Search for millicharged particles at J-PARC

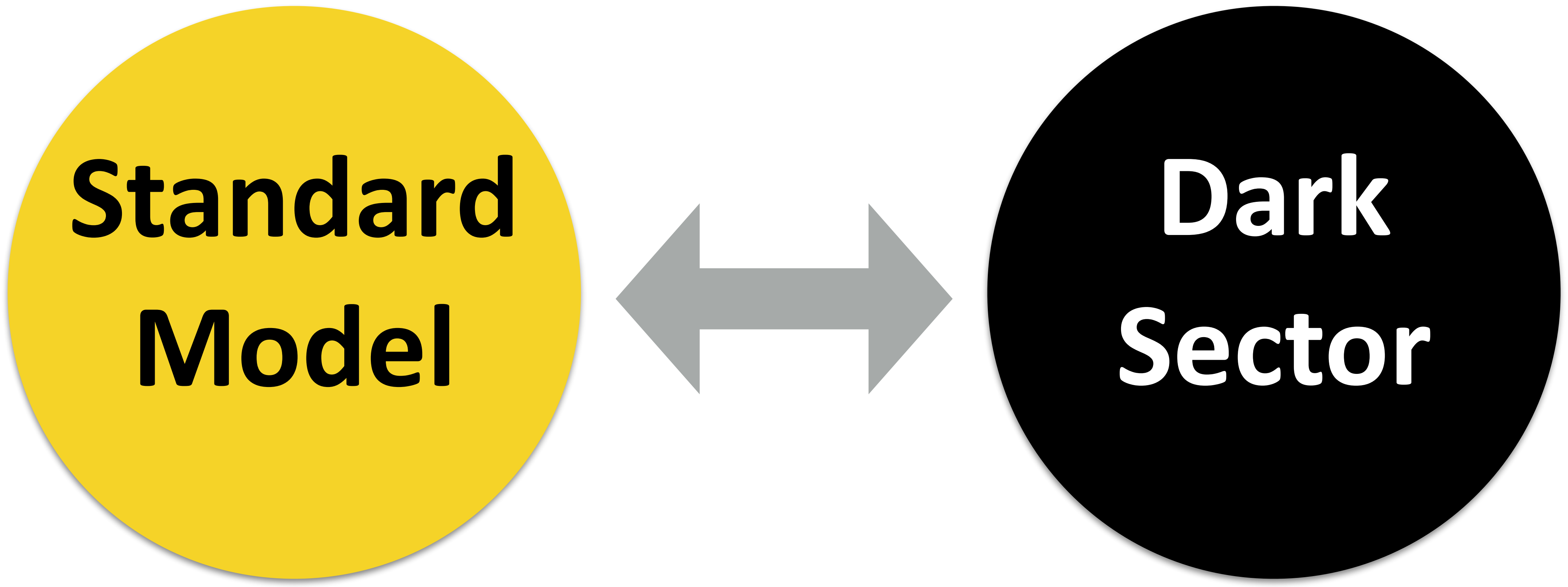
SUb-Millicharge ExperimenT (SUBMET)

Jae Hyeok Yoo (Korea University)

5/26/2026

NPN2026 @Hirosawa City Hall, Mito

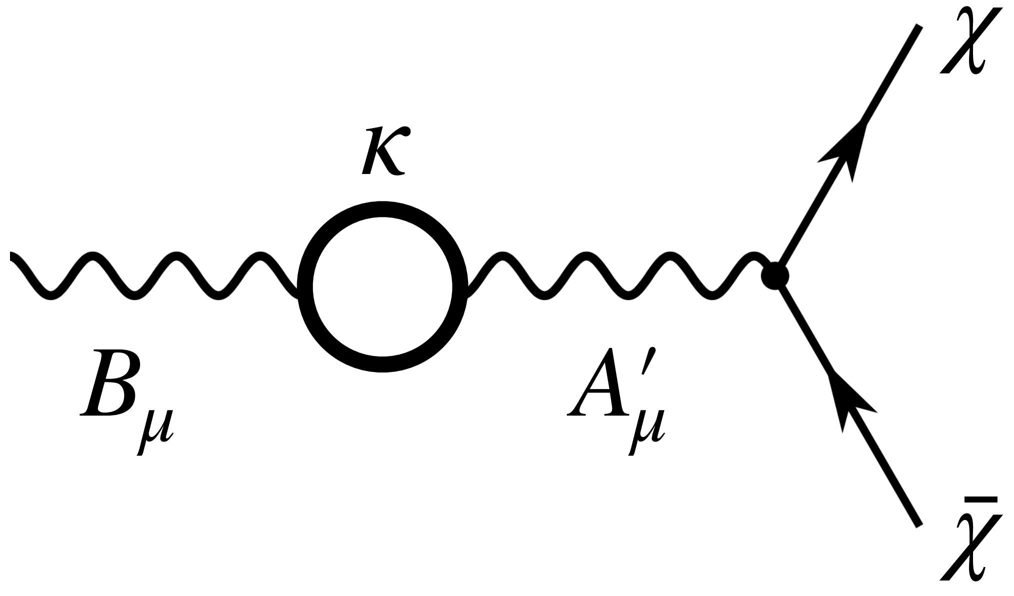
Motivation and model



- Quantization of electric charge is a long-standing question in physics
- Well-motivated dark-sector models have been proposed to predict the existence of millicharged particles while preserving the possibility for unification
- Assume new dark sector U(1) with massless dark-photon (A') and massive dark-fermion (χ)

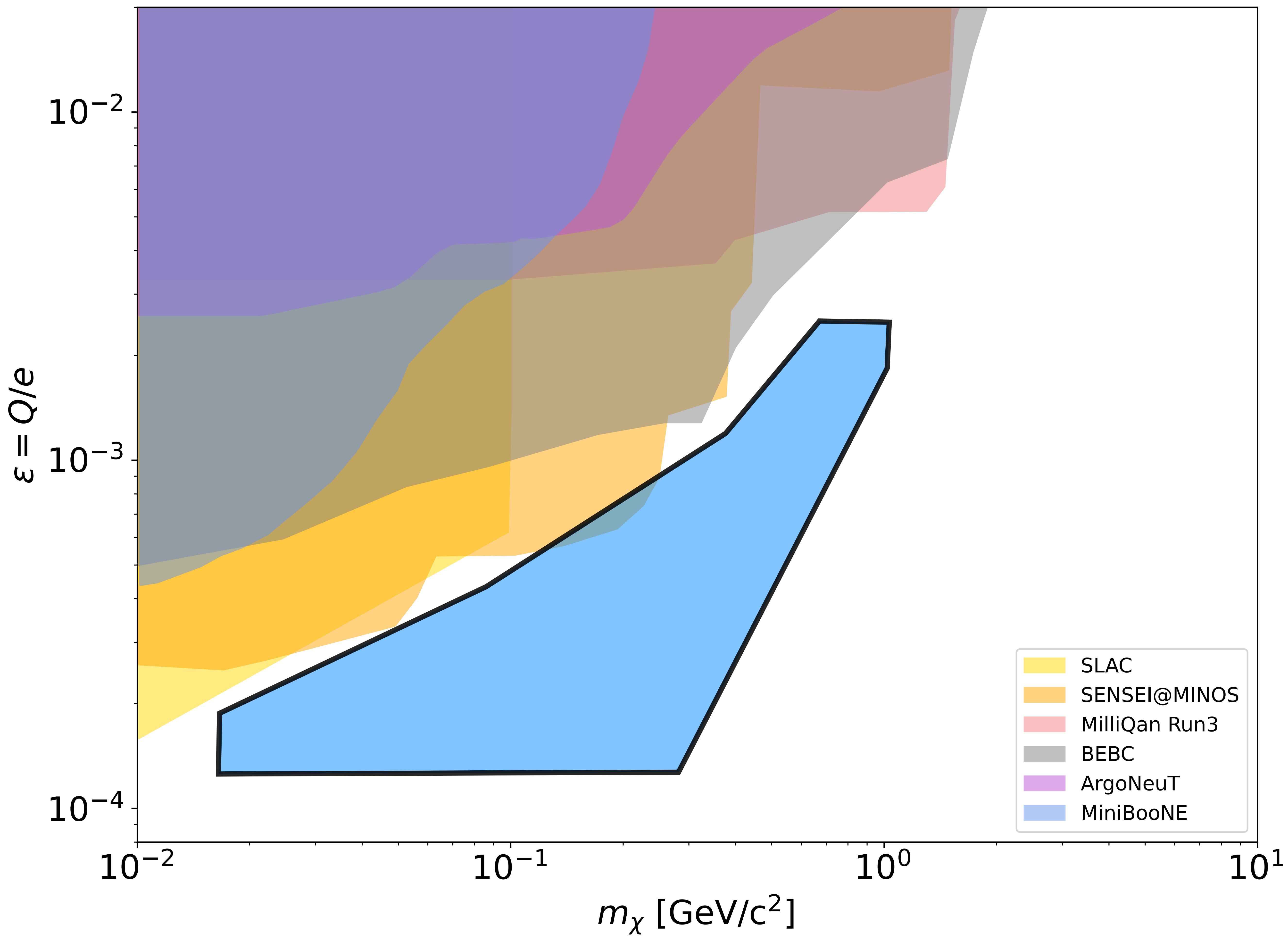
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}\left(\partial\!\!\!/ + ie'A\!\!\!/' + i\kappa e' B\!\!\!/ + iM_{\rm mCP}\right)\chi$$

coupling between ψ and SM photons with effective coupling (charge) $\kappa e'$



- A' and B (in SM) kinetically mix, then charge of χ is proportional to the strength of mixing (κ)

SUB-Millicharge ExperimenT (SUBMET)



- Search for millichaged particles (χ) using 30 GeV proton fixed-target collisions at J-PARC
- Target low-mass ($m_\chi < 1.6$ GeV) and small-Q ($Q < 10^{-3}e$) region

SUB-Millicharge ExperimenT (SUBMET)

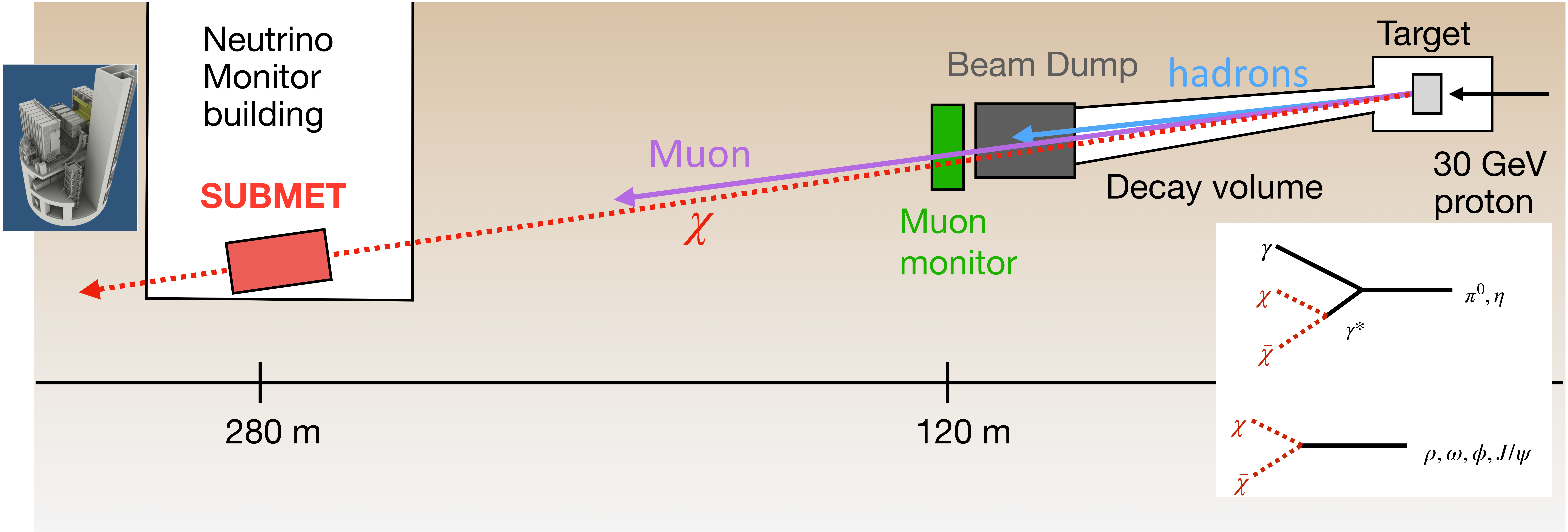
PTEP 2025, 123H03

- Search for millichaged particles (χ) using 30 GeV proton fixed-target collisions at J-PARC
- Target low-mass ($m_\chi < 1.6$ GeV) and small-Q ($Q < 10^{-3}e$) region
- Detector installation in May 2024

SUB-Millicharge ExperimenT (SUBMET)

- Search for millichaged particles (χ) using 30 GeV proton fixed-target collisions at J-PARC
- Target low-mass ($m_\chi < 1.6$ GeV) and small-Q ($Q < 10^{-3}e$) region
- Detector installation in May 2024
- Data-taking since June 2024

