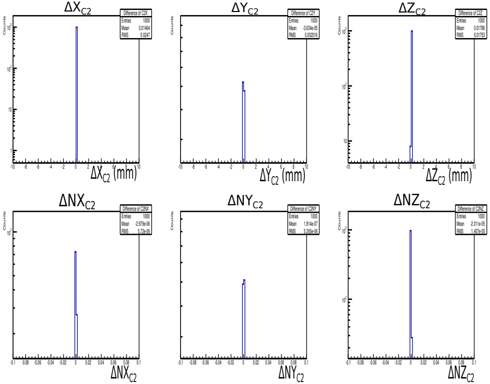
Tracking Package and the e36g4MC Comparison





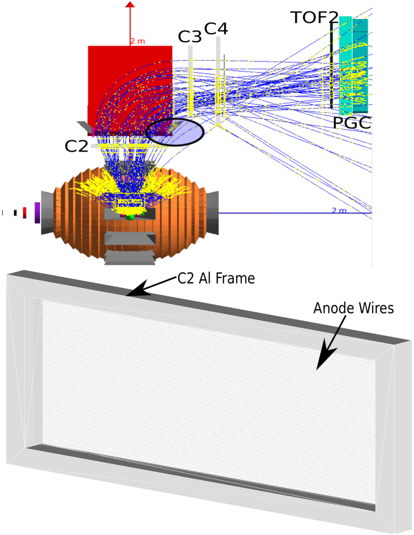
TOSCA generated field (P. Monaghan)

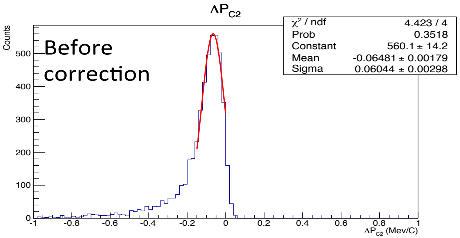
- Consistency check: propagation and magnetic field evaluation
- Simulated data: tracks propagated and reconstructed with Kalman Filter (KF)
- Compared differences at C2 coordinates ΔX_{C2}, ΔY_{C2}, ΔZ_{C2}
- Compared differences at C2 direction cosines ΔNX_{C2}, ΔNY_{C2}, ΔNZ_{C2}
- KF tracking/propagation fully consistent with G4

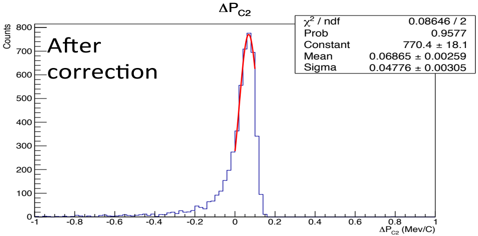


Tracking Package and the e36g4MC Comparison

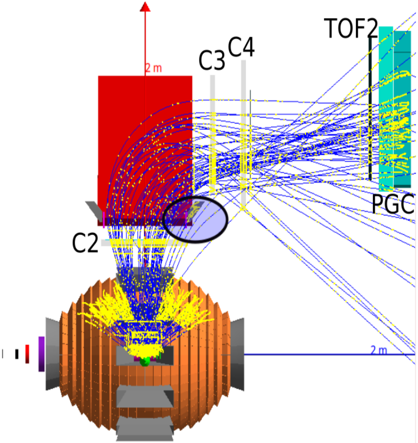
- Energy loss check & e36g4MC material budget
- ΔP_{C2}: momentum difference at C2 between reconstructed MC from tracking package and MC
- Anode plane $\rightarrow$ anode wires



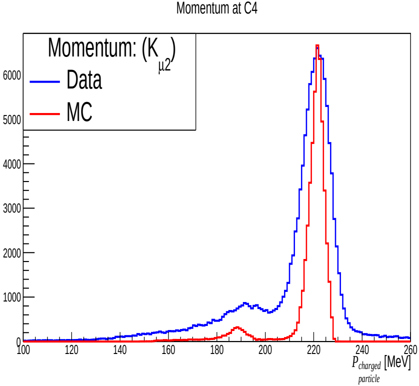




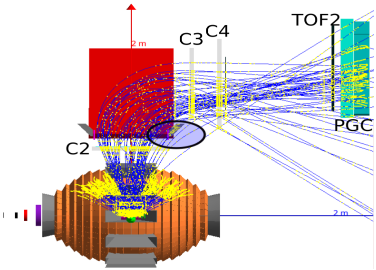
Tracking Package and the e36g4MC Comparison



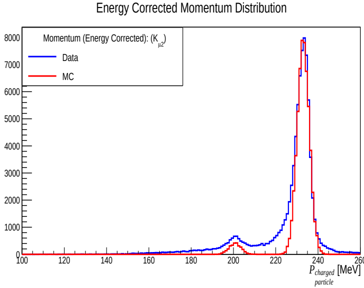
- Energy loss check & e36g4MC material budget
- Charged particle momentum at C4
- Applied offset (-2.5 MeV) to MC due to incorrect field map
- No detector resolution in the simulation

