SIPM READOUT CHOICE INTRO

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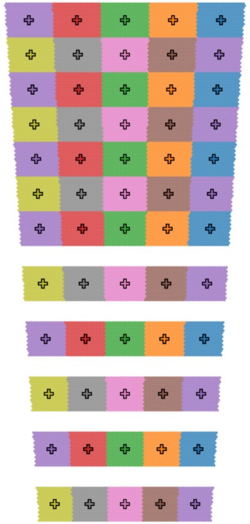
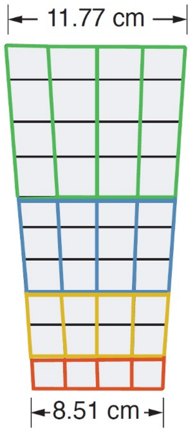
READOUT CONSIDERATIONS

- 5760 Readout channels
  - Each channel sees the summed signals of 4 or 16 SiPMs
- High dynamic range desirable, few N_{pe} to ~20k
- Application slightly different than the other ePIC calorimeters due to the time-projection aspect
  - Real signals can arrive fairly late w.r.t a bunch crossing
  - Travel time for light from one side to the other is ~20 ns
- Signal ToA is important to know well for matching hits in SciFi to hits in AstroPix
  - Also important for attenuation length correction
- Power dissipation (and fluctuations thereof) of electronics should not affect the SiPM & AstroPix temperature during stable running



GLUEX READOUT

- One array = 4x4 3mm SiPMs in parallel
- GlueX scheme used JLab 250 MHz fADCs as well as TDCs
  - Achieved time resolution of O(few 100) ps and intrinsic risetime of ~5 ns
- Readout electronics were in racks, not on-detector
  - Helps maintain thermal stability of SiPMs & electronics
- Summed signals from multiple arrays into a single readout channel, 16 ADCs per sector
  - 4 arrays for back (green), 3 arrays for 2^{nd} to back (blue), etc.
- Exclude single-side hits



T.D. Beattie et al.

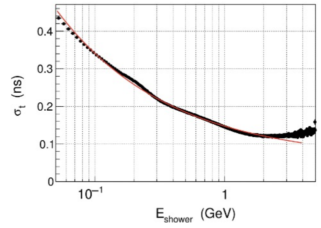


Fig. 28. Time resolution for neutral showers as a function of shower energy. The curve is a fit to Eq. (2) with parameters c = 0.089 $\sqrt{\text{GeV}}$ ns and d = 0.058 ns, which gives a good qualitative description of the data between 0.08 and 2 GeV. (Color online).

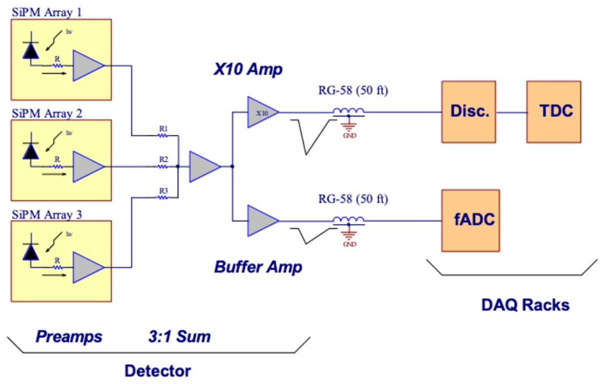
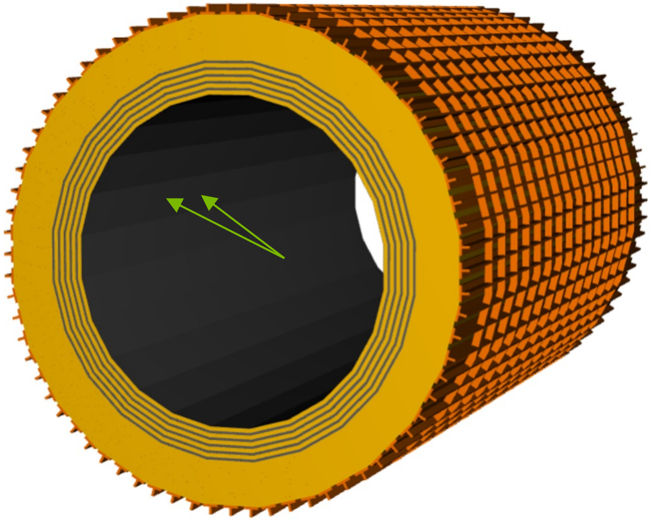


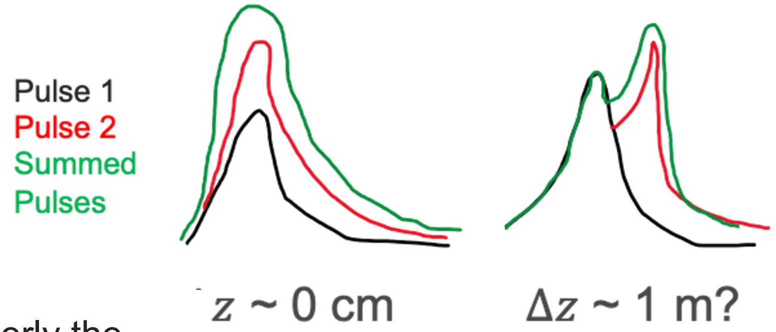
Fig. 1 – BCAL Readout Architecture

https://halldweb.jlab.org/DocDB/0017/001795/002/The%20BCAL%20SiPM%20Array%20Readout.pdf

SAME-CELL HITS

- In high occupancy events like jets at high Q^2, can have two energy deposits close to each other in azimuth
  - This poses a challenge, can we independently measure the *energy* of two clusters in the same cell of the SciFi?
    - I.e. similar ϕ but different Z
    - Cluster positions known from AstroPix
    - But energy of each cluster needed for e.g. π^0 reconstruction
- In these cases, the pulse shapes will not conform to a template
  - Unique shapes depending on the Δz between the clusters
  - Would need a well-digitized waveform & algorithm to disentangle

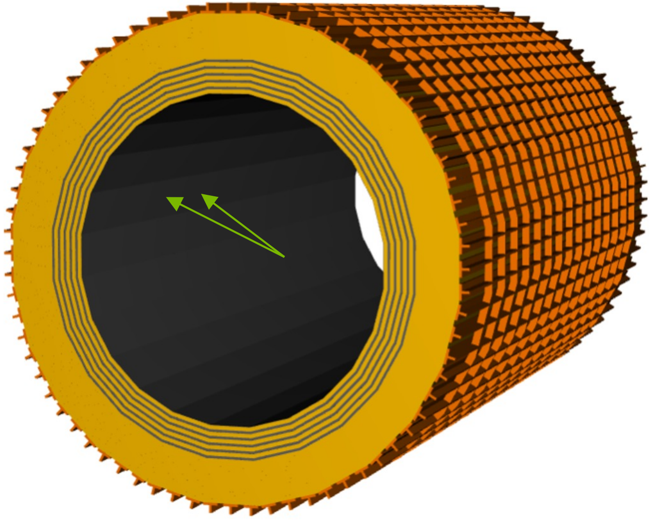




If we can resolve properly the *sum* of the two clusters, can use AstroPix to split cluster energy

SAME-CELL HITS

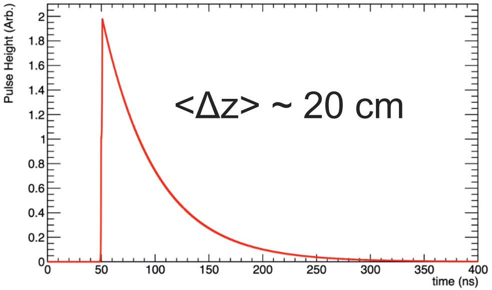
- Impact of same-cell hits on physics
  - Compared to GlueX, KLOE, much higher multiplicities expected
- Most challenging events are at high Q^2
  - Use Pythia8: $Q^2 > 500\ \text{GeV}^2$
    - Benchmarked against H1 data, provides a reasonable description of the hadronic final state for these events
  - Typically collimated single-jet events
  - Kinematically favored to be in the barrel
- Currently just looking at azimuthal angle of particle production
  - Ignoring shower size

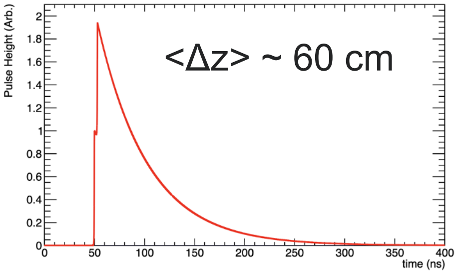


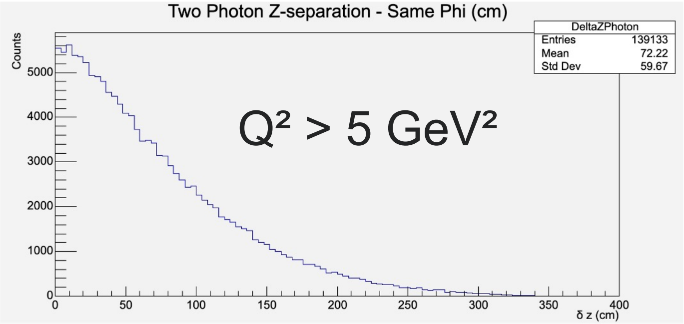
SAME-CELL HITS

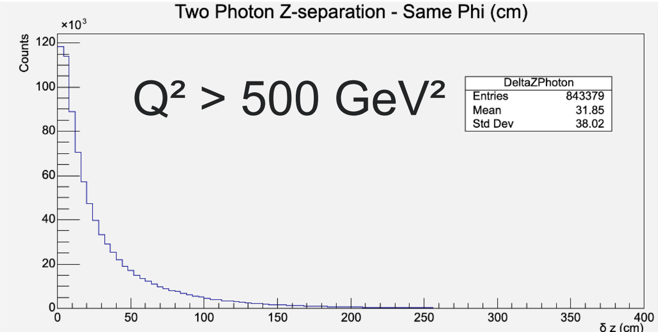
- In ~60% of $Q^2 > 500$ GeV² events, there will be at least two particles in the same phi cell
  - In ~40% of events, those two particles will be photons with $\langle E \rangle \sim 1.5$ GeV
  - For ~15% of $Q^2 > 5$ GeV² events, have two photons in same phi cell
  - In either case, this is a non-trivial occurrence rate
    - Driven largely by decays

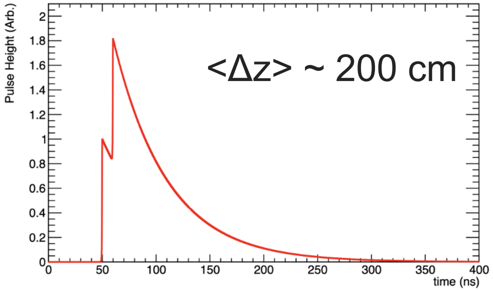
- In ~25% of $Q^2 > 500$ GeV² events, those same-cell photons will be within $\Delta z = 20$ cm ($\langle \Delta z \rangle = 32$ cm)
  - $\Delta z = 20$ cm ~ 1 ns of Δt
  - Fastest we could imagine digitizing a waveform is probably ~ 1 GHz (HDSoc), still need 3 ns ~ 60 cm to actually resolve the two pulse heights











OPEN/DISCUSSION QUESTIONS

- Do we want to use HGCROC?
  - What do we gain/lose if we do?
  - Are there other options? HDSoC?
- Can we use “templated” readout?
- Is trading precise ToA for more precise waveform digitizing worth it?
- Will we require hits on both sides?
- How much bandwidth will we have & what does streaming readout look like for us?
  - At what step in the readout chain will we analyze the waveforms?

BACKUP

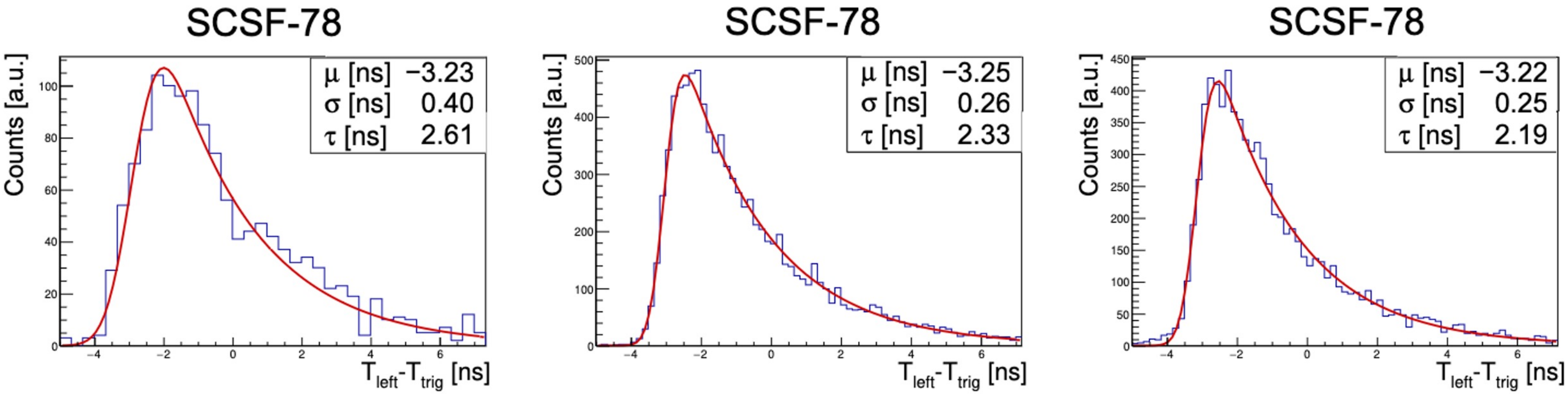


Figure 7. Decay time distribution for $n_{ph} \leq 5$ (left), $10 < n_{ph} \leq 15$ (center), and $n_{ph} > 20$ (right) for the SCSF-78 fiber fitted with the EMG distribution.

