The Hidden Universe: Illuminating the Dark

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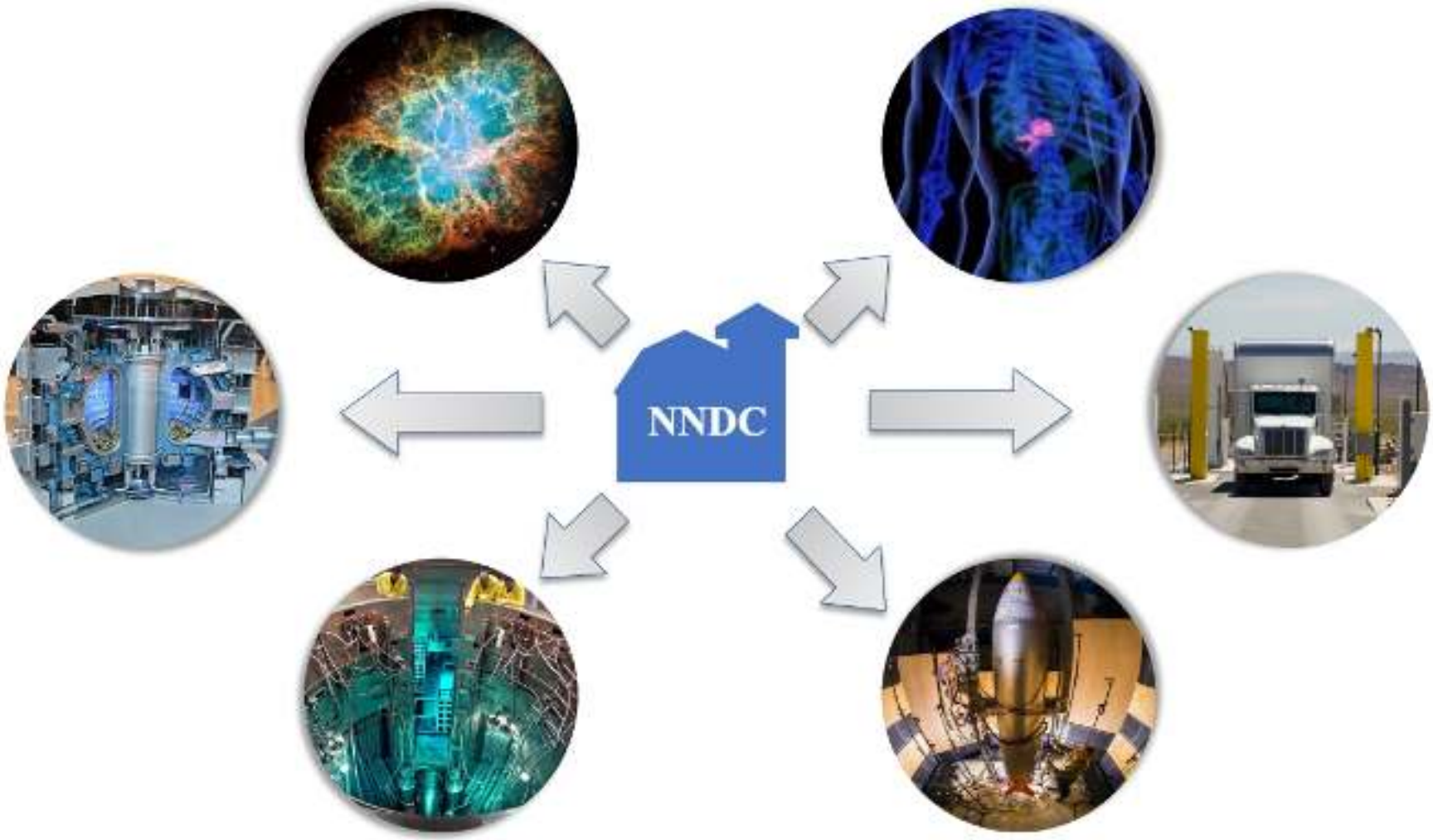
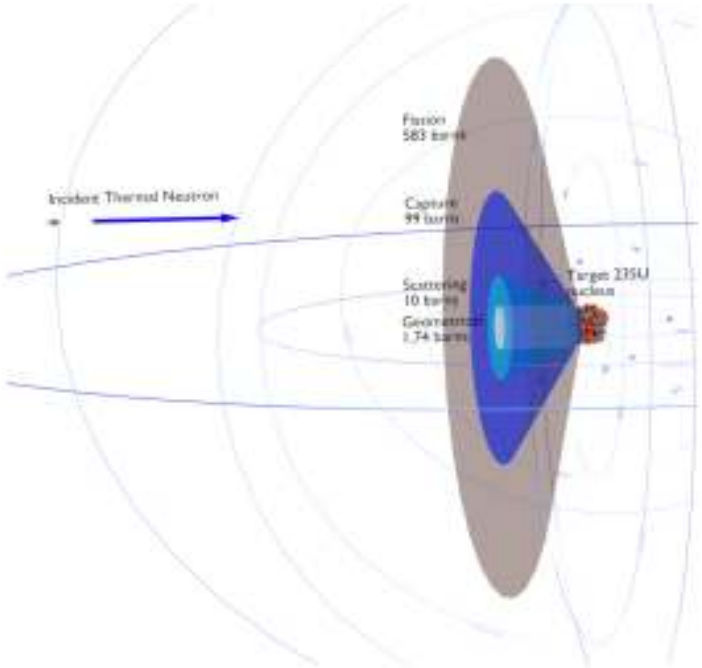
October 20, 2023

From Namibia → Montezuma, NM → Fulton, MO→ Tokai-Mura (Hampton, VA)

Fission

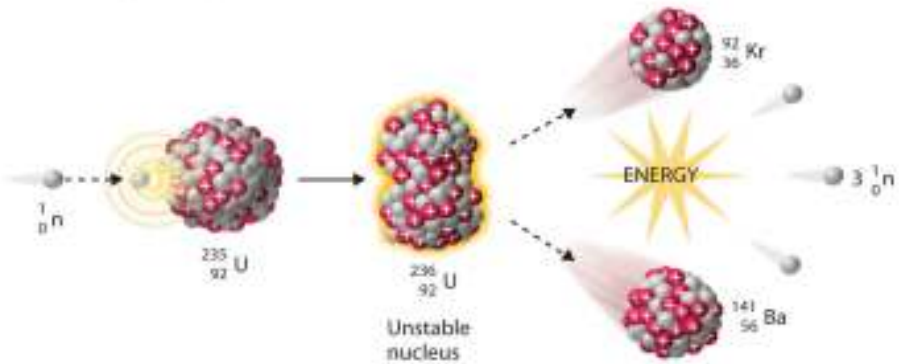


Neutron Induced Fission



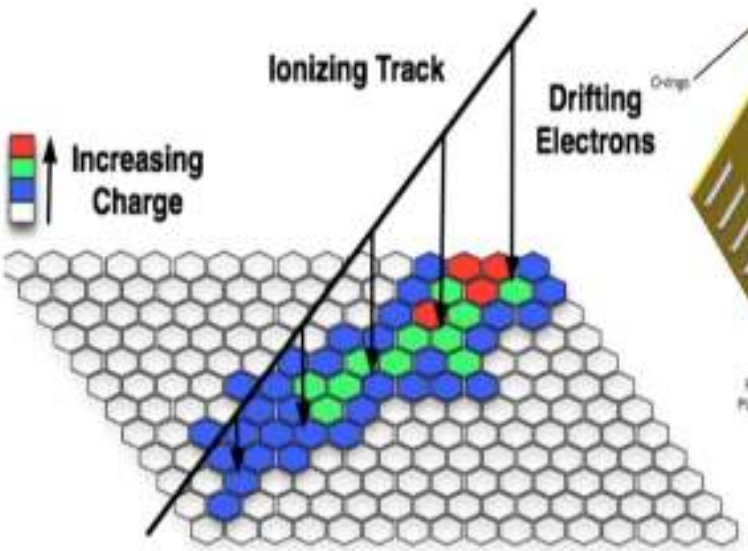
$$R = \Phi \sigma \rho$$

R = Reaction Rate
Φ = Neutron Flux
ρ = Target Density
σ = Cross Section

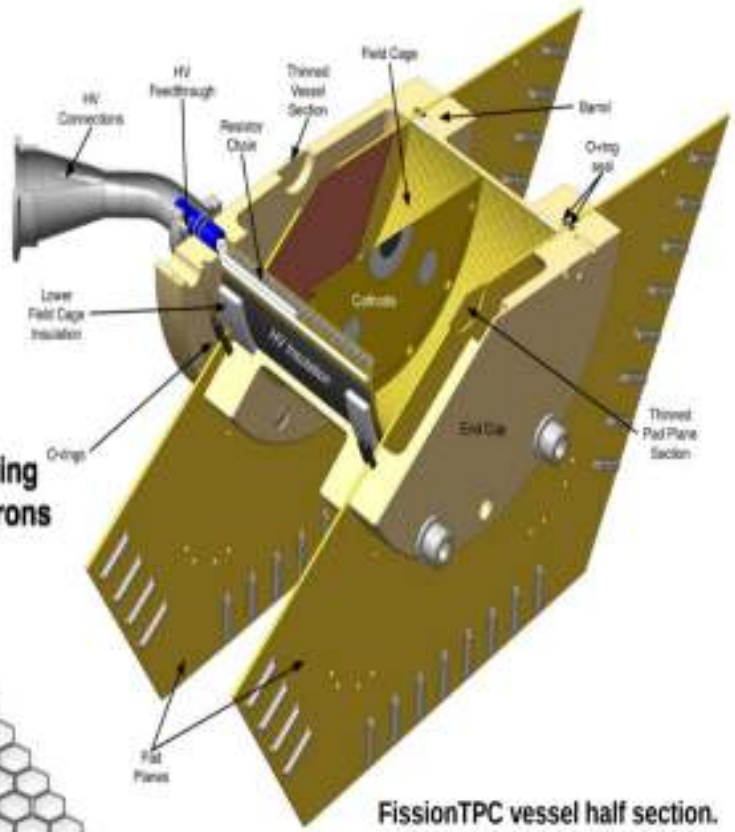


FissionTPC Detector

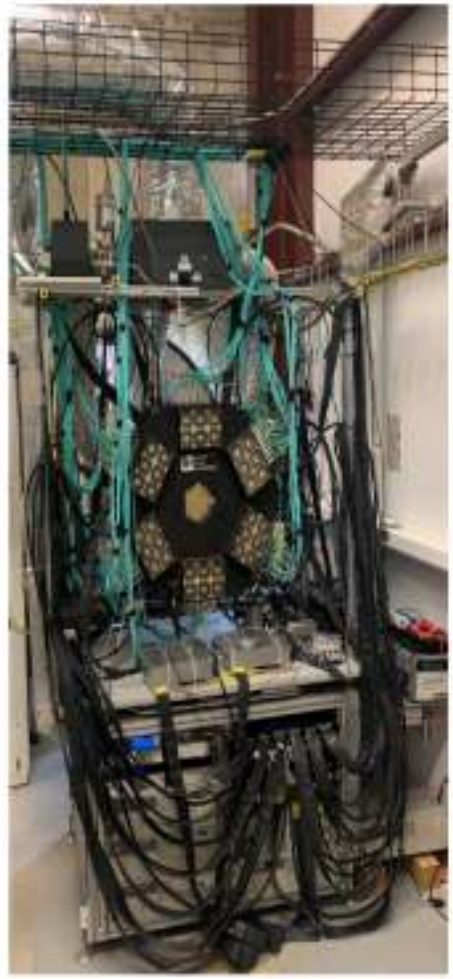
Extensive details can be found in:
NIM A 759 (2014) 50-64



The constant drift velocity of electrons in a gas allows for 3D reconstruction of the ionization left by fission fragments and other charged particles.

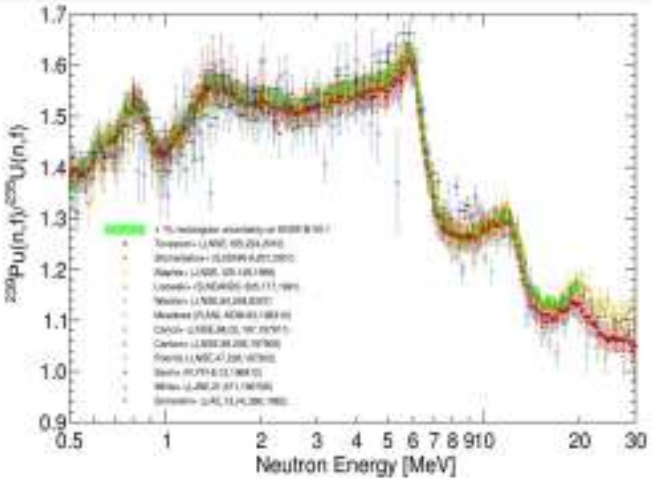


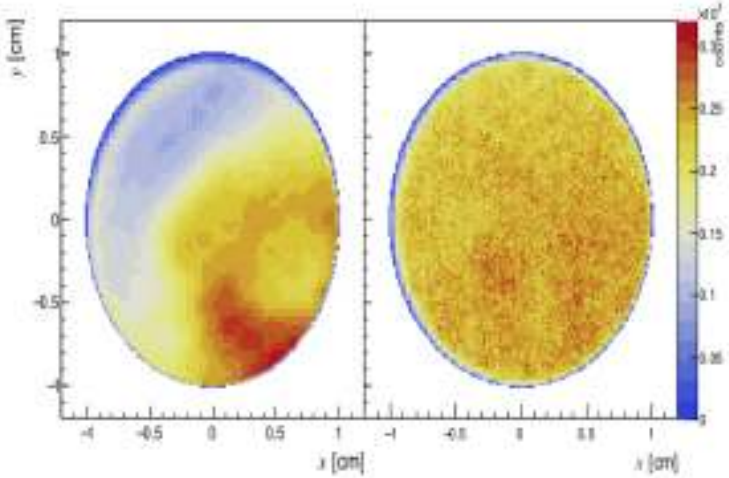
FissionTPC vessel half section.