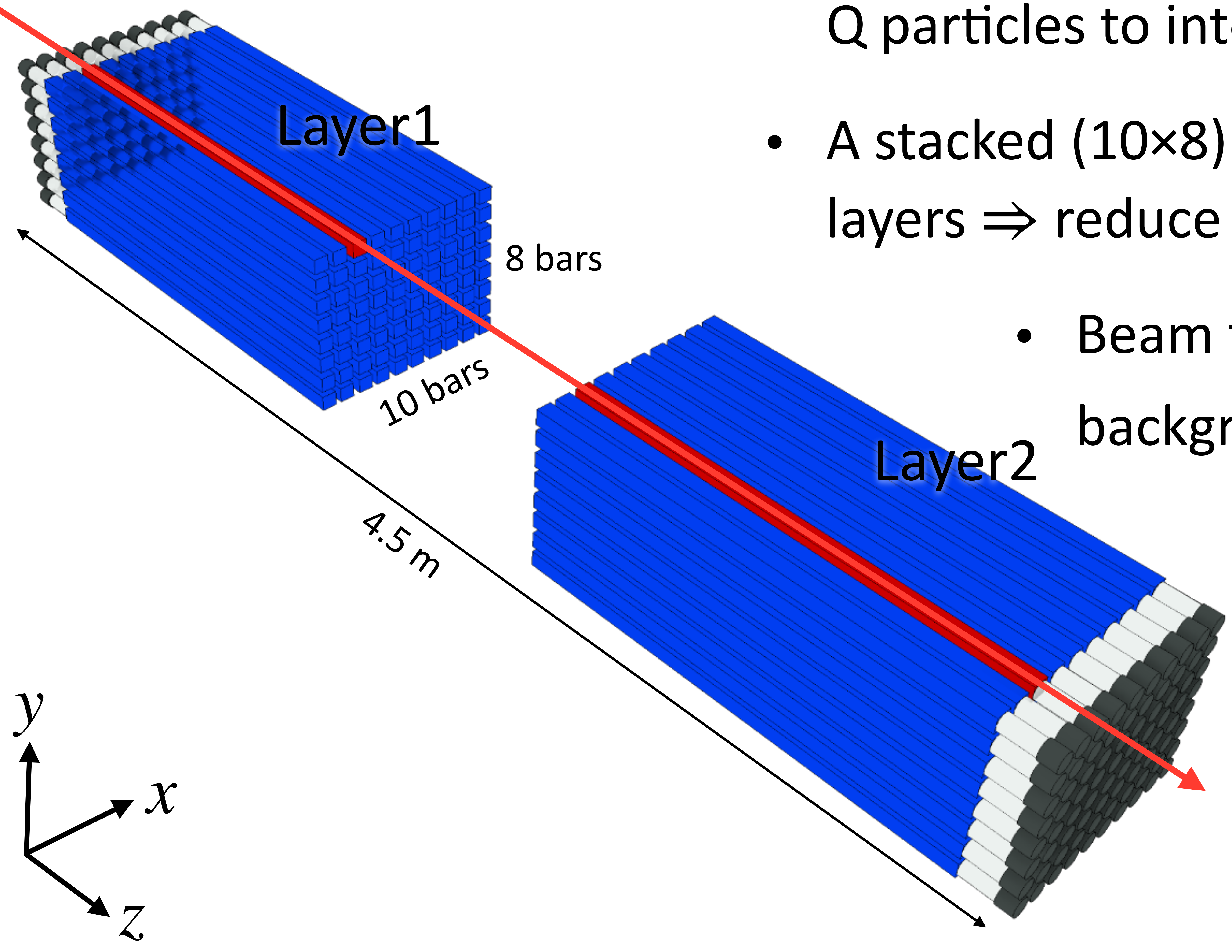
Basic idea of detecting χs



Only χs (and neutrinos) reach the detector

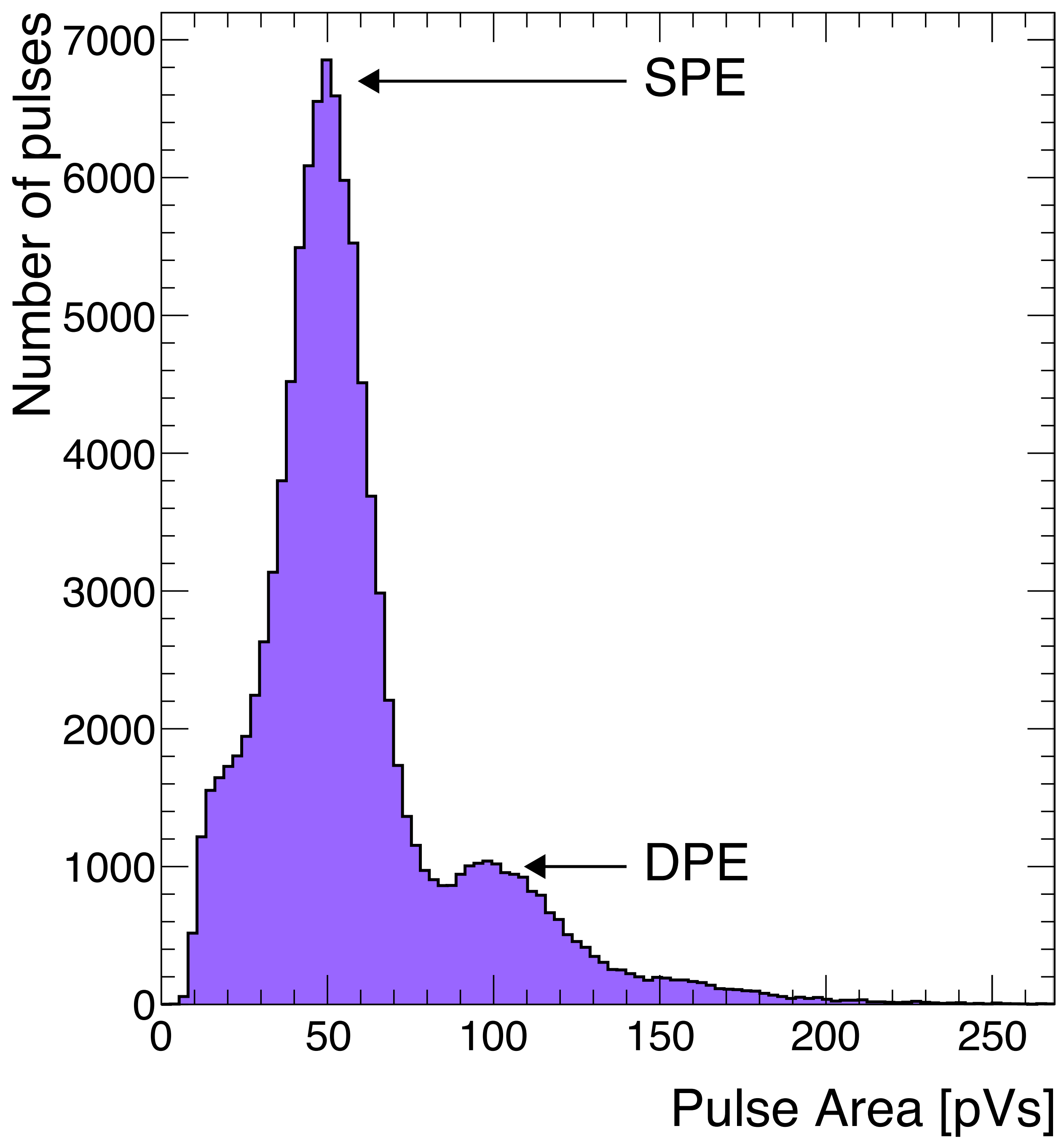
(energy loss for χs with $Q = 10^{-3}e$ is <0.1 MeV)

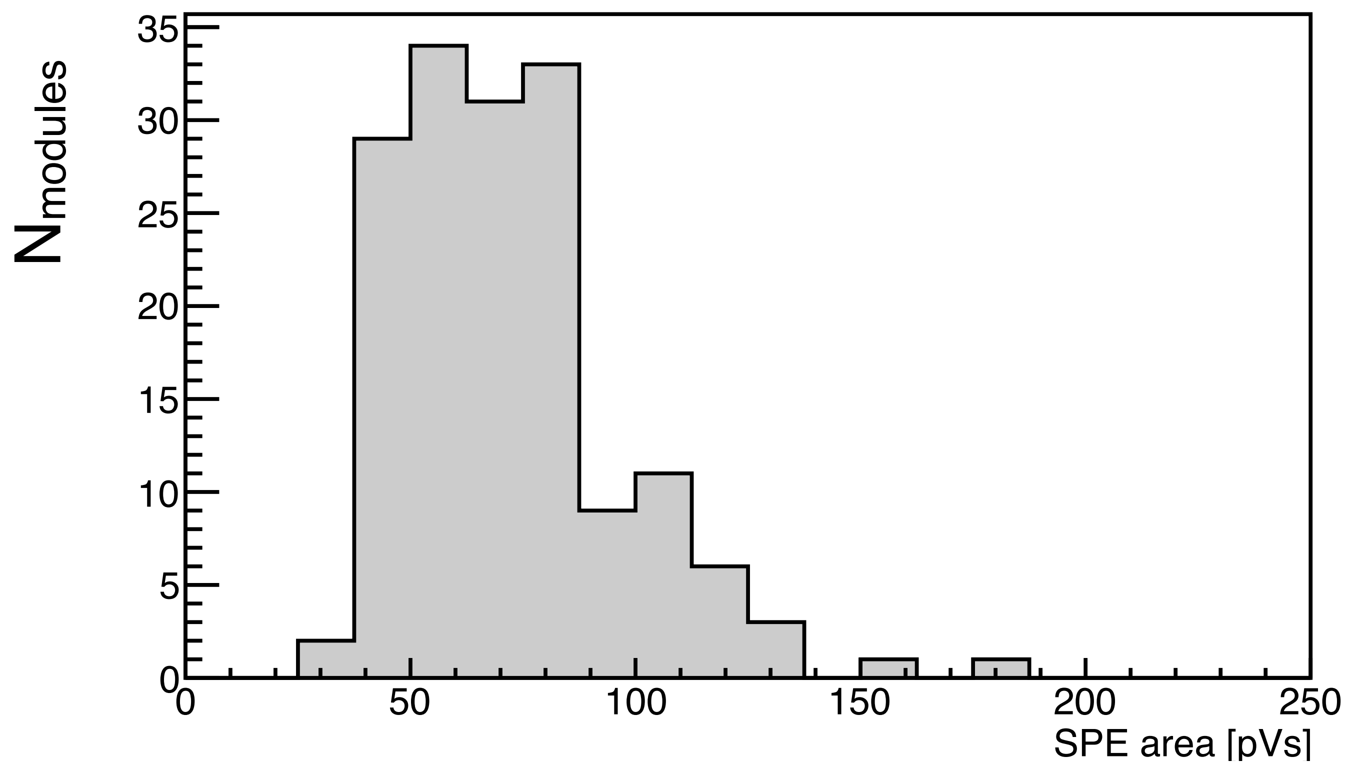
Detector Design



- Long (1.5 m) scintillator bars ⇒ sufficient path length for small-Q particles to interact ⇒ SPE signal
- A stacked (10×8) array of modules ⇒ increase volume; two layers ⇒ reduce backgrounds
    - Beam timing (trigger on beam signal) ⇒ effective background suppression ($O(10^{-6})$)
- Layers aligned with the direction of χs so they traverse both in a short period of time
- **Signature of χs: coincident ($\Delta t < 30$ ns) SPE signals in two aligned modules**

Detector calibration: SPE

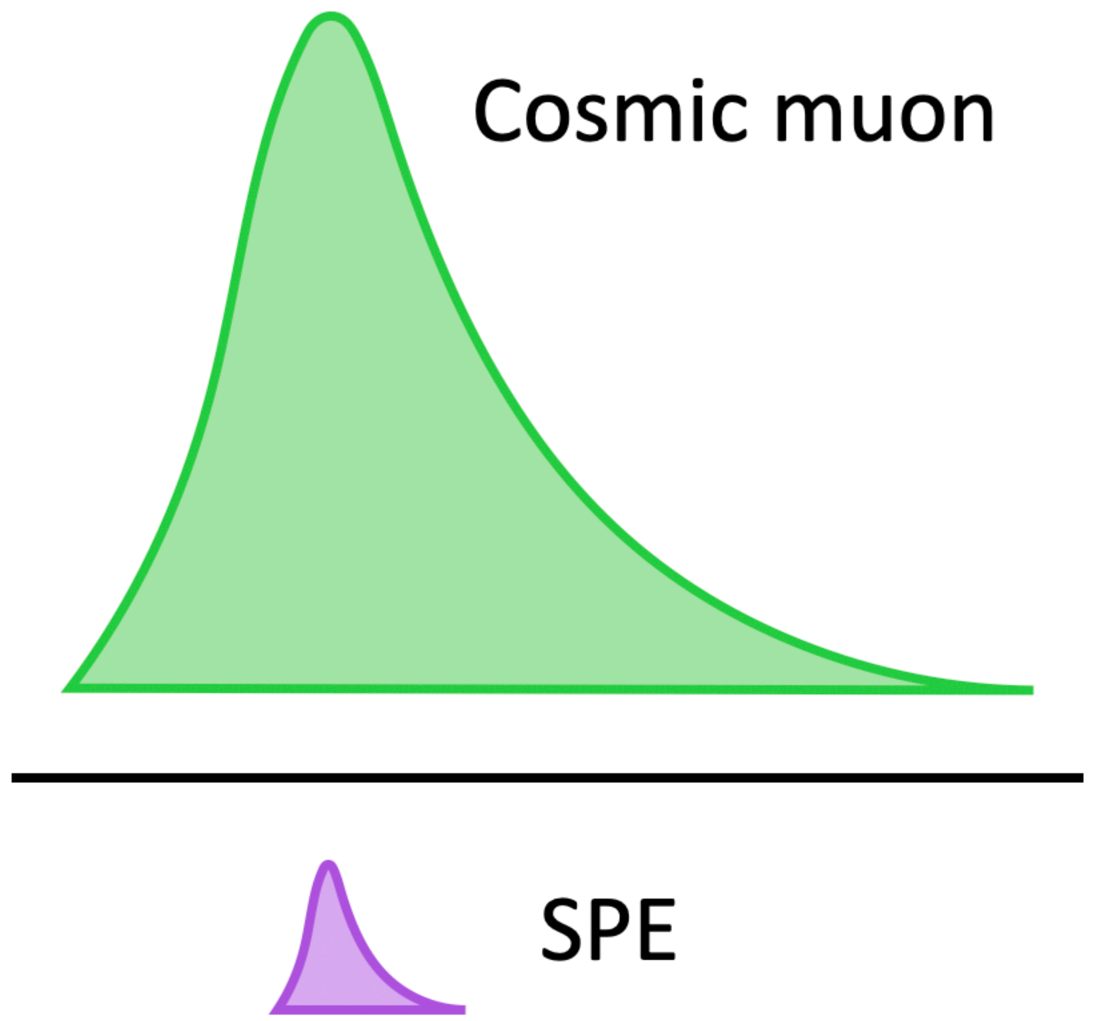


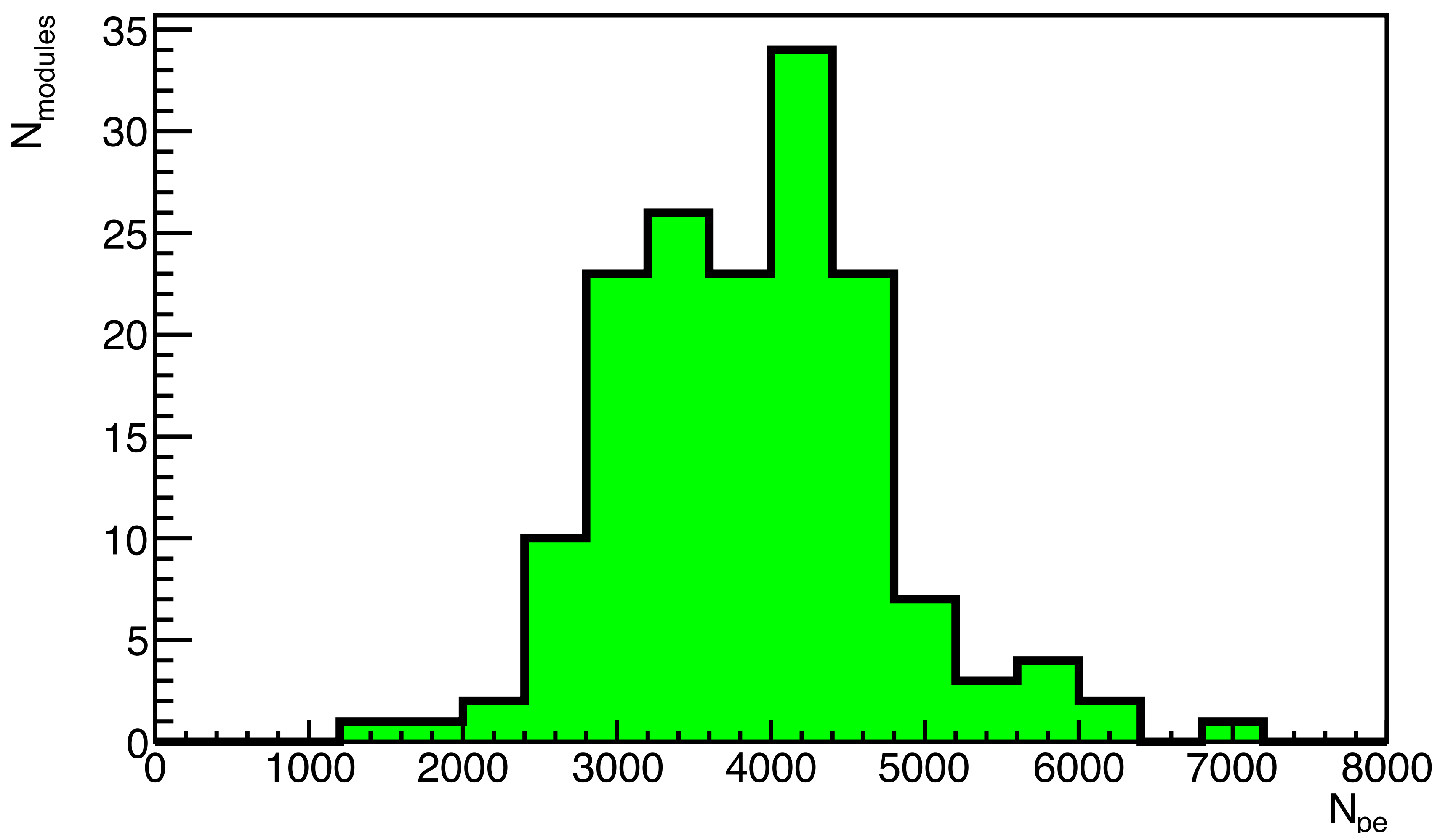


- Identifying and understanding SPEs are crucial
- Use weak LED light as a single-photon source
- Measured pulse area distribution of each module
    - Mean of SPE area is about 70 pVs
- Use this calibration results for channel-by-channel SPE selection ($\pm 2\sigma$)

