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

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PhD Oral Defense
The TREK Collaboration

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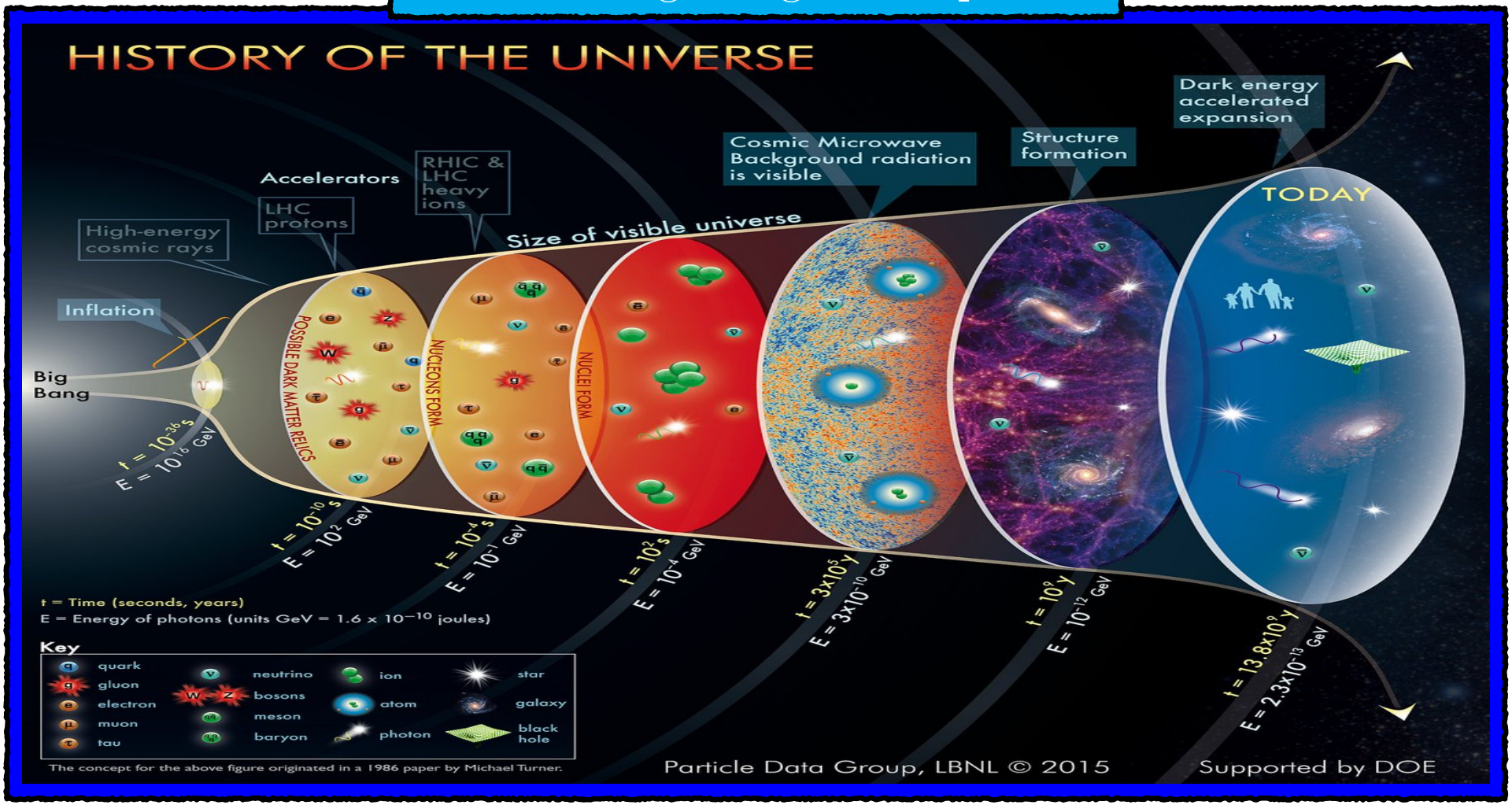
The TREK/E36 Experiment at J-PARC: An Overview

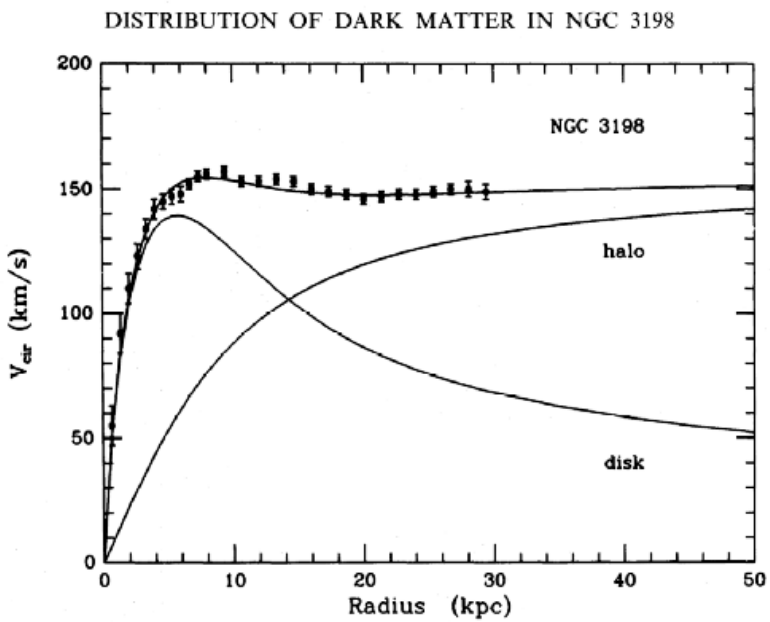
Big Bang Nucleosynthesis to Present

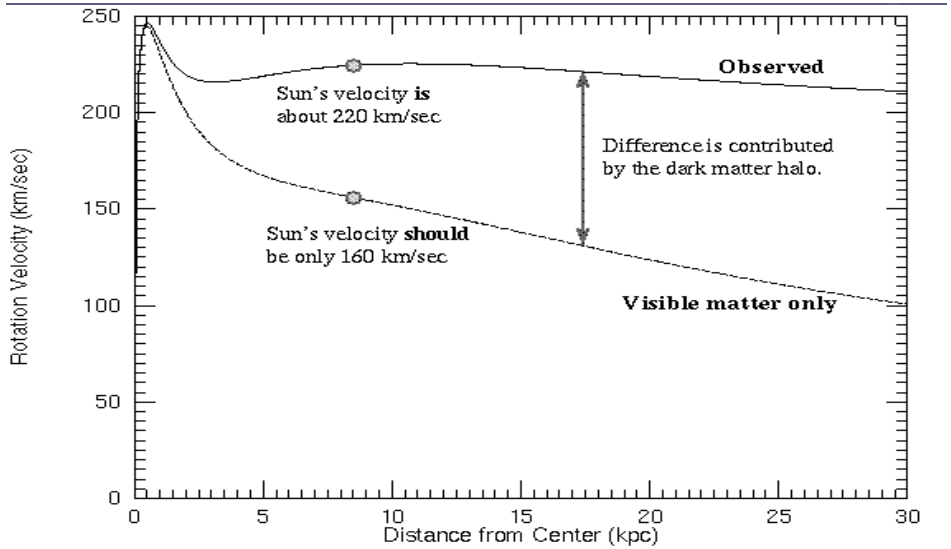
From the Big Bang to the present



Rotation Curves of Galaxies

Vera Rubin



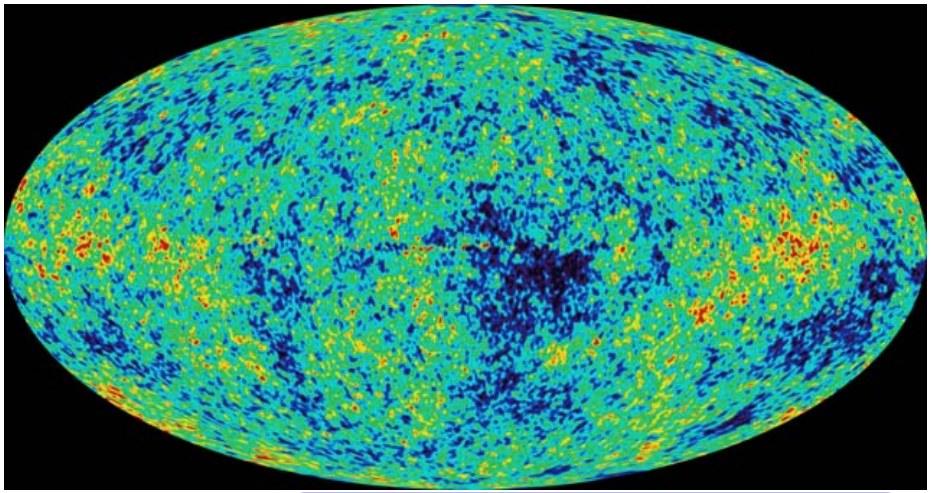


Vera Rubin:

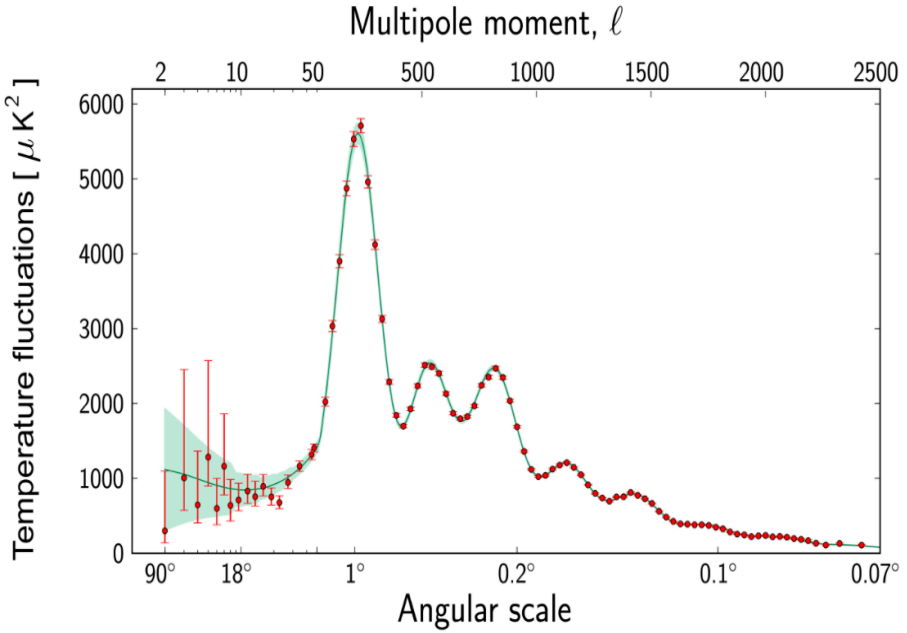
- Zwicky noticed that galaxies in the Coma Cluster were moving too rapidly to be explained by the amount of stella material
- Rubin studied rotation curves of galaxies
- Velocity of objects (stars or gas) orbiting the centers of galaxies, rather than decreasing as a function of the distance from the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

▸ Katherine Freese (Public lecture)

Cosmic Microwave Background (CMB)



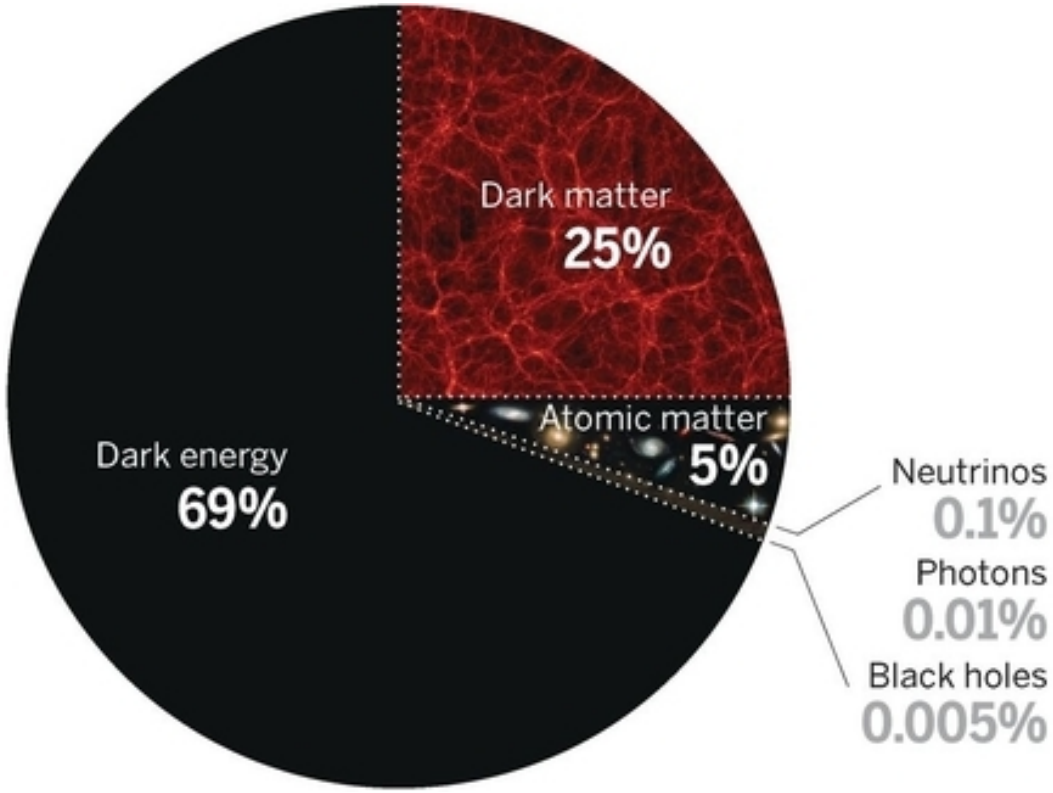
Jeff Filippini (▸ UC Berkeley Cosmology Group)



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 degree is consistent with a flat geometry of the universe, the height of the second peak with 5%, and the second and third peaks with 26% dark matter

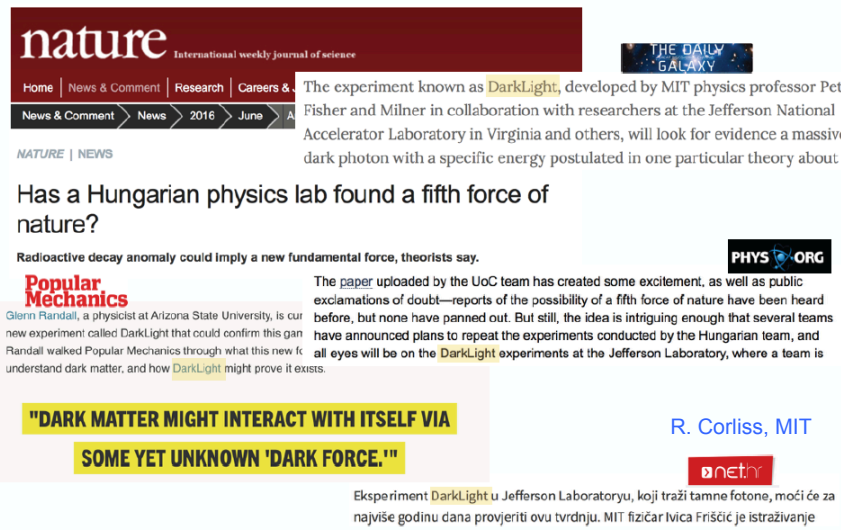
Energy of the Universe

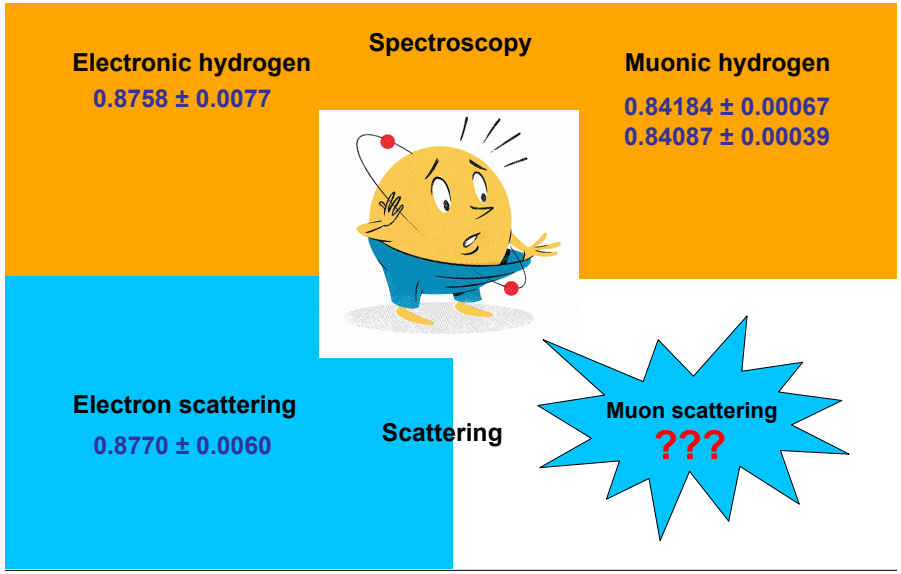


2014 P5 report

"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





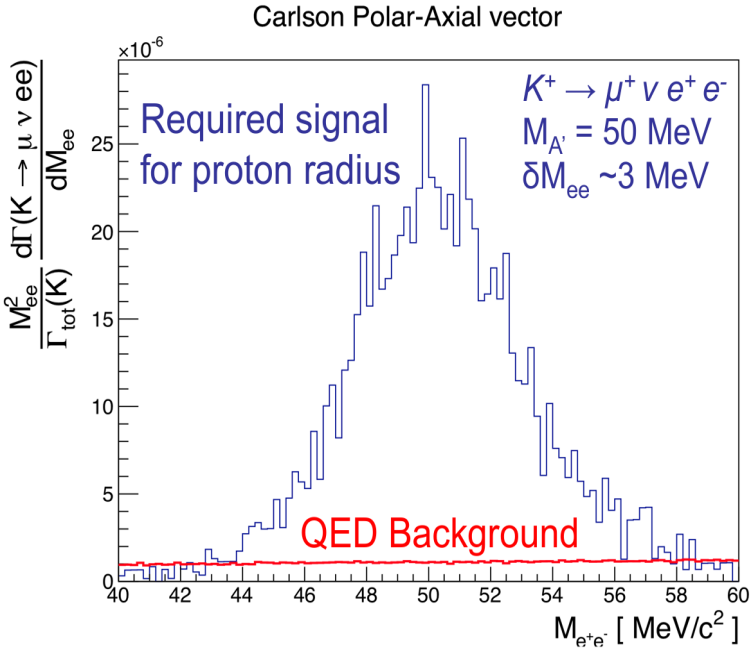
- Proton radius puzzle, $(g-2)_\mu$
- Strong CP problem
- Positron excess and ^{8}Be anomaly

Neutral Boson Search in Stopped K^+ Decays

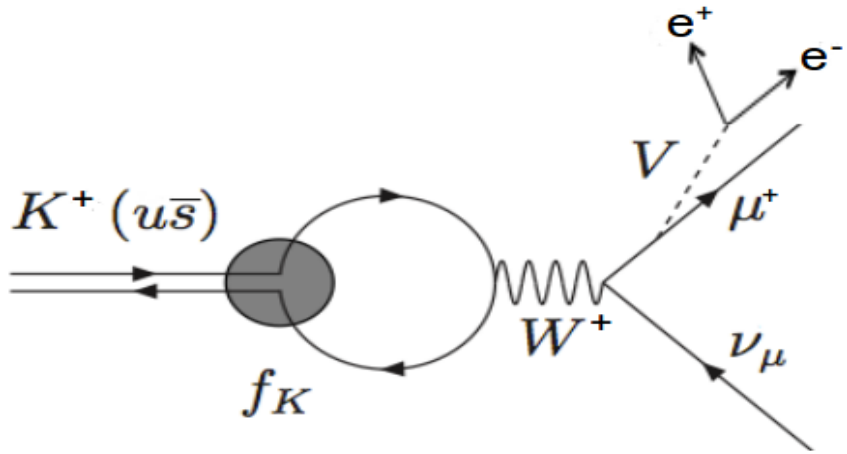
K^+ decays ~ 10^{10}
Signal 1: $K^+ \to \pi^+ A'$, $A' \to e^+e^-$
Background: BR($K^+ \to \pi^+ e^+ e^-$) ~ 2.9 x 10^{-7} ~ 2,900 ev.

Signal 2: $K^+ \to \mu^+ \nu A'$, $A' \to e^+e^-$
Background: BR($K^+ \to \mu^+ \nu\ e^+ e^-$) ~ 2.5 x 10^{-5} ~ 250,000 ev.
Add. background from $K^+ \to \mu^+ \nu \pi^0 \to \mu^+ \nu\ e^+ e^- (\gamma)$

π^0 decays 1) 3x10^8 2) 2x10^9
π^0 production: $K^+ \to \mu^+ \nu \pi^0$ (3.3%) $K^+ \to \pi^+\pi^0$ (21.1%)
Signal 3: $\pi^0 \to \gamma A'$, $A' \to e^+e^-$
Background: BR($\pi^0 \to \gamma\ e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) x$10^7$ ev.