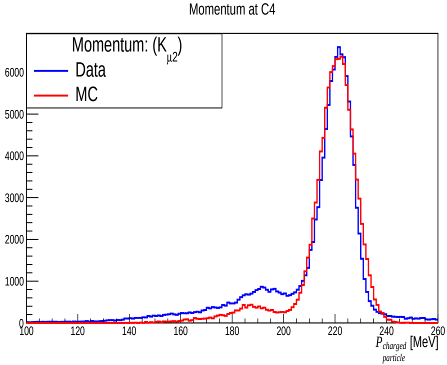


Tracking Package and the e36g4MC Comparison

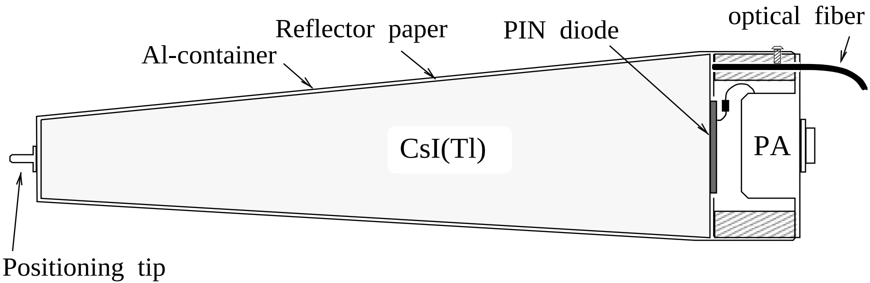


- Energy loss check & e36g4MC material budget
- Charged particle momentum at C4
- Applied offset (-2.5 MeV) to MC due to incorrect field map
- Energy corrected momentum distribution
- Applied smearing of 2.86 MeV (energy corrected) and 6.01 MeV (C4)
- Smearing value was obtained by fitting a Gaussian 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 µs shaping time
- VF48 flash ADCs used to record shaping amplifier outputs

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

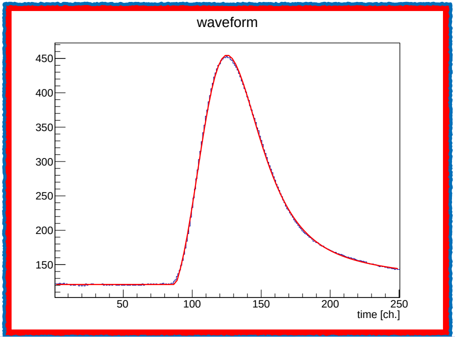
CsI(Tl) Waveform Analysis

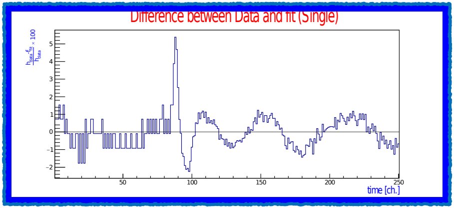
- μ rising factor

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

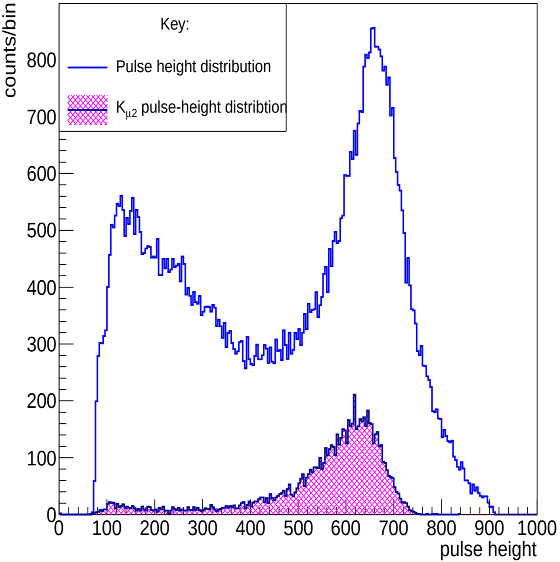
- λ is slow shape constant
- τ_0 is rise time
- τ_1 decay constant
- τ_2 local decay constant

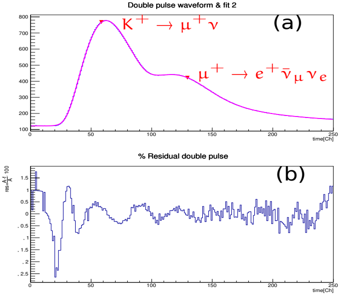
H. Ito (Nucl. Instrum. Meth., A901 2018)





