Direction-Sensitive Dark Matter R&D with the Dark Matter Time Projection Chamber (DMTPC) Project

Cygnus Update

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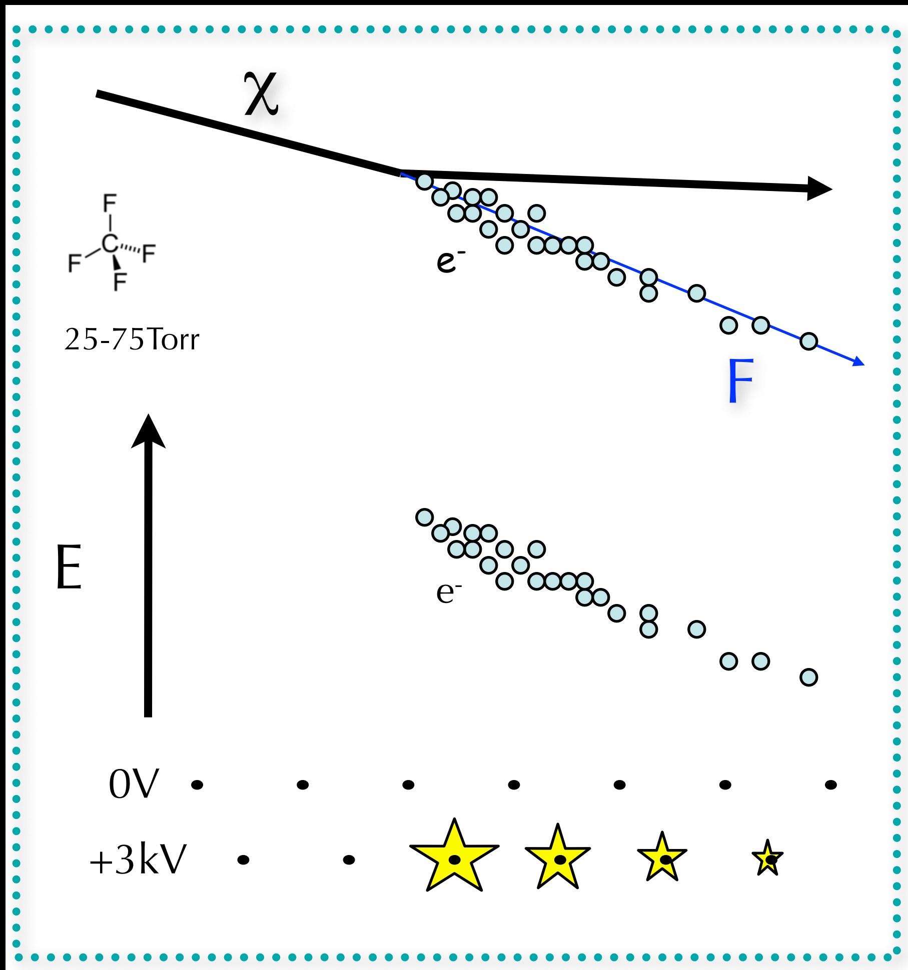
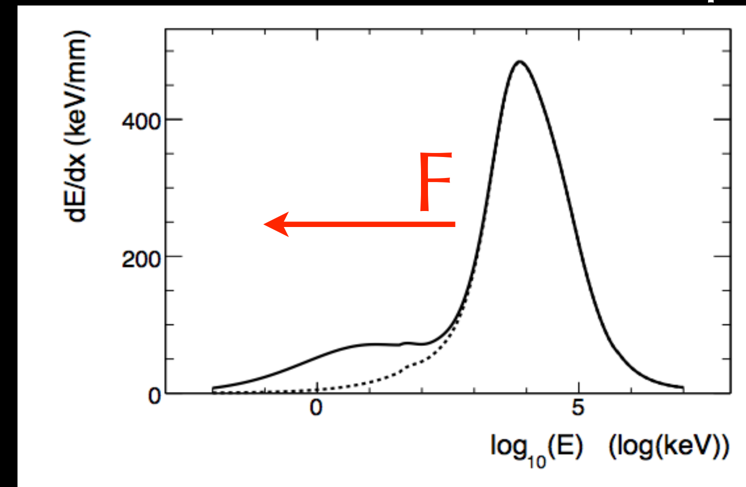
Dark Matter Time Projection Chamber (DMTPC) Principle

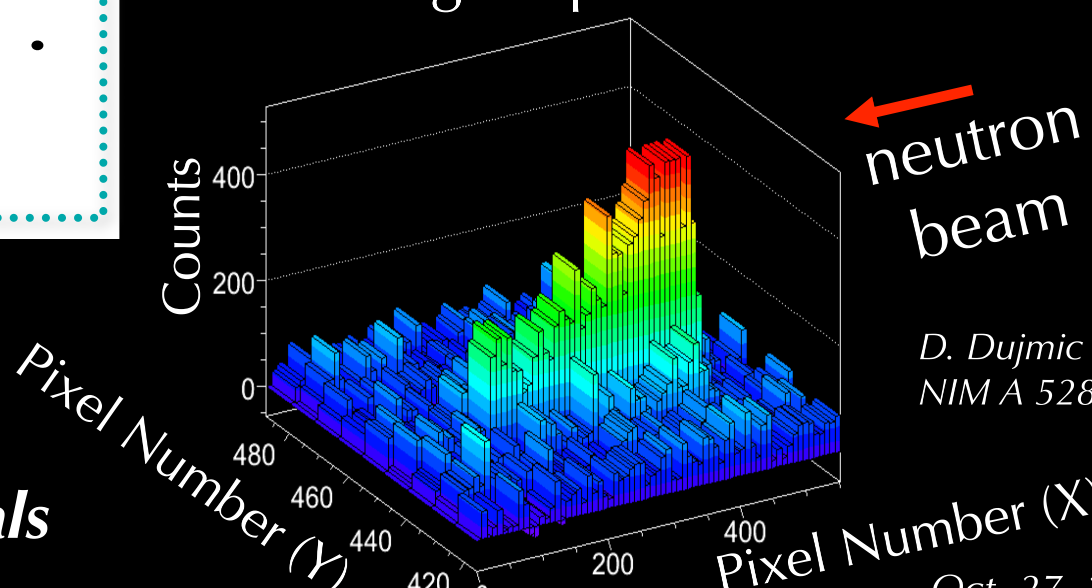


minimum wetted materials

1. primary ionization encodes track direction via dE/dx profile



2. drifting electrons preserve dE/dx profile if diffusion is small
3. multiplication in amplification region produces e- + scintillation



D. Dujmic et al., NIM A 528 (2008) 327

DMTPCino 1 m3 Prototype Science Goals

1. demonstrate 35º angular resolution (~straggling limit) at 50 keVr threshold (at SURFACE, prior to deployment U/G)

@SNOLAB

2. develop stable, remote U/G operations for the module to maximize livetime

3. (a) measure the background level associated with internal detector components
   (b) identify, mitigate, and replace major background emitters
   -measure angular distribution of backgrounds (particularly neutrons)
   -study extent to which directional information can be used to reject backgrounds
   -use directional background PDF in dark matter search analysis

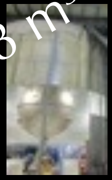
4. develop a design for a N module follow-on experiment, in coordination with global directional detection community CYGNUS

Eventually: dark matter observatory
(potential for low-energy nus too)

4100 m^3 for
10^{-46} cm^2
sensitivity

Directional Observatory
$16 \times 16 \times 16$ m^3

DEAP veto
$5 \times 5 \times 8$ m^3



1 ton of CF_4
@50Torr

Cube Hall:
$20 \times 16 \times 16$ m^3

SNO:
$21 \times 21 \times 34$ m^3

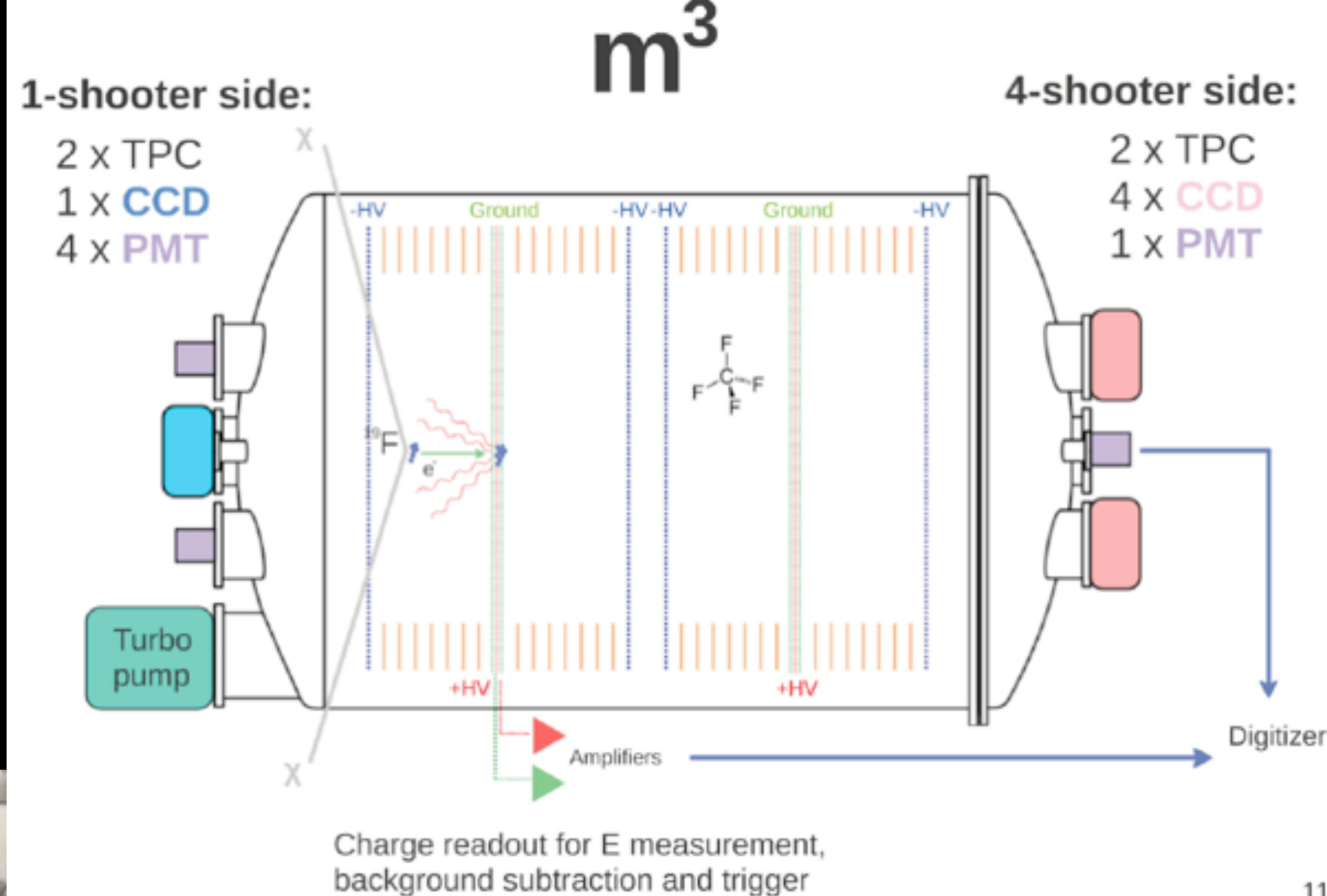
Recent Progress

Detector Milestones:
1. Completion of first m^3 TPC
2. Completion of new amplification stage
3. First light!
4. Gain measurement, ~4x increase

Physics Milestones:
1. Complete microphysics simulation
2. Directionality analysis for detector optimization

DMTPCino: $1m^3$ Module

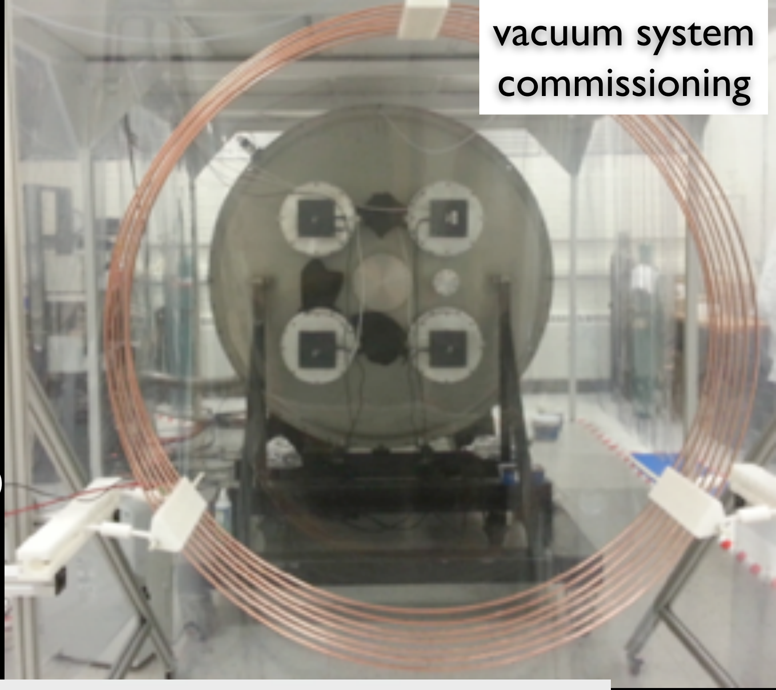
prototype for very large detector:
build many $1m^3$ modules, because of diffusion limit.