GOALS & SETUP

- Determine necessary SciFi resolution in Z
- Most challenging for us will probably be jets at very high Q^2
  - High multiplicity & likelihood to be in the barrel
- Pythia 8.303 + Dire
  - Used in HERA high Q^2 event shape analysis
  - Acceptable to first order, but fewer multi-jet events than in data
  - Non-radiative, lepton PDF off
- Study Q^2 > 500 GeV^2
  - Cross section of ~280 pb
  - 10M events simulated, corresponds to something like 35 fb^{-1}

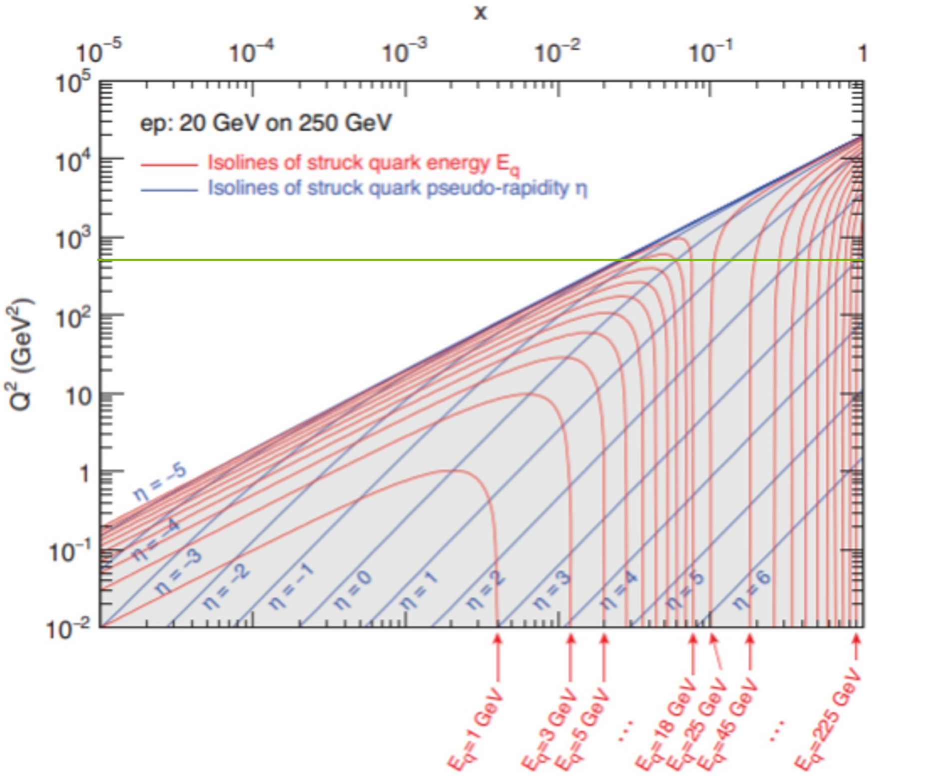


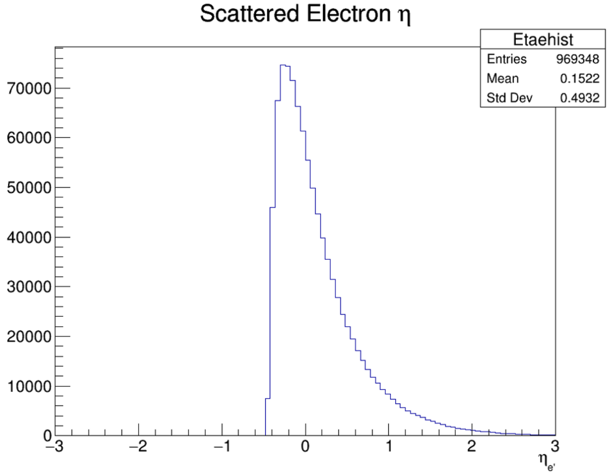
Figure 4 : Isolines of the struck quark energy E_q and pseudorapidity η for 20 GeV on 250 GeV ep collisions.

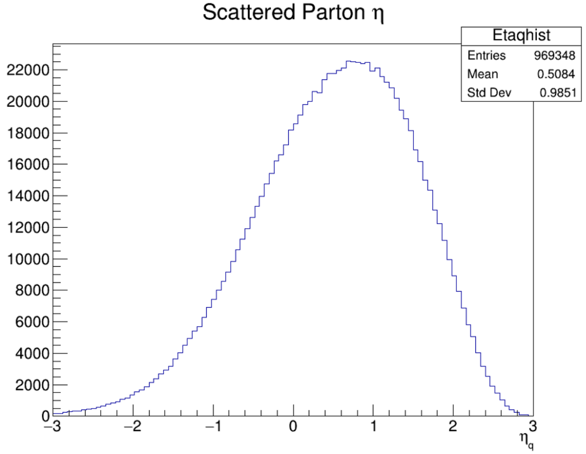
MOTIVATION

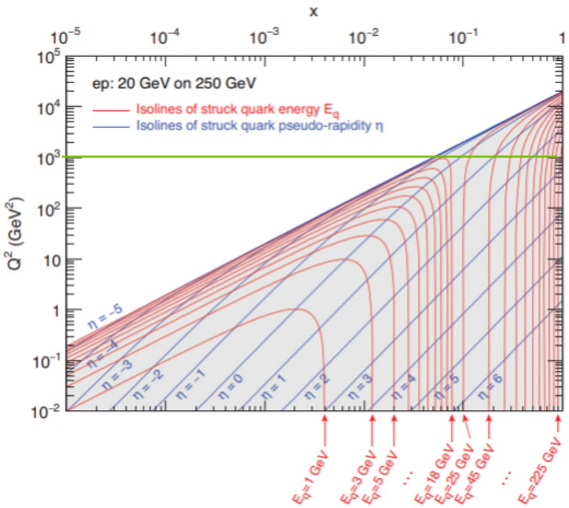
Pulse 1
Pulse 2
Summed Pulses

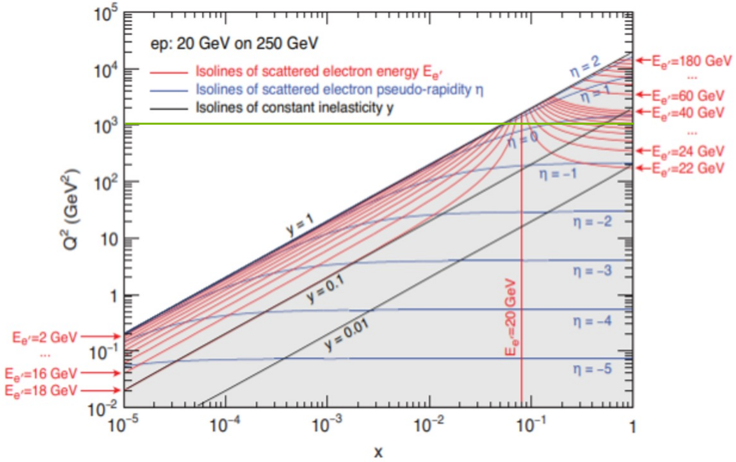
- If two photons land in the same phi slice of the SciFi, likely that their energy will be summed unless we do something beyond GlueX
  - GlueX signals ~ 80 ns long, rise time ~ 8 ns
  - 8 ns corresponds to something like a meter in Z
  - Time resolution much much shorter than pulse length, only need first few samples to determine time of arrival
  - Likely need first pulse to start falling before second pulse can be distinguished
- This presents an issue for π^0, AstroPix can tell us that there were two photons, but without E_1 and E_2 separately can't determine the invariant mass

KINEMATICS









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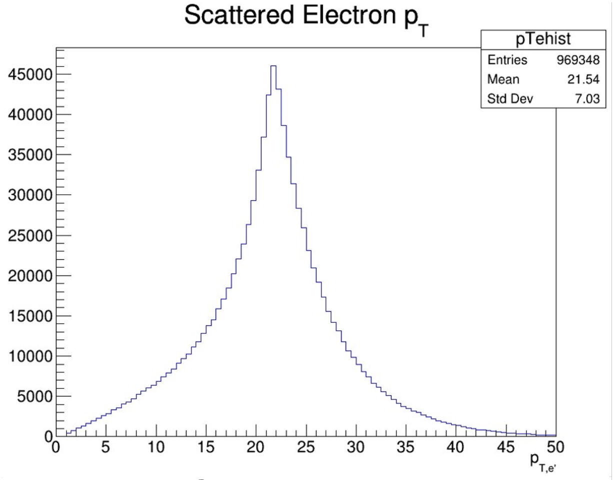
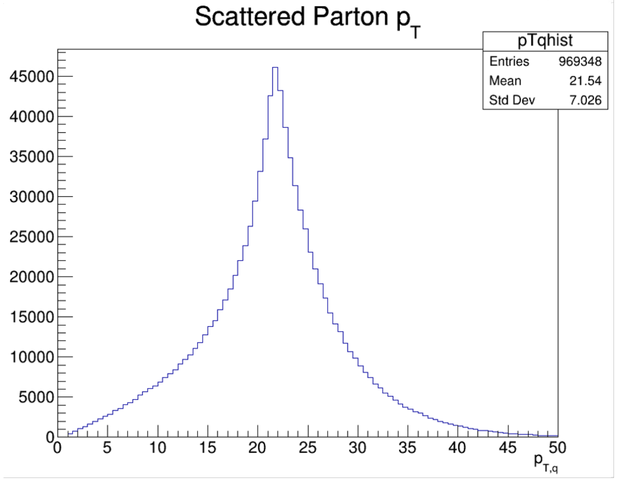
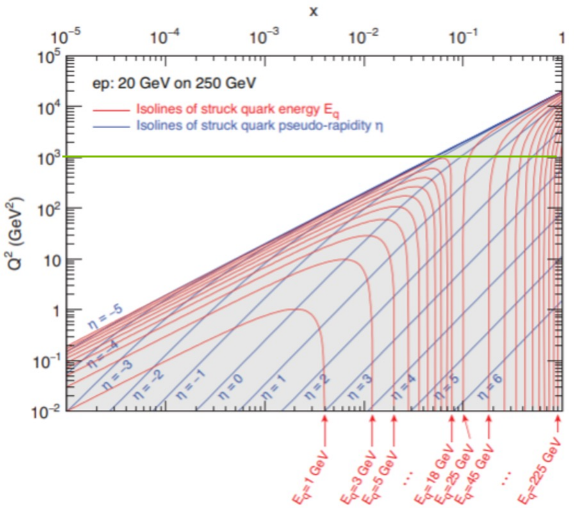
KINEMATICS



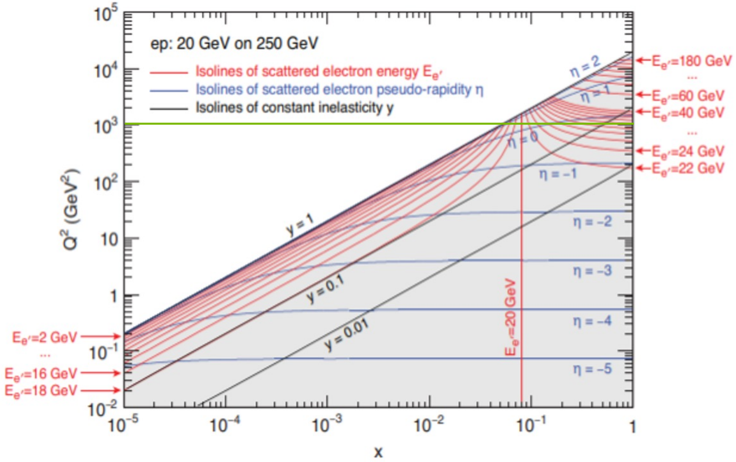
Scattered Electron p_T
pTehist
Entries 969348
Mean 21.54
Std Dev 7.03
$p_{T,e'}$



Scattered Parton p_T
pTqhist
Entries 969348
Mean 21.54
Std Dev 7.026
$p_{T,q}$

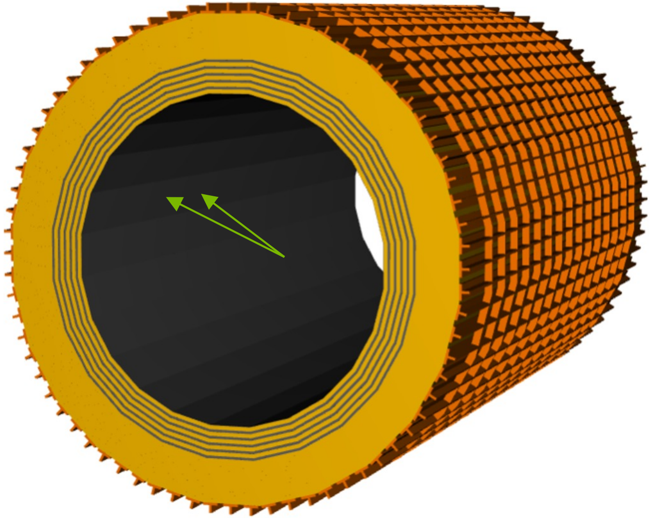


x
Q^2 (GeV^2)
ep: 20 GeV on 250 GeV
Isolines of struck quark energy E_q
Isolines of struck quark pseudo-rapidity η
E_q=1 GeV
E_q=3 GeV
E_q=5 GeV
E_q=18 GeV
E_q=25 GeV
E_q=45 GeV
E_q=225 GeV



ep: 20 GeV on 250 GeV
Isolines of scattered electron energy $E_{e'}$
Isolines of scattered electron pseudo-rapidity η
Isolines of constant inelasticity y
Q^2 (GeV^2)
x
y = 1
y = 0.1
y = 0.01
$E_{e'}$=180 GeV
$E_{e'}$=60 GeV
$E_{e'}$=40 GeV
$E_{e'}$=24 GeV
$E_{e'}$=22 GeV
$E_{e'}$=20 GeV
$E_{e'}$=2 GeV
$E_{e'}$=16 GeV
$E_{e'}$=18 GeV

