Updates from the Dark Matter Time Projection Chamber Group (DMTPC)

Cygnus 2013 Workshop on Directional Dark Matter Detection
Toyama, Japan
2013 June 10

James Battat (Wellesley College)
for the DMTPC collaboration

DMTPC Collaboration

Brandeis University

A. Dushkin, H. Wellenstein*

Bryn Mawr/Wellesley

T. Ananna, E. Barbosa de Souza, J. Battat*, **V. Gregoric**, **K. Recine,**, *L. Schaefer*

University of Hawaii

`I. Jaegle`, **S. Ross**, S. Vahsen*

MIT

H. Choi, **C. Deaconu**, P. Fisher*, **S. Henderson**, **W. Koch**, **J. Lopez**, `H. Tomita`

Royal Holloway (UK)

G. Druitt, **R. Eggleston**, **P. Giampa**, J. Monroe*

*=PI, `postdoc`, **grad student**, *undergrad*

Gallery of DMTPC Detectors

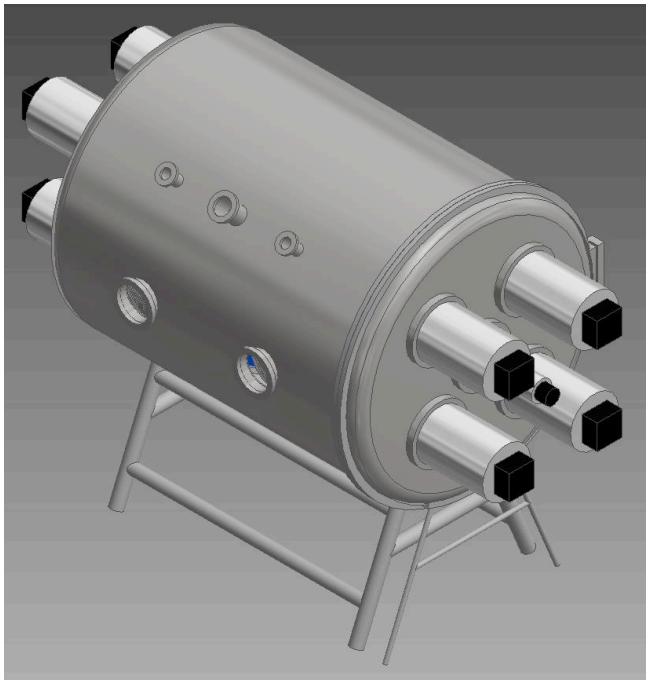
10L

Underground at WIPP

4Shooter (20L)

At MIT

DMTPCino (m^3)



Under development

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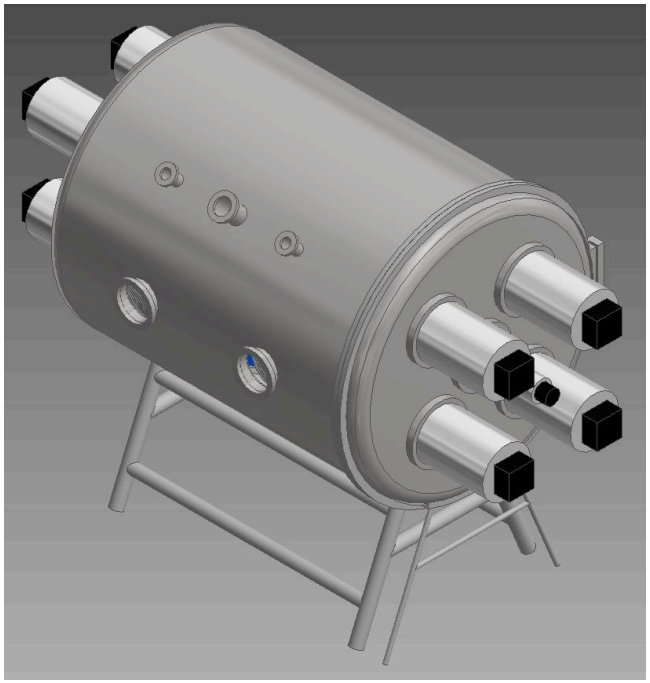
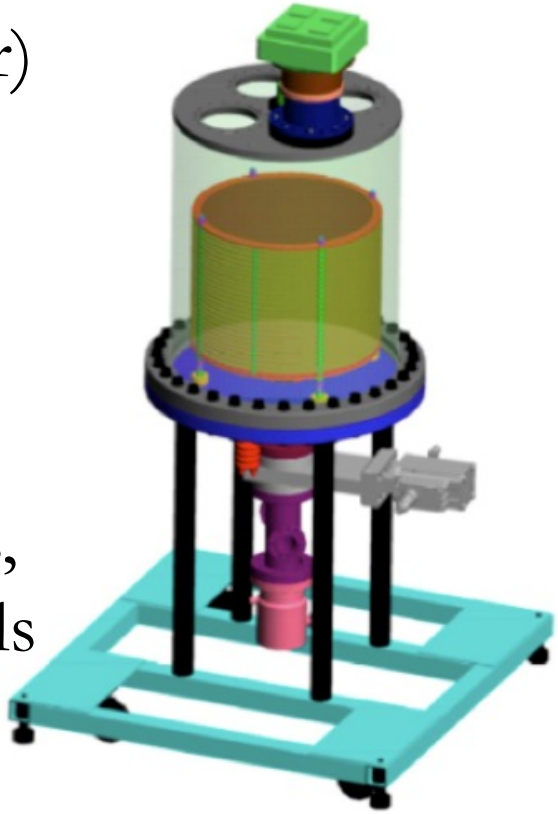
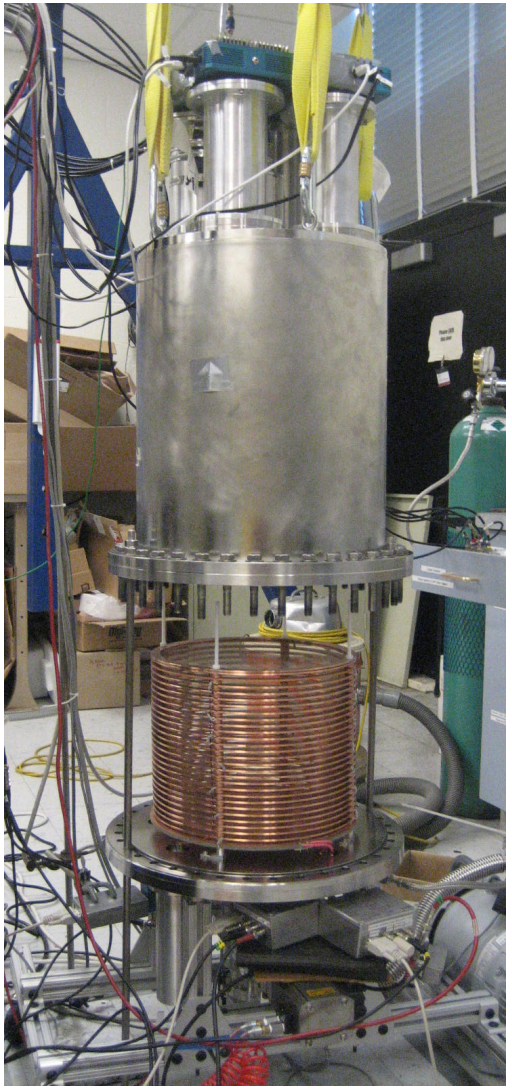


Under development

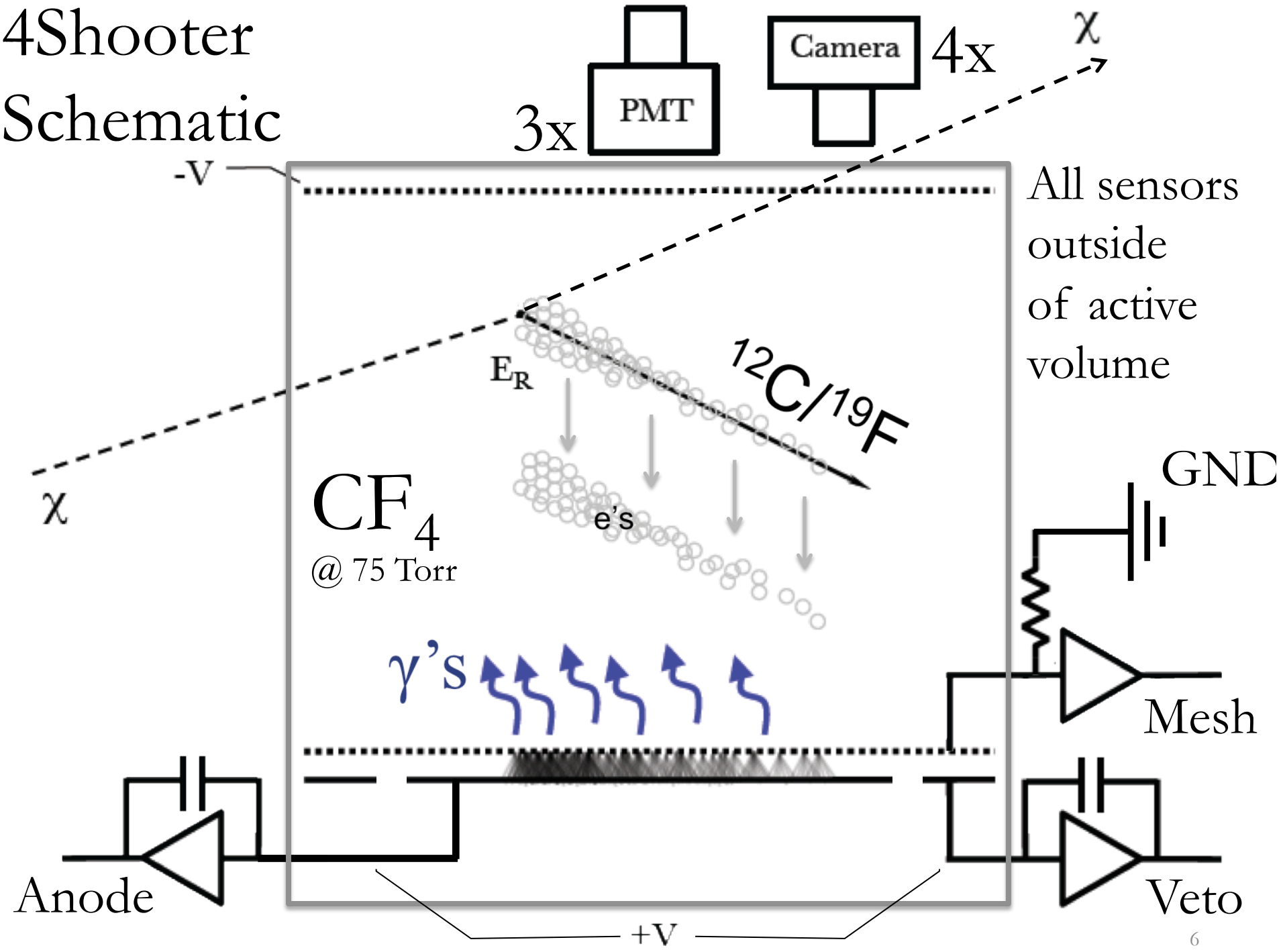
4Shooter Overview

- 20L (4.5g F)
- Higher vacuum (10^{-5} torr) between fills
- Material selection (OFHC copper, acetal, stainless steel, G-10)
- 4 CCD cameras, 3 PMTs, 3 charge readout channels



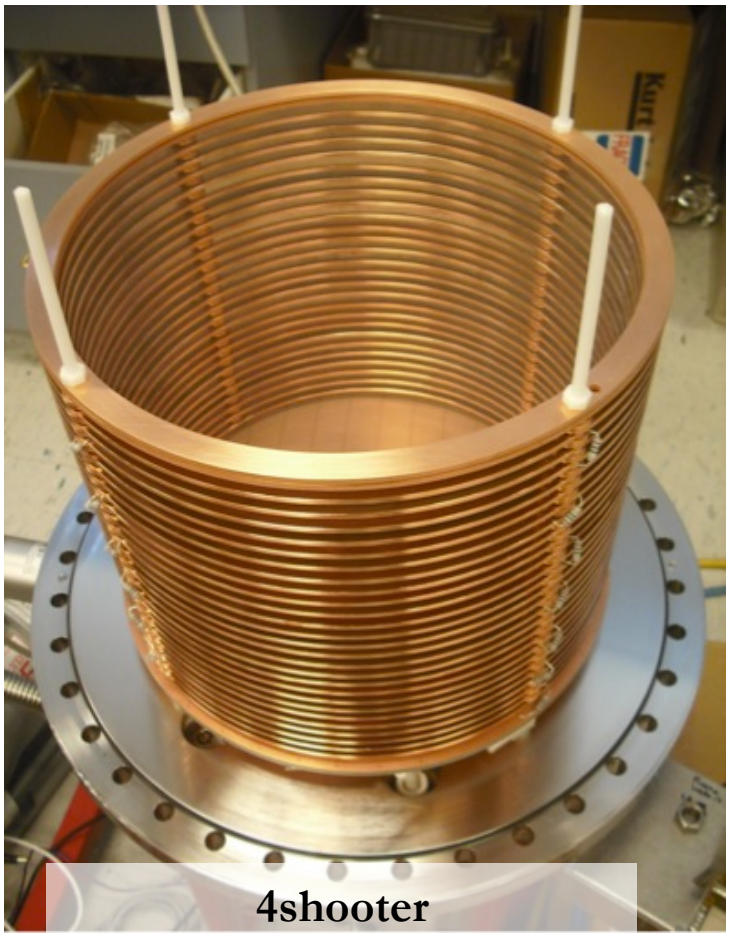


4Shooter Schematic



4Shooter Construction

Improved Field Cage (spacers), and amplification region fabrication scheme → More gain, lower spark rate. Repeatable amplification region construction technique in a clean-room environment.



4shooter

vs.