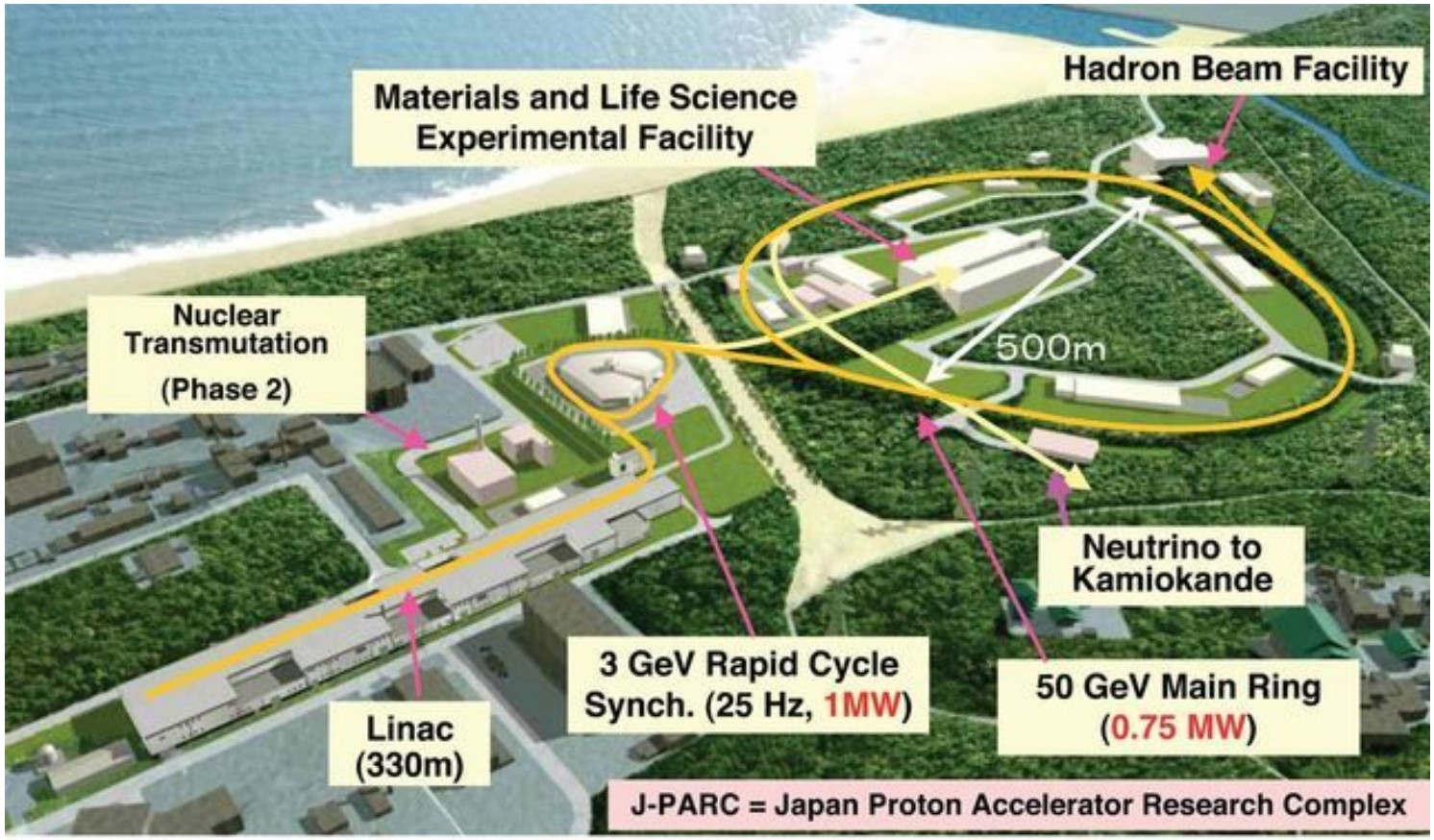


- Can light neutral bosons explain both dark matter and particle physics anomalies (muon magnetic moment, ^{8}Be decay & proton radius)?
- Search for light neutral bosons in channels involving a muon (Signal: 2)



PRD 89, 0350003 (2014)

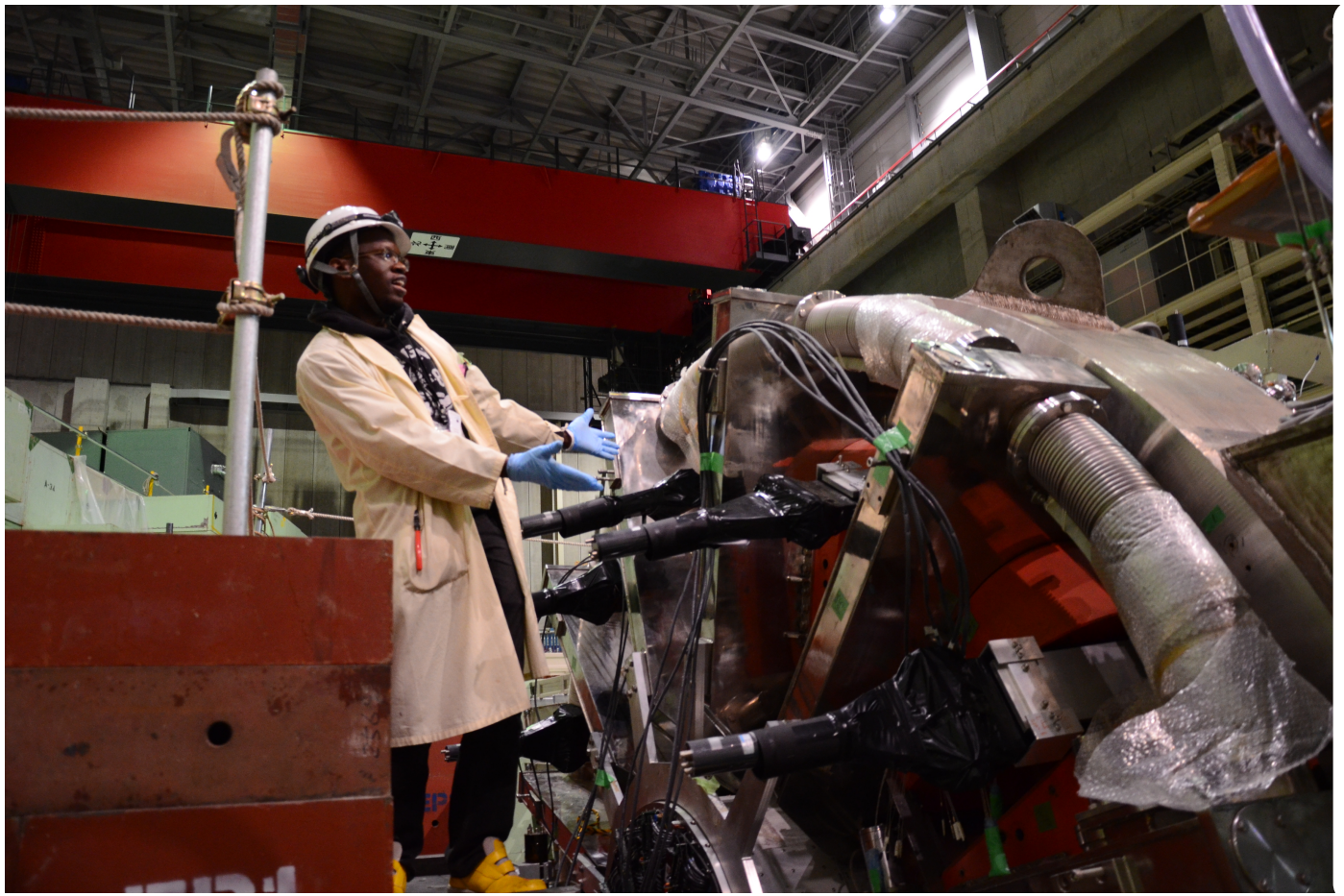
Bird's Eye View of J-PARC



Joint Project between KEK and JAEA

Timeline of TREK/E36

TREK: Time Reversal Experiment with Kaons



December 2014

- Installed detector components

February - June 2015

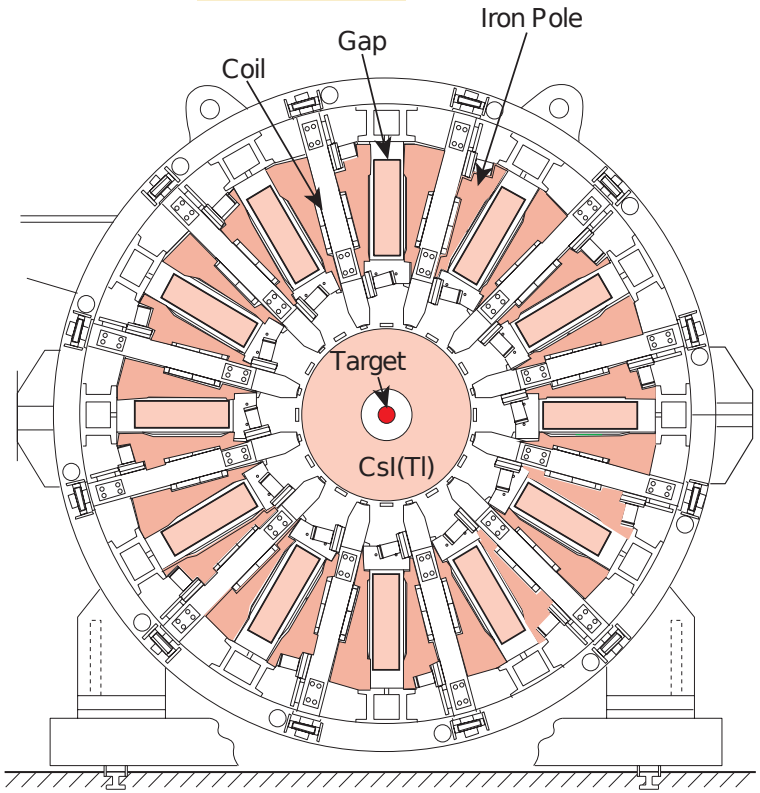
- Completed installation of C3 & C4
- Cabling
- Detector maintenance

September - December 2015

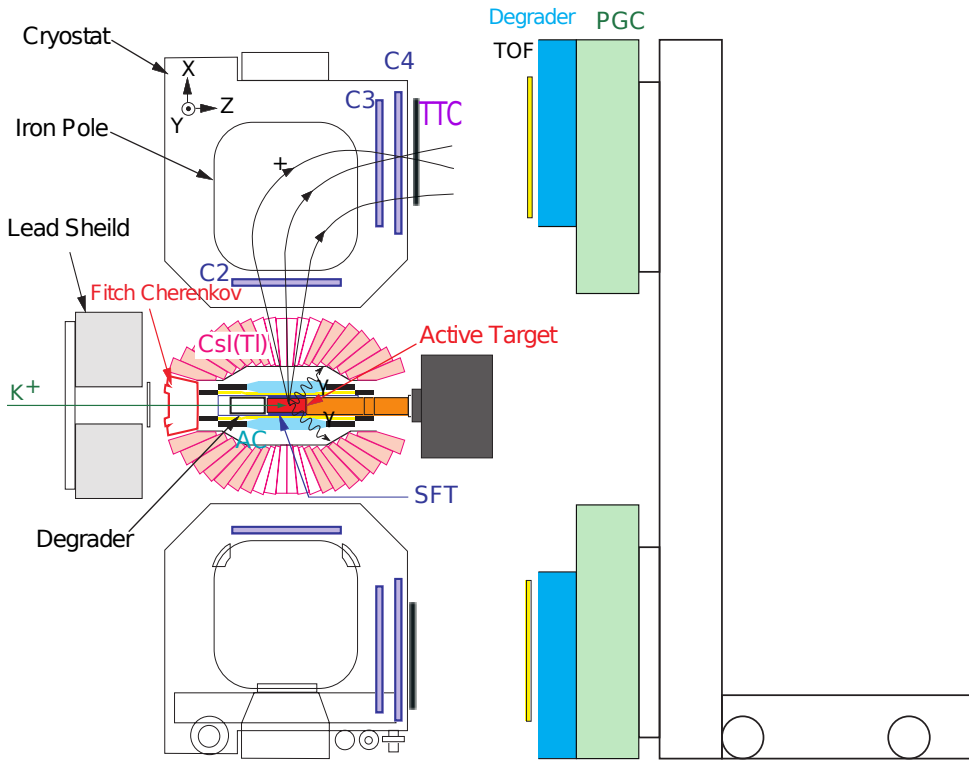
- Physics run
- Data taking

E36 Detector Geometry

End view



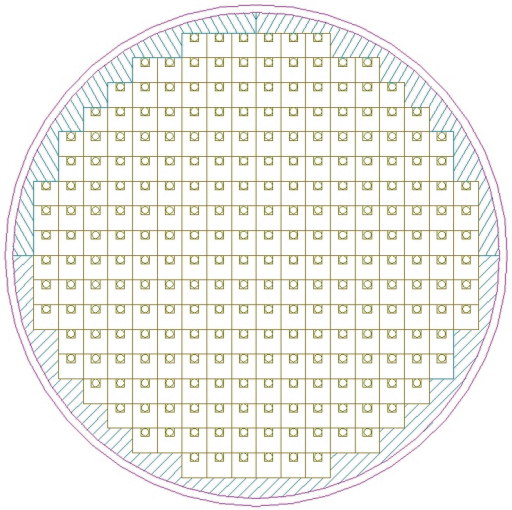
Side view

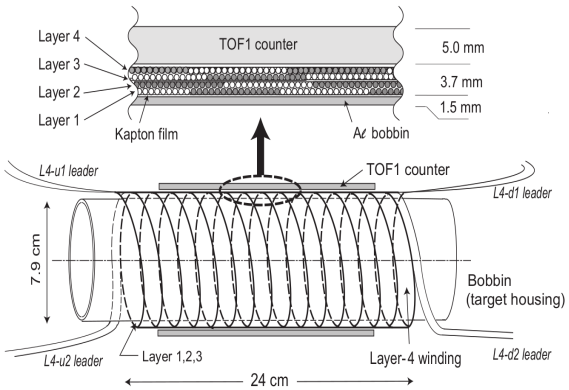


Stopped K^+ method	Momentum measurement	Particle ID	Gamma ray
K1.1BR beamline	MWPC (C2, C3, C4)	TOF	CsI(TI)
K^+ stopping target	Spiral fiber tracker (SFT)	AC	
	Thin trigger counter (TTC)	PGC	