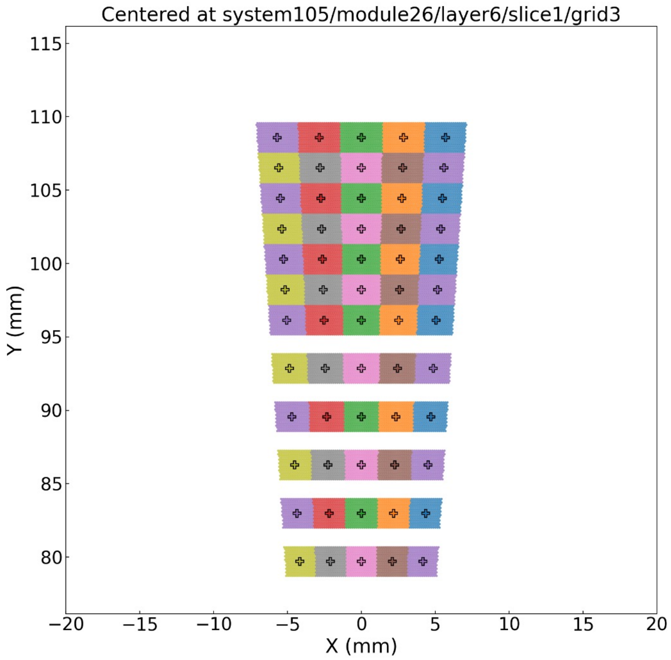
SAME-CELL HITS



- Impact of same-cell hits on physics
  - Compared to GlueX, KLOE, much higher multiplicities expected
- Most challenging events are at high Q^2
  - Use Pythia8: $Q^2 > 500$ GeV^2
  - Typically collimated single-jet events
  - Kinematically favored to be in the barrel
- In ~60% of $Q^2 > 500$ GeV^2 events, there will be at least two particles in the same phi cell
  - In ~50% of events, those two particles will be photons $\langle E \rangle \sim 1.5$ GeV
  - In ~25% of events, those photons will be within $\Delta z = 20$ cm of each other
    - $\Delta z = 20$ cm ~ 1 ns Δt, very challenging to resolve
  - This ignores the physical size of the showers
  - For 15% of $Q^2 > 5$ GeV^2 events, have two photons in same phi cell

SIMULATION

- For these high Q^2 events, how likely are we to have two photons in the same event registered by the same SiPM*
  - 48 Modules, 5 SiPMs wide, each SiPM covers 1/240th of the azimuth
- Assume for now that particles striking the same phi slice are integrated
- Charged particles will have energy well measured by inner detectors, likely to deposit only MIP energy
  - Can subtract tracker energy from total measured in Ecal
- Big worry is neutrals, especially photons



*If signals are too slow, could even have photons from different events overlapping

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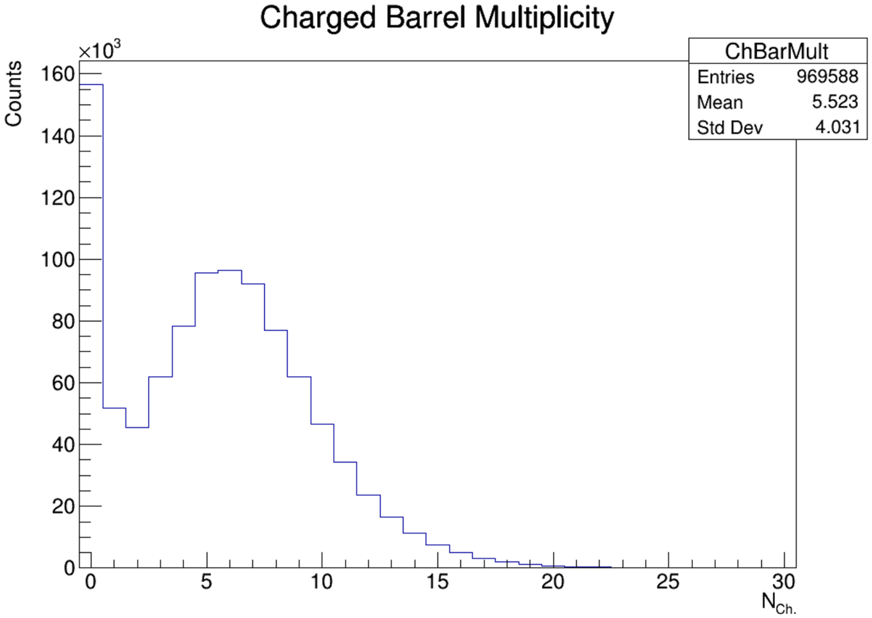
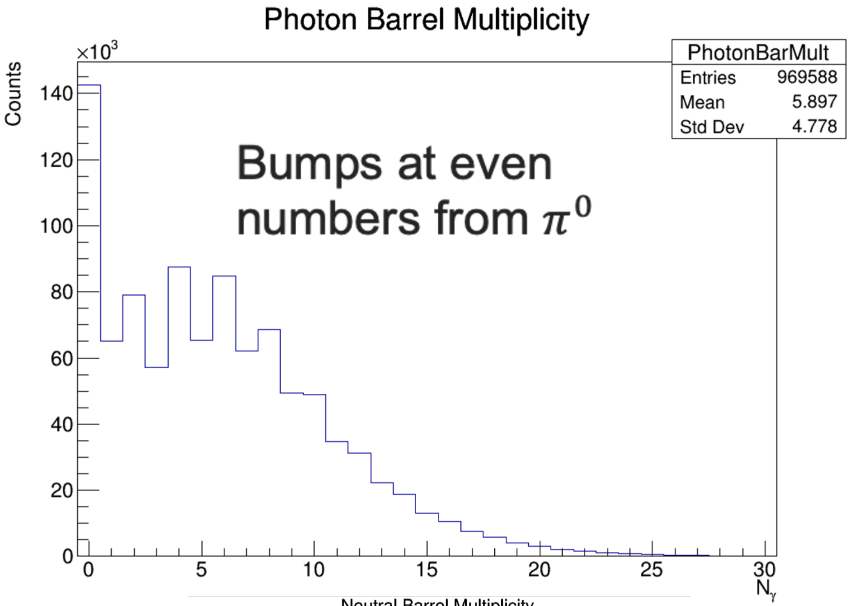
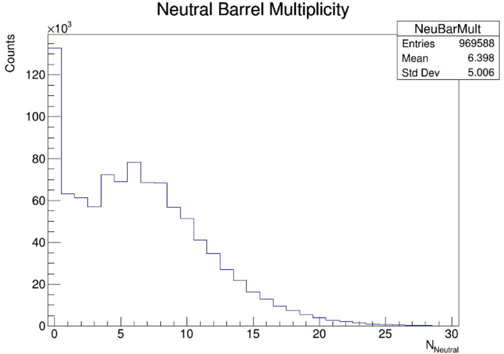
MULTIPLICITIES IN BARREL

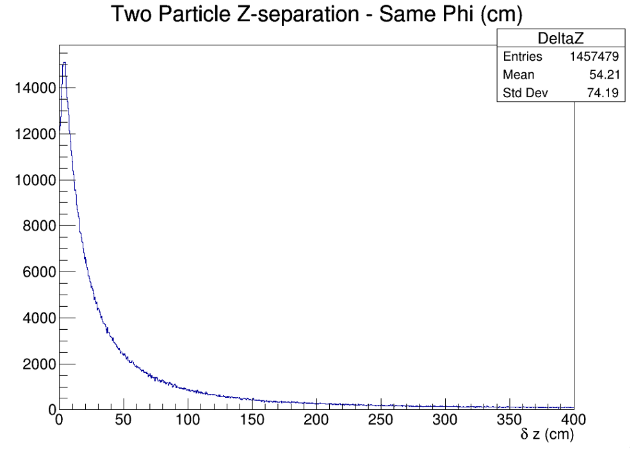


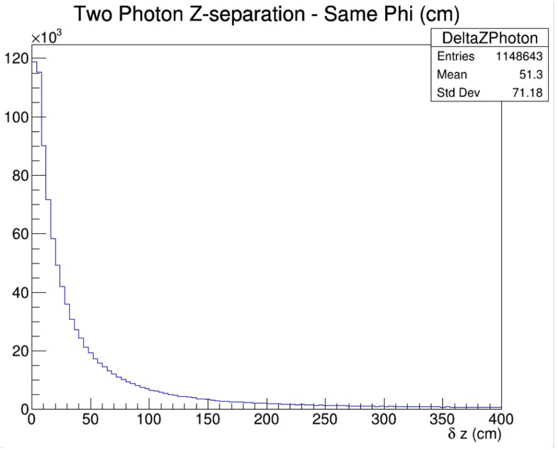


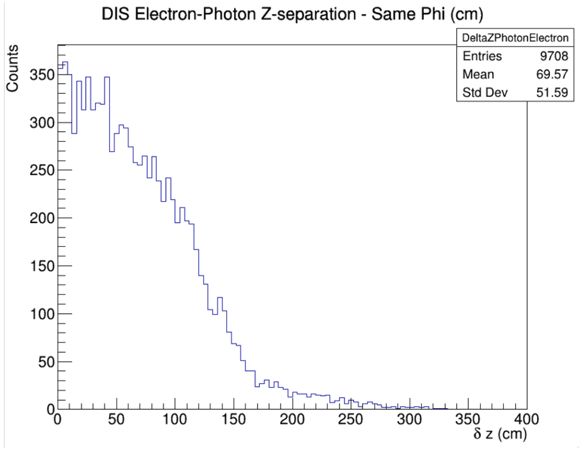


Peaks at 0 could be an artifact
Barrel defined as pseudorapidities between -1.7 and 1.3