Detector calibration: charge

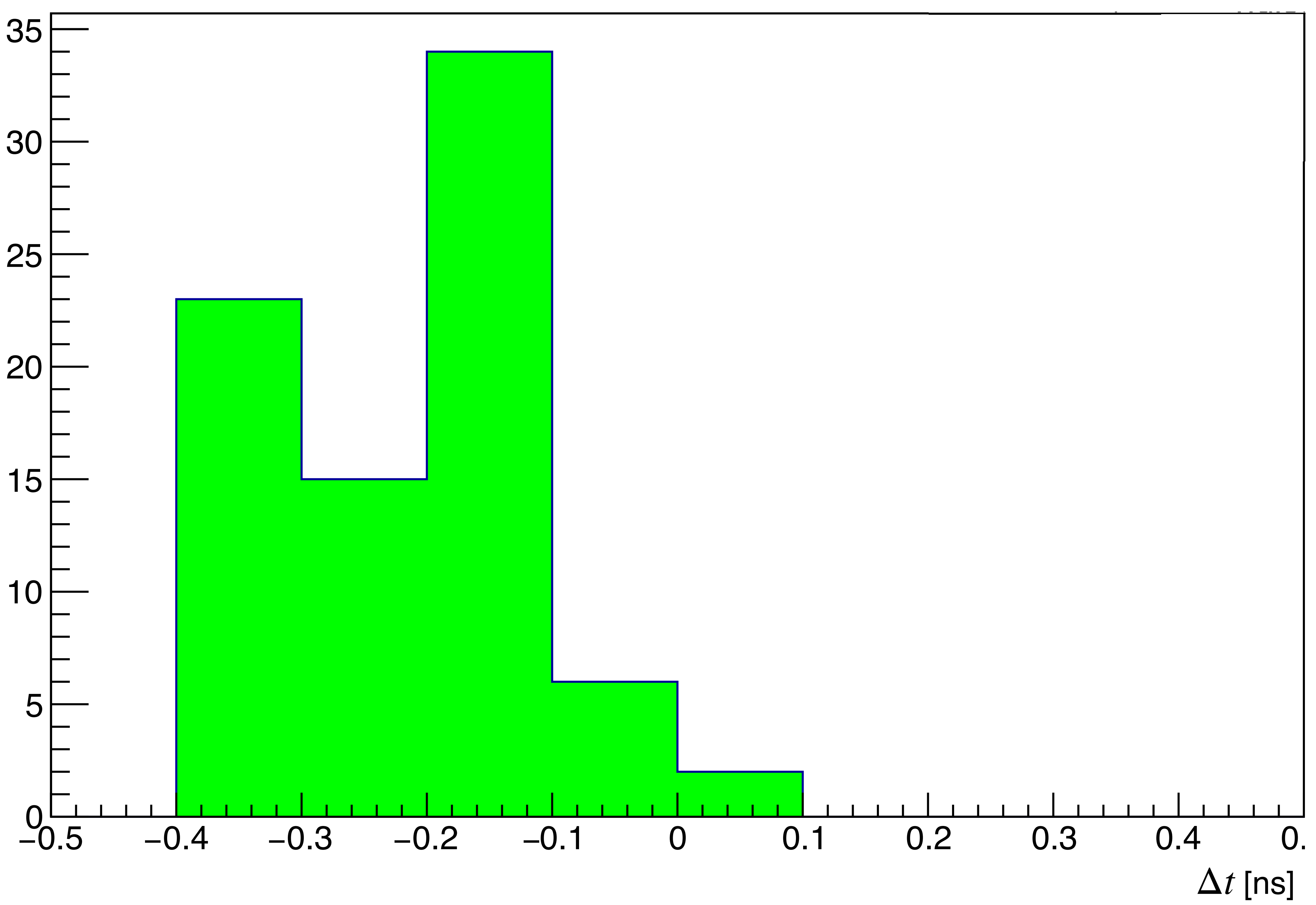
N_{PE} =



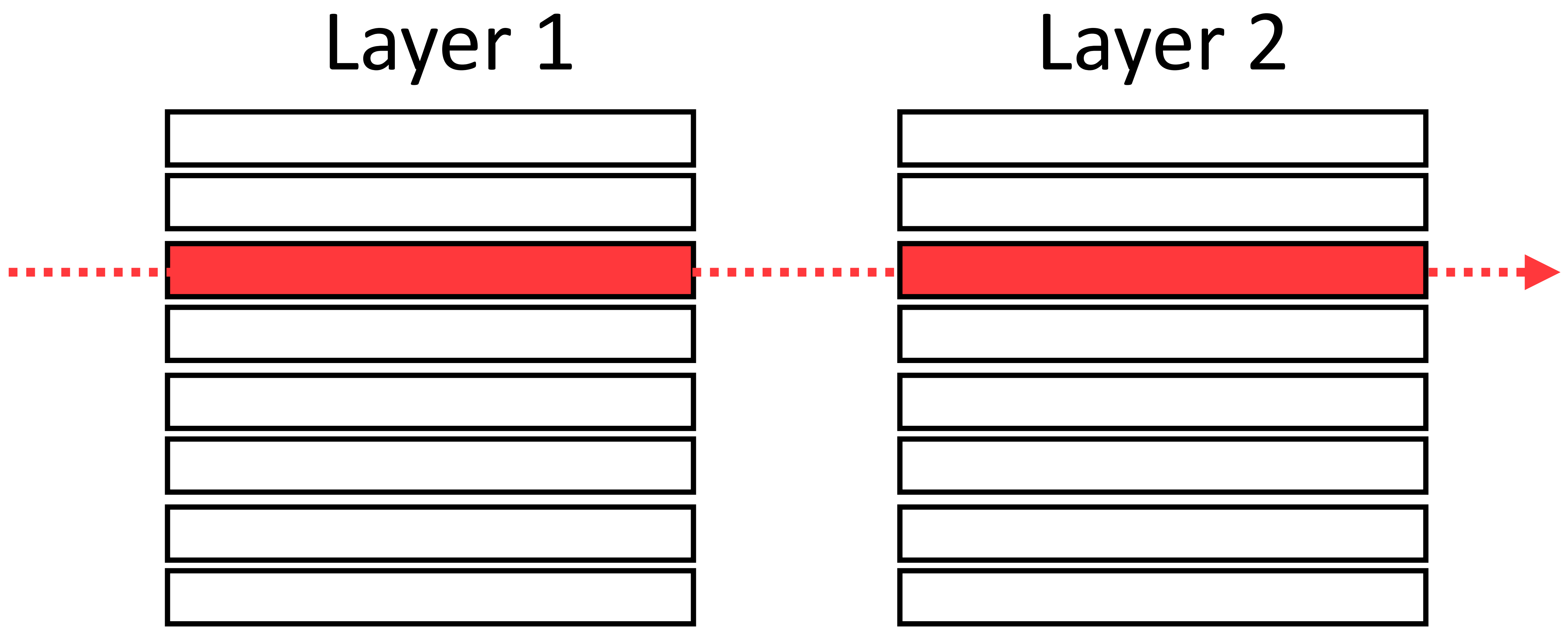


- Important to know the average number of photoelectrons for a given charge and energy
  - Higher N_{PE} per energy means better sensitivity to lower charge
- Measure N_{PE} per energy *in situ* by using vertical cosmic muons in combination with SPEs
- Calculate Area(cosmic muon)/Area(SPE) to get N_{PE} for muons ($\Rightarrow$ per keV)
- Mean N_{PE} by muons is $\sim$4000 $\Rightarrow$ $\sim$0.4/keV
  - Consistent with lab measurement using Cd-109 source before installation

Detector calibration: time

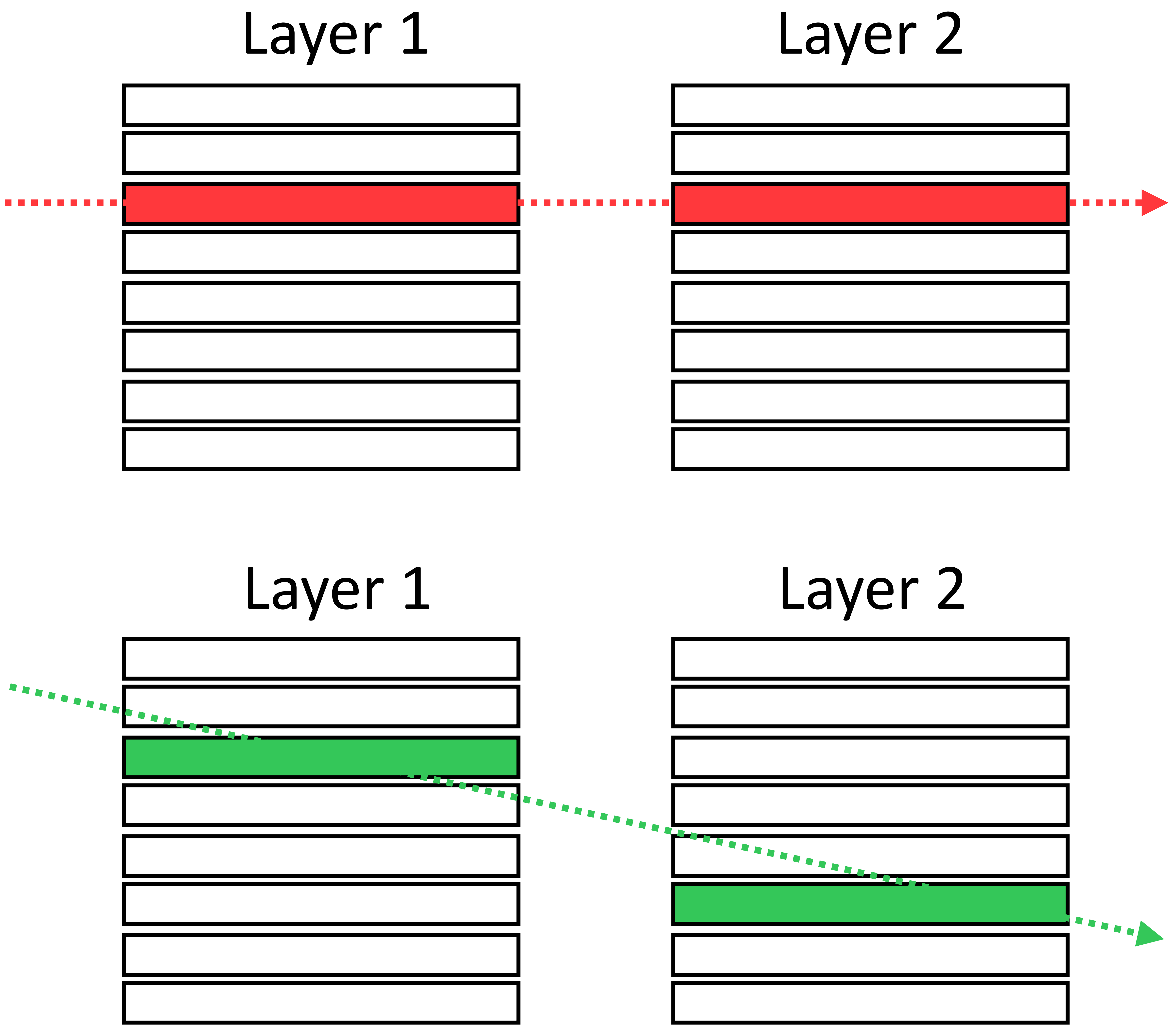


- Time alignment between two channels in layer 1 and 2 is crucial to determine the coincidence window