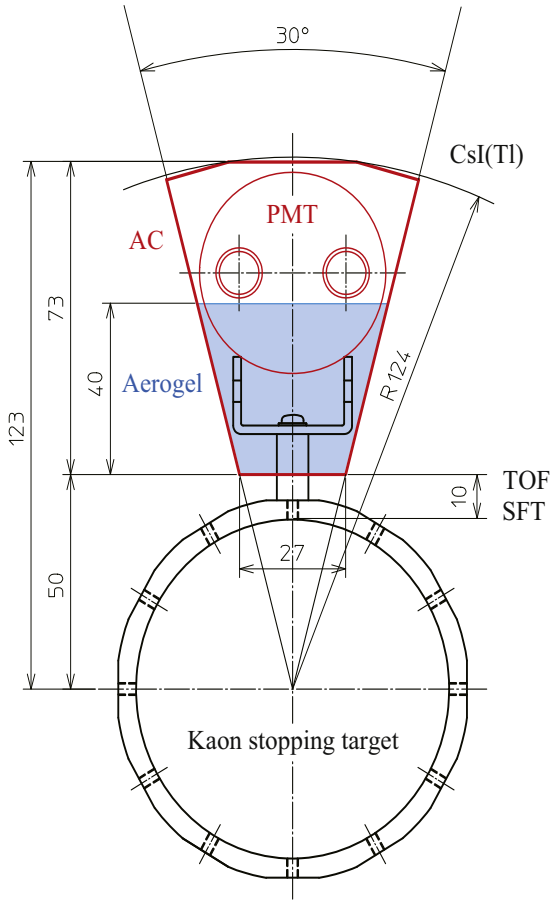
E36 Central Detector Geometry

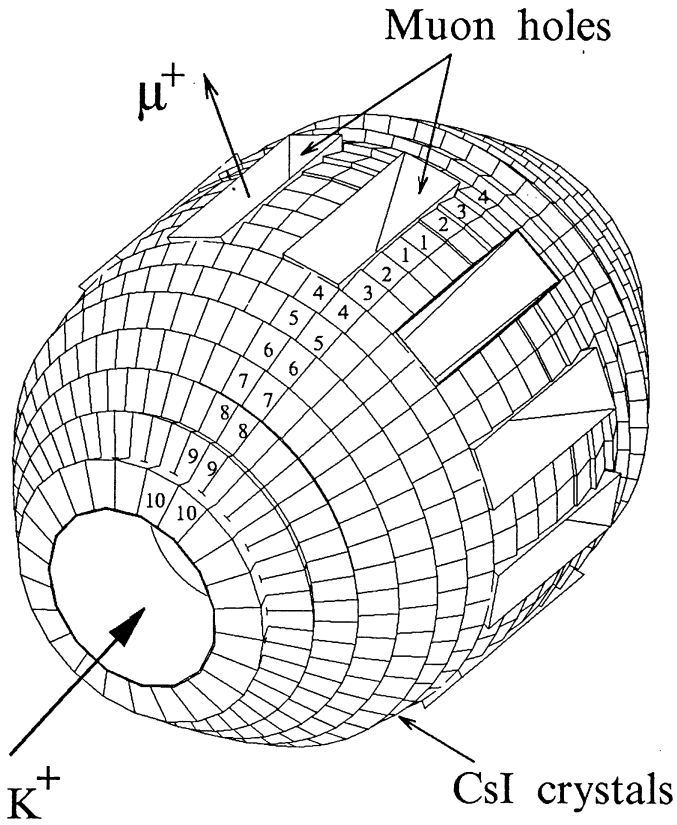
Target & SFT



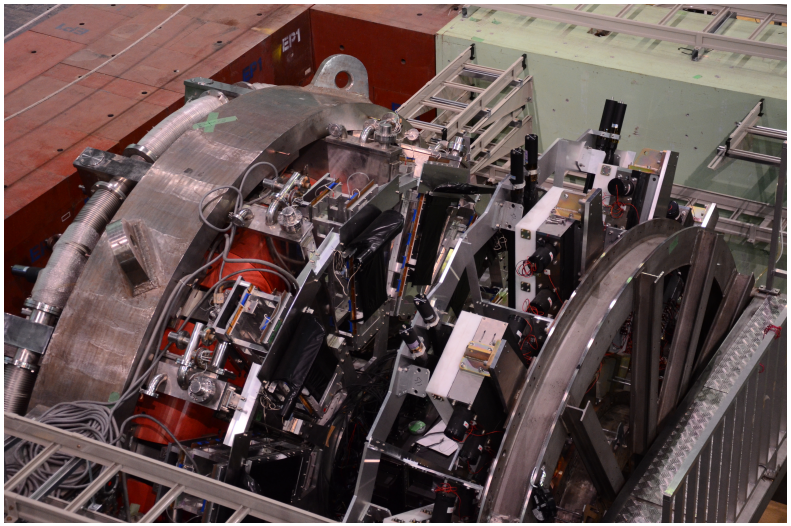


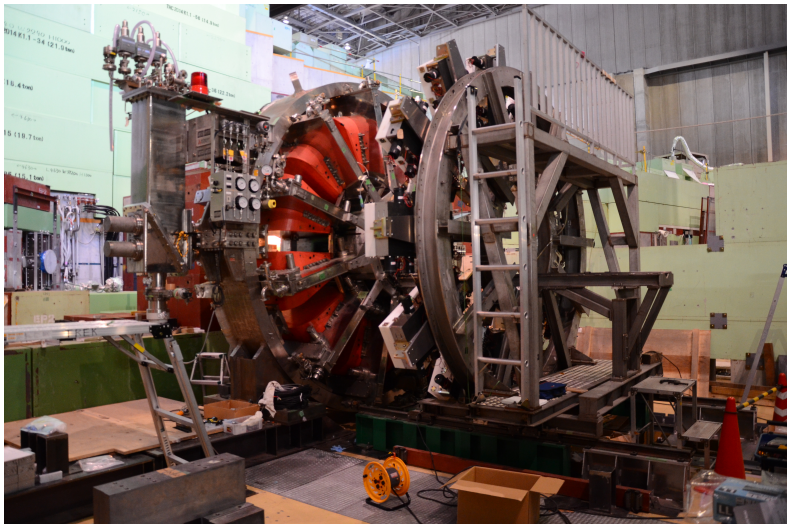
Aerogel Čerenkov



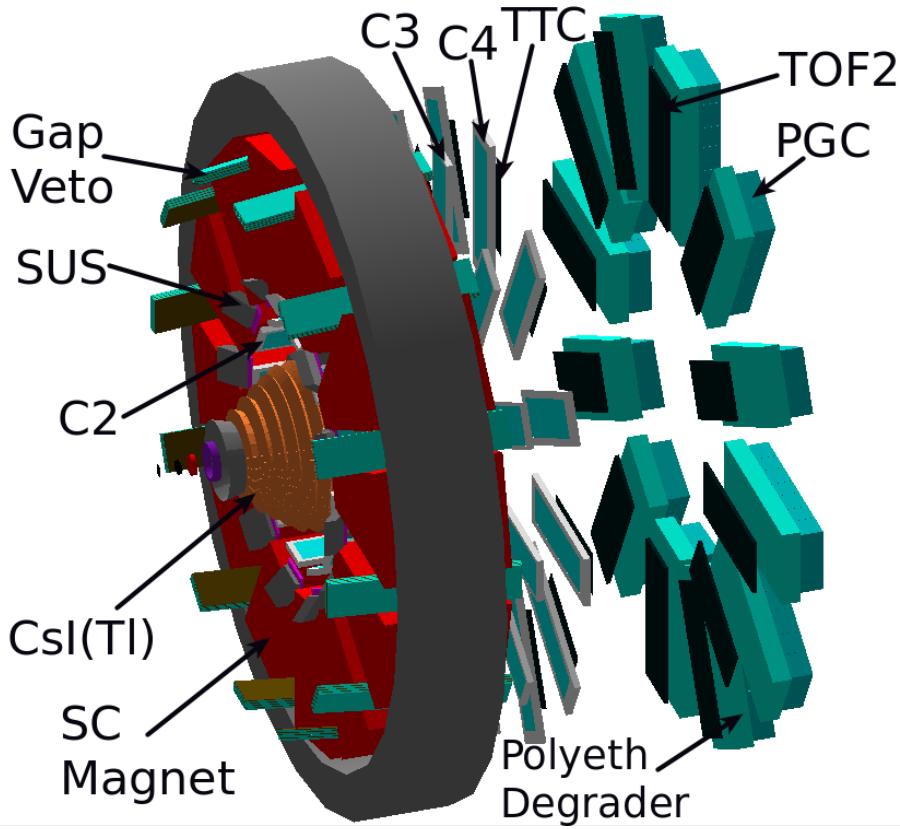


Geant4 Generated Geometry



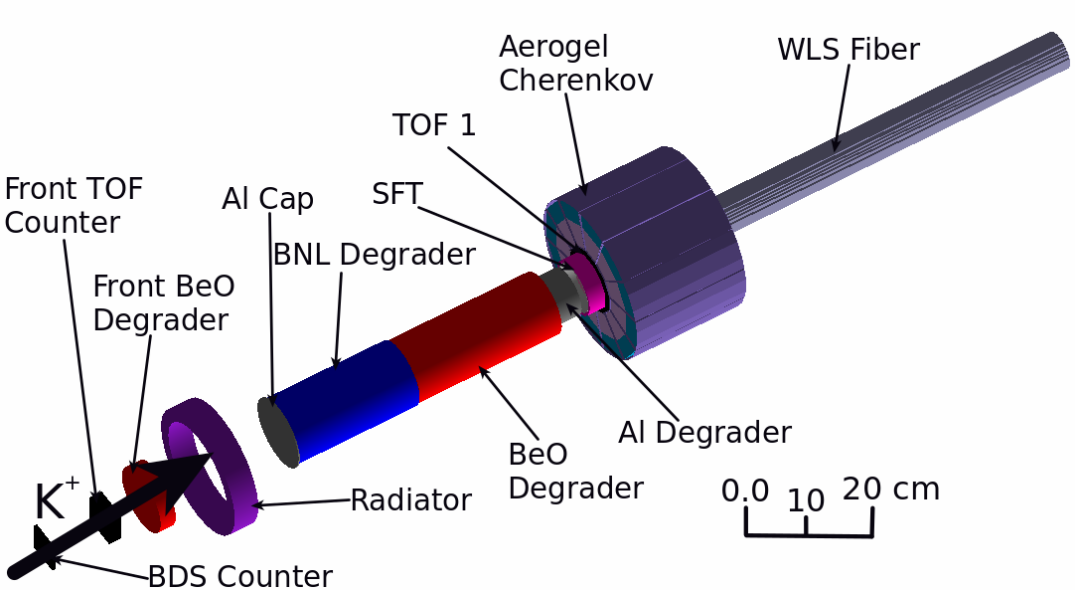


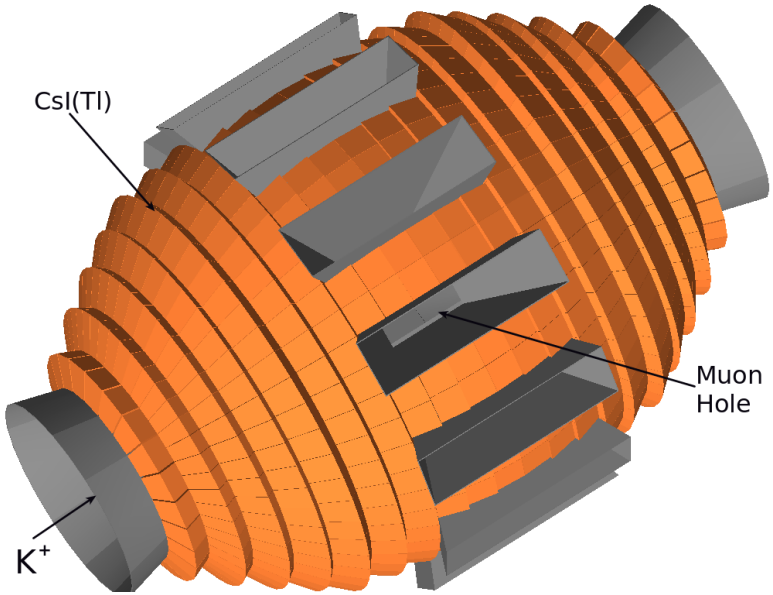
- Detector Assembly



- e36g4MC detector geometry

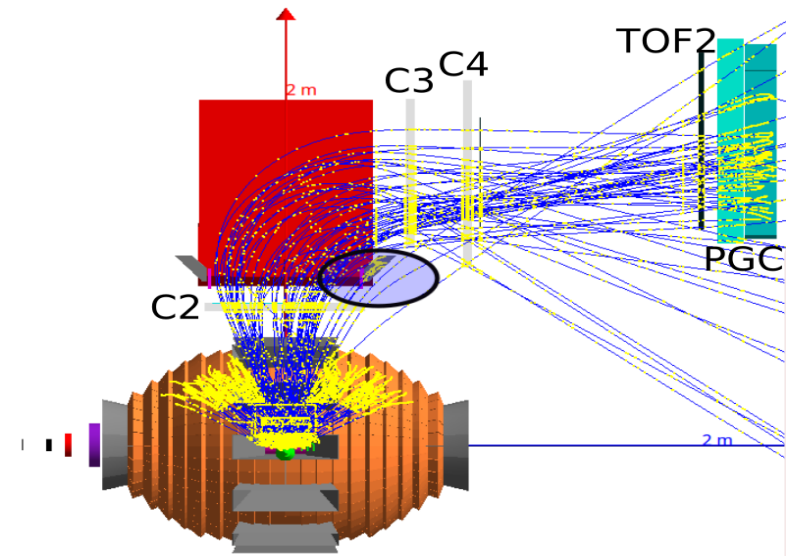
Geant4 Cont.: Central Detector

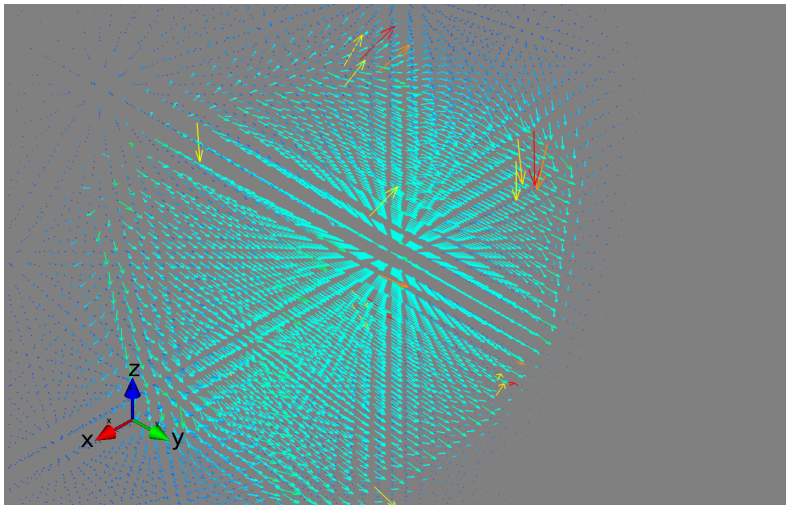




- Central Detector

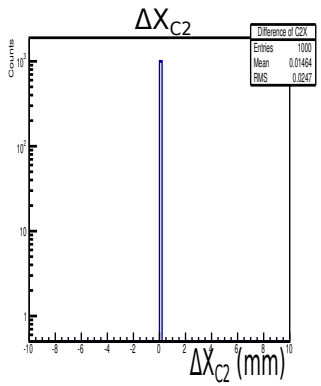
Tracking Package and the e36g4MC Comparison

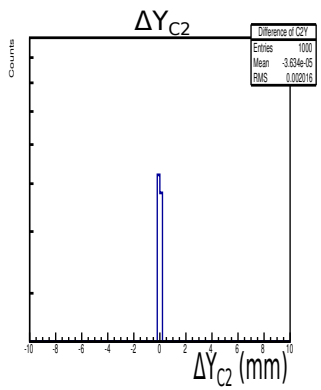


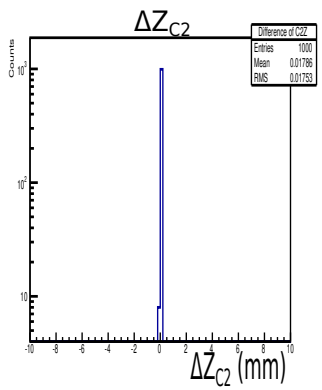


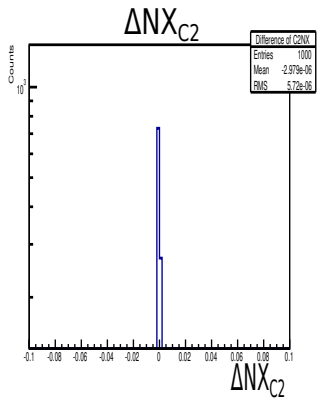
TOSCA generated field (P. Monaghan)

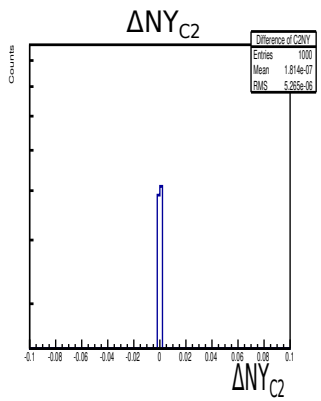
- Consistency check: propagation and magnetic field evaluation
- Simulated data: tracks propagated and reconstructed with Kalman Filter (KF)
- Compared differences at C2 coordinates ΔX_{C2}, ΔY_{C2}, ΔZ_{C2}
- Compared differences at C2 direction cosines ΔNX_{C2}, ΔNY_{C2}, ΔNZ_{C2}
- KF tracking/propagation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

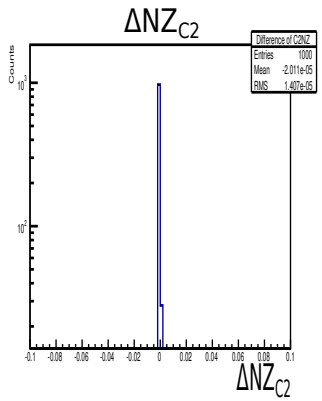




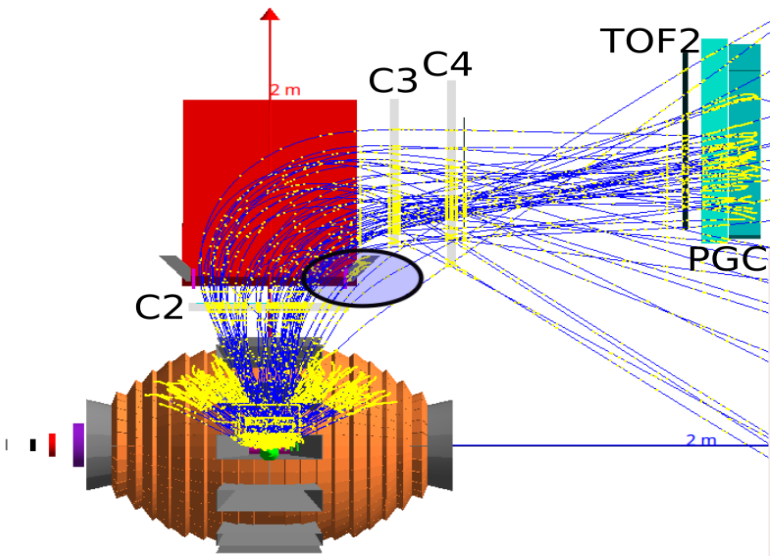


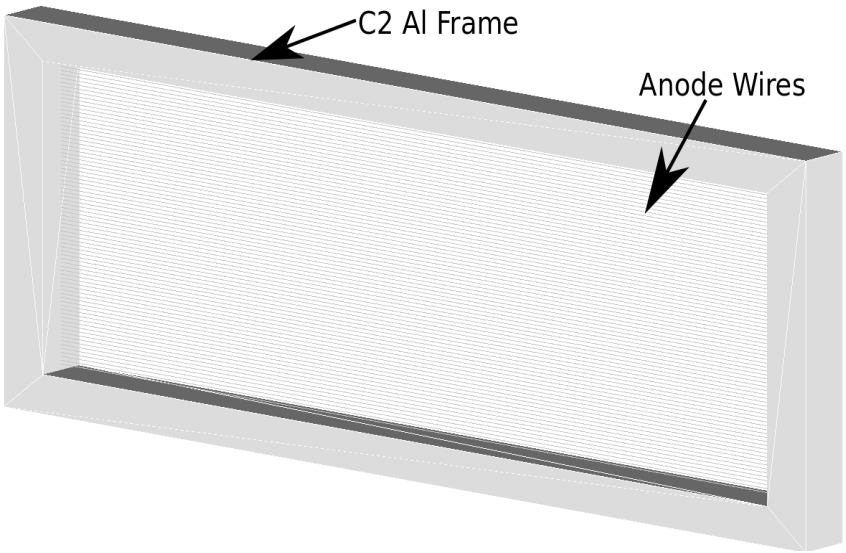




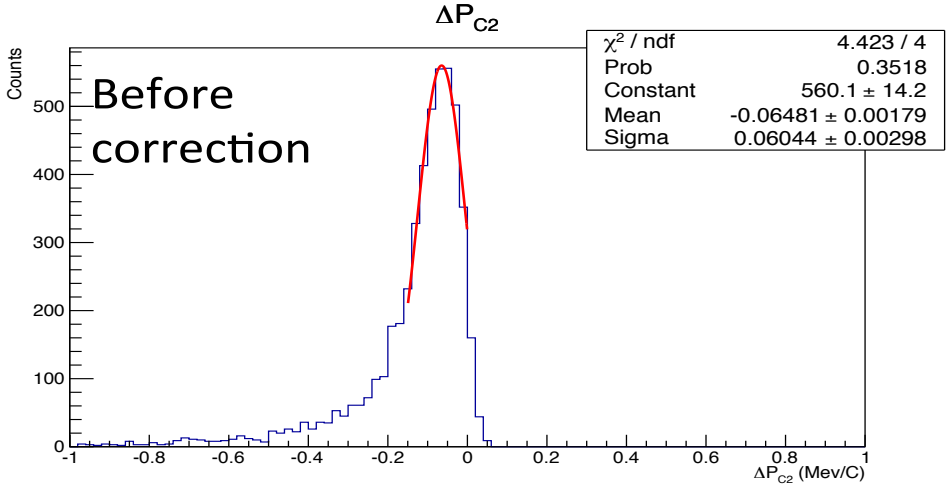


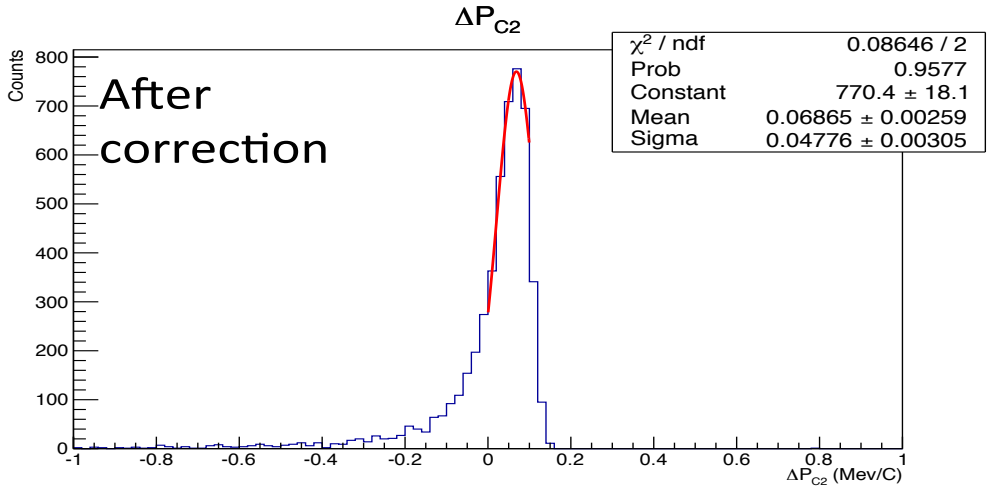
Tracking Package and the e36g4MC Comparison





- Energy loss/material budget comparison
- ΔP_{C2}: momentum difference at C2 between reconstructed MC from tracking package and MC
- Anode plane → anode wires





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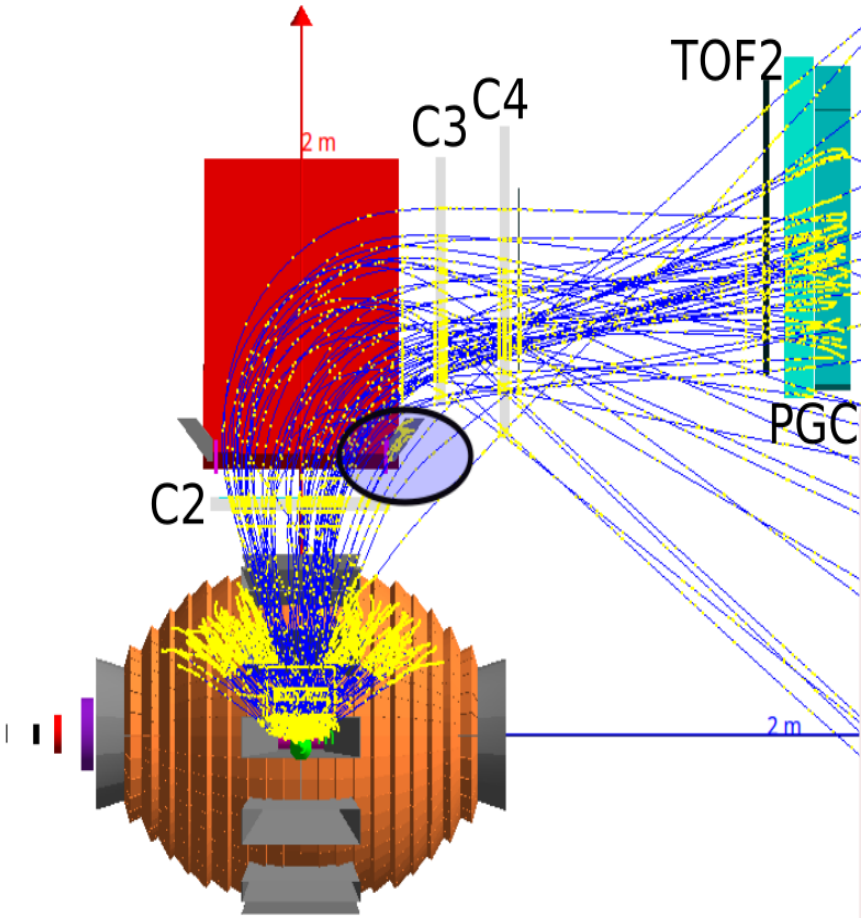
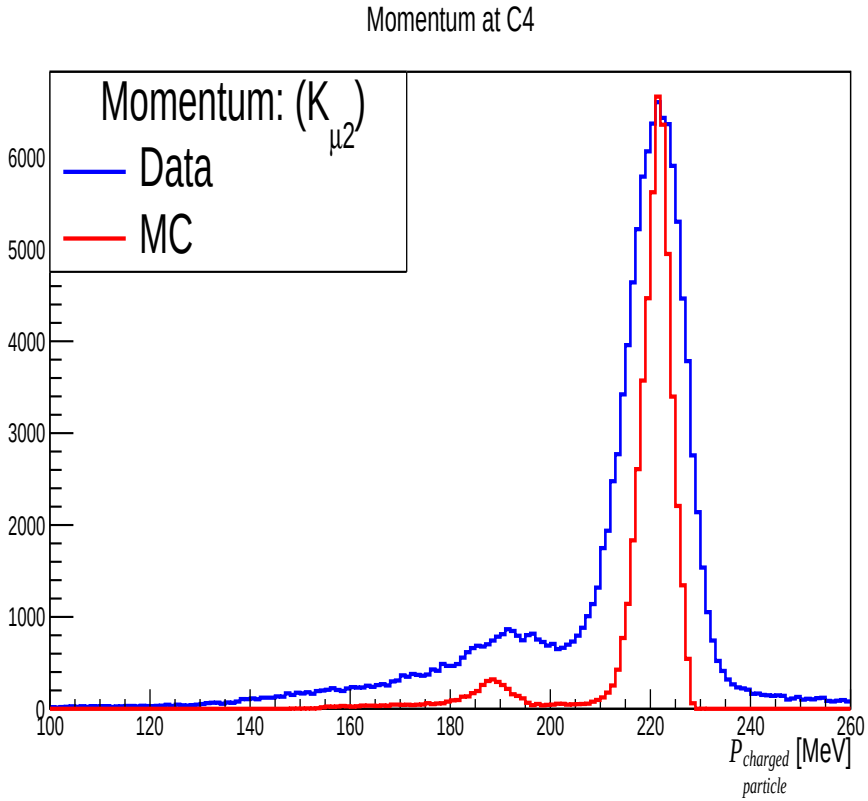
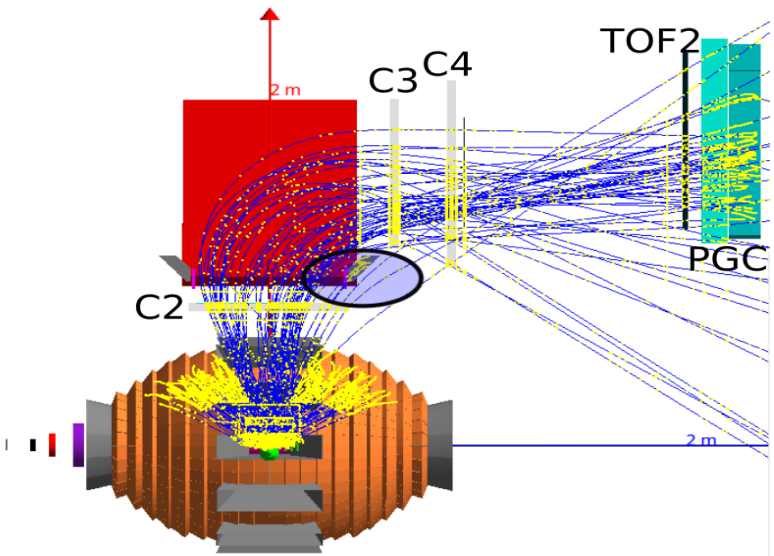


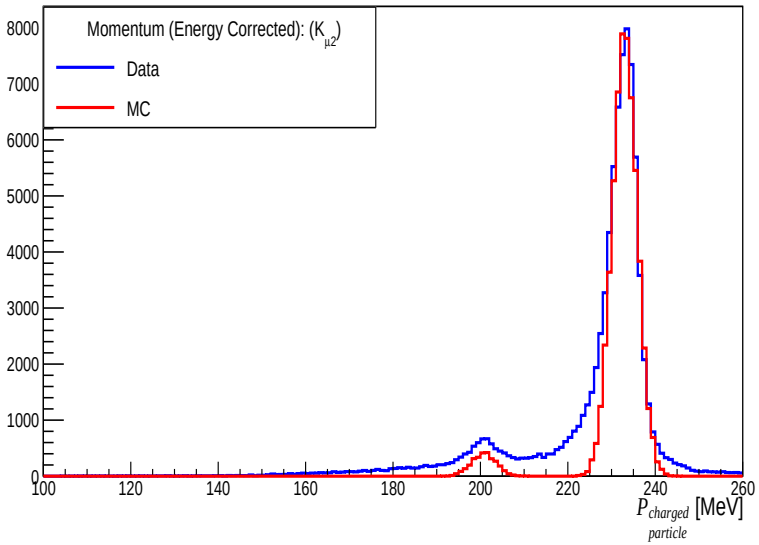
- Energy loss/material budget comparison
- Charged particle momentum at C4
- Applied offset (-2.5 MeV) to MC due to incorrect field map
- No detector resolution in the simulation