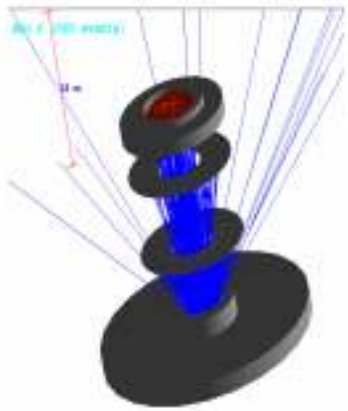


The fission TPC collecting data at Los Alamos National Laboratory

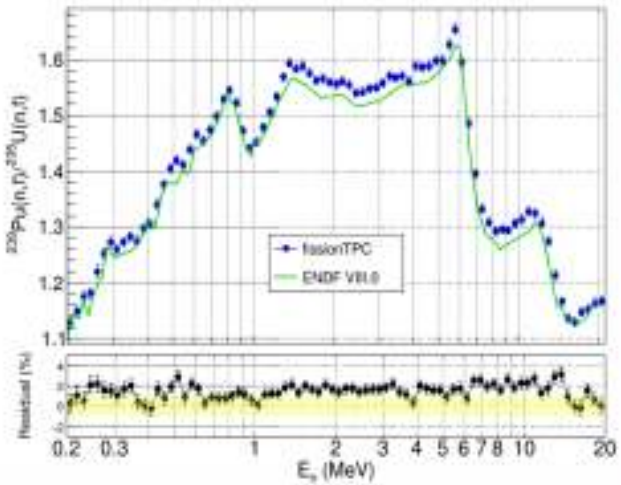
Physics Case for $^{239}Pu/^{235}U$ *Fission Fragment* Ratio







[Monterial et. al., Nucl. Inst. and Methods in Phys. Research A (2022)]

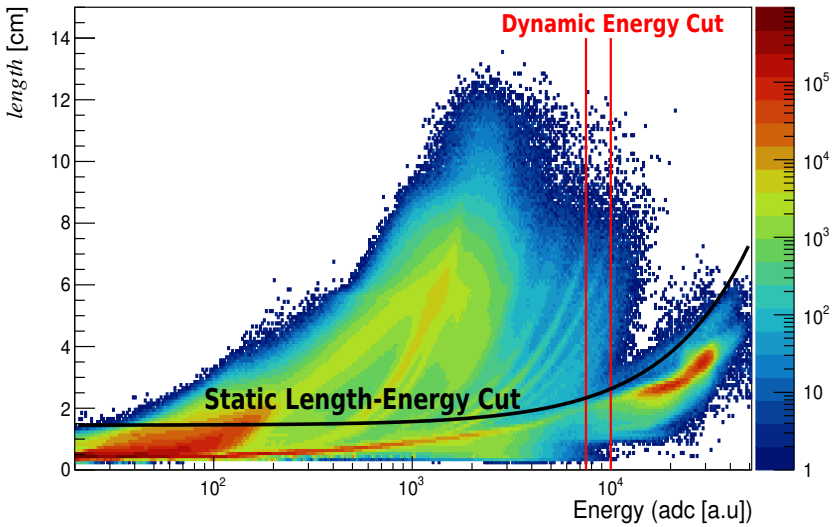


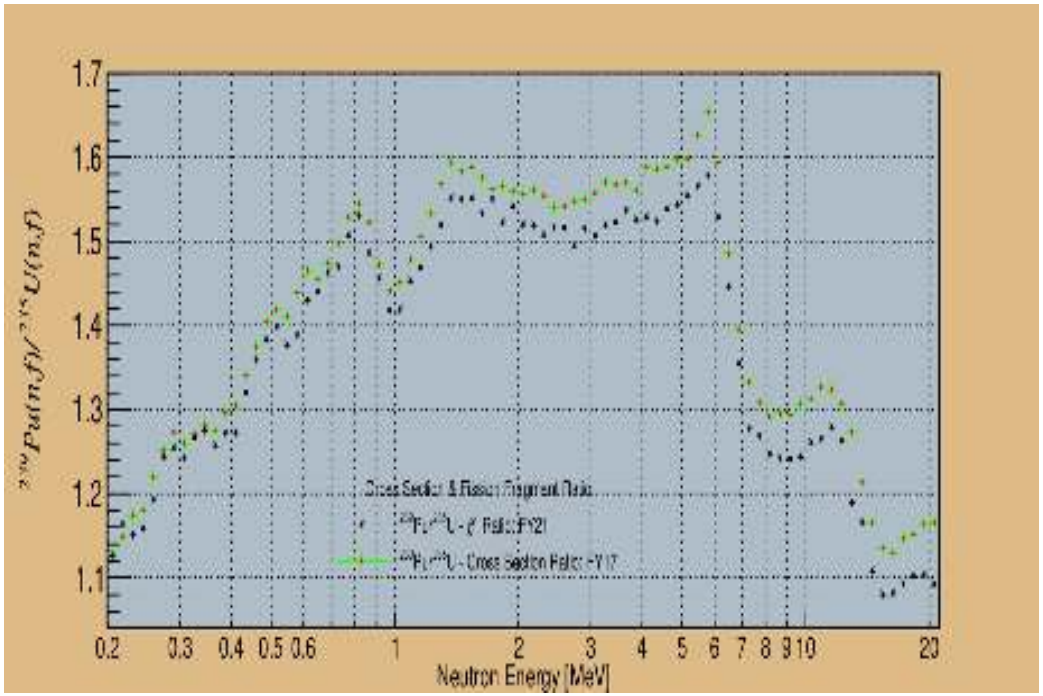
[Snyder et. al., Nucl. Data Sheets 178 (2021)]

Cross-section Data & Results From 2017 Run

- Nuclear data uncertainties strongly influence design and operation margins in nuclear defense and energy applications
- Spread of existing data suggest uncontrolled and/or unrecognized systematic uncertainties
- Data taken with fissionTPC has 2% deviation from ENDF VIII
- Data from 2017 had non-uniform beam on non-uniform target
- Possible systematic and/or unknown effects
- Study of Si detector efficiency showed no systematic effects when comparing uniform and non-uniform targets

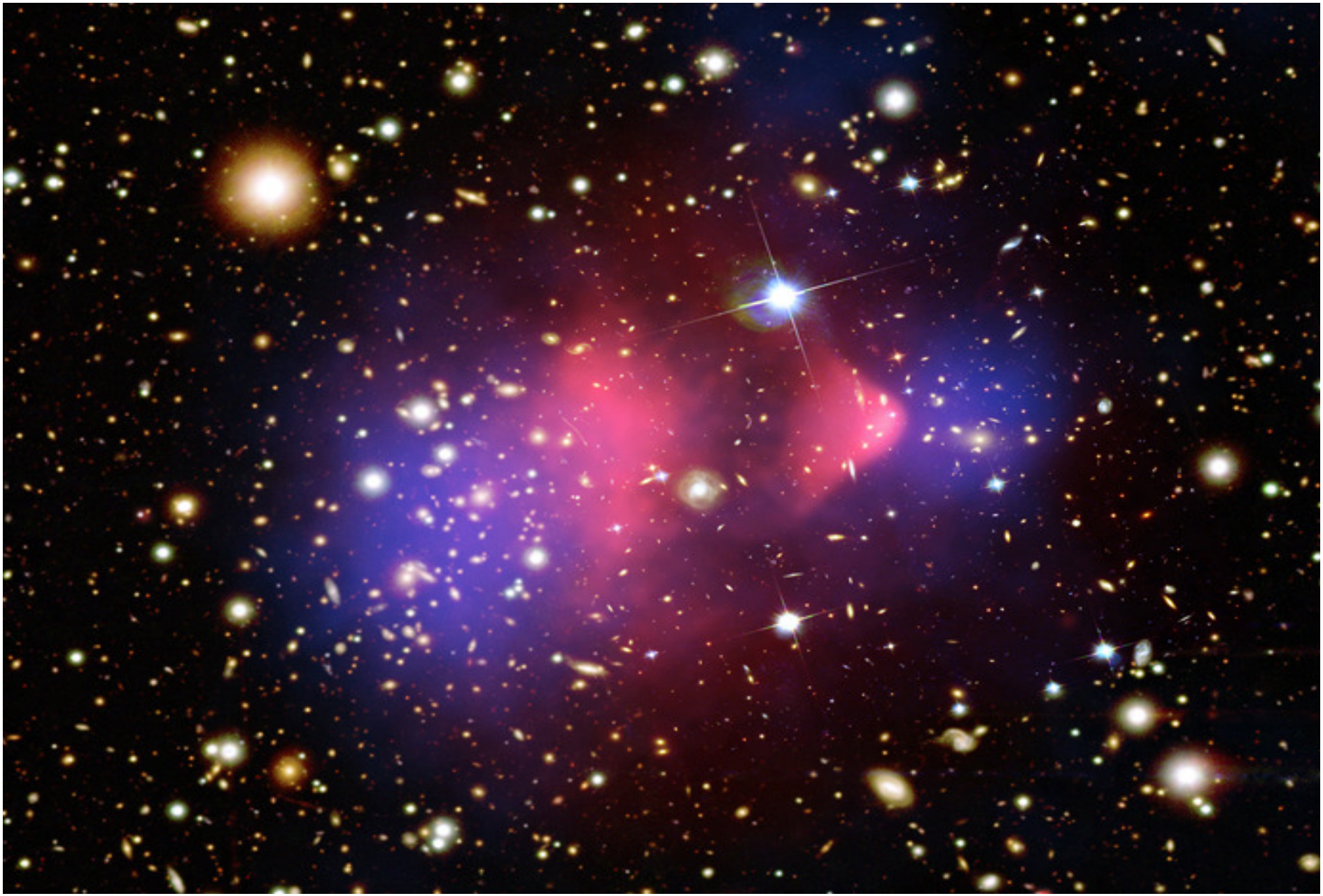
FissionTPC Detector



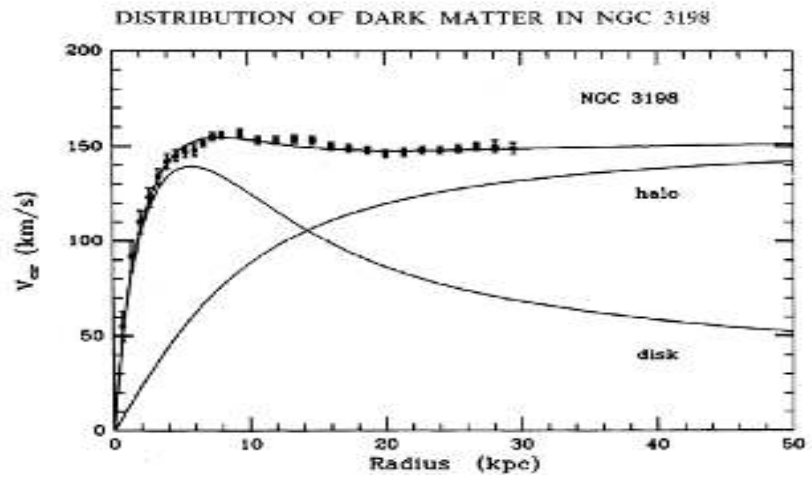


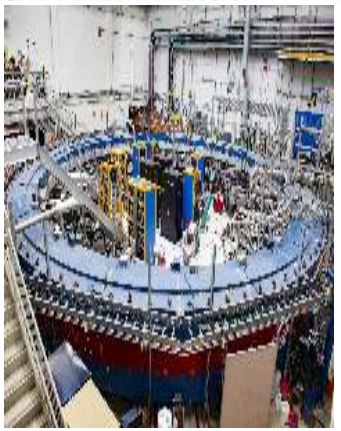
- Measure a cross-section ratio with high precision: less 1% (stat. and sys.)
- Target normalization correction
- Wraparound & efficiency correction
- Finalizing corrections for publication: SOON

Anomalies



Anomalies



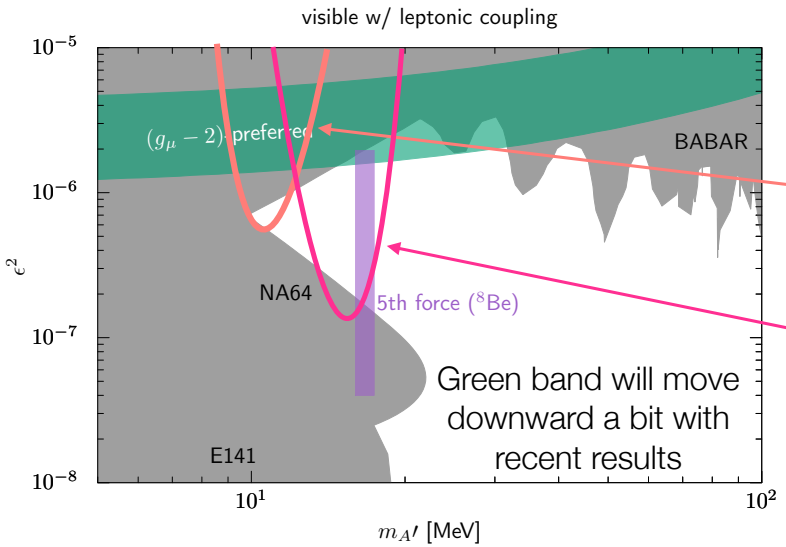


- Proton radius puzzle, $(g-2)_\mu$
- Strong CP problem
- Positron excess and ^{8}Be anomaly

DarkLight @ARIEL/TRIUMF

Dedicated search for the 17 MeV `fifth-force carrier`

This plot: limits on possible new bosons from e+e- interactions only



X17 and **muon g-2** anomalies both appear in lepton interactions. "Protophobic" new boson would avoid constraints from pion interactions but can be cleanly probed at e- machine.