PARTICLES IN SAME PHI SLICE

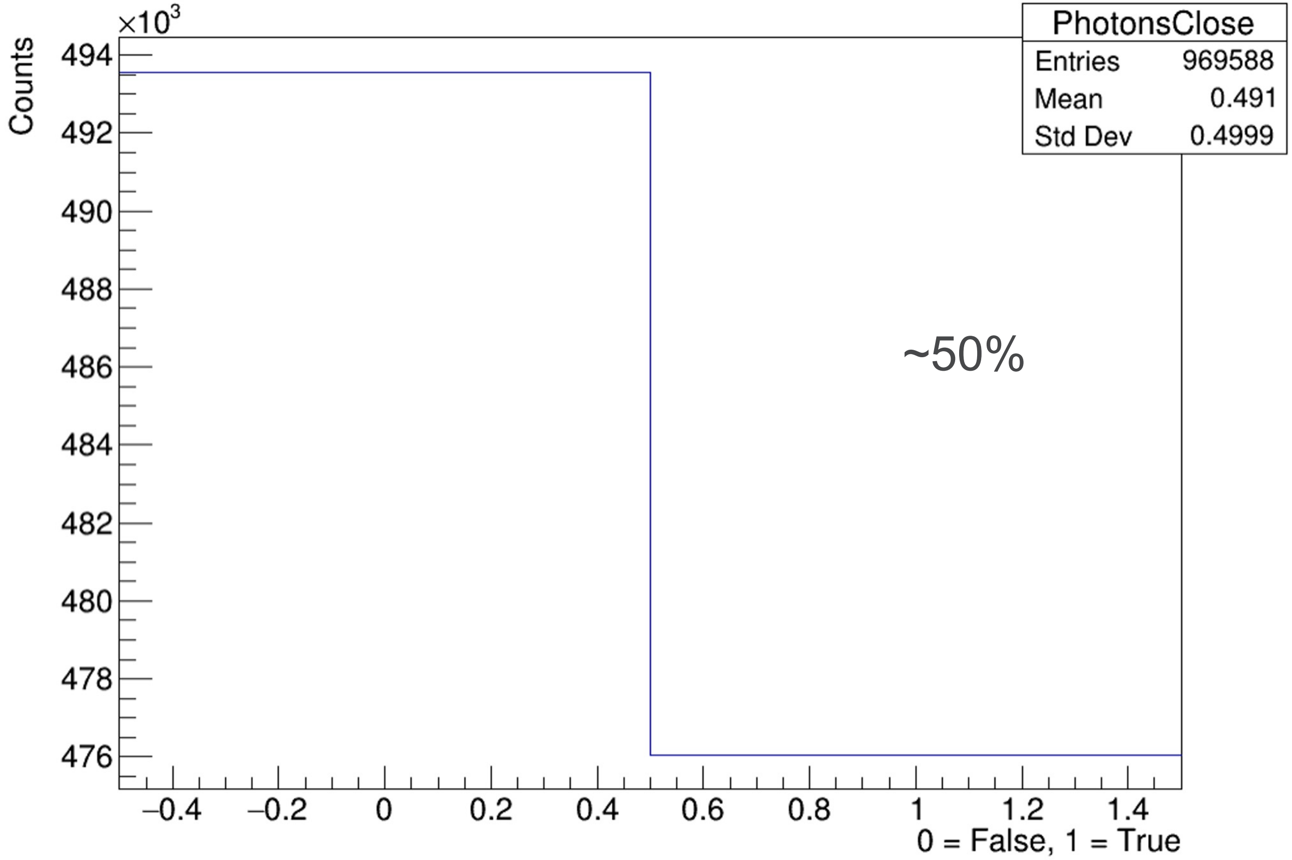




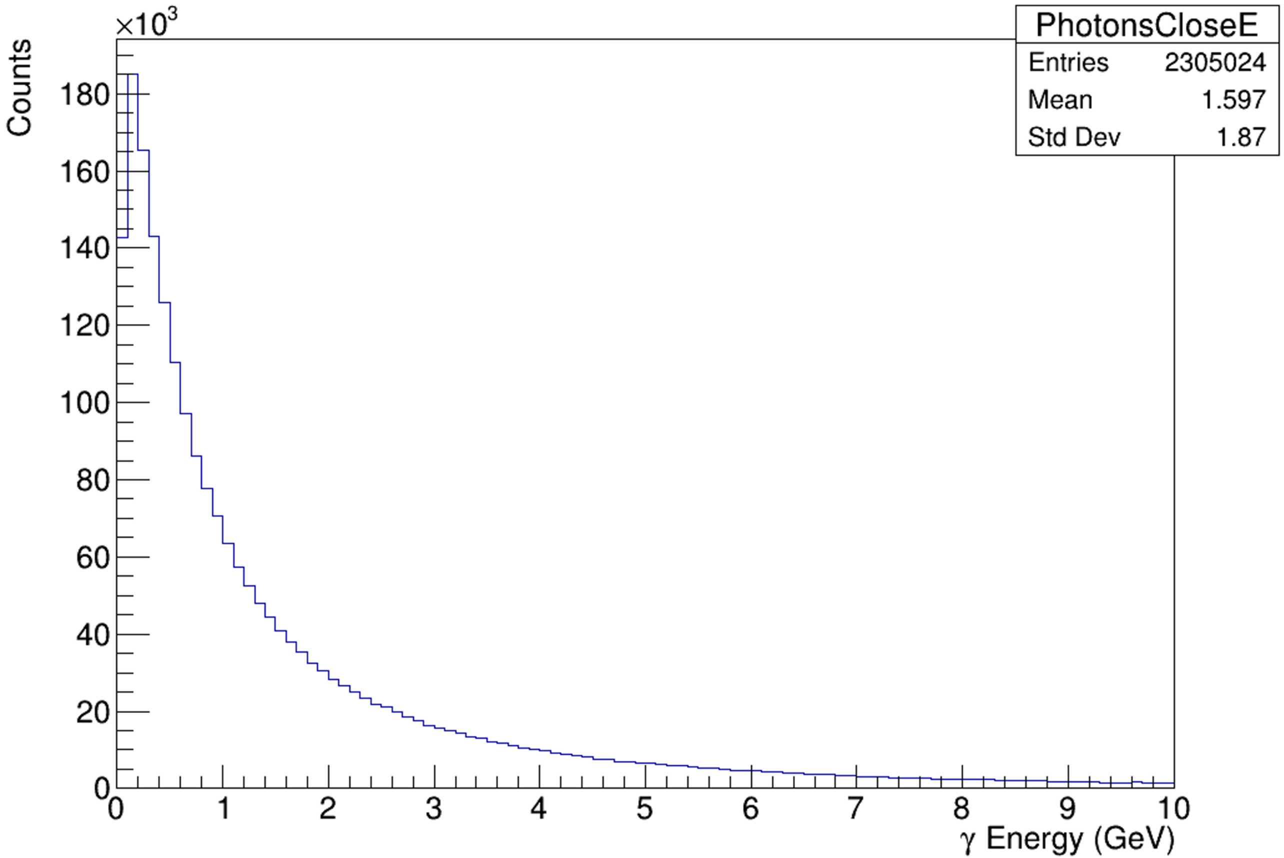


- Unfortunately, particles in the same phi slice tend to also be close in Z
  - Imagine a Gaussian jet in x,y space

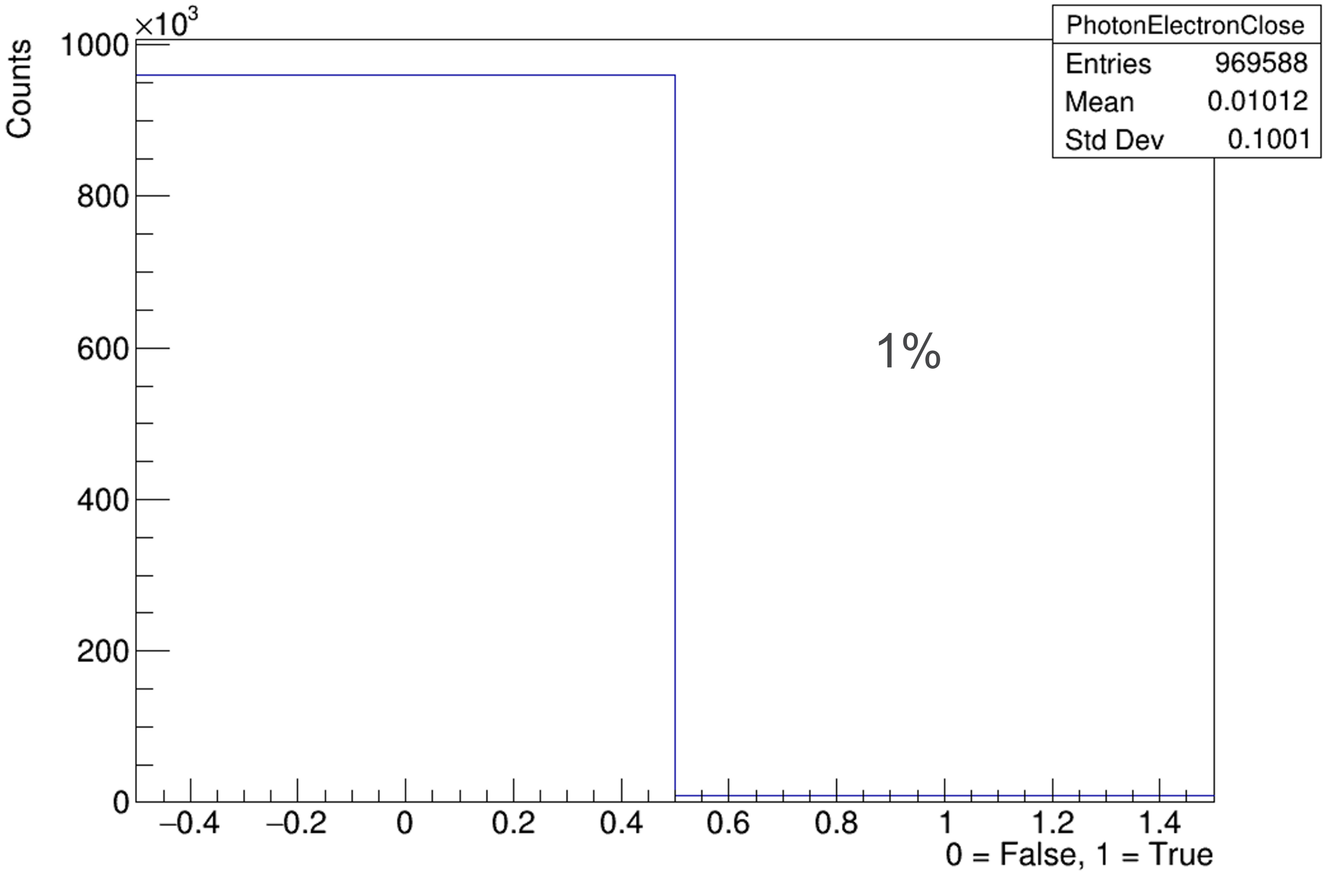
LIKELIHOOD THAT AN EVENT HAS TWO PHOTONS IN THE SAME PHI SLICE



ENERGY OF THOSE TWO PHOTONS IN THE SAME PHI SLICE



LIKELIHOOD THAT AN EVENT HAS A PHOTON IN THE SAME PHI SLICE AS THE DIS ELECTRON



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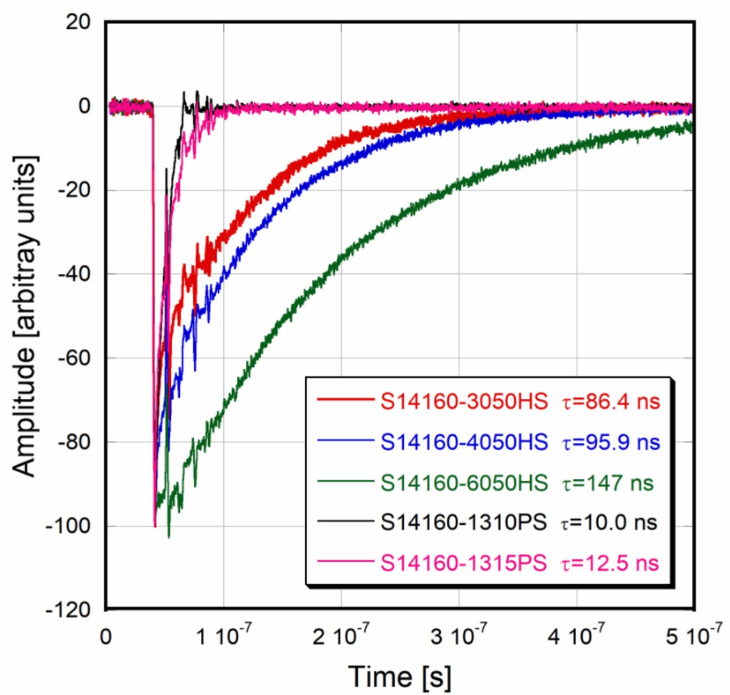
CONCLUSION

- High Q^2 will be challenging on the SciFi
  - Considering here only impact position, no spreading of showers between SiPMs which will certainly happen, real case is likely worse

- Would be nice if we could somehow distinguish two hits in the same phi slice
  - Faster SiPM? Faster scintillation? Higher refractive index fiber?
  - Which factor dominated the GlueX pulse width?



Amplitude [arbitray units]
Time [s]
S14160-3050HS τ=86.4 ns
S14160-4050HS τ=95.9 ns
S14160-6050HS τ=147 ns
S14160-1310PS τ=10.0 ns
S14160-1315PS τ=12.5 ns

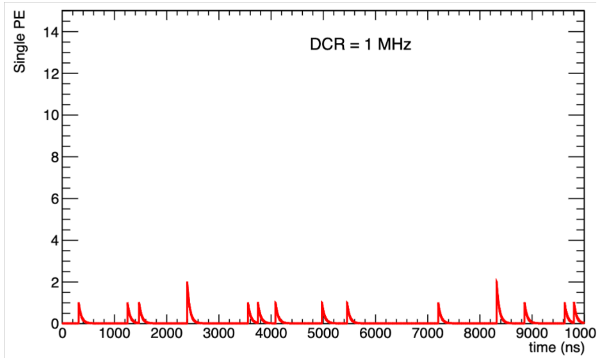
NOISE

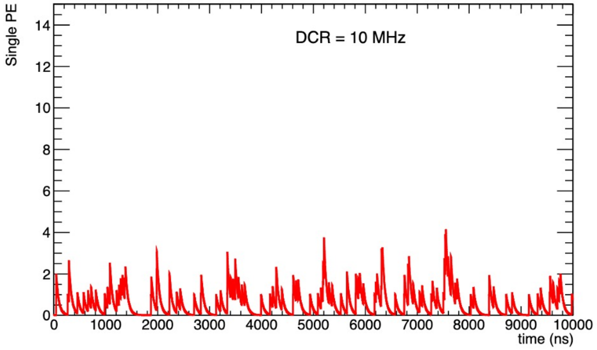
- Dark count rate (DCR) determines threshold
  - MIPs at midrapidity will generate 3-6 N_{pe} on average
    - Would be good to have threshold slightly below MIP
- DCR above a few 10s of MHz will endanger the MIP

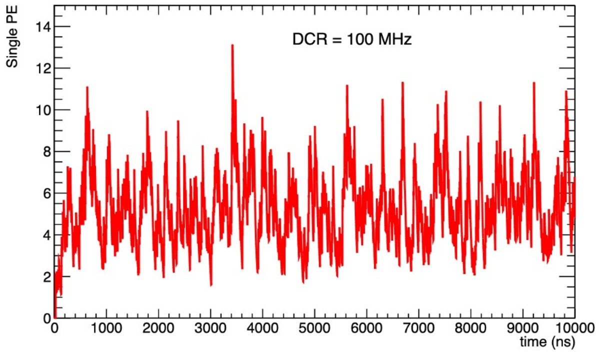
Specification	S13360-3050 (3x3 mm)	S14160-3050 (3x3 mm)
DCR (Typ.)	500 kHz	1 MHz***
Crosstalk (%)	3	7

*** Differing values in literature

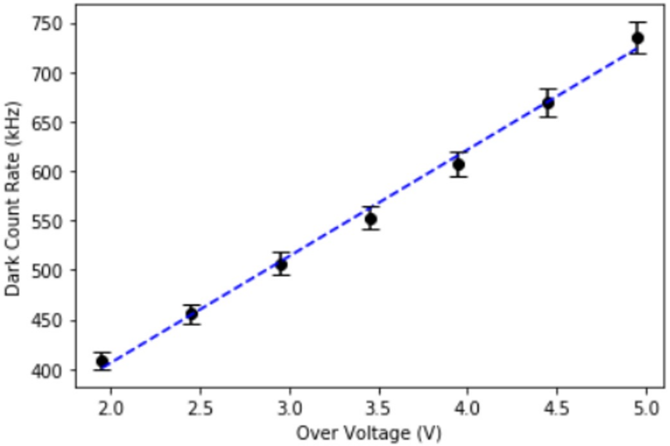
- Signal will gang 1.2 cm x 1.2 cm area (16 3x3 mm or 4 6x6 mm)
  - DCR for one BIC channel will be ~16x value in table
- Plan to test S14160 SiPMs at ANL & Regina

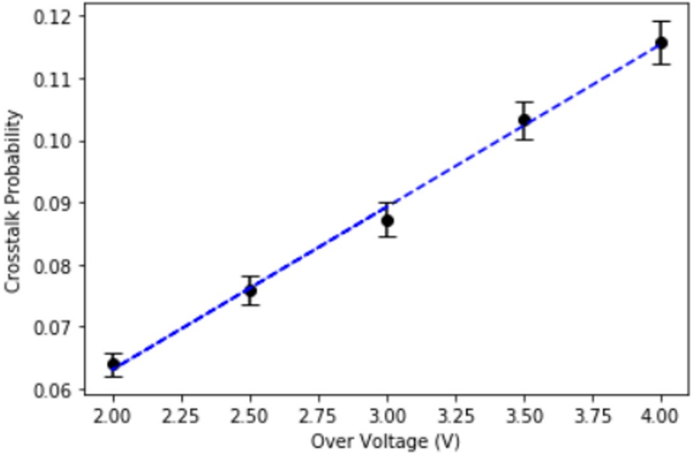




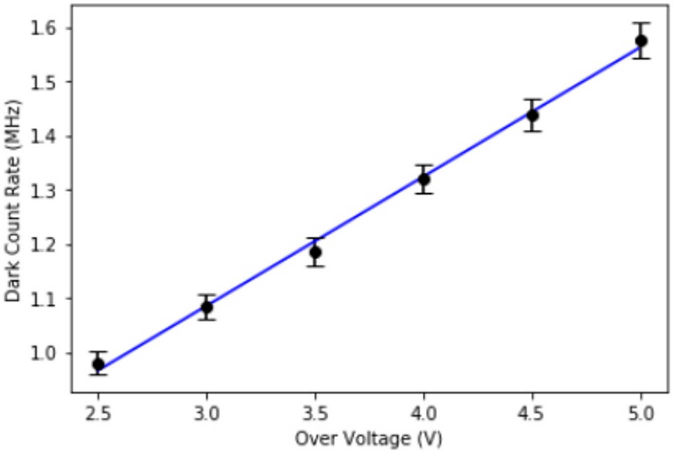


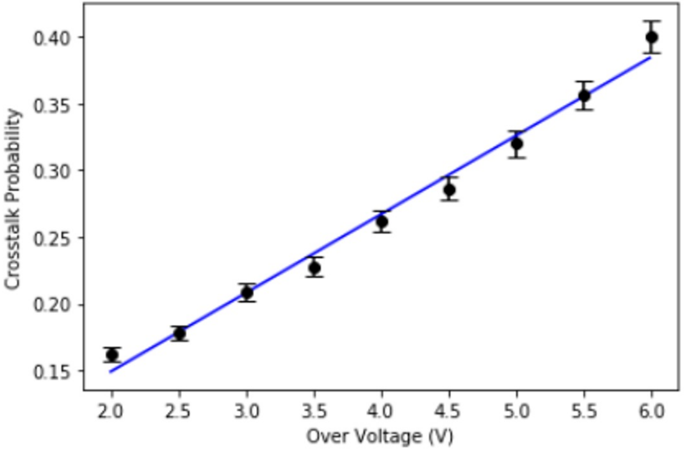
S13360-3050 (3x3 mm)