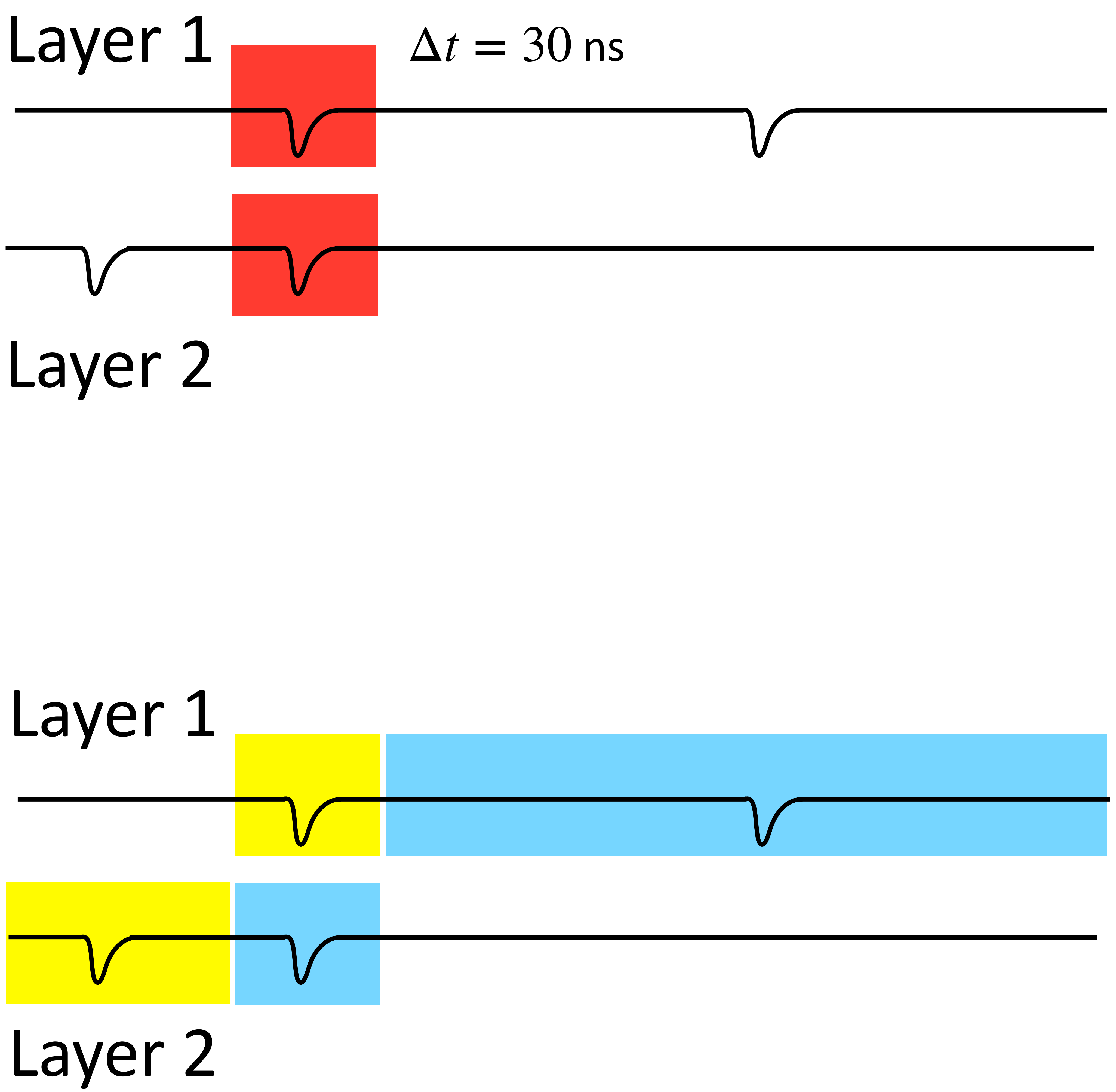
- Measured time difference Δt of the two channels: $\Delta t < 0.5$ ns in all pairs

Beam-off backgrounds



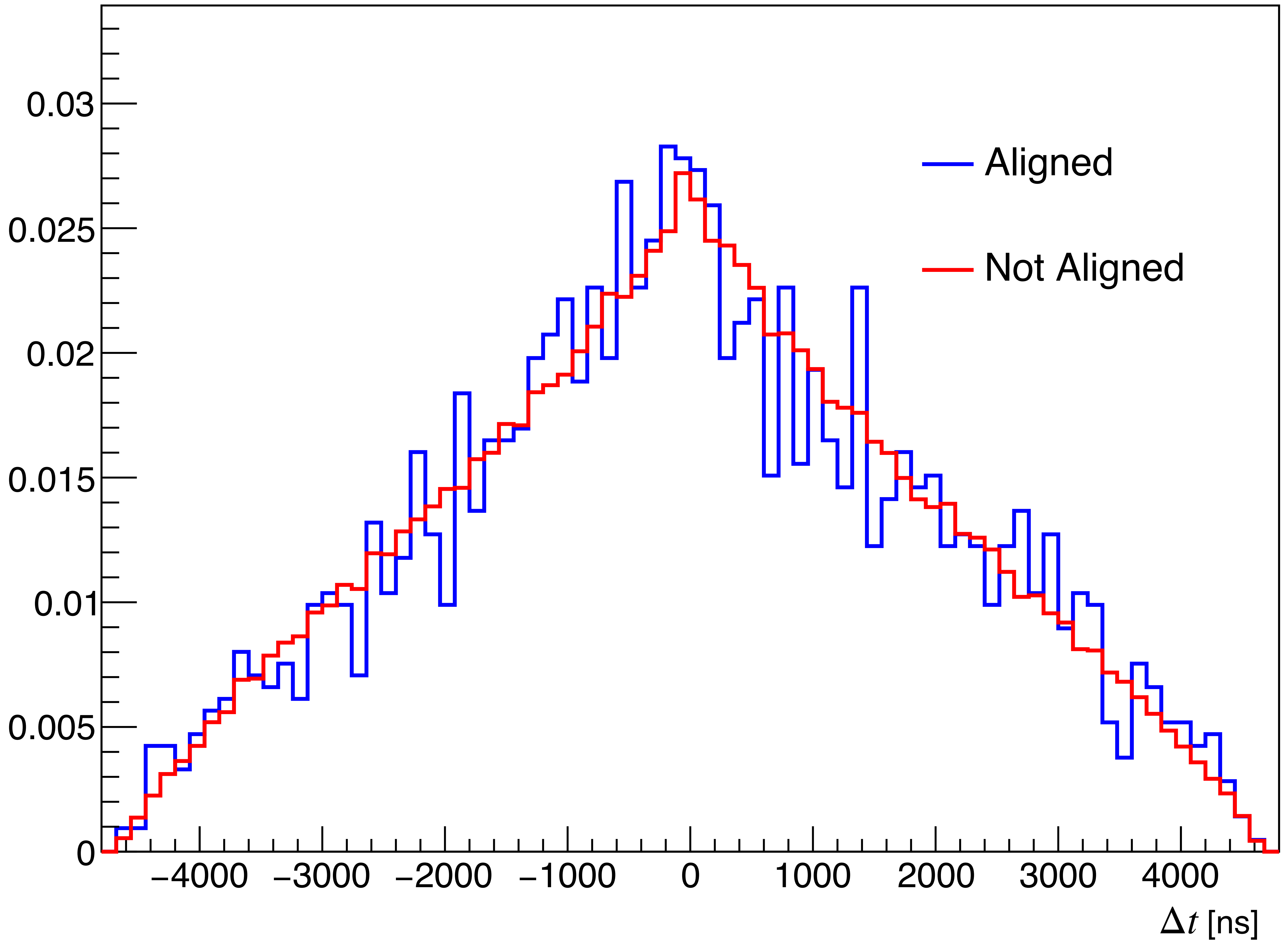
- Validate background prediction method and find potential issues in data/detector system, using beam-off data
  - Random trigger in the absence of beam
- Background prediction done by using two uncorrelated variables [ref]
  - **Directionality** (**aligned** or **not**)

Beam-off backgrounds



- Validate background prediction method and find potential issues in data/detector system, using beam-off data
  - Random trigger in the absence of beam
- Background prediction done by using two uncorrelated variables [ref]
  - **Directionality** (aligned or not)
  - **Coincidence** ($\Delta t < 30$ ns or not)

Beam-off backgrounds



- Δt between aligned and not aligned modules
  - SPE pulses are selected
- Same shape $\Rightarrow$ negligible correlation
- Can use “ABCD method”

Beam-off backgrounds

	Aligned	Not aligned
$\Delta t > 30$ ns	**B** **2112**	**C** **150597**
$\Delta t < 30$ ns	**A (signal region)** **Pred: 14.3 ± 0.5**	**D** **1017**

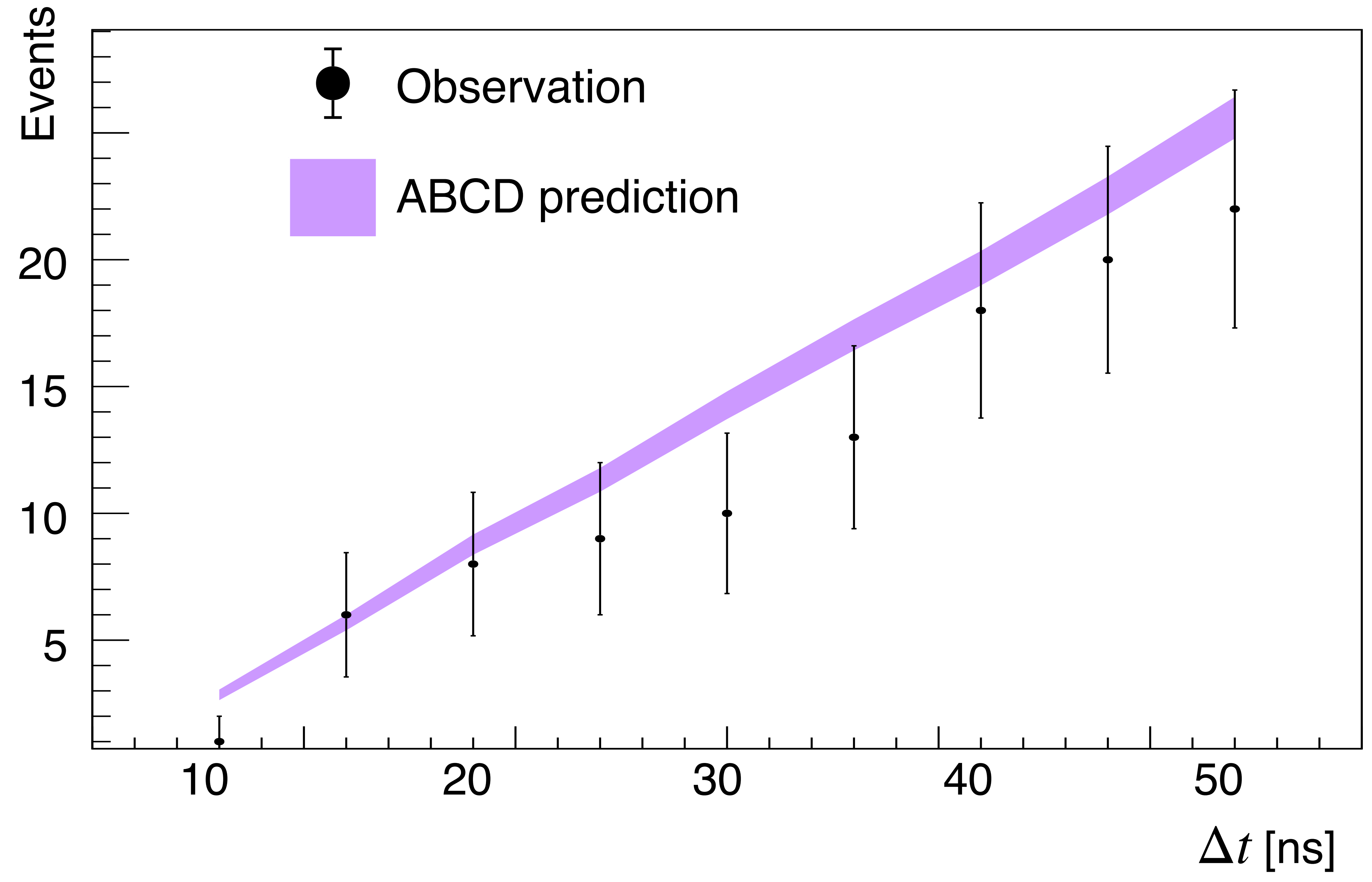
- Predict yield in A by B*D/C
- Results with 2.1M events
  - **Prediction: 14.3 ± 0.5**

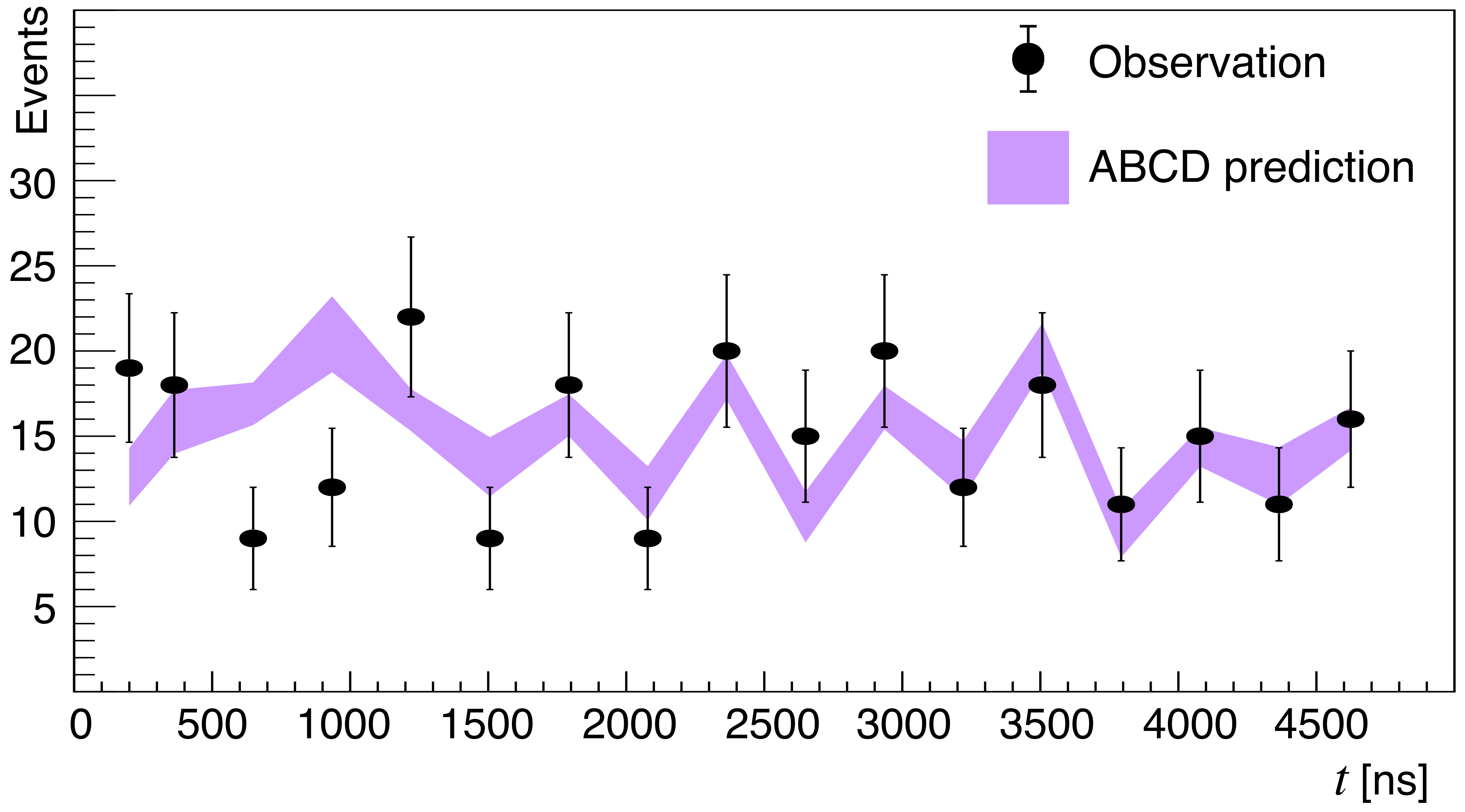
Beam-off backgrounds

	Aligned	Not aligned
$\Delta t > 30$ ns	**B** **2112**	**C** **150597**
$\Delta t < 30$ ns	**A (signal region)** **Pred: 14.3 ± 0.5** **Obs: 10**	**D** **1017**

- Predict yield in A by B*D/C
- Results with 2.1M events
  - **Prediction: 14.3 ± 0.5**
  - **Observation: 10**
- Tested further by varying the size of coincidence window and the location of readout window

