The milliQan Experiment at the LHC

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Research Techniques Seminar
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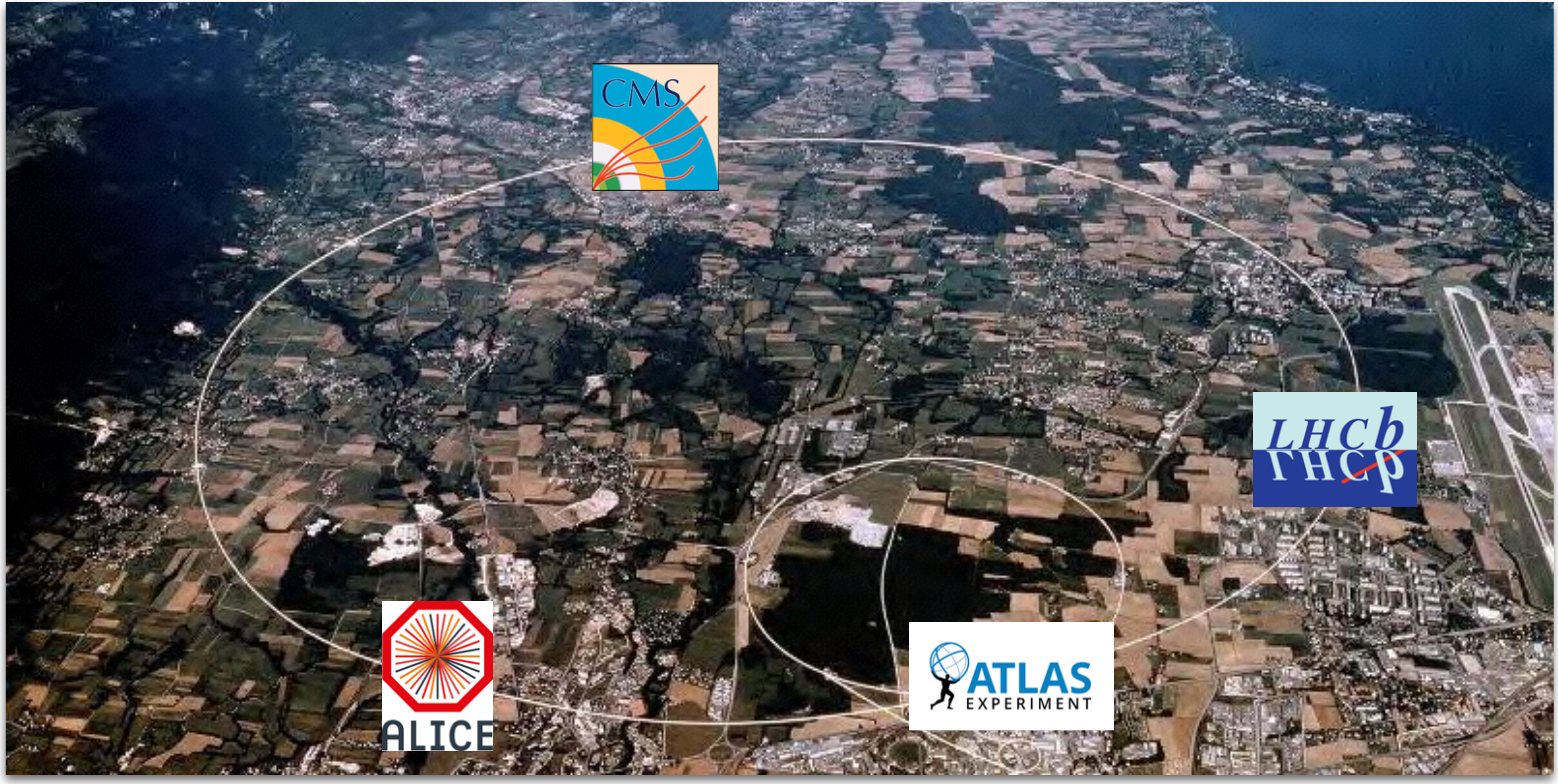
No sign of new physics at the LHC



What could we be missing?

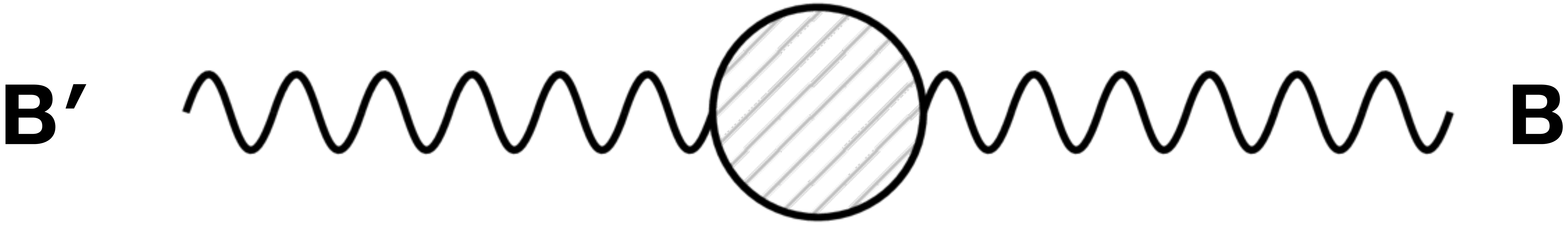
Milli-charged particles

- Many SM extensions include “hidden” or “dark” sectors

“Dark EM”

Mixing of dark photon and SM photon

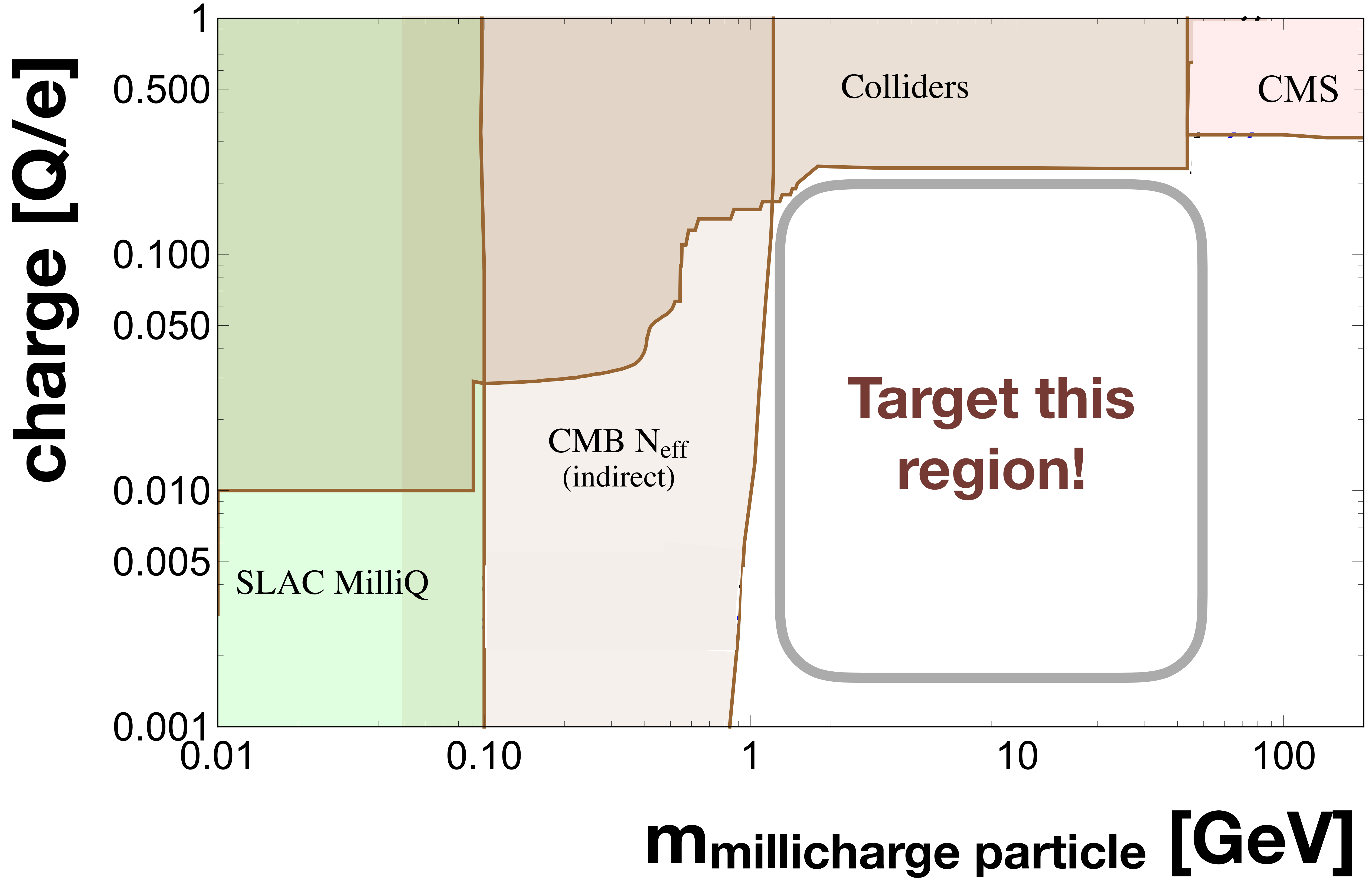
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}B^{'}_{\mu\nu}B^{\mu\nu'} - \frac{\kappa}{2}B^{'}_{\mu\nu}B^{\mu\nu}$$



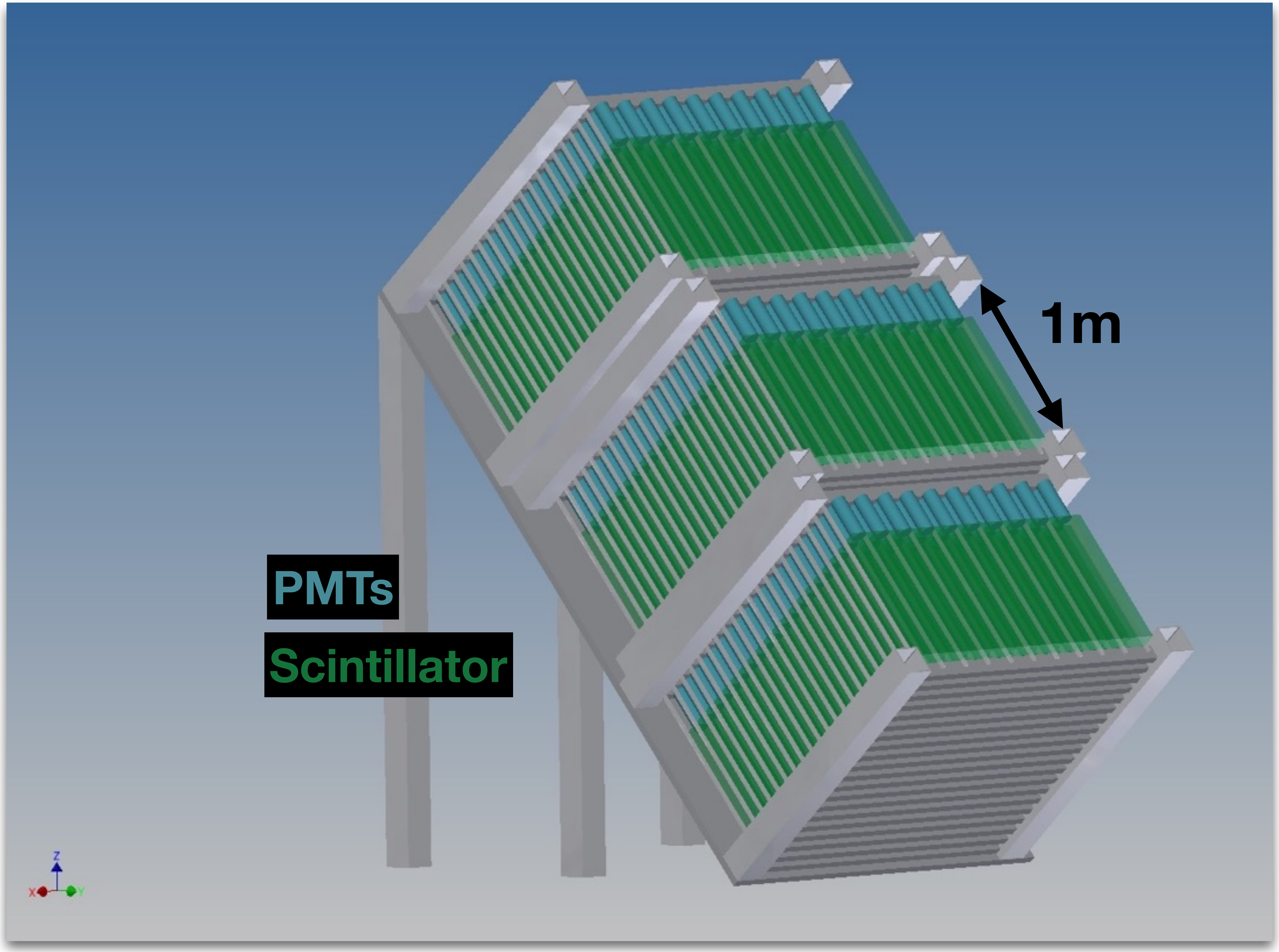
- Dark sector particles could acquire small SM charge through mixing

Searches for milli-charged particles

- Strong astrophysics constraints for millicharge particles < m_e
- SLAC beam dump: m < 0.1 GeV
- Collider searches: Q/e > 0.1
- **GeV range unprobed, and would be produced at LHC**

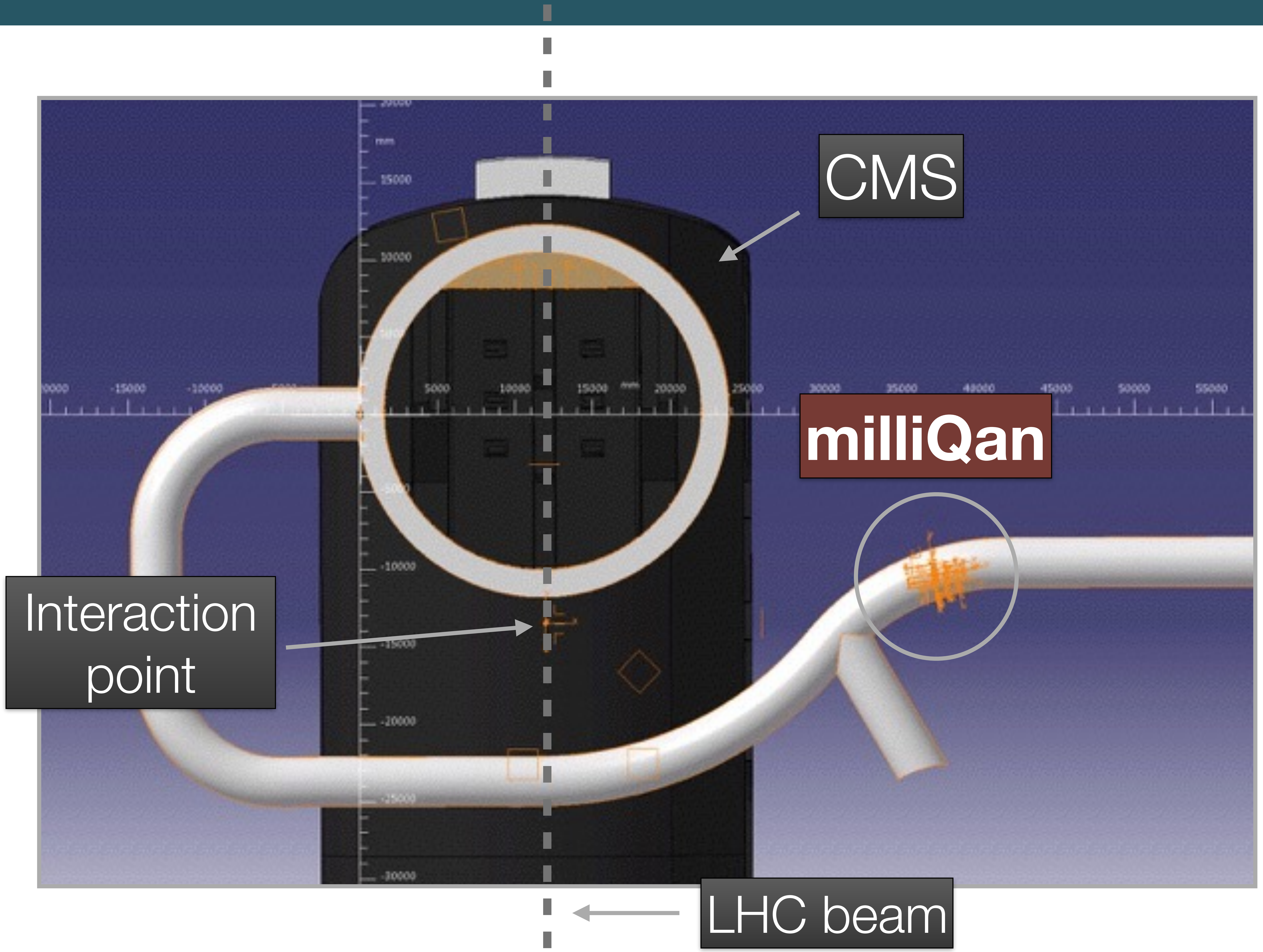


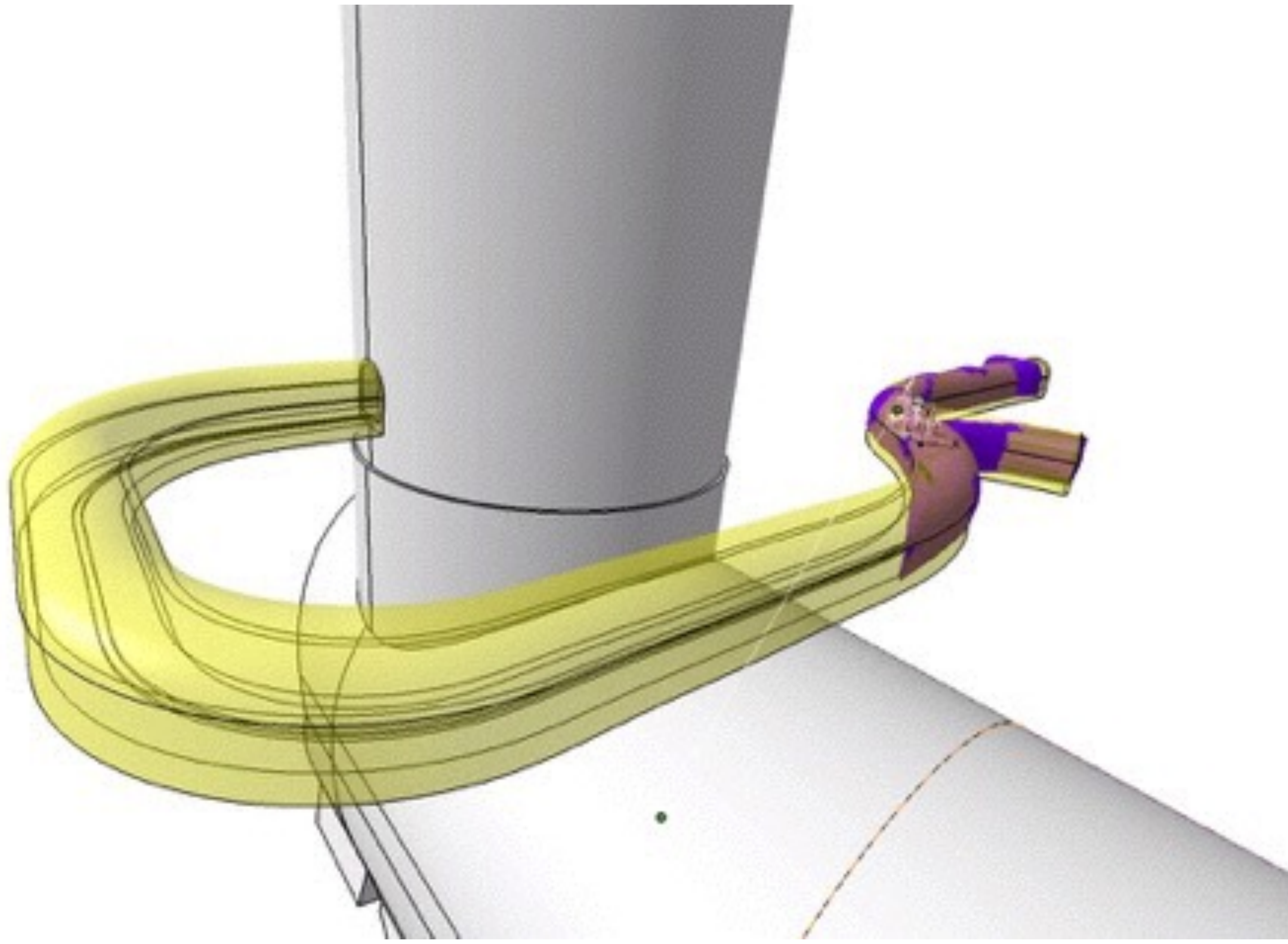
Detector to find millicharge particles



- Looking for **very** weakly ionizing particles: need long path through active material
- milli-Q signal: few scintillation photons in each layer
- LHC backgrounds (muons): huge signals, easy to reject
- Require coincidence in three layers to remove random backgrounds

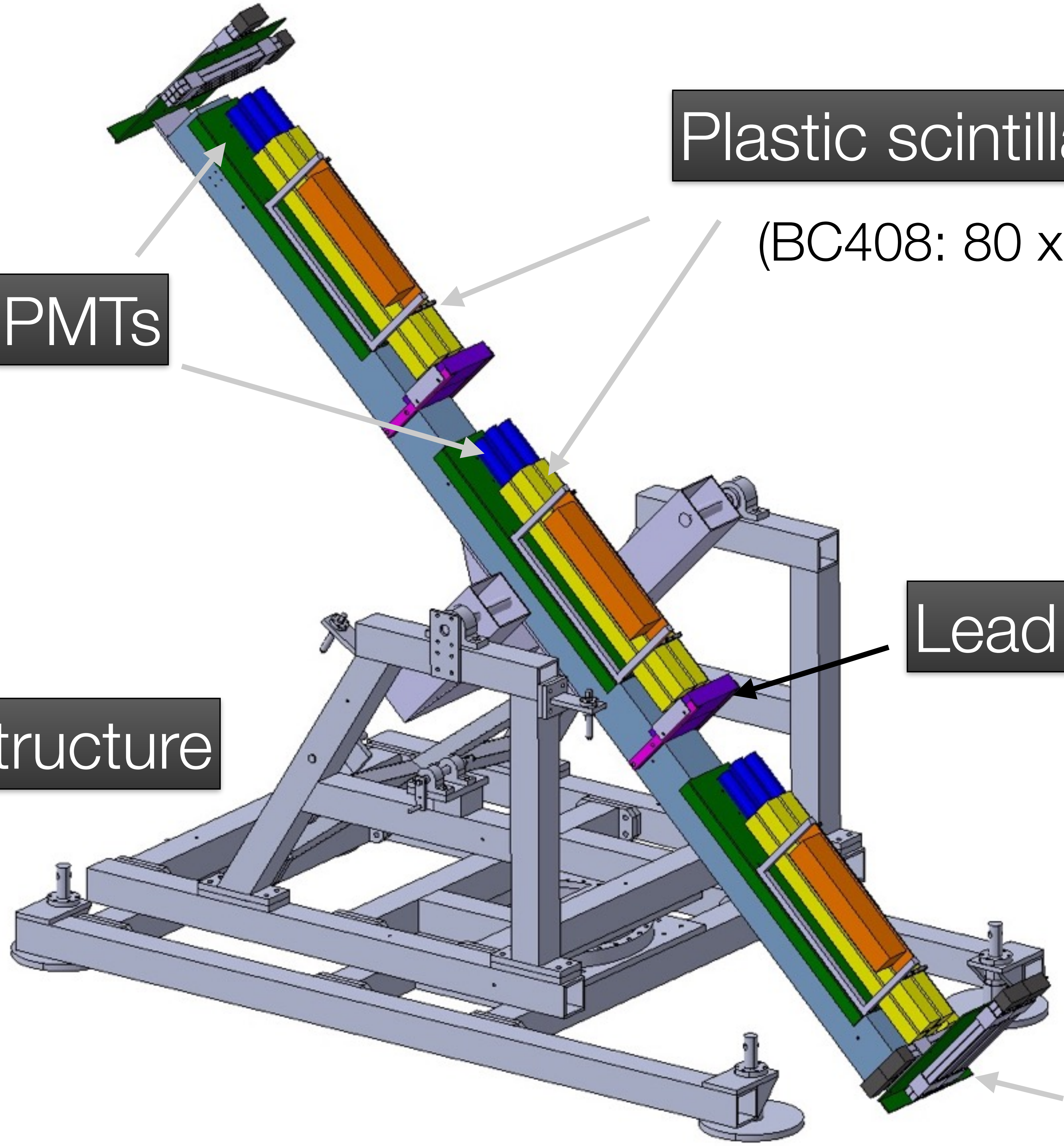
Proposed location





- 15 m of rock between milliQan and CMS: few beam particles

1% prototype



Plastic scintillator

(BC408: 80 x 5 x 5 cm^3)

PMTs

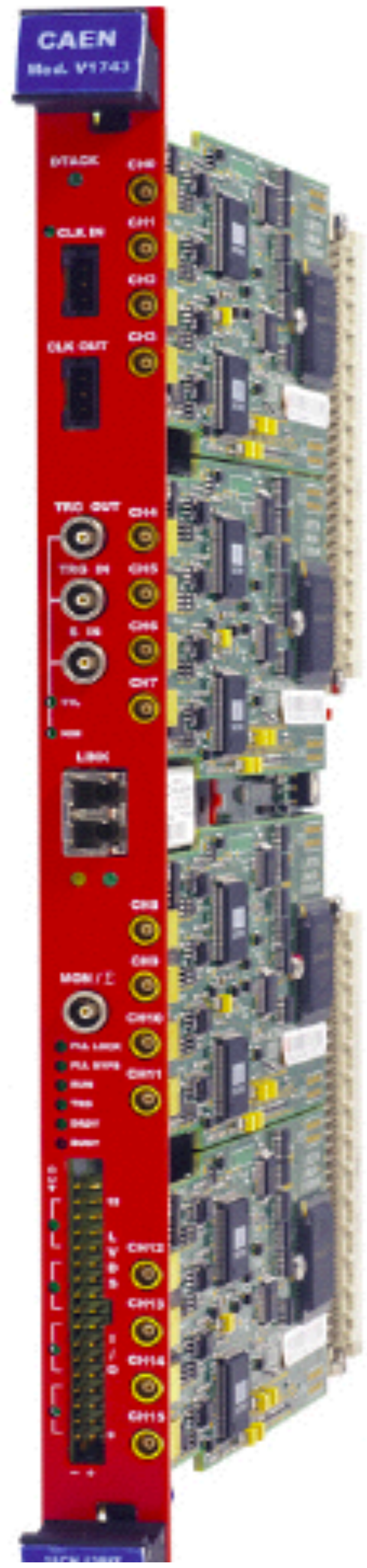
Lead shielding

Support structure

Hodoscope

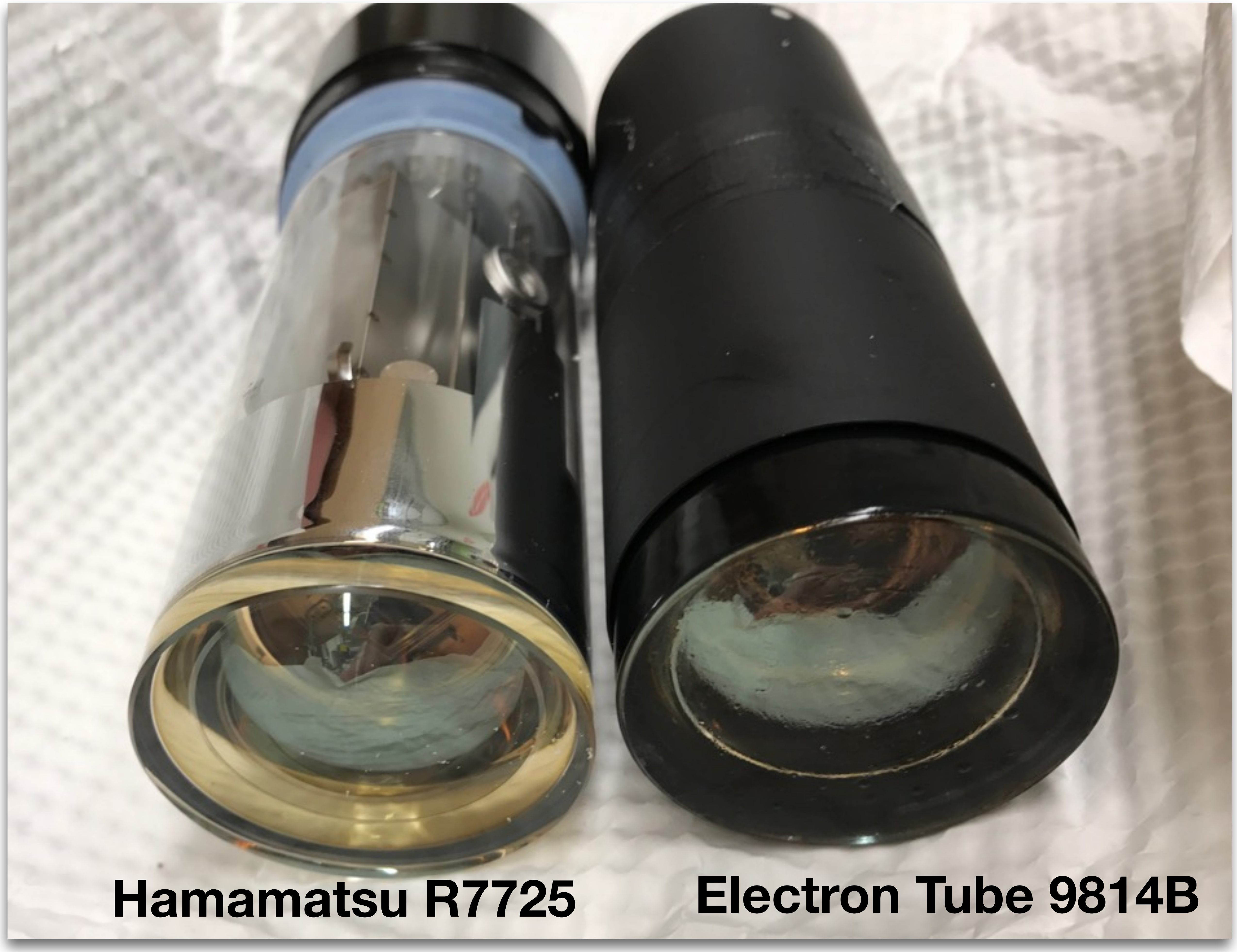
CAEN V1743 digitizer

16 chan, 1.6 GS/s,
640 ns window



PMTs

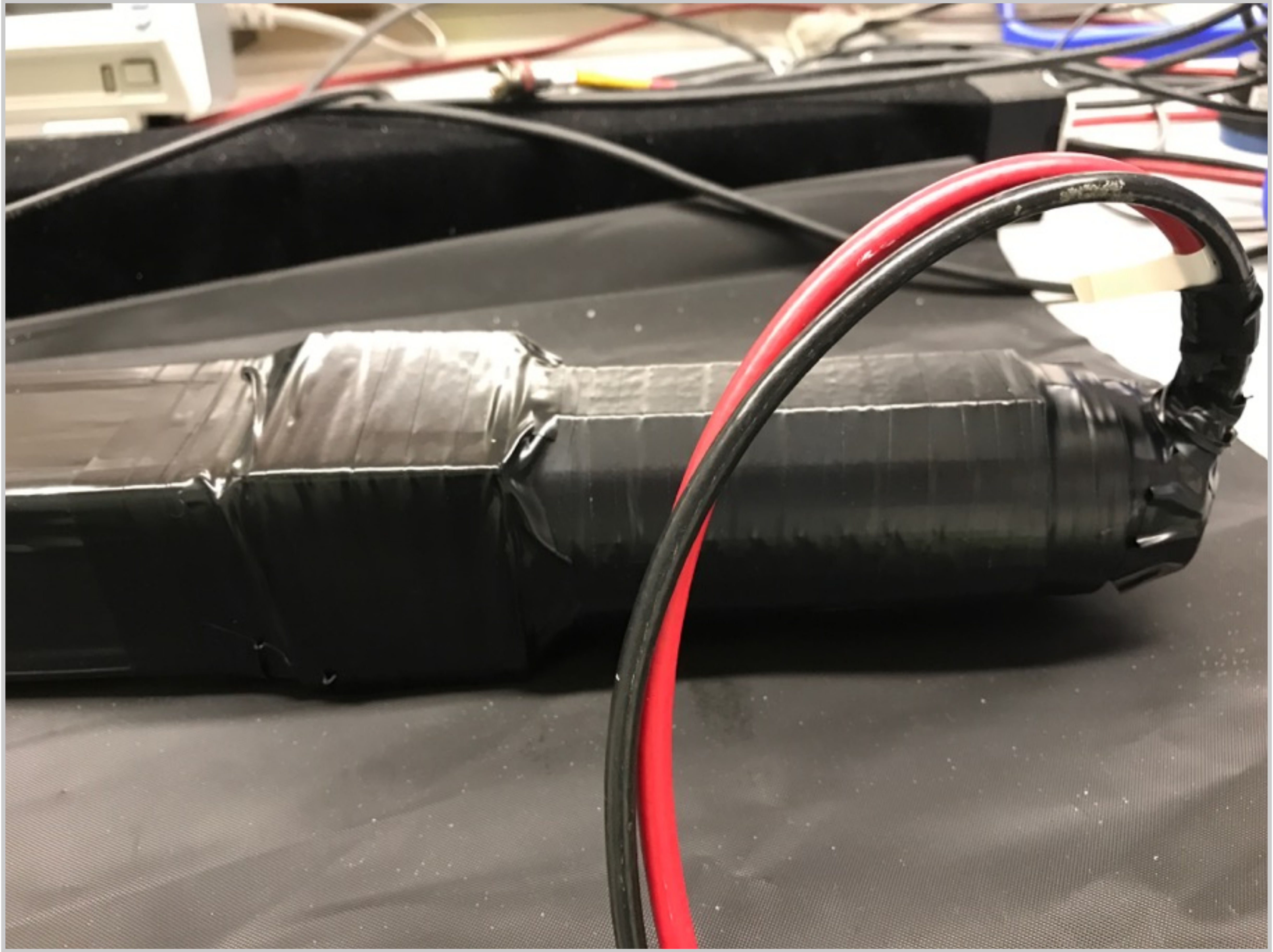
High gain, fast PMTs
($$)



Older, slower PMTs
(effectively free!)