S14160-3050 (3x3 mm)

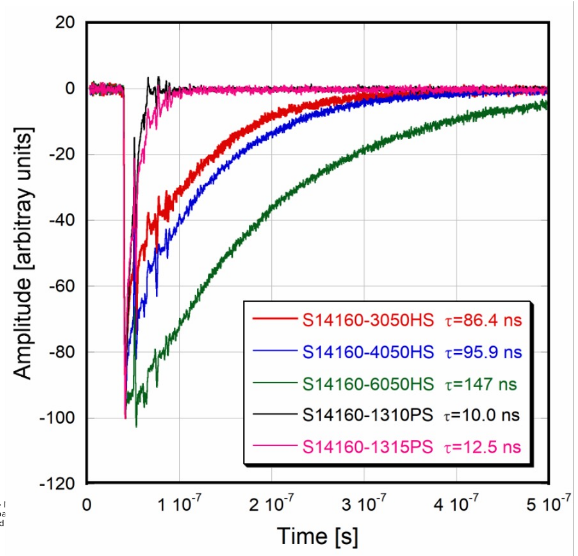


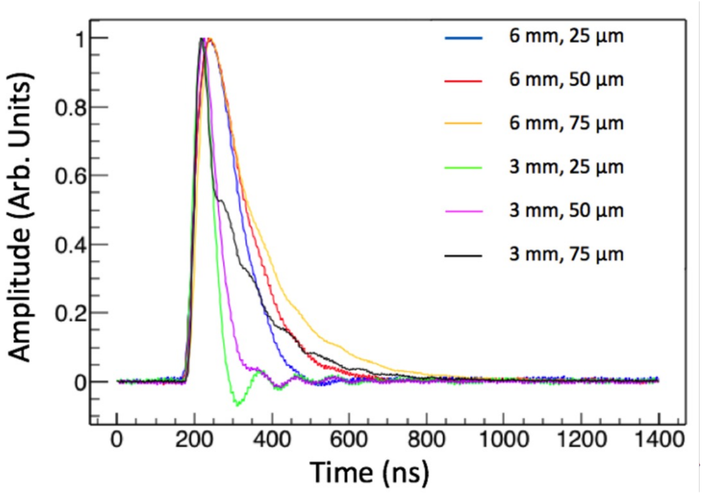


PULSE SHAPE

- Pulse shape strongly defined by how signals are handled
- S14160 has faster rise time, slower fall time

- Larger SiPMs (6x6 mm) have ~2x longer fall times due to capacitance
  - Can we mitigate this in our ganging scheme?

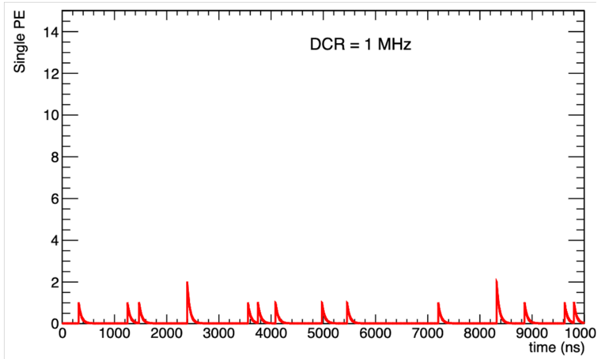


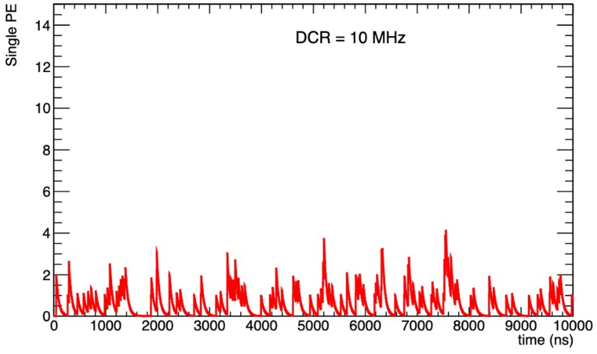


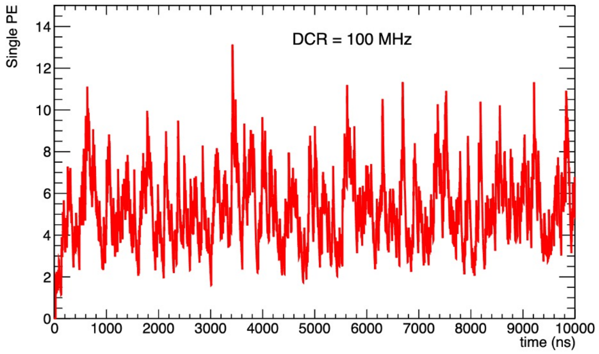
NOISE

- Dark count rate (DCR) determines threshold
  - MIPs at midrapidity will generate 3-6 N_{pe} on average
    - Would be good to have threshold slightly below MIP
- DCR above a few 10s of MHz at the readout will swamp the MIP

- Literature seems divided on noise characteristics of S14160 series
  - Plan to test S14160 SiPMs at ANL & Regina

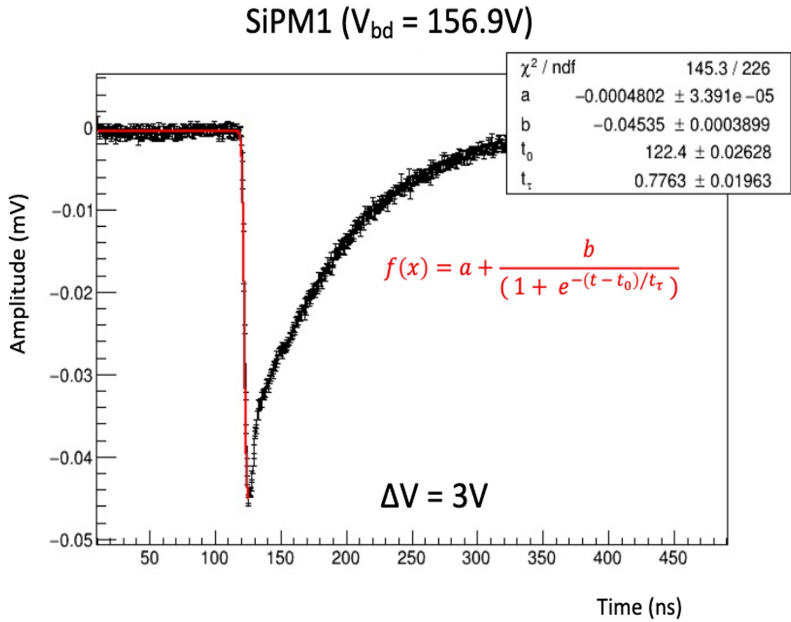


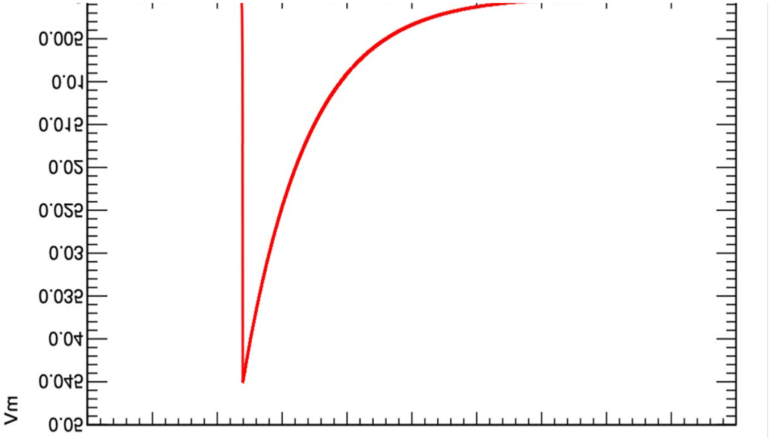




WAVEFORMS

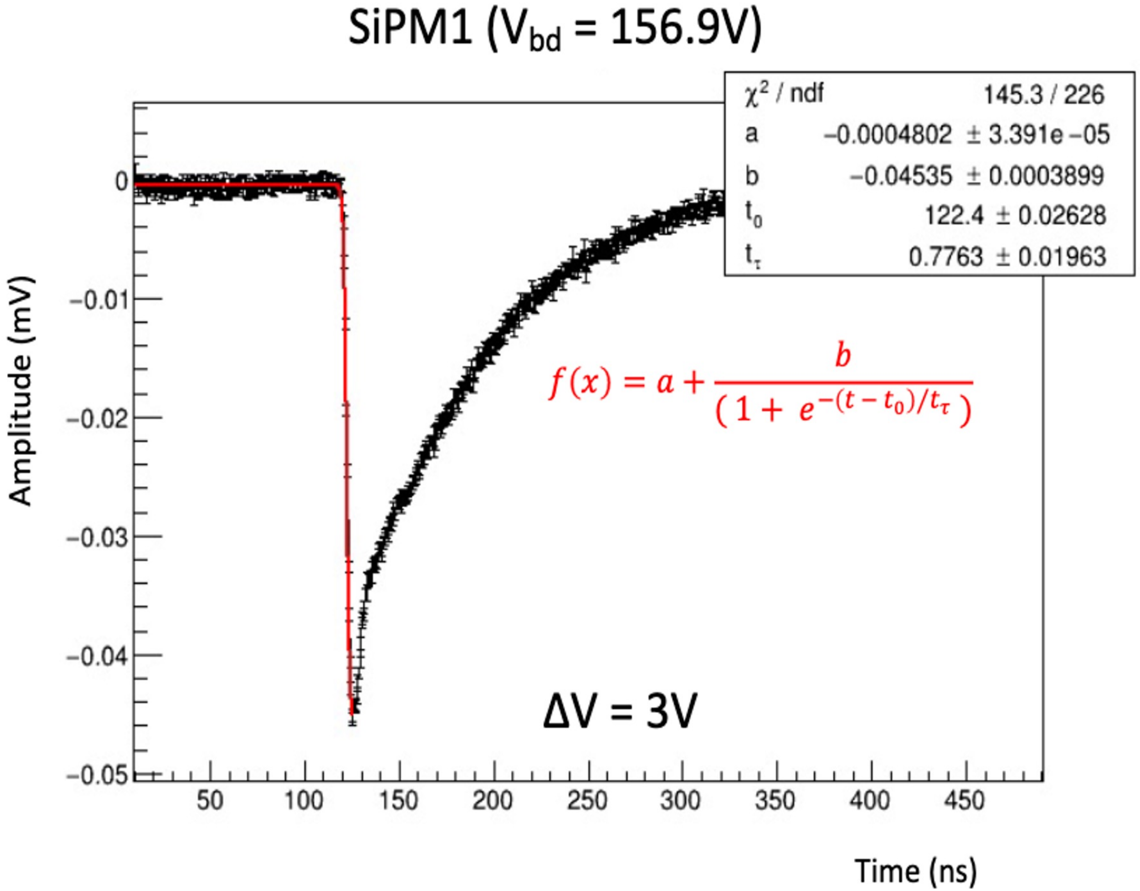
- Parameterize S14161 waveform based on presentation from AMS-100 (here)
- Exponential rise and exponential fall
  - Different time constants
- Pulse height around 0.045 mV
  - Take this as 1 Npe