Tracking Package and the e36g4MC Comparison

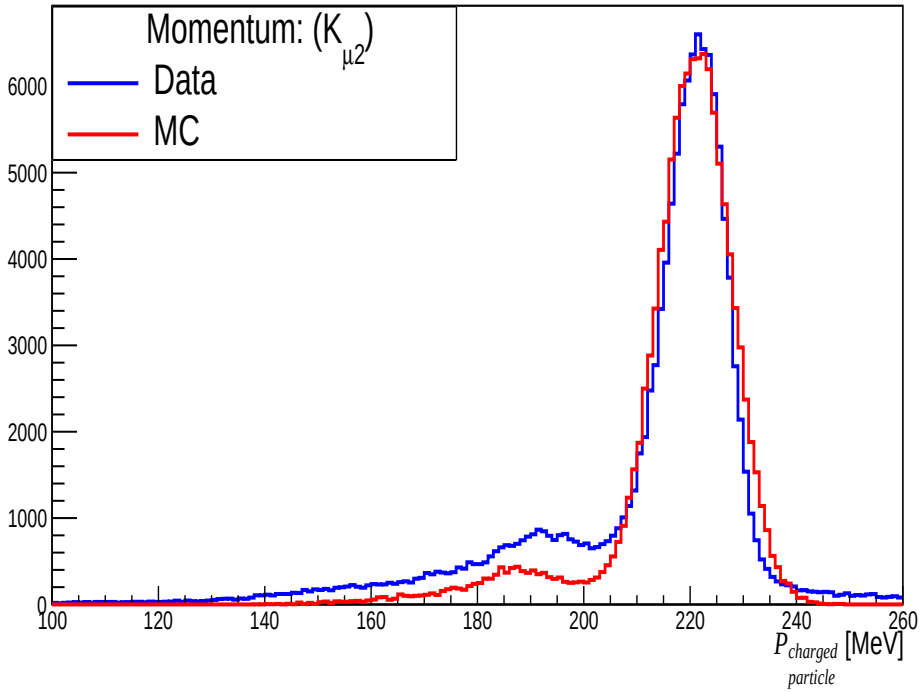


Energy Corrected Momentum Distribution

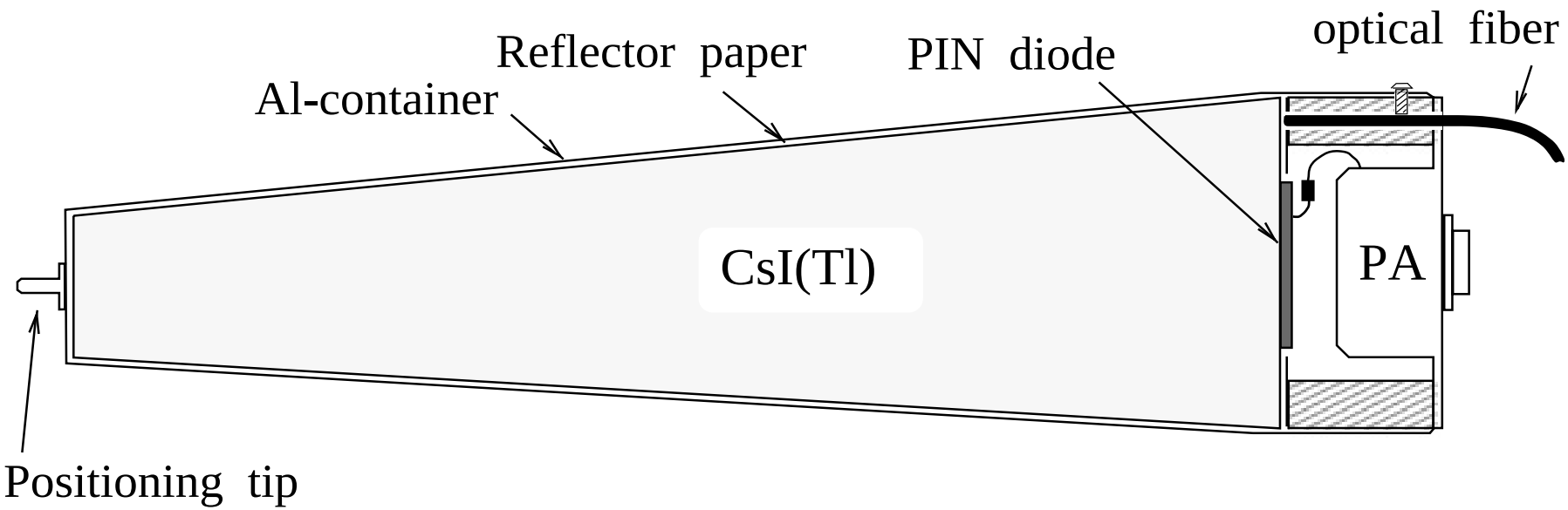


- Energy loss/material budget comparison
- Charged particle momentum at C4
- Applied offset (-2.5 MeV) to MC due to incorrect field map
- Energy corrected momentum distribution
- Applied smearing of 2.86 MeV (energy corrected) and 6.01 MeV (C4)
- Smearing value was obtained by fitting a Gaussian to data

Momentum at C4



CsI(Tl) Analysis



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

- 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)

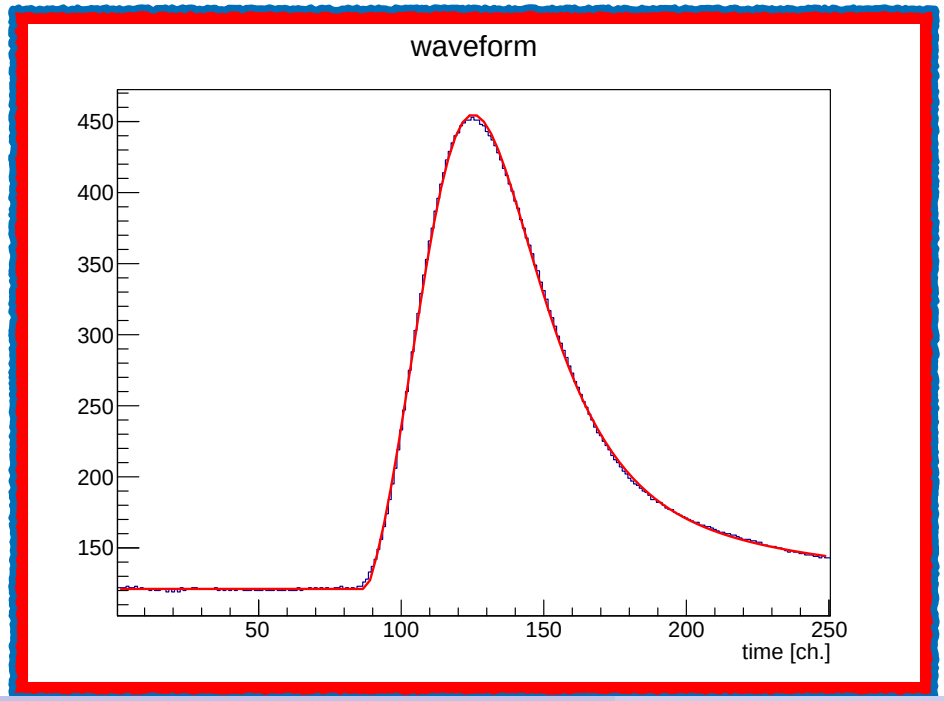
CsI(Tl) Waveform Analysis

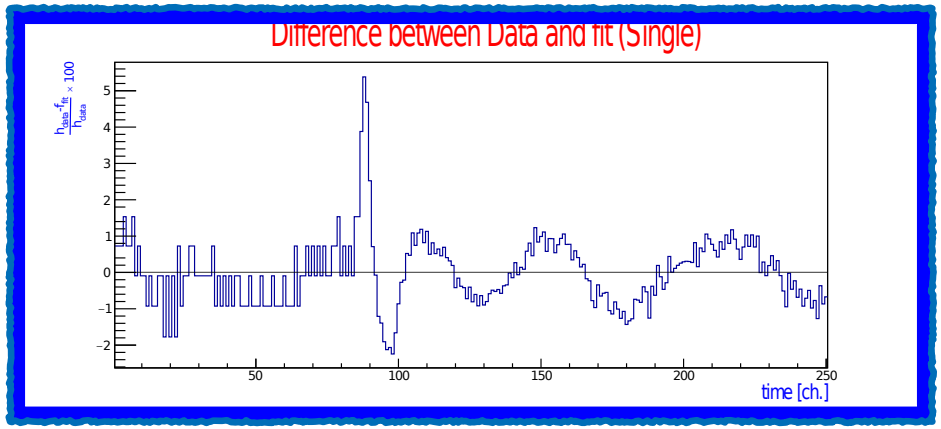
- μ rising factor

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

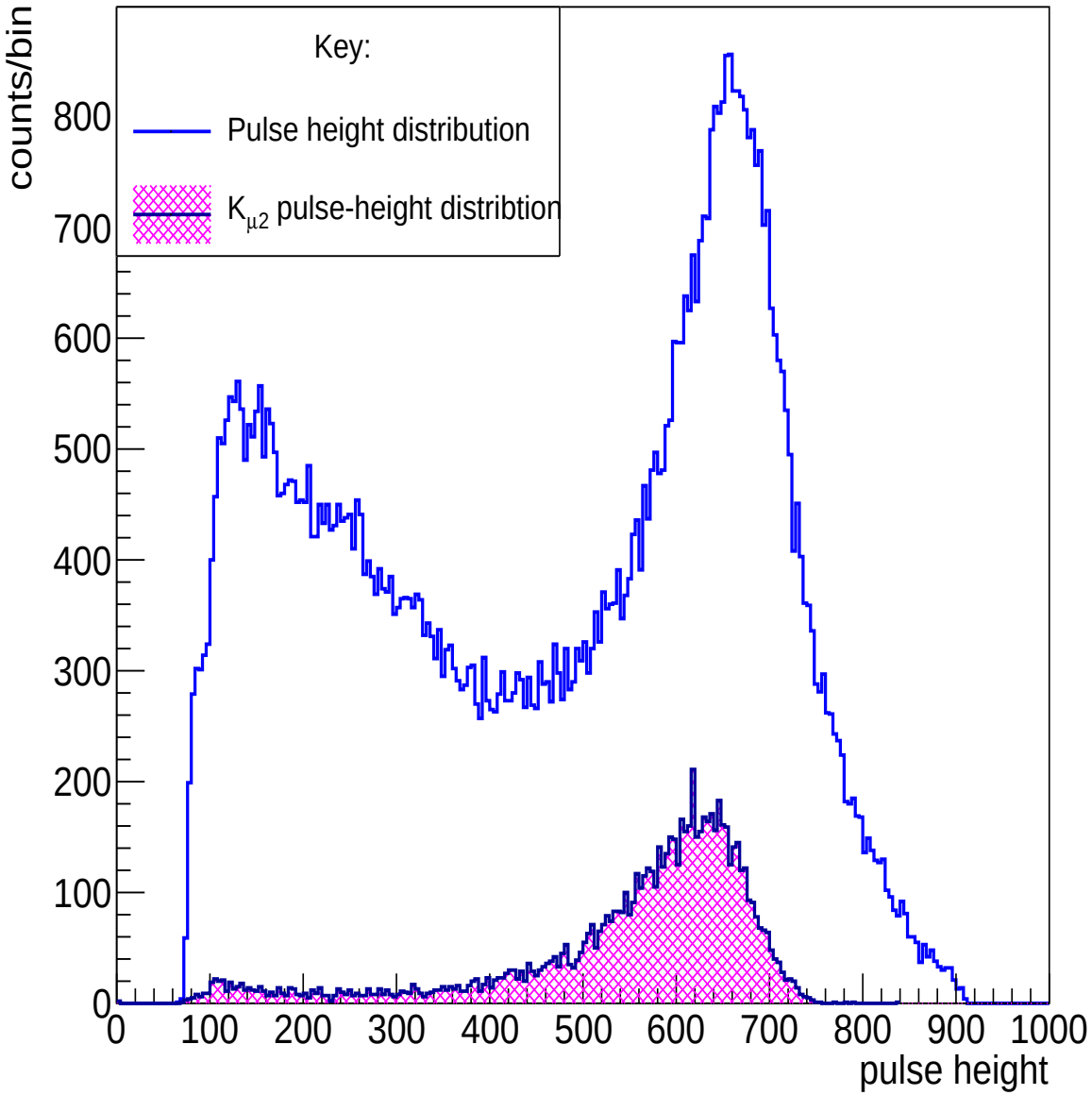
- λ is slow shape constant
- τ_0 is rise time
- τ_1 decay constant
- τ_2 local decay constant

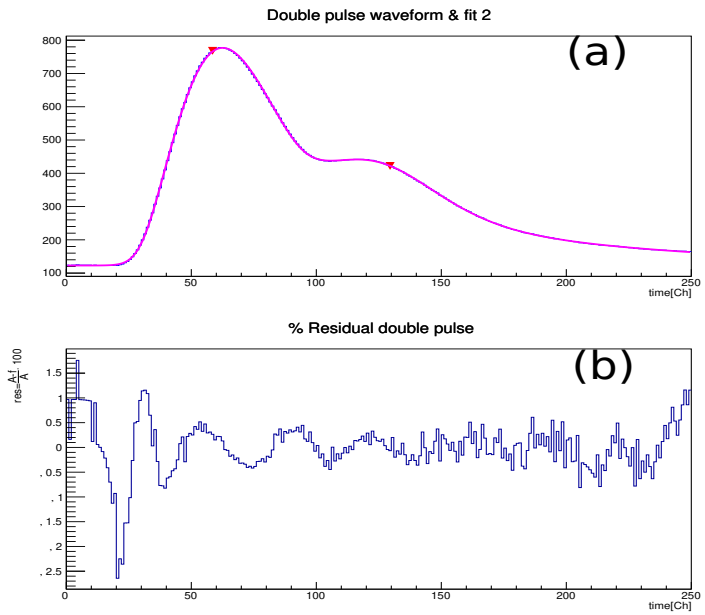
H. Ito (Nucl. Instrum. Meth., A901 2018)





Pulse Fitting in Action: Pulse Height Distribution



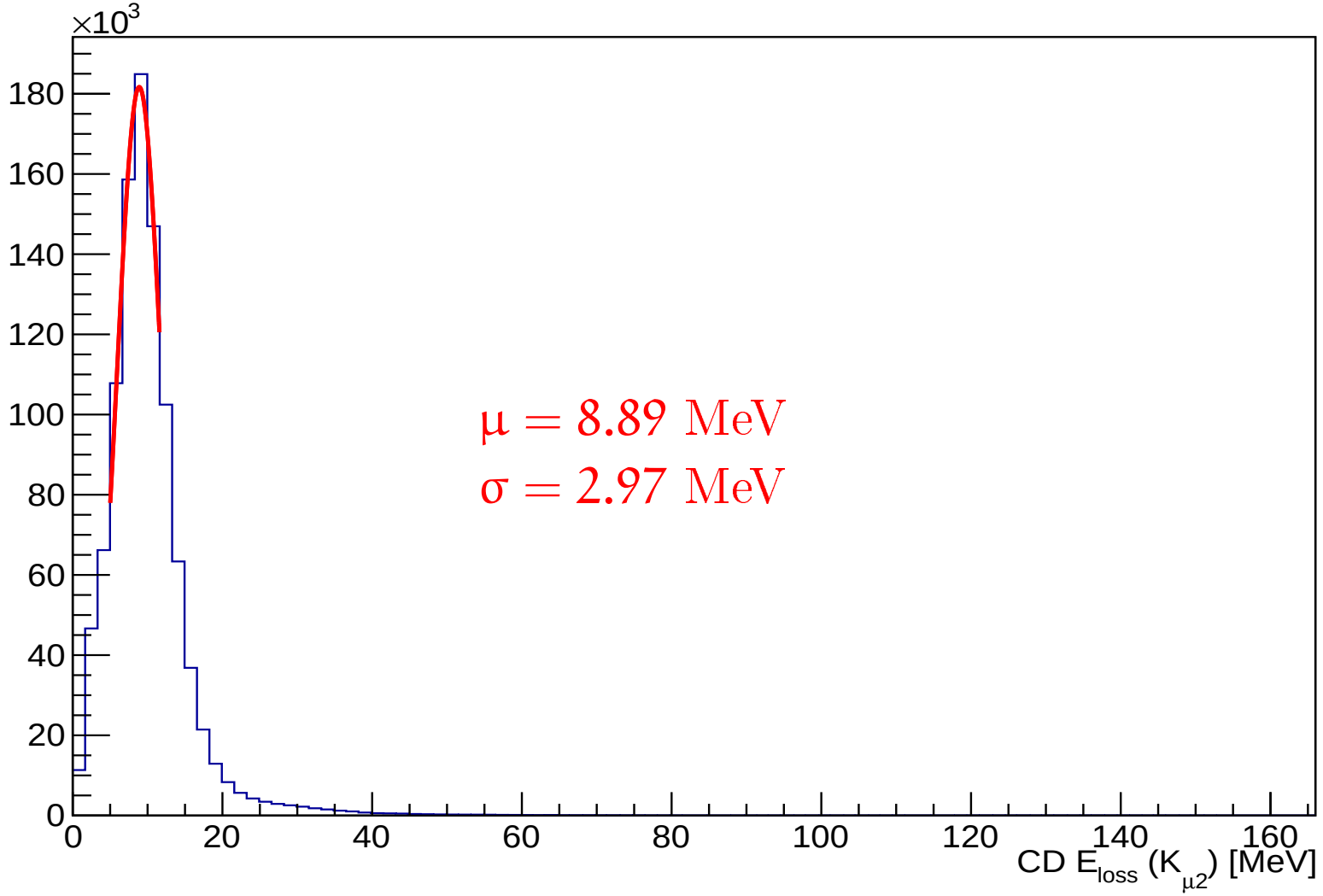


$K_{\mu 2}$ selection criteria

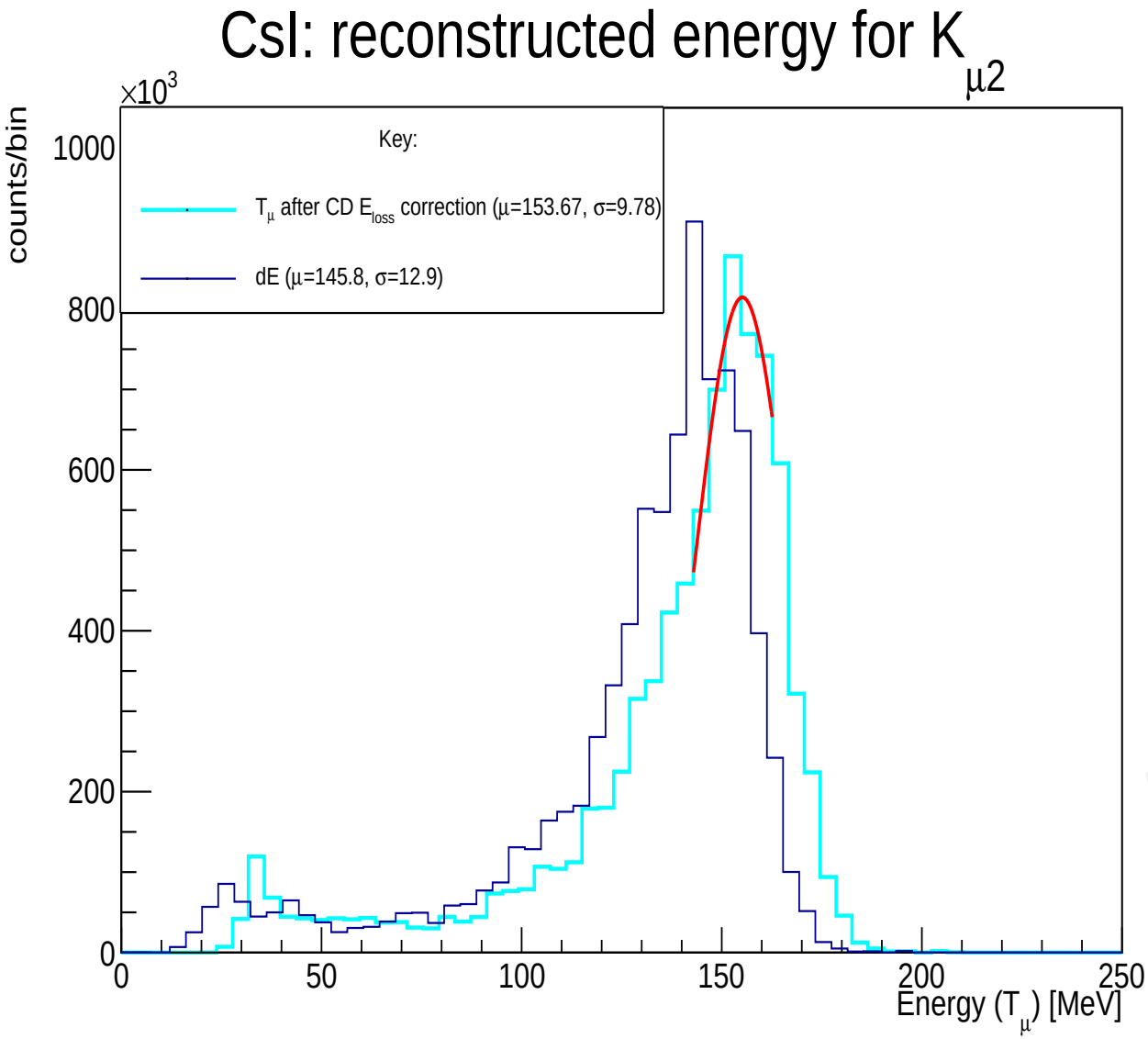
- Require single crystal per event
- First pulse time coincides with the K^+ decay
- Require a second peak