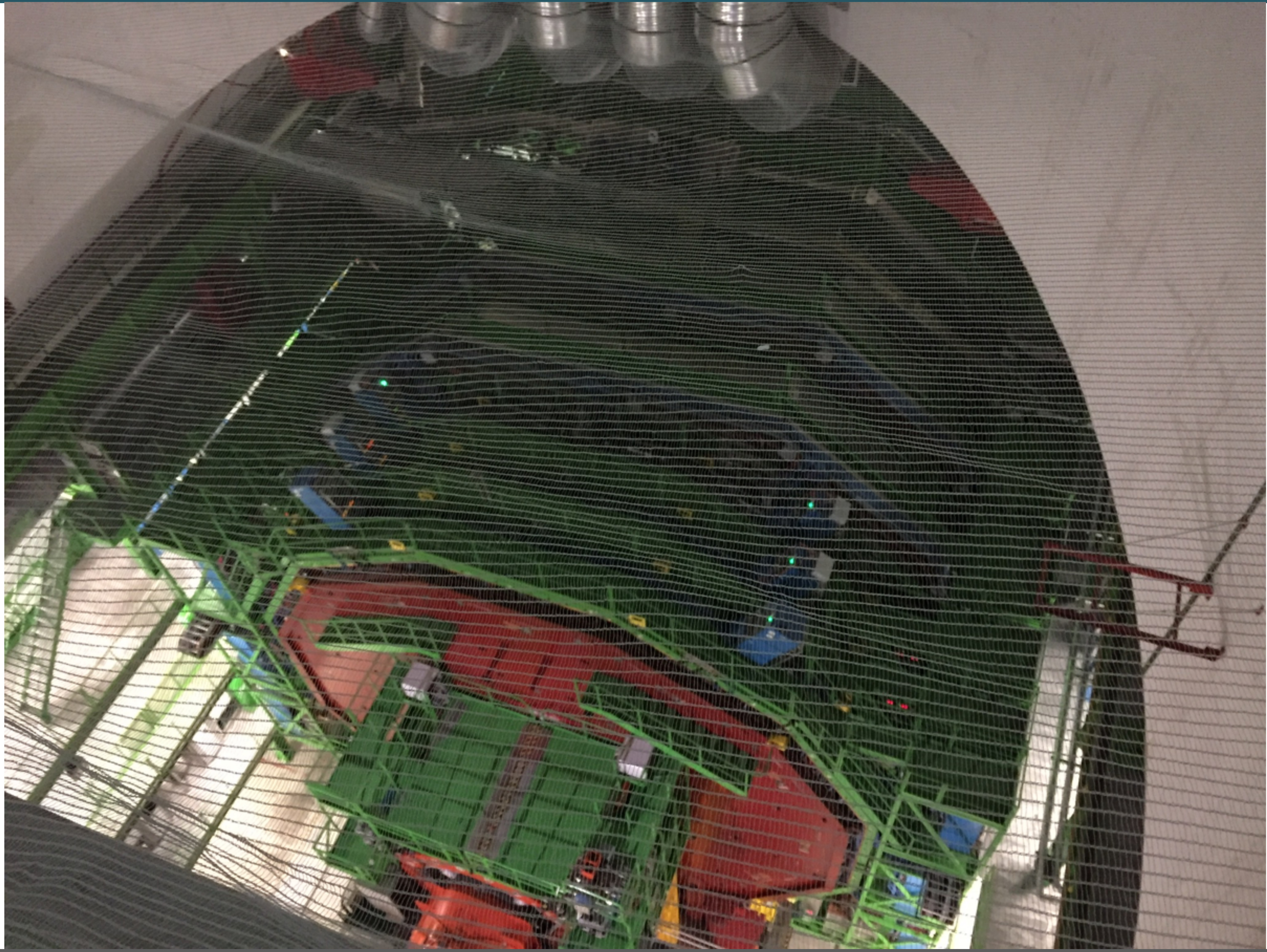
Hamamatsu R878

Module assembly

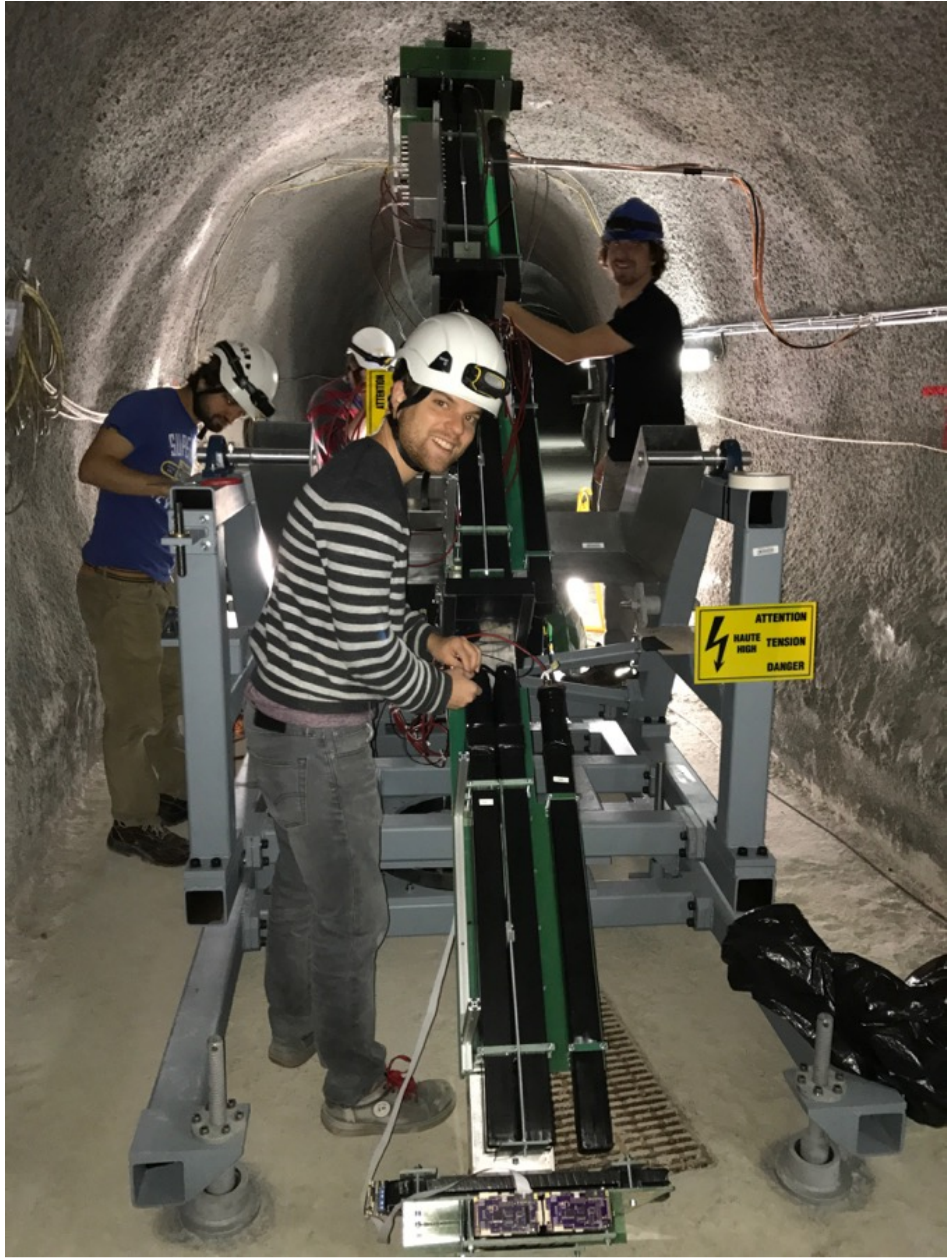


Setup and installation at CERN

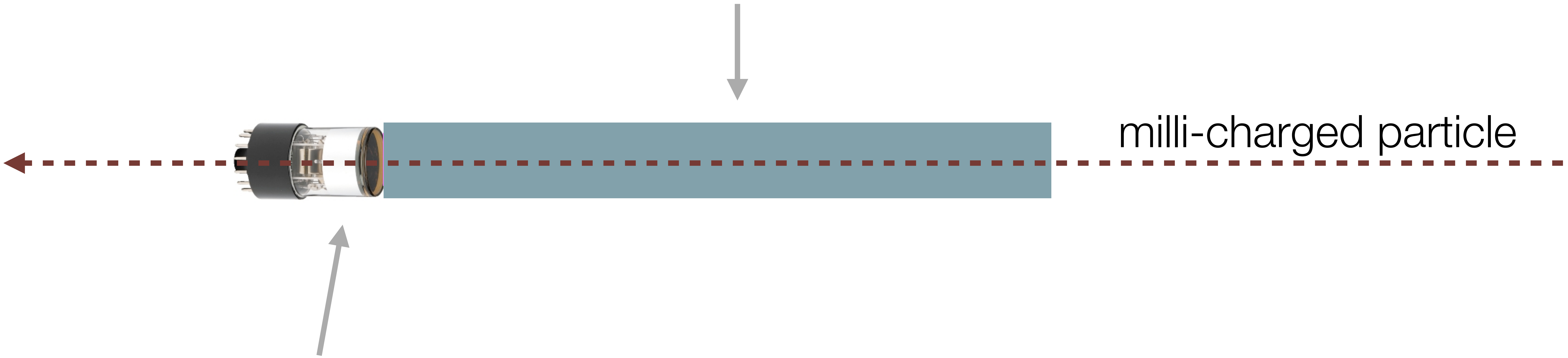
Lowering down the shaft



Finished prototype



Key calibration questions



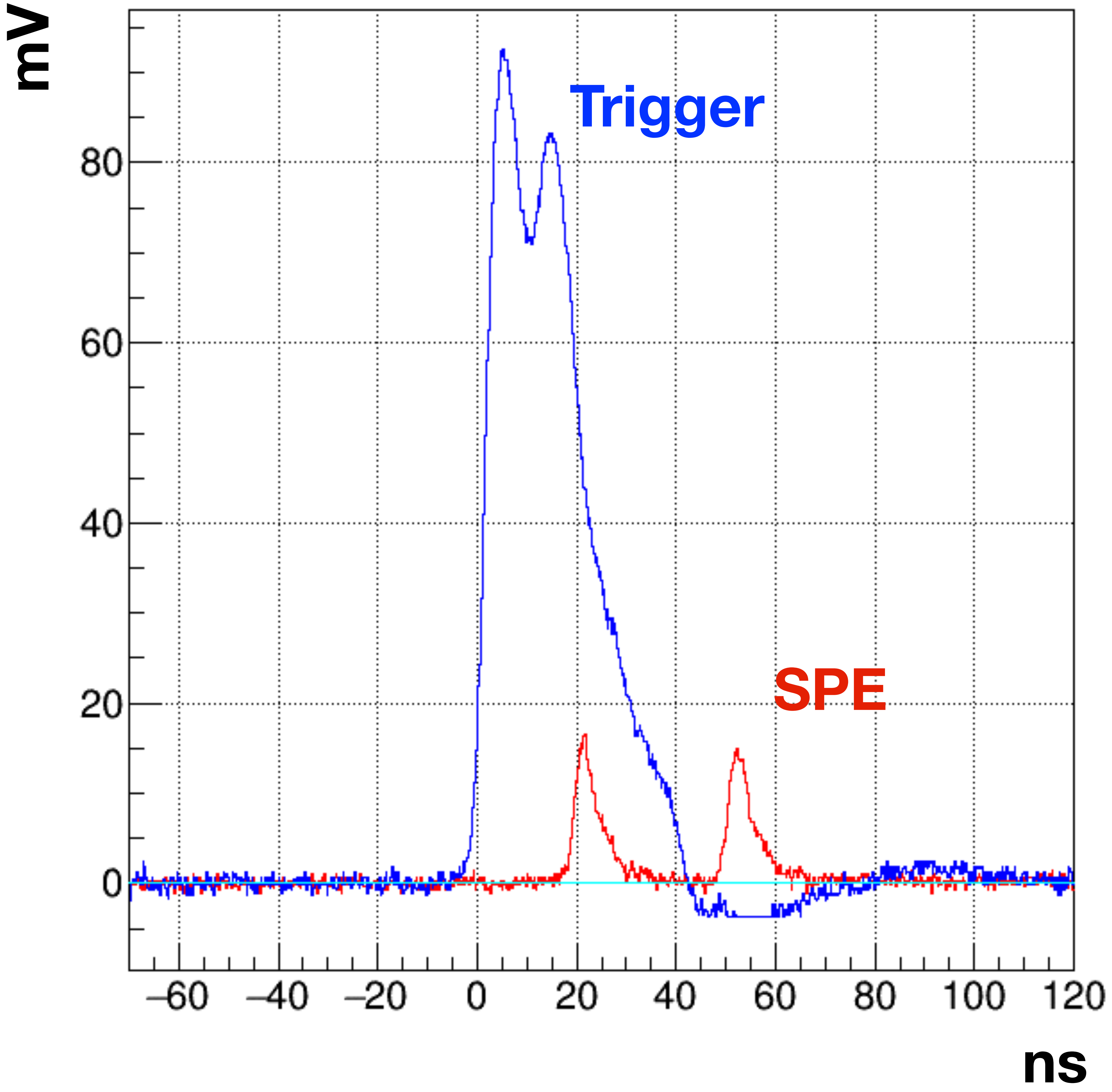
How many photons are collected?

What does a single photoelectron look like?

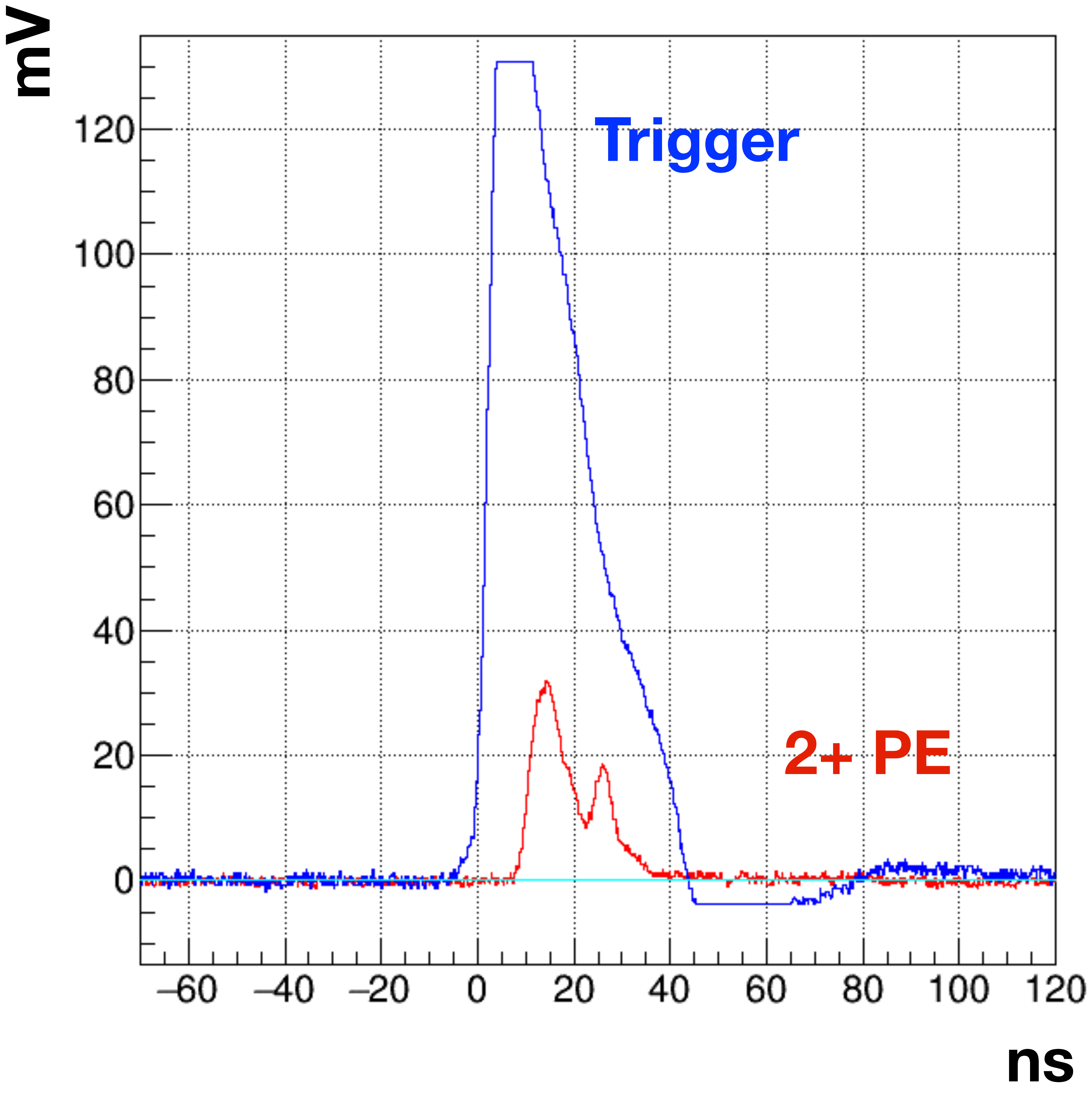
Finding single photoelectrons

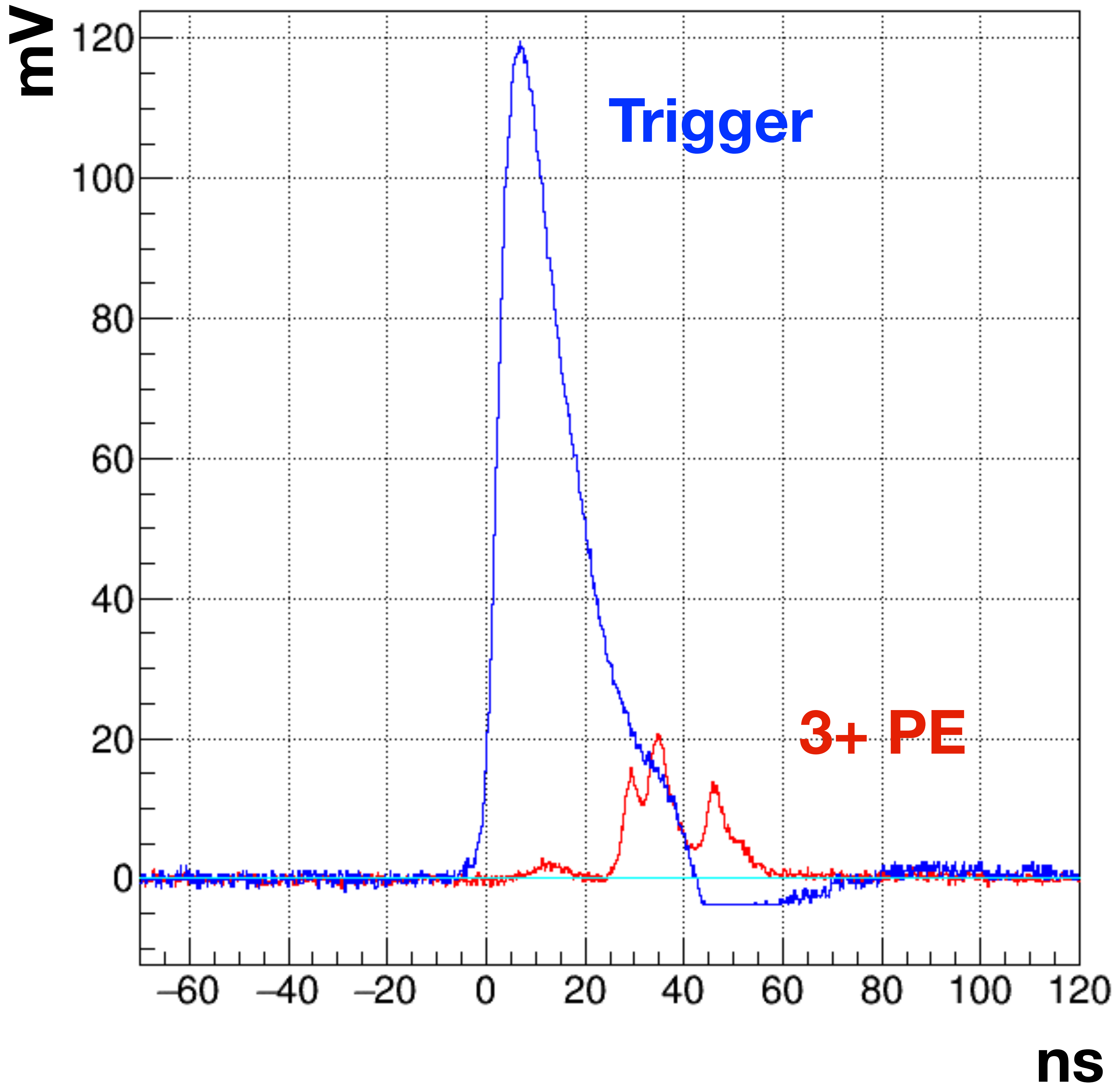
Bench setup at UCSB

- Special configuration: two PMTs on one bar
- Trigger on large pulse, look for SPEs in masked tube

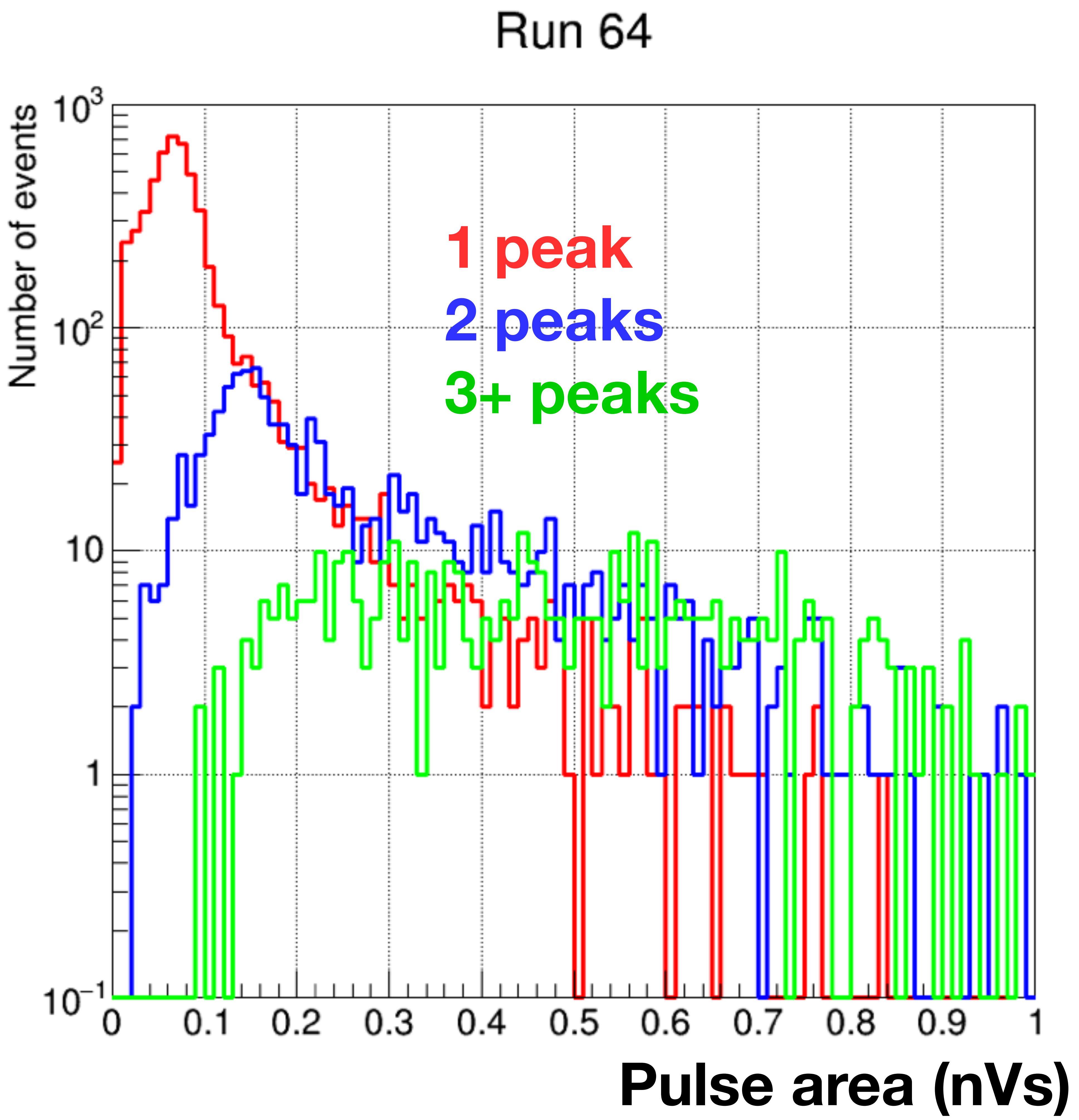


Finding single photoelectrons





Charge distributions

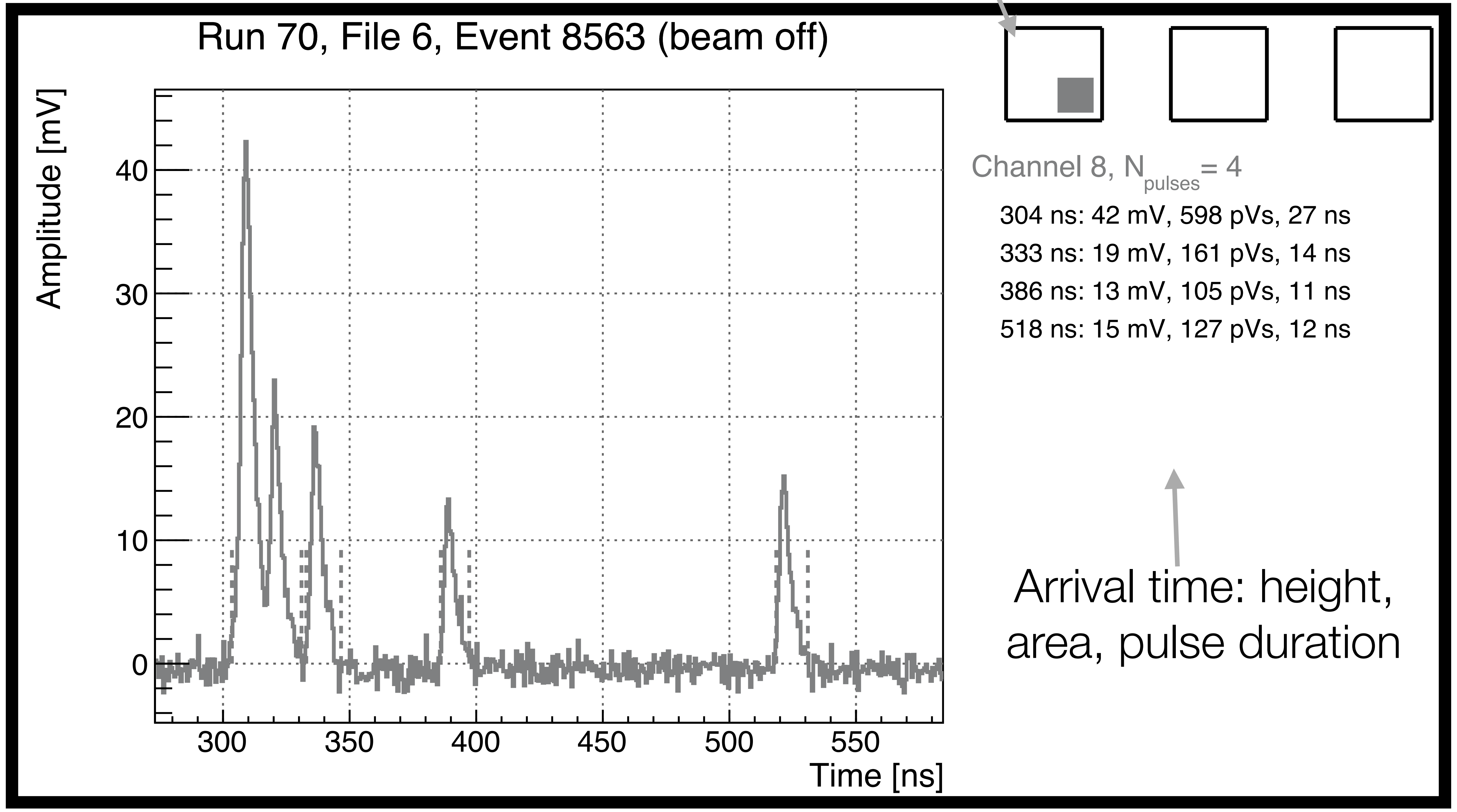


Each peak offset by SPE gain, ~0.07 nVs

- Peakfinding easily reveals SPE spectrum
- Validate other SPE sources: thermal SPEs, early afterpulses

Pulses in milliQan

Channel map

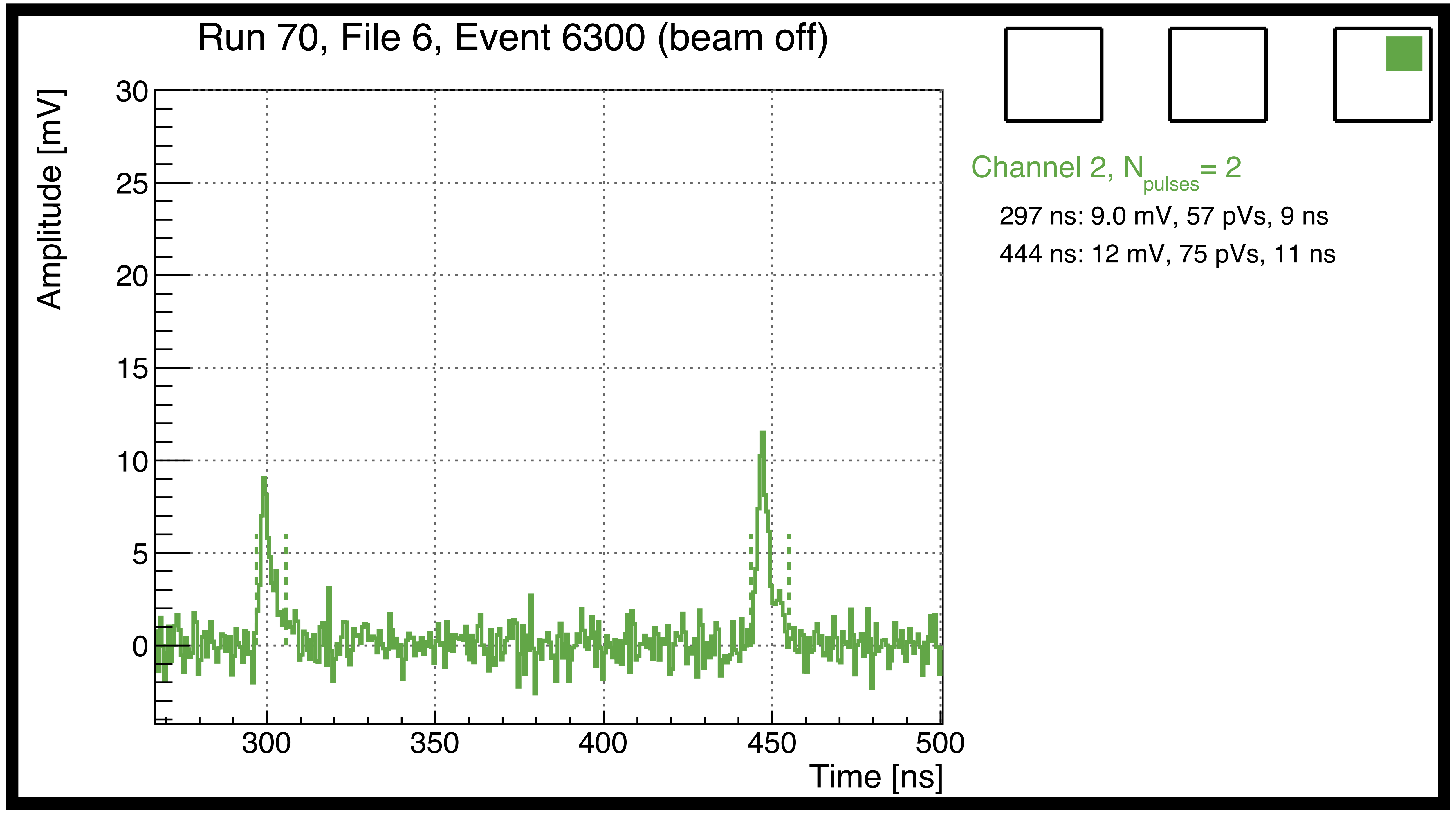


Channel 8, N_{pulses} = 4

```
304 ns: 42 mV, 598 pVs, 27 ns
333 ns: 19 mV, 161 pVs, 14 ns
386 ns: 13 mV, 105 pVs, 11 ns
518 ns: 15 mV, 127 pVs, 12 ns
```

Arrival time: height, area, pulse duration

Hamamatsu R7725, 1600 V

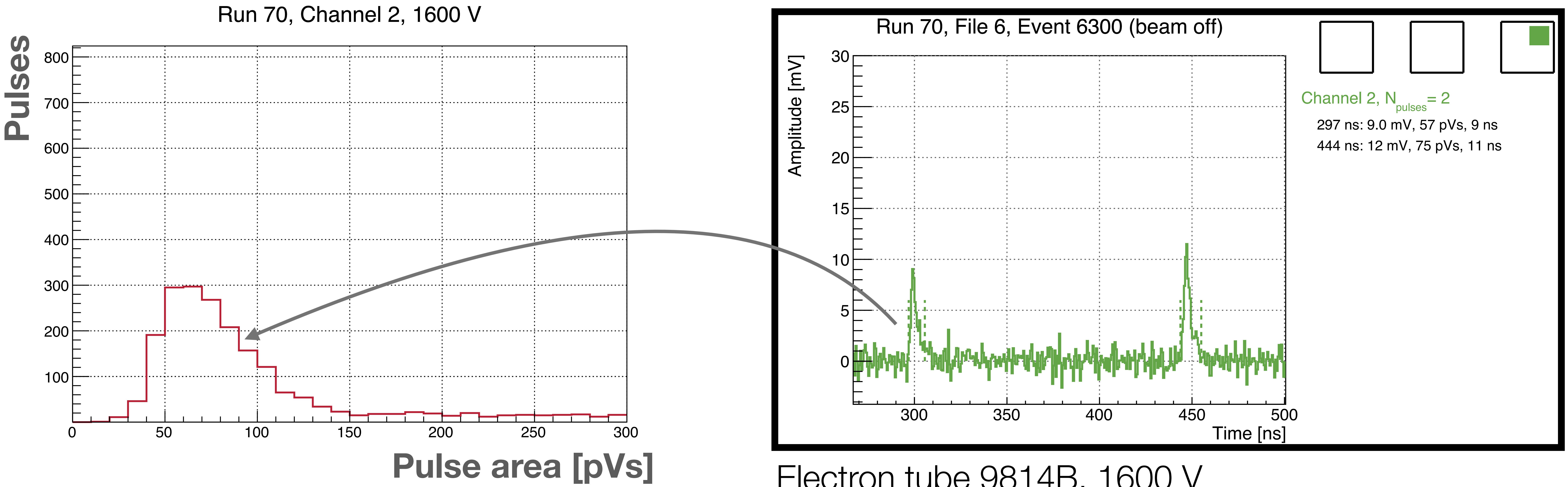


Channel 2, N_{pulses} = 2

```
297 ns: 9.0 mV, 57 pVs, 9 ns
444 ns: 12 mV, 75 pVs, 11 ns
```

Electron tube 9814B, 1600 V

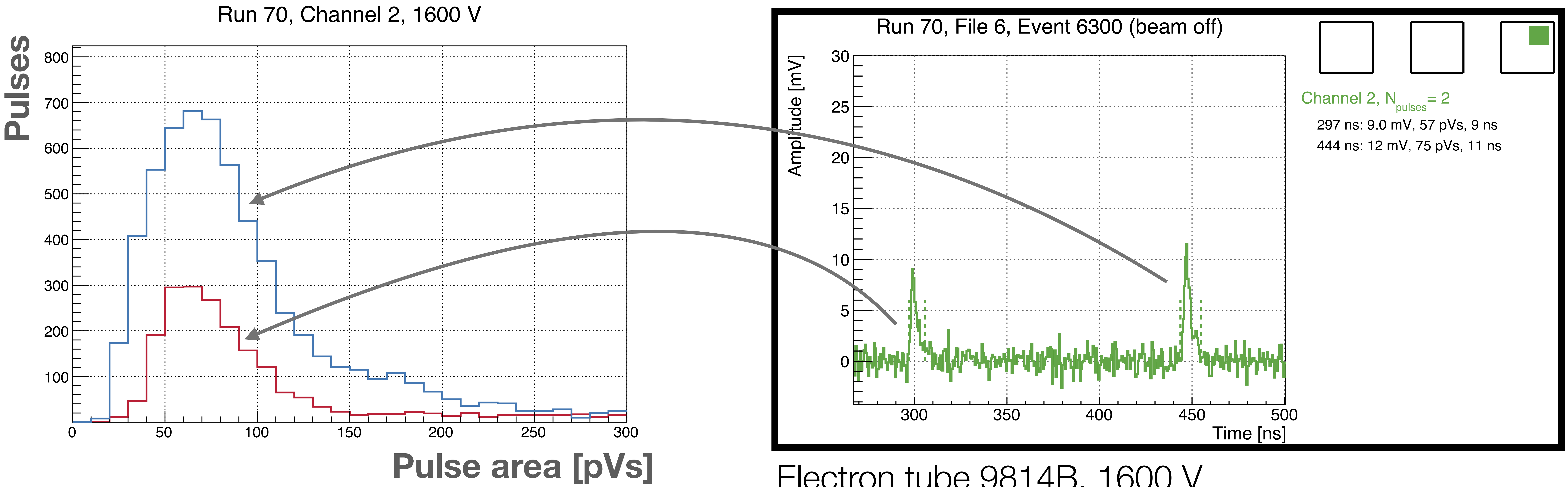
SPE measurement



First pulses (trigger)