Beam-off backgrounds



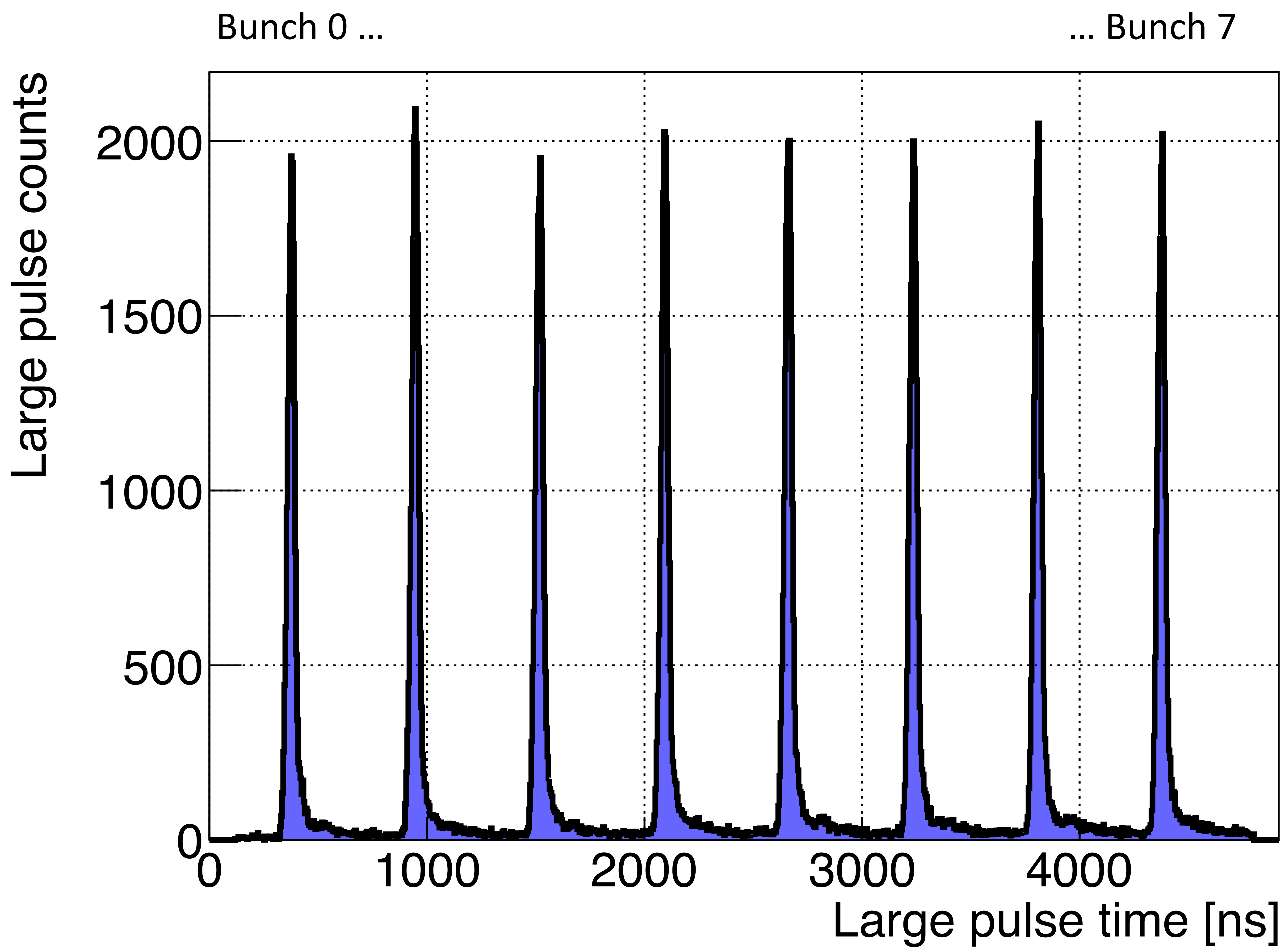


- Varying size of the coincidence window Δt ($10 \rightarrow 50$ ns)
- Good agreements ⇒ beam-off backgrounds are mostly random coincidence (uncorrelated)

- Varying location of the readout window
- No window-dependent issue

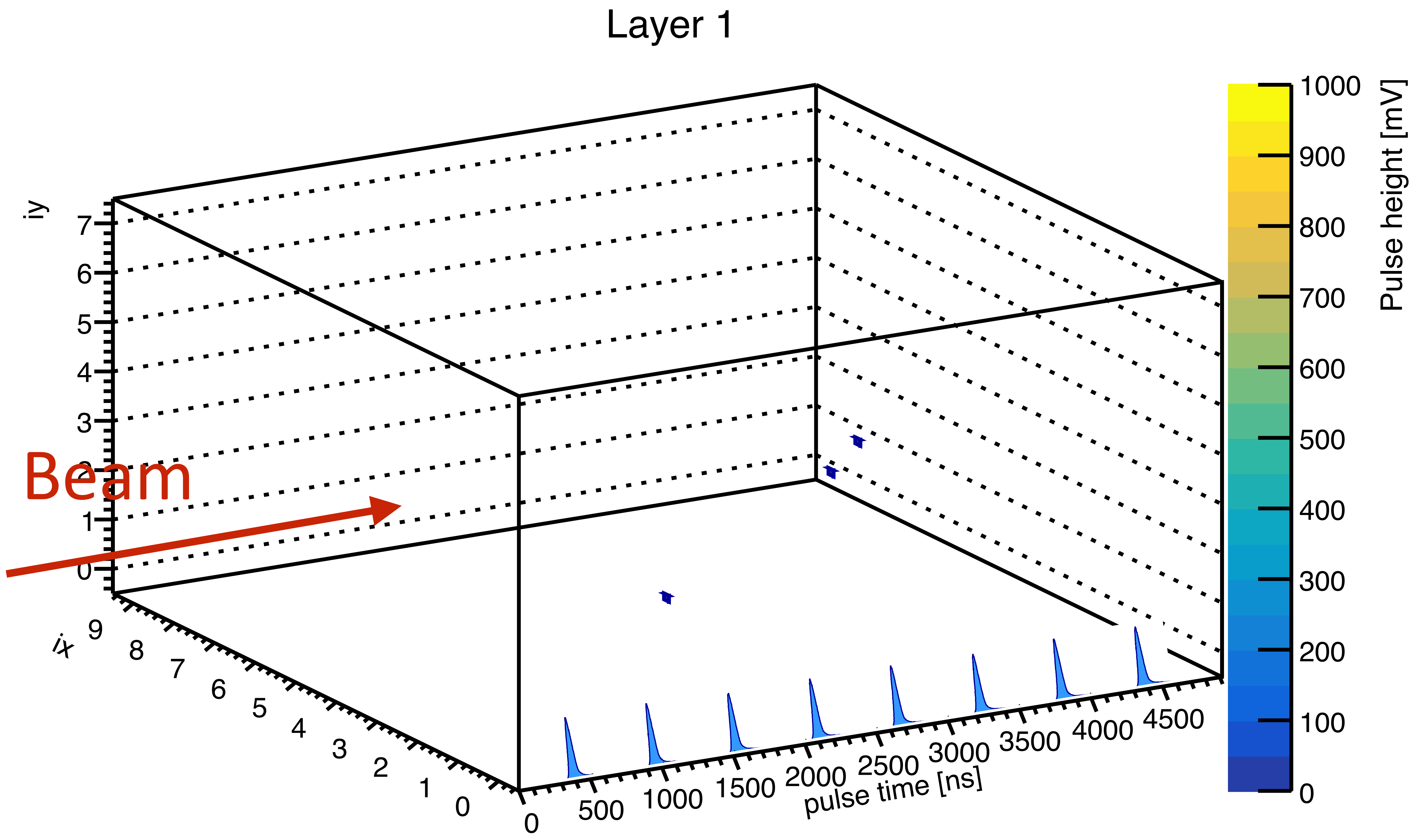
Robustness of background prediction
No issues with detector/DAQ flow
⇒ **Ready to analyze beam-on data**

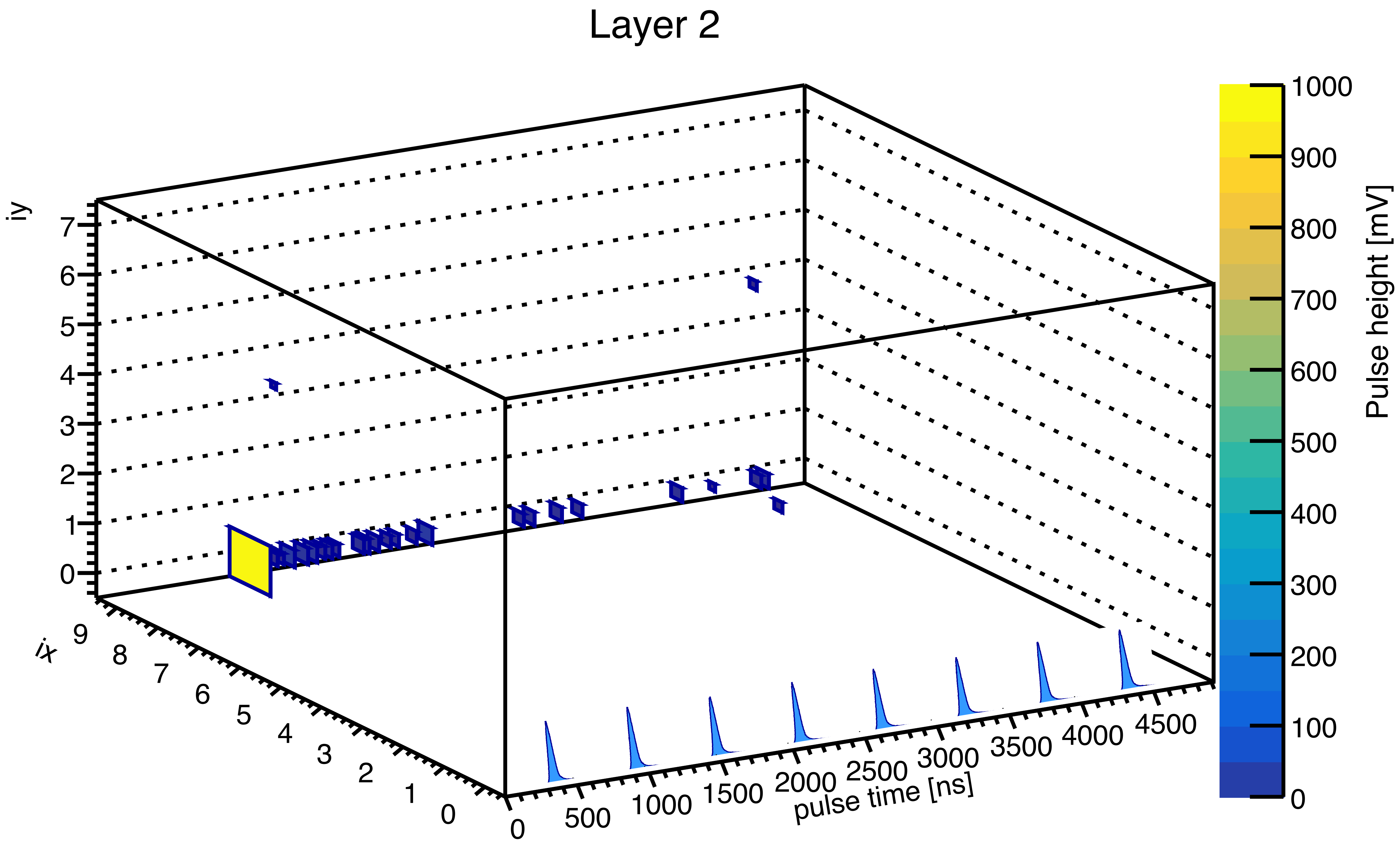
Beam structure

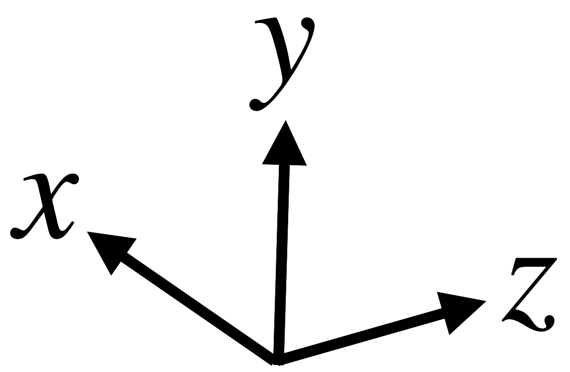


- Time distribution of pulses produced by sand muons
- Can see the beam structure Cleary
- Our readout system can store a whole spill

