Guidance from Monte Carlo Studies for Detector Design

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Outline

- The proto-detector for neutron-antineutron oscillations at the ESS
- MC Acceptance Results
- Background Analysis and Challenges

NNBar at ESS

Adapt detector to pulsed cold neutron source driven by 5 MW spallation target with very large increase in flux due to concentrating optics

- Goal: **0 background events, ε > .5 for annihilation events**

Background Challenges:

- High energy n/p backgrounds present during proton beam
- Larger CN fluxes and optics will increase capture gamma rates
- Fast n's (0-10 MeV) present due to beta-delayed n's
- Larger detector volume will increase cosmic and capture gamma rates
- Must be sufficient for longer running periods (1y for ILL→3y+)

NNBar (Dream) Proto-Detector Simulation: a Work in Progress

Geant simulations by D. G. Phillips, II

- All sims use Geant 4.9.6 (with every known library installed).

- GENIE nnbar event generator (5e4 events available).

- In this preliminary study, randomly selected 5e3 nnbar events.

- Generated 5e4 background events (n & p singles).

- Detector geometry consists of target, straw tube tracker & Minerva-style polystyrene/Pb calorimeter.

- Target is 100 um, 2 m diameter ^{12}C disk.
  Vacuum tube is 2 cm thick Al.

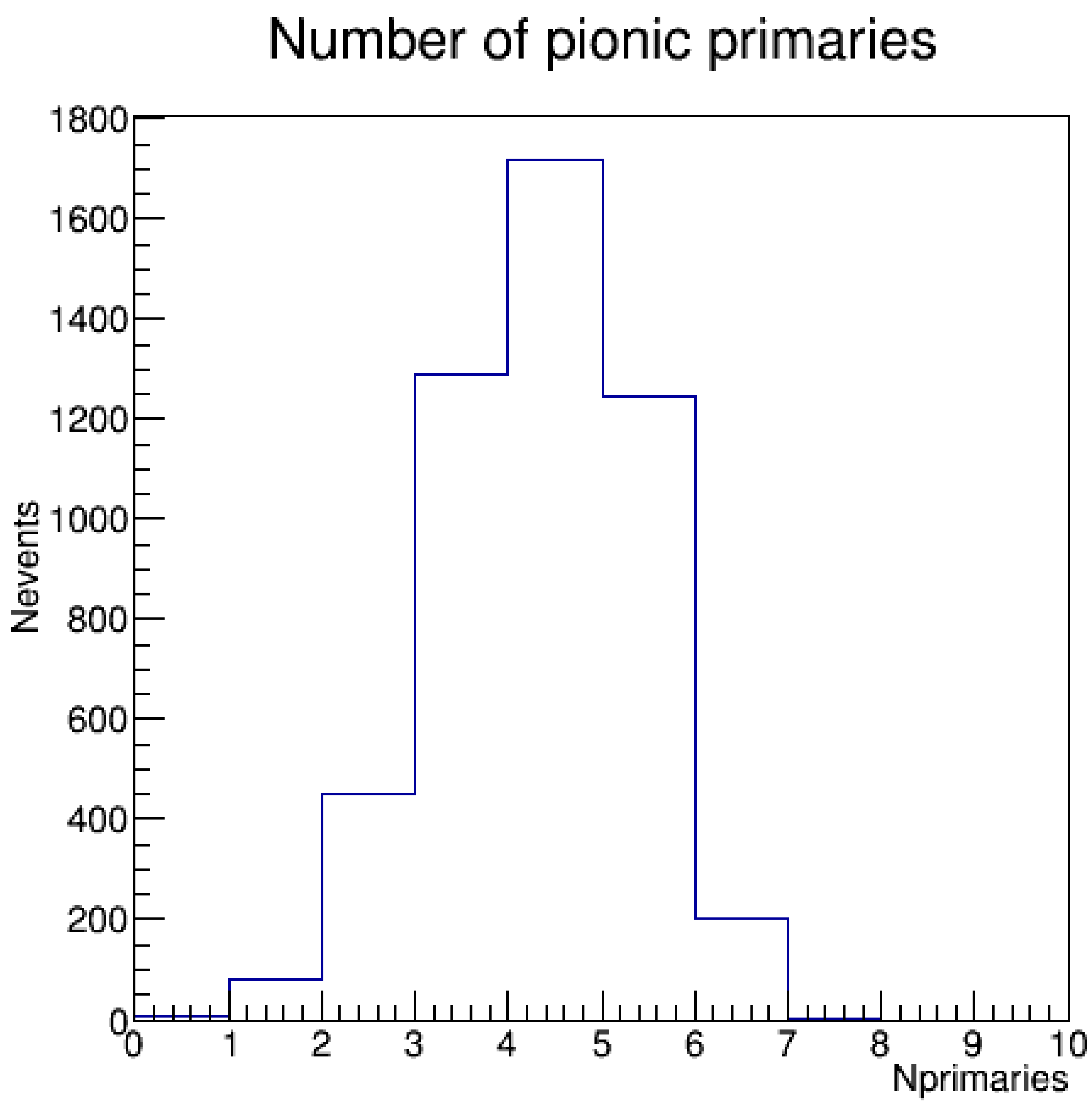
GENIE: NNBar Final State Primaries

Preliminary

Final state list prepared by R. W. Pattie

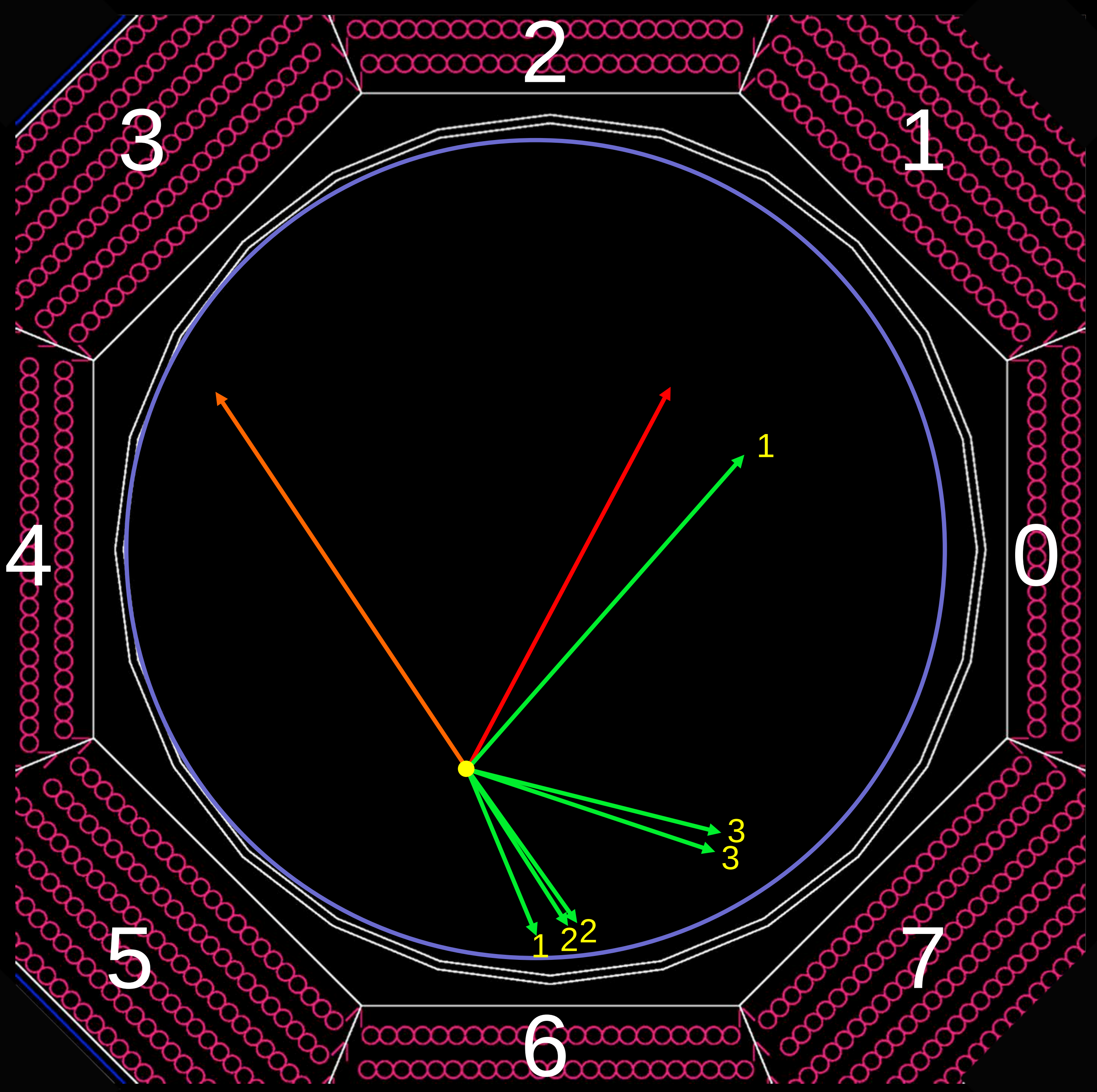
GENIE-2.0.0: intranculear propagation based on INTRANUKE

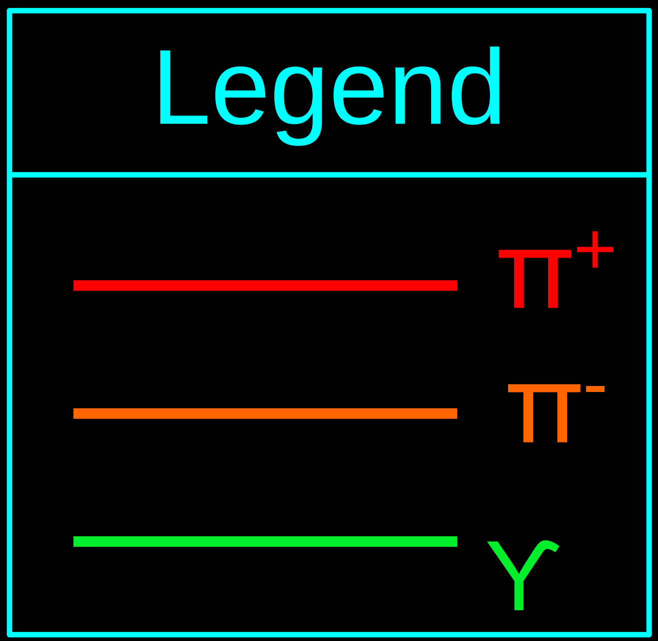
C.Andreopoulos et al., The GENIE Neutrino Monte Carlo Generator, Nucl.Instrum.Meth.A614:87-104,2010.



Final State Pionic Mode	Nevents	% Total
$\pi^+\pi^-2\pi^0$	530	10.60%
$2\pi^+\pi^-\pi^0$	486	9.72%
$\pi^+\pi^-\pi^0$	417	8.34%
$2\pi^+\pi^-2\pi^0$	409	8.18%
$\pi^+\pi^-3\pi^0$	329	6.58%
$2\pi^+2\pi^-\pi^0$	315	6.30%
$\pi^+2\pi^0$	290	5.80%
$\pi^+3\pi^0$	219	4.38%
$\pi^+\pi^-\omega$	145	2.90%
$\pi^+\pi^0$	137	2.74%
$\pi^+2\pi^-\pi^0$	132	2.64%
$2\pi^+2\pi^-$	124	2.48%

NNBar Proto-Detector Simulation





Annihilation Mode Event

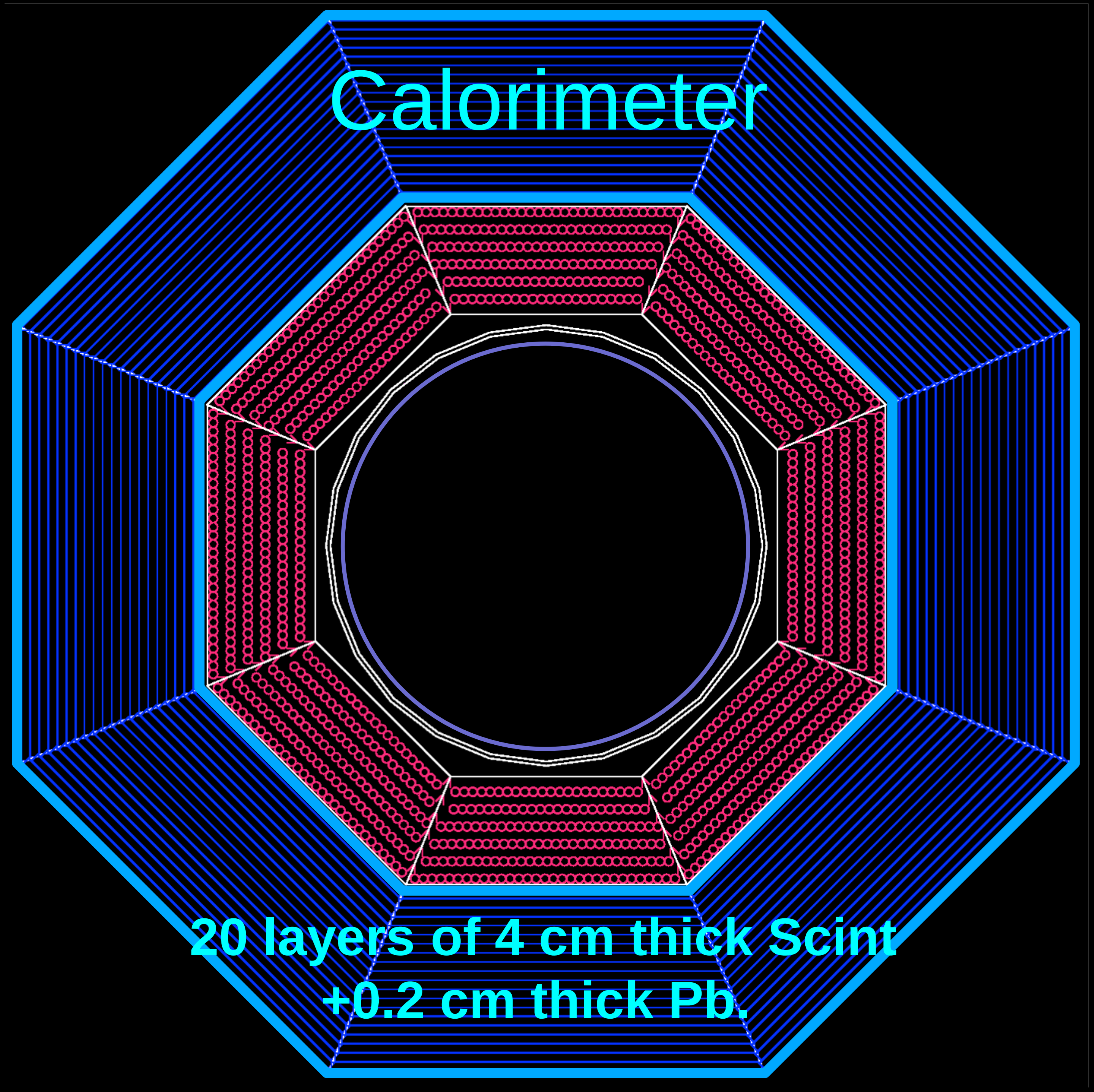
$\bar{n} + {}^{12}C \rightarrow {}^{11}C$

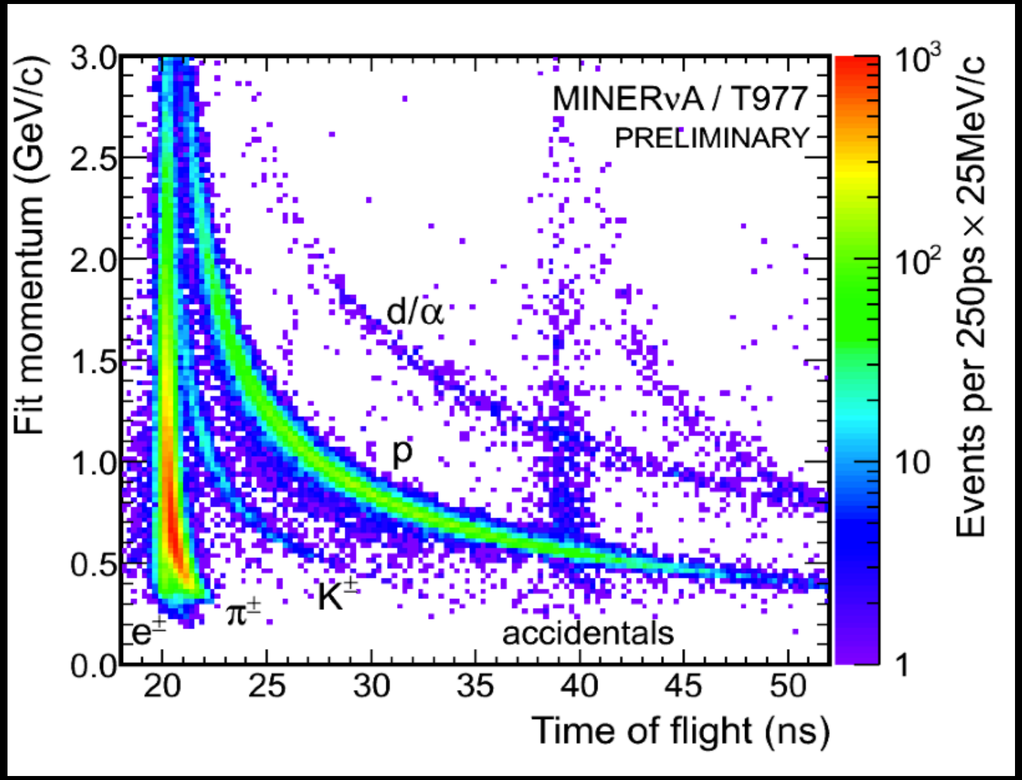
$+ 3\pi^0$ (45, 268, 320 MeV)

$+ \pi^+$ (81 MeV)

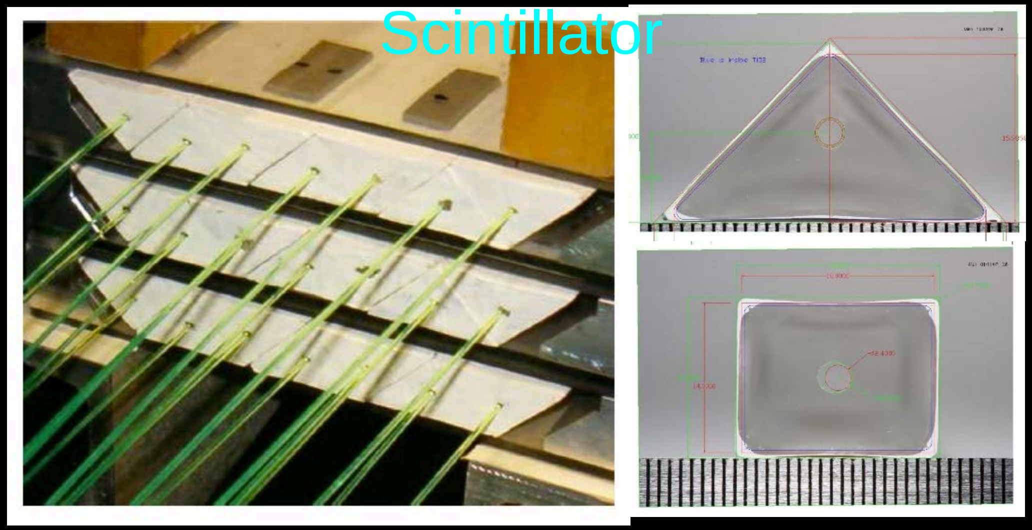
$+ \pi^-$ (207 MeV)