Electron tube 9814B, 1600 V

SPE measurement



Channel 2, $N_{pulses} = 2$

297 ns: 9.0 mV, 57 pVs, 9 ns

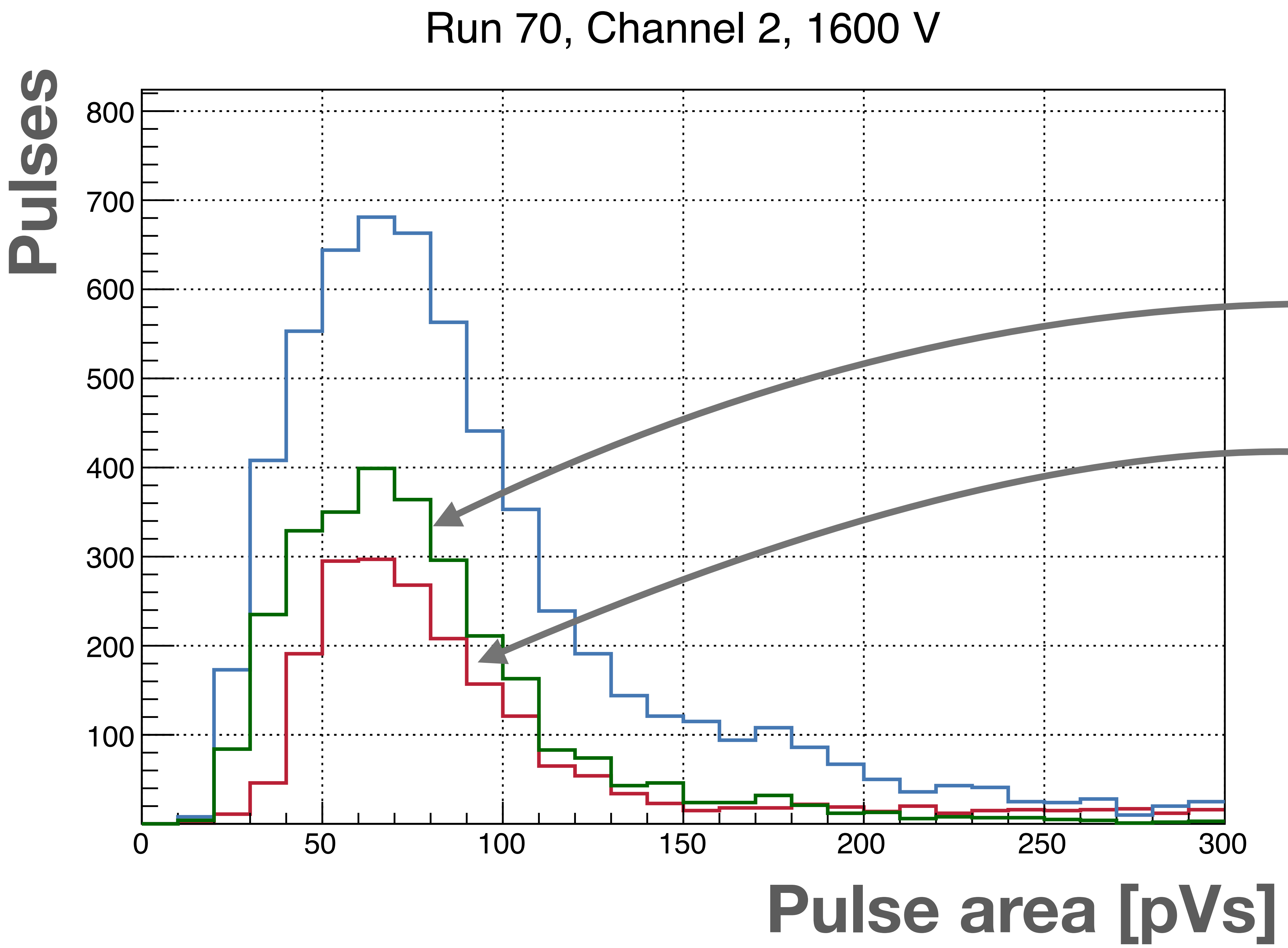
444 ns: 12 mV, 75 pVs, 11 ns

Electron tube 9814B, 1600 V

First pulses (trigger)

Late pulses

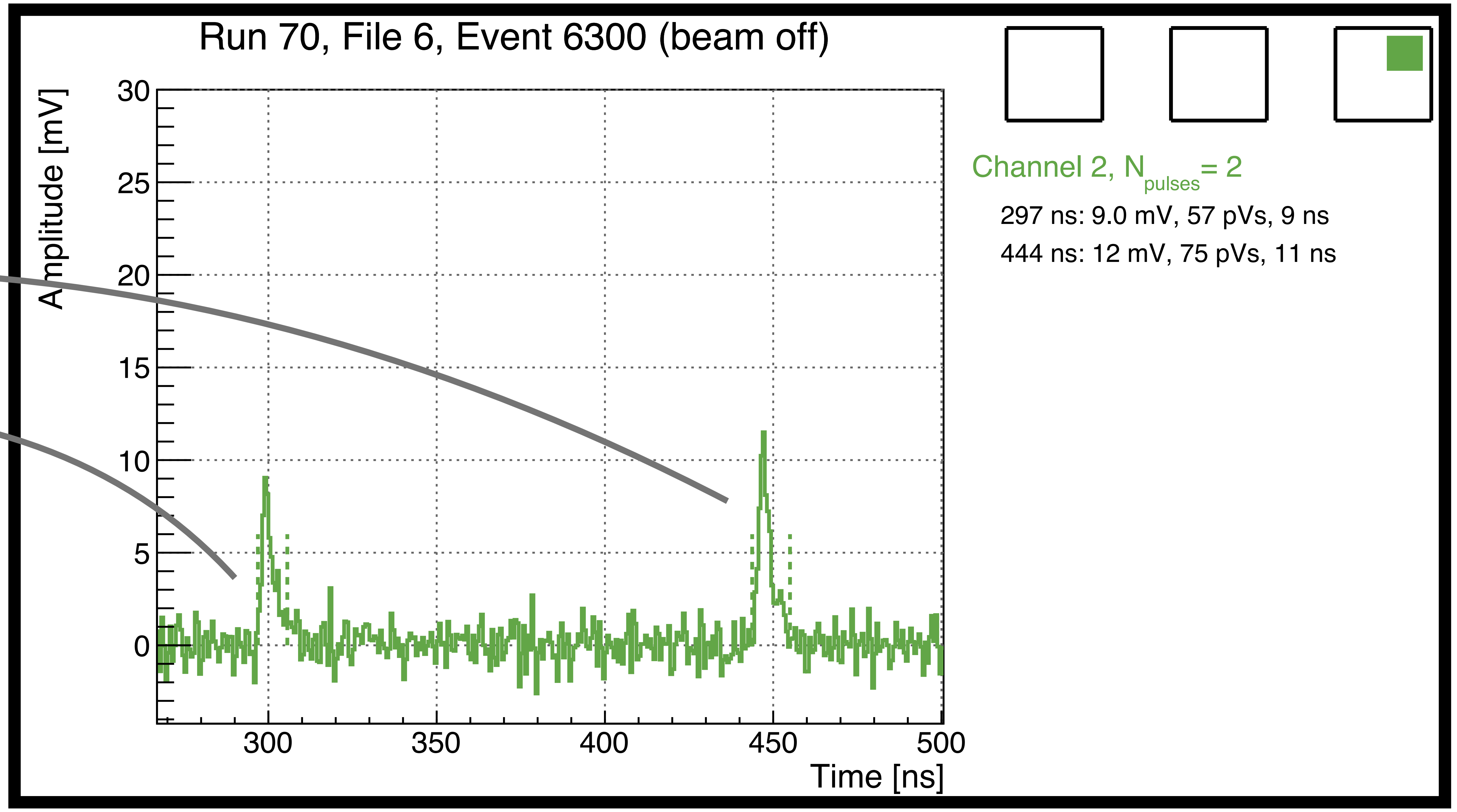
SPE measurement



First pulses (trigger)

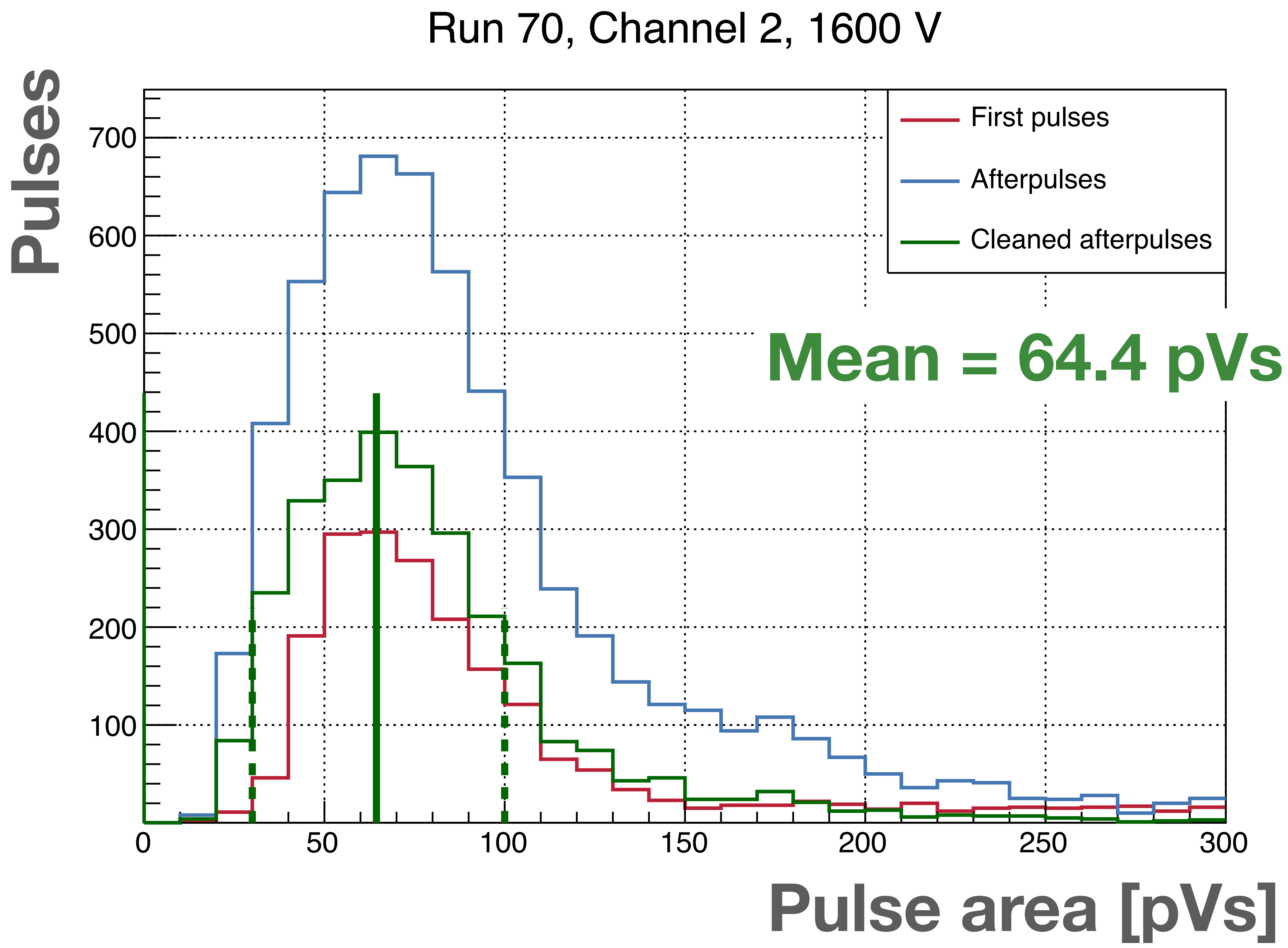
Late pulses

Cleaned late pulses (quiet for previous 20ns)



Electron tube 9814B, 1600 V

SPE measurement

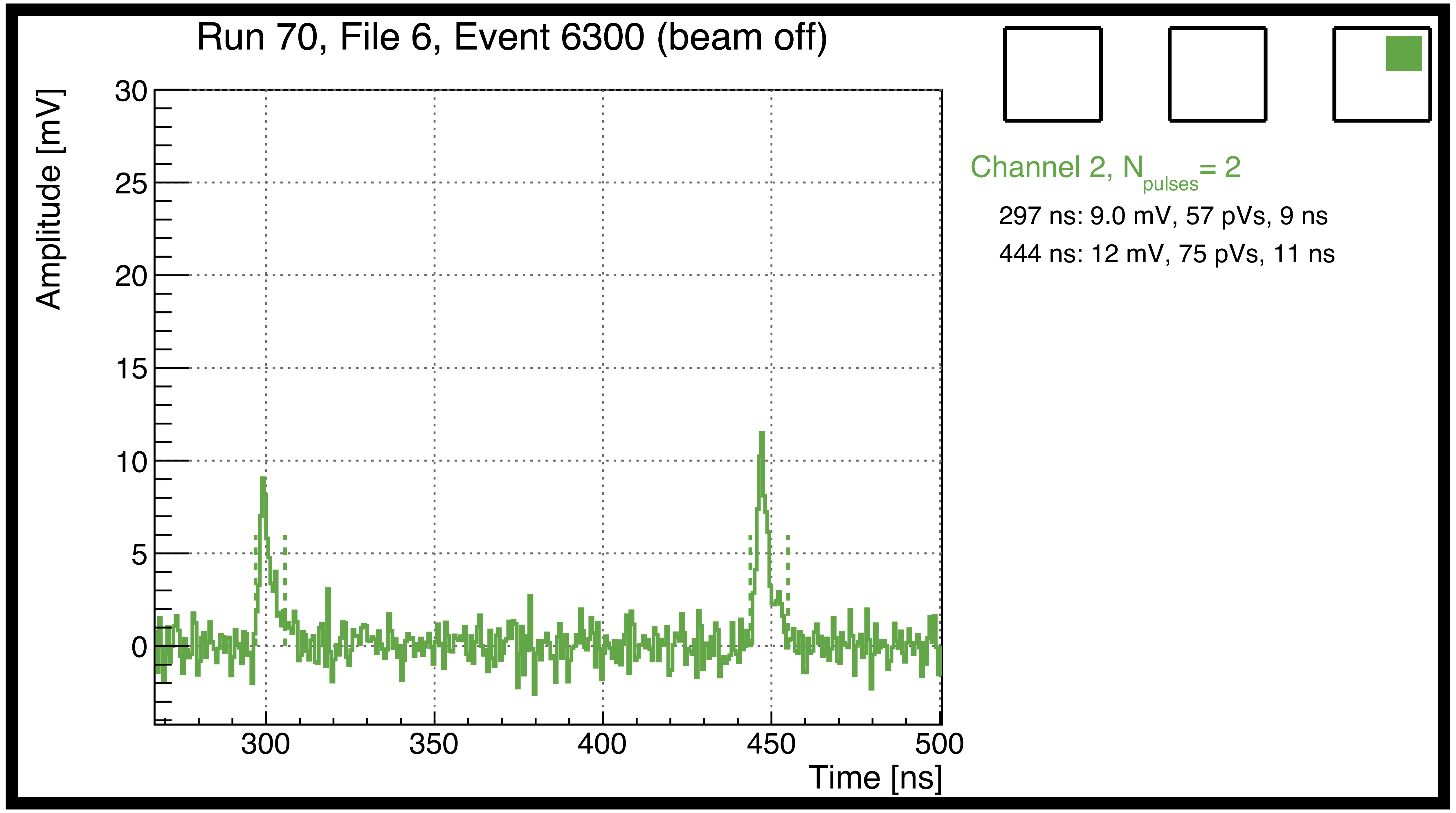


Mean = 64.4 pVs

First pulses (trigger)

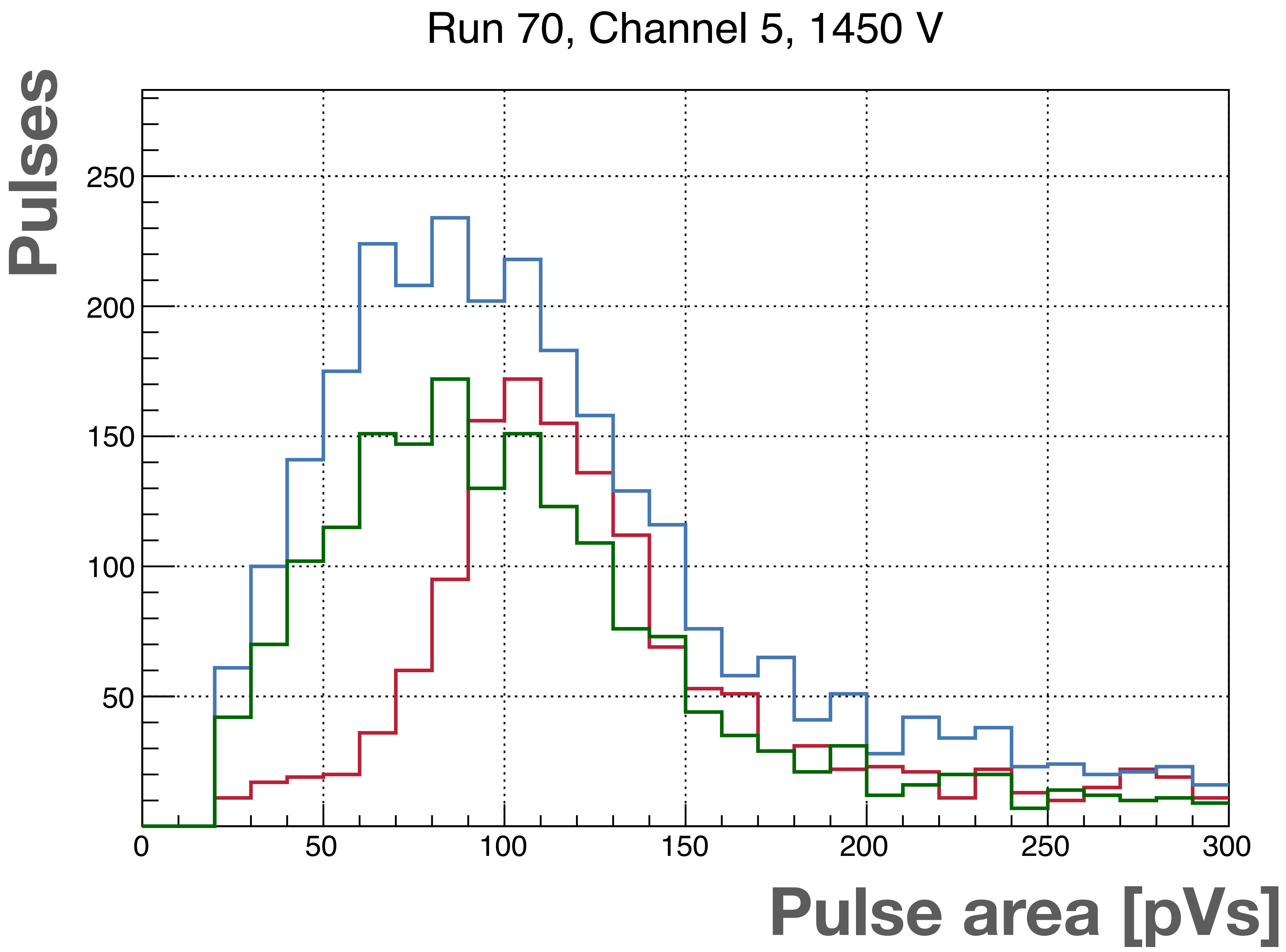
Late pulses

Cleaned late pulses (quiet for previous 20ns)



Electron tube 9814B, 1600 V

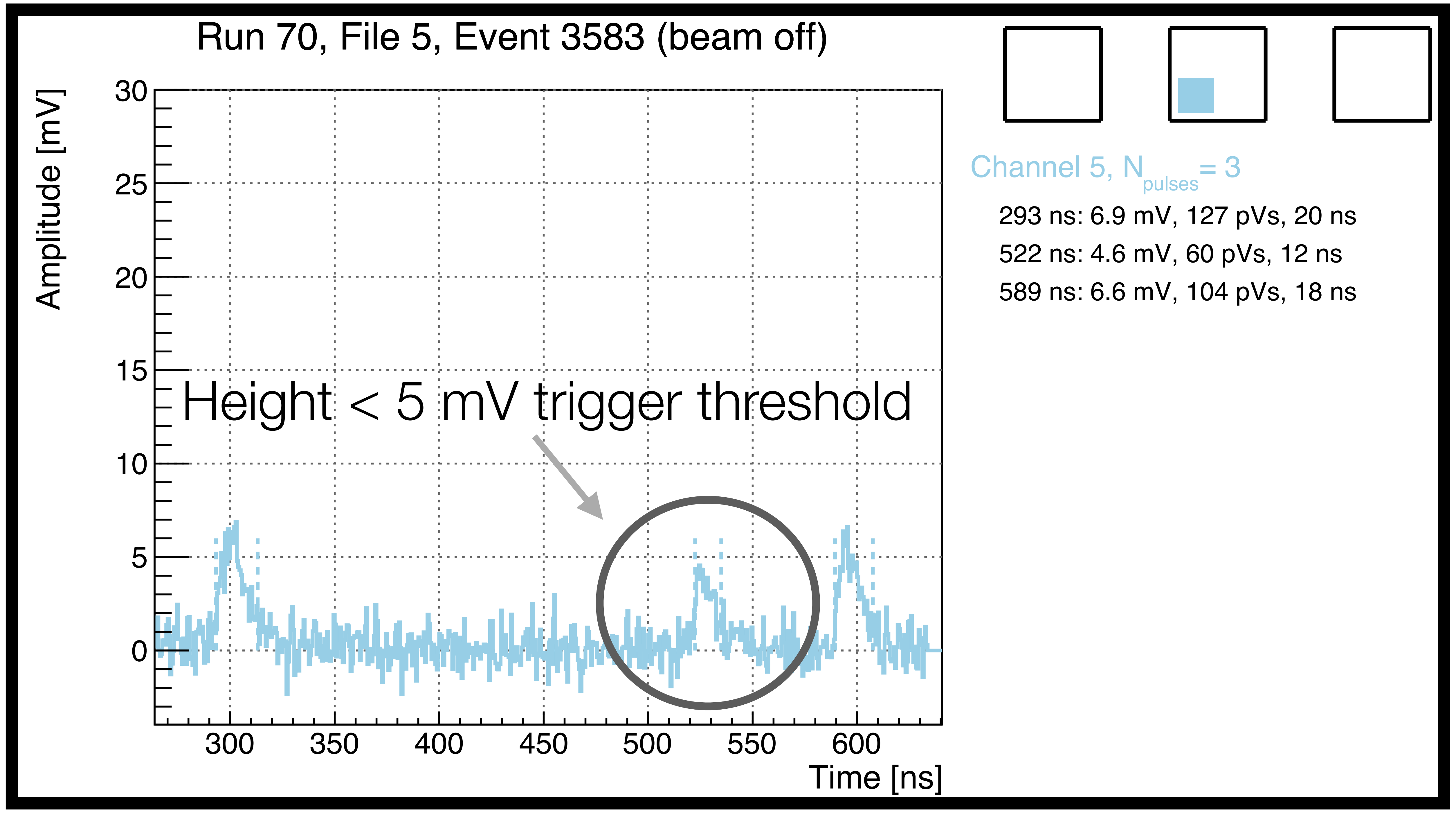
SPE measurement



First pulses (trigger)

Late pulses

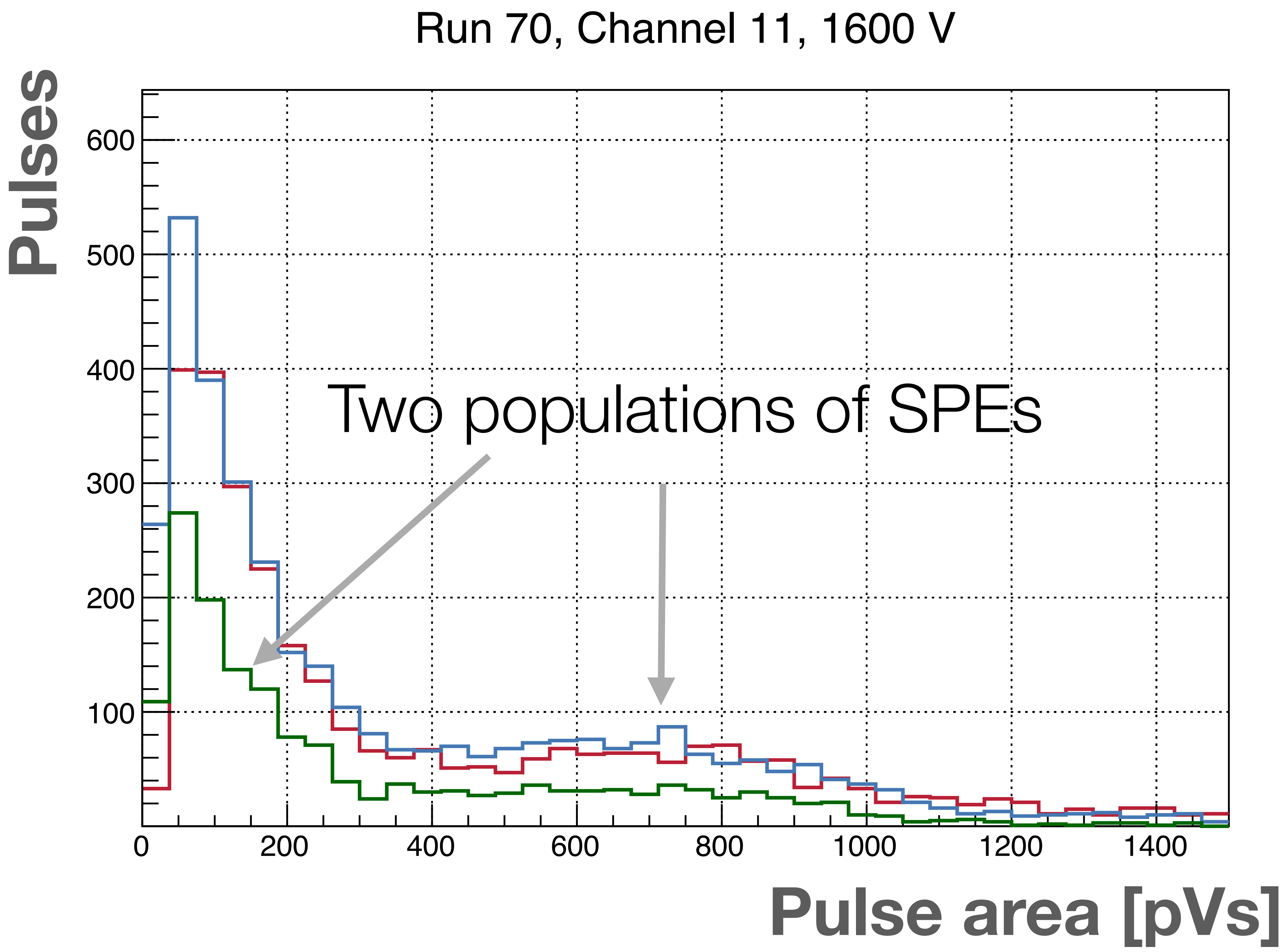
Cleaned late pulses (quiet for previous 20ns)



Hamamatsu R878, 1450 V

First pulse: susceptible to sculping by trigger

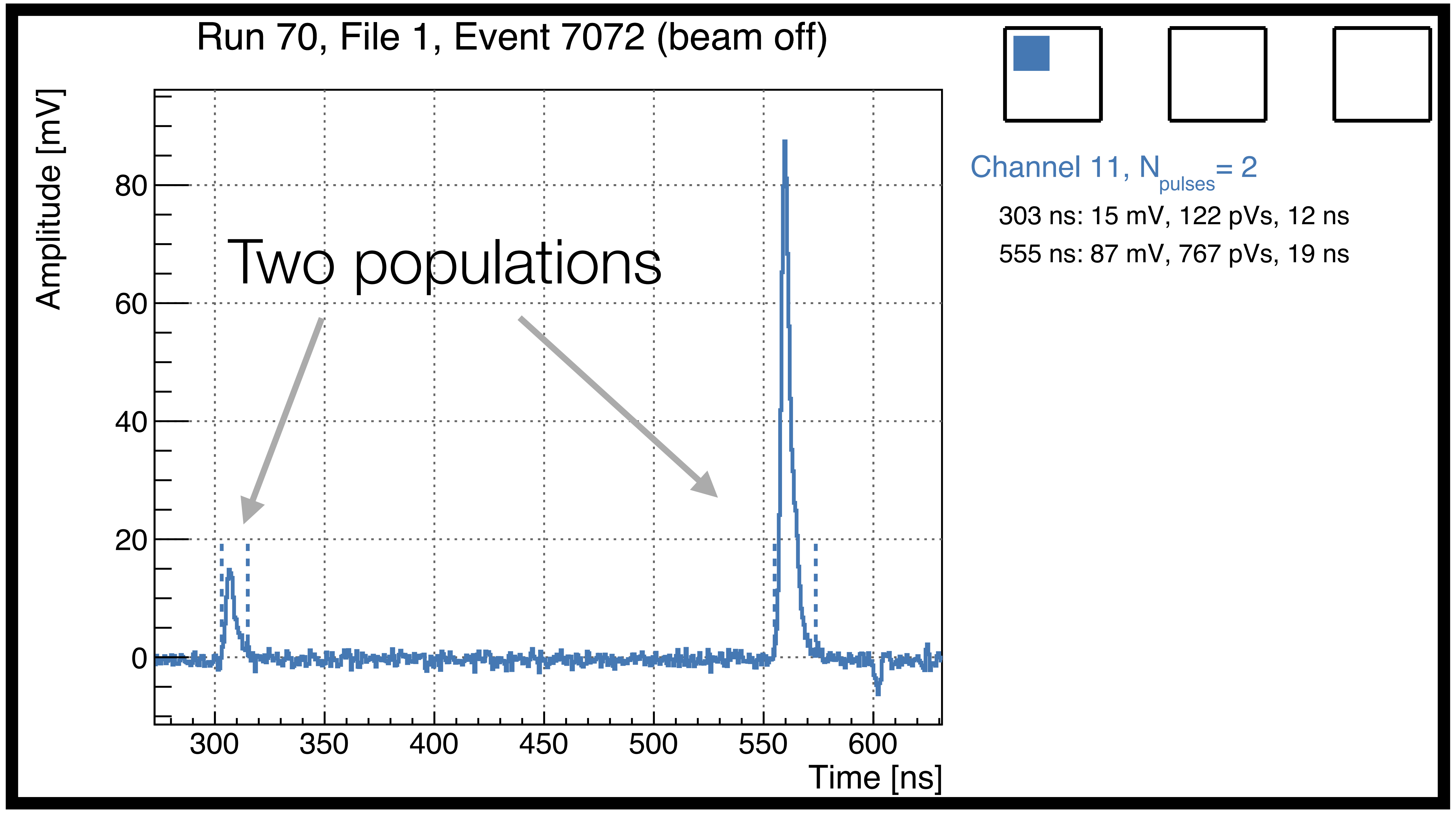
SPE measurement



First pulses (trigger)

Late pulses

Cleaned late pulses (quiet for previous 20ns)



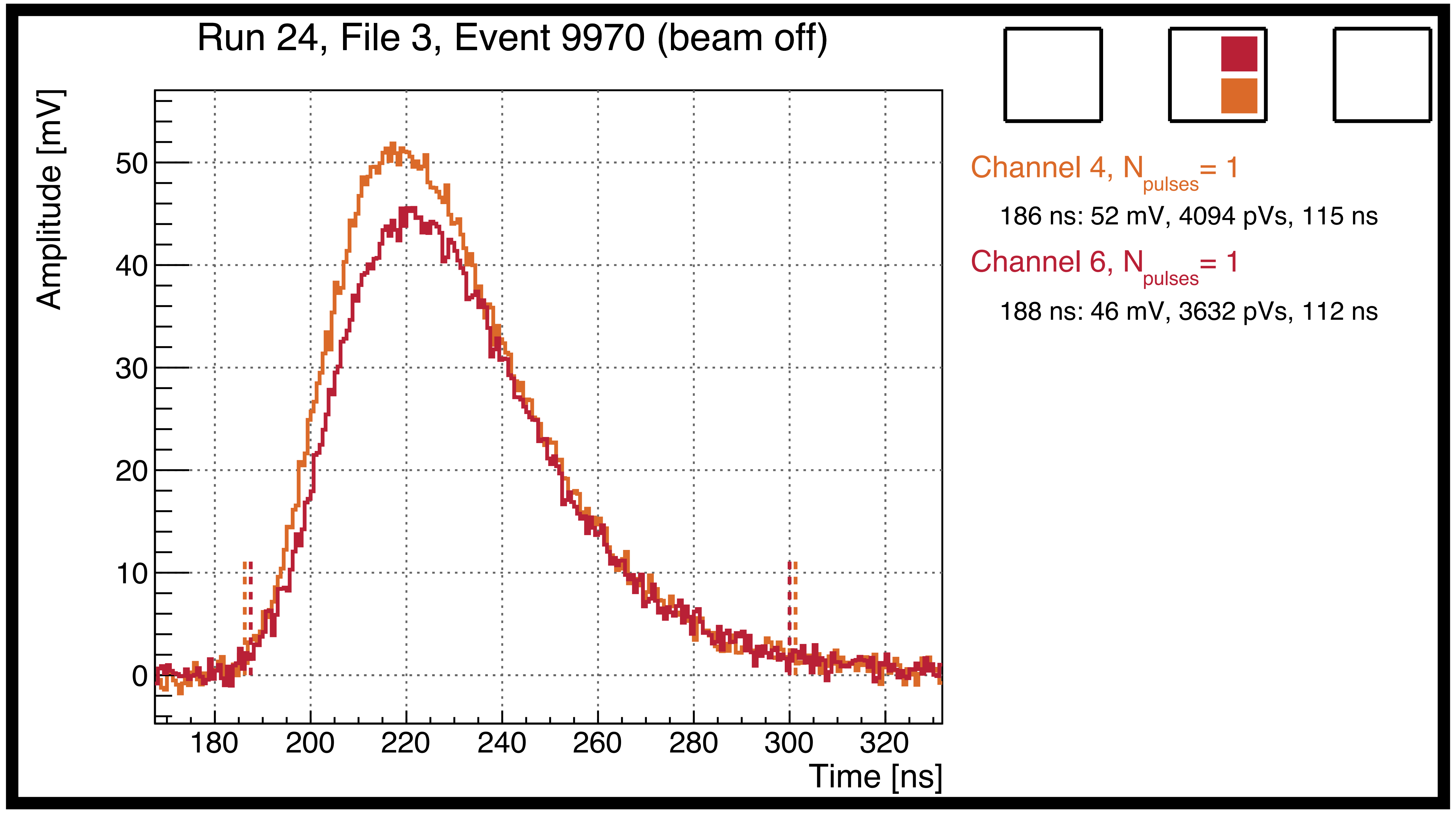
Hamamatsu R7725, 1600 V

Starting bench study to understand 2 strange PMTs

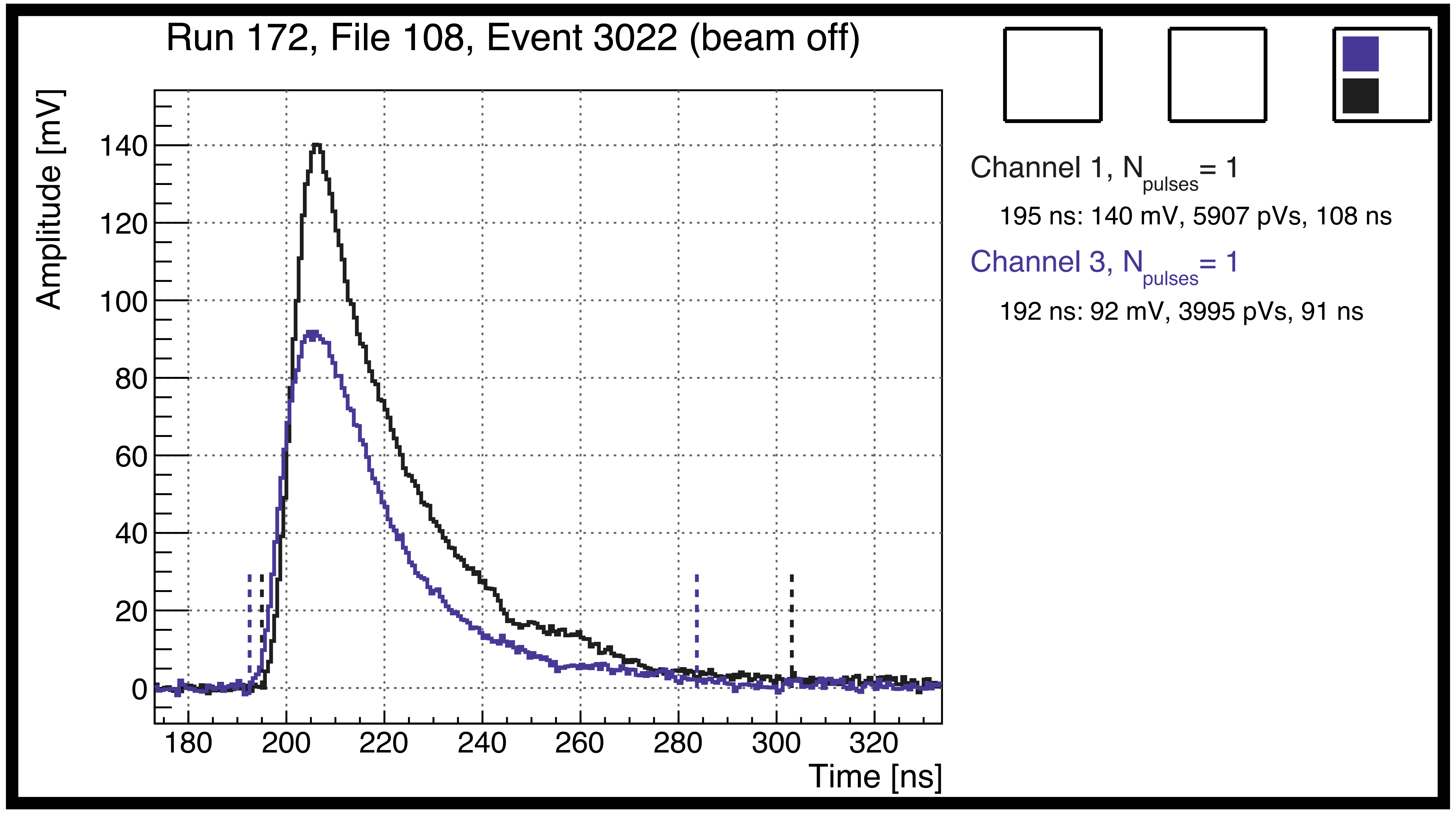
Light yield calibration

- How many photons do we collect for given energy deposition?
  - **Gamma sources**:
    - well-known energy, high rate
    - logistically difficult
  - **Cosmic muons**:
    - always there
    - low rate, unknowns: angle of incidence, presence of secondaries
- Ideally use both: source calibration when possible, monitor with cosmics