What a collision event looks like

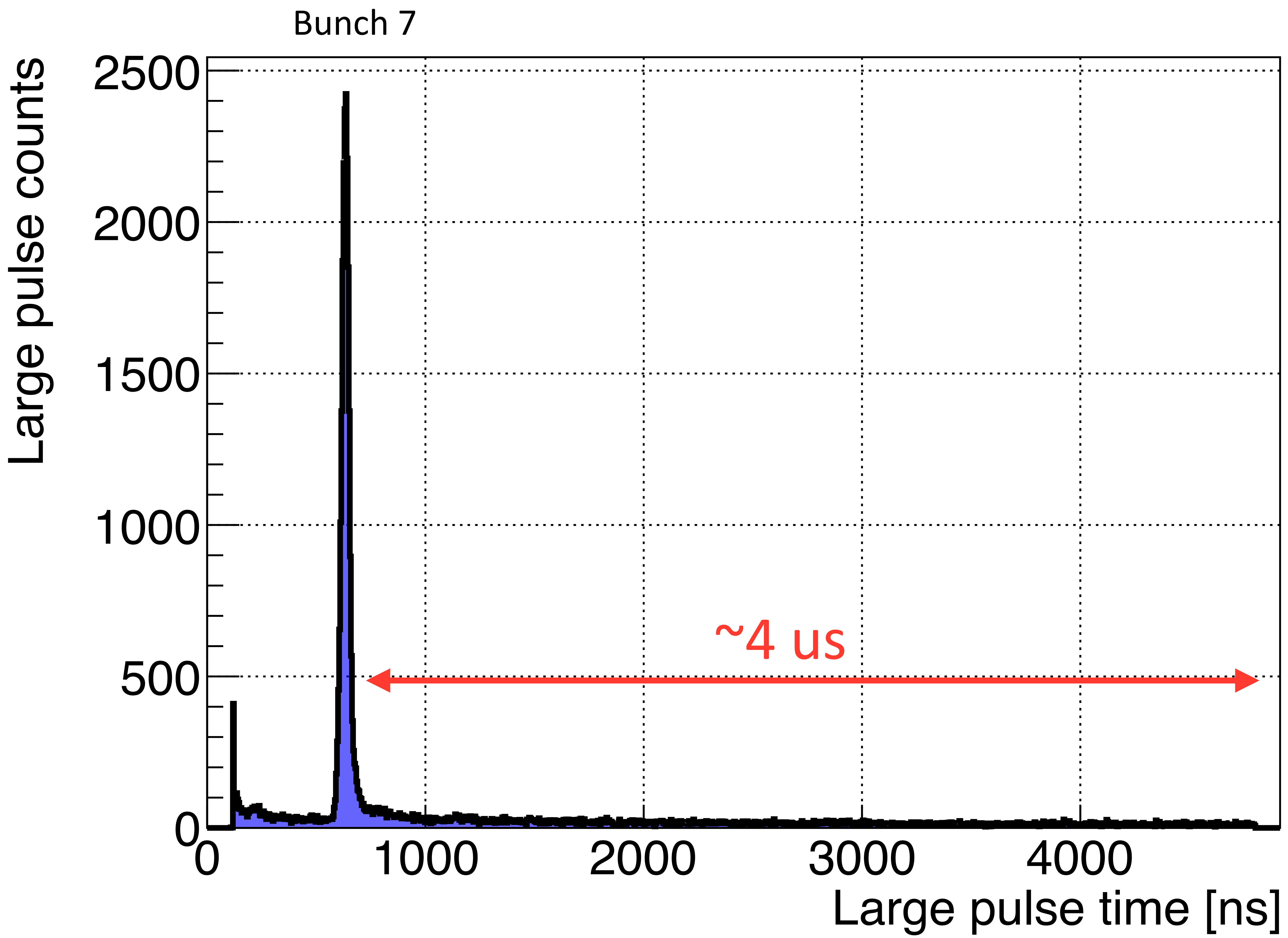






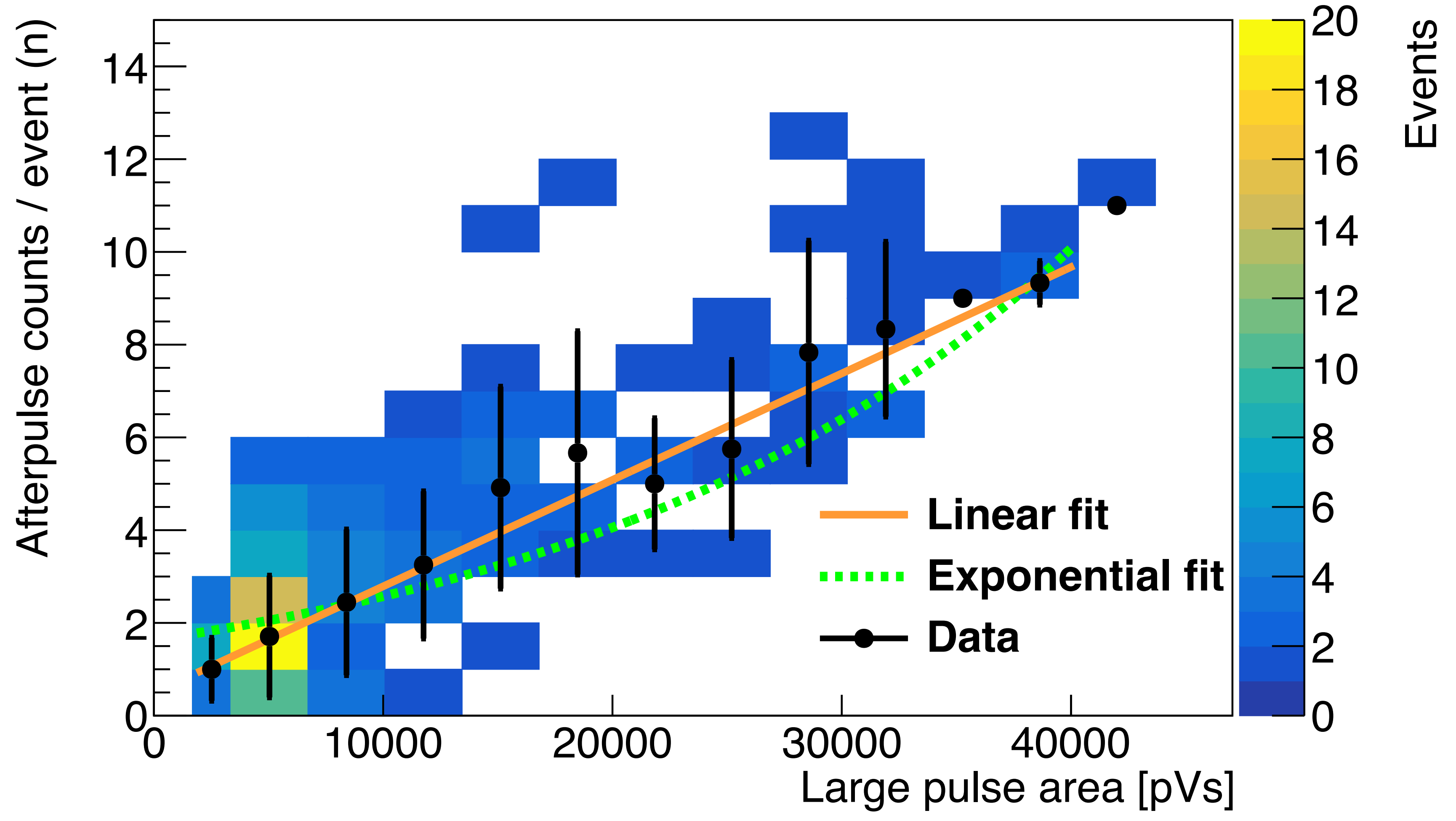
- Multiple pulses after a large pulse in layer 2 → afterpulses
- How to deal with them?
  - Incorporate them in background prediction
  - Use samples not affected by them

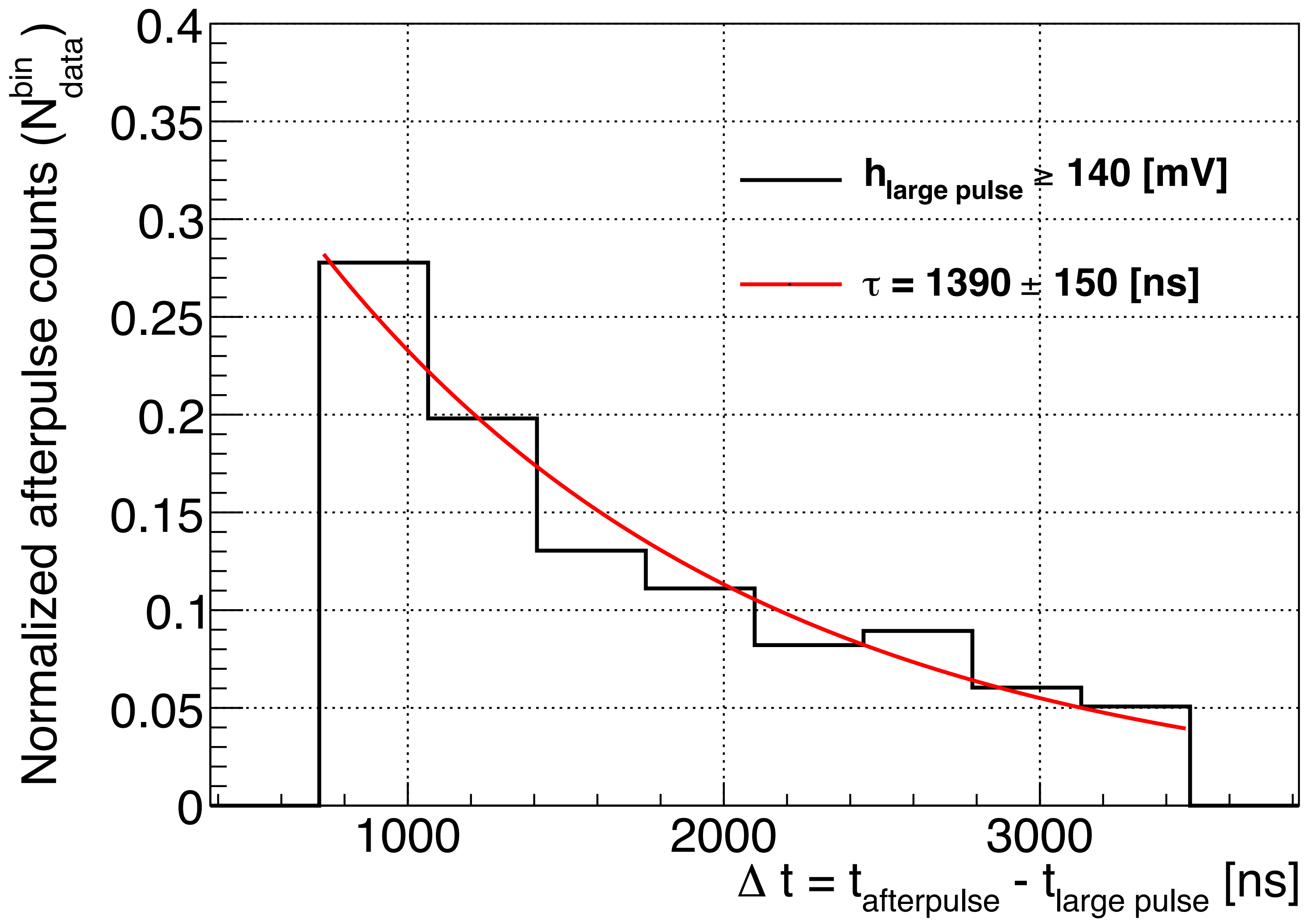
Afterpulses



- Developed a model to predict the rate (or count) of after pulses
- Took data with a larger trigger delay such that only the last bunch is in the daq window
- ~ 4 us to study after pulses

Afterpulses

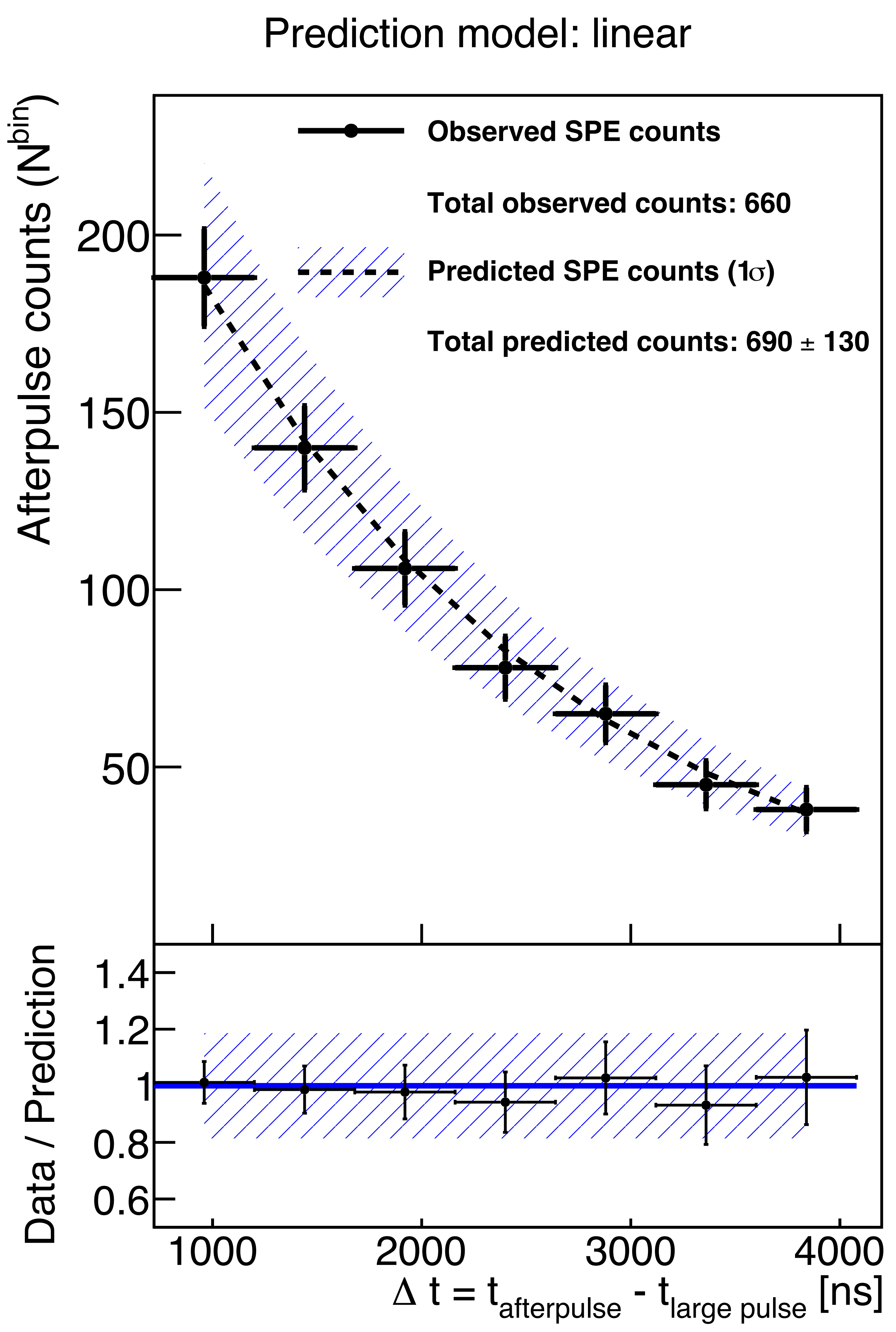




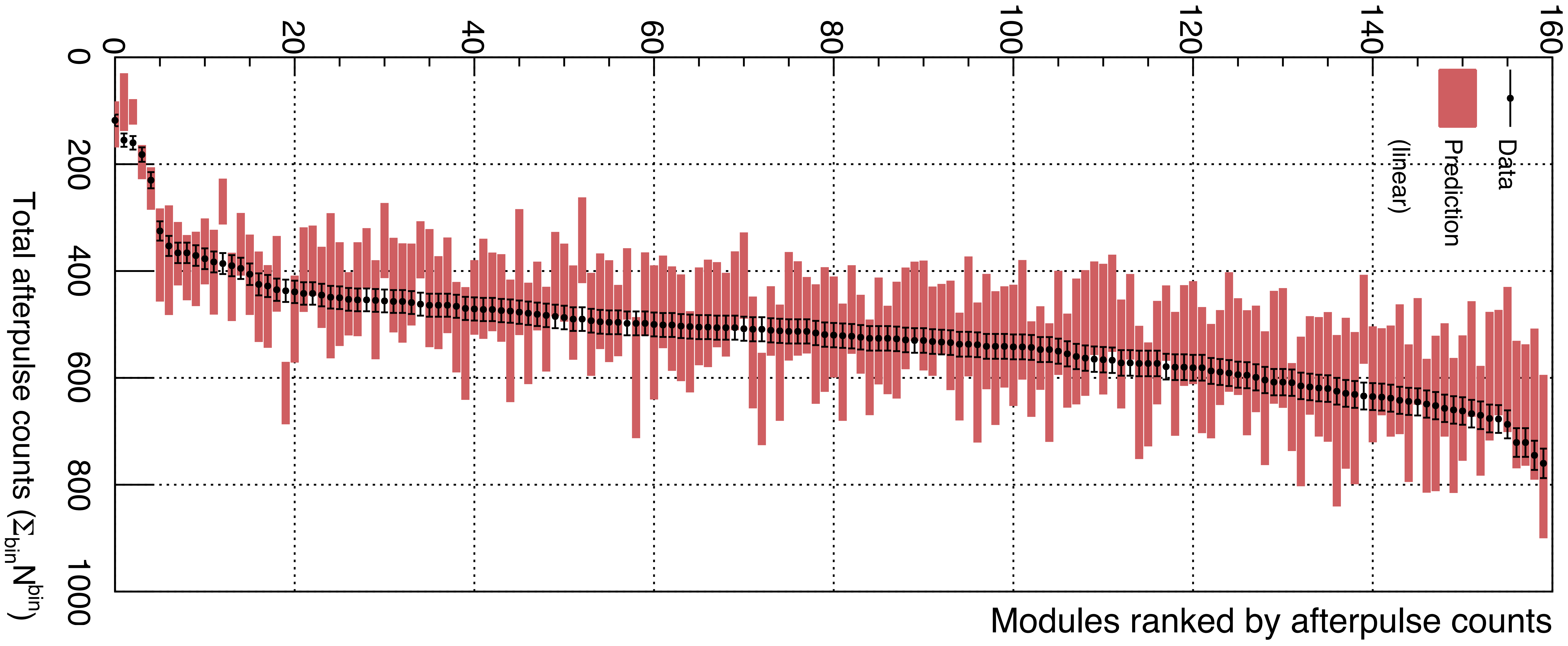
- Constructed a model that predicts the afterpulse counts $R(A, t)$ where t is time of an afterpulse and A is the area of the primary pulse
  - Counts vs. area: ~linear ($p_0 + p_1 A$)
  - Counts vs. t: exponential ($e^{-t/\tau}$)
- Used half of data for estimation of parameters and other half for validation (total $50k$ events)