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

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

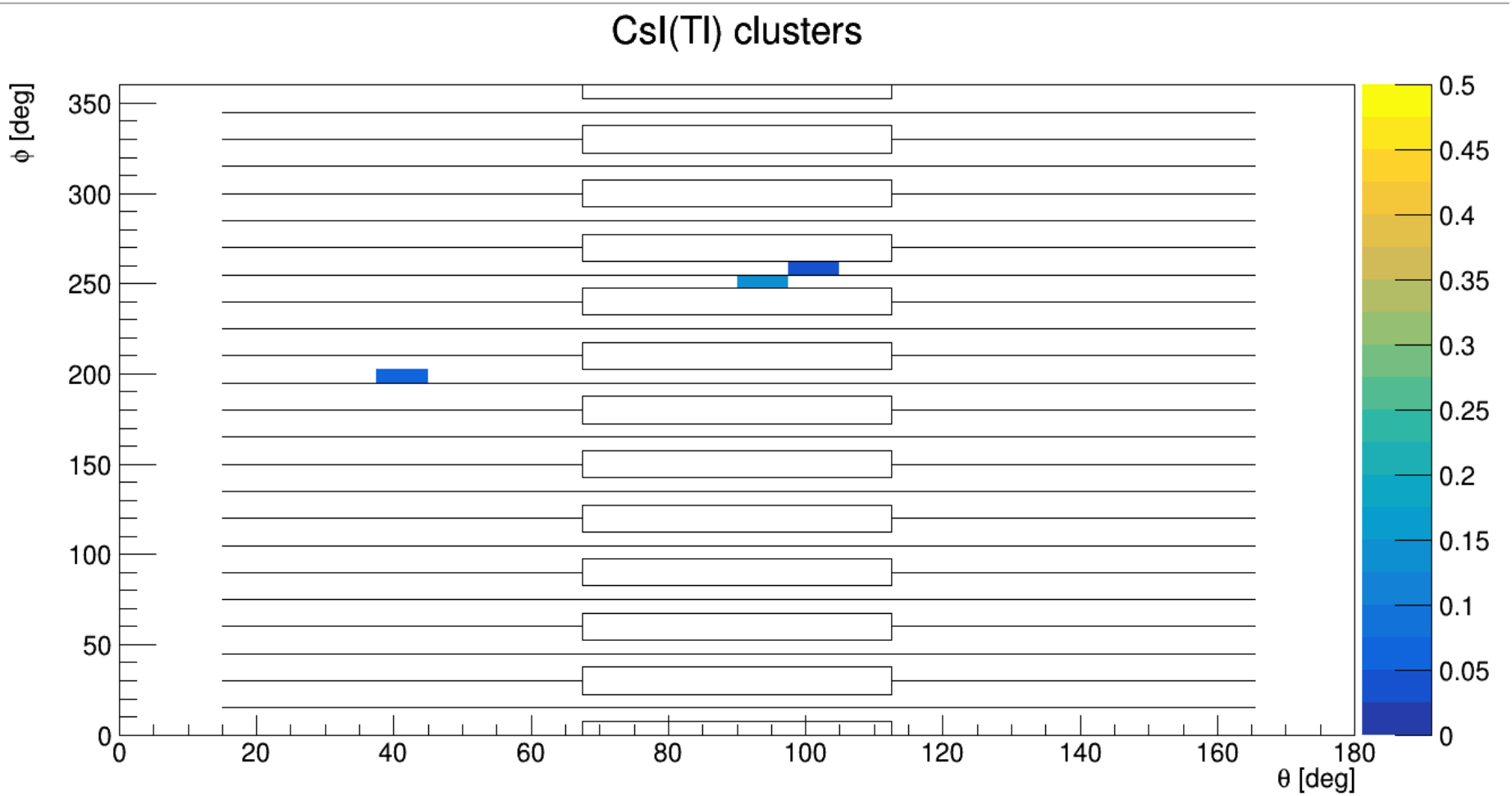


Pulse Fitting in Action: Energy Calibration from $K_{\mu 2}$



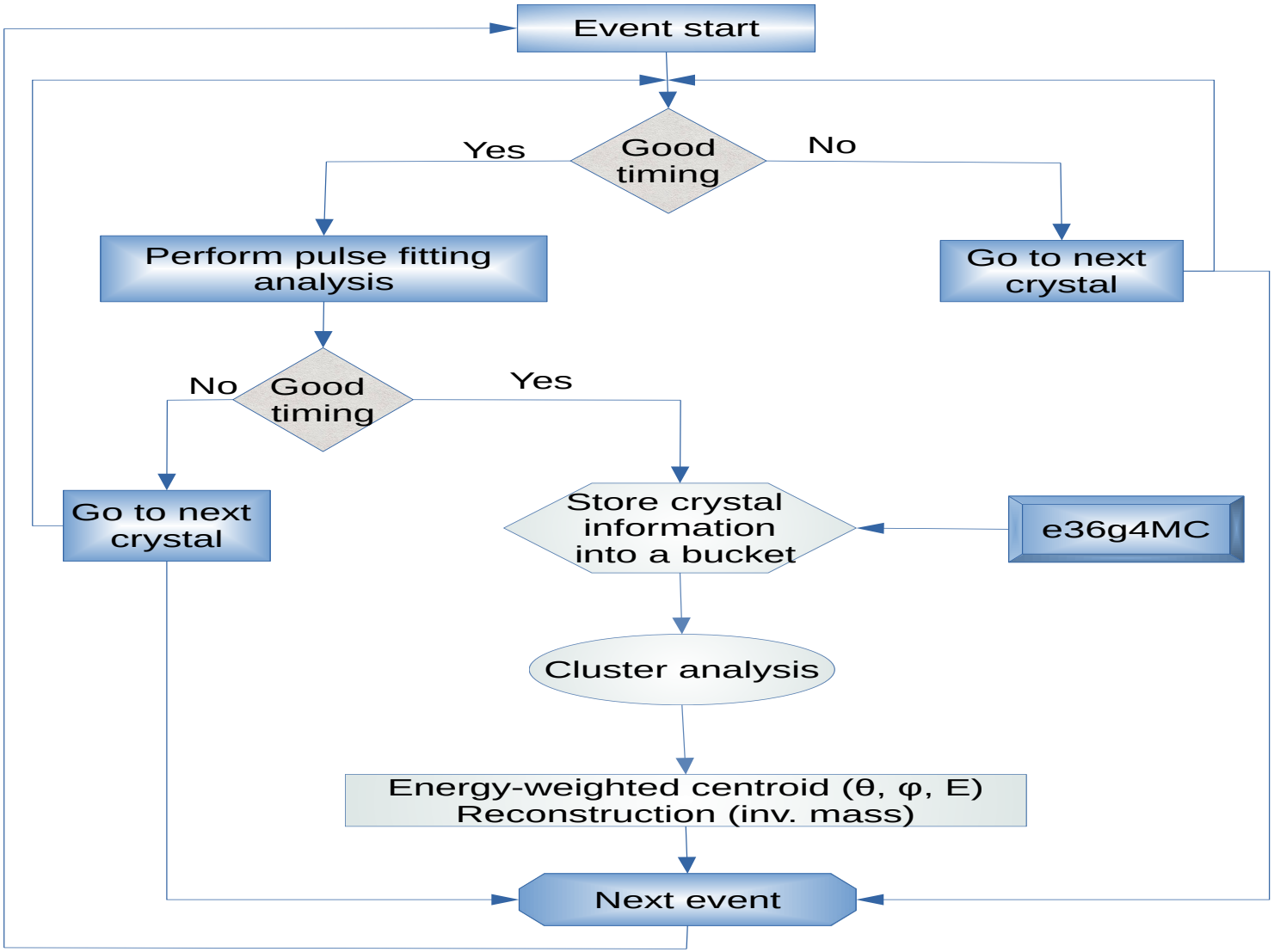
- $C_i = \frac{dE_{CsI}}{(A-P)_i}$, $i = 1, ..., 768$
- A is the waveform amplitude and P is the baseline
- $T_\mu = dE_{CsI} + CDE_{loss}$
- Correction for energy loss from CD system

Cluster Analysis: Event Viewer

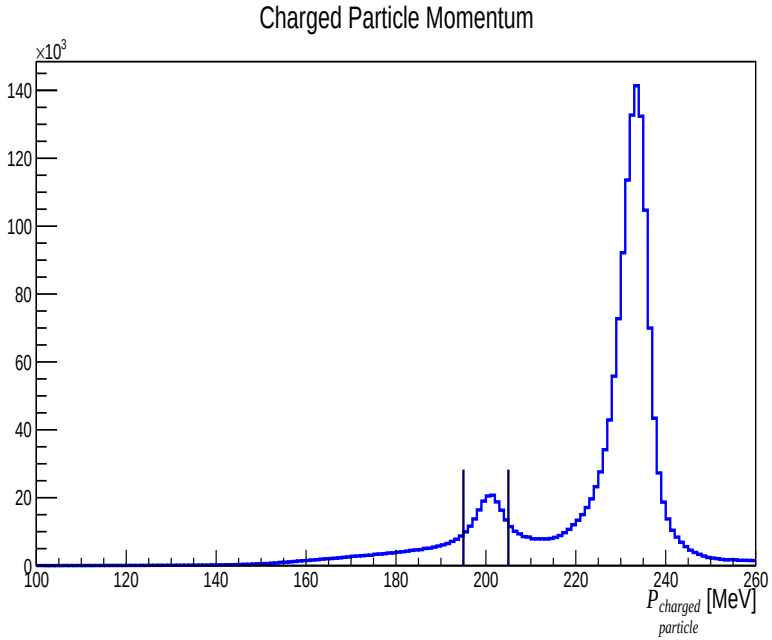


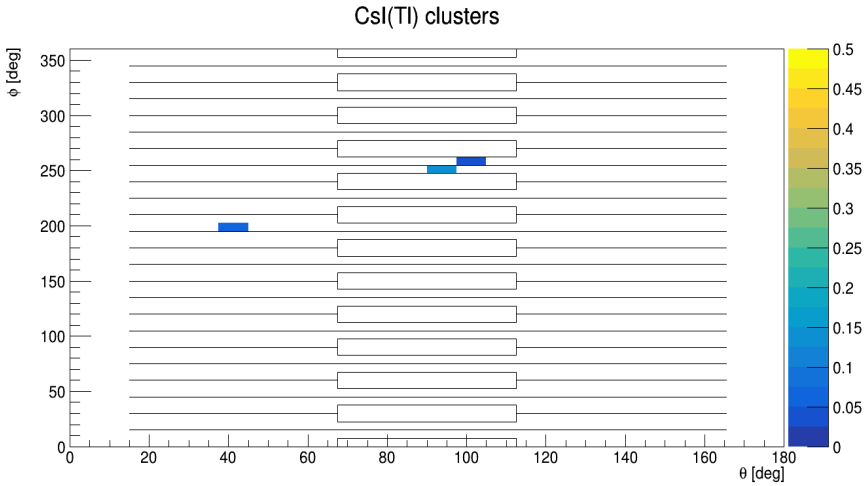
- Reconstructed m_{π^0} from $M_{\gamma\gamma} = 123.7$ MeV/c^2
- PDG: $m_{\pi^0} = 134.9766$ MeV/c^2

CsI Cluster Analysis



CsI Cluster Analysis Cont...

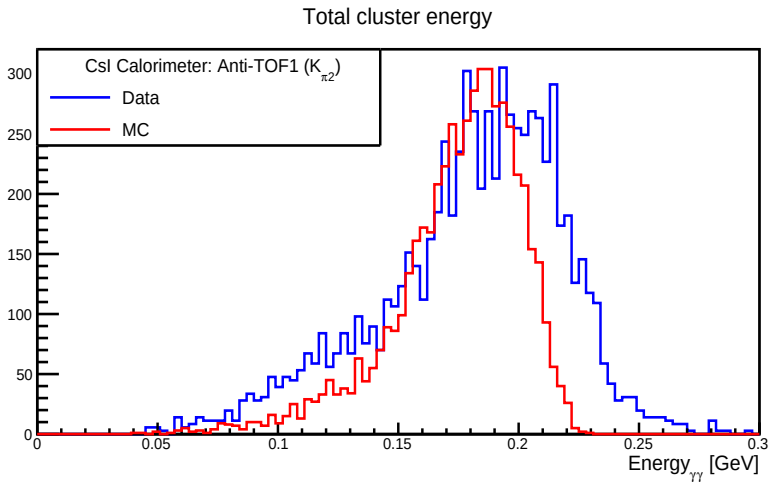


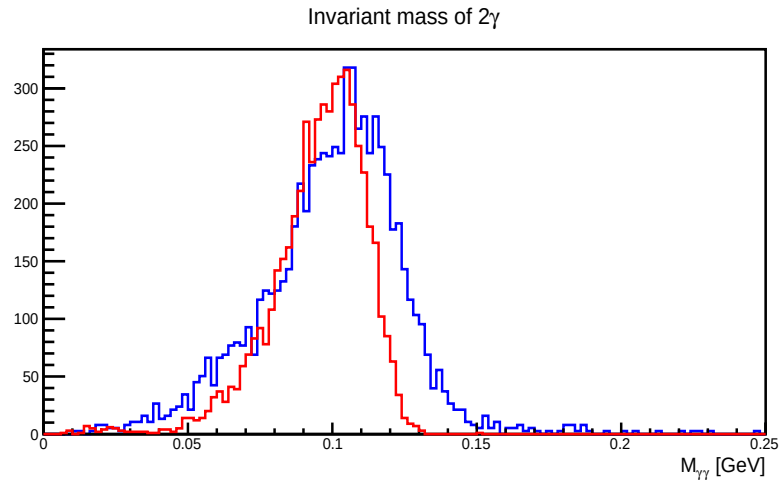


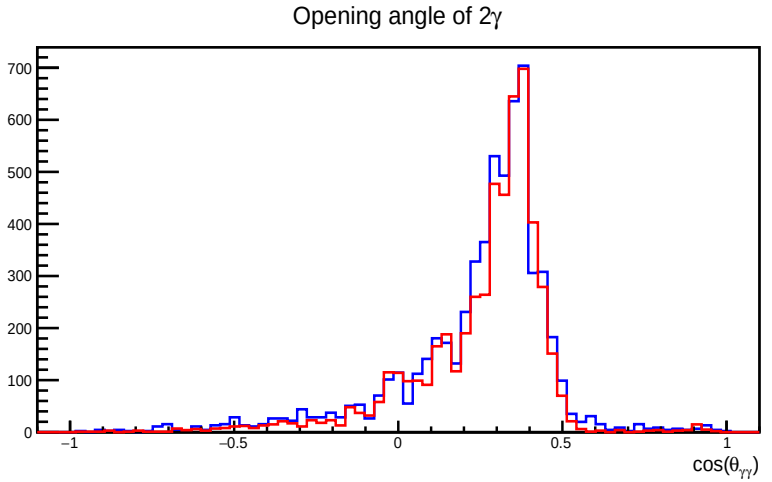
Cluster criterion:$K^+ \rightarrow \pi^+\pi^0$

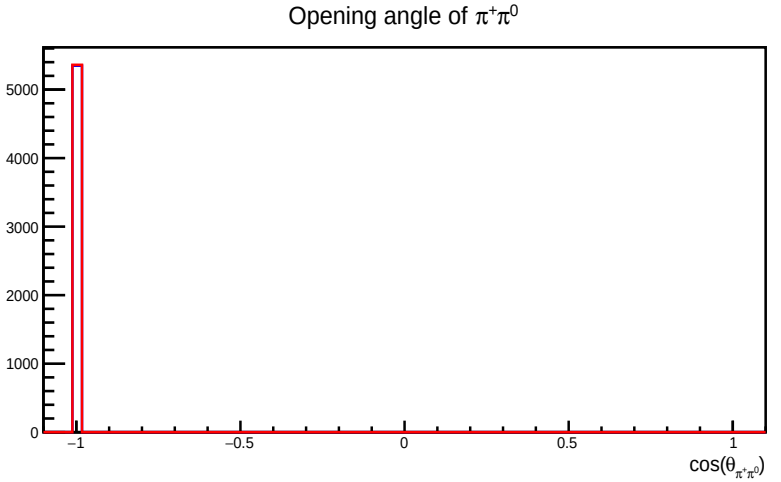
- High hardware trigger due to high rate
- Several clustering patterns need to be considered
- Currently single crystal clusters are considered as well
- Analysis is performed for prompt $\pi^0 \rightarrow \gamma\gamma$, while only considering two cluster events
- Suppress backgrounds by requiring only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

CsI $K_{\pi 2}$ Cluster Analysis



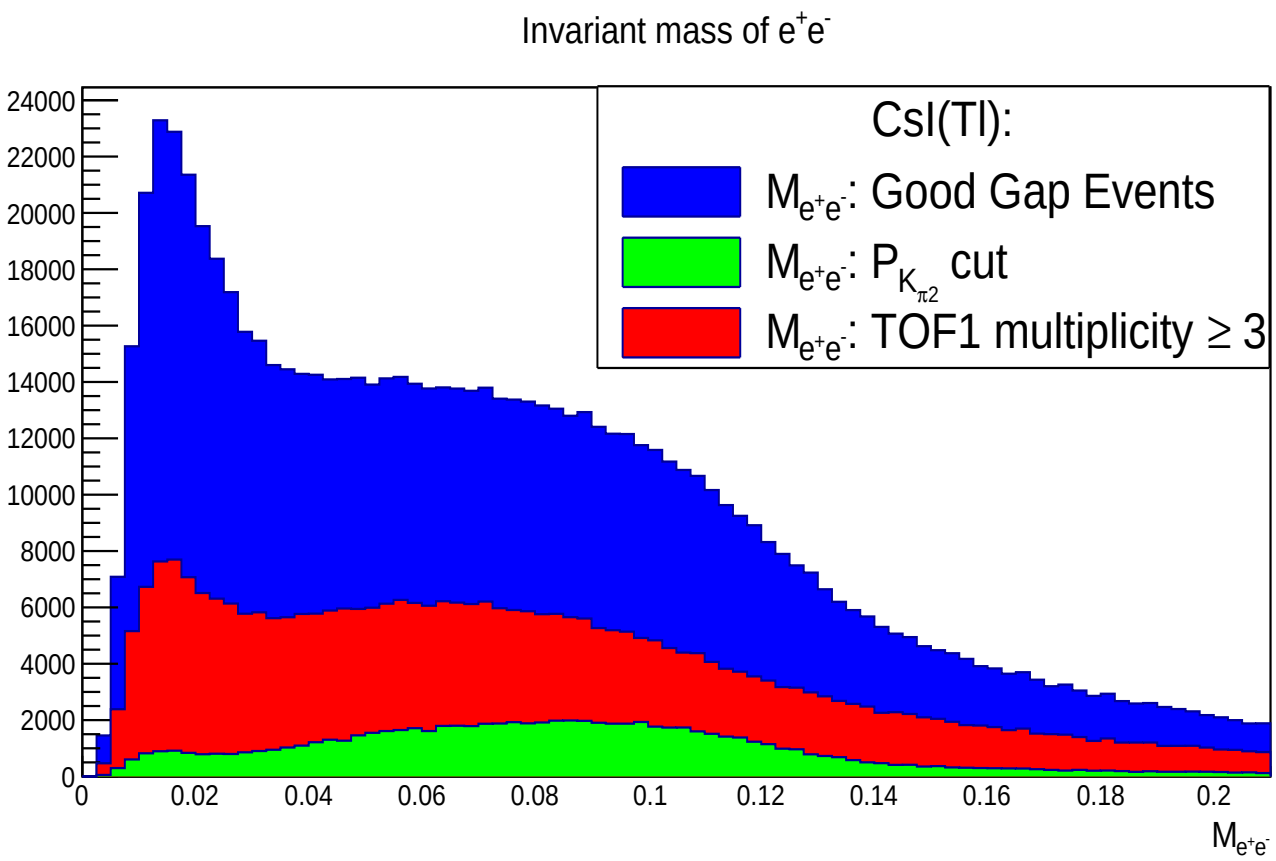






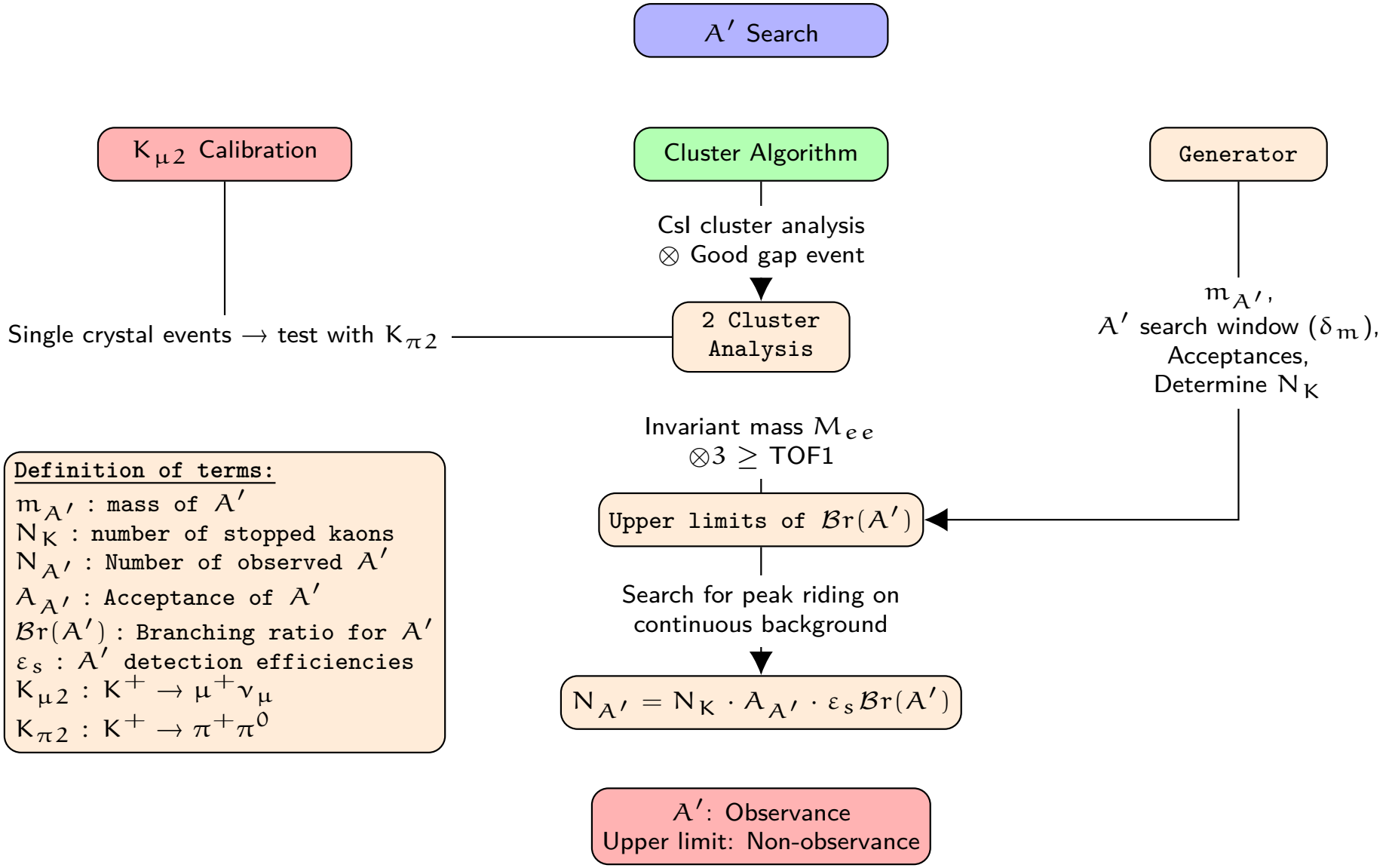
- Preselected $K_{\pi 2}$ events (from two CsI clusters)
- $\cos(\theta_{\pi^+\pi^0}) \leq -.99$: tight opening angle cut