Cosmic events



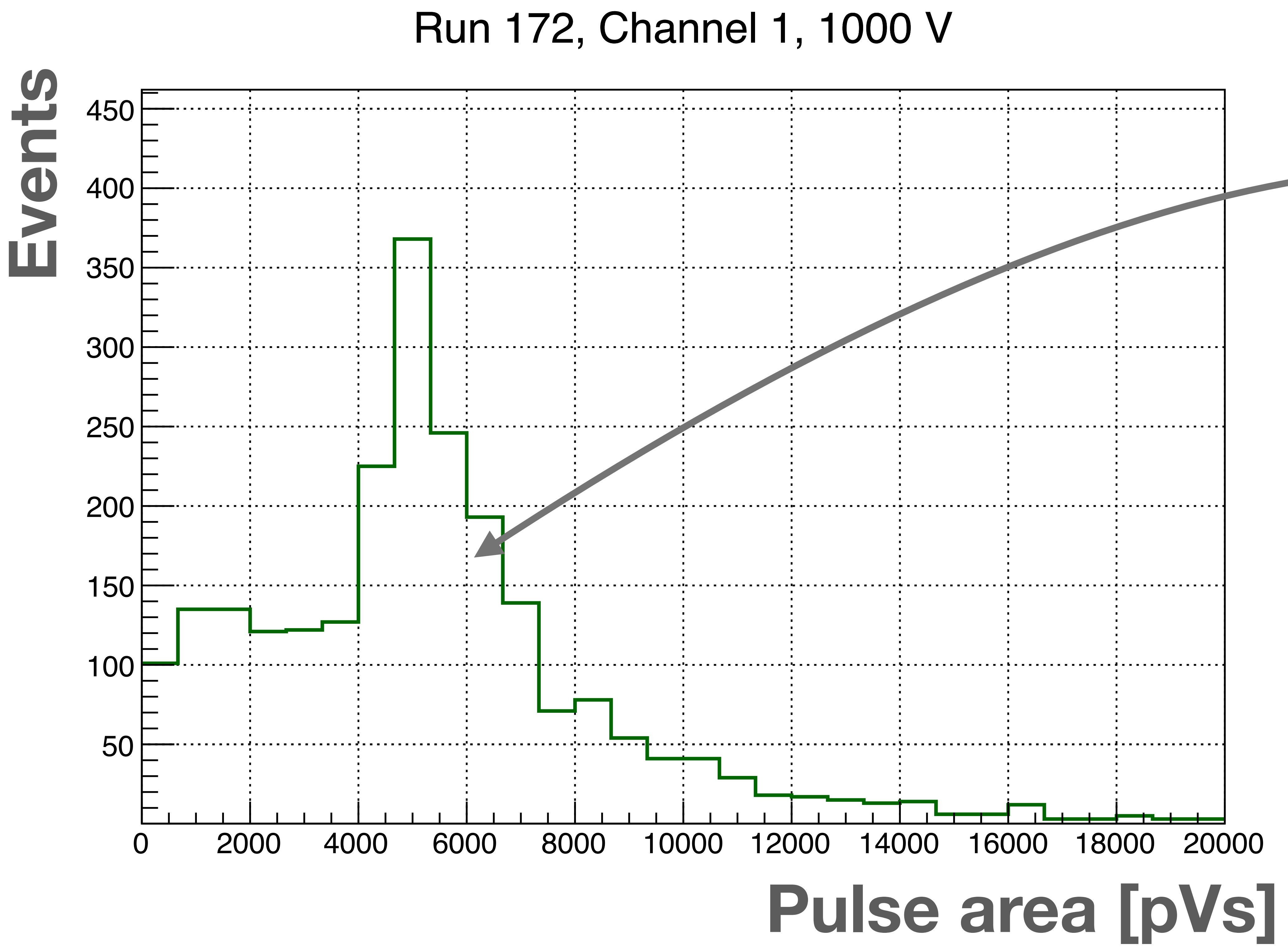
Hamamatsu R878, 1000 V

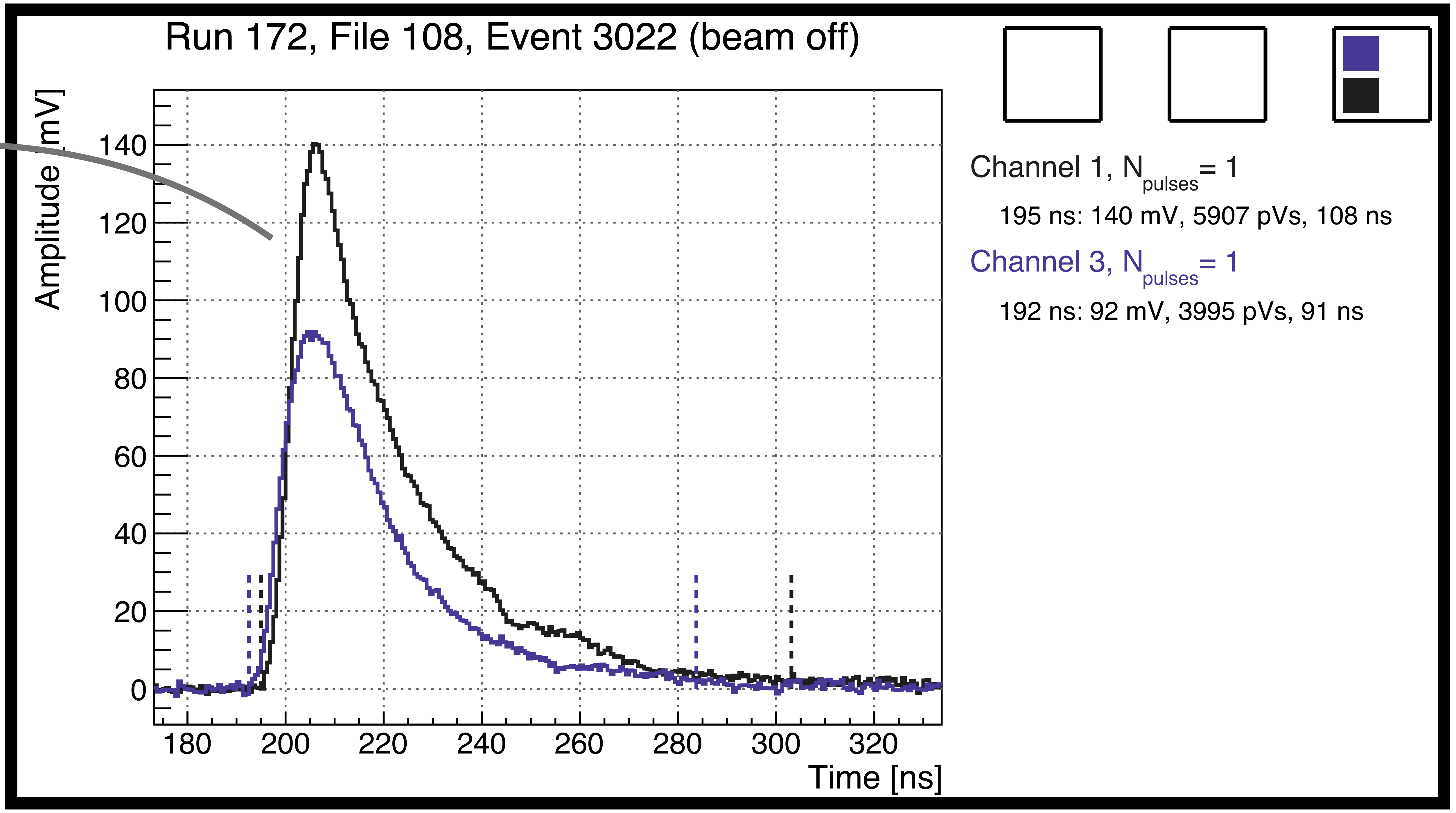


ET 9814B, 1000 V

Have to turn voltage way down to measure cosmics (1600 V → 1000 V)

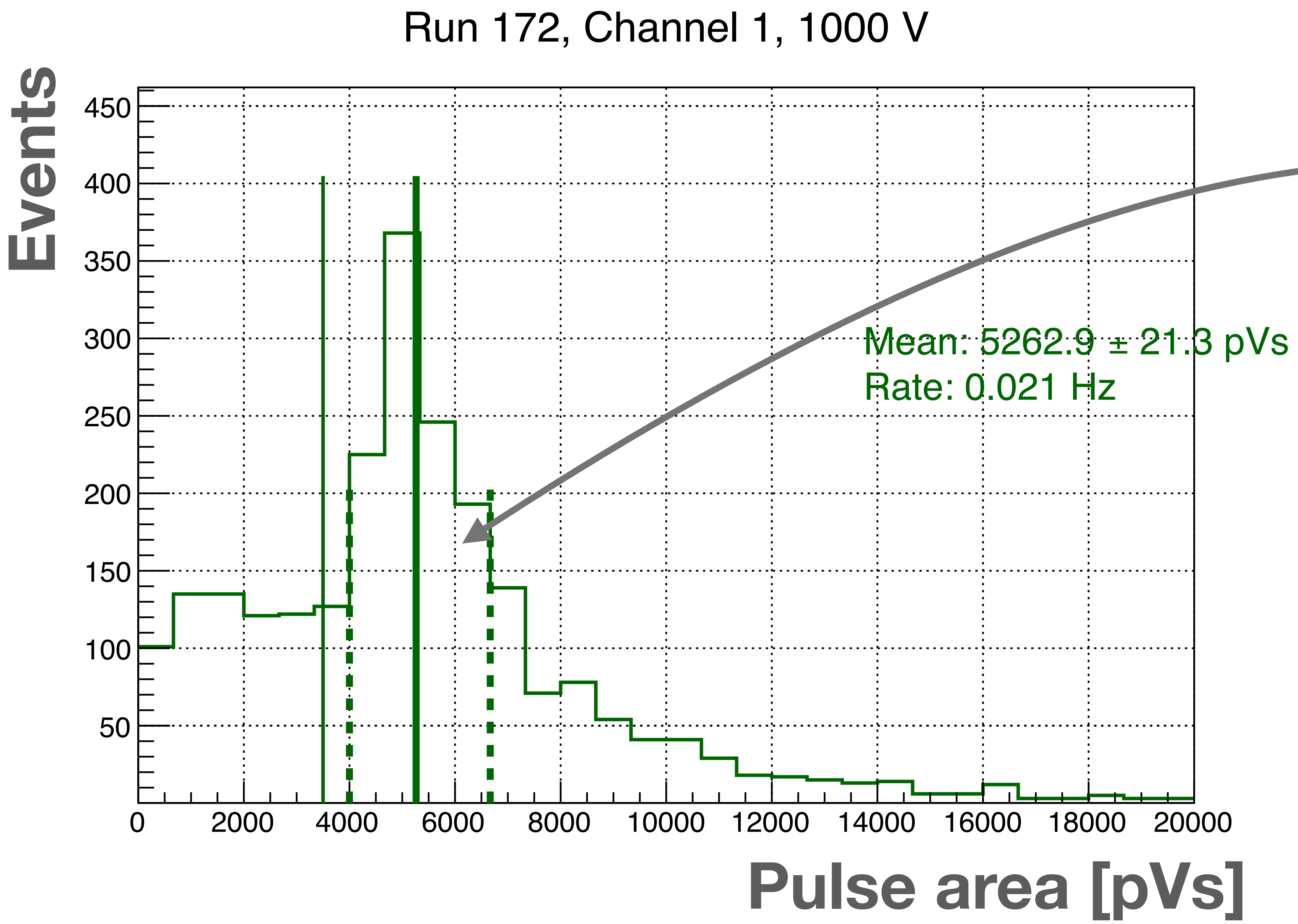
Cosmic charge measurement

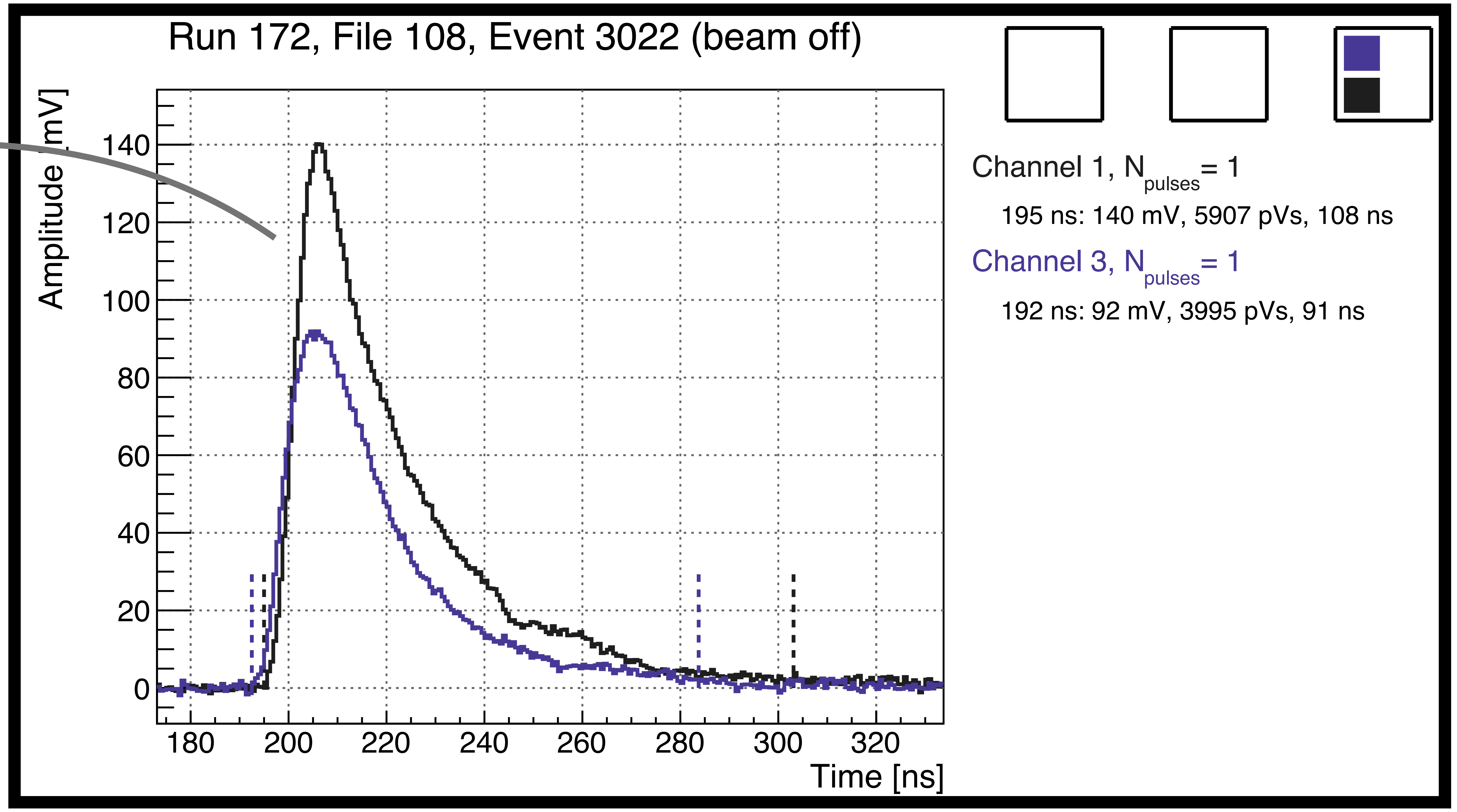




ET 9814B, 1000 V

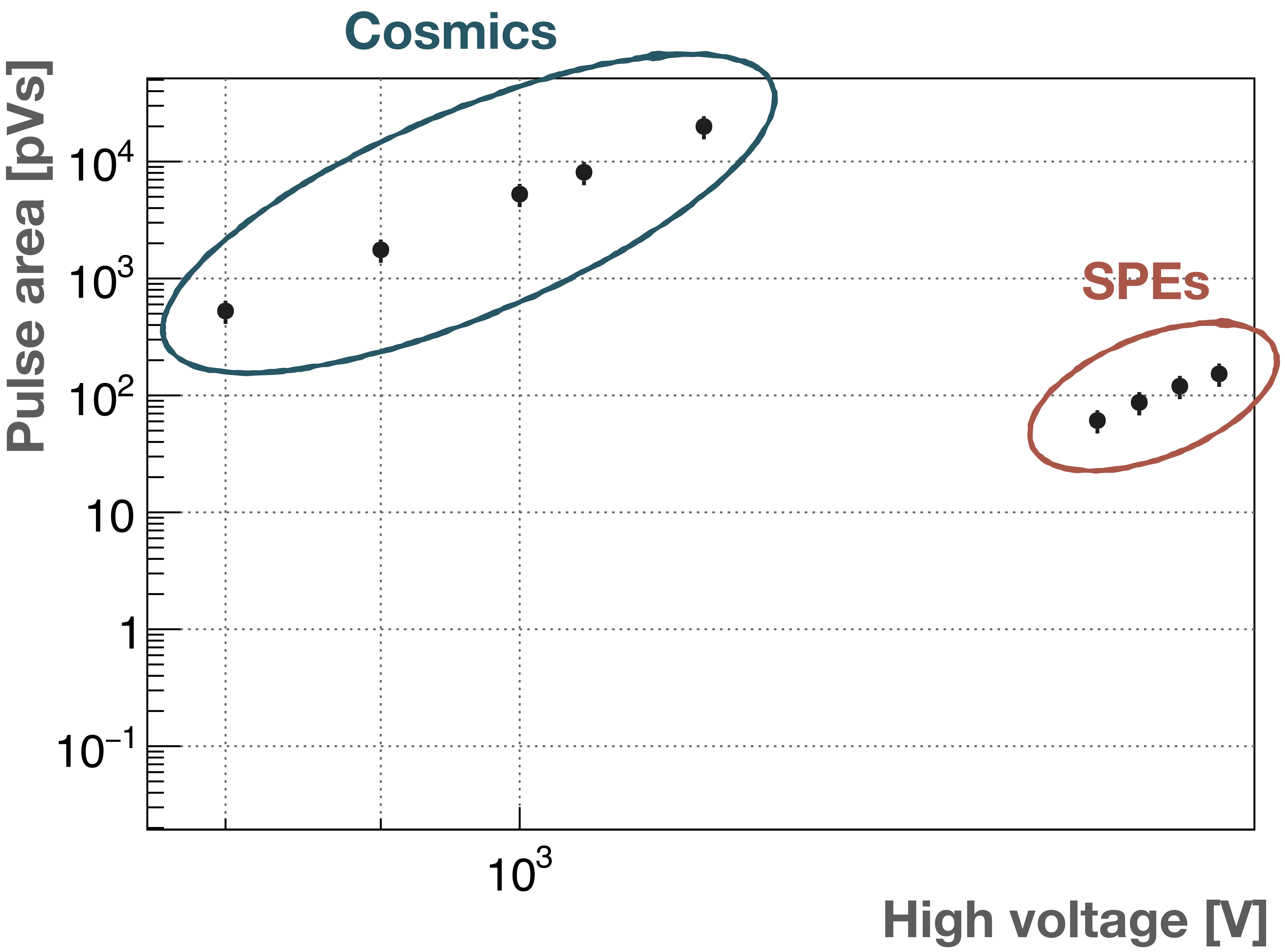
Cosmic charge measurement



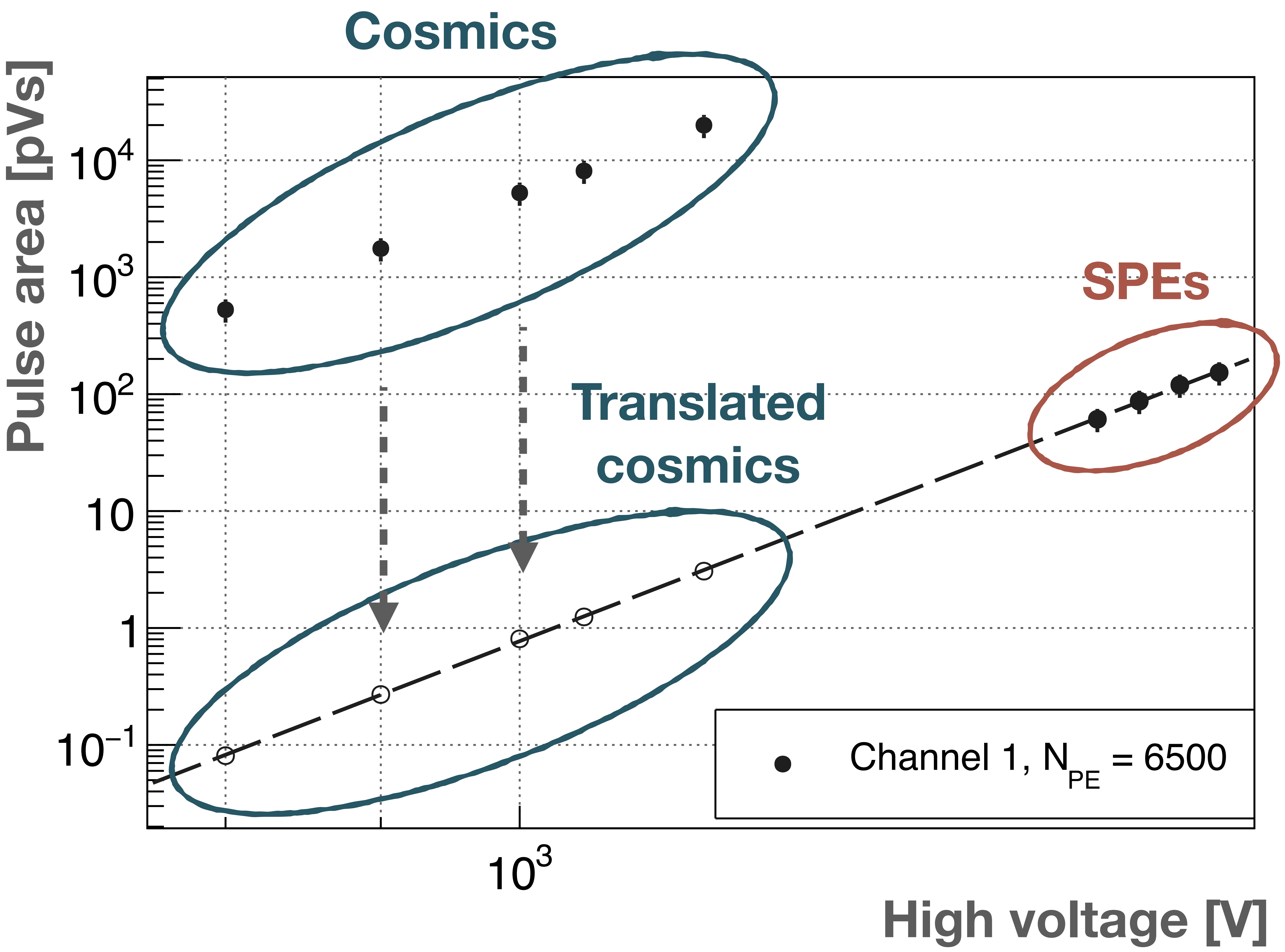


ET 9814B, 1000 V

Extracting cosmic light yield

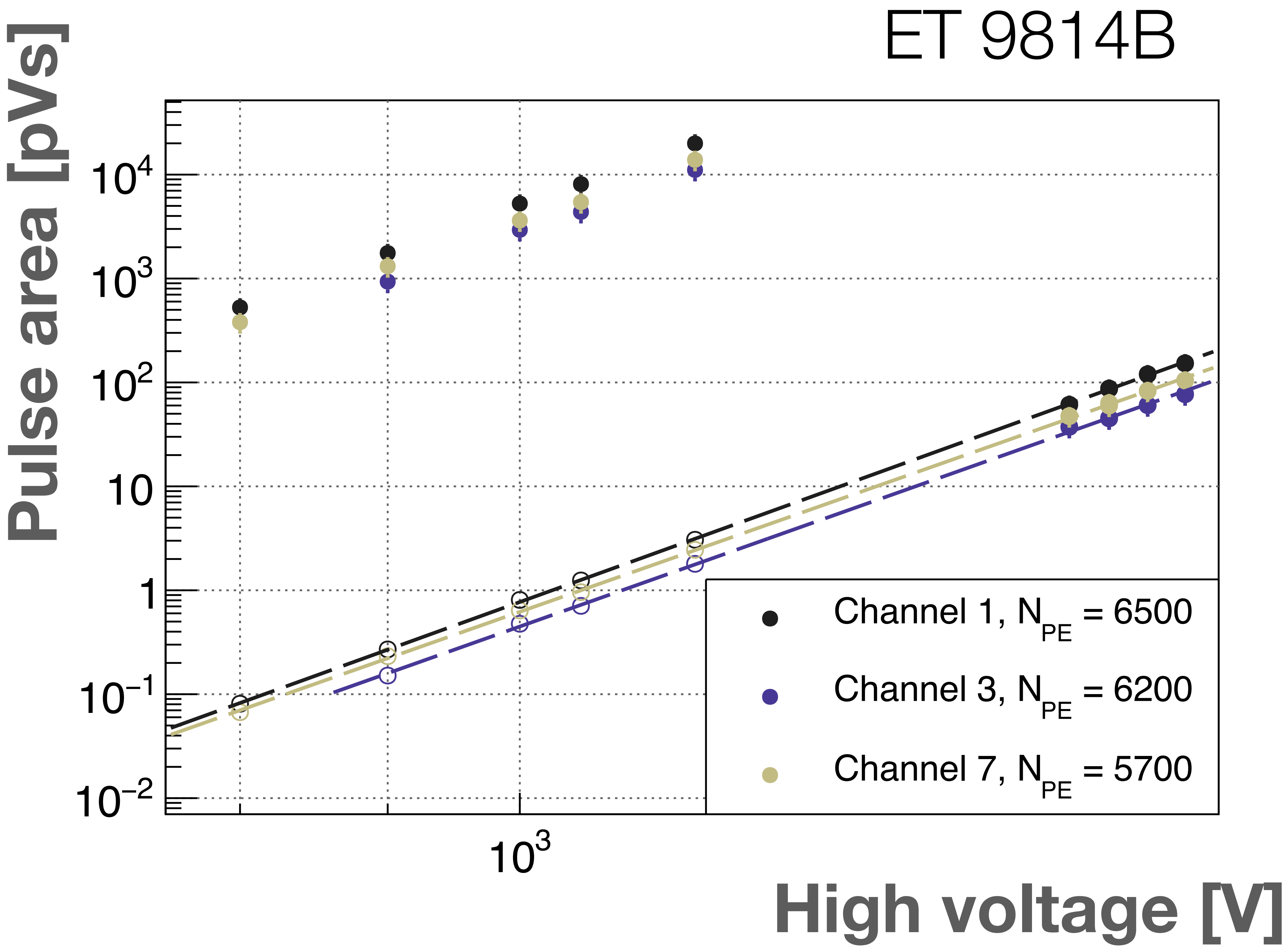


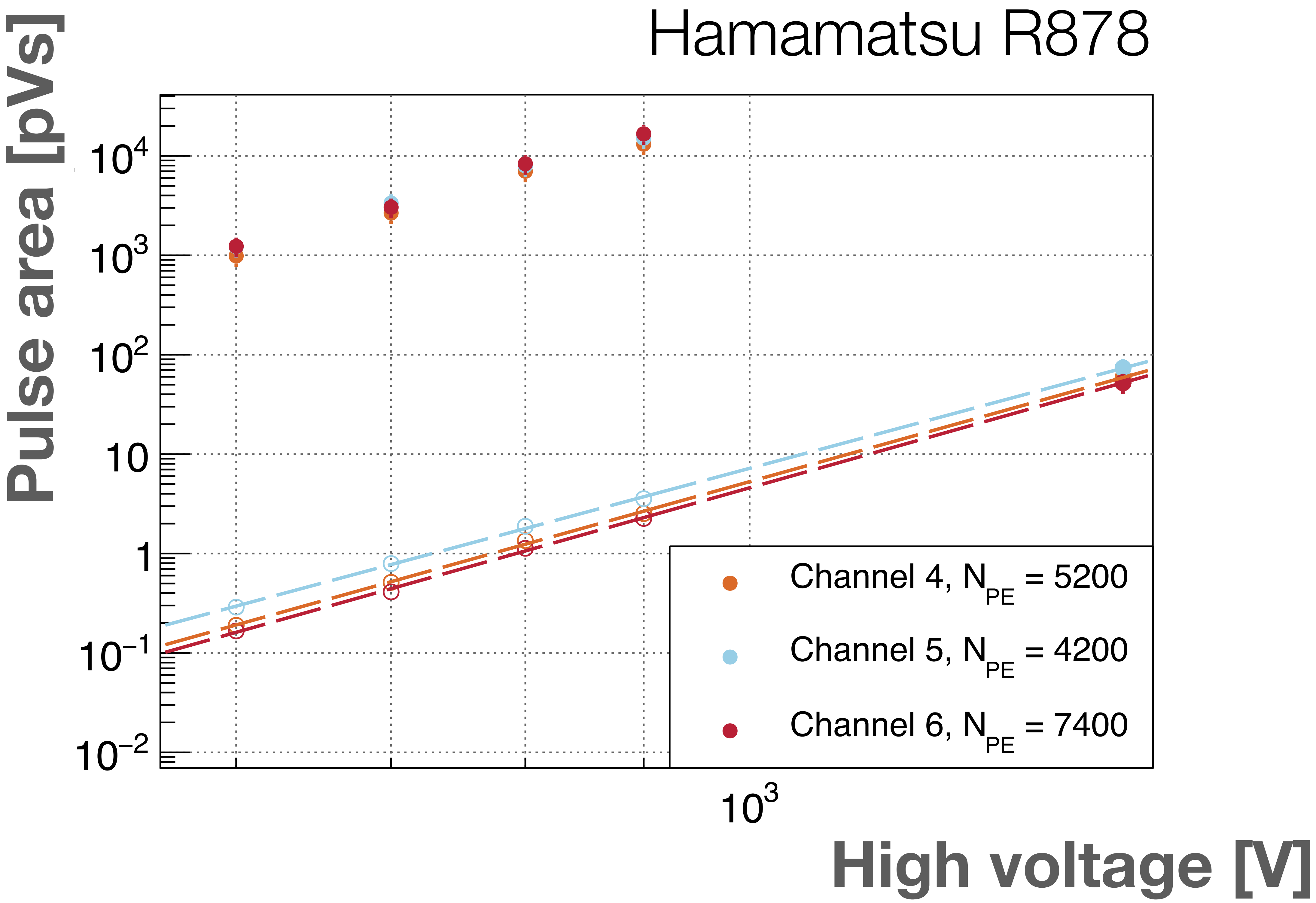
Extracting cosmic light yield



- Can’t measure cosmic and SPE at single HV
- Scale cosmic yields by N_{PE}
- 3-parameter fit: **slope, intercept, N_{PE}**