10L

Lower alpha background rate & better tagging capability

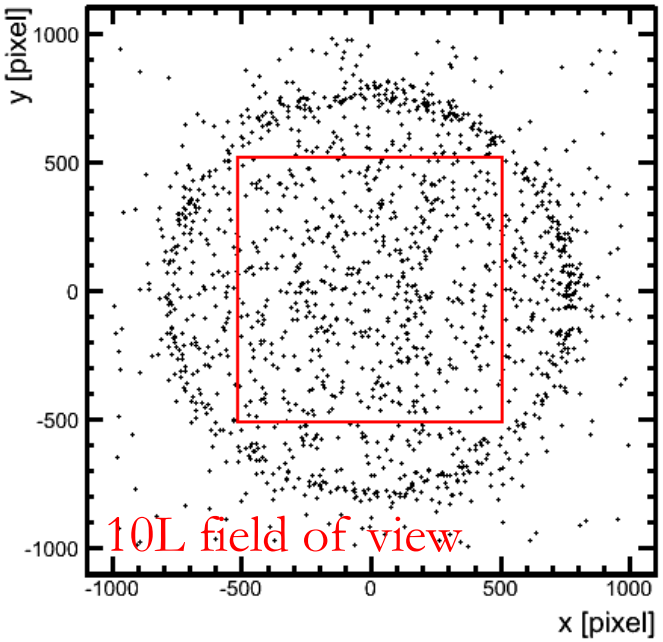
Raw α rate is 19x lower

10L 210 mHz

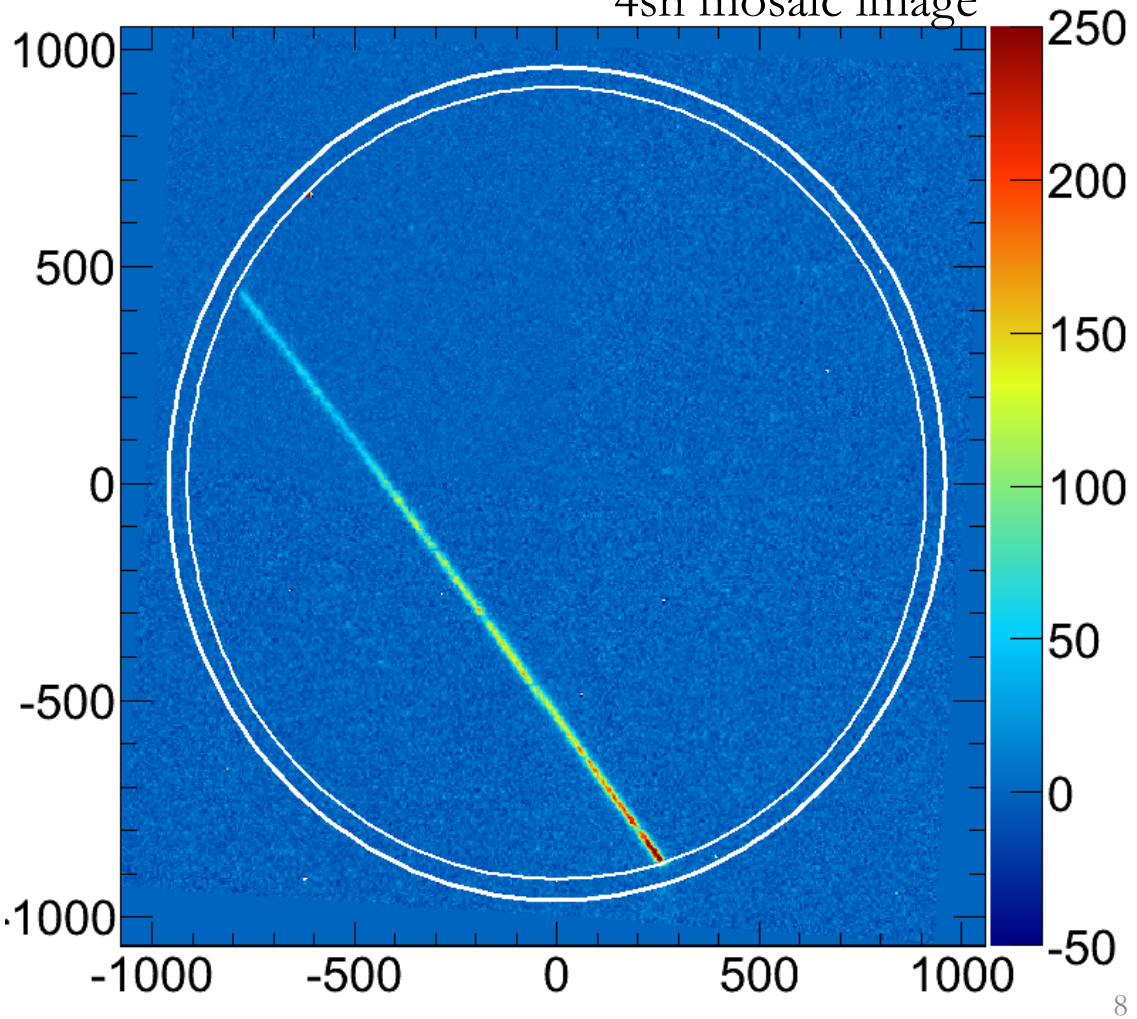
4sh 11 mHz

And 4sh field cage has 3x more internal surface area

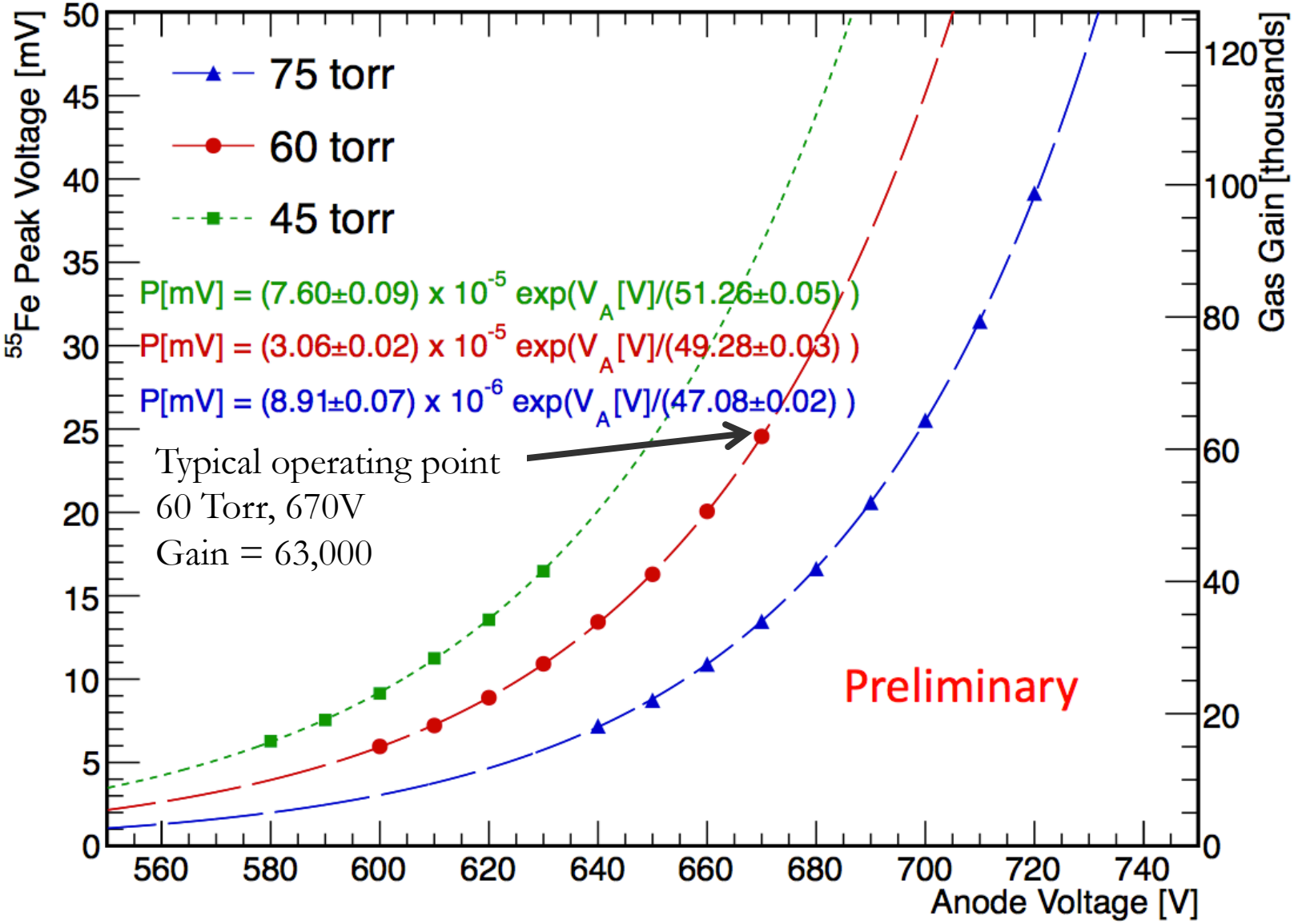
10L: inferred alpha start points



4sh mosaic image

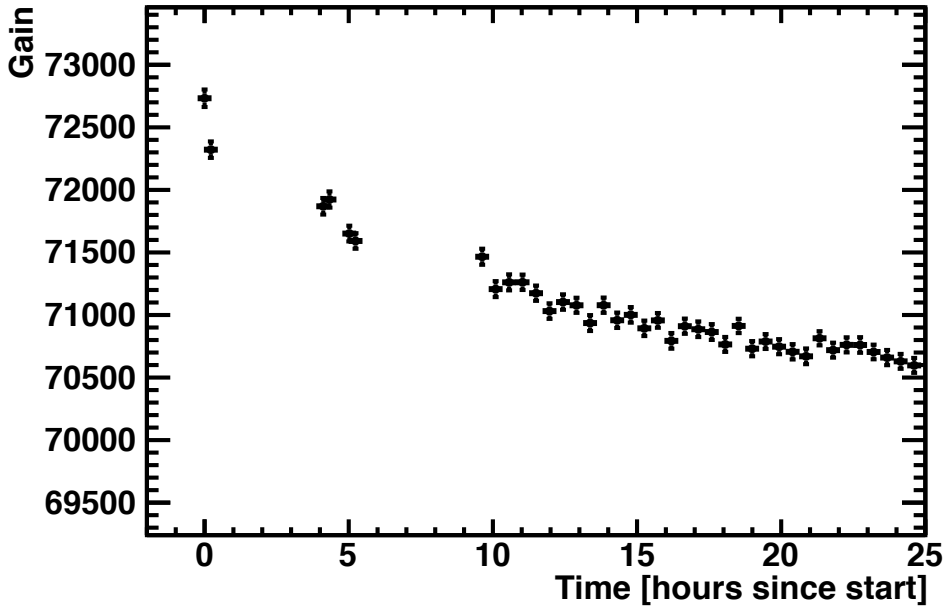


4sh gas gain measurements

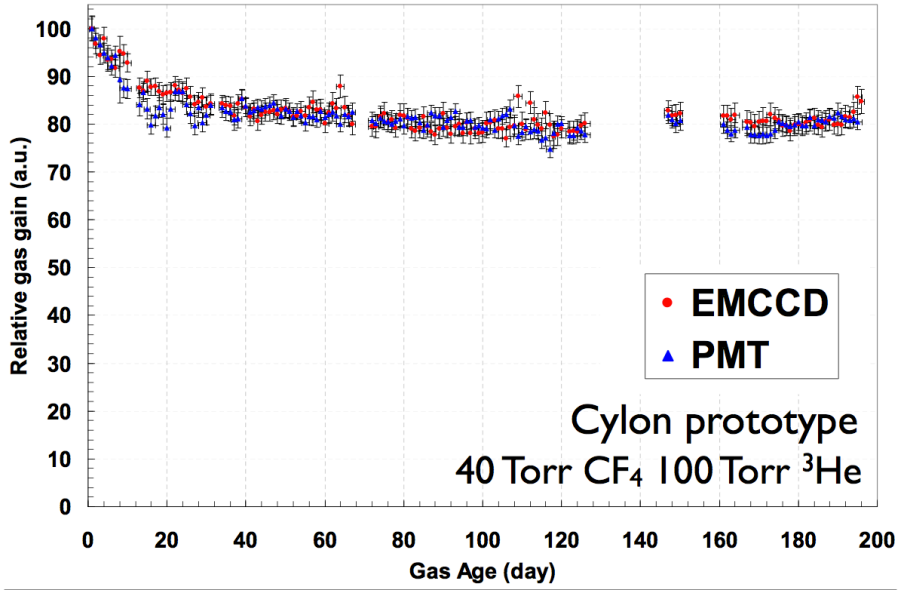


Lesson 1: gain degradation vs. time

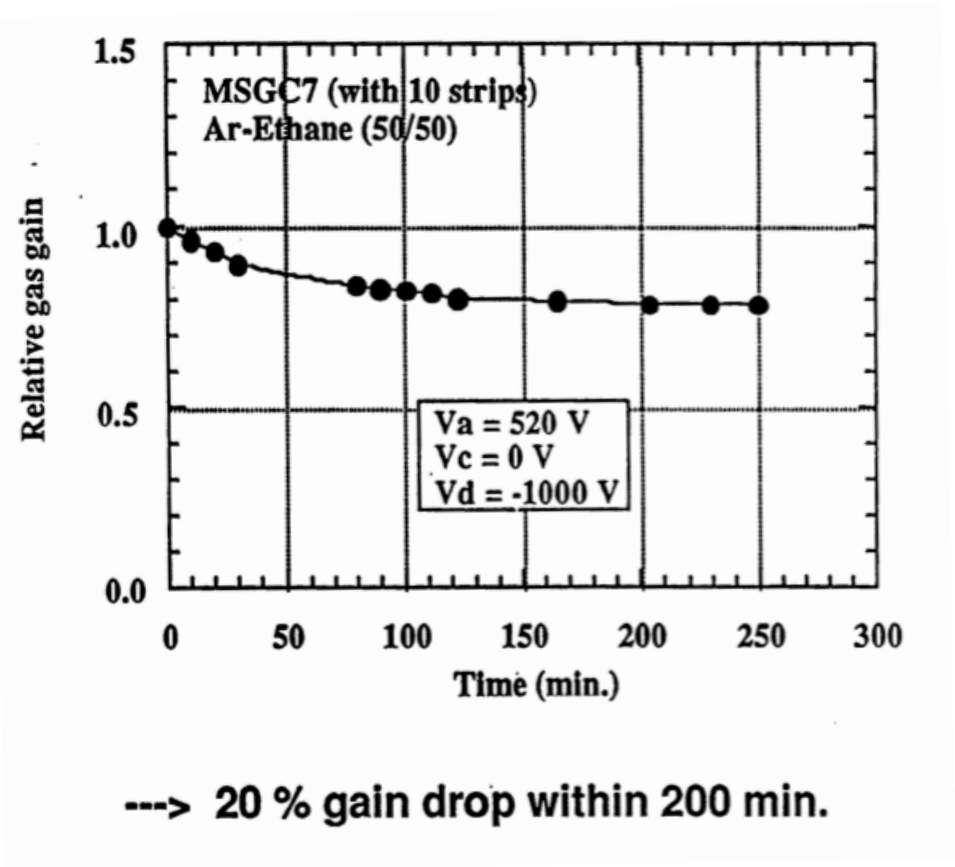
4sh over 1 day (~3% drop)



Cylon over 200 days
(20% drop then stable)



Gain degradation over time is well-known

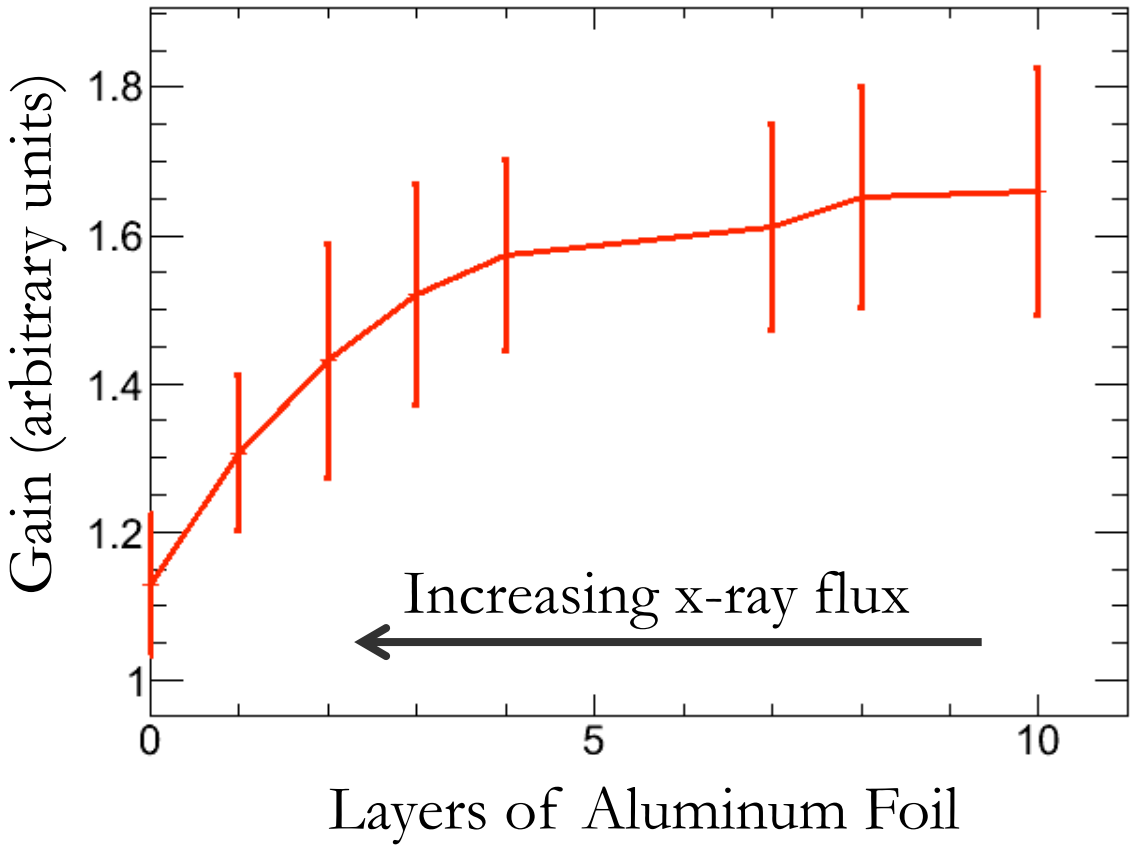


Initial gain decay is well-known and seen in many detectors. For example:

Kadyk 1998 (SLAC Detector Techniques Lectures)
http://www-group.slac.stanford.edu/sluo/lectures/Detector-Lectures.html

Lesson 2: gain decreases with x-ray flux

Likely due to space-charge in amplification region



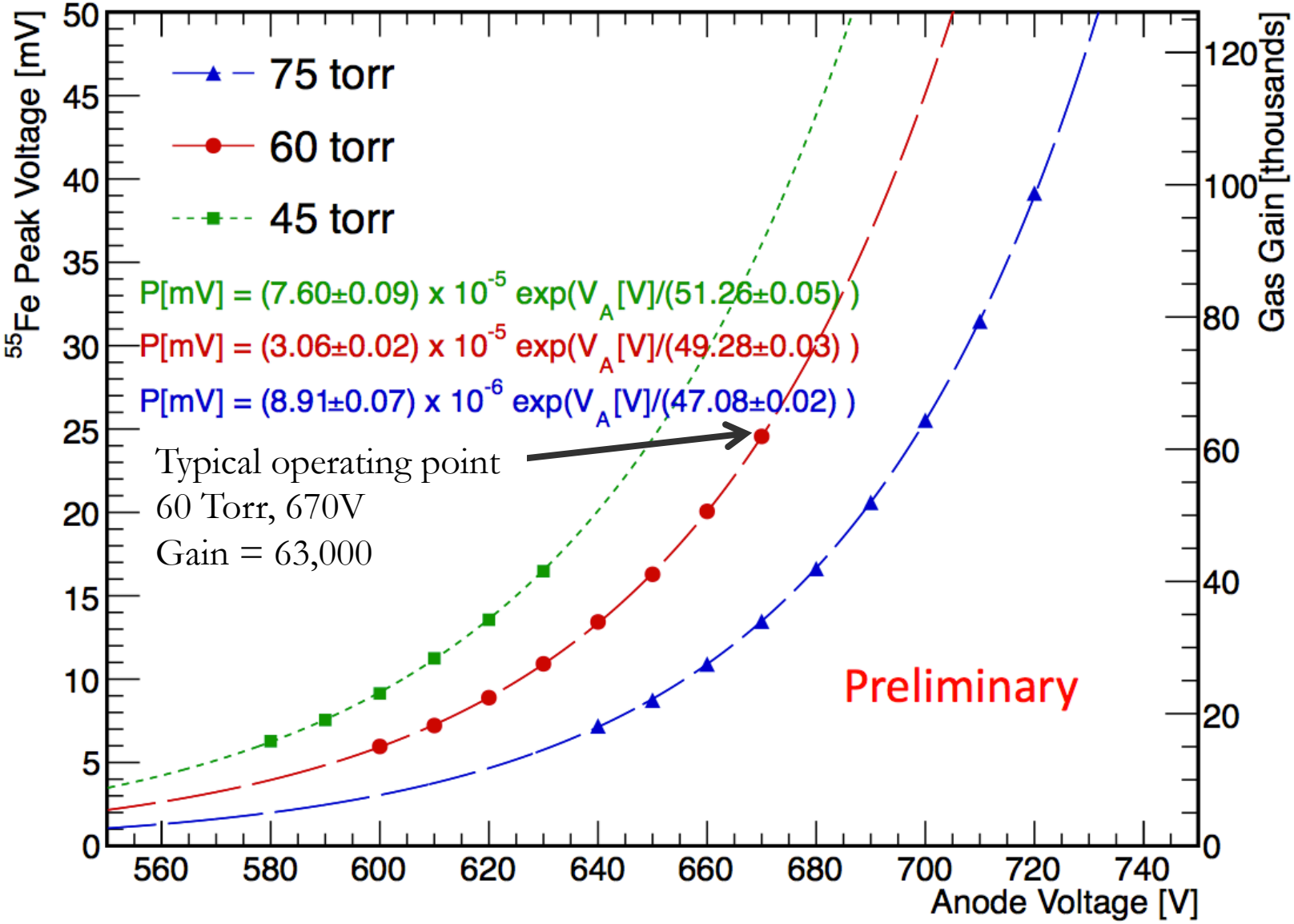
Calibration with a strong source can underestimate the gas gain by ~30%.

High rate behavior and discharge limits in micro-pattern detectors

A. Bressan[a], M. Hoch[a], P. Pagano[a], L. Ropelewski[a], F. Sauli[a,*], S. Biagi[b], A. Buzulutskov[c], M. Gruwé[d], G. De Lentdecker[e], D. Moermann[f], A. Sharma[g]

Nuclear Instruments and Methods in Physics Research A 424 (1999) 321–342

Gain limited by streamer discharges



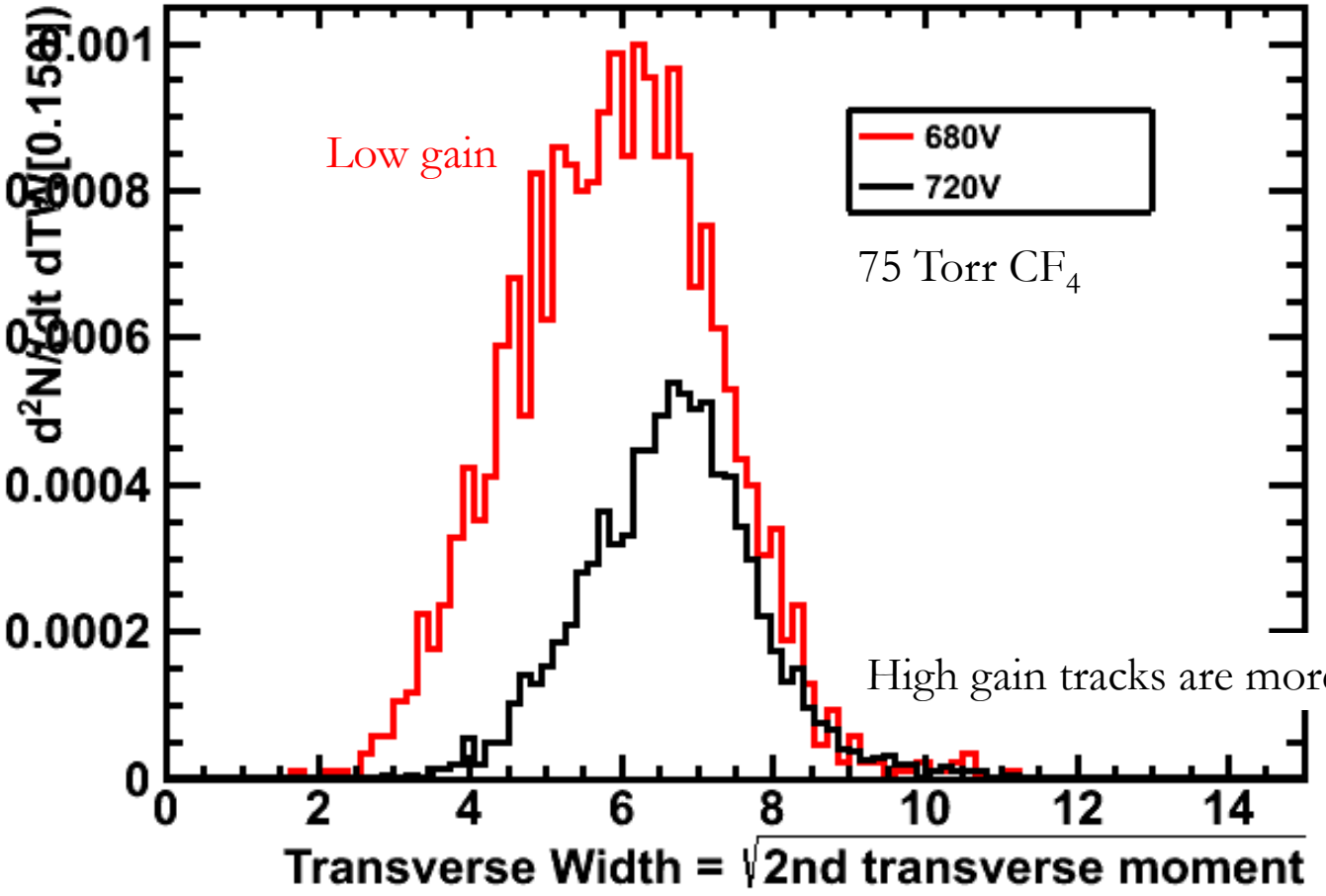
Sparking and Raether limit

- "Raether's criterion: a spontaneous transition from avalanche to streamer, followed by a discharge, when the avalanche size reaches a value of a few 10^7."