NNBar Proto-Calorimeter Geometry



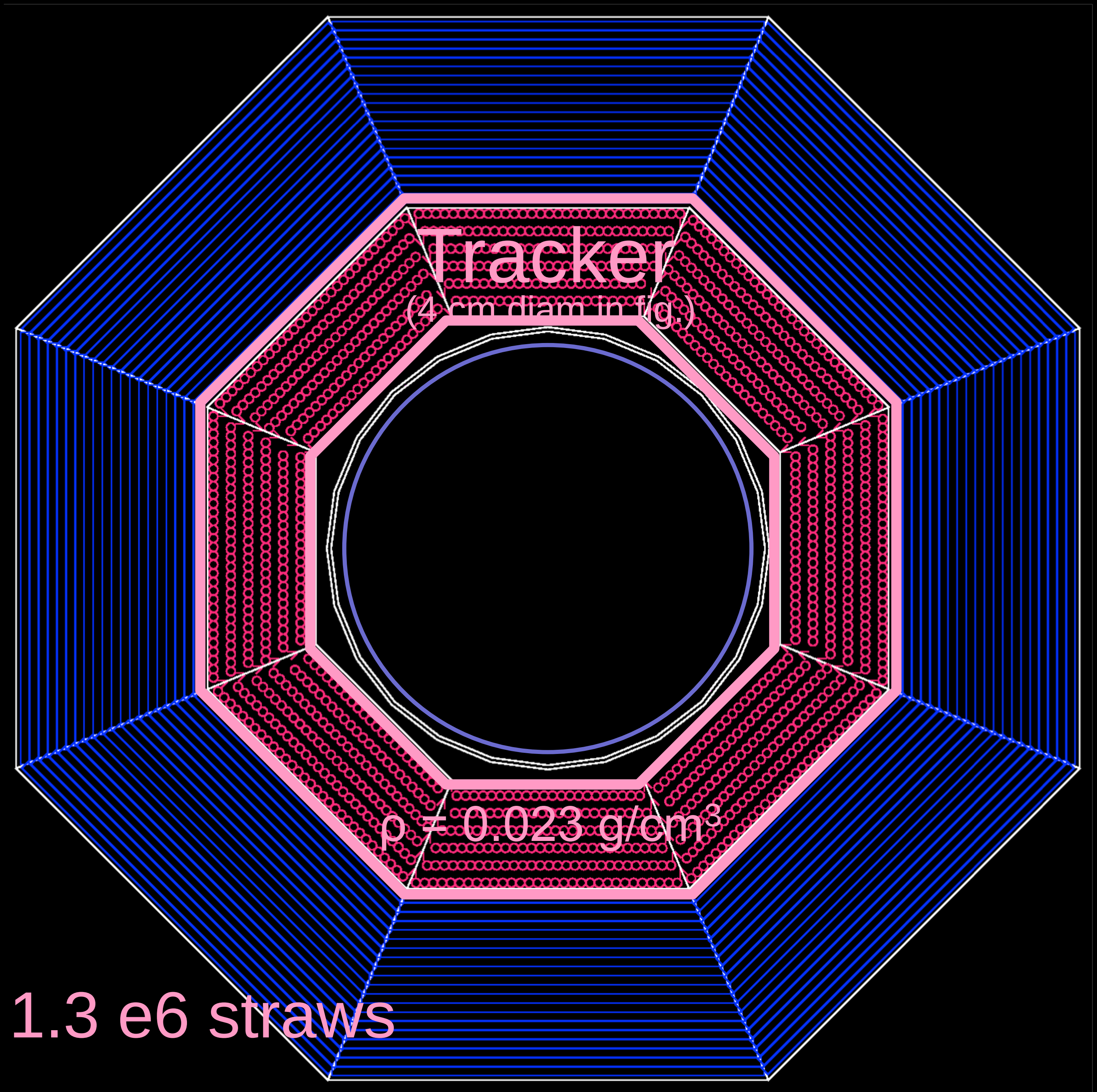


MINERvA-style Extruded Scintillator

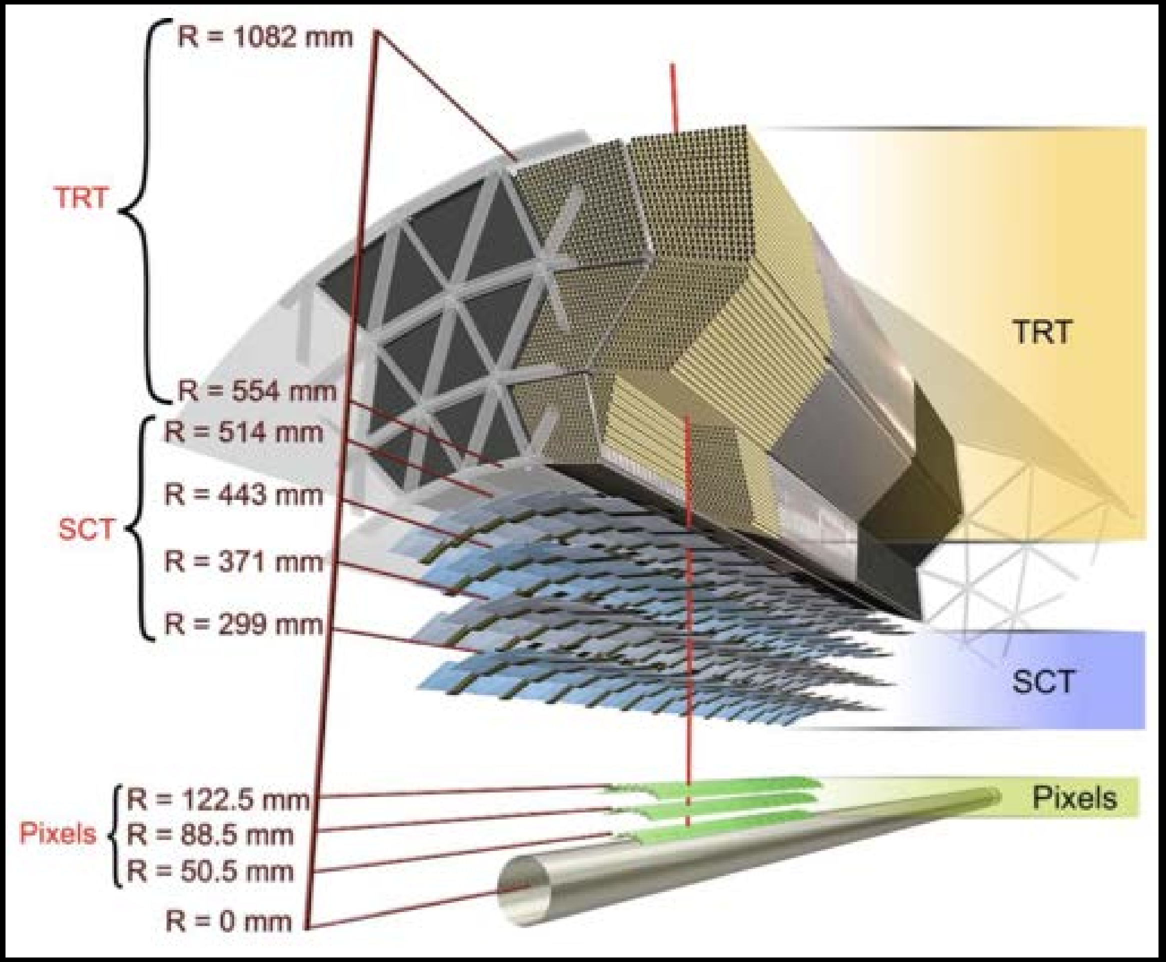


MINERvA images credit: E. Ramberg (FNAL)

NNBar Proto-Tracker Geometry

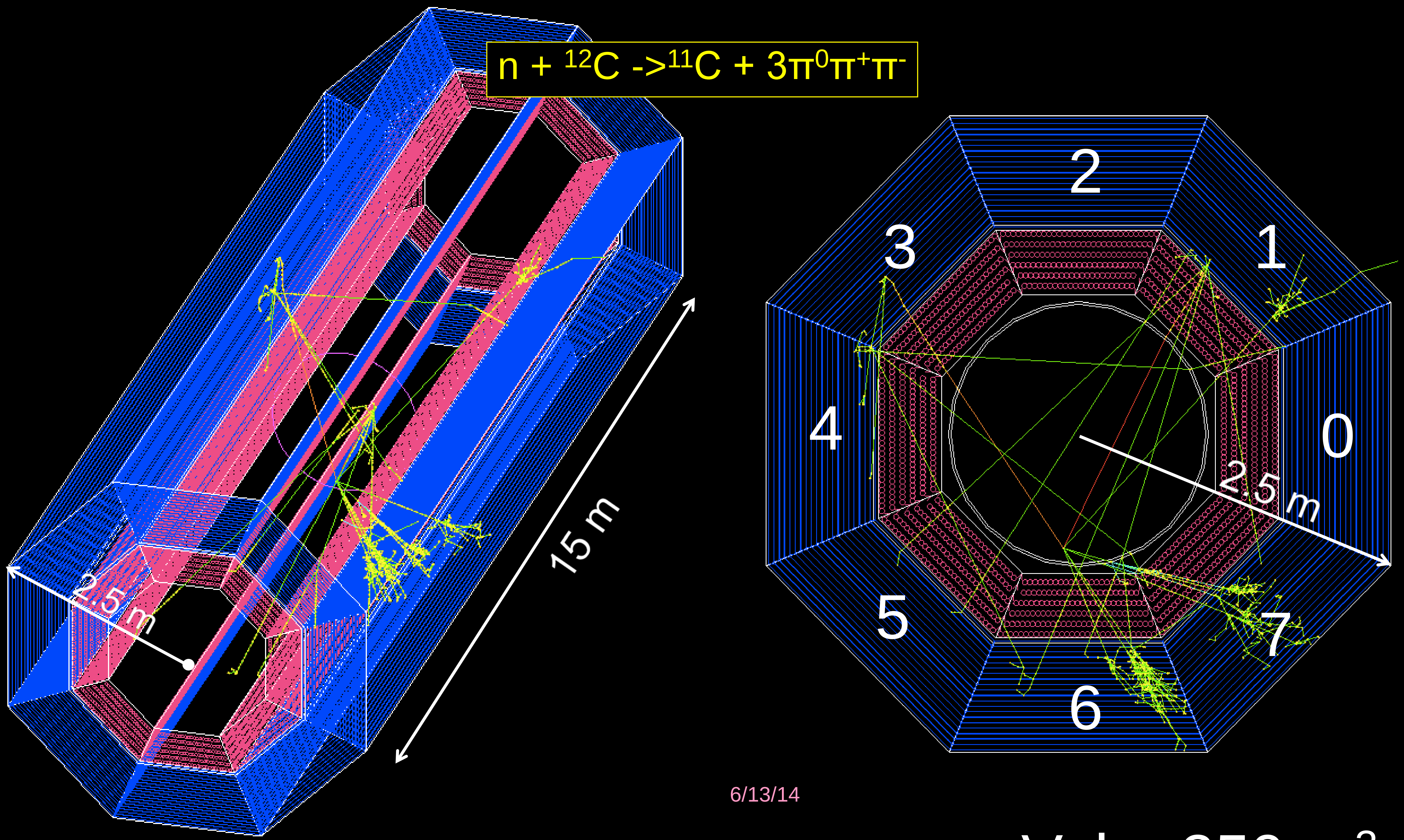


- 5 mm kapton straws
- Fill gas: 70% Ar, 30% CO_2.
- 50XY planes (0.5 m thick).



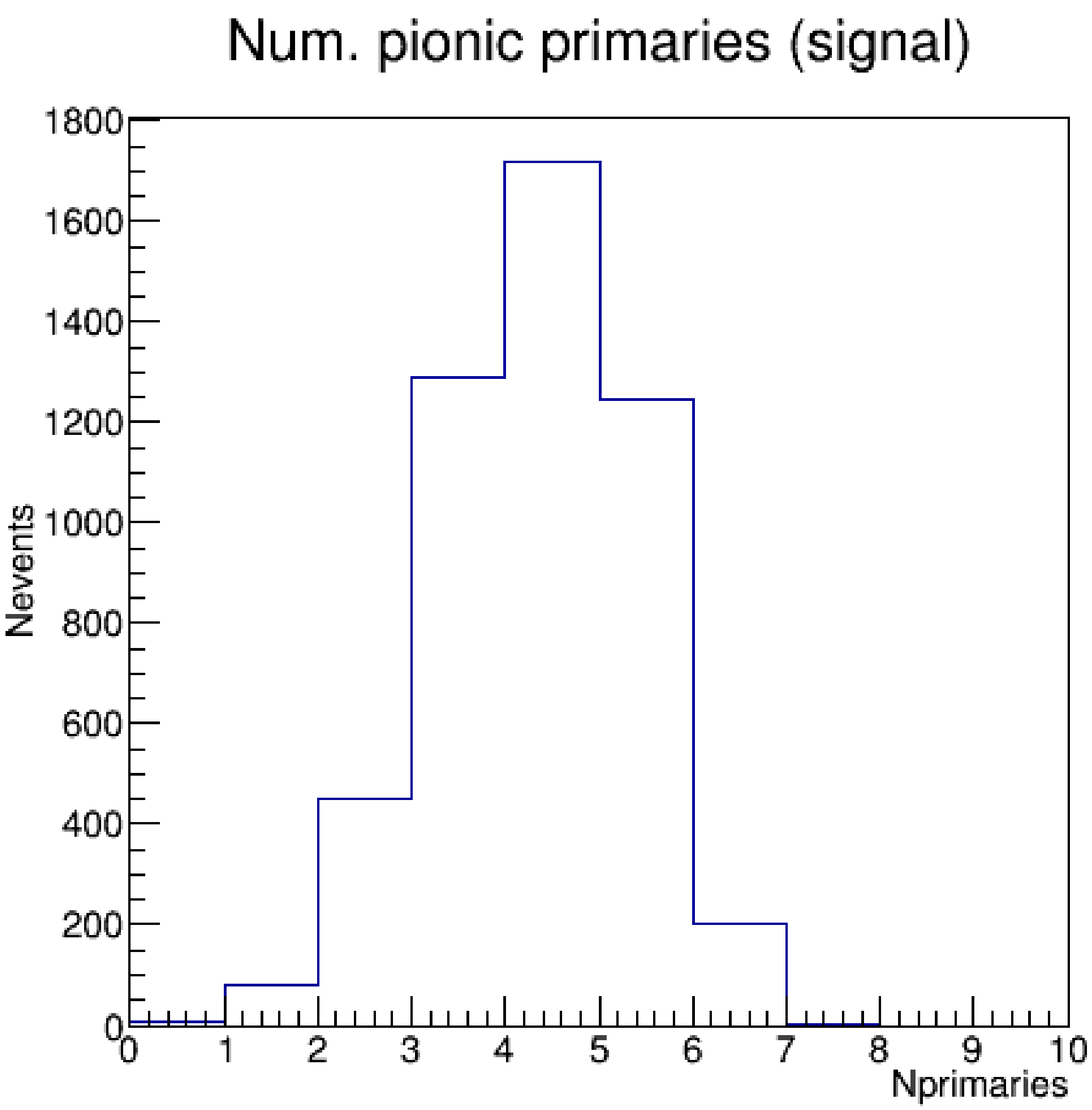
ATLAS TRT Assembly at Indiana University

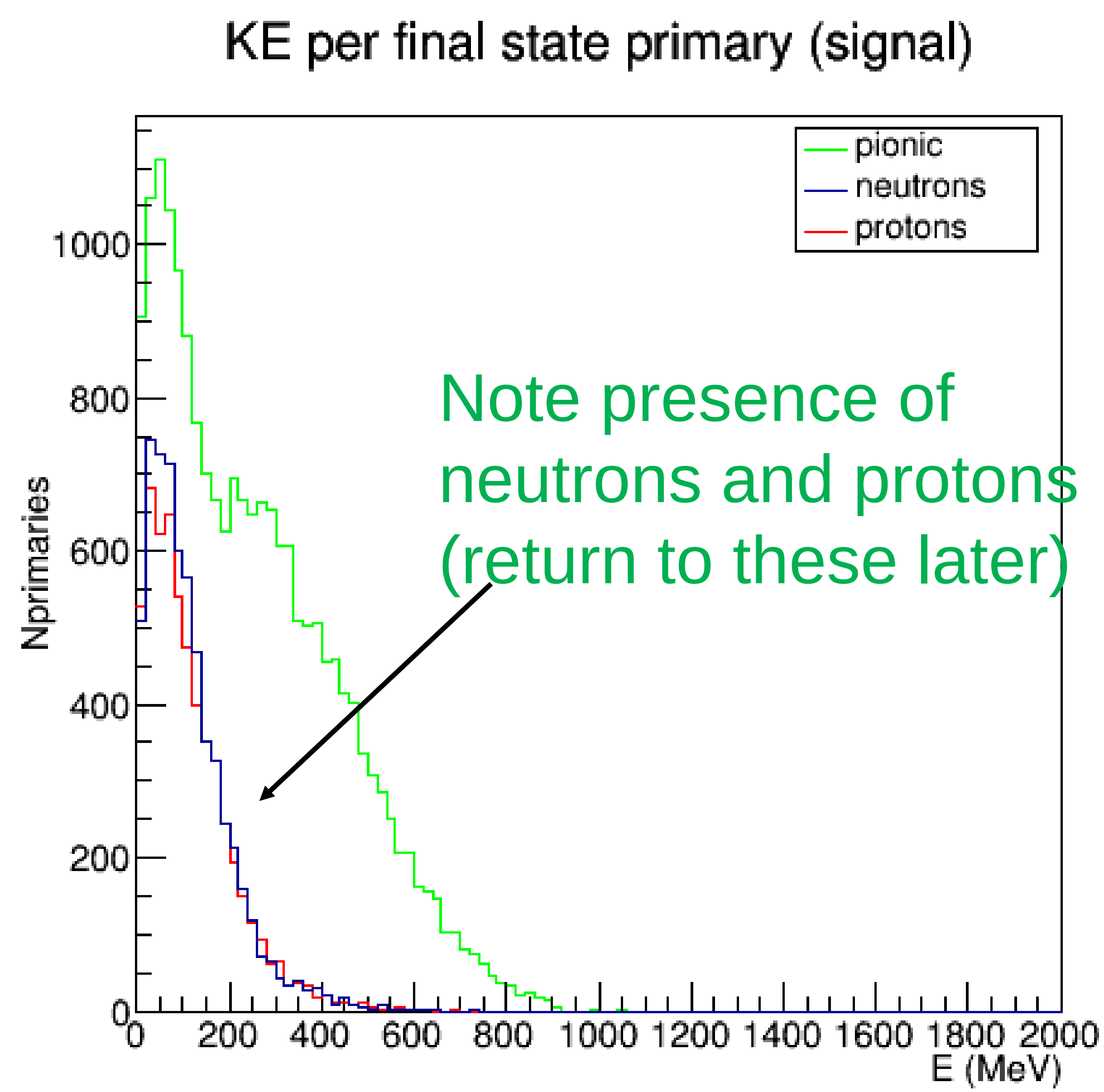
Event Reconstruction



Vol ~ 250 m^3

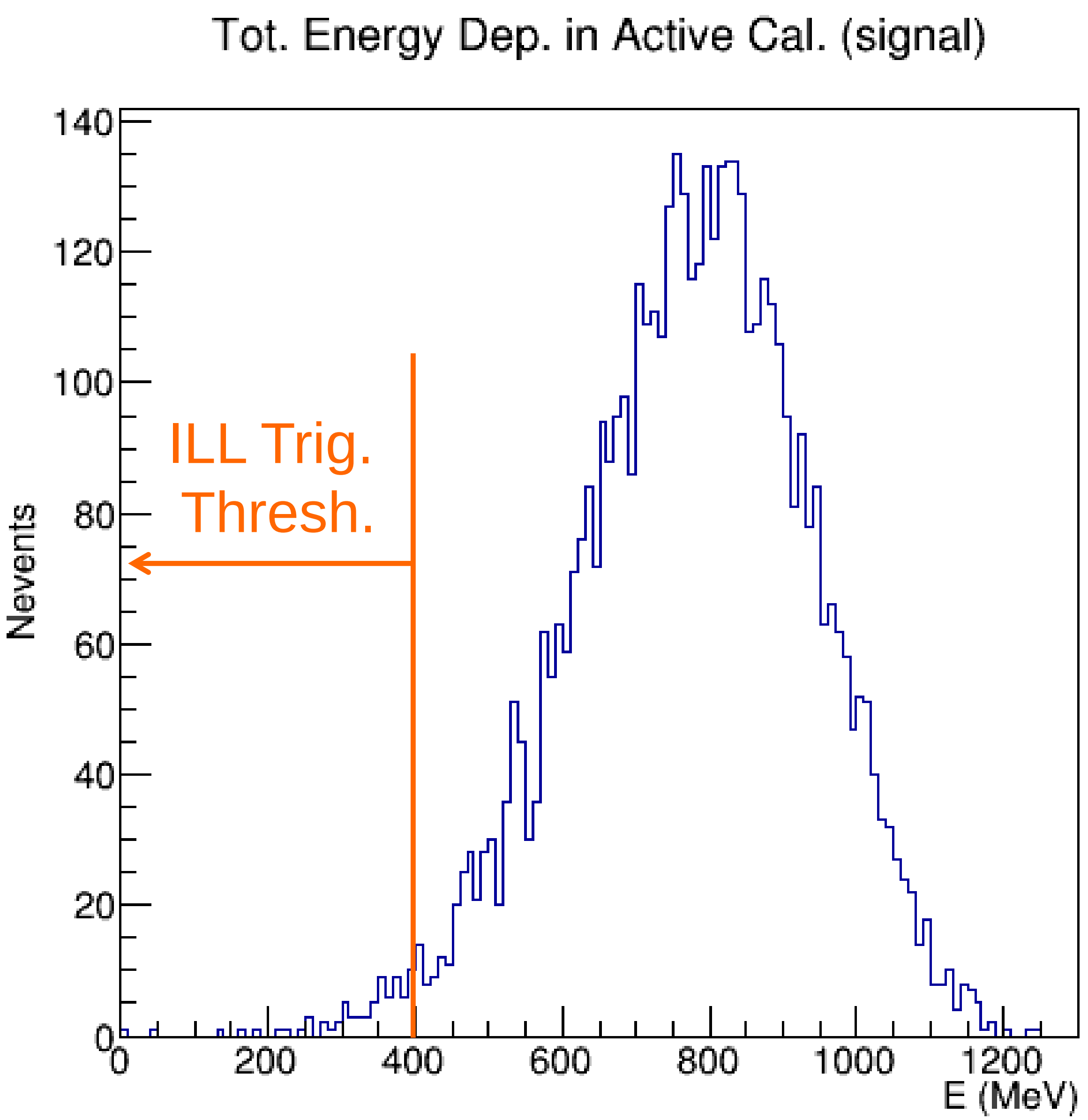
NNBar Final State Primaries (Signal)