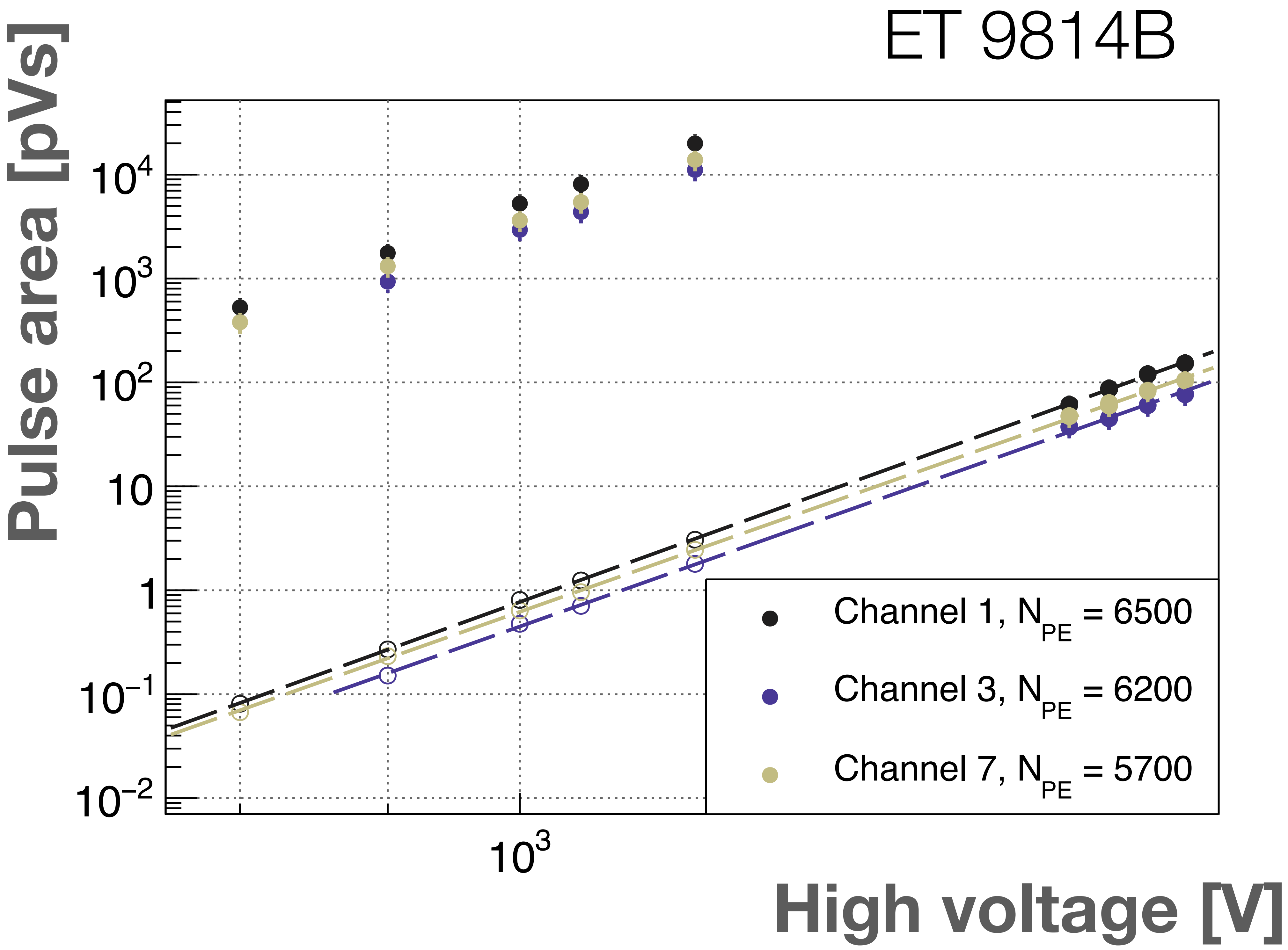
Cosmic light yields

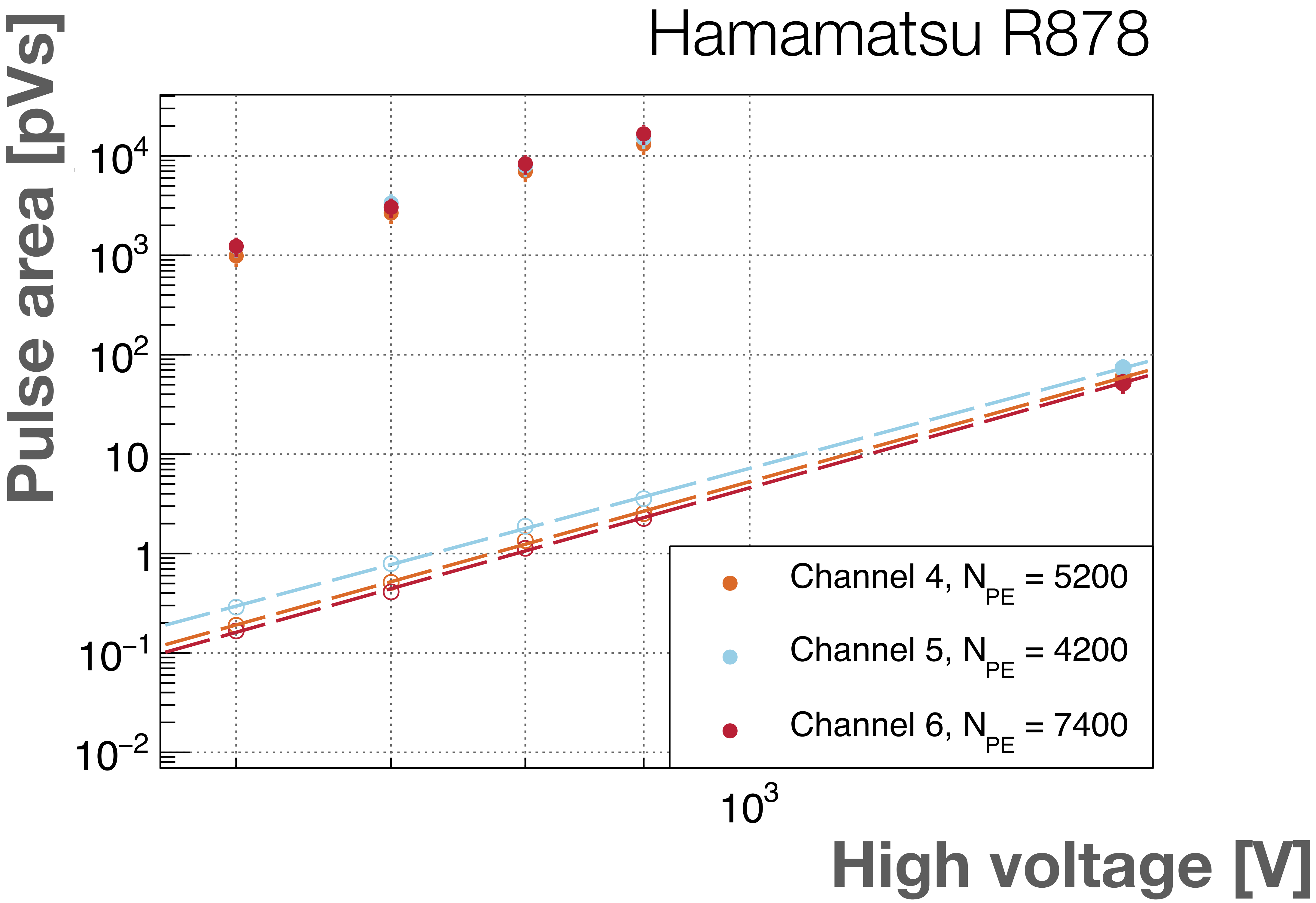




O(5000) photons for vertical muon

Cosmic light yields



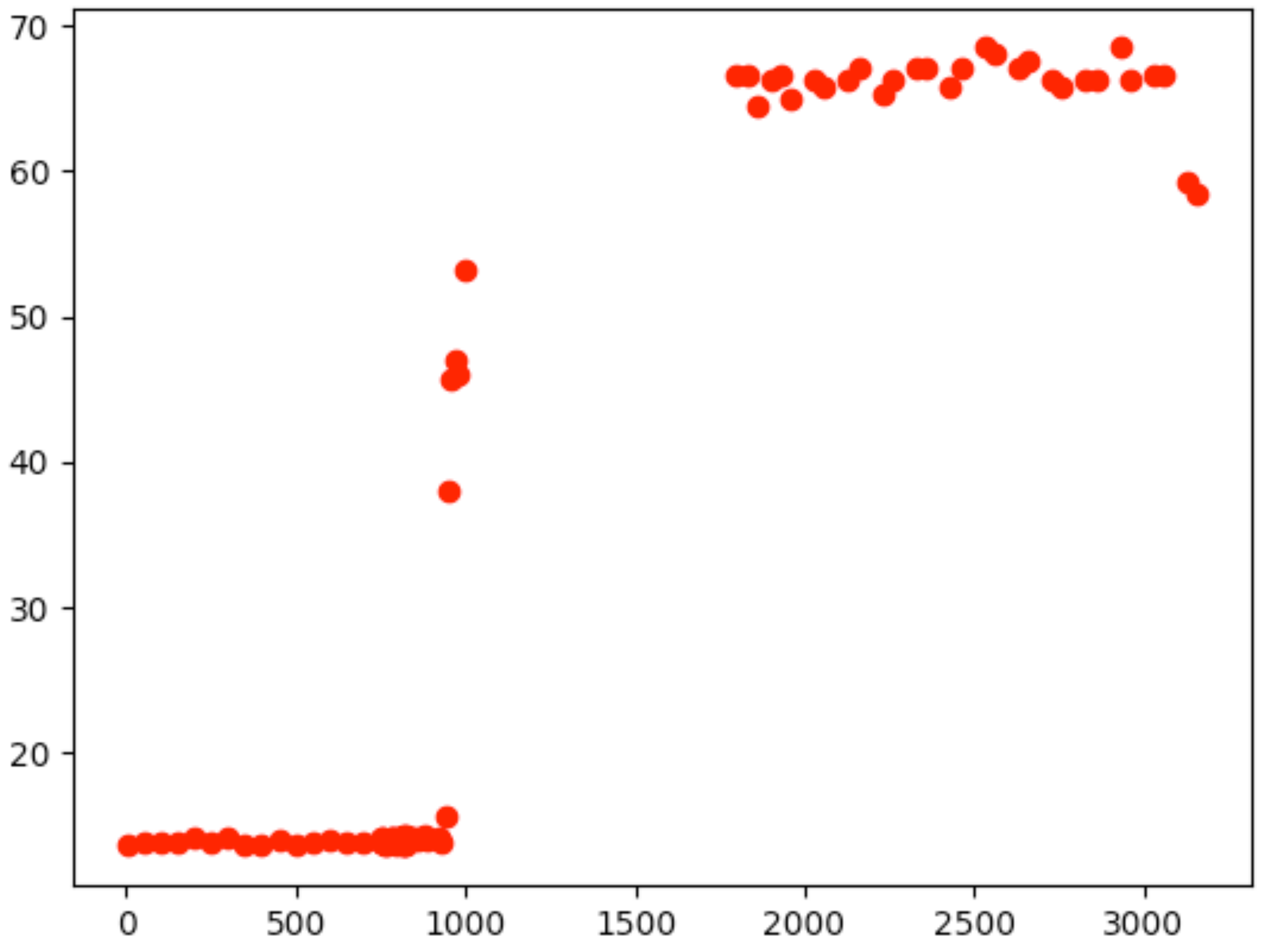


O(5000) photons for vertical muon →

Q=0.01: ~5 photons
Q=0.005: ~1 photon

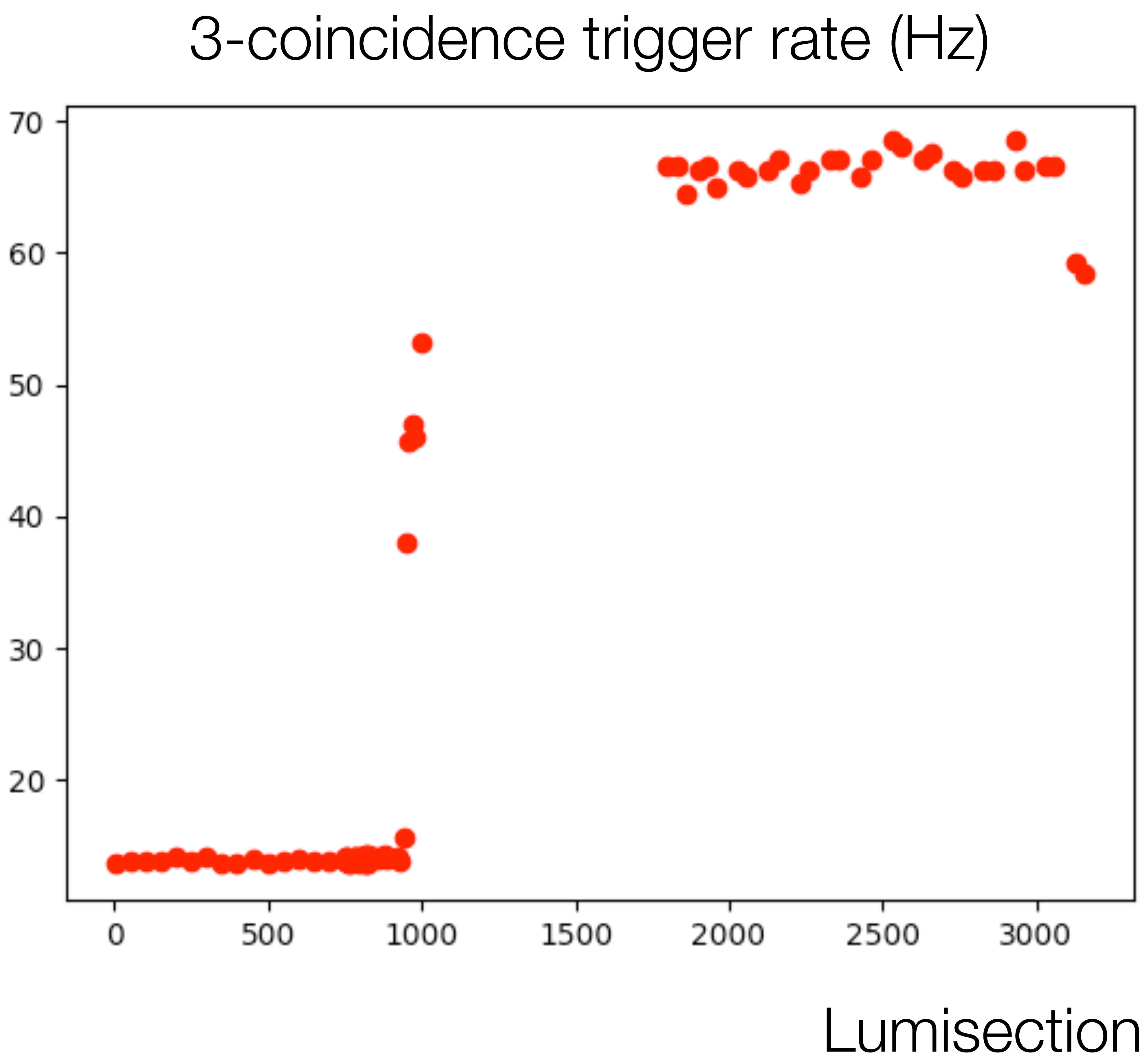
Trigger rate spike

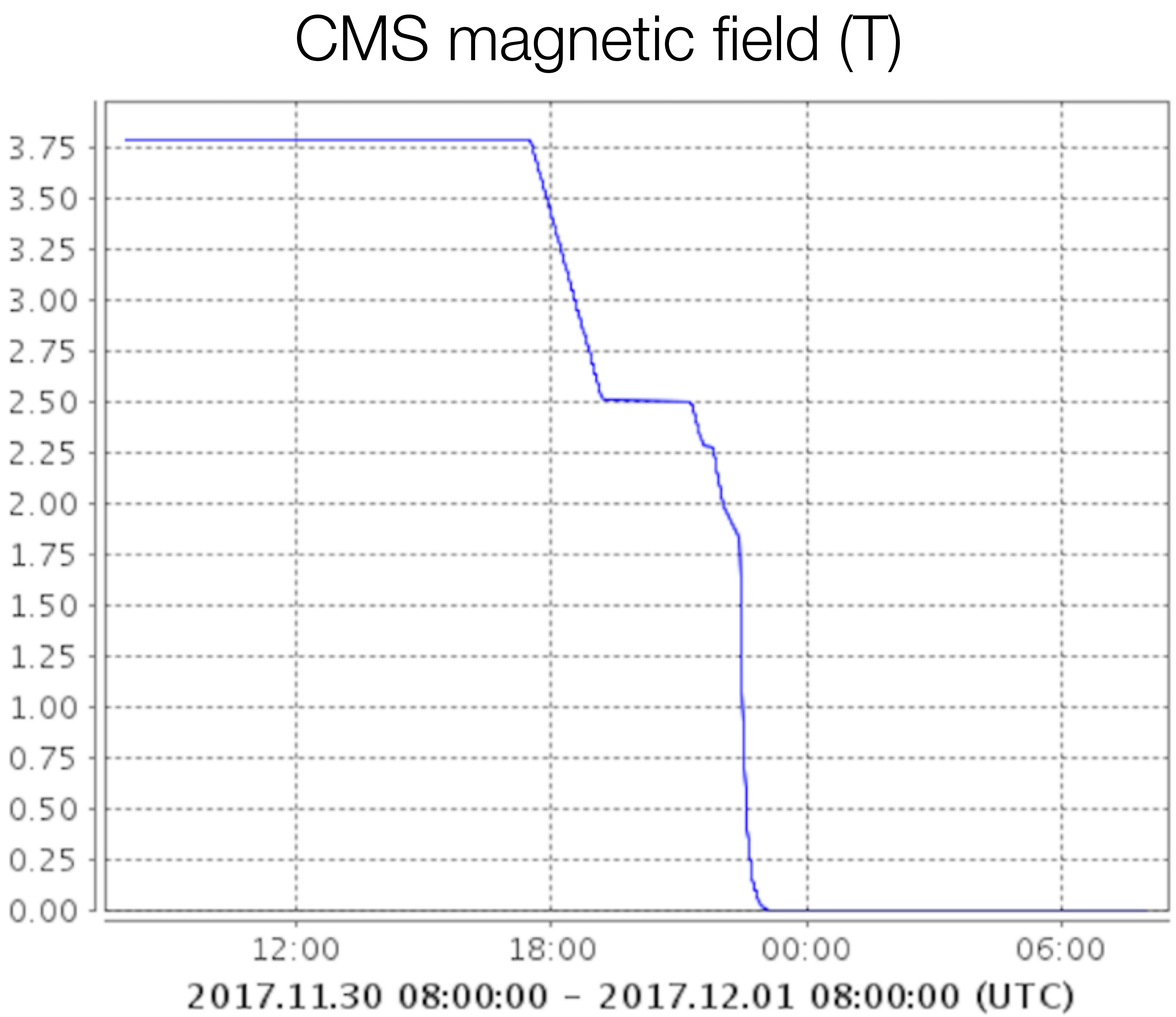
3-coincidence trigger rate (Hz)



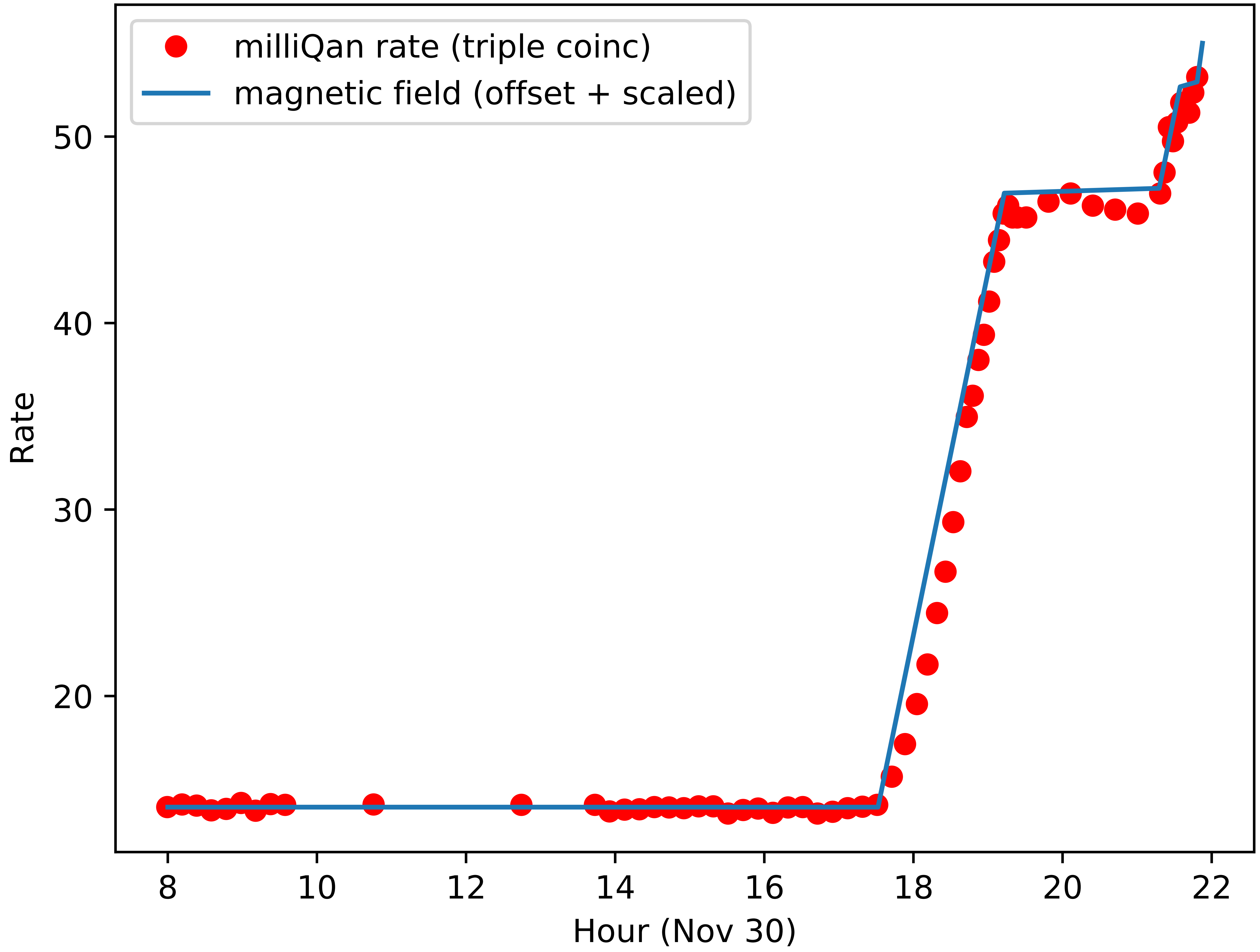
Lumisection

Trigger rate spike

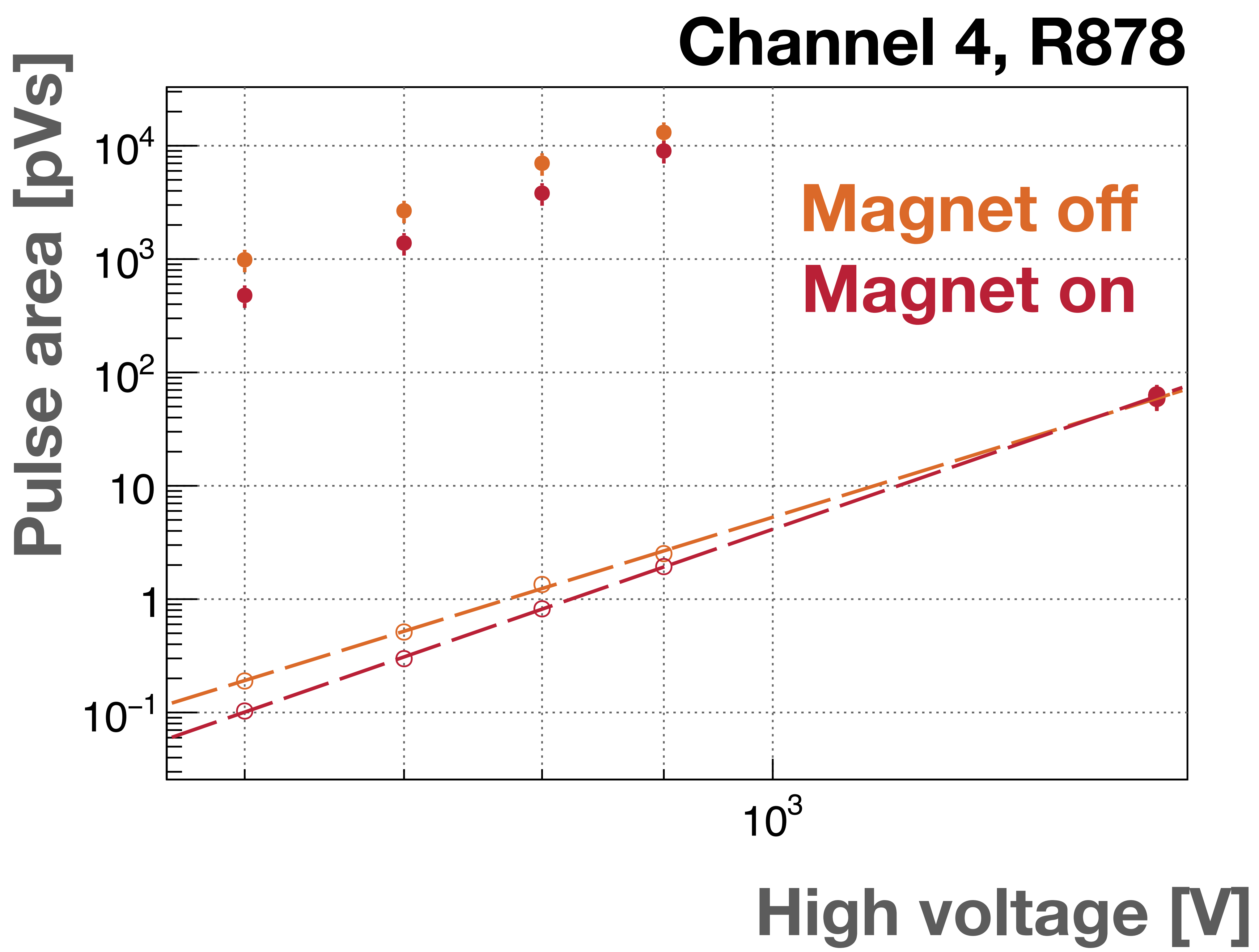


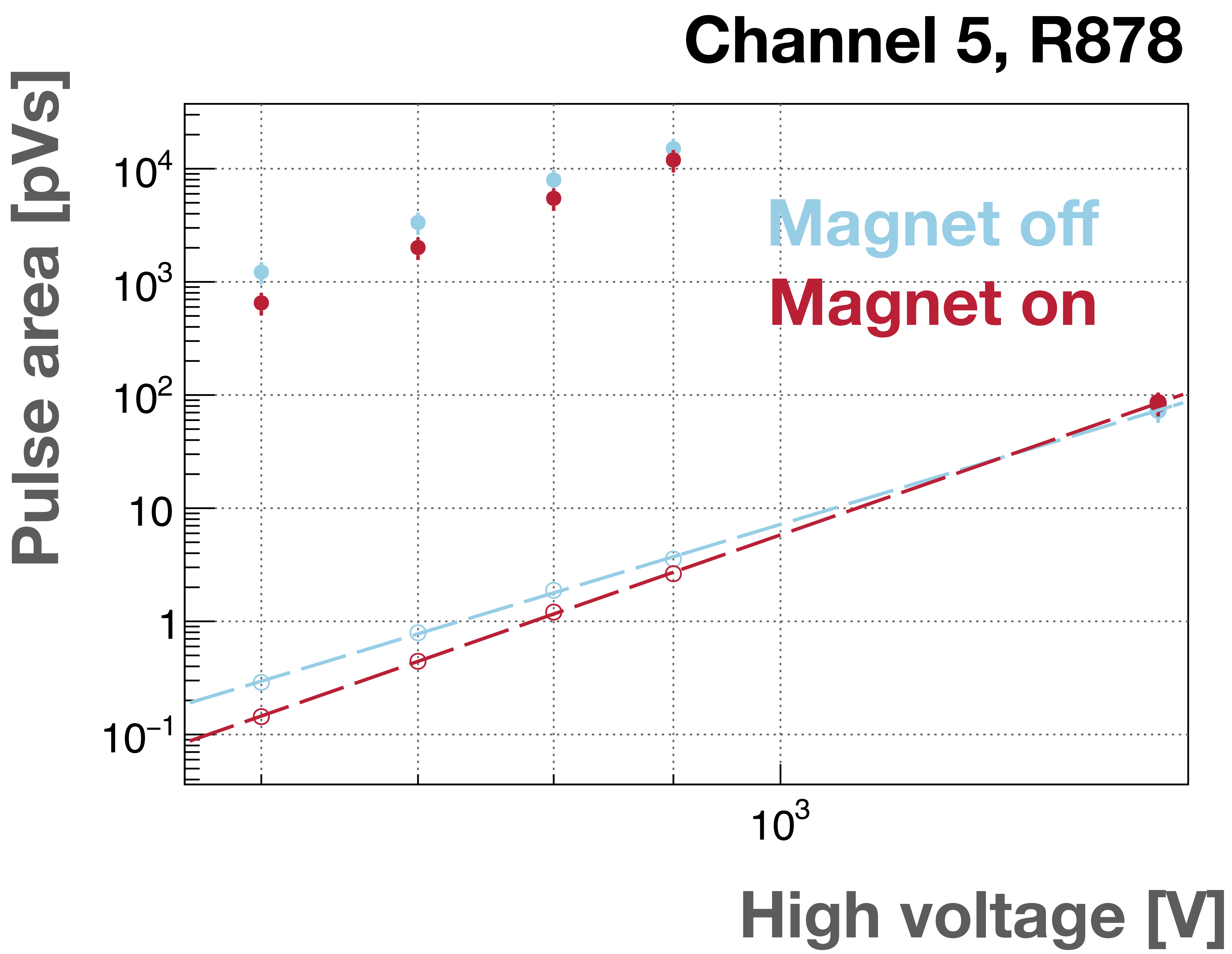


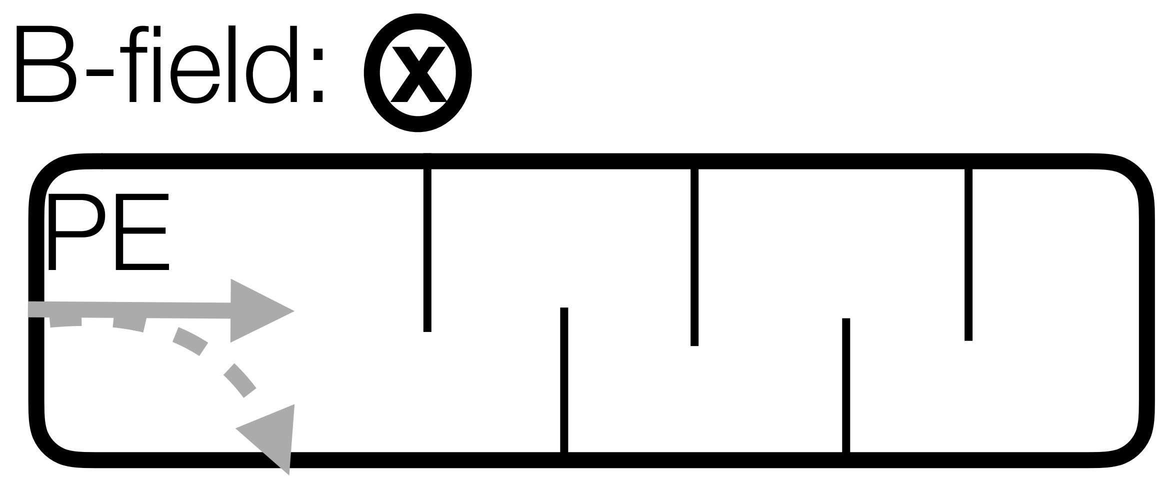
Magnetic field and trigger rate



Cosmic monitoring before/after

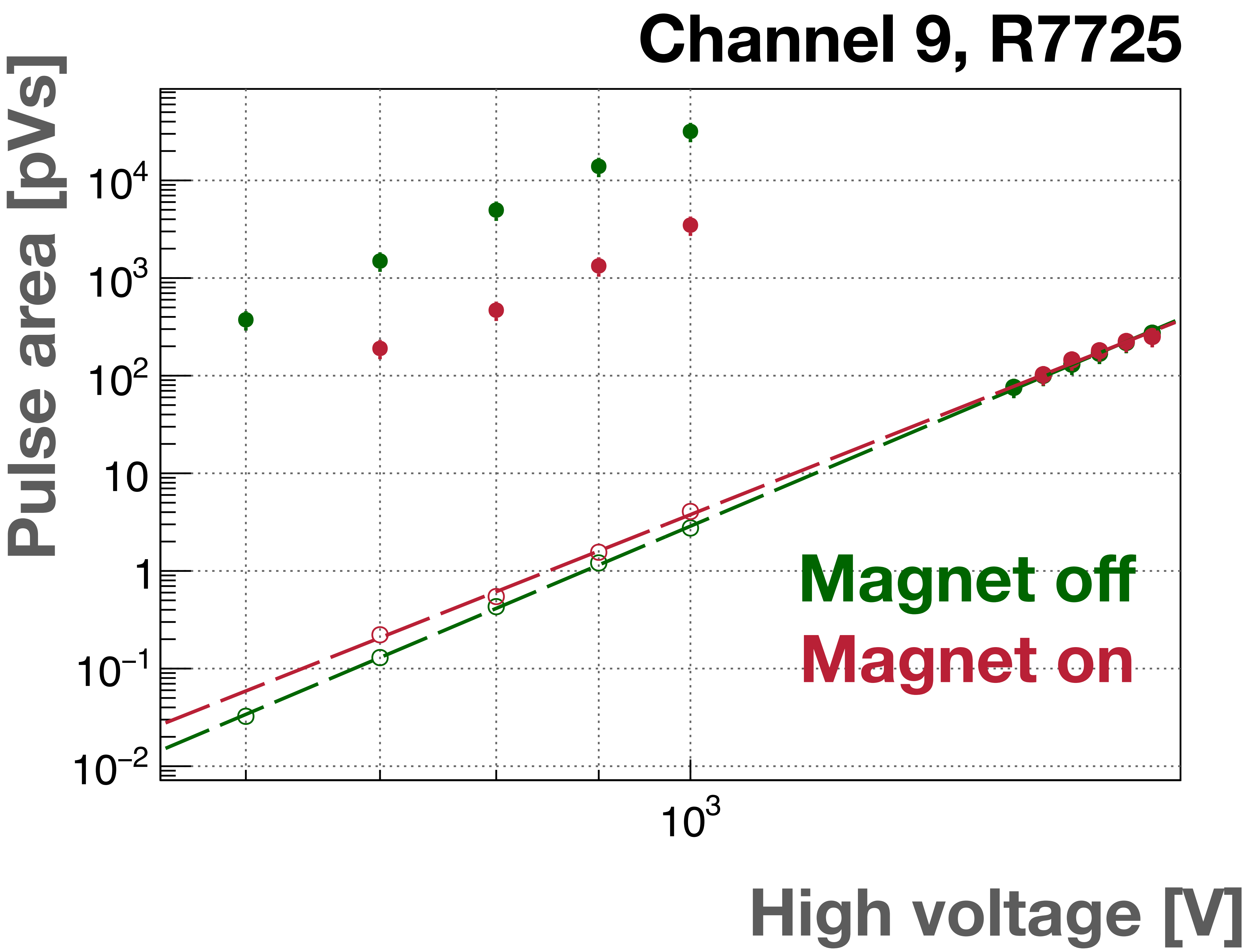


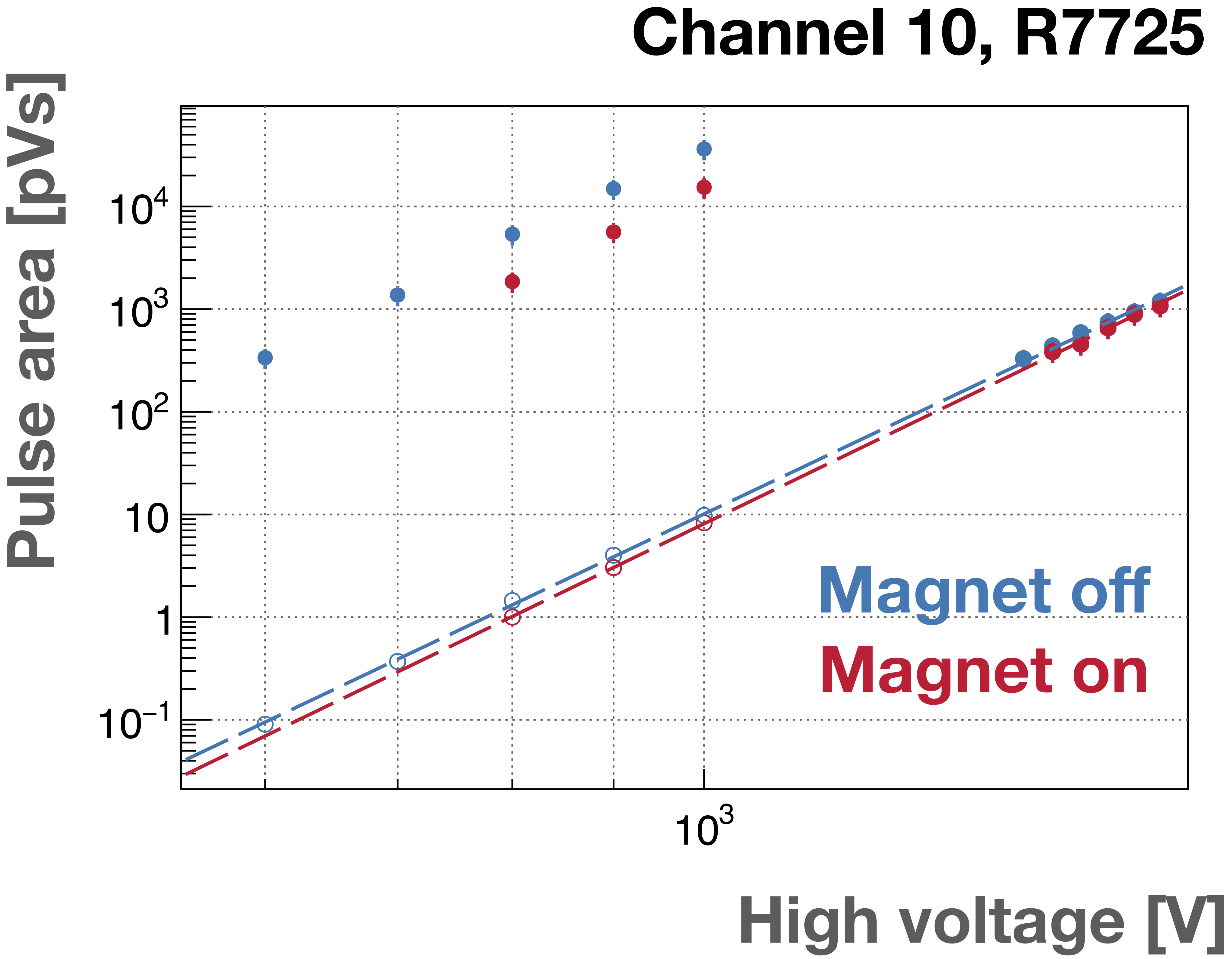




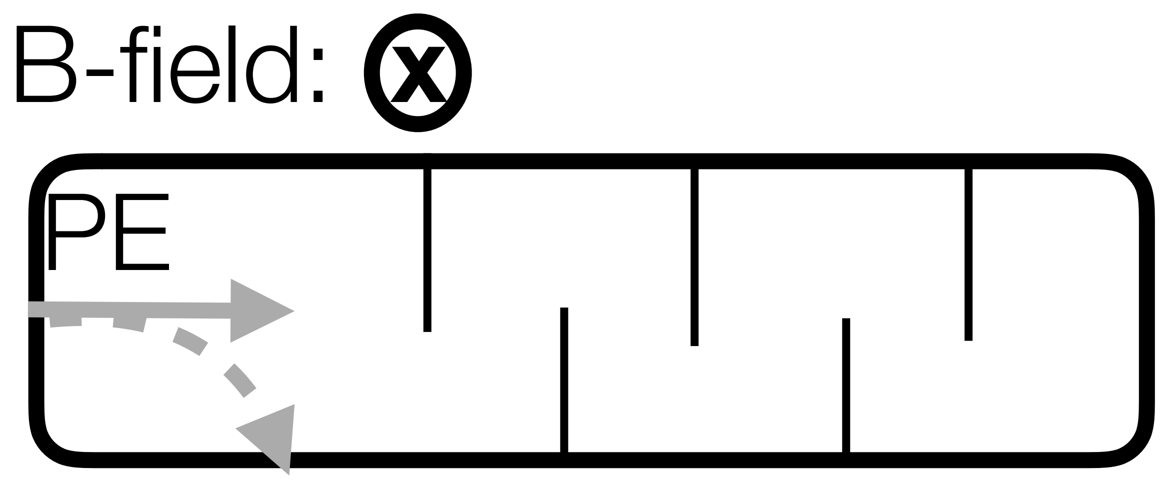
Residual magnetic field reduced collection efficiency!
SPE charge unaffected