Pulse Fitting in Action: Pulse Height Distribution



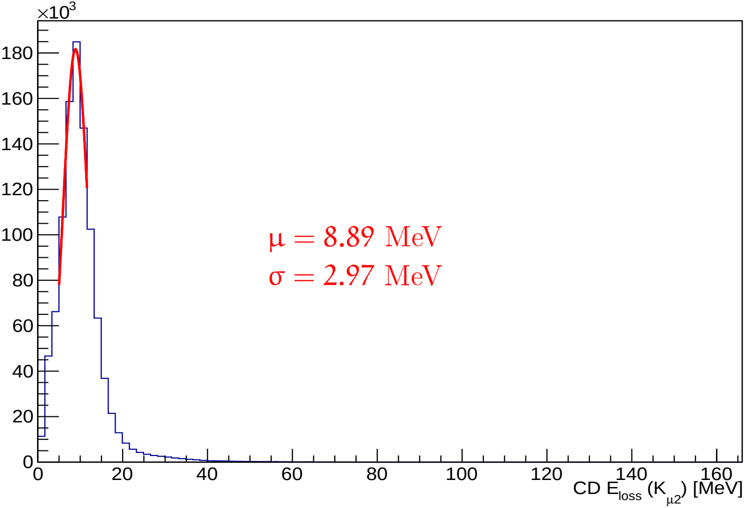


$K_{\mu 2}$ selection criteria

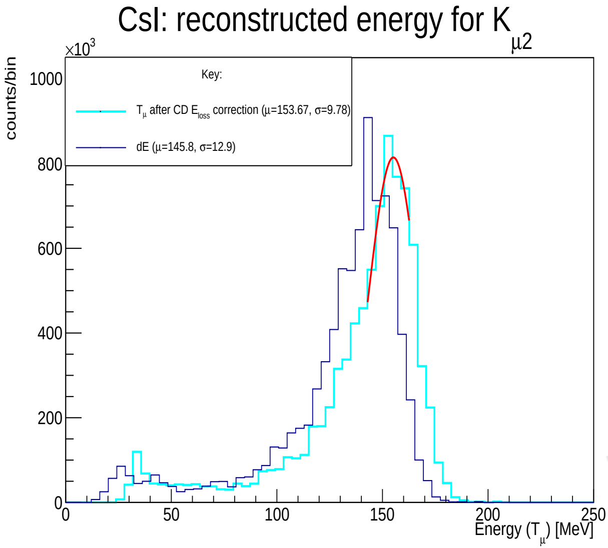
- Require single crystal per event
- First pulse time coincides with the K^+ decay
- Require a second peak

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

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

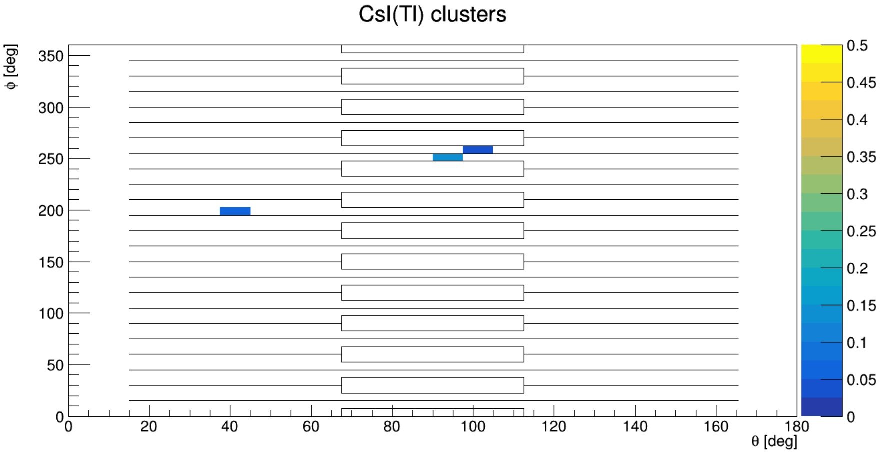


Pulse Fitting in Action: Energy Calibration from $K_{\mu 2}$



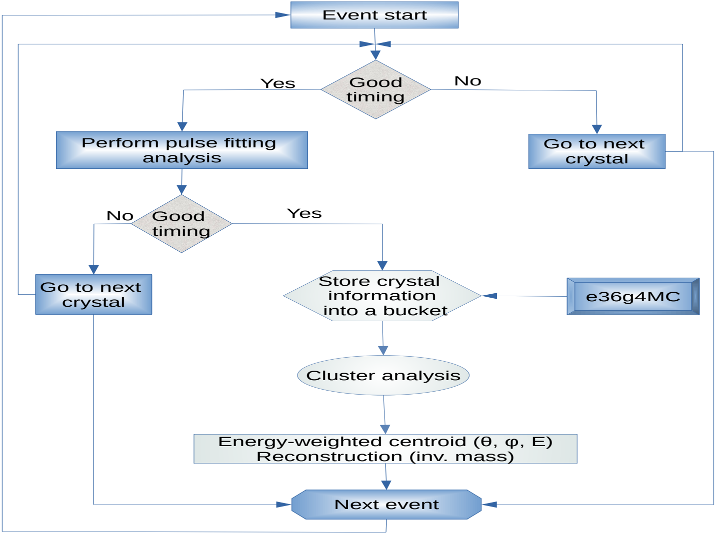
- Calibration coefficients C_i to convert pulse heights into energy
- $C_i = \frac{dE_{CsI}}{(A-P)_i}$, $i = 1, ..., 768$
- dE_{CsI} : deposited energy
- A : waveform amplitude
- P : baseline
- $T_\mu = dE_{CsI} + CDE_{loss}$
- Correction for energy loss from CD system

Cluster Analysis: Event Viewer

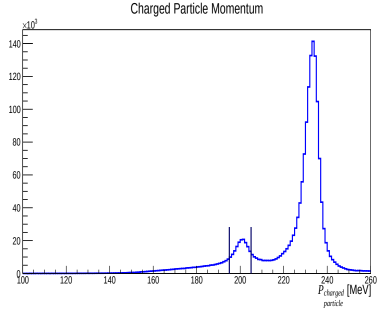


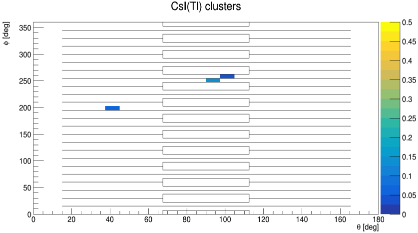
- Single event
- Reconstructed m_{π^0} from $M_{\gamma\gamma} = 123.7$ MeV/c^2
- PDG: $m_{\pi^0} = 134.9766$ MeV/c^2

CsI Cluster Analysis



CsI Cluster Analysis Cont...