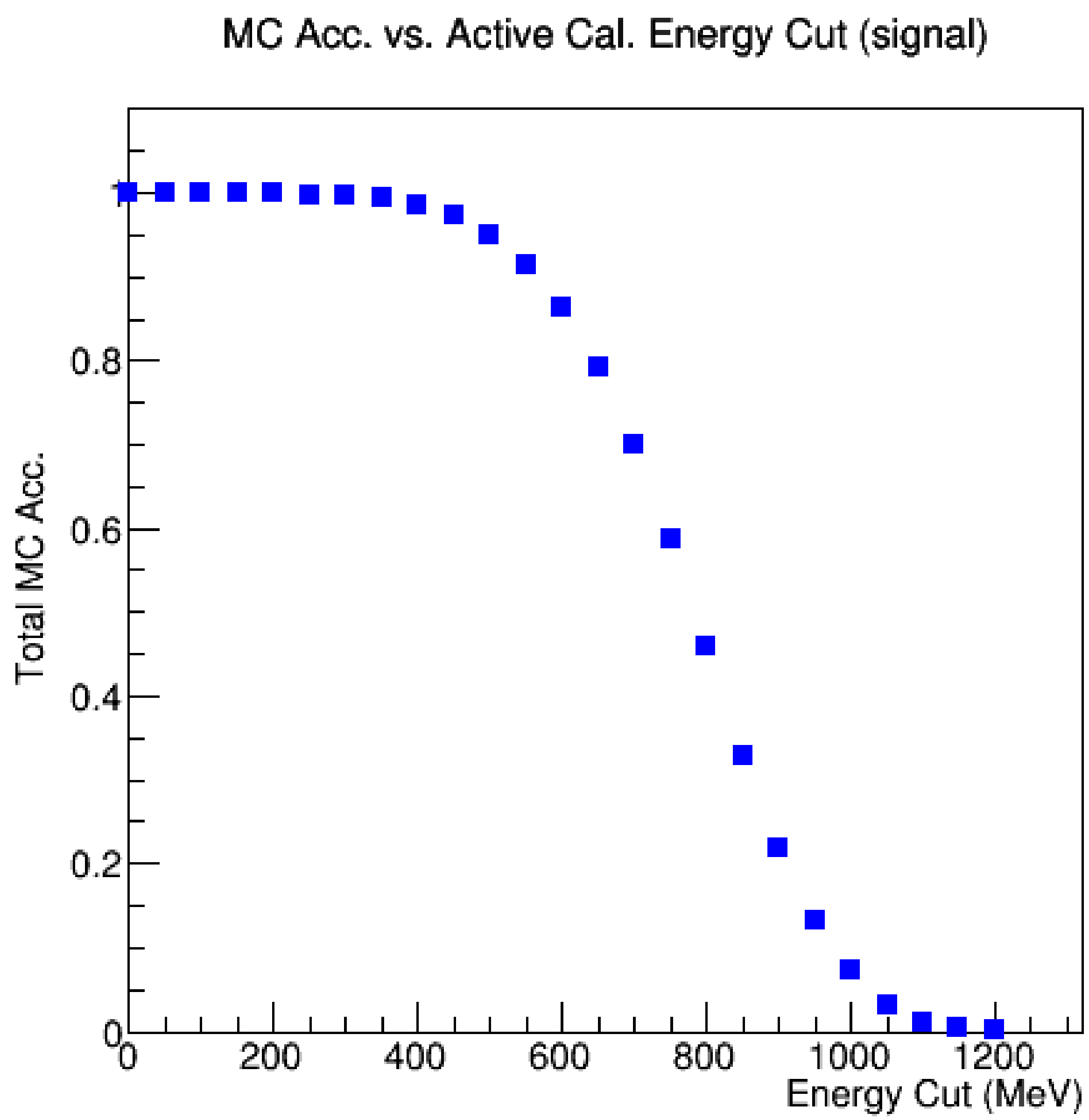




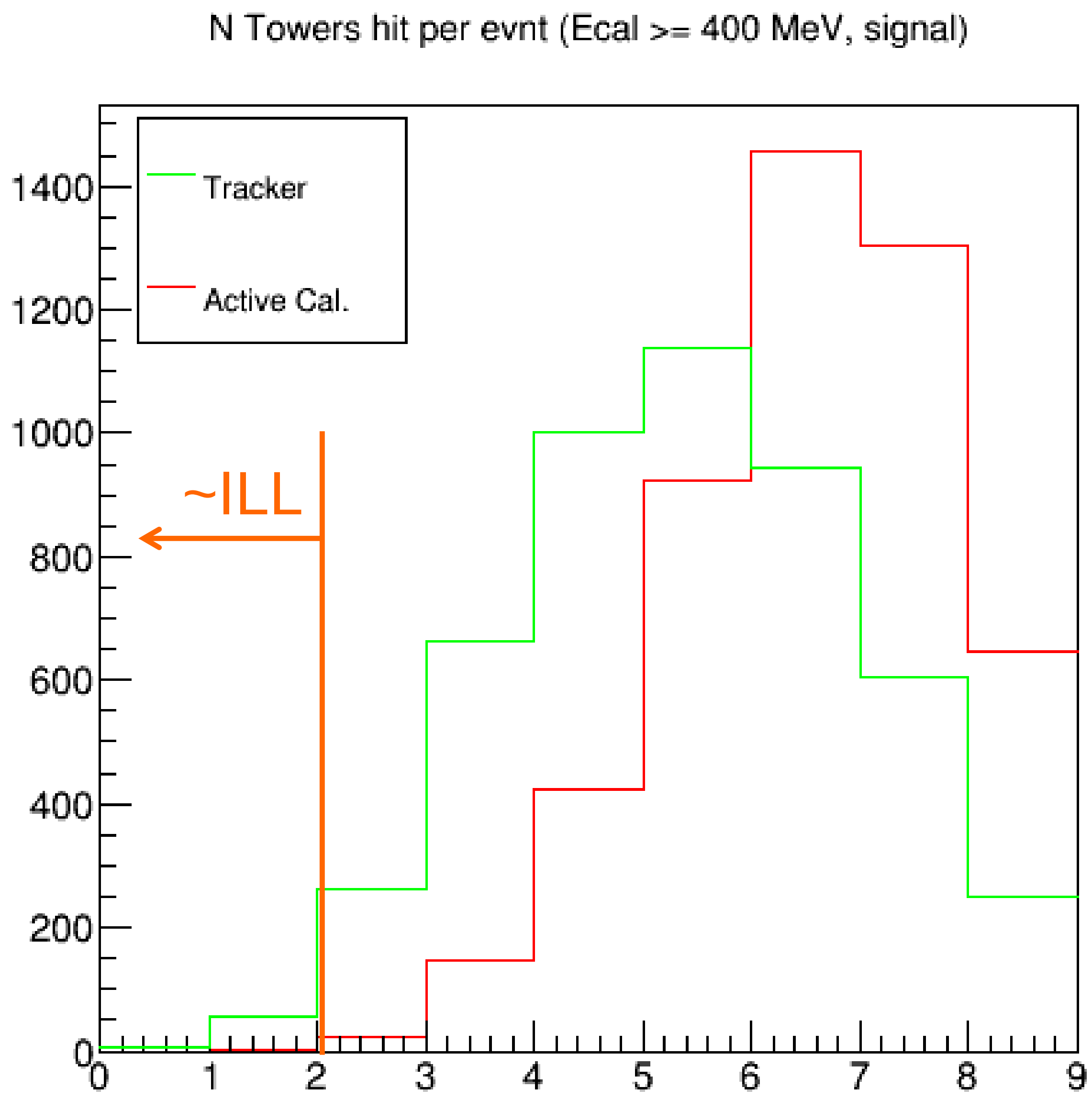
Note presence of neutrons and protons (return to these later)

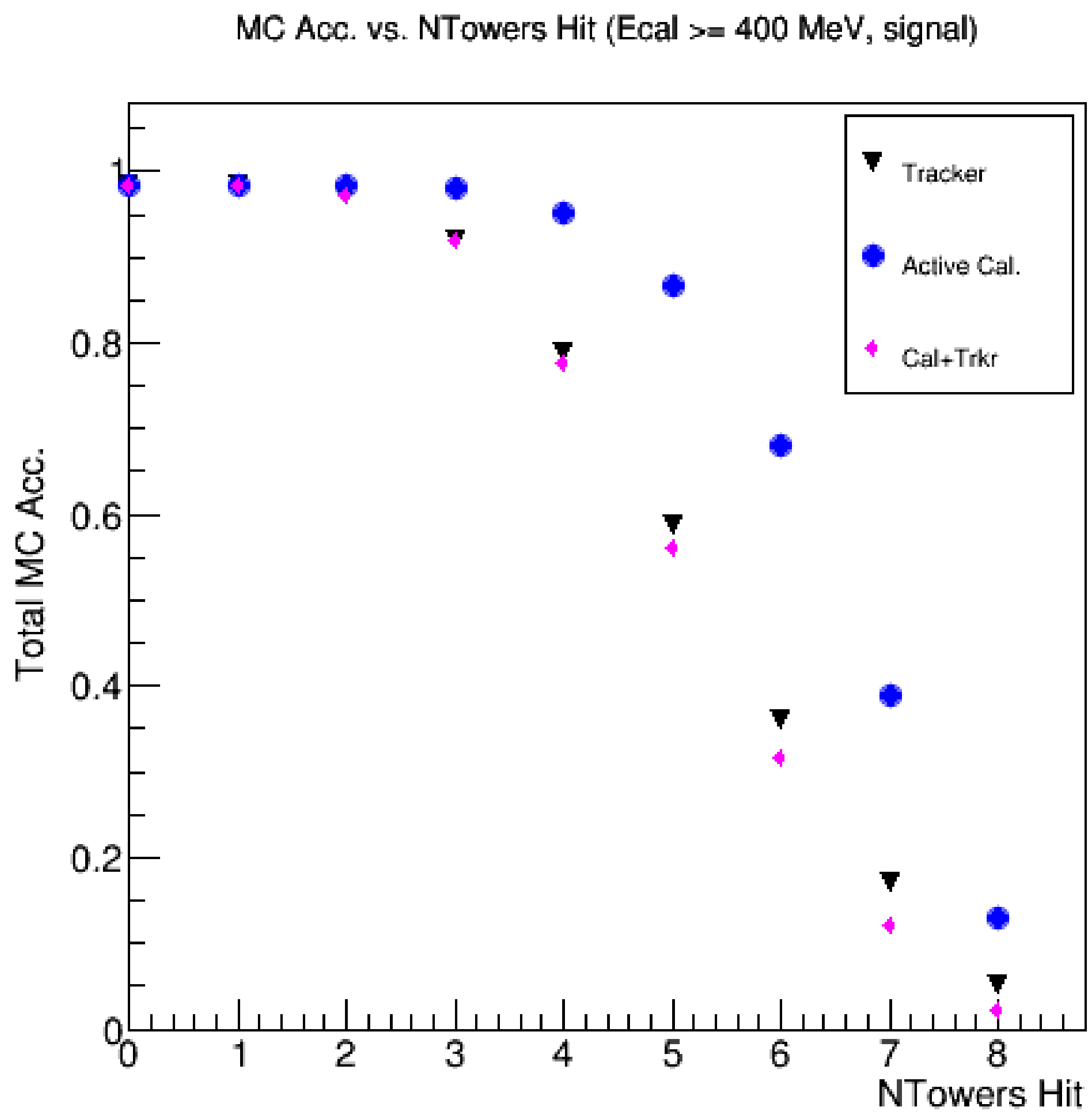
Energy Threshold Acceptance (Signal)



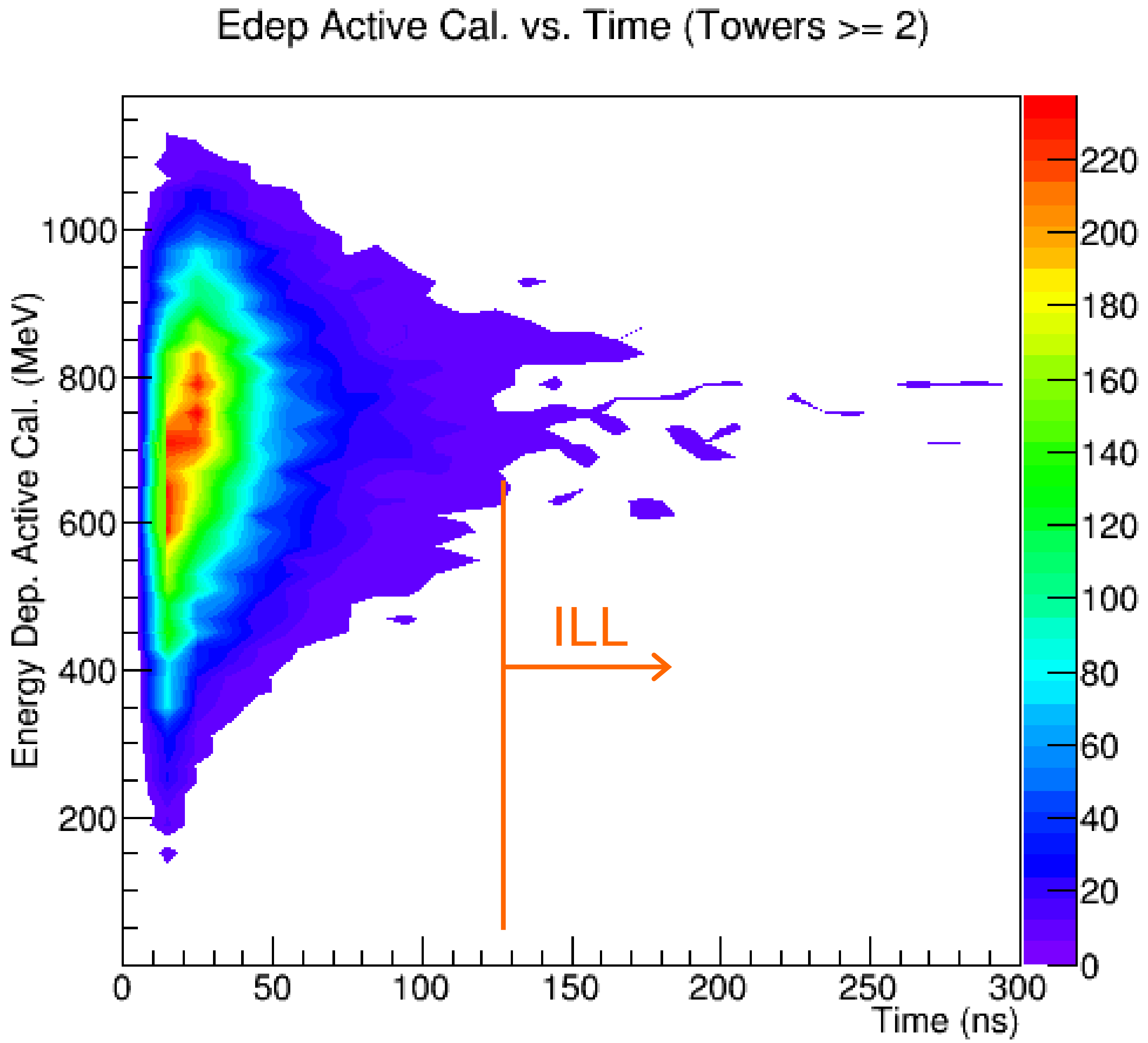


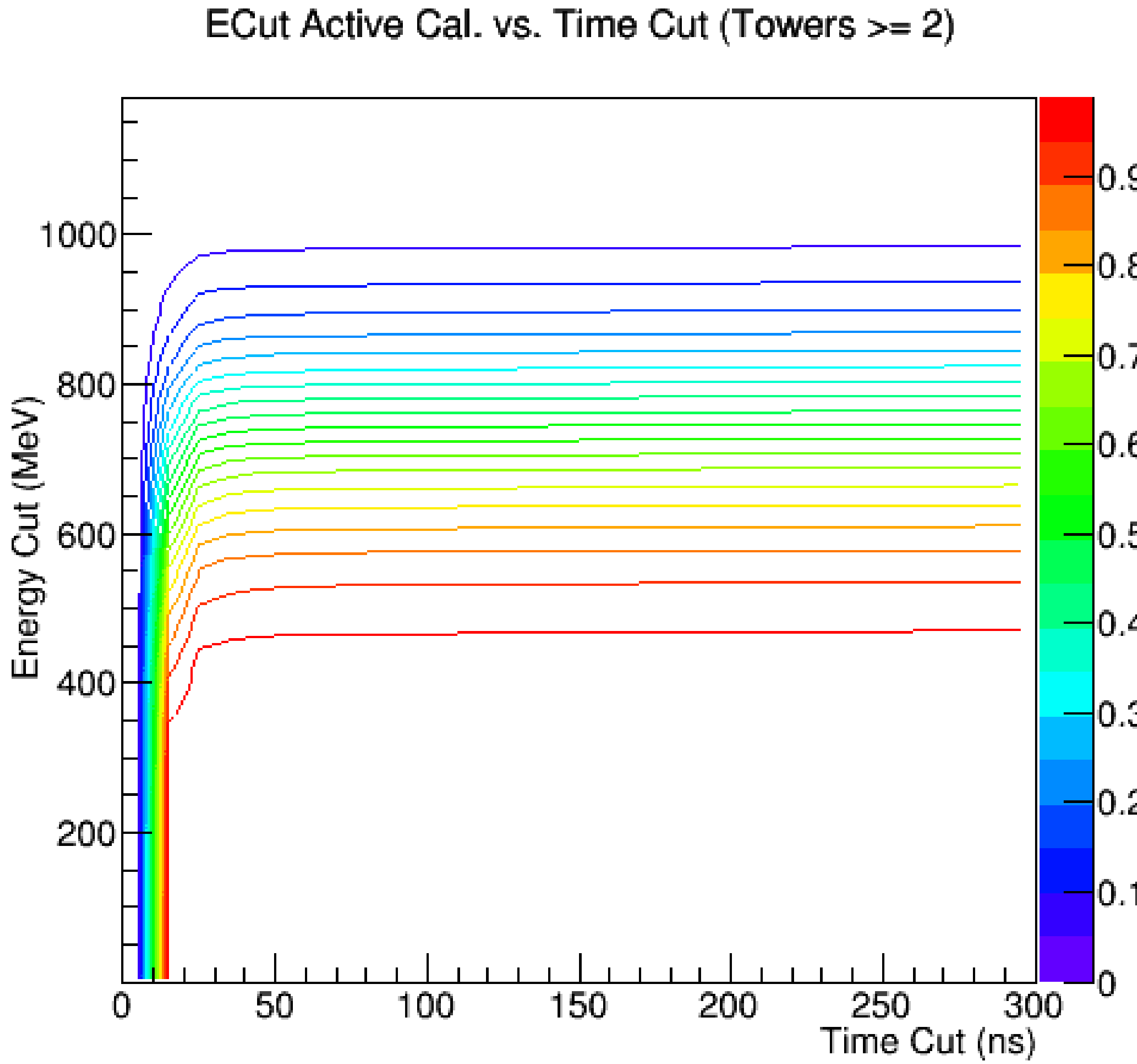
Tower Hit Acceptance (Signal)





Timing Window Acceptance (Signal)





MC Acceptance Summary: Guidance for Detector Systems

Cut Description	Signal Acc.	Bkgd Acc.
Cut 1: E_{cal} < 400 MeV	98.50%	0.22%
Cut 2: Cut 1 + (NTrkrTowerHits & NCal TowerHits) > 1	97.26%	0.00%
Cut 3: Cut 2 + E_{cal} < 500 MeV w/in 50 ns	**91.74%**	**0.00%**

Conclusion: we can reduce the timing window to 50 ns without impacting detection efficiency– a high granularity, large volume detector can implement more stringent track cuts without sacrificing NNbar acceptance

Challenges: how to minimize cost and meet background rejection goals

Background Simulations: A Prospectus

Simulation which addresses problem of a false positive is challenging: must suppress rate after cuts to < 10^{-8} Hz!