DarkLight is essentially a dark photon search, providing unique coverage because it uses no pions/protons

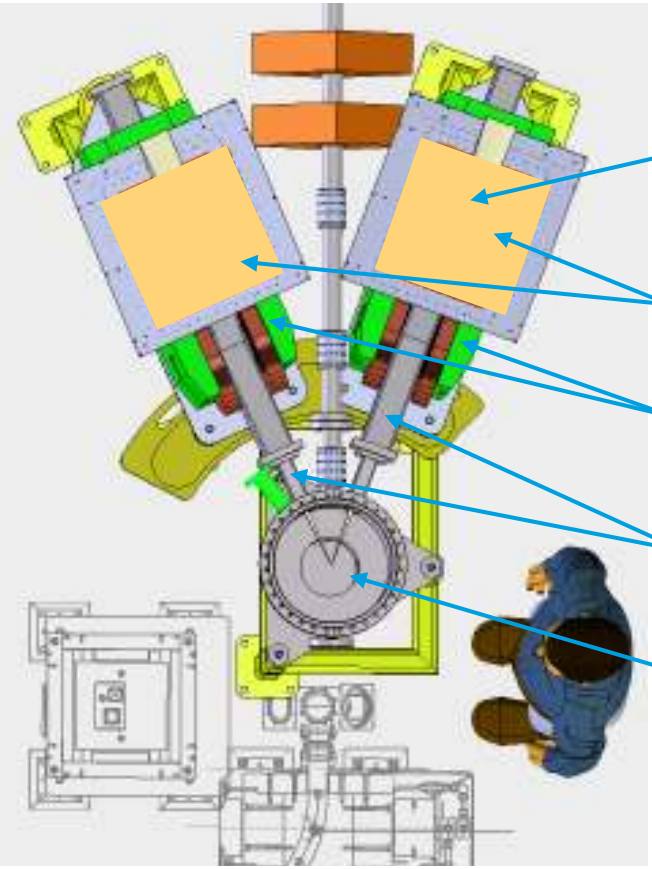
Sensitivity will cover interesting mass ranges in this plot

Especially with an eventual energy upgrade (not up for approval today)

ARIEL e-linac's low energy and high current make it appealing accelerator to do this search

$$e^+ + Z(_{73}Ta) \rightarrow e^- + A' + X,\ A' \rightarrow e^+e^-$$

Apparatus



(Not in drawing)
Trigger detectors

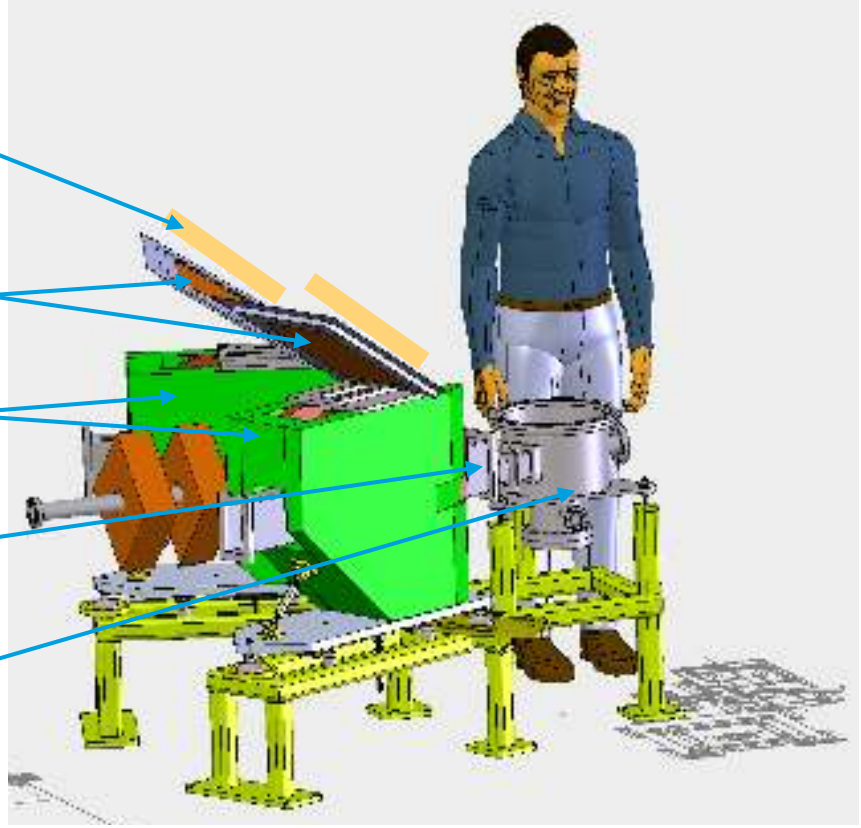
Tracking detectors

Dipole magnets

One fixed arm; one with two angles

Target chamber

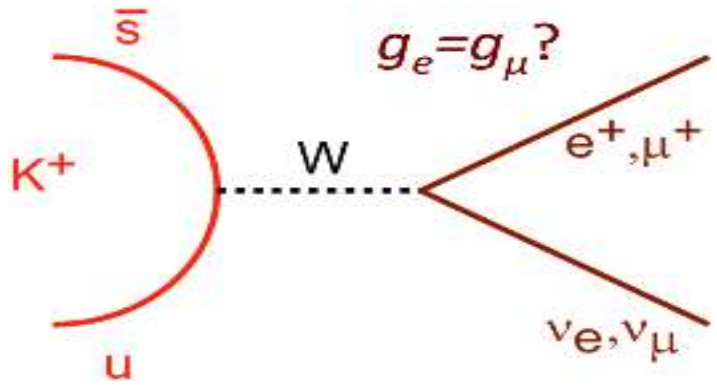
Part of vacuum system



Lepton Universality in the E36 Experiment

- LHCb, Belle & BaBar observed lepton non-universality at 3σ level
- E36 will test lepton universality with stopped K^+

LHCb (Phys. Rev. Lett. 113)



2-body decay of K^+

Decay width ratio of electronic (K_{e2}) and muonic ($K_{\mu 2}$) decay modes

$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$$

- Hadronic uncertainties cancel
- Strong *helicity* suppression of electronic channel enhances sensitivity to effects beyond SM
- SM prediction is highly precise: $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

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.

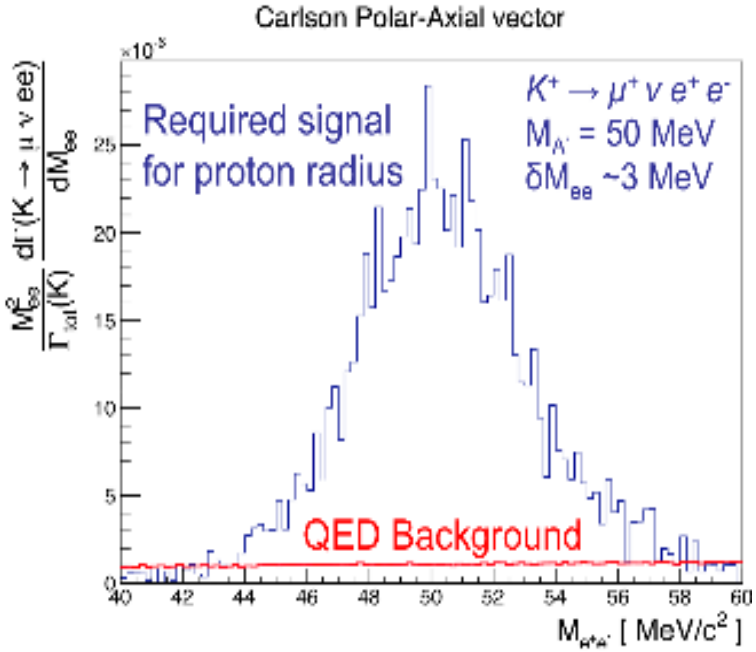
Add. background from $K^+ \to \mu^+ \nu \pi^0 \to \mu^+ \nu\ e^+ e^- (\gamma)$

π^0 decays 1) 3x10^8 2) 2x10^9

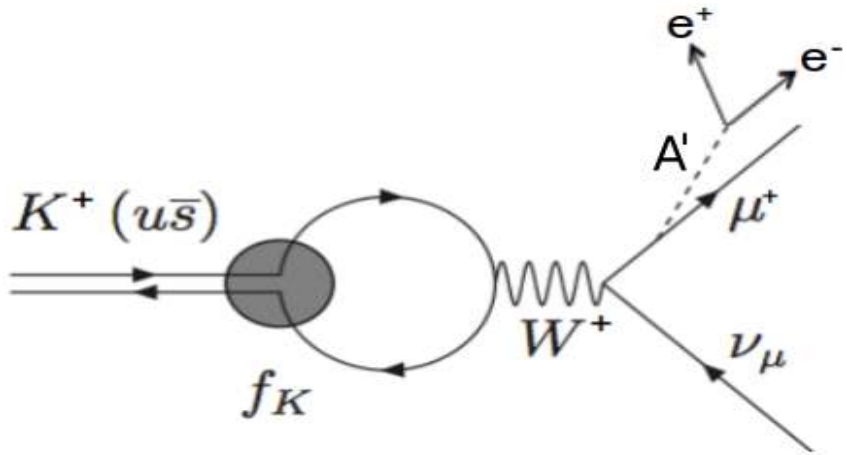
π^0 production: $K^+ \to \mu^+ \nu \pi^0$ (3.3%) $K^+ \to \pi^+\pi^0$ (21.1%)

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

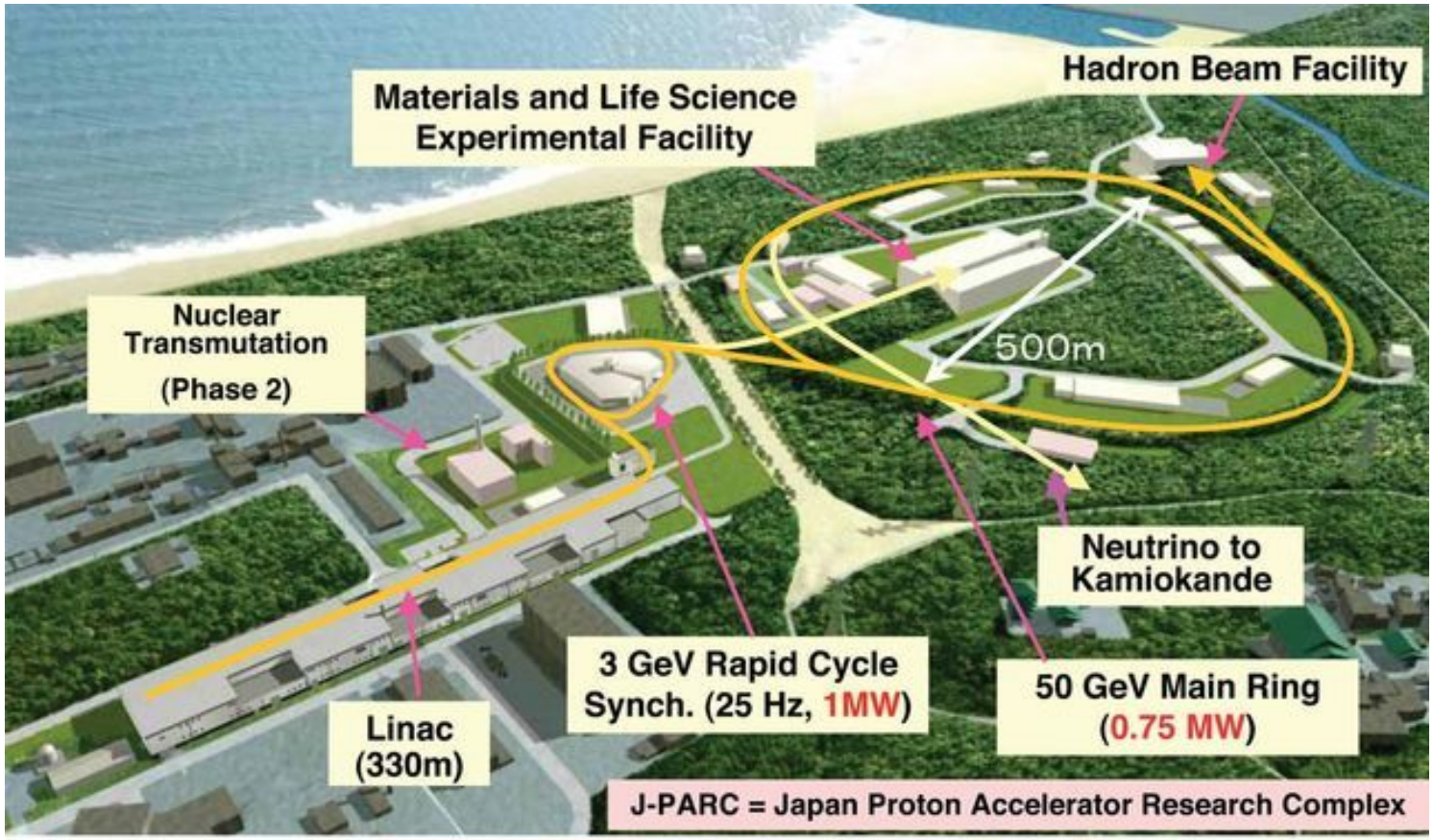
Background: BR($\pi^0 \to \gamma\ e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) x$10^7$ ev.



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

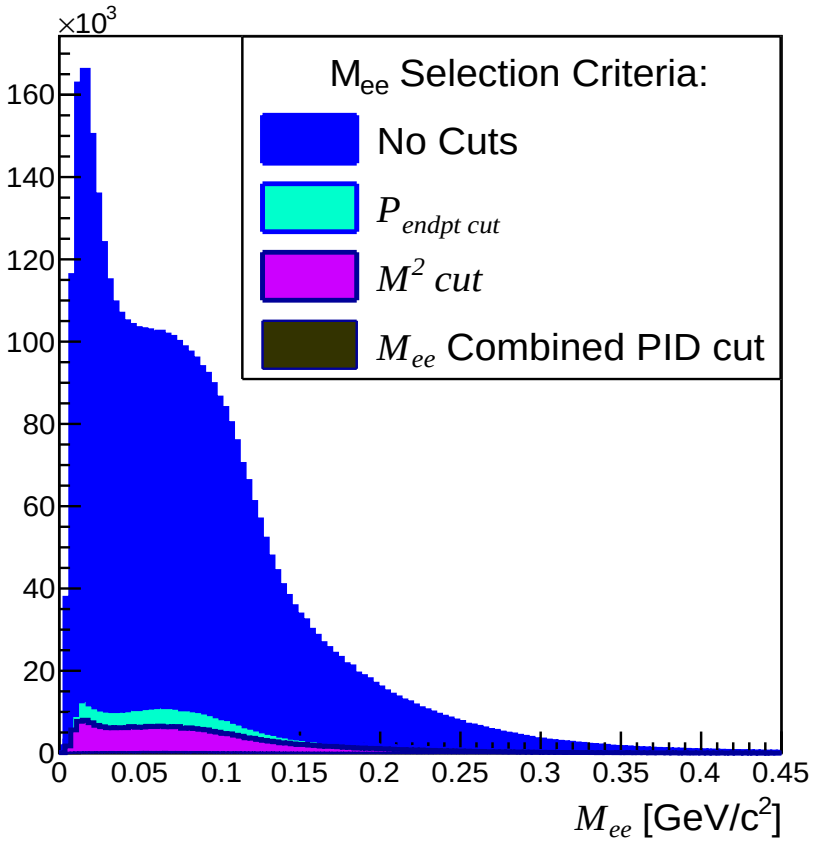


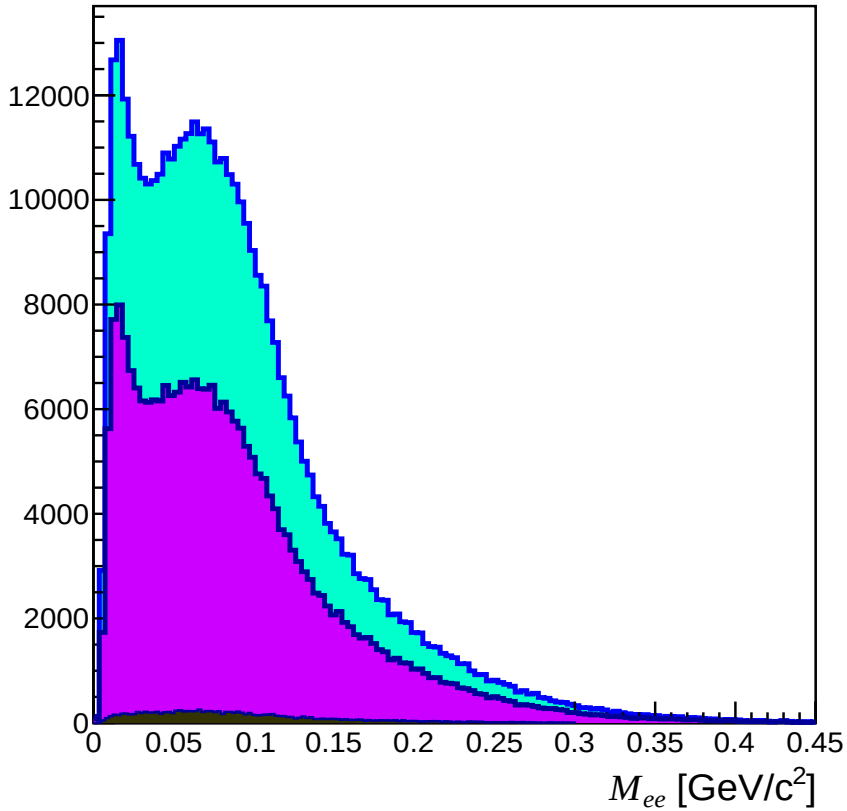
PRD 89, 0350003 (2014)