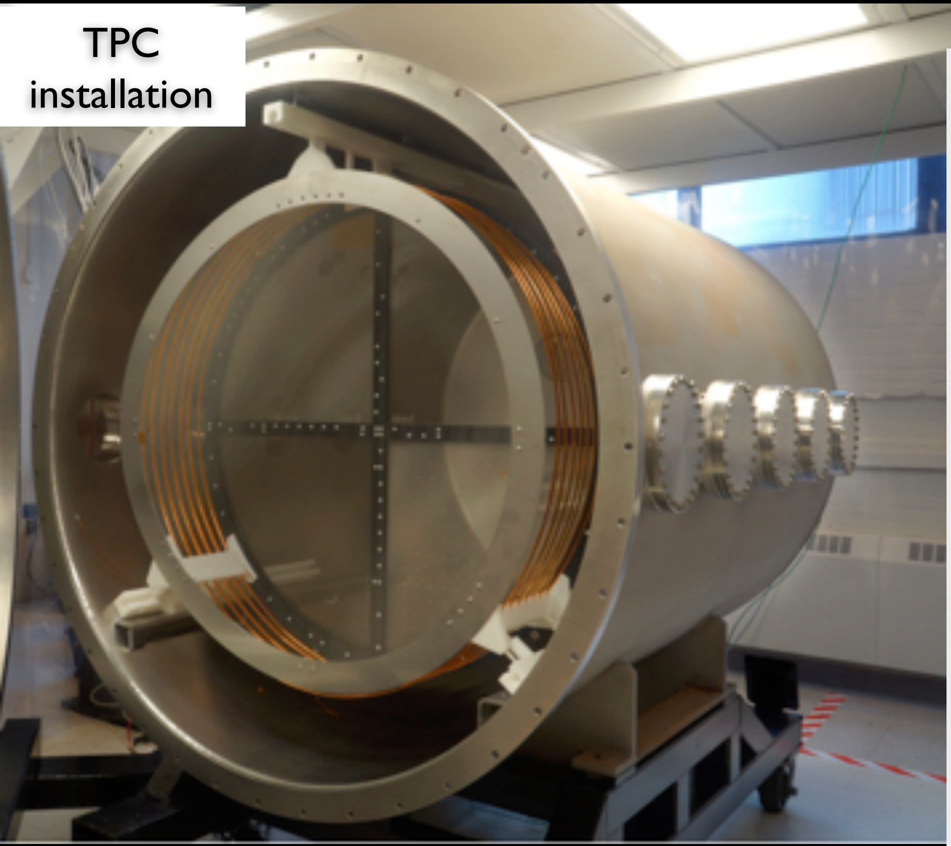


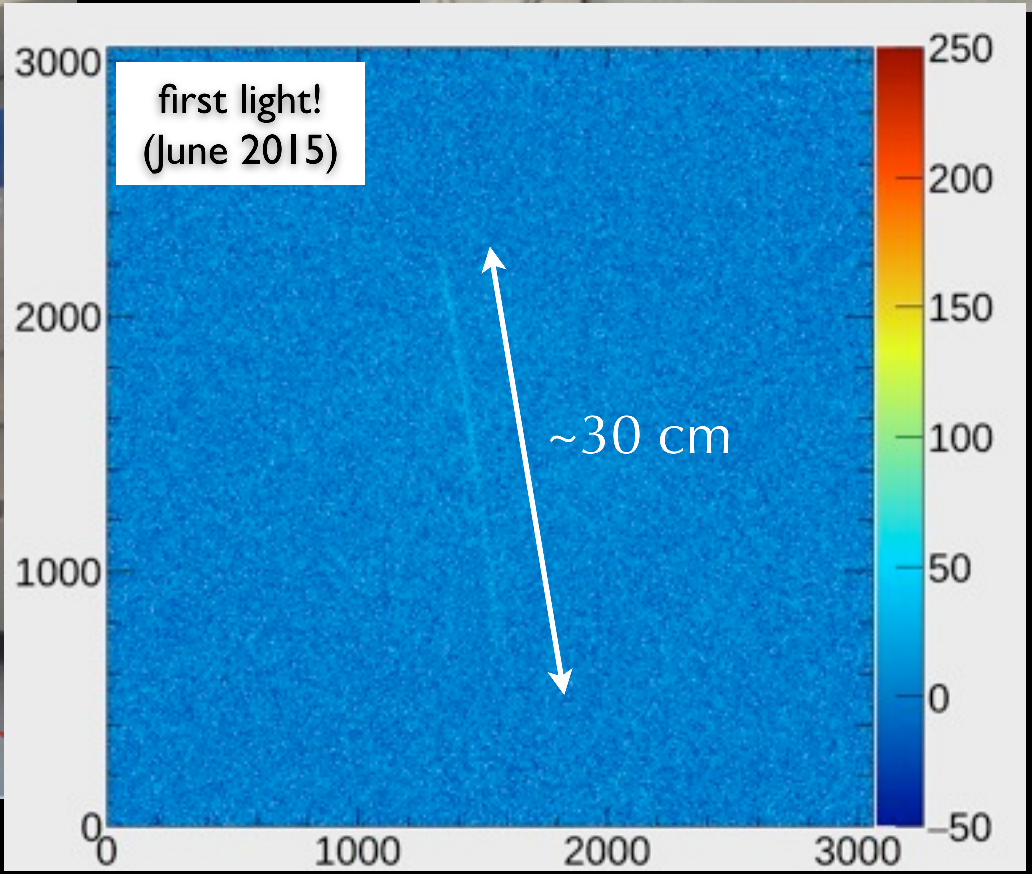
where we were at March 2015 EAC:
-vacuum acceptance test
-first field cage rings fabricated
-camera mounts fabricated

at CYGNUS'15: New TPC Integration

- first detector module installation complete
- upgraded optical system, charge readout, PMTs
- re-design of field cage to reduce Rn backgrounds
- new segmented amplification region
- now 5/5 of detector CCDs running, 4/5 with new DAQ
- new charge readout hardware

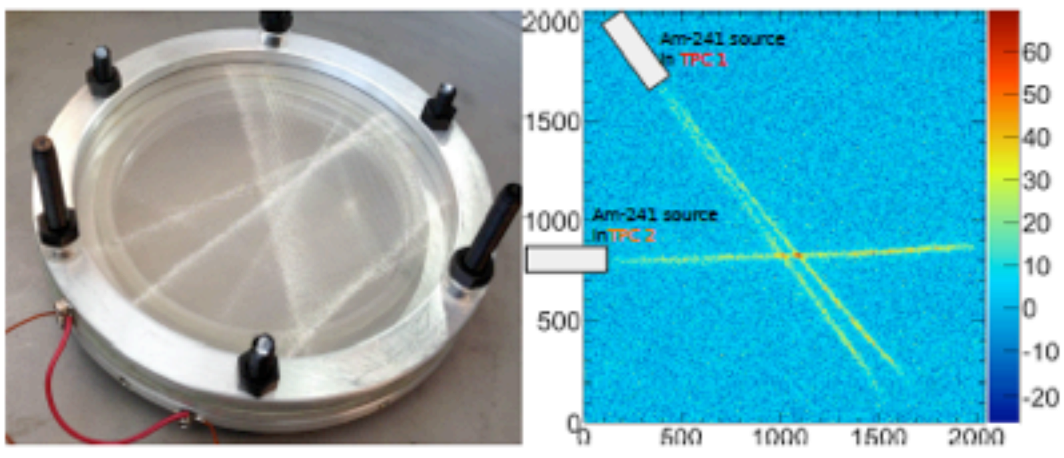


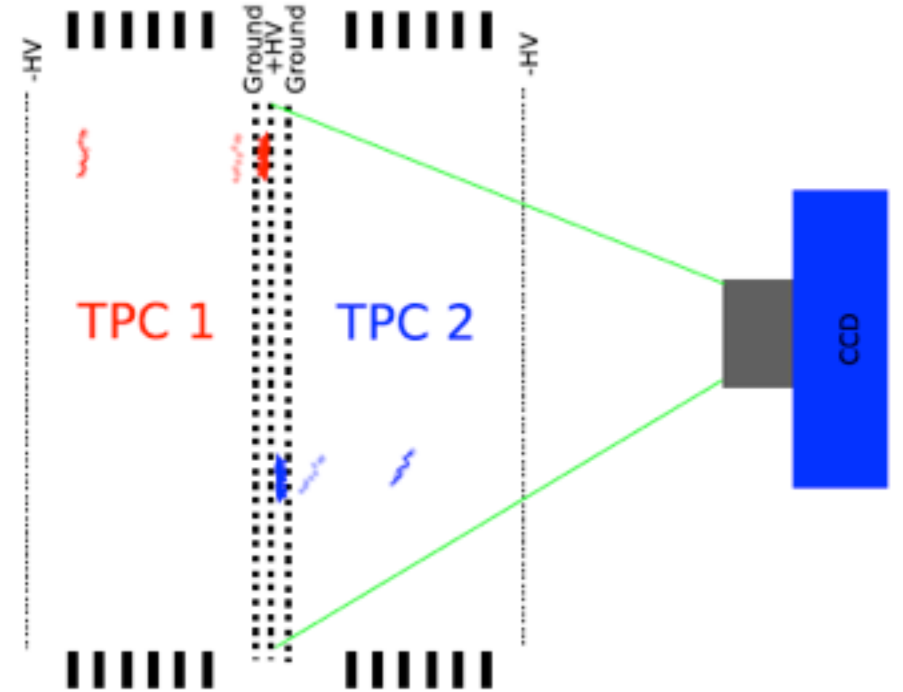




Amplification Region

new amplification region scheme uses triple mesh: one camera images 2x 25 cm drift regions





demonstrated high gain in small prototypes, 50-200k

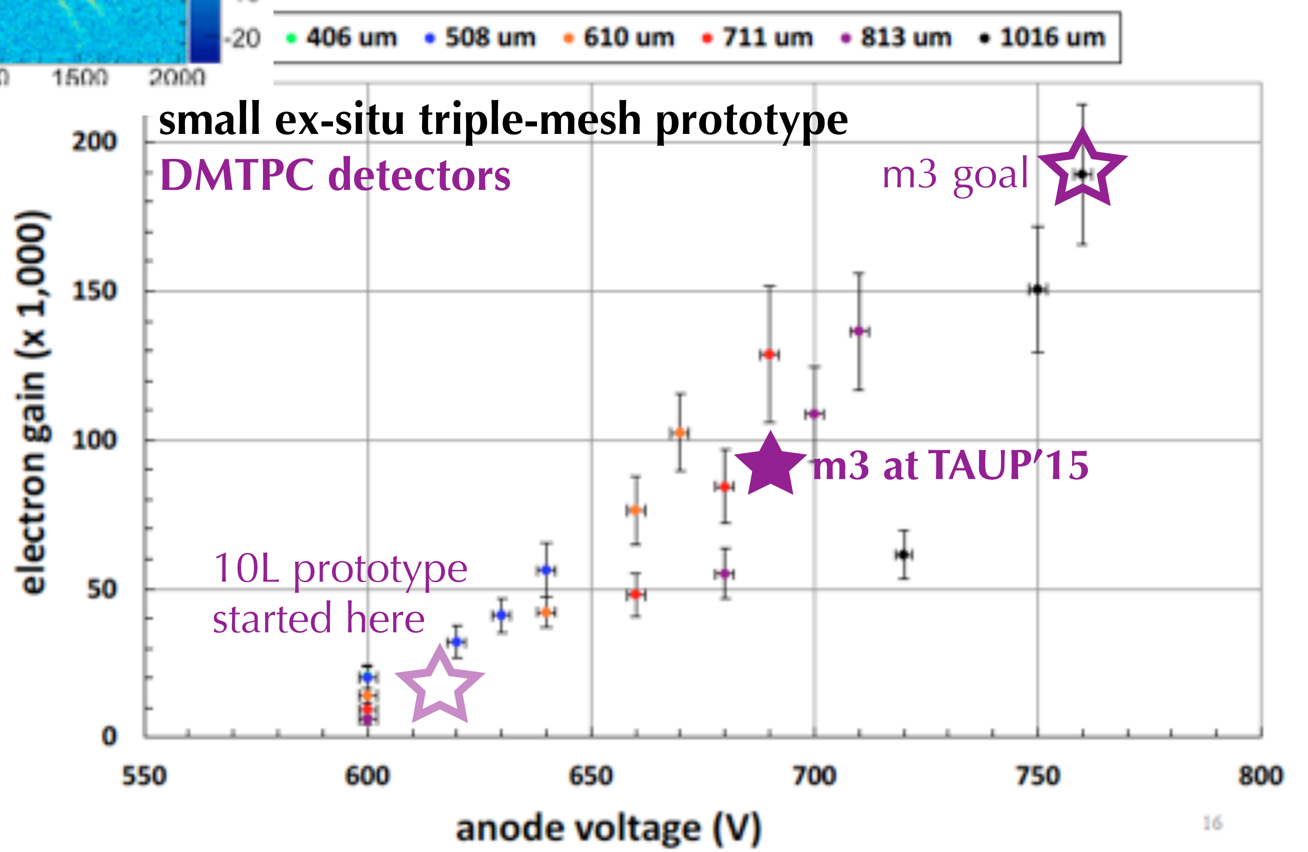
D. Dujmic et al., Astropart. Phys. 30 (2008), C. Deaconu, UCLA DM'14