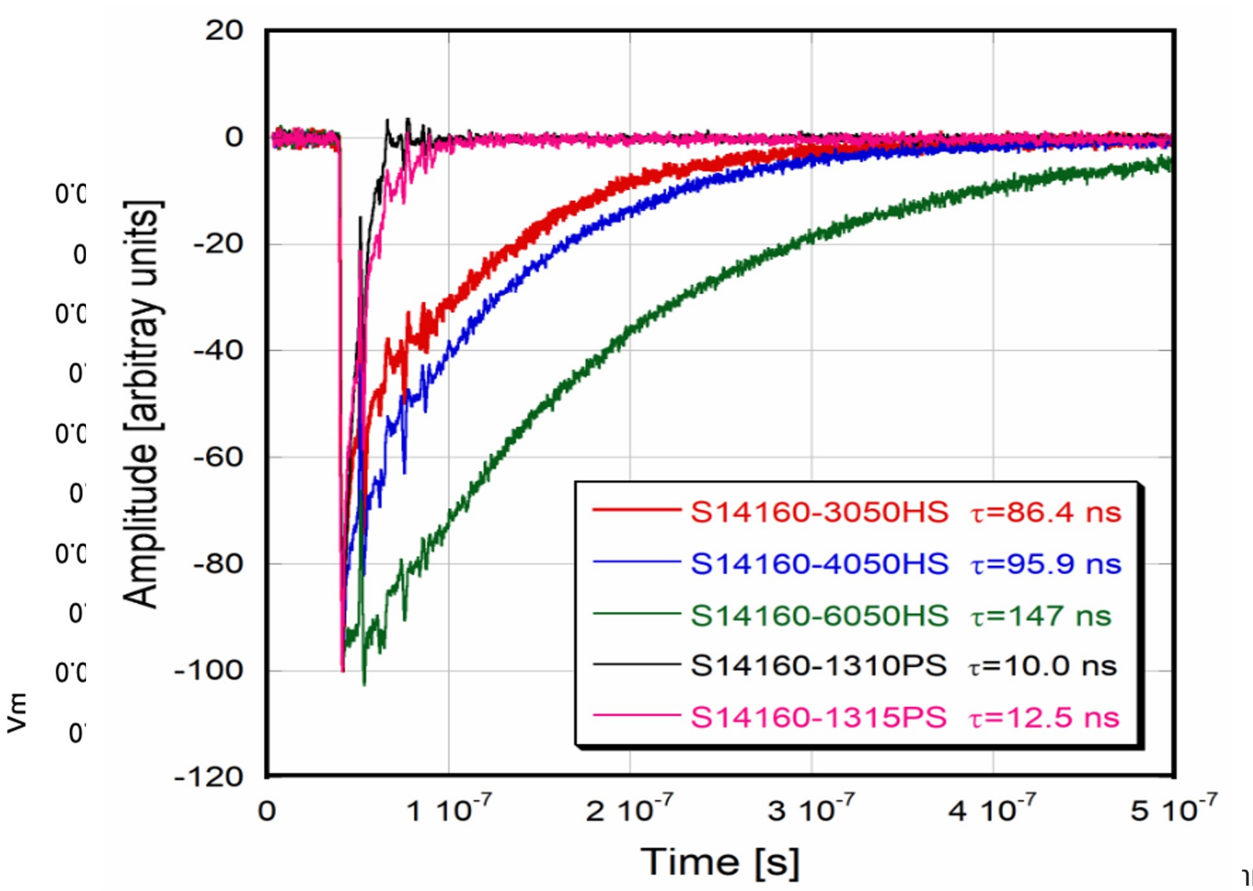
WAVEFORMS

- Agreement not good but also not so terrible
- Tail a bit wider in the data
- Good enough for now



WAVEFORMS

- Agreement not good but also not so terrible
- Tail a bit wider in the data
- Good enough for now



WAVEFORMS

- Ag
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- Go
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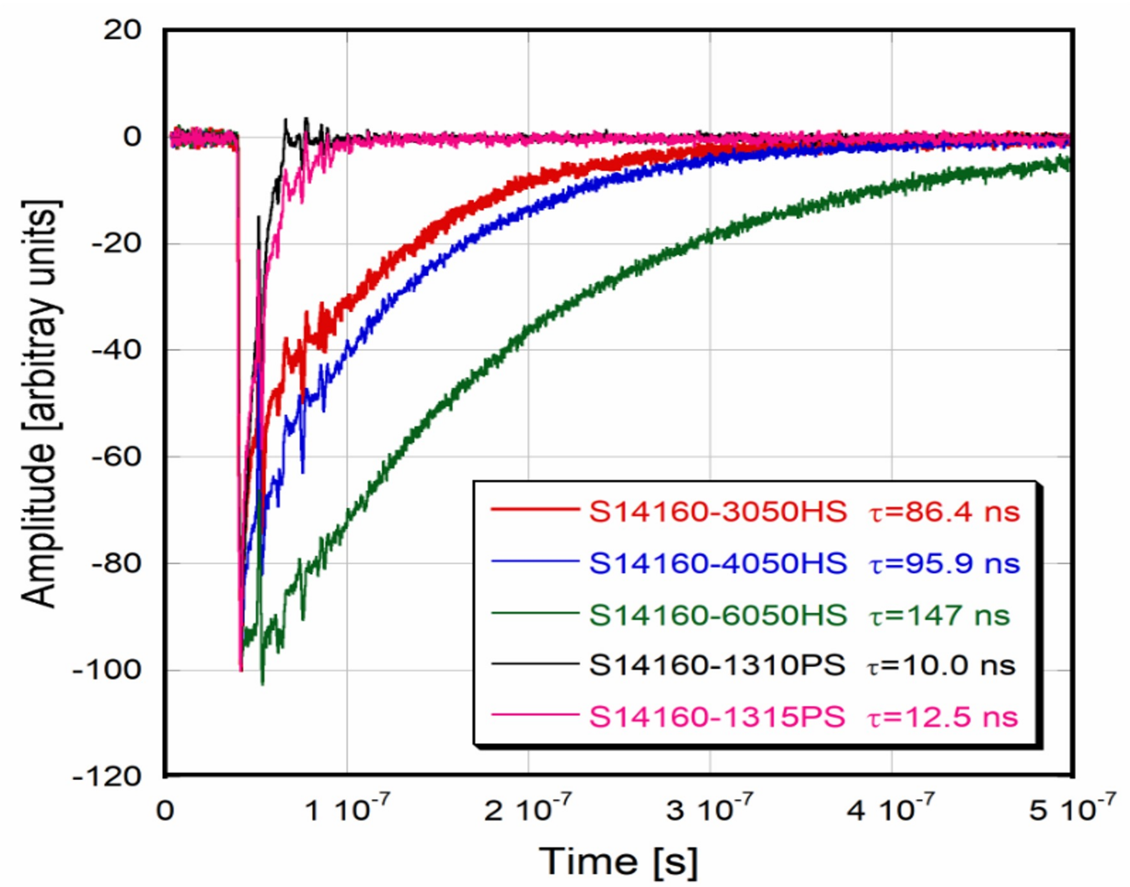
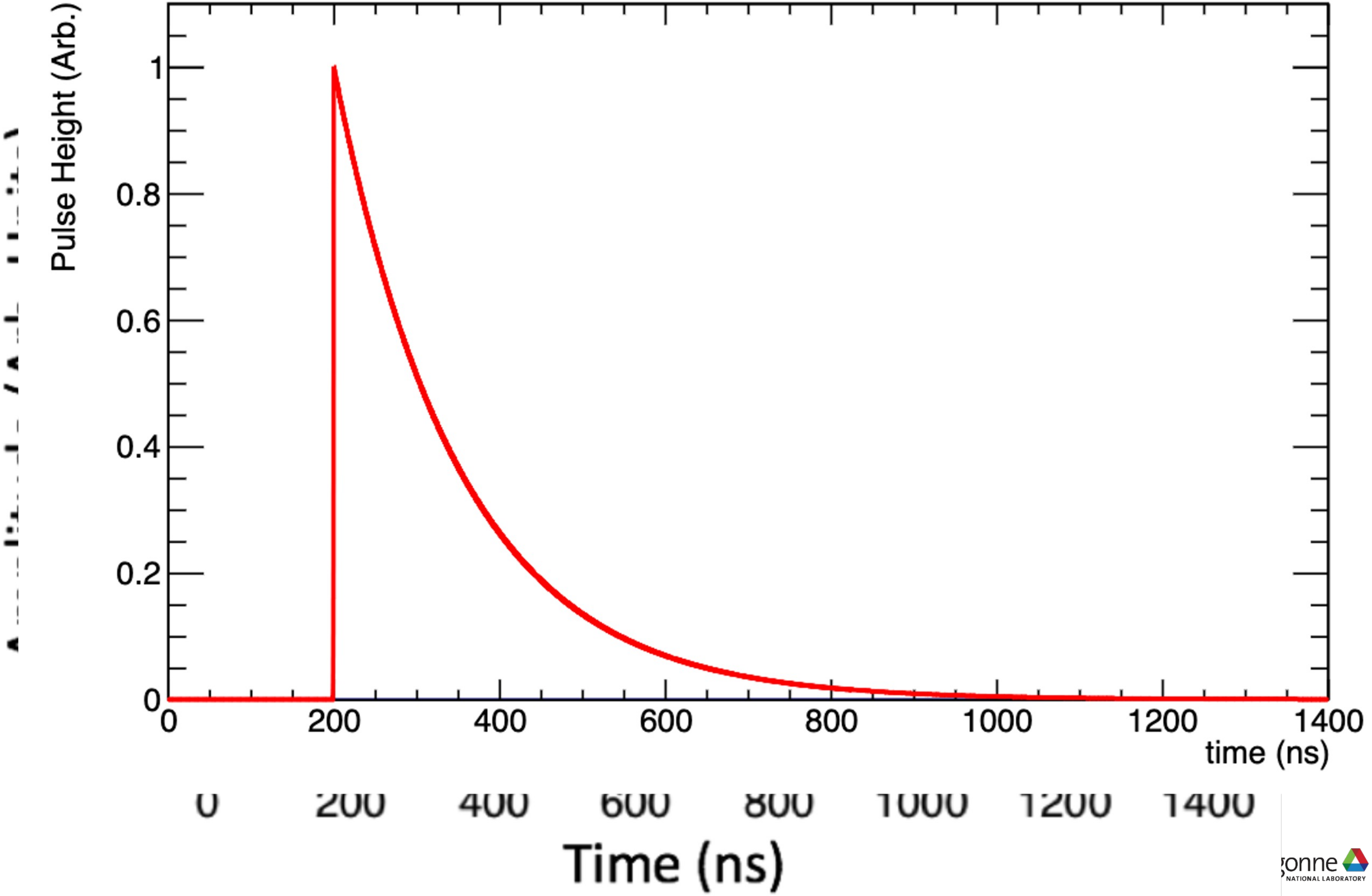
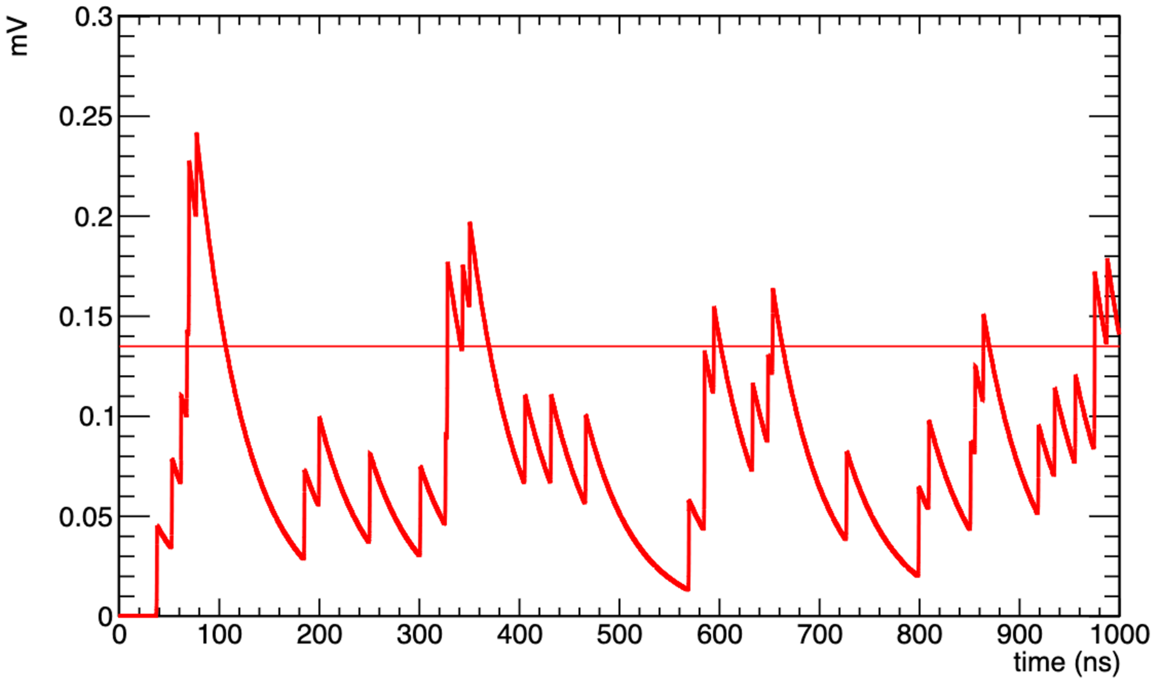



Pulse Height (Arb.)
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
1400
time (ns)
Time (ns)

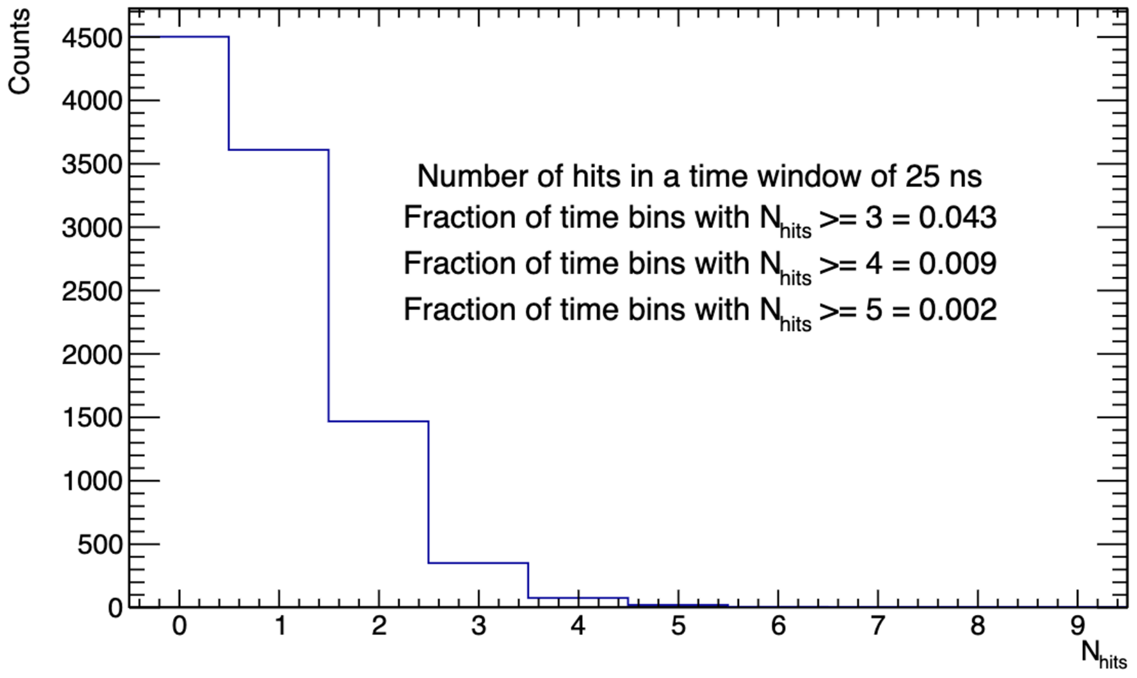
WAVEFORMS

- Monte Carlo throwing signals with expected rate
  - 32 MHz
  - 1 microsecond
- Crosstalk probability of 7% included (should it be, or is it included in the number from Hamamatsu?)
  - Up to two crosstalk hits
    - 3 and greater is a less than 1% effect
- Line drawn at 3 * single photoelectron peak