- "In multiple structures, where the gain is shared between two devices in cascade, the maximum overall gain under irradiation is increased by at least one order of magnitude; we speculate this to be a consequence of a voltage dependence of Raether's limit, larger for low operating potentials."

A. Bressan et al., Nuclear Instruments and Methods in Physics Research A 424 (1999) 321—342

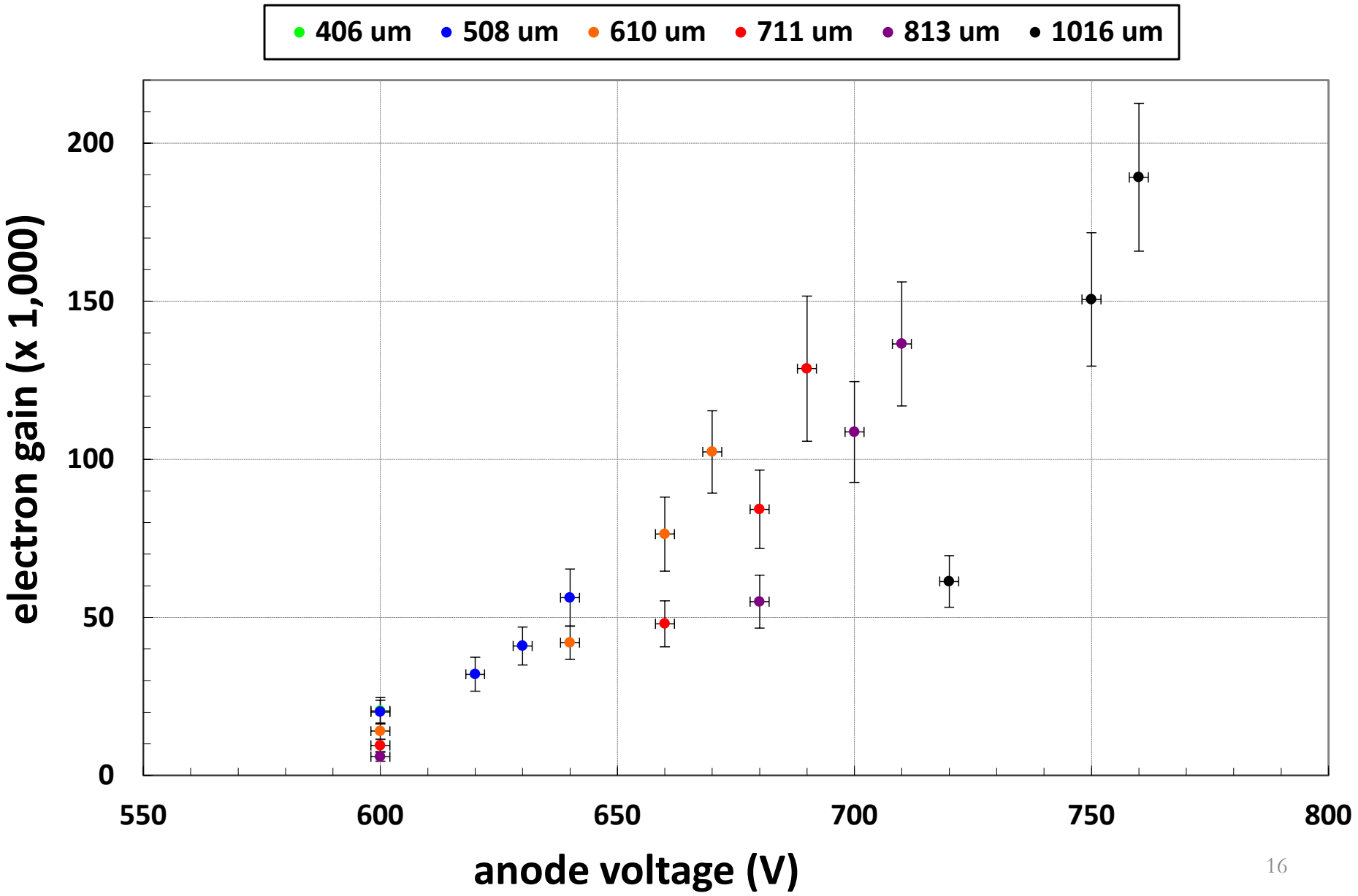
Lesson 3: Recoils can trigger sparks



High gain tracks are more diffuse (long drift)

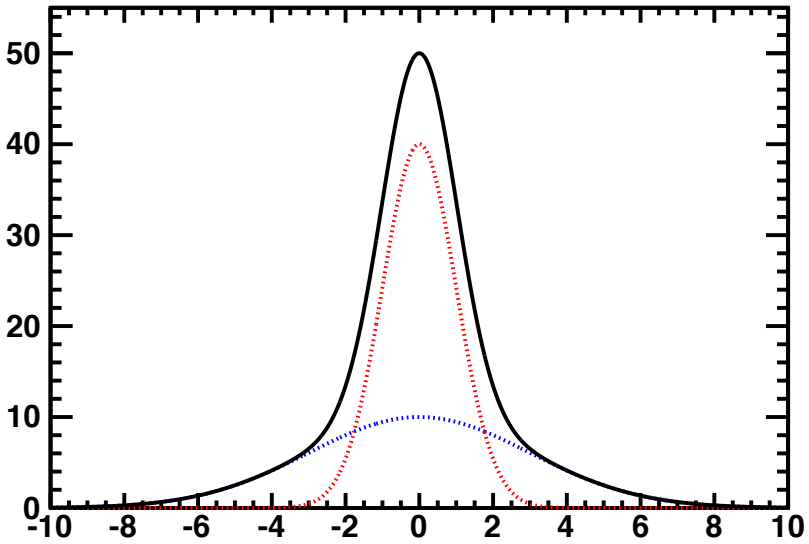
If electron density is too high, the avalanche becomes a streamer, rendering the detector insensitive. In practice, compact (low-drift) tracks preferentially generate streamers/sparks. The lower part of the TPC is not "active" anymore! Also this can lead to an angular dependence as well (vertical tracks lead to sparks)

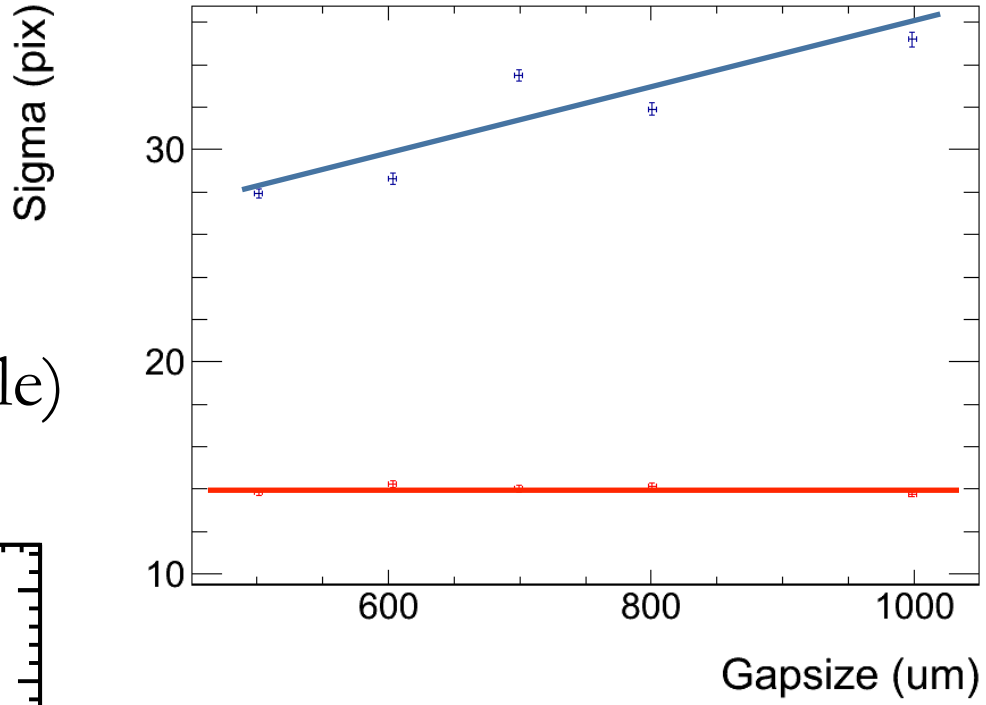
Electron Gain in the amplification region measured with ^{241}Am α tracks in 40 torr CF_4 gas



Diffusion vs. amplification gap size

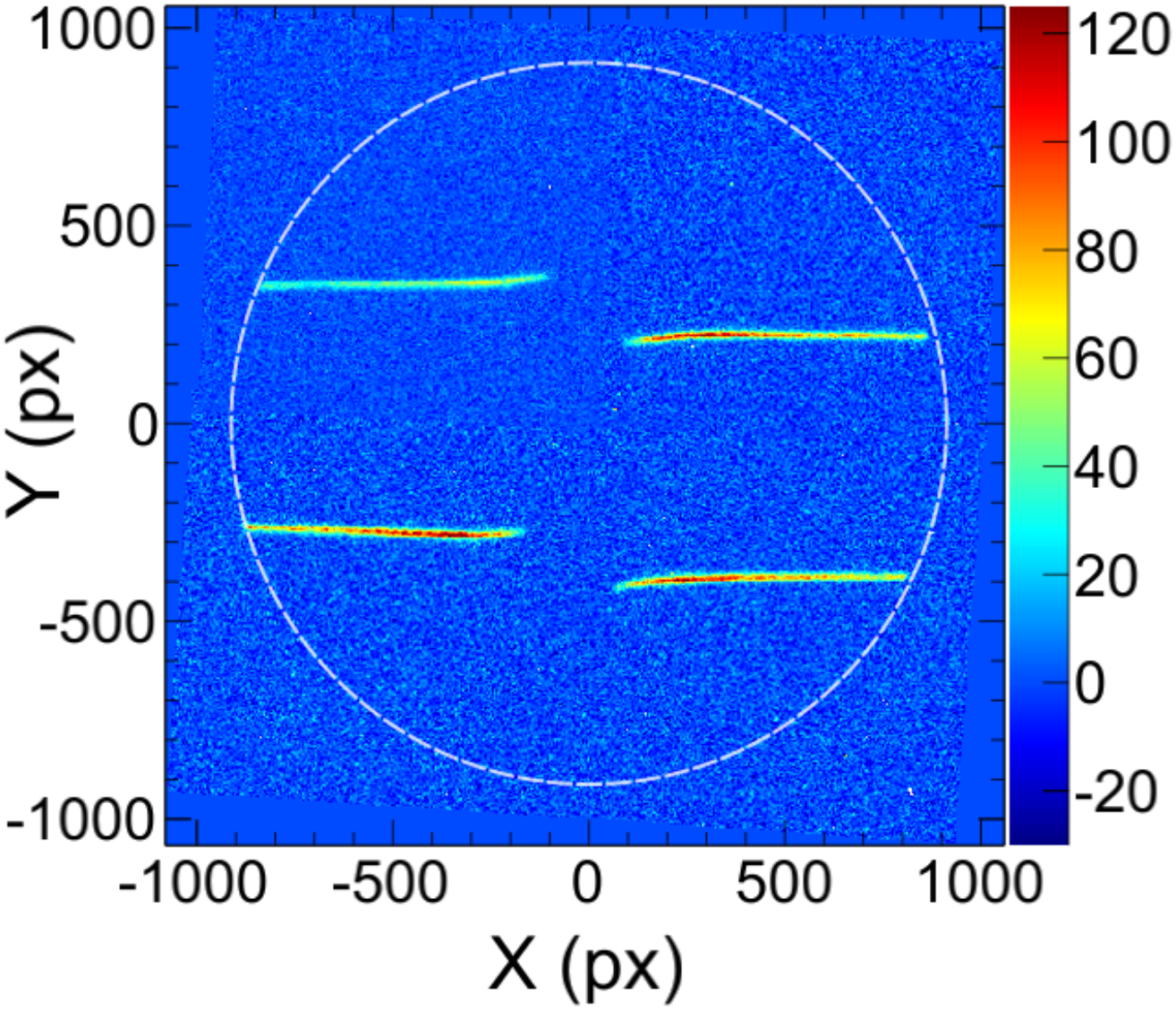
Projected alpha tracks
well fit by double (not single) gaussian





As gap doubles, the core is unchanged, but wings widen by 25%.

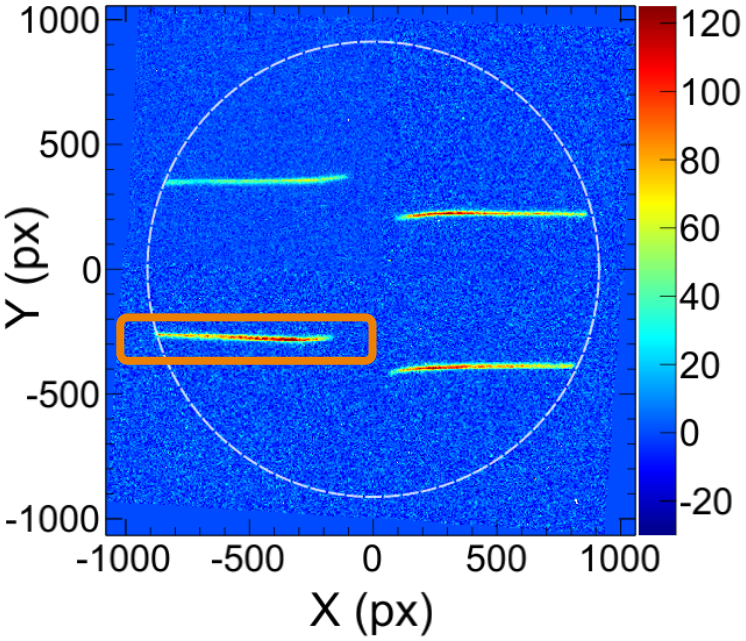
CCD Energy Calibration



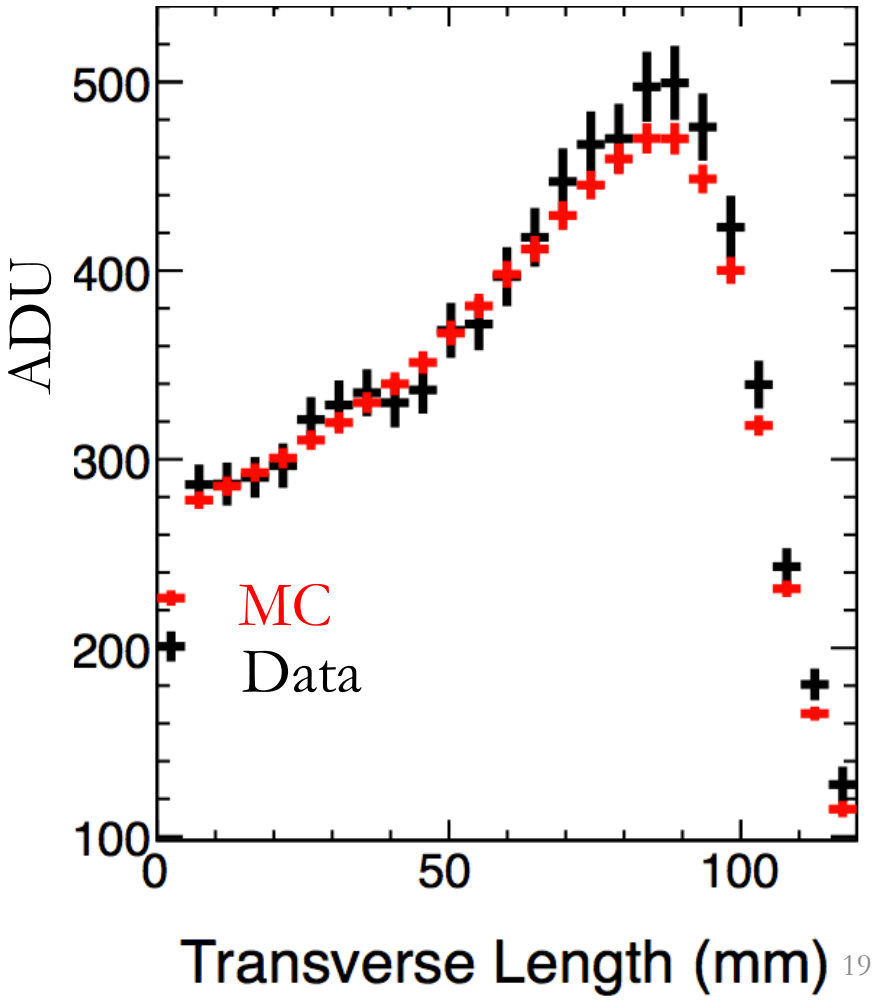
One ^{241}Am for each camera.