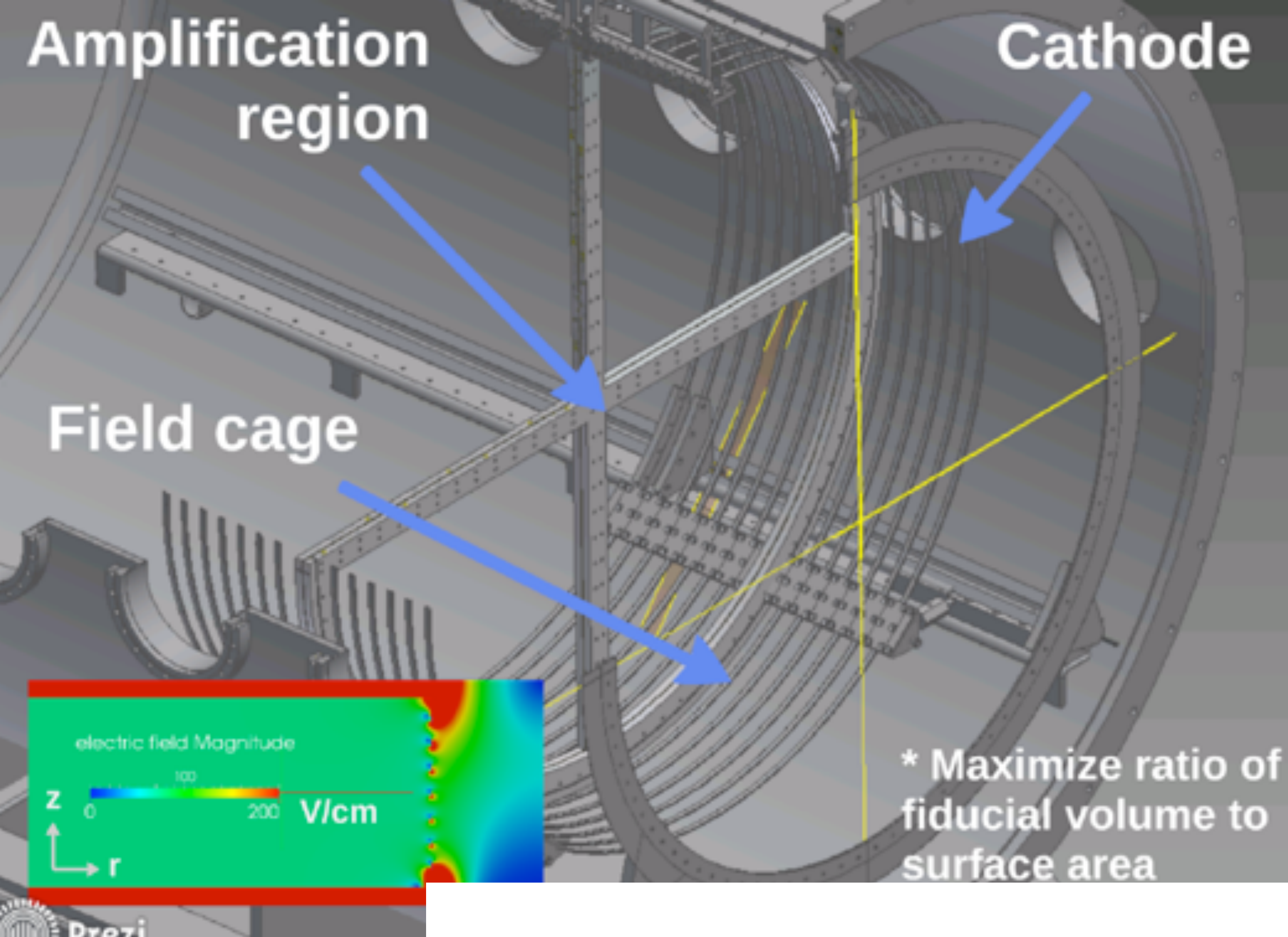
optimizing gap size, pitch to maximize pixel signal:noise,

•10x gain with 2x gap size

price: 25% amplification region diffusion tails increase

H. Tomita, PhD thesis, J. Battat, Cygnus'13





TAUP'15: *(M. Leyton)*

First source calibration campaign complete.

- gain x50% increase over previous detectors at ~moderate anode V
- but, complicated crosstalk and ground loop issue!

2nd campaign for gain, uniformity measurement

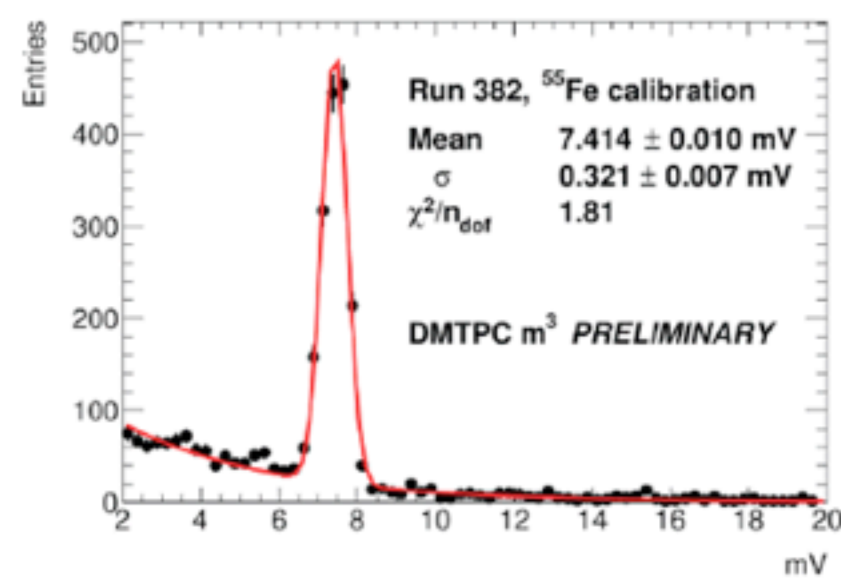
2x surface A
100x Volume

see O(10x) background reduction from field cage

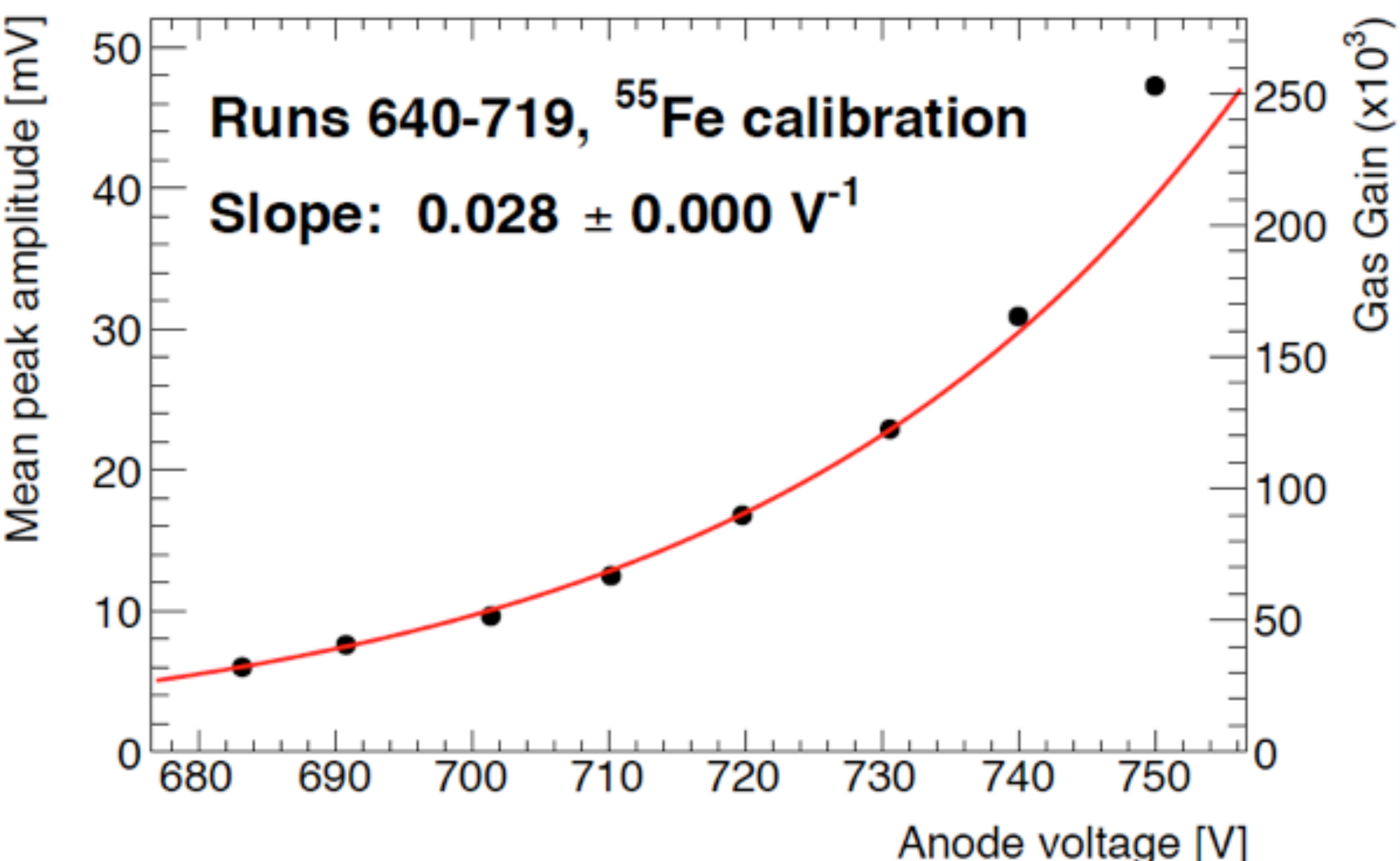
$$G \sim \frac{(V_{out} \,/\, \text{Amplifier gain})}{(5.9\ \text{keV} \,/\, W)}$$

W for CF_4 = 33.8 ± 0.4 eV

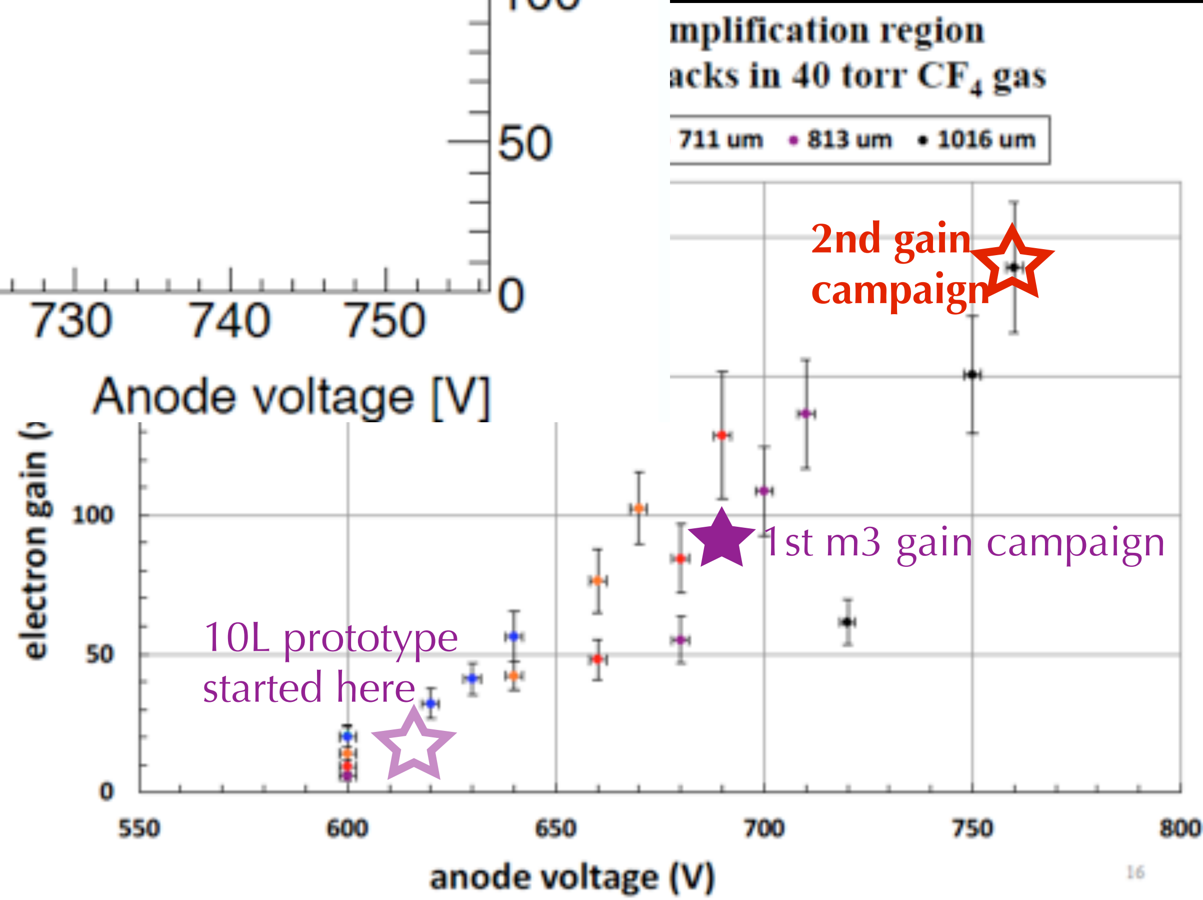
For anode at 690 V:



New: 2nd Gas Gain Calibration Campaign



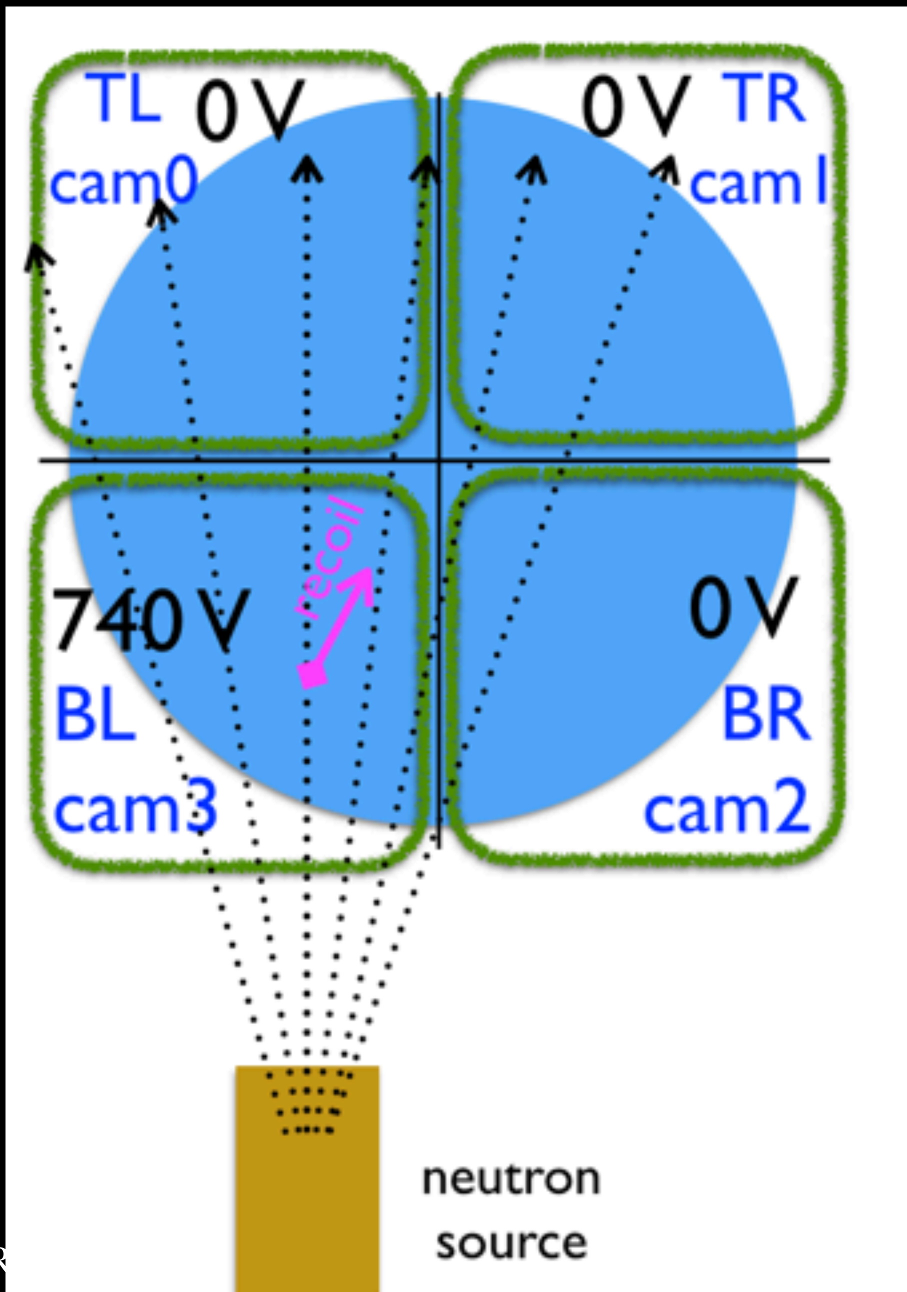
updates: grounding problem solved, breakdown problem identified as associated with pre-amp, work-around in place but permanent solution needs investigation.

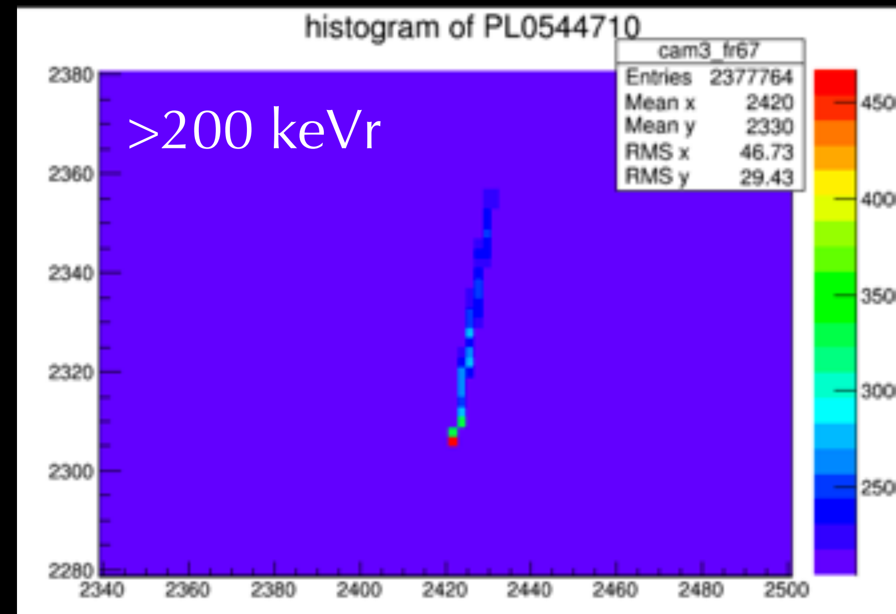


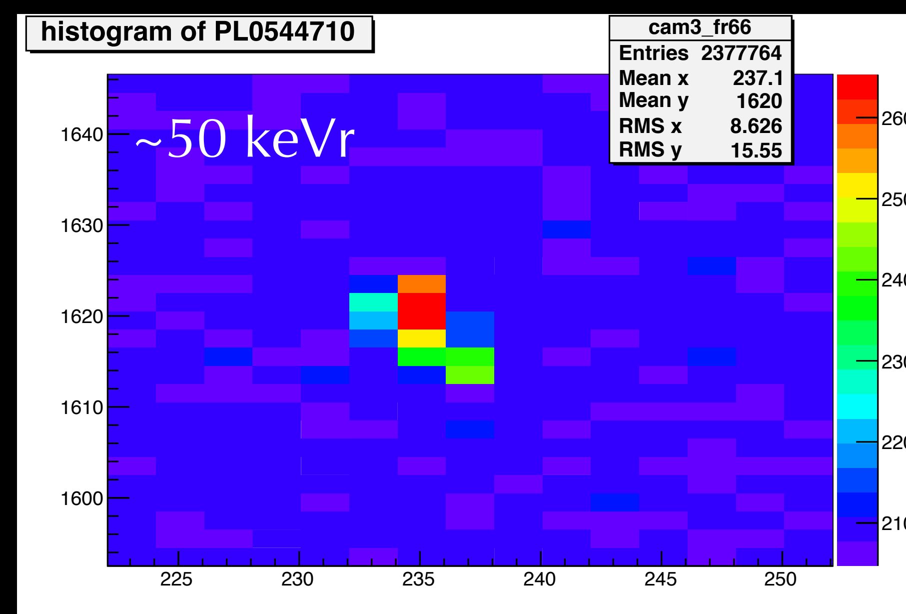
result: gain>250,000 can be achieved = factor of 4x higher than previous operating point of 65,000 (in 4shooter prototype), 25x 10L prototype operating point.

New: First Neutron Calibration Data

AmBe neutron source deployed for directionality commissioning, first events!
See tracks consistent with 50 keVr (estimated from range, not energy calibration)







DMTPCino Milestones (from LOI)

BOLD = since March EAC

- Amplification region
  - -complete segmentation R&D, Dec. 2014 (DONE)
  - -commission 1st full prototype amplification region, Jan. 2015 (DONE)
  - -complete amplification region production, Mar. 2015 **(DONE*)**
- Field cage
  - -Rn emanation of materials, Nov. 2014 (DONE)
  - -complete production, Dec. 2014 **(DONE)**
  - -commission field cage, Jan. 2015 -> Mar. 2015 **(campaign #2 in progress)**
- readout
  - -complete integration of cameras with multi-thread DAQ, Dec. 2014 (DONE)
  - -complete integration of charge digitizers with DAQ, Feb. 2015 **(DONE)**
- vacuum system
  - -complete integration with slow control, Oct. 2014 (DONE)
- surface commissioning
  - -measure detector performance with calibration sources, Jul. 2015 **(in progress)**
  - -measure directionality with d-d source, Aug. 2015 **(in progress)**
  - -measure in-situ backgrounds in surface run, Oct. 2015 **(in progress)**

target: ready for deployment underground Summer 2016

Recent Progress

Detector Milestones:

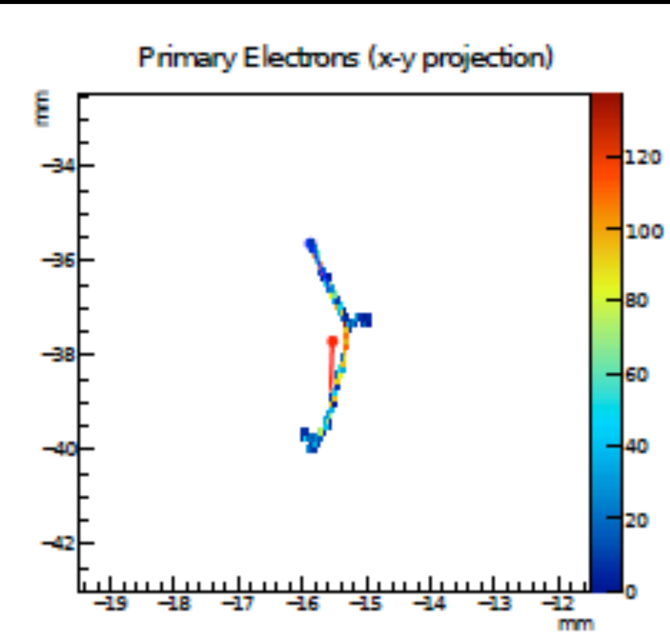
1. Completion of first TPC
2. Completion of new amplification region scheme
3. First light!
4. Gain measurement, 50% increase

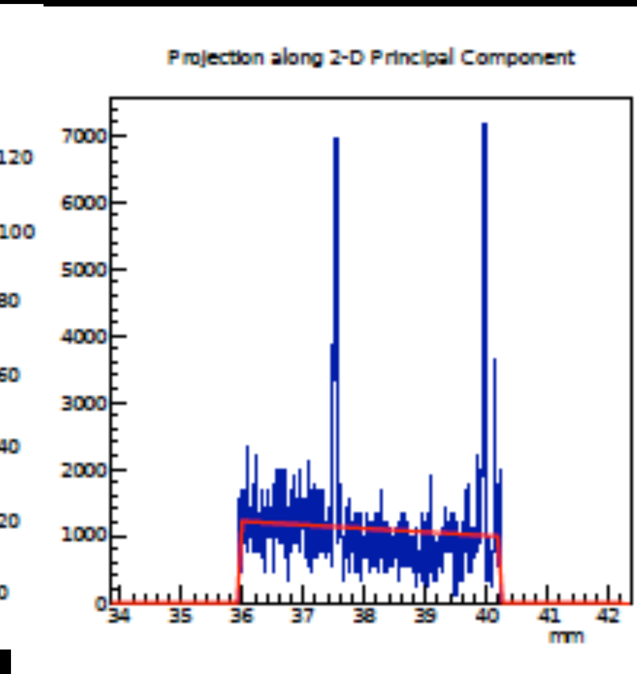
Physics Milestones:

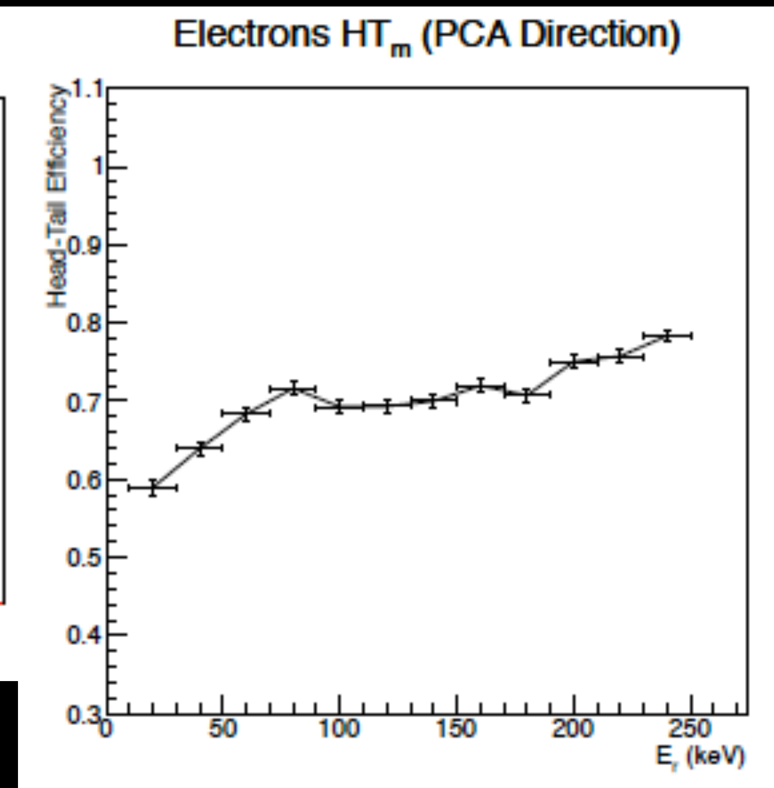
1. Complete microphysics simulation
2. Directionality analysis for detector optimization

Full Microphysics Simulation *(C. Deaconu CYGNUS'15)*

Generated Ionization:







(TRIM simulation)

Full Microphysics Simulation *(C. Deaconu CYGNUS'15)*

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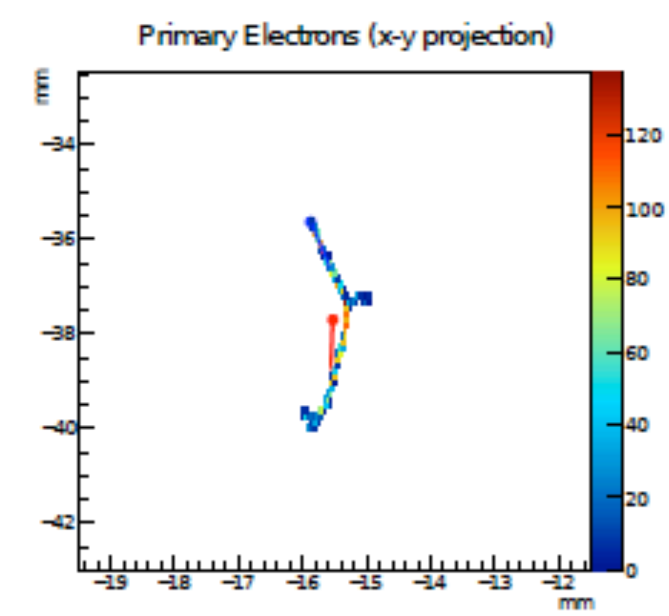
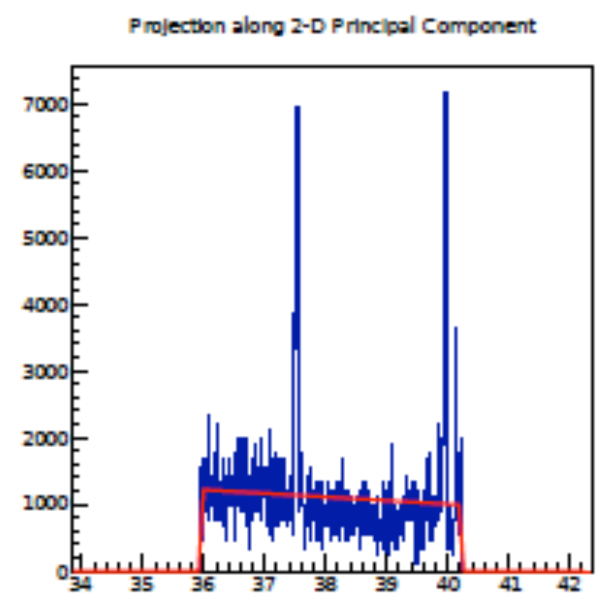
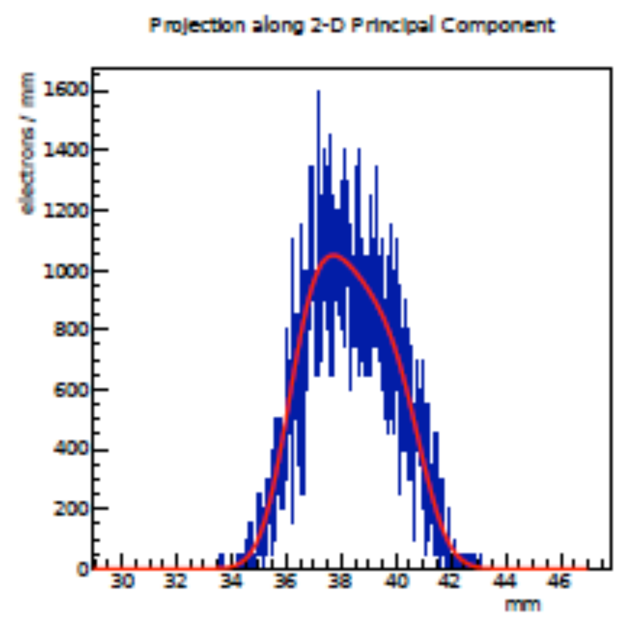
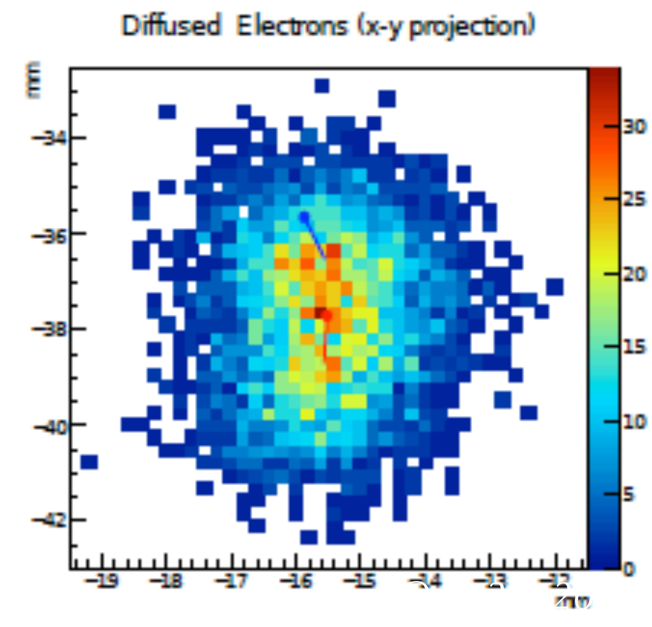




TRIM simulation
+ HEED cluster generation
+ MagBoltz

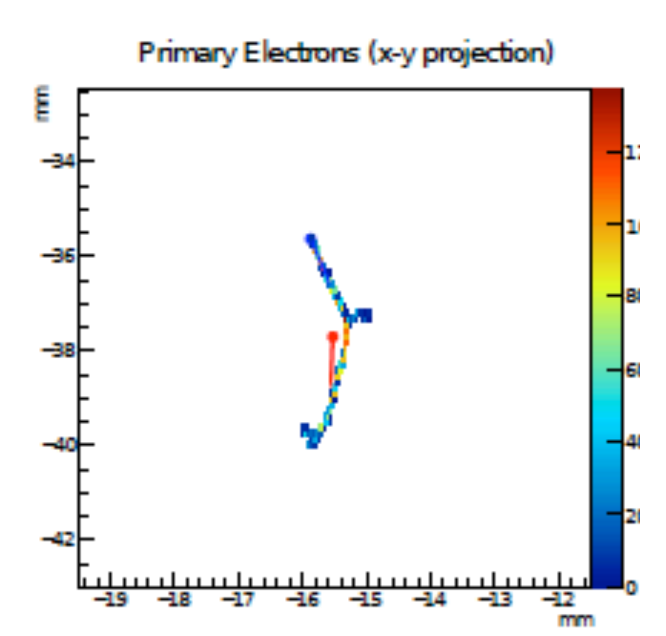
+ diffusion =

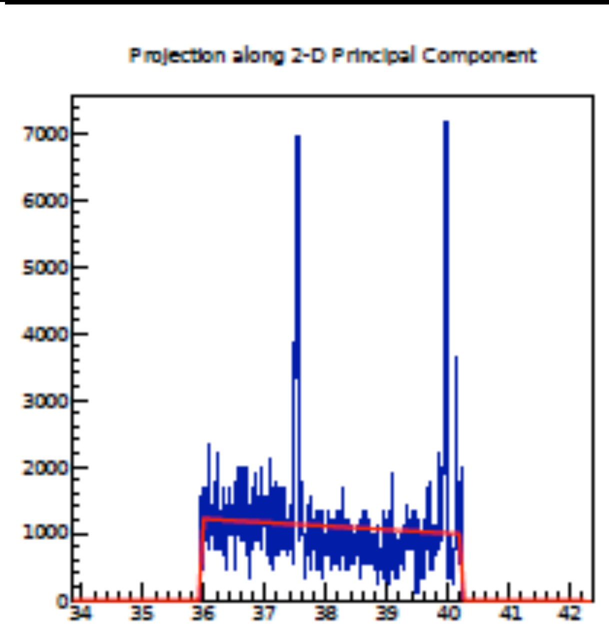




Full Microphysics Simulation *(C. Deaconu CYGNUS'15)*

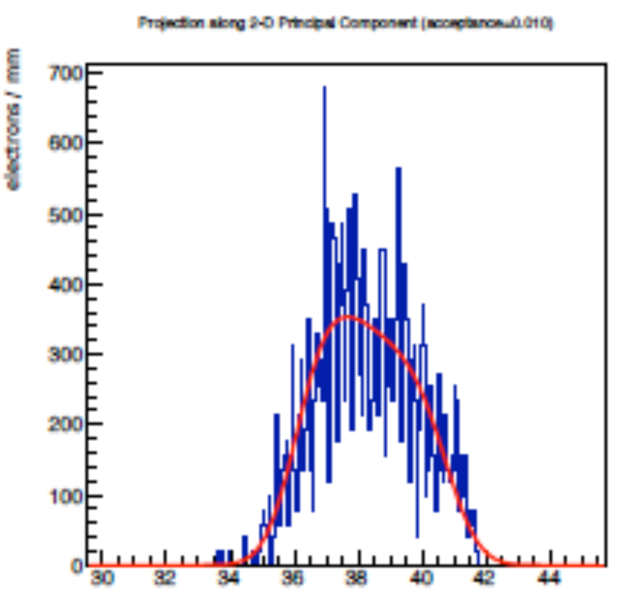
Generated Ionization:

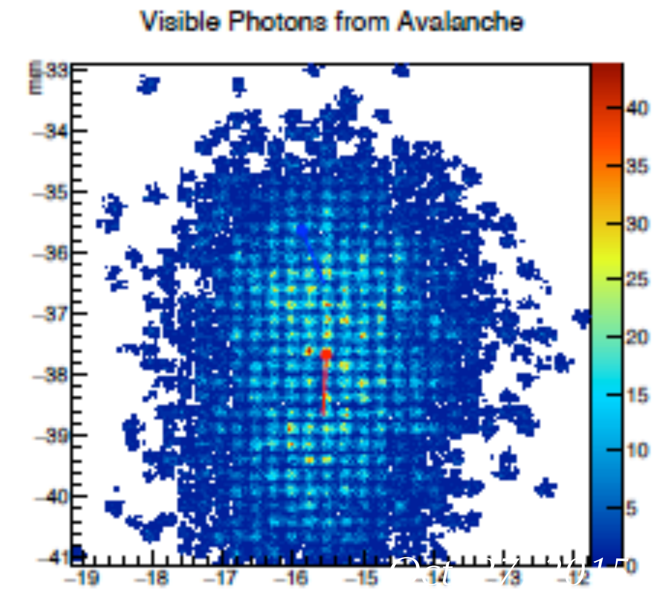




TRIM simulation
+ HEED cluster generation
+ MagBoltz
+ GARFIELD

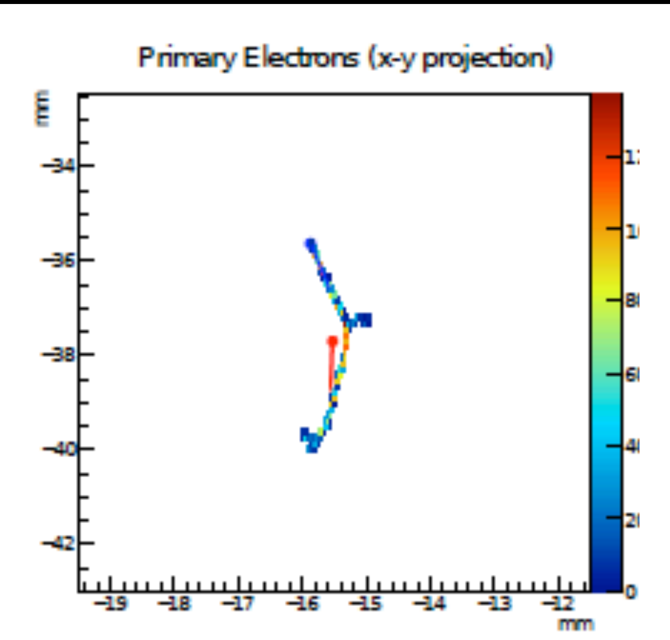
+ diffusion and amplification =

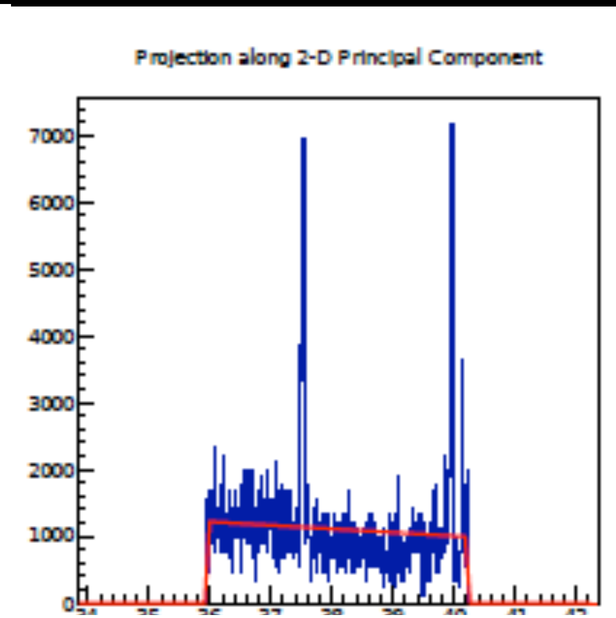




Full Microphysics Simulation *(C. Deaconu CYGNUS'15)*

Generated Ionization:

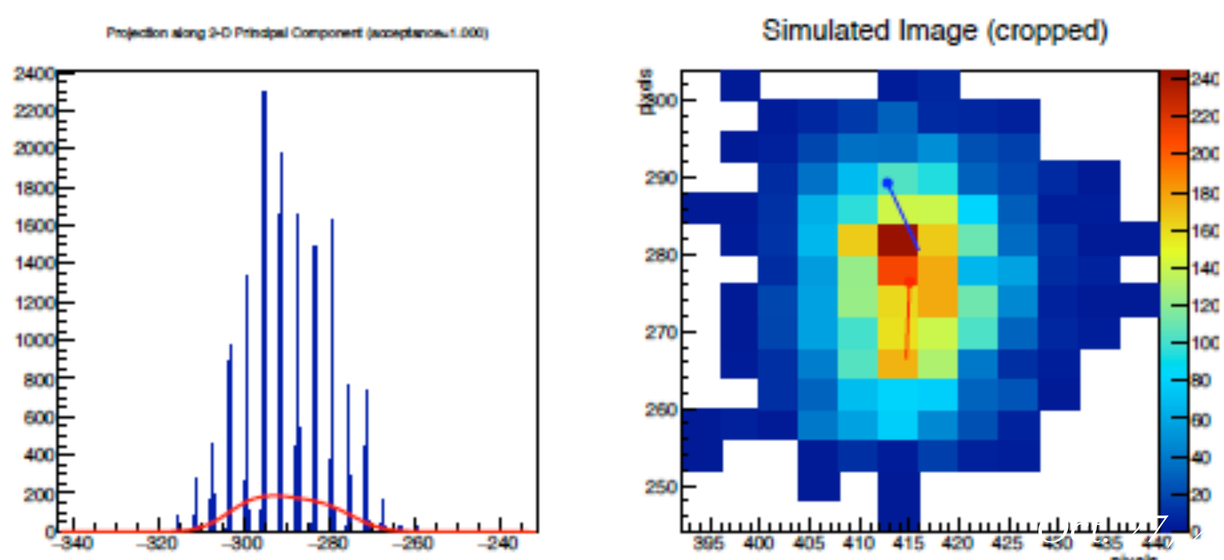




TRIM simulation
+ HEED cluster generation
+ MagBoltz
+ GARFIELD
+ readout model

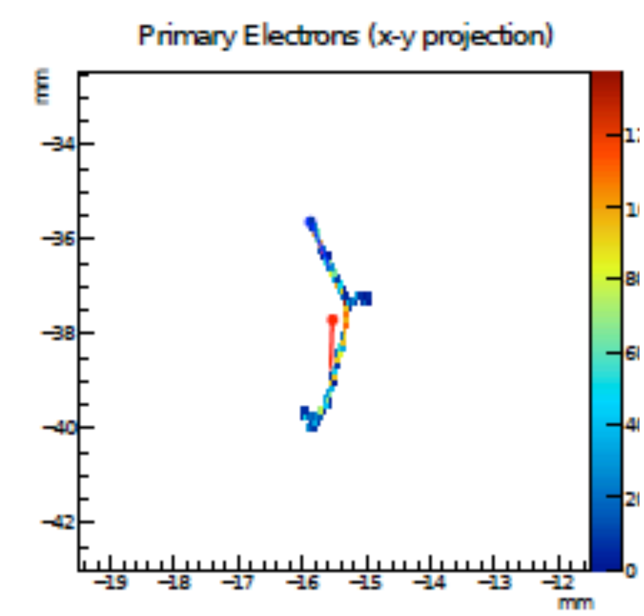
+ diffusion, amplification, attrition, binning

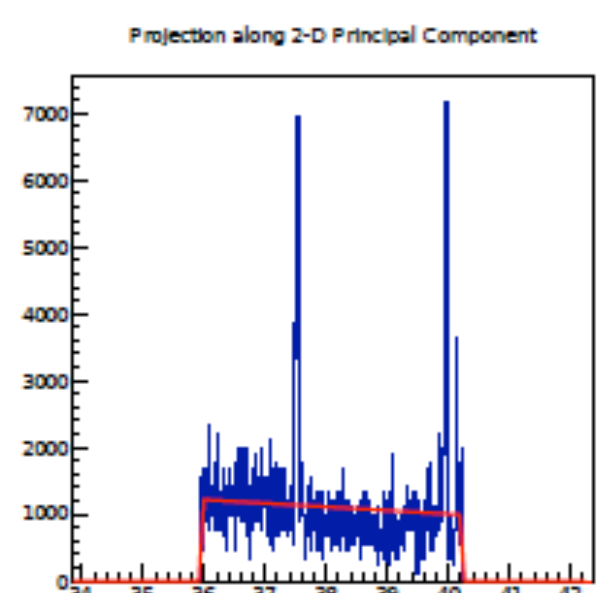
=



Full Microphysics Simulation *(C. Deaconu CYGNUS'15)*

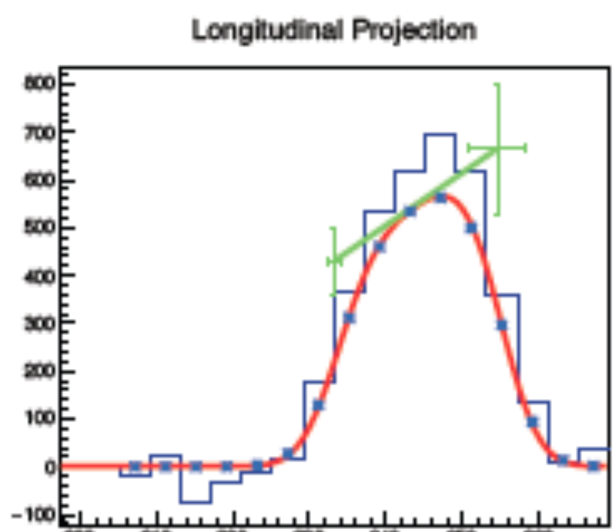
Generated Ionization:

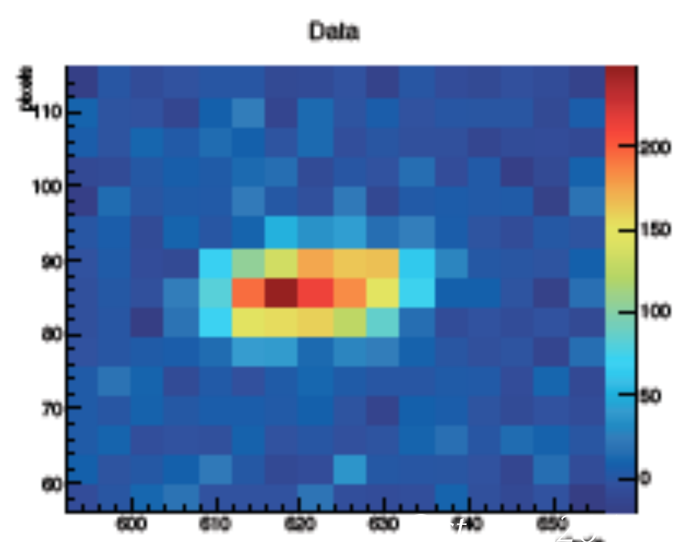




TRIM simulation
+ HEED cluster generation
+ MagBoltz
+ GARFIELD
+ readout model
+ cluster finding
+ 2D likelihood

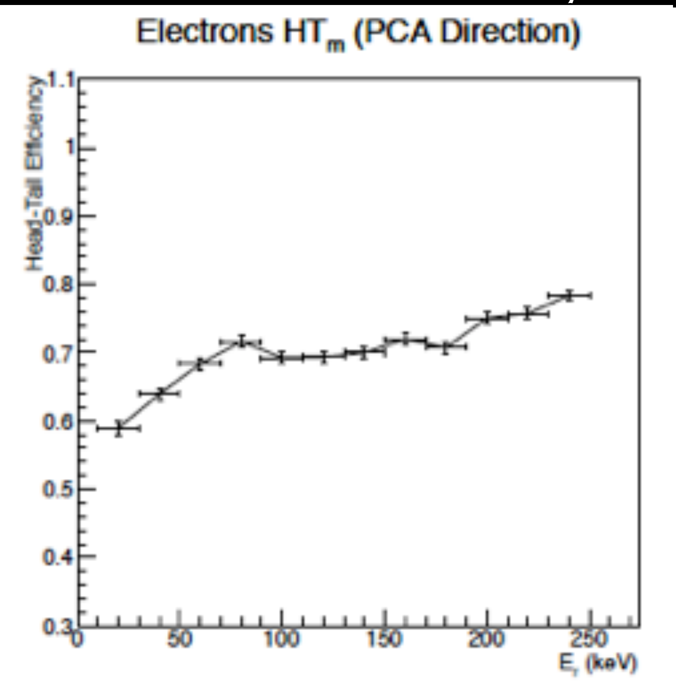
+ track reconstruction



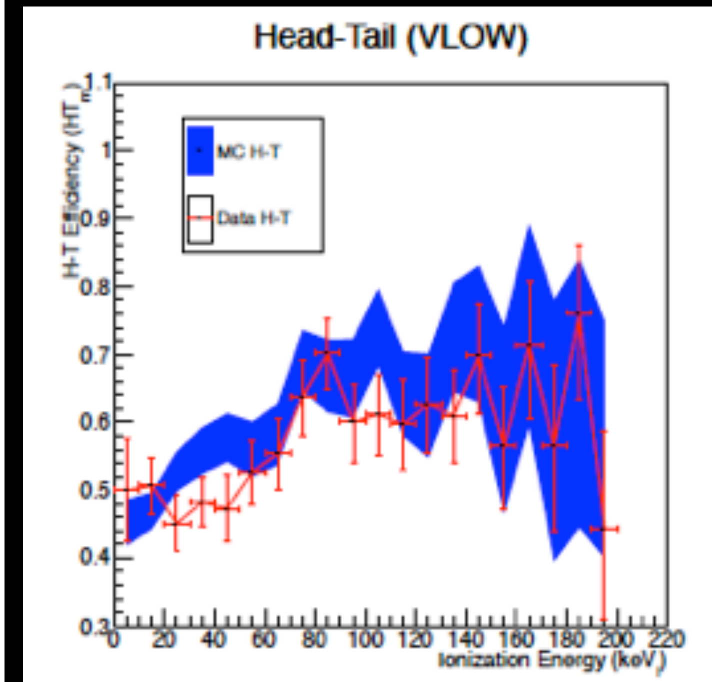


Full Microphysics Simulation *(C. Deaconu CYGNUS'15)*

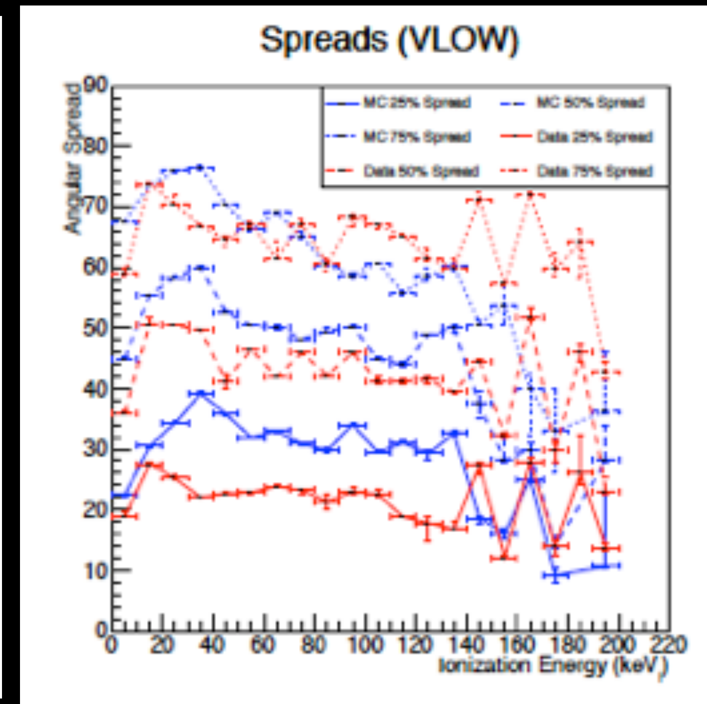
Generated at Primary:



Reconstructed:



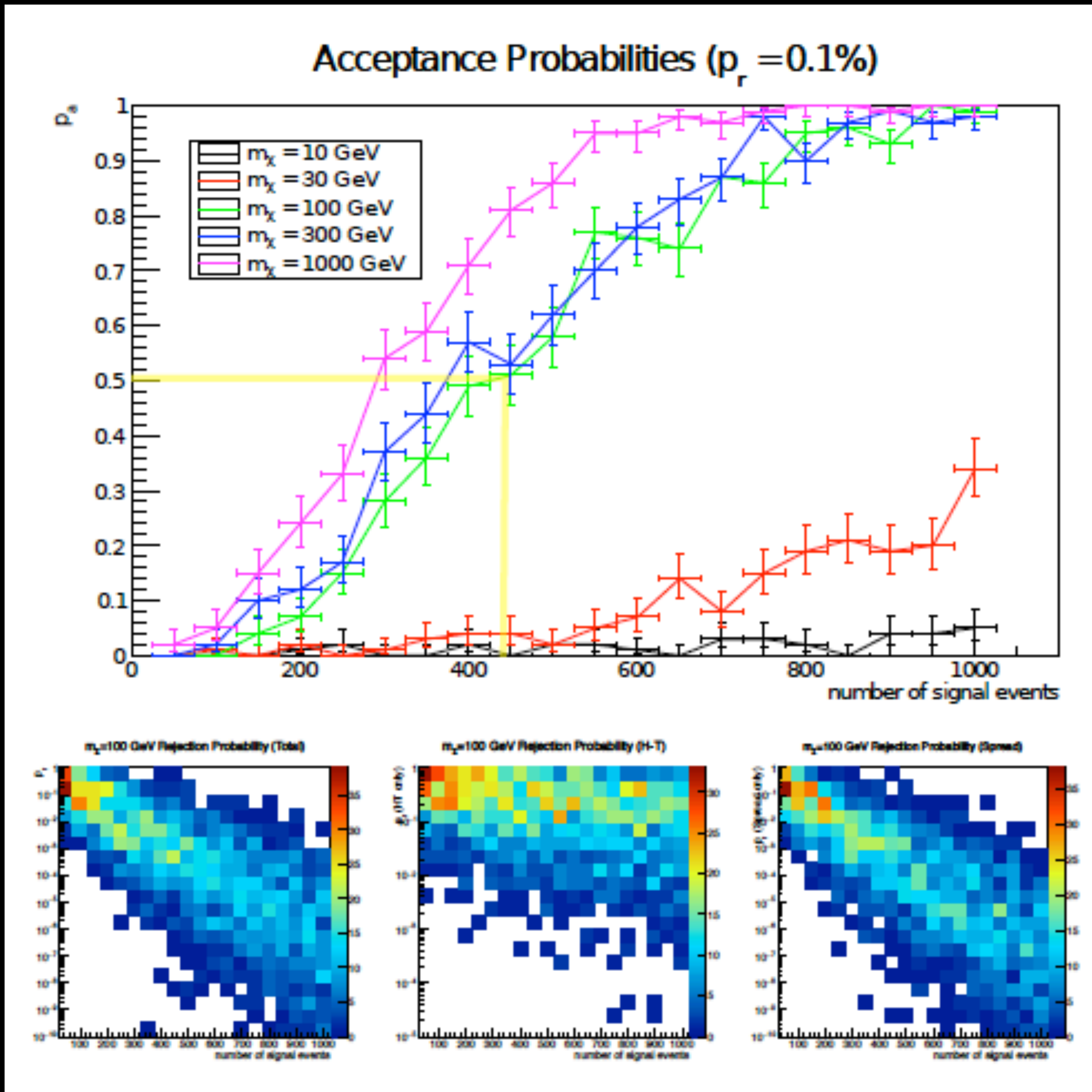
Resolution:



Bottom lines:

- we are reconstructing vector direction (including head-tail) at ~physics limit from straggling of primary F ion. Need to reduce ion straggling!
- axial resolution is ~40 degrees (FWHM) at 50 keVr
- MC predicts ~50% larger spread in angle than we observe

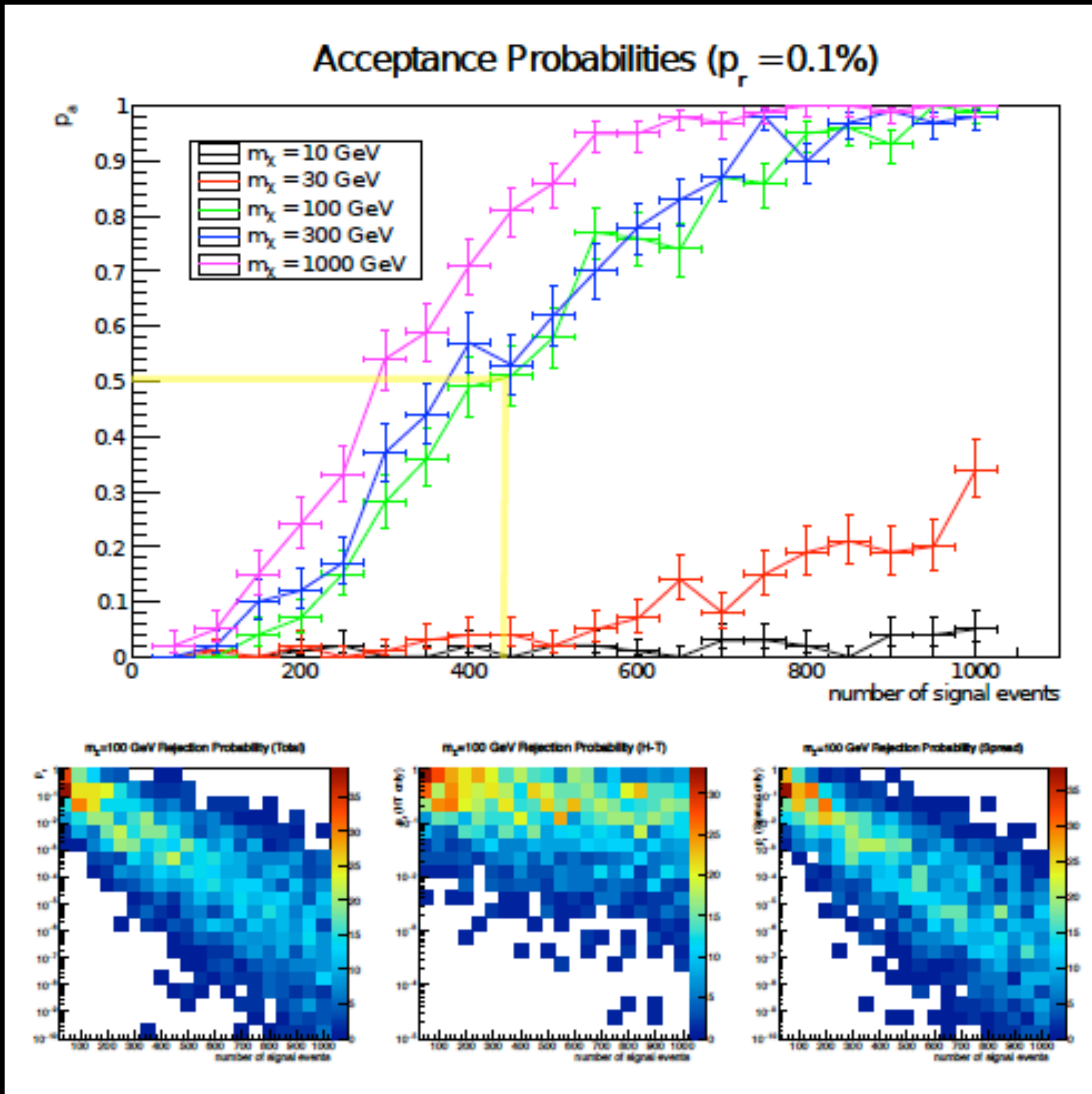
m3 Physics Sensitivity Projection



<u>Analysis assumptions</u>

- Use physics model tuned on data, assume 100k gain
- simulate *n* experiments, compute forward fraction and axial spread per bin
- calculate *p* of obtaining these values from isotropic distribution, and combine bins using Fisher's method
- Result: need 450 events to measure anisotropy at 3σ in >50% of experiments

m3 Physics Sensitivity Projection



Analysis assumptions

e.g. DEAP veto: 200 m^3

- Result: need 450 events to measure anisotropy at 3σ in >50% of experiments

(= 500 [300] m3-years for 100 (1000) GeV/c^2 DM at 1 fb SD xsec on F)

(=25 kg-years)

Outlook

Aboveground To Do Before U/G Deployment:

1. integration for 1Shooter CCD (in progress)
2. PMT installation for 1Sh trigger (in progress)
3. gas purification loop (under design now)
4. neutron direction calibration (in progress)
5. *CH-4 and He mixture studies to reduce straggling (if promising, redo step 4)*
6. Vessel electropolishing (+support rail alignment issue to resolve)

Deployment preparation:

1. SNOLAB Technical review
2. get deployment funding! (UK-CONACyT submitted, H2020?)

CYGNUS-Jan'15, for Discussion

Physics goals for next step: have to be **competitive**

- measure directionality: need O(100 events) = O(100 m3-yrs) = 25 kg-yrs in DMTPC *now* (assumes DMTPC threshold, resolution, CF4 target, etc.)
- current limit is 1E-39 cm2, experiments will reach 1E-40 cm2 in next yr or so. To be competitive we should aim for sensitivity to ~1E-42 cm2. (yikes! 1E-41 cm2 sensitivity is 4m x 4m x 4m, in DMTPC now)

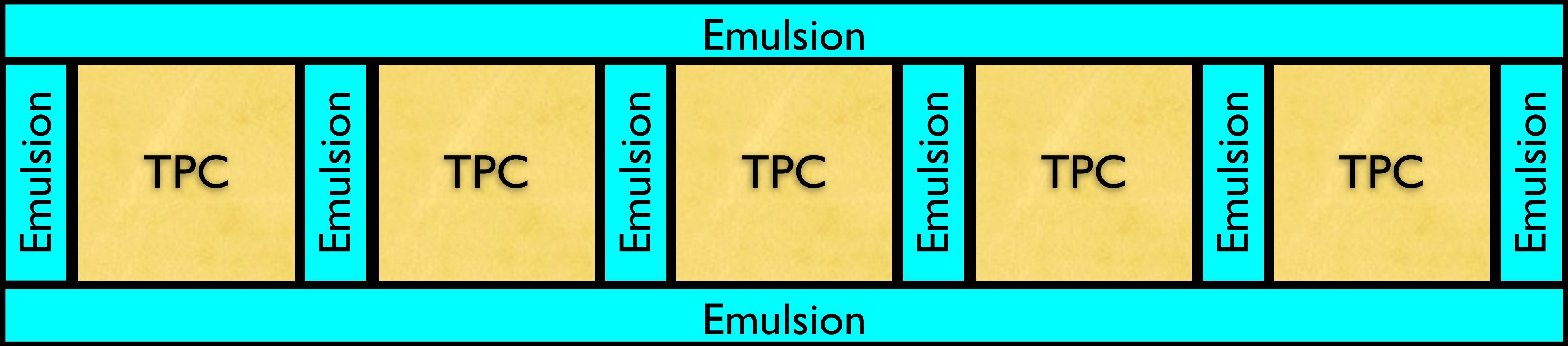
How to get there:

- This is a macroscopic detector so every factor of 2 matters!
  (Yes, 1D vs. 2D is a factor of 2-3, but I think we need this factor! Same comment w.r.t. head-tail. This needs to factor into figure of merit.)
- we can reconstruct vector direction (including head-tail) at ~physics limit from straggling of primary F ion. Need to reduce on straggling! Different, heavier gas? Or mixture of targets? Even mixture of modules?
- need microphysics input, situation might be better than this(?) since MC predicts ~50% larger spread in angle than we observe

CYGNUS-Jan'15, for Discussion

Inclusive concept… multi-target detector

Bonus: emulsion detector as neutron shielding! May be able to use neutron multiple scattering tag?