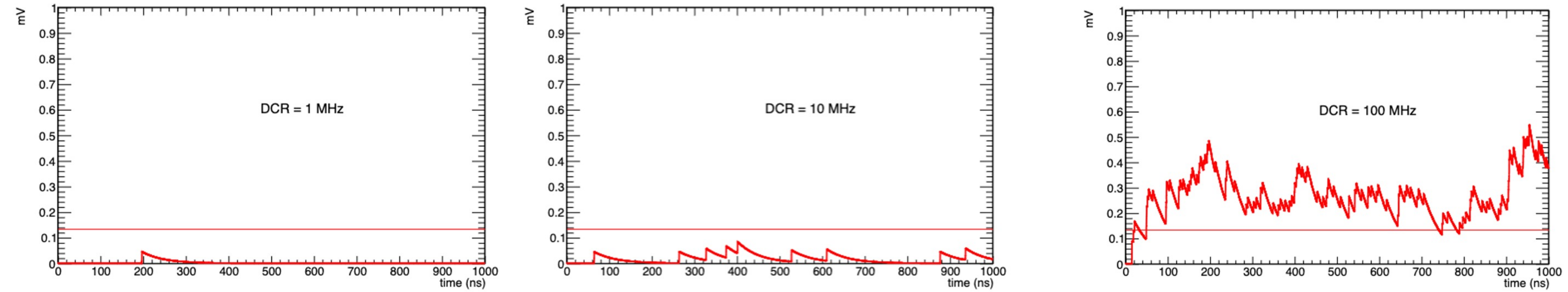


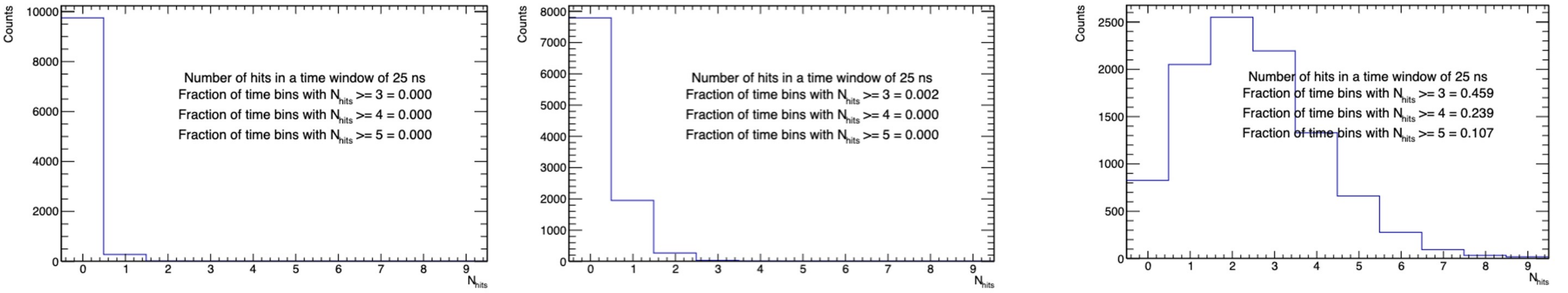
HITS IN HGCROC WINDOW

- Take 25 ns window of HGCROC
- Poissonian distribution with a mean of 0.8
  - 25 ns * 32 MHz
- If threshold is set to 3 * SPE pulse height, 4% of time bins will be triggered
  - 4% of the channels of the detector will be active in ToT mode at any given time



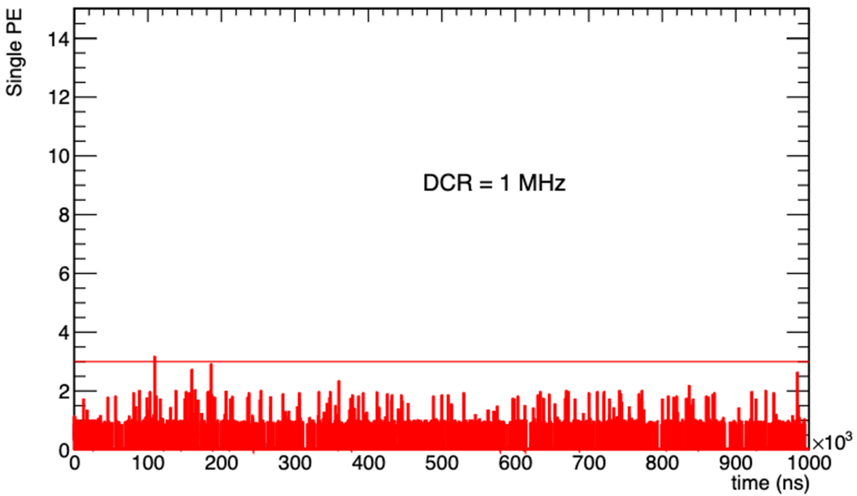
- Threshold of 3 p.e. likely excluded if DCR reaches 100 MHz
  - This also poses an issue because we can't get around it with timing cuts in the same way as the dRICH, the detector could have a signal at any time
    - Bunch crossings every 10 ns, shorter than light propagation time





Threshold (p.e.)	Prob. Above threshold @ 1 MHz	Prob. Above threshold @ 10 MHz	Prob. Above threshold @ 30 MHz	Prob. Above threshold @ 50 MHz	Prob. Above threshold @ 100 MHz
2	0.01%	2%	29%	69%	99%
3	0.0005%	0.3%	8%	36%	94%
4	0%	0.04%	1.7%	14%	79%
5	0%	0.005%	0.2%	4%	57%
6	0%	0%*	0.03%	1.1%	35%
7	0%	0%*	0.005%	0.4%	17%

Numerical uncertainty of 0.03%



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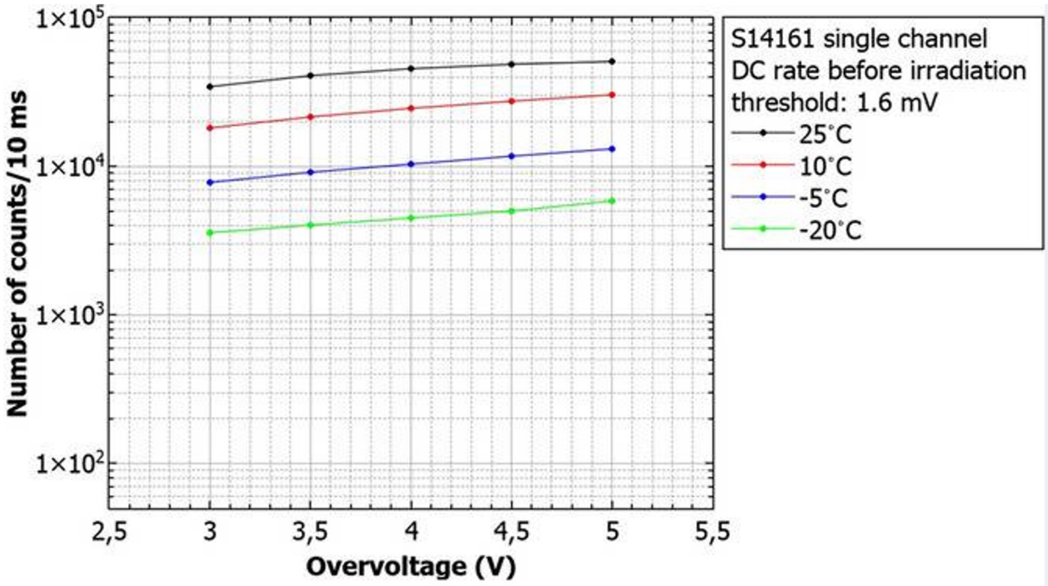
TEMPERATURE DEPENDENCE

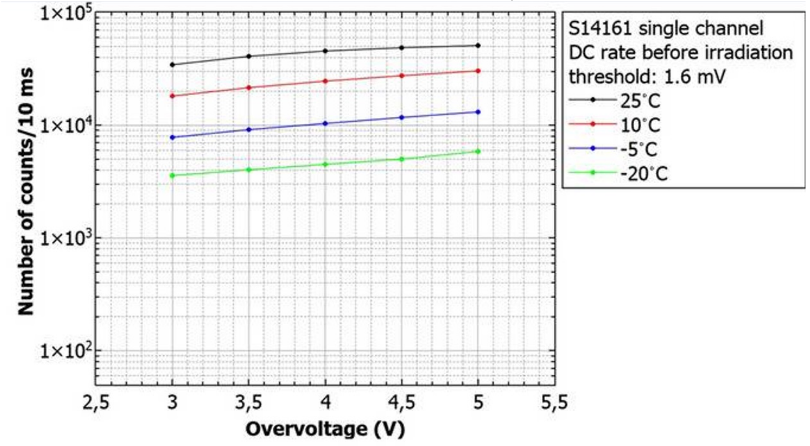
- Conventional wisdom is that DCR is halved for every decrease of 10° C
- "Single-channel" here refers to 1/16 of a 4x4 array (S14161-6050HS-04)
  - DCR numbers for ganged array should be 16x higher
- To reach the ~4 MHz of GlueX with S14161-6050HS-04, need to go to -20° C or lower

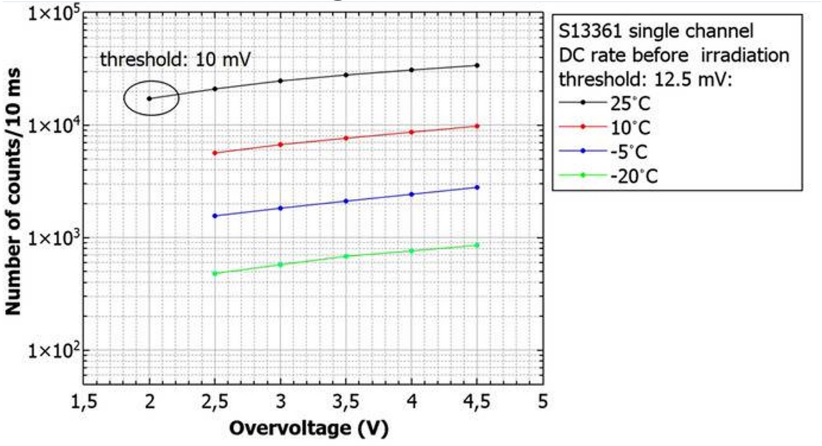
Proton irradiation of SiPM arrays for POLAR-2



TEMPERATURE DEPENDENCE

- The authors of this paper report that DCR of the S14161 is 60% higher than S13361 at 25° C, and a factor of 5 higher at -20° C
  - The DCR of the S14161 is apparently a much slower function of temperature
  - This is bad, because it renders less effective the only handle we have over the DCR
  - On the flip side, probably the DCR increases less if we go above 25° C…



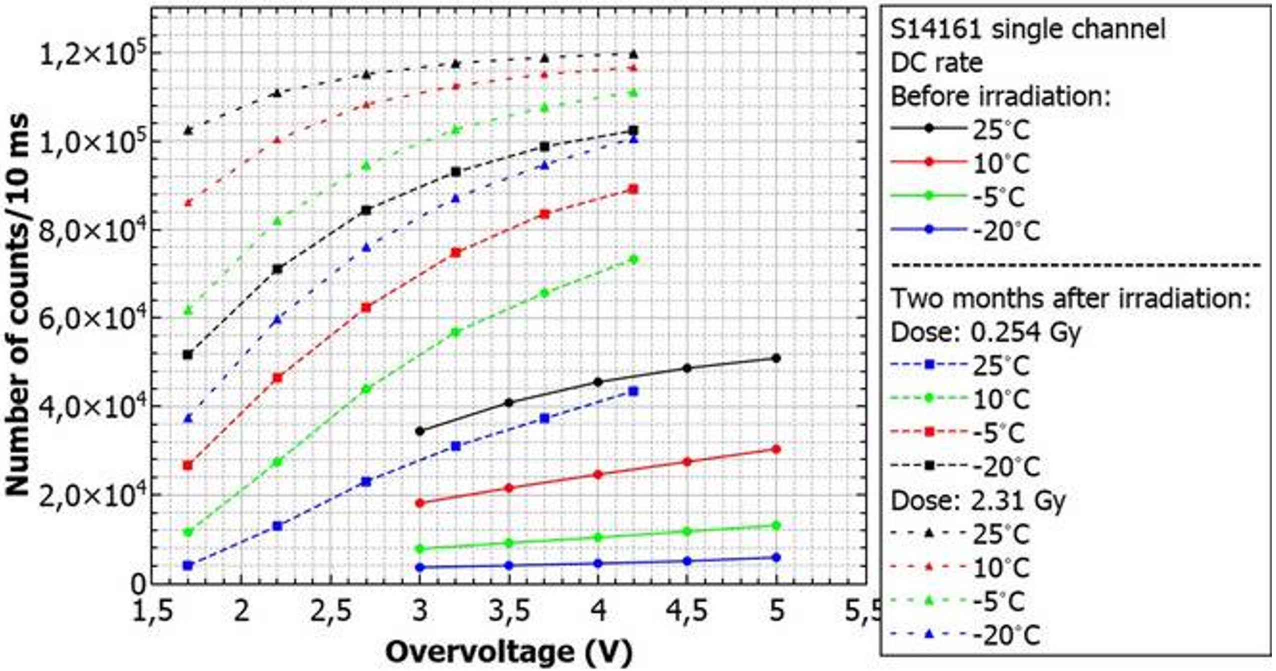


On such a critical point, should consult an expert (Hamamatsu directly?) to see if this behavior is expected or not