ILL experiment provides a baseline from which we can scale…

→ ESS: CN flux on target $\times$100
CN "lost" in transit $\times$3000
Detector volume ~ x6
Operating time ~x5

Sources of Background

- Stochastic gamma backgrounds
  - Capture in beam-tube (distributed,shieldable) ~10^{12}/s
  - Capture on target (not shieldable) ~10^{10}/s
  - CN scatter from target into detector
- High energy n,p (~20 n/p at source)
- Beta-delayed n
- Cosmic rays
  - Scale with detector volume
  - Depend on overburden

Dominant source of background

Target Gammas

- Ensure contaminants (H, N) at adequately low levels – H < 0.1%
- Relatively straightforward event generator for ^{12}C (dominated by emission of one 4.95 MeV gamma) – see next slide

- Simulation task: evaluate suppression based on absence of pion-like tracks which point to target
  - Tied closely to trigger logic
  - Signal proportional to time window → factor of 3 improvement possible w/ modern dets -- 7500 MeV/(50 ns window), so want roughly factor 100 improvement in suppression
  - Tracklike cuts" at trigger level

Conclusion: implementing the trigger is a significant requirement for the detector!

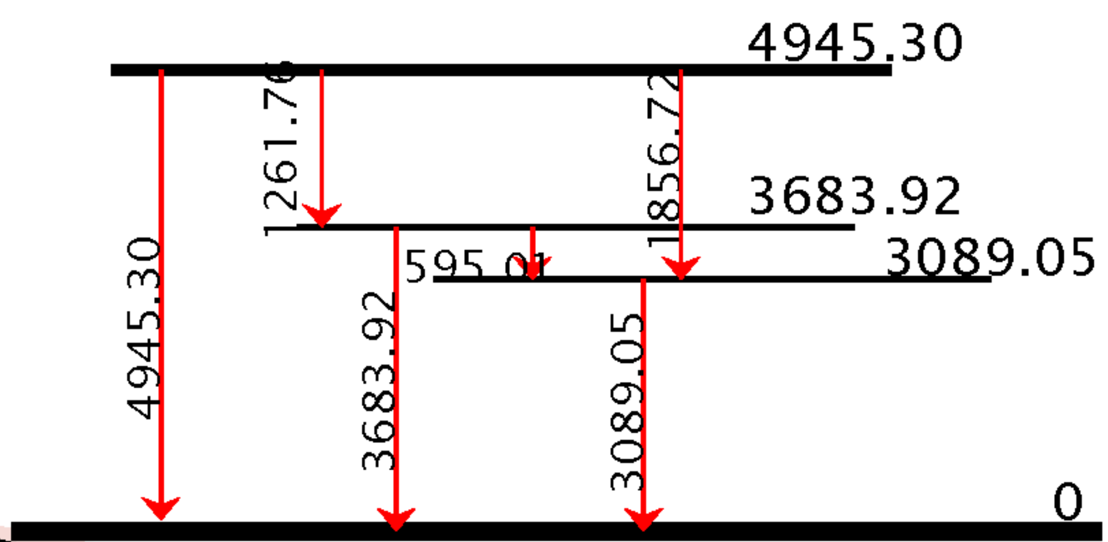
Target γ Event Generator

Prepared by B. M. Vorndick

Capture gammas from $n+^{12}C$ and $n+^{10}Be$

May be advantages to Be target (thanks to P. Bently)

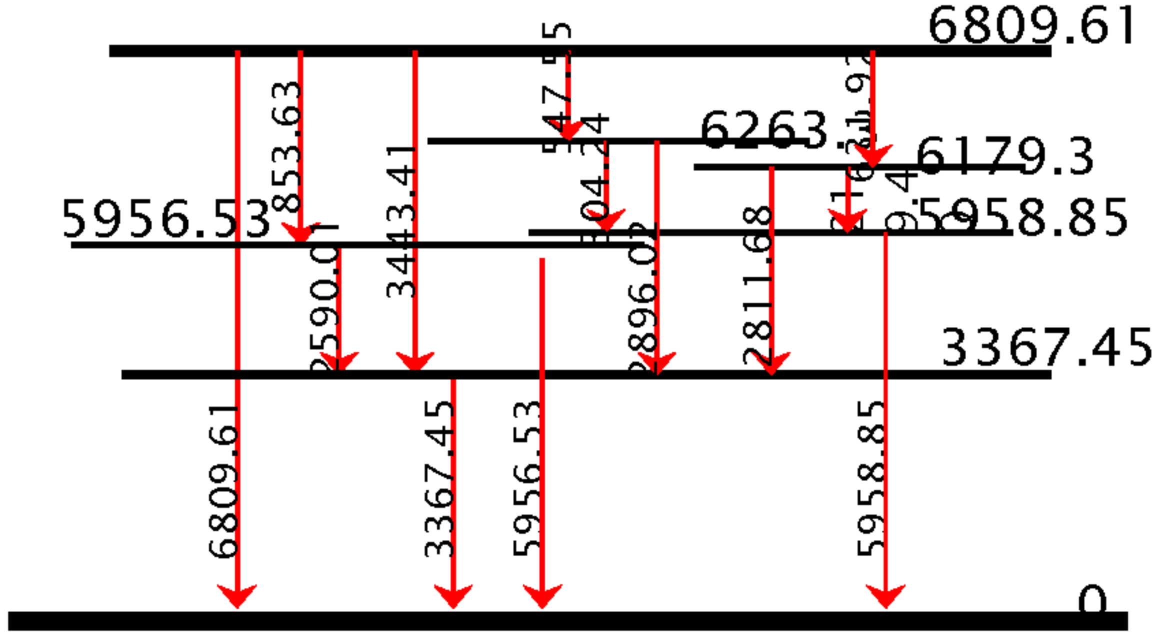
Gamma Energy (keV)	Probability
4945.30	0.6752 ± 0.0163
1261.76 + 3683.92	0.32097 ± 0.01339
1261.76 + 595.01 + 3089.05	0.00243 ± 0.00017
1856.72 + 3089.05	0.0014 ± 0.0001



C-13

In keV

Gamma Energy (keV)	Probability
6809.61	0.6532 ± 0.1239
3443.41 + 3367.45	0.1097 ± 0.0308
853.63 + 5956.53	0.0165 ± 0.0049
853.63 + 2590.01 + 3367.45	0.2174 ± 0.0785
631.92 + 2811.68 + 3367.45	0.0011 ± 0.0007
631.92 + 219.40 + 5958.85	0.0009 ± 0.0005
547.55 + 2896.02 + 3367.45	0.00094 ± 0.00037
547.55 + 304.24 + 5958.85	0.00024 ± 0.00013



Be-10

In keV

(Essentially 100% prob. for ~5 MeV in ga

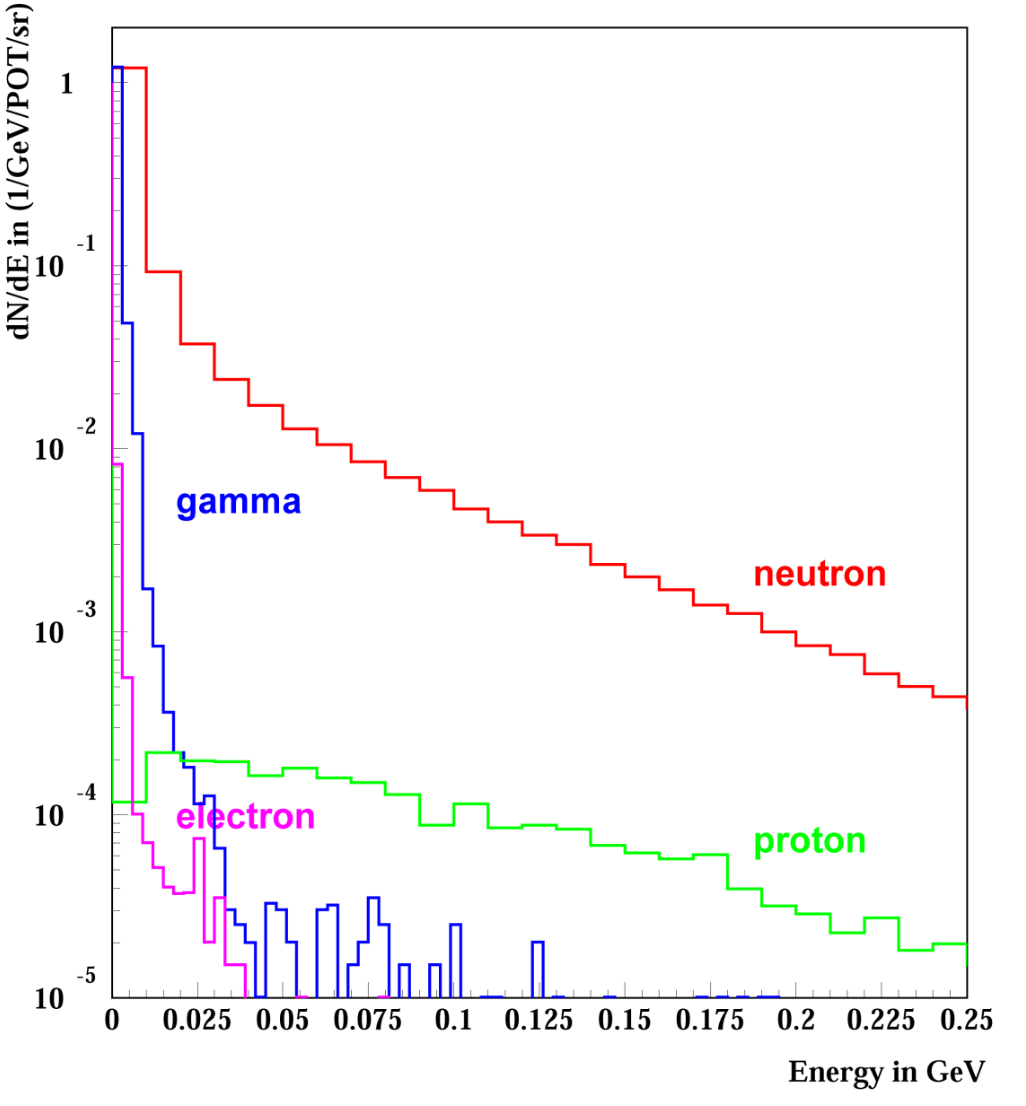
High Energy n,p Backgrounds from Beam

- Serious consideration for experiments at a CW spallation source

  (Performed studies of CW fast n backgrounds using MCNP)

- 5 μs cut around primary proton beam pulse adequate to complete suppress H.E. primaries at ESS! (CN mean transit time a few ms, ESS pbeam pulse every 71 ms)

- ESS Shielding strategy important



High energy products from 1 GeV proton beam incident on W target (at 90 degrees) – MARS calculation by S. Striganov

A. R. Young, D. G. Phillips II, R. W. Pattie Jr.

Beta-delayed neutrons

- Beta-delayed neutrons come from the beta-decay of spallation products either into nuclei unstable to particle emission or into targets for (γ,n) reactions, e.g. (^{9}Be, ^{2}H and ^{17}N):
  - ^{9}Be + >1.7 Mev photon → neutron + 2 ^{4}He
  - ^{2}H (deuterium) + >2.26 MeV photon → neutron + ^{1}H
- At level of few tenths of percent in cold beam at SNS (time independent cold flux)
- Need to characterize higher energy (MeV scale) neutron backgrounds to ensure not a problem…MCNP reasonable tool for simulations, but measurements needed too!

Note: may be able to characterize in time interval near end of standard cold neutron beam pulse…

Cosmic Ray Backgrounds

- Primary source of triggers
- For ILL detector, trigger rate $\sim \frac{6.8\times10^7}{2.4\times10^7} = 2.8\ Hz$ (after veto and timing cut)
- Vertex reconstruction is the primary cut -- timing cut may not help with correlated cosmic ray showers, and some events expected to reconstruct near the target!
- Roughly equal number of neutrons and protons in cosmic ray showers but cosmic ray neutrons evade veto -- historically considered critical contribution to background

Important question for simulation campaign: what are the cosmic ray event topologies?

Cosmic Ray Neutrons

- Spectrum measured on surface: F. Ashton et al., Phys. Rev. A, **4**, 352 (1971)--probably more recent measurements as well…will follow up
- Modern tool for simulations: CRY code

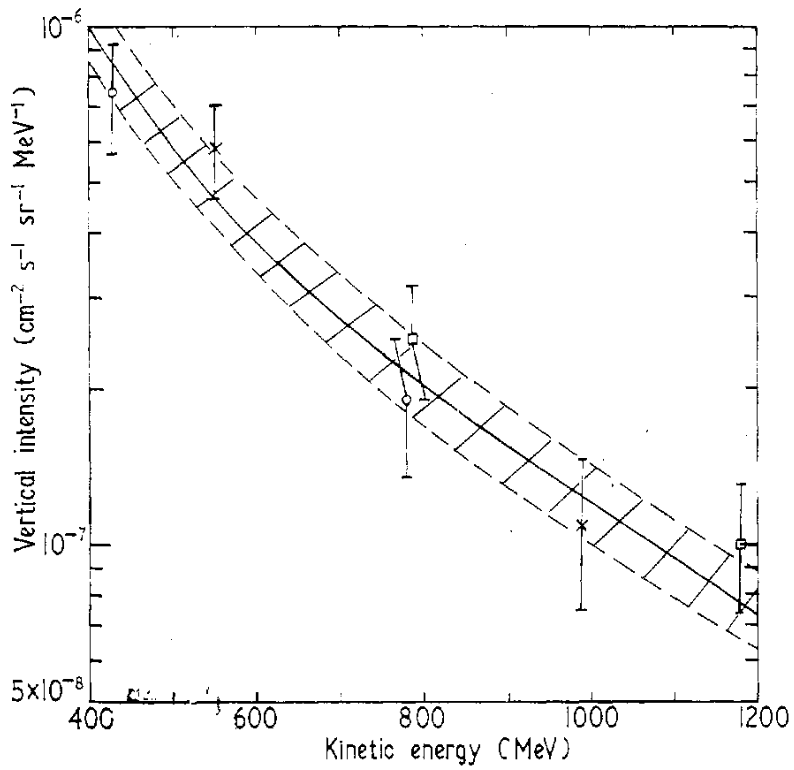


Figure 4. Neutron intensities derived from the present work. The full line i the vertical intensity calculated from the global spectrum of Hughes and Marsde and the hatched area the upper and lower standard deviation bounds to the bes fit to the spectrum as suggested by the present work. The circles and square refer to the data in table 6 containing respectively the lower- and higher-energ proton samples. Interaction losses in both cases were allowed for by simpl exponential reduction. The crosses refer to all the data given in table 7 an interaction losses were accounted for by a Monte Carlo technique. All th experimental points are plotted at the mean neutron energy of the energ range contributing to the observed events.

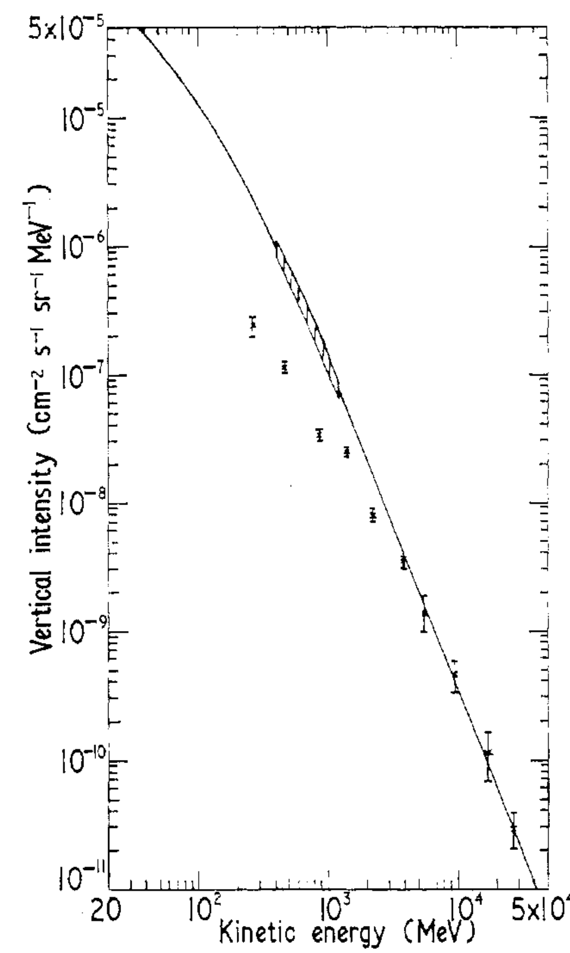


Figure 5. Summary of the sea level vertical neutron and proton spectra in the range 20 MeV to 50 GeV. The full line is the vertical neutron spectrum calculated from the global spectrum given by Hughes and Marsden (1966). The crosses are the proton measurements of Brooke and Wolfendale (1964) and the hatched area the results of the present work for neutrons.

Cosmic Ray Backgrounds at the ESS

- Expected total number of events = ILL x 6 (detector volume) x 5 (running time) = ILL x 30

- Possible strategy to reduce contribution of backgrounds
  1. Optimizing shielding overburden to minimize neutrons (requires a careful study, small overburden layers can increase net hadronic component to cosmic ray showers) -- CRY code important here
  2. Possibility: use two charged particle tracks as primary trigger cut (make vertex tracker neutron “invisible”) – & use improved reconstruction to improve cuts
  3. Veto events with neutrons in calorimeter with dE/dx

Trigger on 2 Charged Particle Tracks

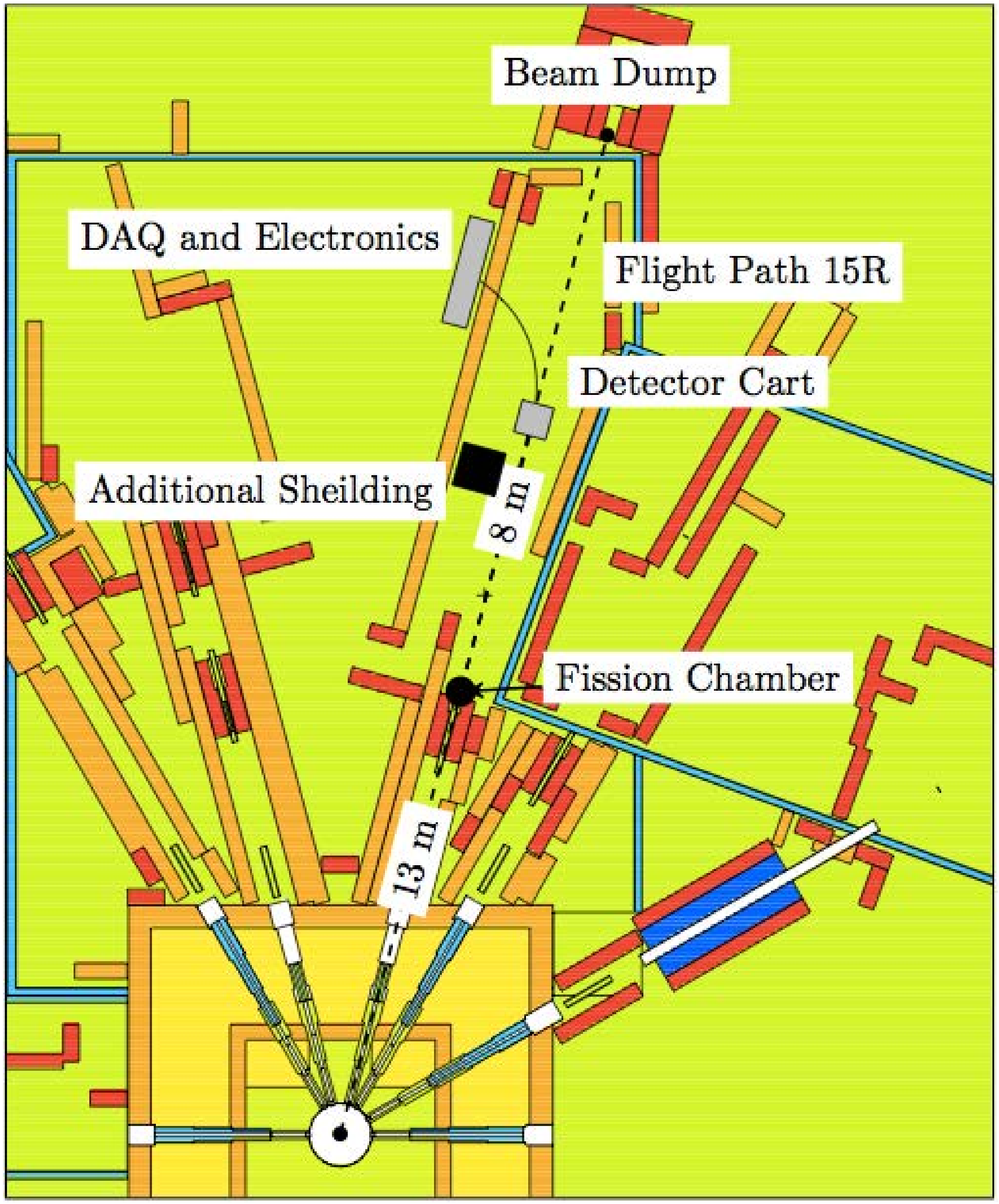
- Advantage: Neutrons don't contribute to primary trigger criterion – (rate reduction roughly at veto efficiency ~ 0.01 (?))