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



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}

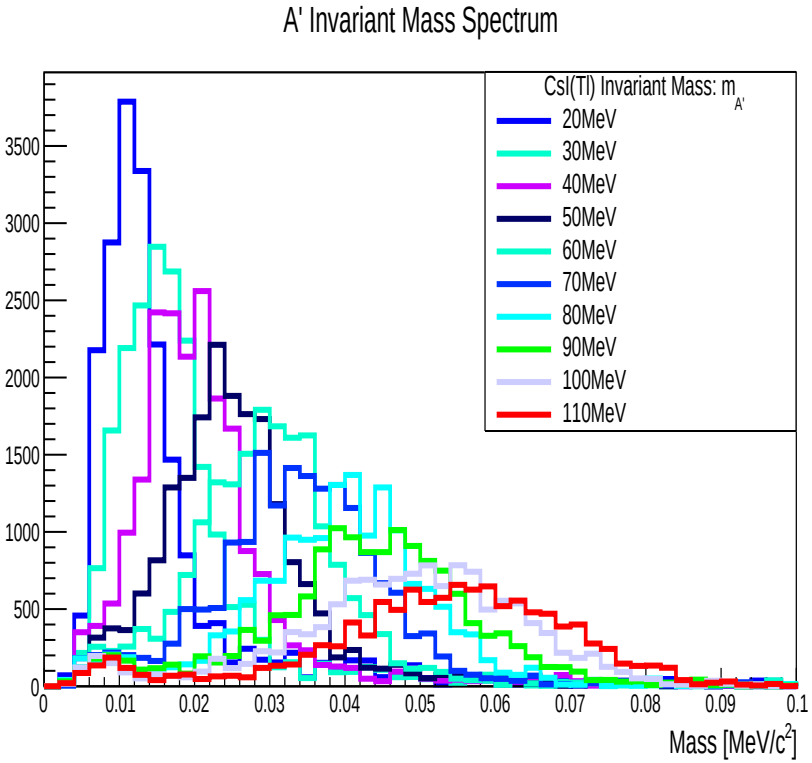
π^0 Channels

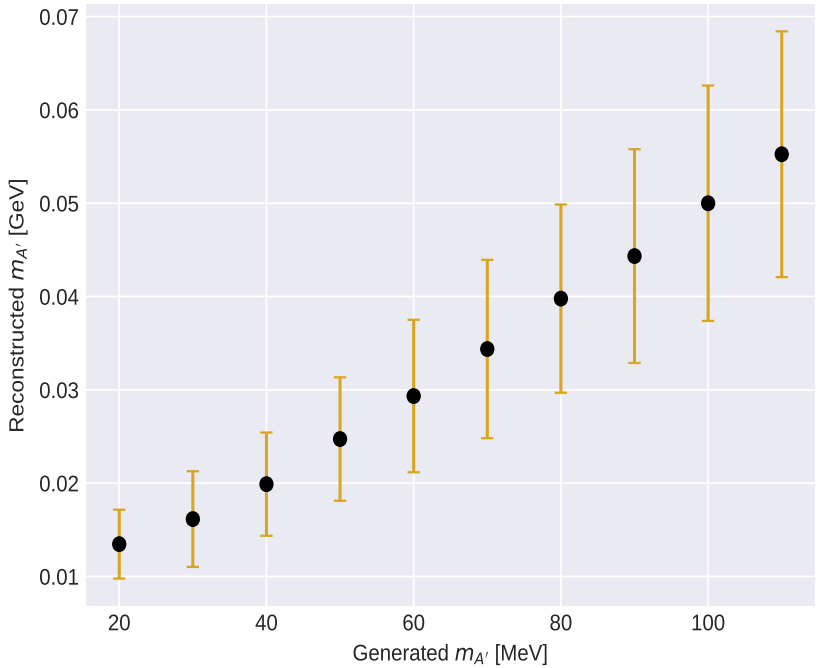
Label	Branch	Ratio
0	$\pi^0 \to \gamma\gamma$	9.8823×10^{-1}
1	$\pi^0 \to e^+e^-\gamma$	1.174×10^{-2}
2	$\pi^0 \to \gamma A'$	$\epsilon^2 \times ratio\ of\ channel\ 2$

ROOT based generator

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

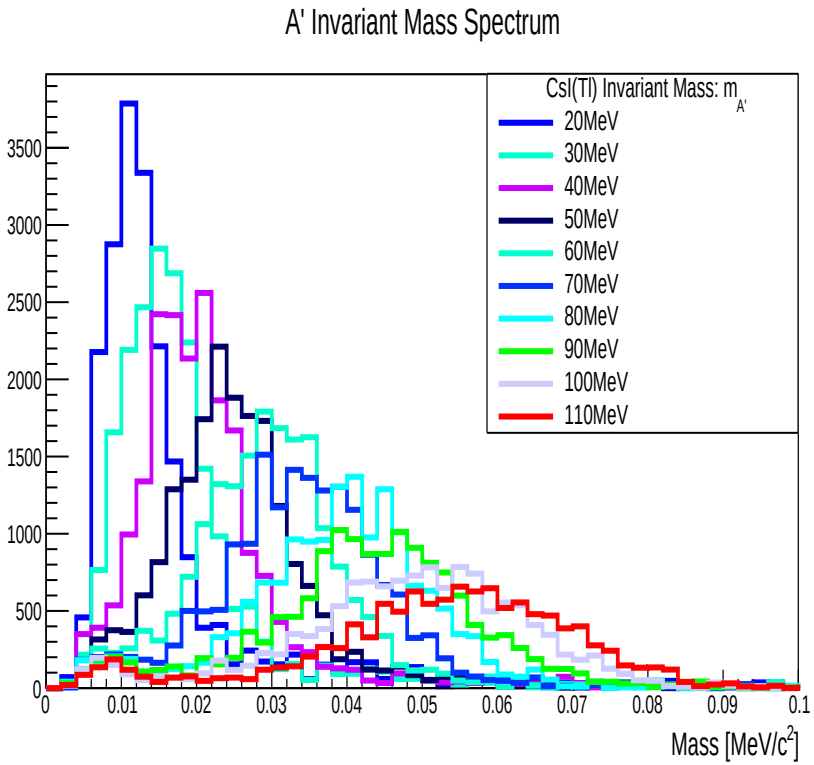
A′ Acceptance and $m_{A'}$ Distribution

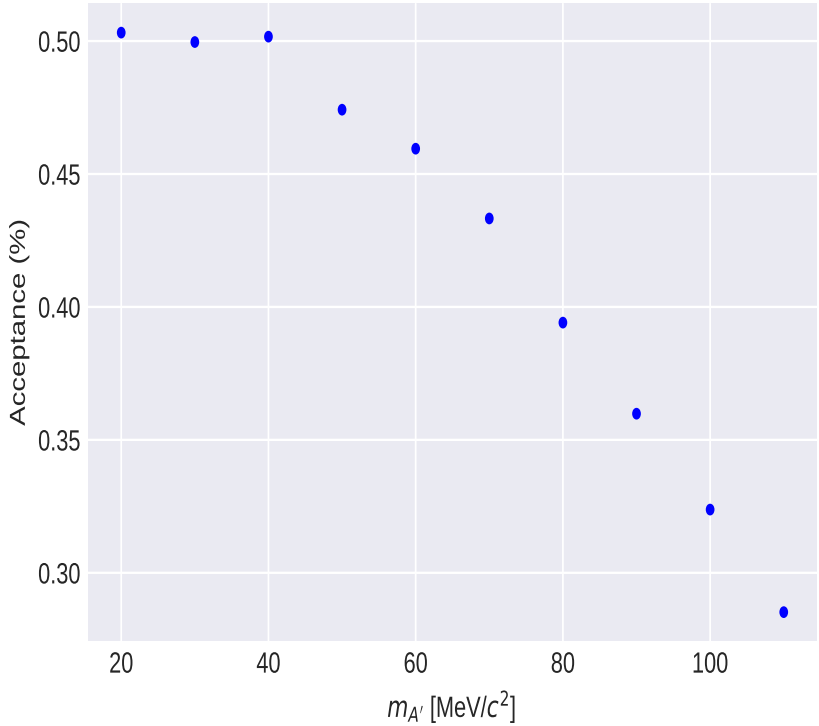




- A′ masses generated on interval $20 - 110$ MeV
- $m_{A'}$ reconstructed from e^+e^- clusters in the CsI
- Mean $m_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(m_{A'})$ was obtained from fit

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





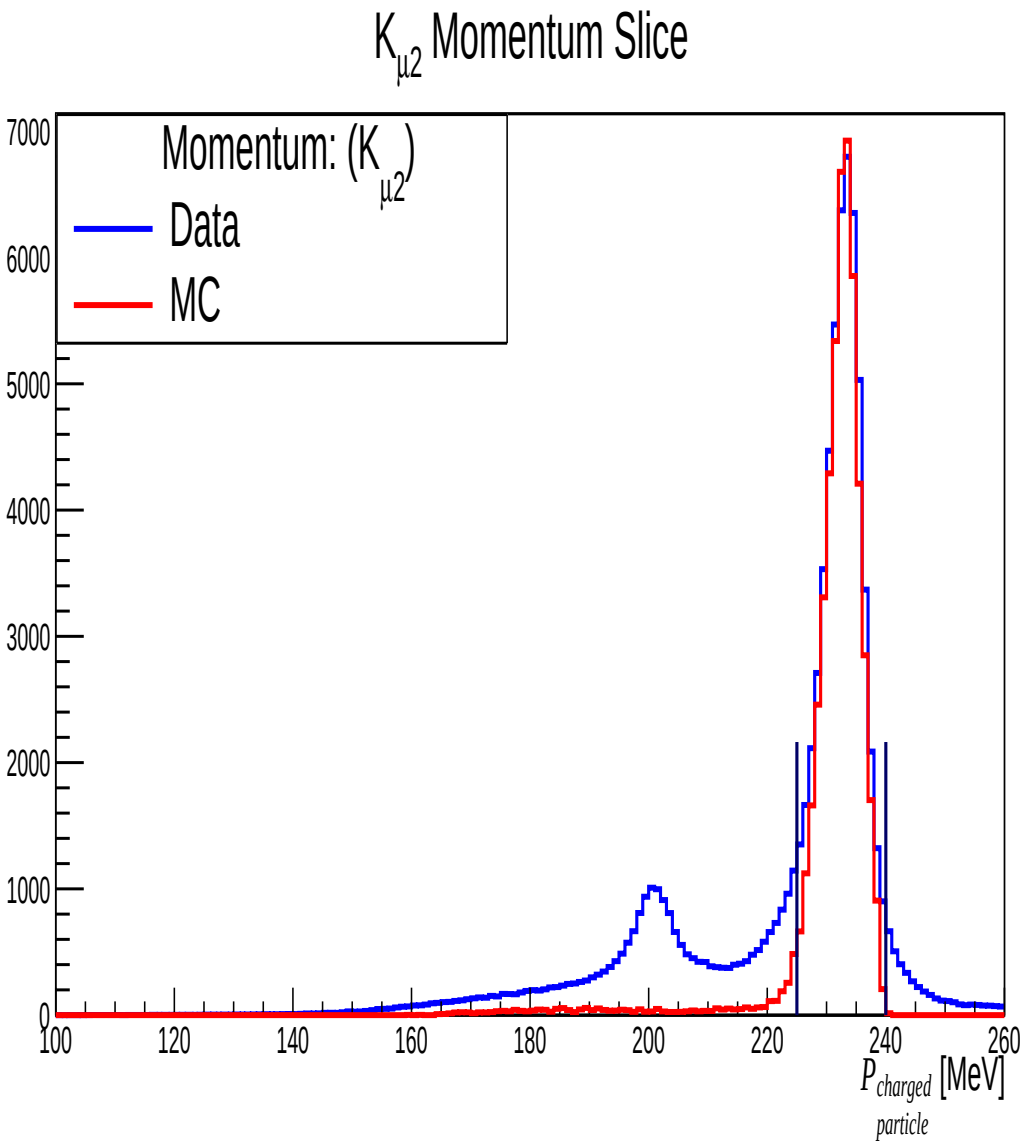
- A′ masses generated on interval $20 - 110$ MeV
- $m_{A'}$ reconstructed from e^+e^- clusters in the CsI
- Mean $m_{A'}$ obtained by fitting Gaussian
- Mass window of $\sigma(m_{A'})$ was obtained from fit

Number of Stopped K^+

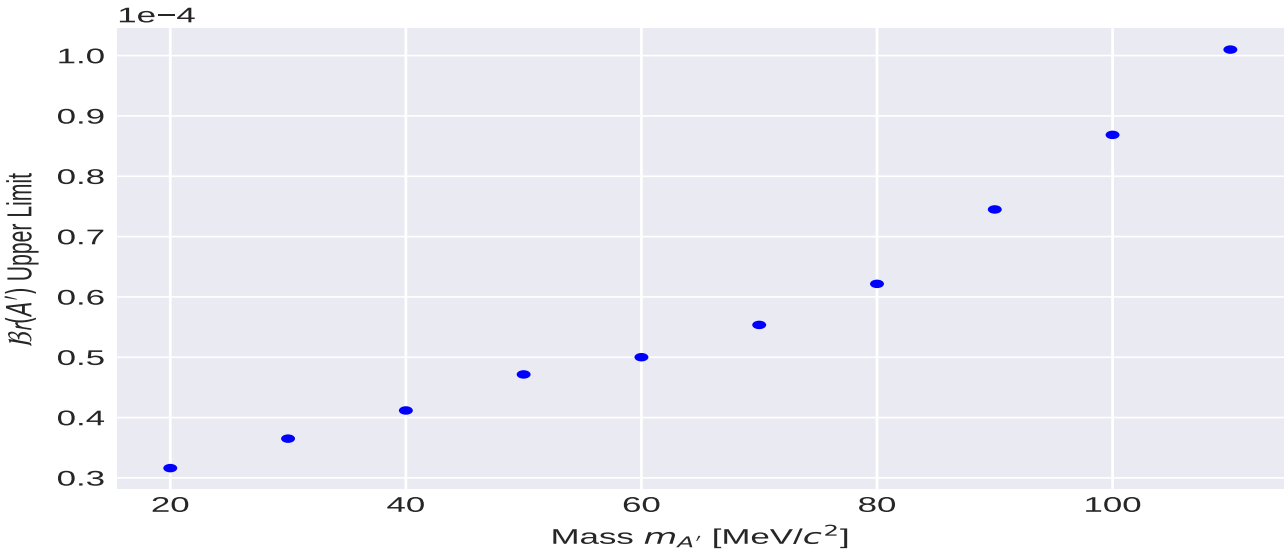
- Charged particle momentum as evaluated at K^+ stopped vertex within the target volume
- Number of tracked muons $N_{\mu 2}$ obtained from good target events (events with target vertices)
- Acceptance of μ^+, A_μ was calculated from e36g4MC
- Muon momentum selection was based on energy corrected tracks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

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

$Br(\mu 2)$ is the $K_{\mu 2}$ branching ratio, $PS(\mu)$ is the μ prescale factor, A_μ is the muon acceptance and $LT(\mu)$ is the lifetime fraction



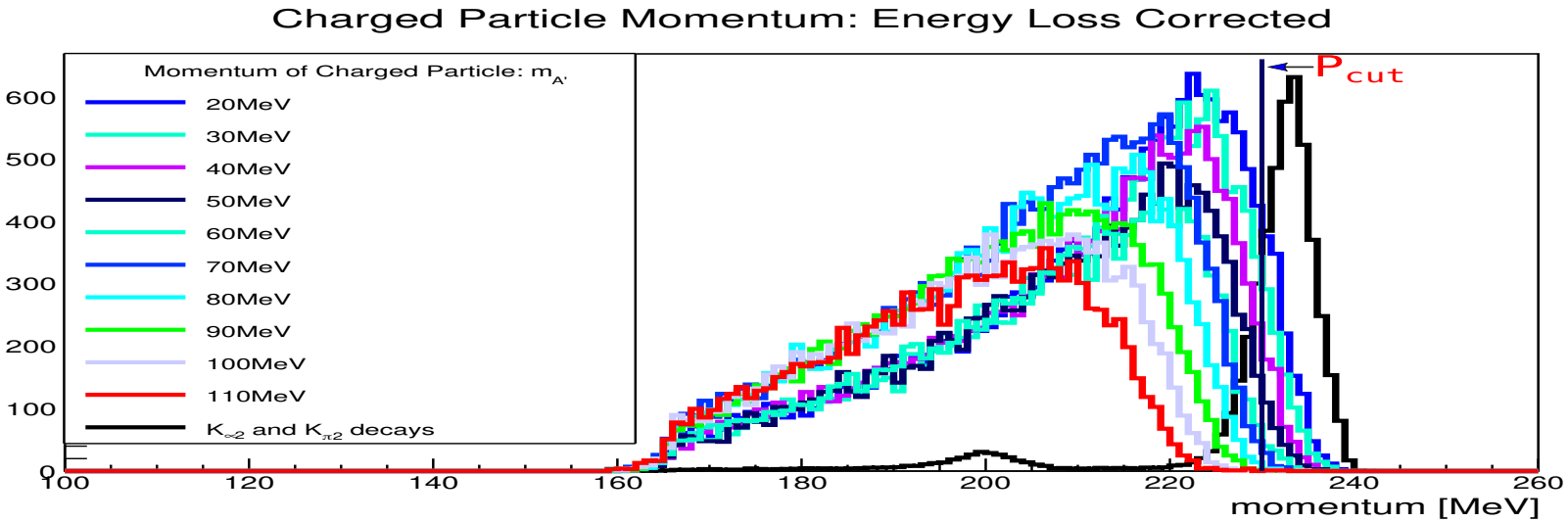
Upper Limit Extraction

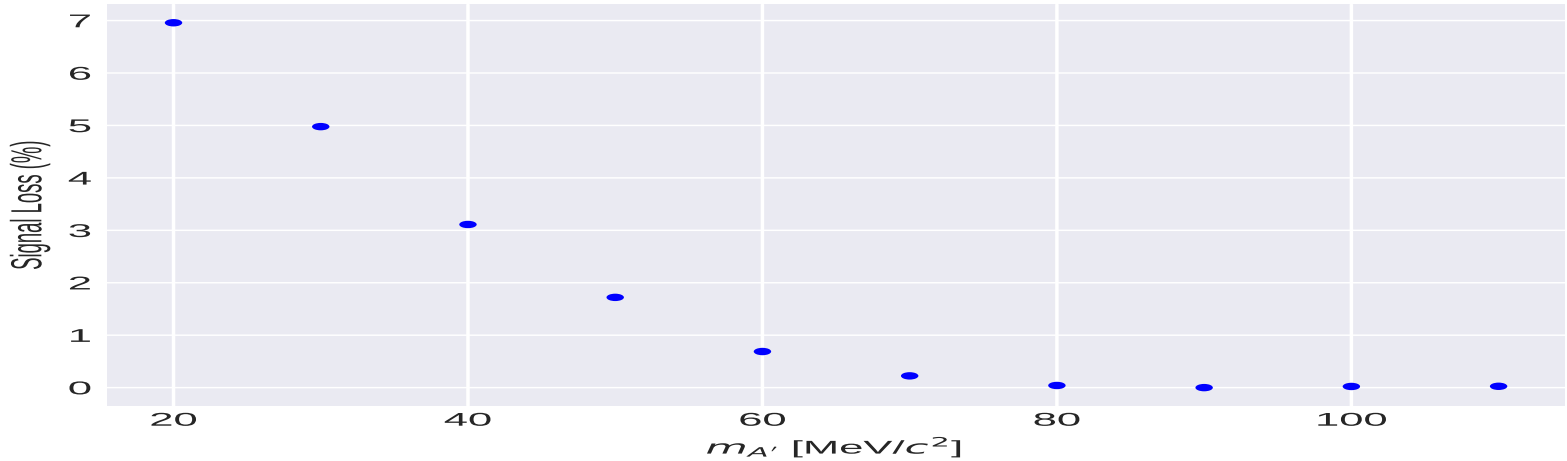


Upper Limit

- Require 3 charged particles, one of which is tracked, corresponding to 3 TOF1 hits
- $\mathrm{Br}(A') \cdot \varepsilon_s < \frac{2\sqrt{N_{\mu\nu ee}}}{N_K A_{A'} \cdot LT}$
- $A_{A'}$ is 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
- ε_s : A' signal loss factor
- The search window $\delta(m_{A'})$ is determined fitting a Gaussian around peak of the reconstructed A' mass $m_{A'}$
- Integrating the number of events in a given search window yields the number of background events $N_{\mu\nu ee}$