Joint Project between KEK and JAEA

Invariant Mass Distribution

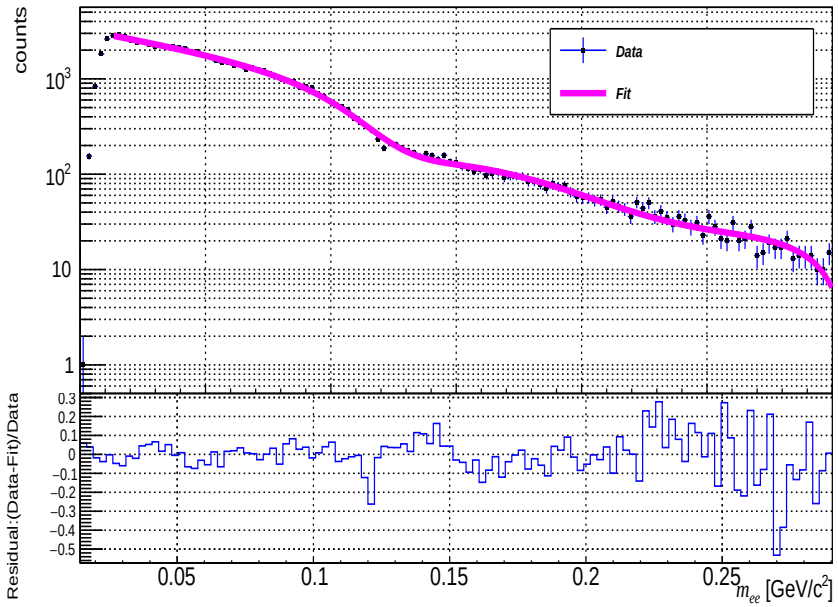


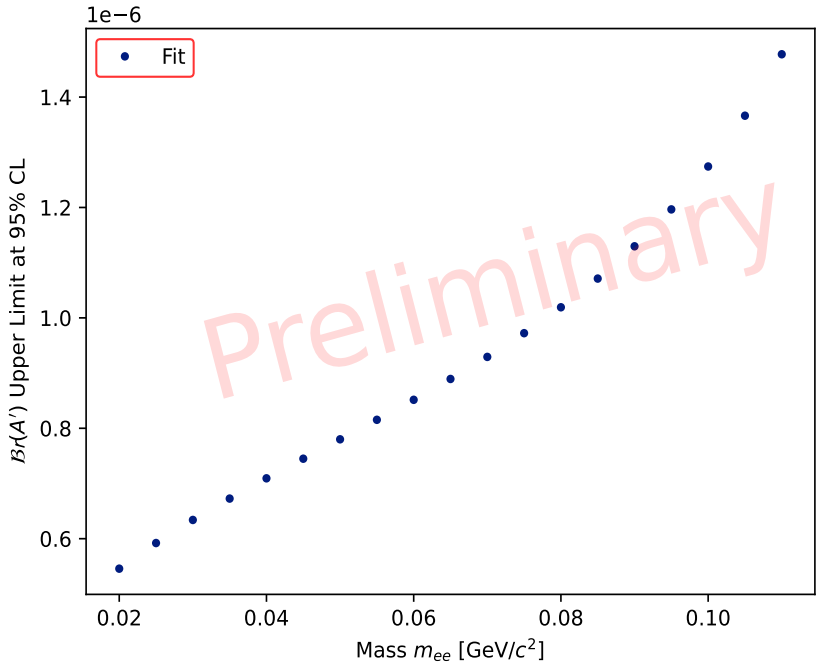


- Applied PID selection from the target system and tracking
- Applied end point momentum cut
- M^2 cut applied (magenta)

- M_{ee} distribution used for analysis has both $P_{endpoint}$ and M^2_{cut} (magenta)
- Combined PID cut: $P_{endpt} \otimes M^2 \otimes$ TOF1

Upper Limit Extraction

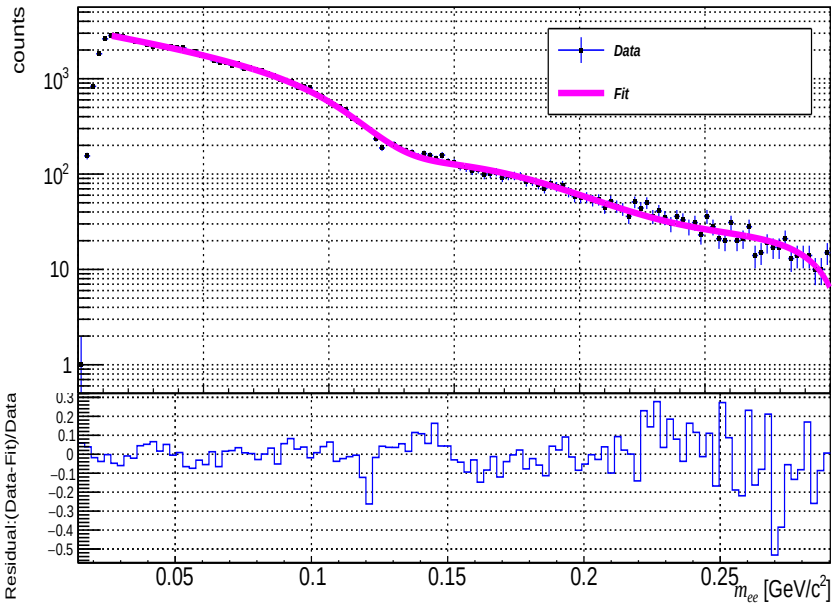


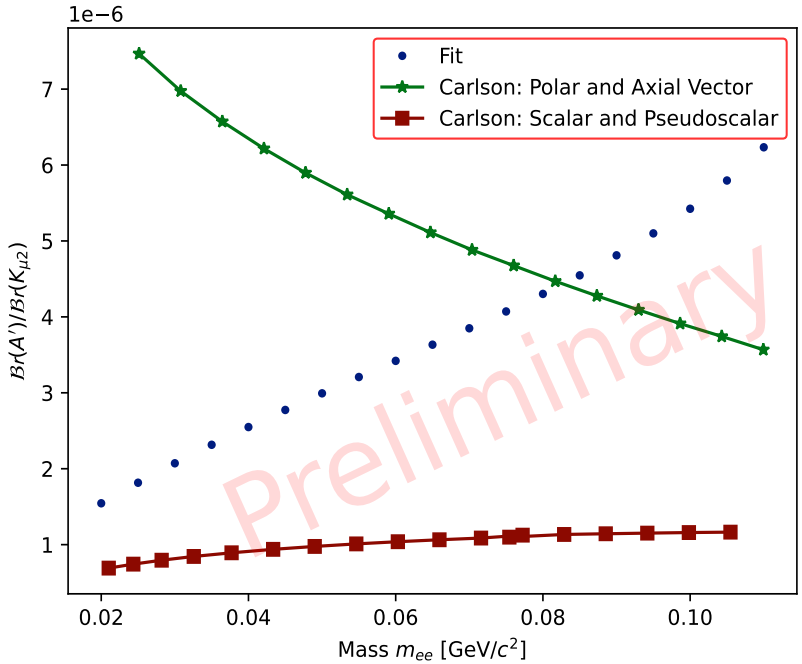


$$\mathcal{B}r(A') < \frac{2\sqrt{N_{\mu\nu ee}}}{N_K A_{A'} LT(\mu)}$$

- N_K: Number of K^+, $LT(\mu)$: muon livetime fraction
- $A_{A'}$: 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
- 2σ limit: $\sim$ 95% CL of no signal observance
- Upper limit obtained from $\sim$ 30% if the data

Upper Limit Extraction





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- $A_{A'}$: acceptance ratio of the A' with a given mass, determined from e36g4MC
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- 2σ limit: $\sim$ 95% CL of no signal observance
- Upper limit obtained from $\sim$ 30% if the data
- Theoretical predictions: polar and axial vector or Scalar and Pseudoscalar couplings

[Dongwi, J.Phys.Conf.Ser. 2446 (2023) 1, 012030]

Sharing the Fun

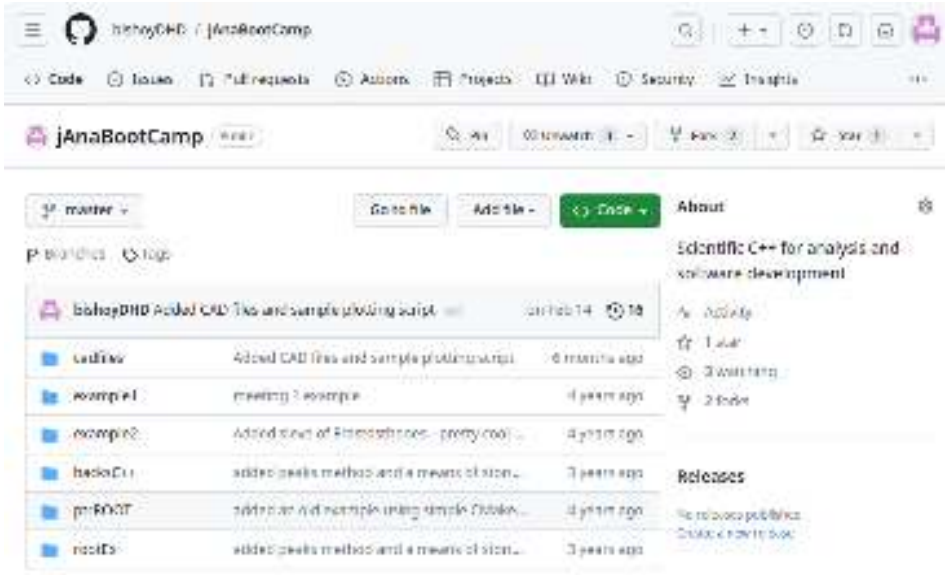
Outreach Activities

girls who code

replit

- COVID-19 caused many students to lag behind
- Especially in STEM and mostly from underrepresented groups
- I volunteered with `Girls Who Code` to help those students
- Used `Replit` as means of monitoring and assisting students with their projects
- Participating in community events and physics luncheons/public lectures

Outreach Activities



Coding Bootcamp:

- Tailored graduate students who wanted to improve their software and analysis skills
- C++ scientific coding using ROOT software
- Placed emphasis on teaching object-oriented paradigm for sophistication and abstraction

Community:

- Participated physics day: VUU Physics Club
- Encourage and provide direction for undergraduate students from MSI
- Judge for Science Bowl

The End

Back Up Slides

Summary and Future Work

- Universe is littered with anomalies that must be explained (exciting times!)
- Currently finalizing results of $^{239}\mathrm{Pu}(n,f)/^{235}\mathrm{U}(n,f)$
- Final verdict on 2% discrepancy with ENDF
- DarkLight has been approved at TRIUMF
- Detector elements have been constructed
- Commissioning, and installation of detectors this year, and production data data 2024
- Lepton universality is the flagship for Beyond Standard Model Physics
- e36g4MC has been developed from ground-up
- K^+ decay generator has been implemented into the e36g4MC
- 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

Edward Bouchet Fellowship

- Combines my two passions: Physics and STEM Outreach
- Broad outreach and mentoring experience, throughout my academic career
- Significant physics overlap (BSM, ML/AI) interest
- Extensive Geant4 background/Software experience
- Opportunities for detector development and construction

Collaborators

Spokespeople:
M. Kohl, S. Shimizu

CANADA
University of British Columbia
Department of Physics and Astronomy
TRIUMF

USA
University of South Carolina
Department of Physics and Engineering
Iowa State University
College of Liberal Arts & Sciences
Hampton University
Department of Physics

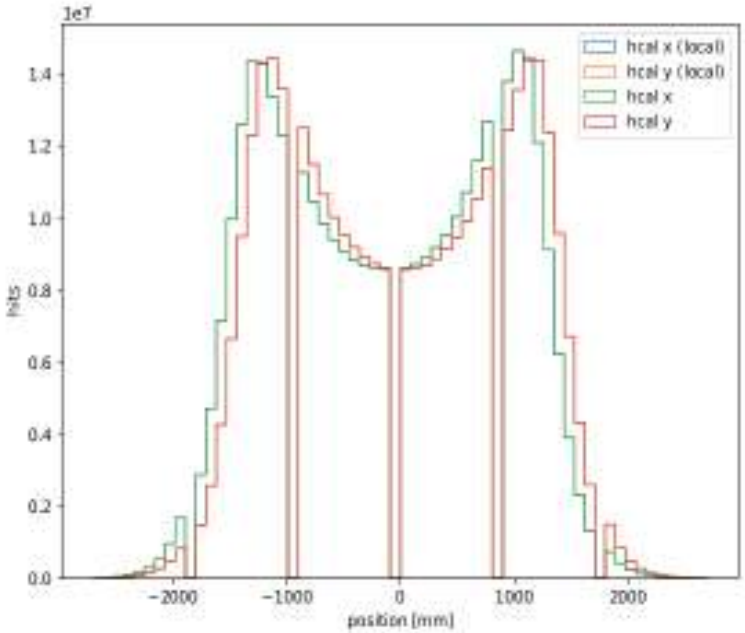
JAPAN
Osaka University
Department of Physics
Chiba University
Department of Physics
High Energy Accel. Research Organization (KEK)
Institute for Particle and Nuclear Studies