- Requirement of two charged particle tracks (in vertex) permits strong constraints on timing (for trigger) and event reconstruction (expect improvement in z and r reconstruction from ~4 cm to roughly mm scale – at least factor of 100 suppression) -- note cosmics have been observed to reconstruct to Al vacuum wall (Bressi), "internal" events dangerous!

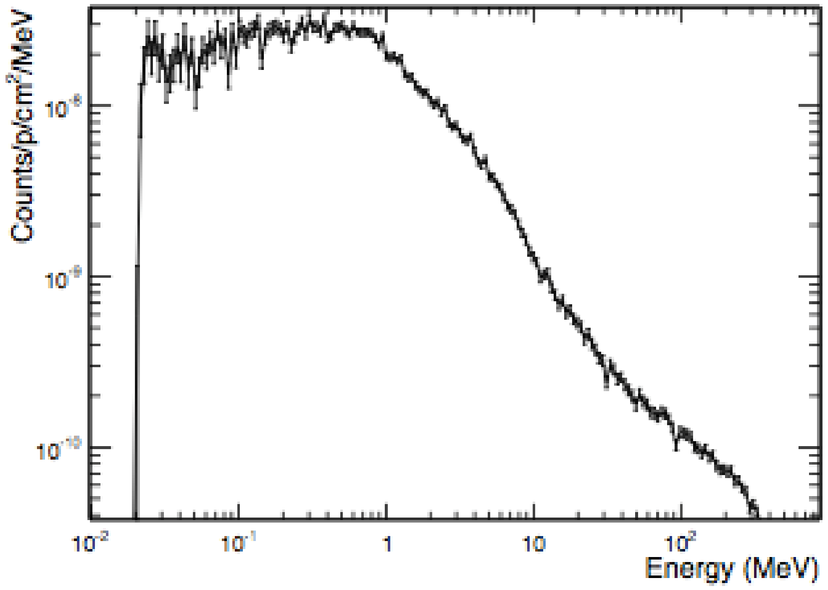
- Also requires neutron "invisible" tracker -- demonstrated gas tube tracker sensitivity below 10^{-4}

WNR Tests - Layout

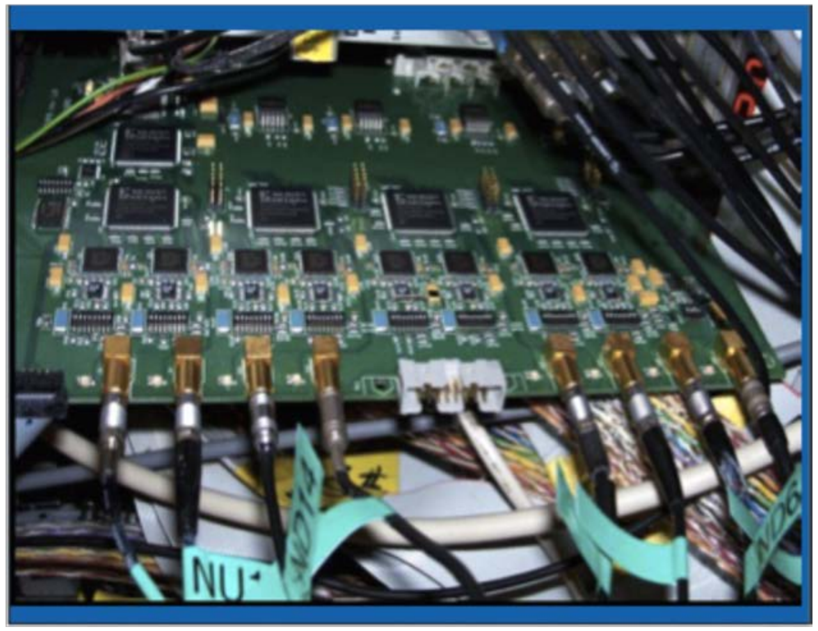
LANL WNR-15R Beamline



Predicted *n*-flux 20m from target

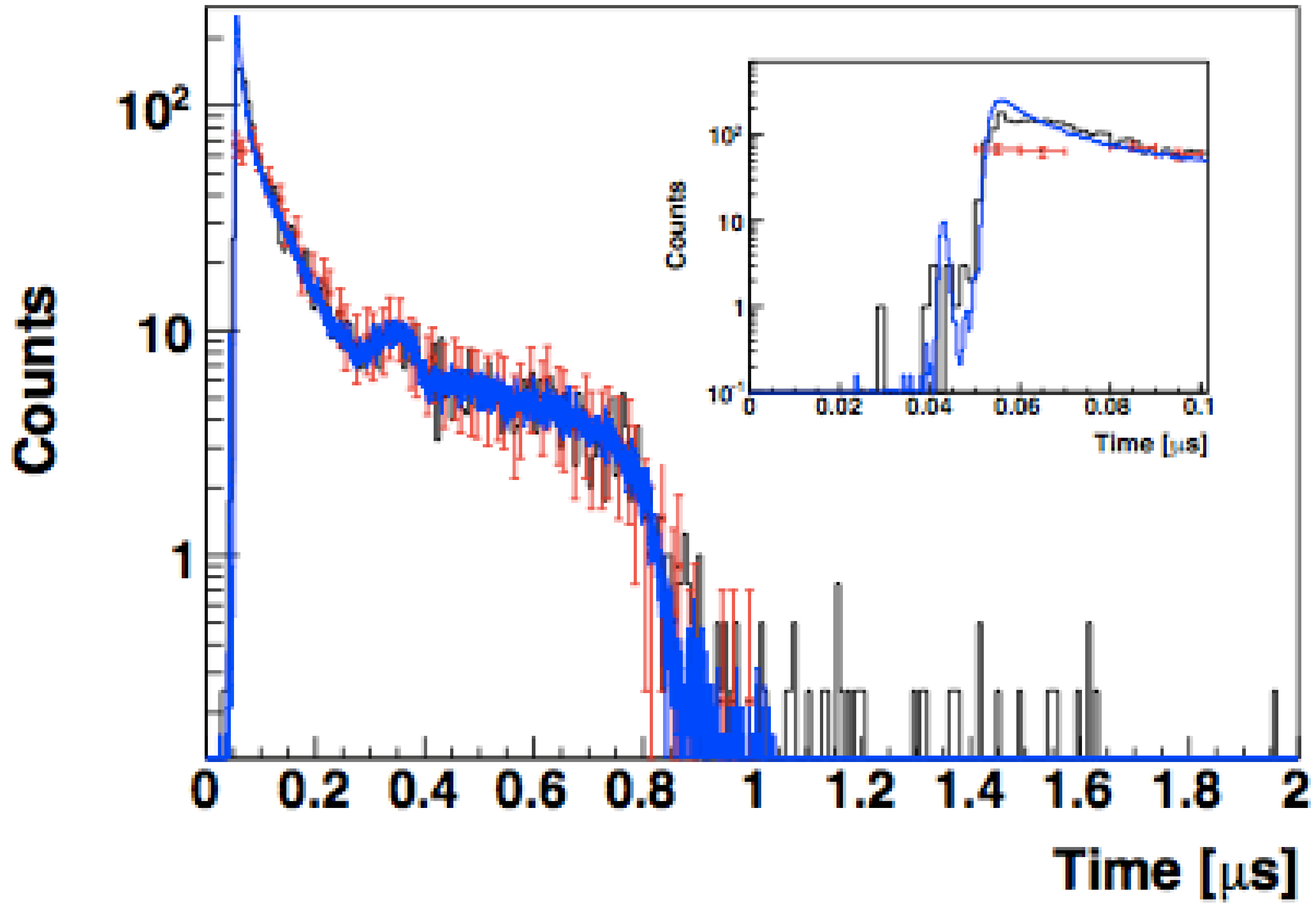


250 MHz 8-chnl 12-bit fADC



WNR Tests - Fission Foil

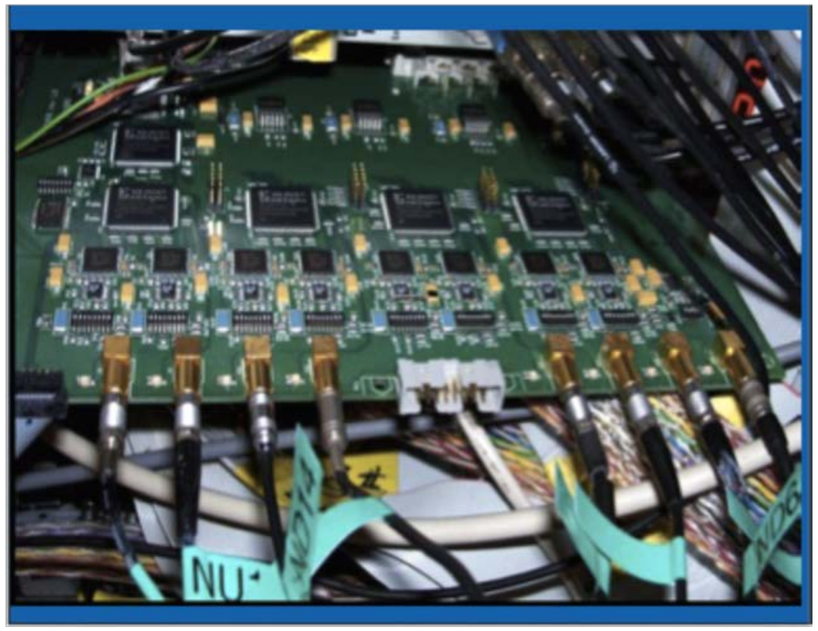
Fission Chamber TOF Spectra



WNR TAC: blue
Our ADC: red

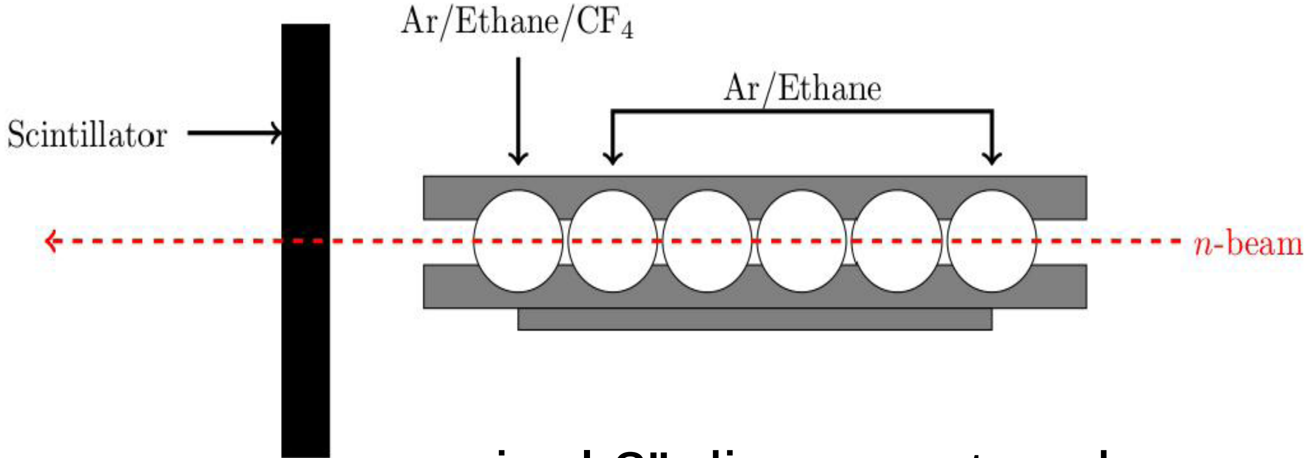
Data obtained from WNR DAQ and from our digitizers

250 MHz 8-chnl 12-bit fADC



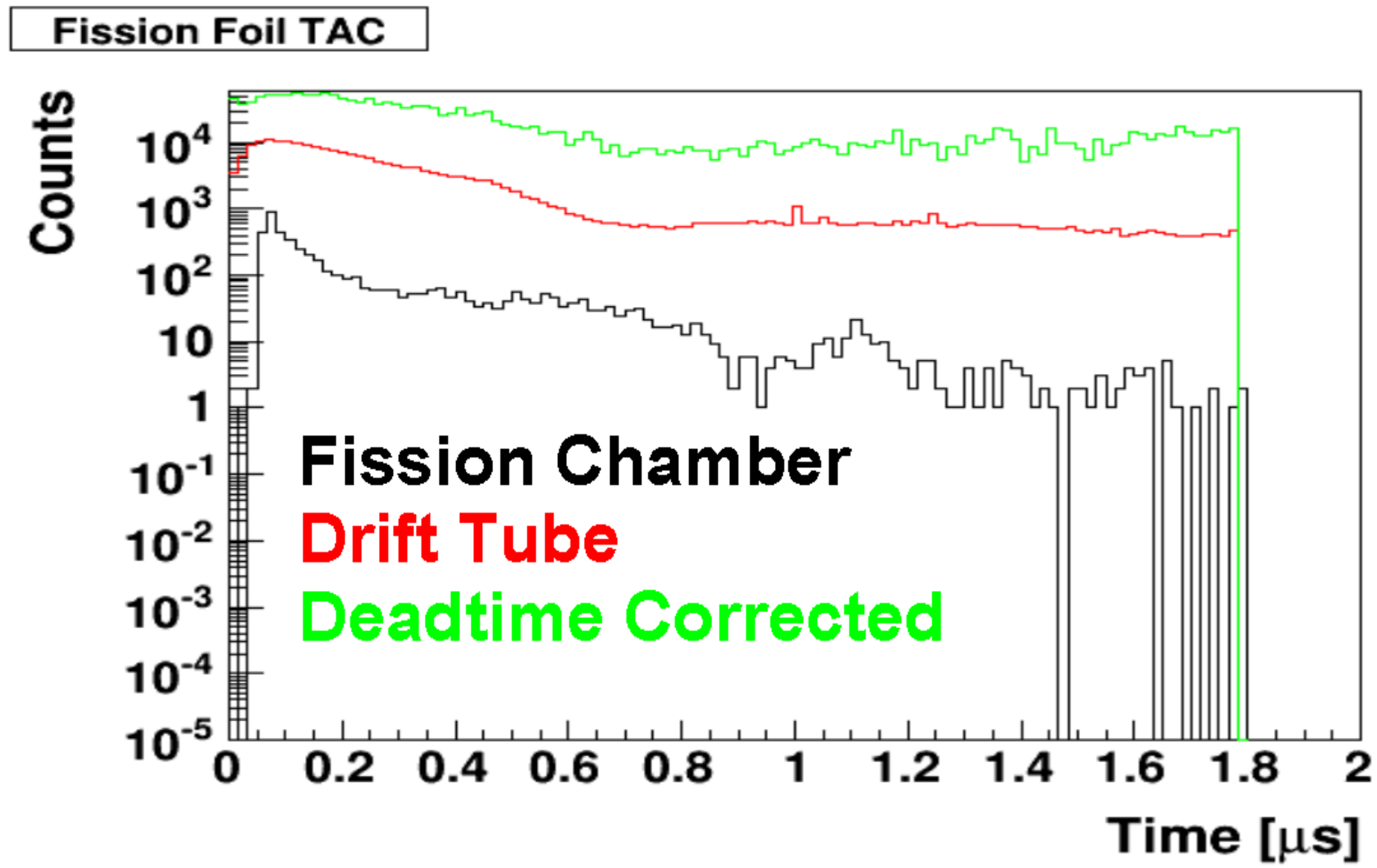
Timing from ADC time-stamps

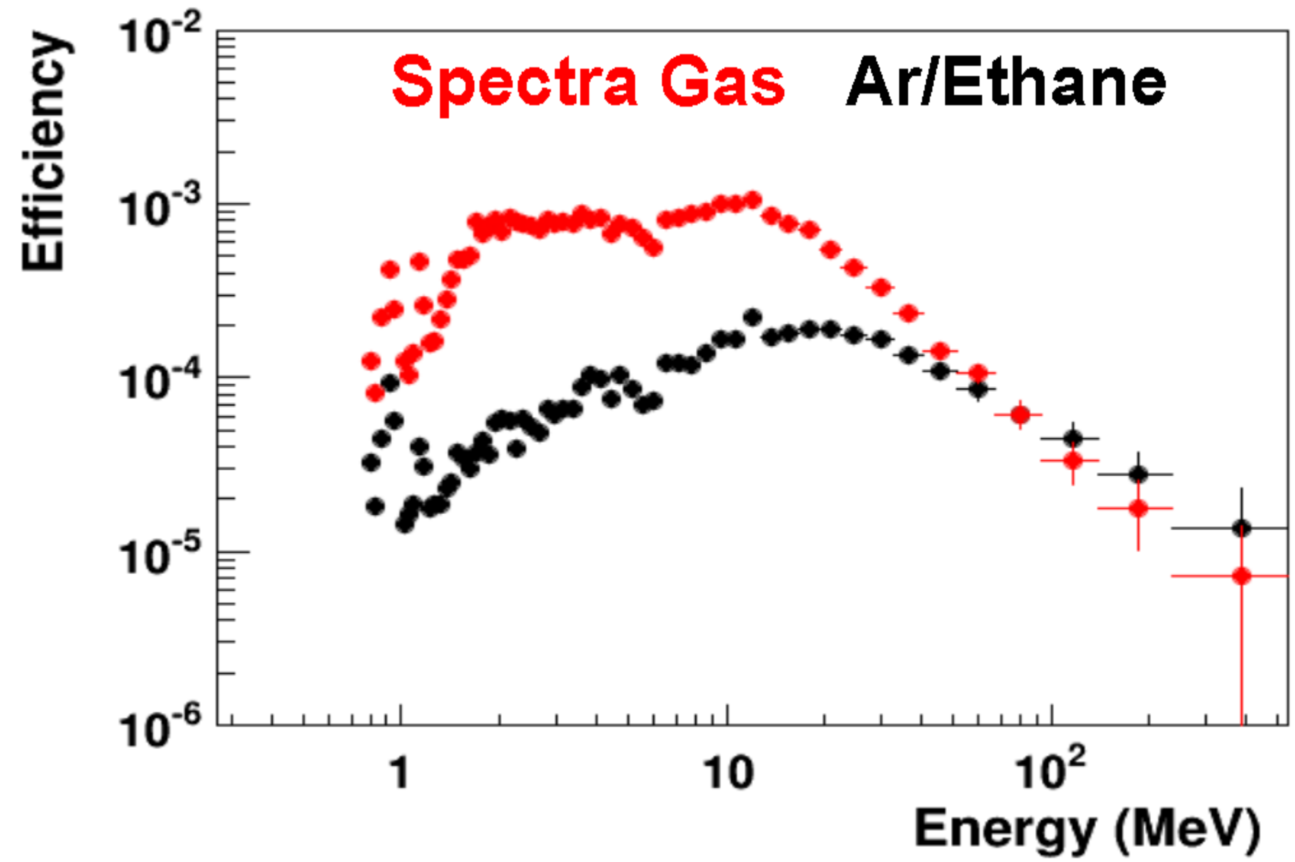
Preliminary Drift tube Efficiency Results



nominal 2” diam. neutron beam

- Efficiencies (E>100MeV):
  - Ar/Ethane $<10^{-4}$
  - Ar/Ethane/CF$_4$ $<10^{-4}$
- Large deadtime corrections associated with attempting to digitize beam gate





GENIE: impact of cuts on the neutrons

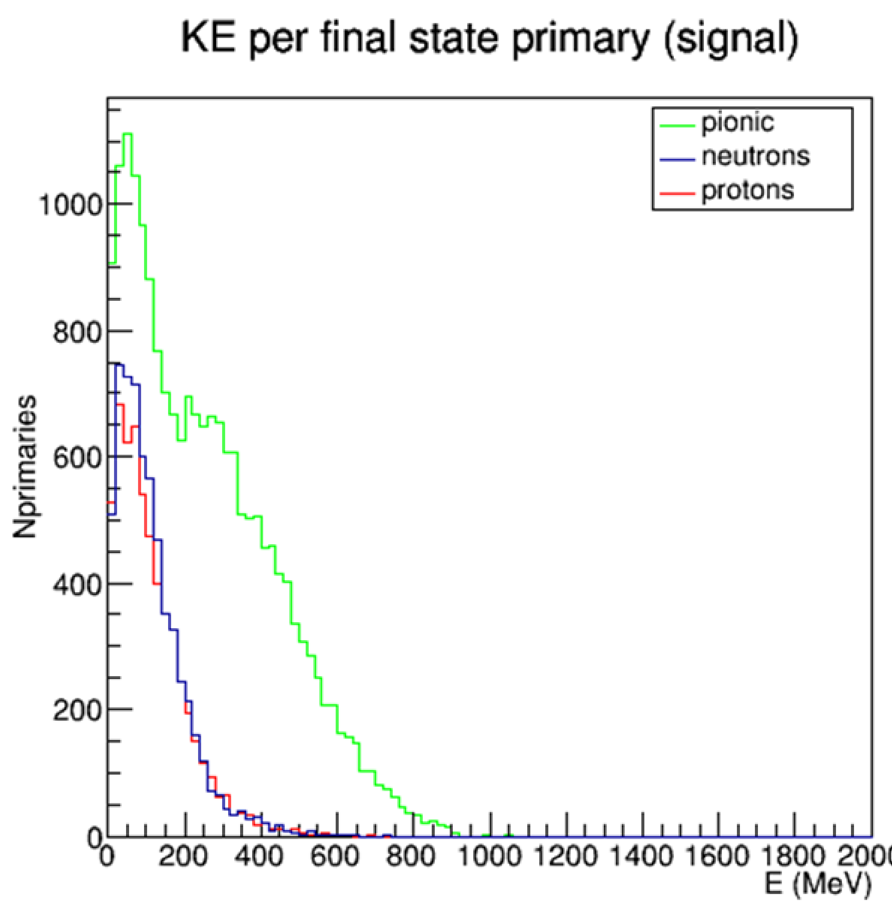
From Genie we see that neutron events come from pion interactions in nucleus – accurate interaction model needed! (U. Mosel and Jlab)?