High gain R7725s in B-field

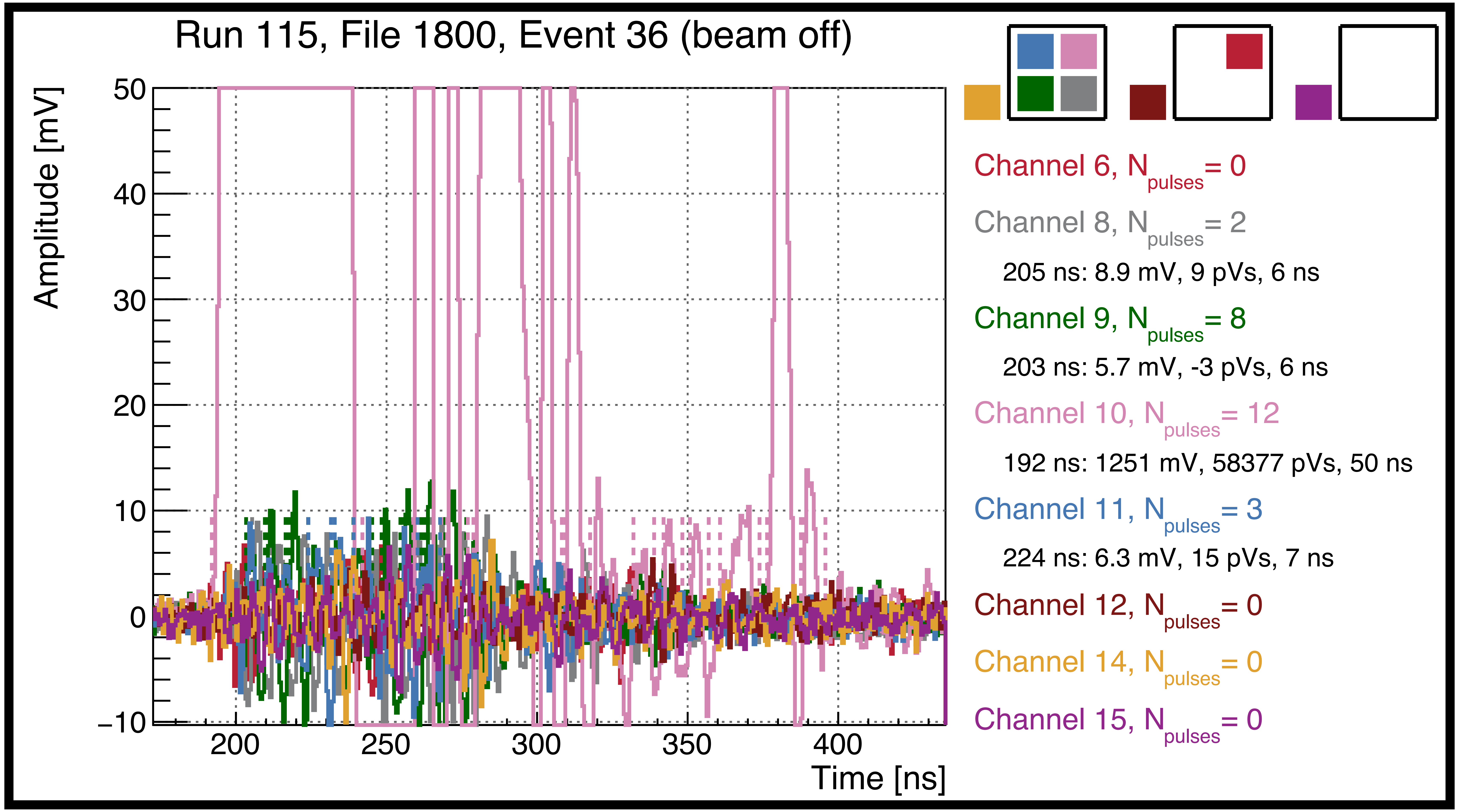




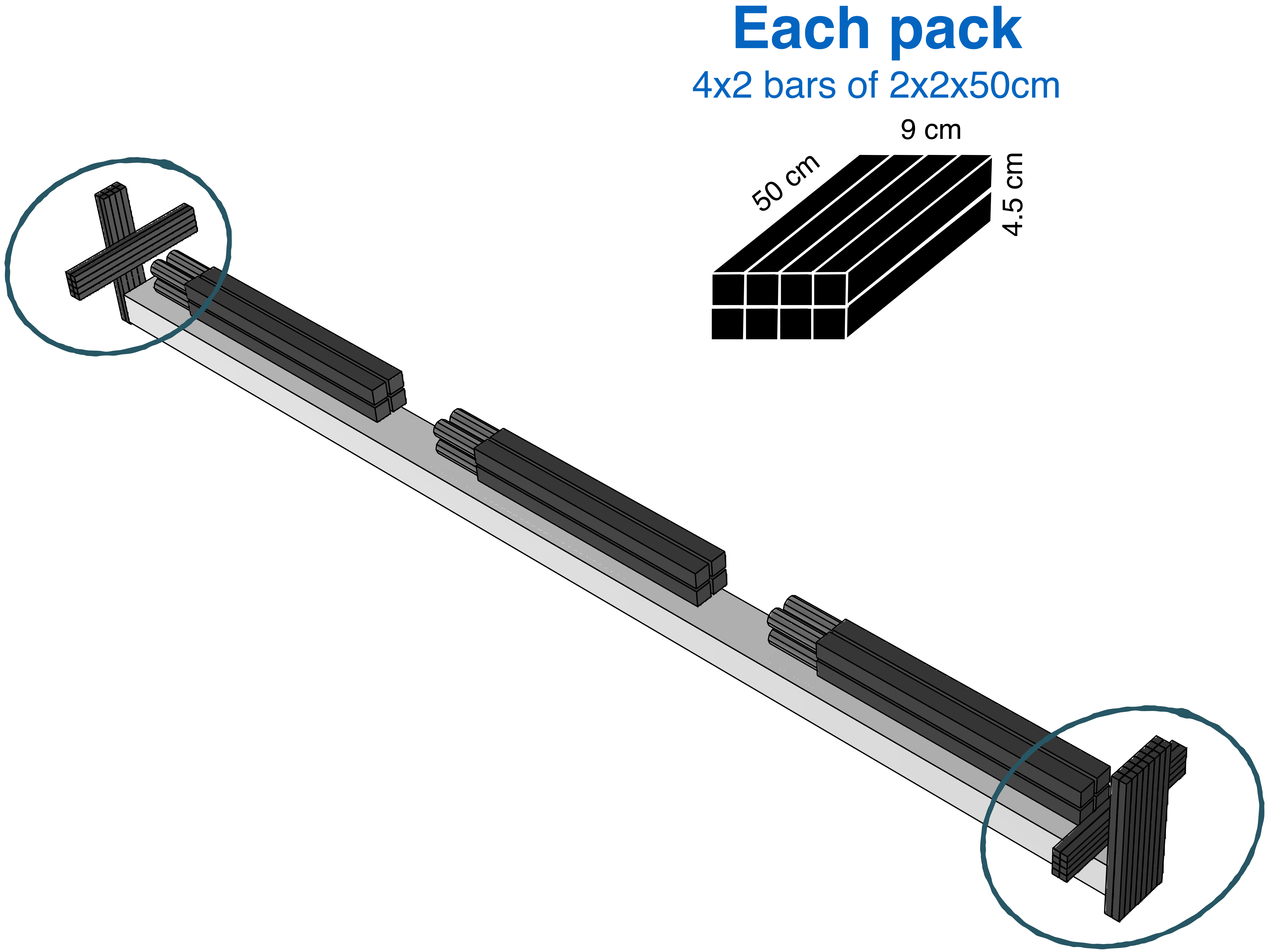
Much more dramatic effect in R7725s



Noise triggers from huge pulses

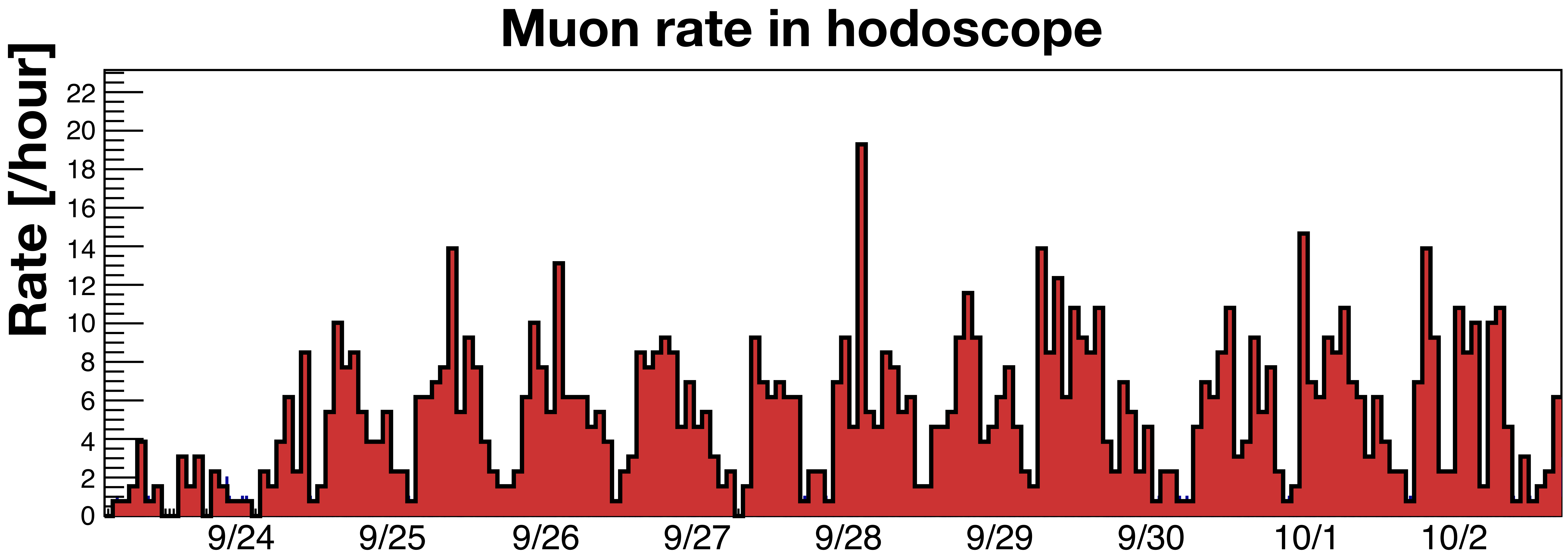


Hodoscope

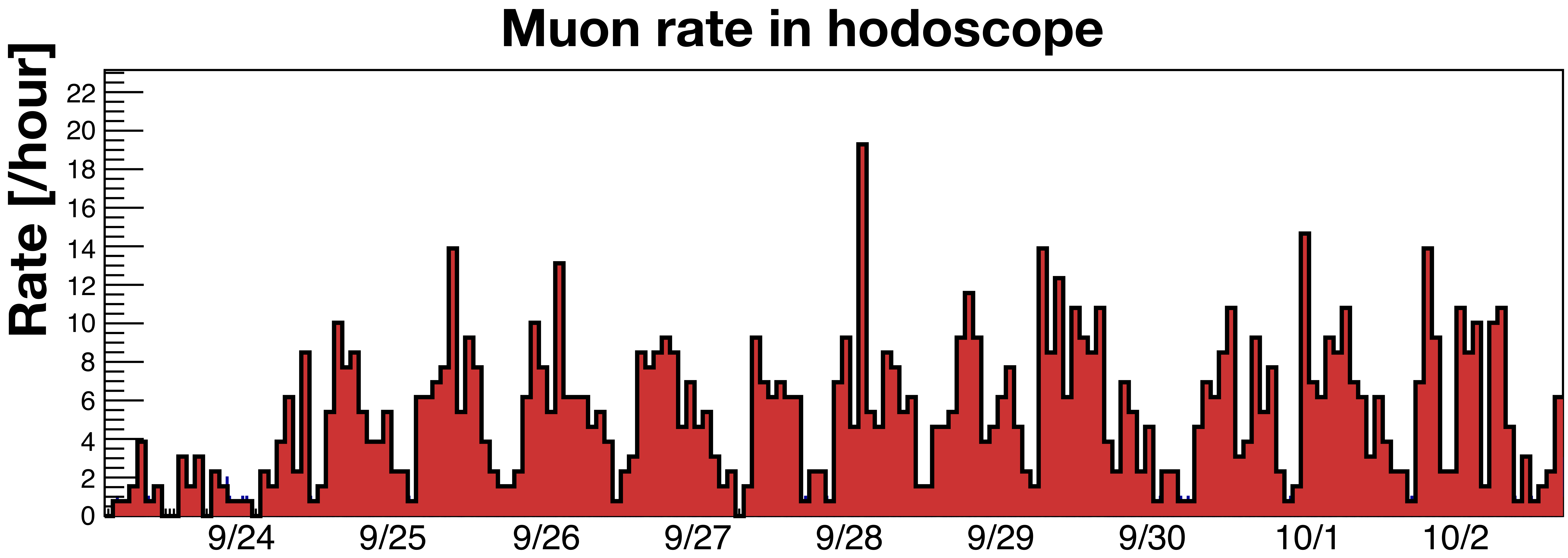


- Tracking hodoscope: narrow scintillators+ SiPMs
- Many uses:
  - Alignment check
  - Event characterization (identify showers)
  - Active veto

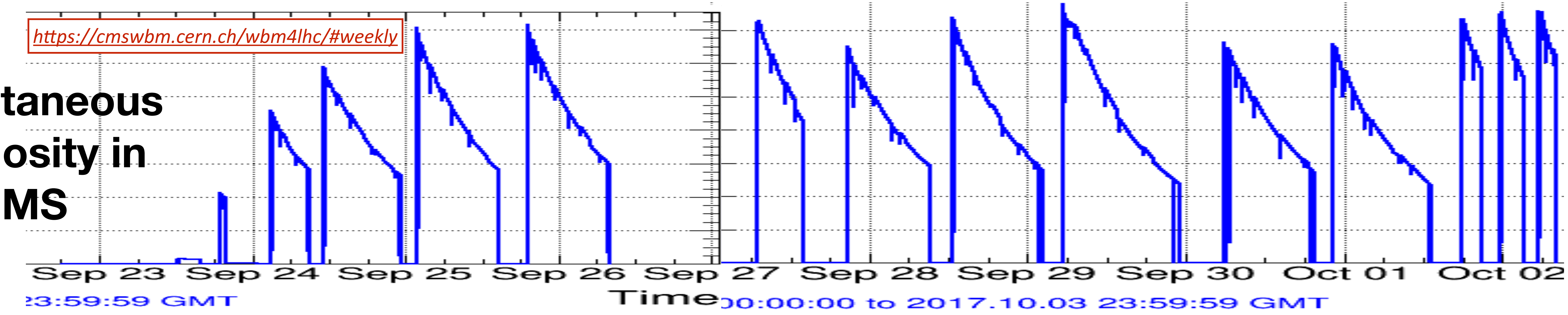
Muons in hodoscope



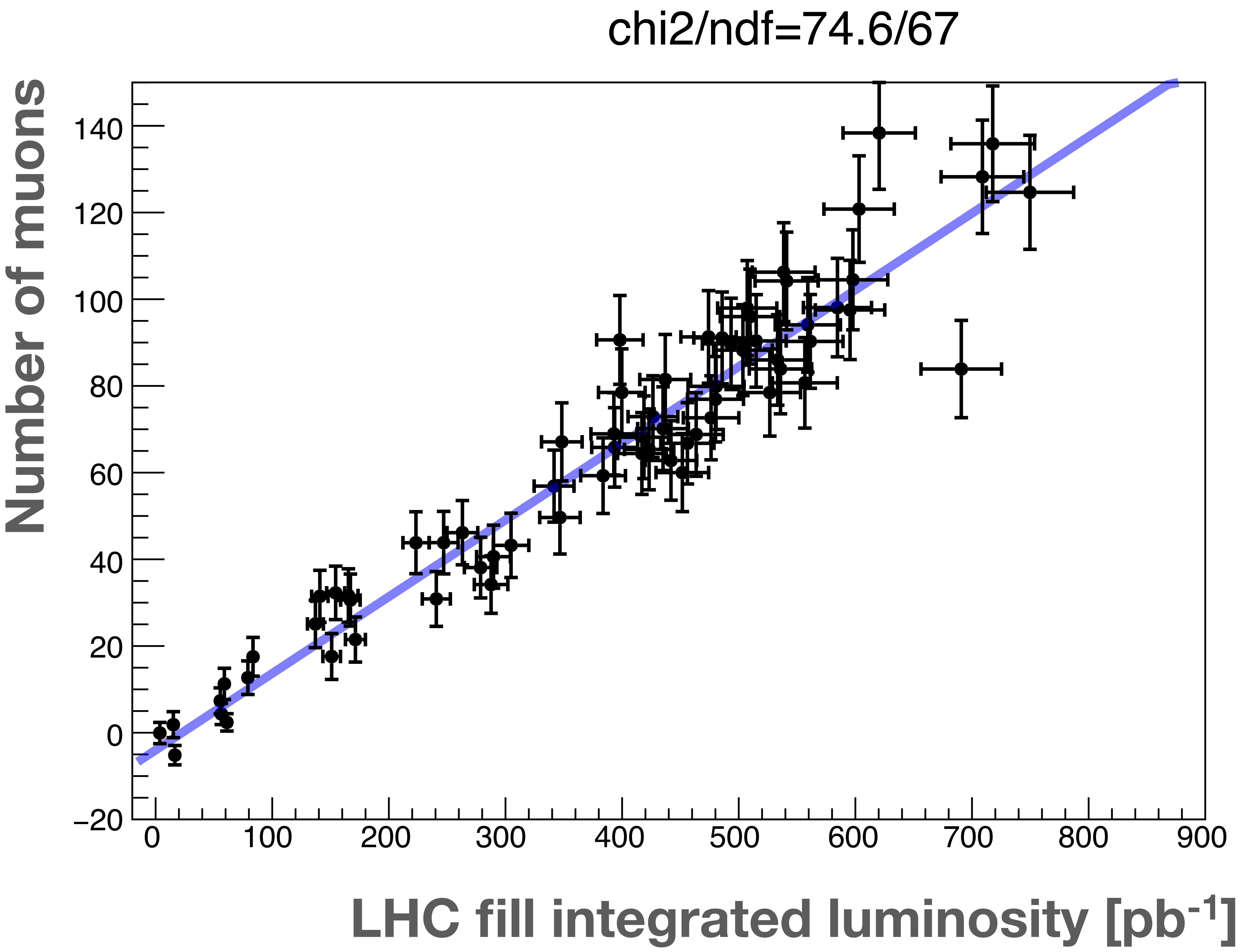
Hodoscope: backup luminometer



Instantaneous luminosity in CMS

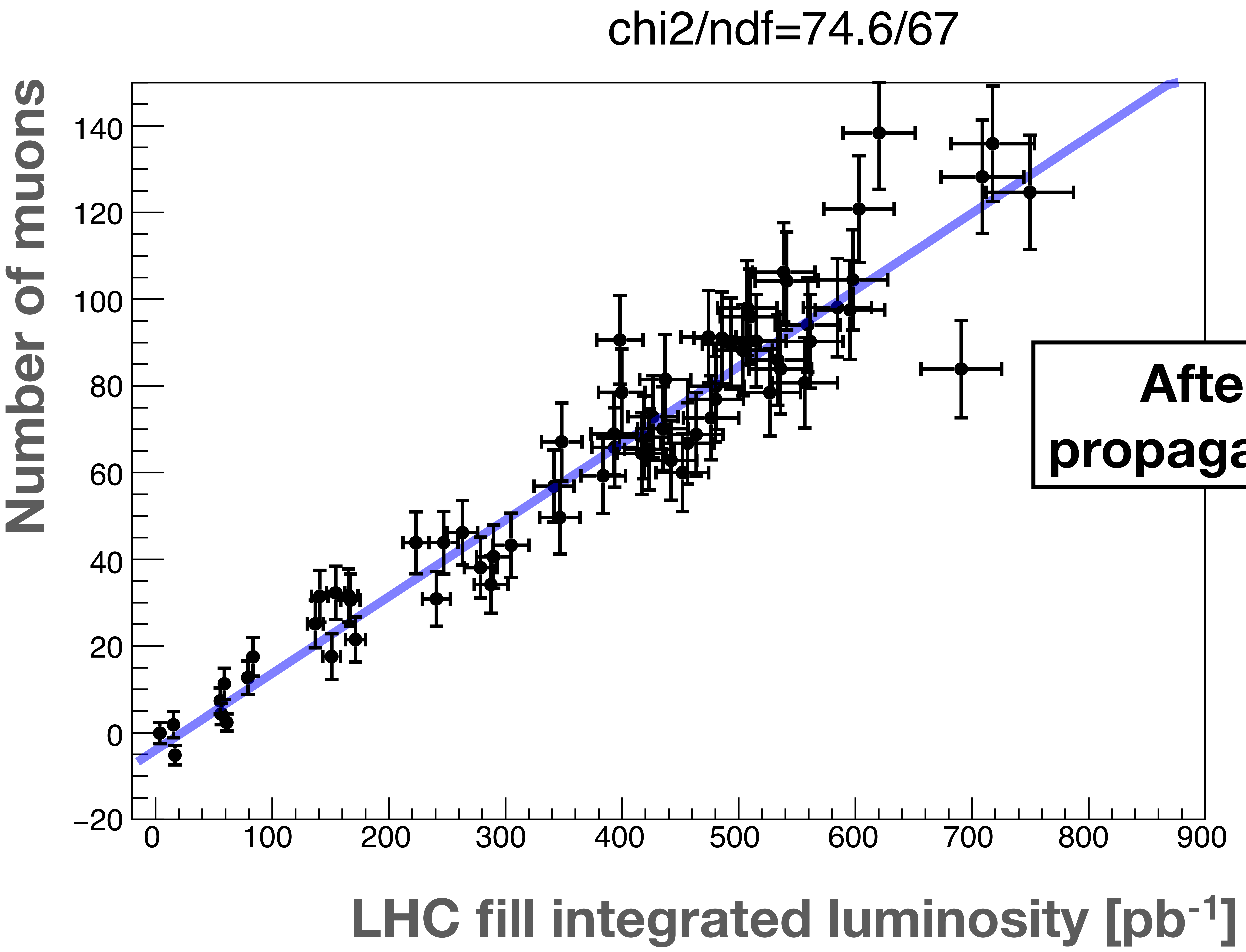


Measure hodoscope muon rate

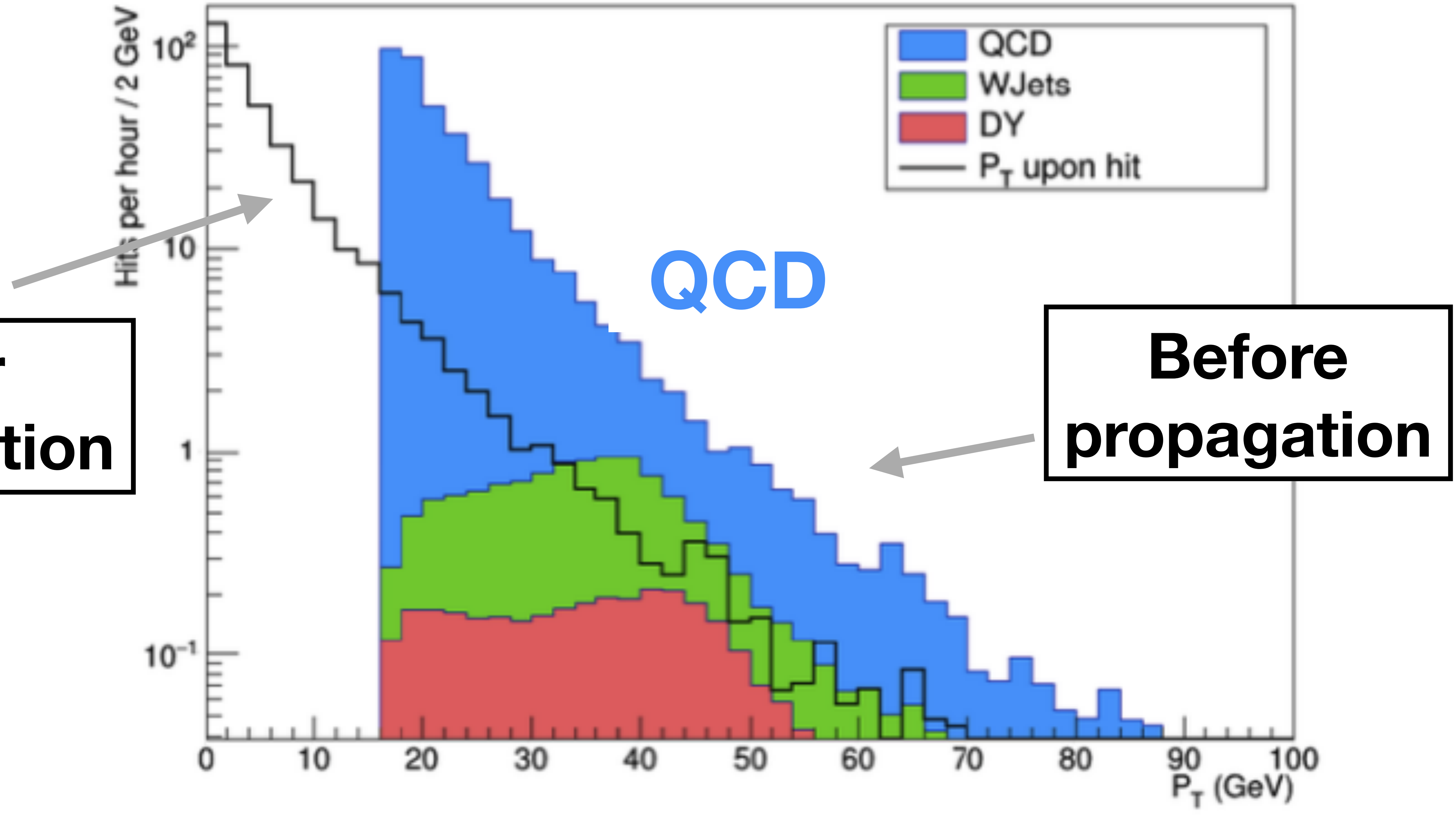


- Plot N_{muons} vs luminosity for each fill
- Extract rate: **0.18 muons / pb^{-1}**

Measure hodoscope muon rate



Simulate propagation of muons from CMS

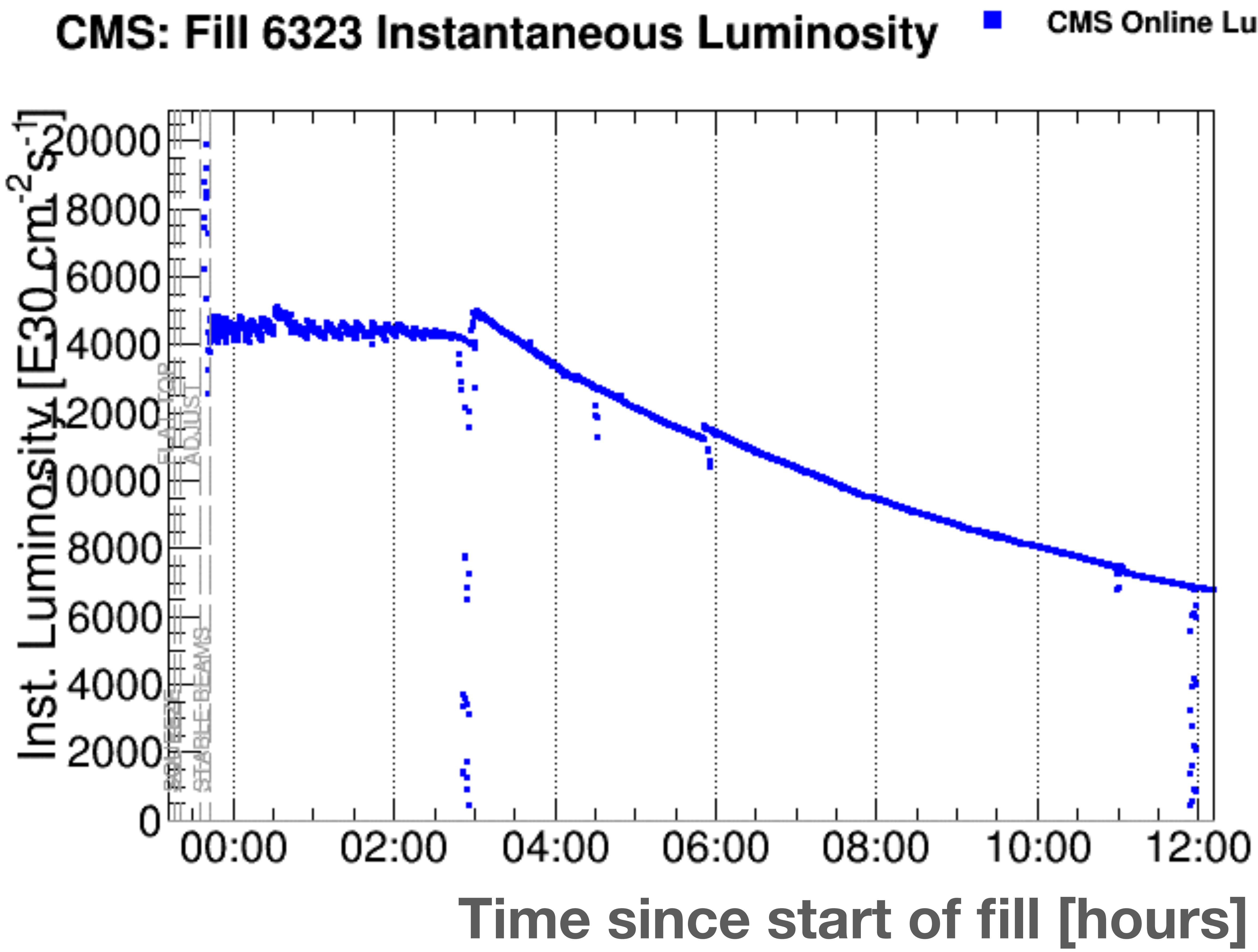


After propagation

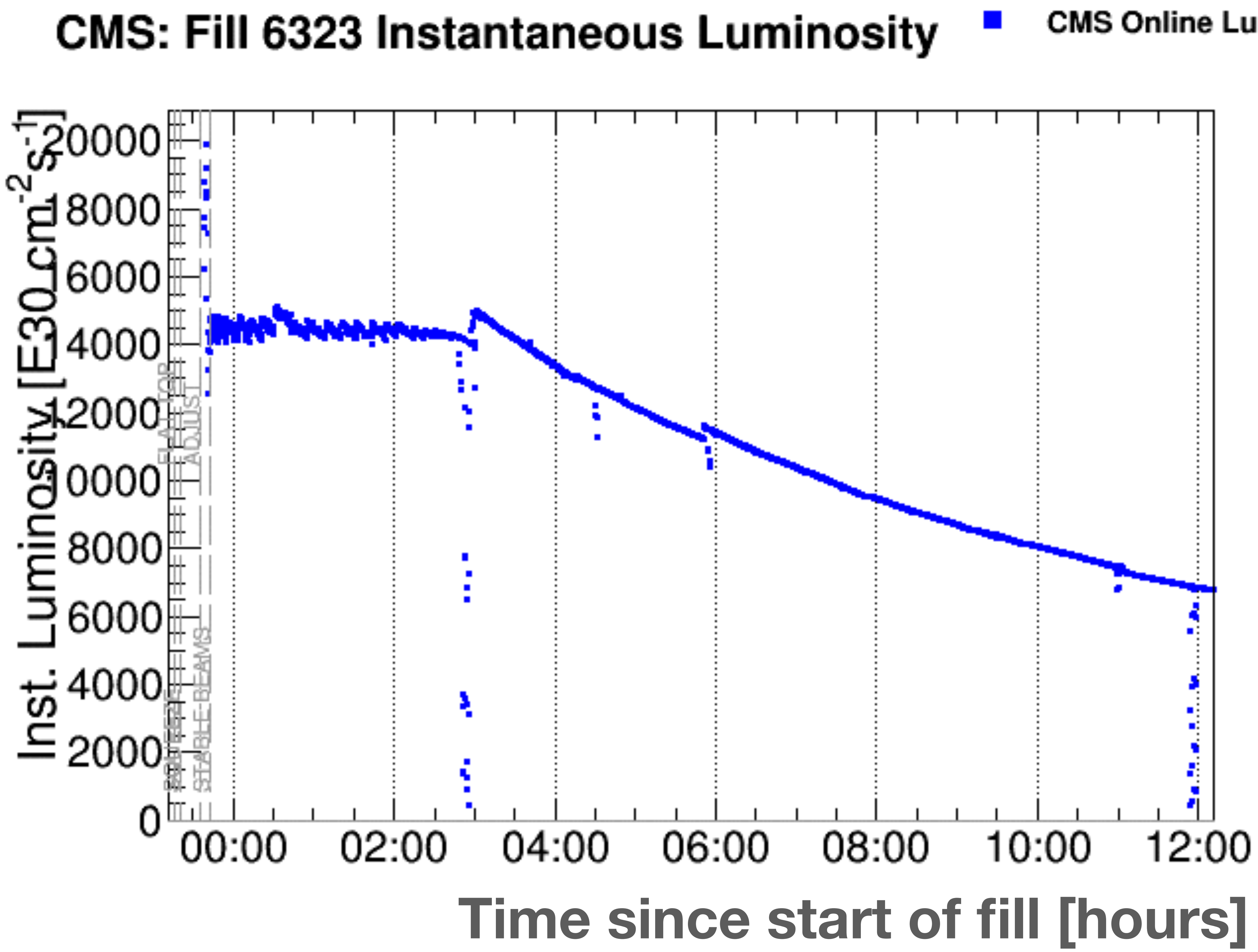
Before propagation

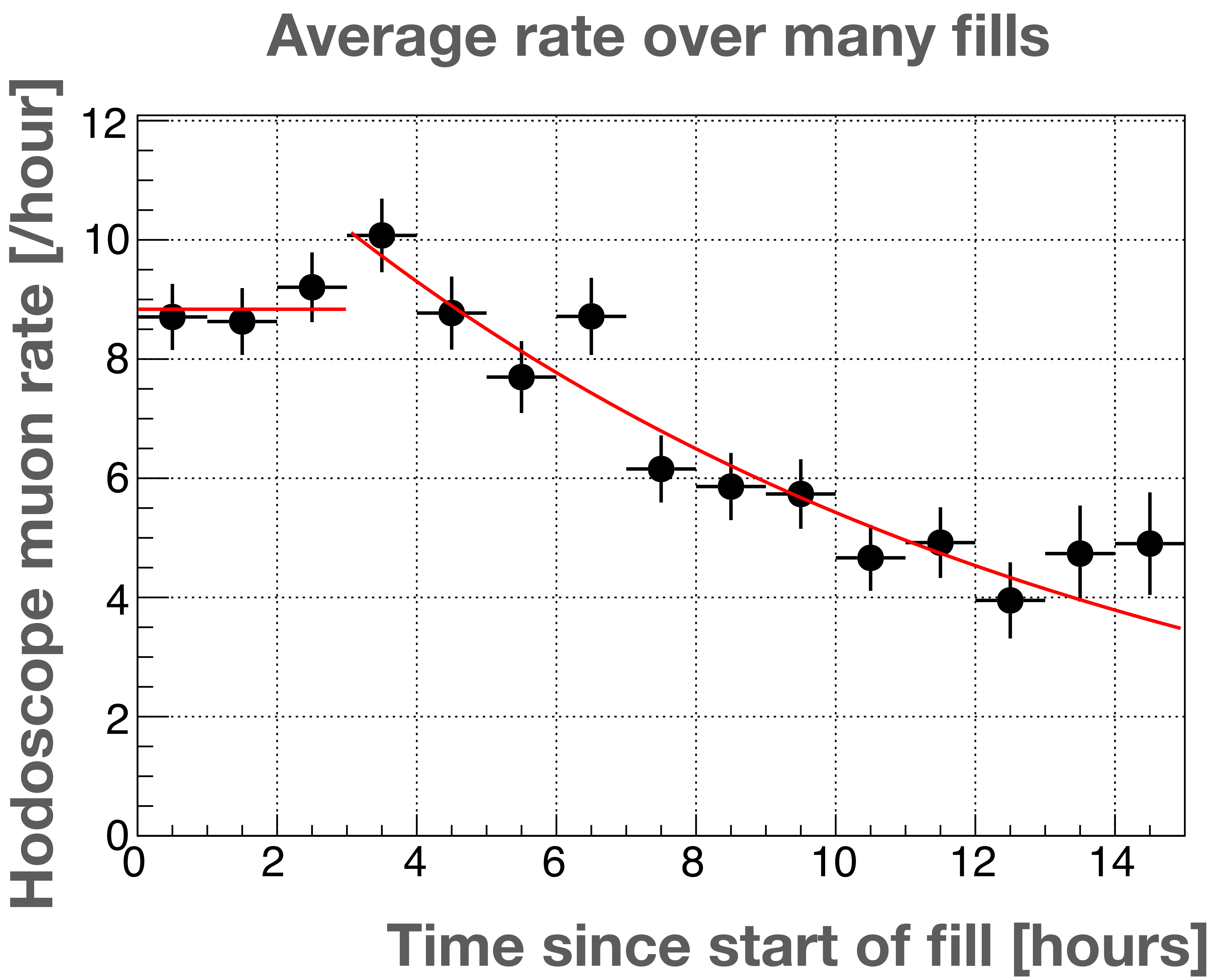
- Measured rate: **0.18 / pb^{-1}**
- Expected rate: **0.22 / pb^{-1}**