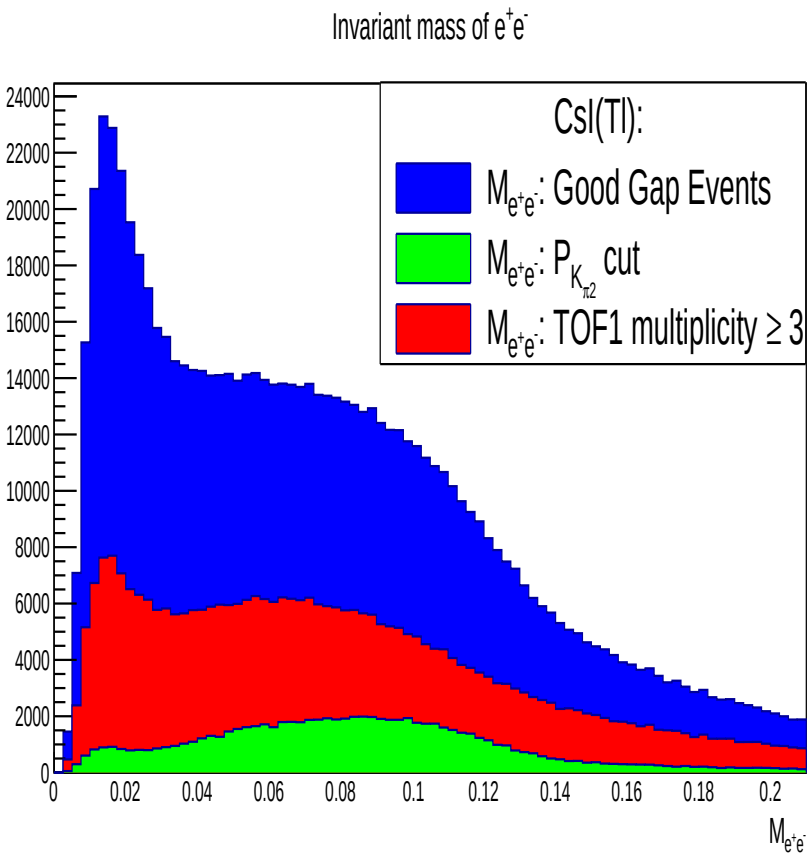
$K_{\mu 2}$ Contamination Reduction

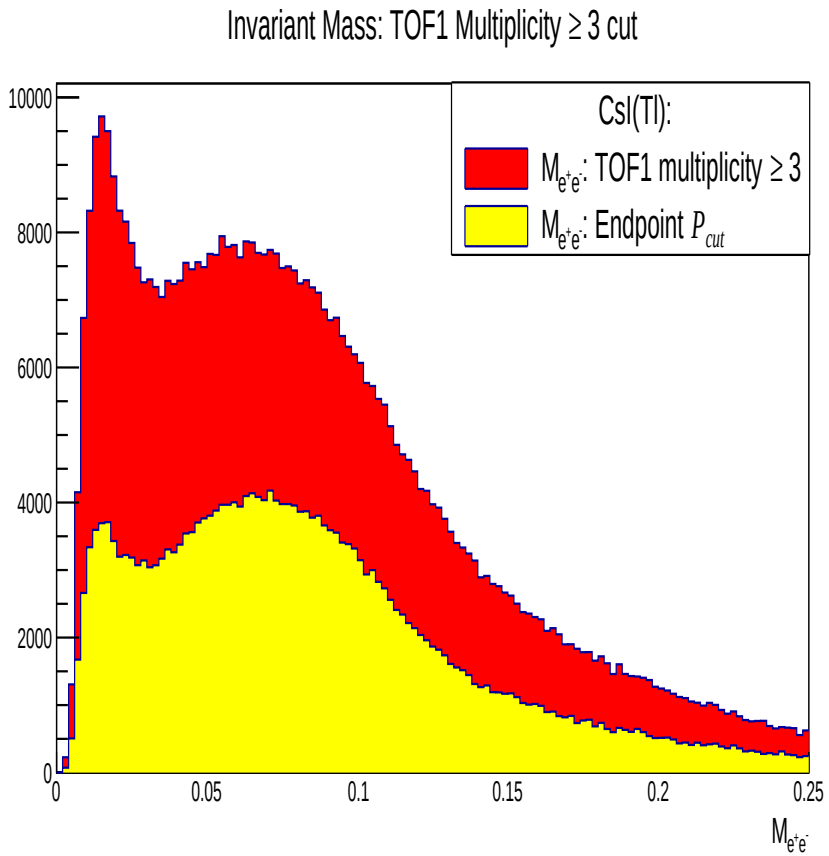




- Signal Loss $S_L = \frac{S_{cut}}{S_{tot}}$
- S_{cut} is integrated signal that survives cut
- S_{tot} is total integrated signal

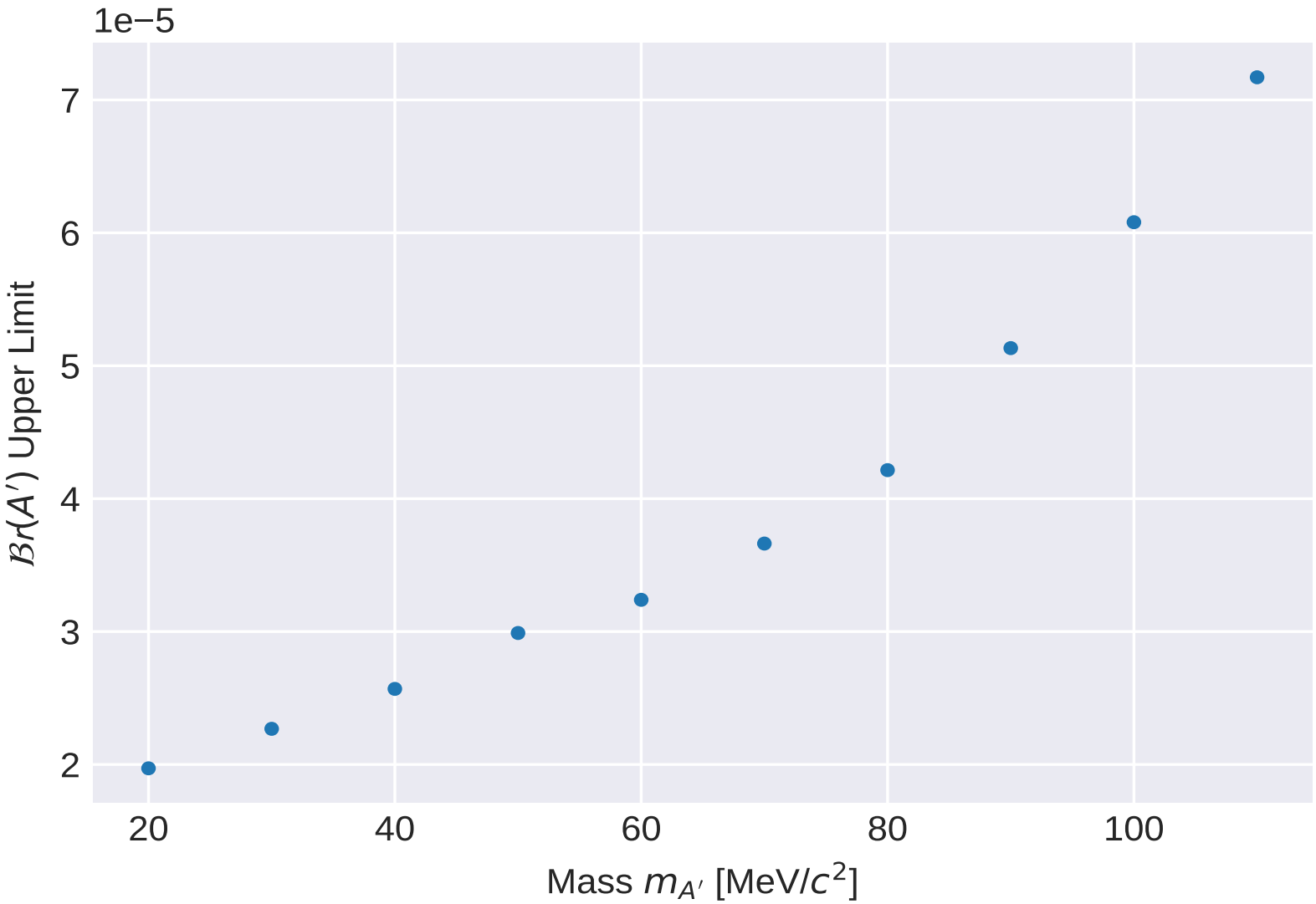
Invariant Mass Spectrum M_{ee} after $K_{\mu 2}$ Cut





- From 75 runs ($\sim 5.8\%$ of total Fall data)
- Analysis of more data files is currently underway

Background Suppressed Upper Limits



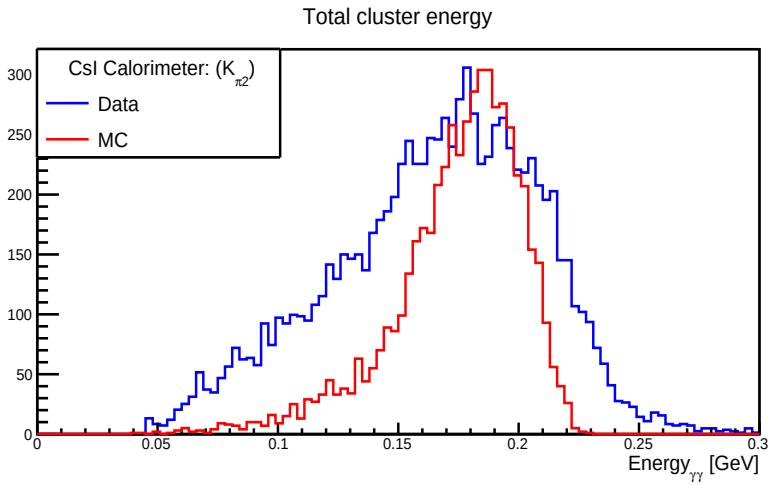
Summary

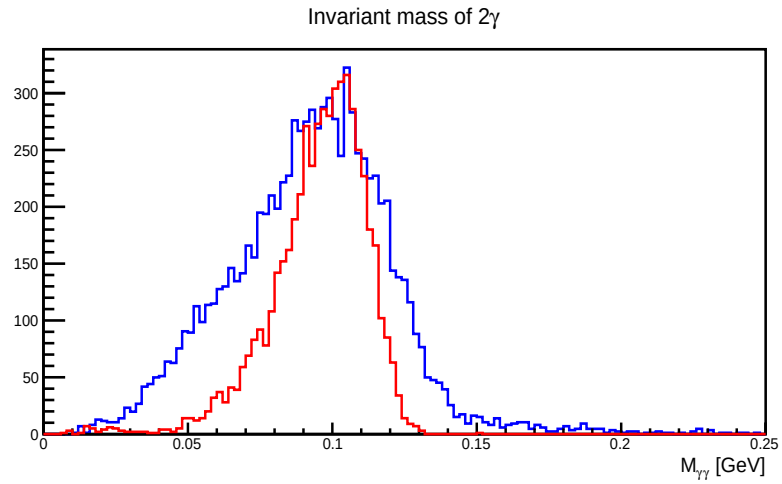
Summary and Future Work

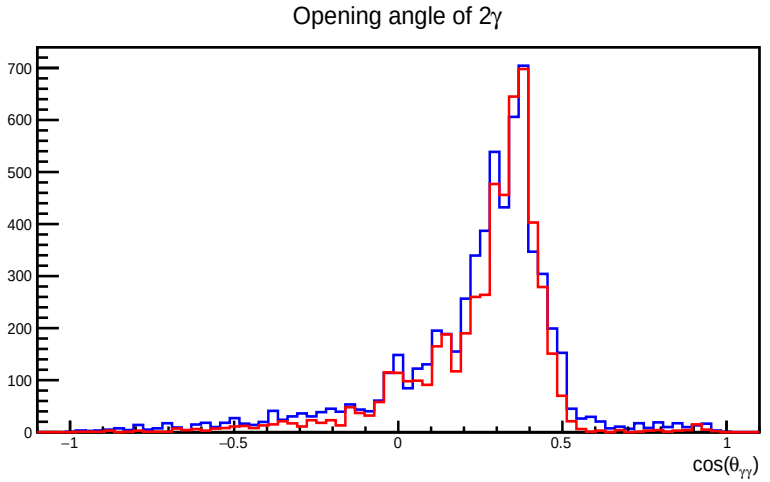
- Universe is littered with anomalies that must be explained (exciting times!)
- TREK/E36 experiment has been successfully conducted, completed data-taking, decommissioned and analysis is currently underway
- e36g4MC has been developed from ground-up
- K^+ decay generator has been implemented into the 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

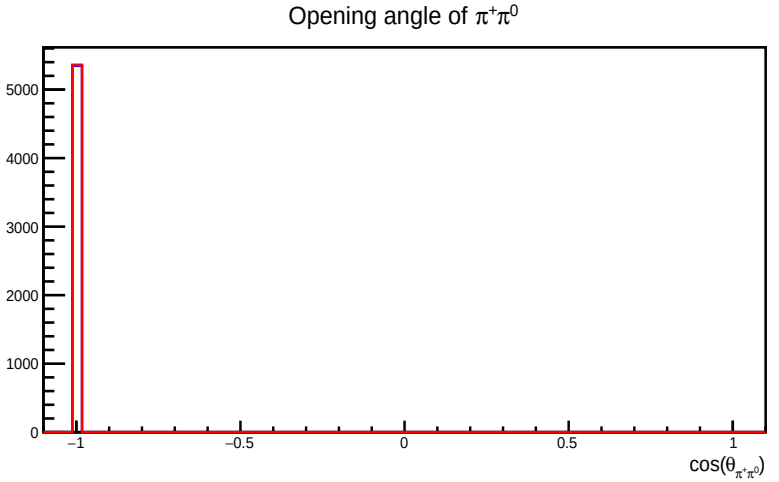
Backup

CsI 2 Cluster Events



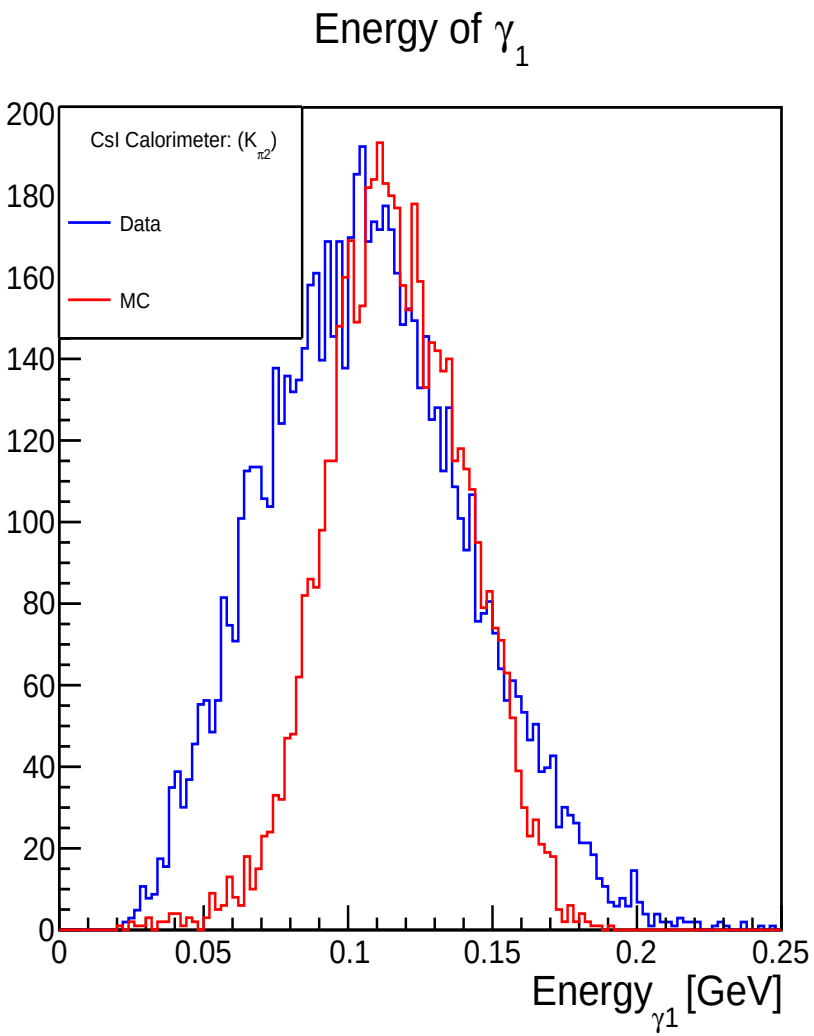


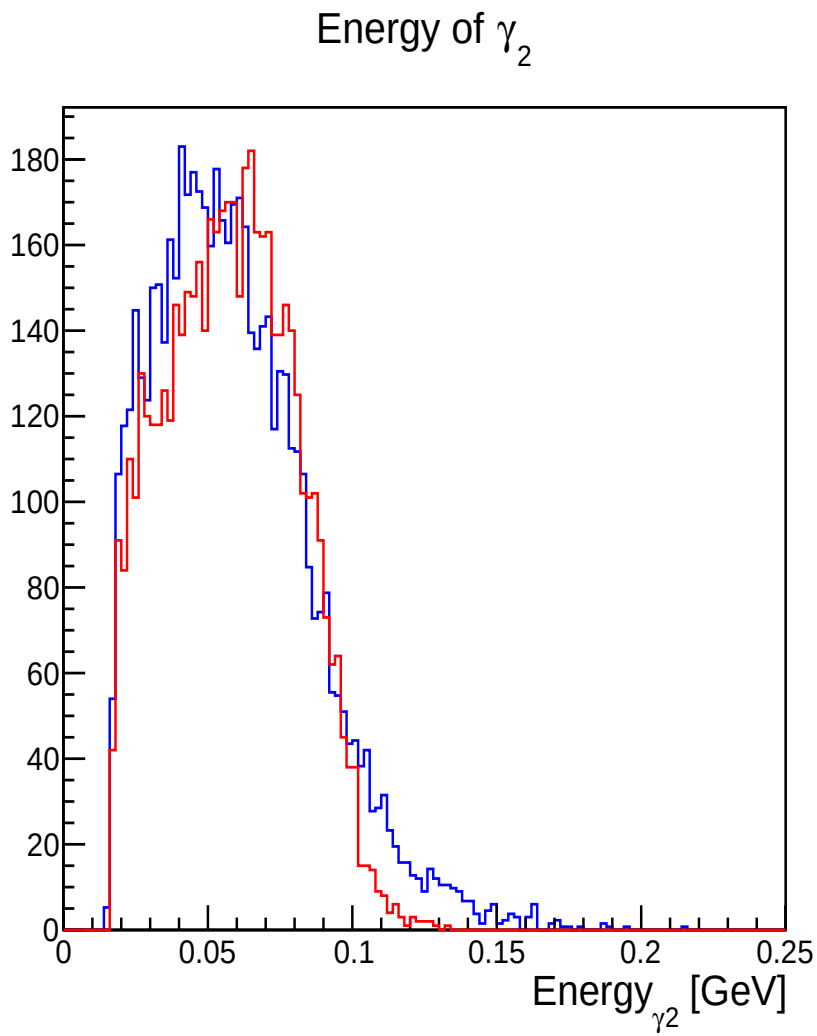




- Two cluster events under $K_{\pi 2}$ momentum cut
- e36g4MC: Generator channel 7 was used