Afterpulses

PTEP 2026, 033C02



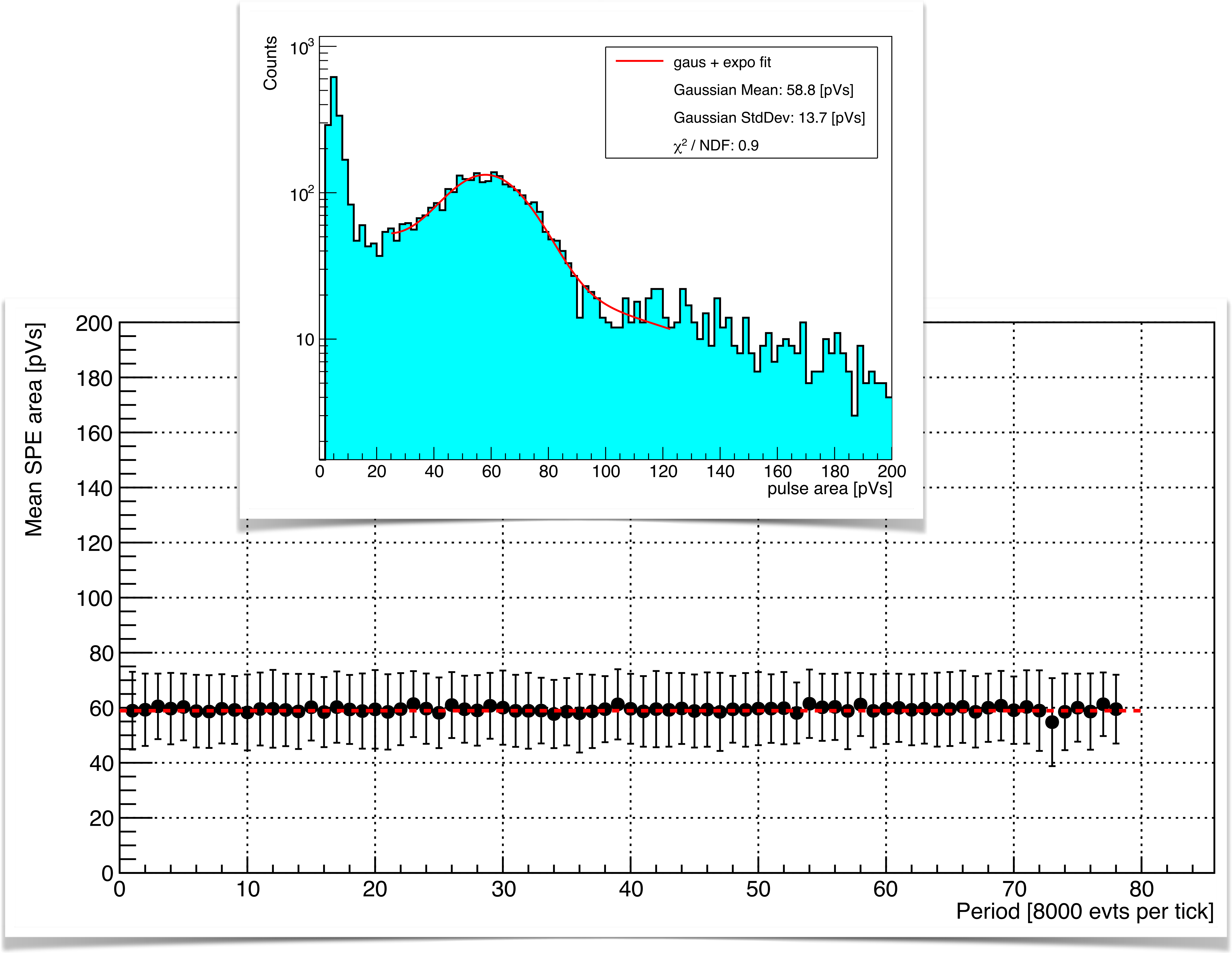
Afterpulse counts vs prediction for one channel



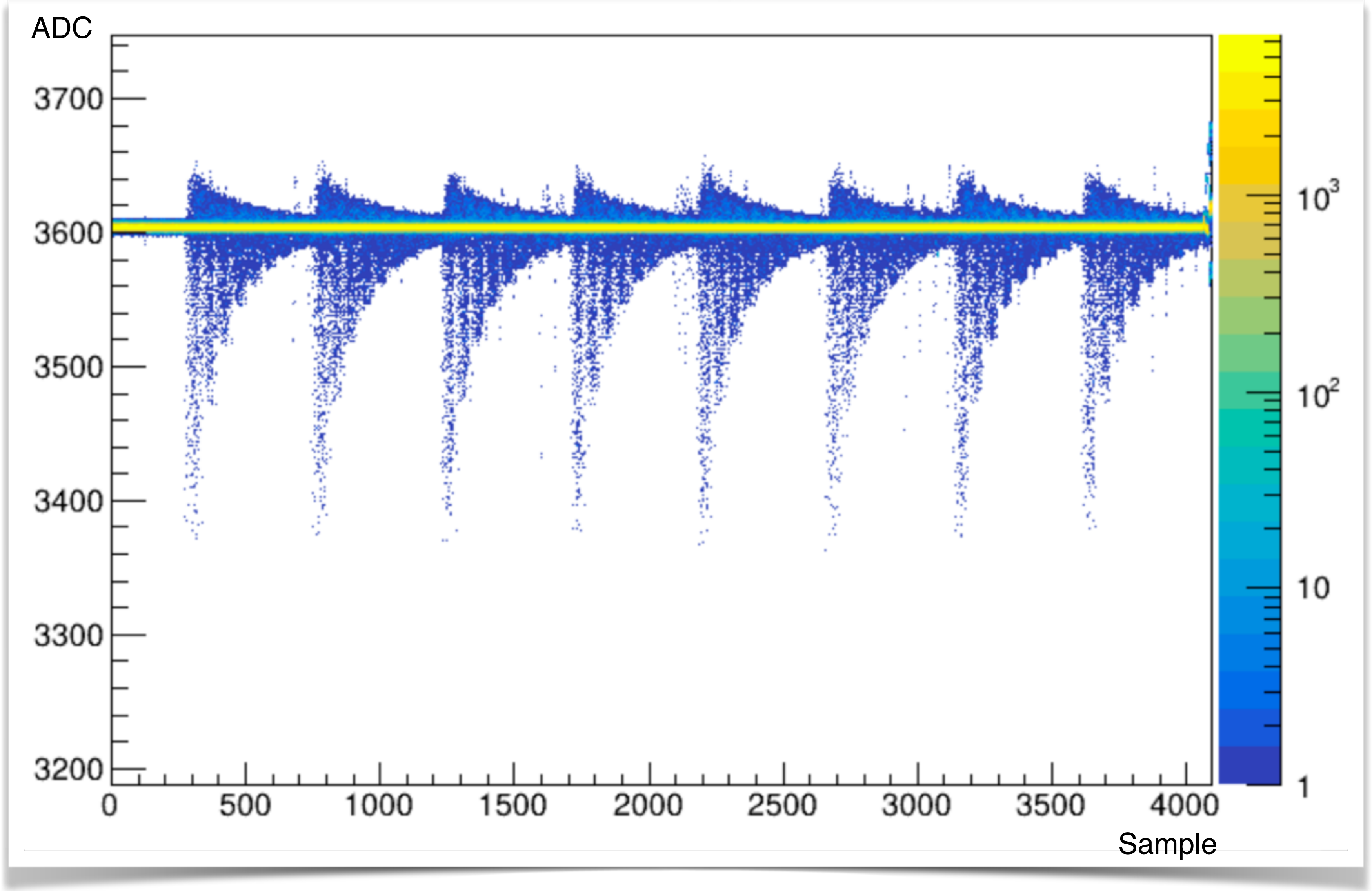
Afterpulse counts vs prediction for all channels (integrated over t)

- Prediction works quite well and can be incorporated in the search analysis

Data certification (2024/06 data)



- One problematic channel with anomalous signals



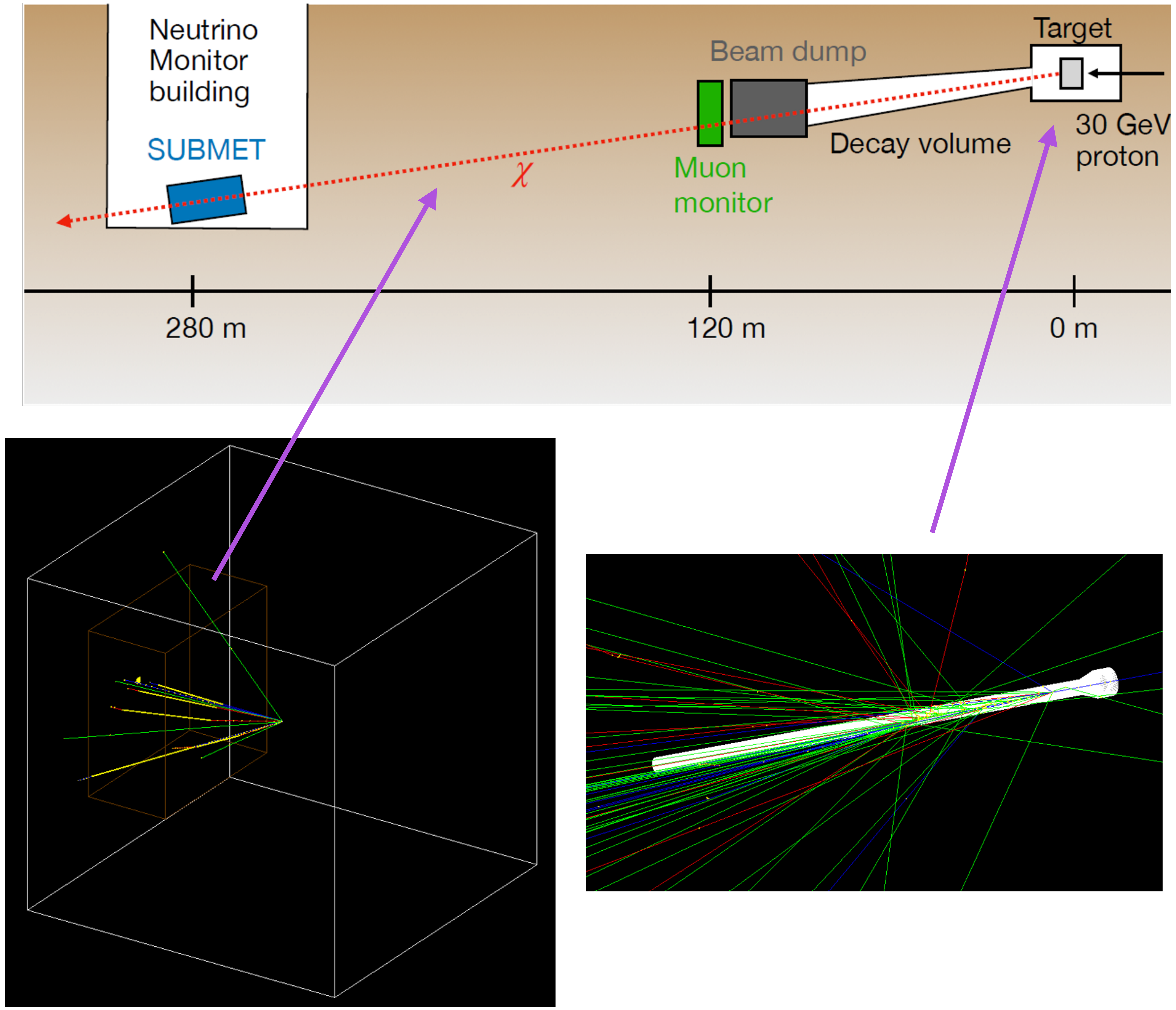
- Gain stability throughout the whole data-taking period (~3 weeks)

Beam-on background prediction

	Aligned	Not aligned
$\Delta t > 30$ ns	**B** 17	**C** 1075
$\Delta t < 30$ ns	**A (signal region)** Pred: 12 ± 3	**D** 776

- Use only the first of the 8 bunches to avoid after pulse contributions
- Event and pulse selection: equivalent to that of beam-off
- $N_{POT} = 1.6 \times 10^{19}$
- Result: $N_{pred} = 12 \pm 3$