Side question:
do ^{241}Am x-rays degrade the gain?
(59 keV from ^{241}Am, plus 14, 17, 21 keV lines from ^{237}Np)

CCD Energy Calibration



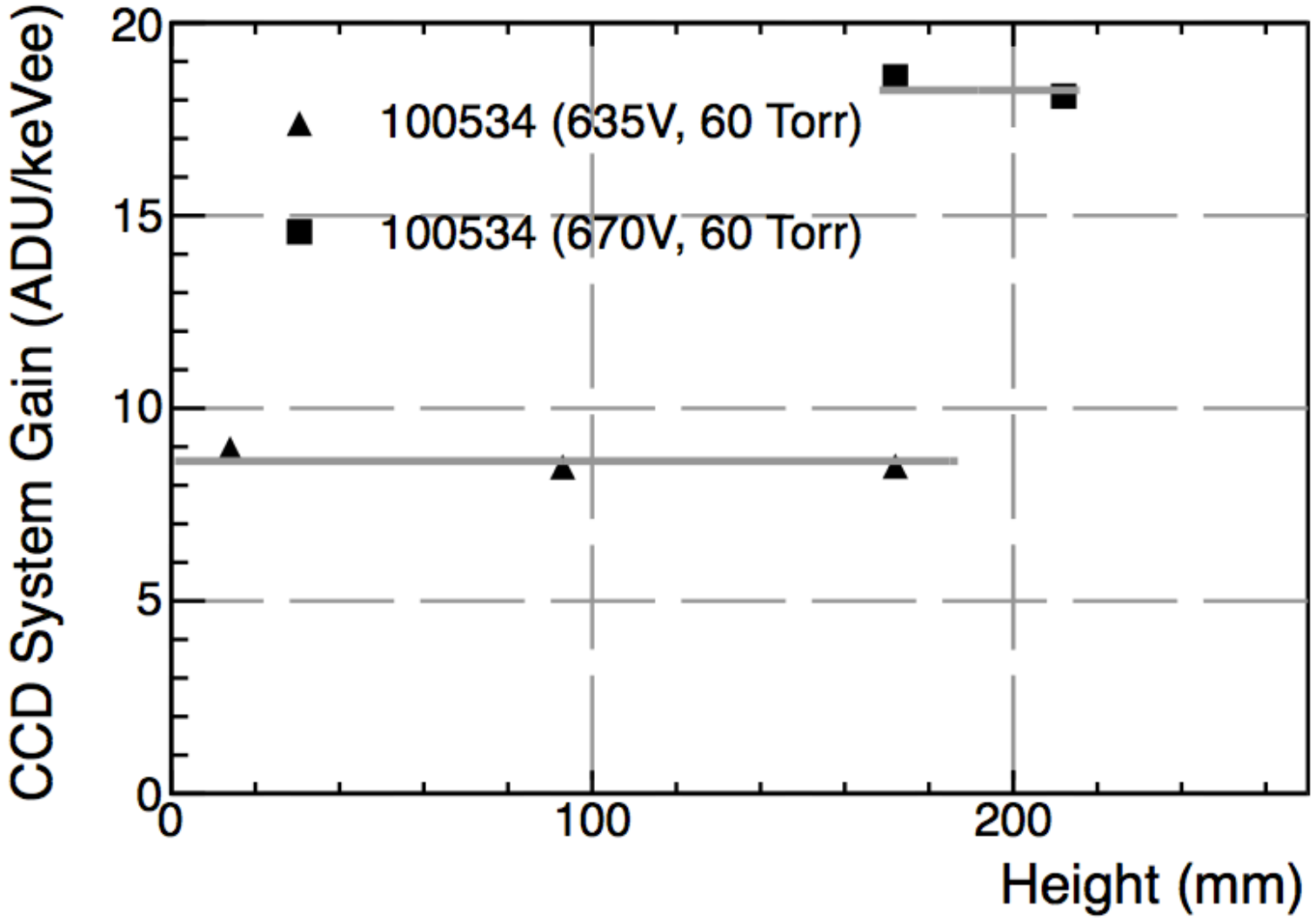
Average of projections for many tracks (single camera)



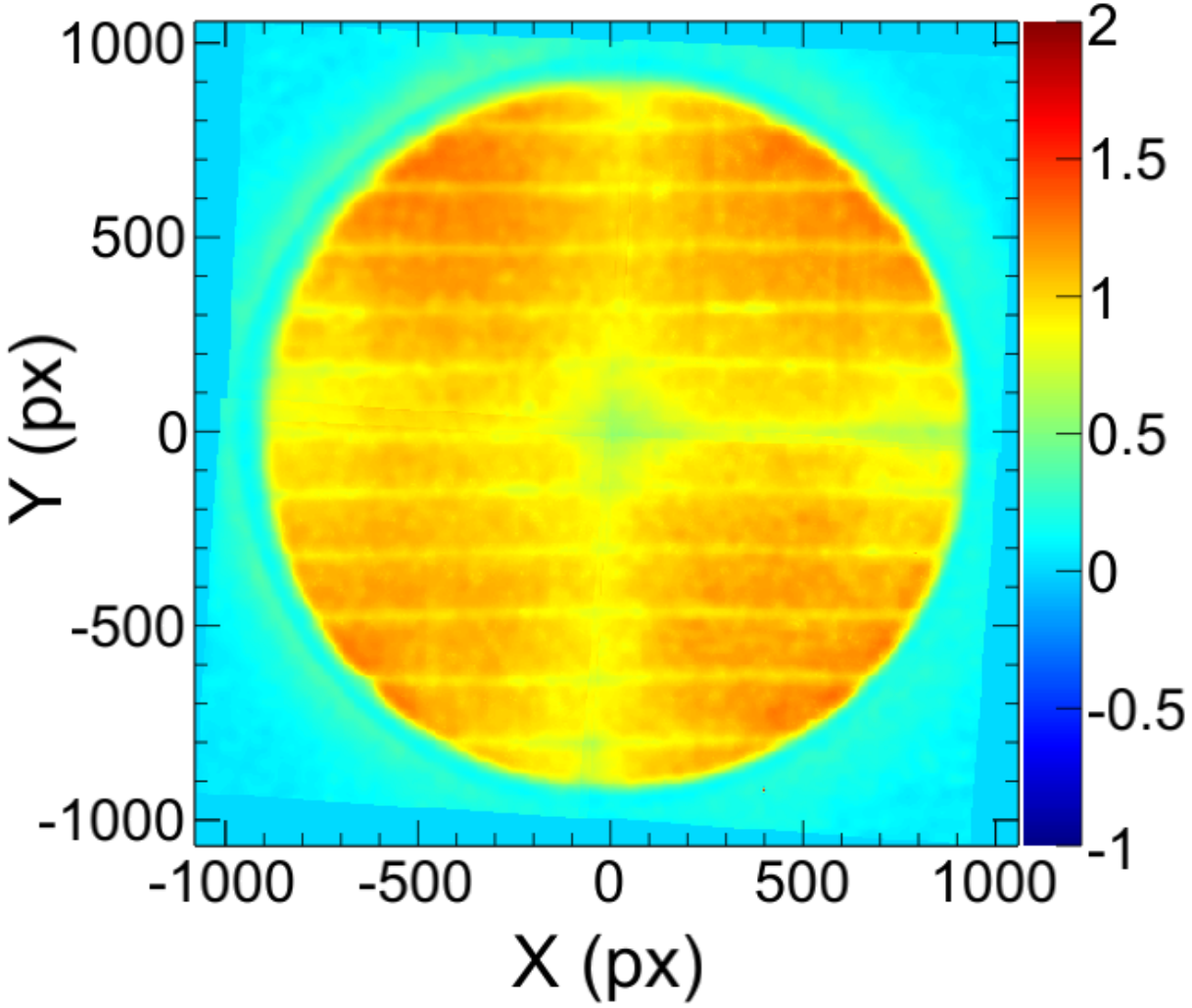
Tune electron diffusion and "gain" (ADU/keVee) until MC matches data (for transverse and longitudinal projections).

CCD Energy Calibration

As expected, the energy calibration depends on amplification region voltage (gas gain), but not on alpha source height (diffusion)



Spatial variation in detector response

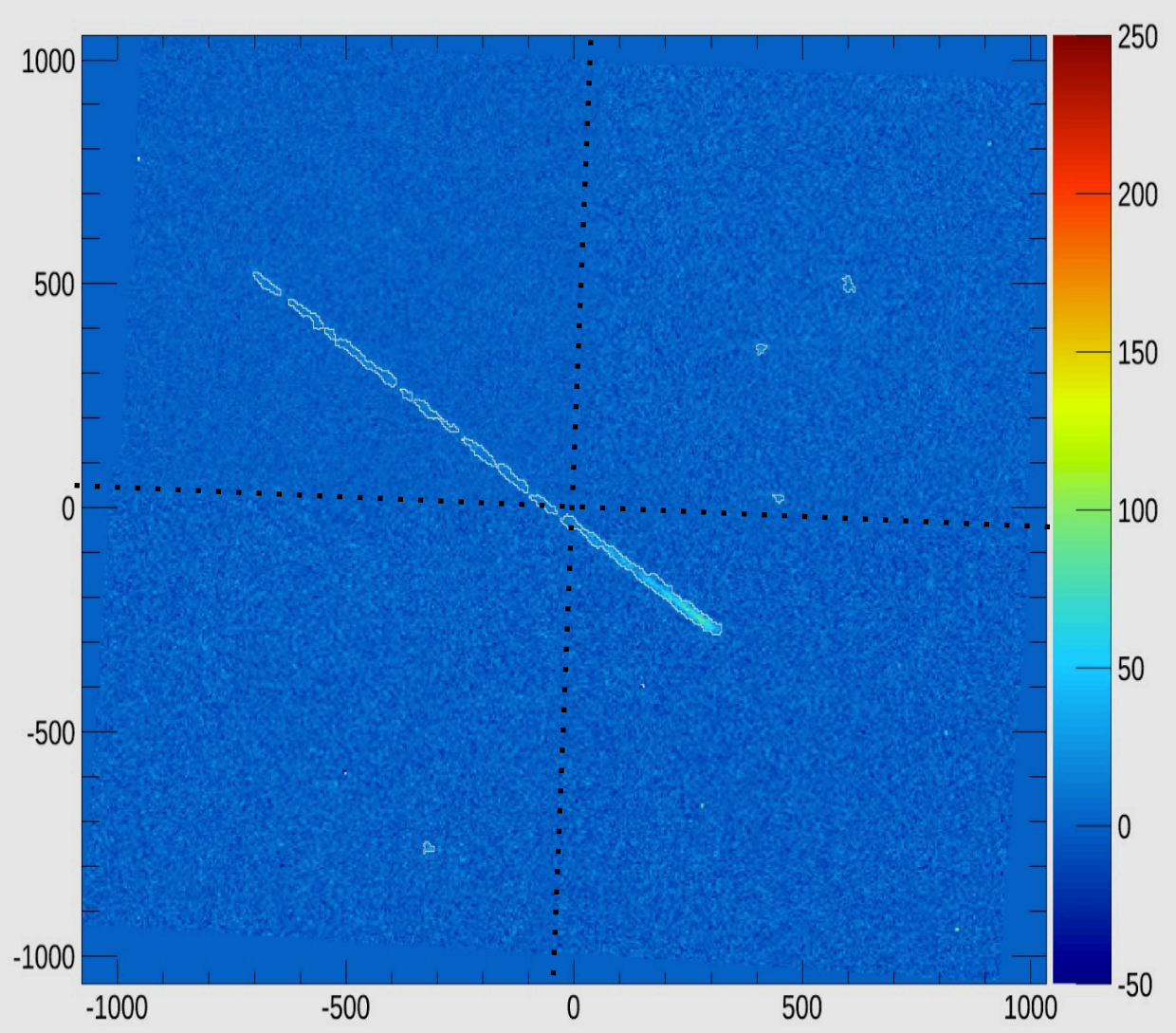


^{57}Co 122 keV γ
MFP = 4 m

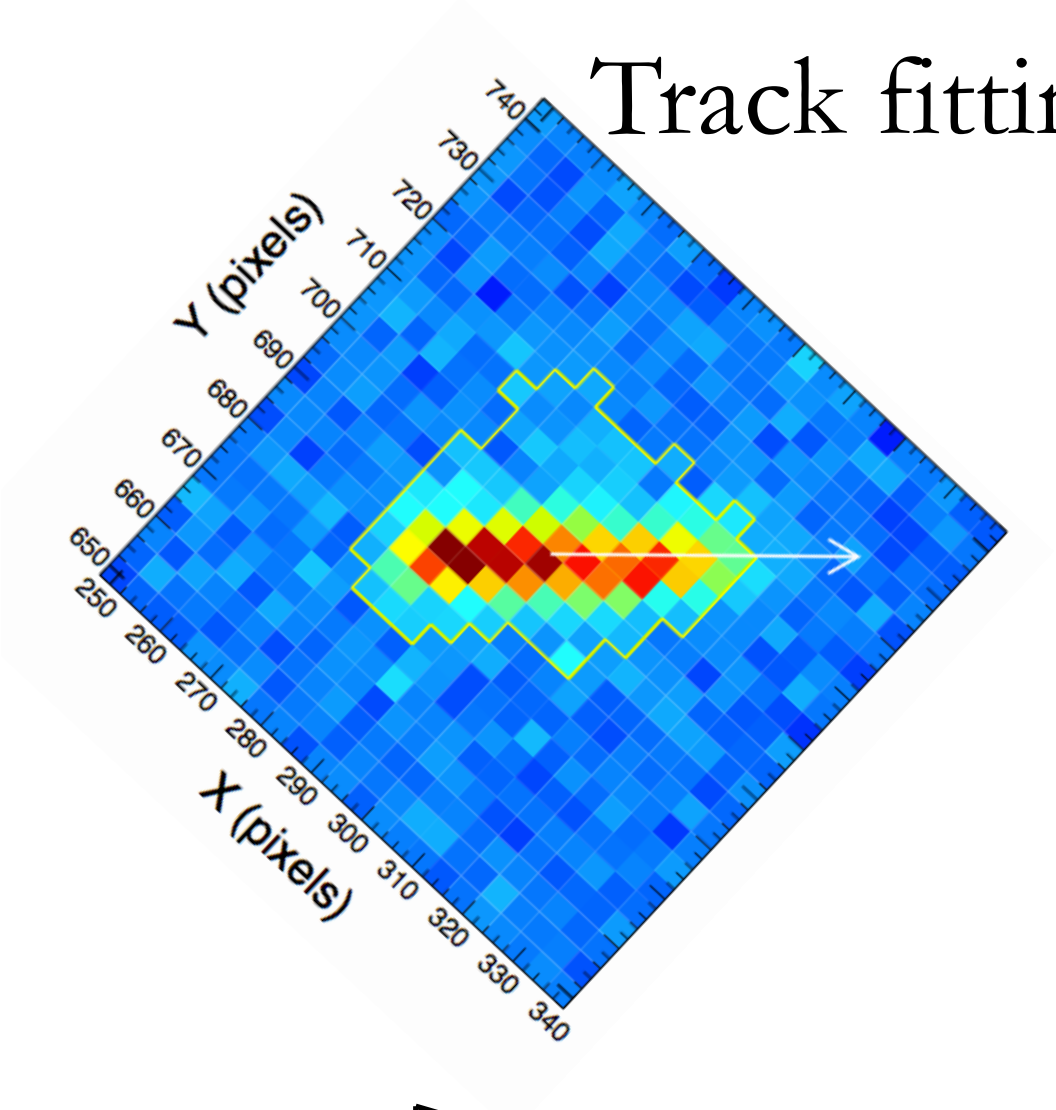
Each of the 4 cameras has a smooth rotational symmetry to the gain pattern.

The amplification region (especially the spacers) shows higher-frequency variations

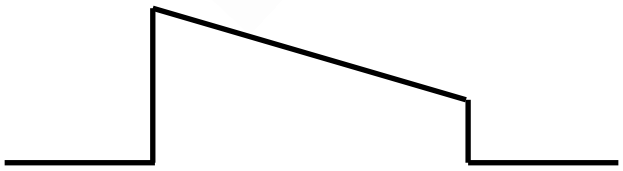
Track reconstruction in mosaic image



Track fitting with confidence

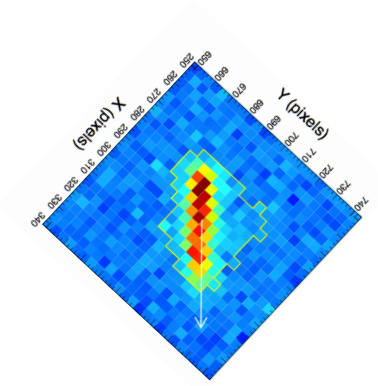


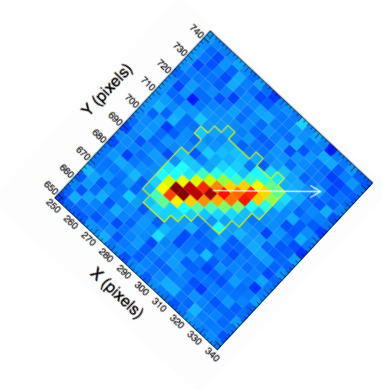
Make use of the known profile of a NR (from the Bragg curve) to
(1) fit for the Head/Tail and
(2) assign a confidence in the H/T determination

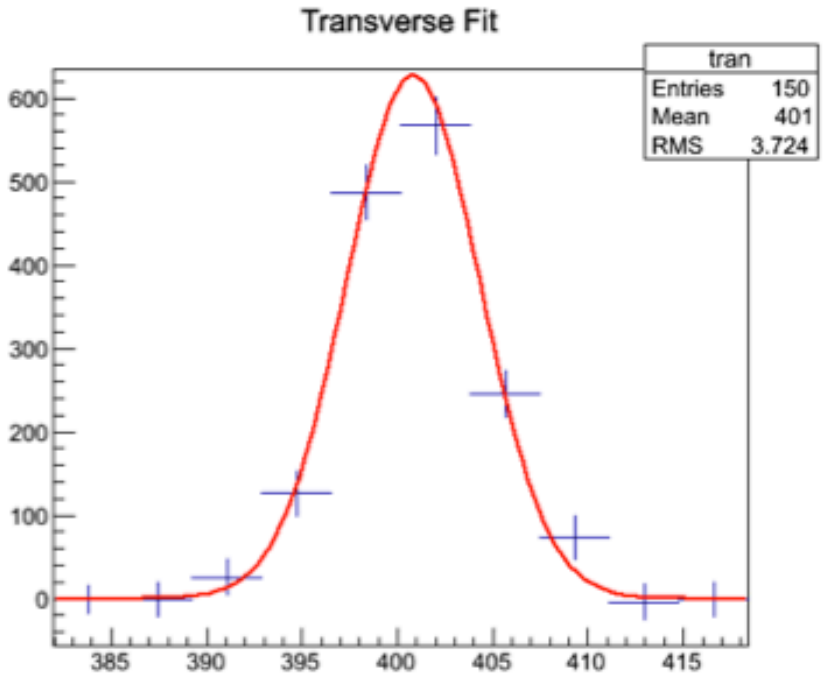


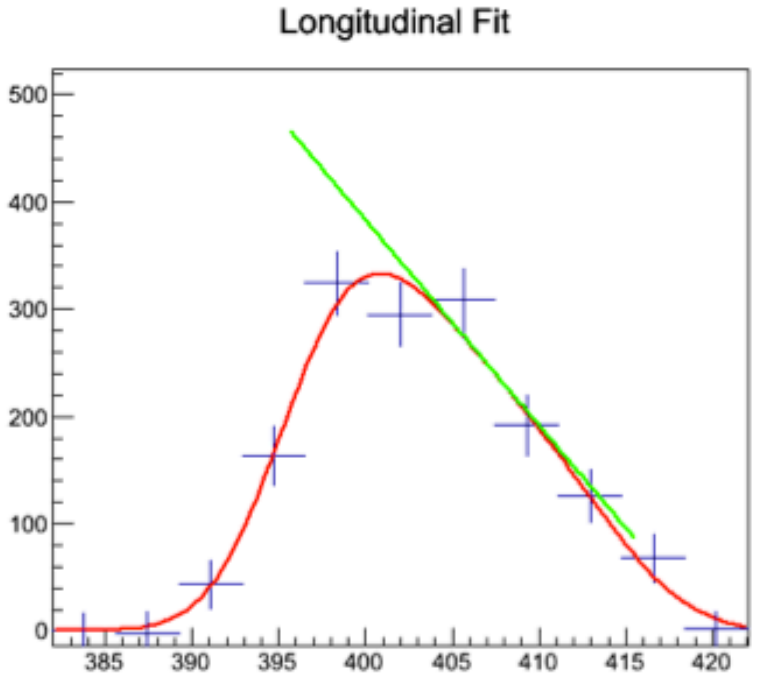
convolved with gaussian

Track fitting with confidence



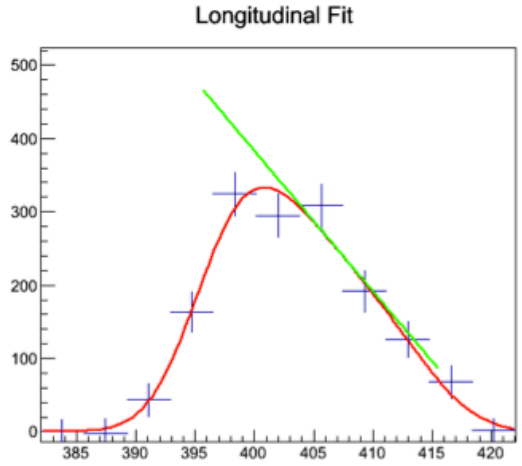






(CCD image is just to illustrate point)