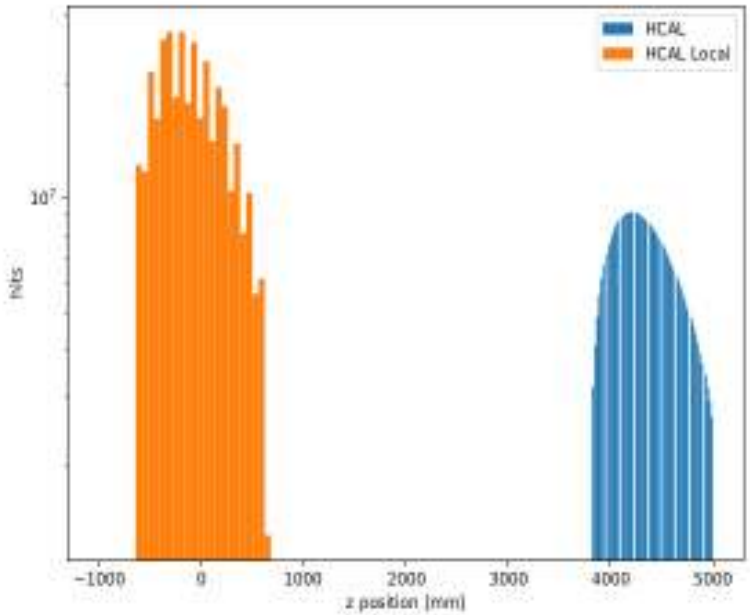
RUSSIA
Russian Academy of Sciences (RAS)
Institute for Nuclear Research (INR)

AI-Driven Detector Design for the EIC

- Use ANL EIC container to run Geant4 simulation of ECal & HCal for the purposes of training regression models
- Converted Geant4 produced `ROOT files` into `HDF5 format`
- Used PFNs for training on `HDF5 image files`
- Realized several problems in `Geant4` and I decided to investigate angles (θ, ϕ)

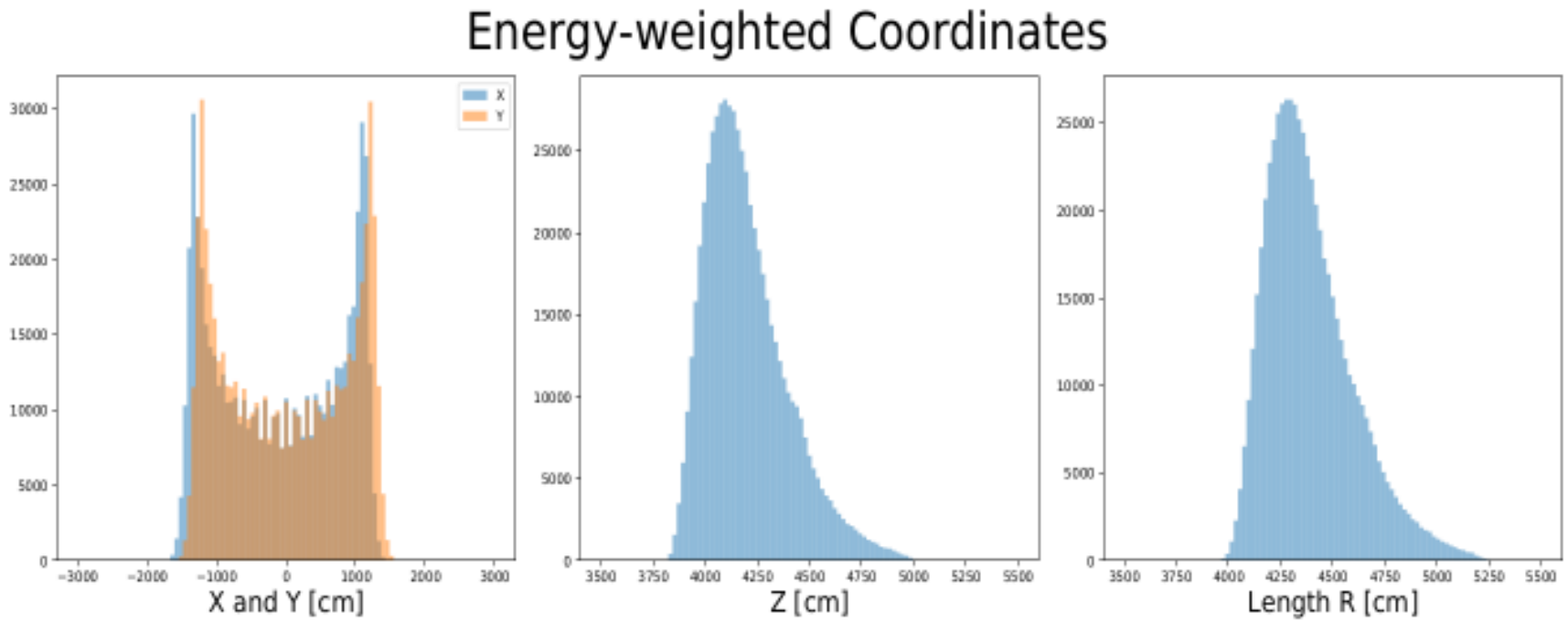
Energy-Weighted Coordinate: Reconstruct Angles





- Extracted calorimeter hit positions (X, Y, Z) [cm]
- Z has both local (orange) and global (blue) coordinate

Energy-Weighted Coordinate: Reconstruct Angles

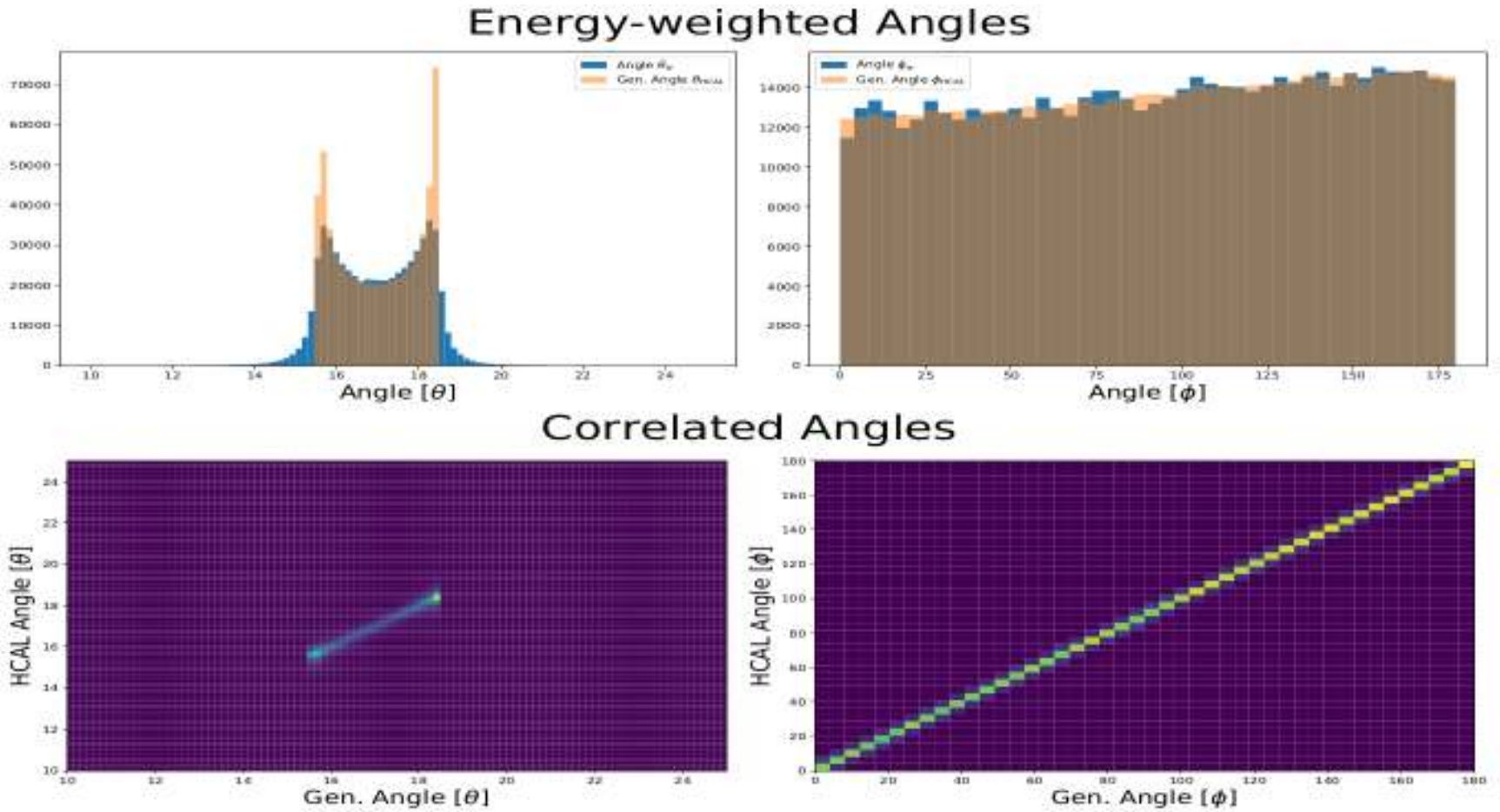


- Energy-weighted HCAL coordinates:

$$X = \frac{1}{\sum_{j=1}^{N} E_j} \cdot \sum_{i=1}^{N} E_i \cdot X_i$$

- Used to calculate the corresponding angles: θ and ϕ
- Strange bump around Z=4400 cm

Energy-Weighted Coordinate: Reconstruct Angles



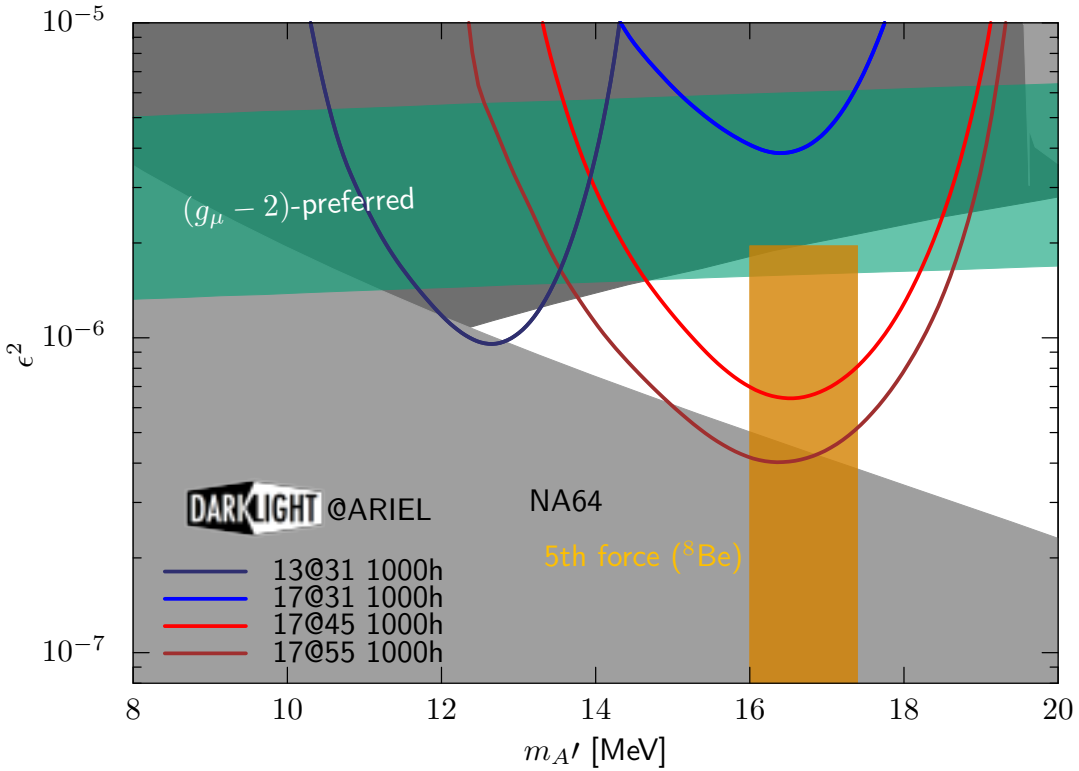
- Good agreement in θ and ϕ: **energy-weighted coord.**
- Both angles are well correlated: 2D profile plots
- Smearing from HCAL angle reconstruction

Milestones

Proposal submitted	**March 2021**
Proposal approved	**April 2021**
Canadian groups funded	**April 2022**
Technical design of experiment completed	**Sep. 2022**
Technical review by TRIUMF	**Oct. 2022**
US groups funded	**Oct. 2022**
Construction of experiment	**Oct. 2022 – Oct. 2023**
Experiment installed	**Nov. 2023**
Commissioning of experiment	**Nov. 2023 – March 2024**
Data taking begins	**April 2024**
Data taking completed	**Sep. 2024**

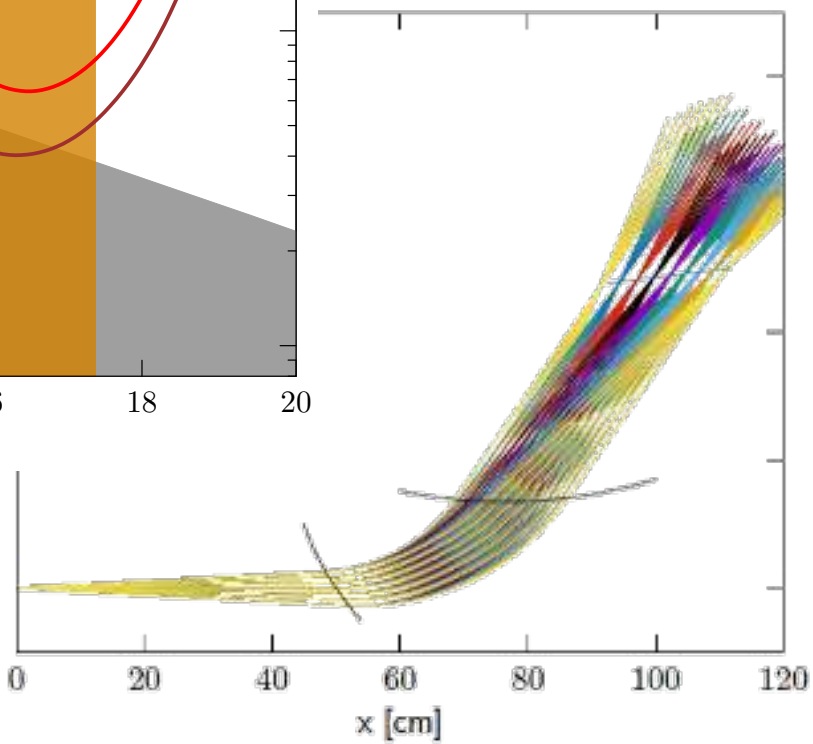
GEM Detectors for DarkLight

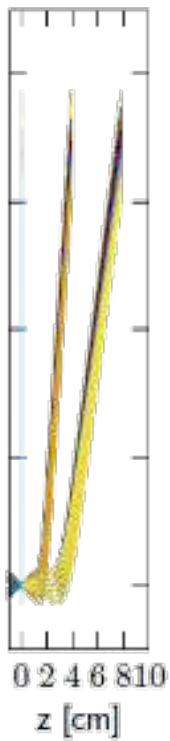
- **Low-energy electroproduction of X17 (DP), LERF@JLab → ARIEL@TRIUMF**