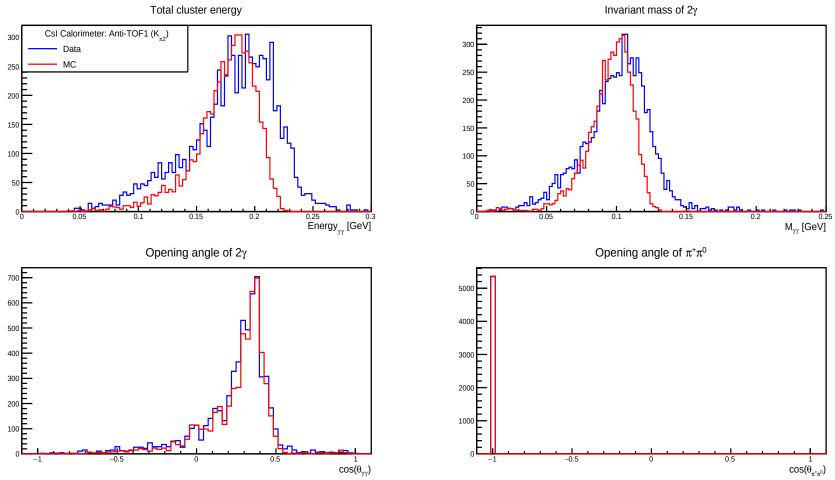




Cluster criterion: $K^+ \to \pi^+\pi^0$

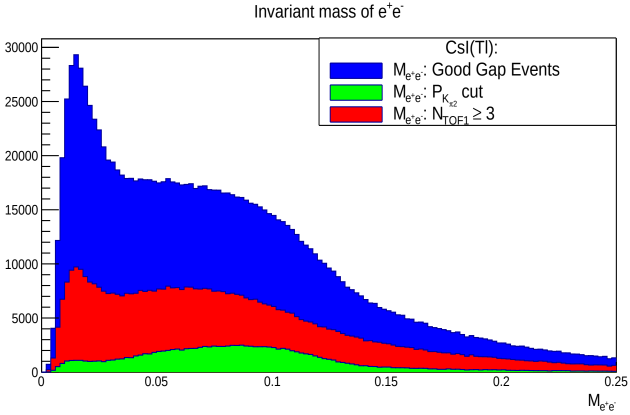
- High hardware trigger due to high rate
- Several clustering patterns need to be considered
- Currently single crystal clusters are considered as well
- Analysis is performed for prompt $\pi^0 \to \gamma\gamma$, while only considering two cluster events
- Suppress backgrounds by requiring only single TOF1 counter has fired
- Apply tight angle cut: $\cos(\theta_{\pi^+\pi^0}) \leq -.99$

CsI $K_{\pi 2}$ Cluster Analysis



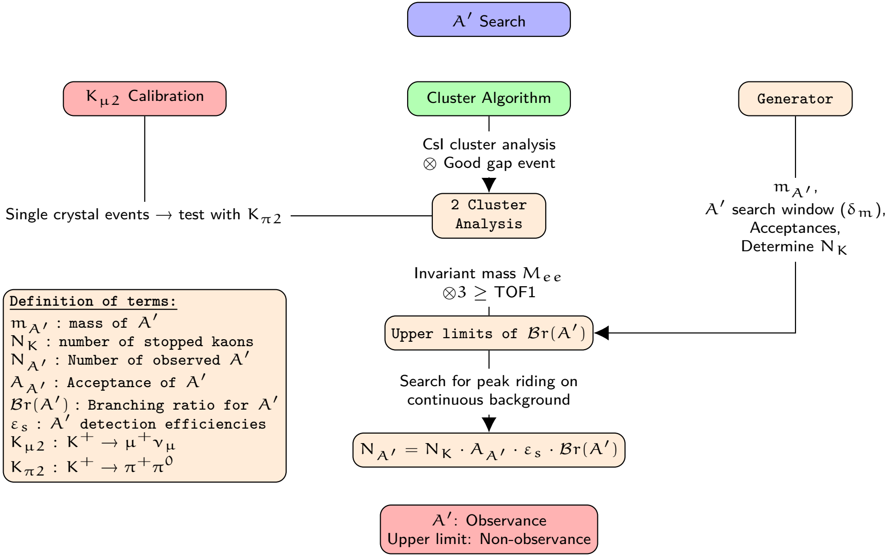
- Preselected $K_{\pi 2}$ events (from two CsI clusters)
- $\cos(\theta_{\pi^+\pi^0}) \leq -.99$: tight opening angle cut