Track fitting with confidence



χ^2/ndof : 4.352148/10 = 0.435215

x0: 395.668893 +/-0.625993 (-0.664133,0.598328)

y0: 466.210150 +/-51.341684 (-56.980963,46.037852)

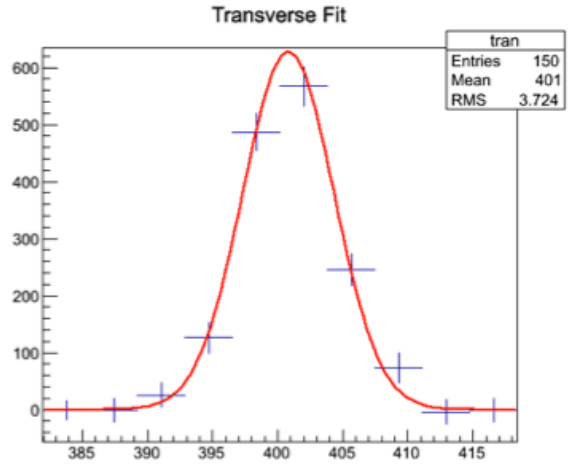
y1: 85.021626 +/-103.864438 (-64.085506,99.278767)

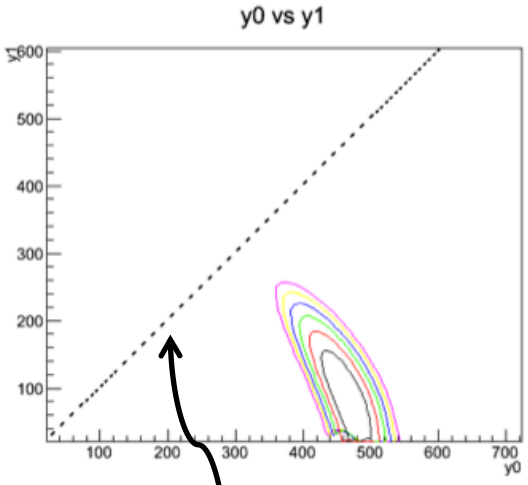
E: 1505.203272 +/- 9.356560 adu (62.716803 +/- 0.389857 keVee)

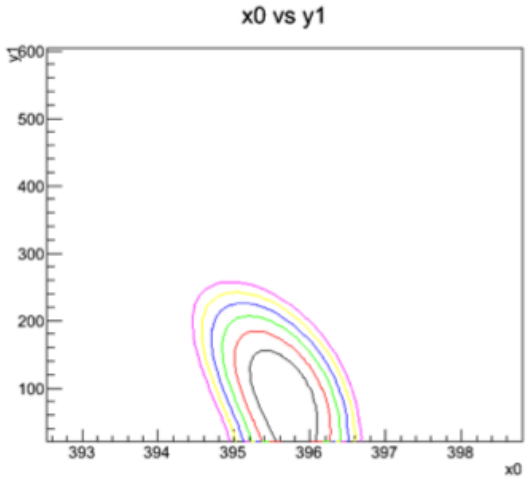
Range: 19.912867 +/- 8.374463 pixels (3.186059 +/- 1.339914 mm)

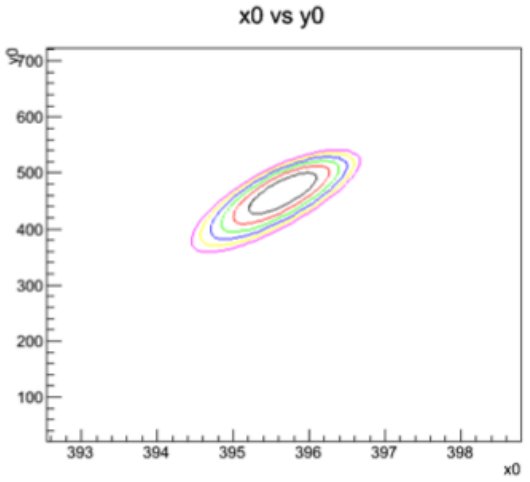
sin θ (from range): 0.888838 (from min): 1.237788

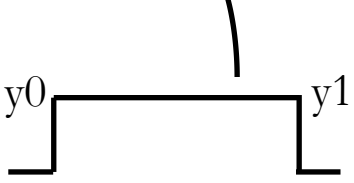
Implied Probability: 0.967850



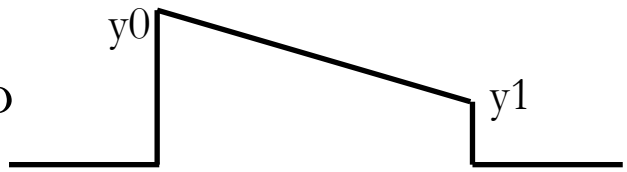




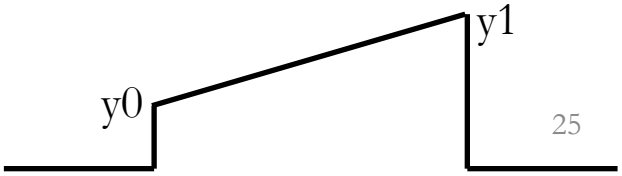




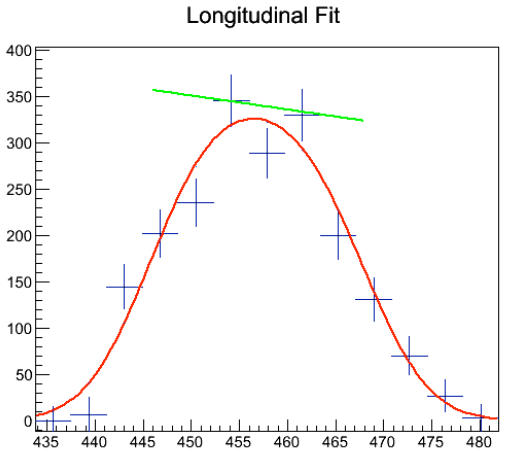
so



not



Track fitting with confidence



χ^2/ndof : 15.027260/12 = 1.252272

x0: 445.931635 +/-1.318754 (-1.449950,1.237641)

y0: 356.582855 +/-99.450537 (-102.434698,97.579702)

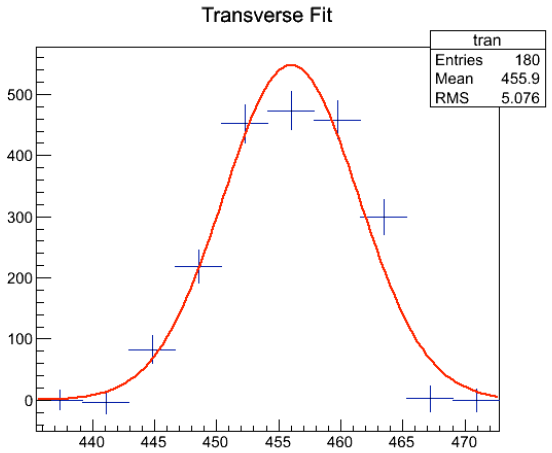
y1: 323.325790 +/-106.787317 (-114.698638,102.019991)

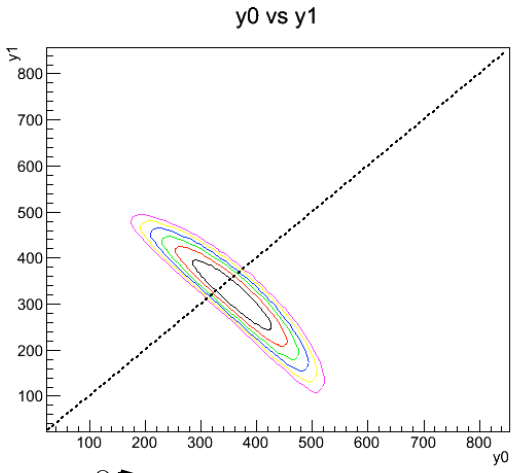
E: 2018.897334 +/- 6.212286 adu (80.755893 +/- 0.248491 keVee)

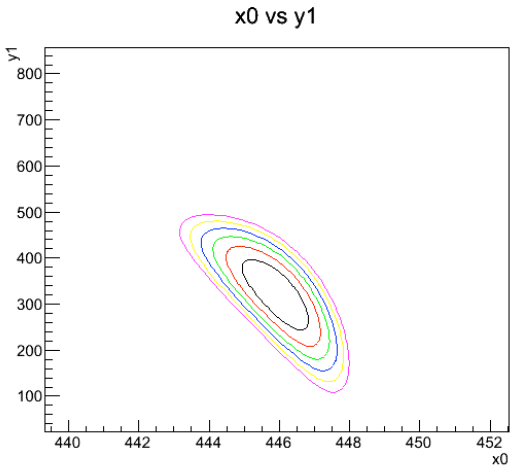
Range: 21.993059 +/- 9.441429 pixels (3.518889 +/- 1.510629 mm)

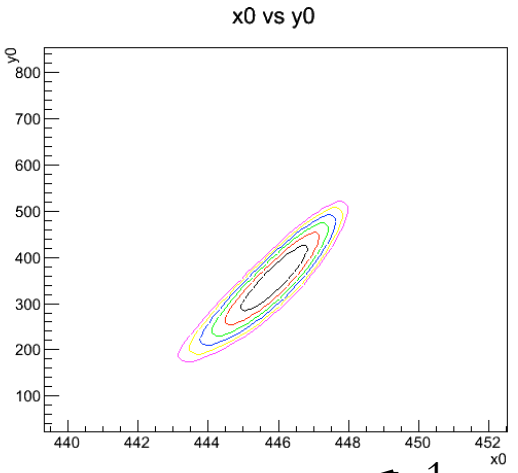
sin θ (from range): 0.843616 (from min): 0.348456

Implied Probability: 0.579762

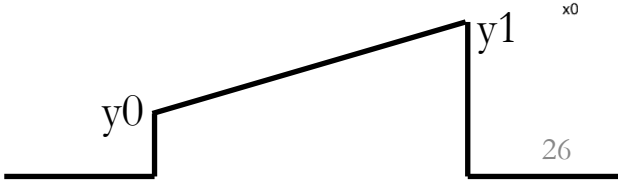






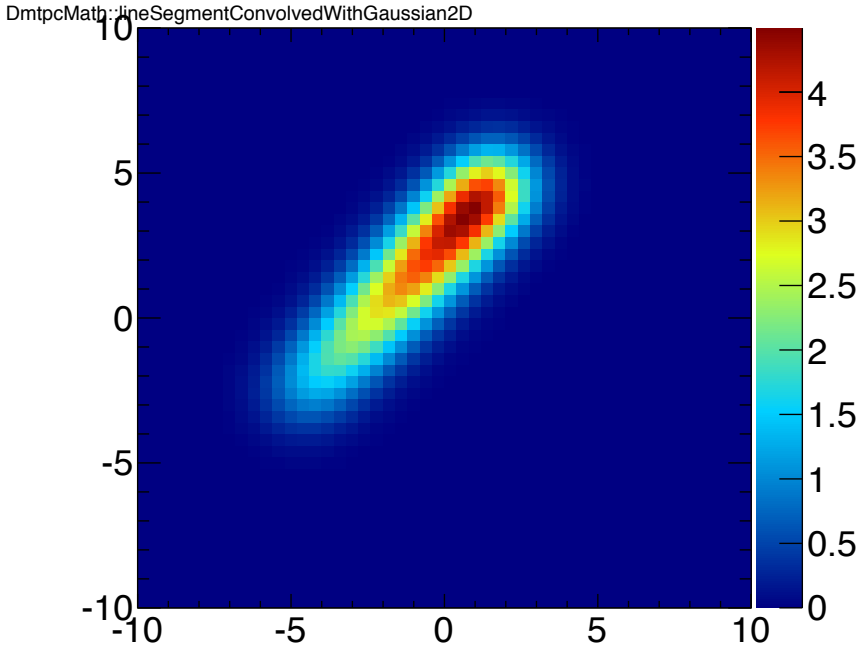


indistinguishable from



Track fitting with confidence: next steps

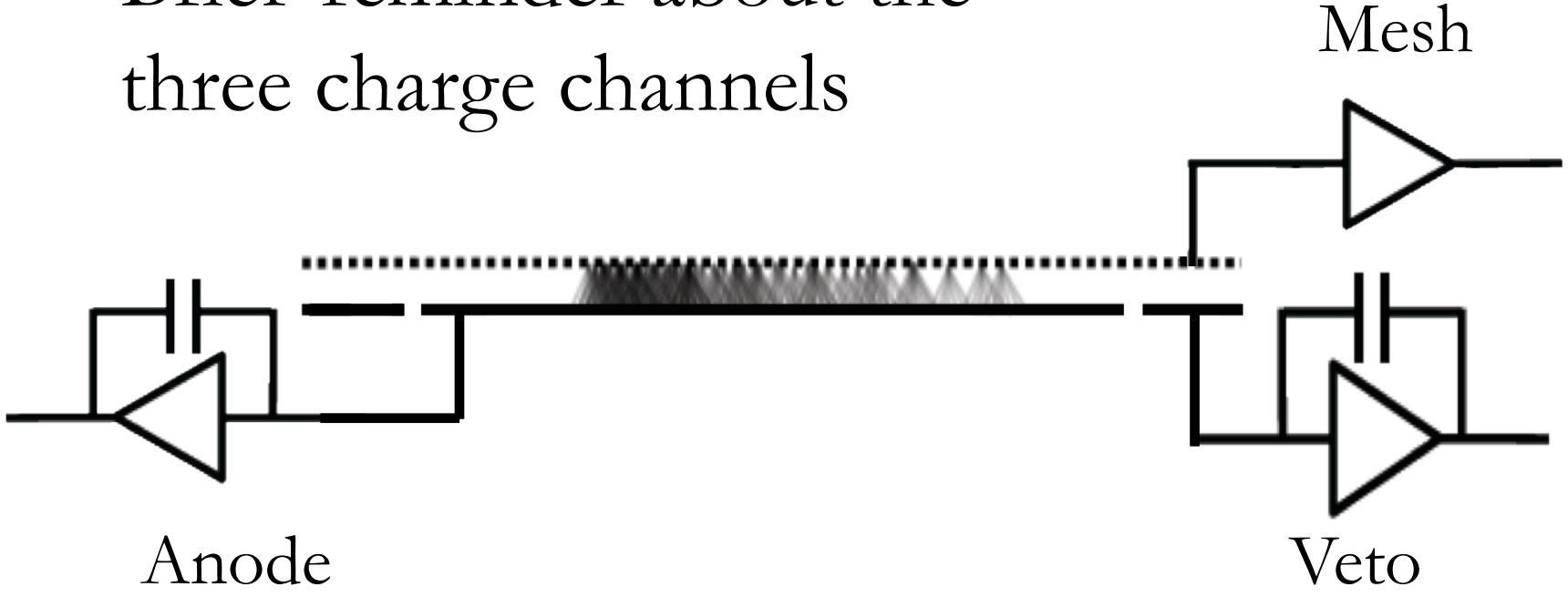
- Evaluate benefits of restricting DM analysis to "high confidence" tracks only?
- Extend the track fitting to 2D



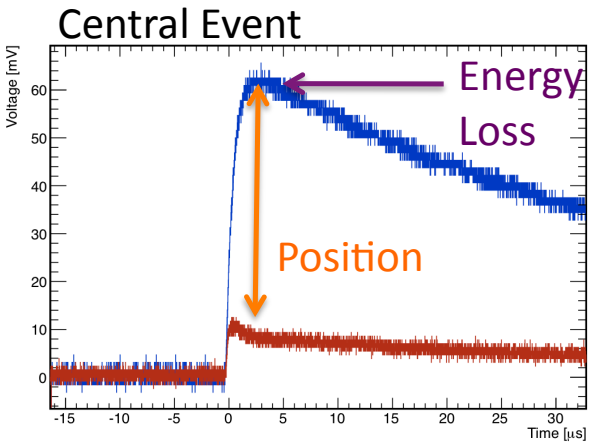
Nuclear recoil model

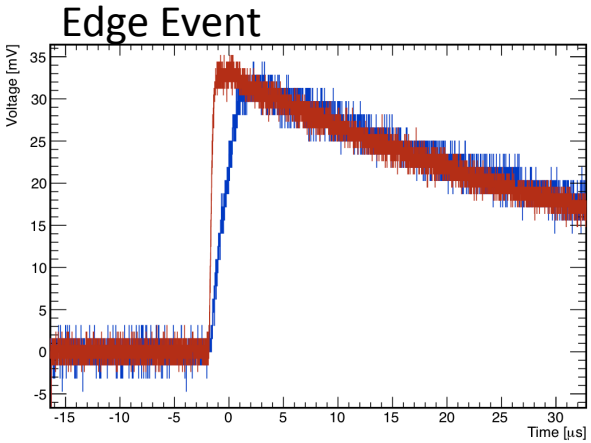
Charge readout: going beyond energy reconstruction