Dedicated search for the 17-MeV fifth-force carrier

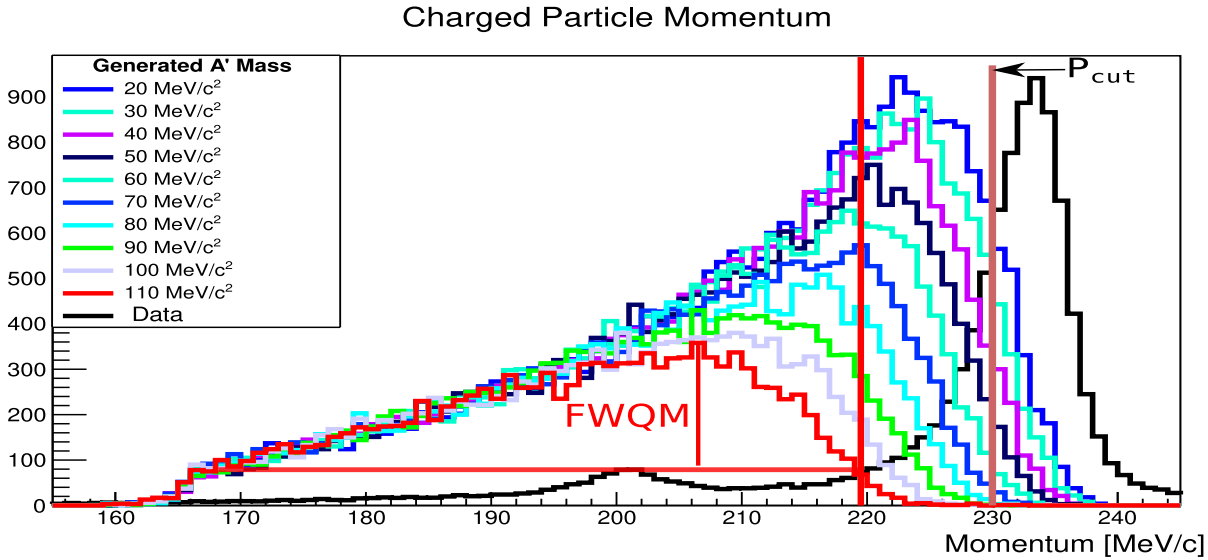
$e^- + Z(_{73}Ta) \rightarrow e^- + A' + X$
$A' \rightarrow e^+ + e^-$

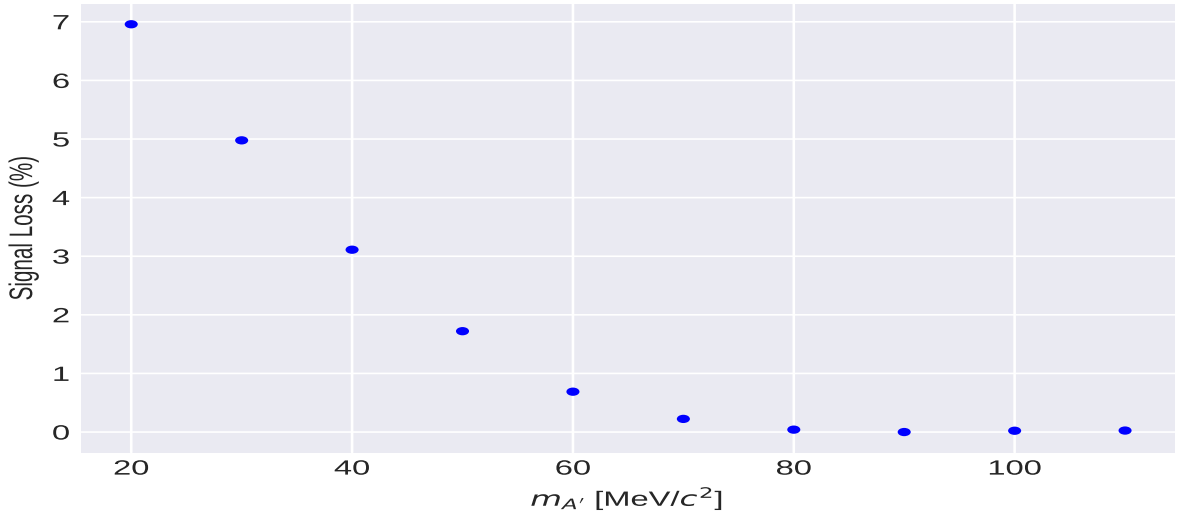




Two-spectrometer solution to detect e+e- pair

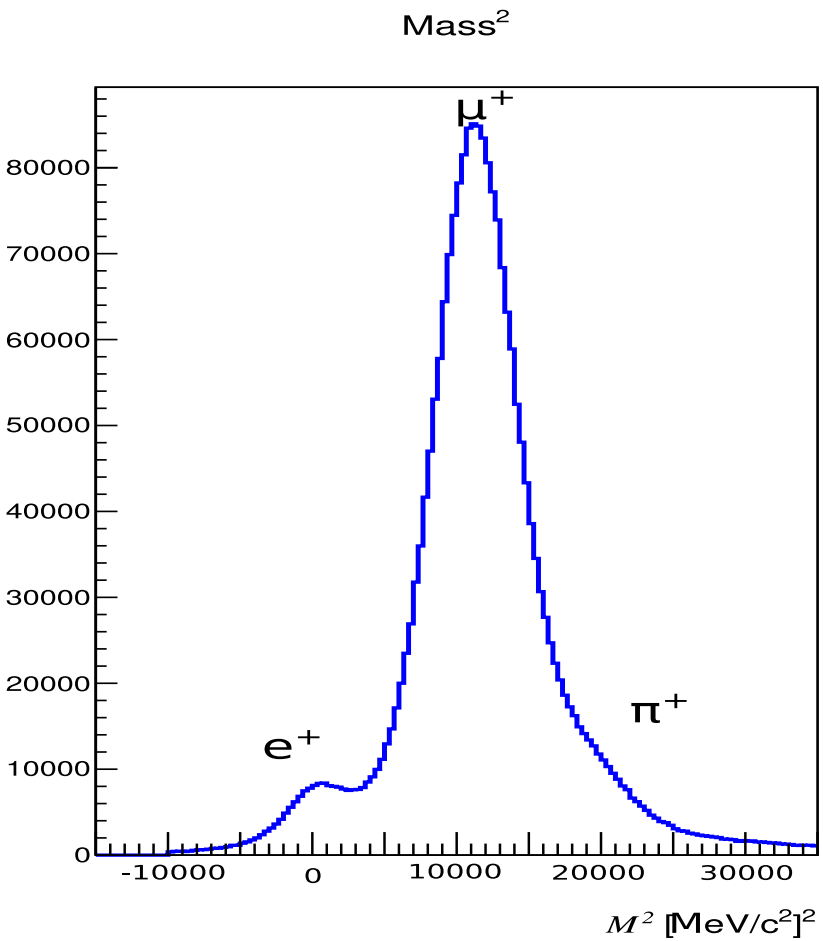
$K_{\mu 2}$ Contamination Reduction

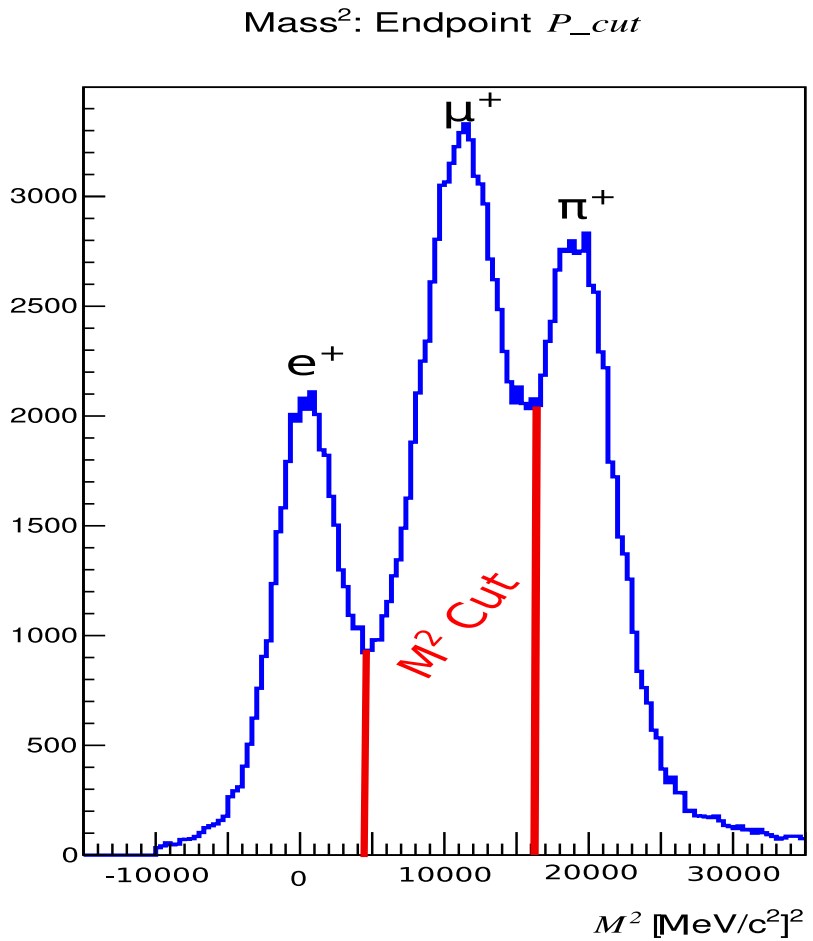




- Signal Loss $S_L = \frac{S_{cut}}{S_{tot}}$
- S_{cut} is integrated signal that survives cut
- S_{tot} is total integrated signal

M^2 Spectrum with End Point Momentum Cut

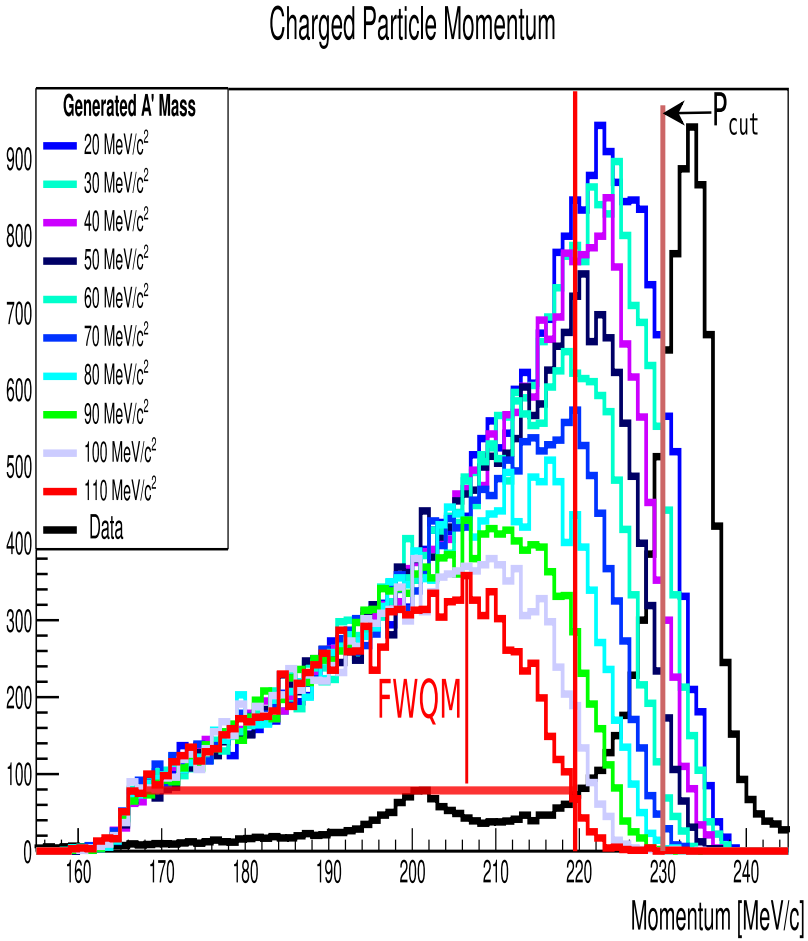


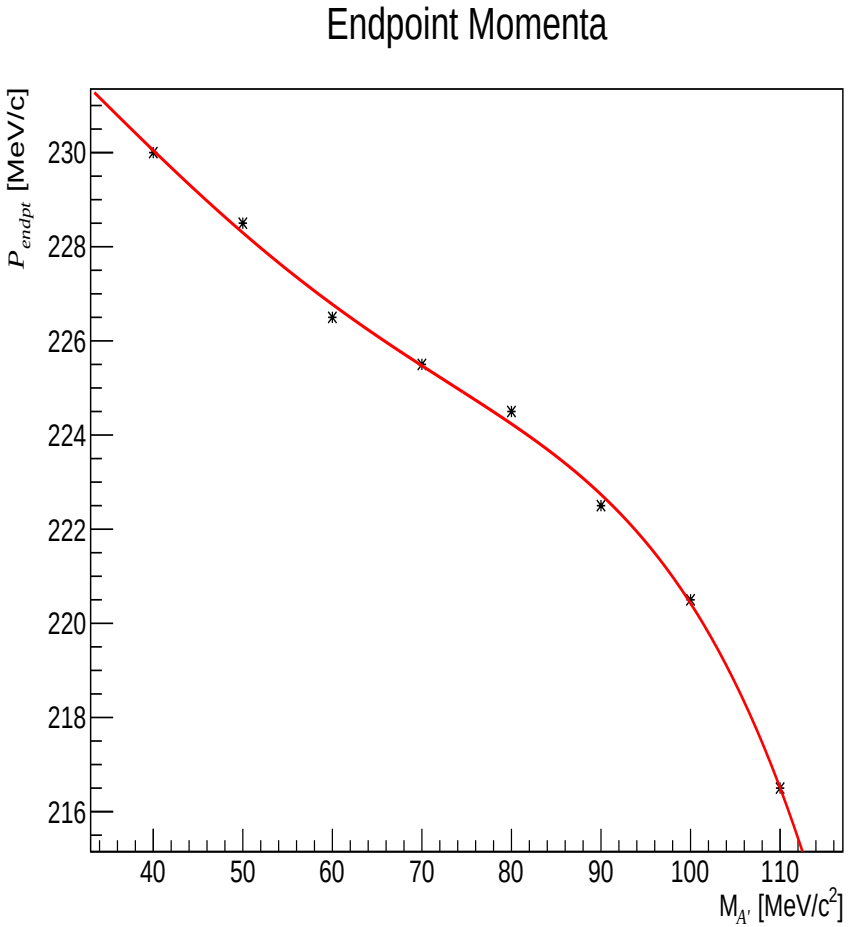


Selection condition for M^2

- Select for M^2_μ by imposing $4900 \leq M^2 \leq 15700$

End Point Momentum Cuts





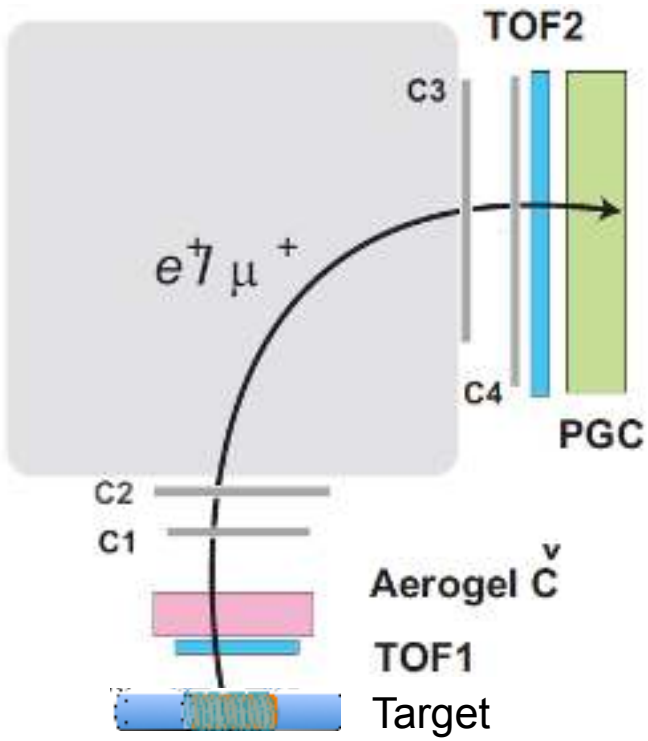
Full Width at Quarter Max.