RADIATION DAMAGE

- Pre-radiation DCR around 3 MHz (single channel)
  - At 3V overvoltage
- After ~200 Rad of proton radiation (and two months of waiting), DCR larger by factor of 4
  - Half our expected dose

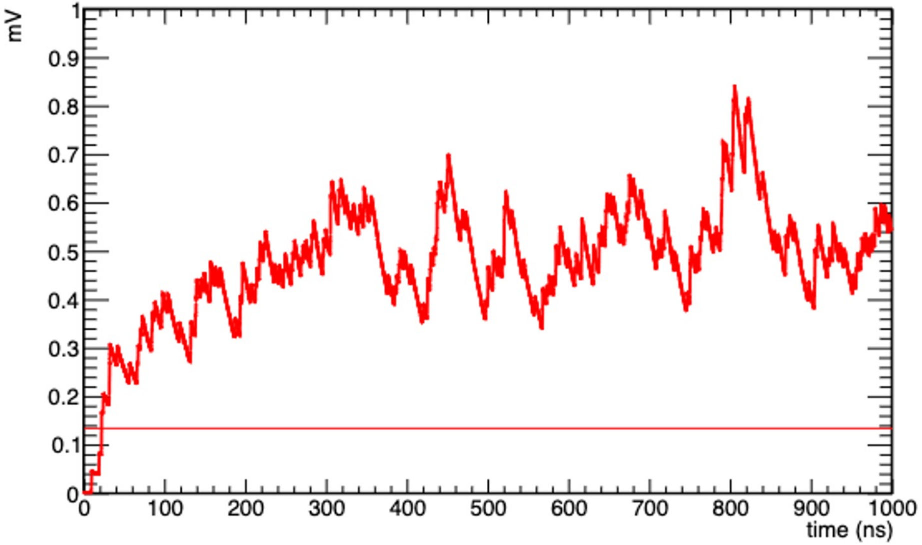
Proton irradiation of SiPM arrays for POLAR-2

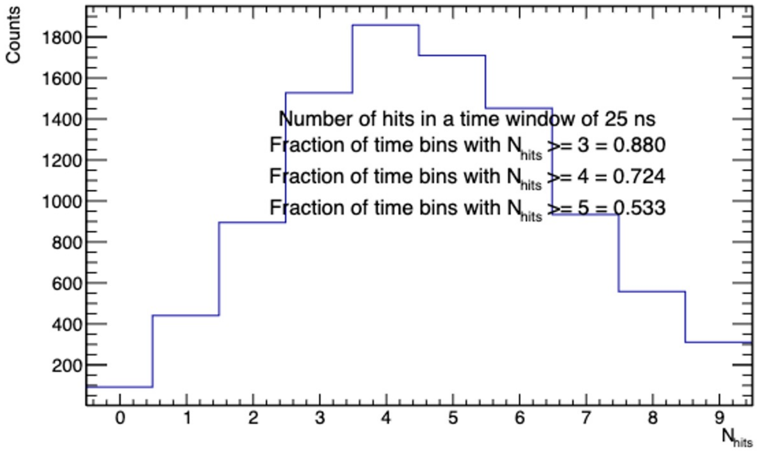


RADIATION DAMAGE

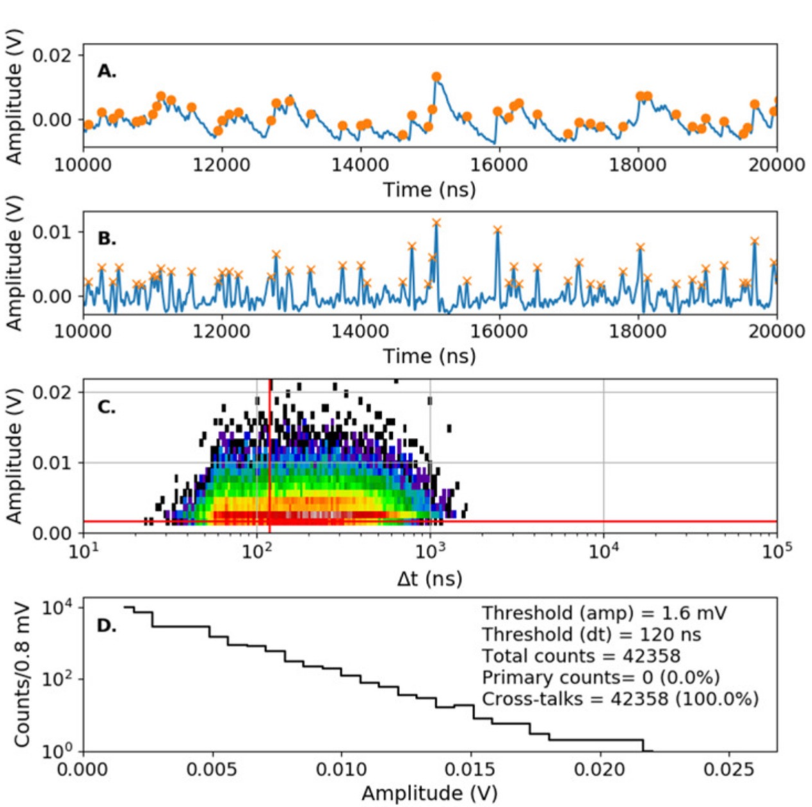
- If we take the numbers provided in this paper seriously, expect 192 MHz of DCR after 200 Rad of radiation damage at room temperature

- This is clearly too large, likely would swamp the MIP
  - Threshold would need to be set at something like 9 Npe or higher

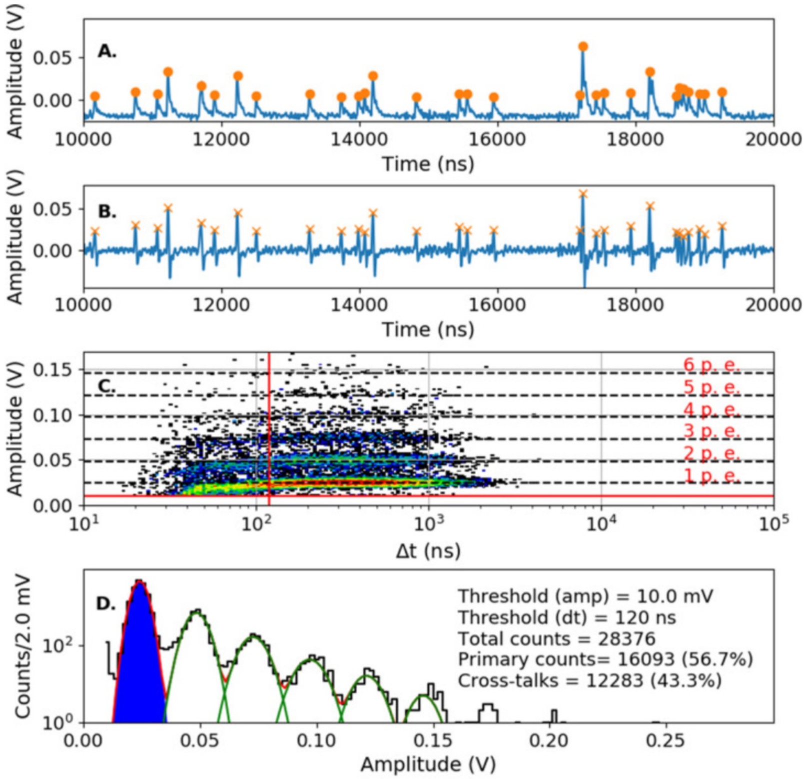




S14161



S13361



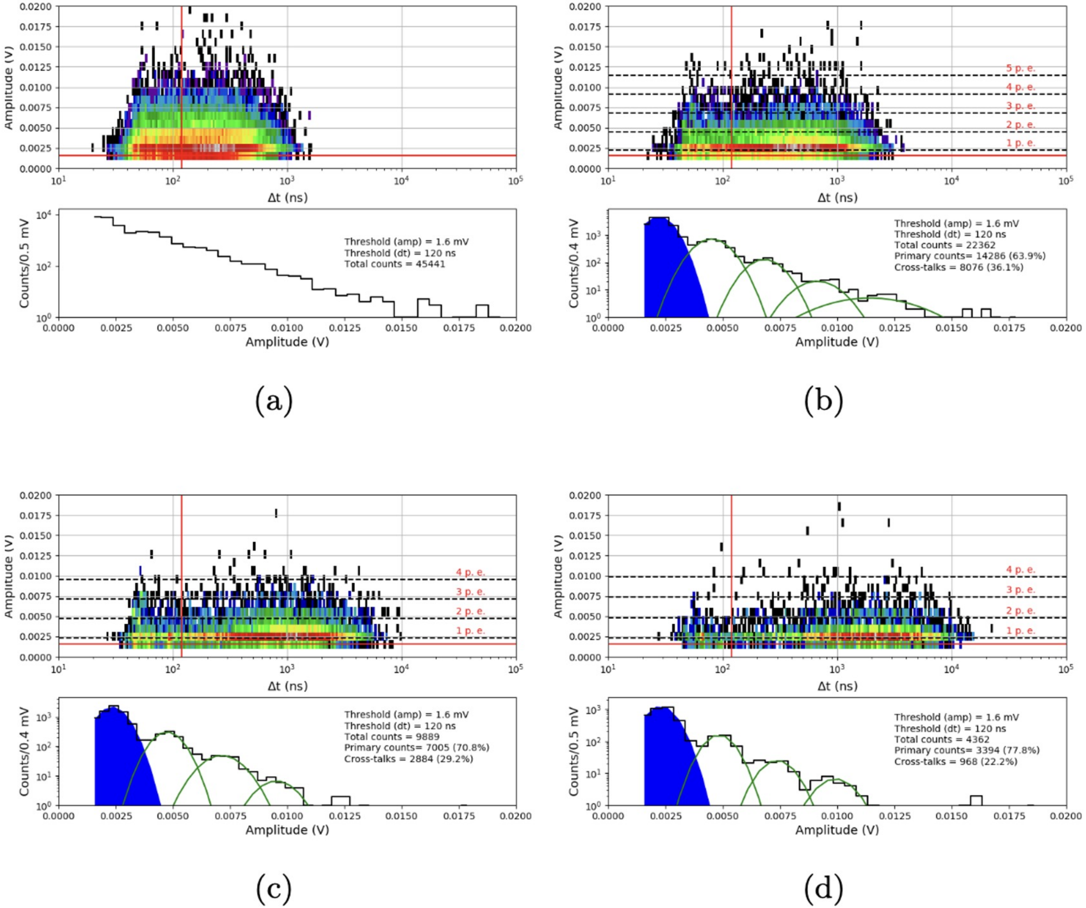


Fig. 14 S14161 single channel DC spectra measured before proton irradiation for various temperatures and the same V_{ov}=3.5 V: a) 25 °C, b) 10 °C, c) −5 °C, d) −20 °C. The Z-axis is represented here by a colour scale.

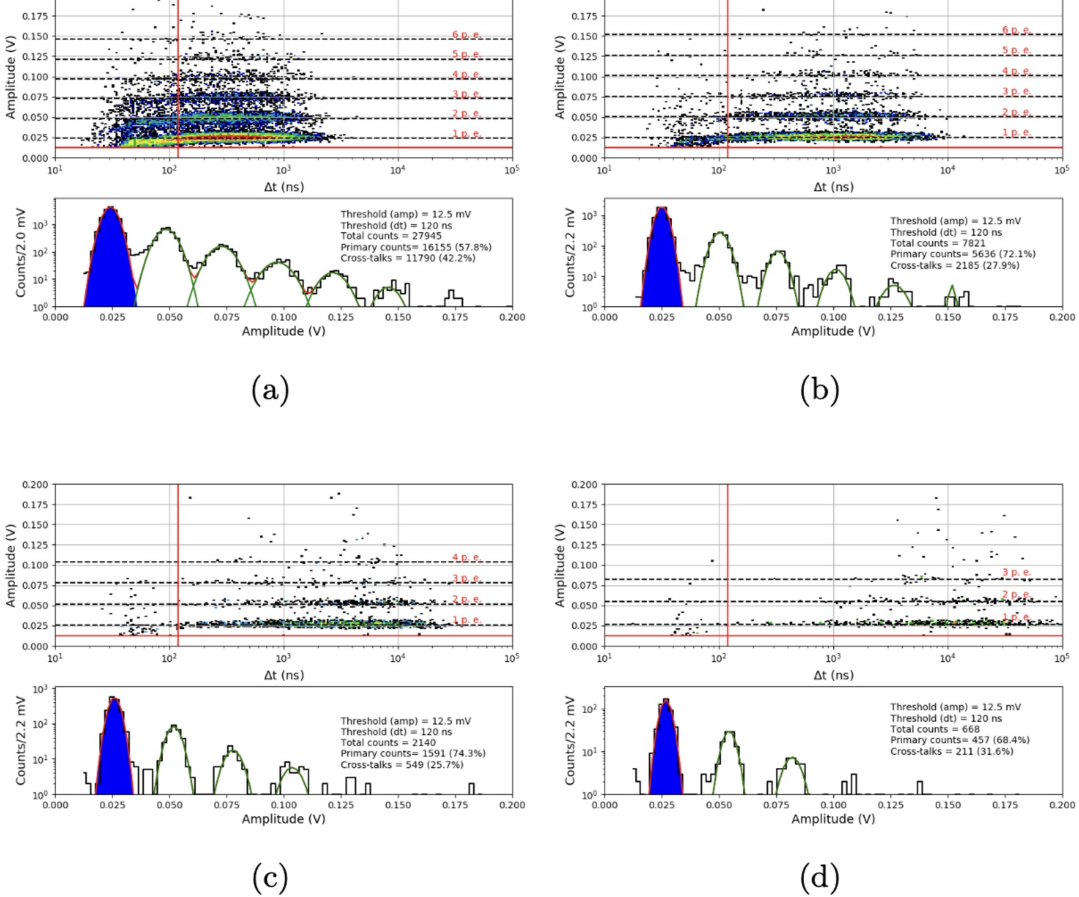


Fig. 13 S13361 single channel DC spectra measured before proton irradiation for various temperatures and the same V_{ov}=3.5 V: a) 25°C, b) 10°C, c) -5°C, d) -20°C. The Z-axis is represented here by a colour scale.