Generic Nnbar events

With final state neutron : 46.4%

E_n > 20 MeV : 11.6 %

Sharply falling with E (optimize cut)



Nnbar vertex simulation…

GENIE Results: Cuts

Final state 2 charged pions 82.2%

E_n > 20 MeV && N_p(+-) >= 1 : 11.4 %

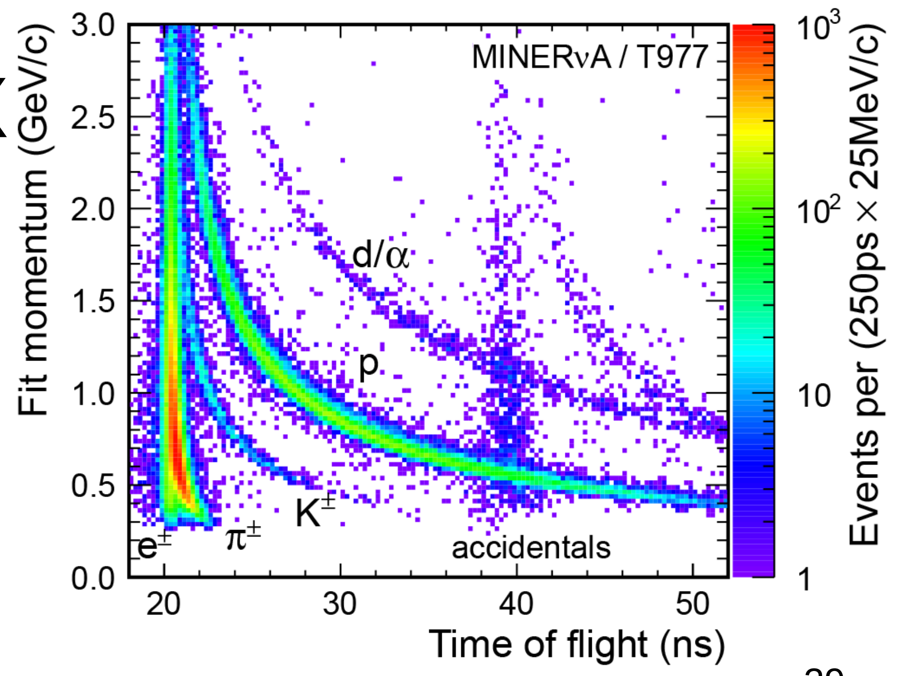
E_n > 20 MeV && N_p (-+) >= 2 : 9.8%

NNbar acceptance for combined cut ~ 72%

-- not so bad

Neutron cut implemented by dE/dx

dE/dX cut from Minerva probably very effective … need to check!



Summary Cosmic Rays

- Naïve scaling would suggest we need at least a factor of 30 improvement in our cosmic ray rejection
- We can expect significant reduction in candidate events from cosmic rays by altering our trigger criterion and making cuts
- Base level improvements in tracking should also provide significant improvements
- Understanding the event topology may be very important for events which reconstruct to points inside the detector volume

What more can we do?

Real-time tests for spurious events

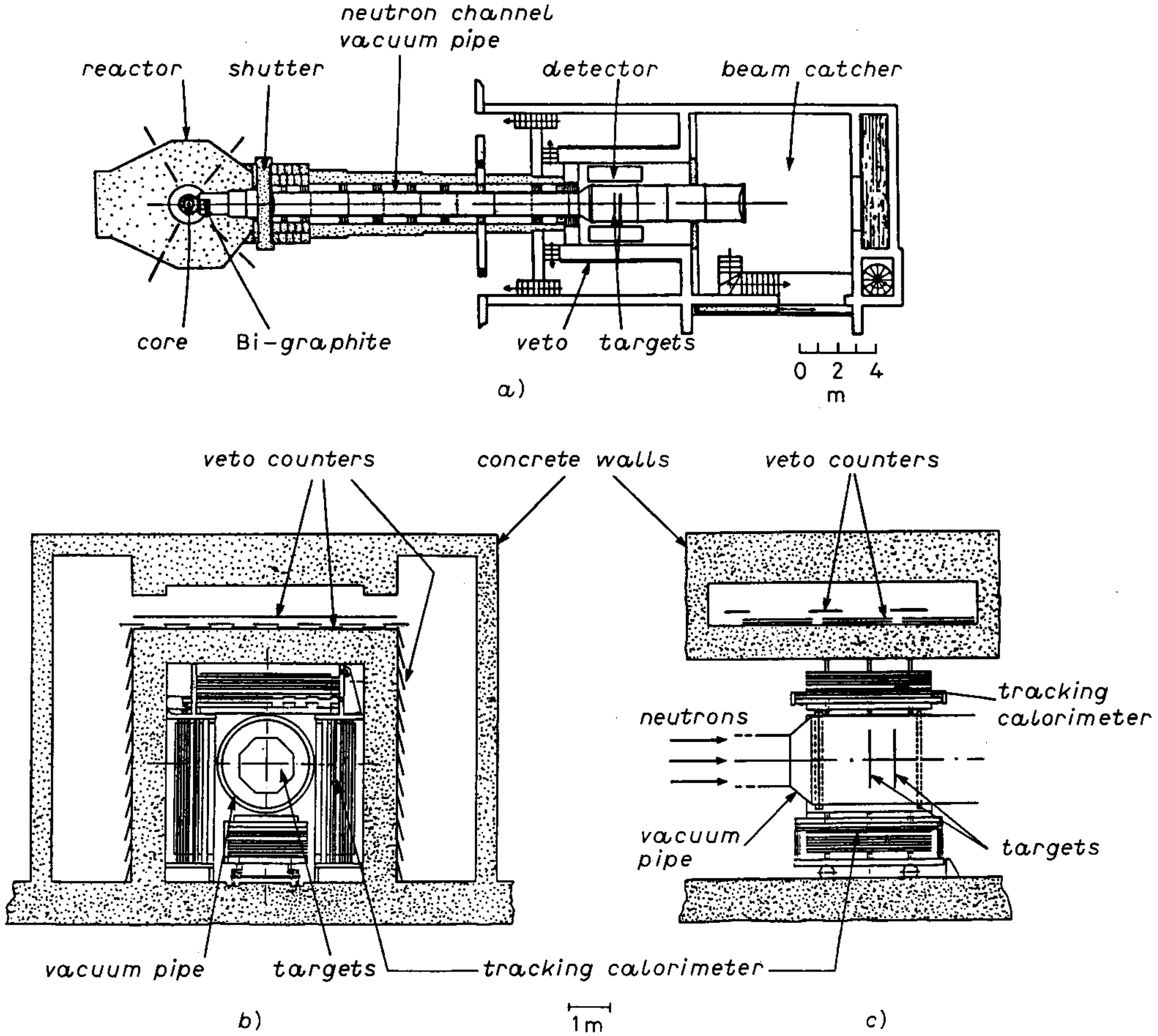


Fig. 1. – *a*) General view of the experimental layout; *b*) transversal and *c*) longitudinal cross-sectional view of the apparatus.

2 targets!

Bressi et al, Il Nuovo Cimento, **103 A,** 175-179 (1989)

Conclusions

- Starting points for discussion seem to be that somewhat improved efficiency and shorter trigger time-windows can probably achieved with modern detector
- Targets for detector design to control background seem to include:
  - **Accurate track reconstruction to target**
  - **Triggering on tracks**
  - **Cuts based on particle ID**
  - **Good separation of neutral and charged events**
  - **Hermetic veto and timing cuts (**timing calorimeter)
- Immediate priority is to develop track-ID (and dE/dx) capability for simulation and implement cosmic ray shower models

NNbarX Working Group

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ILL Triggers, Cuts, Acceptance

1 MHz raw triggers due to capture gammas…

Trigger Requirement	Trigger Rate (Hz)
1) Coinc. Of Inner & Outer SC (same det. quad.) in anticoinc. w/CRV.	2000
2) Cond. 1) + 1 track in same vtx. det. quad. as SC coinc.	800
3) Cond. 2) + 1 SC hit (diff. quad.) + 2^{nd} track (in vtx. det. or calor.)	6
4) Cond. 3) + ≥ 120 hits in LST det. (>500 MeV)	4
Spurious triggers from high beam radiation	2.7
Cosmics w/out CRV trigger	0.3

ε_{trig} = 77%

SW Filter Requirement	Data Acceptance	MC Acceptance
2.0 GeV > E_{vis} > (0.87 ± 0.17) GeV, $R_{orig} \leq 80$ cm	10.0%	85.0%
TOF: $T_{SC,OUT} - T_{SC,IN} < 5$ ns	16.4%	96.0%
Vertex: $R_{orig} \leq 60$ cm, $\lvert z \rvert < 32$ cm, $\theta_{track} > 170^o$	1.2%	89.0%
Total	0.018%	72.0%

ε_{filter}

ILL Triggers, Cuts, Acceptance

N_{events} surviving SW Filter: 1.2×10^4

Analysis Requirement	Remaining Events
Incorrectly reconstructed vtx. (visual inspection)	403
Charged CR	335
$R_{orig} \leq 55$ cm, $\|z\| \leq 15$ cm	5
$E_{vis} > 800$ MeV	2
$y_{vb} > -60$ cm	0

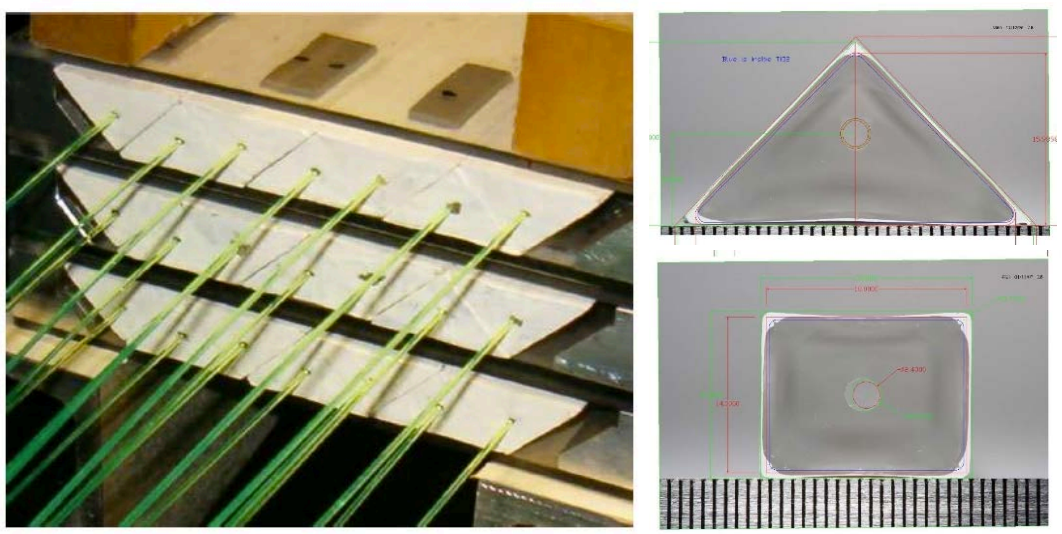
$\varepsilon_{analysis}$ = 95%

$\varepsilon_{trig} \bullet \varepsilon_{filter} \bullet \varepsilon_{analysis} = (52 \pm 2)\%$ [1]

Final cuts correspond to: E_{thresh}> ~800 MeV, at least 1 charged particle track, at least two "tracks", vertex reconstructs to target

NNBarX Scintillator Candidates

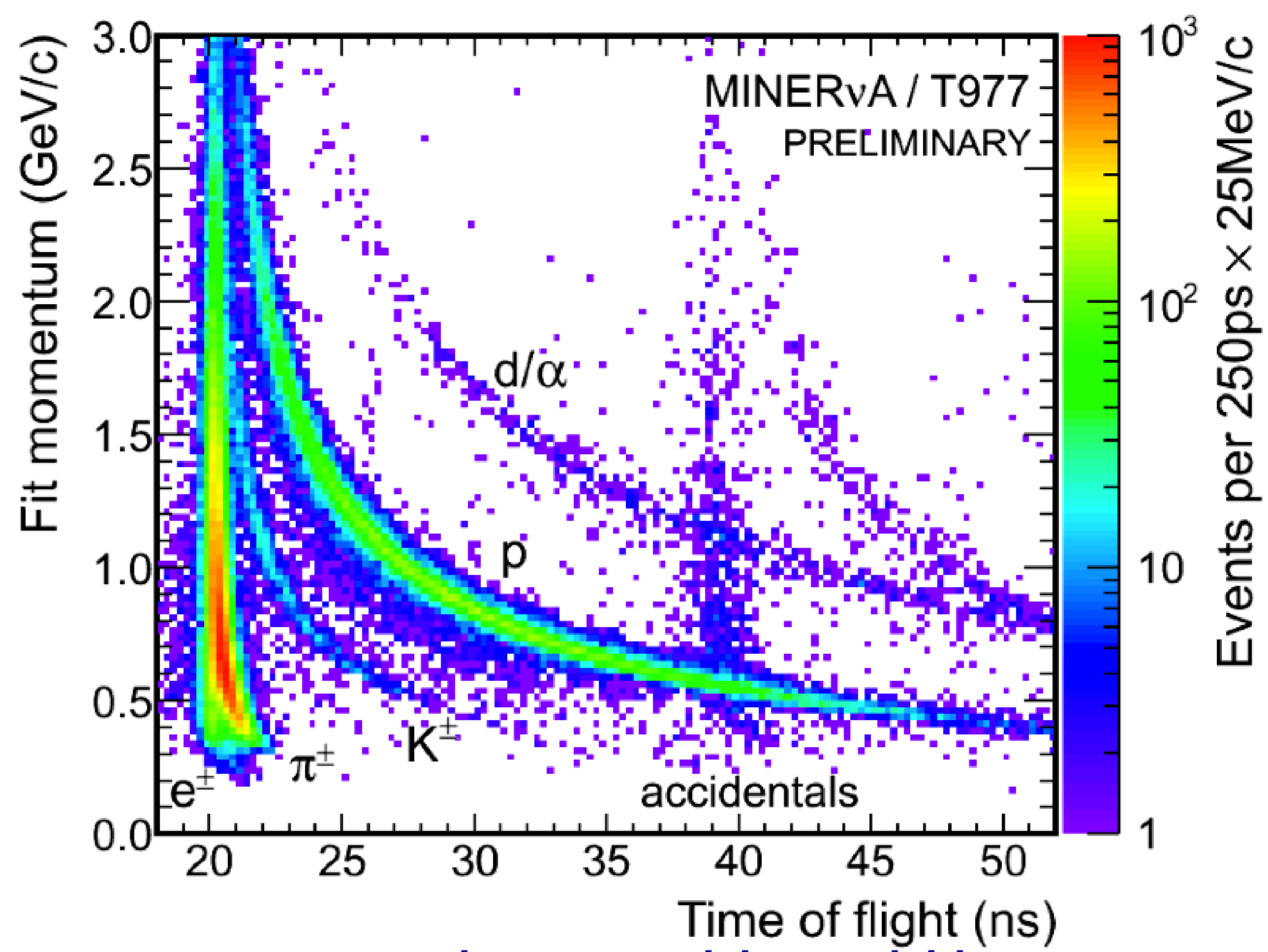
MINERVA Extruded Scintillator
(Affordable & Produced at FNAL)



MINERvA images credit: E. Ramberg (FNAL)

PMT or SiPM

Content of Tertiary Beam from TOF System –
MINERVA T977 Test Beam Experiment Data



Need to consider add'l alternatives.

NNBarX Tracker Candidates

- Straw tube array in barrel and end-cap configuration (ala ATLAS).

- ATLAS TRT – hit precision: ~130 μm, ε ~ 94%, rad. L. = $0.264X_0$ (η = 0) & $0.219X_0$ (η = ±1.8) [18].

- Straw tube fill gas options need to be identified and tested.

<u>Other Options</u>

- Range stack MWPC's., polystyrene scintillating bars.