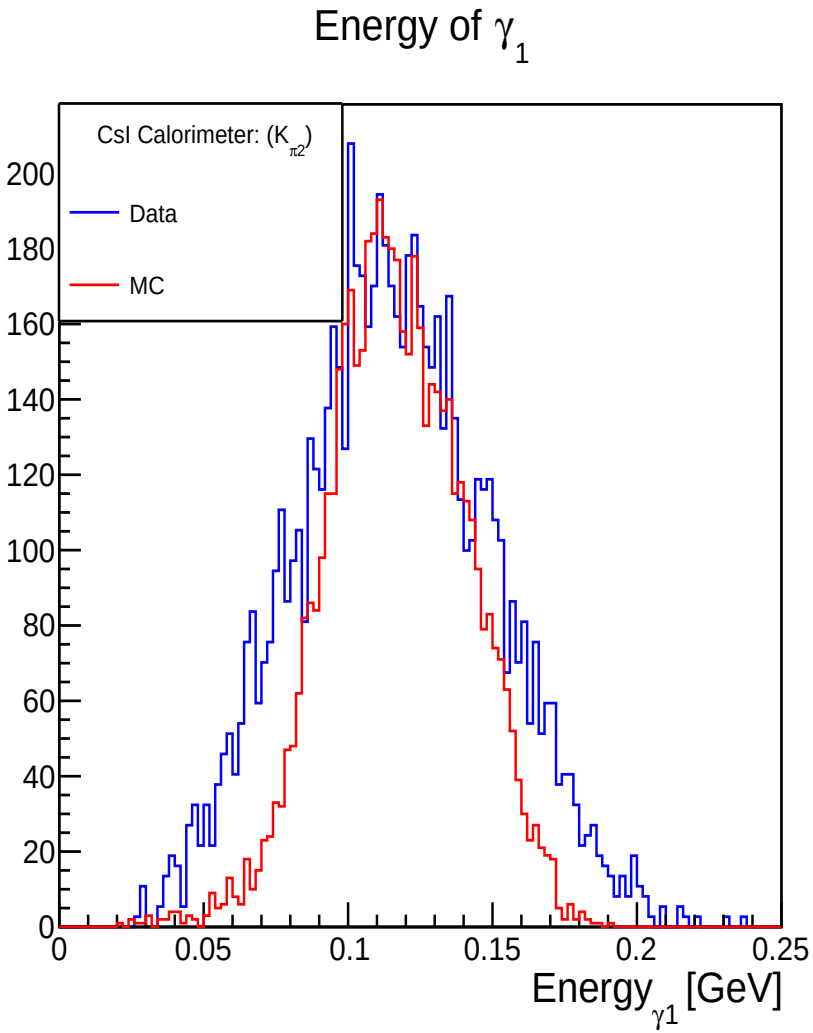
Energy of $\gamma 1$ and $\gamma 2$

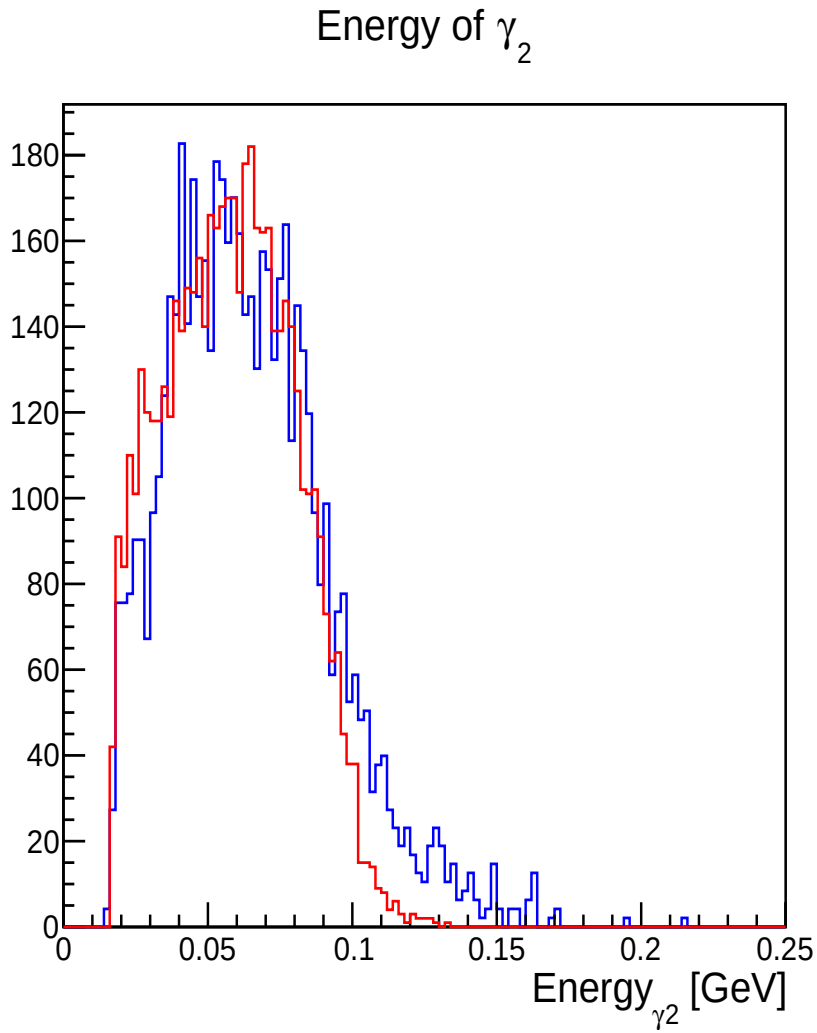




- $\cos(\theta_{\pi^+\pi^0}) \leq -0.995$

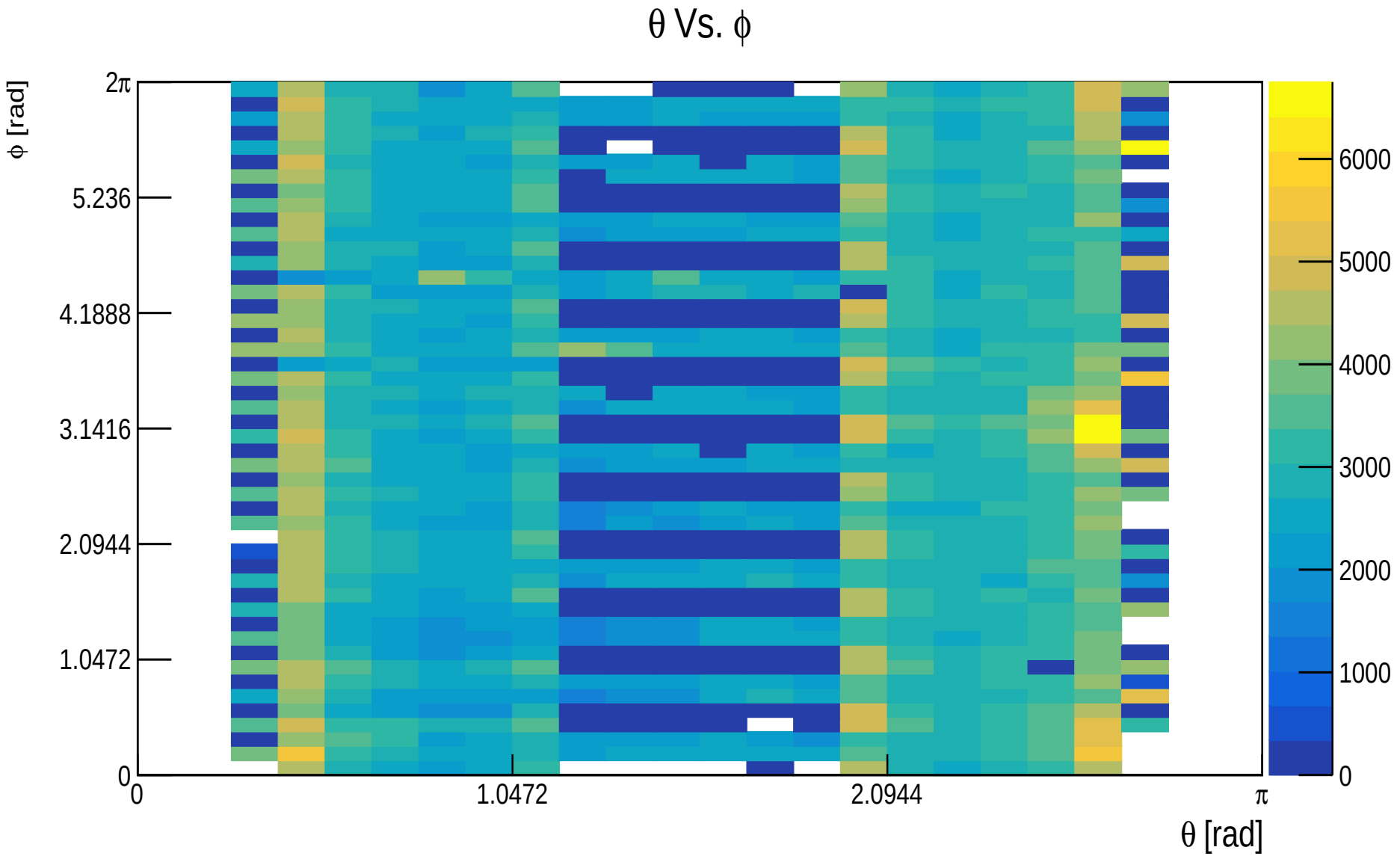
Energy of $\gamma 1$ and $\gamma 2$ TOF1 cut



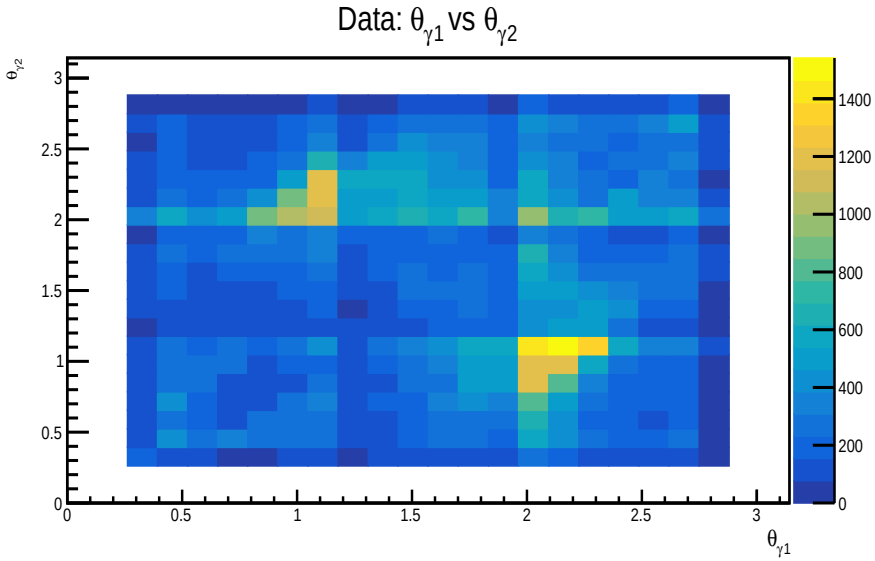


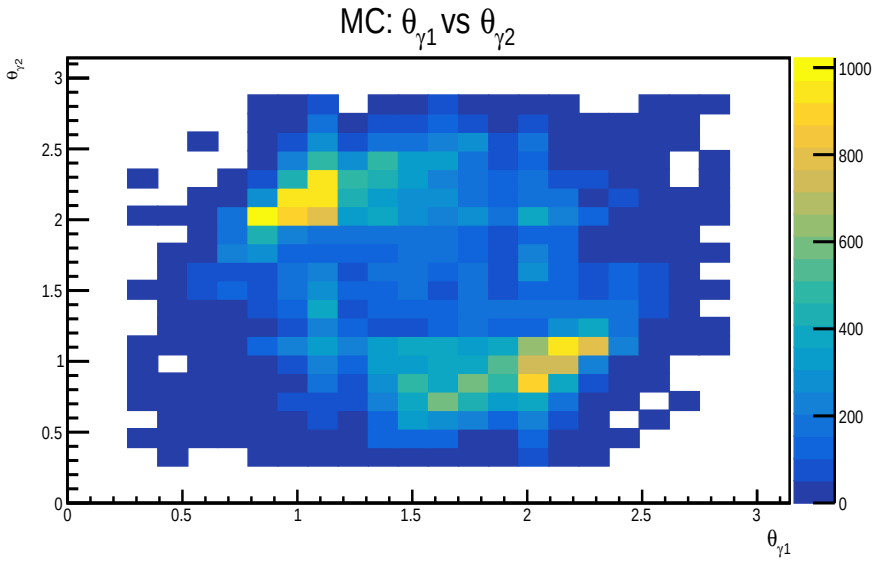
- $\cos(\theta_{\pi^+\pi^0}) \leq -0.995$
- only one TOF1 counter has fired

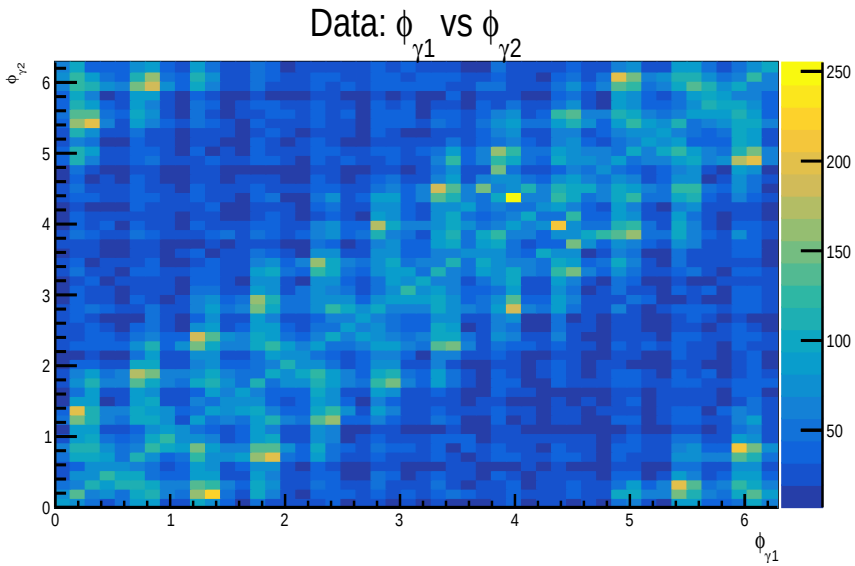
Theta Vs Phi

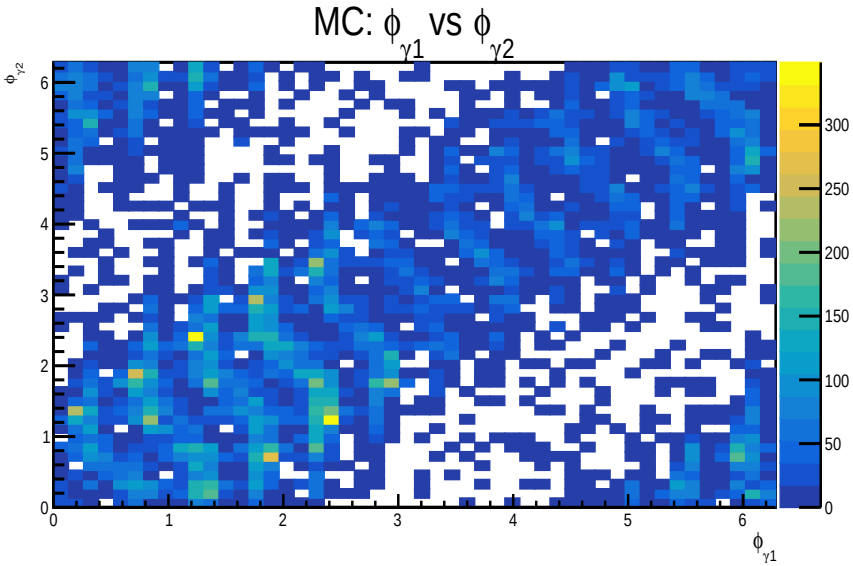

θ Vs. ϕ
ϕ [rad]
2π
5.236
4.1888
3.1416
2.0944
1.0472
0
0
1.0472
2.0944
π
θ [rad]
6000
5000
4000
3000
2000
1000
0

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

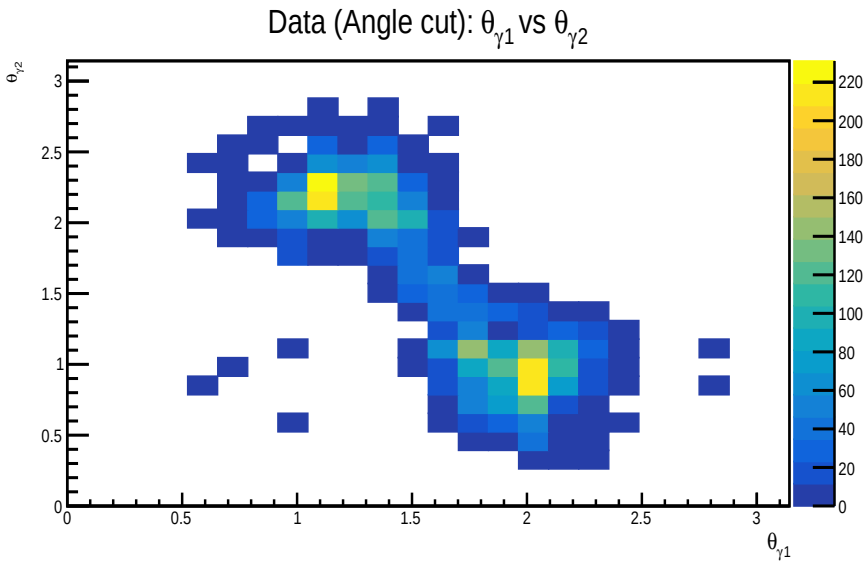


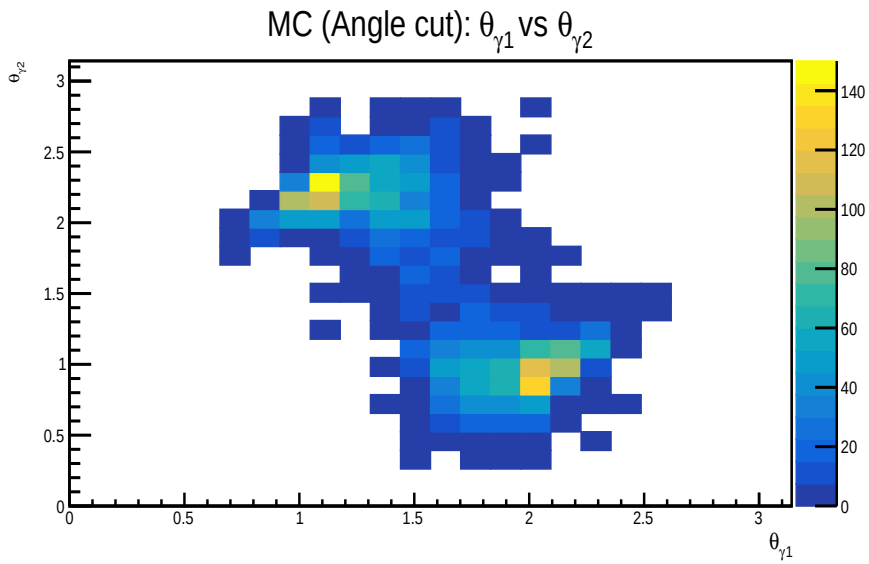


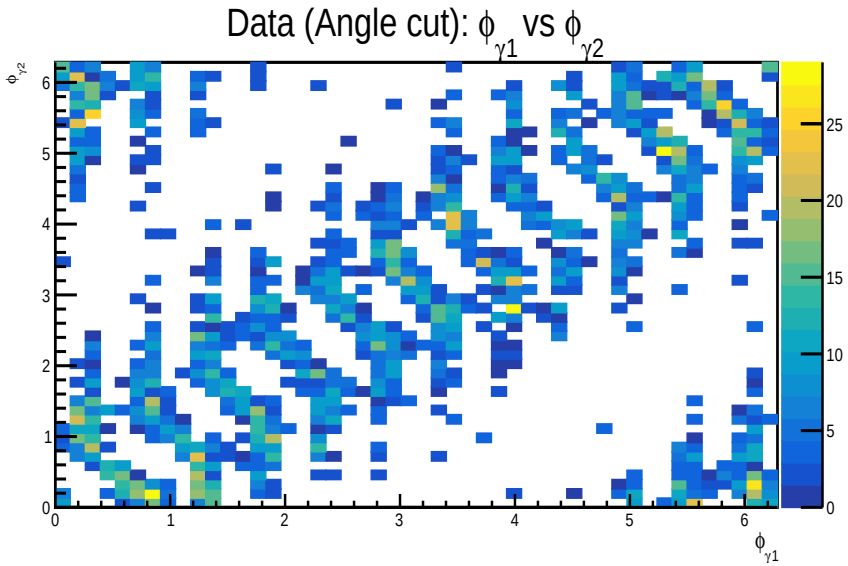


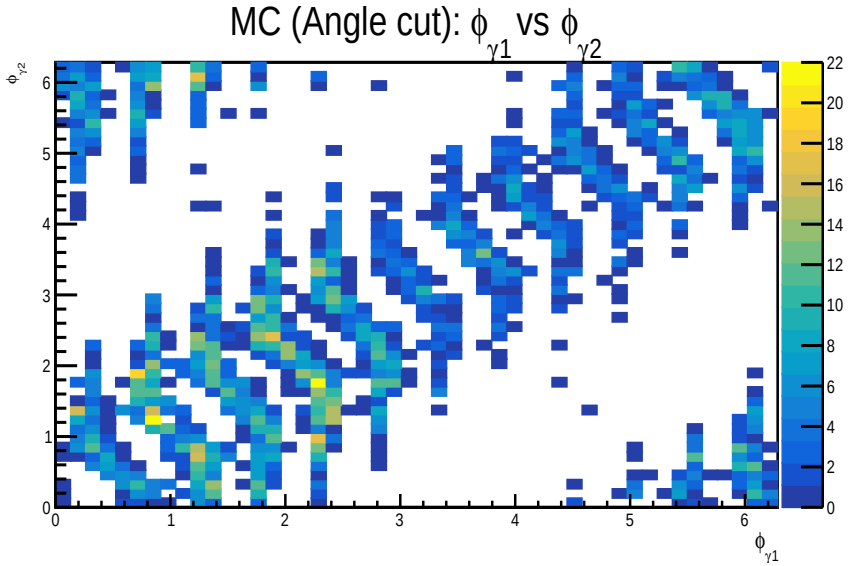


Angular Correlations: $\theta_{\gamma 1}$ vs. $\theta_{\gamma 2}$ ($\cos(\theta_{\pi^+\pi^0})$ cut)

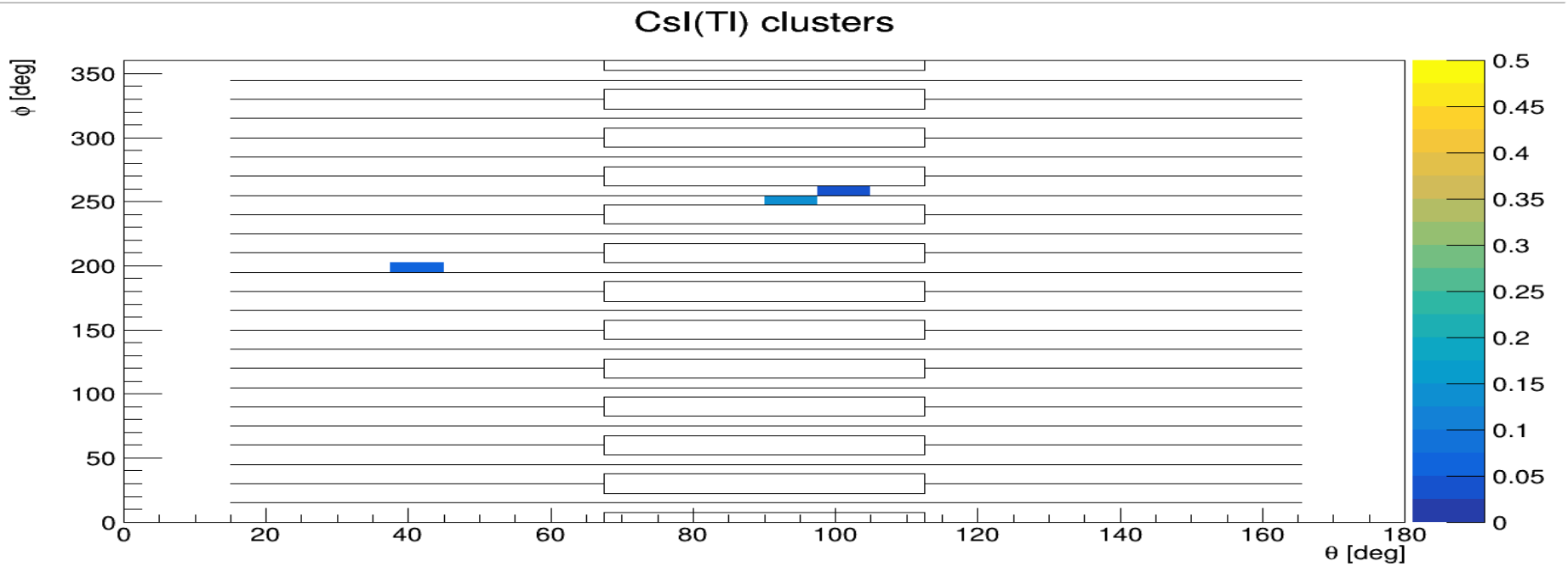








Cluster Analysis




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