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

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
$K_{\mu 2}$: $K^+ \rightarrow \mu^+ \nu_\mu$
$K_{\pi 2}$: $K^+ \rightarrow \pi^+ \pi^0$

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}

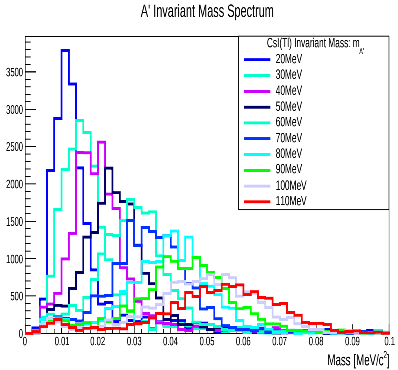
π^0 Channels

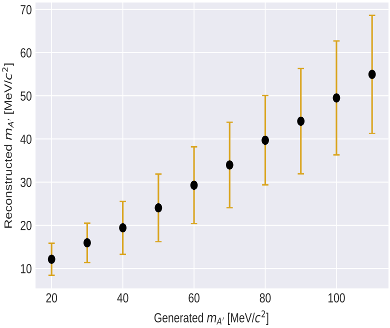
Label	Branch	Ratio
0	$\pi^0 \to \gamma\gamma$	9.8823×10^{-1}
1	$\pi^0 \to e^+e^-\gamma$	1.174×10^{-2}
2	$\pi^0 \to \gamma A'$	$\epsilon^2 \times ratio\ of\ channel\ 2$

ROOT based generator

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

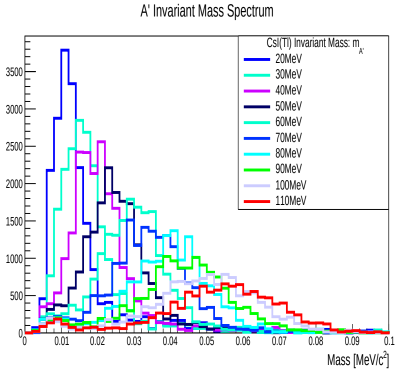
A' Acceptance and $m_{A'}$ Distribution

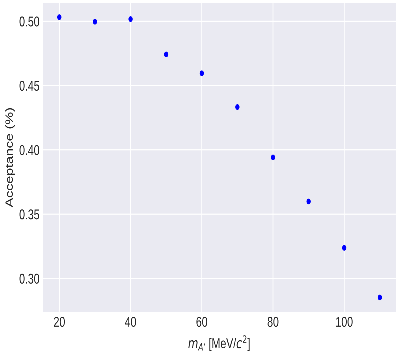




- A' masses generated on interval $20 - 110$ MeV
- $m_{A'}$ reconstructed from e^+e^- clusters in the CsI
- Mean $m_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(m_{A'})$ was obtained from fit

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





- A' masses generated on interval $20 - 110$ MeV
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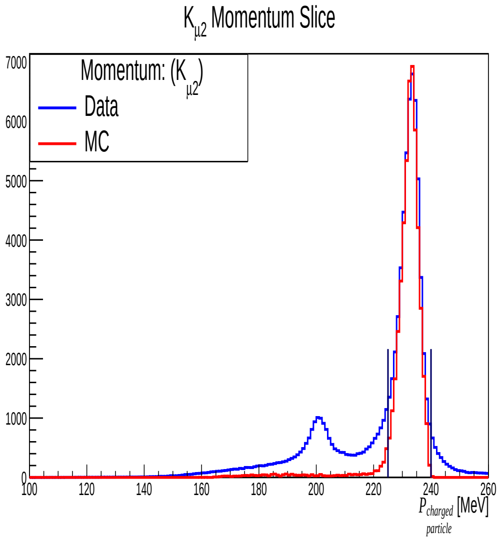
Number of Stopped K^+ (N_K)

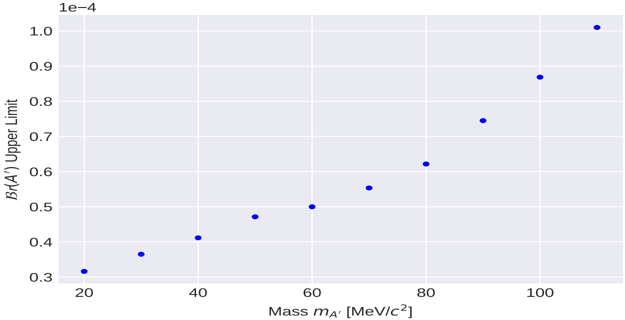
$$N_K = \frac{N_{\mu 2}}{\mathcal{B}r(\mu 2) PS(\mu) A_\mu LT(\mu)} = 2.81 \cdot 10^9$$