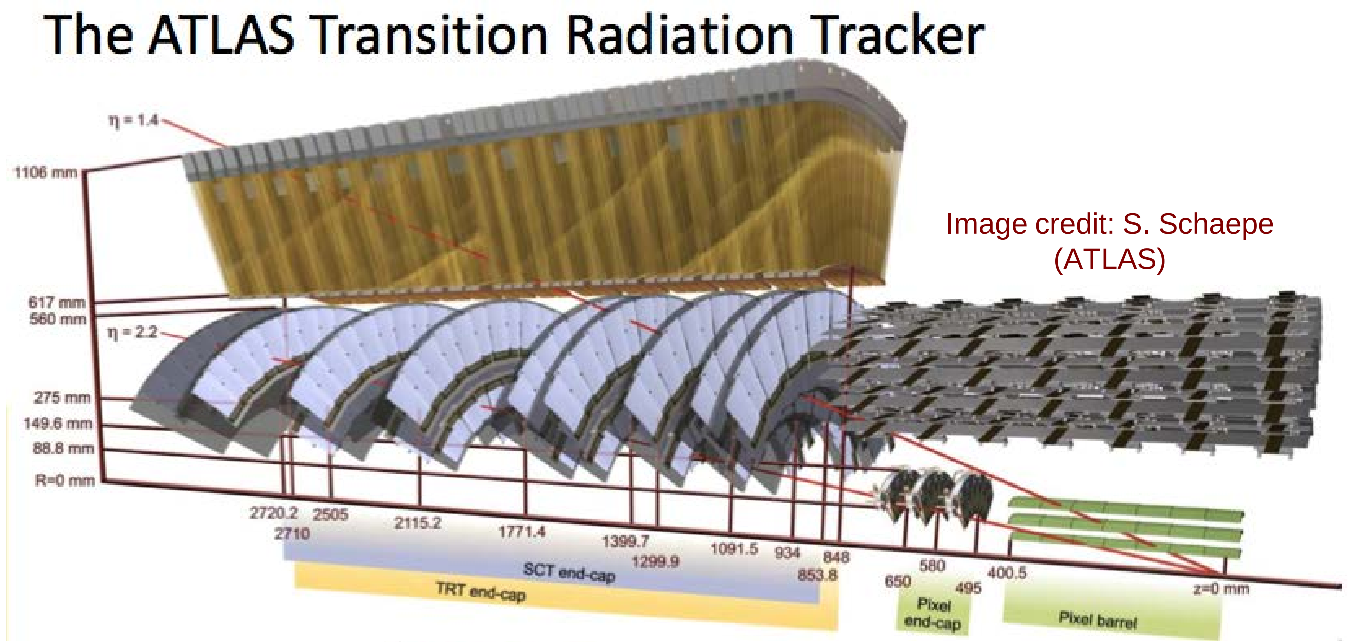
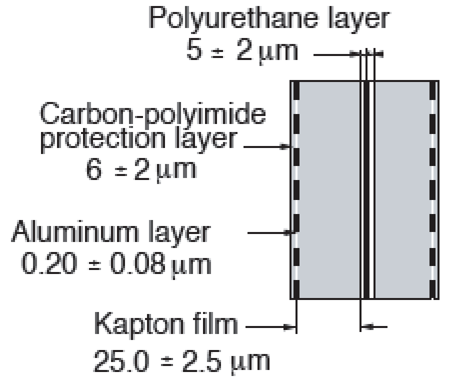
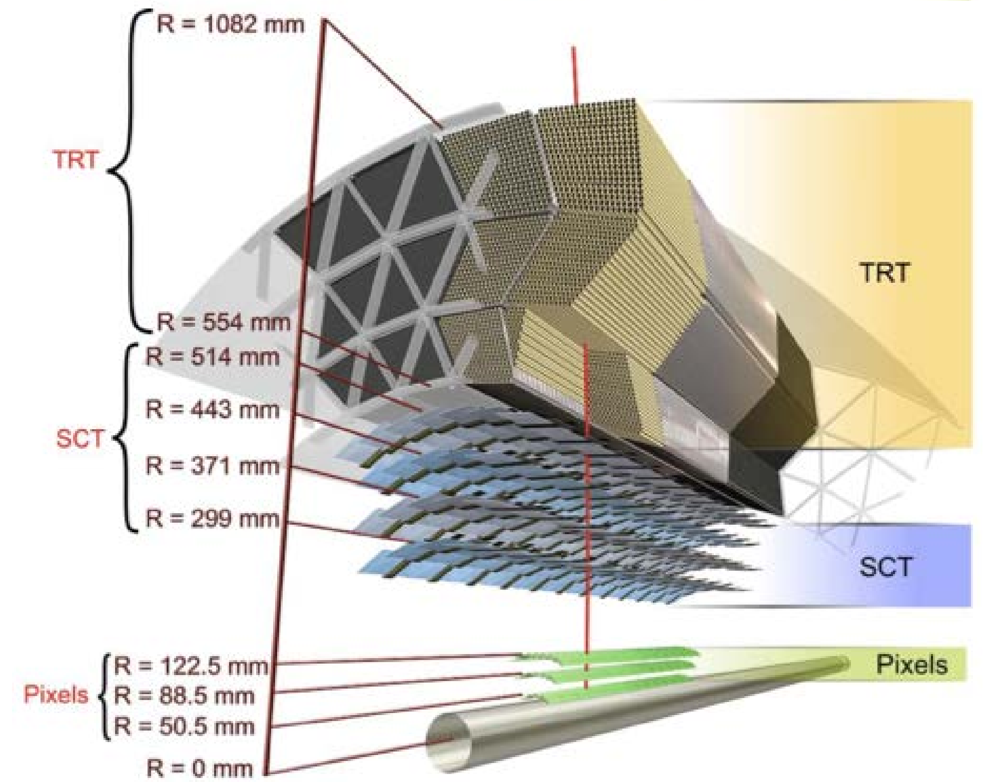


Image credit: S. Schaepe (ATLAS)

Straw Tube Schematic





TRT Assembly at Indiana University

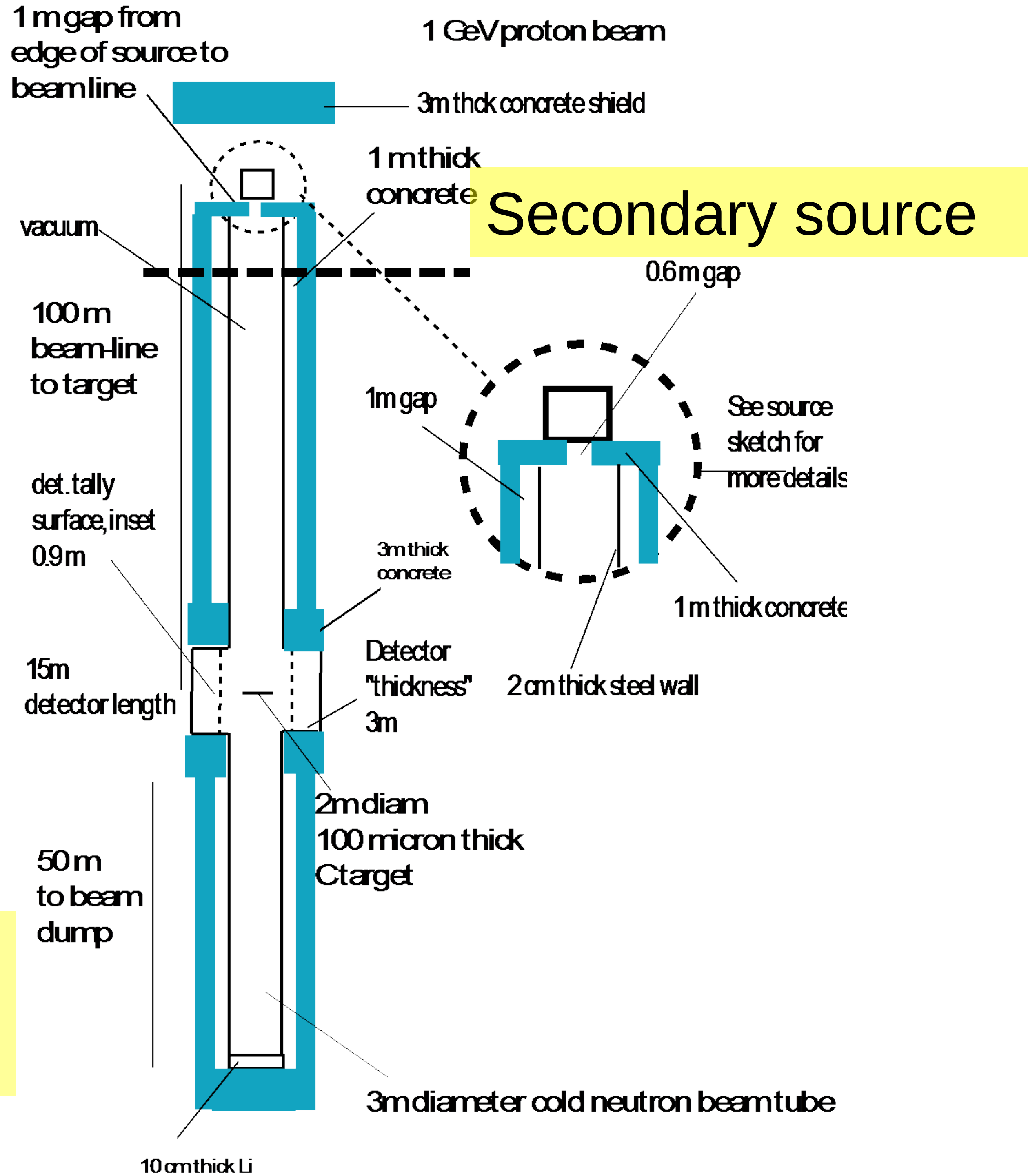
NNBarX Layout

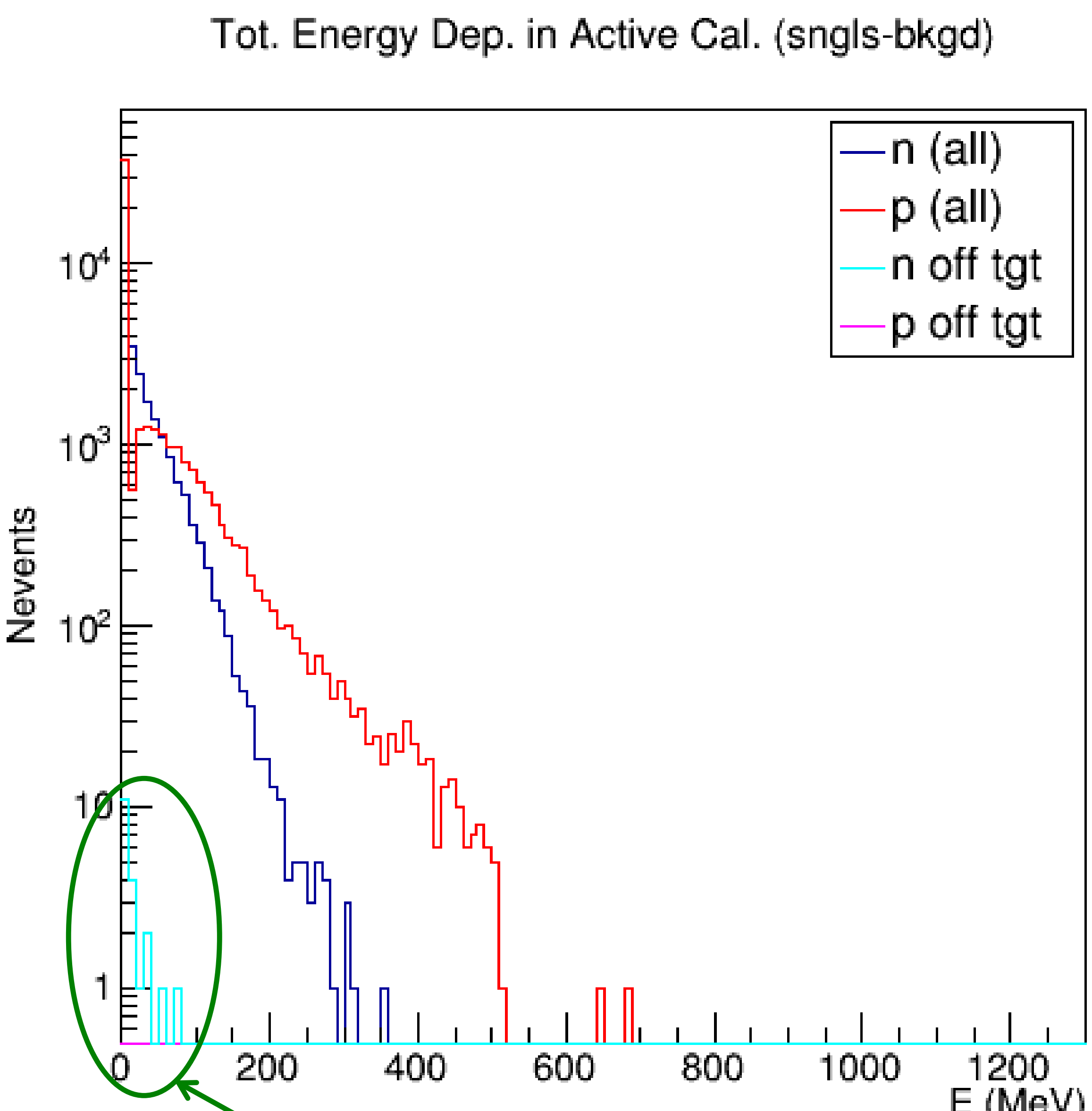
Default geometry will suppress fast backgrounds using passive shielding wherever possible

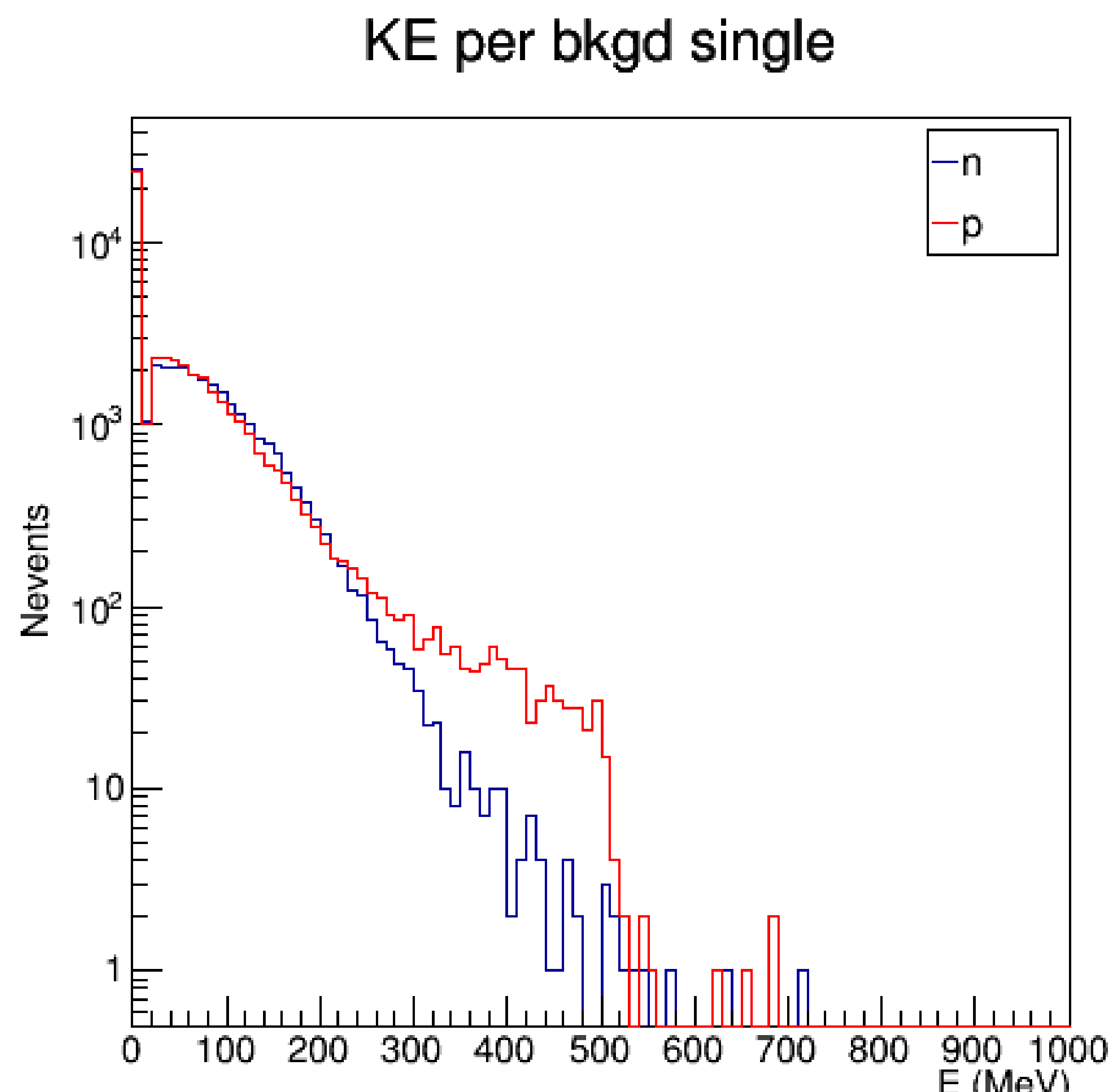
Experiment design and simulation requires integrated treatment of CN source, beamline and detector to model backgrounds

also

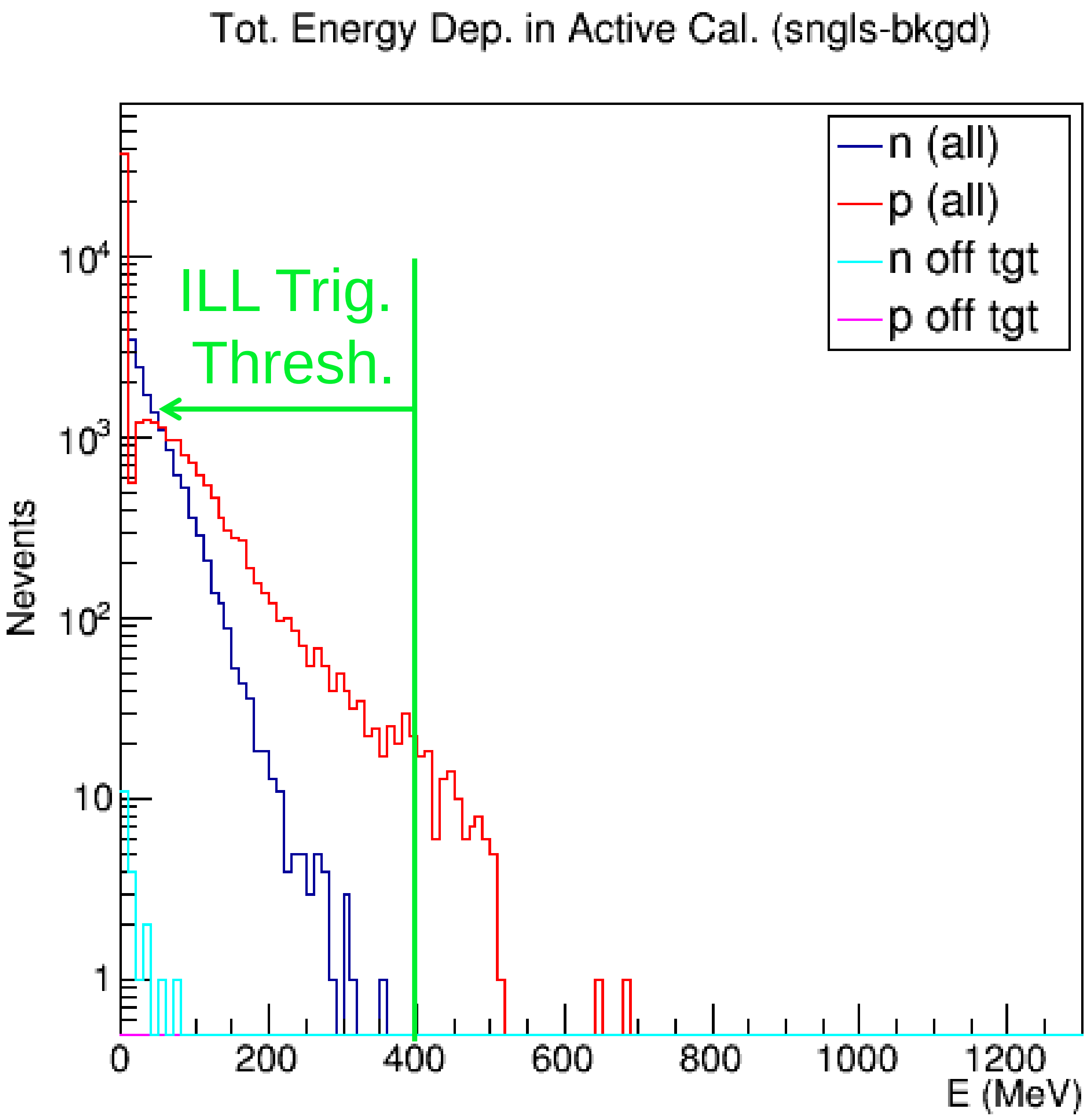
evaluate detector response to fast n's to vet MC