- For variable endpoint momentum cuts, the FWQM was taken
- If FWQM > 230 MeV$/c$ then the endpoint cut is 230 MeV$/c$
- Used 5^{th} order polynomial function on range of $[210.0, 230.]$

μ/e Mis-identification

PID with:

- TOF
- Aerogel Č
- Lead glass

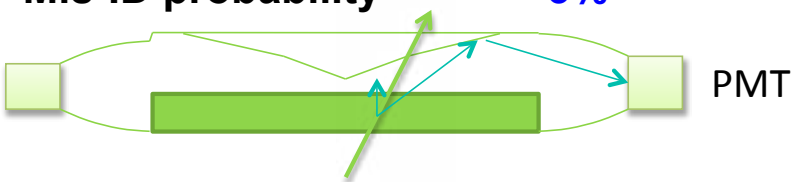


TOF

Flight length	250 cm
Time resolution	<100 ps
Mis-ID probability	7×10^{-4}

Aerogel Č counter

Radiator thickness	4.0 cm
Refraction index	1.08
e^+ efficiency	>98%
Mis-ID probability	3%



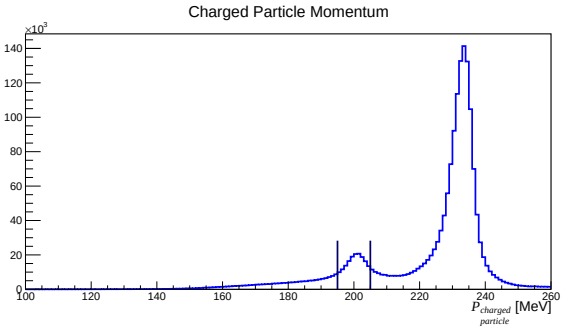
Lead glass (PGC)

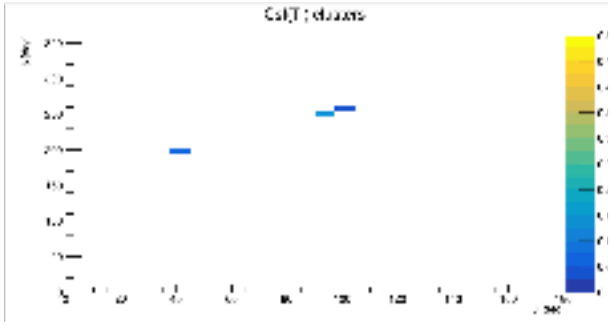
Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

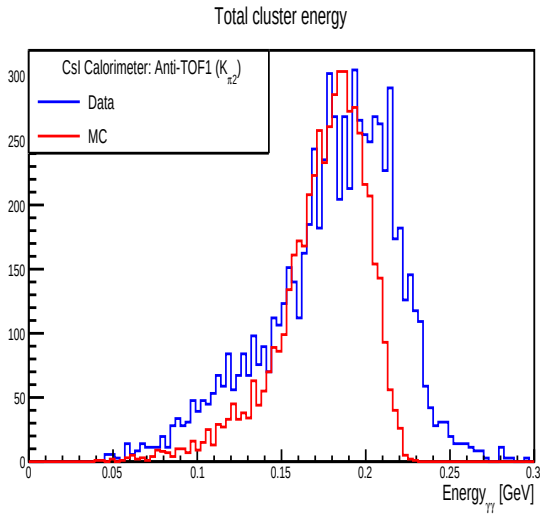
$$P_{mis}\,(\text{total}) = P_{mis}\,(\text{TOF}) \times P_{mis}\,(\text{AČ}) \times P_{mis}\,(\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

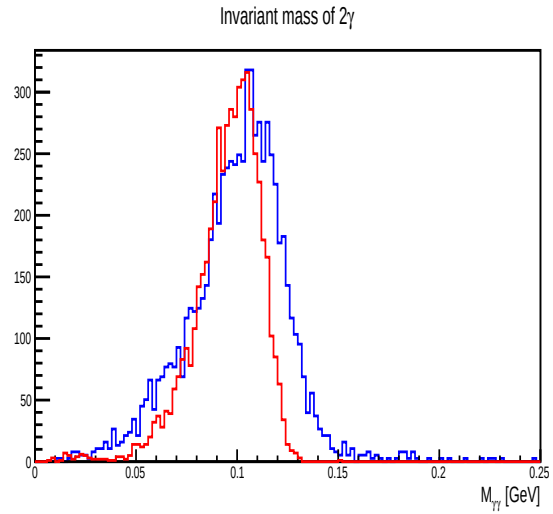
(Suguru & Keito)

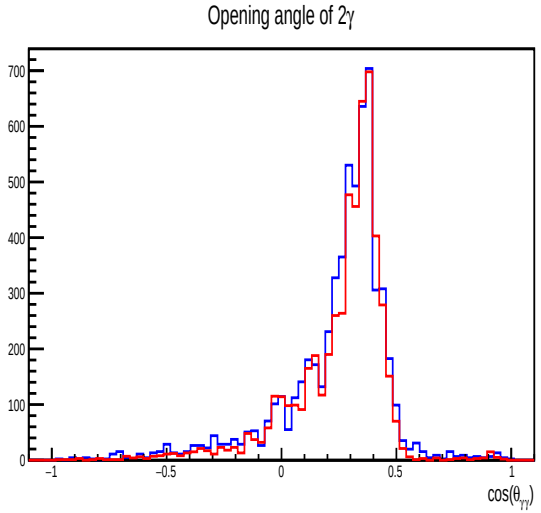
CsI Performance: $K_{\pi 2}$ ($K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$) Cluster Analysis

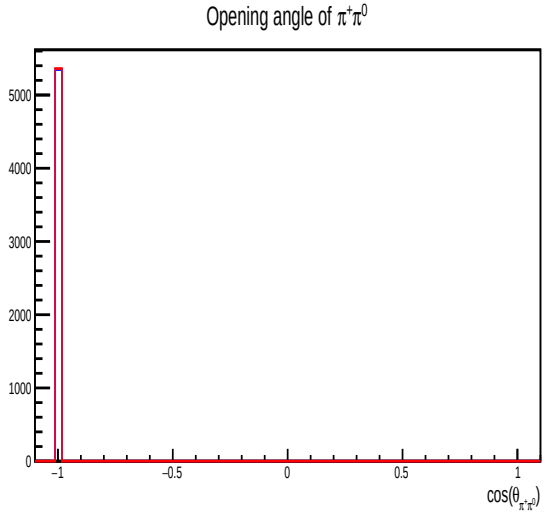










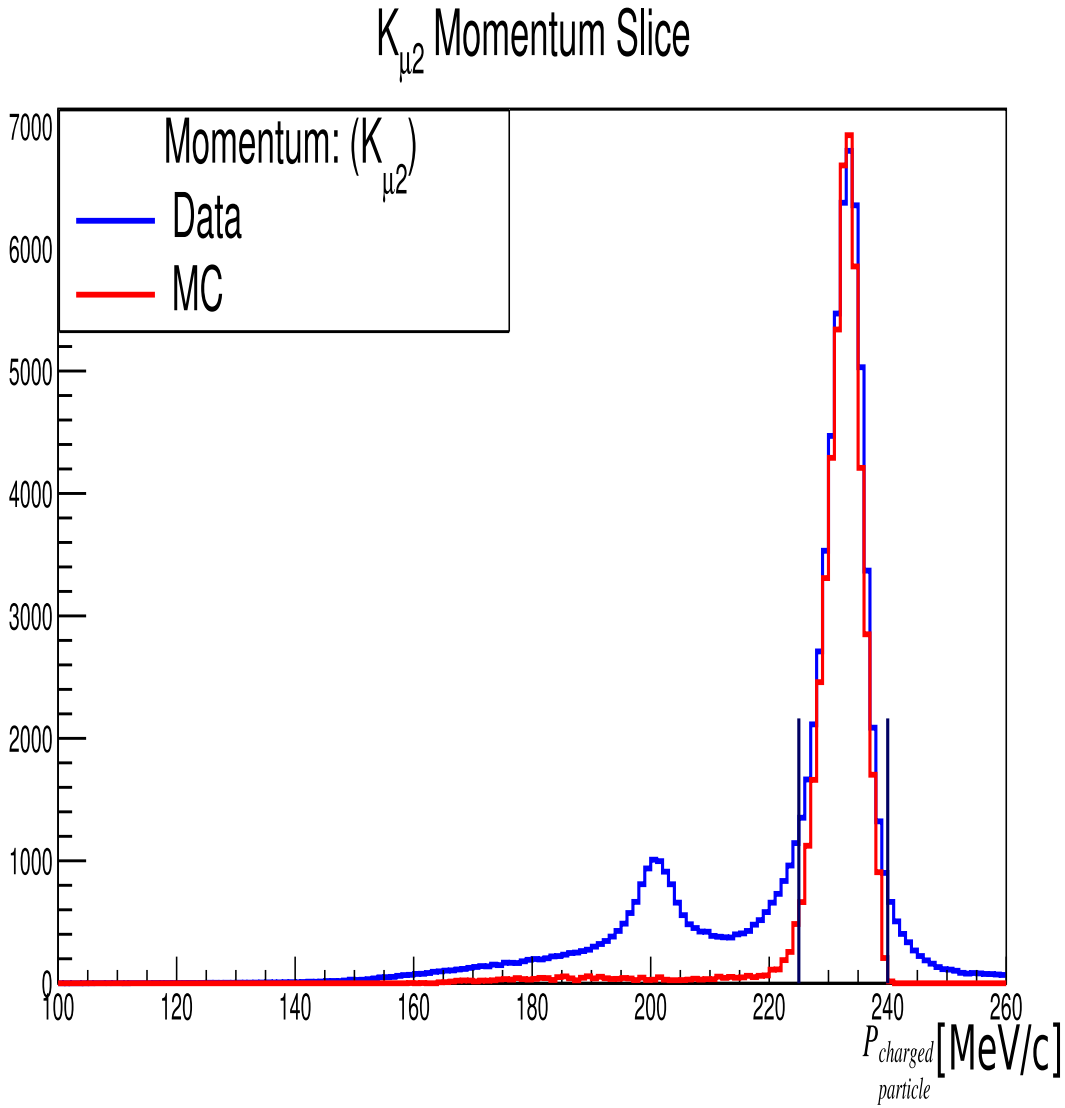


- Preselected $K_{\pi 2}$ events (from two CsI clusters)
- $cos(\theta_{\pi^+\pi^0}) \leq -.99$: tight opening angle cut

Number of Stopped K^+ (N_K)

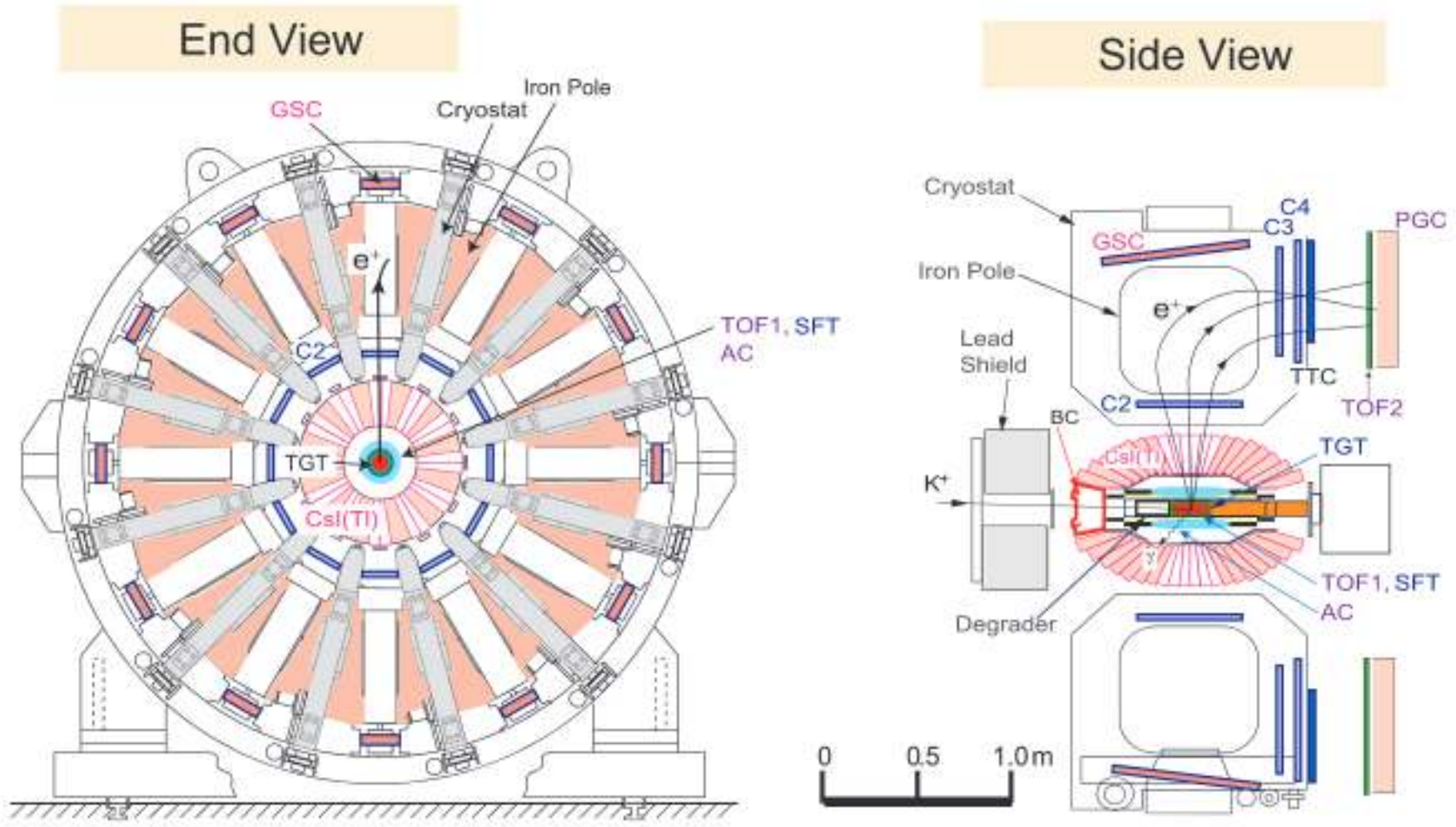
$$N_K = \frac{N_{\mu 2}}{\mathcal{B}r(\mu 2)PS(\mu)A_\mu LT(\mu)}$$
$$= 7.428 \cdot 10^9$$