Brief reminder about the three charge channels



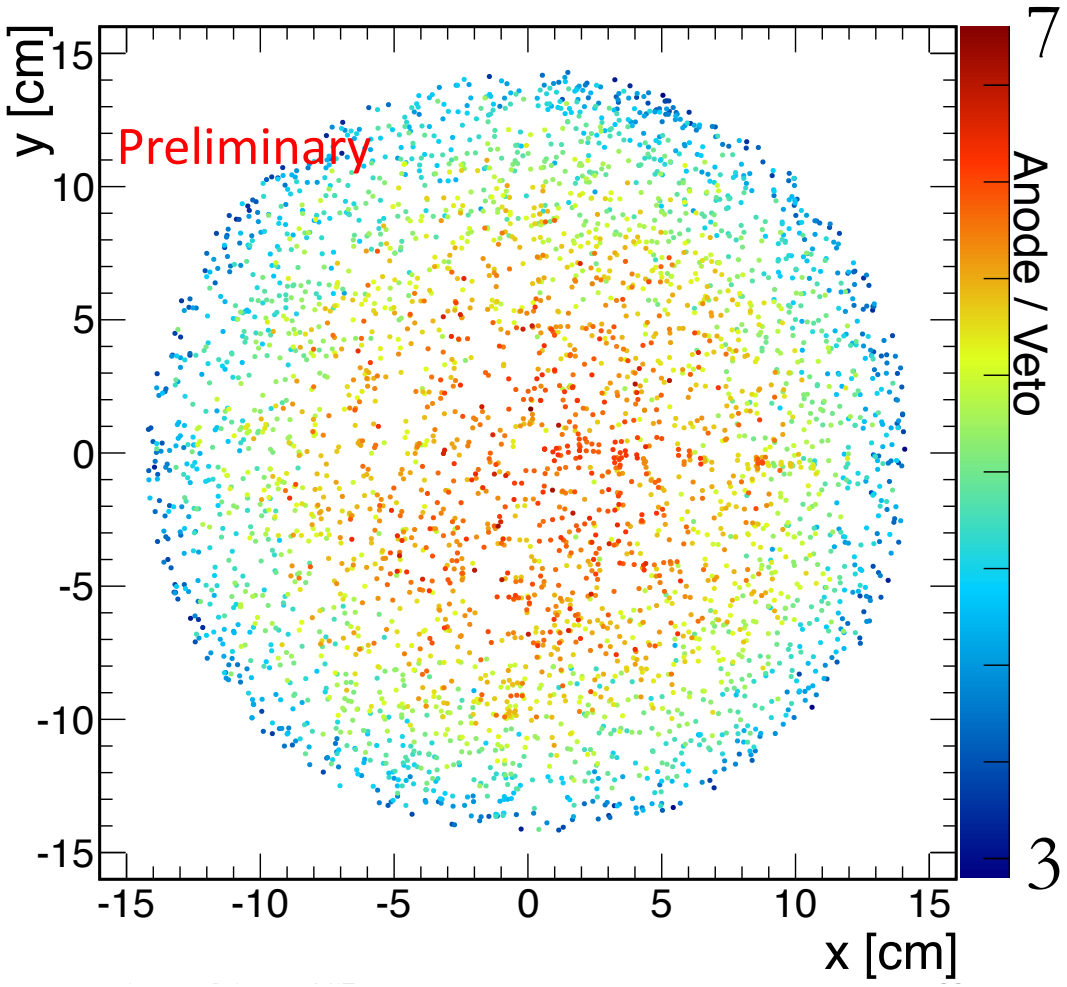
x-y position information from charge alone (useful in ccd/charge matching)



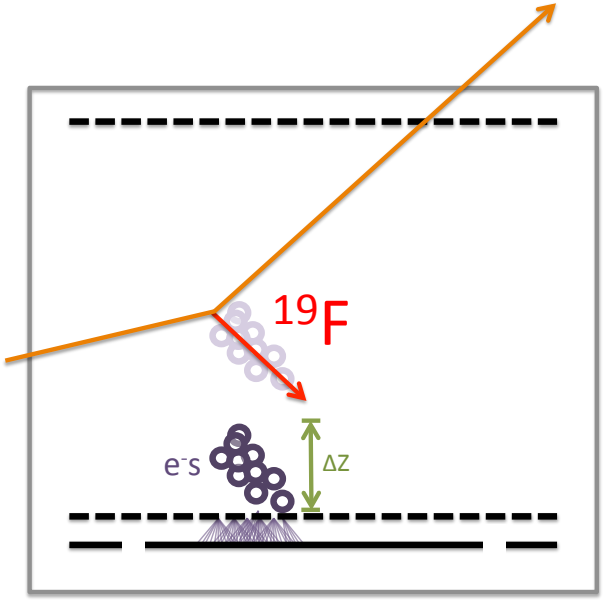


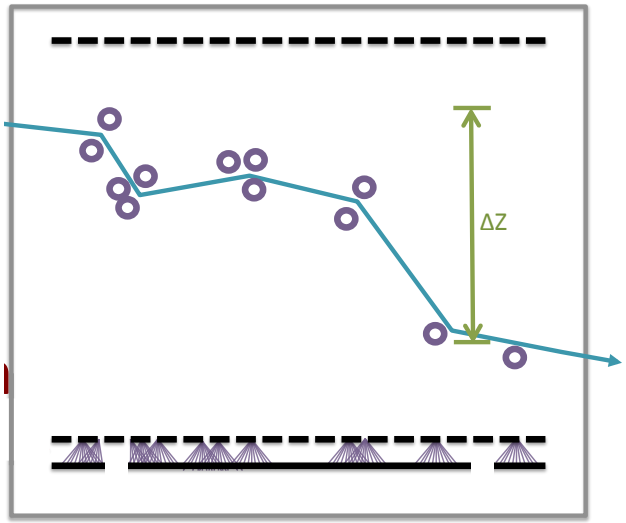
Central anode channel

Veto channel



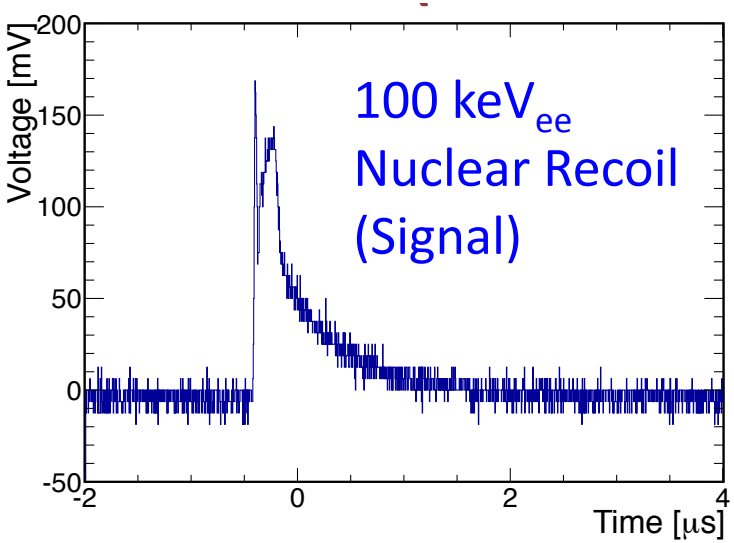
Event discrimination based on mesh pulse shape

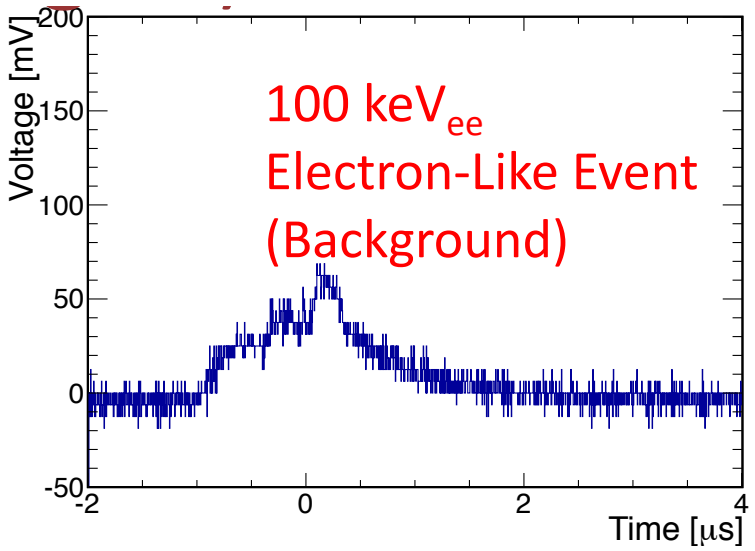




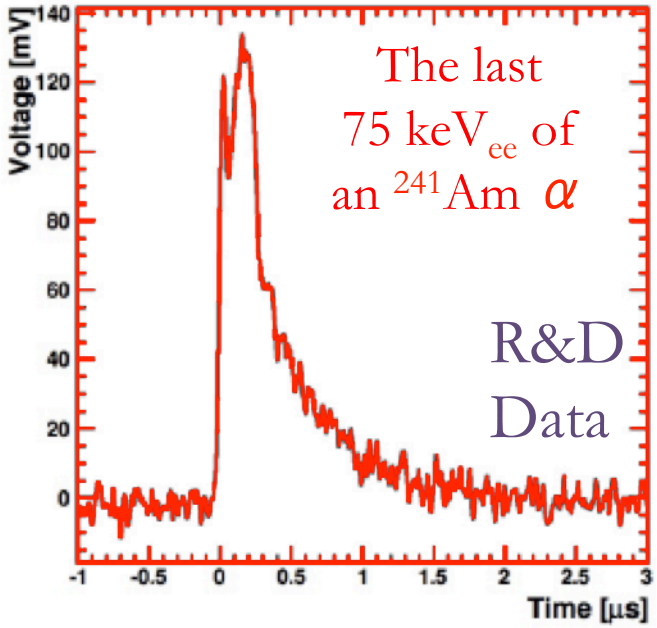
Nuclear recoil

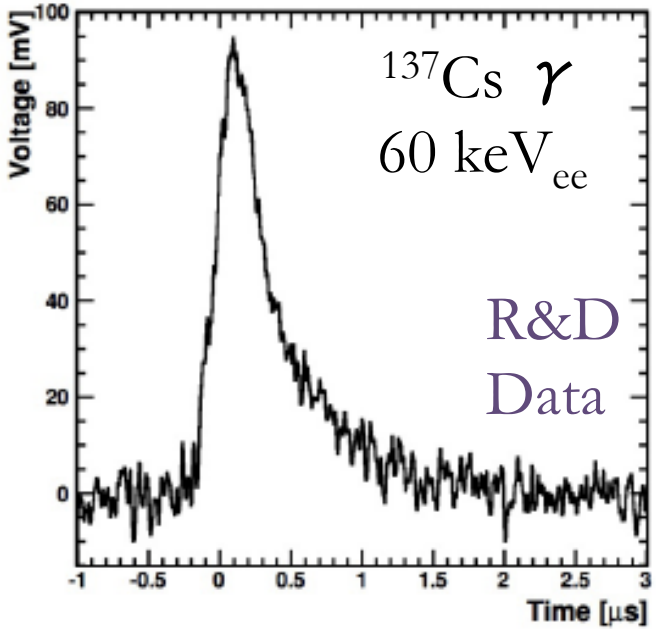
Electron recoil

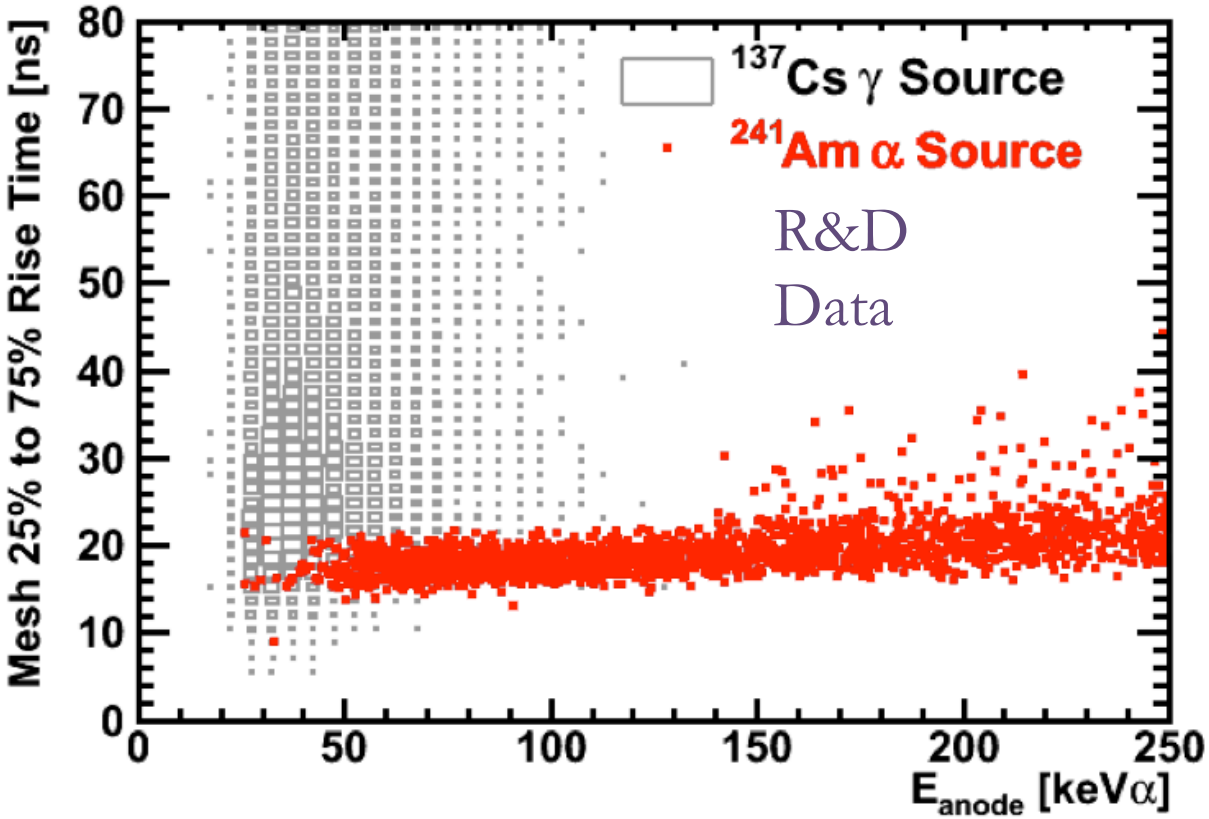




PID with Mesh Readout (different detector)



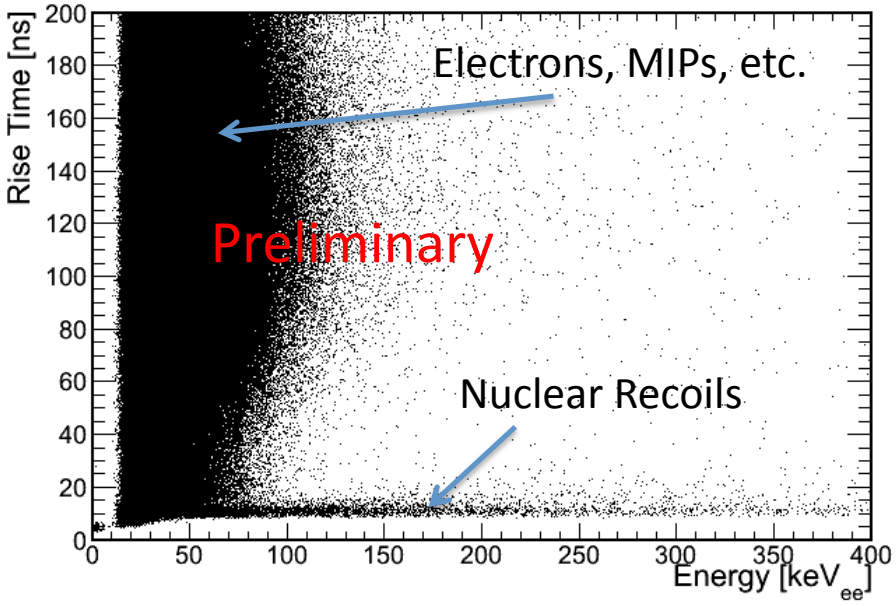


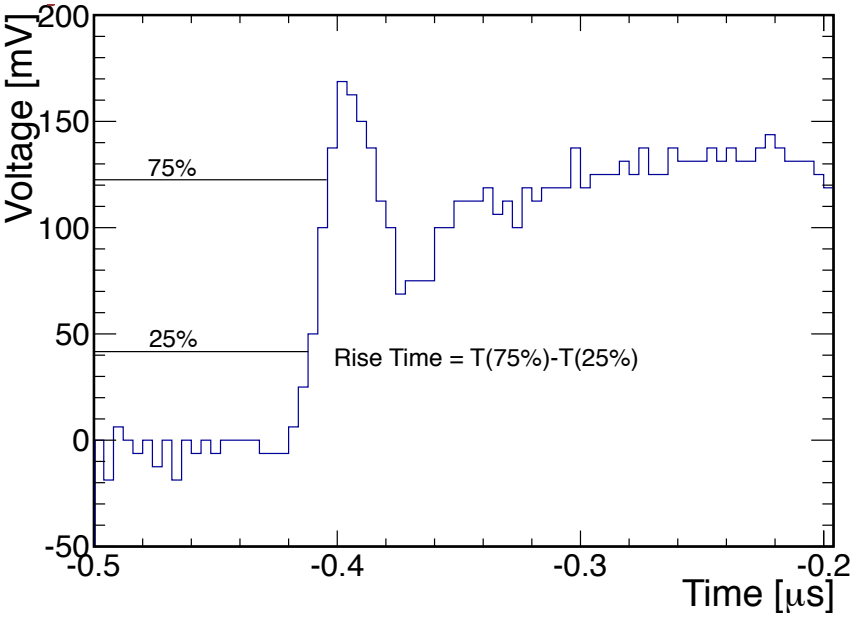


Demonstrated rejection of ^{137}Cs γ's between 40 keV$_{ee}$ < E < 200 keV$_{ee}$ of 10^5 (90% CL upper-limit) using CCD+veto+mesh

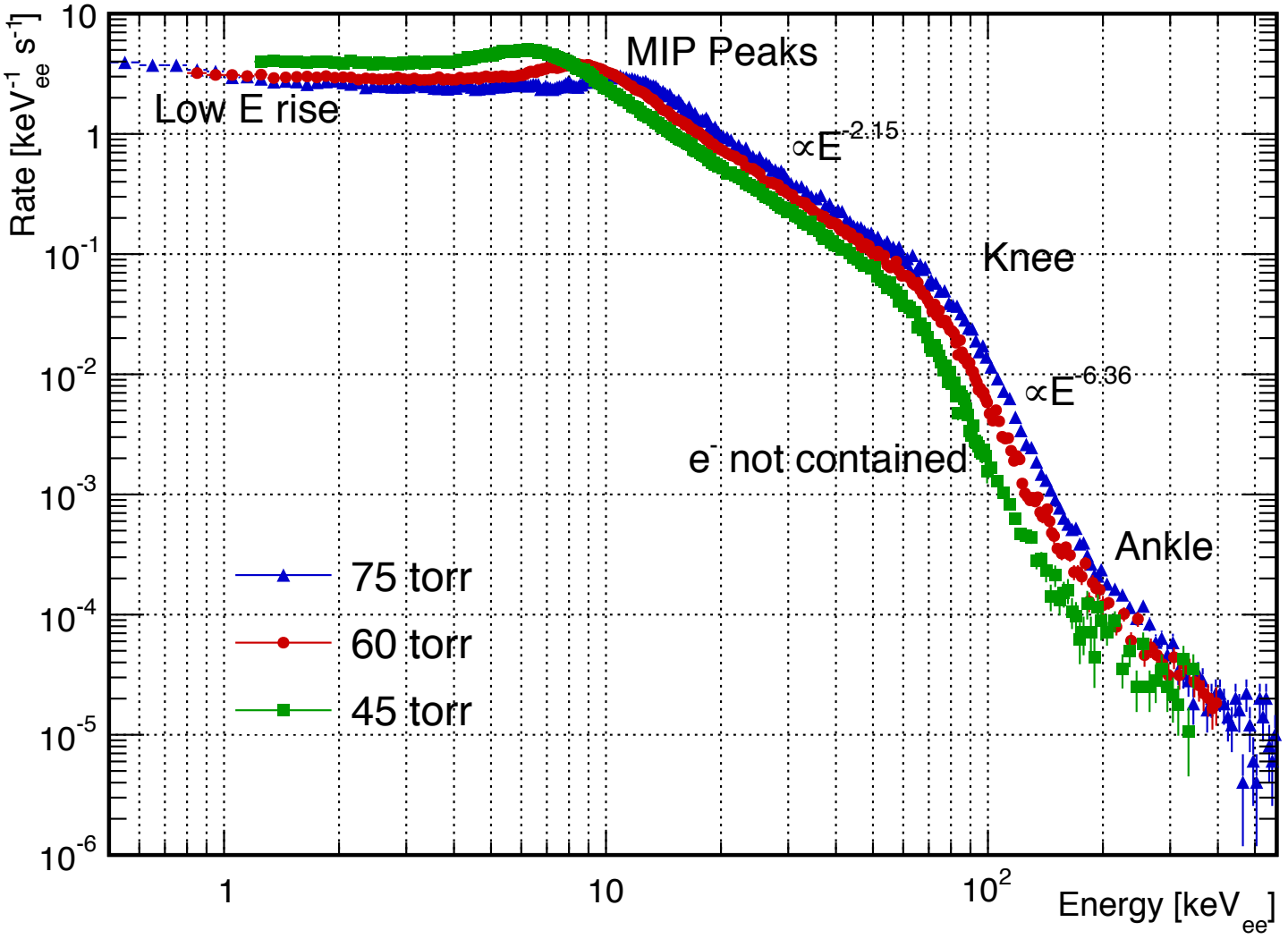
J. Lopez *et al.* NIMA 696, 2012

4sh data looks even better (though analysis ongoing)