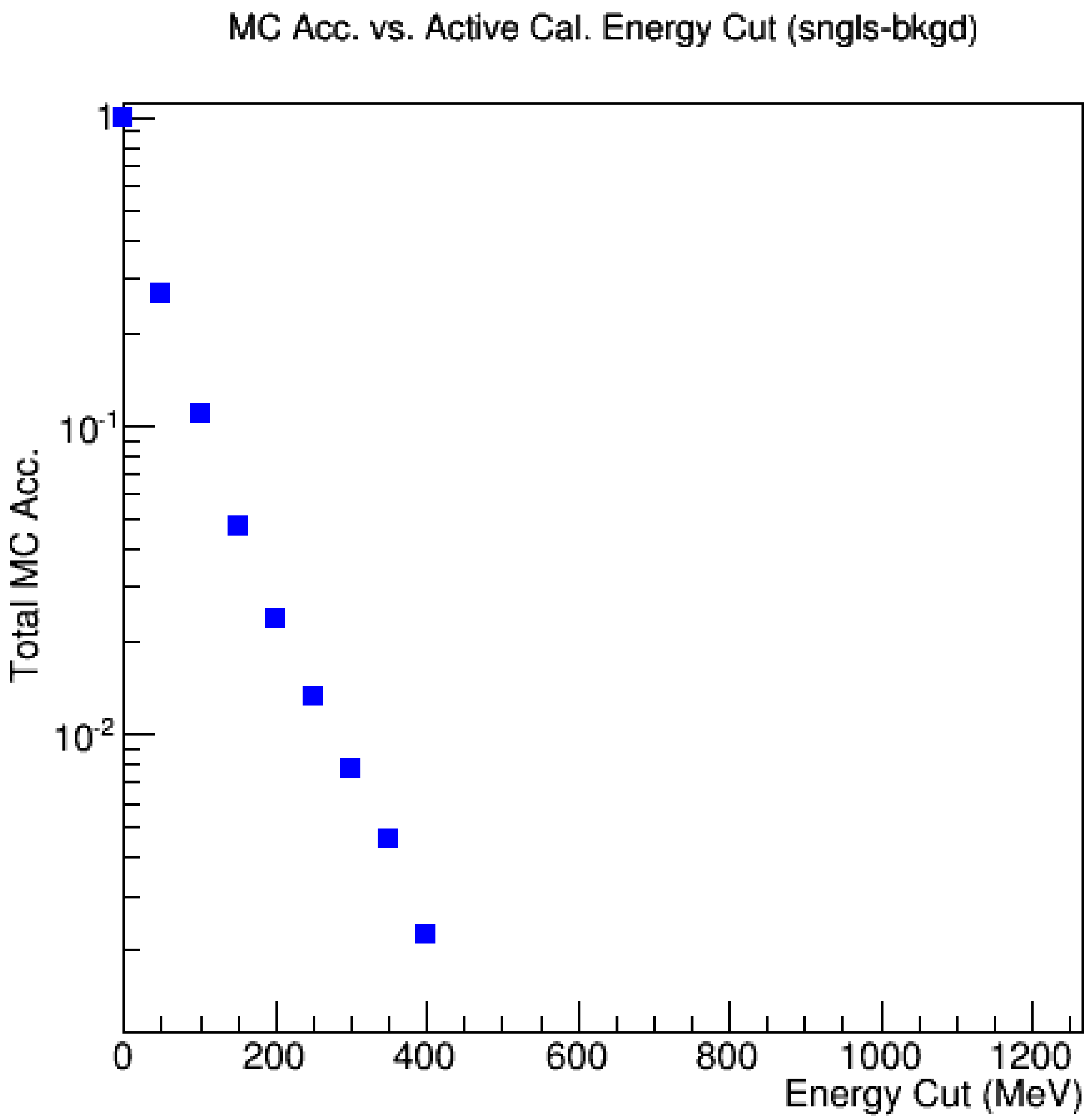


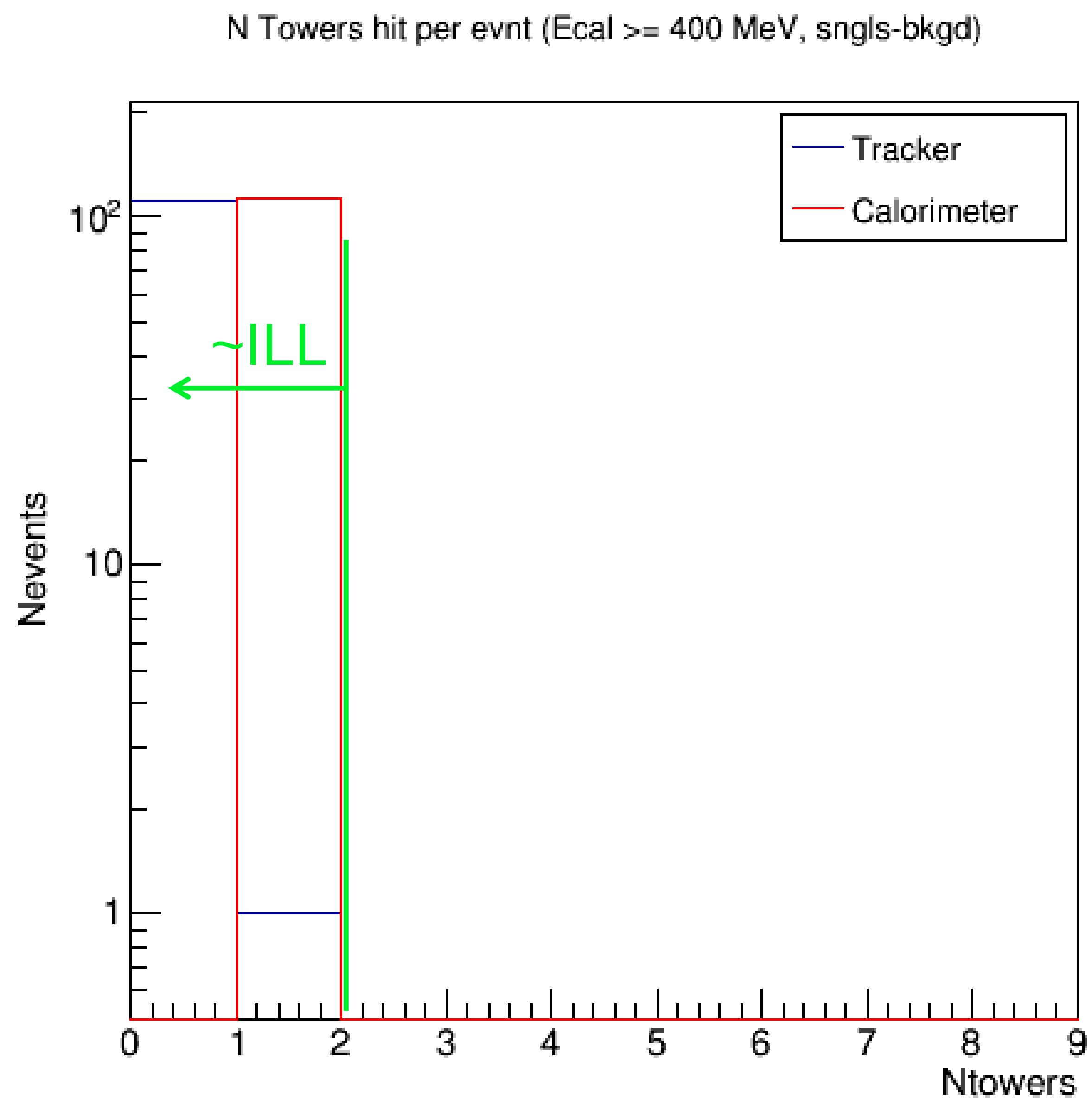




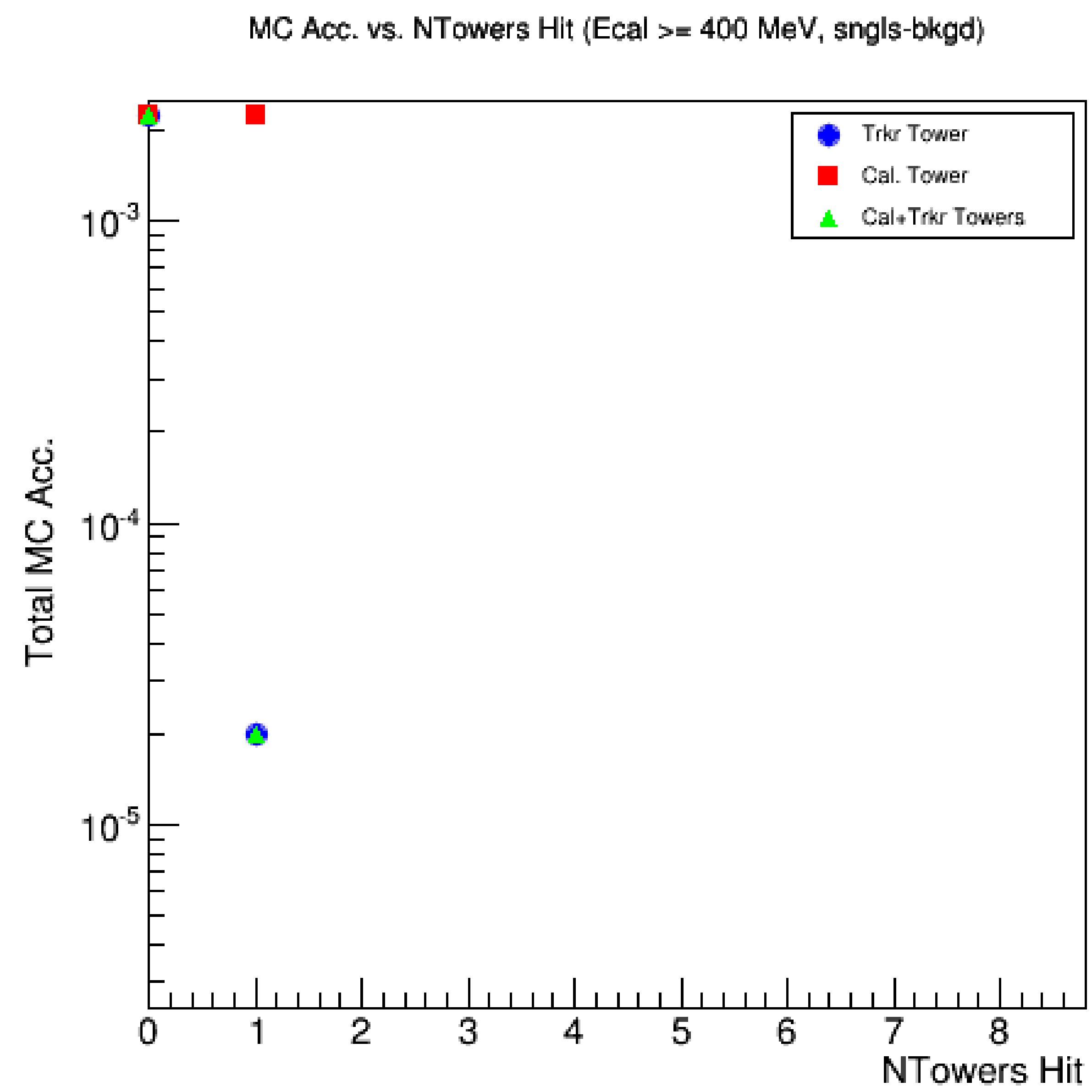
23 out of 50k events w/n-scatter off tgt and deposit energy in active cal.


Tot. Energy Dep. in Active Cal. (sngls-bkgd)
Nevents
E (MeV)
n (all)
p (all)
n off tgt
p off tgt
ILL Trig.
Thresh.

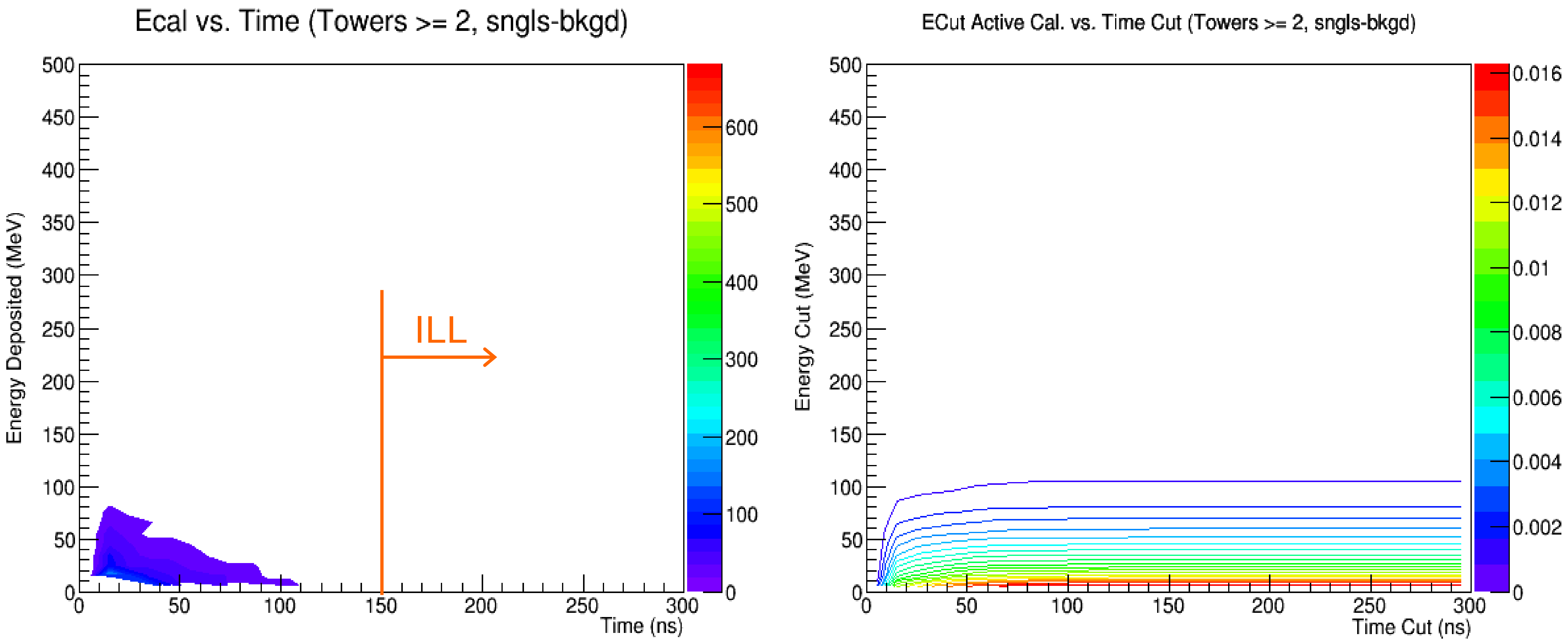

MC Acc. vs. Active Cal. Energy Cut (sngls-bkgd)
Total MC Acc.
Energy Cut (MeV)



N Towers hit per evnt (Ecal >= 400 MeV, sngls-bkgd)
Tracker
Calorimeter
~ILL
Nevents
10^2
10
1
0 1 2 3 4 5 6 7 8 9
Ntowers

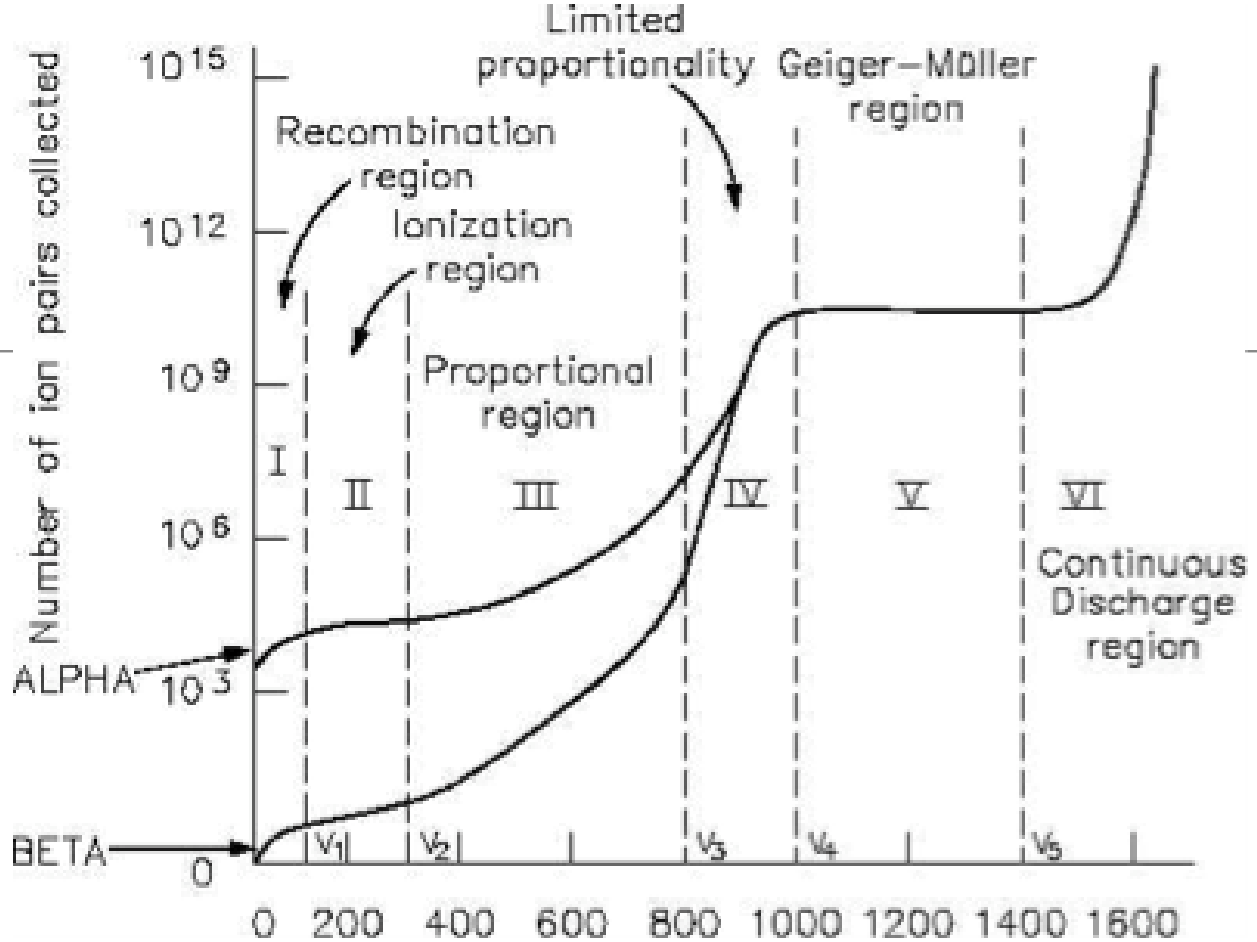


MC Acc. vs. NTowers Hit (Ecal >= 400 MeV, sngls-bkgd)
Trkr Tower
Cal. Tower
Cal+Trkr Towers
Total MC Acc.
10^{-3}
10^{-4}
10^{-5}
0 1 2 3 4 5 6 7 8
NTowers Hit


Ecal vs. Time (Towers >= 2, sngls-bkgd)
Energy Deposited (MeV)
Time (ns)
ILL
ECut Active Cal. vs. Time Cut (Towers >= 2, sngls-bkgd)
Energy Cut (MeV)
Time Cut (ns)

LST Characteristics

- One application of the limited streamer tube (LST) is the Iarocci tube [6,7].



- conducting cathode surface.

- equiv. to single wire drift chamber.

- Long (recent) history of usage in large experiments to detect muons: *CLEO* [8], *OPAL* [9,10], *ZEUS* [11], *D0* [12,13,14], *BaBar* [15].

0.003x1e-24x.01x2200/900x1e23=.007

Al decay: 2.24 min, Q=4.65, gamma-1.8 MeV

emitted velocities entering the reflector: average 1264 m/s , most prob. 1100 m/s, extending from 40 to 3000 m/s
velocities exiting the reflector: average 900 m/s , most prob. 800 m/s, extending from 240 m/s to 1600 m/s
Number of neutrons per sec average
- emitted into 2pi from the moderator surface (cylinder) 9.00E15
- entering reflector 6.00E13
- exiting reflector 2.46E13
- hiting the target 1.39E13

Configuration details you can find in the posted report. Let me give you some geometry numbers that might be relevant for your estimates:

moderator at z=0 has area 12x12 cm2
reflector entrance at z=10 m has radius 0.8749 m
reflector exit at z=50 m has radius 1.7369 m
target at z=200 m has a radius 1 m

The integral of the neutron flux in his model is 2e-2 n / primary proton. Looking back at his input file, this if for about 3 m from the source.
So you can probably directly scale this number by the solid angle at 100, 150, or 200 m. Also the file used by geant to input these fluxes
are directly from Michel's model so dave just needs to integrate them over the energy range of interest to get a scaling to primary protons.
The same can be done for proton flux.

Missing Events

Final State Pionic Mode	NMissEvnts	% Total
$\pi^+\pi^-\pi^0$	40	9.59%
$\pi^+\pi^-$	34	36.96%
$2\pi^+\pi^-\pi^0$	25	5.14%
$\pi^+2\pi^0$	23	7.93%
$2\pi^+2\pi^-\pi^0$	23	7.30%
$2\pi^+2\pi^-$	22	17.74%
$\pi^+\pi^-2\pi^0$	22	4.15%
$2\pi^+\pi^-$	21	19.44%
$\pi^+2\pi^-\pi^0$	19	14.39%
$\pi^+2\pi^-$	16	31.37%
$2\pi^0$	12	17.39%
$\pi^-2\pi^0$	12	10.26%