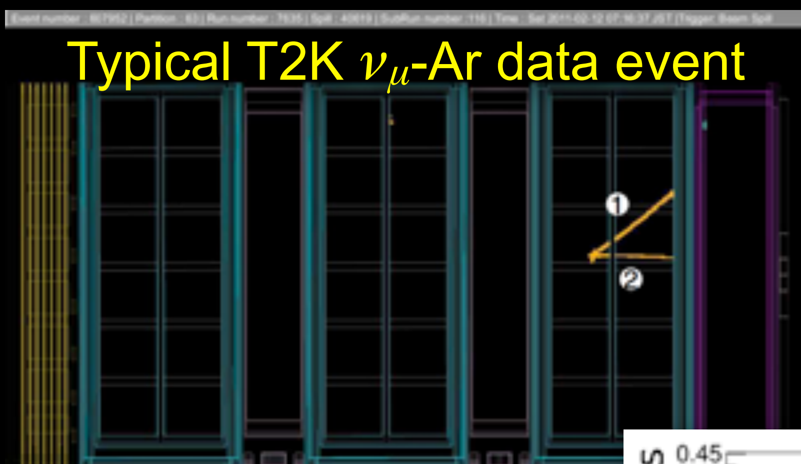


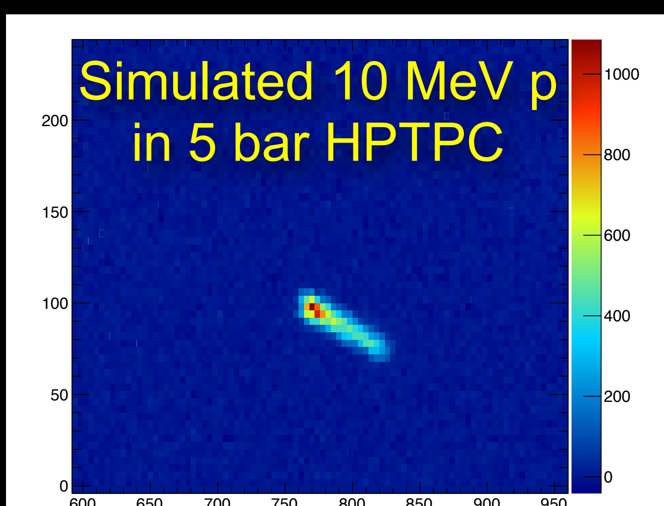
Connection with R&D for Neutrinos:

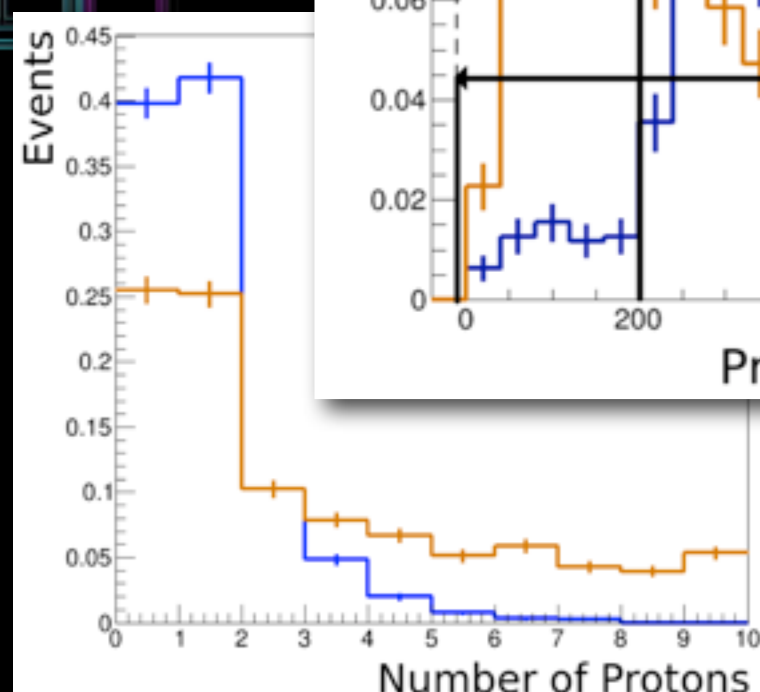
High Pressure Gas TPC for Neutrino Physics:

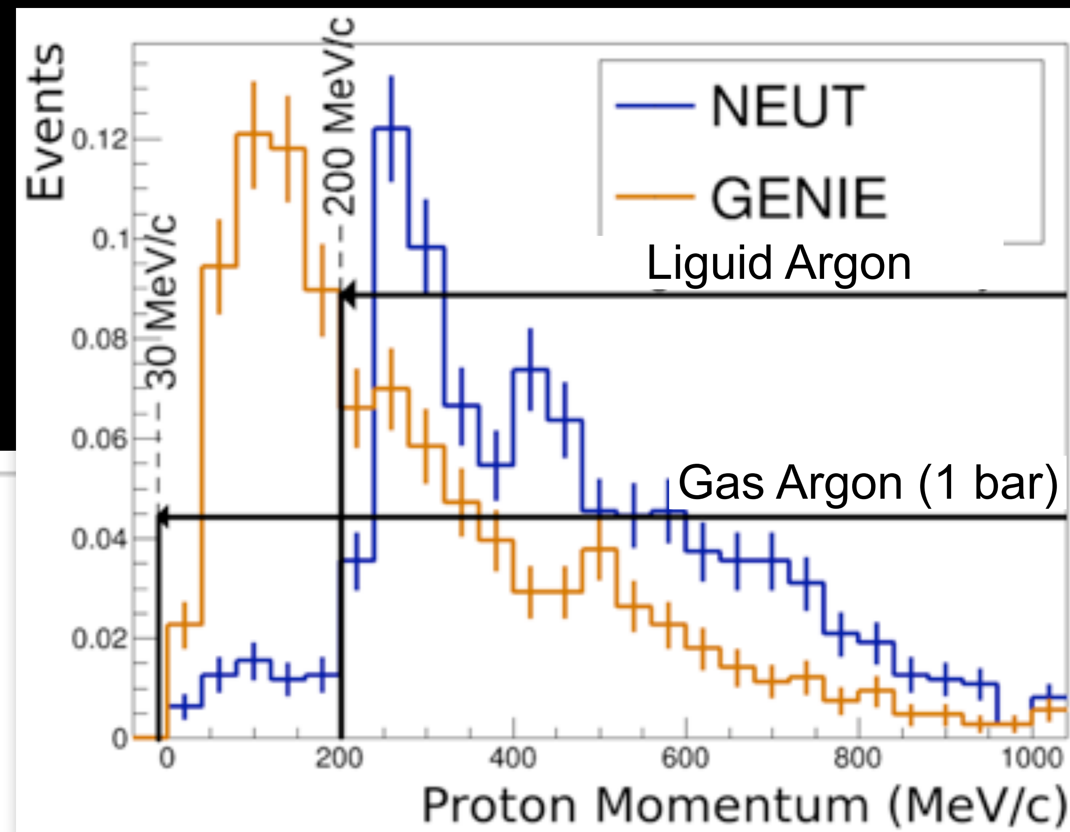
goal: reduce neutrino cross section systematics to 1-2% for CP violation search in long-baseline neutrino oscillation experiments, with HPTPC near detector

- have STFC funding to build HPTPC prototype for beam test at CERN









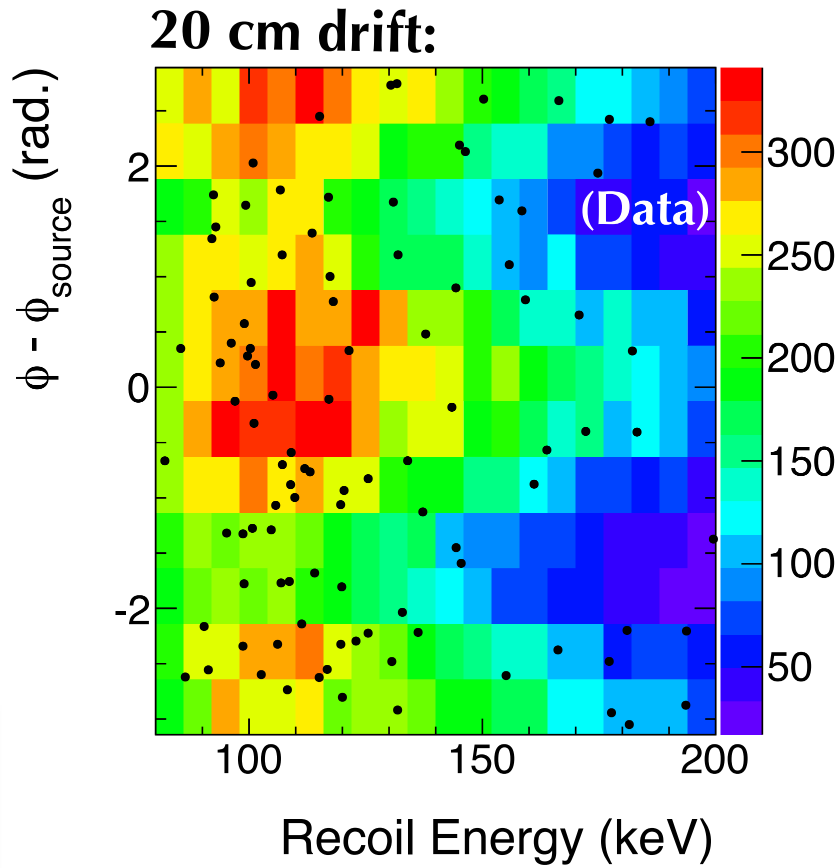
P. Hamilton (Imperial), NuInt14

Additional

Directionality

diffusion has a big impact!

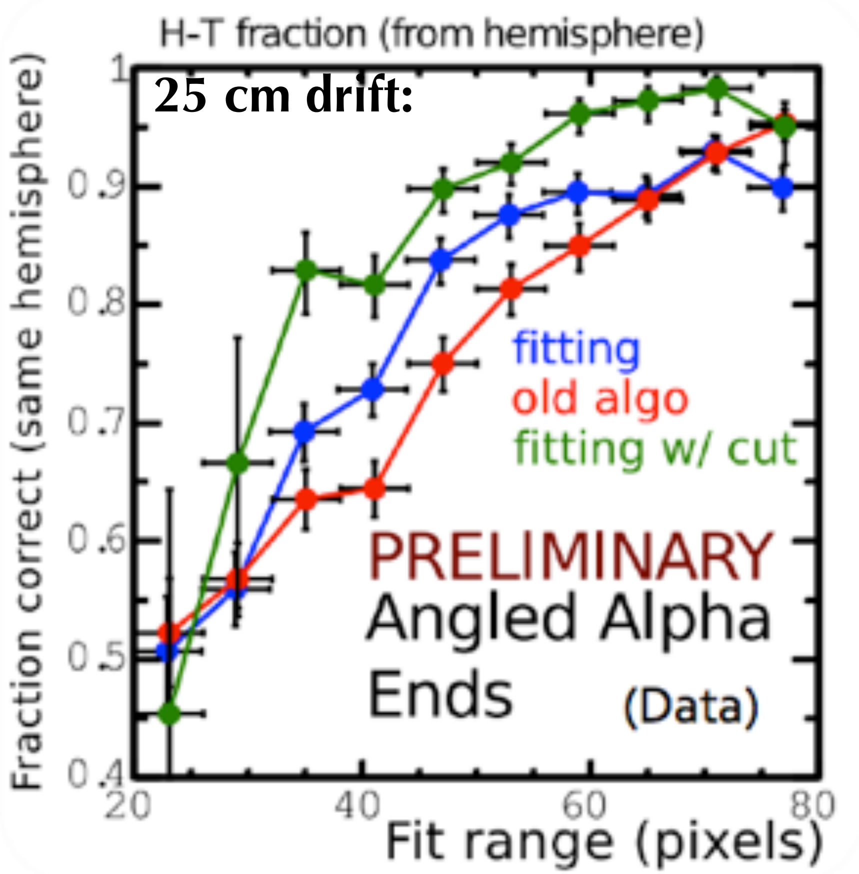
- measure with 20, 25 cm drift, in 10L and 4sh prototypes
- find direction reconstruction depends most on track length
- head-tail ID correct in >75% of events when length/width>3



angle vs. E:
^{252}Cf source (color hist.)
“WIMP ” data (black points)

S. Ahlen et al., Phys. Lett. B 695 (2011)

A. Kaboth PhD,



Energy range equivalent ~50-200 keV