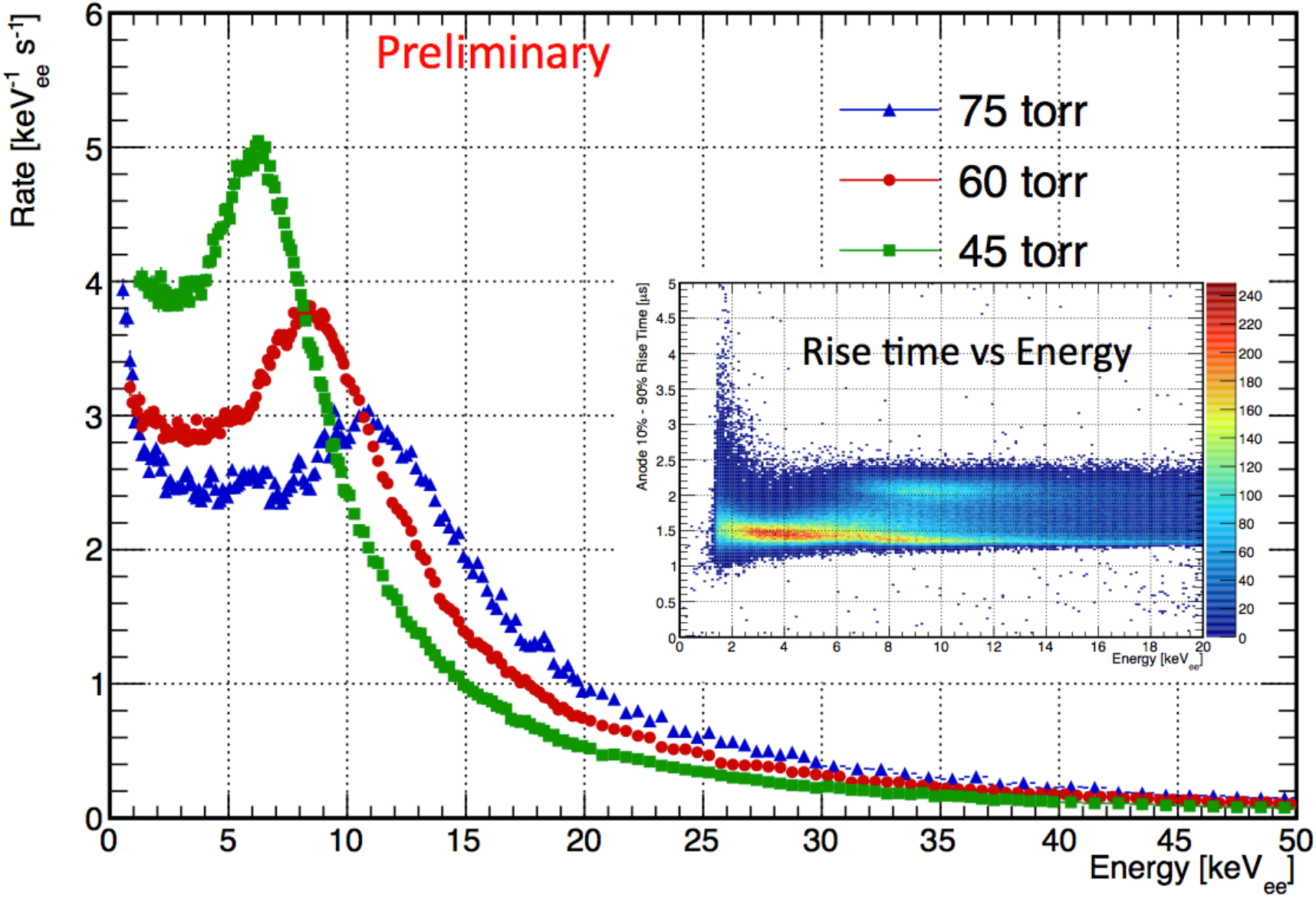




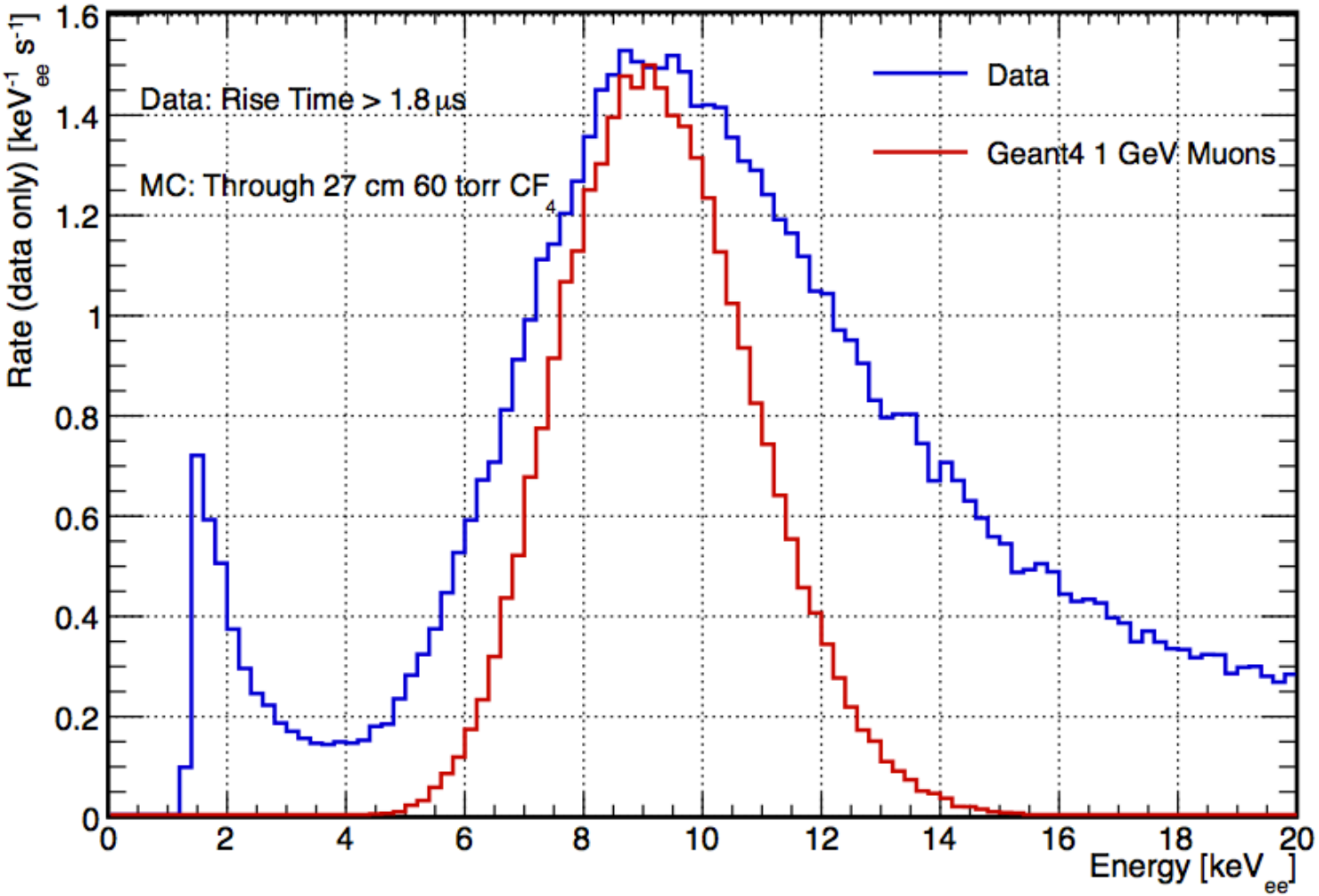
Charge background spectra



Charge background spectra



See MIPs in high rise-time events



Data expected to be wider due to detector resolution, angular distribution, and possible multi-particle events. Simulation is vertical only.

Nuclear recoil directional sensitivity analysis underway (with AmBe source)

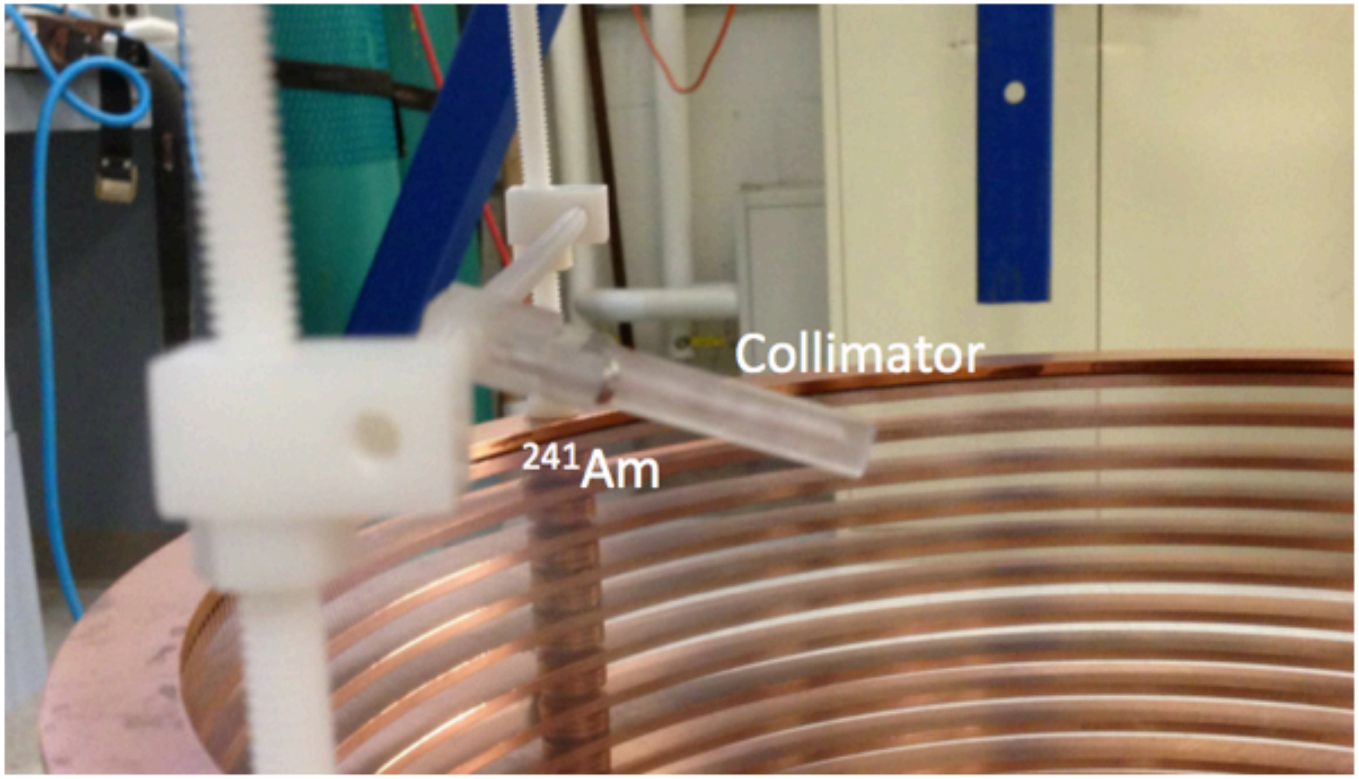
An Assessment of the Sensitivity of a Low Pressure Time Projection Chamber to the Direction of WIMP-Induced Nuclear Recoils

by

Shawn Wesley Henderson

(MIT Ph. D. thesis to be submitted inAugust)

Direction reconstruction at low energy

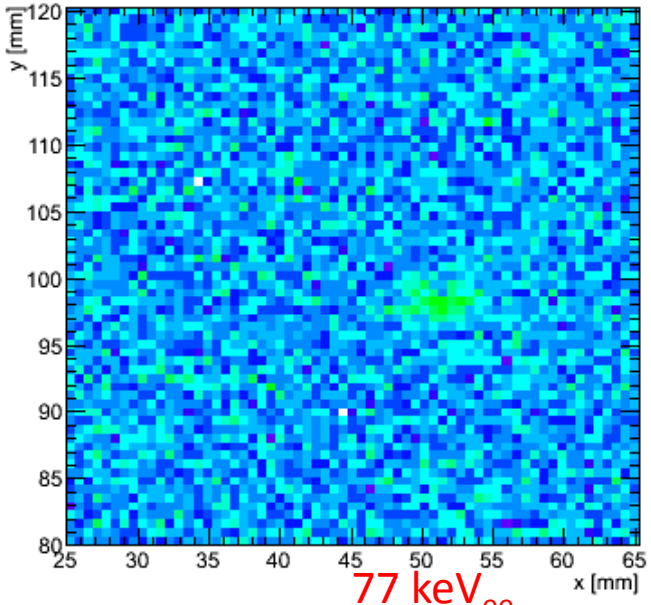


All tracks drift full length

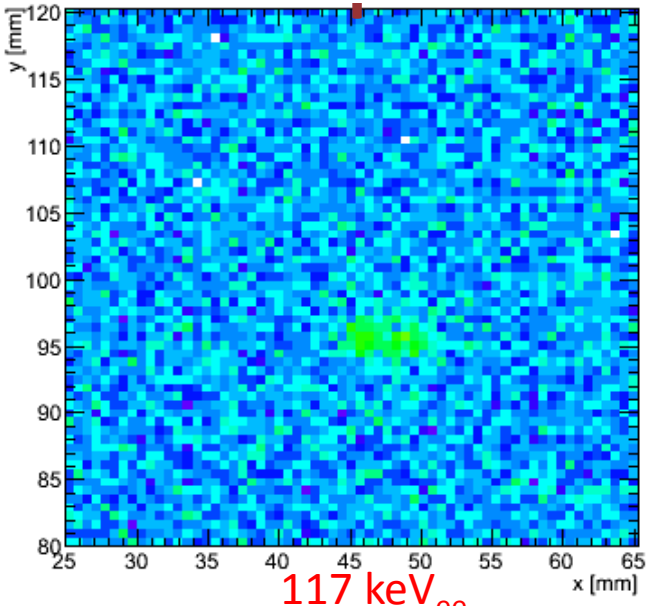
Smaller dE/dx than NR

Only the tail end of the alpha track makes it into the active region → low energy recoils.