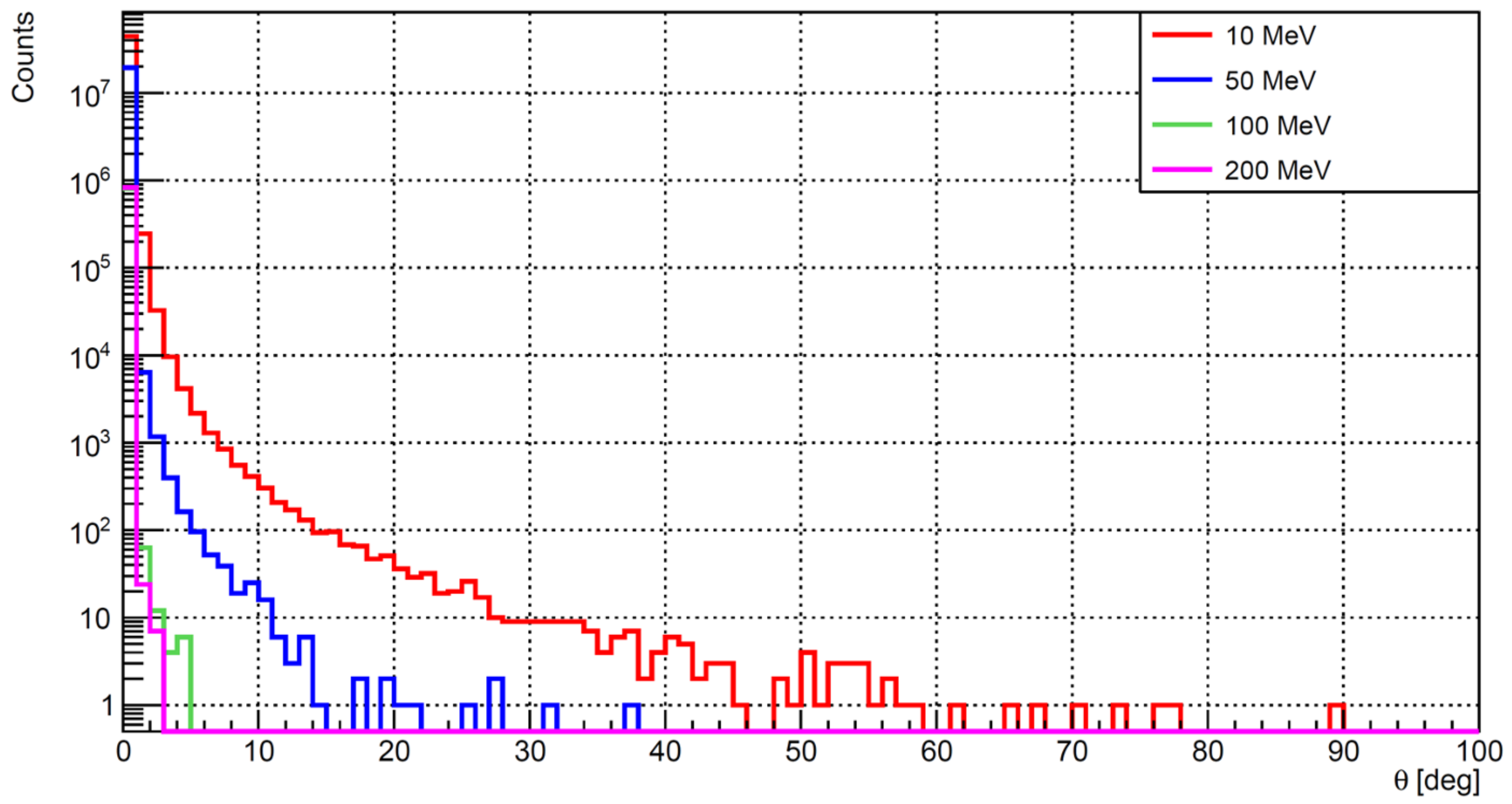
Signal simulation



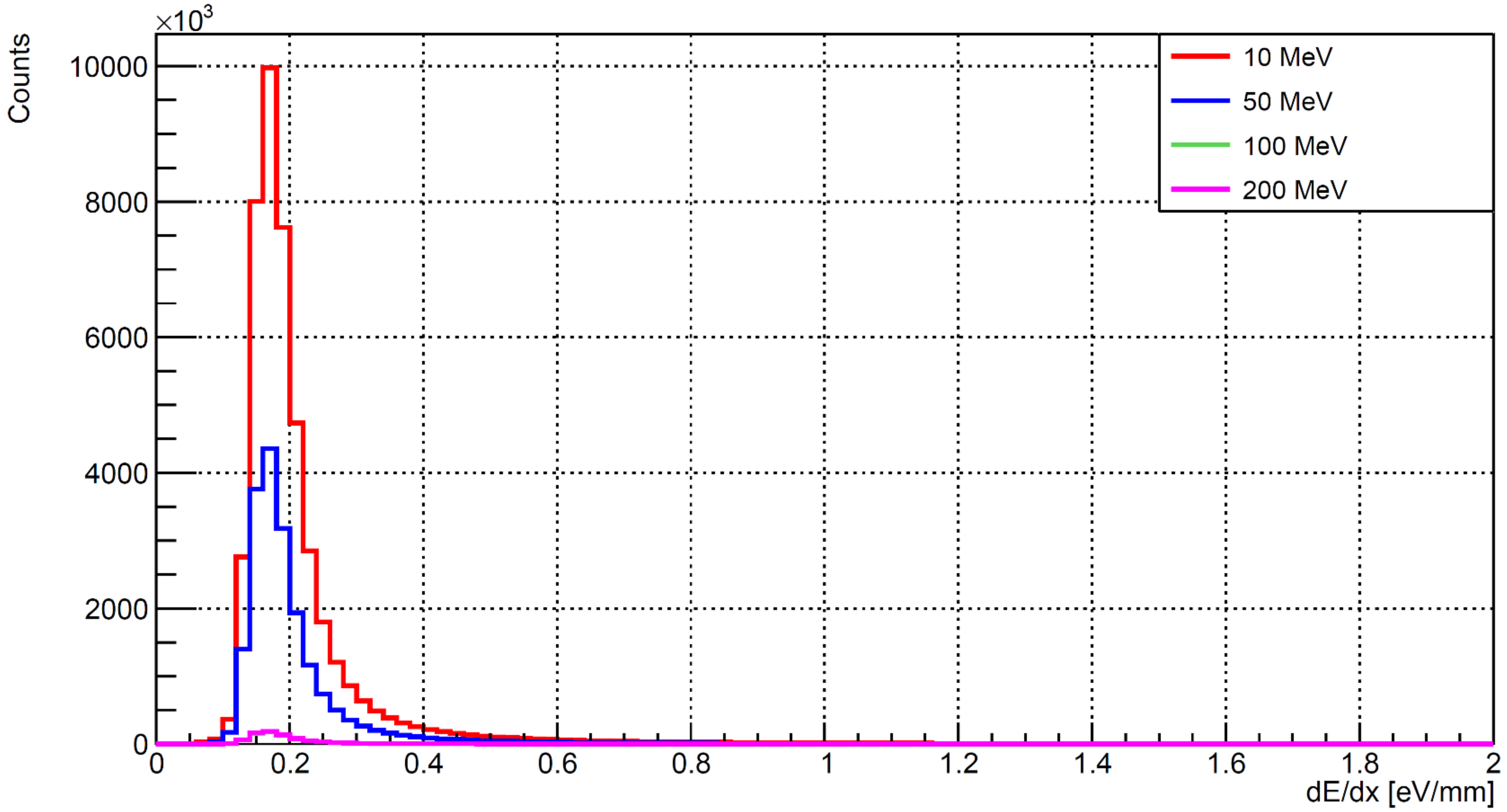
- Signal simulation needed for interpretation
- Meson/χ production by Pythia fed into Geant4
  - Pythia production cross-checked with Geant4
- Simulate Interaction with materials (target, sand, etc) by Geant4
  - Multiple scattering and ionization (+ default Geant4 interactions)

Signal simulation

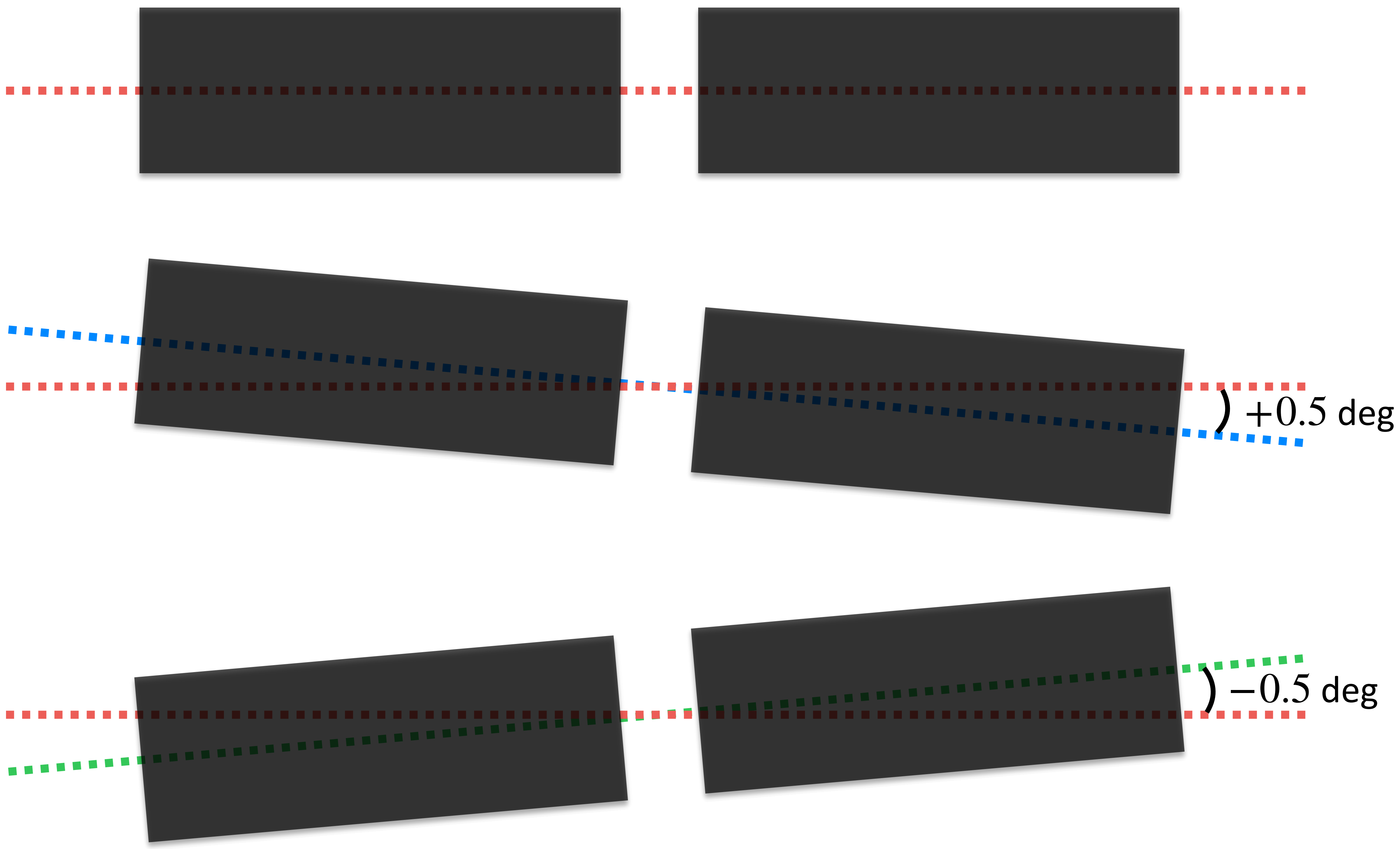
Scattering angle ($Q = 10^{-3}e$)

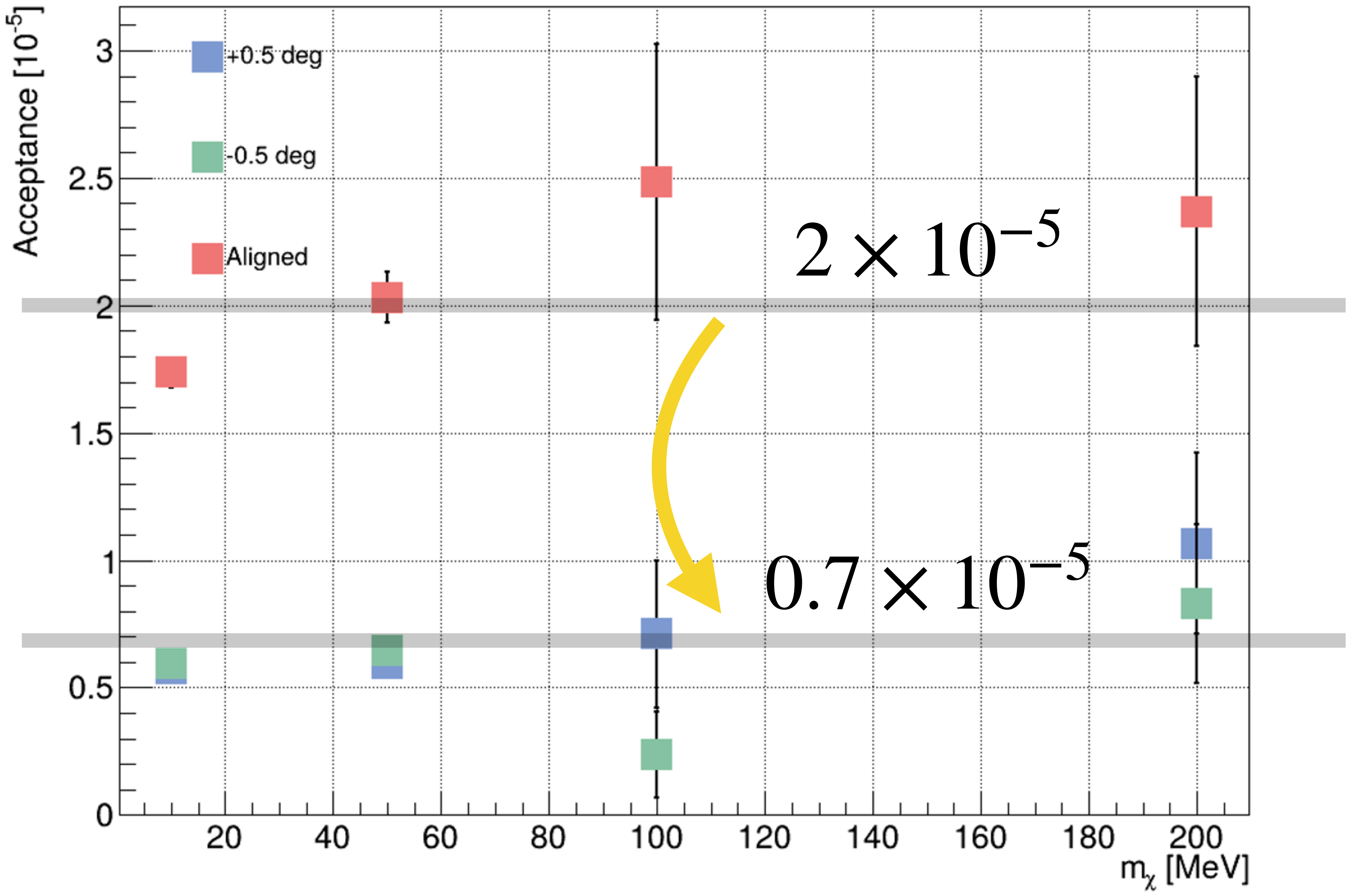


Energy loss ($Q = 10^{-3}e$)



Signal simulation





Estimate geometrical acceptance due to misalignment of the detector by $\pm 0.5^\circ$
(0.5° is very conservative; $< 0.2^\circ$ in reality)

Summary and Plan

- We search for millicharged particles at J-PARC
- Installed detector in summer 2024 and taking data since then
- Established good understanding about detector performance: SPE/charge/time calibration
- Background estimation method validated using beam-off data
- Simulation studies close to completion
- Plan
  - Data-taking until mid 2027 (before HK)
  - First search results this year and the results with full data late 2027 or early 2028
- Expansion of ideas: LANL [PRD 113, 015038 (2026)] and Fermilab/CERN [arxiv:2512.11027]