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



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

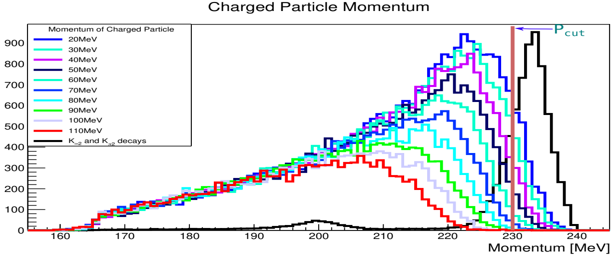
Upper Limit Extraction

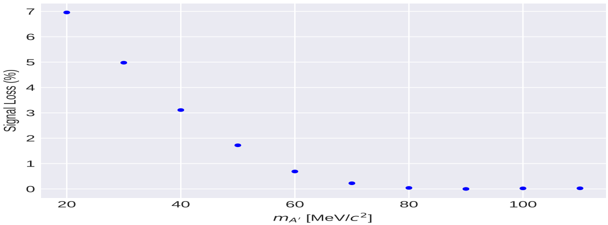


$$\mathcal{B}r(A') < \frac{2\sqrt{N_{\mu\nu ee}}}{N_K A_{A'} LT}$$

- No peak in M_{ee} spectrum → twice background fluctuation in search window
- 2σ limit: ~ 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

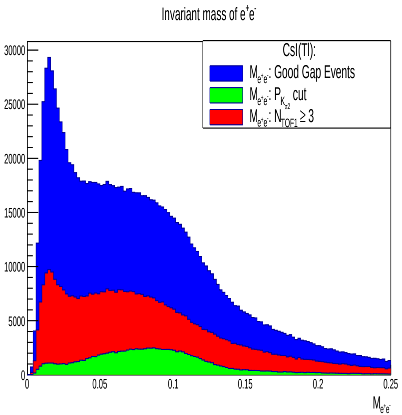
$K_{\mu2}$ Contamination Reduction

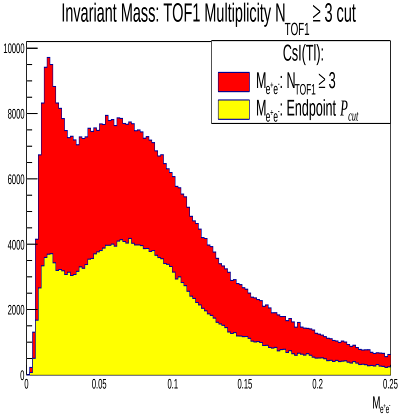




- Signal Loss $S_L = \frac{S_{cut}}{S_{tot}}$
- S_{cut} is integrated signal that survives cut
- S_{tot} is total integrated signal

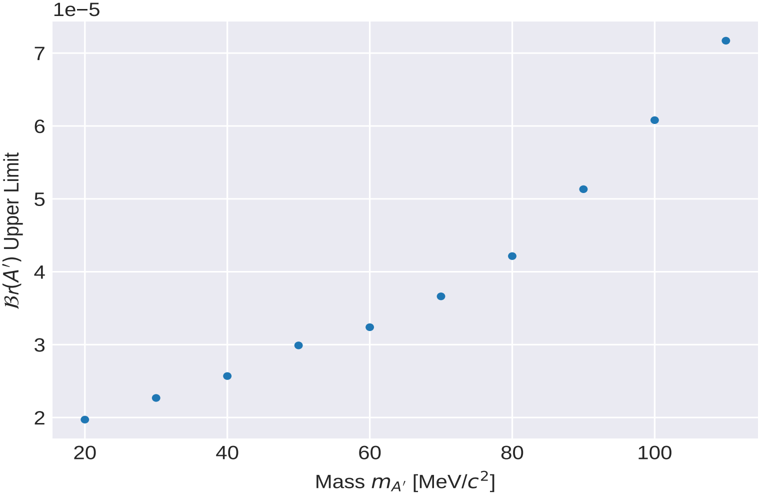
Invariant Mass Spectrum M_{ee} after $K_{\mu 2}$ Cut





- From 105 runs ($\sim 8.08\%$ of total Fall data)
- Improvements to tracking, M^2_{TOF}, 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 $\mathcal{B}r(K^+ \to \mu^+ \nu A')$ 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

Spokespeople:
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Chiba University
Department of Physics
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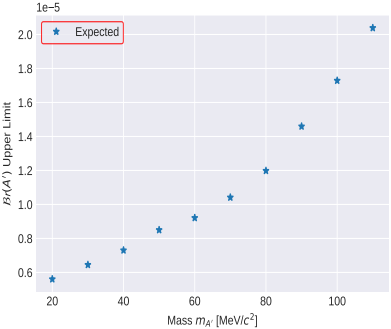
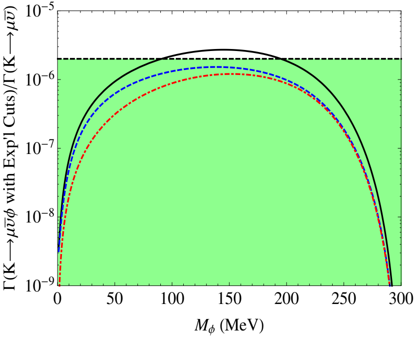
Institute for Particle and Nuclear Studies