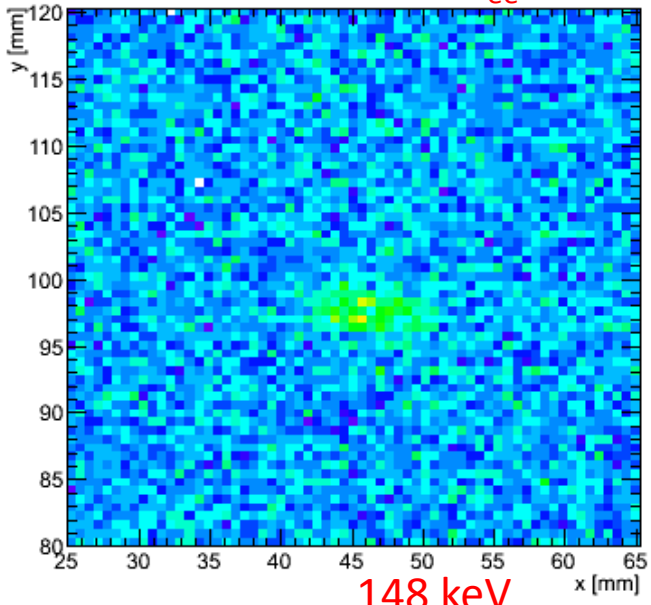
Sample low-energy alpha track images



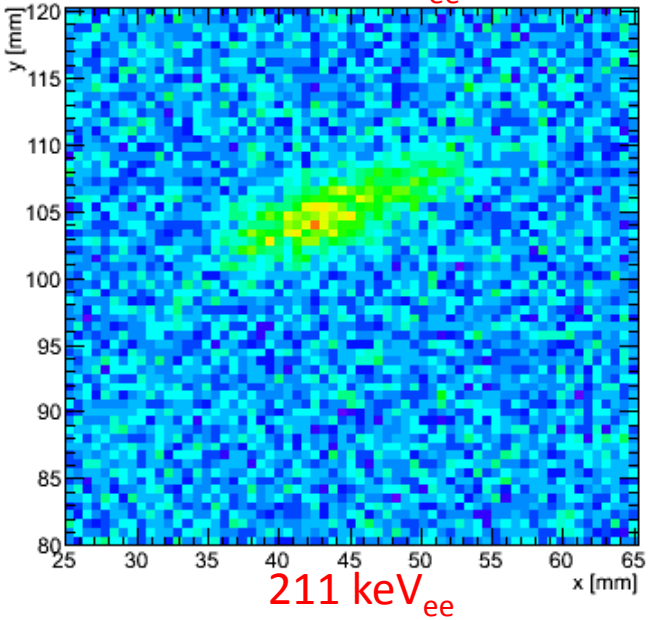
77 keV_{ee}



117 keV_{ee}

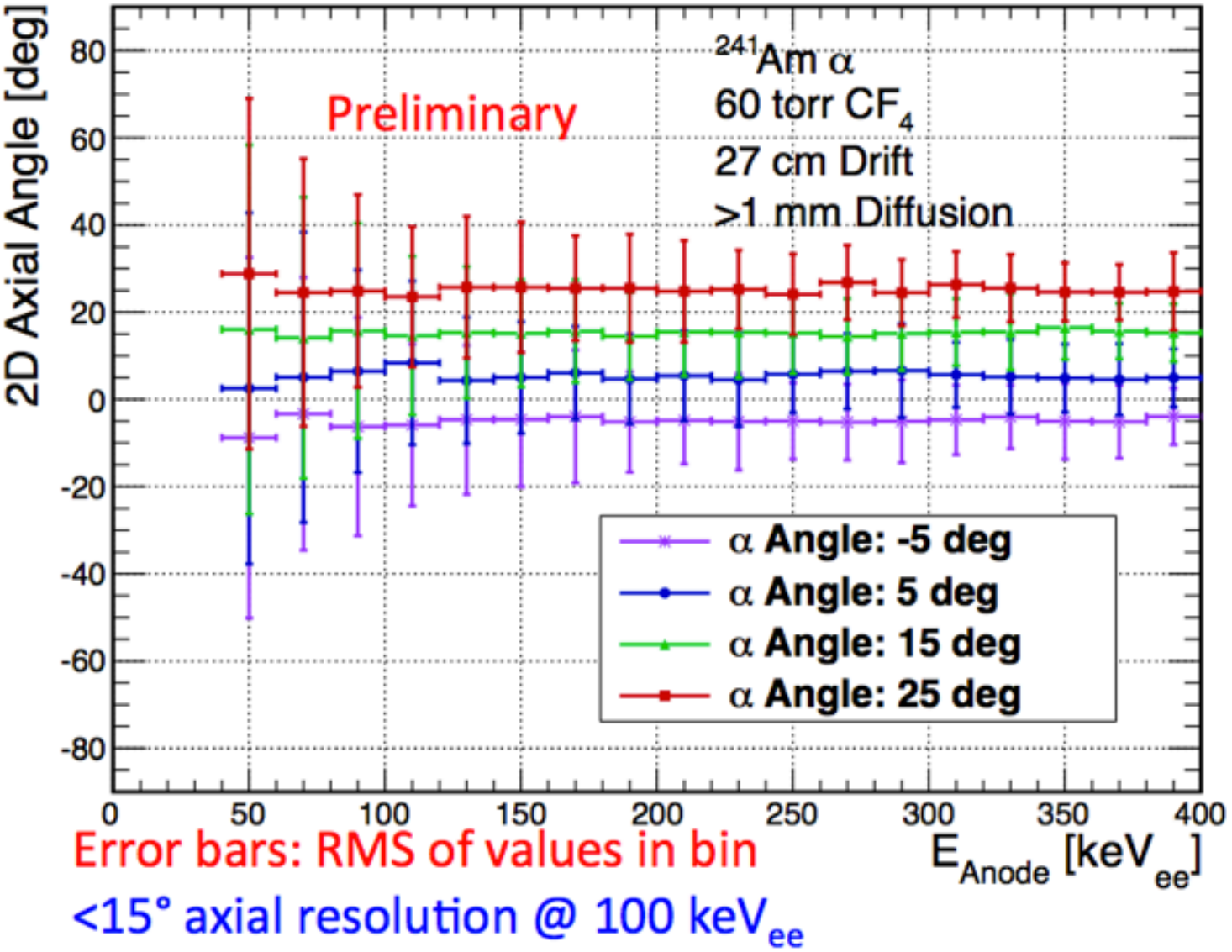


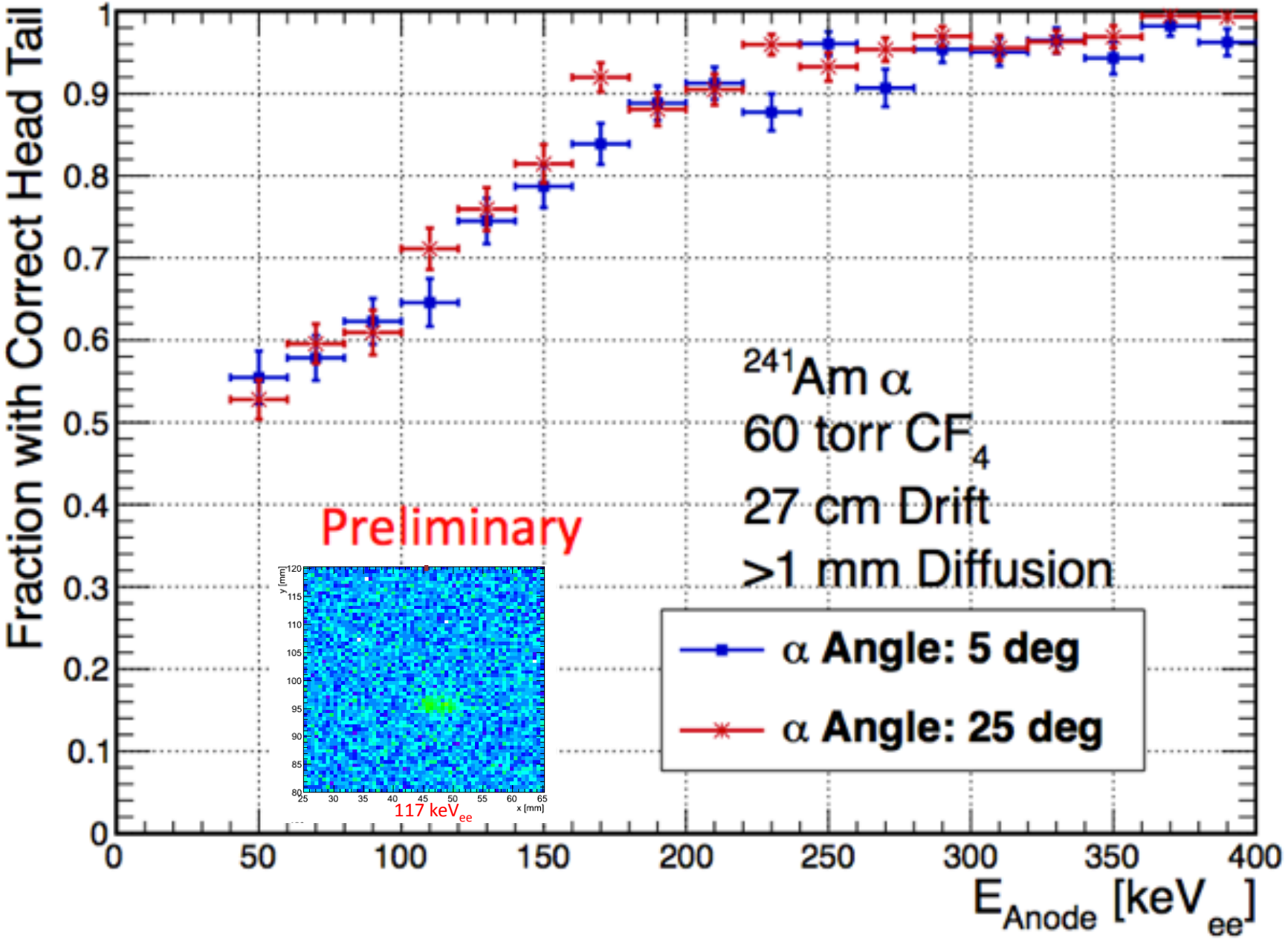
148 keV_{ee}

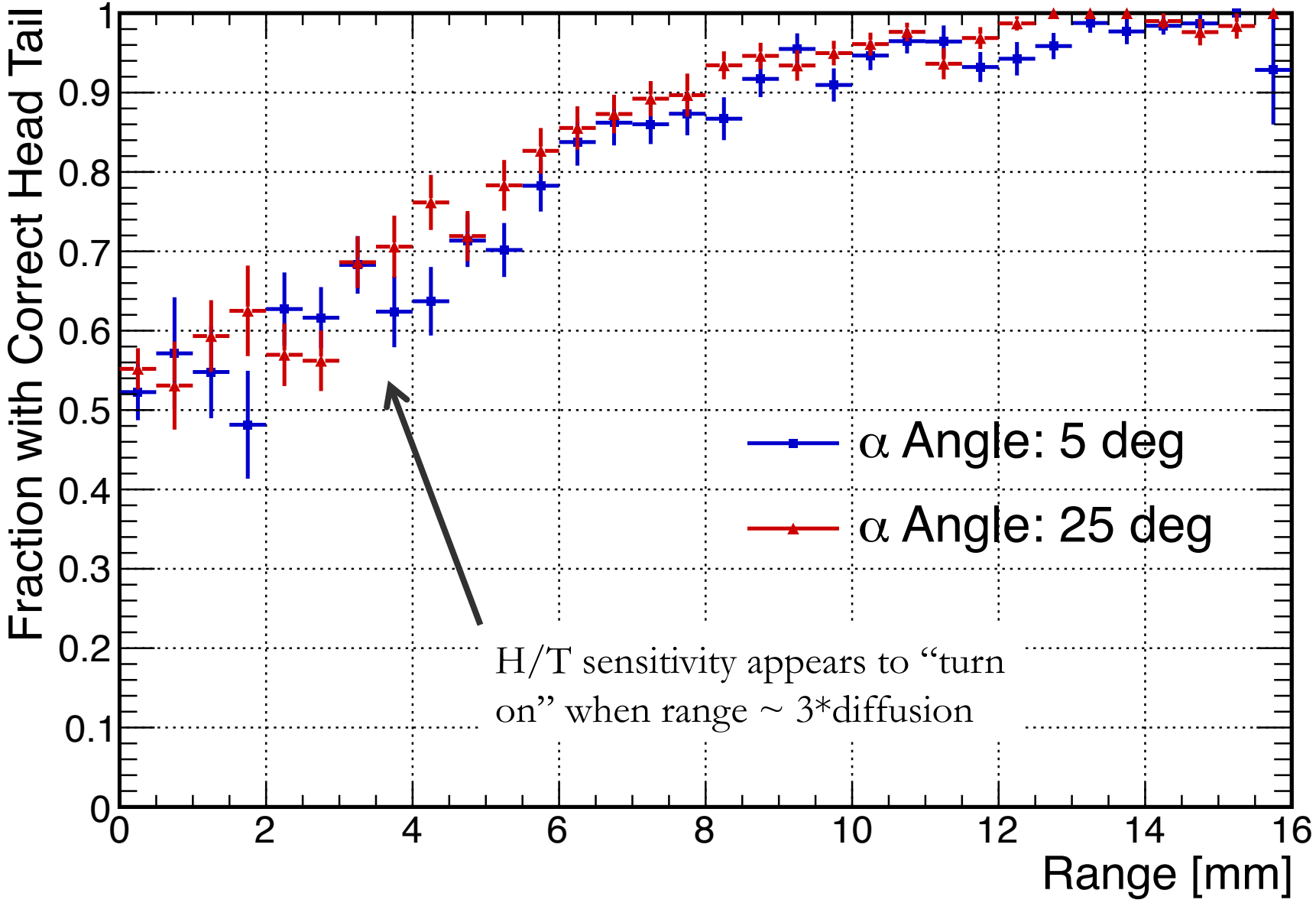


211 keV_{ee}

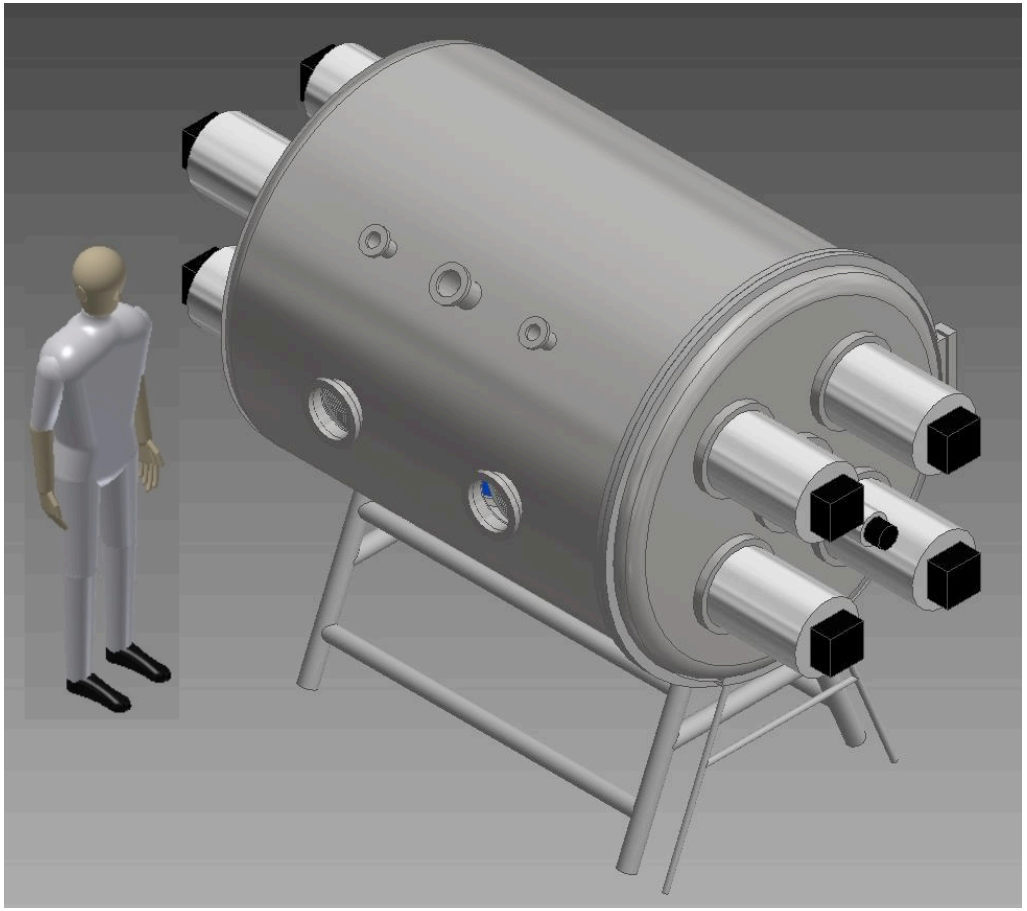
Directionality with low-energy alpha tracks

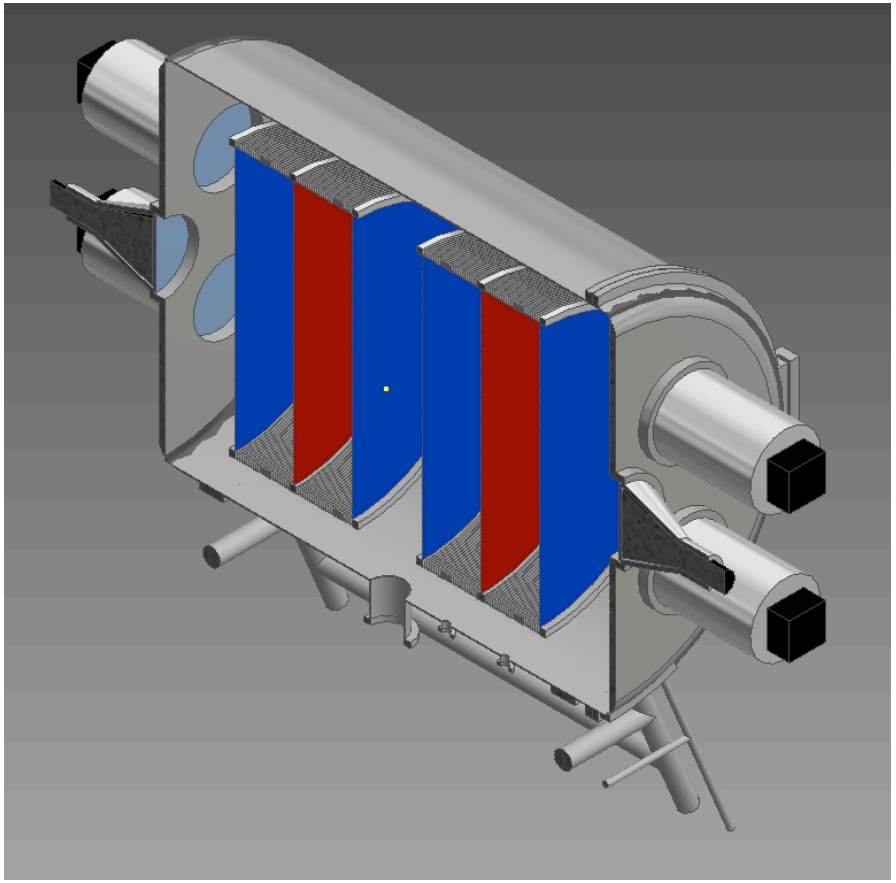



Fraction with Correct Head Tail
E_{Anode} [keV_{ee}]
^{241}Am α
60 torr CF_4
27 cm Drift
>1 mm Diffusion
Preliminary
α Angle: 5 deg
α Angle: 25 deg
117 keV_{ee}
y [mm]
x [mm]


Fraction with Correct Head Tail
Range [mm]
α Angle: 5 deg
α Angle: 25 deg
H/T sensitivity appears to "turn on" when range ~ 3*diffusion

DMTPCino ($1\ m^3$)



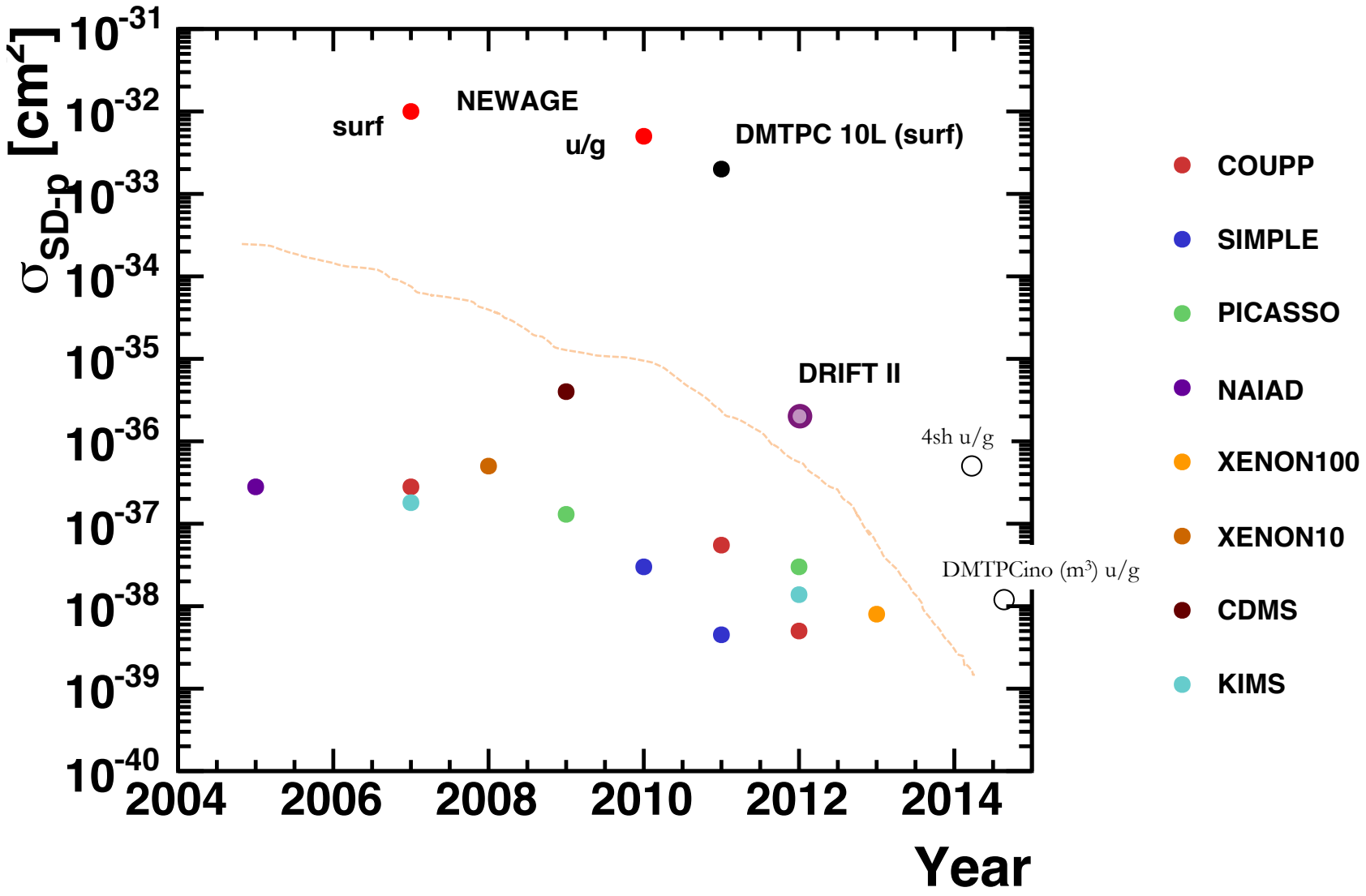


Amplification region = triple-mesh
One camera images two TPCs

Detector will fit in existing underground laboratory at WIPP

Triple mesh prototype built and under test now.
Vessel fabrication expected in the Fall.

Spin-dependent (proton) limits vs. time



Thank you