Luminosity leveling

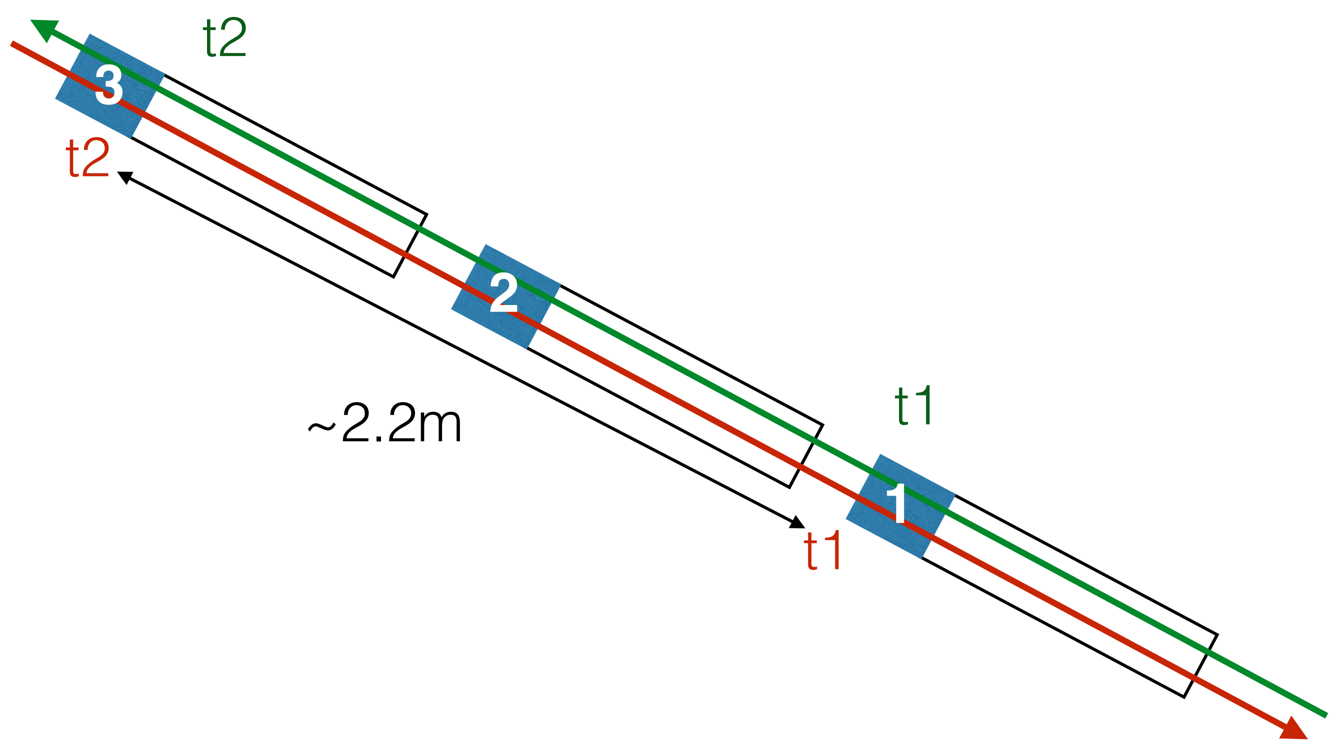


Luminosity leveling



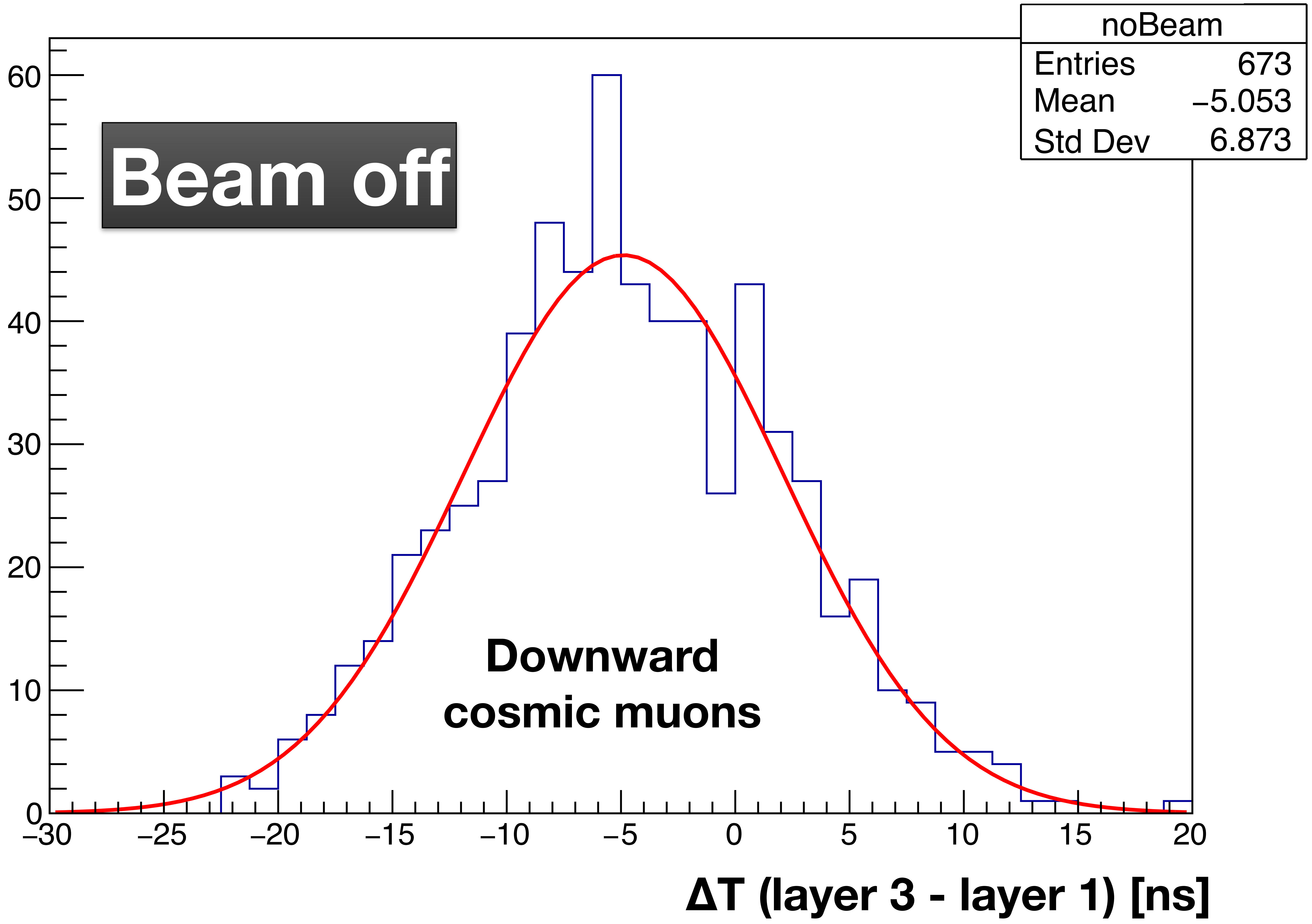


Discovering the beam

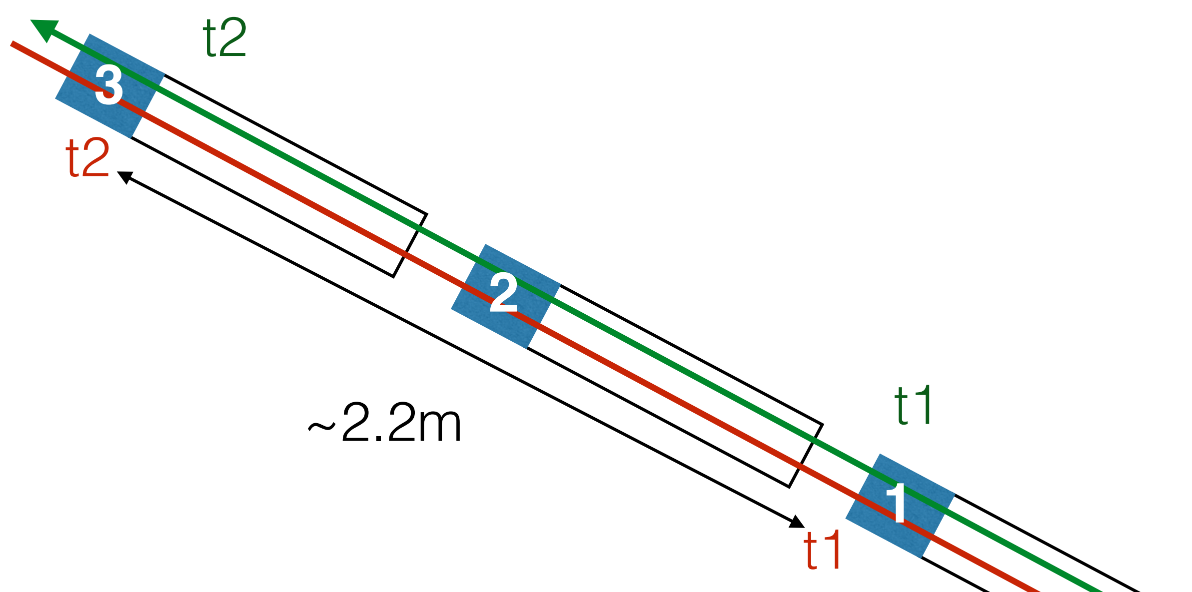


2.2 m path length between layer 1 and 3

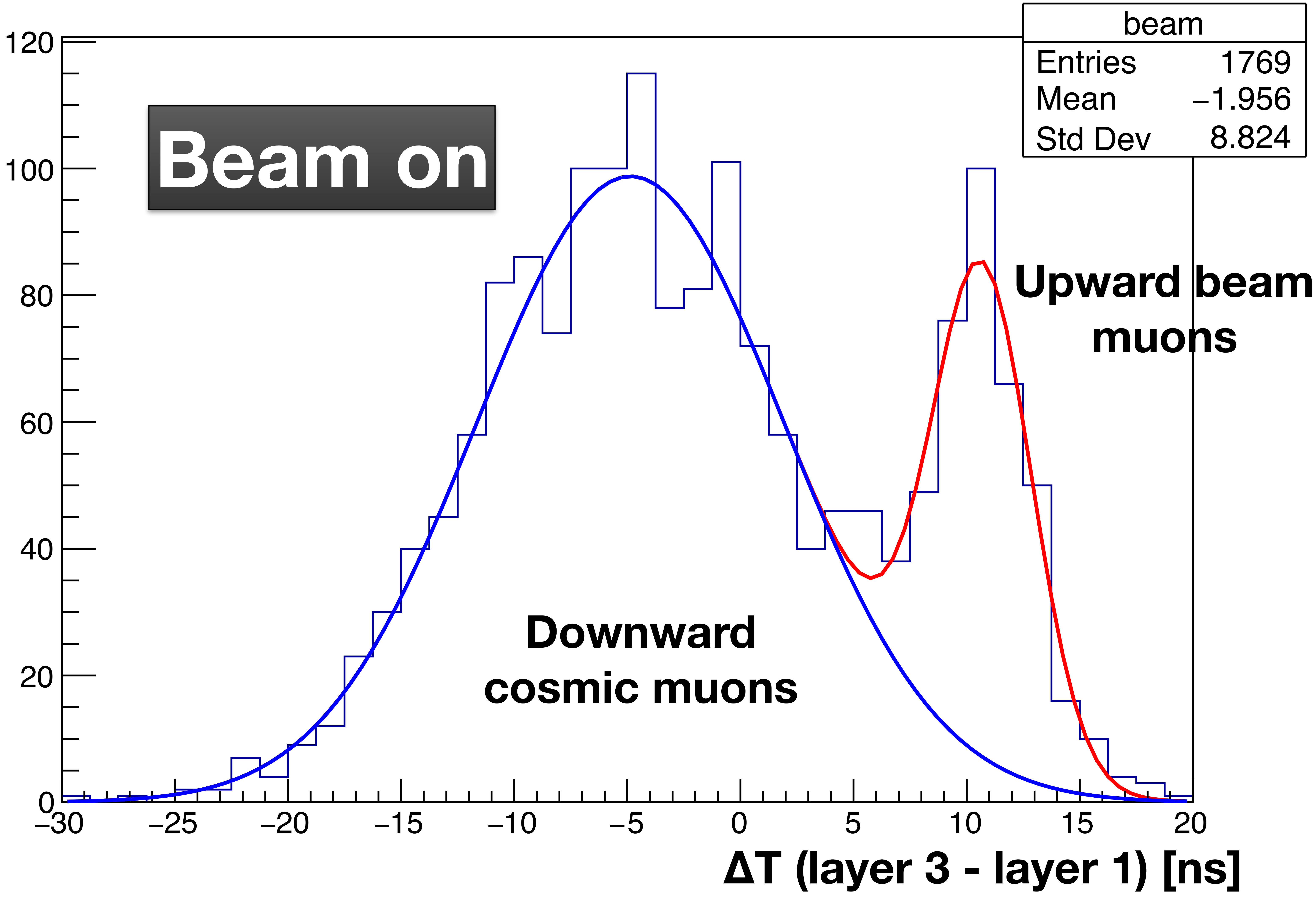
Expected time difference between upward and downgoing muons: 2.2 m x 2 / 0.3 m/ns = 15 ns



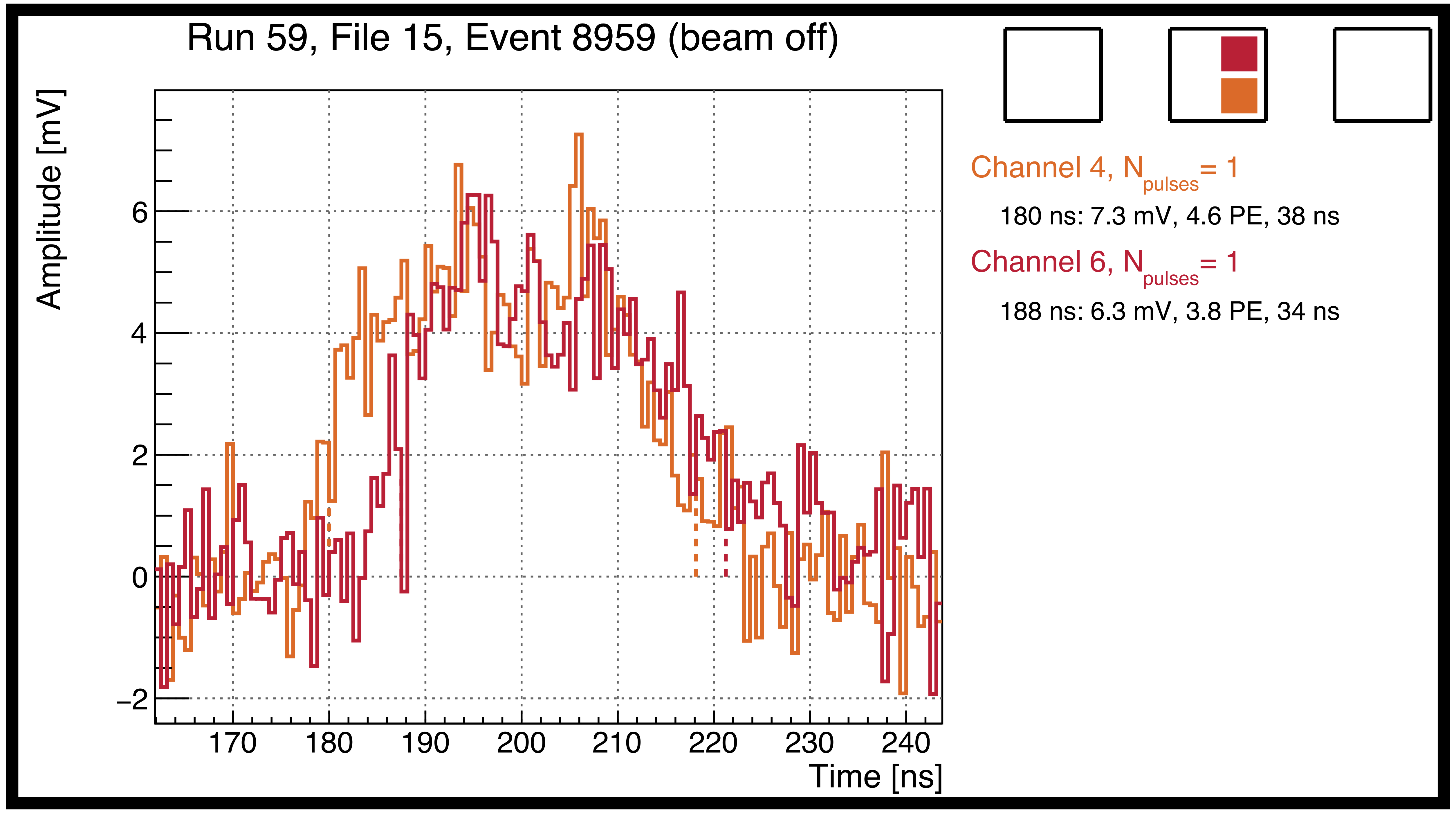
Discovering the beam

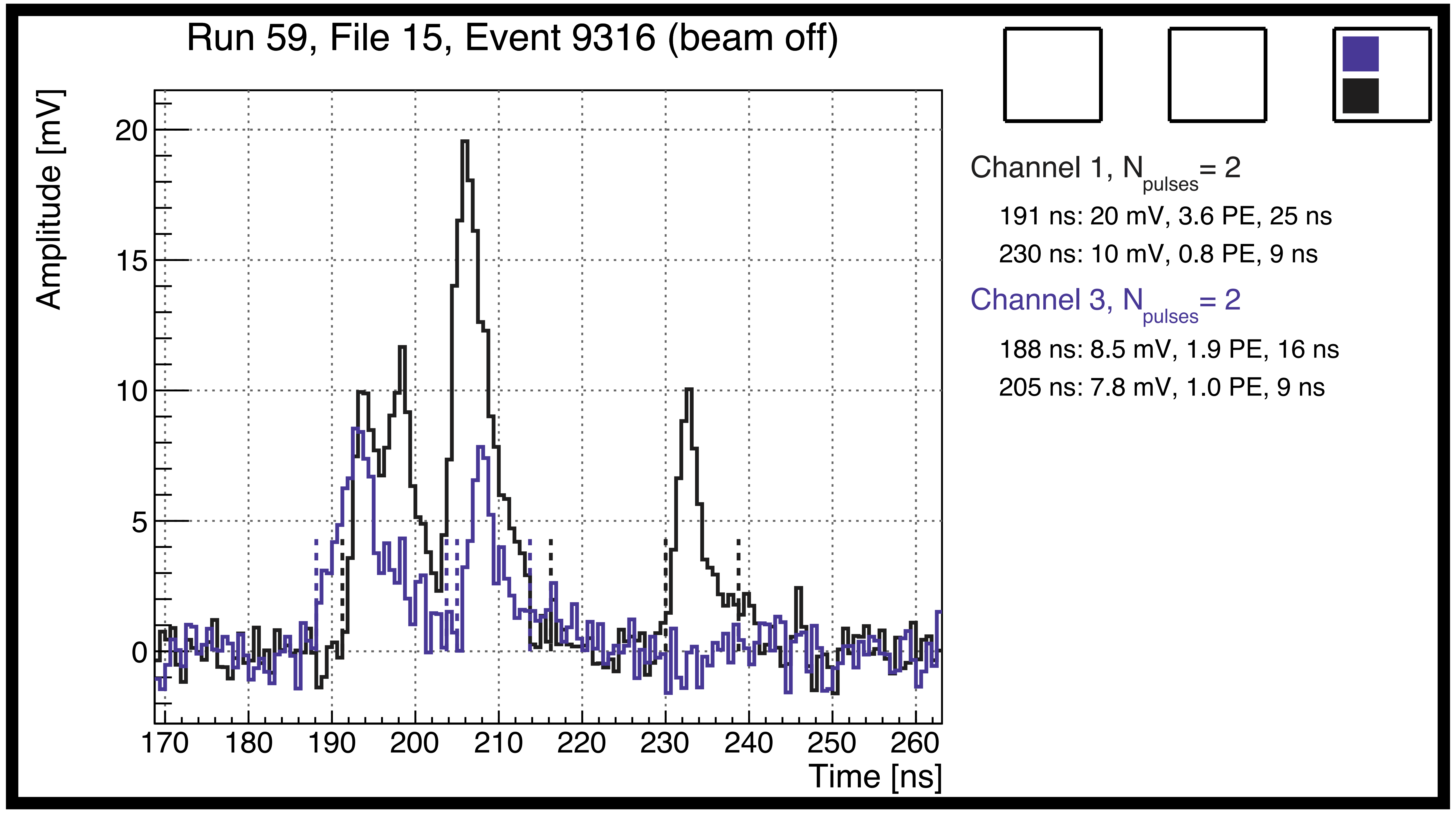


Time difference for beam muons is 15 ns!



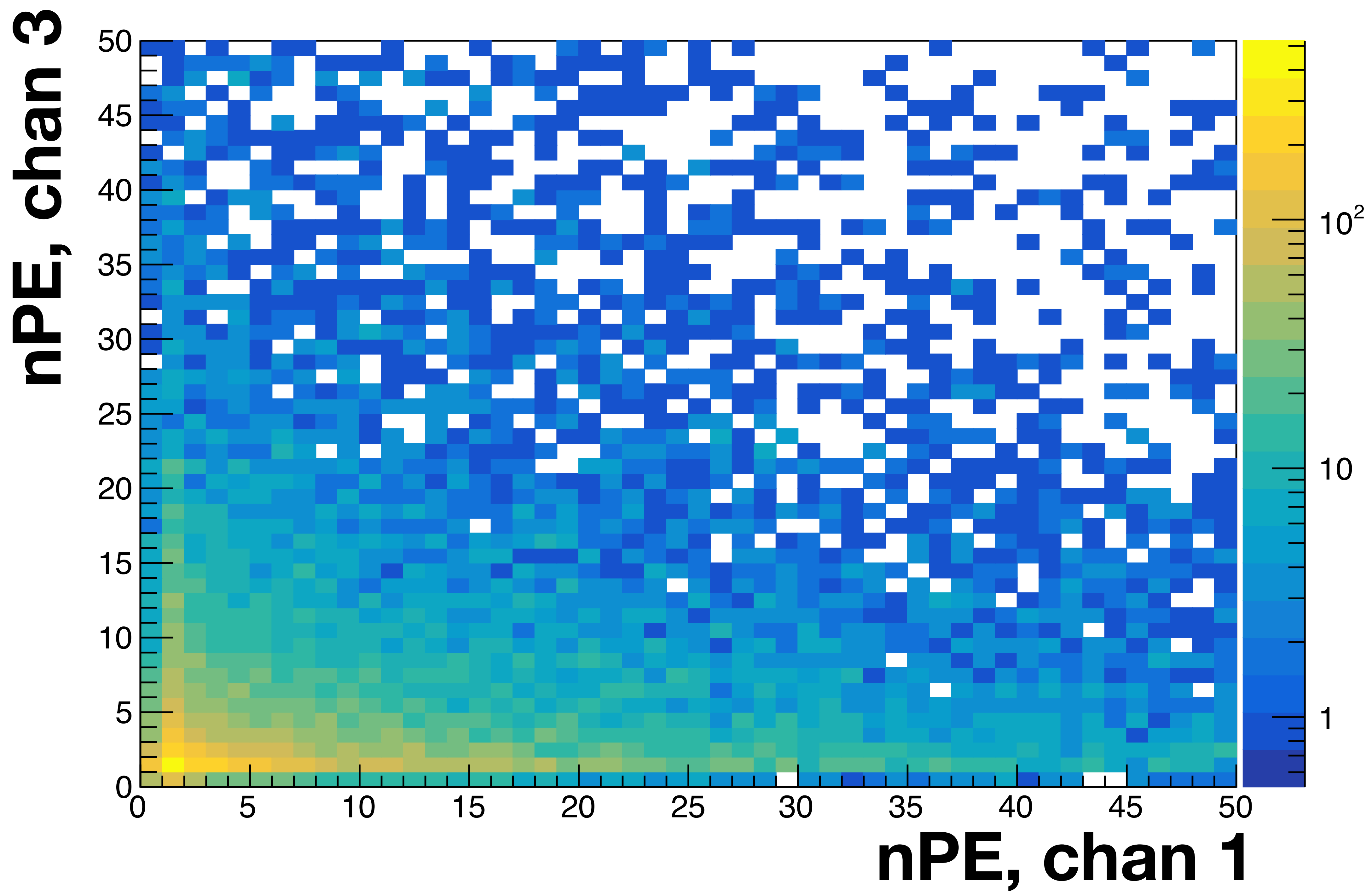
Radioactive background

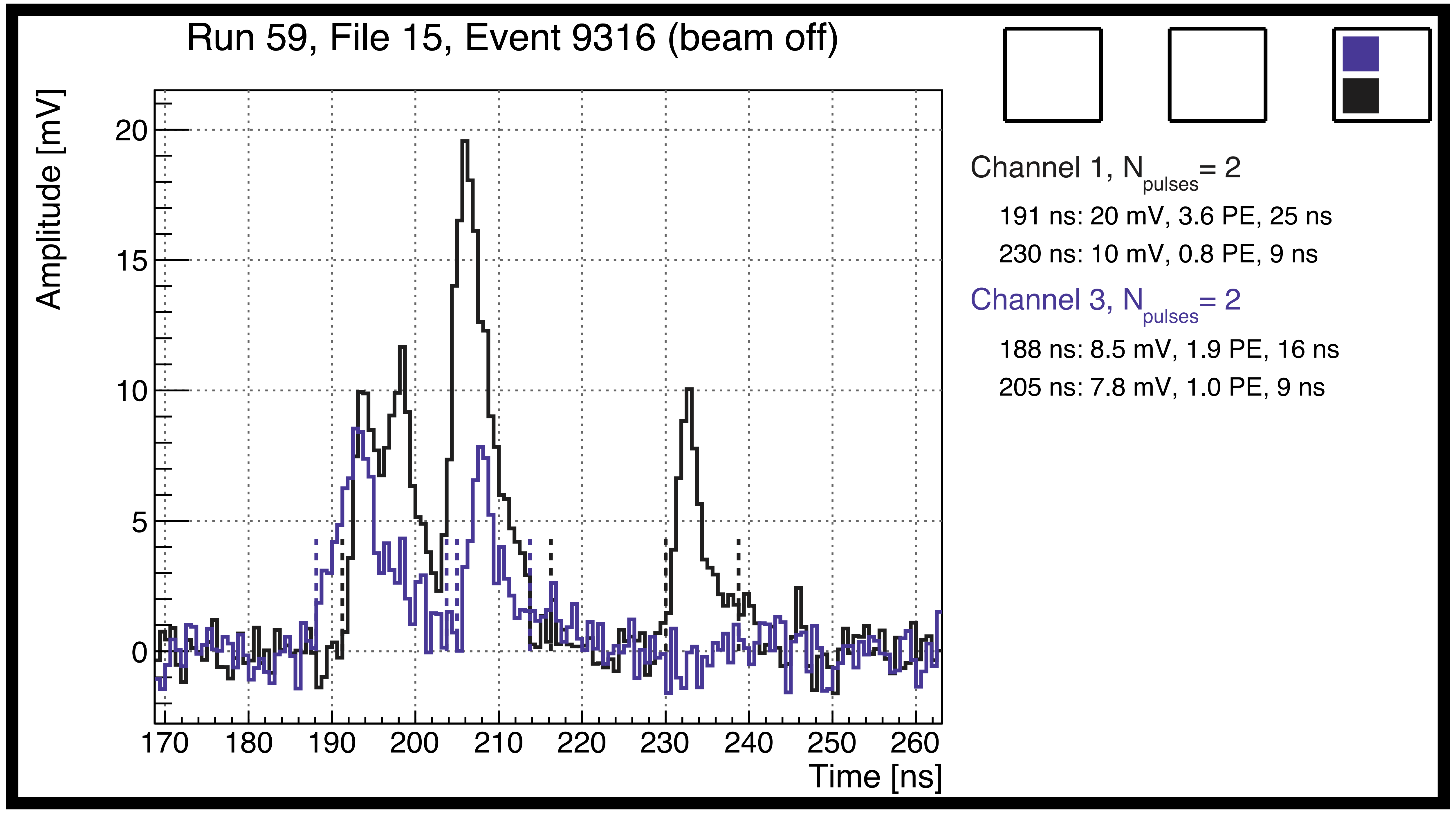




Radioactive background

Fill with largest pulse from each channel

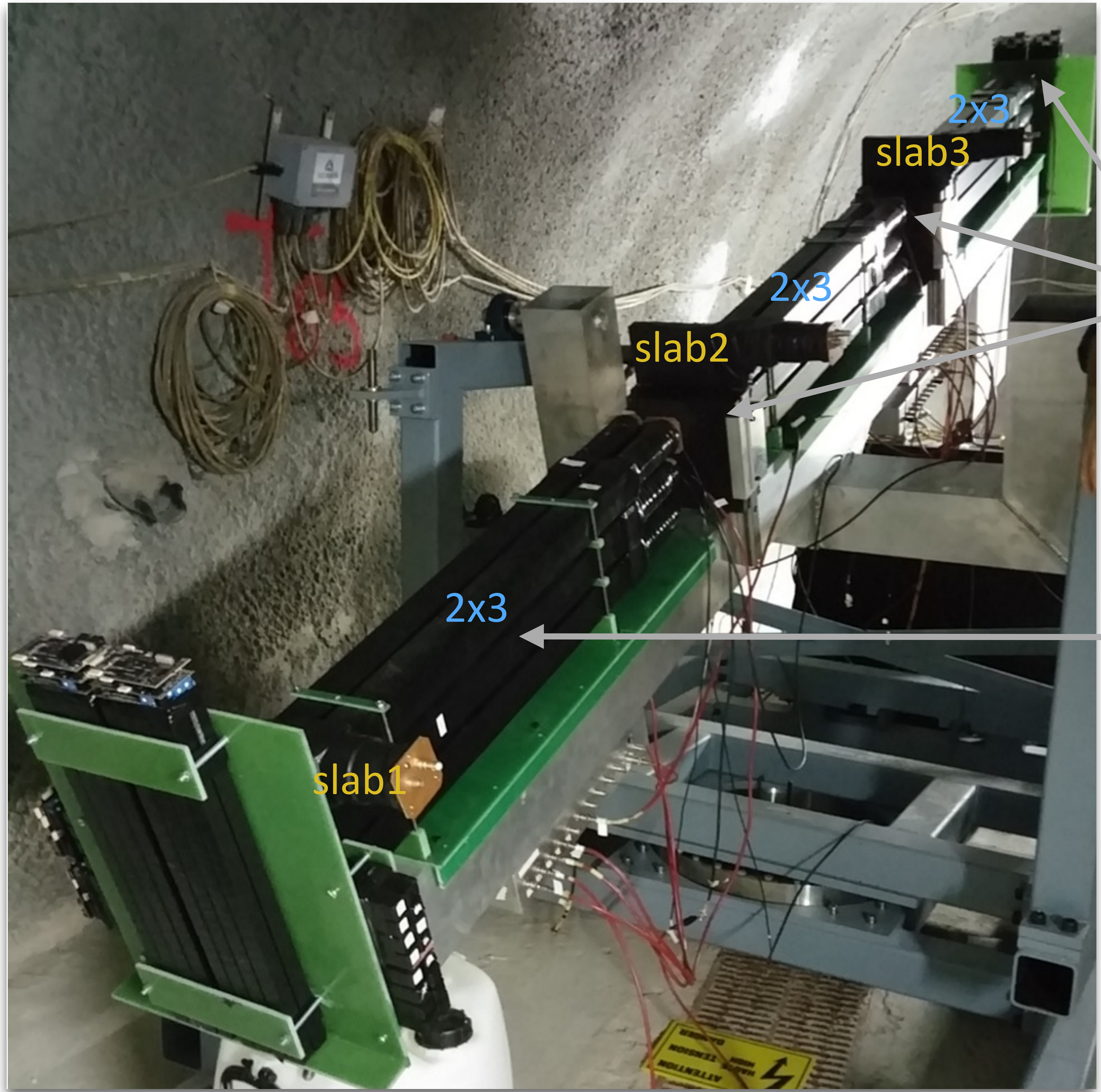



Run 59, File 15, Event 9316 (beam off)

Coincidence peaks at 1 photon, tail to 25+
Adjacent bar coincidence rate is 50-100 Hz!