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

Backup

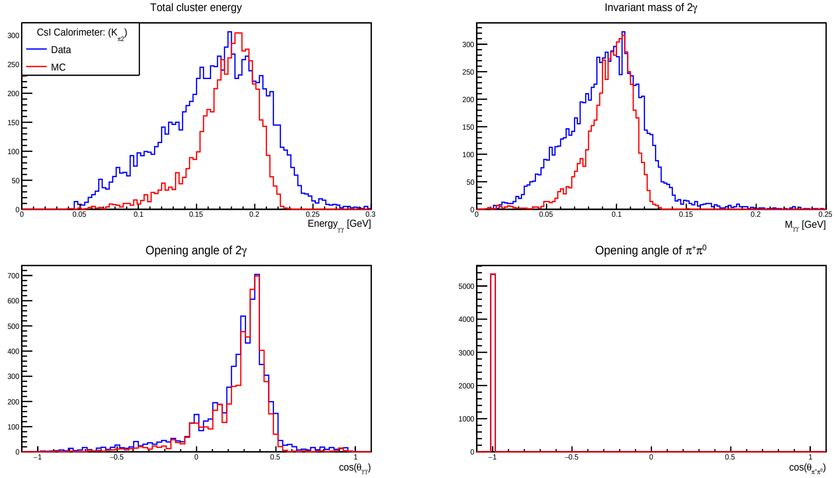
Expected Upper Limits





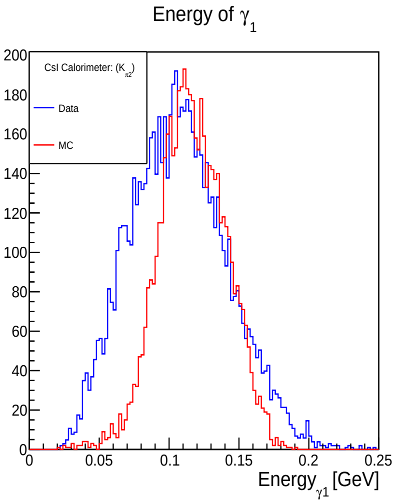
- Solid curve full result satisfying proton radius and $(g-2)_\mu$
- Shaded region is allowed: $< \mathcal{O}(-6)$

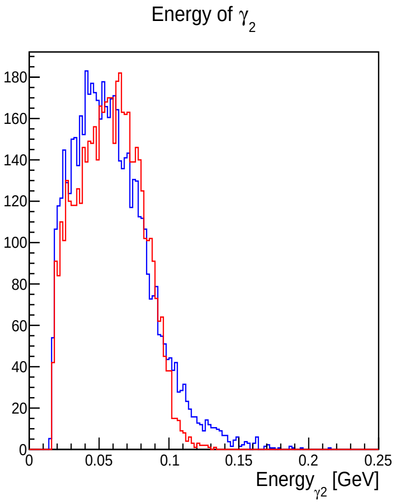
CsI 2 Cluster Events



- Two cluster events under $K_{\pi2}$ momentum cut
- e36g4MC: Generator channel 7 was used

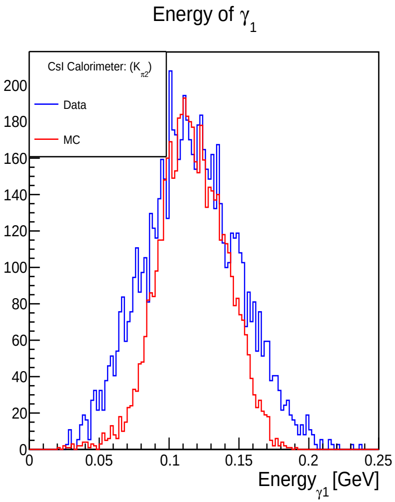
Energy of $\gamma 1$ and $\gamma 2$

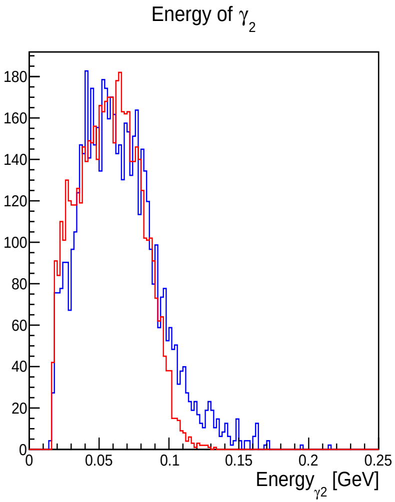




- $\cos(\theta_{\pi^+\pi^0}) \leq -0.995$

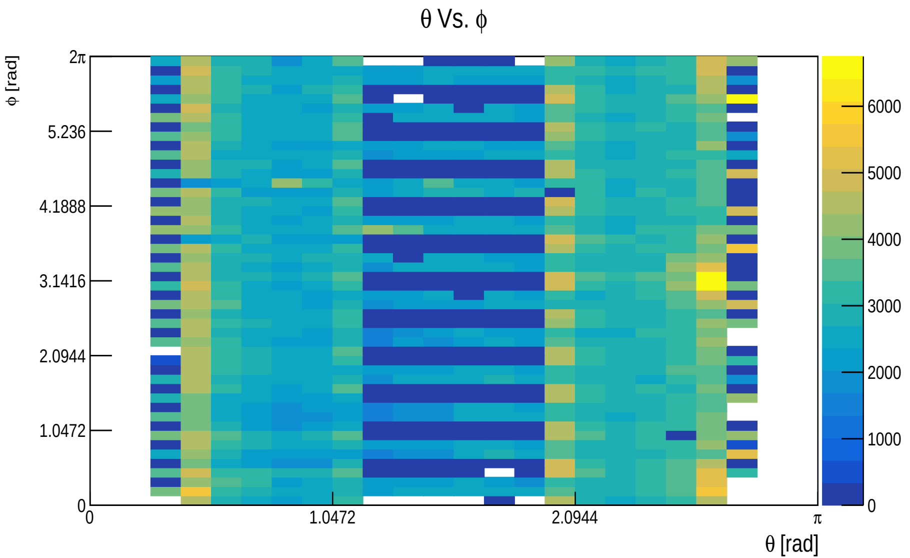
Energy of $\gamma 1$ and $\gamma 2$ TOF1 cut