- 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 livetime fraction
- $\mathcal{B}r(\mu 2)$: $K_{\mu 2}$ branching ratio
- Select 1 σ cut around mean P_μ, from $K_{\mu 2}$ decays



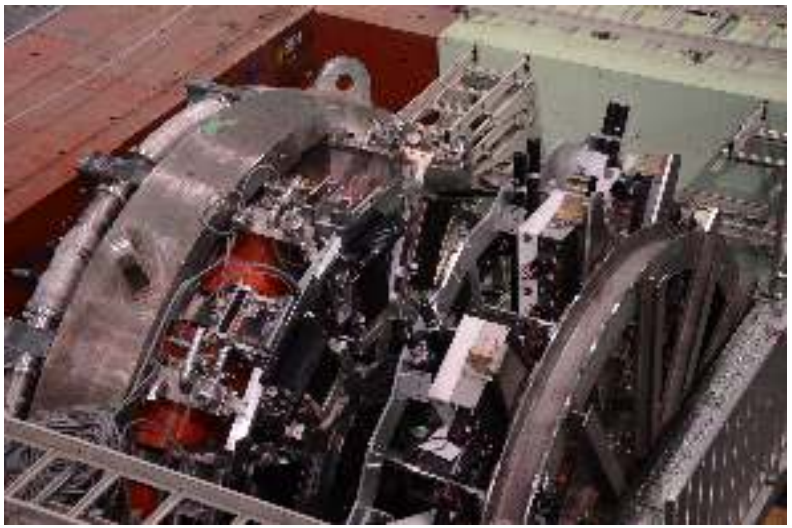
- **Vertex momentum of charged particle in the magnet gap**
- Clean momentum distribution

J-PARC TREK/E36 Detector Geometry

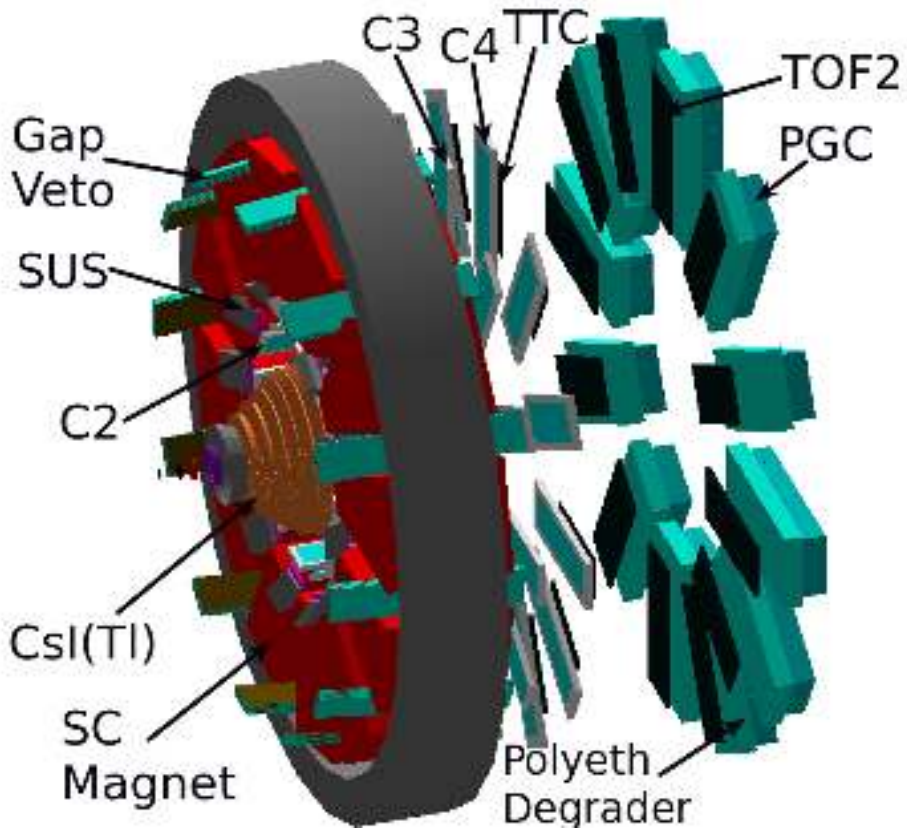


Stopped K^+ method	**Momentum measurement**	**Particle ID**	**Gamma ray**
K1.1BR beamline	MWPC (C2, C3, C4)	TOF	CsI(Tl)
K^+ stopping target	Spiral fiber tracker (SFT)	AC	
	Thin trigger counter (TTC)	PGC	

e36g4MC Geometry

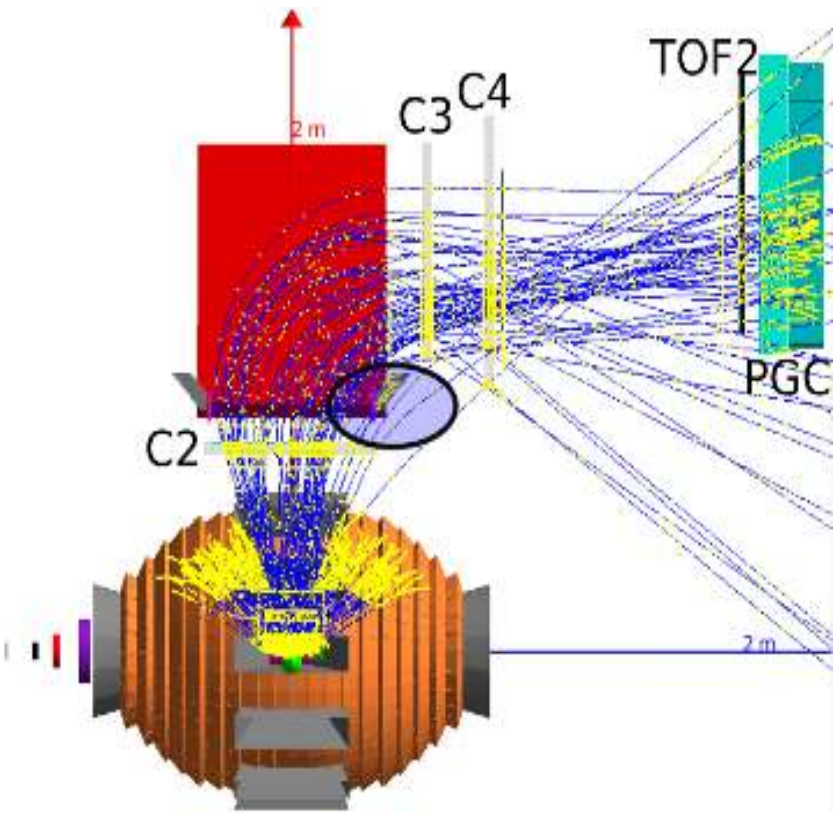


- Detector Assembly

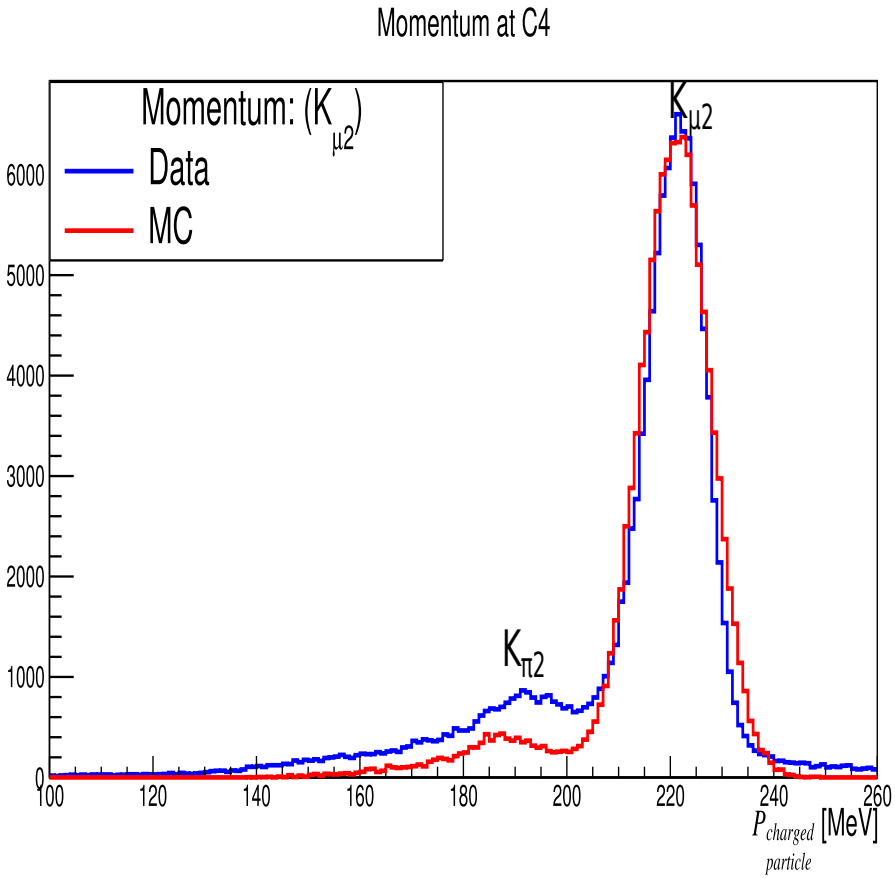


- Geant4 E36 detector

Tracking Package and The *e36g4MC* comparison



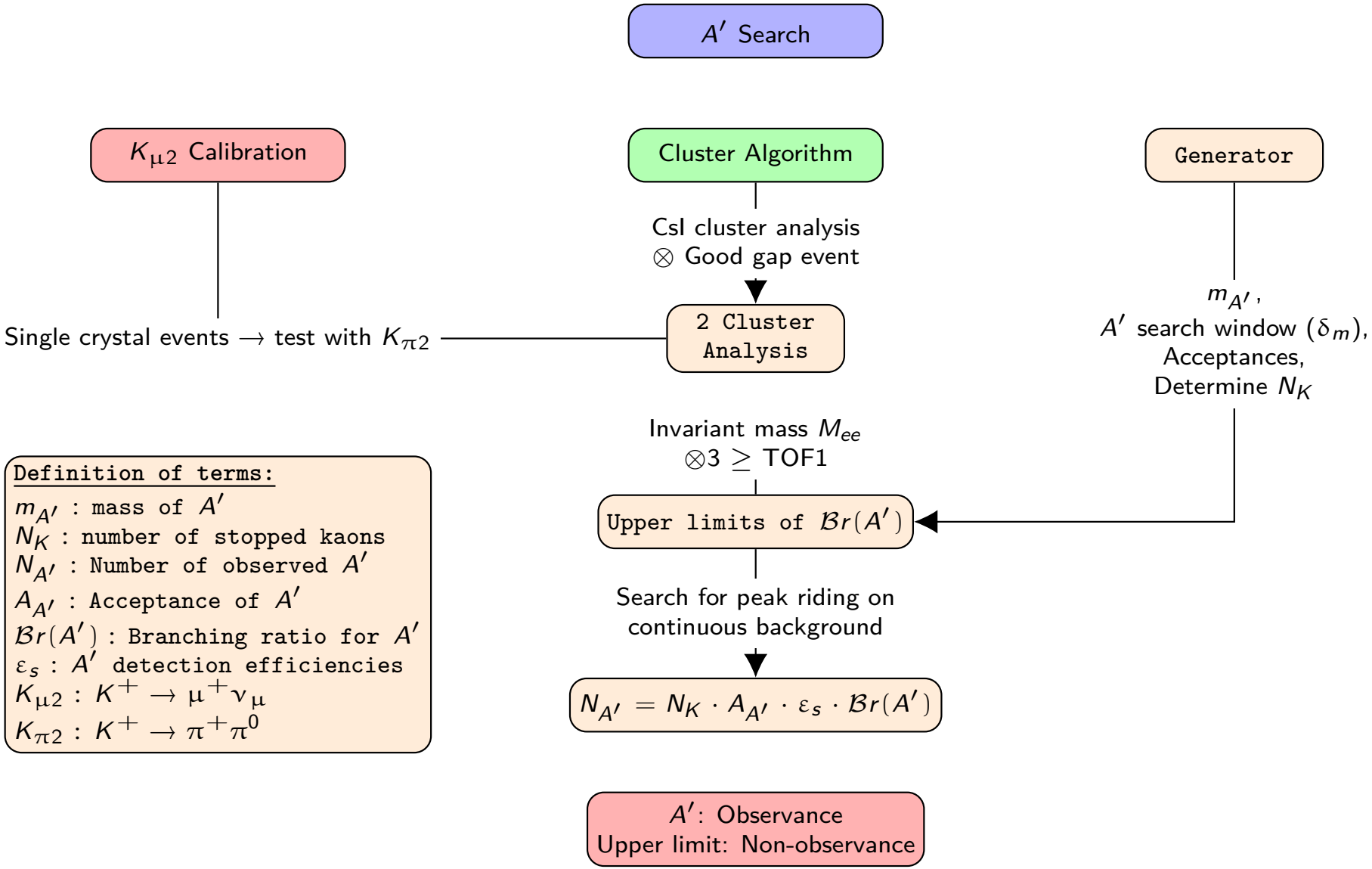
- Momentum distribution of $K_{\mu 2}$ and $K_{\pi 2}$ at C4
- E_{loss} and material budget well described
- Magnetic field integral is well described
- MC smeared with detector resolution



Terminology:

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

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