Layer crossing is very rare, but likely a major contribution to milli-charge background

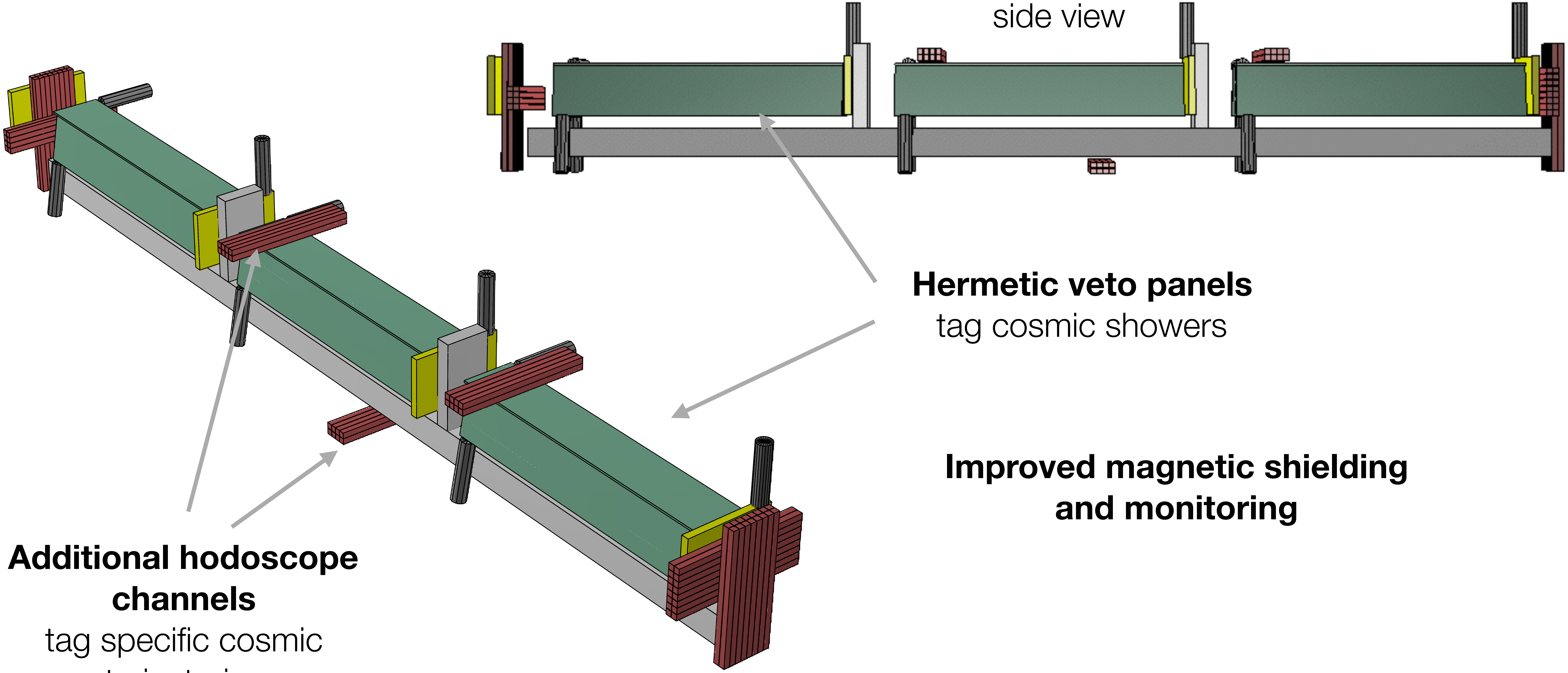
Prototype upgrades



Active shielding slabs:
neutron moderator
tag radioactivity

Additional channels (1.5% prototype)

Prototype upgrades



Hermetic veto panels
tag cosmic showers

Improved magnetic shielding and monitoring

Additional hodoscope channels
tag specific cosmic trajectories

Other avenues for background reduction

- Correlated radioactivity across layers:
    - Increase lead shielding
- Random coincidence of thermal SPEs:
    - Cooling
    - Add PMT at both ends of bar!
        - Targetting Q ≥ 0.01: use cheaper PMTs
        - Improves time/energy resolution as well

milliQan Collaboration

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Eder Izaguirre

KIT
Karlsruhe Institute of Technology


Ralf Ulrich

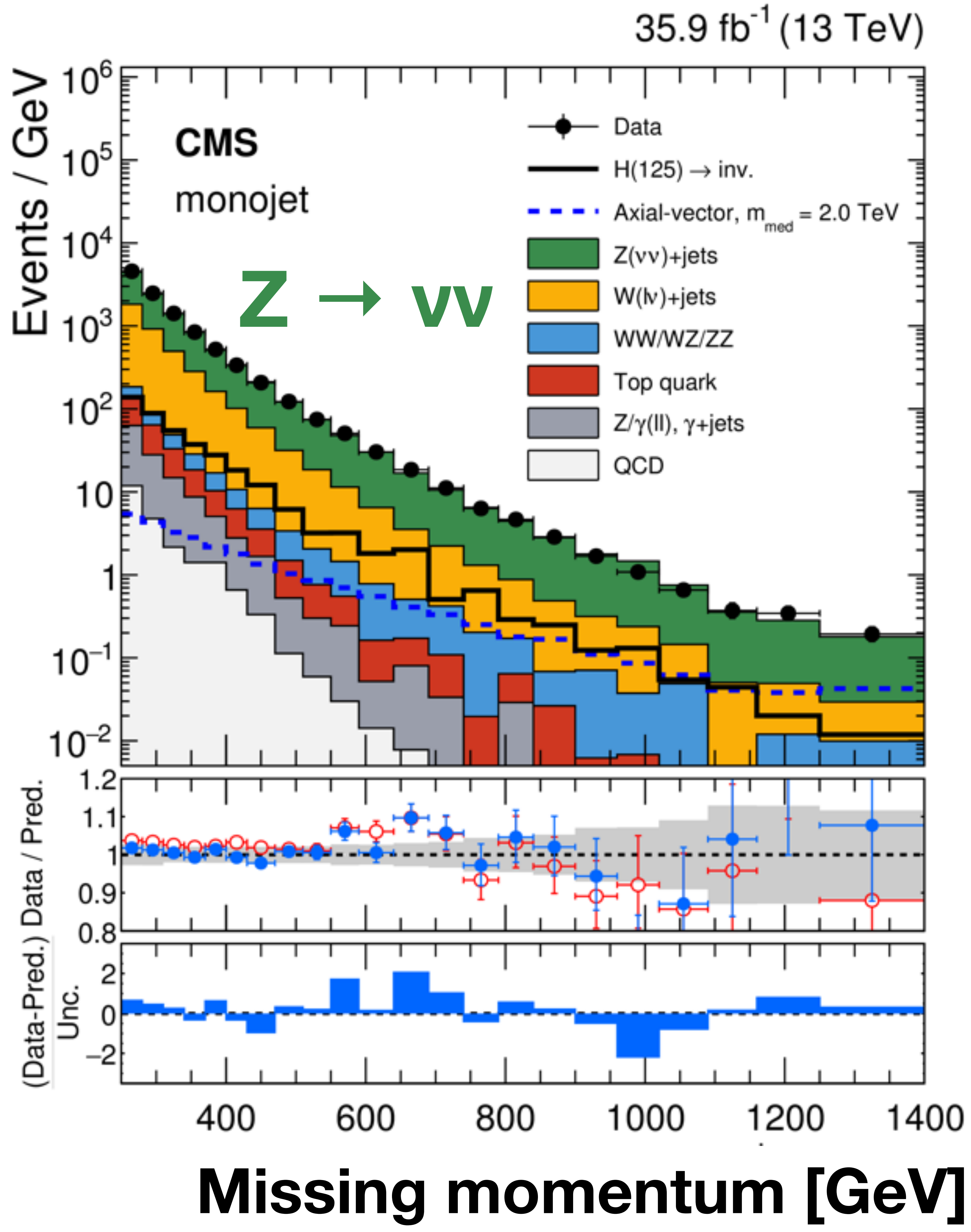
BROOKHAVEN
NATIONAL LABORATORY

Conclusion

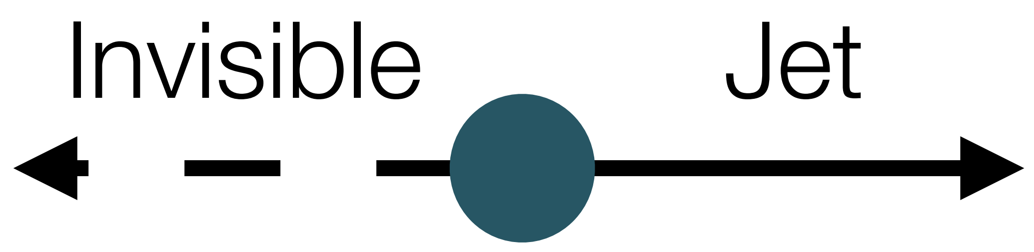
- Very optimistic about first results from prototype
- Learning valuable information about backgrounds and operation of detector
- Many interesting ideas to explore for the full experiment!

Backup

Prospects for general-purpose detector search



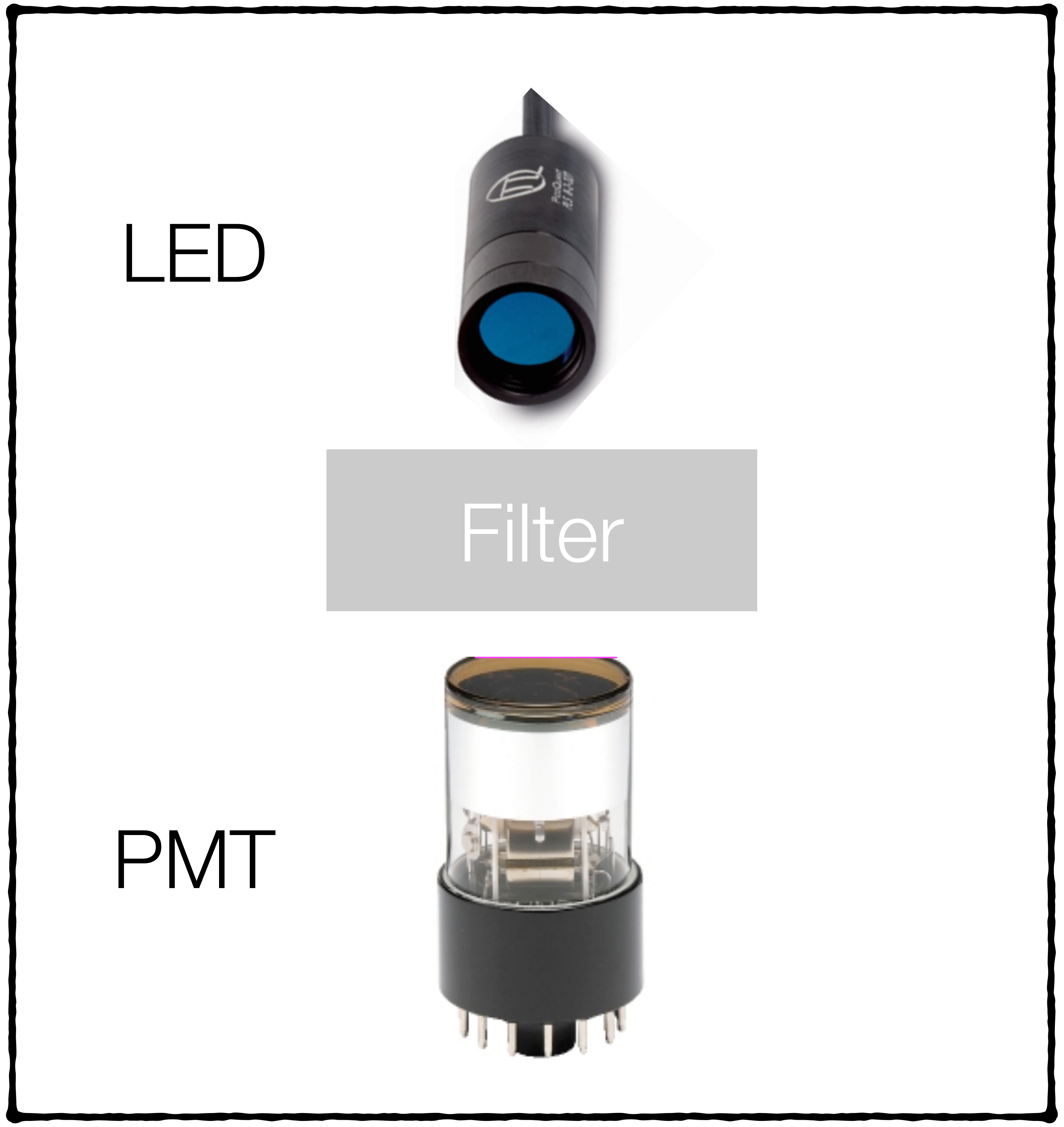
- Less than Q/e = 0.1: invisible to CMS/ATLAS
- Classic dark matter search: look for unbalanced momentum from hadronic recoil



- Key problem: huge background from Z → νν
- millicharge S/B ~ 1/1000, and σ(B) ~ 10%
- **Unlikely to see sensitivity at traditional LHC experiments**

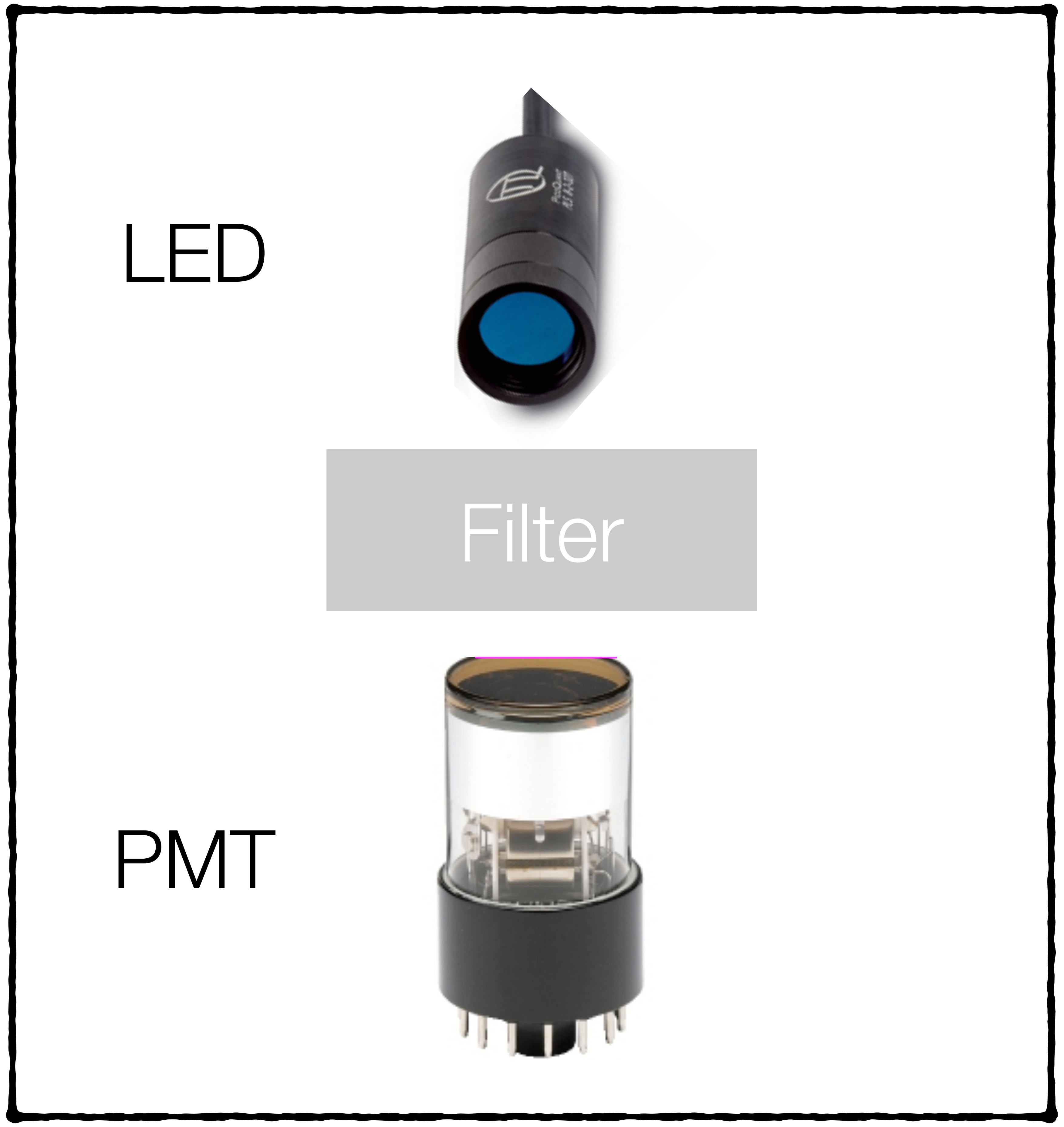
Further PMT bench studies

- Planning SPE measurement with dim LED

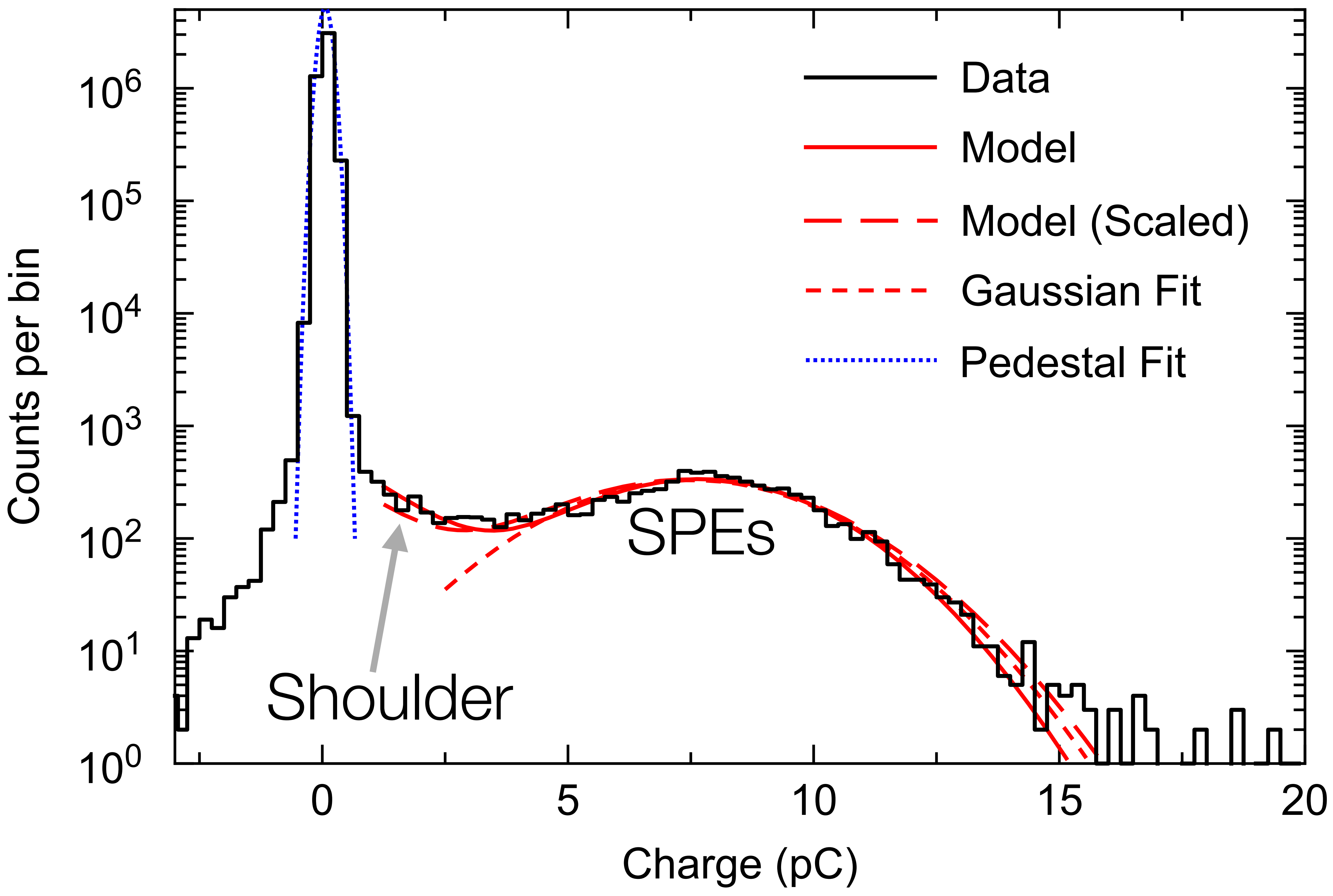


Further PMT bench studies

- Planning SPE measurement with dim LED



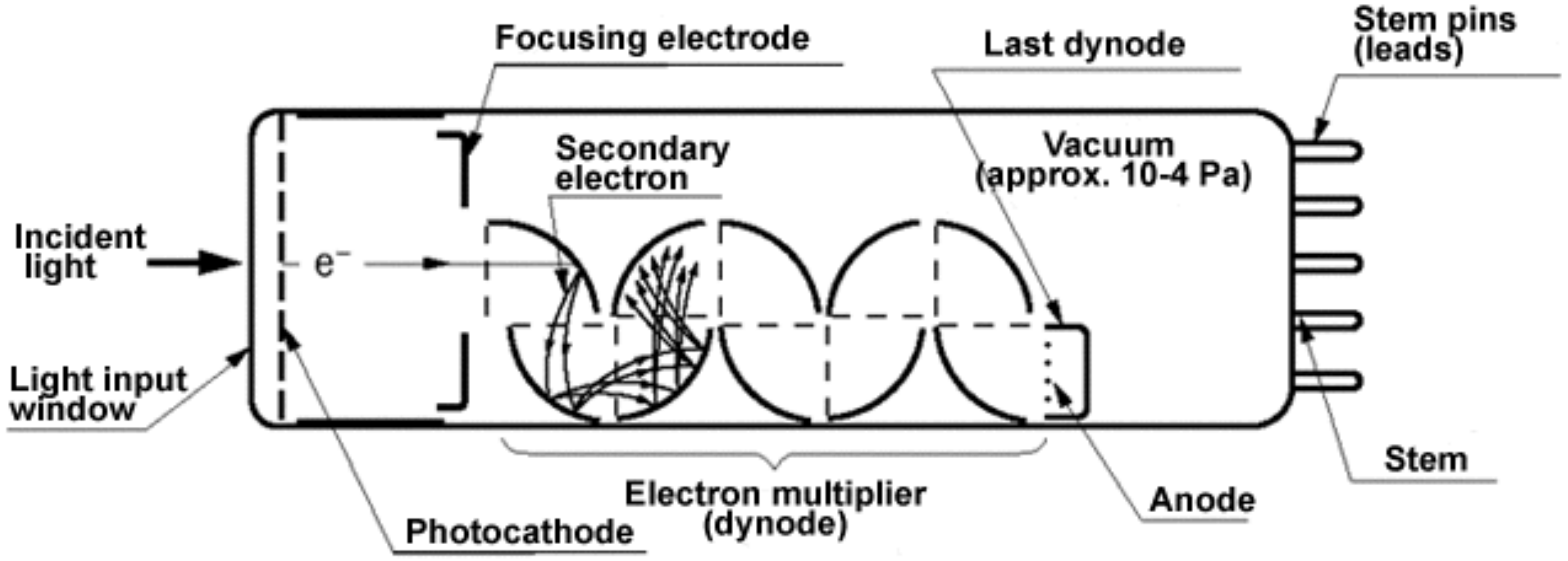
Result from IceCube PMTs



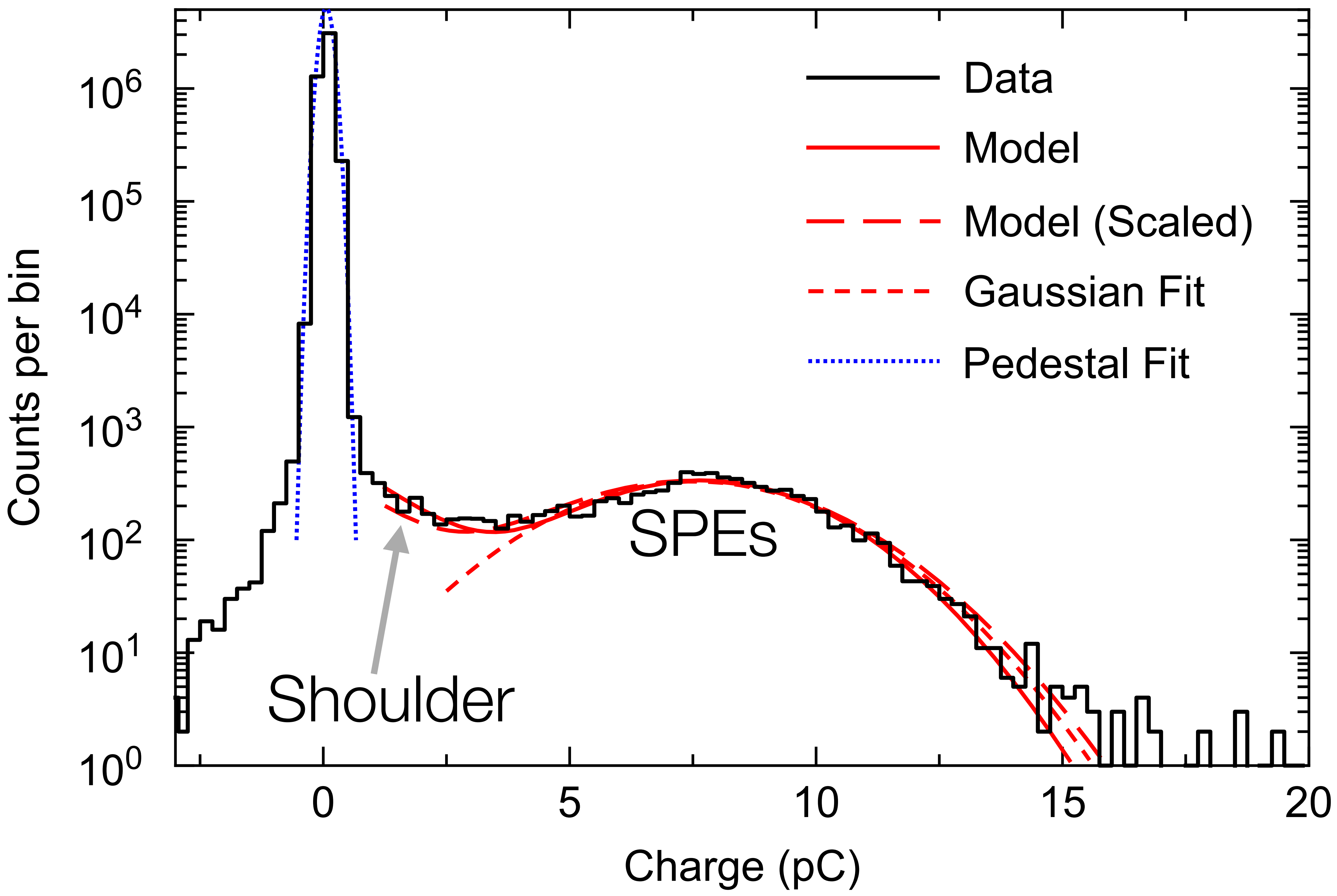
IceCube PMT calibration

Further PMT bench studies

- Planning SPE measurement with dim LED

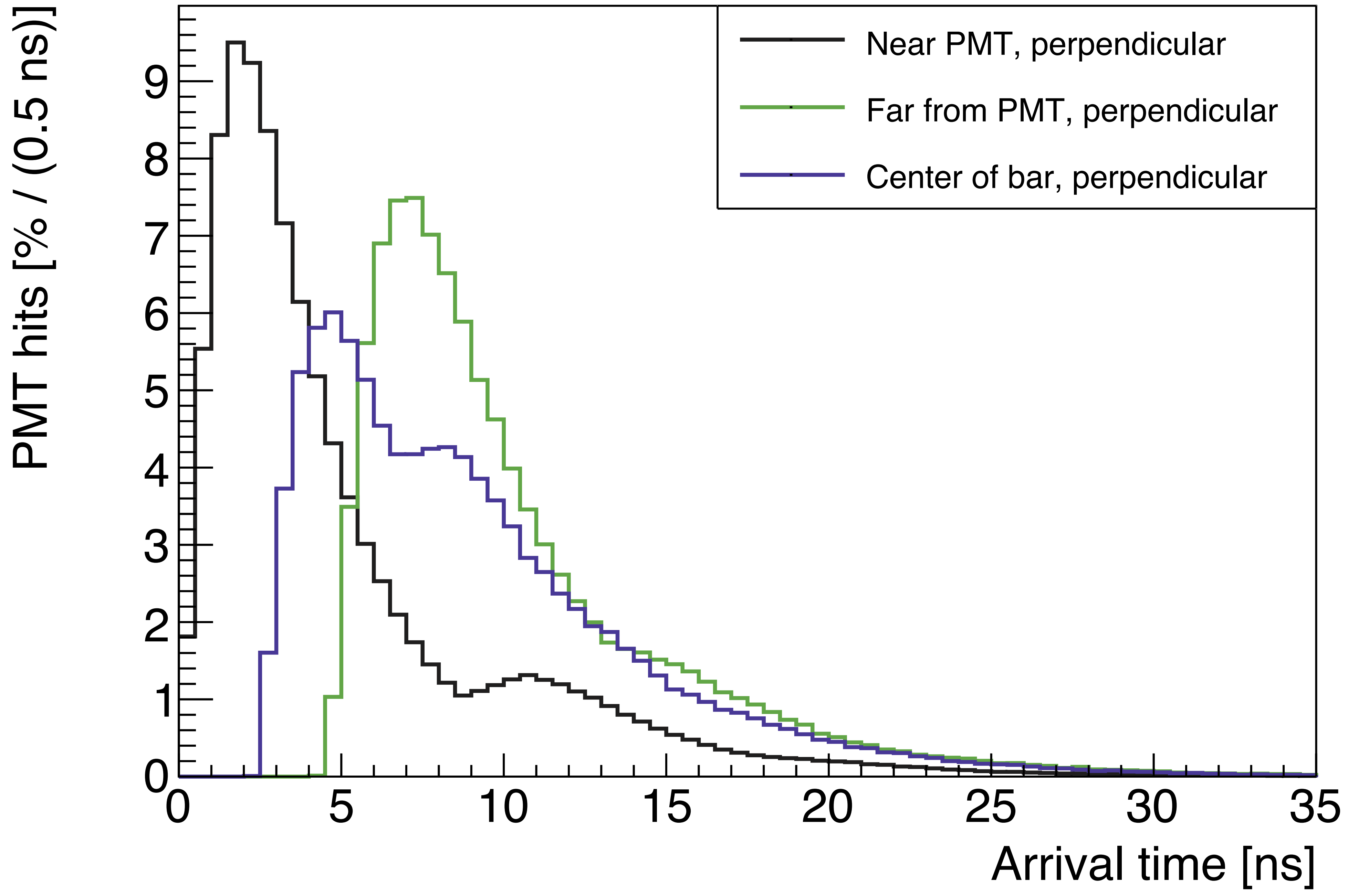


Result from IceCube PMTs

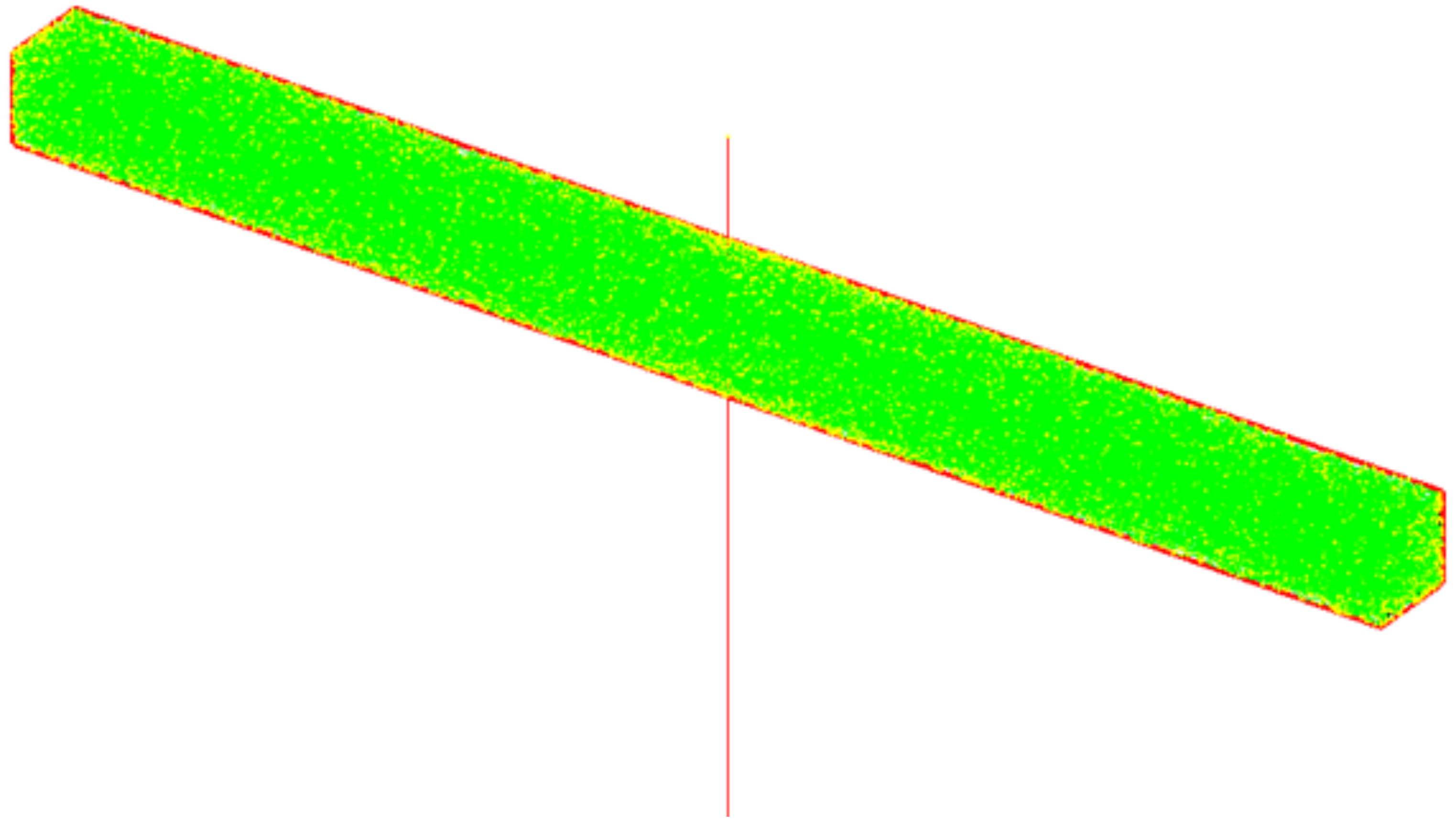


[IceCube PMT calibration]

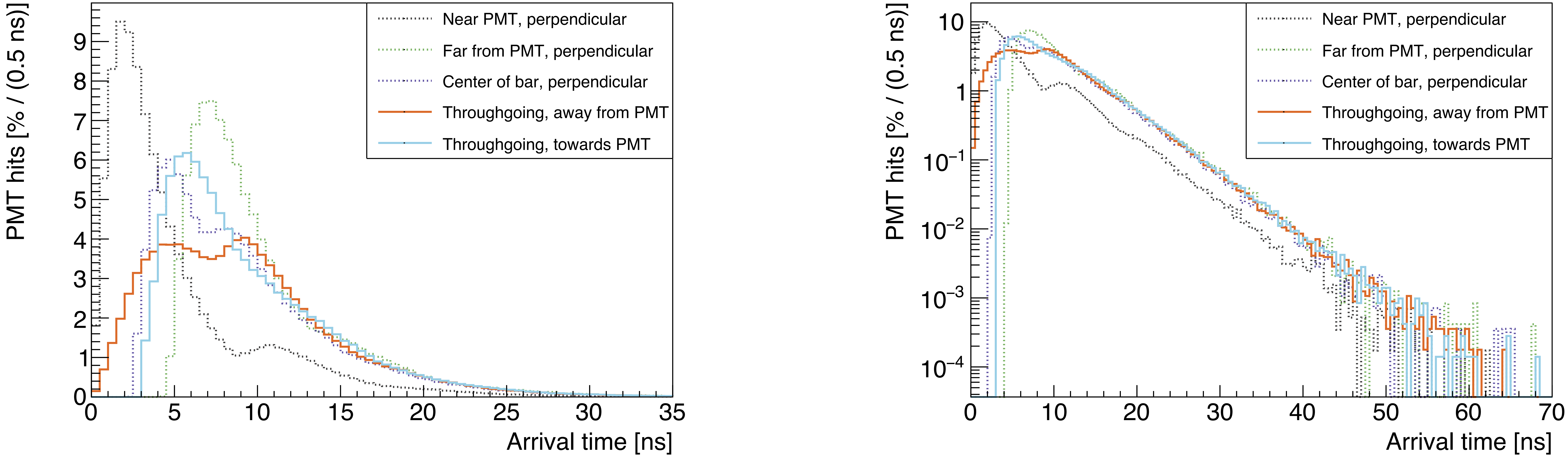
Geant simulation of photon propagation in bar



Shoot 3 GeV muon at bar, perpendicular



Throughgoing muons



Signal with few photons: sample this distribution a few times

Dispersion in time over ~10 ns