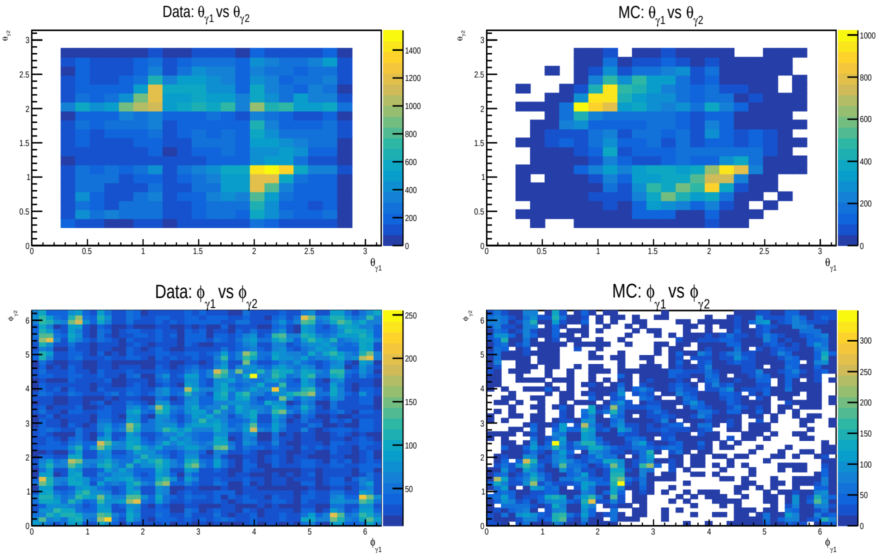


- $\cos(\theta_{\pi^+\pi^0}) \leq -0.995$
- only one TOF1 counter has fired

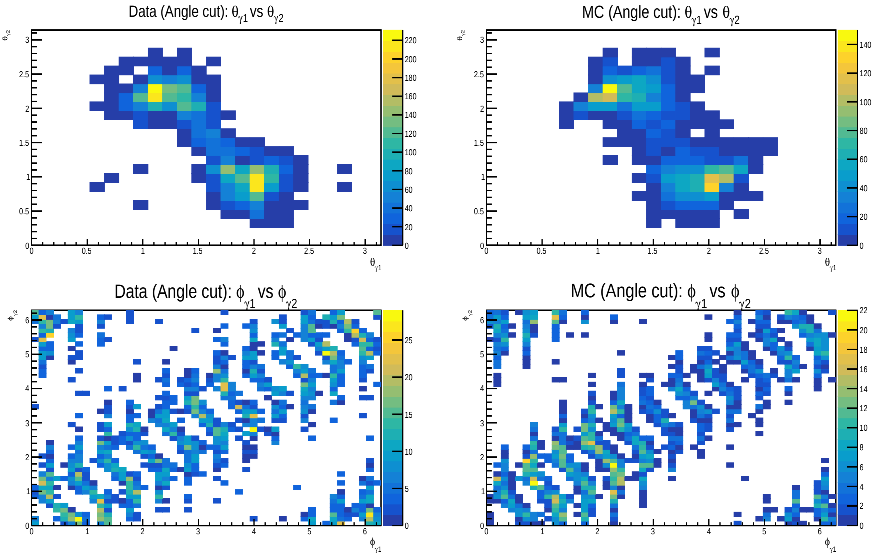
Theta Vs Phi


θ Vs. ϕ
ϕ [rad]
2π
5.236
4.1888
3.1416
2.0944
1.0472
0
0
1.0472
2.0944
π
θ [rad]
6000
5000
4000
3000
2000
1000
0

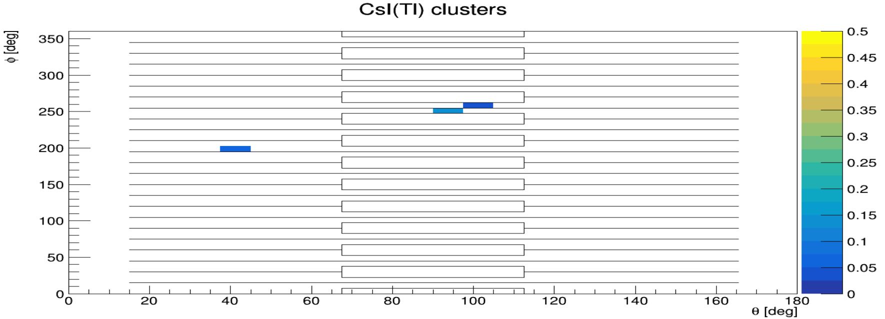
Angular Correlations: $\theta_{\gamma 1}$ vs. $\theta_{\gamma 2}$



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
*************************************************************************
```